A Study of the Impact of Traffic Type and Node Mobility on the Performance of an IEEE 802.16 WiMAX

By

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the qualification of any other degree of diploma or a University or other institution of higher learning, except where due acknowledgement is made in the acknowledgements.

James Kangwook Byeon

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12/10/2011

Abstract

Mobile WiMAX is becoming an attractive solution for providing high-speed internet access in a cost-effective way to people living in both sparsely populated rural areas and densely populated urban areas. This popularity is a result of the flexibility, low-cost and user mobility offered by the technology. While WiMAX handoff and quality of service (QoS) provisioning have been explored by many network researchers, the effect of traffic type and node mobility on WiMAX has not been fully investigated yet.

This thesis reports on an empirical study of the impact of traffic type, node mobility and handoff on the performance of a typical mobile WiMAX IEEE 802.16 network. It analyses WiMAX performance for small, medium and large network scenarios under FTP, HTTP, VoIP and Video conferencing traffic with varied node mobility (0~90km/h) through extensive simulation experiments.

It is observed that both FTP and HTTP are satisfactorily transmitted regardless of the volume of traffic on the network. Packet delay of less than one second is maintained regardless of increased node speeds. Packet loss ratios for VoIP and Video conferencing are irregularly high and increase when the traffic volume of the network also increases. Another observation is that average throughput of Video conferencing and m-VoIP is decreased and packet loss ratio is irregularly increased causing loss of connection.

When handoff is allowed, delays in all traffic types are slightly increased, average throughput is fairly increased and packet loss ratio is also fairly decreased. As expected, both FTP and HTTP traffic are transmitted well over WiMAX because they can tolerate a certain amount of delay. However, both m-VoIP and Video conferencing packets were not moderately transmitted over the network due to high packet loss. Finally, the impact of handoff on system performance is also investigated.

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List of Abbreviations

AAA	Authentication, Authorization, Accounting
AMC	Adaptive Modulation and Coding
AP	Access Points
ASN	Access Service Network
ASN_GW	Access Service Network Gateway
BE	Best Effort
BPSK	Binary Phase-shift keying
BS	Base Station
BSs	Base Stations
BW	Bandwidth
BWA	Broadband Wireless Access
CAC	Call Admission Control
CBR	Continuous Bit Rate
CDMA	Code Division Multiple Access
CPE	Customer Premises Equipment
CPS	Common Part Sublayer
CS	Convergence Sublayer
DHCP	Dynamic Host Configuration Protocol
DL	Downlink
DSL	Digital Subscriber Line
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction

FTP	File Transfer Protocol
FFT	Fast Fourier Transform
HARQ	Hybrid Automatic Repeat Request
HSPA	High Speed Packet Access
HTTP	Hyper Text Transfer Protocol
ICI	Interface Control Information
I/Q	In-phase / Quadrature
IEEE	Institute of Electrical and Electronic Engineers
IP	Internet Protocol
LOS	Line-Of-Sight
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MOS	Mean Opinion Score
MS	Mobile Station
NLOS	No-Line-Of-Sight
NS	Node Speed
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDV	Packet Delay Variation
PER	Packet-Error-Ratio
PHY	Physical Layer
PMP	Point-to Multipoint

PP	Point-to-Point
QAM	Quadrature Amplitude Modulation
QoS	Quality Of Service
QPSK	Quadrature Phase Shift Keying
RSVP	Resource Reservation Protocol
SeS	Security Sublayer
SINR	Signal-to-Interference-and-Noise-Ratio
SNR	Signal-to-Noise-Ratio
SS	Subscriber Station
TCP	Transfer Control Protocol
UDP	User Datagram Protocol
UL	Uplink
VOD	Video on Demand
UGS	Unsolicited Grant Service
Videocon	Video conferencing
VoIP	Voice over internet protocol
WiBro	Wireless Broadband
Wi-Fi	Wireless Fidelity
WIMAX	Worldwide Interpretability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network

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Chapter 1

Introduction

World Interoperability for Microwave Access (WiMAX) is an emerging and exciting wireless technology that can support a variety of business and consumer applications, from network backhauling and interconnecting with Wi-Fi and LANs, to voice, audio, data and mobility support[3]. Mobile WiMAX may change the way people access data, e-mail, audio and video communication services as it provides a faster transmission speed than 3G, broader coverage than Wi-Fi and higher mobility than LAN [3]. According to articles related to WiMAX, mobile WiMAX can provide services up to a mobile speed of 120km/h at 3.8GHz bandwidth. By adopting a scalable PHY architecture and OFDMA, mobile WiMAX is able to support a wide range of bandwidths (1.25MHz to 20MHz) and coverage (12~15km in LOS) [10].

Accordingly, performance of mobile WiMAX is reviewed and reported by numerous researchers [2, 7-10]. However, most researchers have focused on WiMAX performance studies based on QoS or handoff. Therefore, diverse traffic types or node speeds are not seriously considered in their studies. However, users do not normally use a single application and do not move at the same speed all day long. Experimental results may change depending on which type of applications are used and how fast nodes move as applications characteristics differ and user speed is undefined and random.

This thesis investigates how mobile WiMAX performs in various network conditions and how this performance changes due to traffic type and node mobility. Therefore, this thesis does not evaluate the technical aspects of mobile WiMAX such as MCS and handoff. To provide realistic results for end users, diverse traffic types (FTP, HTTP, VoIP, and Video conferencing) that are frequently used on wireless networks and diverse node movement speeds(0~90km/h) are also used in the experiments. The impact of traffic type on system performance has been explored by increasing the size of the network and impact of the node mobility on system performance has been investigated by increasing speed of nodes. By comparing each application`s throughput and packet loss ratio changes by handoff, the effect of handoff on system performance was also investigated.

1.1 Research Objective

The main objective of this thesis is to investigate the impact of traffic type and node mobility on the performance of a mobile WiMAX network.

To achieve the objective, the following key parameters have been considered in the empirical study.

- Traffic type: FTP, HTTP, VoIP and Video conferencing.
- Traffic load: Light, medium and heavy traffic loads.
- Node density: 10, 25, 50, 75 and 100 nodes in one cell (2km x2km).
- Node mobility: 0, 10, 30, 50, 70 and 90 km/h.

From the literature review, four frequently used traffic types were selected. Additionally, in order to conduct various experiments traffic load size is categorized into three groups, the number of nodes in one cell and the node speed are segmented and categorized.

In this thesis, an empirical investigation of the traffic type and node mobility influencing system performance is presented. The primary research questions for this research were to investigate:

- The impact of increasing network size on system performance.
- The impact of increasing node speed on system performance
- The impact of handoff on mobile WiMAX.

1.2 Thesis organization

Chapter 2 provides an overview of WiMAX (IEEE 802.16) standards. Advanced features of mobile WiMAX are discussed along with other wireless network technologies such as Wi-Fi and WiBRo. Chapter 3 reviews relevant literature on performance evaluation of mobile WiMAX. Chapter 4 discusses the research methodologies adopted in this thesis. The strengths and weaknesses of analytical modelling, test bed and computer simulation methodologies are highlighted. The characteristics and suitability of OPNET Modeler, which is used as a network modelling and performance evaluation tool are also discussed. Chapter 5 describes the performance metrics used in this thesis. General parameters and configurations of Mobile Stations (MS) and Base Stations (BS) are also highlighted. Details of nine experimental scenarios are discussed. Experimental results are presented in Chapter 6. Chapter 7 concludes the thesis by summarising the research findings.

Chapter 2

WiMAX and IEEE 802.16

2.1 Introduction

Chapter 1 outlined the motivations for a performance evaluation of mobile WiMAX with various traffic types and node mobility. A primary objective of this thesis is to measure and evaluate the impact of traffic type and node mobility on the performance of mobile WiMAX. To achieve this objective, a general understanding of Mobile WiMAX is required. Accordingly, this chapter aims to provide an introduction to the various features of mobile WiMAX needed for the experiment design and performance evaluation.

Section 2.2 outlines the development and properties of the IEEE 802.16, a, d, e standards. Section2.3 presents the advanced features of Mobile WiMAX technology that may influence its performance such as Orthogonal Frequency Division Multiplexing (OFDM), Orthogonal Frequency Division Multiple Access (OFDMA), handoff, mobile IP, Multiple Input and Multiple Output (MIMO) and network architecture. Section 2.4 discusses other issues related to Mobile WiMAX in terms of power saving functionality. Section 2.5 provides comparisons with other wireless and wired broadband technologies. Finally, the chapter is summarised in Section 2.6.

2.2 Overview of IEEE 802.16 and WiMAX

2.2.1 IEEE 802.16 standard family

Table2.1. Characteristics of IEEE 802.16 standards

Types	802.16	802.16a	802.16d	802.16e
Frequency Band[GHz]	10-66	2-11	2-11 for fixed	2-11 for fixed 2-6 for mobile
Channel Bandwidths	20, 25, 28 MHz	20, 25, 28 MHz	1.75, 3.5,7, 14, 1.25, 5,10,15,8.75 MHz	
LOS/NLOS	*LOS	*NLOS	Fixed NLOS	Fixed and mobile NLOS
Duplex	*TDD/FDD	TDD/FDD	TDD/FDD	TDD/FDD
MAC Architecture	*PP	*PMP		
Modulation	*BPSK, *QPSK,*16QAM,*64QAM	*OFDM, 256BPSK,QPSK, 16QAM,64QAM		
Mobility	Not supported			Supported
PHY Operation	*SC	SC, SCa, OFMA,OFDMA		
Time of Completion	Completed in 2001	2003	2004	2005

*SC: Single Carrier, *LOS: Light of Sight, *NLOS: Non-Light of Sight, *PP: Point to Point, *PMP: Point to multipoint, *TDD: Time Division Duplexing, *FDD: Frequency Division Duplexing, *BPSK: Binary Phase Shift Keying, *QPSK: Quadrature Phase Shift Keying, *QAM: Quadrature Amplitude Modulation, *OFDM: Orthogonal Frequency Division Multiplexing * OFDMA Orthogonal Frequency-Division Multiple Access

2.2.2 IEEE 802.16

The IEEE 802.16 group was formed in 1998 to develop an air interface standard for Broadband Wireless Access (BWA) and to support the development and deployment of a wireless Metropolitan Area Network (MAN) [3]. The IEEE 802.16 standard supports air-interface for 10-60GHz also known as a Local Multipoint Distribution Service. It was released in late 2001 and became a standard for Point to Multipoint (PMP) wireless broadband transmission in the 10-66GHz band, with Line of Sight (LOS) functionality.

IEEE802.16 provides a single carrier (SC) physical standard (PHY). The aim of the IEEE 802.16 group was primarily to address wireless technology application to link commercial and residential buildings to high-rate core networks and thereby provide access to those networks. This link was called “last mile”. The initial standard IEEE802.16 has adapted many concepts from the cable modem Data Over Cable Service Interface Specification (DOCSIS) standard related to the Media Access Control (MAC) layer[3] and thereby the 802.16 has evolved through several conceptual updates to standards such as 802.16a, 802.16b, 802.16c, 802.16d (Fixed WiMAX) and 802.16e(Mobile WiMAX). The first update (802.16 to 802.16a) added a wide range of spectrum (2GHz to 11GHz) with NLOS. Each subsequent update added a new functionality to and enhancement of existing features, such as scheduling of quality of Service (QoS) and FEC (Forward Error Correction) in the MAC layer.

2.2.3 IEEE 802.16a

IEEE 802.16a is an amendment to the standard of wireless communications specification for a Metropolitan Area Network (MAN). IEEE 802.16a was certified in early 2003 and released in mid 2003[11].

The IEEE802.16a standard complements the older IEEE802.11 (Wi-Fi). Interestingly, IEEE802.16a was started to support Non-Light-Of-Sight (NLOS) in the 2-11GHz band instead of Light-Of-Sight (LOS) in 2-66GHz band. The significant difference between these two frequency bands lies in the ability to support NLOS operation in the lower frequencies, something that is not possible in the higher frequency band[12].

Additionally, three new PHY-layer specifications have been introduced (A new Single Carrier (SCa), 256 point FFT OFDM and 2048point FFT OFDM PHY). Orthogonal Frequency Division Multiple Access (OFDMA) and forward error correction (FEC) were also added in the MAC-layer to improve the performance of WiMAX. Consequently, IEEE 802.16a facilitates the transmission for advanced communication applications such as Voice over IP (VoIP) and Video on Demand (VoD) as both require low jitter and delay.

2.2.4 IEEE 802.16d

IEEE802.16d was the first practical standard of the IEEE 802.16 standards group and it is often called Fixed WiMAX. IEEE 802.16d standard was released in October 2004 and replaced all previous versions of the IEEE 802.16 standards[8, 13]. IEEE 802.16d has integrated and re-edited the previous versions' PHY and MAC layers in order to improve system performance (bandwidth). Although IEEE 802.16d supports fixed access, the actual application supports limited mobility. Limited mobility means that the user device can move as long as it does not operate while doing so. Accordingly, subscribers can access the service network from various locations where network signal is available.

IEEE802.16d is often used for small network for stationary clients. Accordingly, no connections handoffs between base stations are needed. Therefore, each cell can act as a little network of its own. The complete edition of IEEE 802.16d was approved in December 2004[13].

2.2.5 IEEE 802.16e

The IEEE Group completed and approved the IEEE 802.16e in December 2005, as an amendment to the IEEE 802.16d standard. IEEE 802.16e is often referred to as “Mobile WiMAX”. Mobile WiMAX creates a new market for mobile broadband services[1]. To enable users to move from one cell site area to another the introduction of seamless handoff and a roaming scheme would be needed. Moreover, added 2048 FFT modes facilitate a Scalable OFDMA(S-OFMA) which can support various FFT sizes to address variable bandwidth from1.25 to 20MHz. In addition, S-OFDMA optimises the efficient use of network resources.

The IEEE 802.16e is an interesting technology that delivers carrier classes, high speed and wireless broadband at a much lower cost than cellular and provides much greater coverage than Wi-Fi[14, 15]. Mobile WiMAX does not provide significant improvement in speed, throughput or capacity. However, it provides stable mobile services to portable end user devices, such as laptops and smart phones.

2.3 Features of mobile WiMAX

This section provides details of the added features of mobile WiMAX which may play a role in mobile WiMAX operation.

2.3.1 Mobile IP

"Mobile IP is a protocol to be used with the existing internet to allow a user terminal to be attached at a different point from its home network" [16]. When a user moves from one base station to another (handoff), the mobile WiMAX provides a physical and MAC layer connection via the new base station. This would be processed via a CSN (Connectivity Service Network).

"Mobile IP is an IETF solution, which is designed for conservation of the mobility of receiver transparent to the application by being able to correlate any new IP address of the mobile station with the old IP address as known to the application" [17].

Therefore, mobile IP is one of the key solutions to ensure that streaming remains connected whenever user moves from BS in ASN/CSN to another a BS in a ASN/CSN (handoff). We will use mobile IP in handoff experiments to reduce handoff delay.

2.3.2 The Physical Layer

IEEE 802.16e in a physical layer uses scalable OFDMA to carry data and supports channel bandwidths from 1.25MHz to 20MHz with up to 2048 subscribers [18].

Moreover, various types of adaptive Modulation and Coding Scheme (MCS) can be implemented in the PHY. Normally, the highly effective 64 Quadrature Amplitude Modulation (QAM) coding scheme which is also very complex is often used when throughput is considered to be more important than coverage area. When the signal is poor, more burst BPSK coding schemes are often preferred as they are light and simple. Schemes such as 16 QAM and Quadrature Phase Shift Keying (QPSK) can be employed and are often used under normal conditions. In the node mobility experiment, QPSK is used as the default.

Multiple In Multiple Out (MIMO) was invented to provide good throughput in NLOS environments and Hybrid Automatic Repeat Request (HARQ) will be used for good error correction performance in the PHY layer[18, 19].

2.3.3 The Media Access Control Layer

IEEE 802.16e has three MAC sublayers: the Convergence Sublayer (CS), the Common Part Sublayer (CPS) and the Security Sublayer (SeS).

Convergence Sublayer (CS)

The CS`s aim is to enable 802.16e to better accommodate the higher layer protocols placed above the MAC layer. CS classifies frames that are received from the higher layer and then compresses the payload header before passing the frames to the MAC CPS. If the peer CS has performed any type of processing, the receiving CS will temporarily store the data frame before passing it to a higher layer [19].

Common Part Sublayer (CPS)

The CPS manages common functions, such as network entry and initialization, duplexing, framing, channel access and QoS in the MAC layer.

Security Sublayer (SeS)

The SeS provides privacy and strong protections against attacks to the users throughout the wireless network. SeS is used to store information about how transmission is secured by using secure key exchange during authentication and which encryption tool is used during data transfer[19].

2.3.4 Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) is an advanced form of Frequency Division Multiplexing (FDM) where the multiplexed frequencies are orthogonal to each other and their spectra overlap with the neighbouring carriers. The significant difference between OFDM and FMD is the overlapping as shown in Fig. 2.1 [3].

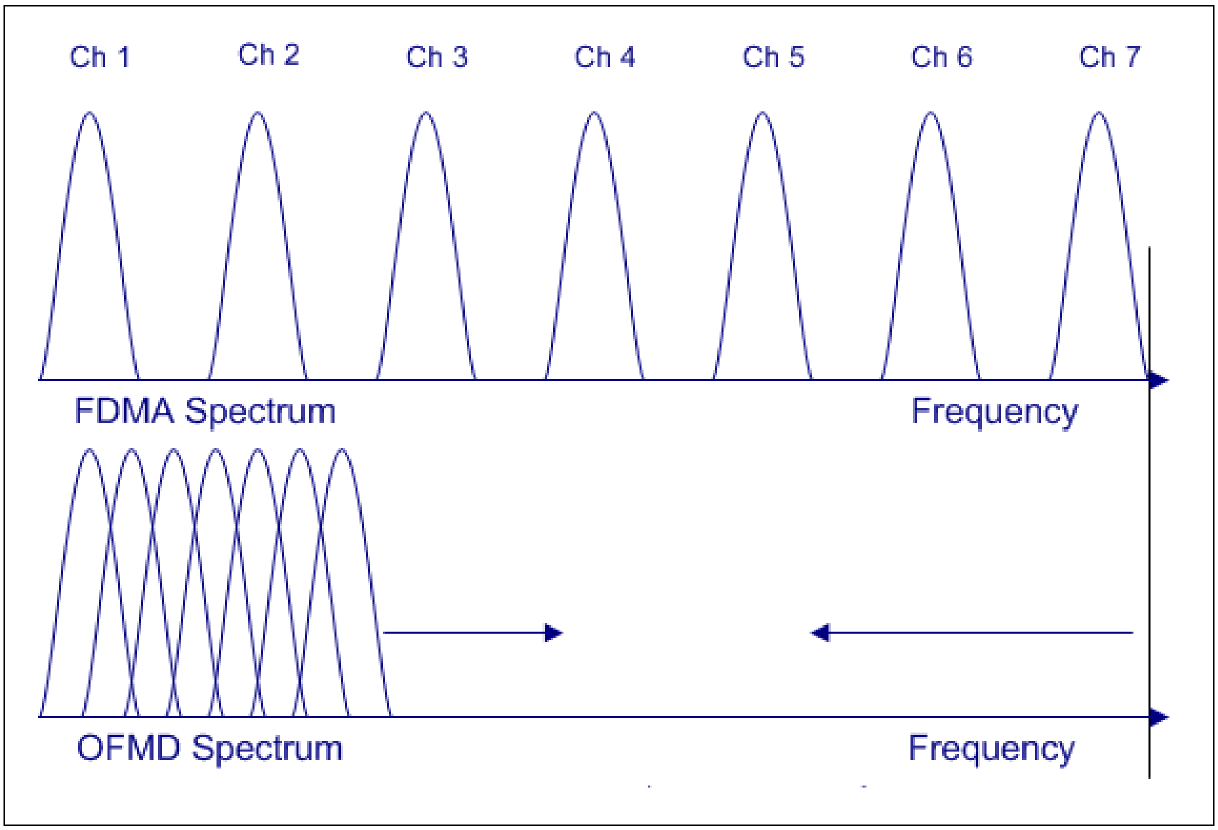

Figure2.1. Comparison between FDMA and OFMA spectra [3].

In FDM, carriers are spaced apart. Signals are received using conventional filters and demodulators resulting into reduced spectral efficiency[20].

However, in OFDM, the sideband of the individual subcarriers overlap and the signals are still received without adjacent carrier interference, hence each of the radio streams experience almost flat fading channel. This is the major advantage of OFMD in mobile WiMAX. Accordingly, Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI) are avoided with a small loss of energy using a cyclic prefix in a slowly-fading channel. Moreover, an orthogonally overlapping transmitting spectrum is essential in order to ensure the high speed spectral efficiency of the sub channel waveforms. This is because the orthogonality allows the transmission of signals over a common channel without interference[21]. An absence of orthogonality results in a wobble between transmitted signals and loss of information[3]. In an OFDM signal, the peak point of one subcarrier coincides with the nulls of the other subcarriers, and therefore no extensive interference occurs even though spectrums overlap.

2.3.5 Orthogonal Frequency Division Multiple Access (OFDMA)

The IEEE 802.16 group decided that the 256 OFDM should be left out of the IEEE 802.16e standard. Instead, it was decided to add OFDMA. In the OFDM physical layer, users transmit and receive packet one after another using all available sub-channels. Conversely, OFDMA allows users to transmit and receive data simultaneously in different sets of sub channels, and thereby link usage efficiency is significantly increased to a corresponding degree. In addition, OFDMA facilitates MIMO (Multiple Input and Multiple Output).

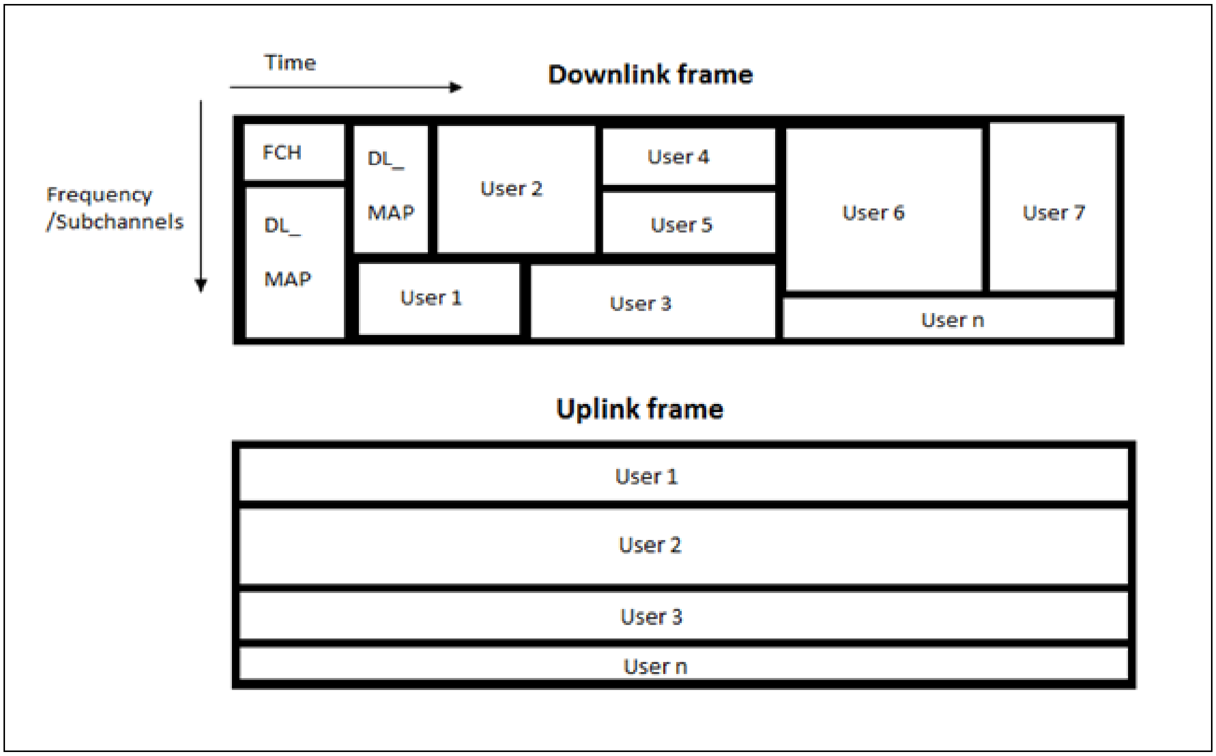

Figure2.2. OFDMA sub channelization in the uplink and downlink direction format [22]

2.3.6 MIMO (Multiple Input and Multiple Output)

The IEEE802.16e standard adapted the MIMO algorithm to further increase transmission efficiency for the network and client devices. MIMO provides significant increases in data transmission rates and link coverage by using multiple antennas that can process more bits per second with reduced fading problem (diversity). Mathematically, more antennas can process more data than a single antenna.

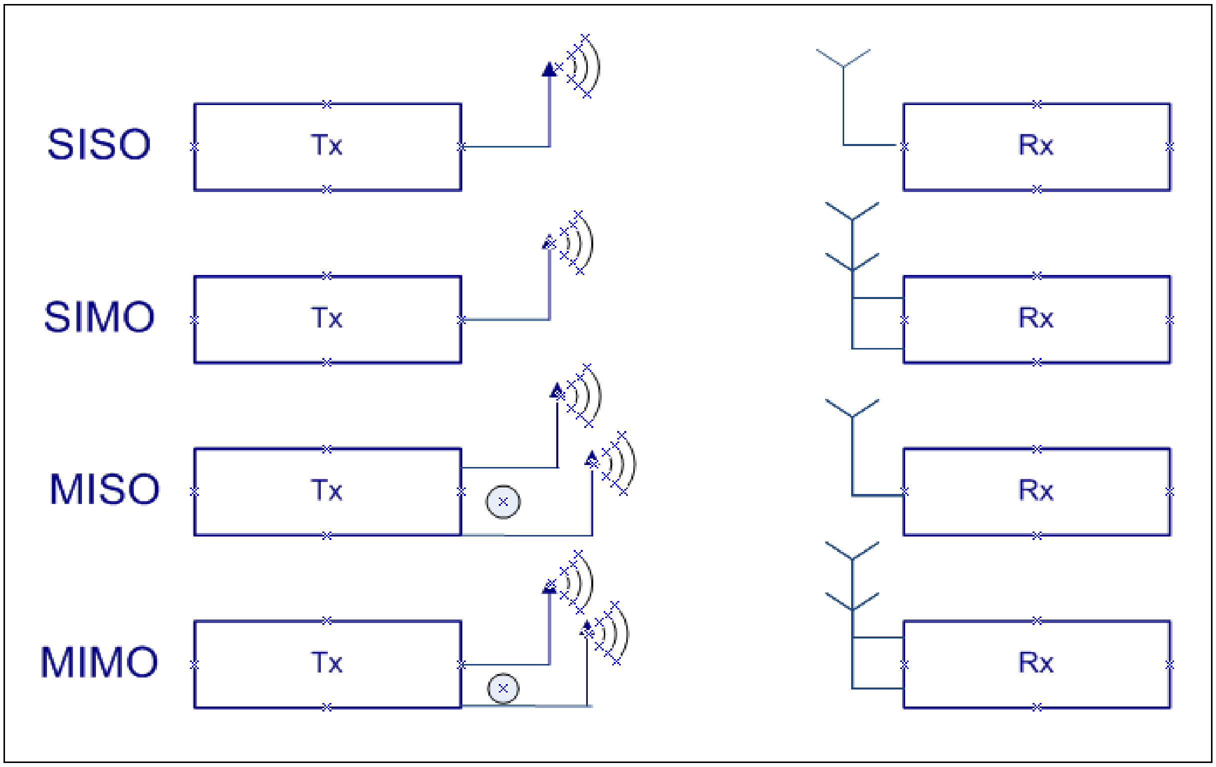

Figure2.3. Diagrams of SISO, SIMO, MISO and MIMO diagrams [18]

MIMO uses dedicated multiple antennas. These antennas are located on both the receiver (multiple inputs) and transmitter (multiple outputs) to send data on various channels with the same frequency [22].

Typical MIMO systems make use of two or four paths which requires two or four antennas respectively. Accordingly, two such antennas are required when four individual data streams need to be sent on the same frequency and must be separated in space by at least a quarter of a wavelength[23]. Moreover, MIMO can augment the overall bandwidth of base stations by using HARQ (Hybrid Automatic Repeat Request), AMC (Adaptive Modulation and Coding) and AAS (Adaptive Antenna Systems)[18, 22].

2.3.7 Line-Of-Sight / Non-Line-Of-Sight

A wireless communication system is often described as being either LOS or NLOS.

Line of Sight (LOS) is when a signal travels directly over an air path from the transmitter to a wireless signal receiver without passing obstructions; hence the signals can reach longer distances with better signal strength and higher throughput [24].

Non Line of Sight (NLOS) is a condition where a signal passes several obstructions from the transmitter to a wireless signal receiver. In the transmitting of a signal, It may be reflected, refracted, diffracted, absorbed or scattered, so multiple signals could be made and these signals would be arriving at a receiver at different times, via different paths and with different signal strength [15, 24].

NLOS is closer to a real wireless network environment than LOS. Consequently, WiMAX technology has developed advanced techniques for overcoming critical problems arising from NLOS conditions. To the end, WiMAX can transmit data in NLOS conditions without losing a significant number of packets and without much delay by using advanced features such as OFDM, Sub-channelization, Adaptive Modulation Coding (AMC) and AAS. MIMO are also used in WiMAX to make it perform better in NLOS conditions. Sub-channelization empowers transmission of sub-channels to reach further distances. AMC adjusts the code rate while modulation is based on each sub-channel`s condition and MIMO helps to improve signal strength and throughput. These added features provide a quality transmission in NLOS conditions.

2.3.8 Handoff

"The handoff is a process during which a mobile station (MS) immigrates from air interfaces for its current BS to air-interfaces of adjacent BS. Handoff is an important process of mobility support in wireless network"[3].

Handoff is unavoidably incurred when a cell is overloaded or a MS moves out of a BS`s signal coverage. Therefore, mobile WiMAX allows both the MS and the network are allowed to do initial handoff like a 3G cell network where the network is always responsible for initiating a handoff[25]. Four typical handoff types are explained below: hard handoff, soft handoff, vertical handoff and horizontal handoff.

Hard handoff

The principle of hard handoff is that the MS discontinues the communication to the serving BS and then makes a new transition to the target BS. The MS has to register with target the BS before starting to communicate with it. Hard handoff is often referred to as a "Break before make handoff" and it is the most commonly used handoff type.

Soft handoff

The principle of Soft handoff is opposite to that of hard handoff. In soft handoff, a MS keeps communicating with both the serving and target BSs, until registration with the target BS is complete, so it is often referred as "Make before Break". Moreover, as the MS is connected throughput the handoff process, handoff is more robust against shading and fast fading. However, overload for handoff increases at the same time. Soft handoff is often used where stability or upper-layer application performance is of great importance.

Vertical handoff

Vertical handoff is often used where the BS is attached to different network technologies such as, Wi-Fi and WiMAX. This arrangement is often called a heterogeneous network. Vertical handoff can be either soft or hard handoff. Soft handoff is more complex and requires more collaboration between different components in the network than hard handoff and thereby hard handoff is usually used with vertical handoff.

Horizontal handoff

Horizontal handoff is used where handoff takes place between BSs within the same type of network technology. This arrangement is often called a homogenous network. The horizontal handoff can also be either soft or hand. In horizontal handoff, soft handoff is more commonly used, because collaboration between components in the same type of network can be more easily achieved.

In this thesis, we will observe the handoff between two BSs, where vertical handoff does not apply. Therefore, mainly hard handoff will be used and soft handoff will be used for VoIP and Video conferencing traffic as they require seamless handoff.

2.3.9 Mobility

Mobility was not seriously considered up to IEEE 802.16d which is the fourth version of IEEE 802.16. Mobility has been considered since the introduction of IEEE 802.16e in 2005. Indeed, IEEE 802.16d partially supports mobility (roaming only) where BS moves belong to the coverage area. Theoretically mobility in 802.16e is guaranteed for a vehicle driving at speed (120km/h) within a nomadic roaming area (12~15km LOS)[26].

Indeed, mobile WiMAX does not provide a transmission speed higher than that in a LAN. However, users may be tolerant of a slower transmission speed when they are provided with mobility, something that LAN cannot provide. Therefore, how mobility influences system performance or how well a system works while providing mobility will be undoubtedly be investigated in this thesis.

In addition, several practical challenges are highlighted below. However, investigating some of these challenges is beyond the scope of this thesis and will be left for future study.

- Scalability – roaming from one access network to any other access network (Wi-Fi, Ethernet and WiBro).
- Standard handoff interfaces – interoperability between different vendor equipment.
- Cross-layer solutions – extensions to layer 1 and 2 functionalities in order to optimize higher layer mobility architecture (MIPv4, MIPv6, SIP)
- QoS guarantee during handoff – no disruption to user traffic: extreme low latency, signalling messages overhead and processing time, resources and routes setup delay, near-zero handoff failures and packet loss rate
- Security – user maintains the same level of security when roaming across different access networks.

2.3.10 802.16 Mesh Network Operations

Coverage area of a single BS is limited to a radius of two to five kilometres around the BS. This is similar to the coverage areas of other systems like UMTS and HDSPA [22, 25]. The coverage area of a BS can be smaller in urban areas or under NLOS conditions. Coverage areas can be larger if using directional antenna for subscribers in LOS condition, but at this is not practical, hence mesh network was introduced. The principle of operation behind mesh networks is that not all BSs communicate with all other BSs. Distant subscriber stations communicate with nearest neighbouring subscriber stations which forward data packets to a BS or another neighbouring station, if they are too far away from the BS themselves [27, 28].

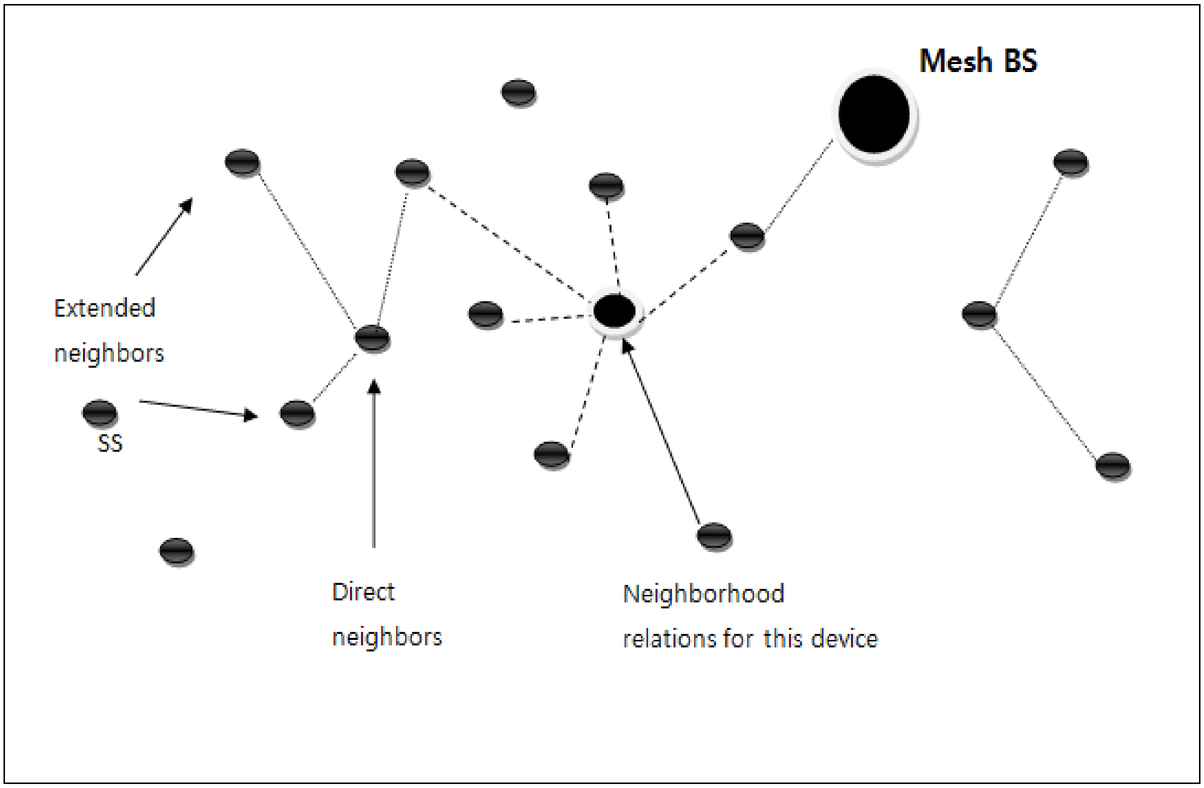

Figure2.4. Diagram for 802.16 mesh network architecture and operations

A mesh network allows the coverage area of an IEEE 802.16 network to be extended. Mobile Station (MS) independently send a broadcast message to all stations to find neighbouring stations. The broadcasting message contains information about the number of hops to the closest BS.

To avoid congestion due to simultaneous transmissions in a neighbourhood, only one station is allowed to send a packet at a time. Due to this constraint, three scheduling algorithms are commonly used: Distributed scheduling, Mesh-based Station scheduling, a

Combination of Distributed and Mesh based[28]. Distributed scheduling is self organized among the subscriber stations and a ‘requesting a grant’ scheme is used to reduce simultaneous transmission.

Mesh-based scheduling comprehends the scheduling pattern by using the available bandwidth and delay of each subscriber station in the same network. Therefore, the scheduling pattern is shared with all MSs in the same network. The combination algorithm allows a combination of distributed scheduling and mesh-base station scheduling [22].

2.3.11 Mobile WiMAX Network Architecture

The typical architecture of WiMAX is comprised of an Access Service Network (ASN). The ASN is also connected to external networks via an Access Service Network Gateway (ASN_GW) as shown in Fig.2.5.

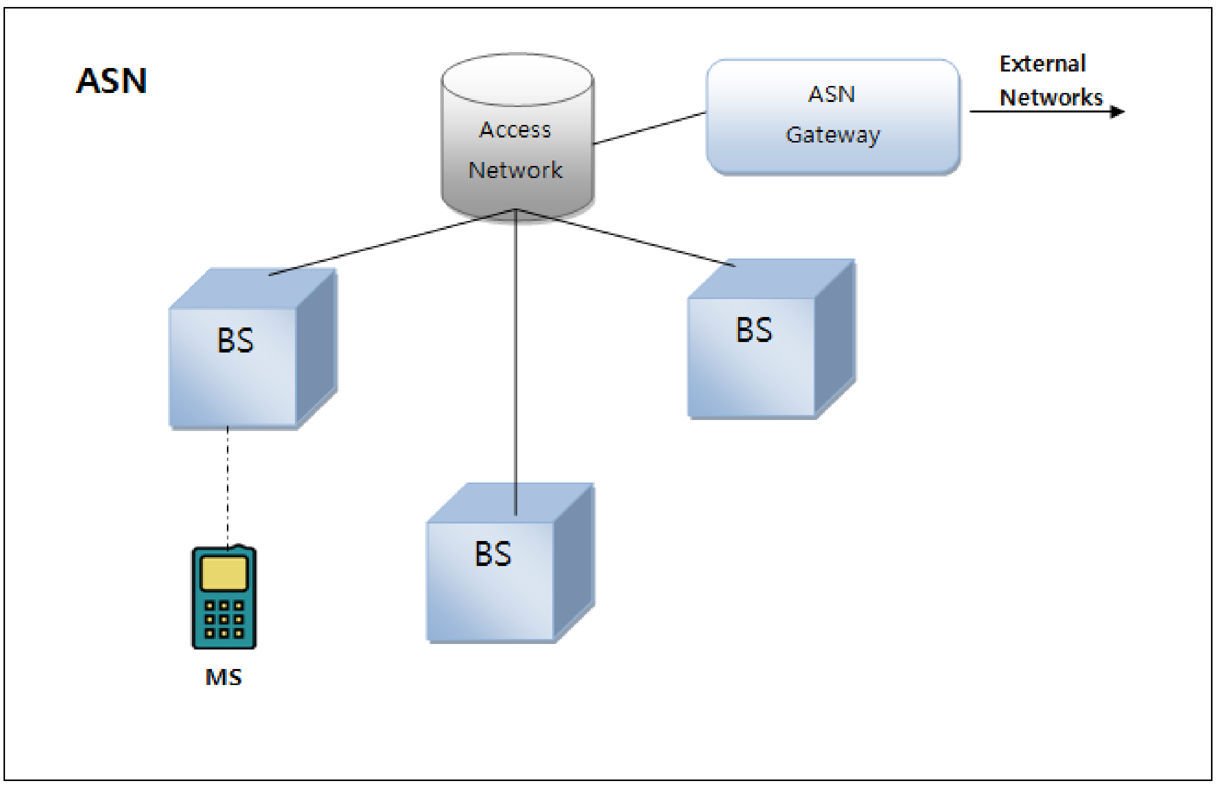

Figure2.5. A diagram of Access Service Network Topology(ASN) [17]

The BS provides DHCP proxy and maintains its status with MSs (idle or active). The BS provides QoS and traffic scheduling to the MS. The ASN_GW is the location where all packets from the BSs congregate for interface with external networks. ASN_GW also perform QoS management and AAA functionality[29].

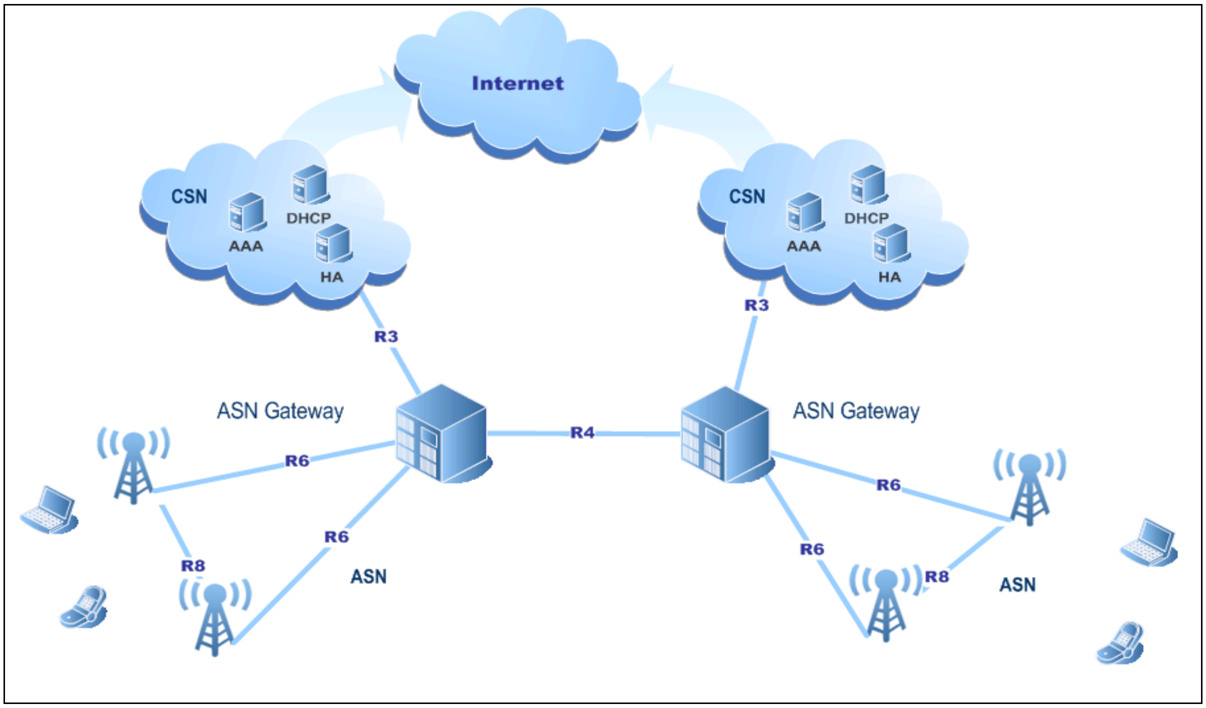

Figure2.6. Network Architecture of Mobile WiMAX[17]

As shown in Fig. 2.6, CSN has an AAA Server and performs Policy Functions (PF). This AAA server and PF provide security and an authentication framework for MS in the network. Mobile WiMAX network architecture must be characterized by several key features including:

- All networks in a WiMAX network are based on IP protocol based on IEEE 802.16.
- Supports fixed network, nomadic or mobile usage.
- The core network is not organized for any specific service, such as voice, video, elastic data. It is a multi-service core network with QoS
- QoS is always based on policy functions.

2.4 WiMAX issues

2.4.1 Power-Saving Functionality

All mobile devices need a power supply. Typically it is a battery. A MS operates with a battery energy supply, hence power saving is a crucial issue for WiMAX. While a connection is active, a mobile terminal requires a sizeable amount of battery energy to prepare to receive incoming packets. Moreover, a lack of battery energy causes degradation in WiMAX performance.

To reduce energy consumption and extend battery operating time, a power-saving mode was designed. There are several power saving standards and an individual service flow may use a different power saving mode. Powers-saving modes are categorized into three priority levels:

Power saving Class 1 is activated by the MS and is confirmed by the BS. As the length of the sleeping mode increases, power consumption is accordingly reduced, thus power saving Class 1 is suitable for non-real time service and background service flow.

Power saving Class 2 is mostly used for real-time data transmission. It introduces the concept of fixed activity time which alternates with predefined sleeping modes. Normally, real-time services do not require the full bandwidth, they only require a constant bandwidth. Thus power saving Class 2 limits transmission period and bandwidth, which helps to save the battery by deactivating the transceiver in a MS. Choosing appropriate activity and sleeping time is very important.

Power saving Class 3 has been introduced to manage connections and broadcast services. The BS calculates a sleep window when an MS requests to be set into sleeping mode, which means that no broadcast data or management message need to be sent in a downlink directions [25]. The MS goes into sleep mode to reduce battery consumption and will automatically be activated once the sleeping period expires.

2.5. WiMAX and other wireless standards

2.5.1 Fixed and Mobile WiMAX

The mobile WiMAX (802.16e) has added mobility to the fixed WiMAX (802.16d). WiMAX technology is intended to provide broadband connectivity to both fixed and mobile users in a Wireless Metropolitan Area Network (WMAN). WiMAX uses microwave radio technology to connect computers (or mobile devices such as a smart phone) to the internet instead of wired network connections (DSL, ADSL, Cable modem). Mobile WiMAX operates very much like a cell phone service in reasonable proximity to a BS when required to establish a data link to the internet [3].

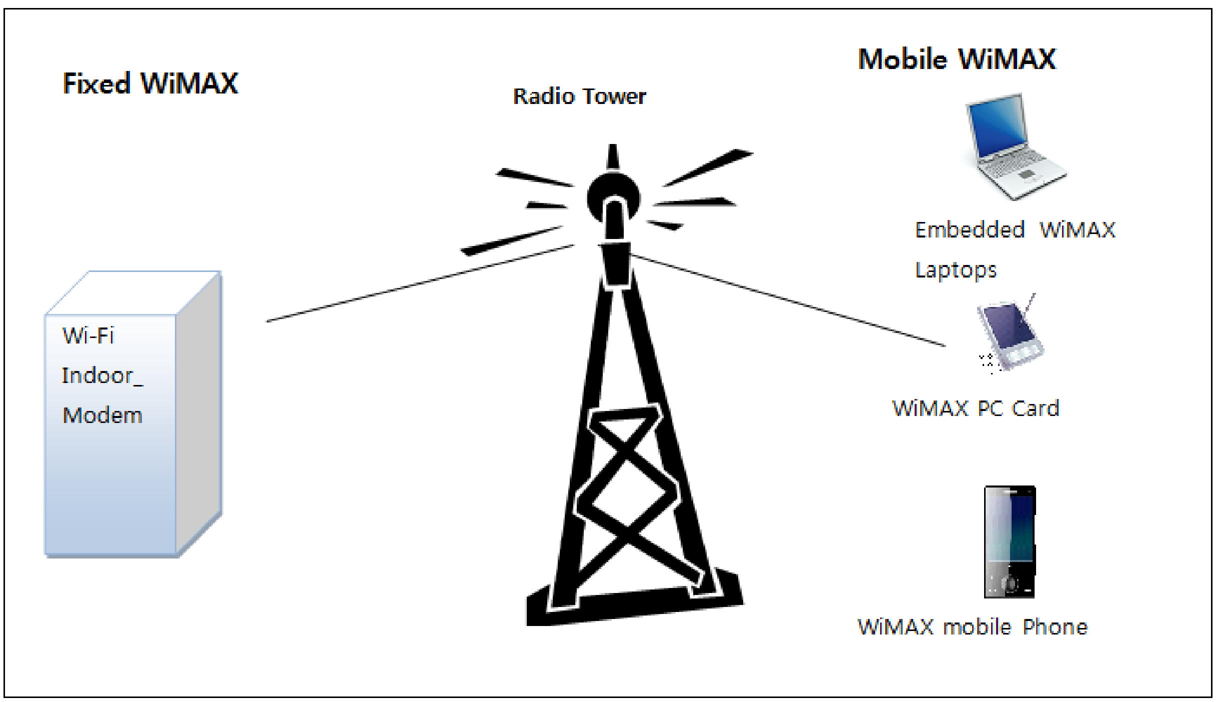

Figure2.7. Fixed and Mobile WiMAX operation[3]

The individual features of Fixed WiMAX and Mobile WiMAX are summarised in Table 2.2

Table2.2. Comparison of Fixed and Mobile WiMAX [1, 12]

Parameter	Fixed WiMAX	Mobile WiMAX
Definition	Only allow BWA when subscriber is in the range of a WiMAX BS	Allows handoff of data sessions as the user moves between radio towers
Standard	802.16d	802.16e
Frequency	2- 11 GHz	2-6 GHz
Key features	Allows LOS and NLOS Selectable channel bandwidth ranging from 1.25 to 20MHz	Provide mobile wireless broadband up to vehicular speed.
Application	Fixed and nomadic access	Mobility and nomadic access
CPE requirement	Outdoor directional antenna, Indoor modem	PC data Card, Mobile handset with embedded CPE- required WiMAX chips

As shown in Table 2.2, mobile WiMAX uses licensed frequency and requires dedicated CPE to connect to the internet. Mobile WiMAX can provide services that are not supported by fixed WiMAX up to a certain driving vehicular speed.

However, there are various external factors that influence the performance of mobile WiMAX such as traffic type, network size, traffic load and node mobility (trajectory).

To get more accurate and realistic information about mobile WiMAX performance, a performance evaluation with different scenarios needs to be conducted.

2.5.2 Comparison between WiMAX and XDSL

For XDSL it is essential to lay wires up to the last mile in order to provide stable connectivity. This is expensive and difficult work whereas for wireless no such work is required [3]. WiMAX also eliminates the mess created by Ethernet cables around the home. Moreover, users can seamlessly roam from one location to another, as mobility is fully supported. Roaming while being connected to the network is not possible at all with DSL, whereas this is not a critical problem in the case of WiMAX. Interestingly, according to[30], WiMAX would be suitable for developing countries which do not have the required network infrastructure. The value proposition for developing countries is to provide an economical, flexible and quickly-deployed solution, to enhance internet access rate and reliability.

Table2.3. Comparison between the basic features of WiMAX and xDSL [3]

Characteristics	WiMAX	XDSL
Media Specific	Shared media between Subscribers	Dedicated Media
Maximum coverage	~12-15Km(LOS) ~1-2km(NLOS)	5-7km
QoS	Native MAC QoS support service differentiation levels	N/A
Bit Rate(Maximum)	Up to 40Mpbs	DL: 2-20Mbps UL:800kbps – 1Mbps
Symmetry	Asymmetrical and symmetrical	
Roaming	Yes	No
Architecture	Central end-DSLAM Subscriber-XDSL NT	Central end-base Station Subscriber – Subscriber station
Power requirements for SS	Battery / mains	Mains

2.5.3 Comparison between WiMAX and Wi-Fi

The IEEE 802.16, WiMAX is a recent wireless broadband standard that has promised high bandwidth for long-range transmission[18].

Similar to the IEEE 802.11 (Wi-Fi) standards, many variations of the IEEE 802.16 standard have been developed to meet the specific needs of end-users. The initial standard, IEEE 802.16, was originally developed to cover the frequency range of 10 to 66 GHz, which is generally known as the "licensed range" which only licensed users have the right to use. To accommodate the problem of limited spectrum use, the IEEE 802.16a standard includes the license free range of 2 to 11 GHz [18, 31].

Many professionals in the mobile wireless networking field have realised that mobile WiMAX has numerous advantageous features when compared to Wi-Fi networks. The features include: allowing the building of scalable networks with the use of mesh networks, point to multipoint architecture that provides reasonable throughput and reasonable coverage area [27, 31-35].

The key features and differences between IEEE 802.16 and IEEE802.11 are presented in Table 2.4.

Table2.4. Features of WiMAX (IEEE802.16) and Wi-Fi (IEEE802.11) [33]

	WiMAX (IEEE 802.16)	***Wi-Fi (IEEE 802.11)***
Range	• Optimised for users within 7~10 km radius • Mesh network increases the coverage area	• Optimised for users within a 100 meter radius • Add access points or high-gain antenna for greater coverage
Coverage	• Optimised for outdoor environments (trees, buildings, user spread out over distance) • Standard support for advanced antenna techniques, including the point-to multipoint architecture	• Optimised for indoor environments. E.g. Home/Office • Users are condensed within the range and uses point-to-point architecture
Scalability	• Channel bandwidth is flexible from 1.5 MHz to 20 MHz for both licensed and non-licensed bands • Non-overlapping channels are limited only by available spectrum • Enables cell planning for commercial service providers	• Channel bandwidth of 20 MHz is fixed • Only 3 non-overlapping 802.11b channels, 5 for 802.11a
Bit Rate	Up to 75 Mbps	Up to 54 Mbps
QoS	Supported	Partly supported
Application	MAN,WAN	LAN
Scalability	High	Low
Interoperability	High	Very high

Six years after WiMAX release, Wi-Fi does not present a threat to WiMAX. In general use, WiMAX and Wi-Fi are complementary as WiMAX belongs to MAN and Wi-Fi to LAN[3]. In addition, QoS feature was added later in IEEE802.11. IEEE802.11e supports a form of QoS with several priorities. However, the IEEE802.16 MAC QoS has been designed as an internal part of the MAC functions and is more efficient than Wi-Fi for outdoor applications, with packing, ARQ and dynamic fragmentation.

2.5.4 WiBRo

Wireless Broadband (WiBRo) belongs to the WiMAX standards and is being developed by the Korean telecommunication community. Initially, WiBRo was intended to provide better data transmission than 3G cellular systems and an affordable internet service anywhere within large cities of South Korea [15]. Consequently, the WiBRo service was launched commercially by Korea Telecom and SK Telecom in early 2006. WiBRo supports users travelling at speeds up to 120km/h (initially, it was limited to 60km/h) with the peak user data rate of 3Mbps for downlink and 1Mbps for uplink [15]. A comparison between the PHY layer and MAC layer of mobile and fixed WiMAX and WiBRo is shown in Table2.5.

Table2.5. Comparison of WiBRo and Fixed and Mobile WiMAX

Parameter	WiBRo	Mobile WiMAX	Fixed WiMAX
Frequency	2.3-2.4GHz (100Mhz)	~ 11GHz Mobile	~ 11GHz Fixed
Duplexing	TDD	TDD/FDD	TDD/FDD
Multiple Access	OFDMA	OFDMA	OFDMA
Channel Coding	CTC sub channel concatenation	Concatenated RS-Convolutional code BTC	RS-Convolutional Code BTC
Modulation	QPSK/16QAM, 64 QAM,AMC on CQI		
Coverage	1-1.5km	3-7km	3.5-7km

As the WiBRo standard has been focused on the mobile user, QoS are all available except QoS scheme for CBR. ARQ, PHS, Packing, fragmentation and QoS service layer of 802.16 are also available in WiBRo. The WiBRo standard has similar features to WiMAX. Therefore, WiBRo is another name for WiMAX, but it is restricted for use only in Korea at the moment.

2.6 Summary

In this chapter, essential background information about the IEEE 802.16 standards, the advanced features of Mobile WiMAX and comparisons with wireless broadband technologies was provided. Advanced features of the PHY and MAC layer have been in particular focus. The issues related to Mobile WiMAX in BS power-saving mode are also discussed. Characteristics of OFMD, OFDMA, and Mobility were also described. Four types of handoff, typical network architecture, Mesh network and LOS/NLOS were outlined. Comparisons with Fixed WiMAX, Wi-Fi and WiBRo were reviewed in detail.

As the primary objective of this thesis is to investigate the impact of traffic types and node mobility on the performance of mobile WiMAX, a literature review of existing research is essential. There is a large number of research papers that have evaluated WiMAX performance with particular node types and node mobility. In order to establish an experiment framework (i.e. to assign value on parameters) and decide on result analysis methods (i.e. performance metrics), a literature review is conducted in chapter 3.

Chapter 3

Literature Review

3.1 Overview

Chapter 2 outlines the evolution of IEEE 802.16 standards and the details of the advanced features of mobile WiMAX. Comparisons with other wireless networks are provided. There is a large body of literature that has evaluated WiMAX performance with particular node types (i.e. VoIP, VoD or FTP) and node trajectory. In order to establish an experiment framework and to choose result analysis methods (i.e. performance metrics), a literature review is needed.

Section 3.2 emphasizes the need for conducting the literature review. Section 3.3 reviews the QoS provided in mobile WiMAX. Section 3.4 describes four types of handoff schemes that are frequently used in wireless broadband networks. Section 3.5 overviews the properties of traffic types in the Mobile WiMAX environment. Section 3.6 discusses the correlation between performance, network size and traffic size. Section 3.7 discusses the use of realistic mobility patterns and trajectory in the experiments described in the existing literature. Finally, this chapter is summarised in Section 3.8.

3.2 Review of Literature on Mobile WiMAX

The demand for broadband mobile services continues to grow worldwide [36]. Mobile WiMAX as a wireless access technology offers a more flexible and cost-effective solution than the wired broadband technologies [26]. Mobile WiMAX equipment comes to the market at a lower price than current 3G solutions. Over 260 service providers deploy fixed, portable and mobile WiMAX systems in 110 countries. WiMAX was developed to provide greater mobility and better performance than 3G solutions [36] [37]. Therefore, by using mobile WiMAX, users can access high-speed internet services more easily and at a lower cost than through comparable wired network access technologies. In addition, mobile WiMAX carries a promise of ubiquitous computing where the user can access real-time, multimedia applications and internet anywhere and anytime [38].

Accordingly, a large number of researchers who have been investigating the performance of WiMAX have also proposed new techniques or algorithms to improve WiMAX performance. Therefore, selected research papers regarding QoS, handoff, node mobility, packet types and network architectures are thoroughly reviewed here.

Interestingly, there are a few articles that have focused on the correlation between traffic type and performance. The results reported in those articles will be used for validating the experimental results of this study.

3.3 QoS in Mobile WiMAX

QoS stands for “Quality of Service” and QoS is an integral part of both wired and wireless networks [39][40]. QoS provisioning is firstly considered for real time traffic types over wireless networks (i.e. VoIP and video conferencing) as real time traffic-types are more delay-sensitive than non-real-time traffic types (i.e. FTP or HTTP) and necessarily require connection stability.

The operation principle of QoS is to prioritize network traffic, that is, to ensure that the highest-priority packets get over the network as soon as possible. In order words, QoS postpones transmission of low-priority packets and sometimes entire packets are discarded in cases of heavy network traffic. Although QoS cannot speed up packet transmission, it certainly contributes to the improvement of packet transmission[41].

However, Tung et al (2008) [42] emphasize that QoS provisioning requires a high operational cost. Accordingly, both Call Admission Control (CAC) and bandwidth allocation schemes are needed to provide reasonable QoS and low cost services. The CAC prevents unwanted and unauthorized packet transmission while the bandwidth allocation algorithm manages all available channels according to traffic load size. Therefore, Tung et al (2008) have proposed an adjustable Quadra-Threshold Bandwidth Reservation (QTBR) dynamic call admission and a QoS aware bandwidth allocation algorithm.

The experimental results show that resource utilization was maintained up to 100% with less than 1% packet dropping/blocking probability. However, transmission delay was not sufficiently considered and they only focused on the rate of the utilization of resources. In addition, overall performance indexes (transmission rate and end to end delay) are not presented. Interestingly, packet scheduling is used in many experiments [39, 40, 42]. Packet scheduling is a method to regulate bandwidth allocation depending on the priority of the packet and the condition of channel and buffer [36]. The role of packet scheduling is significant for wireless networks. This is due to that fact that overflows or scarcity of bandwidth may result in the inefficiency of packet transmission (i.e. channel starvation).

Therefore, mobile WiMAX has five QoS scheduling classes to provide appropriate bandwidth to each traffic type (Table 3.1).

Table3.1. Summary of QoS categories[36]

QoS category	Applications	QoS specifications
UGS (Unsolicited Grant Service)	VoIP	Maximum sustained rate Maximum latency tolerance Jitter tolerance
rtPS (Real-time polling service)	Streaming audio and video	Maximum sustained rate Minimum reserved rate Maximum latency tolerance Traffic priority
ErtPS (Extended real-time polling service)	VoIP	Maximum sustained rate Minimum reserved rate Maximum latency tolerance Jitter tolerance Traffic priority
NrtPS (Non-real-time polling service)	File Transfer Protocol (FTP)	Maximum sustained rate Minimum reserved rate Traffic priority
BE (Best effort service)	Data transfer, Web browsing, etc.	Maximum sustained rate Traffic priority

UGS is designed to support VoIP by providing Constant Bit Rate (CBR) while rtPS is designed to supports real-time video files by providing Variable Bit Rate (VBR). ErtPS is an extended service rtPS to support real- time service flows that generate variable size data packets on a periodic basis. NrtPS is designed to support FTP which generally requires a minimum data rate and delay tolerance. BE is not designed to support particular packet type, so it is often used for HTTP and data transfer.

The main idea of the five QoS scheduling classes is to provide appropriate bandwidth to where it is needed based on priority. However, since bandwidth is provided by borrowing from other traffic flows it is also limited. Accordingly, long delay and transmission times may occur in non-priority packet types as a side effect of QoS.

3.4 Handoff

Handoff is one of the key factors that can affect the performance of mobile WiMAX and node mobility. Hard handoff was often used as mandatory but then seamless handoff, without significant packet loss and delay, become essential conditions for providing full mobility [43]. Jiao et al (2007) [44] found that long handoff operation time causes long transmission delays and temporary disconnections. These effects are demonstrated in performance degradation.

Accordingly, a large number of researchers have proposed new handoff schemes that effectively conduct handoff improved performance in terms of low packet loss, delay and latency [43] [45] [38, 44].

Anh and Kawai (2009) [43] have proposed an Adaptive Mobility Handoff scheme (AMHO) that detects the handoff trigger point by analysing the MS`s movement pattern to reduce the handoff processing time, and then the AMHO modifies the MAC layer exchange message to reduce latency.

According to their experimental results, handoff latency is reduced by 40%, the downlink and uplink transmission packet drop rates are also reduced by 69.5% and 52% respectively. They have tested their handoff scheme in a cell radius of 500m with 1-30milliseconds of mobile node speed only. Despite these gains, the area for their experiment was relatively small, and so it would be hard to know if their experimental results can be applied to all mobile WiMAX networks successfully.

Accordingly, Jiao et al (2007) [44] used a different mobile node speed (60km/h) and a wider distance (2800m site to site distance and 300m overlap distance) in their experiments. They proposed a passport handoff scheme to reduce handoff processing time. Notably, they added a CID (Connection ID) assignment strategy to avoid collision between continued services and up-coming services. According to their experimental results, overall handoff performance was improved in terms of service interruption and system complexity.

Interestingly, Lee et al (2006)[45] also proposed a fast handoff algorithm. They used an analytical modelling method that describes the network in a mathematical equation. Modelling methods are discussed further in Chapter 4.

Lee et al [45] pointed out the waste of channel resources in the general handoff process, thus their fast handoff algorithm is focused on the optimization of the handoff initialization process. They reported that the overall handoff process time was reduced from 600ms to 300ms depending on its usage. However, despite the reduced overall process time, all of other results are calculated by using their equations. Therefore, it is yet to be seen if it is possible to obtain accurate results like that in difficult and complex network environments.

In order to obtain realistic results concerning the impact of handoff on performance, we need to examine at least two types of handoff in various mobile WiMAX network environments with varied mobile node speeds.

3.5 Traffic type

According to Juan et al (2007) [46], mobile WiMAX has flexibility and efficiency and provides many kinds of multimedia services, such as VoIP, Video conferencing, web browsing and file transfer. Colda et al (2010)[47] have classified the DL QoS requirements for several multimedia services that are frequently used in wired and wireless networks. Their finding are presented in Table 3.2 below.

Table3.2. Download QoS requirements for different services [47]

Service	Capacity(kb/s)	Delay	Jitter (ms)	BER	PER
Video on Demand(VoD)	1-10^4	< 2s	< 500	<-10^{-7}	<$8 \cdot 10^{-5}$
VoIP	10-50	< 50 ms	< 10	<-10^{-6}	<$8 \cdot 10^{-4}$
Video conferencing	100-2000	<150 ms	< 50	<-10^{-7}	<$8 \cdot 10^{-5}$
Online Gaming	10-200	< 50 ms	< 10	<-10^{-6}	<$8 \cdot 10^{-4}$
File Sharing	50-500	< 500 ms	< 250	<-10^{-6}	<$8 \cdot 10^{-4}$
Web Browsing (HTTP)	50-500	< 500 ms	< 250	<-10^{-7}	<$8 \cdot 10^{-5}$

Most real time traffic types (VoD, VoIP, Video conferencing and online gaming) require a higher throughput with lower delay and jitter than non real-time traffic types (FTP, HTTP). Mengke et al. (2010)[48] have evaluated the performance of transmission of video packet s under four different scenarios. Four connection scenarios and experimental results were presented:

A) Scenario with one BS and one MS as a streaming client: the receiver bit rate is slightly lower than the sender bit rate. However, the transmission performs well, because a small amount of interference is inevitable.

B) Scenario with one BS and multiple MSs as streaming clients: as the number of MSs increases, the packet delay increases too while, throughput decreases. This is due to the fact that all BSs in the network share equally in the limited bandwidth. Overall performance was worse than in Scenario A.

C) Scenario with one BS streaming server and multiple MSs: when nine or more MSs are used, the video received is totally corrupted and performances are much worse than in Scenario B, because the allocated MS uplink bandwidth of MS was insufficient to have video packets from a wire-linked video server. Accordingly, the bit rate for both sender and receiver decreased dramatically due to excessive packet loss.

D) Scenario with one MS as a streaming client and handoff between two BSs: packet delay and throughput fluctuation were observed when handoff occurred. Overall performance was worse than Scenario A due to delay caused by handoff [48].

The performance results above confirm that as the number of MSs Increases, delay also increased while, throughput per node decreased (overall throughput increased). Moreover, handoff incurred an extra time delay. For the effective transmission of a video packet which is delay-sensitive, CBR and proper QoS settings should be provided. However, bandwidth is usually limited, thus the QoS setting is of significance.

Prasath et al (2008) [41] have investigated the group mobility issue with QoS support in mobile WiMAX networks. They devised an adaptive scheduling algorithm to minimize end -to-end delay for VoIP. A proposed scheduling algorithm provides additional bandwidth to the real-time flow by borrowing from non-real-time flow only if the delay is increases in real-time flow. In the meantime, the non-real-time flow buffer is well controlled. Experimental results show that there was an improvement of performance in terms of delay and throughput. However, there is a concern about the validity of the results as the researchers only used simple parameters in their experiments. To get reliable experimental results, various types of multimedia traffic types need to be examined in various mobile WiMAX network environments.

3.6 Network size and traffic load

Mach and Bestak (2007) [49], asserted that a system`s capability is strongly dependent on its channel size and other configurations (i.e. coding rate, frame duration time, etc.).

Ball et al (2005) [50] examined the performance of mobile and fixed WiMAX with various cell areas (radiuses of 300m, 1000m and 2000m), frequency reuse schemes (1x1, 1x3) and traffic loads (FTP with moderate file size).

In the experiments, they used a typical 3.5 MHz OFDM-256 channel (a single channel that has 256 sub-carriers) with no optional features. Performance is measured in terms of Application throughput (Mbps), Modulation and Code Scheme (MCS) utilization rate (%), FTP download time (Seconds), call blocking rate (%) and Channel load (%).

According to their experimental results, both fixed and Mobile WiMAX showed an excellent application throughput. Mobile WiMAX works reasonably well for up to 1000m cells but could not provide reliable service at 2000m. The call-blocking rate increased beyond 20% and they confirmed that mobile WiMAX was affected significantly when the cell-area (coverage) was increased even for light FTP traffic loads.

3.7 Node mobility and trajectory

As the provision of high-mobility is a major feature of Mobile WiMAX, a large number of research papers have also been published. The major difference between mobile WiMAX and fixed WiMAX is mobility support. However, speed and trajectory of node are unpredictable and can vary even in identical circumstances. Thus, this research is conducted to investigate the correlation between performance and node mobility (especially, speed and trajectory of node movement) under various network circumstances.

Accordingly, Tarhini and Chahed (2008)[51] have tried to identify the impact of mobility on mobile WiMAX performance. In the experiments, VoIP packets (inelastic) and data packets (elastic) were tested in intra-cell mobility. This means that handoff (inter-cell mobility) was not allowed.

Experimental results show that as a node moved away from the BS, signal degraded and the Signal Interference Noise Ratio (SINR) increased. Interestingly, they observed that mobility caused a decrease in the blocking rate when a higher number of nodes moved inward (intra-cell) rather than outward (inter-cell). This is because as nodes moved inward, fewer resources (power) are required, so the overall blocking rate drops.

To study mobility in a driving vehicle, Colda et al (2010)[47] conducted mobility experiments with two vehicular speeds (60km/h and 120km/h) and various modulation schemes (QPSK1/2, 16QAM3/4, 64QAM2/3, 64QAM3/4 and 64QAM5/6).

When the MS moved at 60km/h, SNR increased proportionally to the Packet Error Rate (PER) increase and the 64QAM5/6 modulation scheme showed the best performance.

In an MS moving at 120km/h, 64QAM5/6 had the highest total link throughput and link throughput per user. QPSK1/2 showed the lowest total link throughput and the link throughput per user in downlink. However, QPSK1/2 provided the broadest operating coverage while 64QAM5/6, which is the most complex modulation scheme, provided the narrowest operating coverage in the experiments. Their experiments confirmed that coverage area and bandwidth are inversely proportional.

However, the researchers did not consider the trajectory of the vehicular node. The results might be totally different when the MS moves toward to a BS or away from a BS.

Mach and Bestak (2007)[49] focused on the importance of node trajectory. Their experimental results showed that when MSs move towards the BS, the throughput increased. However, when MSs moved away from the BS, overall throughput decreased.

Chan et al (2007)[52] also emphasized the importance of using realistic MS trajectory and MS movement patterns in experiments for obtaining realistic experimental results. They modelled three typical NLOS/LOS environments: High-speed highway, Variable speed and Urban City.

- The high-speed highway scenario used 40 MSs, a 12,100mX100m area, various vehicular speeds from 10km/h to 120km/h.
- The variable speed scenario used 40 MSs, a 4000mX100m area, various vehicular speeds from 10km/h to 30km/h.
- The urban city scenario used 95 MSs with one BS, a 900mX900m area and 30km/h vehicular speed.

The scenarios described above are more realistic than testing one or two nodes with one or two MS movement speeds. Therefore, network size, node speeds, traffic types and traffic loads should be considered as factors that influence the performance of mobile WiMAX.

3.8 Summary

This chapter extensively reviews the important features of mobile WiMAX networks. The importance of using proper QoS is discussed and properties of five QoS that are supported in mobile WiMAX are reviewed. In addition, some proposed new QoS schemes are reviewed. The effect of handoff on the performance of mobile WiMAX in terms of delay and throughput are reviewed. How previous researchers have tested handoff and the strengths and weaknesses of their experiments are presented. Transmission differences between real-time traffic types and non real-time traffic types are also reviewed. The importance and difficulty of setting node trajectory are discussed and the need to use various node speeds in experiments is also emphasised. The research methodologies adopted in this study are to be discussed in Chapter 4.

Chapter 4

Research Methodology

4.1 Overview

In Chapter 3, a review of literature on mobile WiMAX was presented. It is noted that previous researches have emphasised the importance of investigation of the impact of varying traffic types and realistic node mobility on the performance. This chapter reviews the methodologies used in previous studies for evaluating mobile WiMAX performance.

A primary objective of this thesis is to investigate the impact of traffic types and node mobility on the performance of mobile WiMAX. To achieve this objective, a general understanding of research methodology is required. This chapter aims to provide information regarding methodologies for experiment design, deployment of nodes and performance evaluation.

Section 4.2 describes the characteristics of methods such as analytical modelling, real world experiment (test-bed) and computer simulation which are most commonly used in the area of network modelling and performance evaluation [10, 49, 53]. Section 4.3 presents the characteristics of OPNET modelling and the verification of the OPNET simulator. Finally, the chapter is summarised in Section 4.4.

4.2 Justification of research methodology

The performance of wireless networks can be analysed using analytical modelling, test-bed and computer simulation modelling methodologies [10, 54-56].

An analytical modelling is based on mathematical calculation and analysis, and by this means results can be acquired by varying parameters within into mathematical equations[57].

Although analytical modelling method is affordable for formulating a new algorithm, there are weaknesses in experiment controllability and operation [57]. Moreover, analytical modelling cannot represent the dynamic nature of data communication and is only a prediction (approximation) and always produces discrepancies when compared to a real-world experiment.

In this research, numerous experiments are conducted and many network circumstances are considered. It could be very difficult to represent every single factor in a test networks in a mathematical formula within a limited time.

Real world experiment is an effective method to acquire fairly accurate results [54, 58]. As noted in [59], test bed design is regarded as the most accurate form of experimental research, in that it tries to prove or disprove a hypothesis mathematically and/or, statistically. Moreover, the results from real world experiment minimize the need for validation. Having said this, not all tests were conducted as Real world experiment due to the difficulties associated with setting-up complex networks, indefinable human error and the high cost for both set-up and operation.

Computer simulation is widely used as a research methodology for analysing the performance of wireless networks [55, 57]. Computer simulation provides a virtual environment for the design and deployment of components [53]. The user can relatively easily modify the properties of components such as nodes, link and MAC/PHY parameters according to the desired setup. Moreover, there is no restriction on number of simulation runs. Computer simulation is often used for the analysis of a new system design, the retrofitting of an existing system, testing the efficiency of a proposed algorithm and performance evaluation [54, 60, 61]. However, the problems can occur where the simulator dose not generate accurate results every time. To this end, the user must have an extensive knowledge of the simulator to discover the problems or errors in the results.

Furthermore, the creditability of results obtained by computer simulation depends on use of a good simulator, as well as on following a proper process for validation and verification of the results. The process consists of parameter validation, event validation comparison, and historical data validation to compare with other simulation findings in order to prove their viability [53, 62, 63]. In addition, computer simulation provides more flexibility in model development, validation and performance evaluation than analytical modelling and real experiment methodology [63].

As stated before, the aim of this research is to investigate the impact of traffic types and node mobility on the performance of mobile WiMAX. To obtain results relevant to this research topic, a computer simulation methodology has been selected to examine the impact of traffic types and node mobility on the performance of mobile WiMAX. For the investigation, various network scenarios will be used to study the impact of FTP, HTTP, VoIP and Video conferencing traffic on mobile WiMAX performance.

4.3 Optimized Network Engineering Tool (OPNET)

OPNET is an object-oriented, discrete event and general purpose network simulator and provides a comprehensive modelling library for easy simulation and analysis of network performance [64]. Moreover, it has distinct functions for creating a network environment such as a comprehensive library of network protocols, GUI analysis tool, OPNET modeller, modifiable source codes, graphical results and auto-generated statistical results [65]. Due to these features that listed above, OPNET is one of the most widely-used simulation tools in the field of evaluation and analysis of network performance.

The OPNET has gained considerable popularity in both academia and industry by a providing number of sample network models that are commercially available network components [66]. Interestingly, one major reason for the wide use of OPNET is that it provides more than just basic features to academic institutions free of charge. Thus, OPNET is the preferred tool in the academic area[66].

On the other hand, as pointed out by Salah and Alkgoraidaly(2006) [66], there is no formal approach to deploying VoIP or video conferencing into an existing network in OPNET. OPNET also requires high PC specifications and consumes large amounts of memory [67]. Fortunately, in this research, the latest PCs will be used which can satisfy the requirements of OPNET. For consistency, construction of the mobile WiMAX network will be based on topologies recommended by previous researchers.

OPNET provides four hierarchical editors (Network, Node, Process and Parameter) that allow the development of a detailed network model. A model developed at one layer can be used by another model at a higher layer and detailed setting can be added at each editing stage. Consequently, these hierarchical editors play a significant role in the modelling and later in operation of the network. In addition, OPNET provides open interfaces with the C language, so the user can easily modify operation rules or add their own restrictions by using the Probe editor. Therefore, the user can collect numerical results and capture every single moment of the simulation process. Interestingly, data can be collected both as animation type and graphical type by its analysis tool which makes data analysis easier [55].

Five main advantages of OPNET are summarised below:

1) Simulate real-life network scenarios by using commercially available network components;

2) Easily reuse and modify network scenarios;

3) Cost and time efficient;

4) Possible to propose network protocol using C language;

5) Possible to insert real-time data from other compatible software.

4.4 Summary

The analytical modelling methodology has shortcomings when dealing with the nature and complexity of a WiMAX network. Real word experiment (test-bed) methodology was not considered an appropriate method for setting-up the mobile WiMAX network due to higher set-up costs and the complexity of mobile WiMAX.

Although computer simulation has its own shortcoming, it is considered the best method since it allows the simulation of various WiMAX scenarios with robust validation and verification rules. If the rules are followed, this will countermand the drawbacks of simulation. Consequently, the OPNET simulator is selected for the experiments. The usability of OPNET is sufficient to conduct network modelling and performance evaluation at this stage. Detailed scenarios and parameters for performance evaluation are discussed in detail in Chapter 5.

Chapter 5

Modelling the Network

5.1 Overview

Chapter 4 reviewed, the research methodology adopted in this thesis. In order to observe the impact of traffic type and node mobility on the performance of mobile WiMAX from various points of view, composition of appropriate experimental scenarios is essential. Moreover, selection of parameter values and appropriate assumptions are also of vital importance. Accordingly, this chapter comprehensively presents the experimental design, which includes; parameter values, performance metrics, hardware and software equipment specifications, assumptions, network modelling and experimental scenarios.

Section 5.2 presents performance metrics and characteristics for each application. Specification of hardware and software used for this thesis are presented in Section 5.3. As all experiments are conducted with the computer simulator, all assumptions for the virtual experiments are presented in Section 5.4.

Section 5.5 presents the design of the experiments and all parameters for each of the tested applications. Section 5.6 describes the nine distinctive experimental scenarios each of which has a different purpose. Finally, the chapter is summarised in Section 5.7.

5.2 Performance metrics

In the telecommunications field, the metric represents cost and best route to a destination and performance metrics provide a measure of a network`s performance[68]. Throughput, end-to-end delay and packet error ratio are representative performance metrics of the WMAN. In this experiment, four different traffic types (FTP, HTTP, VoIP, Video conferencings) are used. The performance metrics should be used where required. For instance, upload/download response times are metrics for the FTP, page/object response times are metrics for HTTP, jitter and Mean Opinion Score (MOS) are significant for the VoIP and Packet Delay Variation (PDV) and end-to-end delay are metrics for Video conferencings. In order to evaluate mobile WiMAX performance from various perspectives, some explanations of performance metrics are provided below.

Throughput is a measure of how fast data can be sent through a network. In other words, throughput is the average rate of data packets received successfully through a network. Although bandwidth is a potential measurement for link capacity, throughput is an actual measurement for how fast data can be sent. Changes in throughput will clearly show the impact of traffic types and mobility on performance. Commonly used units for throughput measurement are: bits per second (bps), packets/second, packets/slot, and channel utilization (%).

Download and upload response time is the elapsed time between sending a request and receiving the response packet for the application. Measured from the time a user requests a service to the time the service is granted. Any increase in response time is a critical serious condition as it is an indication that the network is working above its capacity. Accordingly, download and upload response times are used to measure performance of FTP traffic.

Object and Page response time is the time that an http server or system takes to react to a given input.

Object response time specifies the response time for each object from an HTML page to be received, while page response time specifies the time required to retrieve an entire page with all contained objects. Interestingly, these metrics are used to determine the success of a website. Object and page response times are used to measure the performance of HTTP traffic.

End-to-end delay defines how long it takes for an entire message to arrive at the destination from the time the first bit is sent out from the source. End-to-end delay is a sum of propagation time, transmission time, queuing delay and processing delay. Changes in end-to-end delay can determine how each traffic type and mobility impacts on the performance of mobile WiMAX not only for Video conferencing.

Packet delay variation (PDV) is the variance among end-to-end delays for packets in a flow with any lost packet being ignored.

Jitter measures the tendency of packet delay variation between two consecutive packets. Although PDV is sometimes referred to as jitter, the impacts from these two are different as they have different calculation schemes. High value of jitter and PDV can be a problem in time-sensitive packet transmissions (i.e. VoIP and Video conferencing). Consequently, jitter and PDV are used to measure the performance of VoIP and Video conferencing respectively.

Mean Opinion Score (MOS) is a method for expressing real-time video and voice quality. MOS gives a numerical indication of the perceived quality of media traffics (Video conferencing, VoIP). Numbers are easy to grade: 5-Excellent, 4-Good, 3-Fair, 2-poor, and 1 – Bad.

Packet loss (%) denotes the number of data packets that are lost in transmission from the sender to the receiver. It is measured as a percentage of packets lost from the total number of packets. The most frequent cause of packet loss is network overload.

5.3 Hardware and software requirements

This section provides the specifications of hardware and software that were used in the research and experiments.

Hardware Specifications

A dedicated workstation was provided for thesis writing and the OPNET modeller by AUT University. It met the requirements of the OPNET modeller.

- Vendor: Cyclone
- Processor: Intel® Core™ i5 @3.20 GHz
- Installed Memory (RAM):   4.00 GB
- System type: Window 7 64bits Operating System

Software Specifications

Microsoft Office Visio 2007 and Excel2007, R, MATLAB and OPNET Modeller 15.0 Education version was provided by AUT University. R is a free software environment for statistical computing and graphics.

Mobile WiMAX models were developed using OPNET Modeller 15.0. This educational version of OPNET 15.0 allows the user to construct a mobile WiMAX model and to perform various mobile WiMAX experiments. Results were exported from OPNET Modeller to Microsoft Excel 2007 sheets and were then used to generate graphics for observation and comparison purposes. R and MATLAB were used to generate 95% confidence interval and to discover outliers.

5.4 Assumptions

Mobile WiMAX Simulation models are developed using the OPNET Modeller to observe the impact of diverse traffic types and node mobility on system performance. There are a large number of variables (i.e. interferences) that can affect the performance of mobile WiMAX and so testing the effect of every single variable in OPNET is nearly impossible. Furthermore, there is no standard for measure of signal interference. Therefore, to stay focused on the objective of this research and acquire comparative results, several essential assumptions had to be made and are described below:

- ***The network sizes*** are N= 10, 25, 50, 75, 100 nodes. The network size of 10 nodes in one cell represents a small network, 50 nodes in one cell represent a medium network and 100 nodes in one cell represent a large network.

- **The node speeds** are 0, 10, 30, 50, 70, 90 kilometres per hour (km/h). The node speed of 0 km/h represents a stationary user, 10-30km/h represents the movement of people walking or cycling, 40-60km/h represents a bus driving in an urban area and 70-90km/h represents a vehicle driving in a high-speed area.

- ***File size*** (bytes) and ***Inter-request time*** (seconds) are constant and exponential, respectively.

- The mobile stations can be arbitrarily spaced and moved within the transmission coverage area and movement patterns are configured using the ***Random Waypoint mobility model*** which is provided by OPNET. It purposely moves nodes randomly to re-create indefinable node movement.

- ***Hidden and exposed station problems*** (interference) do not exist in the simulations.

- Experimental results are obtained under network ***steady state conditions.***

5.5 Experimental design

The four applications FTP, HTTP, VoIP, and Videoconferencing are the traffic types used in the experiments. Each application is tested under various scenarios. IEEE802.16e is the network standard used and all nodes are mobile.

5.5.1General parameters used in the simulations

The empirical study is conducted by varying network size, node mobility with handoff and node mobility without handoff.

Experiments are performed in a cell size of 2000m X 2000m. Networks sizes of 10, 25, 50, 75 and 100 nodes are used. The random waypoint mobility model is used for trajectory. Traffic loads are classified into three traffic load groups: light, medium and heavy. In addition, network size is also classified in to three groups: Small (10nodes), Medium (50nodes) and large (100 nodes). There is no standard amount for small, medium or heavy traffic type and so traffic load is based on previous research data [10, 41, and 72].

In FTP, 1000, 5000 and 50000 bytes indicates light, medium and heavy traffic load respectively.

In HTTP, 500 bytes with 720*s* page interval time represents light, 1000 bytes with 360*s* interval time represents medium and 1000 bytes with 60*s* interval time represents heavy traffic load.

In VoIP, G.723 codec (6.3Kbps with silence compression) implies light, G.729.A codec (8Kbps with silence compression) implies medium and G.711 (64Kbps with silence compression) implies heavy traffic load.

Lastly, in Video conferencing, 10frames/sec with 128X120 pixels suggests light, 15frames/sec with 128X240 pixels suggests medium and 20frames/sec with 352X240 pixels suggests heavy traffic load. Finally, all simulations are carried out in blocks of 15minute (900 seconds) simulation time and run at least three times to minimize statistical error. Initially, simulation time was 60mintues; however this caused blue screen error and memory usage problems. Therefore 15minutes of simulation time was considered. All previous WiMAX research simulation times which reviewed in literature review chapter did not exceed 20mintues. All the above parameters are presented in tabular form in Table 5.1.

*Table5.1.*Mobile WiMAX parameters used in the experiments

Parameters	Value		
OFDM PHY Profiles (default)	Wireless OFDMA 20MHz		
Number of Subcarriers	2048		
Frame Duration (milliseconds)	5		
Power (Watts)	0.005		
Bandwidth (MHz)	25		
Area (m)	2000 X 2000		
Traffic Types	FTP, HTTP, VoIP, Video conferencing		
Traffic loads	**Light**	**Medium**	**Heavy**
FTP(bytes)	1,000 bytes	5,000 bytes	50,000 bytes
HTTP(bytes/inter arrival time)	500 / 720secs	1000/ 360secs	1000 / 60secs
VoIP (codec)	G.723.15	G.729A	G.711
Video conferencing (bytes)	10f/s_128X120	15f/s_128X240	20f/s_352X240
Network Sizes(Number of Nodes)	10, 25,50,75, 100		
Mobility (km/h)	0,10,30,50,70,90		
Mobility patterns(trajectory)	Random waypoint mobility modelling		
Simulation Time	15 minutes (900 Seconds)		
Handoff	Disabled(Scenarios1-6)/enabled(Scenarios 7-9)		

5.5.2 Application parameters

The parameters for all four applications used for the experiments are presented in Tables 5.2, 5.3, 5.4 and 5.5.

Table5.2. FTP parameters

Parameters	Value(light)	Value(heavy)
Command Mix (Get/Total)	50%	50%
Inter-Request Time (Seconds)	3600	360
File Size (Bytes)	1000	50,000
Type of Service	Best Effort	Best Effort
RSVP parameter	None	None

Table5.3. HTTP parameters

Parameters	Value(light)	Value(heavy)
HTTP Specification	HTTP 1.1	HTTP 1.1
Page Interval arrival Time(Seconds)	720	60
Object Size (Bytes)	500	1000
Location	HTTP Server	HTTP Server
Type of Service	Best Effort	Best Effort

Table5.4. VoIP parameters

Parameters	Light(PCM)	Heavy(GSM)
Encoder Scheme	G.723	G.711
Type of Service	Interactive Voice(6)	Interactive Voice(6)
Compression and decompression Delay (Seconds)	0.02	0.02
RSVP parameter	None	None

Table5.5. Video conferencing parameters

Parameters	Value(light)	Value(heavy)
Frame Interval arrival Time (frames/Second)	10	30
Frame Size (bytes)	128 X 120 pixels	352 X 240 pixels
Type of Service	Best Effort	Best Effort
RSVP parameter	None	None

Figure 5.1 illustrates the OPNET simulation environment with a network size of 100 nodes in 10 cells. In the experiments, one cell will contain 10 nodes, 25 nodes, 50nodes, 75 nodes or 100 nodes only. However, in handover experiments, the node number in one cell will be random. The objects in the OPNET simulation are a mobile station (or Subscriber Station), Base Station, ISP_Backbone, Gateway Routers, PPP_DS3 full duplex cable, WiMAX_config, Profile_config, Application_config, Mobility_config and four application servers. Each Subscriber Station has a unique identification number, auto-assigned IP address or manually configured mobile IP address for handoff, random way point trajectory. Four servers are configured to respond to each of the application`s requests.

PPP_DS3 full duplex cable is used between Server and ISP Backbone. A gateway Router is used to provide routing information when handoff occurs. A Base Station is configured to transmit and receive the WiMAX signal as the hub of the local wireless network. It can act as a gateway between a wired network and a wireless network.

The Application_Config object specifies the available application types and the parameters properties.

The Profile_Config object is used to create user profiles. Only applications that are defined in the "***Application_Config***" object can be used in ***Profile_Config***. Consequently, a ***Profile_Config*** object has all the information about the applications and it assigns type and amount of transmission traffic to each SS.

The WiMAX_Config object is used to store profiles of PHY and service class. Therefore all nodes in the networks have identical WiMAX parameter values.

Mobile WiMAX provides four efficiency modes. In this research, "Efficiency enabled" and "Mobility and Ranging enabled" modes are used.

The Mobility_Config contains mobility profiles that contain node speeds, node trajectory, domain range and start and stop time.

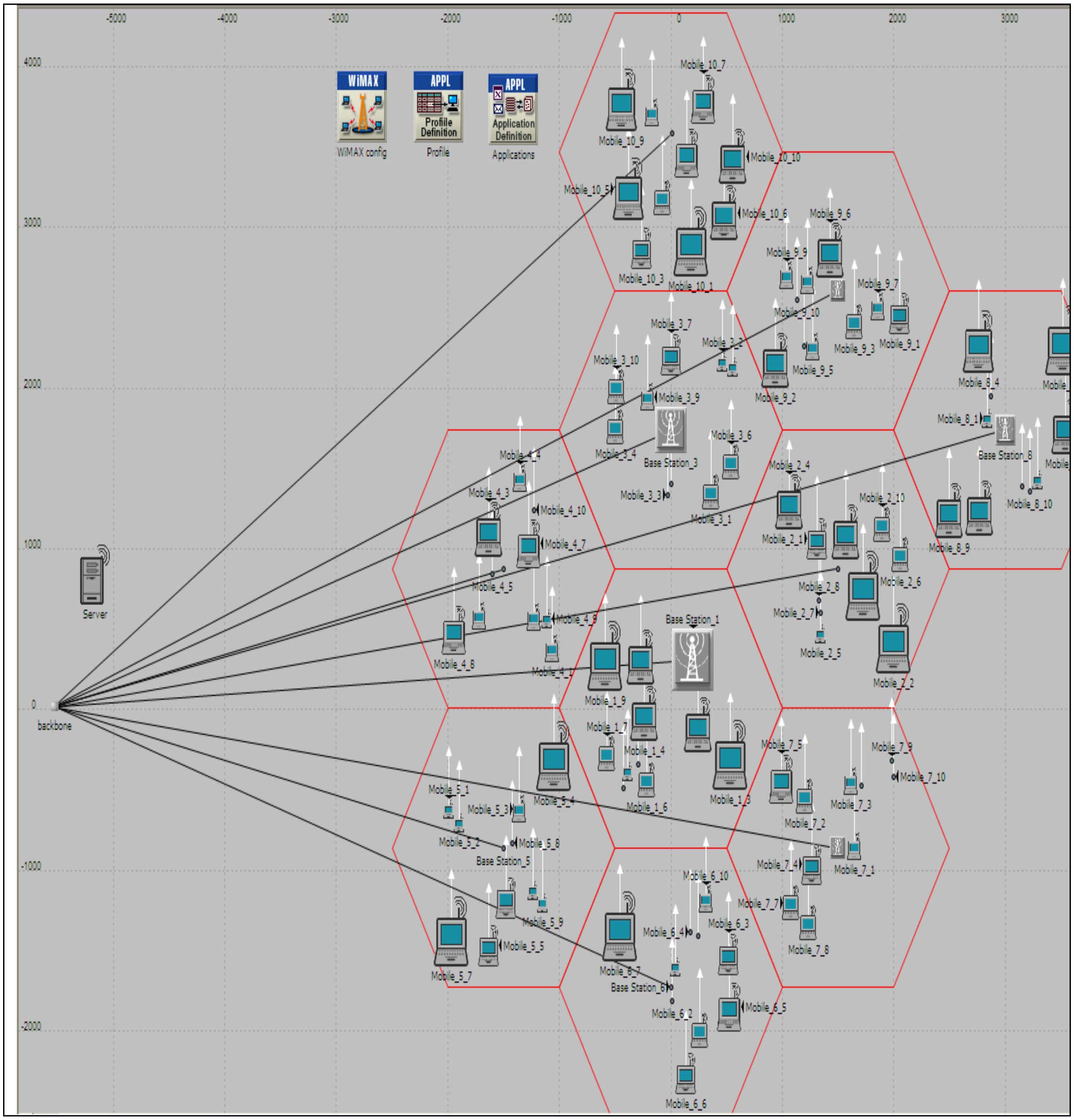

Figure 5.1. Capture of mobile WiMAX simulation when nodes move randomly within two AP`s signal cell.

5.6 Simulation scenarios

Nine Scenarios are created and experiments for each scenario are conducted multiple times. The aim of the experiments for scenario 1-3 is to see how an increasing number of users influence the performance of a WiMAX network. Each scenario`s experimental results will summarized in a separate graph. Therefore, the graphs will clearly indicates how system performance has been influenced by increasing network size. Scenarios 4 to 6 will present data in the same way and will clearly describe how node speed influences the performance of WiMAX. Lastly, Scenarios 7-9 will show how borderless node movements influence the performance of Mobile WiMAX and how performance changes with node speed at the same time.

Network Size (N = 10, 25, 50, 75, 100 nodes in one cell)

Table 5.6 presents the three scenarios for investigating the impact of traffic load on the performance of mobile WiMAX in various network sizes.

Table5.6. Network size experiment scenarios

Node density investigation	
Scenario	**Description**
1	Scenario 1 consists of nine experiments (throughputs, End-to-end delay, upload /download response time, page/object response time, MOS, PDV and Jitter). All experiments used the network environment and configuration illustrated in Table 5.1. Scenario1 is used to investigate the impact of light traffic load on WiMAX performance in varying network sizes. Accordingly, four applications (FTP, HTTP, VoIP, and Video conferencing), network size of 10, 25, 50, 75, 100 nodes and for each application a light traffic load is used. In scenario 1, 2 and 3 all nodes are assumed to be sedentary users, for example, users in the offices, libraries or coffee shops and node speed is 0km/h (fixed).
2	Scenario 2 also consists of nine experiments and the general parameters and configurations are identical with those in scenario 1. In Scenario 2, the traffic load is medium. Scenario2 is used to investigate the impact of medium traffic load on the performance of mobile WiMAX in varying network sizes.
3	Scenario 3 also consists of nine experiments and the general parameters and configurations are also identical with those in Scenario 1. In scenario 3, the traffic load is heavy. Scenario3 is used to investigate the impact of heavy traffic load on the performance of mobile WiMAX in varying network sizes.

Node Mobility (NS= 0, 10, 30, 50, 70, 90Km/h)

Table 5.7 presents the three scenarios for investigating the impact of node mobility on the performance of mobile WiMAX

Table5.7. Node mobility experiment scenarios

Node mobility investigation	
Scenario	**Description**
4	Scenario 4 also consists of nine experiments (throughputs, End-to-end delay, upload /download response time, page/object response time, MOS, PDV and jitter). All experiments used the network environment and configuration presented in Table 5.1. Scenario 4 is proposed to investigate the impact of node mobility on the performance of mobile WiMAX in a small network. Accordingly, four applications (FTP, HTTP, VoIP, and Video conferencing), six node speeds (0, 10, 30,50,70,90 km/h) and 10 nodes with light traffic load are used. Moreover, results from Scenario 4 will also be used to analyse the effect of handoff in small mobile WiMAX networks when compared with results from Scenario 7.
5	Scenario 5 also consists of nine experiments and the general parameters and configurations are also identical with those in Scenario 4. In scenario 5, network size and traffic load are 50 nodes and medium load respectively. Scenario 5 is used to investigate the impact of node mobility on the performance of mobile WiMAX in a medium mobile WiMAX network. Moreover, results from Scenario 5 will also be used to analyse the effect of handoff in medium sized networks by comparing them with results from Scenario 8.
6	Scenario 6 also consists of nine experiments and the general parameters and configurations are also identical with those in Scenario 4. In Scenario 6, traffic load and network size are heavy and 100 nodes respectively. Scenario6 is used to investigate the impact of node mobility on the performance of mobile WiMAX in large sized networks. Moreover, results from Scenario 6 will also be used to analyse the effect of handoff in large mobile WiMAX networks by comparing them with results from Scenario 9.

Node Mobility with handoff (NS= 0, 10, 30, 50, 70, 90Km/h)

Table 5.8 presents the three scenarios for investigating the impact of handoff on the performance of mobile WiMAX.

*Table5.8.*Handoff experiment scenarios

Node mobility with handoff investigation	
Scenario	**Description**
7	Scenario 7 also consists of nine experiments (throughputs, end-to-end delay, upload /download response time, page/object response time, MOS, PDV and jitter). All experiments use the network environment and configuration as shown in Table 5.1 Scenario 7 is used to investigate the impact of handoff on the performance of mobile WiMAX in a small network. Four applications (FTP, HTTP, VoIP, and Video conferencing), six node speeds (0, 10, 30, 50, 70, 90 km/h) and 10 nodes with a light traffic load are identical to those used in Scenario 4. However, here handoff is enabled. Experimental results from Scenario 7 will also be used to analyse the effect of handoff in small mobile WiMAX networks by comparing them with results from Scenario 4.
8	Scenario 8 also consists of nine experiments and the general parameters and configurations are identical to those in Scenario 5. However, in this scenario, handoff is enabled. Accordingly, experimental results from Scenario 8 will also be used to analyse the effect of handoff in medium mobile WiMAX networks by comparing them with results from Scenario 5.
9	Scenario 9 also consists of nine experiments and the general parameters and configurations are identical with those in Scenario 6. All detailed settings are also identical with those in Scenario 5 except that in this scenario, handoff is enabled. Accordingly, experimental results from Scenario 9 will also be used to analyse the effect of handoff in large mobile WiMAX networks by comparing them with results from Scenario 6.

5.7 Summary

In this chapter, the detailed mobile WiMAX system profile and its configurations are presented. In detail, each application`s performance metrics such as throughput, end to end delay, response times, jitter, PDV, MOS and packet loss ratio are discussed and assumptions about the experimental simulation are presented. Hardware and software specifications are also presented and it is shown that they meet the system requirements of OPNET.

Nine distinct scenarios are introduced. Scenarios 1, 2 and 3 put the focus on the impact of network size, while Scenarios 4, 5 and 6 are focused on the impact of node mobility on performance. Lastly, Scenarios 7, 8 and 9 focused on the impact of handoff on performance. The experimental results for performance metrics such as throughput, response time, jitter and delay are provided in the following chapter along with evaluation and analysis of the findings.

Chapter 6

Results and Analysis

6.1 Overview

In Chapter 5, the mobile WiMAX network modelling and experimental design are presented in detail. As noted in Chapter 5, four different traffic types (FTP, HTTP, VoIP and Video conferencing) typically used in wireless networks, three different traffic load sizes (light, medium and heavy) and six node speeds (0, 10, 30, 50, 70 and 90km/h) are used in the simulation experiments to examine the impact of traffic type and node mobility on the performance of mobile WiMAX. The findings of the experiments carried out in the above scenario are discussed in this chapter.

The impact of four different traffic types and load (FTP, HTTP, VoIP and Video conferencing) on the WiMAX performance is discussed in Section 6.2 and the impact of node mobility (0, 10, 30, 50, 70 and 90km/h) is discussed in Section 6.3. The impact of handoff on the performance of mobile WiMAX is discussed in Section 6.4. Lastly, the chapter is concluded in Section 6.5 with a brief summary of the main findings.

6.2 Impact of traffic types on system performance for varying network sizes

This section investigates the impact of four traffic types (FTP, HTTP, VoIP and Videoconferencing) on the performance of mobile WiMAX in networks of different sizes and the results of experimental Scenarios 1, 2 and 3 are provided. As the section aims to investigate the impact of traffic type on system performance, node speed is fixed at 0 km/h in the experiments. Averages of the results are presented for a simulation time of 900 seconds.

6.2.1 FTP in networks of different sizes

Figures 6.1 and 6.2 show the results for download and upload response times respectively for three different FTP traffic loads when network size increases. Download and upload response times are excellent performance metrics for FTP performance, as they reflect the efficiency and effectiveness of download and upload activities.

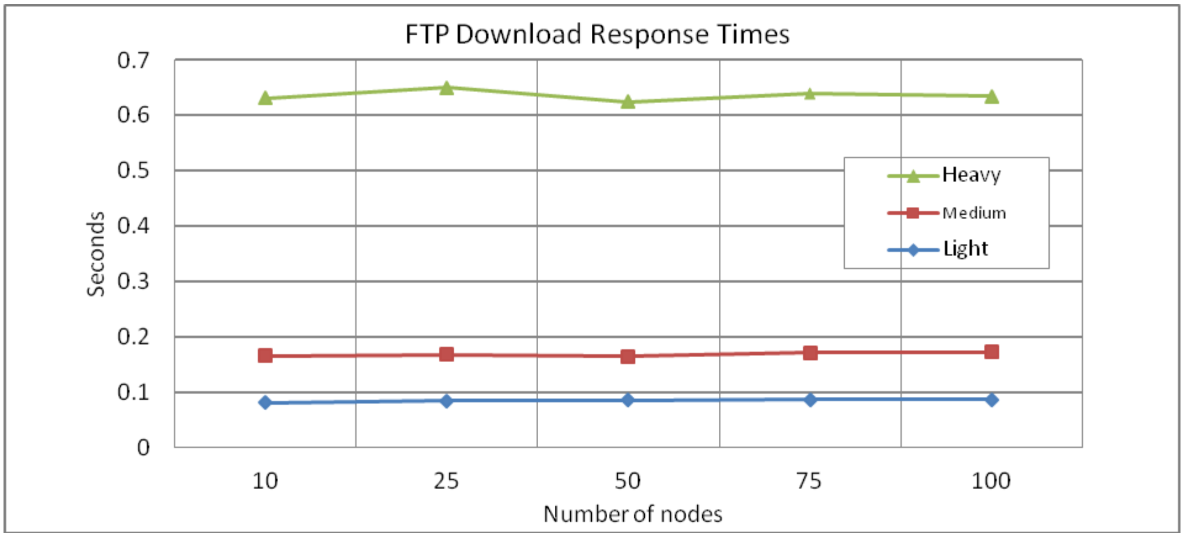

Figure6.1. Average FTP download response times versus number of nodes

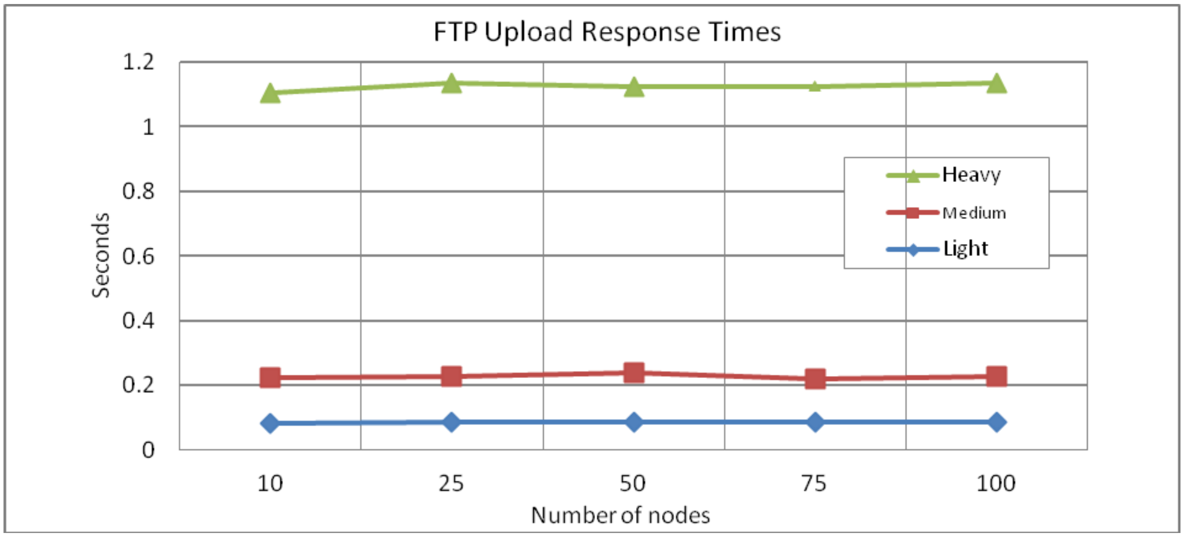

Figure6.2. Average FTP upload response times versus number of nodes

As shown in Figures. 6.1 and 6.2, there was a noticeable difference between light, medium and heavy traffic loads.

Figure 6.1 also shows that the FTP download response times slightly increase when the number of nodes increases.

Light, medium and heavy FTP download response times increase by 5.86%, 4.00% and 0.55% respectively when the number of nodes increases from 10 to 100. In addition, for all network sizes the download response times are less than one second. Light FTP traffic download response times vary between 0.082 and 0.086 seconds, medium FTP traffic times vary between 0.165 and 0.1732 seconds while heavy FTP traffic times vary between 0.624 and 0.651 seconds. Figure 6.1 shows that there is no significant relationship between a download response time and the number of mobile nodes (up to 100 nodes). The trend line is almost a straight line for all network sizes, meaning download response time is not affected significantly by increasing the number of nodes. On the other hand, download response time itself does increase when there is an increase of traffic and this is an expected outcome.

Figure 6.2 also shows that the FTP traffic upload response times only slightly increases with the increase in the number of nodes. Light, medium and heavy FTP traffic upload response times increased by 2.47%, 1.72% and 2.69% respectively when the number of nodes increased from 10 to 100. Light FTP traffic upload response times are between 0.082 and 0.087 seconds, medium FTP traffic upload response times are between 0.22 and 0.24 seconds while heavy FTP traffic upload response times are between 1.106 and 1.135 seconds. Figure 6.2 shows that there is no direct relationship between the upload response time and the number of nodes as the trend line is almost straight for all network sizes. This means that upload response time is not affected significantly when the number of nodes increase (up to 100 nodes). On the other hand, upload response time does increase when there in an increase in the amount of traffic and this is also an expected outcome.

6.2.2 HTTP in networks of different sizes

Figure 6.3 and 6.4 show the experimental results for object and page response times for three different HTTP traffic loads over increasing network size.

The HTTP object and page response times are excellent performance metrics to measure WiMAX performance, as they reflect the efficiency and effectiveness of activities related to retrieving on object and a webpage respectively. The focus here is on how the HTTP response times change with an increasing the number of nodes.

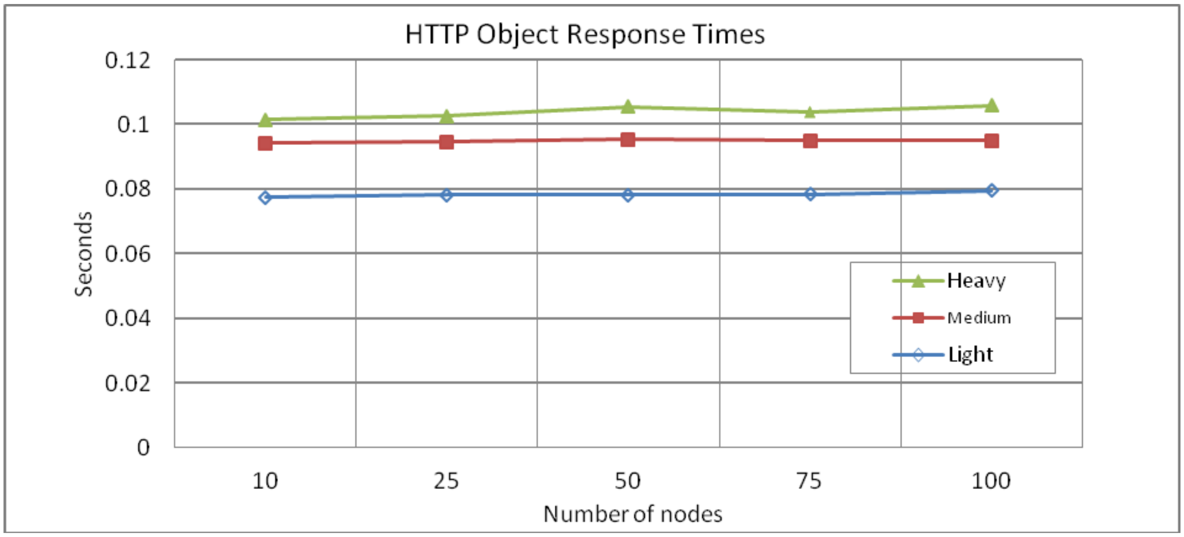

Figure6.3. Average HTTP object response times versus number of nodes

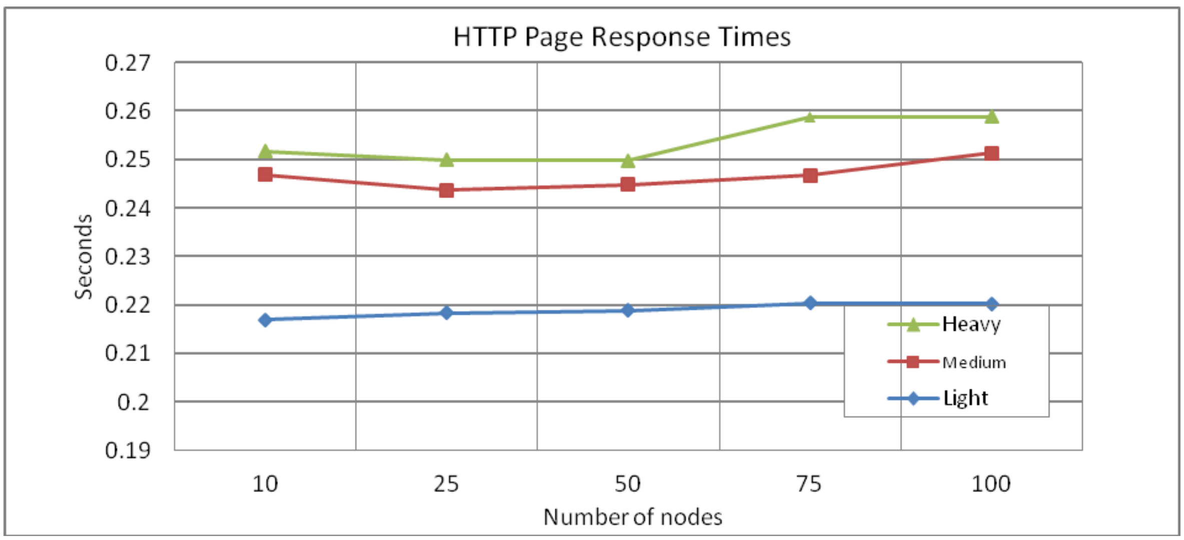

Figure6.4. Average HTTP page response times versus number of nodes

Figure 6.3 shows that increasing the number of nodes leads to a slight increase in HTTP traffic object response times.

Object response times for heavy, medium and light traffic increased by 2.54%, 0.74% and 4.34% respectively when the number of nodes increased from 10 to 100. In addition, all object response times are less than 0.12 seconds for all network sizes. Light HTTP traffic object response times are between 0.077 and 0.0795 seconds, for medium HTTP traffic load they are between 0.0943 and 0.0950 seconds and for heavy HTTP traffic the times are between from 0.1015 and 0.1059 seconds.

As shown in Figure 6.3, there is no significant relationship between object response time and the number of mobile nodes. The trend line is almost straight for up to 100 nodes, meaning that HTTP object response time is not affected significantly when the number of mobile nodes is increases. On the other hand, object response time does increase when there in an increase in traffic size and this is an expected result.

Figure 6.4 shows that page response times increase slightly for all types of HTTP traffic when the number of nodes is increased. The page response times for light, medium and heavy HTTP traffic increased by 1.56%, 1.81% and 2.84% respectively when the number of nodes increased from 10 to 100 nodes. In addition, all object response times are less than 0.3 seconds for all network sizes. Page response times for light HTTP traffic are between 0.2169 and 0.2203 seconds, for medium traffic they are between 0.2469 and 0.2514 seconds while for heavy HTTP traffic page response times are between 0.2517 and 0.2588 seconds.

Figure 6.4 shows that there is no strong relationship between page response time and the number of mobile nodes. The trend line is almost straight for networks of up to 100 nodes, meaning HTTP page response time is not affected significantly when the number of mobile nodes is increases. On the other hand, page response time does increase with an increase in traffic size and this is also a predicted outcome.

6.2.3 Video conferencing in networks of different sizes

Figures 6.5 and 6.6 show the results for packet delay variation (PDV) and end-to-end delay for three different Video conferencing (Videocon) traffic loads with network size increasing from 10 to 100 nodes. The PDV and end-to-end delay are excellent performance metrics to measure the quality of Video conferencing, as they represent the time difference between source and destination. High PDV and end-to-end delay result in degradation of voice and audio quality (i.e. echoes). The aim of this experiment is to investigate how the PDV and end-to-end delay time change with an increase in node numbers and traffic load

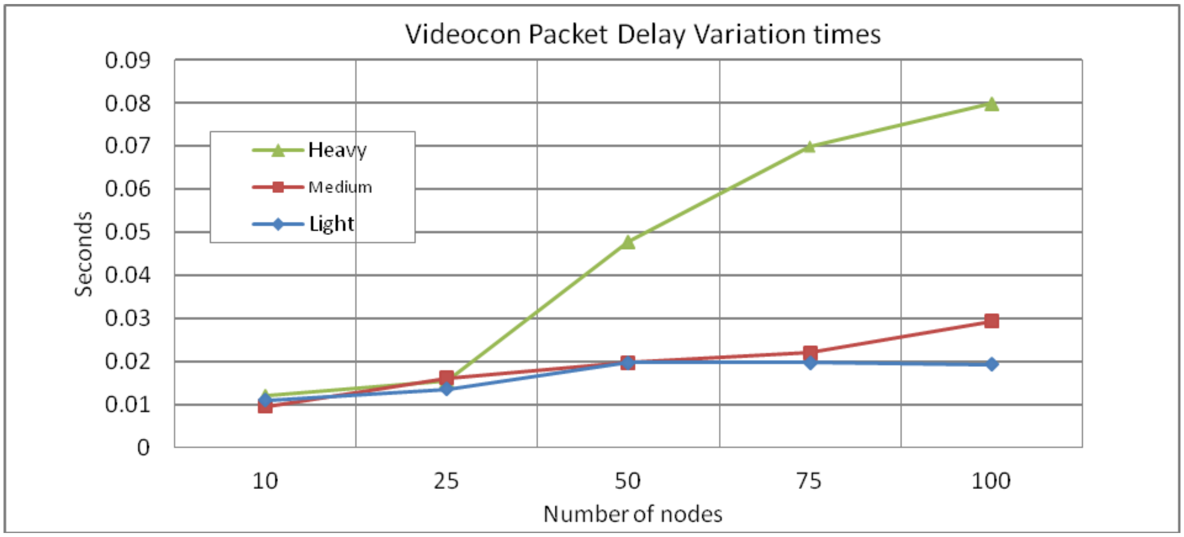

Figure6.5. Average Packet Delay Variation (PDV) versus number of nodes

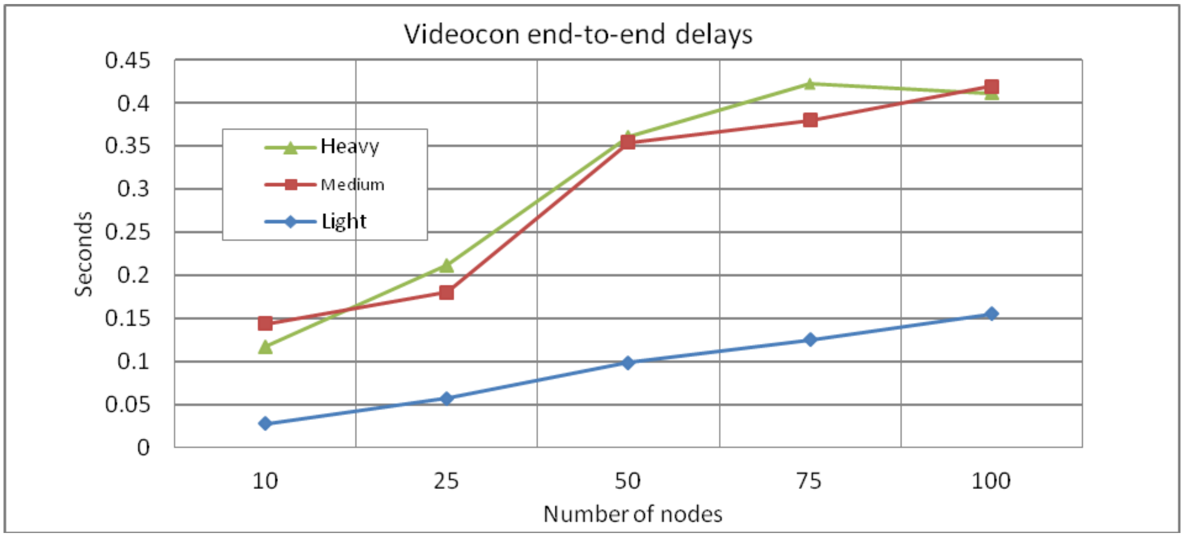

Figure6.6. Average end-to-end delay versus number of nodes

Figure 6.5 shows that PDV for all three types of Videocon traffic increase with an increase in the number of nodes. PDV for light, medium and heavy Videocon traffic increases by 75.26%, 207.22% and 564.3% respectively while the node number increases from 10 to 100nodes. The delay for heavy Videocon traffic PDV exceed 50ms once the number of nodes is higher than 50.

PDV for light Videocon traffic is between 0.011 and 0.198 seconds, for medium traffic it is between 0.009 and 0.029 seconds and PDV for heavy traffic is between 0.012 and 0.079 seconds. The graph shown in Figure 6.5 demonstrates that there is a direct relationship between PDV and the number of mobile nodes. At the same time, PDV increases when Videocon traffic load increases. Figure 6.6 shows that for all types of Videocon traffic end-to-end delay increases when node number increases. For light, medium and heavy Videocon traffic end-to-end delays increases by 449.25%, 191.87% and 248.70% respectively, while the number of mobile nodes increases from 10 to 100 nodes. For Videocon of any type the end-to-end delays exceed 100ms which is on the border of the human perception of delay[69]. End-to-end delay of more than 100ms may lead to video and audio being unsynchronized [69, 70]. End-to-end delays for light Videocon traffic vary between 0.028 and 0.155 seconds, for medium traffic the variation is between 0.143 and 0.430 seconds and for heavy traffic the delay varies between 0.011 and 0.422 seconds. Figure 6.6 shows that there is a direct relationship between end-to-end delay and the number of mobile nodes. The graph shows clearly that the delay and the number of nodes are directly proportional. Videocon end-to-end delay is affected significantly when the number of mobile node increases. End-to-end delay also increases when Videocon traffic increases.

6.2.4 VoIP in varying network sizes

Figure 6.7 and 6.8 show results for jitter and Mean Opinion Score (MOS) for three different VoIP traffic loads with increasing network size. Jitter and MOS are excellent performance metrics to measure VoIP performance, as they represent the time difference between source and destination and a measurement of voice quality respectively. The focus in this experiment is to investigate how jitter and MOS change in VoIP as the number of nodes increases.

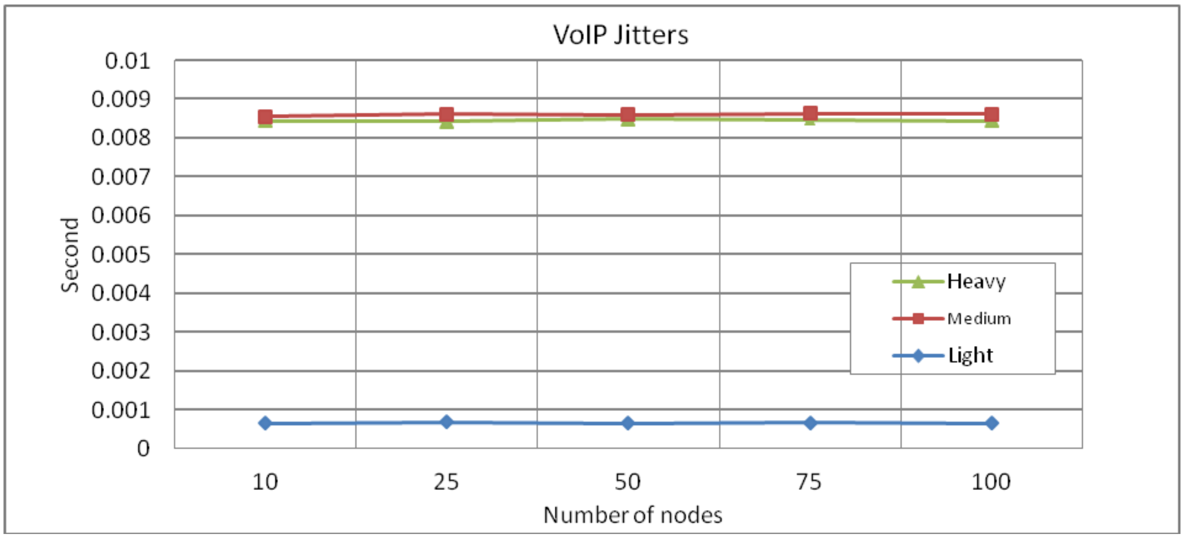

Figure6.7. Average VoIP jitter versus number of nodes

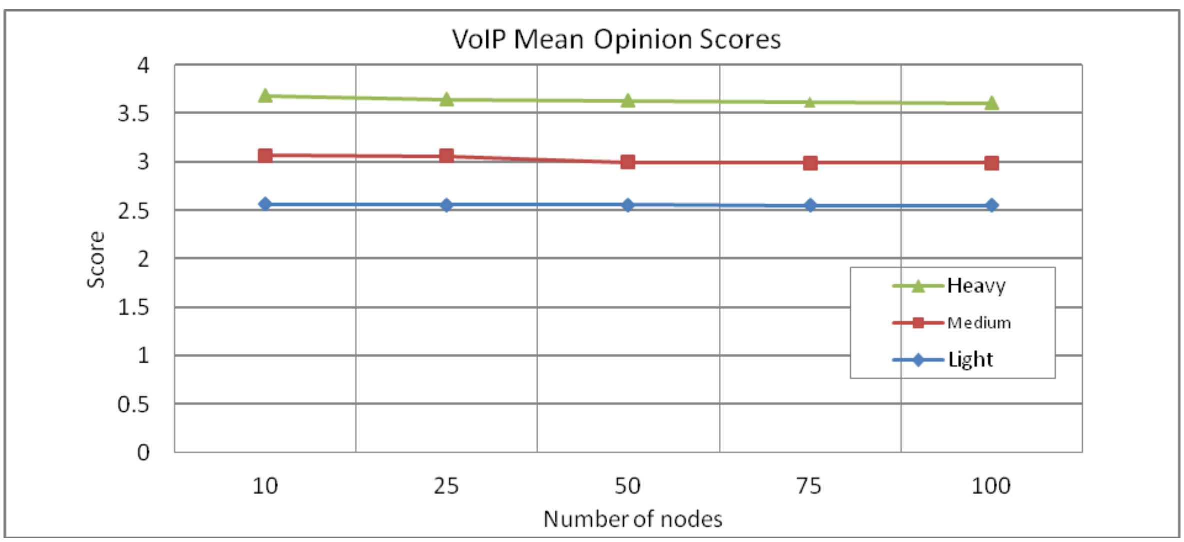

Figure6.8. Average VoIP Mean Opinion Score (MOS) versus number of nodes

Figure 6.7 demonstrates that for any type of VoIP traffic (light, medium and heavy) jitter remains nearly unchanged regardless of the increase in the number of nodes.

The jitter increases for the three types of traffic load are 0.01%, 0.71% and 0.00% (2sf) respectively when the number of nodes increases from 10 to 100. It is also noted that none of the jitter times exceed 9ms for any network size. Jitter for light traffic is measured at between 0.0662 and 0.0692ms, jitter for medium traffic is measured at between 8.56 and 8.64ms and for large VoIP traffic jitter, varies between 8.43 and 8.46ms.

Figure 6.7 shows that there is no direct relationship between jitter time and the number of nodes. The trend line remains nearly horizontal for all network sizes, meaning VoIP jitter does not get affected even slightly by increasing the number of node (up to 100 nodes). Figure 6.8 demonstrates that MOS remains nearly constant for any type of VoIP traffic regardless of the increase in the number of nodes. More precisely, for light, medium and heavy traffic loads MOS decreases by 0.55%, 2.61% and 1.99% respectively as the number of nodes increases from 10 to 100 nodes. The average MOS score is 2.56 for light, 3.00 for the medium and 3.62 for heavy traffic loads respectively.

MOS is not affected significantly with increasing in the number of nodes. MOS does increase when there in an increase in traffic load, but it doesn’t reach the level of 4 points for any network sizes. The score of 4 still represents good quality voice communication.

6.2.5 Overall throughput and packet loss ratio

Figures 6.9, 6.10 and 6.11 show the average throughputs and packet loss ratios (traffic sent/received) for four applications (FTP, HTTP, VoIP and Videocon) in three typical network environments (light traffic load with 10nodes, medium traffic load with 50nodes and heavy traffic load with 100nodes). The focus in these experiments is to investigate the throughput and packet loss when the size of the network is increased.

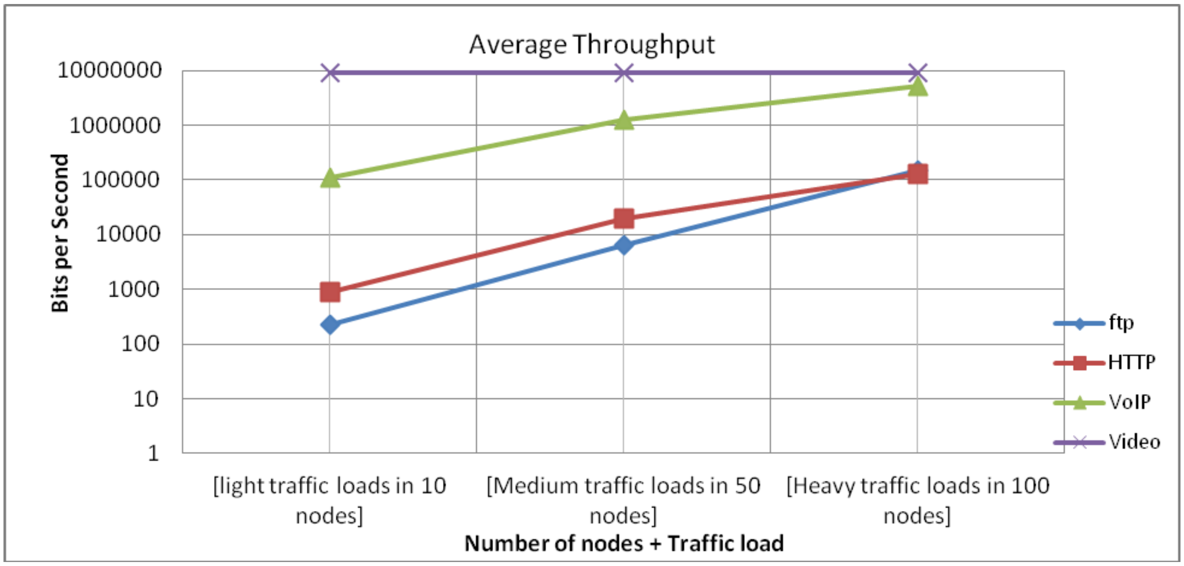

Figure6.9. Average Throughputs versus three typical network environments

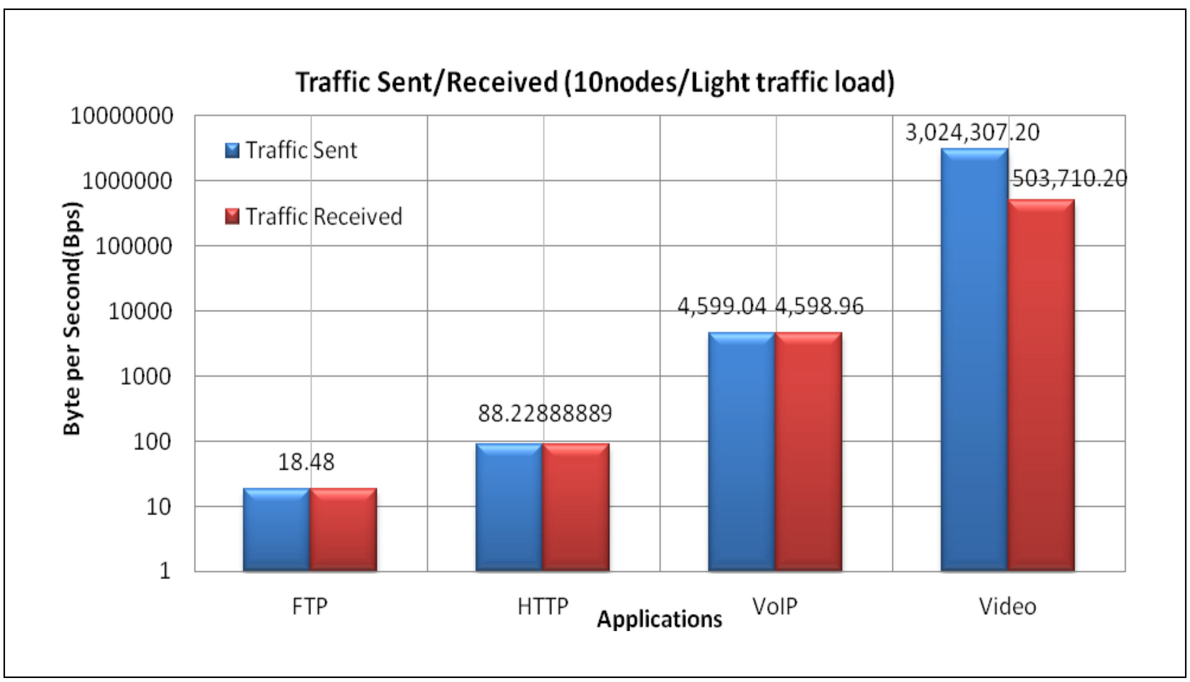

Figure6.10. Log scaled histogram of traffic sent and received with 10 fixed nodes with light traffic loads

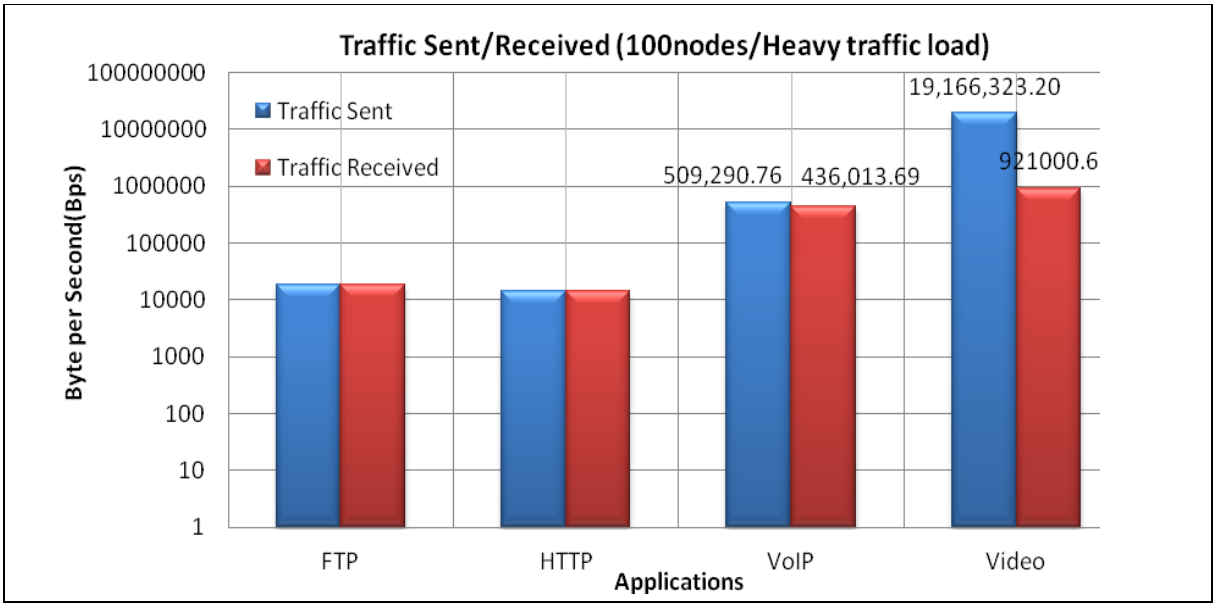

Figure6.11. Log scaled histogram of traffic sent and received with 100 fixed nodes with heavy traffic loads

As shown in Figs. 6.9, 6.10 and 6.11, there are noticeable differences between FTP, HTTP, VoIP and Video conferencing traffic. Figure 6.9 shows the average throughput of the four applications in three different network environments. Figure 6.10 shows the difference in the amount of traffic sent and received for the four applications in a small network. Numbers above the blue-coloured bar indicate how many packets have been sent (requests) from the nodes and numbers above the red-coloured bar indicate how many packets have been received (responses) by the nodes. Figure 6.11 shows the difference in the amount of traffic sent and received for the four applications in a large network. As in the case of Figure 6.10, numbers above blue-coloured bar indicate how many packets have been sent (requests) from the nodes and numbers above the red-coloured bar indicate how many packets have been received (responses) by the nodes. Figures 6.10 and 6.11 represent packet loss ratio (traffic sent/received) and data is presented in *Appendix B; packet loss ratio*.

Figure 6.9 shows that the throughput for Video conferencing remains constant at approximately 9Mbps regardless of increase in network size and traffic load. However, throughput for VoIP, HTTP and FTP increase in direct proportion to the increase in network size and traffic load. Throughput for VoIP, HTTP and FTP are approximately 110kbps, 904bps and 225bps respectively in a small network environment; for heavy traffic load in a large network their throughputs increase up to approximately 5Mbps, 126kbps and 153kbps. Figure 6.9 demonstrates that except for video conferencing which almost reaches peak throughput in the experiment, there is a direct relationship for the other three applications between the throughput and the size of the network. The trend line goes up when the network size and traffic loads are increased. Moreover, throughputs for delay-sensitive traffic types (i.e. VoIP and Video conferencing) are certainly higher than throughputs for delay-tolerant traffic types (i.e. FTP and HTTP).

Figure 6.10 and 6.11 show that packet loss ratios for both FTP and HTTP remain nearly unchanged (approximate change is ±0.01%) with increasing traffic load and network size.

However, for the delay-sensitive packet types (VoIP and Video conferencing) packet loss ratio increases in direct proportion to the increase in traffic load and network size. Packet loss ratio for VoIP increases from 0.0% to 14.39% when the size of the network increases and packet loss ratio for Videoconferencing increases from 84% to 95% when the size of the network is increased. Packet loss ratios for FTP and HTTP remain almost 0.0% for all network and traffic load sizes, meaning that packet loss ratio is not even slightly affected when traffic load and network size are increased. On the other hand, packet loss ratio for VoIP and Video conferencing are significantly affected when traffic load and network size are increased.

6.2.6 Discussion

It is observed that WiMAX performance with the four applications (FTP, HTTP, VoIP and Videoconferencing) changes when traffic load and the size of the network increase. Our assumptions about these applications are as follows: FTP reflects the general file downloading and uploading activities. HTTP reflects general web browsing activities such as web surfing. VoIP reflects the voice communication services between two mobile nodes such as Skype; Video conferencing represents a combination of video and voice communication such as Apple Face time [18, 36, 71].

Four servers are used in the experiment and the configurations of all mobile nodes are assigned by **profile_config** and **application_config** command nodes. In order to prevent server overload, each server manages only one traffic type. Normally, **ping** time to a popular server (e.g. Google) only takes 1ms or slightly more. However, the efficiency of server functions is beyond the scope of this thesis.

Four different applications are selected to test the performance of WiMAX and the throughput and packet loss ratios (*refer to Appendix B. Packet loss ratios*) for all those applications should be presented in one graph for ease of comparison. However, as they have different characteristics and performance metrics, results are presented separately.

According to the experimental results, one can tentatively state that the FTP traffic load is a significant factor that influences the WiMAX performance much more than the number of nodes. Download and upload response times for heavy FTP traffic in a network of 10 nodes were longer than those for light FTP traffic in a network of 100 nodes. This indicates that the performance of mobile WiMAX may be more affected by traffic loads than by the number of nodes in the network.

According to the experimental results, one can also tentatively infer that mobile WiMAX has sufficient capacity to transmit any FTP traffic load from/to any number of nodes. When the network size and traffic load increase, the throughput also increases and packet loss ratio remains 0 % (*refer to Appendix B. Packet loss ratios*). This means that there are almost no retransmission or packet drops which are usually seen as the main indicator for inefficient use of mobile WiMAX network resources. The conclusion here is that, FTP transmission does not present a significant challenge to the mobile WiMAX for any network size or any traffic load.

Object and page response times for heavy HTTP traffic in a network of 10 nodes were also uniformly longer than those for light HTTP traffic in a network of 100 nodes, meaning that the performance of mobile WiMAX is likely to be affected much more by the size of HTTP traffic load than by the number of nodes in the network.

When the network size and traffic load are increased, throughput increases proportionally and packet loss ratio increases slightly from 0% to 0.016% (*refer to Appendix B. Packet loss ratio*). Packet loss ratio of 0.016% is negligible in a wireless network. In addition, page/object response times remain less than one second for any size of network. Accordingly, we can conclude that HTTP transmission does not present a significant problem to the performance of mobile WiMAX.

It appears that transmission of FTP and HTTP over a mobile WiMAX network may work reasonably well for networks of up to 100 nodes with a large traffic load.

Performance of Videoconferencing is significantly affected by changes in traffic load and network size. According to experimental results, PDV and end-to-end delay increase proportionally with the increase in node number and traffic load. At the same time, packet loss ratio is unusually high (84%) and increases up to 95% while throughput remains nearly unchanged (approximately 9Mbps). This means that video conferencing packets may not be efficiently transmitted for any size of network.

Moreover, its remarkably high packet loss ratio indicates that transmission has not been successfully completed and this could cause numerous retransmissions which usually result in a waste of network resources.

Therefore, we have changed the QoS settings from BE to UGS and the MCS setting from QPSK1/2 to 64 QAM3/4 which can provide high throughput with narrower coverage. Subsequently, average packet loss ratio is decreased by 9% (*refer to Appendix B. Packet loss ratio*) and throughput is also decreased from 9Mbps to 6Mbps. It is apparent that change in the QoS and MCS settings do not lead to a dramatic improvement in performance. A video conferencing provides two- or multiple-way interactive video communication. Normally, as the number of participating users increases, traffic load may exponentially increase. Consequently, without multiple numbers of APs, we can conclude that a video conferencing service over mobile WiMAX may not work even moderately in a small network.

According to the experimental results, quality of audio (MOS) of VoIP service does not reach a fair level (point4) for any network volume. Interestingly, all average jitter values are less than 10ms. When jitter is greater than 50 ms, it is difficult to transfer the packets smoothly and this causes noticeable degradation in the quality of audio (echoes) or dropout in audio. In terms of jitter, VoIP jitter in all experiments is reasonably low. Ironically, quality of audio in terms of MOS, does not reach a fair level for any network sizes or traffic load.

We can cautiously state that this phenomenon is due to the fact that jitter and MOS have different computing schemes and a compressed VoIP codec is used in the experiment. Jitter indicates a time difference between previous packet and subsequent packet arrival. However, MOS is a relative scale and is built upon various factors such as latency of connection, packet loss and jitter [66, 72]. In addition, a compressed codec consumes less bandwidth, but the compression process lowers voice clarity and introduces delay.

On the other hand, average packet loss ratio for VoIP is nearly 0% in a small network, although it increases up to 15% in a network with heavy traffic (*refer to Appendix B. Packet loss ratios*). VoIP does not tolerate packet loss and even 1% packet loss can result in significant degradation of voice quality. In addition, according to [51], the default G.729 codec used in the experiment requires packet loss of far less than 1% to avoid audible errors. Thus, there should be no packet loss for VoIP. Consequently, we can state that the impact of VoIP on the performance of mobile WiMAX increases when traffic load increases. Although the quality of audio for any network size is not as good as an ordinary landline, users can use the voice communication service with some echo and noise, provided the network is small.

6.3 Impact of node mobility on WiMAX

In section 6.2, the impact of four traffic types (FTP, HTTP, VoIP and Video conferencing) on the performance of mobile WiMAX are reviewed. This section aims to analyse the impact of node mobility on the performance of mobile WiMAX. The combined results of Scenarios 4, 5 and 6 are presented and discussed here. Scenario 4 uses a small network with 10 mobile nodes and a light traffic load and we call this scenario “light”. Scenario 5 uses a medium size network with 50 mobile nodes and a medium traffic load and we call it “medium”. Scenario 6 uses a large network with 100 mobile nodes and a heavy traffic load and we call it “heavy”. Experiments are conducted in each scenario using four traffic types (FTP, HTTP, VoIP and Video conferencing) with various mobile node speeds (NS=0, 10, 30, 50, 70 and 90km/h). As described in chapter 5, a node speed of 0~30km/h is considered “slow speed”, 30~50km/h is “medium speed” and 70~90km/h is considered “high speed”. Four servers for each traffic type are set up in all experiments. Simulation time is 900 seconds.

6.3.1 FTP with diverse node speeds

This section presents the experimental results for the download/upload response time for three different types of FTP traffic loads and increasing node speed. Download and upload response times are excellent performance metrics for FTP data traffic, as they measure the efficiency and effectiveness of download and upload activities when nodes move. Our interest is to find out how the FTP upload and download response time changes with an increase in mobile node speed.

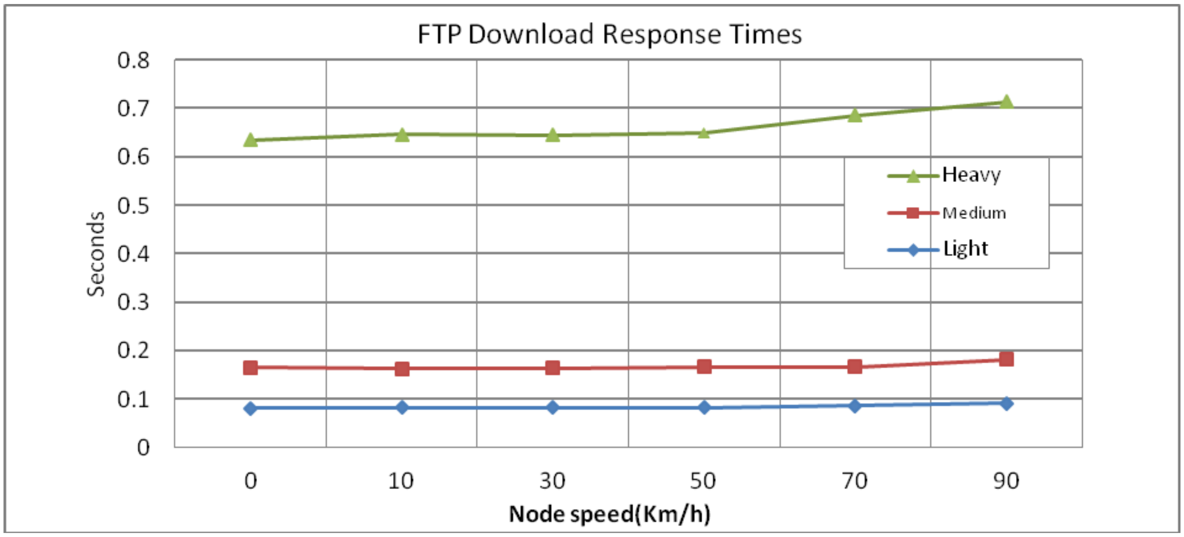

Figure6.12. Average FTP download response time versus node speed

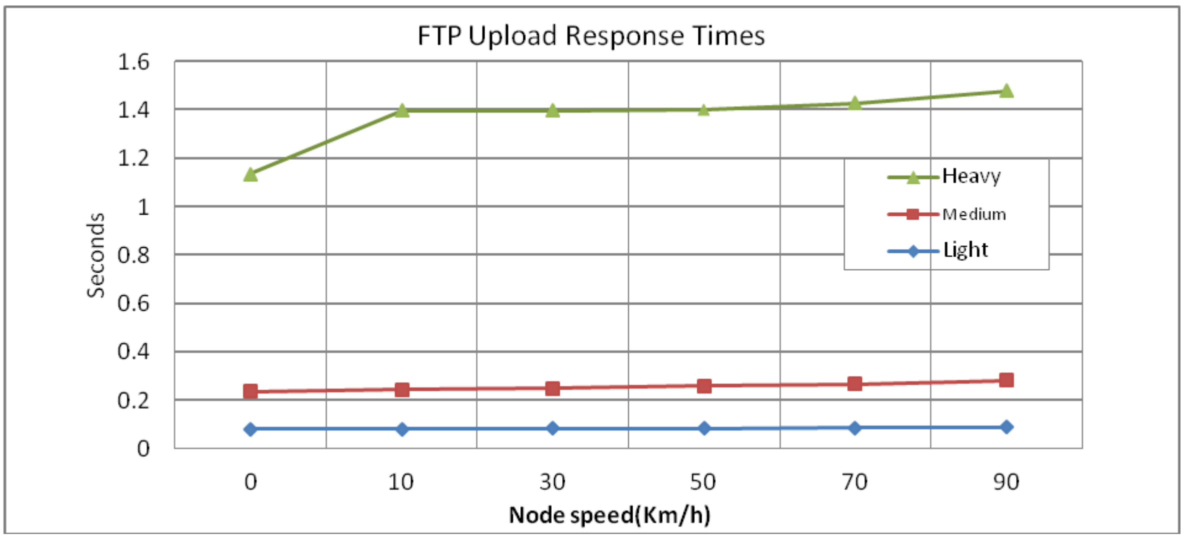

Figure6.13. Average FTP upload response time versus node speed

Download and upload response times for light FTP traffic slightly increase when the node speed increases. The average download response time increases by 11.7% and upload response time increases by 8.3% when the speed of the nodes is increased from 0 to 90 km/h. Download response times are between 0.082 and 0.092 seconds and upload response times are between 0.083 and 0.090 seconds.

Download and upload response times for medium FTP traffic increase slightly when the node speed increases. The download response time increases by 9.8% and the upload response time increases by 18.7% when node speed increases from 0 to 90km/h. Download response times are between 0.16 and 0.18 seconds and upload response times are between 0.23 and 0.28 seconds. The average download and upload response times for medium traffic are almost twice as long as those for light traffic.

Download and upload response times for heavy traffic increase moderately when the speed of nodes is increased. Download response time increases by 12.3% and upload response time increases by 30.1% when node speed increases from 0 to 90km/h.

Download response times are between 0.63 and 0.71 seconds and upload response times between 1.13 and 1.47seconds. The download and upload response time for heavy FTP significantly increased from 50km/h to 90km/h (medium to high speed). The average download and upload response for heavy traffic are almost four or five times longer than for medium traffic.

6.3.2 HTTP with diverse node speeds

This section presents experimental results for object and page response times for three different HTTP traffic loads and increasing node speed. Object and page response time are excellent performance metrics for HTTP data traffic, as they evaluate the efficiency of retrieving objects and web pages when nodes move. Our interest in these data is to find out how the speed of mobile nodes affects performance.

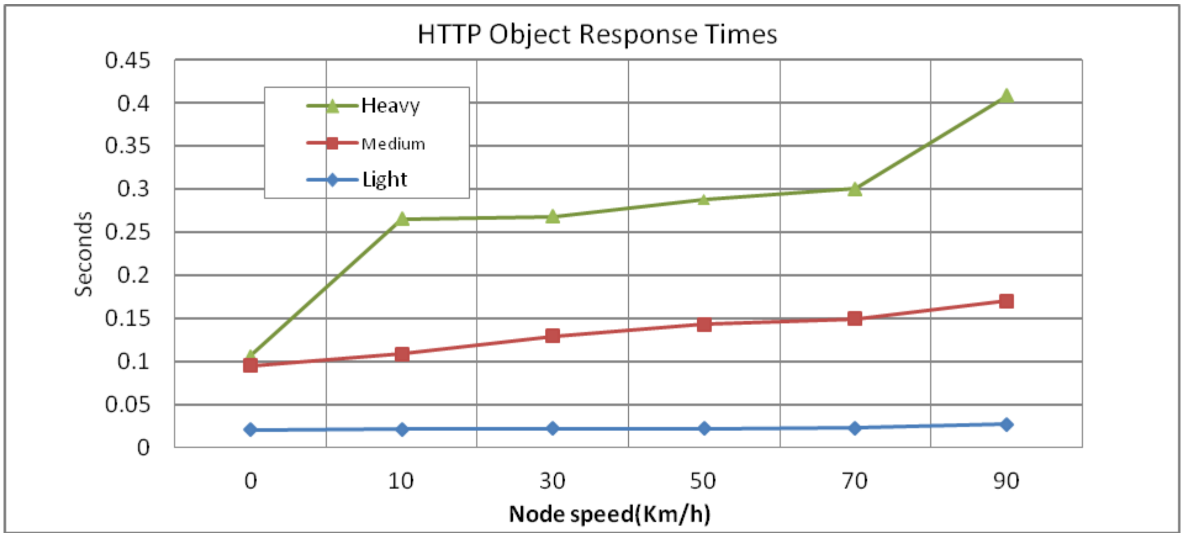

Figure6.14. Average HTTP object response time versus node speed

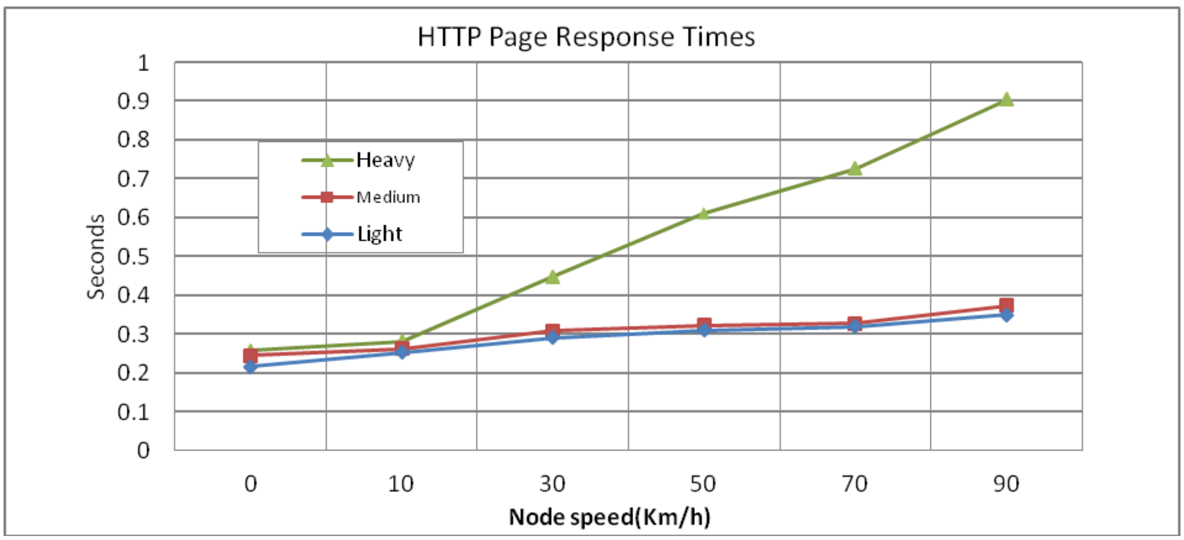

Figure6.15. Average HTTP page response time versus node speed

As shown in Figures 6.14 and 6.15, there is a noticeable difference in response times for the three types of HTTP traffics.

For light traffic, object response time increases by 31.1% and page response time increases by 61.9% when the node speed is increased from 0 to 90km/h. HTTP object response times are between 0.020 and 0.027 seconds and HTTP page response times are between 0.22 and 0.35 seconds.

For medium traffic, object response time increases by 78.6% and page response time increases by 53.1% when the node speed is increased from 0 to 90km/h. Object response times are between 0.095 and 0.171 seconds and page response time are between 0.242 and 0.375seconds. The average object response time for medium traffic is almost five times longer than for a light traffic load. The average page response time for medium traffic load is almost 1.3 times longer than that for a light traffic load.

The object and page response times for heavy traffic load increase in direct proportion to node speed. Object response time increases by 285.6% and page response time increases by 266.0% when the node speed is increased from 0 to 90km/h. Figures 6.14 and 6.15 present clearly the relationship between response time and the speed of mobile nodes. This means that heavy HTTP traffic load object and page response times are affected by the increasing speed of mobile nodes. Average object and page response times for a heavy traffic load are almost twice as long as those for a medium traffic load.

6.3.3 Video conferencing with diverse node speeds

This section presents experimental results for PDV and end-to-end delay for Video conferencing (Videocon) for three different traffic loads and increasing node speed. The PDV and end-to-end delay are realistic performance metrics for the quality of Videocon as they represent the quality of video conferencing communication numerically. Our interest is to find out how Videocon performance changes when the speed of mobile nodes is increased. Figures 6.16 and 6.17 show the results

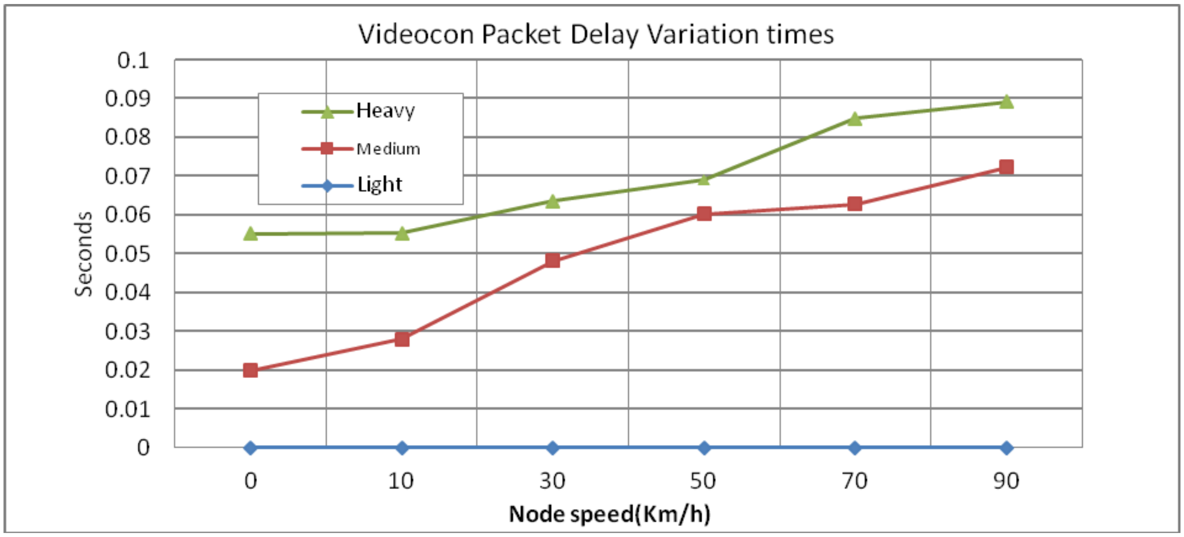

Figure6.16. Average Packet Delay Variation (PDV) versus node speed

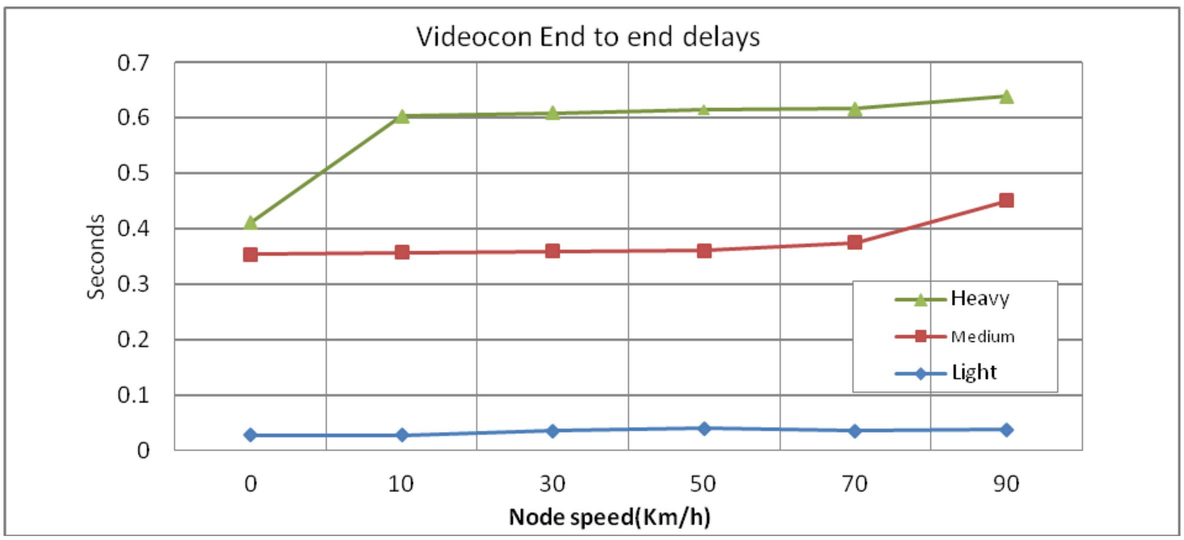

Figure6.17. Average end-to-end delay versus node speed

PDV and end-to-end delay for a light traffic load increase as the node speed increases. PDV is increased by 143.7% and end-to-end delay increases by 34.6% when the speed of nodes is increased from 0km/h to 90km/h. However, PDV time only increases by 0.02 ms and end-to-end delay also increases by only 12ms.

PDV and end-to-end delay for a medium traffic load increase when the node speed increases. PDV time increases by 264.3% and end-to-end delay increases by 27.5% when the node speed is increased from 0 to 90km/h. The PDV for medium traffic Video conferencing increases rapidly from the beginning. However, end-to-end delay for medium traffic video conferencing only increases slightly for speeds up to 50km/h and then from 70km/h (high speed), increases more steeply. PDV and end-to-end delay for a heavy traffic load both increase when the node speed increases. PDV time increases by 61.7% and delay increases by55.3% when the node speed increase from 0 to 90km/h. PDV and end-to-end delay for heavy traffic start increasing as soon as the mobile nodes start to move. However, for speeds between10km/h and 70km/h, end-to-end delay stops increasing, but from 70km/h increases sharply. Average PDV times are between 55ms and 89ms; end-to-end delays are between 41ms and 64ms.

6.3.4 Mobile VoIP with diverse node speeds

This section presents and discusses the experimental results showing the effect on jitter and MOS for three different types of traffic load in m-VoIP when node speed is increased. M-VoIP is a VoIP service with added mobility. Jitter and MOS are reasonably performance metrics for the quality of audio, as jitter represents the transmission time difference between source and destination and MOS provides a voice quality score. Our interest in these data is to investigate how m-VoIP performance changes when the speed of mobile nodes increases.

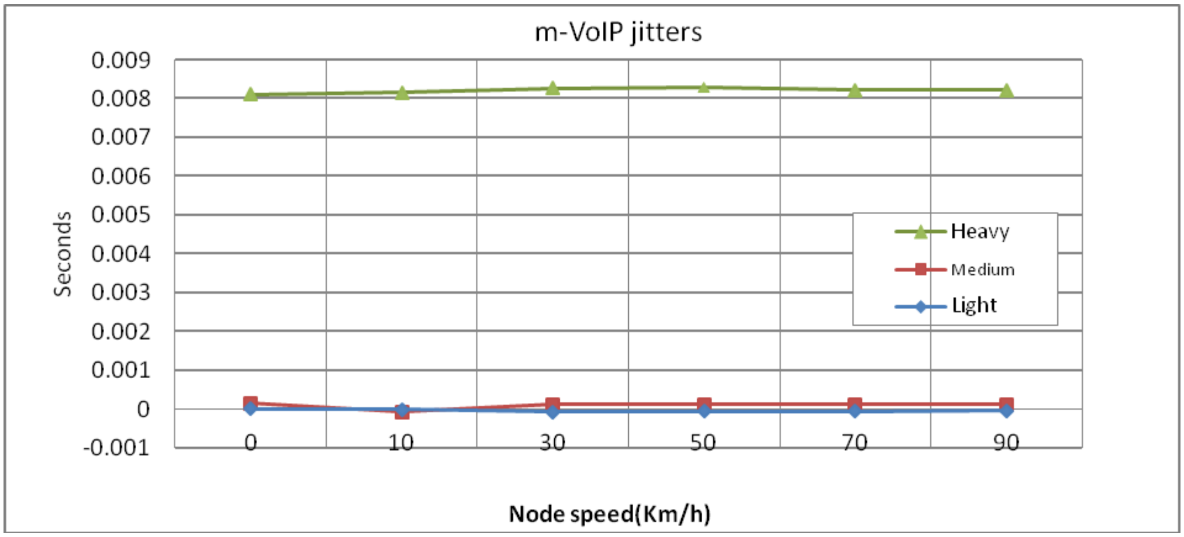

Figure6.18. Average Jitter versus node speed

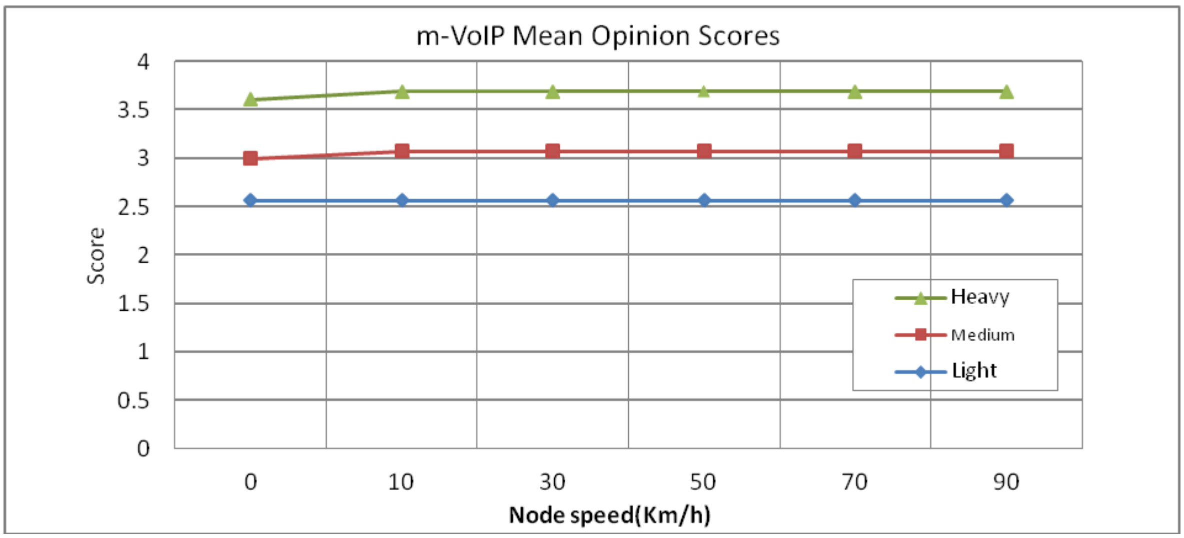

Figure6.19. MOS score versus node speed

Jitter and MOS for light m-VoIP traffic are nearly unchanged regardless of the increase in node speed. Jitter and MOS only changed within the a range of ±0.1% when node speed increased from 0km/h to 90km/h. Jitter was between 0.0057ms and 0.0062ms and MOS between 2.5650 and 2.5653 points.

Similarly, jitter and MOS for medium m-VoIP traffic remain nearly the same regardless of the increase in node speed. Jitter and MOS increase and decrease by ± 0.1% while node speed increased from 0 to 90km/h. Jitter was between 0.073 and 0.15ms and MOS between

3.0005 and 3.0736 points. There is no significant difference between in jitter between light and medium traffic m-VoIP. However, MOS for medium m-VoIP traffic is approximately 0.5points higher than for light traffic m-VoIP.

Jitter and MOS for heavy m-VoIP traffic also remain nearly unchanged regardless of the increasing speed of mobile nodes. However, there is a significant difference between jitter for heavy m-VoIP traffic and that of light and medium traffic. Jitter for heavy m-VoIP traffic is between 8.1ms and 8.3ms, almost 50times greater than that for a medium traffic load. In addition, MOS for a heavy traffic load is approximately 0.6points higher than for m-VoIP with a medium traffic load.

6.3.5 Overall mobile WiMAX throughput

This section discusses the average throughputs and ratios of traffic received/sent (packet loss) by four applications (FTP, HTTP, m-VoIP and Videocon) in three network environments (light traffic loads in a 10 node network with 10km/h node speed, a medium traffic load in 50 node network with 50km/h node speed and a heavy traffic load in 100 node network with 90km/h node speed). Our interest in this section is to find out how throughput and packet loss ratio change in these different network environments.

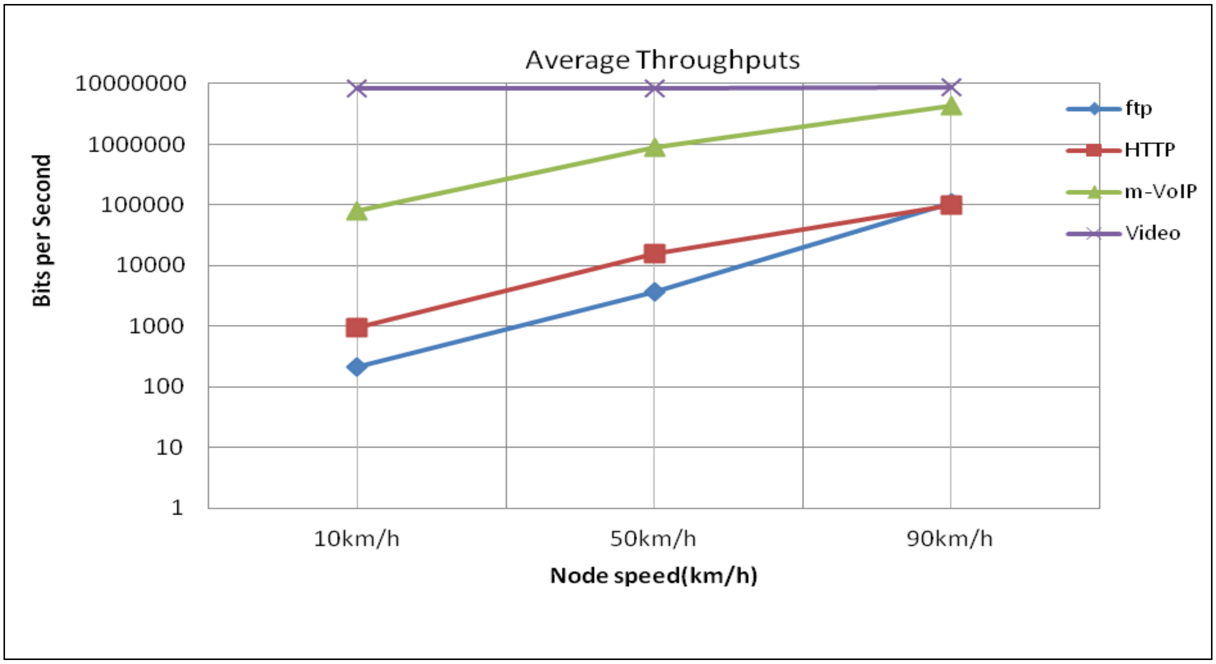

Figure6.20. The average throughputs for four applications

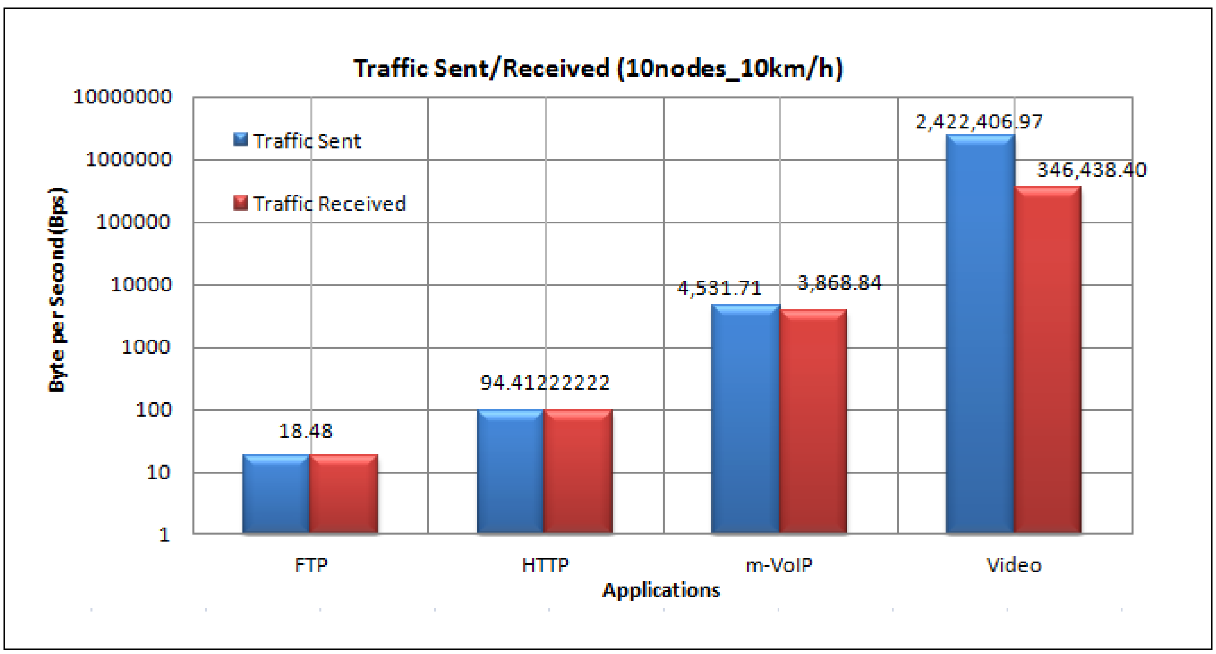

Figure6.21. Log scaled histogram of traffic sent and received in light traffic in a 10 nodes network with a node speed of 10km/h

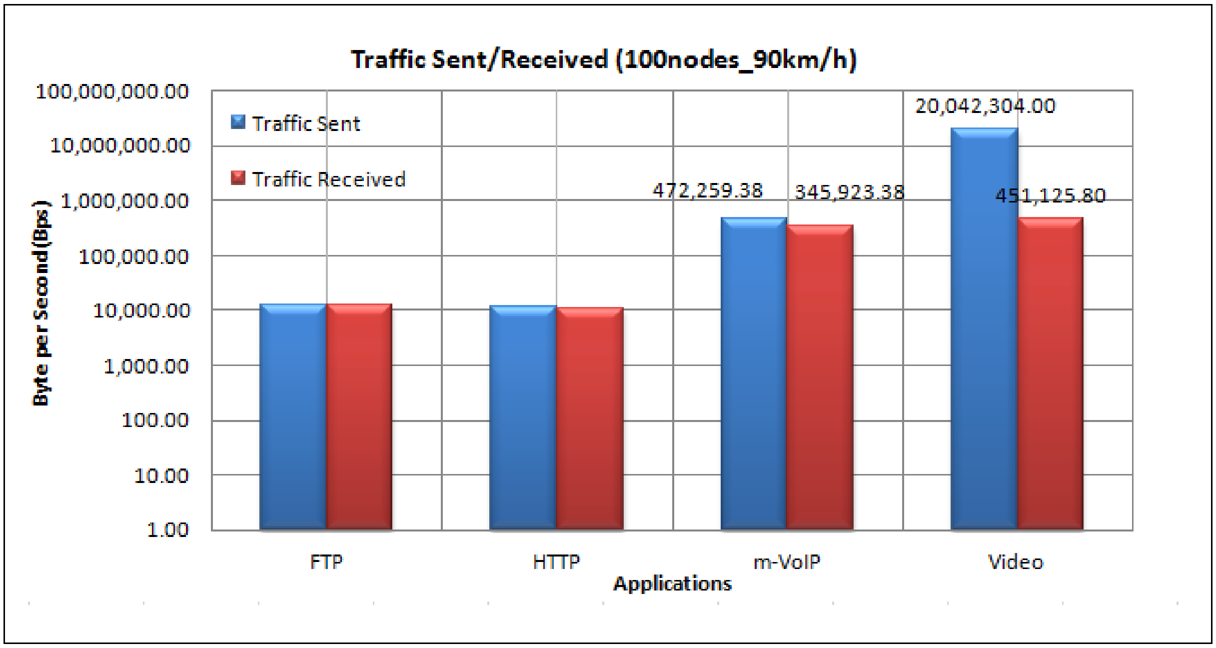

Figure6.22. Log scaled histogram of traffic sent and received in heavy traffic in a 100 nodes network with a node speed of 90km/h

Figure 6.20 presents the average throughput of four applications in three different network environments. Figures 6.21 and 6.22 present the traffic sent/ received ratio (packet loss ratio).

As shown in Figure 6.20, Video conferencing throughput remains 8.5Mbps regardless of the increase in mobile node speed and throughput does not significantly change when compared with stationary node. However, throughput of VoIP, HTTP and FTP increase in direct proportion to the increasing amount of traffic and node speed.

Initially, throughputs are 78.5kbps, 960.5bps and 217.1bps respectively when 10 nodes transmit small traffic loads. Throughputs increase up to approximately 4.4Mbps, 98.3kbps and 106.8kbps respectively when a network of 100 nodes transmits a large traffic load. In addition, average throughputs of the delay-sensitive traffic types (VoIP and Video conferencing) are certainly higher than those of the delay-tolerant traffic types (FTP and HTTP).

Figure 6.21 and 6.22 show that packet loss ratio for all four traffic types increases when the node speed increases. For both FTP and HTTP the packet loss ratio is nearly 0.0% when the speed of node is 10km/h (slow speed). However, after speed of nodes increases to 90km/h (high speed); we can observe that packet loss ratio for FTP and HTTP go up to 2.17% and 0.90% respectively. On the other hand, packet loss ratio for m-VoIP and Video conferencing go up to 14.6% and 85.7% respectively with a 10km/h node speed (slow speed). However, when the node speed increases to 90km/h (high speed), we can see that packet loss ratios for m-VoIP and Video conferencing go up to 26.5% and 97.8% respectively.

6.3.6 Discussion

In the experiments, to observe performance changes when node speed increases, each traffic type ran at various mobile nodes speeds (0, 10, 30, 50, 70 and 90km/h). In addition, Random Waypoint Mobility, which causes the nodes to move randomly, was used to simulate an ordinary user`s movement pattern and avoid bias problems. When a node is close to an Access point (AP), the wireless signal is powerful, as it moves away, the signal weakens.

Signal interference also needs to be considered. However, there is not enough information about and no standard for how much signal interference is generated in any particular environment and it depends on so many factors. Accordingly, as explained in Chapter 5, signal interference is not considered in experiments for Scenarios 4 to 9.

Average FTP download and upload response times increased by 11% and 19% respectively when mobile node speed is increased from 0km/h to 90km/h. When mobile nodes stop moving, the download response time is approximately 0.65seconds. When mobile nodes move at 90km/h, download response time increases up to 0.72second. On the other hand, average packet loss ratio increases by 2.2% when mobile node speed increased to 90km/h. Normally, 1% packet loss is treated as a significant problem and generally any amount of packet loss is not acceptable as packet loss means damage to the packet. However, 2.2% packet loss ratio is deemed acceptable in this thesis. Even though traffic is generated continuously, experimental results are captured during a simulation time of 900 seconds, thus this small packet loss may recover throug later retransmission. Consequently, there are no significant problems that affect FTP transmission up to 90km/h (high speed) node mobility.

Unexpectedly, object and page response times for HTTP increased linearly with increasing mobile node speed. Average HTTP object and page response times increase by 131.8% and 126.7% respectively. This means that response time delay is significantly affected by mobile node speed. However, object and page response times does not exceed one second for any speed. In addition, throughput increases linearly and packet loss ratios do not been exceed 0.90% with any traffic size, network size or node speed. Delay; however, does increase. This phenomenon can be attributed to transmission distance and node mobility. As the speed of mobile nodes increases, transmission distance between BS and MS is proportionally increased resulting in longer delay than when nodes do not move. Moreover, we have configured the simulated network so that nodes move randomly, thus mobile nodes have to constantly update their location info (routing info) to a BS for further communication. Update activity may be a major factor in making delay longer. Consequently, HTTP transmission over a mobile WiMAX network made up of nodes moving at 90km/h may work reasonably well. Node mobility does not significantly affect system performance for HTTP.

When users make use of delay-tolerant FTP or HTTP services while moving, it is acceptable to have a delay that is slightly longer than that of stationary node. There are no significant problems that affect system performance up to 90km/h node speed.

According to experimental results, average PDV and end-to-end delay definitely increase with increasing node speed. Average PDV and end-to-end delay times increase by 156.4% and 39.1% respectively. Also, the average end-to-end delay greately exceeds 150ms for any node speed. In other words, video conferencing is not satisfactory. In addition, average throughput is approximately 1Mbps lower and the average packet loss ratio is 1~3% higher when compared to experimental results for fixed nodes. Therefore, high or even medium quality videoconferencing service cannot be expected even when nodes move at a slow speed. However, a low quality video conferencing service (i.e. 10frame/second with 128X120 pixels) can be provided with little delay and few echoes or temporary disconnection. Consequently, Video conferencing over a mobile WiMAX network made up of nodes moving at 90km/h cannot be maintained without heavy MCS or high priority QoS settings and node mobility has a significant effect on system performance.

Although m-VoIP has similar properties to videoconferencing, the experimental results for m-VoIP are different to those for video conferencing. Jitter and MOS for m-VoIP remain nearly unchanged regardless of the increase in node speed. Moreover, average jitter is less than 50ms and average MOS does not change significantly for any node speed. This means that mobile WiMAX has the capability to provide m-VoIP service to mobile users. However, MOS does not reach a fair level (point 4) at any node speed. In addition, average throughput falls by approximately 0.5Mbps and average packet loss ratio increases to values that make communication impossible. The conclusion is that, an m-VoIP service over a mobile WiMAX network with nodes moving at high speed (90km/h) can be satisfactory with a high priority QoS setting. However, node mobility has a significant effect on m-VoIP system performance.

From the mobile WiMAX perspective, packet loss ratio for all four application increases proportionally with the increasing node speed. Interestingly, HTTP packet loss ratio only increases by less than one percent while node speed increases to 90km/h. Thus we can infer that HTTP is the traffic type that is most tolerant to node mobility. FTP packet loss ratio is only increased to 2.17% and so we can assume FTP is relatively tolerant of the increase in node mobility. On the other hand, average packet loss ratio of m-VoIP and video conferencing increase continuously with an increasing node speed and that makes conversation unfeasible. Interestingly, experimental results for both m-VoIP and Video conferencing are much worse than previous researcher`s results [66, 72, 73]. We can tentatively infer that this phenomenon is due to the QoS and MCS settings in the experiments. As m-VoIP and video conferencing are delay-sensitive traffic types, priority QoS settings are needed to provide sustainable transmission and minimise packet loss. We observe performance changes when using priority QoS setting. However, BE is used in this research since priority QoS would have affected the transmission of other traffic types that have low QoS. Consequently, node mobility has more effect on real-time applications performances (m-VoIP and Videoconferencing) than on non-real time applications performances (FTP and HTTP).

6.4 Impact of handoff on system performance

Section 6.3 discussed the impact of node mobility on the performance of mobile WiMAX. This section reports on the impact of handoff on the performance of mobile WiMAX. It discusses the combined results from the experimental Scenarios 7, 8 and 9. In order to compare those results to those from Scenario 4, 5 and 6 the latter are added to each graph. Handoff is forced between two Access points. Averages of the experimental results are presented for a simulation time of 900seconds.

6.4.1 Impact of varied node speeds on handoff on FTP

This subsection presents the relevant data (Figures 6.23 and 6.24) and discusses changes in FTP download and upload response times when handoff is enabled.

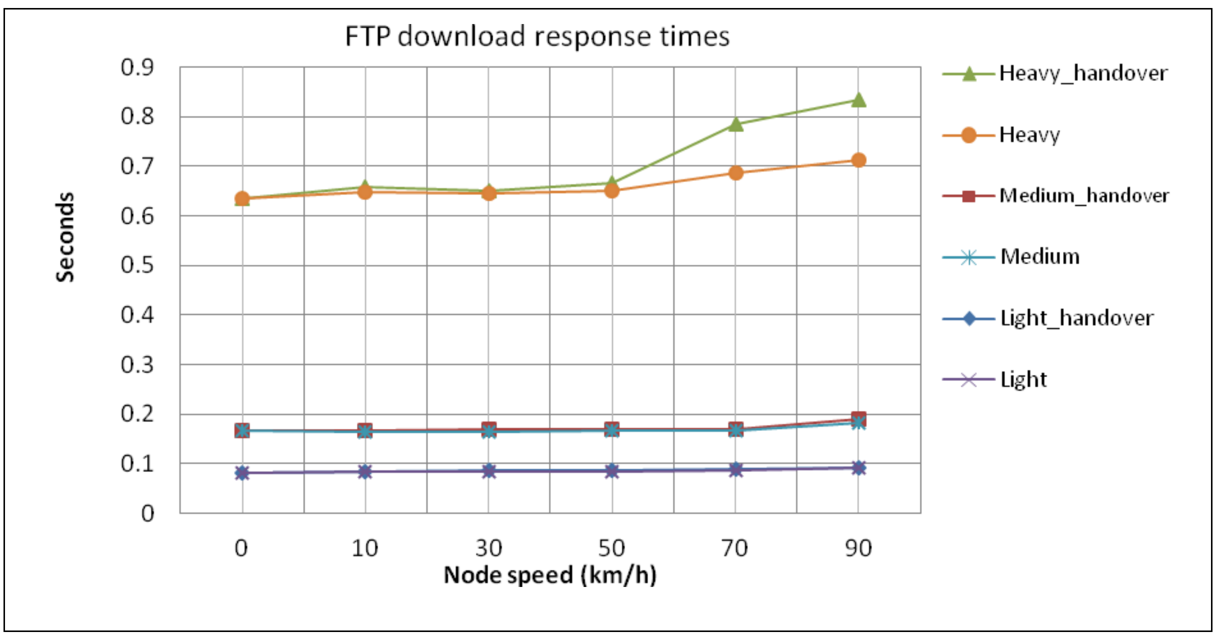

Figure6.23. FTP Download response times with and without handoff

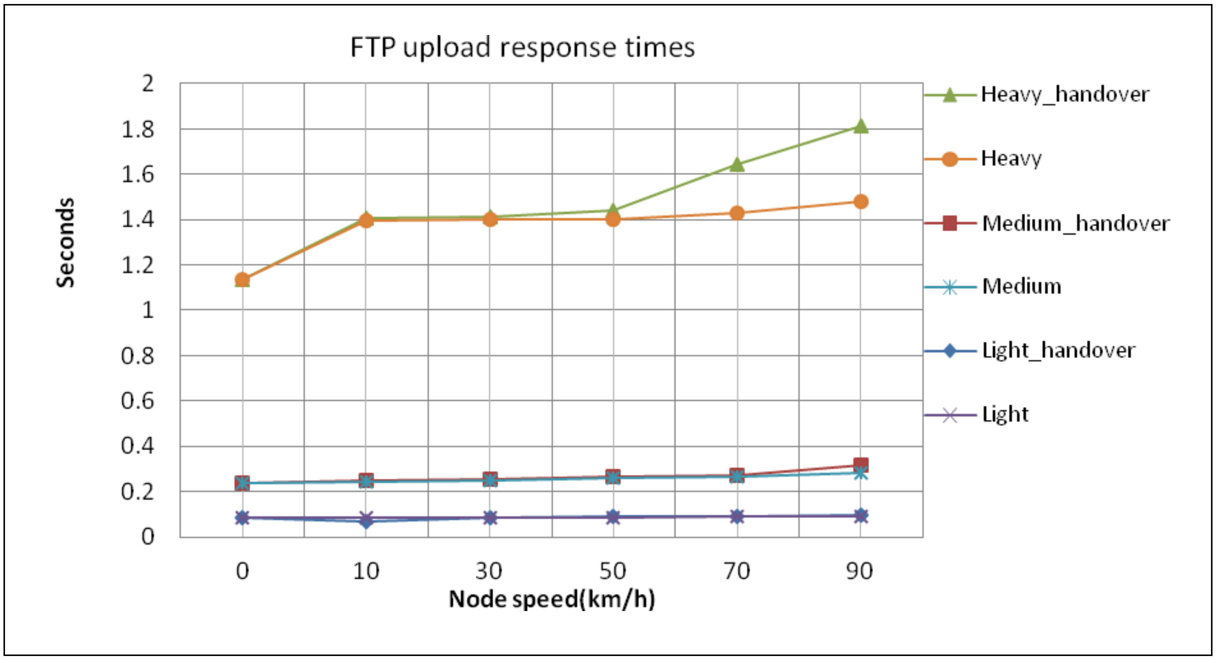

Figure6.24. FTP Upload response times with and without handoff

When light FTP traffic is transmitted, there is no significant difference in download/upload times in regards to whether handoff is enabled or disabled. For any node speed, download/upload response times are nearly unchanged. Less than 0.01second time differences are observed.

When medium FTP traffic is transmitted, there are no significant download/upload time differences whether handoff is enabled or disabled up to a 70km/h node speed. For speed above 70km/h, download/upload response times both increase by less than 0.5 seconds.

For heavy FTP traffic, there is no significant download/upload time difference between handoff being enabled or disabled, up to a 50km/h node speed. For speeds 50km/h or higher, enabling handoff appears to have an impact on these times. Download and upload response time increase by 0.1 second and 0.3 second respectively when node speed is increased from 50km/h to 90km/h.

6.4.2 Impact of handoff on HTTP with varied node speeds

This section presents and discusses the experimental results for changes in HTTP object and page response times when handoff is enabled.

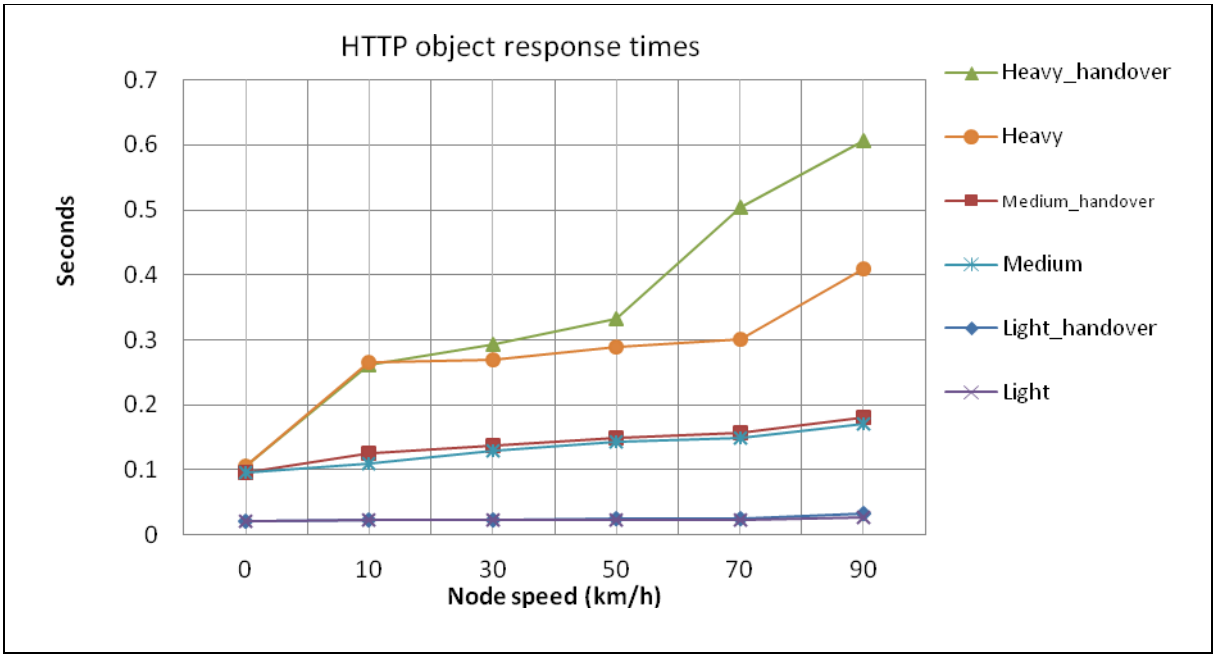

Figure6.25. HTTP Object response times with and without handoff

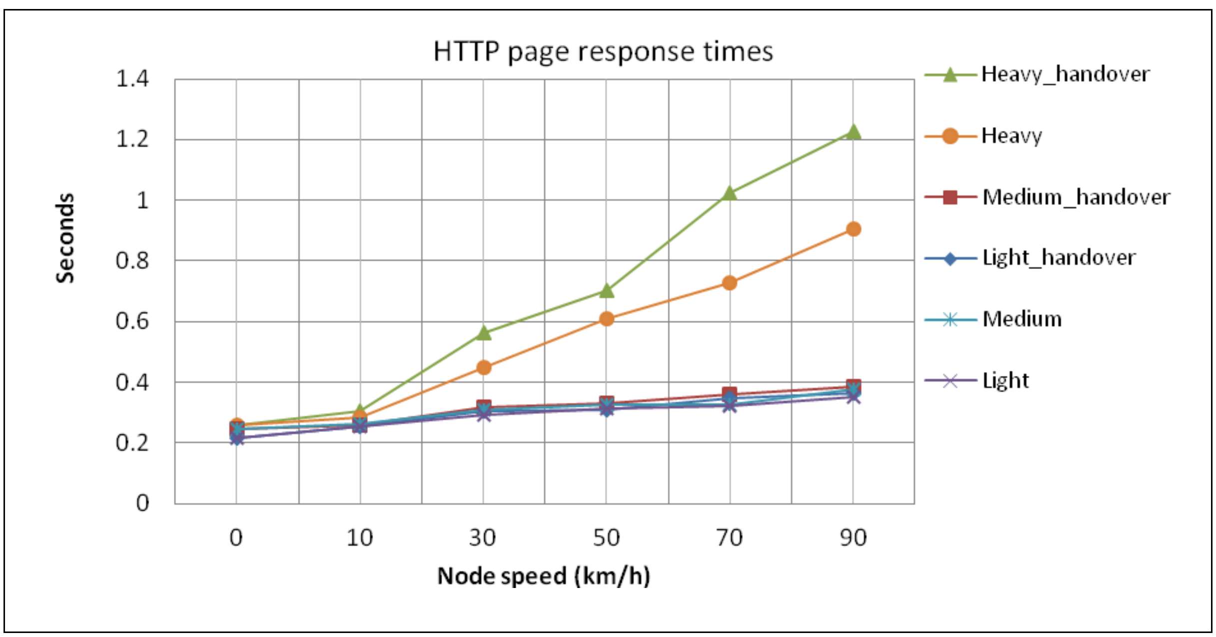

Figure6.26. HTTP Page response times with and without handoff

There is no significant object and page response time changes when using handoff for light and medium HTTP traffic transmitted at any node speed. Download and upload response times are nearly unchanged for light HTTP traffic regardless of whether handoff is enabled or disabled. Object and page response times for light and medium HTTP traffic have little increase when handoff is enabled. Average object and page response times increase by 0.02seconds and 0.05seconds respectively. There is no clear evidence that handoff has influenced the HTTP page and object response time for light and medium traffic.

For heavy HTTP traffic transmitted between a server and moving nodes, enabling handoff causes an increase in response time which is clearly observed for mobile node speeds 30km/h and greater. The impact of handoff becomes stronger has node speed increases. When the speed is 90km/h, page and object response times increase by 0.21seconds and 0.32seconds respectively when compared to those without handoff.

6.4.3 Impact of handoff on Video conferencing with varied node speeds

This section presents and discusses the experimental results of Video conferencing`s PDV and end-to-end delay changes in video conferencing traffic when handoff is disabled and enabled. Our interest is to find out how enabling handoff impacts on PDV and end-to-end delay.

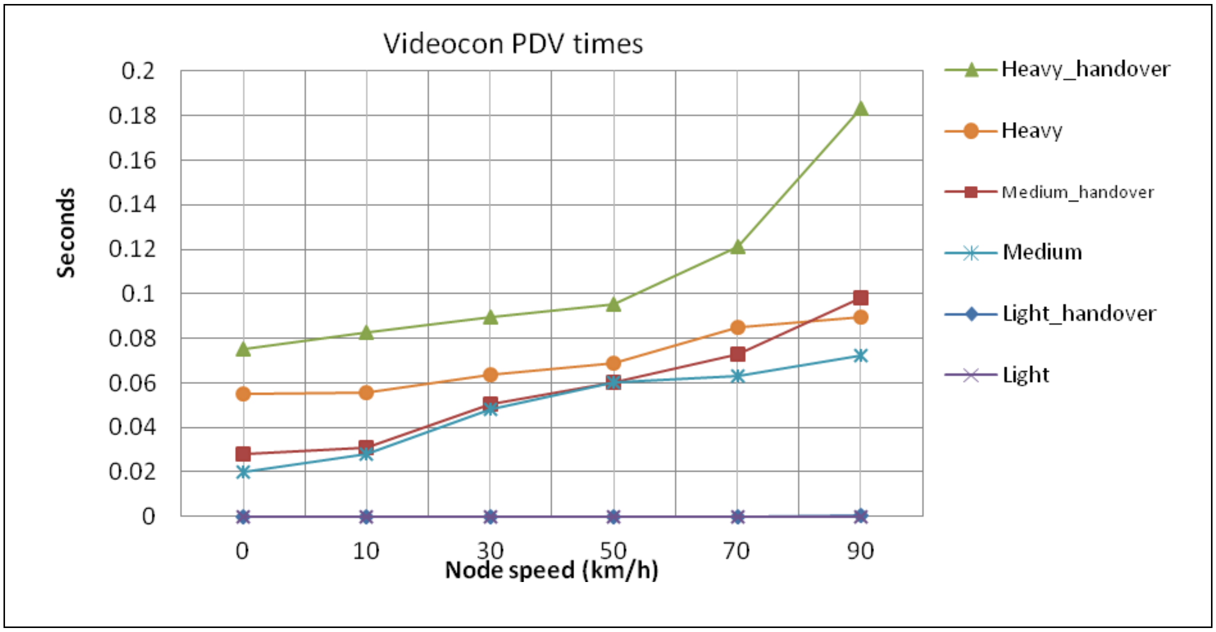

Figure6.27. Video conferencing PDV with and without handoff

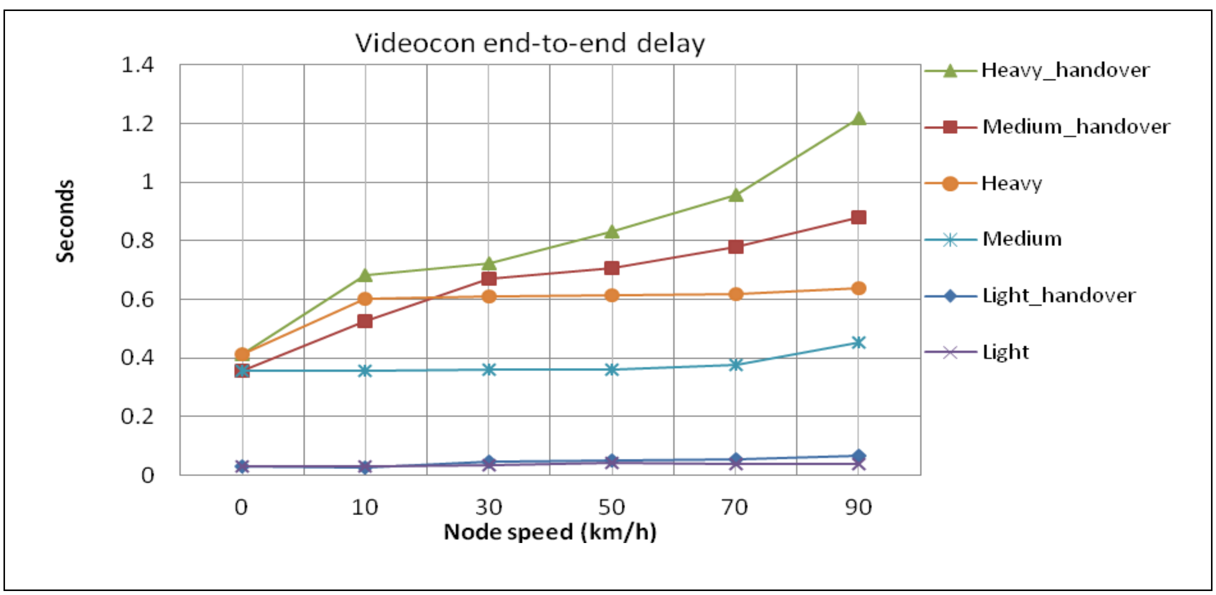

Figure6.28. Video conferencing end-to-end delay with and without handoff

As seen in Figures 6.27 and 6.28, when a small amount of video conferencing traffic is transmitted between moving nodes, handoff had no significant impact of handoff on WiMAX performance for any node speed. PDV and end-to-end delay increased by 0.001seconds and 0.03seconds respectively when handoff is enabled.

Inversely, when medium video conferencing traffic is transmitted between moving nodes, the impact of handoff is clearly observed at any node speed.

When handoff is enabled at a30km/h node speed, PDV only increases by 0.002seconds and end-to-end delay increases by 0.32seconds. However, for a node speed of 90km/h speed of nodes, PDV increases by 0.02seconds and end-to-end delay increases by 0.49seconds.

The impact of handoff for heavy video conferencing traffic is clearly shown in Figures 6.27 and 6.28. When handoff is enabled at a node speed of 30km/h, PDV increases by 0.03seconds and end-to-end delay increases by 0.08seconds while, for a node speed of 90km/h, PDV increases by 0.1seconds and end-to-end delay increases by 0.6seconds.

6.4.4 Impact of handoff on m-VoIP with varied node speeds

This section reports and discusses the experimental results for m-VoIP jitter and MOS when handoff is enabled. Our interest in this section is to find out the impact of handoff on m-VoIP jitter and MOS.

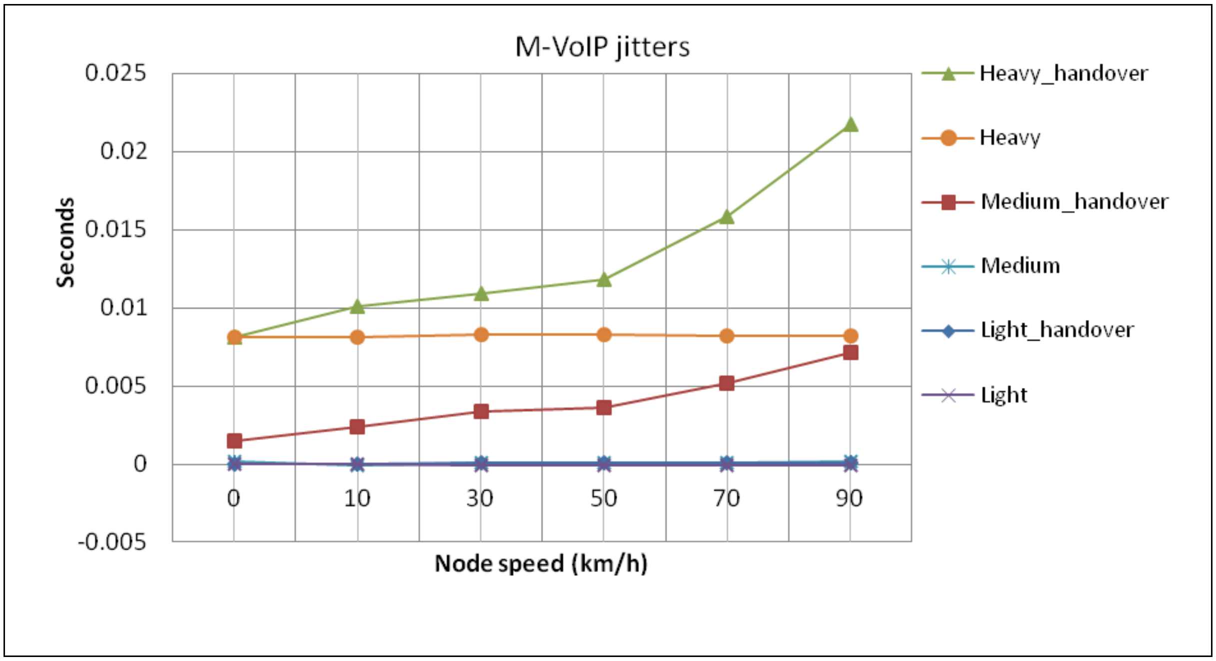

Figure6.29. M-VoIP jitter with and without handoff

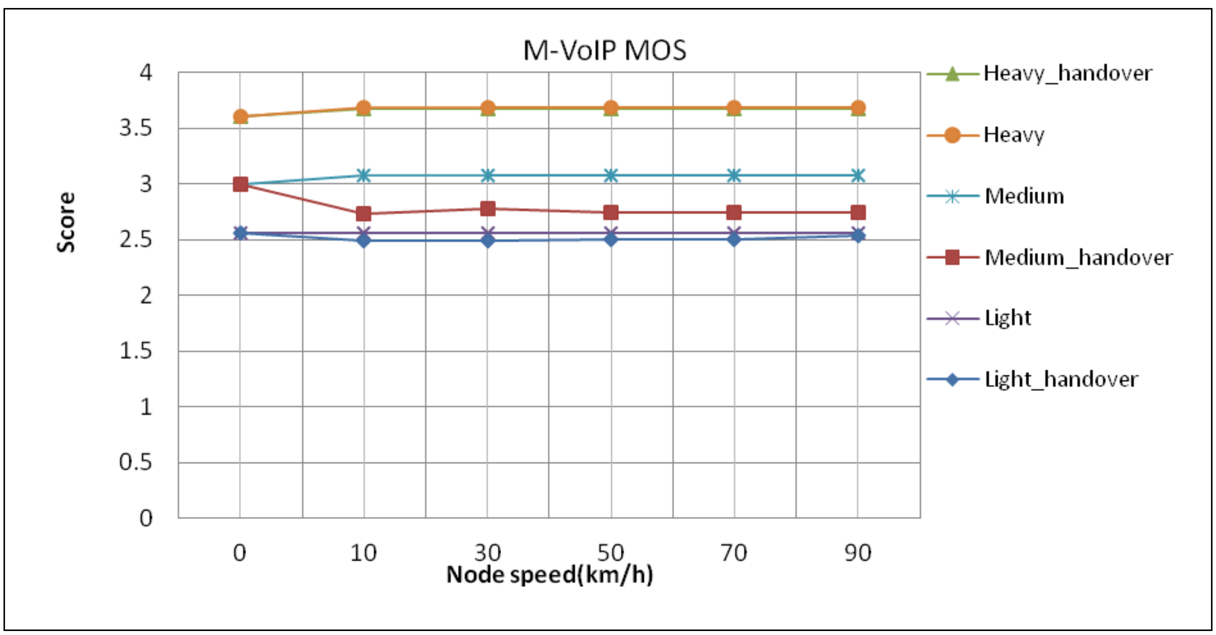

Figure6.30. M-VoIP MOS for with and without handoff

As shown in Figures. 6.29 and 6.30, when handoff is enabled, average jitter and MOS are nearly unchanged for light m-VoIP traffic at any node speed. Jitter does not exceed 1ms for any node speed. However, although jitter is maintained at less than 1ms, MOS does not reach a fair level, 4 points at all and is about 2.5 points for any mobile node speed.

On the other hand, when handoff is enabled, average jitter for medium and heavy m-VoIP traffic increases linearly with an increase in node speed. For a 30km/h node speed, jitter increases by 0.002 seconds and 0.003 seconds respectively while for a 90km/h node speed, jitter increases by 0.007seconds and 0.013 seconds respectively. MOS remains nearly unchanged for all three amount of m-VoIP traffic regardless of the increasing node speed. However, once handoff is enabled, MOS for medium m-VoIP` traffic is about 0.3 points lower and for heavy traffic, MOS is about 0.6 points lower than those before handoff was used. Consequently, even though jitter remains at less than 50ms for any node speed, MOS does not reach a fair level, 4 points, at all.

6.4.5 Overall performance of mobile WiMAX

This section presents and discusses the impact of handoff on the average throughputs and ratios of traffic received/sent (packet loss) for four applications (FTP, HTTP, m-VoIP and Video conferencing). In order to make a comparison with the experimental results from previous sections, their graphs are also presented in Figures. 6.32 and 6.33. Our interest in this section is to investigate the impact of handoff on throughput and packet loss.

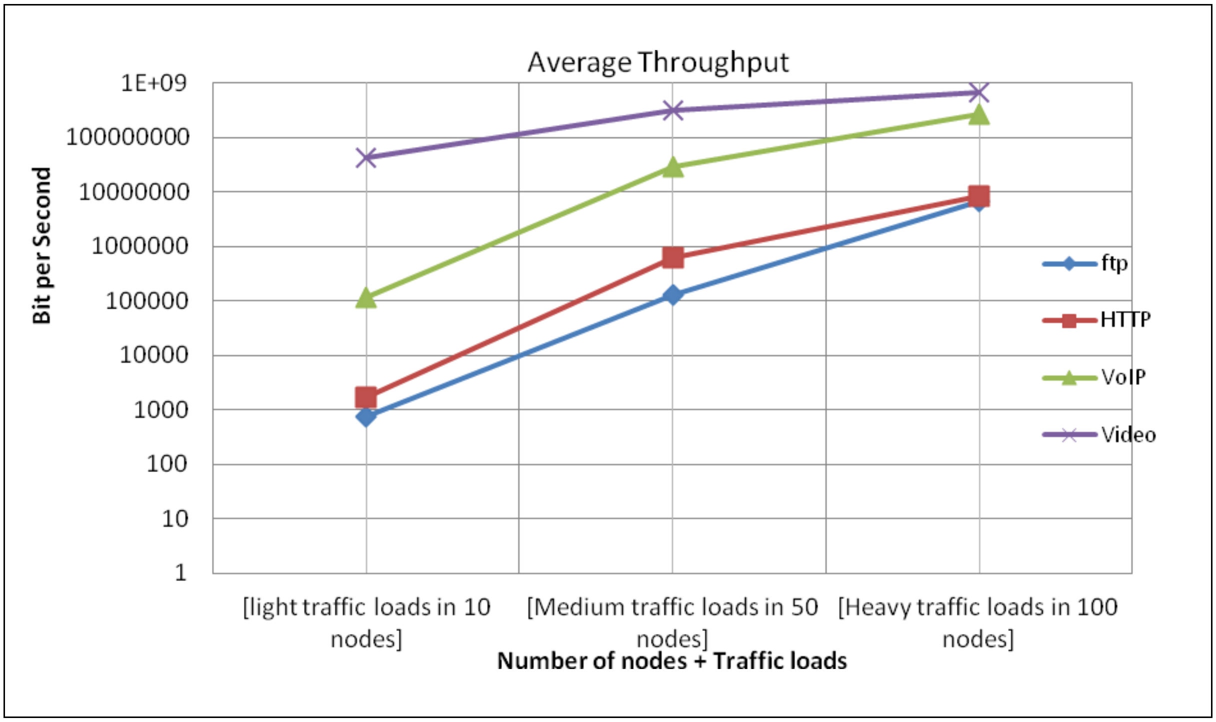

Figure6.31. Log scaled average throughputs of four traffic types when handoff is enabled

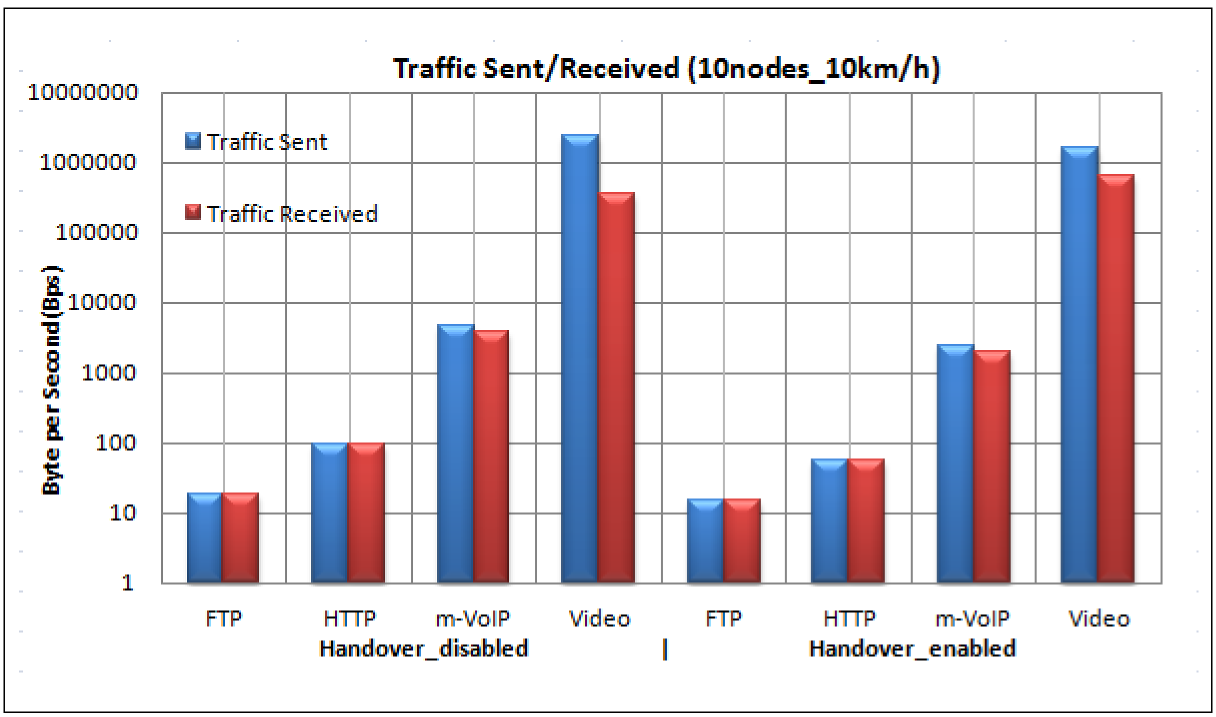

Figure6.32. Traffic Sent and Received with and without handoff (10nodes_10km/h)

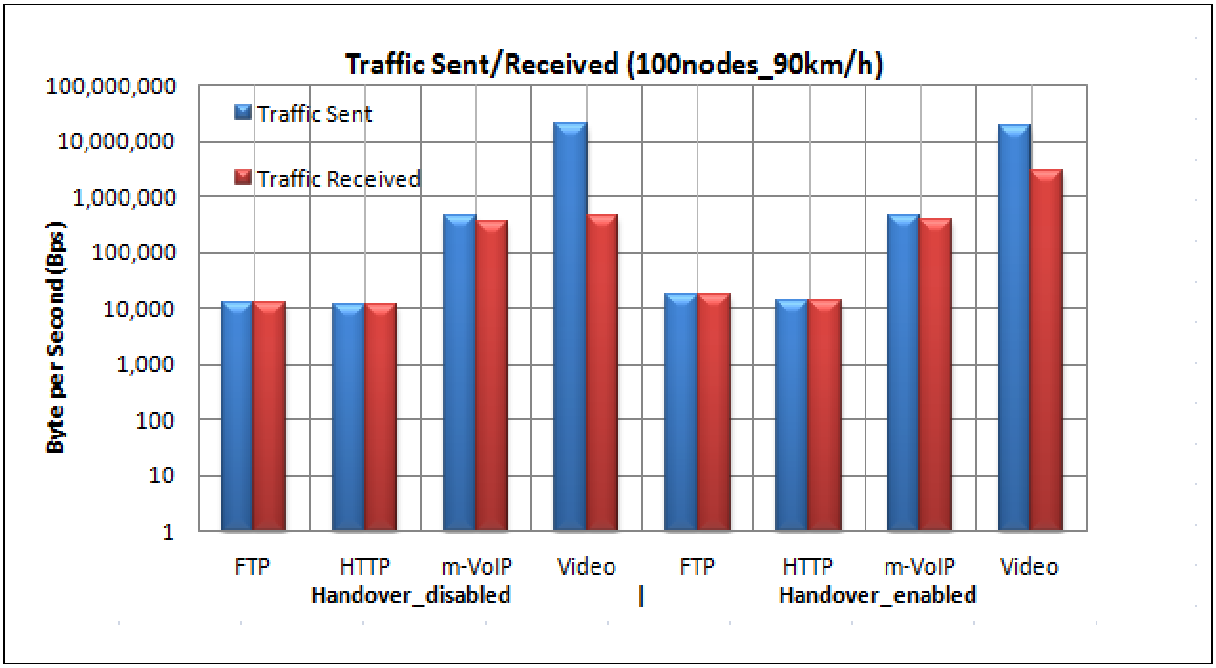

Figure6.33. Traffic Sent and Received with and without handoff (100nodes_90km/h)

Figure 6.31 presents average throughput for four applications when handoff is allowed. Figure 6.32 and 6.33 show traffic sent/ received and packet loss ratio. Throughputs for all four traffic types increase exponentially. As shown in Figure 6.31, after handoff is enabled FTP average throughput is 37kbps and increases to 2.3Mbps, while HTTP average throughput increases from 38kbps to 3.0Mbps. Video conferencing average throughput increases from 8.5Mbps to 35.2Mbps and m-VoIP average throughput increases from 1.8Mbps to 9.8Mbps.

As shown in Figure 6.32 and 6.33, when handoff is enabled average packet loss ratios for all four traffic types decrease slightly.

Figure 6.33 shows that when handoff disabled, packet loss ratio for heavy FTP traffic is 2.17% and when handoff is enabled it decreases to 2.10%. Similarly, the average packet loss ratio for HTTP also slightly decreases from 0.89% to 0.85%. Interestingly, when handoff is enabled, packet loss ratios for both m-VoIP and video conferencing decrease significantly when compared to those in non-handoff situations. In heavy traffic, Video conferencing packet loss ratio is 97.7% in networks of 100 nodes that move at a speed of 90km/h within the cell. However, after handoff is enabled packet loss ratio decreases to 83.74%. In the same environment, the average packet loss ratio for m-VoIP traffic also decreases moderately from 26.8% to 20.6%.

6.4.6 Discussion

In the handoff experiments, a hard handoff scheme is used. In hard handoff, a MS only communicates with one BS. In other words, when the MS moves from one cell to another, communication must be terminated with first BS before it can be established with the new BS.

It appears that handoff has little impact on light and medium FTP. However, when handoff is enabled for heavy FTP traffic over a network with a 70km/h node speed, delay gradually increases. We can then infer that handoff for FTP traffic over a 70km/h speed is a factor that seriously degrades FTP performance. Therefore, it is only for networks with node speed of 70km/h or more that the delay increase caused by handoff needs to be seriously considered.

The patterns observed in experiments with handoff enabled for HTTP traffic are similar to those for FTP. The experimental results show that performance for light and medium HTTP traffic, is only marginally influenced by handoff. However, when handoff is allowed for heavy HTTP traffic, experimental results are different to those of heavy FTP traffic. As node speed increases, the delay of heavy HTTP traffic increases linearly when compared to results where handoff is not allowed.

Therefore, we can infer that handoff does not significantly influence transmission for light or medium HTTP traffic loads up to a 90km/h node speed. However, when heavy HTTP traffic is transmitted, handoff may impact on the delay of HTTP transmission even at 30~50km/h node speed. On the other hand, when handoff is enabled average throughput increases and packet loss decreases for both FTP and HTTP. Before handoff is enabled, all traffic with mobile nodes converges on one BS, which may result in longer processing time and overload. However, after handoff is enabled, nodes are able to communicate with the proximate BS which shortens transmission time and delay. This means that traffic can be dispersed to two or more BSs with an extension of coverage. Therefore, we can state that while handoff may cause slightly longer delay, it facilitates better operation of mobile WiMAX by dispersing (dividing) traffic and widening coverage.

The experimental results show that the impact of handoff is insignificant when light videoconferencing traffic is transmitted. When handoff is enabled, PDV and end-to-end delay for any node speed remain nearly unchanged when compared to those before handoff is allowed. However, as amount of traffic and node speed increase, the impact of handoff on videoconferencing transmission is clearly observed on both. PDV and end-to-end delay increase when compared to before handoff. This means that whenever handoff is enabled, transmission delay will increase. Moreover, experimental results show that there is packet loss of over 80%, meaning that a high quality videoconferencing service cannot be expected with moving nodes.

In experiments with m-VoIP, we observe patterns similar to those ofh Video conferencing. Performance for light amount of m-VoIP traffic is only marginally influenced by handoff.

However, jitter for medium and heavy m-VoIP traffic is significantly influenced. The experimental results show that handoff may cause longer jitter time at any node speed.

Interestingly, experimental results for FTP and HTTP are completely different to those with VoIP and Videoconferencing. We can assume that this phenomenon is due to the different characteristics of traffic types, such as duplex types or node trajectory. Normally, Video conferencing and m-VoIP require a more constant bit rate (CBR) and higher bandwidth than those required by FTP or HTTP[48, 72]. However, we used the default handoff type known as “hard handoff”. Hard handoff needs to terminate the previous communication in order to communicate with a new BS. Accordingly, temporary disconnection or mismatch of video and audio may occur while conducting handoff. In addition, since nodes move randomly some extra handoff processing time may be needed to locate the new mobile node. In other words, handoff may put greater pressure on VoIP and Videoconferencing than FTP and HTTP which are delay-tolerant types.

Therefore, the use of soft handoff schemes for reducing the impact of handoff on Videoconferencing and m-VoIP is recommended. Since a soft handoff scheme maintains the connection with the old BS while handoff is completed, it may reduce the probability of temporary disconnection. As noted in Section 6.4, throughputs for all types of traffic increase exponentially and packet loss ratios moderately decrease. In the experiments, nodes keep moving for the full duration of the simulation. Therefore, we can infer that node movement results in a division of traffic between two BSs. The initial aim of handoff is to extend WiMAX coverage and to provide node mobility to end users. Handoff contributes to preventing traffic converging on a single BS.

Consequently, we can state that handoff facilitates a greater throughput and less packet loss although the delay for all four traffic types increases either slightly or moderately. In addition, soft handoff is recommended for reducing the impact on transmission of VoIP and videoconferencing packets. However, soft handoff may impose more constraints on the BS than hard handoff. Soft handoff causes mobile nodes to receive the same traffic from two different BSs; an MS also has to continuously update its status to two different BSs while in handoff. Although handoff time does not normally exceed one second, handoff may lead to a waste of network resources. Therefore, a handoff scheme should be selected on the basis of the available network resources and frequent traffic types or QoS.

6.5 Summary

This chapter investigates the impact of traffic type and node mobility on the performance of mobile WiMAX by reviewing extensive simulation experiments. Four traffic types are investigated, namely FTP, HTTP, VoIP and Video conferencing. The simulation model makes use of four servers, 10, 25, 50, 75 or 100 mobile nodes, 0, 10, 30, 50, 70 and 90km/h node speeds. The performance is measured in terms of download/upload response time, object/page response time, jitter, MOS, PDV, end-to-end delay, depending on the traffic type being investigated. Impact on the performance of mobile WiMAX is measured in terms of throughput and packet loss ratio. A detailed analysis of the impact of traffic type and node mobility on the performance of mobile WiMAX is presented in each section with recommendations that may improve performance. Considerations are also presented. The next chapter concludes the research and provides some guidelines for future research.

Chapter 7

Conclusions and Future Work

This thesis investigates the impact of traffic types, node mobility and handoff on the performance of mobile WiMAX using OPNET-based simulation experiments. As a result of this investigation, we believe that each traffic type may influence the performance of mobile WiMAX differently. The growing demand for mobile networks and the need to provide a substantial performance evaluation of them are the major motivations for this research. As mobile WiMAX is a relatively unfamiliar technology and not yet widely used, providing background information about mobile WiMAX is essential. A review of the advantages of mobile WiMAX and comparisons with other wired or wireless networks are provided in Chapter 2.

In order to set up an experimental framework and define the direction of progress for this thesis, a literature review is presented in Chapter 3. The main theme of the review is how performance of mobile WiMAX performance is influenced by factors such as QoS, node mobility, traffic type and handoff. The appropriateness of using OPNET for this research, experimental parameters, performance metrics, experimental scenarios, hardware and software specifications and assumptions are all presented in Chapters 4 and 5. Based on the parameters presented in Chapter 5, the impact of node mobility (0, 10, 30, 50, 70 and 90km/h) and handoff on system performance for FTP, HTTP, VoIP and Videoconferencing are reviewed.

Average download and upload response times for any amount of FTP traffic are not significantly affected by increasing the number of nodes (size of network). Average throughput increases and average packet loss ratio remains about 0%, when the number of nodes increases. Similarly, average object and page response time for any amount of HTTP traffic does not change significantly when the number of nodes is increased. Average throughput increases and average packet loss ratio only increases only by 0.1%, which is negligible. Consequently, for up to 100 nodes, FTP and HTTP transmission is not influenced significantly by the number of nodes (size of network) increasing. In other words, Mobile WiMAX facilitates effective FTP and HTTP packet transmission between nodes and server for a large-size network.

However, PDV and end-to-end delay for any amount of Video conferencing traffic increase proportionally with an increasing number of nodes. Moreover, although average throughput is higher than for FTP and HTTP, average packet loss ratio increases exponentially when the number of nodes increases and it exceeds 80% in a large network.

Ironically, jitter and MOS for VoIP remain nearly unchanged regardless of the increased number of nodes. However, average packet loss ratio increases up to 14.4%. VoIP is not tolerant to packet loss (no retransmission) and even 1% packet loss can cause significant degradation in voice quality. In addition, according to [51], the default G.729 codec needs a packet loss of far less than 1% to avoid audible errors. Accordingly, priority QoS and heavy MCS are applied to the network and, even then, the average packet loss ratio only decreases by 7~10%.

Consequently, as the number of nodes increases, the quality of VoIP and Video conferencing communication decreases. In addition, without proper QoS and MCS settings, high quality audio and video communication cannot be expected.

The experimental results from Scenarios 4 to 6 show that FTP and HTTP, which are delay tolerant traffic types, are not significantly affected when node speed is increased. Although the average response time certainly increases, it does not increase to an unacceptable level. Moreover, their packet loss ratios remains at a low level (0~5%) meaning the packet can be recovered by retransmission and throughput increases as well. However, the delay-sensitive traffic m-VoIP and Video conferencing, is certainly influenced when node speed increases. Although jitter and MOS for m-VoIP and end-to-end delay for Videocon do not increase significantly with increasing node speed, throughputs decreases by about 1Mbps and packet loss ratio increases up to levels that would makes it impossible to communicate effectively. High average packet loss ratio indicates that the audio and video packets may not be delivered to their destination in time without data loss.

Consequently, one can conclude that increasing the speed of nodes has either a slight or a significant influence on the performance of all four traffic types. Node mobility does not seriously affect delay-tolerant traffic types (FTP and HTTP) for any node speed. However, node mobility significantly affects delay-sensitive traffic types (VoIP and Video conferencing). Fortunately, the impact of node mobility on real-time traffic types can be reduced by the use of priority QoS and MCS settings. However, this cannot reduce the packet loss ratio to a level which would allow mobile communication to maintain land-line call quality.

Lastly, the impact of handoff on the performance of mobile WiMAX is also investigated in this study (Scenarios 6-9). In FTP transmission, there is no noticeable difference in performance with or without handoff for a node speed up to 70km/h. From 70km/h on some difference gradually appears. In HTTP transmission, there is no noticeable difference in performance between enabled handoff and disabled handoff at any node speed. However, when a webpage contains heavy-traffic objects (i.e. Flash), the influence of handoff is easily observed at any node speed and its influence escalates with increasing node speed. As expected, for any amount of transmitted video conferencing and m-VoIP traffic, the effect of handoff is clearly observed with an increasing node speed. Delay increases linearly after handoff is adopted. Unexpectedly, the throughput for all four traffic types increases significantly and packet loss ratio decreases either slightly or moderately after handoff is adopted. This phenomenon seems to be due to the fact that handoff allows the traffic to be divided (distributed) between two BSs. In addition, although handoff increases delay slightly, it also allows wider coverage and higher throughput and reduces packet loss ratio. Consequently, we recommend the use of soft handoff to minimise the impact of handoff on real-time traffic transmission. However, the use of handoff and its type should be selected on the basis of the available network resources and the characteristics of the traffic types.

While this study investigates the impact of node mobility and handoff on the performance of mobile WiMAX, some practical issues such as the design of a mobile WiMAX network could also be of interest. One can recognise that network design may significantly influence its performance. Interestingly, there are no standards for deployment (design) of mobile WiMAX networks yet. As life style and attitude towards the use of internet may differ between urban and rural users or between developed and developing countries, WiMAX network design should reflect these differences. In addition, the level of signal interference, node density, node trajectory and frequency of use of applications differ greatly in different circumstances. Thus, investigating and possibly devising a guideline (standard) for the design of mobile WiMAX network could be a topic for future study. It would have to consider issues such as deployment and configuration, QoS setting, MCS setting and handoff types. Also, surveys of the demographics and other characteristics of mobile WiMAX subscribers would need to be conducted at the same time. Survey findings could be very helpful when deciding on parameter values and configuration of nodes and APs.

Appendix A

OPNET simulator configurations

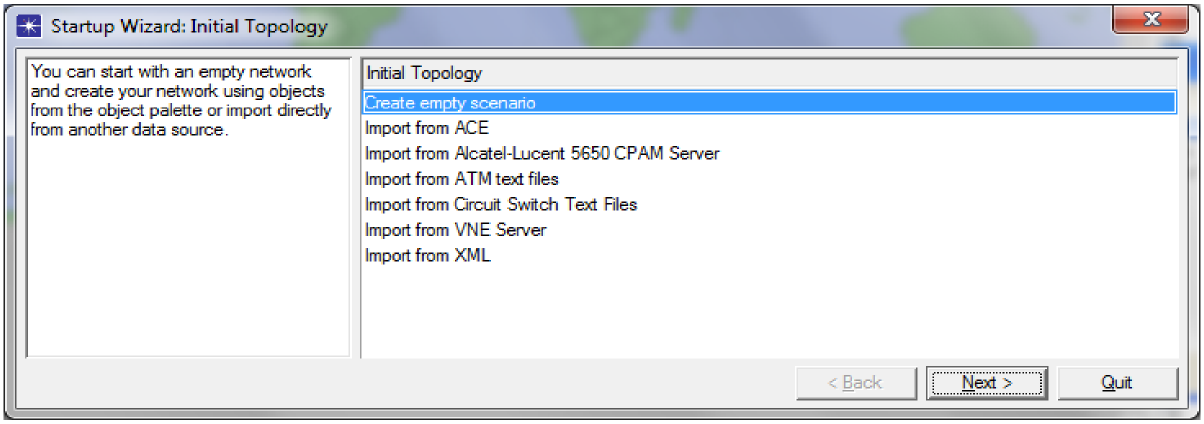

Figure A.1. Create an empty scenario

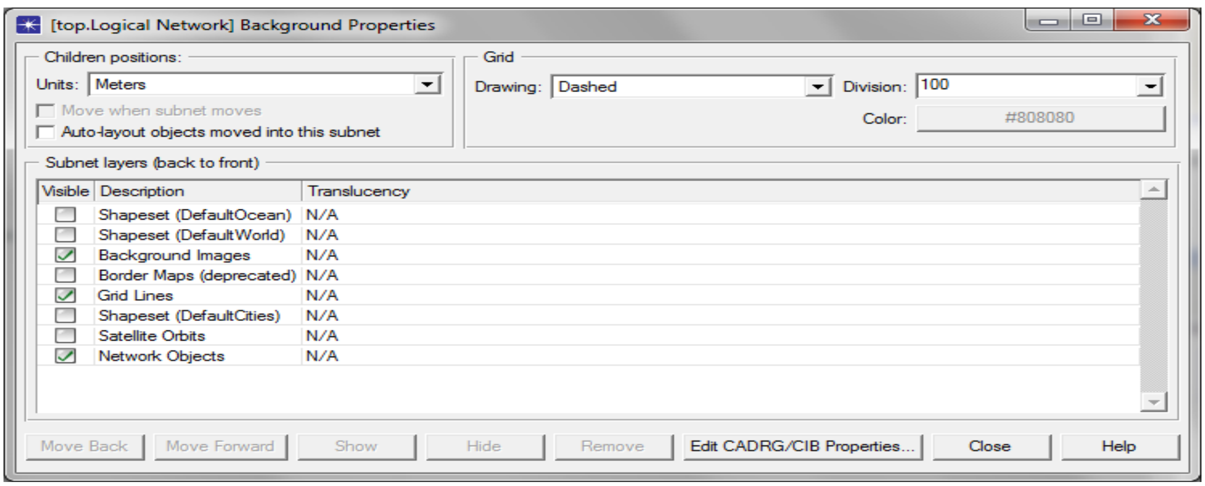

Figure A.2. Select a modeling scale

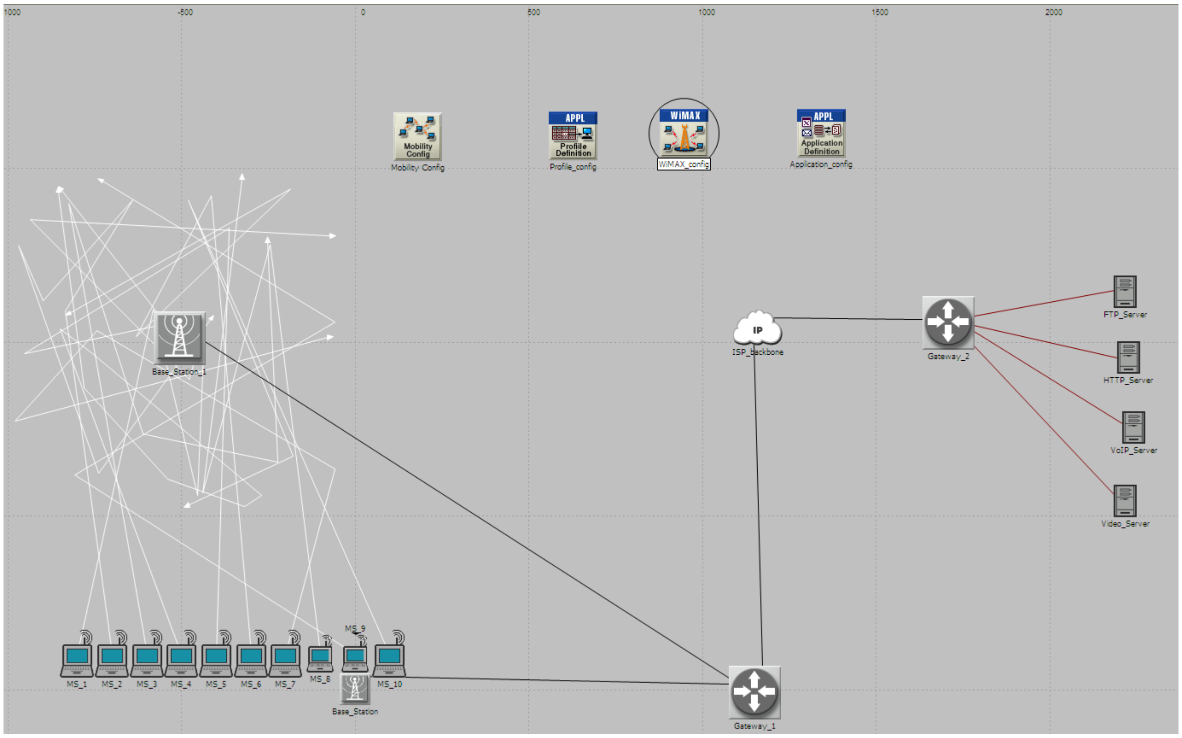

Figure A.3. OPNET modeling of simplified Mobile WiMAX network

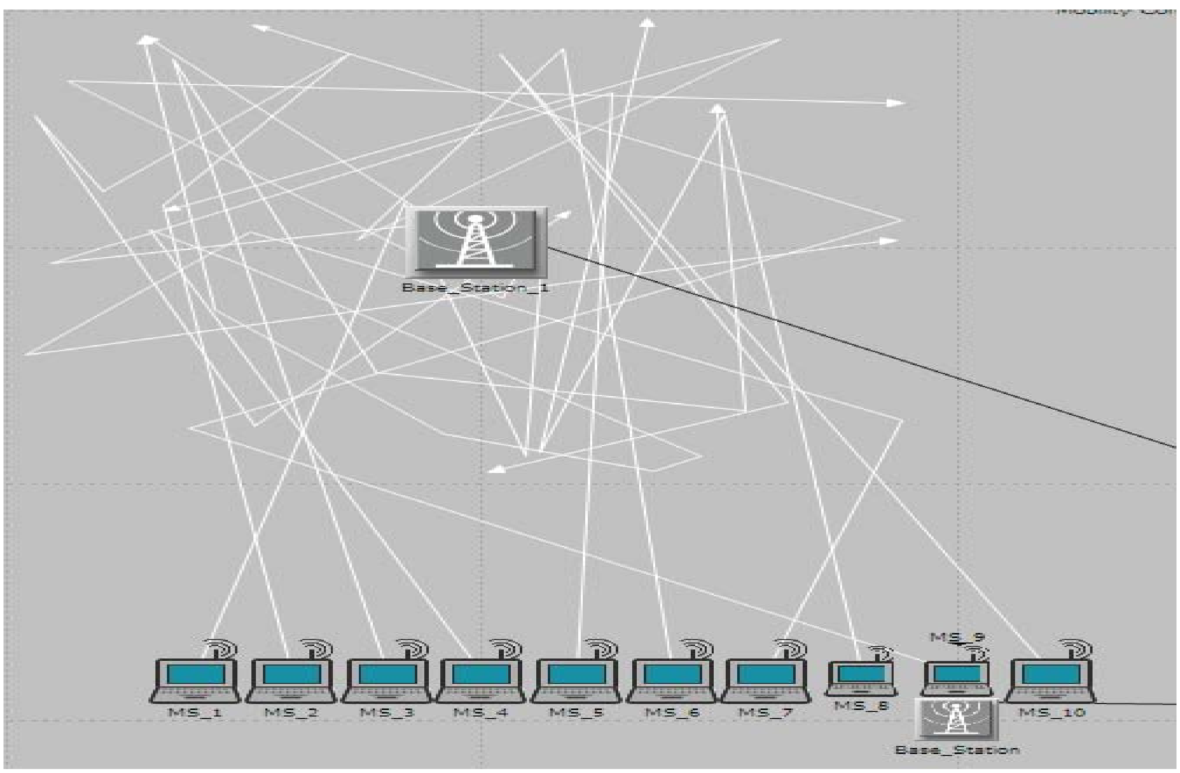

Figure A.4. Node mobility with random trajectory

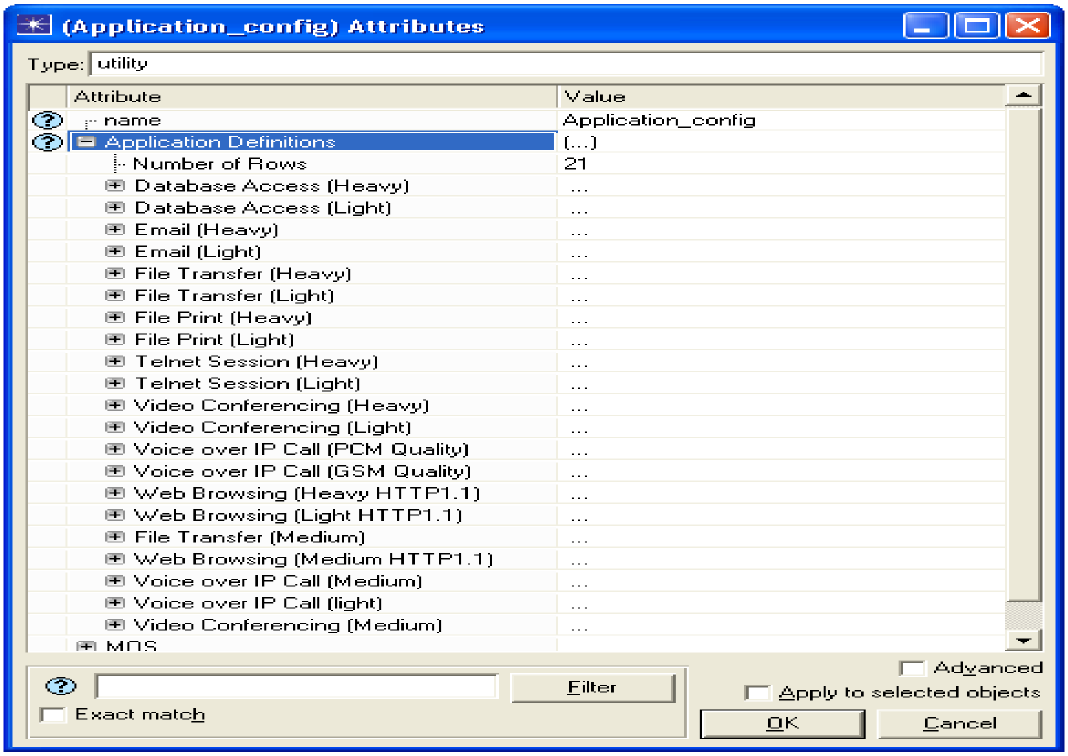

Figure A.5. Application configuration

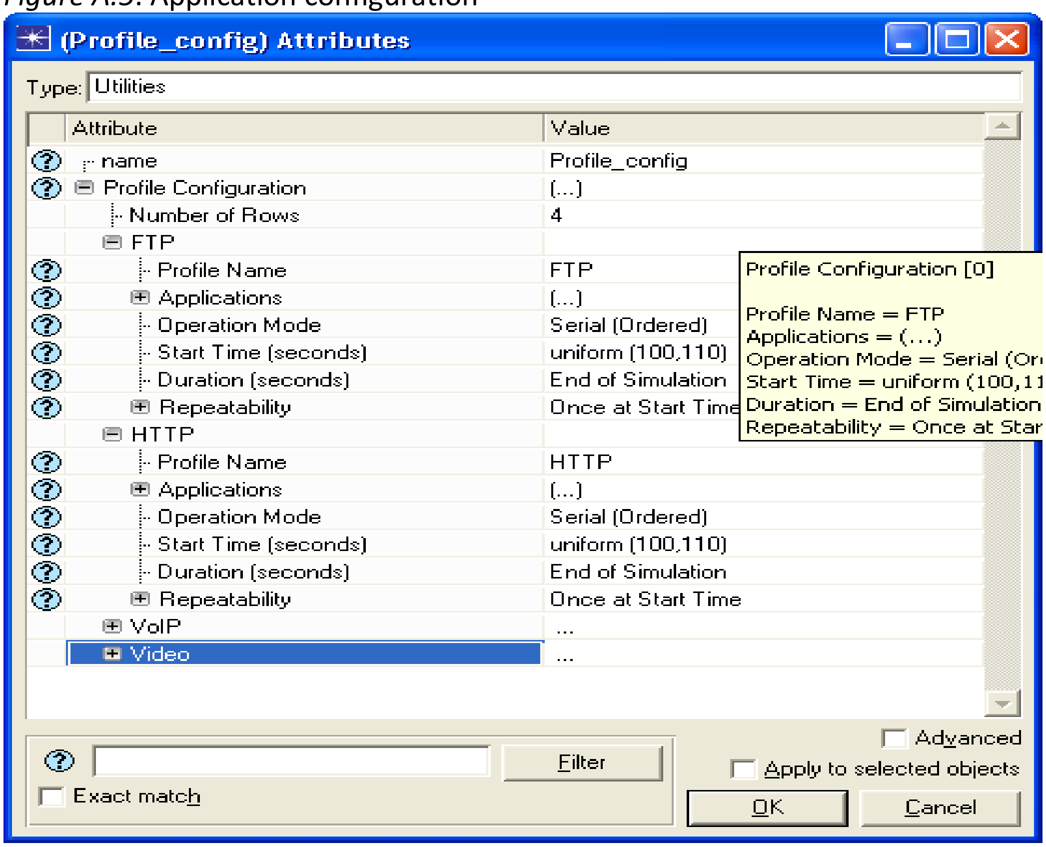

Figure A.6. Profile configuration

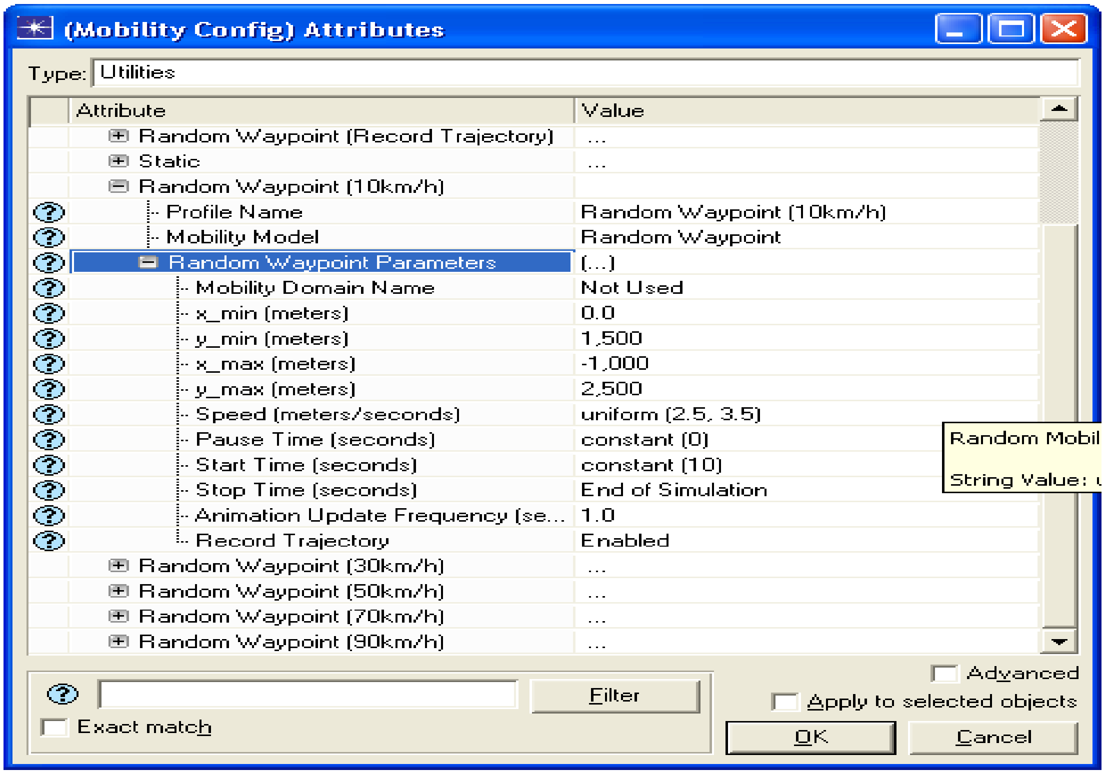

Figure A.7. Mobility configuration

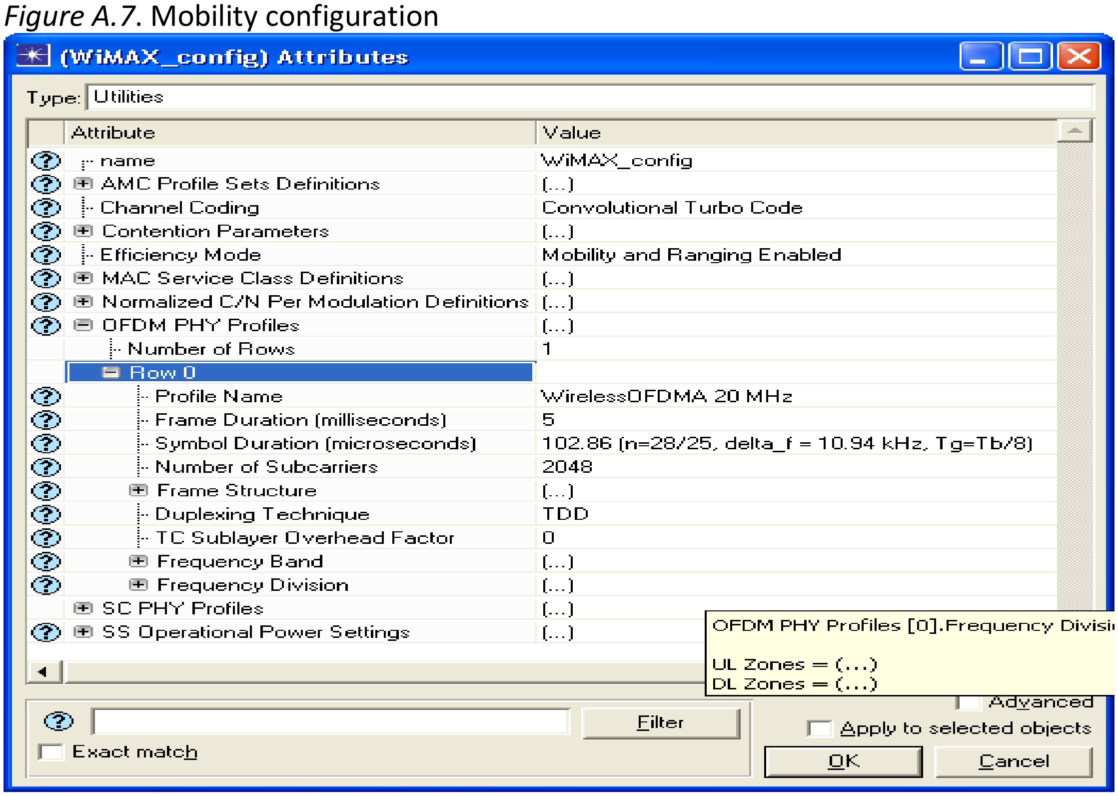

Figure A.8. Mobile WiMAX configuration

Appendix B :Additional results for Chapter 6

Table B.1: Scenarios 1 to 9, Experimental results

Scenario 1

Traffic load / No. of nodes	FTP Download response times(s)	FTP Upload response times(s)	HTTP Object response times(s)	HTTP Page response times(s)	Video conferencing PDV(s)	Video conferencing End to end delay(s)	VoIP Jitter(s)	VoIP MOS
10	0.082101	0.083022	0.080549	0.232201	0.011025	0.028309	0.000661	2.565088
25	0.085558	0.086716	0.079246	0.216977	0.013674	0.057876	0.000690	2.561221
50	0.086454	0.087752	0.080359	0.224363	0.019851	0.099254	0.000662	2.561635
75	0.086816	0.085280	0.080515	0.220515	0.019778	0.125830	0.000671	2.555722
100	0.086915	0.085071	0.077575	0.221430	0.019323	0.155489	0.000661	2.550979

Scenario 2

Traffic load / No. of nodes	FTP Download response times(s)	FTP Upload response times(s)	HTTP Object response times(s)	HTTP Page response times(s)	Video conferencing PDV(s)	Video conferencing End to end delay(s)	VoIP Jitter(s)	VoIP MOS
10	0.166597	0.224699	0.094377	0.251739	0.009588	0.012033	0.008557	3.070011
25	0.168690	0.227566	0.094748	0.249942	0.016256	0.015483	0.008628	3.063557
50	0.165594	0.238862	0.095519	0.248764	0.019867	0.047887	0.008604	3.000572
75	0.171598	0.219291	0.095124	0.253915	0.022068	0.069855	0.008644	2.990202
100	0.173264	0.228563	0.095077	0.251884	0.029458	0.079943	0.008617	2.989757

Scenario 3

Traffic load / No. of nodes	FTP Download response times(s)	FTP Upload response times(s)	HTTP Object response times(s)	HTTP Page response times(s)	Video conferencing PDV(s)	Video conferencing End to end delay(s)	VoIP Jitter(s)	VoIP MOS
10	0.631688	1.105981	0.101557	0.246922	0.143775	0.117984	0.008445	3.684206
25	0.650630	1.134061	0.102615	0.253749	0.190275	0.152420	0.008432	3.644919
50	0.624188	1.125371	0.105661	0.246804	0.354295	0.360736	0.008499	3.630473
75	0.639184	1.125784	0.103846	0.247834	0.580341	0.422059	0.008467	3.616653
100	0.635138	1.135678	0.105962	0.247402	0.419641	0.411410	0.008445	3.611058

Scenario 4

Traffic load / Speed of nodes (Km/h)	FTP Download response times(s)	FTP Upload response times(s)	HTTP Object response times(s)	HTTP Page response times(s)	Video conferencing PDV(s)	Video conferencing End to end delay(s)	VoIP Jitter(s)	VoIP MOS
0	0.08210112	0.08302239	0.020344	0.2322015	1.23126E-05	0.02830965	5.70E-06	2.56508871
10	0.08290632	0.08319406	0.021804	0.2527608	1.79012E-05	0.02808428	-1.35769E-05	2.56536985
30	0.08285916	0.08464922	0.022637	0.2915785	1.27715E-05	0.03563964	-0.00006392	2.56468327
50	0.08350765	0.08585376	0.022214	0.3114316	2.87772E-05	0.04072109	-6.21707E-05	2.56507899
70	0.08661963	0.08790285	0.023137	0.3205318	2.83073E-05	0.03635929	-5.0517E-05	2.56531208
90	0.09173854	0.08992975	0.027316	0.3511297	3.00023E-05	0.03810574	-3.99811E-05	2.56509941

Scenario 5

Traffic load / Speed of nodes (Km/h)	FTP Download response times(s)	FTP Upload response times(s)	HTTP Object response times(s)	HTTP Page response times(s)	Video conferencing PDV(s)	Video conferencing End to end delay(s)	VoIP Jitter(s)	VoIP MOS
0	0.16559427	0.23886218	0.095519	0.248764	0.01986755	0.35429591	0.00015173	3.00057278
10	0.16373485	0.24491742	0.109022	0.2429902	0.02799502	0.35771061	-7.33E-05	3.07362650
30	0.16429931	0.24978331	0.129634	0.2498889	0.04830722	0.35942582	0.00012093	3.07342861
50	0.16717475	0.25995994	0.143182	0.2741735	0.06028611	0.36146627	0.00011774	3.07317043
70	0.16745637	0.26838332	0.149586	0.3077552	0.06281224	0.37599052	0.00011774	3.07280747
90	0.18188391	0.28367834	0.170567	0.3749027	0.07238260	0.39164633	0.00012599	3.07268959

Scenario 6

Traffic load/ Speed of nodes (Km/h)	FTP Download response times(s)	FTP Upload response times(s)	HTTP Object response times(s)	HTTP Page response times(s)	Video conferencing PDV(s)	Video conferencing End to end delay(s)	VoIP Jitter(s)	VoIP MOS
0	0.63513822	1.13567891	0.105962	0.2474028	0.05523452	0.41141035	0.00811840	3.61105853
10	0.64710283	1.39751505	0.265572	0.2826611	0.05535215	0.60312482	0.00906561	3.68912762
30	0.64470103	1.39851201	0.268832	0.4488672	0.06367585	0.60952592	0.00827904	3.68922016
50	0.65020236	1.40014379	0.288685	0.6104094	0.06913473	0.61546907	0.00830792	3.68929193
70	0.68583121	1.42771008	0.300741	0.7278791	0.08493699	0.61708514	0.00822197	3.68923891
90	0.71388629	1.47801123	0.408596	0.905631	0.08331942	0.63878837	0.00822450	3.68917488

Scenario 7

Traffic load / Speed of nodes (Km/h)	FTP Download response times(s)	FTP Upload response times(s)	HTTP Object response times(s)	HTTP Page response times(s)	Video conferencing PDV(s)	Video conferencing End to end delay(s)	VoIP Jitter(s)	VoIP MOS
0	0.08210112	0.08302239	0.020834	0.2322015	5.23126E-05	0.02830965	5.70393E-06	2.56508871
10	0.08483887	0.0703979	0.021941	0.2552426	7.79012E-05	0.02721498	4.18525E-05	2.49040565
30	0.08535916	0.08405843	0.022637	0.3055109	8.27715E-05	0.04647343	6.33431E-05	2.49569315
50	0.08671075	0.08850573	0.025667	0.3104207	0.00010877	0.05117216	7.39768E-05	2.50193544
70	0.08804121	0.08821828	0.025274	0.3489249	0.00012830	0.05351131	7.61238E-05	2.50290865
90	0.09213279	0.09358631	0.032316	0.3659437	0.00015000	0.06499100	9.04745E-05	2.53852437

Scenario 8

Traffic load / Speed of nodes (Km/h)	FTP Download response times(s)	FTP Upload response times(s)	HTTP Object response times(s)	HTTP Page response times(s)	Video conferencing PDV(s)	Video conferencing End to end delay(s)	VoIP Jitter(s)	VoIP MOS
0	0.16559427	0.23886218	0.095519	0.248764	0.02798675	0.35429591	0.00151738	3.00057278
10	0.16729496	0.24947874	0.124568	0.2587779	0.03099502	0.52355193	0.00237065	2.73882799
30	0.16891767	0.25531239	0.137023	0.3160485	0.05030722	0.67190879	0.00337549	2.77934154
50	0.16925297	0.26283238	0.149055	0.3288107	0.06028611	0.70658945	0.00360525	2.74251749
70	0.17050928	0.2711721	0.156537	0.3598138	0.07281224	0.77914026	0.00515517	2.74245466
90	0.189791	0.31580823	0.181289	0.3834246	0.09838260	0.87914524	0.00715517	2.74882799

Scenario 9

Traffic load / Speed of nodes (Km/h)	FTP Download response times(s)	FTP Upload response times(s)	HTTP Object response times(s)	HTTP Page response times(s)	Video conferencing PDV(s)	Video conferencing End to end delay(s)	VoIP Jitter(s)	VoIP MOS
0	0.63513822	1.13567891	0.105962	0.2474028	0.07523452	0.41141035	0.00811840	3.61105853
10	0.65749576	1.40788355	0.260417	0.3046269	0.08256571	0.68234592	0.01005599	3.68009284
30	0.6507064	1.41440154	0.292759	0.5635648	0.08935215	0.72423074	0.01090445	3.68027128
50	0.66725023	1.43861446	0.332816	0.7021218	0.09534734	0.82990916	0.01184897	3.68079766
70	0.78475907	1.64174477	0.50375	1.0256867	0.12093699	0.95739986	0.01581741	3.68084740
90	0.83379906	1.8124254	0.607161	1.2262359	0.18331922	1.21739986	0.02171888	3.68124075

PACKET LOSS RATIOS

No		N	Movespeed	Traffic load		througput	Throughput	Traffic sent	Traffic received	Packet loss ratio
1	Scenario 1			[light traffic loads /10 nodes]		bPS	Per node	Byte per second	Byte per second	%
2		10	Fixed	Light_FTP	FTP	225.4933333	22.54933333	18.48	18.48	0.000000000%
3		25	Fixed	Light_HTTP	HTTP	904.0177778	90.40177778	88.22888889	88.22888889	0.000000000%
4		50	Fixed	Light_VoIP	VoIP	110,411.91	11041.19111	4,599.04	4,598.96	0.001932768%
5		75	Fixed	Light_Video	Video	9,049,335.29	904933.5289	3,024,307.20	503,710.20	83.344608643%
6		100	Fixed							
7	Scenario 2			[Medium traffic loads / 50 nodes]		Bit per second	Per node	Byte per second	Byte per second	%
8		10	Fixed	medium_FTP	FTP	6,398.22	127.9644444	704.3111111	704.3111111	0.000000000%
9		25	Fixed	medium_HTTP	HTTP	20,012.09	400.2417778	2259.928889	2259.928889	0.000000000%
10		50	Fixed	Medium_VoIP	VoIP	1,278,141.78	25562.83556	31950.93333	31949.02222	0.005981394%
11		75	Fixed	medium_Video	Video	9,040,312.68	180806.2535	16816204.8	1354878.4	91.943019153%
12		100	Fixed							
13	Scenario 3			Heavy traffic loads / 100 nodes]		Bit per second	Per node	Byte per second	Byte per second	%
14		10	Fixed	Heavy_FTP	FTP	152,918.33	1529.183289	18184.32	18184.32	0.000000000%
15		25	Fixed	Heavy_HTTP	HTTP	125,919.82	1259.198222	14326.68889	14324.46667	0.015511066%
16		50	Fixed	Heavy_VoIP	VoIP	5,232,547.91	52325.47911	509,290.76	436,013.69	14.388061410%
17		75	Fixed	Heavy_Video	Video	9,037,935.00	90379.35004	19,166,323.20	921000.6	95.194693367%
18		100	Fixed							
19	Scenario 4			[light traffic loads /10 nodes]		Bit per second	Per node	Byte per second	Byte per second	%
20		10	0	Light						
21	1	10	10	Light_FTP	FTP	217.1022222	21.71022222	18.48	18.48	0.000000000%
22	2	10	30	Light_HTTP	HTTP	960.4888889	96.04888889	94.41222222	94.41222222	0.000000000%
23	3	10	50	Light_VoIP	m-VoIP	78,483.84	7848.384	4,531.71	3,868.84	14.627293100%
24	**4**	10	70	Light_Video	Video	8,373,582.54	837358.2542	2,422,406.97	346,438.40	85.698588039%
25	5	10	90	Light						
26	Scenario 5			[Medium traffic loads / 50 nodes]		Bit per second	Per node	Byte per second	Byte per second	%
27		50	0	medium						
28	6	50	10	medium_FTP	FTP	3,681.00	73.61991111	397.52	391.9644444	1.397553722%
29	7	50	30	medium_HTTP	HTTP	15,967.97	319.3594667	1,803.65	1,794.17	0.525661821%
30	8	50	50	Medium_VoIP	m-VoIP	883,749.40	17674.98809	28,322.46	22,089.40	22.007468750%
31	**9**	50	70	medium_Video	Video	8,412,481.17	168249.6235	15,605,337.60	984,120.80	93.693691061%
32	10	50	90	medium						
33	Scenario 6			Heavy traffic loads / 100 nodes]		Bit per second	Per node	Byte per second	Byte per second	%
34		100	0	Heavy						
35	11	100	10	Heavy_FTP	FTP	106,809.85	1068.098489	12,795.24	12,517.46	2.170946964%
36	12	100	30	Heavy_HTTP	HTTP	98,377.26	983.7726222	11,208.69	11,108.60	0.892997517%
37	13	100	50	Heavy_VoIP	VoIP	4,391,415.40	43914.15396	472,259.38	345,923.38	26.751401019%
38	**14**	100	70	Heavy_Video	Video	8,775,553.85	87755.53849	20,042,304.00	451,125.80	97.749132036%
39	15	100	90	Heavy						
40	Scenario 7			[light traffic loads /10 nodes]		Bit per second	Per node	Byte per second	Byte per second	%
41		10	0	Light						
42	1	10	10	Light_FTP	FTP	748.1155556	74.81155556	15.12	15.11	0.066137566%
43	2	10	30	Light_HTTP	HTTP	1,684.30	168.4302222	56.57	56.37222222	0.353530394%
44	3	10	50	Light_VoIP	VoIP	113,591.86	11359.18559	2,376.85	2,026.76	14.729181670%
45	**4**	10	70	Light_Video	Video	42,958,338.49	4295833.849	1,659,427.20	627,091.20	62.210381992%
46	5	10	90	Light						
47	Scenario 8			[Medium traffic loads / 50 nodes]		Bit per second	Per node	Byte per second	Byte per second	%
48		50	0	medium						
49	6	50	10	medium_FTP	FTP	127,654.76	2553.095111	685.9377778	678.38	1.101492847%
50	7	50	30	medium_HTTP	HTTP	638,288.69	12765.77387	2,109.92	2,098.08	0.561105465%
51	8	50	50	Medium_VoIP	VoIP	28,640,727.35	572814.547	31,908.82	26,566.49	16.742496154%
52	**9**	50	70	medium_Video	Video	325,894,219.75	6517884.395	14,285,260.80	3,297,120.60	76.919423130%
53	10	50	90	medium						
54	Scenario 9			Heavy traffic loads / 100 nodes]		Bit per second	Per node	Byte per second	Byte per second	%
55		100	0	Heavy						
56	11	100	10	Heavy_FTP	FTP	6,824,850.11	68248.50111	17,120.07	16,759.42	2.106574497%
57	12	100	30	Heavy_HTTP	HTTP	8,641,985.29	86419.85289	13,679.70	13,563.55	0.849100748%
58	13	100	50	Heavy_VoIP	VoIP	265,142,140.99	2651421.41	474,958.53	377,054	20.613280205%
59	**14**	100	70	Heavy_Video	Video	687,434,197.81	6874341.978	17,841,369.60	2,900,123.80	83.744948594%
60	15	100	90	Heavy						

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