A PERFORMANCE COMPARISON OF FRAME STRUCTURES IN
WIMAX MULTI-HOP RELAY NETWORKS

by

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Abstract

Wireless multi-hop relay systems are the newest amendment to the IEEE 802.16 standard for local and metropolitan area networks, else known as WiMAX. Relay systems come in different flavours, based on their capabilities and have the potential to offer many advantages over the single-hop technology. Upcoming broadband wireless technologies, that utilize multi-hop relays, need good network planning and design in order to achieve their full potential.

There are two main types of multi-hop relay stations: transparent, which are not able to transmit control information and non-transparent, which have the capability to transmit such information. This study focuses mainly on non-transparent relay stations due to their complexity and ability to operate in a more than two hop environment. Currently, the latest IEEE amendment provides two different frame structures – single and multi-frame – for utilization in multi-hop relay networks, to allocate bandwidth.

The purpose of this thesis is to evaluate the two proposed frame structures, in various network scenarios in terms of delay, throughput, rate, and user capacity. In addition, we will discuss some of the issues that need to be considered to cost effectively plan and design a multi-hop relay network. The evaluation methodology that we utilize is in accordance with the Multi-hop Relay System Evaluation Methodology developed by the IEEE 802.16 Broadband Wireless Access Working Group.

To evaluate the above frame structures we developed an evaluation model for use in the network simulator 2 (ns2) from University of California Berkeley, by modifying
the light WiMAX (LWX) add-on from Taiwan University. Unlike the original LWX module, which supports only transparent relay configurations, our module supports both multi-frame and single frame structures, as well as non-transparent multi-hop relay environments.

To our knowledge there is no previous work, which analyzes the performance of the single frame and multi-frame system in multi-hop relay environments using the guidelines from the latest amendment to the standard (IEEE 802.16j-2009). Moreover, there is no publicly available software that will enable the study of such performance. The resulting source code of our work has been made publicly available and can be obtained from our website.
Acknowledgements

Although my name is printed on the cover of this thesis, the word “I” does not appear within its chapters. I do this to pay tribute to the countless contributions of my advisors and the support of my family and friends.

First I would like to thank Queen’s University and the School of Computing for giving me the opportunity to be a part of such a great family.

To, Dr. Hossam Hassanein I am extremely grateful to you. I would have never had the opportunity to get involved in this great project without you. It was a very valuable experience being part of the Queen’s University, School of Computing, Telecommunications Research Lab (TRL) and I consider myself one of the luckiest people for that. I would also like to thank you for your support during this the course of this work and for giving me so much freedom to explore and discover new areas of broadband wireless technologies. Your wonderful personality and most of all encouragement during difficult times in my research kept me going.

To, Dr. Abd-Elhamid M. Taha, your assistance right from the topic selection to the analysis of the results was invaluable in the successful completion of this work. Your technical assistance, moral support and motivation are the main reasons for timely completion of such a challenging project. Your deep-rooted knowledge of the system and experience in this field enabled me to produce a high quality work and gain valuable knowledge in conducting research and I am very grateful to you for that.
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On a personal note, I want to give a huge thank you to my Mom and Dad, who laid the foundation of my education. You have been wonderful role models and teachers my entire life. Without your continuous support and prayers, this work would not have been accomplished. I will also like to thank my sister Evdhoksia for her support during difficult times and for sharing my successes when things were going well. I am grateful for all the life lessons learned from my grandparents, which are the cornerstones of my success. And most of all I am forever thankful to my loving, encouraging, and patient wife Klodiana whose unconditional support during the final stages of this work is so appreciated. You have been a terrific partner and a valuable advisor. Thank you.

Finally, I express my deepest gratitude to my new born daughter Eva, whom I dedicate this thesis. You were and always will be a great motivation for my success.
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<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
</tr>
<tr>
<td>4G</td>
<td>4th Generation</td>
</tr>
<tr>
<td>AAA</td>
<td>Authentication Authorization and Accounting</td>
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<tr>
<td>AAS</td>
<td>Adaptive Antenna System</td>
</tr>
<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>AMC</td>
<td>Adaptive Modulation and Coding</td>
</tr>
<tr>
<td>ARQ</td>
<td>Automatic Repeat Request</td>
</tr>
<tr>
<td>ASN</td>
<td>Access Service Network</td>
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<tr>
<td>ATM</td>
<td>Asynchronous Transfer Mode</td>
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<td>AZ</td>
<td>Access Zone</td>
</tr>
<tr>
<td>BE</td>
<td>Best Effort</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
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<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>CBR</td>
<td>Constant Bit Rate</td>
</tr>
<tr>
<td>CID</td>
<td>Connection Identifier</td>
</tr>
<tr>
<td>CS</td>
<td>Convergence Sub-layer</td>
</tr>
<tr>
<td>CSN</td>
<td>Connectivity Service Network</td>
</tr>
<tr>
<td>DCD</td>
<td>Downlink Channel Descriptor</td>
</tr>
<tr>
<td>DHCP</td>
<td>Dynamic Host Configuration Protocol</td>
</tr>
<tr>
<td>DSL</td>
<td>Digital Subscriber Line</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>ertPS</td>
<td>extended real-time Polling Service</td>
</tr>
<tr>
<td>FBWA</td>
<td>Fixed Broadband Wireless Access</td>
</tr>
<tr>
<td>FCH</td>
<td>Frame Header Control</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FTP</td>
<td>File Transfer Protocol</td>
</tr>
<tr>
<td>GW</td>
<td>Gate Way</td>
</tr>
<tr>
<td>ICI</td>
<td>Intra-Cell Interference</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>ITS</td>
<td>Intelligent Transportation Systems</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-of-Sight</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
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<tr>
<td>MAN</td>
<td>Metropolitan Area Network</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>MMRN</td>
<td>Mobile Multi-Hop Relay Network</td>
</tr>
<tr>
<td>MRTR</td>
<td>Minimum Reserved Traffic Rate</td>
</tr>
<tr>
<td>MSTR</td>
<td>Maximum Sustained Traffic Rate</td>
</tr>
<tr>
<td>MT</td>
<td>Mobile Terminal</td>
</tr>
<tr>
<td>NAP</td>
<td>Network Access Provider</td>
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<tr>
<td>NLOS</td>
<td>Non-Line-of-Sight</td>
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<tr>
<td>NRM</td>
<td>Network Reference Model</td>
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>NSP</td>
<td>Network Service Provider</td>
</tr>
<tr>
<td>ntRS</td>
<td>non transparent Relay Station</td>
</tr>
<tr>
<td>NWG</td>
<td>Network Working Group</td>
</tr>
<tr>
<td>tRS</td>
<td>transparent Relay Station</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplex</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiplexing Access</td>
</tr>
<tr>
<td>OSI</td>
<td>Open System Interconnection</td>
</tr>
<tr>
<td>PDU</td>
<td>Protocol Data Unit</td>
</tr>
<tr>
<td>PMP</td>
<td>Point to Multi-Point</td>
</tr>
<tr>
<td>PHS</td>
<td>Packet Header Suppression</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical Layer</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Control</td>
</tr>
<tr>
<td>RR</td>
<td>Round Robin</td>
</tr>
<tr>
<td>RRM</td>
<td>Radio Resource Management</td>
</tr>
<tr>
<td>RS</td>
<td>Relay Station</td>
</tr>
<tr>
<td>RTG</td>
<td>Receive/Transmit Time Gap</td>
</tr>
<tr>
<td>R-RTI</td>
<td>Relay Receive to Transmit Transition Interval</td>
</tr>
<tr>
<td>rtPS</td>
<td>real-time Polling Service</td>
</tr>
<tr>
<td>R-TTI</td>
<td>Relay Transmit to Receive Time Interval</td>
</tr>
</tbody>
</table>
RZ  Relay Zone
SC  Single Carrier
SCa Single Carrier access
SDN Service Data Network
SDU Service Data Unit
SNR Signal to Noise Ratio
SS Subscriber Station
STR Simultaneous Transmit and Receive
TCL Tool Command Language
TDD Time Division Duplex
TDMA Time Division Multiple Access
TTG Transmit/Receive Time Gap
TTR Time-Division Transmit and Receive
TZ Transparent Zone
UL Uplink
UE User Equipment
UGS Unsolicited Grant Service
VoIP Voice over Internet Protocol
WiMAX Worldwide Interoperability Microwave Access
WirelessHUMAN Wireless High Speed Unlicensed Metro Area Network
WirelessMAN Wireless Metropolitan Area Network
Chapter 1

Introduction

1.1 Wireless Broadband

Wireless Broadband is a cell-based technology designed to provide last-mile high-speed wireless internet and data network access. In the last few years, such technology has gained tremendous attention due to the lower cost of deployment and its ability to serve a higher number of users – compared to the wired technology. Broadband wireless networks such as Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) can be categorized into a single-hop or a multi-hop network. A single-hop network contains a central entity such as a Base Station (BS) that makes and delivers decisions to all subscribed users, known as mobile terminals (MTs), under its coverage area.

The geographical area covered by a single BS is called a cell and is the smallest unit in a wireless broadband network configuration. In a multi-hop network a single BS is not able to communicate directly with all the MTs, either because of large distances or different obstacles between them. To enable the BS signal to reach all the MTs in such a network, a relay mechanism is required which is responsible for communicating information from the BS to the MTs that are not in direct contact with the BS.
1.2 Relay Networks

Relay stations (RS) will play an important role in upcoming broadband wireless networks such as WiMAX and LTE-Advanced. Such relays can be utilized either to increase a cell’s capacity or expand a cell’s coverage; all at much lower cost compared to the alternative solution of using more BSs. Employing RSs also has the advantages of: reducing power consumptions for MTs, improving service delivery zones and overcoming patched coverage. Low cost relay technology is also an attractive choice for the early stages of the network deployment, which enables the coverage of a larger area, than the single BS solution. For WiMAX, specifications have already been made in j [1] amendment for the IEEE 802.16-2009 release [2]. In contrast, the 3GPP [3] has only recently outlined deployment alternatives for relay stations to be considered for Release 10, which is the release to describe LTE-Advanced [4].

Both standardization bodies classify relay stations into two main types based on the deployment objective: transparent (Figure 1-1), and non-transparent relays (Figure 1-2). Transparent RSs (tRS) operate with a BS’s cell coverage where MTs fully recognize the BS’s control message, but have their uplink (UL) transmission go through the RS. Transparent RSs are hence aimed at expanding a cell’s capacity. The second class, non-transparent RS (ntRS), are utilized in instances in which MTs are beyond a BS’s coverage, and rely fully on the RS for both downlink and uplink signaling and data transfer. It is this latter class that is aimed at expanding a cell’s coverage.
Figure 1-1: Transparent Relay Station (tRS) Configuration

Figure 1-2: Non Transparent Relay (ntRS) Configuration
Relay stations however, are dependent on a well-designed frame structure to achieve the full potential of the above applications. Such frame structure should be capable of supporting the single cell legacy configuration as well as multi-hop relaying. In point to multipoint (PMP) networks and mobile multi-hop relay networks (MMRN), the frame structure is of particular importance since it manages the channel access in both time and frequency domains. Frame structure, also determines how resources are allocated in a Mobile Multi-Hop Relay Network (MMRN). In a MMRN, traffic is classified as uplink (UL) from MT to BS, and as downlink (DL) from BS to MT. To deal with the UL and DL traffic, usually different scheduling algorithms are employed. Scheduling algorithms ensure that Quality of Service (QoS) requirements for new and existing MT in the network are satisfied. Naturally the design of the frame structure will also play a critical role in the performance of scheduling algorithms, which in turn will affect the overall network performance.

Frame structures in multi-hop relay networks can be categorized into two main groups: frame structures utilized for transparent relay configurations, and frame structures utilized for non-transparent relay configurations. The former is less complex since tRS are not required to transmit frame control messages and is intended for networks with a maximum of two hops. For WiMAX ntRSs, the amendment allows for two types of frame structures. The first, called the single frame, is one where the BS and its children ntRS are scheduled in the duration of one point to multipoint (PMP) frame duration. In the second frame type, the multi-frame structure, the ntRS can be scheduled
in a periodic fashion over the duration of multiple PMP frames. However, in both frame structure types the BS is always granted its downlink and uplink transmissions.

1.2 Motivation and Objectives

To our knowledge there is no previous work which analyzes the performance of the single frame and multi-frame system in multi-hop relay environments using the guidelines from the latest amendment to the standard (IEEE 802.16j-2009) [1]. Moreover, there is no publicly available software that will enable the study of such performance.

The intent of this thesis is to examine the effect of the frame structure type on WiMAX network employing ntRSs. Specifically, our interest is to investigate the effect of the frame structure type on certain operational metrics such as throughput, delay, and user capacity.

1.3 Thesis Contribution

In this thesis, we have surveyed and categorized frame structure proposals for utilization in multi-hop relay environments. In addition, we have detailed the IEEE standard’s choice of the frame structure for multi-hop relay environments, and conducted a performance evaluation.

To facilitate the multi-hop relay frame structure examination, we have identified several performance metrics and developed an evaluation environment per the IEEE 802.16j amendment. We developed an add-on [5] for ns2 [6] [7] [8] through modifying the light WiMax (LWX) add-on contributed by Lai and Chen in [9] (The LWX add-on
itself can be downloaded from [10]). We expanded the LWX to consider ntRS as the LWX was only aimed at evaluating setups with tRS. We also implemented both frame structure types with sufficient flexibility to allow possible manipulation by an independent scheduling module.

The evaluation environment was able to provide certain insights as to the specific advantages that both single frame and multi-frame have to offer. The single frame structure has shown that it is able to achieve a better performance on average compared to the multi-frame structure. The multi-frame structure however, is able to support a higher number of users. Results also show that the role of scheduler is important in WiMAX networks employing non-transparent relay structures.

1.4 Thesis Outline

The remainder of this thesis is organized as follows: Chapter 2 presents an overview of the next generation broadband wireless access technologies and a more detailed description of the IEEE 802.16 standard and relay technology. Chapter 3 discusses some of the research contribution to the frame structure for multi-hop relay technology and provides specific details on the single frame, multi-frame, and transparent frame, adopted by the IEEE 802.16 standard; some of the efforts to evaluate relay performance and utilizing various frame structures are also reviewed. In Chapter 4, we develop a comprehensive simulation model and utilize it to observe the behavior of the frame structures, adopted by the IEEE 802.16 standard, under various network configurations. We report on the strengths and weaknesses of each frame structure and
make suggestions on their utilization. Finally, Chapter 5 presents our conclusions and future work.
Chapter 2

Background

In this chapter we present some of the characteristics of wireless broadband networks and their architecture. In addition, a detailed description of the MAC and PHY layer of the WiMAX [11] and WiMAX relays [1], as described by the IEEE 802.16 standard, is presented. Resource allocation techniques utilized by the different broadband technologies are also discussed. Furthermore, we explain the types of WiMAX cells, introduce WiMAX relay stations and their modes of operation; illustrate the different RS types and data transmission schemes.

2.1 Introduction to Broadband Wireless Technology

Wireless broadband is a technology which has the capability to provide instantaneous bandwidth and high data rates over a wide coverage area. The technology operates in line-of-sight (LOS) configurations, where the BS and subscriber station (SS) have a clear view of each other and non-line-of-sight (NLOS) configurations, where the radio transmission path is partially obscured. LOS configurations are estimated to have a range of up to 50km and achieve download speeds of over 100 Mbit/s. NLOS configurations, on the other hand, communicate in a much smaller range and are able to achieve lower data rates, depending on the level of obscurity.
Mobile wireless broadband or short mobile broadband is a technology which enables user mobility. More modern portable devices have a build-in wireless broadband adapter which allows subscribers to connect to the BS. These connections can experience speed limitations and their distance from the BS is limited to a maximum of 2000 meters, due to the power limitations of the mobile devices.

2.1.1 Drivers

Traditional broadband technologies, such as cable and DSL, have changed the way people conduct business and utilize technology. A number of new applications have been developed to help users do research, communicate, share files, play games, and perform many other activities. As a result, it is difficult and almost impossible for traditional fixed broadband technologies to provide a flexible and on demand service to users. Moreover, traditional cell phone technologies – intended mainly for voice traffic – lack the ability to support such services [12].

Technology is a major aspect of the modern health services. Telecommunications and computer applications enable health care professionals to deliver a higher quality health care to more people at a lower cost. Current narrow band platforms, however, cannot deliver the full potential of such applications. Widespread access to high bandwidth connections can enable a variety of clinical applications: remote surgery, remote consultation, teleradiology, remote monitoring, and much more.

Wireless broadband technology is a major contributor in the development of the intelligent transportation system (ITS) solutions. Being able to extend real time
monitoring and data collection by utilizing wireless broadband equipment, railways, highways, and other transportation operations, will become more efficient and cost-effective. Some of the many broadband wireless solutions include: video surveillance, traffic control, bridge monitoring, transit management, travelers information systems to name a few.

Public services and education are two more areas that can benefit from broadband wireless technology. This is of particular significance in remote areas where access to online: education, professional development, and skilled medical staff is of critical importance.

2.1.2 Technologies (LTE & WiMAX)

Multiple private companies have attempted, in the late 1990s and early 2000s, to establish an alternative wireless broadband technology [13]. They, however, were not very successful due to the lack of a standardized protocol for such high speed broadband technology. In order for such technology to gain acceptance and be able to grow it must first be a standard that could be used by various vendors that produce wireless devices. So far there are only two technologies being developed to lead the next generation of wireless technologies else known as 4th Generation (4G). The 3rd Generation Partnership Project (3GPP) [3] with the Long Term Evolution (LTE) project, and the Institute of Electrical and Electronics Engineers (IEEE) with the Worldwide Interoperability for Microwave Access (WiMAX) [11], are identified as the technologies featured to meet the consumers growing demands.
WiMAX has come a long way since the first meeting in 1999 of the IEEE working group – to develop a standard protocol for wireless metropolitan area network (WMAN) – and the birth of IEEE 808.16 (WiMAX) standard in 2001. It currently supports approximately 14.9 million users worldwide and it is expected to reach a total of 133.66 million users by the end of 2012 [14]. Complementary technology, LTE, still a newbie in the wireless broadband market, is predicted to have a much higher user subscription, approximately 450 million by the year 2015 and achieve revenues of more than $200 billion CDN [15].

Both WiMAX and LTE have All-IP network architecture, capable of supporting a variety of different applications. Both underlined technologies, are capable of achieving higher data rate, more efficient spectrum utilization and handle high speed mobility better, by adapting Orthogonal Frequency Division Multiple Access (OFDMA) as their method of choice for radio frequency utilization [16], [17].

Broadband wireless networks consider OFDMA to be one of the prime multiple access schemes. OFDMA is a special case of multicarrier multiple access schemes, which assigns each sub-channel to only one user; thus eliminating the intra-cell interference (ICI). Where the frequency selective channels slowly very for fixed or portable applications, OFDMA has the ability to exploit the multiuser diversity embedded in multipath channels. Other advantages of OFDMA include its ability to easily decode at the receiver (thanks to the absence of ICI) and to provide finer granularity and better link budget for the uplink transmission.
2.1.3 Worldwide interoperability of Microwave Access (WiMAX)

The IEEE 802.16 standard [18] is defined only for the first two layers: physical layer (PHY) and medium access control (MAC), of the open system interconnection (OSI) reference model [19]; leaving the rest of the layers to be defined by the different applications. Moreover, the standard has identified several types of PHY layers and gives a clear description on the various characteristics of the MAC layer such as bandwidth request mechanisms and the scheduling services supported.

The WiMAX forum [20], a consortium of about 420 members including major corporations like AT&T, Fujitsu, Intel and Siemens, was setup in June 2001 to support the WiMAX technology and promote its commercial use. The forum is responsible for preparing profiles for systems that comply with the IEEE 802.16 standard and create interoperability tests to ensure that different vendors’ implementations can work together. The first version of the IEEE 802.16 standard was completed in October 2001 and since then several versions have emerged addressing issues such as: Non-Line of Sight (NLOS) operation, mobility, multiple traffic classes for QoS, operation in the licensed and unlicensed frequency bands [2].

2.1.3.1 WiMAX History

The first standard produced by the IEEE 802.16 group was approved by the end of 2001[18]. This standard supported only point-to-multipoint and mesh architecture, using frequency bands of 10GHz to 66GHz, with a channel band-window of 20MHz, 25MHz and 28MHz. It was also based on a single carrier (SC) physical layer (PHY). The
medium access control (MAC) layer supports time division multiplexing (TDMA), a channel access method that allows multiple users to share the same frequency and orthogonal division multiplexing (OFDM) technology, a multicarrier modulation scheme utilized by the physical layer (PHY) to transform the message signal.

In 2004 another modified standard [21] – which replaced the previous 2001 version – was published. The new version of IEEE 802.16-2004 [11], included NLOS applications which supported frequency bands from 2GHz to 11GHz, with 1.75MHz, 3.5MHz, 7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, and 8.75 MHz channel bandwidths. In addition to SC, the new standard also supported orthogonal division multiple access (OFDMA) technology, which can be scaled to utilize bandwidth more efficiently. Both OFDM and OFDMA modulation techniques allow subcarriers to be modulated at different rates (QPSK, 16QAM, and 64QAM) to account for signal loss due to noise in the medium and distance.

The IEEE 802.16e, also known as mobile WiMAX, was announced at the end of 2005. This new standard was designed to equip WiMAX networks with the ability to support mobility at vehicular speeds for 2GHz – 6GHz frequency bands.

One of the latest amendments to the IEEE 802.16 family of standards was ratified by the end of the 2009 [1]. The new amendment introduced relay stations to the existing WiMAX technology. Relay stations (RS) have different capabilities and are meant to assist the WiMAX base station (BS) by improving coverage and capacity. The last section of this chapter will present a more detailed description of this relay technology.
Figure 2-1 below is a summary of how the IEEE 802.16 standard has evolved over the years.

![Evolution of IEEE 802.16 standard](image)

**Figure 2-1: Evolution of IEEE 802.16 standard**

2.1.3.2 Network Architecture

In 2005 a Network Working Group (NWG) was formed by the WIMAX forum to specify an end-to-end network architecture. The new architecture had to be compatible with the system characteristics of the fourth generation (4G) networks. As a result, NWG adopted various design principals such as: optimization of radio Access Service Network (ASN) interconnectivity, logical separation of connectivity service networks and application service networks and support for different access technologies.
A logical illustration of the WiMAX network reference model (NRM) is shown in Figure 2-2. The WiMAX NRM makes a distinction between network service providers (NSP) and network access providers (NAP.) The former is an entity which enables internet protocol (IP) connectivity and also provides the available services for the customer’s WiMAX equipment, with the help of one or more connectivity service networks (CSN).

Figure 2-2. WiMAX Network Reference Model

NAPs provide the hardware infrastructure to the subscriber by utilizing one or more access service network (ASN). A mobile terminal (MT) or else known as a
subscriber station (SS), or user equipment (UE), is usually a customer’s equipment that facilitates the connection to the WiMAX network. In addition ASN provides an entry point for the MT and as such is required to support the following functionalities: layer-2 connectivity, authentication authorization and accounting (AAA) message transfer, service and network discovery, facilitate layer-3 connectivity by utilizing relay functionality, radio resource management (RRM), QoS, tunnelling between ASN and CSN, location management, anchored mobility and paging for both ASN and CSN.

WiMAX MTs obtain IP connectivity from the CSN, which consists of user databases, routers, AAA, and interworking gateway devices. The following functionalities are supported as well: IP address allocation, AAA services, policy and addition control, roaming, mobility, Internet access, billing, and connectivity for WiMAX services.

WiMAX reference model specifies six reference points, R1 to R6, which help to interconnect each of its different components illustrated in Figure 2-2. Each of these reference points represents various procedures and functionalities, such as: procedures defined by the IEEE standard, AAA policy management and enforcement, IP configurations and management, mobility management, and tunnelling. In addition, ASN and NSP do not necessarily belong to the same network operator. For instance, two different NSPs can have access to the same ASN and vice versa.

ASN logical entity is represented in a physical WiMAX network by two components, the base station (BS) and the ASN gateway (GW). The BS provides
connectivity for MT via radio frequencies, as well as coordinates transmissions via uplink and downlink scheduling. Meanwhile, the ASN-GW provides connectivity for the BSs to other ASN or the CSN. The ASN-GW is responsible for data routing as well [22].

2.1.3.3 IEEE 802.16 MAC and PHY layers

As mentioned in the previous section the IEEE project is mostly concerned with the first two layers of the OSI model, PHY (physical layer) and MAC (medium access control). The PHY is responsible for the transmission of physical signals from one device to the other, by utilizing radio frequencies or any other signal transmitting mediums. In addition, the PHY is not aware of the application type and QoS requirements, for the transmitted signal. On the other hand, the MAC layer is responsible for packet construction, encryption, and scheduling. It also takes care of packet transmission or retransmission, by determining the appropriate power level and burst profile.

2.1.3.3.1 IEEE 802.16 PHY layer and Frame Structure

The WiMAX physical (PHY), or else known as the layer 1 of the OSI model, is responsible for the transmission of information between the sender and the receiver utilizing the physical medium. Physical medium can include copper wire, twisted pair cables, light waves, and radio frequencies. The focus of this section is on the radio frequency and how the WiMAX BS utilizes it to allocate resources among MT.

The IEEE 802.16 family of standards has adapted the single carrier (SC), OFDM and OFDMA modulation techniques for point-to-multipoint (PMP) operations in a line of sight (LOS) and non LOS environment, respectively. The OFDM PHY layer operates at
frequencies between 2GHz and 11GHz for non LOS and is used for fixed WiMAX networks. The OFDMA PHY operates also at the same frequencies as the OFDM PHY layer for non LOS; however, OFDMA is adapted for mobile, portable operations, and supports scalability (it has a variable fast furrier transform FFT of 128, 512, 1024, and 2048 points).

Duplex mode supported by the standard include, time-division duplex (TDD), frequency-division duplex (FDD), and half FDD. When FDD is utilized both MT and BS can transmit data to each other at the same time. Asymmetric UL and DL traffic however, cannot be supported, in a FDD setting paired frequency bands are required and channels are not reciprocal. On the other hand, TDD which is also the primary focus of our work, has a higher flexibility for allocating UL and DL traffic, is cheaper and less complex to implement, as well as allowing for more effective multiple input multiple output (MIMO) technology to be implemented. Figure 2-3 is an illustration of the duplex modes supported by the standard.
The BS also is able to adjust the transmission rate based on the channel conditions, for both UL and DL traffic. On the UL the BS is able to measure the receiving signal while on the DL channel quality messages are conveyed by the MTs; as a result the BS will switch to the most appropriate modulation and coding scheme. Modulation schemes of varying robustness and efficiency adopted by the standard include quadruple phase shift keying (QPSK), 16-state quadruple amplitude modulation (16-QAM), and 64-state QAM (64-QAM). Figure 2-4, is a summary of the different modulation and coding schemes that may be utilized by the BS.
As we previously mentioned OFDMA is the primary access mechanism for NLOS communications in the frequency bands under 11GHz. When TDD is utilized, the timeline is partitioned by the BS into contiguous OFDMA frames. Each frame is then further partitioned into two main sub-frames, one for the downlink traffic and the other for the uplink traffic. The basic resource allocation unit in an OFDMA frame is a slot. A slot consists of several symbols in the time domain (the number of symbols and their length may vary from one frame to the other under the control of the scheduling mechanism) and one sub-channel in the frequency domain. When FDD is utilized, both UL and DL are concurrent in time, but are carried through different channels.
Frame structure plays a very important role in resource allocation for both frequency and time domain in WiMAX networks. A basic frame structure shown in Figure 2-5, describes the configuration of an OFDMA frame. The frame is divided into two sub-frames, a UL sub-frame and a DL sub-frame. There is a guard interval between each sub-frame, called Transmit/Receive Transition Gap (TTG), which allows enough time for the BS to switch from transmit to receive mode. Another time gap called the Receive/Transmit Transition Gap (RTG) is inserted between each subsequent frames and allows for receive transmit transition. The downlink sub-frame starts with the preamble, frame control header (FCH), DL-MAP and UL-MAP – or else known as the frame control section – followed by the DL data bursts. The purpose of the preamble is to help the MT synchronize with the BS, while the FCH specifies the burst profile and the length of one or more DL bursts. The DL-MAP, and UL-MAP, as the name suggests is a map that dictates the order, length and sub-channel to be used by the MTs to receive and transmit data using the negotiated burst profiles. The DL data are usually transmitted in order of decreasing robustness to avoid any data loss that can occur as a result of synchronization loss – result of a higher burst profile.

Unlike the DL sub-frame the UL sub-frame starts with ranging (initial, handover, periodic, bandwidth request), acknowledgment (ACK) channel and fast feedback channel, followed by the data burst. Ranging is the process during which MT adjust their transmission power, and also sometimes may request additional bandwidth from BS. The other two channels, as the name suggests, are utilized to acknowledge
successful/unsuccessful transmission of data as well as channel conditions. The MTs transmit in their assigned slots using the burst profiles specified by the UL-MAP. The uplink sub-frame may also contain contention-based bandwidth allocation for broadcast, multicast, and initial system access requests. During initial system access bandwidth allocations are adjusted accordingly, to accommodate for extra guard time that MTs may need, to resolve the transmit time advance, necessary, to offset the round-trip delay to the BS.

Figure 2-5: TDD OFDMA Frame Structure
2.1.3.3.2 IEEE 802.16 MAC Layer

The Medium Access Control (MAC) layer resides above the PHY layer and is responsible for controlling the various services connections and their quality of service (QoS) requirements, for transmission over the same physical medium. Moreover, the MAC layer has the following responsibilities: transforming the service data units (SDUs) – messages received from higher layers – into MAC packet data units (PDUs), scheduling MAC PDUs for transmission over the PHY layer using the appropriate power level and burst profile, providing support for mobility management, retransmitting erroneous PDUs, and handling encryption and security.

As shown in Figure 2-6, the MAC layer is further divided into three sub-layers: MAC convergence sub-layer (CS), MAC common part sub-layer (CPS), and MAC security sub-layer. The CS is responsible for conveying the messages from the above layers to the MAC sub-layers as well as, perform packet header suppression (PHS) and address mapping. It is worth noting that the standard defines a variety of CS for different protocols such as ATM (asynchronous transfer mode) and packet service; however, the WiMAX forum has only implemented IP and Ethernet. The CPS, on the other hand, is responsible for transforming SDUs into PDUs and ensuring their transmission over the PHY layer. In addition, the CPS ensures QoS provisioning according to the different application requirements. Lastly, the goal of the security sub-layer is to police PDUs and ensure confidentiality of information exchanged between the BS and MT.
The MAC layer is connection oriented and as such it is not possible for PHY and MAC to identify higher-layer addresses; the CS enables the MAC layer to establish a virtual connection between BS and MS by utilizing a unidirectional connection identifier (CID). Such CIDs are then associated with SDUs which may belong to different applications; SDUs are assigned CIDs based on their QoS, and service flow requirements. That being said, it is then the responsibility of the CS to keep track of all the destinations that PDUs with different CIDs belong to.

Packet header suppression (PHS) is an optional feature of the WiMAX networks however, it plays a very important role in the efficient utilization of the network and
improving performance for VoIP and other services. Different PHS rules may be utilized, depending on the type of application that SDUs belong, but both BS and MT have to first come to an agreement in order for such rules to work properly. In addition, different PHS verification mechanisms are used to guarantee that PDU are properly assembled into SDU on the destination station.

The MAC CPS is the sub-layer responsible for assembling SDUs into PDUs and vice versa. Packet data units can have a different size from that of SDUs. Service data units can be partitioned or concatenated to accommodate, as seen feasible, based on their QoS requirements and PHY resource availability. Furthermore, PDUs can be transmitted in sequence, without any change in size, or in fixed length blocks if the automatic repeat request (ARQ) mechanism is enabled. To accommodate the ARQ mechanism, the PDUs have to be in a fixed block size; if the length of SDUs does not match the block such size, the last PDU block is padded. In addition when ARQ is used, PDUs will have to remain in a buffer until they are acknowledged by the receiving entity. Acknowledgements can be either selective or cumulative and they are sent as individual PDUs or as part of a regular payload.

There are two types of MAC PDUs specified by the WiMAX standard: generic PDUs and bandwidth request PDUs. The generic PDU is used for data transmission purposes and its header can contain information, such as: encryption control, extender sub-header field, type (used for bandwidth request), reserved, cyclic redundancy check, encryption key sequence, length, CID, and header check sequence. Furthermore, there are
five additional sub-headers defined for the generic MAC PDUs: mesh sub-header, fragmentation sub-header, fast feedback allocation sub-header, and grand management sub-header, containing payload information or identifying the network type. On the other hand, bandwidth request PDUs are mainly utilized for bandwidth request purposes and have a smaller header with the following header fields: header type, encryption control, type, bandwidth request, CID, header check request, and no payload.

2.1.3.3.2.1 Bandwidth Allocation

Bandwidth allocation for the downlink transmission is granted on a per-bytes of information basis rather than the availability of PHY resources. As a result when data arrives on the BS for a particular MT, the BS station will schedule PDUs based on the number of CIDs and QoS requirements. The MT has to send a request to the BS in order to reserve uplink (UL) bandwidth. Uplink bandwidth request can be incremental or aggregate; incremental requests are usually noted on the general MAC PDU header, while aggregated bandwidth requests are made via bandwidth requests PDUs. If the bandwidth requested by a MT station is greater than the bandwidth available at the BS, the MT will have to compromise with the granted bandwidth based on the QoS requirements and amount of traffic for each CID.

Another way for UL bandwidth allocation is via polling. Polling is the process where the BS has extra bandwidth and makes it available for an individual or a particular group of MTs. For individual polling opportunities the MS uses the primary CID – which is assigned to the MS during the network entry procedure and is used to exchange MAC
control messages – to acknowledge the allocation. Subscriber stations are always required to respond to individual polling opportunities, even if there is no need for the extra bandwidth. If there is not enough bandwidth for the polling process, the BS will send a broadcast or multicast message to indicate that there is bandwidth available. In return mobile stations will reply with their bandwidth request messages however, in order to minimize collisions, MTs are required to wait for a random amount of time no greater than a given window frame before they send their request. If the MS does not hear back from the BS after a certain number of requests, it discards the broadcast/multicast message.

2.1.3.2.2 Quality of Service

Because of its flat all IP based architecture, application services that are utilizing WiMAX networks are not dependent on the underlying transport technologies. As such they all have different QoS requirements, such as packet error rate, jitter, data rate, system availability, and the like. To meet all the different QoS requirements WiMAX utilizes different scheduling mechanisms to allocate downlink and uplink transmission opportunities for the different PDUs.

- The unsolicited grant service (UGS) scheduling mechanism provides real time fixed size bandwidth allocation for services that need to transmit packets on periodic bases. This way services such as voice over IP (VoIP) have a lower overhead and minimal latency.
• The real-time polling services (rtPS) similarly to UGS support real time services but generate variable size packets, such as Motion Picture Express Group data. Furthermore the BS provides frequent enough polling opportunities to the MT so there is no need for the MT to make additional bandwidth requests.

• The non-real time polling services (nrtPS) is designed to support non real time service with variable size data. Unlike rtPS, nrtPS can make UL bandwidth requests when the BS broadcasts polling opportunities however, such requests can often result in collisions.

• The best effort (BE) scheduling service utilize only contention based polling opportunities for bandwidth requests and are designed for services with very little QoS requirements.

• The extended real time polling service (ertPS), was introduced at the same time as mobile WiMAX and is a mix of UGS and rtPS; meaning that MTs are periodically provided with unicast polling opportunities and during such opportunities the MT can request additional bandwidth.

To better handle the different QoS parameters WiMAX utilizes a MAC protocol transport service known as service flow. Service flows handle the UL and DL data transmission and have the following components: service flow ID, connection ID, provisioned QoS parameter set, admitted QoS parameter set, active QoS parameter set, and authorization module. Such components are associated with various QoS requirements from higher layer entities and the ability of the MAC layer to accommodate such requirements.
2.1.4 Relay Networks

Mobile Multi-hop Relay (MMR) networks are the latest amendment proposed by the IEEE 802.16 working group. The main goal of this technology is to increase the coverage area and throughput in a WiMAX network, while at the same time remain compatible with PMP mode. Unlike WiMAX PMP and mesh networks MMR networks have a tree like network configuration; where RS are utilized to convey messages to and from the BS to other RSs or MT. An example of a MMR network topology is shown in Figure 2-7.

2-7: WiMAX Mobile Multi-Hop Relay Network Example

2.1.4.1 Network Architecture

Unlike the WiMAX BS, the RS does not perform routing which makes them less complex and less expensive. Relay stations are divided into two groups: transparent and
non-transparent. The main difference between transparent and non-transparent RS is the transmission of frame header information. In non-transparent mode frame header information is transmitted through RSs to MTs or other RSs which are not able to communicate through a direct connection with the BS. Relay stations operating under transparent mode are not allowed to transmit framing information; hence the main purpose of such RS is mainly to enhance capacity under the BS coverage area.

Based on their infrastructure relay stations can be further classified as fixed, nomadic, or mobile. Fixed relay stations are deployed in areas where coverage, capacity, and/or user throughput in areas where coverage of the BS needs improvement. Examples of such deployment include: underground, tunnels, indoor operations, dead zones under the BS coverage area, private clusters outside the BS coverage area, and highways. Nomadic RS are mainly intended for temporary use and can help extend the coverage of the BS in public events outside the BS’s coverage zone, or replace an existing BS in emergency disaster situations. Mobile RS can be installed on public transit systems and provide a static connection to the MT onboard. Mobile stations can also be utilized in dense populated areas and route some of the existing BS loads to avoid congestion and save power to the MT. It also can be used to increase throughput coverage and/or provide services to frequently traveled areas.

There are two ways that data can be scheduled for transmission on a MMR network, centralized scheduling or distributed scheduling. On the centralized scheduling the BS coordinates transmission of data for all the entities on the network; while in the
distributed scheduling RS have the ability to make some scheduling decision for the nodes they communicate with [1].

Nodes in a multi-hop relay network can be associated with each other in various configurations: one BS and multiple MTs, one BS and multiple RSs, one RS and multiple MTs, and/or one RS and multiple RSs. In all previous scenarios, the BS can communicate directly with the MT via one or more RSs. In addition there may be more than one route for MTs to communicate with the BS when multiple RSs are involved.

2.1.4.1 Motivation

High operational frequencies limit the range of the radio interfaces for the existing (3G and 3.5G) and next generation (4G) of mobile networks. Moreover, the data rate achieved by the MT connected to a BS will depend on its distance from it; as a result quality of service (QoS) for each user will vary with distance as well. Consequently, the number of BSs that are needed to be deployed, to cover a certain coverage area, increases dramatically [23]; which in turn will lead to a higher cost of deployment and maintenance for all the BSs. The end effect of this will be a more expensive wireless broadband service not affordable by everyone.

One of the most promising solutions to the problem is the low cost multi-hop relay networks [2]. Unlike the BS, RSs are less complex and do not require wires for the backbone access. In addition they provide higher throughput, increase coverage, lower operational and capital expenditure (OPEX and CAPEX), allow for faster roll out, and a more flexible configuration [24].
2.1.4.3 MAC and PHY Layer Specifications

Three main characteristics of the MAC layer in RS include, initial ranging and network entry, routing and path management, and forwarding scheme [25].

*Ranging and network entry:* There are different procedures associated with ranging and network entry in MMR networks, according to the distribution of RSs (transparent or not). In a transparent mode the BS decides whether to communicate directly with the MT or through a RS based on the ranging codes received from each RS. Meanwhile in a non-transparent environment the MT communicates directly with a RS, then the RS station forwards the information to the BS. The type of information forwarded to the BS will depend whether the configuration is centralized or distributed. When a centralized scheme is used the RS will forward information regarding ranging codes to the BS. However, under a distributed scheme the RS handles the ranging decisions and simply makes a network entry request to the BS.

*Path management:* Although the MMR networks are configured in a tree based structure there are still decisions to be made by the BS regarding the path of communication with the MT. Such paths will be determined based on signal strength, QoS requirements, channel load, and the like. There are two approaches that are followed in MMR networks concerning path selection, embedded, and explicit. In the first approach connection identifiers (CIDs) are allocated in a hierarchical order by the BS. Hierarchical CID allocation simplifies path allocation, since there is no routing table at each RS – CID allocated to the nodes in the sub-tree are a subset of the original CID sets. In the explicit
approach the BS forewords routing information for each connection to all RSs. In the distributed scheduling mode the BS, apart from the CIDs for each flow, may send QoS parameters associated with each CID, to allow RSs to make some independent scheduling decisions.

*Forwarding:* The forwarding scheme consists of two different sub-schemes, tunnel-based and CID based sub-scheme. When the tunnel-based sub-scheme is utilized the BS can assign a tunnel CID to a group of packets that have similar QoS requirements, and forward them to a particular destination. Such a scheme requires that the RSs along the tunnel be notified of the different service flow parameters. On the other hand, the CID based sub-scheme does not allow for traffic aggregation. In the CID scheme the BS provides information, regarding channel characteristics, as well as UL and DL delays, to each RS. In addition, as mentioned previously, in the non-transparent mode the RS has additional information regarding QoS requirements in order to make the appropriate scheduling decisions.

2.1.4.3.1 *Role of the Frame Design*

Two of the main features associated with the frame structure utilized in multi-hop relay networks are its PMP compatibility and at the same time its ability to operate in a multi-hop environment. In addition the frame structure should be able to allow operation of MT without further modifications in the MAC management procedures, such as handover or association, remain the same as in PMP operations.
Type of relaying also plays an important role in the configuration of the frame structure. In transparent RS, control and MAP signals are transmitted by the BS, while the RS is mainly responsible for data transmission. Non-transparent relay frame structure on the other hand is more complicated and, may or may not be configured the same as the BS frame. A detailed description of the relay frame structures will follow in the next chapter.

2.1.4.4 Relaying in 3GPP Long Term Evolution (LTE) Advanced

Although LTE comes from a different family of standards, its technological capabilities are much like the ones described previously for WiMAX. In this section we will briefly describe some of the similarities of LTE and WiMAX.

Like WiMAX, LTE is also an AL-IP based technology designed to accommodate the 4th Generation of broadband wireless networks by increasing capacity and speed of current mobile telephone networks. LTE utilizes an OFDM-based PHY layer and its MAC layer is capable of OFDMA technology. In addition, LTE is capable of supporting both TDD and FTD data transmission. Moreover, according to the latest amendment, 3GPP TR36.814 [4], LTE is also capable of supporting relay technology.

Relays in LTE technology are divided into two main categories inband, and outbound; where inbound relays operate at the same frequency as the UE, and the outbound does not. In addition, much like WiMAX, relays in LTE can be transparent (tRS) or non-transparent (ntRS), with respect to the UE. Transparent relays are inband relays and are not visible to the UE. Non-transparent relays, on the other hand, are
capable of operating both inband and outband. Unlike tRS, ntRS are in control of a particular coverage area and it is their responsibility to deliver control information to the UE.

2.2 Summary

In this chapter we introduced some of the broadband wireless technologies with a focus in WiMAX. We also discussed some of the main driving factors of the wireless broadband and outlined two main providers of such technology. A brief history of the WiMAX family of standards was discussed at the beginning of the chapter, followed by a more detailed description of the current WiMAX standard. We explained some of the major functions for the WiMAX architecture as specified by the WiMAX forum. In addition, we described the PHY and MAC layer, which are the main focus of the IEEE 802.16 working group.

The latest standard of WiMAX has adapted OFDMA as the access method of choice for its PHY layer. Such technology allows for more flexibility in terms of bandwidth allocation, as well as increases the overall network performance. The 802.16 MAC design, is a very flexible one, which supports a variety of QoS requirements for different services. In addition, it provides optional functionalities for mobility support, such as different handoff mechanisms and power saving options. We also described briefly the latest amendment to the WiMAX family of standards, the mobile multi-hop relay stations. Moreover, we summarized the relay architecture, motivation, role of the
frame structure in MMRN, and also reviewed some of the similarities of the LTE relay technology.
Chapter 3

Related Work and Representative WiMAX Relay Frame Structures

In this chapter, we provide a detailed description of the resource allocation mechanisms utilized in mobile multi-hop relay networks. We start by reviewing the related work in the literature and point out significant contributions. We then introduce some of the challenges associated with resource allocation in MMRNs, and discuss in detail the frame structures adopted by the IEE 802.16j standard. Furthermore, we will highlight some of the implementation details of our work. Finally we review some of the alternative resource allocation mechanism proposed in the literature.

The IEEE 803.16j [1] amendment to the standard supports both main duplexing techniques defined by the standard, Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD), where the FDD can follow either half or full duplex mode. The main focus, however for this thesis is, the OFDMA TDD frame structure and this will be the one described in great detail.

3.1 Related Work

In this section, we discuss different studies presented in the literature about resource allocation in MMRN. More specifically our review can be divided into two parts: studies that investigate resource allocations in ntRSs, tRS, and studies that analyze
network optimizations in terms of frequency reuse and relay planning to achieve a better performance in terms of throughput.

An effort to compare the efficiency of single frame structure with the multi-frame structure has been presented in [26]. Such work, however, is very limited in scope since the authors only compare frame efficiency in a two hop network scenario. Also other important metrics, such as throughput, delay, packet loss, and the like, are not taken into consideration. Moreover, authors fail to incorporate propagation loss occurring to the signal as the coverage area increases. To be able to understand the full benefits of each frame structure, it is important that we take into account a range of variables such as: traffic type, modulation and coding rates, and traffic distribution.

Another study done by Genc et al. presented in [27], describes the performance of transparent RS based systems. In this study a star configuration topology is considered with users uniformly distributed over the network. The study shows a thorough investigation of throughput and signalling overhead in transparent multi-hop relay networks. There is no work done however, to show the network performance when ntRSs are utilized.

Other studies that evaluate the design of multi-hop WiMAX relay networks have been carried out in [28], [29] and [30]. In [28] and [29] the authors study frequency reuse and relay planning schemes accordingly, which can lead to maximization of the system throughput. Both studies, however are particular to the deployment of RSs and do not take in consideration other types of network configurations. Moreover, the study in [29]
is based on the TDMA/CDMA system access rather than the OFDMA one specified by the IEEE 802.16j standard. In [30] the authors study the utilization of multiple antenna systems to allocate resources in a relay network versus the omTi-directional antenna system. The study concludes that the directional antenna system significantly improves throughput and at the same time eliminates interference among RSs in the system.

To our knowledge there is no previous work, which analyzes the performance of the single frame and multi-frame system in multi-hop relay environments using the guidelines from the latest amendment to the standard (IEEE 802.16j) [1].

The focus of our contributions is on analyzing and comparing the multi-frame and the single frame resource allocation schemes in terms of delay, throughput, network configuration, capacity, and rate. In the next chapter we present a detailed description of our experiments, choice of parameters, and evaluation matrices.

3.2 Bandwidth Allocation in Mobile Multi-hop Relay Technology

As we emphasized in the previous chapter, broadband wireless technologies are gaining tremendous attention due to the increasing consumer demands. The obstructions that exist on different terrains and transmission power constrains of the MT; however, limit the geographical area that a single wireless broadband BS can cover. One of the solutions to this problem is the utilization of low cost multi-hop relay stations. Multi-hop relays not only increase coverage and capacity, but also improve service, reduce terminal
power consumption, and eliminate dead zones. In order to take advantage of all the benefits one has first to solve some of the challenging resource allocation problems facing the relay networks.

Frame structure is critical in all OFDMA based systems, since it is in charge of controlling both time and frequency domain – the two basic components utilized for resource allocation. In a WiMAX multi-hop relay network, resources are allocated mainly by the multi hop BS (MR-BS) unless distributed scheduling is employed. When distributed scheduling is employed the RSs assist in allocating resources for subordinate stations (other RS or MT) as well. Comparing it to the point-to-multipoint (PMP) OFDMA TDD frame structure, the relay one divides the UL and DL sub-frame into additional sub-sub-frames. Each DL and UL sub-frame contains one access zone (AZ) and one or more relay zones (RZ). The AZ is reserved for communications between MT and the BS or RS and MR-BS. Relay zones, on the other hand, are utilized for data transmission between RSs or RS and MR-BS.

As we mentioned in the previous chapter RS are divided into two categories, transparent and non-transparent. The former type of RS is utilized mainly to increase the cell capacity and cover dead zones; as such transparent RS are limited to a maximum of two hops. Non-transparent RS on the other hand are not limited to a maximum number of hops and can be utilized to serve other subordinate RS in addition to the MS. Hence, we can expect the frame structure for non-transparent RS to have a higher complexity.
3.3 The Standard’s Approach to Allocate Bandwidth in Mobile Multi-hop Relay Networks

In this section we present a detailed description of the resource allocation mechanism adapted by the IEEE 802.16j for multi-hop relay networks (MMRN) transmitting in TDD in the time-division transmit and receive (TTR) mode. The standard also defines the resource allocation scheme for the simultaneous transmit and receive (STR) mode. When STR mode is involved, the serving stations (BS or RS) are able to transmit and receive data at the same time via different channels utilizing multiple physical mediums. The focus of this thesis however, is on the TTR mode, due to its complex nature.

3.3.1 Bandwidth Allocation for Transparent Relays

Due to the limited number of hops transparent RS are relieved from sending any control information to the MS. Transparent relay stations (tRS) are solely responsible for forwarding data to and from the MT. The BS is responsible for the distribution of the MAP and control information to both RS and MS. Relay MAP information are usually transmitted when information send to the second hop MS is buffered first by the RS and send through the subsequent frame. In addition, the RS may utilize a small buffer to receive and send the data to and from the BS or MT. Additional control information transmitted by the BS includes FCH and DCD/UCD.
The frame structure where transparent RSs are utilized contains one access zone (AZ) and one transparent zone (TZ) for both DL and one AZ followed by a relay zone (RZ) in the UL sub-frame – Figure 3-1 illustrates an example of such frame structure. In addition to the TTG and RTG time gaps utilized in the PMP TDD frame, the tpRS frame utilizes two additional R-RTGs. The additional transition gaps allow for the tpRS to switch from transmit to receiving mode and vice versa.

**Frame as Seen at BS**

![Diagram of Frame as Seen at BS]

**Frame as Seen at RS**

![Diagram of Frame as Seen at RS]

3-1: Transparent Relay Frame Structure

The data to the MT can be relayed either by the tRS, or in a cooperative transmission by both tpRS and BS. When cooperative transmission is utilized both BS and tRS have to be synchronized first. In the UL the MS transmits data to the tRS first.
which in turn transmits to the BS, this way MS may utilize higher modulation techniques and achieve a higher throughput.

3.3.2 Bandwidth Allocation for Non Transparent Relays

Non transparent RS (ntRS) are capable of transmitting control information alongside with the BS, as such they might need to be synchronized with the BS to transmit the frame preamble, UL and DL data bursts. Unlike the tRS the ntRS may contain more than one RZ in the DL and have one or more AZ and RZ in the UL. The BS also transmits three different MAPs, one to the MT with direct communication, one for RS-BS communication, and another one called R-MAP for RS-MT communication.

Networks where ntRSs are employed may utilize either centralized or distributed scheduling. In the centralized scheduling the BS is responsible to generate MAP information for all the RS and their subordinates. Such MAPs are transmitted by the ntRS at the beginning of the DL AZ in the subsequent frame. When more than two hops are utilized the BS will generate an R-MAP to be transmitted by RS together with control information generated by RS themselves. When distributed scheduling is utilized, ntRS are responsible for generating their own control information as well as allocating resources to their subordinates. Control and MAP information from the BS are not needed.

In networks where ntRS are utilized, either dual or single radio transmissions could be used. When a single radio is utilized the transmission is called Time Division Transmit and Receive (TTR). TTR frame structure allows for simultaneous transmission
in the AZ of both RS and BS due to the low interference – antenna technologies provide frequency links that are isolated enough not to cause interference. Dual radio transmissions, on the other hand – else known as Simultaneous Transmit and Receive (STR) – allow for ntRSs to receive and send information to their subordinates at the same time. Hence, STR configurations do not require transition gaps to allow for switching between receiving and transmitting mode; these radios, however, operate in different channels.

The standard defines two different approaches for ntRS operating in the TTR mode, multi-frame and single-frame approach. A multi-frame consists of several frames aggregated to a single frame. The transmission of such frame is coordinated in such a way that ntRSs will either transmit or receive during a given time frame. For instance, ntRS that are located at an even number of hops are allowed to transmit simultaneously, and similarly ntRSs located in odd hops will be able to transmit simultaneously. Single-frame structures take a different approach and perform the transmission of data to all ntRSs within the same time frame. The single-frame structure contains multiple RZ, where the number of RZ can be derived as follows:

\[ N_z = h_n - 1 \]

where \( N_z \) is the number of relay zones and \( h_n \) represents the number of hops in the network.
3.3.3 Implementation of Bandwidth Allocation for Non Transparent Relays

To have a better understanding of how the single frame and multi-frame are constructed we have chosen the following example which illustrates their implementation. Figure 3-2 below illustrates a three hop highway scenario configuration. The BS is able to extend its coverage throughout a particular segment of the highway by employing two ntRSs.

Although the standard defines a range of frame lengths (2ms, 2.5ms, 4ms, 5ms, 8ms, 10ms, 12.5ms, and 20ms), for our experiments we have chosen to utilize a 5ms frame length for the 20MHz channel bandwidth. The standard defines only the 5ms frame duration as mandatory for mobile WiMAX system profiles, rendering the rest of them as optional.
Scheduling details and frame partitioning – in terms of the number of relay zones and access zones – will vary based on the specific network configuration and the purpose of the network. In the following subsections we will describe in detail our approach to the implementation of both multi-frame and single frame for the above scenario. Figure 3-3 illustrates both single frame and multi-frame implementation, which is a simplified version of what is to follow in the next subsections. Similar configurations are also implemented for all our experiments described in the next chapter.
Figure 3-3: Simplified version of the Multi-Frame and Single Frame Configuration for the Highway Scenario

3.3.3.1 Single Frame

The single OFDMA TDD frame structure for the above highway configuration is shown in Figure 3-4. Both the MR-BS and RS frames consist of 48 OFDMA modulation symbols in the time domain and several sub-carriers in the frequency domain (1680 data sub-carriers in our case – after subtracting the number of guard sub-carriers).

The TDD single frame is much like the legacy in terms of configuration with a few additions to accommodate ntRSs. Like the legacy, it is also divided into two main sub-frames one for the DL traffic and the other for the UL. Unlike the legacy however, each sub-frame is further divided into one AZ and two relay zones RZ – where each relay
zone is associated with the number of hops in the network. Furthermore, time gaps are inserted between consecutive frames, sub-frames and sometimes among AZ and RZs; abbreviated as RTG, TTG, R-TTI, and R-RTI respectively.

The relay receive to transmit transition interval (R-RTI) in each DL frame and UL frame is a necessity in MRSs to avoid data loss. The R-RTI is the time gap between the last symbol transmitted by the BS to the RS and the first symbol transmitted by the RS to its subordinate. The following equation is utilized to calculate R-RTI which is measured in symbol unit:

\[
R - RTI = \left\lfloor \frac{RSRTG + \frac{RTD}{2}}{OFDMA_{Symbol\_Time}} \right\rfloor
\]

where RSRTG is the time it takes the RS to switch its radio from receive to transmit mode, while RTD is the round trip delay between the RS and its subordinate station.

To calculate the relay transmit to receive transition interval (R-TTI), the time gap between the last symbol transmitted by the RS to the first symbol to be received, is calculated using the following equation:

\[
R - TTI = \begin{cases} 
0 & \text{if } \frac{RTD}{2} \geq RSTTG \\
\frac{RSTTG - \frac{RTD}{2}}{OFDMA_{Symbol\_Time}} & \text{if } \frac{RTD}{2} < RSTTG
\end{cases}
\]

where RSTTG is the time it takes the RS to switch its radio from transmit to receive mode.
Figure 3-4: A Detailed Illustration of the Single Frame Design for the Highway MMRN

Scenario
Relay sub-frames also contain their own control signals, such as FCH and relay MAP, to transmit to their subordinate stations. In addition ranging sub-channels are allocated in the UL RZ if RS have one or more RS attached to them.

During the access zone, both RSs and BS transmit data to the MTs under their coverage area. During the RZ zone; however the RS and BS may do one of the following: remain idle, receive from its parent station, or transmit to its subordinate. Note that RSs and the BS are allowed to transmit simultaneously under the same RZ, as long as they do not interfere with each other and have data to send. For instance in our example, Figure 3-2, if we added an additional RS3 attached to RS2, then it would had been possible for the BS and RS3 to transmit under the same RZ for the DL, while RS1 and RS3 would had been allowed to transmit simultaneously in the UL.

3.3.3.2 Multi-Frame

In this section we describe a detailed implementation of the multi-frame structure for the same network scenario shown in Figure 3-2. Similarly to the single frame and legacy point to multipoint frame, the multi-frame is also divided into two sub-frames UL and DL. Moreover, control and ranging mechanism are similar to that followed by the single frame. The major difference between the single frame and multi-frame structure is the way data is transmitted to nodes beyond the second tier.

In Figure 3-5, we present a detailed description of the multi-frame structure for the BS and first tier RS. The frame structure for the second tier RS2 is not shown in the figure, since it follows a similar pattern to that of Frame m – to obtain the frame of RS-2
in Frame m+1 we subsidize RS-1 with RS-2, and MR-BS with RS-1 in each DL and UL RZs in Frame m.

The multi-frame implementation consists of only one AZ and one RZ, and unlike the single frame it takes two 5 ms frames for the data to reach the third hop. Another way to think of the multi-frame is as the grouping of multiple frame sequences with repenting pattern of RZ. That being said, the amount of data transmitted through a MF is higher than that of a single frame. In configurations where more than three hops are involved transmission of data is simultaneous among odd and even hop serving stations. Considering the previous example when we add an additional RS3; transmission between MR-BS to/from RS1 and RS-2 to/from RS-3 can occur at the same time.
Figure 3-5: A Detailed Illustration of the Multi-Frame Design for the Highway MMRN Scenario
3.3.3.3 Single Frame and Multi-Frame Resource Allocation Algorithms

The resource allocation algorithm assigns each traffic flow to the corresponding queue (access or relay queue). It is very important to schedule traffic flows utilizing the same bandwidth together. Furthermore, AZ flows and RZ flows are processed using two different algorithms. Round Robin and Round Robin with minimum QoS support as described in [8]. Round Robin with minimum QoS support prioritizes traffic flows based on the traffic classes defined by the standard. Once the traffic priority is set, resources are allocated for each connection based on their minimum QoS requirements.

```
1. for n ∈ N  // N is the list of all nodes in the network
2. for f ∈ F_n  // F is the set of all service flows for node n
3. switch f
4. case (f ∈ {BS_TO_SS, RS_TO_SS_TP, RS_TO_SS_NONTP})
5. add_access_flow_dl(f)
6. break;
7. case (f ∈ {BS_TO_RS, RS_TO_RS_NONTP_DL})
8. add_relay_flow_dl(f)
9. break;
10. case (f ∈ {SS_TO_BS, SS_TO_RS_TP, SS_TO_RS_NONTP})
11. add_access_flow_ul(f)
12. break;
13. case (f ∈ {RS_TO_BS, RS_TO_RS_NONTP_UL})
14. add_relay_flow_ul(f)
15. break;
16. default: ERROR
17. end for
18. end for
```

Figure 3-6: Pseudo-code for Single Frame Resource Allocation Algorithm
Proposed Approaches for Bandwidth Allocation

MMRN

To accommodate resource allocation in networks where RSs are being utilized, several alternative frame structures have been proposed. In this section we will go over a
few of such proposals, to better illustrate the challenges and the importance of the frame structure in a MMRN environment.

An overhead hybrid frame structure which supports both TDD and FDD, is proposed by the authors in [31]. The main reason behind such design is the minimization of the inter-carrier interference (ICI) by reducing propagation delays. The FDD, unlike TDD, does not suffer from intra-cell interference, round time delay issues, and guard time between UL and DL sub-frames; therefore, designing a hybrid solution will take advantage of both schemes and at the same time improve performance, in terms of throughput and delay.

The overhead HDD system utilizes three frequency bands: two paired frequency bands one used by the BS and the other by the RS, while the third frequency band is used for the FDD scheme. When the overhead HDD system is utilized the WiMAX cell is divided into two zones, an outer and an inner zone. The outer zone may be covered by RSs or the BS while the inner zone is covered by the BS. The BS utilizes one of the paired bands to communicate with the inner cell MT in TDD for both UL and DL traffic; DL transmission for the outer MT happens in TDD. For the UL traffic FDD is utilized. The second paired band is utilized by the RS to communicate with outer cell MT in TDD, for both UL and DL. In addition TDD frames are composed of the UL and DL sub-frames. Each sub-frame is composed of a number of OFDMA symbols in the time domain and a number of sub-channels in the frequency domain. The sub-channels
utilized for the inner band are composed of adjacent subcarriers, while outer band sub-channels are distributed over the entire frequency band.

Another approach to allocate resources in a multi-hop relay environment is the cooperative strategy presented in [32]. Like the previous approach this one contains an inner zone as well; however, instead of the outer sector the cell is divided into three additional sectors – it is worth noting that the sectors overlap with the inner zone in this case. In addition, transmission of the data is done in the TDD mode, where the frame is divided into DL and UL sub-frames. Each DL and UL sub-frame, is further partitioned into four more sub-sub-frames, corresponding to the inner zone and three sectors accordingly. The main reason behind such structure is to enable MT which are close to the edge of a sector and those in the inner zone, to experience diversity and flexible resource management, by allowing them to pick the best signal from multiple transmissions. In addition, the signal from the MT at the edge of the sector will be picked up by multiple RSs, thus improving the signal quality.

Although not explicitly stated by the authors in the previous two examples, their solutions seem to be targeting only relay networks with a limited number of hops – two numbers of hops to be specific. To address the issue of resource allocation in networks where more than two hops are employed, the authors in [33] introduce two different frame structures: mixed bidirectional and the offset frame structure for TDD transmission. In the mixed bidirectional frame structure the UL and DL sub-frames are partitioned into two more sub-sub-frames called access zone and relay zone; where the
access zone is dedicated for transmission between serving stations and their MT, while the relay zone is reserved for transmissions among serving stations (BS to RS, RS to RS, or RS to BS). The mixed bidirectional frame structure enables relay stations to transmit both in the UL and DL regardless of the relay zone (UL or DL), as long as they do not interfere with each other. For instance, let’s consider an in line relay network with 5 RS, let each RS be represented by a number, from 1 to 5, where RS1 is the closest to the BS and RS5 the furthest from it. Now let’s assume that the BS is transmitting to RS1 in the DL, at the same time RS3 is able to transmit to RS2 and RS4 to RS5. Such transmission is possible because the signal from the BS will not interfere with the signal sent from RS3 to RS2, neither will it interfere with the signal sent from RS4 to RS5 due to the distance from each other.

Offset frame structure, is also divided into four sub-frames. The transmission timing however, varies from one hop to the next. Reconsidering the last network scenario, where instead of the mixed bidirectional frame structure the offset one is utilized. In this case RSs will not start transmitting until they have received control and transmission messages from their predecessors. One of the main advantages of this design is the elimination of time gaps, which are required to switching the radio from transmit to receive mode in the previous design. In addition, the offset frame structure minimizes the amount of control signals send by the BS.
3.5 Summary

In this chapter we began by reviewing some of the most relevant related work in the literature and pointed out their contributions. We then introduced the importance of the frame structure in allocating resources in the MMR network. In addition a detailed description of the frame structure supported by the standard for MMRN was presented, as well as detailed examples of how we implement each of them. At the end we concluded by describing some of the alternative frame structures for resource allocations in MMRN. The next chapter will show the simulation model and results obtained from different network configurations when multi-frame and single frames are employed.
Chapter 4

Performance Analysis

In this chapter, we study the performance of non-transparent multi-hop relay networks utilizing the single and multi-frame structure discussed in Chapter 3. To evaluate the performance of each frame type we employ different network configurations and different traffic mixes. We vary, for instance, the number of relay stations in a network and how they are distributed. We also vary the traffic types going through the network, the number of mobile terminals associated with each traffic type and the distribution of both traffic and users. Furthermore, our simulation methodology follows what was specified by WiMAX Forum [34] and multi-hop relay system evaluation methodology [35], developed by the IEEE 802.16 Broadband Wireless Access Working Group.

Our simulations are based on the University of California Berkeley network simulator version 2 (ns2). This choice was based on ns2’s reliability which has been demonstrated through wide use in various contexts of computer networks. The code for the ns2 simulator is also an open source, facilitating great flexibility in adaptation and programmability. The research community is the main contributor to the ns2 source code – bug fixing, extending support for a range of technologies, and the implementation of many other capabilities. Some of the ns2’s features include support for simulation of various transport protocols, routing, and multicast protocols for a wide family of
networks: wired, wireless, local and satellite. While the main ns2 libraries do not provide support for WiMAX relay technology, two add on libraries have been proposed for use in the literature. The first is the Light WiMAX (LWX) module developed by Cheng [7], which provides a simulation environment for transparent relay stations to be deployed within the coverage of PMP BSs. The second module is provided by the USA’s National Institute of Standards and Technology (NIST) [36]. Similar to LWX, the NIST add on only supports transparent relay stations. Other, non-ns2 simulation environments for WiMAX MMR network evaluation have also been developed; one such environment is NCTUs [37]. To the best of our knowledge, no modules enable the evaluation of non-transparent relay stations.

In order to be able to simulate multi-hop relay environments in WiMAX, we expanded the LWX library to support ntRSs. Furthermore, we enabled the support of both single frame and multi-frame structures. The resulting add-on is capable to facilitate the evaluation of scheduling algorithms designed specifically for WiMAX relay networks. We also have set up a simulation environment which allows for the evaluation of voice capacity in multi-hop ntRS environments, as well as the investigation of various traffic mixes. Our work not only brings the ns2 simulation environment up to date with the advancements in the multi-hop broadband technologies, but also helps new and existing wireless broadband providers make more informed decisions when designing MMRNs. The resulting source code of our work has been made publicly available and can be obtained from [5].
In section 4.1 we describe the LWX ns2 relay module, as well as describe the implementation of the new features we added. Section 4.2 is a detailed description of our simulation scenarios and the main motivations of their choice. Selection of parameters, channel models, and traffic models are discussed in Section 4.3. A detailed description of the evaluation metrics is presented in Section 4.4. In Section 4.5 we evaluate different simulation scenarios and discuss the obtained results.

4.1 Simulation Software

In this section we describe the nature of the simulation software utilized to evaluate the different types of frame structure supported by the IEEE 802.16j amendment. We also describe our implementation and contribution to the simulation environment.

4.1.1 Overview of the ns2

The ns2 is an open source, event driven simulator developed to evaluate the performance of computer networks. It was developed at the University of California, Berkeley, written in C++ and OTcl. The ns2 provides support for numerous network architectures and protocols for any layer of the OSI model. Available libraries enable the simulation of various networks such the 802.3 and 802.11; protocols for network routing, traffic transport (TCP, UDP, HTTP), file transfer (FTP); and traffic types (voice, video, CBR). These protocols can be evaluated in satellite, wired, and wireless networks. The ns2 also allows the control of various measurements between any two nodes including round trip time (RTT), jitter, and delay.
The block fading model is adopted for the wireless channel configuration. In this model independent and identically-distributed Rayleigh distributed fading gains are assumed to remain constant along the entire frame duration, before allowing it to change to new independent realizations. As a result, we are able to incorporate the adaptive modulation and coding rates as described by the standard IEEE 802.16 – 2004 [5] (64QAM3/4, 64QAM2/3, 16QAM3/4, 16QAM1/2, QPSK3/4, and QPSK1/2), according to each connection’s Carrier to Interference-plus-Noise Ratio (CINR) [7].

To simulate a network, an OTcl script is needed to set up the network topology by utilizing library functions and network objects [7], [8]. The script further initiates event schedules indicating when to start and end packet transmission flows.

4.1.2 Overview of the LWX add on

The LWX module [9] is an ns2 extension for IEEE 802.16 and IEEE 802.16j support. LWX implements the WiMAX MAC functionalities with QoS support, traffic relay support, as well as different modulation and coding rates, all in accordance with the specifications of the IEEE 802.16 [1] standard, and the IEEE 802.16j [2] amendment, and is based on ns2 version 2.29 [6]. Figure 4-1 outlines the different components of the LWX add on.

The module implements the following components, grouped in several classes: Traffic Handler, MAC Handler, PHY Handler, LWX OTcl Script Transformer, and LWX simulation Log Generator. The Traffic Handler oversees traffic aggregation and mapping, while the MAC handler oversees bandwidth allocation, call admission control (CAC),
generation of PDUs (packet data units), ranging, and other tasks that are defined by the IEEE 802.16 MAC layer. Modulation and signal coding, part of the radio frequency transmission, are the responsibility of the PHY Handler. Translation, of the OTcl script settings, into LWX components is handled by the LWX OTcl Script Transformer. Finally, the LWX Simulation Log Generator is utilized to record simulation processes, specific to the IEEE 802.16 standard, which are not supported by the original ns2 simulation log tracer.

Figure 4-1: A detailed illustration of the modified LWX MAC module. The modified components are highlighted in colour.
Each MT is allowed to have more than one type of connection (i.e. VOIP, FTP, HTTP). Bandwidth allocation is done in a Round Robin fashion with minimum QoS support as specified by each QoS class, (see Table 4.1 for details), for each MT. For instance, each traffic flow is characterized by its QoS parameters (i.e. maximum and minimum packet latency, jitter, minimum and acceptable rates). Based on these parameters, the Round Robin algorithm will then ensure that each flow’s minimum QoS requirement are satisfied. Traffic is then transmitted through the path with the best channel conditions, either direct transmission or through multiple retransmissions, via RSs.

4.1.3 Our Modifications to the LWX Module

Examining the code and the performance of the LWX module, we observed a simple yet effective design for evaluating multi-hop WiMAX environments. However, our intent in this study was to investigate the WiMAX networks deploying ntRSs. More specifically, our objective was to compare network performance under single frame and multi-frame structures in ntRSs. To facilitate this objective, we decided on expanding on the LWX module, completing its support for the 802.16j standard (see workflow diagram Figure 4-1).

Our modifications include the implementation of the frame structure as described by the IEEE 802.16j [1], extending support for more than two hop relay connections, as well as making changes to the uplink and downlink scheduler. These modifications entailed implementing the following components, grouped in several classes and objects.
Single Frame and Multi-Frame handler, Packet Drop handler, and traffic aggregation and mapping for ntRS. We also modified the LWX logger, the LWX OTCL Script Transformer and the LWX Simulation Log Generator to support ntRS traffic.

Additional parameters associated with non-transparent relay connection settings, such as traffic flow direction, and parameters associated with the five types of service flow (maximum/minimum packet system rate, and maximum/minimum latency) were adjusted through the TCL script. We also modified the implementation of the bandwidth management functions to create the ULMAP and DLMAP configuration messages according to the transmission parameters defined by each frame structure. Researchers interested in acquiring the modified LWX add-on may find it referenced at [5].

4.2 Simulation Scenarios

As explained in the previous chapters the IEEE 802.16j amendment categorizes RS into two main groups, transparent and non-transparent. Transparent relays are designed to operate under the BS’s coverage area and are invisible to the MTs. As such a network where tRS are utilized cannot operate on more than two hops, and their sole purpose is to increase capacity. On the other hand, ntRSs do not operate under the same coverage area as the BS and can extend in more than two hops, enabling the BS to cover a larger area. Although the standard describes the duties of each of the two types of RSs, it is the responsibility of the network designer to decide on their proper configuration and utilization. As we will show from the results of our experiments, employing the right
number of RSs and type of frame structure, for a specific scenario, significantly influences the network performance in terms of capacity, throughput, and packet delay.

To evaluate the performance of each frame we have chosen two different network configurations, star and inline, with a fixed and a variable coverage respectively. When choosing our simulation scenarios we have tried to be as practical and as generic as possible and at the same time account for real life observations.

4.2.1 Fixed Coverage

Fixed Coverage is represented by the star topology. Smaller deployment cost and the ability to accommodate more nodes at a smaller communication delay, while requiring interconnection hardware, renders the star topologies the most popular among wired and wireless network configurations [38]. Moreover, to ensure fairness when comparing tRS with ntRS frame configurations, we have chosen the coverage area for the star topology to remain the same, despite the increase in the number of RS.

In the first coverage experiment we study the voice capacity for each of the different star network configurations shown in Figure 4-2, Figure 4-3, Figure 4-4 and Figure 4-5. To do so we observe how the behaviour of the network traffic changes when more subscriber stations are added. We start each experiment with a minimum user load (one MT per serving station), and keep increasing the number of users until at least one user in the network starts experiencing a bad connection. A bad connection is experienced when the minimum requirements for at least one of the QoS parameters are
not met, Table 4-2. Once a bad connection is observed we then consider the network to have reached its maximum user capacity.

To maintain the same coverage area and at the same time avoid intra-cell interference when ntRS are employed, the radius of the BS decreases, and ntRSs cover the remaining network area.

Resource allocation for the scenarios where ntRS are utilized is done either through a single frame or multi-frame. Each of the resource allocation methodologies is treated as a different network scenario.

![Figure 4-2: Single BS PMP](image-url)
Figure 4-3: Star Configuration with 6 tRS

Figure 4-4: Star Configuration with 6 ntRS
4.2.2 Variable Coverage

Considering the increased research interest in vehicular *ad hoc* networks (VANETs) [39], we chose the line topology as our second network configuration. In addition, lower operational expenditure (OPEX) and capital expenditures (CAPEX) of RSs, instead of BSs deployment [23], render the line configuration ideal to provide broadband coverage on highways and in underground tunnels. Unlike the star topology, the line configuration provides variable coverage which increases as the number of ntRS increases.
Similarly to the previous scenario we start our experiments with the basic configuration scenario; one BS and MTs uniformly distributed around its coverage area. Relay stations then are added to extend the coverage of the BS. Every time a RS is added, user load is uniformly redistributed, among the serving stations, and within the coverage area of each serving station – BS or RS.

In our second network configuration of the line topology we have also observed the network performance utilizing tRS. To fairly compare tRS with ntRS; however, we have configured the network in such a way that tRS will be utilized to “extend” the coverage area of the BS. More specifically, when tRS are utilized the original coverage area of the BS will increase, to include the area covered by the tRS – for instance if the original radius, of the area covered by the BS, was 1000m it will be extended to 2000m. On the other hand, when ntRS are utilized the coverage area of the BS remains the same.
4.3 Evaluation Setup

In this section we will go over several of the assumptions made in our simulations. In addition we describe traffic models and channel models we utilized in our experiments, as well as our choice of parameters.

4.3.1 Assumptions

The following are the main assumptions made in our simulations:

1. Channel conditions remain the same; throughout the simulation period the channel conditions do not change for all active connections in the network.

Figure 4-6: Line configuration, may be utilized in a highway, or tunnel scenario.
2. All subscriber stations are active; each node has enough power to remain active throughout the simulation period.

3. Network conditions remain the same; we assume that all MT in the network have completed initial ranging and authentication. That being said, all MT remain under the coverage of the same subordinate station throughout the simulation period. Hence there is no handover between RSs, BS and RS, or two different BSs.

4.3.2 Channel Models

The radio propagation models utilized by our add-on are the free space model, two ray ground model, and shadowing model. These channel models are part of the existing code in the original ns2 implementation. Furthermore, channel conditions for individual connections are set up via the TCL script [8]. Such channel conditions will then determine the way the bandwidth is allocated to each connection. Values shown in Table 4-1 are in conformance with the IEEE 802.16 standard for the channel bandwidth of 20 MHZ.

<table>
<thead>
<tr>
<th>Modulation and Coding Rate</th>
<th>BPSK 1/2</th>
<th>QPSK 1/2</th>
<th>QPSK 3/4</th>
<th>16QAM 1/2</th>
<th>16QAM 3/4</th>
<th>64QAM 2/3</th>
<th>64QAM 3/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR (db)</td>
<td>3</td>
<td>6</td>
<td>8.5</td>
<td>11.5</td>
<td>15</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>Bits/Symbol</td>
<td>96</td>
<td>192</td>
<td>288</td>
<td>284</td>
<td>576</td>
<td>768</td>
<td>864</td>
</tr>
</tbody>
</table>
4.3.3 Traffic Model

In our simulations we have modelled the following types of services: rtPS, erTPS, nrtPS, and BE; each of these services is associated with: voice (Class 2), video (Class 3), FTP (Class 4) and HTTP (Class 5) data traffic models, respectively.

Our voice and video follow the International Telecommunication Unit [40] standard codes G.711 and H.263. Such encoding schemes are utilized to transform the signal from analog to digital. Furthermore, the resulting signal is transformed to packet data units (PDUs) [41] and passed on to the physical layer.

The sending rate and packet payload are configured via the TCL script. In order to simulate a real traffic environment, we have attached a traffic source for each connection following the Poissonian distribution. The following is a detailed description of our traffic models:

- The traditional voice model is characterized by the presence of a talk spurt and a silence spurt [42], [43]. To generate voice traffic we are utilizing Variable Bit Rate (VBR) traffic with a talk spurt length of 147ms and silence length of 167ms. According to G.711, a CBR voice packet is created every 20ms with a rate of 64kbit/s hence each packet has a size of 1280 bits [44], [45]. After considering a 25% overhead plus the IP, RTP and UDP headers the payload becomes 1600 bits and the rate 80kbit/s [46].

- To reduce the bandwidth requirement for video signals, H. 263 video coding technology is utilized which compresses the signal. Based on the discussion in
H. 263 encoder generates a variable bit rate (VBR) which can be mapped to a CBR. Furthermore H. 263 is capable of sending compressed video packets at a CBR of multiples of 64kbit/s, as well as rates lower than 64kbit/s. In our simulation we consider a CBR of 240kbit/s, including 25% overhead (representing low quality video).

- We have implemented data traffic which consists of FTP and HTTP traffic. In ns2 an input file is not needed to generate FTP traffic. The transport layer agent is informed by the module of the file size (a random one) and starts generating packets to accommodate the file size. Since FTP belongs to the nrtPS service class and as such does not have a minimum delay requirement, we need to take in consideration its bandwidth requirements. A value of 80kbps and 5MB for Minimum and Maximum Sustained Traffic Rate is utilized for each FTP source [47]. Since BE class traffic do not have to satisfy any delay or bandwidth requirement parameters, we have adopted CBR traffic at a rate of 4Mbps and a packet size of 500 bytes.

Table 4-2 describes the QoS requirements for real time traffic (RTT) for each of the classes mentioned previously [48], [49], [50], and [51].
### Table 4-2: QoS parameters

<table>
<thead>
<tr>
<th>Service Class</th>
<th>Data rate</th>
<th>Packet loss</th>
<th>Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>ertPS</td>
<td>4Kbps–80KBps</td>
<td>&lt; 1%</td>
<td>&lt; 30ms</td>
</tr>
<tr>
<td>rtPS</td>
<td>5Kbps–395Kbps</td>
<td>&lt; 2%</td>
<td>&lt; 40ms</td>
</tr>
<tr>
<td>nrtPS/BE</td>
<td>0.01Mbps–100Mbps</td>
<td>0</td>
<td>Flexible</td>
</tr>
</tbody>
</table>

### 4.3.4 Simulation Parameters

The main variables that are going to change and in turn affect the network configurations are: frame structure (multi-frame, single frame, tRS frame structure), distance (the size of the coverage area), and traffic (only one type of traffic, only one type of traffic plus background traffic, or a mix of different traffic ratios). Tables 4-3 and 4-4 list the parameters used in our simulations. Table 4-3 describes fixed parameters which are constant throughout our simulation experiments. Variable parameters are listed in Table 4-4, as well as detailed in the simulation results, Section 4.3. Parameters for the simulation grid size and serving nodes coverage are derived from [52].
Table 4-3: Fixed Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Grid Size</td>
<td>2500m x 2500m, 2500m x 12000m</td>
</tr>
<tr>
<td>System Bandwidth</td>
<td>20MHz</td>
</tr>
<tr>
<td>Physical Layer</td>
<td>Wireless MAN-OFDMA</td>
</tr>
<tr>
<td>OFDMA Symbol Duration</td>
<td>100.94 µs</td>
</tr>
<tr>
<td>Frame Structure</td>
<td>TDD</td>
</tr>
<tr>
<td>Number of Symbols per Frame</td>
<td>48</td>
</tr>
<tr>
<td>Number of Frames per Second</td>
<td>200</td>
</tr>
<tr>
<td>Number of Sub-channels for Downlink</td>
<td>60</td>
</tr>
<tr>
<td>Number of Sub-Channels for Uplink</td>
<td>70</td>
</tr>
<tr>
<td>Slot Size of Downlink (subchan. x symbol)</td>
<td>1 x 2</td>
</tr>
<tr>
<td>Slot Size of Uplink (subchn. x symbol)</td>
<td>1 x 3</td>
</tr>
<tr>
<td>Downlink/Uplink Bandwidth Ratio</td>
<td>2:1</td>
</tr>
<tr>
<td>Access/Relay Zones Bandwidth Ratio</td>
<td>1:3</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>15 sec</td>
</tr>
<tr>
<td>Frame Duration</td>
<td>5 ms</td>
</tr>
</tbody>
</table>
Table 4-4: Variable Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Value (single frame)</th>
<th>Value (multi-frame)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Hops</td>
<td>1 – 6</td>
<td>1 - 6</td>
</tr>
</tbody>
</table>
| Traffic Ratio
  (UGS:ertPS:rtPS:nrtPS:BE)            | Variable             | Variable            |
| Number of MT per Serving station (RS/BS) | 1 – 120              | 1 – 120             |
| Number of RS                              | 0 – 18               | 0 – 18              |

4.4 Evaluation Metrics

To collect data from our simulation runs, we utilize the voice user capacity metric, average packet delay per user metric, average packet loss ratio per user, average per user throughput, and average per user rate metric. The following metrics have been adapted from the WiMAX system: evaluation methodology [34] and Multi-Hop Relay System Evaluation Methodology [35].

- **Voice user Capacity (vc)** determines the number of MT that can achieve a satisfactory packet loss ($\Delta$), and delay requirements ($\Lambda$) for VoIP service. This metric assumes a uniform user distribution under a given coverage area. Furthermore, the scheduling algorithm provides equal throughput to all MTs. Given that the required coverage for a particular service is $x\%$ and the minimum
latency requirement \( \Lambda \); we can calculate voice capacity using the following formula:

\[
\forall i \in k \subseteq U \iff \exists ((\delta_i < \Delta) \lor (\lambda_i < \Lambda)) \iff vc = 0
\]

else

\[
vc = \frac{k}{\sum_{i=1}^{k} \frac{\Lambda}{\lambda_i}}
\]

where \( k \) represents the \( x\% \) from \( U \) number of users, where all the \( U \) users are sorted in descending order and only the top \( x\% \) is considered. Furthermore, \( \lambda_i \) represents the packet latency, and \( \delta_i \) represents the packet loss, for user \( i \), where \( i \in U \) (set of all users).

- **Average packet delay per user:** is the average time it takes each packet to travel from source to destination.

- **Throughput** is the amount of data forwarded by the network from a certain source to a certain destination during a specified period of time. We express throughput in bytes and calculate it as follows:

\[
\vartheta = \sum_{t=0}^{T} p_t
\]

where \((T - t_0)\) represent the time period during which throughput is calculated, and \( p_t \) represents the amount of data (bytes) per unit time – unit time can be 0.5 sec, 1sec, etc.
• **Average Receiving Rate** is the amount of data received by a user per unit time. Unlike the throughput, when calculating the rate, the unit time corresponds to 1 sec. The value is expressed in kbps and calculated as follows:

\[ r = \frac{\sum_{t=0}^{t=\eta} \sum p_t}{\eta} \times \beta \]

where \( \eta \) is the number of \( t \) unit time intervals, \( p_t \) represents the number of packets received during the \( t \) interval, and \( \beta \) represents the size of the packet in bits.

• **Packet loss ratio per user** \((rPLR)\) is calculated by:

\[ rPLR = \frac{\rho}{\tau} \]

where \( \rho \) is the total number of successfully received packets and \( \tau \) is the total number of successfully transmitted packets.

### 4.3 Simulation Results

In this section, we study the performance of the two frame structures, proposed by the IEEE 802.16j amendment, under different network configuration settings. To analyze the performance of each frame structure, we have considered various real life network settings. To be more specific, we studied the coverage extension scenarios for rural and metropolitan areas (small and high user density environments). Furthermore, we analyzed the different effects that the MT distribution, channel conditions, frame structure configuration, and number of RS may have on certain network configurations. We have gathered our data by averaging the outcome of multiple simulation runs; results with 90% confidence level and a 10% confidence interval are maintained [53].
4.3.1 Fixed Coverage

4.3.1.1 Effect of the star configuration on voice capacity

The DL traffic in the network is directed from the BS to each user in the network, either through a direct transmission, or through a RS (transparent or non-transparent, according to each configuration). Conversely MTs generate the UL traffic destined for the BS. The total number of users in the network for each simulation scenario is different while the number of users served by each RS remains always the same (x users per relay station). Table 4-5 lists the variable parameters used for this experiment.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of RS – Number of Hops</td>
<td>0-1, 6-2, 18-3</td>
</tr>
<tr>
<td>Number of MT</td>
<td>1 – 120</td>
</tr>
<tr>
<td>Traffic Type</td>
<td>ertPS (Voice)</td>
</tr>
<tr>
<td>Relay Mode</td>
<td>Transparent/Non-Transparent</td>
</tr>
<tr>
<td>Frame Structure</td>
<td>Single Frame, Multi-Frame, and Transparent Relay Frame Structure</td>
</tr>
</tbody>
</table>

Column 4, Figure 4-7 represents the capacity for the configuration where tRS are being utilized. Compared to the single BS scenario, when tRS are utilized, the network is able to achieve higher, voice user, capacity. Such performance comes as a result of better channel conditions. The improvements on the channel conditions are the result of shorter
distances which in turn enable the serving station to transmit at a higher modulation and coding rate – translating to a higher number of data bits per frame symbol. As a result, the BS is able to fit more data in one frame, satisfying that way more MTs while using the same resources.

Another observation, resulting from the voice user capacity with fixed coverage is, that the number of voice users is also influenced by the number of RSs deployed in the network. As the number of RSs, directly (communicate directly with the BS) or indirectly (communicate with the BS through one or more RSs) attached to a single BS, increases; the voice user capacity begins to decline. Such decline occurs as a result of the increase in overhead as the number of RS increases. We also observed that to achieve the maximum user capacity the number of RSs deployment should not be greater than 12 children RSs per BS.

As we can see in Figure 4-8, the overall throughput increases when RS are utilized. Only the subscribers served by the BS; however, will experience better throughput when tRSs are utilized. Employment of tRS increases the signalling overhead in the network, influencing that way throughput and rates for second hop MTs. In reality MTs closer to the BS will be the only users who will truly enjoy the benefit of tRS. Hence, when designing a tRS network, measurements to reduce signalling overhead must be taken into consideration.
Figure 4-7: Voice Capacity utilizing different network configurations while maintaining the same coverage area – illustrating how user capacity decreases as number of hops increases.

In terms of delay, the users in the network experience overall higher delays when the network reaches its maximum voice user capacity, under a tRS configuration, Figure 4-12 and Figure 4-13. This is to be expected, since the number of symbols (resources) available for bandwidth allocation remains the same, leading to longer wait times for each user to transmit their data. Moreover, we can see that on average users experience better DL delays than UL delays, when tRS are utilized. Such behaviour is attributed to the UL/DL sub-frame ratio – DL sub-frame is twice as large as the UL sub-frame. A bigger DL sub-frame means more resources available to MTs, leading to smaller wait
times for each user. Hence, UL to DL sub-frame ratio is an important parameter that can significantly impact the voice user in multi-hop TDD configuration.

Observing the voice capacity for ntRS (Figure 4-7), we note that the multi-frame structure is able to support an increase of 25% to 30% in the number of users compared to the single frame. Such improvement is attributed to the number of symbols each of the frames is able to allocate at each user. The number of symbols in the single frame, available for bandwidth allocation, is reduced with the addition of more hops in the network. As the number of hops and the number of users increases, the single frame does not have enough capacity to meet the minimum resource requirement for all the users in the network. Increasing the number of hops means creating more relay zones while keeping the same frame length, limiting the number of symbols that can be allocated for each user in a single frame configuration.

The multi-frame structure, on the other hand, does not require increase in the number of relay zones as the number of hops increases, enabling the network to support more users. The overall processing time however, for each packet increases as the number of hops increases. Hence, edge users eventually start experiencing bad connections due to higher packet delays (Figure 4-10).
Figure 4-8: Average overall network rate for different UL configuration scenarios – average per user rate increases with the addition of more RS.

Figure 4-9: Average overall network rate for different DL configuration scenarios – behaviour of average per user rate for DL traffic when DL sub-frame is underutilized.
Figure 4-10: Average overall delay for different network configurations UL – average per user packet delay increases as the number of hops/RSs increase.

Figure 4-11: Average overall delay for different network configurations DL – average per user packet delay increases with the addition of more hops/RSs in the network.
Figure 4-12: Average per hop DL traffic delay in a 2-hop network configuration – users achieve similar average per packet delays when different frame structures are utilized.

Figure 4-13: Average per hop UL traffic delay in a 2-hop network configuration – single frame utilization enables user to achieve better average delays when network operates under full user capacity.
Figure 4-14: Average per hop UL traffic rate in a 2-hop network configuration – when transparent frame structure is utilized second hop users experience smaller on average rates compared to first hop users.

Figure 4-15: Average per hop DL traffic rate in a 2-hop network configuration – first hop users experience better on average rates when the network is underutilized.
Figure 4-16: Average per hop DL traffic delay in a 3-hop network configuration – both single frame and multi-frame users achieve similar delays when the network is underutilized.

Figure 4-175: Average per hop UL traffic delay in a 3-hop network configuration – single frame users achieve better delays when the network operates under full user capacity.
Figure 4-18: Average per hop DL traffic rate in a 3-hop network configuration – multi-frame and single frame second and third hop users experience different rates when the network is underutilized.

Figure 4-19: Average per hop UL traffic rate in a 3-hop network configuration – average per hop user rates when the network operates under maximum user capacity.
In Figure 4-10 and Figure 4-17, we observe that multi-frame users experience higher delays compared to the single frame ones. Because of the nature of the multi-frame, incorporating multiple frame sequences into a multi-frame, data transmission occurs in consecutive order; thus making higher queuing delays inevitable. Despite the fact that multi-frame achieves higher delays, such delays are still within the minimum QoS requirements for the VoIP traffic. Furthermore, as it can be seen in Figure 4-11 and Figure 4-16, when the network is not fully loaded, differences in delay between the single frame and the multi-frame are insignificant. Once more this confirms that the main reason for multi-frame users to experience higher delays than the single frame ones is because of the queuing delays.

In Figure 4-14 and Figure 4-15 we show the average rates and in Figure 4-12 and Figure 4-13 we show the average delays achieved by the MTs in both UL and DL when single frame and multi-frame are utilized. In the UL where the full capacity of the network is reached, there is no significant difference in rates and delays achieved by the multi-frame and the single frame configurations. Considering that the single frame behaves much like the multi-frame, in a two hop network configuration, this explains the delay and rate outcome. Furthermore, we observe a similar behaviour in the three-hop experiments as well, Figure 4-8 and Figure 4-9. The overall average rates achieved by both frames are similar.

Observing Figure 4-19 and Figure 4-18 however, we can see that the average per user rate at each hop differs and the difference has the opposite effect for DL and UL
traffic. In the UL, where the network is operating under the maximum user capacity, average per hop rates achieved by multi-frame utilization start to decline after the second hop. This behaviour is attributed to the increases in average user delay as the number of hops increase, resulting this way in lower average per user rates. In the DL where the network is operating under a lighter user load, both multi-frame and single frame users achieve similar per hop average delays. Unlike the single frame, the multi-frame structure is able to maintain a constant amount of resources as the number of hops increases. Hence, third hop multi-frame users, are able to achieve higher average rates compared to the single frame ones.

A general observation which can be made regarding the fixed coverage topology is that, ntRS utilizing a single frame configuration offers the best performance in a two hop network configuration scenario. Increasing the number of hops will lead to higher delays and lower rates. Increasing the number of hops results in more RZ for a single frame configuration, which in turn reduces the amount of resources available for data transmission for each frame. We also note that, MMRN utilizing a single frame configuration are not able to support more than three hops; after the third hop the network becomes unusable due to high delays, low rates and high packet loss. Mobile multi-hop relay networks which utilize ntRS with a multi-frame configuration, on the other hand, are able to support more than three hop operations. High packet delay however, renders them unusable for ertPS, and rtPS delay sensitive traffic.
Despite the fact that multi-frame configuration is able to support a higher number of MTs; in terms of average delay and rate (Figure 4-8, Figure 4-17 and Figure 4-19), the single frame configuration seems to slightly overcome the multi-frame configuration. Considering that wireless broadband networks rarely operate under full capacity, utilization of the single frame structure would be a better choice for MMRN utilizing a star topology.

4.3.2 Variable Coverage

4.3.1.2 Effect of the line configuration on voice capacity

In this experiment we test the network capacity in a line topology when ertPS traffic is utilized. Parameters for the ertPS traffic are shown in the Table 4-5 below. A visualization of the inline topology is depicted in Figure 4-6.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of RS – Number of Hops</td>
<td>0-1, 1-2, 2-3, 3-4, 4-5, 5-6</td>
</tr>
<tr>
<td>Number of MT</td>
<td>1 – 240</td>
</tr>
<tr>
<td>Traffic Type</td>
<td>ertPS (Voice)</td>
</tr>
<tr>
<td>Relay Mode</td>
<td>Transparent/Non-Transparent</td>
</tr>
<tr>
<td>Frame Structure</td>
<td>Single Frame, Multi-Frame, and Transparent Relay Frame Structure</td>
</tr>
</tbody>
</table>
Unlike the previous setup in the star topology, the coverage area extends as the number of RSs increases. Mobile stations are uniformly distributed along all hops in the networks. In addition, we are utilizing a full duplex connection for our experiments, where users are allowed to transmit data at the same time in UL and DL.

To achieve the maximum voice user capacity, we experimented with different numbers of user load. Initially we start with just the BS and one MT and start increasing the number of MTs until the maximum user capacity is reached. Again, similarly to the star configuration the maximum number of users is reached when at least one user in the network starts experiencing a bad connection. Next, we add one RS and repeat the same process by adding more MTs. Once the maximum user capacity is reached we move on to the next network configuration scenario. Note that at each configuration scenario – where relay stations are involved – users are distributed equally among all RSs. The number of users associated with a particular RS varies, unlike the users associated with the BS, who always remain the same. The reason for such behaviour is that each of the DL and UL sub-frames are further divided into RZ and AZ. The RZ either changes size (single frame), or allocates resources to more users (multi-frame), as the number of hops increases. Access Zone, on the other hand, always remains the same length for both type of frame structures. Mobile terminals that are directly connected to the BS are allocated resources via the AZ. Hence, the number of users that can be supported by a single BS will always remain the same no matter the distance or the number of RSs in the network.
Voice capacity results from each network configuration scenario are shown in Figure 4-20. The first bar represents the maximum number of MTs supported by a PMP network configuration. The rest of the bars, similarly, represent the number of voice users in the network when RSs are utilized. More specifically each consequent group of bars represents the voice user capacity achieved by the single frame, and multi-frame, with the exception of the second hop grouping. The group of bars in the second hop includes measurements performed for the tRS configuration as well.

![Voice Capacity Graph](image)

**Figure 4-20:** Voice Capacity in a line topology with variable number of hops – multi-frame utilization enables line network configurations to support a higher number of users.

With the exception of tRS and the PMP configuration, the voice user capacity in a line configuration decreases as the number of hops increases. Once the number of hops in
the network increases to more than five, both frame structures, fail to support any more voice users. High delays, and a high packet loss, make it unfeasible for voice services to be supported at such distances.

![Evaluation of delay in a line topology for UL voice traffic](image)

**Figure 4-21**: Evaluation of delay in a line topology for UL voice traffic – single frame users are able to achieve slightly better average packet delays in a line topology.

Comparing the single frame and multi-frame scenario, we observe that multi-frame provides a higher user capacity. Such performance is attributed to the ability of the multi-frame to always maintain a fairly constant amount of resources as the number of hops in the network increases. The single frame, on the other hand, does not have the ability to allocate enough resources for data transmission as the number of hops increases. The number of RZ in a single frame is proportional to the number of hops in
the network. A large number of RZ will inevitably lead to exhaustion of resources available for data transmission.

In terms of delay, as shown in Figure 4-21, the single frame achieves smaller delays compared to the multi-frame – 6 ms difference, on average. Such performance is attributed to the ability of the single frame to transfer more data in a shorter period of time – unlike the multi-frame; during a single frame transmission all RSs in the network receive the data send by the BS within the same frame period. In order to achieve better delays a single frame configuration, requires a high processing capability by the RSs. To keep processing power to reasonable levels, while still achieving low delay performance, one can experiment with different single frame configurations to keep RRTG gaps to a minimum.

Figure 4-22 and Figure 4-23 show that the average per user throughput and rate, under single frame and multi-frame configuration, decrease as the number of hops increase. Such decrease is attributed to the increasing signaling overhead and increase of MT load. In terms of throughput and rate both the single frame and multi-frame, achieve similar performances. One of the main reasons for such behaviour is the traffic type; in both cases we deal with voice traffic with the same QoS requirements. Hence, all users are treated with the same priority, and their minimum QoS requirements are met equally in both single frame and multi-frame configurations.
Figure 4-22: Evaluation of throughput in a line topology for UL voice traffic – both multi-frame and single frame users achieve similar throughputs in a line network configuration, when network is underutilized.

Figure 4-23: Evaluation of rate in a line topology for UL voice traffic – multi-frame users are able to achieve better average rates in a 5-hop network configuration.
4.3.1.3 Effect of the line configuration on video traffic

In this experiment we observe how the network capacity, average user packet delay, throughput, and rate behave in a line topology when rtPS traffic is utilized. The rtPS traffic is simulated according to the video traffic model presented in Section 4.3.3. The network topology is similar to that presented in Figure 4-6, section 4.2.1. Parameters for the network configuration are shown in Table 4-6.

**Table 4-6: Line Topology, Video Traffic - Parameters**

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of RS – Number of Hops</td>
<td>0-1, 1-2, 2-3, 3-4, 4-5</td>
</tr>
<tr>
<td>Number of MT</td>
<td>1 – 240</td>
</tr>
<tr>
<td>Traffic Type</td>
<td>rtPS (Video)</td>
</tr>
<tr>
<td>Relay Mode</td>
<td>Non-Transparent</td>
</tr>
<tr>
<td>Frame Structure</td>
<td>Single Frame and Multi-Frame</td>
</tr>
</tbody>
</table>
Figure 4-24: Evaluation of delay in a line topology for UL video traffic – single frame users are able to achieve smaller on average delays.

Figure 4-25: Evaluation of rate in a line topology for UL video traffic – both single frame and multi-frame users achieve similar average per user rates.
Figure 4-26: Evaluation of throughput in a line topology for UL video traffic – both single frame and multi-frame users achieve similar throughputs as the number of hops increases.

Figure 4-27: Video Capacity in a line topology with variable number of hops – network configurations utilizing the multi-frame structure is able to support more users.
In Figure 4-24 we show the average packet delay achieved by voice users at different hops. We observe that the average delay increases as the number of hops increases. In addition, when single frame is utilized the average packet delay achieved by each MT at each hop, is smaller than when the multi-frame structure is utilized. The explanation for this behaviour is in the length of each frame structure. Data transmitted via a single frame structure is able to reach the destination in a shorter period of time, due to lower queuing delays, which is not the case in the multi-frame scenario. Networks utilizing the multi-frame structure will experience higher queuing packet delay due to the nature of the multi-frame; resulting in higher overall average delay. Such behaviour will in turn affect the average rate achieved by MTs at different hops (see Figure 4-25).

Another general observation that can be made is the throughput increase, occurring as a result of RSs utilization. Relay stations enable the BS to send data at a higher rate to all users in the network, by maintaining uniform signal strength throughout the network. Choice of frame structure does not seem to affect the average throughput achieved by each MT at different hops. Although, one would expect the multi-frame to have a higher throughput, due to the larger amount of data which can be packed in a multi-frame, this is not the case here. High average rates achieved by the single frame structure compensate for the lower amount of data that can be packed in a single frame (see Figure 4-26).

A line network configuration utilizing only video traffic achieves maximum user capacity when the number of hops is smaller than three. As the number of hops increases
to more than three, the capacity for both single frame and multi-frame utilization decreases (see Figure 4-27). Similarly to the voice traffic experiment, video traffic is delay sensitive; as such increasing the number of hops will translate to higher packet loss due to queuing delays. In addition, the large size of video packets will also have an effect on queuing delays. It will require video packets more symbols to be transmitted through the network; resulting in less video packets per frame, if we were to compare with voice packets. Carrying fewer packets per frame will mean that packets are queued for a longer time, increasing that way average packet drop due to delays. Another observation that can be made in terms of capacity is that the multi-frame structure outperforms the single frame structure. The single frame structure is able to allocate fewer symbols for data transmission as the number of hops increases, due to the increase in the number of the relay zone sub-frames. Such behaviour leads inevitably to higher number of packet loss as the number of MTs increases.

4.3.2 Effect of traffic mix

The objective of this experiment is to study the performance of the single frame and multi-frame structure under mixes of traffic. The traffic mix is supplied by the ertPS and rtPS service classes – voice and video traffic, respectively. The video and voice traffic generated for this experiment are described in section 4.3.3. Each MT consists of one connection – either voice or video. Connections are set prior to each experiment and remain active throughout the simulation time.
Table 4-7: Traffic Mix - Parameters

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of RS – Number of Hops</td>
<td>0-1, 1-2, 2-3, 3-4, 4-5</td>
</tr>
<tr>
<td>Number of MS</td>
<td>1 – 240</td>
</tr>
<tr>
<td>Traffic Type</td>
<td>ertPS (Voice), rtPS (Video)</td>
</tr>
<tr>
<td>Relay Mode</td>
<td>Non-Transparent</td>
</tr>
<tr>
<td>Frame Structure</td>
<td>Single Frame and Multi-Frame</td>
</tr>
<tr>
<td>Ratio of MT (ertPS:rtPS)</td>
<td>1:1, 1:2, 2:1</td>
</tr>
</tbody>
</table>
(a) Average per hop Delay for 1:1 Traffic Ratio – errPS

(b) Average per hop Delay for 1:1 Traffic Ratio – rtPS
(c) Average per hop Delay for 1:2 Traffic Ratio– ertPS

(d) Average per hop Delay for 1:2 Traffic Ratio– rtPS
(e) Average per hop Delay for 2:1 Traffic Ratio – ertPS

(f) Average per hop Delay for 2:1 Traffic Ratio – rtPS

Figure 4-28: The effect of MT Ratio – Average per hop Delay; user performance is not affected by the type of frame structure utilized.
In general, the average packet delay per MT from both traffic classes increases as the number of hops in the network increases (see Figures 4-28(a), (b), (c), (d)). This is to be expected in a multi-hop environment due to queuing delays at each hop. When either, the single frame or multi-frame structure is utilized, the effect on average packet delay per MT for both traffic classes appears to be minimal. Although this may seem at first to contradict previous findings, where single frame achieves lower average delays per MT, it is not the case with this scenario. For this experimental setup, MT load among RSs, does not equal the maximum network capacity. The reason for not loading the network to its maximum capacity, is to achieve the desired ratio between ertPS and rtPS traffic for each experiment.

Another reason for observing similar on average packet delays, for both single frame and multi-frame structures, is the size of rtPS traffic packets. Unlike voice traffic, video traffic packets have a larger size hence, the number of symbols required to transmit a video packet is larger compared to the number of symbols required for a voice packet transmission. Video packet will then have to spend a longer time in the queue, increasing the average delay per packet. The larger video packet size will also reduce the number of symbols available for voice packet transmission in each frame; increasing the average queuing delays for voice packets as well. As a result, both single frame and multi-frame structures behave almost the same in terms of packet delay.
(a) Average per hop Rate for 1:1 Traffic Ratio – ertPS

(b) Average per hop Rate for 1:1 Traffic Ratio – rtPS
(c) Average per hop Rate for 1:2 Traffic Ratio—ertPS

(d) Average per hop Rate for 1:2 Traffic Ratio—rtPS
Figure 4-29: The effect of MT Ratio – Average per hop rate; both single frame and multi-frame users achieve similar performance.
Figure 4-29 shows average per hop rates for both ertPS and rtPS traffic users, obtained from the mix traffic experiments. In general, we observed that regardless what type of frame structure is utilized, the average data rates achieved by each MT decrease as the number of hops increase. The main reason for such behaviour is the increase in the average packet delay for each MT, as the number of hops increases.

As the concentration of the MTs of the ertPS class increases, single frame utilization yields higher on average packet rates per MT. On the other hand, when the multi-frame structure is utilized, MTs are able to achieve higher on average packet rates when the ertPS to rtPS class ratio is lower. Such behaviour is the result of symbol allocation for each frame structure. When there is a smaller concentration of voice users in the network, single frame does not have enough symbols to allocate to each voice user; increasing the queuing delays for voice packets. Multi-frame structure, on the other hand, contains enough symbols to allocate to ertPS users; enabling voice users to achieve higher rates. We also observe that utilizing the single frame structure when the concentration ertPS class MTs increases, average rates achieved by ertPS class users increase as well. Although there are still video traffic packets in the network, on average there are enough symbols available per frame to satisfy more voice users; enabling them to achieve higher on average data rates.

Users utilizing rtPS class traffic show to experience on average somewhat better data rates – regardless of their concentration – when single frame is utilized.
Nevertheless, the difference is not significant to claim that single frame should be given preference over the multi-frame structure.

Average throughputs achieved by voice and video users have a similar behaviour to that of the rate results (see Figure 4-30). This is due to the fluctuation of the total provisioning for the rtPS class as the number of MTs for the voice traffic changes.

In the traffic mix observations we note that choice of the frame structure – single frame or multi-frame – does not seem to have a major affect in terms of average overall user performance in the traffic mix experiments. Such observation is more apparent in the results obtained from the rtPS traffic, more so from the throughput results in Figure 4-30b.

Considering that we are utilizing a static frame structure, the frame length does not change dynamically according to the traffic load. Also the choice of frame structure utilization in the voice traffic experiments affects the user performance differently from the traffic mix scenario. We can conclude that the role of scheduler is important in WiMAX networks employing ntRS.
Figure 4-30 (a), (b): The effect of MT Ratio – Average per hop Throughput; both single frame and multi-frame users achieve similar performance.
4.4 Summary

In this chapter we studied the single frame and multi-frame configurations, used in mobile multi-hop networks which utilize non-transparent relays. We presented the simulation environment, including the simulation parameters for the MAC and PHY layers, as well as traffic and channel models. Our simulation environment is an ns2 add-on which enhances the ns2 capabilities by bringing it up to date with the advancements in the multi-hop broadband technologies. A detailed description of the configuration scenarios and evaluation metrics was also provided. We performed a series of experiments and observed the performance of the frame structures adopted by the IEEE 802.16j standard. Our work will help new and existing wireless broadband providers to make more informed decisions when designing MMRNs.

Our experiments showed that choice of frame structure under different network configurations can significantly impact the average performance of each MT. Single frame structure achieves better average delays and rates – when only one type of traffic is utilized – as the number of hops increases in a multi-hop environment a single type of traffic. Multi-frame, however, is able to support more users for the same network configuration.

Traffic mix ratios also seem to play an important role on the type of frame utilization. Without taking into consideration the choice of the scheduling algorithms, we observe that single frame utilization will be a better choice for networks where eRTS
MTs have a higher concentration. The multi-frame structure, on the other hand, will be a better choice for networks where MTs utilize services which generate a large packet size.
Chapter 5

Conclusions and Future Work

In the recent years the popularity for broadband wireless access on the go has increased due to the advancements in the hardware technology. Applications such as video conferencing, online gaming, IPTV, and VoIP, running on small and portable hardware, demands wireless broadband coverage even in the most remote areas. WiMAX and LTE technology are designed to enable high speed internet access “on the go” at an affordable cost. The IEEE 802.16 standard and the IEEE 802.16j amendment define the basic functionalities for the MAC and PHY layers in PMP and multi-hop operations. The IEEE 802.16j amendment defines two types of PMP operations: utilizing transparent and non-transparent relay stations. For networks employing non-transparent relay stations there are two frame structure types suggested by the standard, single frame and multi-frame. The choice of frame structure can have a significant impact on the network performance.

In this thesis, we investigated several network scenarios, utilizing both single frame and multi-frame structures. In order to run our simulations we modified the LWX ns2 module to support non-transparent relays and the two frame structures suggested by the standard. The two frame structures were evaluated under different network configurations, traffic mixes, and with respect to the major characteristics of IEEE
The performance metrics utilized to evaluate the frame structures suggested by the standard are user capacity, average packet delay per user, packet loss, average user receiving rate, and throughput. The multi-hop relay system evaluation methodology specified by the WiMAX forum was used to obtain the above metrics. The evaluation methodology is specifically designed to evaluate PMP network configurations where relay stations are utilized. The user capacity metric is designed to calculate the maximum number of users a network can support while guaranteeing their satisfaction by meeting the specified QoS requirements. To effectively study the effect of each frame structure we perform most of our experiments under maximum user capacity, for each configuration scenario.

The evaluation environment was able to provide certain insights as to the specific advantages both transparent and non-transparent relay stations offer over point-to-multipoint setups. The environment also facilitated the comparison of the effects of the frame structure types on network performance. Researchers interested in acquiring the modified LWX add on can find it at [5].

Our work has shown that the single frame structure is able to achieve a better performance on average compared to the multi-frame one, in terms of delay and rate for network configurations utilizing only one type of traffic. The multi-frame structure however, is able to support a higher number of users. Based on the above observations...
we conclude that, single frame utilization will be a better choice in networks where user density is low, such as rural environments. Meanwhile, for dense populated areas utilization of the multi-frame structure would be a better choice. Multi-frame structure will also be a better choice for network configurations that mainly provide none delay sensitive services.

Based on the simulation results, we observe that the distribution of bandwidth among the different traffic classes also has an impact on user satisfaction. We conclude that the role of scheduler is important in WiMAX networks employing ntRS. First, we note that the performance of the multi-frame structure in the voice traffic experiments differs compared to the single frame one; however, in the traffic mix scenario single frame and multi-frame utilization result in almost equal performance. Second, the fact that we are working with static frame structures, coupled with the first observation, reinforces once more the importance of the scheduling algorithm.

In the future, the evaluation of different scheduling algorithms in non-transparent multi-hop relay networks will make a worthwhile issue for further investigation. The study of scheduling algorithms combined with the choice of frame structure utilization will yield critical insights on how to achieve the best performance out of the LTE and WiMAX relay technology.
Bibliography (or References)


