A Performance Comparison of Frame Structures in WiMax Relay Networks

Pandeli Kolomitro
Telecommunication Research Lab
School of Computing Queen's University
Kingston, Ontario, K7L 3N6, Canada
pandeli@cs.queensu.ca

Abd-Elhamid M. Taha
Telecommunication Research Lab
School of Computing Queen's University
Kingston, Ontario, K7L 3N6, Canada
taha@cs.queensu.ca

Hossam Hassanein
Telecommunication Research Lab
School of Computing Queen's University
Kingston, Ontario, K7L 3N6, Canada
hossam@cs.queensu.ca

Abstract—**This study evaluates the effect of the choice of frame structure type in WiMax networks employing non-transparent relay stations (ntRS). The IEEE 802.16j-2009 amendment allows two frame structure types, single frame and multi frame. Thus far, a comparison of the two choices, in terms of network performance, has not been made. To facilitate this evaluation, we expand on Light WiMax (LWX) ns2 add-on to support ntRS, the two frame structure types, in addition to the relevant operational requirements (e.g. QoS support). We observe that while the multi-frame structure allows for higher throughput and voice capacities, the single frame shows some general advantage in terms of delay.**

Keywords-frame structure; single frame; multi frame; 802.16j; voice capacity; ns2 relay add-on

I. INTRODUCTION

Relay stations will play an important role in upcoming broadband wireless networks such as WiMax [1] and LTE-Advanced. Such relays can be utilized either to increase a cell's capacity or expand a cell's coverage. Their introduction was largely motivated by facilitating either advantage (capacity increase or coverage extension) at a reduced cost, offering an alternative to using Base Stations (BSs) in high density or expanded deployments. Employing RS also has the advantages of reducing power consumptions for Mobile Terminals (MTs), improving service delivery zones and overcoming patched coverage. For WiMax, specifications have already been made in *j* amendment for the IEEE 802.16-2009 release [1]. On the contrast, the 3GPP has only recently outlined deployment alternatives for relay stations to be considered for Release 10, which is the release to describe LTE-Advanced [3].

Both standardization bodies classify relay stations into two main types based on the deployment objective. Transparent RSs (tRS) operate with a BS's cell coverage in which Mobile Terminals (MTs) fully recognize the BS's control message, but have their uplink 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.

For WiMax ntRSs, the amendment allows for two types of frame structures. The first, called the single frame, is one in which 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.

The intent of this paper is to examine the effect of the frame structure type on WiMax network employing ntRSs. Specifically, our interest is to examine the effect of the frame structure type on certain operational metrics such as throughput and delay. To facilitate this examination, we developed an evaluation environment per the IEEE 802.16j-2009 amendment. We developed an add-on [4] for ns2 [4] through modifying the light WiMax (LWX) add-on contributed by Lai and Chen in [4] (The LWX add-on itself can be downloaded from [7]). 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 remainder of this paper is organized as follows. Section II presents a brief history of the WiMAX frame structure. We also review some of the available work, in the literature, which evaluates relay performance. In addition, we present a brief description of the available software modules, which enable simulation of the multi-hop relay technology. In section III, we provide specific details on the single frame, multi frame, and transparent frame, adopted by the IEEE 802.16j standard. In section IV, we develop a comprehensive simulation model and utilize it to observe the behavior of the frame structures, adopted by the IEEE 802.16j standard, under various network configurations. We report on the strengths and weaknesses of each frame structure, and present conclusions in Section V.

II. RELATED WORK

One of the main challenges, which came with the addition of relay technology to the WiMAX standard, was the design of a new frame structure. Unlike the legacy frame structure, which was designed to accommodate only point-to-multipoint (PMP) communications, the new frame structure had to take into

978-1-4244-8389-1/10/$26.00 ©2010 Crown

account the resource allocated to the RS subordinates. At the same time the new frame structure should stay compatible with the PMP technology. To solve these challenges several frame structures have been proposed, [8], [9], [10], and [11]. The standard; however, decided to adapt only two of them, the single frame and multi-frame; which will be discussed in detail in the following section.

Since the release of the standard in 2009 there has been little effort to study the performance of each frame structure adopted by the standard.

An effort to compare the efficiency of single frame structure with the multi-frame structure has been presented in [12]. 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 (traffic type, modulation and coding rates, traffic distribution, and the like.)

Another study done by Genc *et al.* presented in [13], 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, showing the network performance when ntpRS are utilized.

Another challenge associated with frame structure evaluation in multi hop relay environments is the simulation environment. It is very costly and time consuming to set up real networks for testing purposes. One of the alternatives will then be to utilize software simulation environments. So far there have been developed only two NS-2 add on modules which provide limited support for WiMAX relay technology. One of them is the Light WiMAX module developed by Yen-Hung-Cheng, Department of Information Management, National Taiwan University of Science and Technology in Taipei Taiwan [14]. The other module is developed by the National Institute of Standards and Technology, a non-regulatory federal agency within the U.S. Department of Commerce [14]. Due to its availability, the former has become our module of choice. To simulate multi-hop relay environments, more specifically the multi-frame and single-frame, we have implemented new functionalities to the original LWX design [4]

To our knowledge there is no previous work, which analyzes the performance of the single frame and multi-frame system in multi-hope 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.

III. OVERVIEW OF THE 802.16J FRAME STRUCTURE

The amendment describes the frame structures for both tRSs and ntRSs. Given that the tRS are only used for capacity enhancements, and given certain end-to-end constraints, a BS employing ntRSs can only allow for one additional hop, i.e. no more than one tRS between the BS and the MT. The frame structure for tRS is hence fixed, as shown in Figure 1. In the figure, the frame consists of an Access Zone (AZ) and a Transparent Zone (TZ) in the downlink subframe, and an AZ and a Relay Zone (RZ) for the uplink subframe. During the downlink subframe, the BS communicates to the MTs within the cell in the AZ. In the uplink, the BS receives MTs transmissions both direct (AZ) and relayed (RZ). In addition to the regular time gaps utilized in the TDD frame, the frame has additional time gaps to allow the tRS to switch from the transmit to the receive mode, and vice versa.

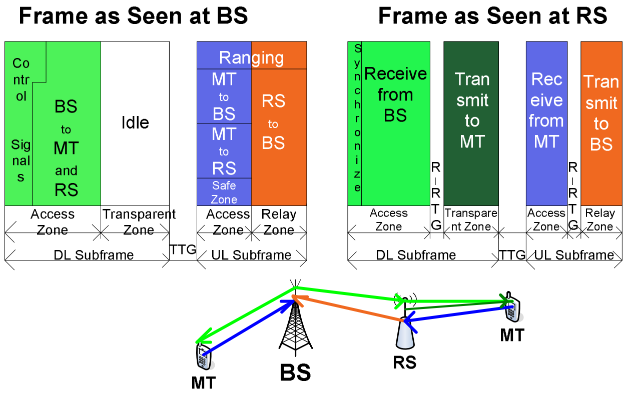

Figure 1. Transparent Relay Frame Structure.

A. *Frame Structure non-Transparent RSs*

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. Since ntRS transmit their own control information, they might need to be synchronized with the BS to transmit the frame preamble, UL, and DL data bursts. The BS also transmits three different MAPS, one to the MS with direct communication, one for RS-BS communication, and another one called R-MAP for RS-MT communication.

When centralized scheduling is used, the BS generates 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:

$$N_Z = h_n - 1 \tag{1}$$

where N_z is the number of relay zones and h_n represents the number of hops in the network.

B. *Example Frame Structures (3 hops)*

A single OFDMA TDD frame structure for a three hop highway scenario, similar to Figure 5, is shown in Figure 2. Both the 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 PMP [1] 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 access zone (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 ntRSs 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 [1]. The following equation is utilized to calculate R-RTI which is measured in symbol unit:

$$\mathrm{R-RTI} = \left\lceil \frac{\mathrm{RSRTG} + \frac{\mathrm{RTD}}{2}}{\mathrm{OFDMA\_Ssymbol\_Time}} \right\rceil \tag{2}$$

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.

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

$$\mathrm{R-TTI} = \begin{cases} 0 \text{ if } \frac{\mathrm{RTD}}{2} \geq \mathrm{RSTTG} \\ \left\lceil \frac{\mathrm{RSTTG} - \frac{\mathrm{RTD}}{2}}{\mathrm{OFDMA\_Symbol\_Time}} \right\rceil \text{ if } \frac{\mathrm{RTD}}{2} < RSTTG \end{cases} \tag{3}$$

where RSTTG is the time it takes the RS to switch its radio from transmit to receive mode.

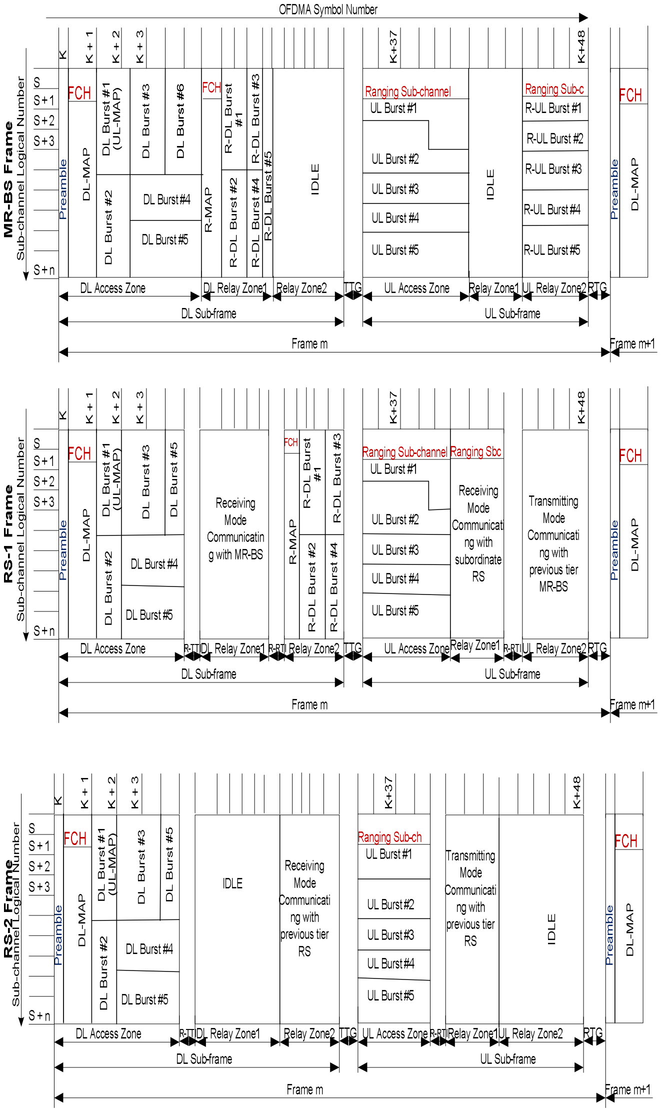

Figure 2. Single Frame Design for a Three Hop Highway Scenario.

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 RSs 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 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.

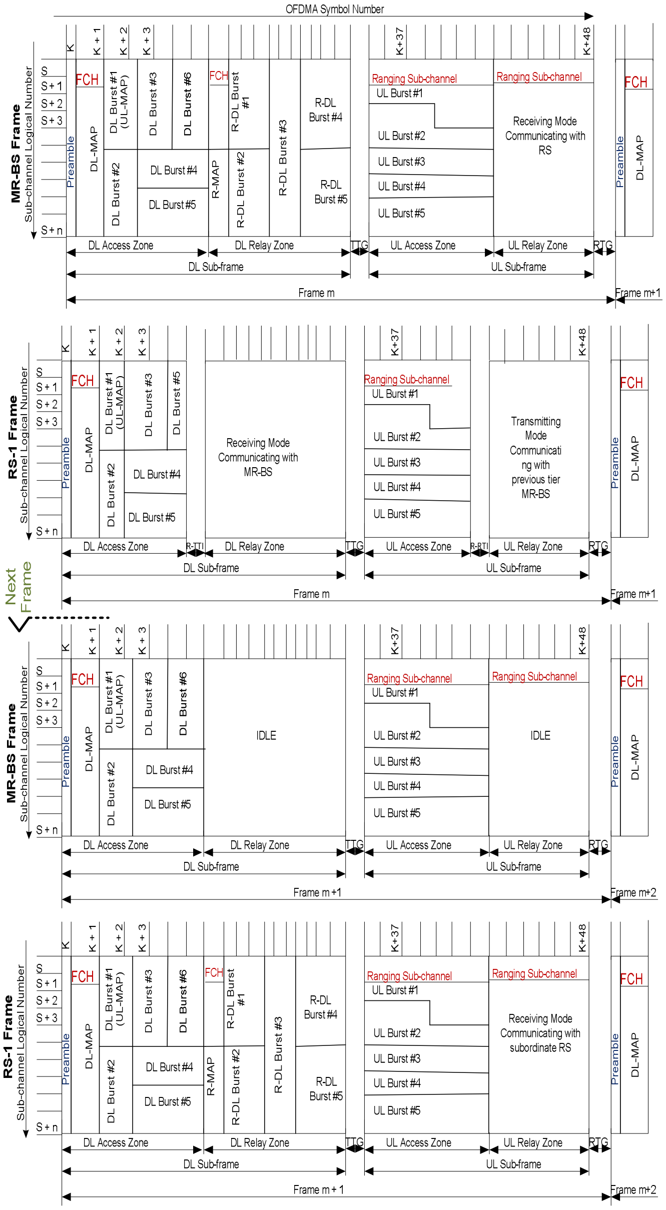

Figure 3. Multi Frame Design for a Three Hop Highway Scenario.

A detailed implementation of the multi-frame structure for a three hop highway scenario is shown in Figure 3. 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 those 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, we describe 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 repeating 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. In a line multi-hop scenario with 3 ntRS; transmission between MR-BS to/from RS1 and RS-2 to/from RS-3 can occur at the same time.

IV. EVALUATION SETUP

Prior to describing our evaluation environment, we provide an overview of the relevant details of the LWX ns2 add-on. We also describe the modifications that we contributed to LWX to facilitate evaluating environments with ntRSs.

A. Overview of the LWX ns2 Add-on

The LWX (Light WiMAX) add-on [6] 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], and IEEE 802.16j [1] standards, and based on ns2 version 2.29 [4]. The add-on implements the following components, grouped in several classes: Traffic Handler, MAC Handler, PHY Handler, LWX OTcl Script Transformer, and LWX simulation Log Generator. Traffic aggregation and mapping is done by the Traffic Handler. Bandwidth allocation, call admission control (CAC), generation of PDUs (packet data units), ranging, and other tasks handled by the IEEE 802.16 MAC layer, are addressed by the MAC handler. 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.

The block fading model is adopted for the wireless channel configuration. In this model the 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 [2] (64QAM1/2, 64QAM2/3, 16QAM3/4, 16QAM1/2, QPSK3/4, and QPSK1/2), according to each connection's Carrier to Interference-plus-Noise Ratio (CINR) [6].

B. Contributed Modifications

Our modifications to the LWX add-on 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 of 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.

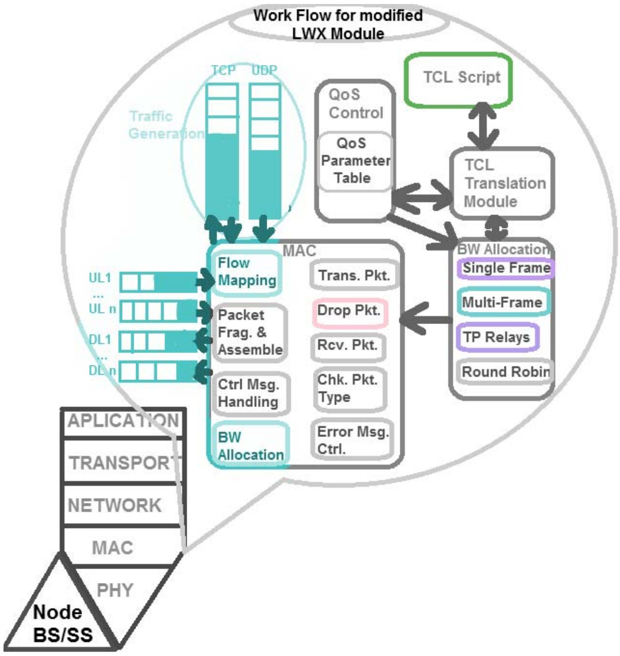

Figure 4. A Detailed illustration of the modified LWX MAC add-on that includes BW allocation, flow mapping, and QoS support, adapted from [7].

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.

C. Performance Evaluation

In this section, we show the results of utilizing the modified LWX module to evaluate the voice capacity of WiMax networks employing ntRS. We use different network configurations using voice traffic. We also vary the number of relay stations, and users in a network and how they are distributed. Our simulation methodology follows that described by the WiMax forum [15] and the IEEE 802.16 WG [16].

In our simulations we have modelled the ertPS and BE service classes. These classes are respectively associated with, voice (Class 2), and HTTP (Class 5) data traffic models. The voice traffic model follows the International Telecommunication Unit [17] standard code G.711. Such encoding scheme is utilized to transform the signal from analog to digital. Furthermore, the resulting signal is transformed to packet data units (PDUs) [18] and passed on to the physical layer. In order to simulate a real traffic environment, we have attached a traffic source for each connection following the Poisson distribution.

Elaborating on the utilized traffic models, we note that the traditional voice model is characterized by the presence of a talk spurt and a silence spurt [19], [20]. To generate voice traffic we utilize Variable Bit Rate (VBR) traffic with a talk spurt length of 147ms and silence length of 167ms. In accordance 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 [18], [21]. After considering a 25% overhead plus the IP, RTP and UDP headers the payload becomes 1600 bits and the rate 80kbit/s [22].

Two network configurations are used in our evaluations; a linear configuration, shown in Figure 5, and a star configuration, shown in Figure 6. Table I further lists the constant and variable parameters used in our simulations.

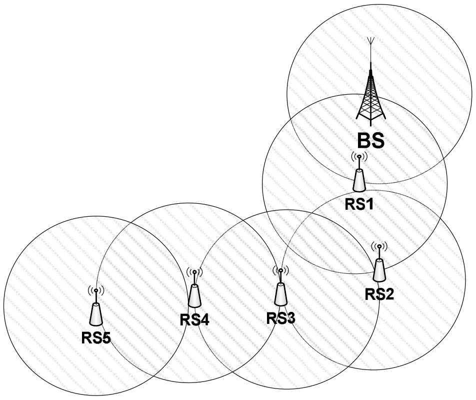

Figure 5. A Line Configuration with 5 ntRS.

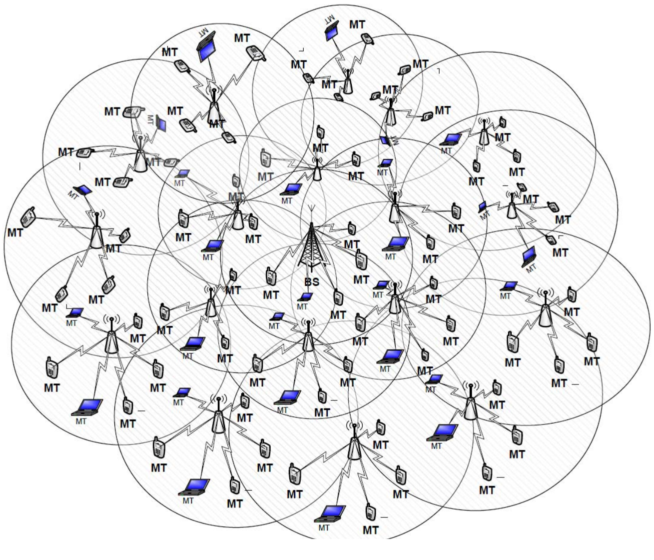

Figure 6. A Star Configuration with 18 ntRS.

Note that, in addition to our evaluations of ntRS configurations, we included tRSs in instances where two hops are utilized. To ensure fair comparison, 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 500m, it will be extended to 1000m. On the other hand, when ntRS are utilized the coverage area of the BS remains the same.

TABLE I. SIMULATION PARAMETERS

Fixed Parameters	*Value*
OFDMA Symbol Time	100.94μs
Frame Structure	TDD
Number of Symbols per Frame	48
Number of Frames per Second	200
Number of Sub-Channels for Downlink	60
Number of Sub-Channels for Uplink	70
Slot Size of Downlink (subchan. x symbol)	1 x 2
Slot Size of Uplink (subchan. x symbol)	1 x 3
Downlink/Uplink Bandwidth Ratio	2:1
Access/Relay Zones Bandwidth Ratio	1:3
Simulation Time	15 sec
Frame Duration	5 ms
Variable Parameters	***Value***
Number of Hops	1 – 6
Number of MT per Serving station (RS/BS)	1 –120
Number of RS	0 – 18
Relay Mode	Transparent/Non-Transparent
Frame Structure	Single Frame, Multi Frame, and Transparent Relay Frame Structure

Finally, we note that the following assumptions were made in our simulations.

- Channel conditions remain the same – Throughout the simulation period the channel conditions do not change for all active connections in the network.
- All MTs are active – Each node has enough power to remain active throughout the simulation period.
- 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 BS.

D. Simulation Metrics

To collect statistics from our simulation runs, we utilize the voice capacity metric, average packet delay per user metric, average packet loss ratio per user, average per user throughput, and average per user rate metric.

Voice Capacity (vc) determines the number of MT that can achieve a satisfactory packet loss, and delay requirements (L, Λ) 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 L; we can calculate voice capacity in the following way:

$$\forall i \in k \subseteq U \; iff \; \exists\big((l_i < L) \vee (\lambda_i < \Lambda)\big) \Leftrightarrow vc = 0 \qquad (4)$$

else

$$vc = \frac{k}{\sum_{i=1}^{k} \frac{\Lambda}{\lambda i}} \qquad (5)$$

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, λ_i represents the packet latency, and l_i represents the packet loss, for user i, where ι 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:

$$\vartheta = \sum_{t=0}^{T} p_t \qquad (6)$$

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 1sec. The value is expressed in kbps and calculated as follows:

$$r = \frac{\sum_{t=0}^{t=\eta} \sum p_t}{\eta} * \beta \qquad (7)$$

where η is the number of t unit time intervals, p_t represents the number of packets received during the t interval, and β represents the size of the packet in bits.

Finally, **Packet loss ratio per user** ($rPLR$) is calculated by:

$$rPLR = \frac{\rho}{\tau} \qquad (8)$$

where ρ is the total number of successfully received packets and τ is the total number of successfully transmitted packets.

E. Simulation Results

Two extensive experiments were performed to compare the effect of the frame structure on the networks' voice capacity. The results, shown in Figure 7, represent the voice user capacity for different numbers of ntRS in a highway scenario. Each 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.

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 traffic to be utilized at such distances.

Comparing the voice user capacity for 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.

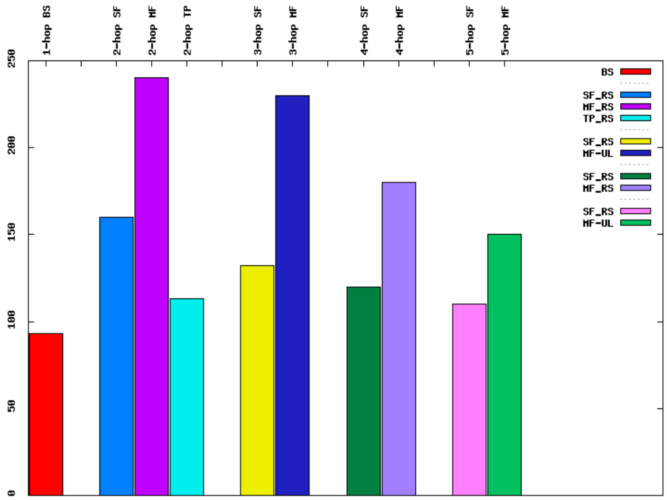

Figure 7. Voice Capacity in a Line Toplogy.

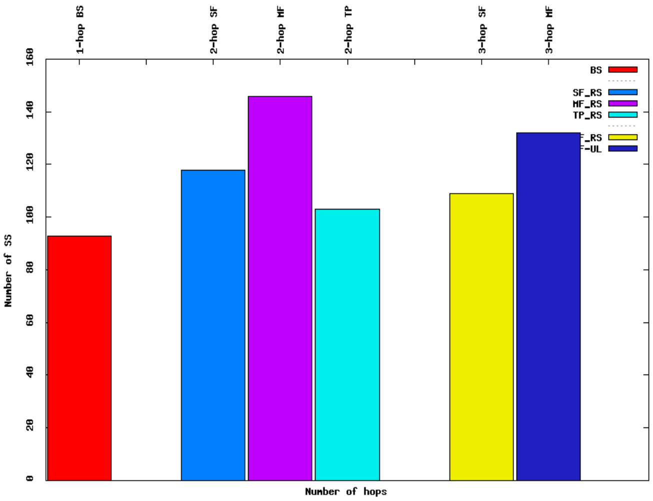

Figure 8. Voice Capacity in a Star Topology.

A similar pattern follows in the star configuration in Figure 8; where multi frame utilization reveals a higher number of voice users. Unlike the line topology; however, the difference in capacity is only 20%.

In terms of rate and throughput both single frame and multi frame follow a similar pattern. Such output is mainly attributed to traffic type, which has the same characteristics for both single frame and multi frame scenarios. Figure 9 shows the average rates per user terminal (UT) for the entire network; while Figure 10 shows the average throughput that users at each hop are able to achieve.

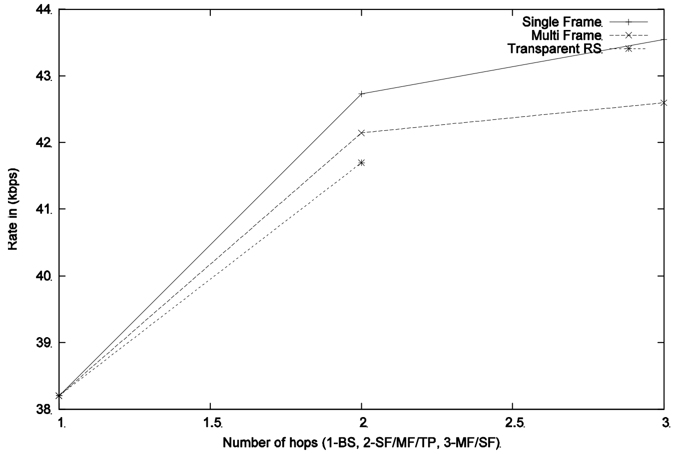

Figure 9. Average UT Rate in a Star Topology.

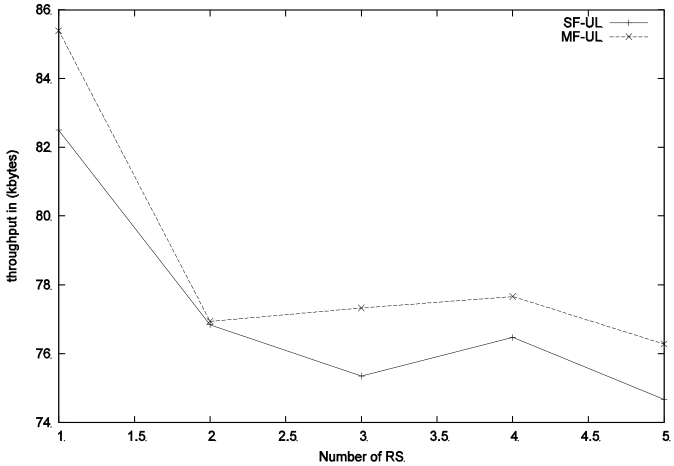

Figure 10. Average per-hopUT Throughput in a Line Configuration.

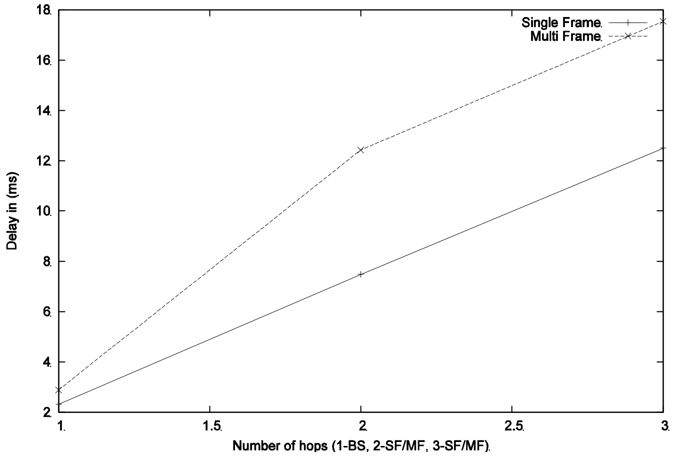

Figure 11. Average per-hopUT Delay in a 2-hop Star Topology with 18 ntRS.

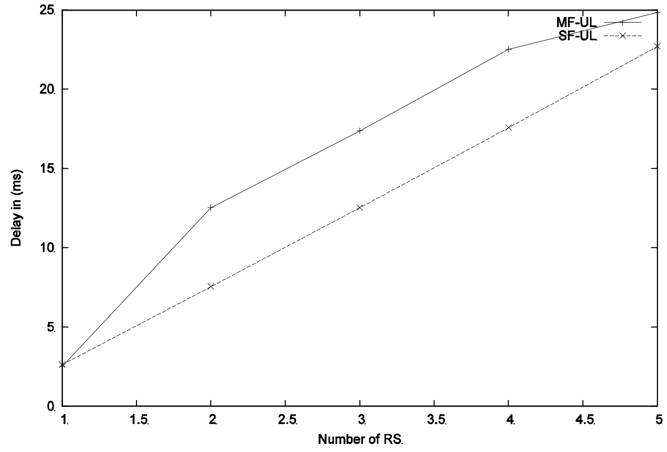

Figure 12. Average per-hopUT Delay in a 5-hop Line Topology.

Single frame, as shown in Figure 11 and Figure 12, achieves smaller delays compared to the multi frame, for both line and star configuration.

V. Conclusion And Future Work

Our modifications to the LWX add-on facilitated the evaluation of the IEEE 802.16 two frame structure types suggested for networks employing non-transparent relay stations. 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 [4]. We are currently investigating the design of scheduling modules for ntRS, together with further modifications which allow for adaptive frame structures that react to varying network load distribution.

References

[1] "IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Broadband Wireless Access Systems," *IEEE Std 802.16-2009 (Revision of IEEE Std 802.16-2004)* , May 2009

[2] "IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Broadband Wireless Access Systems Amendment 1: Multiple Relay Specification," *IEEE Std 802.16j-2009 (Amendment to IEEE Std 802.16-2009)*, June 2009

[3] http://www.3gpp.org/ftp/Specs/html-info/36806.htm, March 25, 2010.

[4] Modified LWX add-on. Available at http://research.cs.queensu.ca/~pandeli/downloads.htm, May 3, 2010.

[5] ns2 Simulator. Available at http://www.isi.edu/nsnam/ns/, April 15, 2010.

[6] Yuan-Cheng Lai; Yen-Hung Chen, "Designing and Implementing an IEEE 802.16 Network Simulator for Performance Evaluation of Bandwidth Allocation Algorithms," *HPCC '09* , pp.432-437, June 2009

[7] Light WiMAX Simulator, http://sites.google.com/site/lwxns2/, April 28, 2010.

[8] Christian Hoymann, Analysis and performance evaluation of the OFDM-based metropolitan area network IEEE 802.16, Computer Networks, Volume 49, Issue 3, Selected Papers from the European Wireless 2004 Conference, pp.341-363, October 19, 2005, ISSN 1389-1286, DOI: 10.1016/j.comnet.2005.05.008.

[9] Can, B.; Portalski, M.; Lebreton, H.S.D.; Frattasi, S.; Suraweera, H.A., "Implementation Issues for OFDM-Based Multihop Cellular Networks," Communications Magazine, IEEE , vol.45, no.9, pp.74-81, September 2007

[10] Zhifeng Tao; Anfei Li; Koon Hoo Teo; Jinyun Zhang, "Frame Structure Design for IEEE 802.16j Mobile Multihop Relay (MMR) Networks," Global Telecommunications Conference, 2007. GLOBECOM '07. IEEE pp.4301-4306, 26-30 November 2007

[11] S. Zheng, A. Zhang, D. Comstock and J. Lee¿ "A flexible multihop frame structure for the IEEE 802.16j". Submitted to the IEEE 802.16 Broadband Wireless Access Group, Project P802.16j. November, 2006

[12] Seung-Yeon Kim; Se-Jin Kim; Seung-wan Ryu; Hyoung-Woo Lee; Choong-ho Cho, "Performance analysis of single-frame mode and multi-frame mode in IEEE 802.16j MMR system," *PIMRC 2008*, pp.1-5, September 15, 2008

[13] Genc, V.; Murphy, S.; Murphy, J.; , "Performance analysis of transparent relays in 802.16j MMR networks," *WiOPT 2008*, pp.273-281, 1-3 April 2008

[14] National Institute of Standards and Technology, http://www.nist.gov/index.html, June 10, 2009.

[15] G. Senarth *et al.*, "Multi-hop Relay System Evaluation Methodology (Channel Model and Performance Metric)," IEEE 802.16j-06/013r3, February 2007.

[16] "WiMAX System Evaluation Methodology", Version 2.0, WiMAX Forum, January 1, 2007.

[17] ITU, http://www.itu.int/en/pages/default.aspx, April 28, 2010.

[18] L.X. Cai, X. Ling, X. Shen, J.W. Mark, and H. Long. Capacity Analysis of Enhanced MAC in IEEE 802.11n. *First International Conference on Communications andNetworking in China*, pp. 1-5, 2006.

[19] M. Schwartz. *Broadband integrated networks*. Prentice-Hall, Inc. Upper Saddle River, NJ, USA, 1996.

[20] P.Wang, H. Jiang, and W. Zhuang, "Capacity improvement and analysis for voice/datatra capacity over WLAN", IEEE Transactions on Wireless Communications, vol. 6, no. 4, pp. 1530-1541, April 2007

[21] T. Szigeti and C. Hattingh, "End-To-End QoS Network Design: Quality of Service in LANs, WANs, and VPNs", Cisco Press, 2004

[22] Lin Cai; Xuemin Shen; Mark, J.W.; Yang Xiao, "Voice capacity analysis of WLAN with unbalanced traffic," *QSHINE 2005*, pp.8-9, August 24, 2005.