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Coverage and Throughput Improvement in Multihop Relaying in Wimax Network

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Abstract:

IEEE 802.16j is an amendment to the IEEE 802.16 broadband wireless access standard to enable the operation of multi-hop relay stations (RS). It aims to enhance the coverage, per user throughput and system capacity of IEEE 802.16e. Compared with base station (BS), RS does not need a wire-line backhaul and has much lower hardware complexity. Using RSs can significantly reduce the deployment cost of the system.

This thesis introduces an approach towards the integration of relaying or multi-hop schemes in IEEE 802.16j networks. In a multi-hop relay network, the users send their data to the base station via a relay station or with direct communication to the base station. These relay stations can either be the nomadic, fixed (as in this thesis) at specific location or users' mobile station (mobile relay station). The main objective of this thesis is to compare the difference in two different network architectures, PMP mode and RS-transparent mode in terms of network capacity and performance by simulating in different software. The results show that under certain conditions the capacity and throughput of the system has been increased in RS-transparent mode over PMP mode with the introduction of the relay station in to base station zone.

Keywords : IEEE 802.16j ,IEEE 802.16 ,Multi-hop relay station, IEEE 802.16e, Base Station, WiMAX, PMP-mode, RS-mode, mobile relay station, Capacity, Coverage and Throughput.

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Contents:

Abstract.....	3
Acknowledgements	4
Acronyms.....	8
List of Figures	10
List of Tables	12

Chapter 1: Introduction

1.1 Motivation.....	13
1.2 Goal of thesis.....	14
1.3 Previous work	14
1.4 Structure of the thesis	14

Chapter 2: Technical Overview of IEEE802.16: Evolution

2.1 Evolution of IEEE 803.16 Standard Series for BW.....	15
2.1.1 IEEE 802.16-2001.....	16
2.1.2 IEEE 8020.16a-2003.....	17
2.1.3 IEEE 8020.16a-2003.....	17
2.1.4 IEEE 802.162004.....	17
2.1.5 IEEE 802.16e2005.....	17
2.1.6 IEEE 802.16j	17
2.1.7 IEEE 802.16m	17

Chapter 3: An Overview of IEEE 802.16j and Architecture

3.1 IEEE 802.16j PHY Layer	20
3.1.1 Frequency Band.....	20
3.1.2 An OFDMA Technique.....	21
3.1.2.1 Sub-channel in OFDMA	21
3.1.2.2 OFDMA Signal Processing by FFT.....	22
3.1.2.3 OFDMA Symbol Description	23
3.1.2.4 OFDMA Frequency Domain Description.....	23
3.2 Adaptive Modulation and Coding.....	24
3.3 IEEE 802.16j Frame Structure.....	25
3.3.1 IEEE 802.16j PMP Mode.....	25
3.3.1.1 PMP Mode frame Structure.....	26
3.3.2 IEEE 802.16j RS-Transparent Mode Frame Structure.....	27
3.4 IEEE 802.16j Medium Access Control Layer(MAC).....	28
3.4.1 Network Entry in PMP Mode	28
3.4.2 MAC Detail of PMP Mode.....	29
3.4.3 MAC PDU Frame Structure.....	30
3.4.4 Bandwidth Allocation	30
3.4.5 Quality of Service and Scheduling	31
3.4.6 QoS Framework.....	31
3.5 MAC in RS-Transparent Mode.....	32
3.5.1 Forwarding Scheme	32
3.5.2 Routing and Path Management	33
3.5.3 Initial Ranging and Network Entry.....	33

3.6 The Link capacity in Multihop Networks	35
3.6.1 Link Capacity in PMP Mode	35
3.6.2 Link Capacity in RS-Transparent Mode	37

Chapter 4: Network Simulators

4.1 NS-2 Network Simulator.....	40
4.1.1 NS-2 Directory Structure.....	40
4.1.2 NS-2 Network Components.....	41
4.2 NCTUns Network Simulator.....	41
4.3 OPNET Network Simulator.....	42
4.4 QualNet/GloMoSim Network Simulator.....	43
4.5 OMNet++ Network Simulator.....	43

Chapter 5: Performance Analysis and Simulation Set Up

5.1 Design and Implement of IEEE 802.16j Transparent Mode Networks over NCTUns-6.0	45
5.1.1 NCTUns-6.0 Installation and Setup	45
5.1.2 NCTUns-6.0 Module-based Platform	45
5.1.3 Supported IEEE 802.16j Transparent Mode Network Topologies in NCTUns-6.0	45
5.1.4 Protocol Stacks of IEEE 802.16j Transparent Mode Networks in NCTUns-6.0	46
5.1.4.1 IEEE 802.16j TMR-BS Node	46
5.1.4.2 IEEE 802.16j T-RS Node.....	47
5.1.4.3 IEEE 802.16j T-MS Node	47
5.1.5 Protocol Stacks of IEEE 802.16j PMP-Mode Networks in NCTUns-6.0	48
5.1.6 Construction IEEE 802.16j Network in NCTUns-6.0	48
5.1.6.1 PMP-Mode Network Construction.....	48
5.1.6.2 RS-Mode.....	55
5.1.6.2.1 MS path selection in RS-Mode.....	57
5.2 Network Scenarios	57
5.2.1 PMP-mode with different distances between BS and T-MS	57
5.2.2 PMP-mode with different number of SSs.....	58
5.2.2 RS-mode with Different Distances Between BS →SS and RS→SS.....	61
5.3 Design and Implementation of IEEE 802.16j Networks over ns2.....	61
5.3.1 WiMAX (IEEE 802.16j) Patch	61
5.3.2 Light WiMAX Simulator (LWX) Patch for IEEE 802.16 and IEEE 802.16j Networks	62
5.3.3 LWX Working flow.....	63
5.3.4 LWX Patch Setting.....	64
5.4 IEEE 802.16j Network Topologies Building with NS-2.....	66
5.5 Design and Implementation of IEEE 802.16J network with directional Antennas in NCTUns6.0	70
5.6 Simulation Result	71
5.7 Simulation Result Analysis and Comparisons.....	72
5.7.1 Graph 1 for PMP-Mode and RS-Mode in Different Distances.....	72
5.7.2 PMP-Mode with Increasing the number of SSs=20.....	74
5.7.3 RS-Mode with increasing number of RS while network size SSs=20.....	74
5.5.4 SNR of Different Directional Antennas Implementations.....	75

Chapter 6: An Example of Comparison and Cost Analysis Between Multihop Relay and Single Hop WIMAX

6.1 Cost Analysis Methodology.....	78
6.2 Cost Components of Network.....	78

Chapter 7: Conclusion and Future Work

7.1 Conclusion	85
7.2 Future Works.....	85
Appendix.....	86
Bibliography.....	92

Acronyms:

3GPP	3G Partnership Project
AAS	Adaptive Antenna System
ADSL	Asymmetric Digital Subscriber Line
AMC	Adaptive Modulation and Coding
ARQ	Automatic Repeat Request
ATM	Asynchronous Transfer Mode
BE	Best Effort
BICM	Bit Interleaved Coded Modulation
BPSK	Binary Phase Shift Keying
BS	Base Station
BWA	Broadband Wireless Access
CAC	Call Admission Control
CBR	Constant Bit Rate
CID	Connection Identifier
CPE	Customer Premises Equipment
CPS	Common Part Sub layer
CR	Contention Ratio
CRC	Cyclic Redundancy Check
CS	Convergence Sub layer
DCD	Downlink Channel Descriptor
DL	Downlink
DSM	Diversity Subcarrier Method
FCH	Frame Control Header
FD	Frequency Diversity
FDD	Frequency Division Duplex
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FRF	Frequency Reuse Factor
FTP	File Transfer Protocol
GMH	Generic MAC Header
GSM	Global System for Mobile communications
HTTP	Hyper Text Transfer Protocol
ID	Identify Data
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISI	Inter-Symbol Interference
LOS	Line Of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MAP	Media Access Protocol
MIMO	Multiple Input Multiple Output
MS	Mobile Station
NLOS	Non Line-of-Sight
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
PDU	Packet Data Unit
PHY	Physical Layer Protocol
PL	Path Loss
PMP	Point-to-Point

PTP	Point-to-Point
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RS	relay Station
SDU	Service Data Unit
SIMO	Single Input Multiple Output
SNIR	Signal to Noise Interference Ratio
SNR	Signal to Noise Ratio
SS	Subscriber Station
TCP	Transport Connection Protocol
TDD	Time Division Duplex
TDM	Time Division Multiplexing
UCD	Uplink Channel Descriptor
UDP	User Datagram Protocol
UL	Uplink
UTRAN	Universal Terrestrial Radio Access Network
VBR	Variable Bit Rate
VoIP	Voice over IP
WiMAX	Worldwide Interoperability for Microwave Access

List of Figures:

Figure 1 IEEE Standardization and WiMAX Group

Figure 2 The IEEE 802.16j Network Topology with several paths and RSs available for relaying between BS and SSs.

Figure 3 Example allocations of resources to users in an OFDMA system

Figure 4 Sub-channelization example (a) ASM method (b) DSM method

Figure 5 Each (modulation) symbol is modulated with a possibility different modulation .

Figure 6 Time domain description

Figure 7 Frequency domain Description

Figure 8 Adaptive Modulation in WiMAX

Figure 9 IEEE 802.16j OFDMA Frame

Figure 10 IEEE 802.16j PMP Network Topology

Figure 11 PMP-Mode Frame Structure

Figure 12 IEEE 802.16j Transparent Relay Mode network Topology

Figure 13 RS-Transparent Relay Mode Frame Structure

Figure 14 Initial ranging in PMP-Mode

Figure 15 Network Entry in PMP-Mode

Figure 16 WiMAX MAC Layer

Figure 17 WiMAX MAC PDU

Figure 18 Centralized Control Diagram in RS-Transparent Mode

Figure 19 MS initial ranging in relay transparent mode

Figure 20 RS initial ranging

Figure 21 RS network entry

Figure 22 Link in PMP-Mode

Figure 23 Link in RS-Transparent Mode

Figure 24 BS→RS link

Figure 25 RS→SS link

Figure 26 NS2 Network Components

Figure 27 NCTUns Network Components

Figure 28 NCTUns Simulation Engine

Figure 29 NCTUns Protocol Module

Figure 30 TMR-BS Protocol

Figure 31 TMR-RS Protocol

Figure 32 T-MS Protocol

Figure 33 The Software Architecture and Workflow of LWX Patch

Figure 34 PMP-Mode for ns2

Figure 35 RS-Transparent Mode for ns2 simulation

Figure 36 Graph of PMP and RS-Transparent Modes in Different Distances

Figure 37 Graph of PMP-Mode with Increasing the number of SSs

Figure 38 Graph of RS-Mode with increasing number of RS

Figure 39 Graph of PMP-Mode with different Antenna Types

Figure 40 Graph of RS-Mode with Different Antenna Types

Figure 41 Cost Analysis Methodology Diagram

Figure 42 An Example Network Scenario for cost analysis and Design

Figure 43 Solution 1 for cost analysis and Design

Figure 44 Solution 2 for cost analysis and Design

Figure 45 Solution 3 for cost analysis and Design

Figure 46 Cost comparison for three solution

List of Tables:

Table 1	IEEE 802.16 Standard Evolutions
Table 2	Air interface and PHY compliance
Table 3	Adaptive Modulation and its Profile
Table 4	WiMAX QoS Parameters
Table 5	WiMAX Application support policy
Table 6	Physical layer and propagation models available in network simulators
Table 7	System parameters for PMP and RS-Transparent Modes
Table 8	PMP-Mode System Model
Table 9	Rs-Transparent Mode System Model
Table 10	Parameters used in LWX simulation
Table 11	Example CAPEX cost elements for scenarios
Table 12	Example OPEX cost elements for scenarios

CHAPTER 1

INTRODUCTION

This chapter provides a brief introduction to the motivation for this thesis and its objective. Finally, it outlines the structure of the document.

1.1 Motivation

Broadband networks have been developed during the past two decades but they mostly focus on wired technology such as digital subscriber line (DSL). With the demand of customers for higher bandwidth to connect and mobility broadband Wireless Access (BWA) has emerged as a promising solution for last mile access technology to provide high speed internet access in the residential as well as small and medium sized enterprise sectors. Practical difficulties in broadband wired deployment have prevented them from reaching many potential broadband internet customers (as many commercial areas are often not covered by cable network) but with BWA these difficulties can be overcome. Owing to its wireless nature, it can be faster to deploy, easier to scale and more flexible, thereby giving it the potential to serve customers not served or not satisfied by their wired broadband alternatives.

IEEE 802.16 standard for BWA and its associated industry consortium, Worldwide Interoperability for Microwave Access (WiMAX) forum promises to offer a high data rate over large areas to a large number of users where broadband is unavailable. This is the first industry wide standard that can be used for fixed wireless access with substantially higher bandwidth than most cellular networks [23]. The first version of the IEEE 802.16 standard operates in the 10–66GHz frequency band and requires line of sight (LOS) towers. Later the standard extended its operation through different PHY specification to 2–11 GHz frequency band enabling non line of sight (NLOS) connections, which require techniques that efficiently mitigate the impairment of fading and multipath [26]. Taking the advantage of OFDMA technique the PHY is able to provide robust broadband service in hostile wireless channel.

802.16j is developing a standard to support relay mode operation for 802.16 systems. A number of different uses are envisaged, transparent mode and non-transparent mode for example. The two main uses can be broadly divided into increased coverage and capacity enhancement. The former can be further subdivided into two slightly different uses; extending the coverage range of a BS using multi-hop techniques and addressing coverage hold problems (e.g., shadows of buildings). Increased system capacity can be achieved through use of multiple links with greater efficiency, as opposed to single-hop links over poor-quality channels; also, multi-hop communications can support spatial reuse, which can result in increased overall system capacity.

1.2-Goal of Thesis

The objective of this thesis is to simulate and compare the IEEE 802.16j network architectures by using ns2 and NCTUns-6 in order to have a better understanding of the standard ,system capacity enhancement and the system performance. This involves studying through simulation various network scenarios, transmitting modes (PMP and RS-Transparent Mode), and capacity enhancement by inserting RS-station to systems and system performance comparisons under referent network topologies.

1.3-Previous work

Capacity enhancement techniques in multi-hop networks have been studied in [25][9] and also in [19]. A description of the IEEE 802.16, .16e and .16j is given in the standard documents [23][19] and [24]. Introduction of multi-hop cellular networks [61], Capacity and coverage enhancement [31] the placement of relay stations [8][16] and its communication models in 802.16j has been described in [31].

1.4 Structure of the thesis

The first chapter is an introduction to the thesis work. The rest of the chapters are organized as follows:

Chapter 2 Technical Overview of IEEE 802.16: Evolutions.

Chapter 3 An overview of the IEEE 802.16J Network Architecture.

Chapter 4 Network Simulators.

Chapter 5 Performance Analysis and Simulation.

Chapter 6 An example of comparison and cost analysis between multi-hop relay and Single-hop relay WiMAX.

Chapter 7 Conclusion and Future Work.

CHAPTER 2

TECHNICAL OVERVIEW OF IEEE 802.16: EVOLUTION

This chapter discusses the evolution of the IEEE 802.16 standard for BWA to form the basis of further discussion. The protocol layers of the standard have been overviewed to get the idea of interaction between different protocol stack.

2.1 Evolution of IEEE 802.16 Standard Series for BWA

At the end of the 90's, many telecommunications equipment manufacturers were beginning to develop and offer products for BWA. But the Industry was suffering from an interoperable standard. Recognizing, the need for a standard, The National Wireless Electronics Systems Test bed (NWEST) of the U.S National Institute of Standards and Technology (NIST) called a meeting to discuss the topic in August 1998 [33]. The meeting ended with a decision to organize within IEEE 802. This led to the formation of the 802.16 Working Group. Since then, the Working Group members have been working hard to develop standards for fixed and mobile BWA. Nowadays, IEEE Working Group 802.16 on Broadband Wireless Access (BWA) standard is responsible for the development of 802.16 and the included Wireless Man air interface, along with associated standards and amendments as shown in figure 1 below.

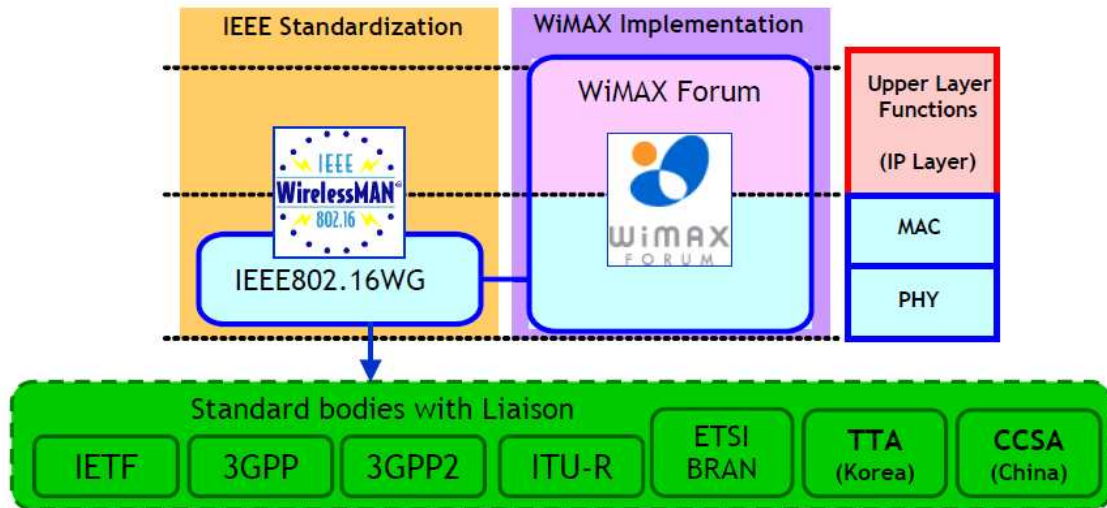


Fig 1: IEEE Standardization and WiMAX Group [IEEE]

The IEEE 802.16 standard contains the specification of the Physical (PHY) and Medium Access Control (MAC) layer for BWA. The first version of the standard IEEE802.16-2001[33] was approved in December 2001 and has gone through many amendments to accommodate new features and functionalities. The most popular version of the standard was IEEE 802.16-2004 [67], approved on September 2004, and consolidates all the previous versions of the standards. This standard specifies the air interface for fixed BWA systems supporting multimedia services in licensee and licensed exempt spectrum [45] but it did not achieve success in the commercial market.

Later, The Working Group approved the amendment IEEE 802.16e-2005 [68] to replace IEEE802.16-2004 in February 2006. To understand the development of the standard to its current stage, the evolution of the standard is presented here.

Table 1: IEEE 802.16 Standard Evolutions

Standard	Description	Status
802.16-2001	Fixed broadband Wireless Access(10-63Ghz)	Superseded
802.16-2002	System Profiles for 10-63Ghz	Superseded
802.16a-2003	Physical layer and MAC definition for 2-11 GHz	Superseded
802.16-2004	Air interface for fixed Broadband Wireless Access system (rollup 802.16-2001,802.16a)	Superseded
802.16e-2005	Mobile Broadband Wireless Access System	Superseded
802.16j-2009	Multihop Relay	Current
802.16m	Advance Air Interface with data rate of 100Mbit/s mobile and 1Gbit/s fixed	In progress

Source: IEEE work group IEEE 802 LAN/MAN Standards Committee)

2.1.1 IEEE 802.16-2001:

This first issue of the standard specifies a set of MAC and PHY layer standards intended to provide fixed broadband wireless access in a point-to-point (PTP) or point-to-multipoint (PMP) topology. The PHY layer uses single carrier modulation in the 10 – 66 GHz frequency range. Transmission times, durations and modulations are assigned by a Base Station (BS) and shared with all nodes in the network in the form of broadcast Uplink and Downlink maps. Subscribers need only hear the base station that they are connected to and do not need to listen to any other nodes of the network. Subscriber Stations (SSs) have the ability to negotiate for bandwidth allocation on a burst to burst basis, providing scheduling flexibility. The standard employs QPSK, 16QAM and 64QAM as a modulation scheme. These can be changed from frame to frame and from SS to SS, depending on the robustness of the connection. The standard supports both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) as duplexing techniques.

An important feature of 802.16-2001 is its ability to provide differential Quality of Service (QoS) in the MAC Layer. A Service Flow ID does QoS checking. Service flows are characterized by their QoS parameters, which can then be used to specify

parameters such as maximum latency and tolerated jitter [10]. Service flows can be originated either from BS or SS. 802.16-2001 which work only in (Near) Line of Sight (LOS) conditions with outdoor Customer Premises Equipment (CPE).

2.1.2 IEEE 802.16-2002

In December 2002, the IEEE Standards Board approved amendment IEEE 802.16c . In this amendment, detailed system profiles for 10-66 GHz were added and some errors and inconsistencies in the first version of the standard were corrected.

2.1.3 IEEE 802.16a-2003

This version of the standard amends IEEE 802.16-2001 by enhancing the medium access control layer to support multiple physical layer specifications and provide additional physical layer specifications. This was ratified by the IEEE 802.16 working group in January 2003[33]. This amendment added physical layer support for 2-11 GHz. Both licensed and license exempt bands are included. Non Line of Sight (NLOS) operation becomes possible due to inclusion of below 11 GHz range, extending the geographical reach of the network. Due to NLOS operation multipath propagation becomes an issue. To deal with multipath propagation and interference mitigation features such as advanced power management technique and adaptive antenna arrays were included in the specification [45]. The option of employing Orthogonal Frequency Division Multiplexing (OFDM) was included as an alternative to single carrier modulation.

Security was improved in this version; many privacy layer features became mandatory while in 802.16-2001 they were optional. IEEE 802.16a also adds optional support for mesh topology in addition to PMP.

2.1.4 IEEE 802.16-2004

IEEE 802.16-2001, 802.16a-2003 and 802.16c-2002 were consolidated and a new standard was created which is known as 802.16-2004. In the beginning, it was published as a revision of the standard under the name 802.16-REVd, but the changes was so significant that the standard was reissued under the name 802.16-2004 in September 2004. In this version, the whole family of the standard is ratified and approved.

2.1.5 IEEE 802.16e-2005

This amendment was included in the current applicable version of standard IEEE 802.16-2004 in December 2005. This includes the PHY and MAC layer enhancement to enable combined fixed and mobile operation in licensed band.

2.1.6 IEEE 802.16j

The 802.16j task group commenced its activities in March 2006. The fifth draft [24] of the 802.16j specification was released in May 2008, and the standard is expected to be ratified in late 2008 or early 2009. It is important to note that this is the first step in a longer process: after ratification it is necessary to define appropriate profiles for interoperability testing within the WiMAX Forum, and then there will be laboratory trials. Rollout of 802.16j systems will not happen for another two to three years.

2.1.7 IEEE 802.16m

The IEEE working group has begun working on a new version of the 802.16 standard, dubbed 802.16m, which "could push data transfer speeds up to 1Gbps while maintaining backwards compatibility with existing WiMAX radios. Potentially more interesting than speed boosts is the group's outright assurance that this protocol will

meet the ITU's requirements for 4G, suggesting that it should be the token choice for further 4G development. Nevertheless, the increased bandwidth is supposedly needed due to convergence between VoIP and various forms of multimedia (IPTV, streaming video, digital downloads, etc.), and however true that may be, some skeptics are still understandably doubtful of the whole "backwards compatibility" aspect. Still, the IEEE working group hopes to have this completed by "the end of 2009 to 2010.

CHAPTER 3

AN OVERVIEW OF IEEE 802.16j ARCHITECTURE

There are a number of different types of multi-hop wireless networks, notably ad-hoc networks, sensor networks, and wireless mesh networks. Each of these network types have different characteristics such as mobility rates, power constraints, scale, form factor, and so on which result in different system designs (e.g., routing protocols, medium access control mechanisms). Another type of multi-hop wireless network IEEE 802.16j that is the subject of some attention is based on relay architecture.

IEEE 802.16 is a series of Wireless Broadband standards authored by the IEEE. The current version is IEEE 802.16-2009 amended by IEEE 802.16j-2009.

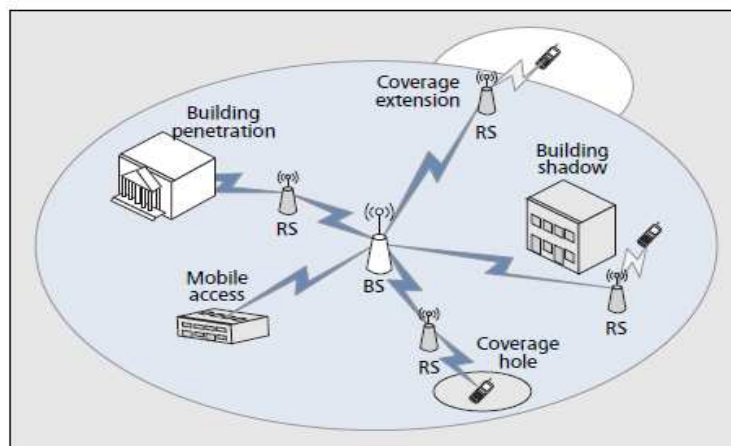


Figure 2: The IEEE 802.16j Network Topology with several paths and RSs available for relaying between BS and SSs [46].

The purpose of IEEE 802.16j is not to standardize a new cellular network that includes multi-hop capability, but to expand previous single-hop 802.16 standards to include multi-hop capability, to expedite the standards process while still maximizing the likelihood of IEEE 802.16j that designer-limited their scope to the point-to-multipoint (PMP) OFDMA PHY mode of 802.16e-2005. Because companies are already well into the development stages of WiMAX-compatible mobile devices, IEEE 802.16j must be compatible with IEEE 802.16e SSs. This severely limits the scope and capabilities of the physical layer, but increases the likelihood that a WiMAX profile based on IEEE 802.16j will be implemented. As we will see, however, the BS must be modified to allow relaying.

Relay-based systems typically comprise low-cost small form factor relays, which are associated with specific base stations (BSs). The relays can be used to extend the coverage area of a BS and/or increase the capacity of a wireless access system [49]. Typically, it is envisaged that they could be used in the early stages of network rollout to provide coverage to a large area at lower cost than a BS only solution. They can also be used to provide increased capacity in more developed networks as well as coverage holes such as areas in the shadows of buildings.

The IEEE 802.16j standard places no limit on the number of hops from BS to SS and the path between the BS and the MS must contain only RSs. However, the station can directly communicate with an MS as the *access station* for that MS. The access station may be a BS or an RS. The station that an RS transmits to in the uplink is its super ordinate station, a relay station that an RS or BS transmits to in the downlink is its subordinate RS.

3.1 IEEE 802.16j Physical Layer

In wireless networks, there are two kinds of frequency terms, Licensed and Unlicensed frequencies. 3G networks have licensed fixed frequency bands. These bands are 18885-2025 GHz and 2110-2200 GHz. Wi-Fi WLANs also have a fixed frequency band: 2410-2480 GHz. This latter band is the ISM (Industrial, Scientific and Medical): a free band also used by systems other than Wi-Fi.

For WiMAX, the IEEE 802.16 standard considers that the system works on frequencies smaller than 11 GHz (for the Physical layers considered for WiMAX). Precise operating frequencies are indicated in WiMAX Forum system profiles which include both licensed bands and license-exempt bands. It is often mentioned that unlicensed frequencies of WiMAX will be used for limited coverage, campuses, and initiatives of private individuals. In other words, operator revenue should come only from licensed frequencies where the service can be more easily guaranteed.

3.1.1 Frequency bands

The multiple versions of PHY layer displayed in Table 2 are listed below:

- **Wireless MAN-SC:** corresponds to the single-carrier version, designed to support LOS operation in the 10 to 66 GHz frequency range. The goal is to provide flexibility in LOS operation scenarios, in terms of planning, cost of service and capacity.
- **Wireless MAN-SCa:** this is a single carrier solution for NLOS operation in frequencies below 11 GHz. The frame structure is designed to be robust against multipath fading. Moreover, it supports channel estimation and equalization, adaptive modulation, multiple error correcting coding schemes, adaptive antennas, transmission diversity, power control and automatic repeat request (ARQ).
- **Wireless MAN-OFDM:** designed to support NLOS operating frequencies below 11 GHz, based on orthogonal frequency division multiplexing (OFDM), which consists of a multicarrier modulation scheme. This version extends the functionalities of the Wireless MAN-SCa version to support Mesh topology and sub-channelization on the uplink.
- **Wireless MAN-OFDMA:** this version supports NLOS also operated in frequencies below 11 GHz based on orthogonal frequency division multiple accesses (OFDMA), to extend the OFDM technique to allow multiple users to access a shared channel.
- **Wireless HUMAN:** to support license-exempt frequency bands based on high-speed unlicensed metropolitan area network (HUMAN), it can operate at frequencies between 5 and 6 GHz.

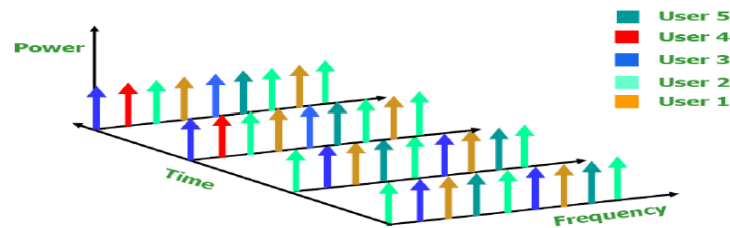
Table 2: Air interface and PHY compliance

Designation	Applicability	Options	Duplexing alternative
Wireless MAN-SCTM	10–66 GHz	-	TDD FDD
Wireless MAN-SCaTM	Below 11 GHz licensed bands	AAS ARQ STC Mobile	TDD FDD
Wireless MAN-OFDM TM	Below 11 GHz licensed bands	AAS ARQ Mesh STC Mobile	TDD FDD
Wireless MAN-OFDMA	Below 11 GHz licensed bands	AAS ARQ HARQ STC mobile Multihop relay	TDD FDD
Wireless HUMAN TM	Below 11 GHz license-exempt bands	AAS ARQ Mesh STC	TDD

Source[29]

3.1.2 An OFDMA Technique

The 802.16j has adopted frequency division multiple access (OFDMA) as the primary channel access mechanism for non-line-of-sight (NLOS) communications in the frequency bands below 11 GHz, wherein separate sets of orthogonal tones are allocated to multiple users so that these users can engage in communication in parallel. We will show how resources can be allocated by using the different sub-carriers and OFDM symbols.

**Figure 3:** Example of resource allocation to users in an OFDMA system

3.1.2.1 Sub-channels in OFDMA

In practice, the allocation in the frequency domain is not addressed at the level of sub-carriers. Sub-channels (the smallest granular units in the allocation) are typically created by grouping sub-carriers in an OFDM symbol in various ways. The formation of these sub-channels from sub-carriers is an important concept in OFDMA systems. The formation can be classified into 2 types: one is the mapping of a contiguous group of sub-carriers into a sub-channel called the adjacent sub-carrier method (ASM) and the other is a diversity/permutation based grouping called the diversity sub-carrier method (DSM) wherein the sub-channel typically contains non-contiguous sub-carriers. An example of the allocation using the two methods is illustrated in Figures 4a and 4b, respectively.

In the ASM method, a sub-channel typically contains a group of contiguous sub-carriers and the channel frequency responses on the sub-carriers in a sub-channel are expected to be strongly correlated. This is based on the fact that sub-carriers falling within the coherence bandwidth have similar responses. The ASM method is suitable for the use of AMC as a strongly correlated block of sub-carriers can be considered together as a unit to enable the simple channel feedback necessary to implement bit-loading. Note that if the sub-carrier responses were uncorrelated, then the channel responses on each sub-carrier would have to feed back to the transmitter resulting in a higher overhead. Thus, the channel feedback, which consumes valuable bandwidth and power, can be simplified when AMC is used along with ASM. Moreover, simplifications to the adaptive loading algorithm used in AMC can be achieved when the adjacent sub-carriers have similar responses [13].

An FSF channel has inherent frequency diversity (FD) due to variations in the channel response in the frequency domain, i.e. the sub-carriers from different positions in the frequency domain are likely to experience different channel fading conditions. This FD has been leveraged in Wi-Fi systems by using suitable error control coding and interleaving. In the DSM, sub-carriers from seemingly random positions in the frequency domain are grouped into a sub-channel. Thus, a sub-channel has potential frequency diversity which can be leveraged when the data to be sent on this sub-channel is suitably coded and interleaved. Such bit interleaved coded modulation (BICM) methods have been used in Wi-Fi and are also being used in WiMAX systems. Frequency hopping methods can also be combined with the DSM method so that the sub-carriers in a particular sub-channel are not constant in time.

The time granularity for ASM and DSM is in multiples of OFDM symbols; for example, the same sub-channel in two OFDM symbols could be the basic allocation unit. Users are typically allotted one or more sub-channels for one or more OFDM symbols depending on the allocation and the requirements. Note that sub-channelization allows us to handle resources as groups of sub-carriers and OFDM symbols. We shall see some practical examples and understand the advantages by considering the WiMAX system.

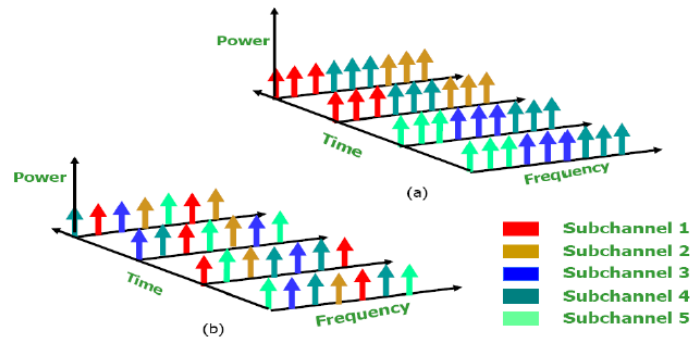


Figure 4: Sub-channelization example (a) ASM method (b) DSM method [31]

3.1.2.2 OFDMA Signal Processing by FFT

FFT is the Fast Fourier Transform operator. This is a matrix computation that allows the discrete Fourier transform to be computed (while respecting certain conditions). The FFT works for any number of points. The operation is simpler when applied for a number N that is a power of 2 (e.g. $N = 256$). IFFT is the Inverse Fast Fourier Transform operator and performs the reverse operation. OFDM theory [21] shows that the IFFT of magnitude N , applied on N symbols, realizes an OFDM signal, where each symbol is transmitted on one of the N orthogonal frequencies. The symbols are the data symbols of the type BPSK, QPSK, QAM-16 and QAM-64. Figure 5 shows an illustration of the simplified principle of the generation of an OFDM signal. In fact,

generation of this signal includes more details that are not shown here for the sake of simplicity.

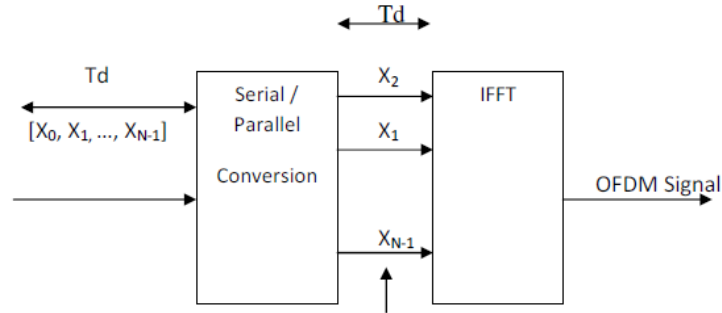


Figure 5: Each (modulation) symbol is modulated with a possibly different modulation [21].

3.1.2.3 OFDMA Symbol Description, Symbol Parameters and Transmitted Signal

Inverse-Fourier-transforming creates the OFDMA waveform; this time duration is referred to as the useful symbol time T_b . A copy of the last T_g of the useful symbol period, termed CP, is used to collect multipath, while maintaining the orthogonality of the tones. Figure 6 illustrates this structure.

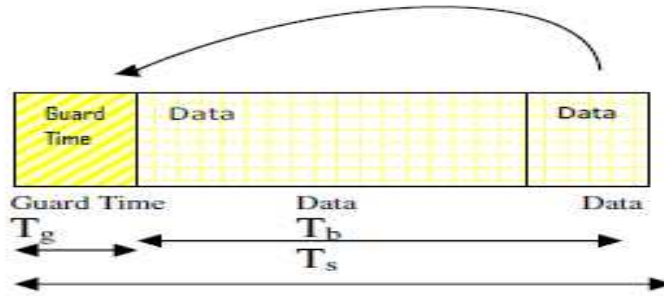


Figure 6: Time domain description [21]

Transmitter energy increases with the length of the guard time while the receiver energy remains the same (the cyclic extension is discarded), so there is a $10 \log(1 - T_g / (T_b + T_g)) / \log(10)$ dB loss in E_b / N_0 . Using a cyclic extension, the samples required for performing the FFT at the receiver can be taken anywhere over the length of the extended symbol. This provides multipath immunity as well as a tolerance for symbol time synchronization errors.

3.1.2.4 Frequency domain description

The frequency domain description includes the basic structure of an OFDMA symbol. An OFDMA symbol is made up of sub-carriers, the number of which determines the FFT size used. There are several sub-carrier types:

- Data sub-carriers: for data transmission
- Pilot sub-carriers: for various estimation purposes
- Null carrier: no transmission at all, for guard bands and DC carrier

The purpose of the guard bands is to enable the signal to decay naturally and create the FFT “brick wall” shaping. In OFDMA mode, active sub-carriers are divided

into subsets of sub-carriers; each subset is termed a sub-channel. In the downlink, a sub-channel may be intended for different (groups of) receivers; in the uplink, a transmitter may be assigned one or more sub-channels, as several transmitters may transmit simultaneously. The sub-carriers forming one sub-channel may be adjacent, but they do need not to be. The concept is shown in Figure 7. The symbol is divided into logical sub-channels to support scalability, multiple accesses, and advanced antenna array processing capabilities.

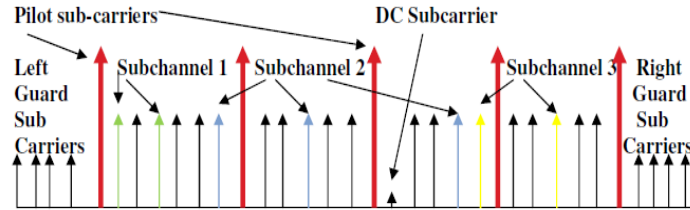


Figure 7: Frequency domain description [21]

3.2 Adaptive Modulation and Coding

Adaptive modulation and coding is adopted in WiMAX systems in order to take advantage of signal level fluctuation due to the different BS-SS distances in the channel quality. For example, when the channel is in good condition with high level modulation, a coding scheme is used to achieve higher data rate (64 QAM, for example). On the other hand, when the channel is poor, low level modulation and coding is adopted to transmit lower data rate (QPSK) in order to improve the robust data transmission and avoid excessive dropped packets.

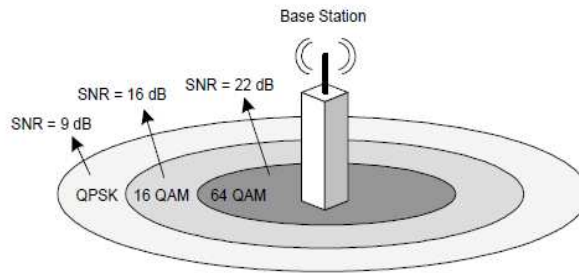


Figure 8: Adaptive Modulation in WiMAX [9]

As shown in the table below, the relation between the signal-to-noise ratio (SNR) for each modulation scheme allows the throughput to increase as the SNR increases following Shannon's formula $C = \log(1+SNR)$. The achieved throughput normalized by bandwidth is defined in the equation below.

$$T = (1 - BLER) r \log(M) \text{ bps/Hz}$$

Where BLER is the block error rate, r is the coding rate, and M is the number of points in the constellation. The WiMAX system protects the feedback channel with error correction to deal with imperfect channel estimation or error in feedback channel. In the OFDMA system, each user is allocated a block of sub-carriers having a different set of

SNR. Then, the transmitter can determine the optimum modulation and coding strategy and transmit power based on the channel SNR.

Table 3 Adaptive Modulation and its Profile

Modulation	Coding Rate	Receiver SNR (dB)	Surface (%)
BPSK	1/2	6.4	39.4
QPSK	1/2	9.4	20.75
	3/4	11.2	28.0
16-QAM	1/2	16.4	4.07
	3/4	18.2	5.14
64-QAM	2/3	22.7	0.9
	3/4	24.4	1.74

3.3 IEEE 802.16j Frame Structure

The physical layer in WiMAX IEEE 802.16j is based on OFDMA access technology which transmits information using a large number of closely-spaced orthogonal sub-carriers. In the flexible OFDMA frame structure offered by IEEE 802.16j, both Frequency (FDD) and Time Division Duplexing (TDD) are supported but TDD will most likely be the preferred choice due to its flexible support of asymmetric downlink and uplink traffic and other benefits such as less complex transceivers. The figure below shows the main part of one OFDMA frame. More comprehensive detail will be explained in a later section.

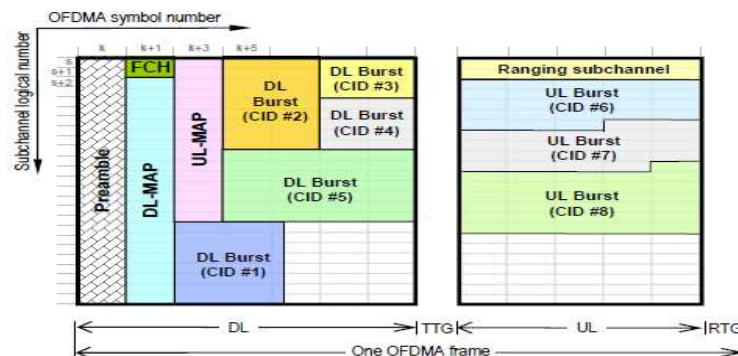


Figure 9 IEEE 802.16j OFDMA Frame [9]

3.3.1 IEEE 802.16j PMP Mode

Point-to-multipoint (PMP) was released by the IEEE working group mainly to support WiMAX IEEE 802.16e in fixed wireless networks. As indicated in the figure,

the concept is that one BS can communicate with various SSs at the same time by allocating different frame time slots.

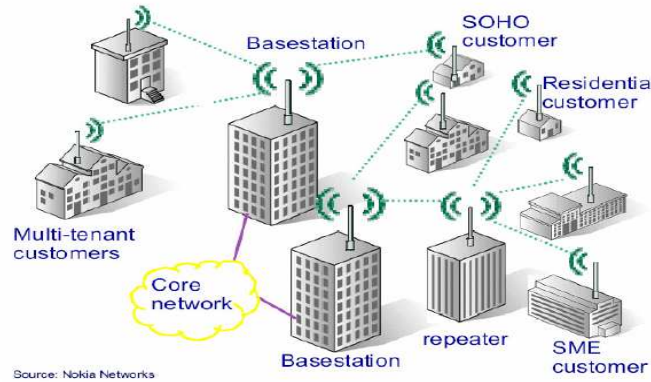


Figure 10 IEEE 802.16j PMP Network Topology

3.3.1.1 Frame Structure

The principal aims of the IEEE Task Group in developing IEEE 802.16j are to make enhancements for a mobile multi-hop operation without any modifications of equipment in the available WiMAX network (IEEE 802.16e). Thus, the frame structure, the MAC management procedures, will be PMP compatible. In Point to Multi-Point (PMP) mode, nodes are organized in a cellular-like structure consisting of a base station (BS) and multiple subscriber stations (SSs). Communication only takes place between the subscriber stations and the BS, where the term downlink is used to refer to data transmission from the BS to the SSs, and uplink to data transmission in the opposite direction. All SSs should be within the transmission range of the BS. If SSs are within the *Line of Sight* (LOS) of the BS, i.e. there are no obstructions that would affect the transmitted signal, frequencies ranging from 10-66 GHz can be used. For *Non-Line of Sight* (NLOS) nodes, the standard allows the use of frequencies in the range 2-11 GHz.

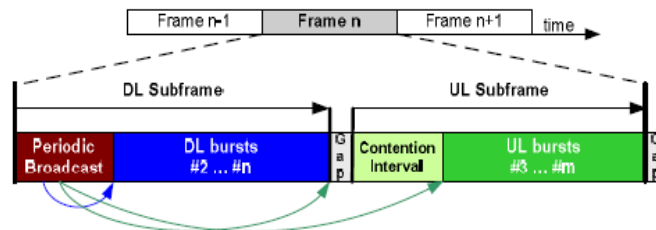


Figure 11 PMP-Mode Frame Structure

Figure 11 presents the frame structure of an OFDMA PHY layer operating in TDD mode. Each frame consists of a DL sub-frame and UL sub-frame. Sub-frames are separated by gaps. The DL frame starts with the periodic broadcast of control information. The arrow in Figure 11 indicates the references of DL and UL-MAP to corresponding DL bursts. MAC PDUs are transmitted during the DL bursts. The UL sub-frame consists of intervals for contention-based access and or multiple UL bursts.

3.3.2 IEEE 802.16j RS-Transparent mode Frame Structure

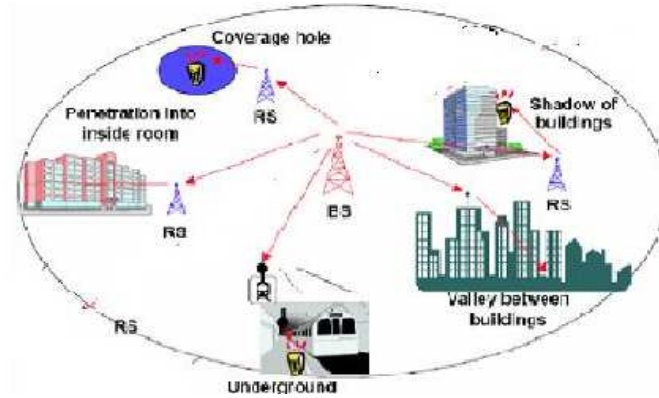


Figure 12 IEEE 802.16j Transparent Relay Mode network Topology [8]

In this mode the RSs do not forward framing information, and hence do not increase the coverage area of the wireless access system; consequently, the main usage case for transparent mode relays is to facilitate capacity increases within the BS coverage area. This type of relay is of lower complexity, and only operates in a centralized scheduling mode and for topology up to two hops.

The centrally controlled relaying approach is an alternative concept where the BS has full control over all its RSs' operations, thereby fully controlling the so-called Relay Enhanced Cell (REC). The BS directly controls all SSs and all RSs associated to the BS. The complexity of the RS can be reduced since it just forwards packets hop by hop. It does not perform any other MAC management functions to allow for multi-hop operation.

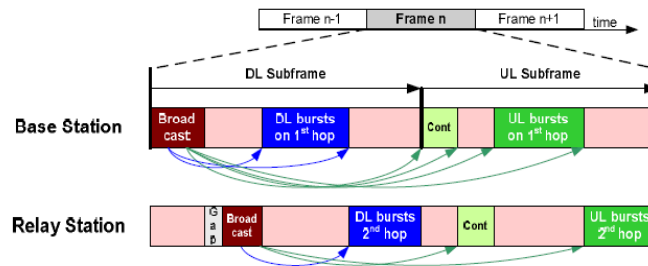


Figure 13 RS-Transparent Relay Mode Frame Structure

Figure 13 shows the centralized multi-hop frame. The BS periodically transmits broadcast control information. The DL preamble indicates the frame start. The subsequent management messages, i.e. FCH and MAPs, specify the entire MAC frame including the bursts scheduled on the second and on any subsequent hop. In order to calculate an appropriate schedule, the BS needs to know which connections are active on the entire REC, which QoS requirements they have, and which connections request UL bandwidth. Once it has received the broadcast information, the RS filters it and forwards only the relevant subset of information to its sub cell. Figure 13 shows that the MAPs forwarded only specify the bursts scheduled for data transmission on the second hop served by a given RS. Before the RS starts transmitting the management messages, it sends the periodic DL preamble.

As in the sub-frame concept, the RS's frame start time has to be strictly periodic. In order to guarantee periodic behavior and to allow the RS to process the BS's broadcast information, a gap is introduced between the BS's and the RS's broadcast

phase. DL bursts for data transmission follow the broadcast phases. The BS may schedule bursts for any hop. The UL sub-frame succeeds the DL sub-frame. Again, phases for data transmission on any hop may be scheduled alternately. This ordering of transmission phases assures that all SSs associated to either the BS (single-hop) or the RS (2-hop) experience a regular, standard compliant MAC frame.

3.4 IEEE 802.16j Medium Access Control Layer (MAC)

The main reason for developing an IEEE 802.16j standard is to increase the system performances (as indicated in previous chapters) and also to keep the change from the previous standard (IEEE 802.16e) transparent. For these reasons, in PMP-Mode, MAC operation will be similar and compatible with IEEE 802.16e.

3.4.1 Network Entry in PMP-Mode

A: Initial Ranging Initial ranging allows an SS to connect to the network to setup correct transmission parameters, time offset, frequency and transmission power, for example. In OFDMA PHY, the initial ranging uses CDMA codes. When the initial ranging transmission opportunity occurs, the SS sends the RNG-REQ message (in CDMA code) as if it were collocated with the BS, as the propagation delay is taken into account in the initial ranging transmission opportunity.

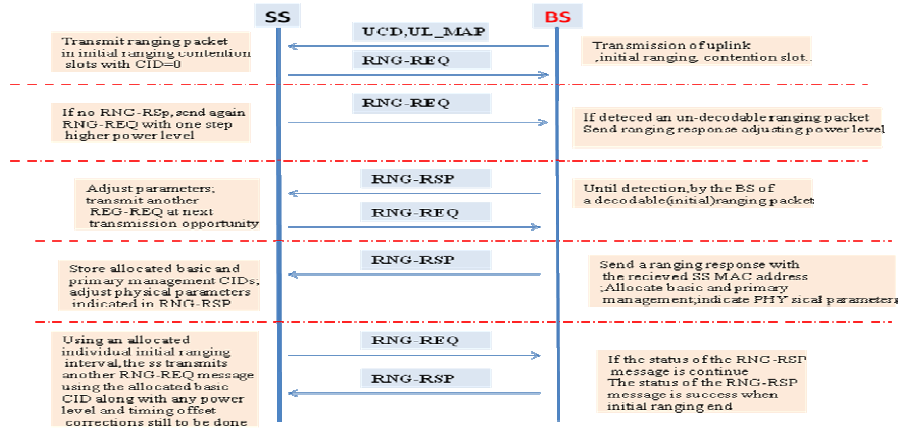


Figure 14: Initial ranging in PMP-Mode

Once the SS scans the UL-MAP message periodically broadcast by the BS to find initial ranging, it will send an RNG-REQ message. If successful, then the BS returns an RNG-RSP message using the initial ranging CID. During this stage, RNG-REQ and RNG-RSP exchange information about all parameters needed for connection. Once there is a successful request-response message, the SS normally joins data traffic in the uplink.

B: Network Entry ; When a new SS wants to enter and register on the network, the network entering procedure needs to be followed:

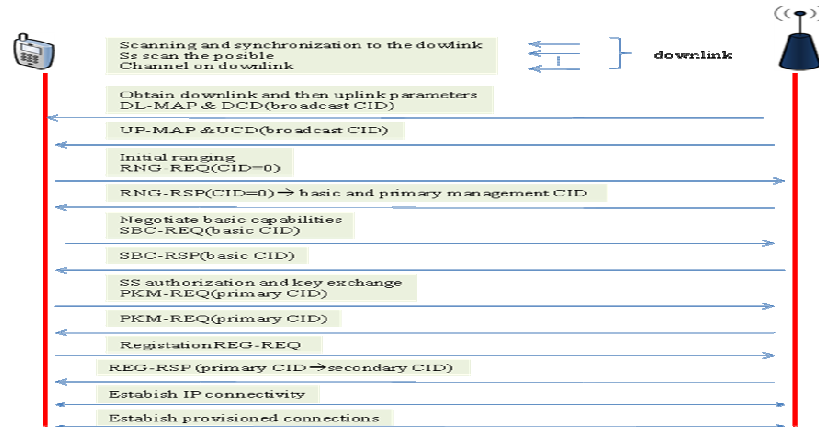


Figure 15: Network Entry in PMP-Mode

- 1) Scan for downlink channel and establish synchronization with BS by searching for DL-Map, DCD, UCD and UL-Map messages.
- 2) Synchronize an SS MAC with a DL-Map message.
- 3) Perform initial ranging (as explained in previous section)
- 4) Negotiate basic capacities, using SBC-REQ messaging which may be necessary for link connection.
- 5) Exchange secure keys by sending a PKM-RSP message.
- 6) Registration to agree on basic MAC, primary and secondary management connections.
- 7) Establish IP connectivity from DHCP server.
- 8) After all the above parameters have been successfully exchanged, registration is successful and the BS sends DSA-REQ message to SS to set up connection for pre-provisioned service flows belonging to the SS.

3.4.2 MAC Detail of PMP-Mode

The WiMAX MAC layer of 802.16e consists of various sub layers as shown in the Figure below:

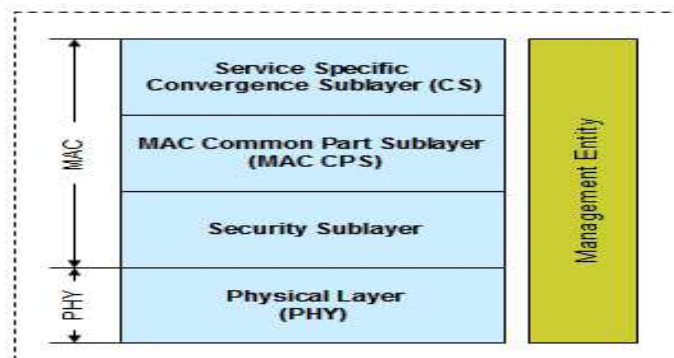


Figure 16: WiMAX MAC Layer [67]

The IEEE MAC Layer reference model follows general IEEE 802 guidelines and specifies only the MAC and the PHY layer. Higher layer protocols as well as the management plane are outside the scope of the standard. Figure 16 shows that the MAC comprises three sub layers. The service Specific Convergence Sub layer (CS) interfaces higher layers. It classifies external Service Specific Data Units (SDUs) and associates them to the proper MAC connection. The CS may also process SDUs, e.g. to reduce

overhead by performing Payload Header Suppression (PHS). Two CS specifications are provided for interfacing ATM as well as packet based protocols such as IP, Point-to-Point Protocol (PPP), or IEEE 802.3 (Ethernet). The MAC Common Part Sub layer (CPS) carries key functions such as system and channel access, connection management, and the application of QoS. Below the MAC CPS resides the security sub layer that provides authentication, secure key exchange, and encryption. The IEEE 802.16 PHY specification defines multiple PHY layers, each appropriate to a particular frequency range and application. Thus, it is free to develop, implement and deploy optimized systems with respect to available frequency bands, cell planning, equipment cost, and targeted services. Another reason for having several PHY specifications was the lack of support for a single specification during standardization.

3.4.3 MAC PDU Frame Structure:

Each MAC PDU (protocol data unit) consists of a *header* followed by a *payload* and a *cyclic redundancy check, CRC*, as can be seen in Figure 17. There are two types of MAC PDUs:

1. The *generic* MAC PDU is used for carrying data and MAC-layer signaling messages. A generic MAC PDU starts with a generic header consisting of 6 bytes and followed by payload and CRC.
2. The *bandwidth request* PDU consists only of a bandwidth request header, with no payload or CRC. The Generic Header may contain other sub headers for different purposes.

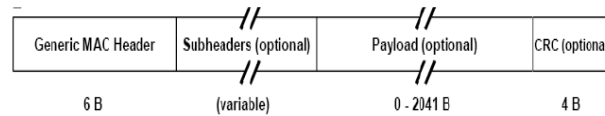


Figure 17 WiMAX MAC PDU

Once a MAC PDU is constructed, it is handed over to the *scheduler*, which schedules the MAC PDU over the PHY resources available. The scheduler determines the optimum PHY resource allocation for all the MAC PDUs, on a frame-by-frame basis. Based on the traffic class, the scheduler can assign the whole frame or a single time slot to a terminal. It is good to note that WiMAX is designed to support all different traffic modules out of 4 different existing ones, namely Background (messages), Interactive (web browsing), Streaming (video) and Conversational (VoIP) in increasing delay-sensitivity order, as explained in Table 4.

3.4.4 Bandwidth Allocation

In the downlink, all decisions related to the allocation of bandwidth to various SSs are made by the BS without the involvement of the SS based on *CID, Connection Identifier*. These CIDs are 16-bit addresses used to distinguish between multiple UL channels (connections) associated with the same DL channel. The Mobile Stations or Subscriber Stations, SS, check CIDs in the PDUs received and retain only those PDUs addressed to them. As mentioned before, the PHY resources allocated for PDU transmission in each connection is indicated in DL-MAP messages.

In the uplink, the MS requests resources by using a bandwidth request sub header on a MAC PDU. The BS allocates dedicated resources (intended for a single SS) or shared resources (intended for a group of SSs) for users periodically and this can be used to request bandwidth. In WiMAX this process is called *Polling*.

3.4.5 Quality of Service (QoS) and Scheduling

Each user can achieve the desired bandwidth based on the Quality of Service defined for it. The system should grant a reliable connection based on the QoS parameters agreed within a connection. A key concept in QoS is *Service Flow*. Each service flow or category is associated with a unique set of QoS parameters, such as latency, jitter throughput, and packet error rate, that the system strives to offer. Table 4 illustrates service flows supported in Mobile WiMAX and gives example applications for each. Before providing any particular type of data service, the BS's MAC establishes a unidirectional connection with its peer MAC layer in the user terminal to discuss the agreed service flow and assign the QoS parameters over the air interface.

The efficiency of resource allocation (time and frequency) in both DL and UL is controlled by the *scheduler* located in each BS. The scheduler controls the traffic trend by monitoring CQICH feedback to provide the best resource allocation to support the QoS parameters for each connection. The scheduling process is done on a frame by frame basis in response to traffic and channel conditions.

Table 4 WiMAX QoS Parameters

QoS Category	Applications	QoS Specifications
UGS Unsolicited Grant Service	VoIP	<ul style="list-style-type: none"> • Maximum Sustained Rate • Maximum Latency Tolerance • Jitter Tolerance
rtPS Real-Time Polling Service	Streaming Audio or Video	<ul style="list-style-type: none"> • Minimum Reserved Rate • Maximum Sustained Rate • Maximum Latency Tolerance • Traffic Priority
ErtPS Extended Real-Time Polling Service	Voice with Activity Detection (VoIP)	<ul style="list-style-type: none"> • Minimum Reserved Rate • Maximum Sustained Rate • Maximum Latency Tolerance • Jitter Tolerance • Traffic Priority
nrtPS Non-Real-Time Polling Service	File Transfer Protocol (FTP)	<ul style="list-style-type: none"> • Minimum Reserved Rate • Maximum Sustained Rate • Traffic Priority
BE Best-Effort Service	Data Transfer, Web Browsing, etc.	<ul style="list-style-type: none"> • Maximum Sustained Rate • Traffic Priority

Source [19]

3.4.6 QoS Framework

With the help of efficient MAC level scheduling, the IEEE 802.16e is able to offer connection oriented QoS in addition to traditional BE scheduling services. The standard defines five different scheduling services that are summarized in Table 4. The Unsolicited Grant Service (UGS) is meant for service flows that generate fixed size data packets on a fixed periodic interval such as Voice over Internet Protocol (VoIP). UGS gives unsolicited data grants, does not even use the bandwidth request mechanism and is therefore ideal for services that are very delay and jitter sensitive. Real-Time Polling Service (rtPS) scheduling service is intended for service flows that generate variable size data packets on a fixed periodic interval such as streaming video and audio. An SS with a service flow using rtPS will be polled on a periodic basis so it can specify the amount of data the service flow has to send.

The Extended Real-Time Polling Service (ertPS) scheduling service combines the strengths of the UGS and rtPS scheduling classes. As in UGS it gives data grants in an unsolicited way but the Data Grant sizes can be dynamically changed (e.g. to zero) in a manner similar to the rtPS class. It is mainly aimed at VoIP with Voice Activity Detection (VoIP with VAD). The Non-Real-Time Polling Service (nrtPS) scheduling service is targeted at service flows that are critical but not time sensitive such as File Transfer Protocol (FTP) transfers. In other words nrtPS guarantees a minimum

throughput but no guarantees in terms of delay or jitter are made. The Best Effort (BE) scheduling service is designed for service flows that carry best effort traffic such as every day web browsing. The different parameters of these QoS services will play an important role when evaluating the efficiency of load balancing and when providing system wide QoS in the case of a rescue handover. What is especially important in our case is the minimum guaranteed throughput.

Table 5 WiMAX Application Support Policy

#	Application	Traffic Category	Mandatory/Optional
1	FTP	Best-effort	M
2	Web Browsing	Interactive	M
3	VoIP	Real-time	M
4	Video Streaming	Streaming	M
5	Live Video	Interactive Real-time	O

Source[43]

3.5 MAC in RS-Transparent Mode

As has already been defined above, in our paper we will consider the case of IEEE 802.16j, RS-transparent mode only since RS-nontransparent mode can be found in the reference paper. In RS-Transparent Mode, IEEE 802.16j uses a centralized control scheme for the MAC layer. There are three main functions in RS-Transparent mode operation of MAC layer that differ from MAC layer in PMP-Mode: the forwarding scheme, routing and path management mechanisms, and initial ranging and network entry mechanisms. The following sections will describe each function in more detail.

3.5.1 Forwarding Scheme

It has been indicated that RS-Transparent mode uses only a centralized control MAC scheme. With centrally controlled RSs, the BS manages the SSs' control and transport connections. RSs just forward packets to the BS and SSs, respectively. Figure 5.5 shows the schematic connection management at the RS. The RS itself has both control and transport connections to the BS. Furthermore, each connection on the second hop corresponds to a connection on the first hop.

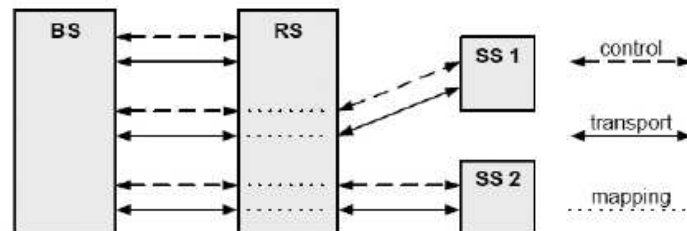


Figure 18 Centralized Control Diagram in RS-Transparent Mode

Every time an SS establishes a management connection to the RS, the RS establishes a corresponding management connection to the BS. Each setup of an SS's transport connection results in a new transport connection on the RS. Mapping is done through mapping tables. After the synchronization of a new SS to the RS, it starts the ranging process by sending the ranging request during the RS's contention interval. The

RS forwards this message to the BS through its own control connection. The BS processes the request and responds to the SSs via the RS. The BS subsequently handles the entire network entry. Currently, the standard compliant message exchange does not comprise all the information necessary for the network entry. Using 1-to-1 mapping, two management CIDs have to be assigned instead of one. One CID is required to identify the connection on the first hop and the other for the second hop. Since the BS schedules both hops, it needs to be aware which CID corresponds to which hop. The set-up of transport connections follows the same principle. The RS just forwards the request and the BS assigns the transport CIDs. All other signaling messages, such as UL bandwidth requests and measurement reports have to be transmitted from the SSs to the BS by means of the RS. Thus, the BS gathers all necessary information to schedule DL and UL bursts for the RSs and for the SSs. It periodically broadcasts the FCH and the MAPs and all nodes behave accordingly.

3.5.2 Routing and Path Management

As multihop is implemented in an IEEE 802.16j network, the way to select the path between the BS and SS is slightly different from a traditional PMP-Mode scheme. Routing and path selection is standard for routing decisions based on metrics parameters like radio resource availability, link quality and traffic load at relay station but does not specify how to establish paths. The particular schemes of path selection are left for vendors to implement for their networks but the IEEE group has scoped in general concepts for implementation in two approaches.

A: The embedded path management approach: In this approach a hierarchical CID allocation scheme is used in the system. The BS allocates CIDs to its subordinate stations so that the CIDs allocated to all subordinate RSs of any given station are a subset of the allocated CIDs for that station. In this way there is no specific routing table in each RS, and a reduced need for signaling to update path information. This is a very simple approach to path management.

B: The explicit path management approach: This mode uses an end-to-end signaling mechanism to distribute the routing table along the path. The BS sends the necessary information to the RSs involved in a path when a path is created, removed, or updated. Each path is identified by a path ID to which the CIDs are bound. This leads to a smaller routing table at the RSs and a reduction in the overhead required to update these tables. Optionally, the BS may include the QoS requirement associated with each CID to allow the RSs to make an independent decision regarding how to schedule the packet in distributed scheduling mode

3.5.3 Initial Ranging and Network Entry

Unlike PMP-Mode in which the SS can be directly connected to the BS, RS-Mode is where a relay station is put between the BS and SS. The network entry procedure can be divided into two stages, for MS and for RS.

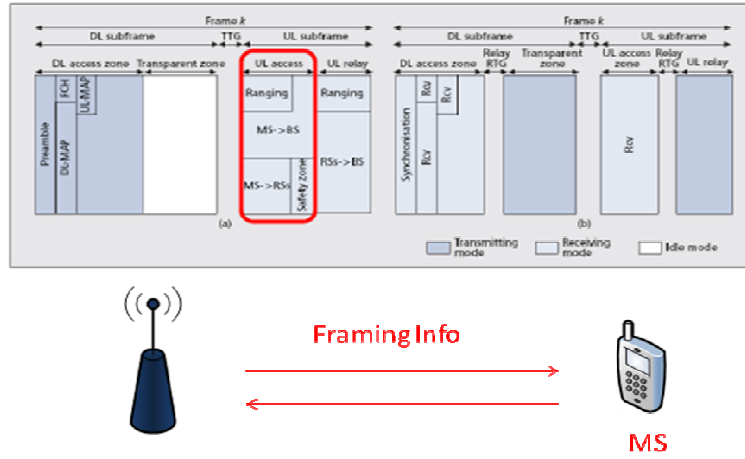


Figure 19 MS initial ranging in relay transparent mode

MS initial ranging in relay transparent mode: In the network entry procedure in transparent RS systems, the MS scans for downlink channel and established synchronization with the MR-BS, then obtains transmit parameters from UCD message.

The initial ranging process starts by sending initial-ranging CDMA codes on the UL allocation dedicated for that purpose. The RS monitors the ranging channel assigned by the MR-BS. The code may be received by the MR-BS and some RSs near the MS. RSs receiving the code with sufficient signal quality transmit an RNG-REQ to the MR-BS with the RS basic CID. The RNG-REQ message contains ranging status, code attributes and adjustment information such as frequency, timing and transmission power.

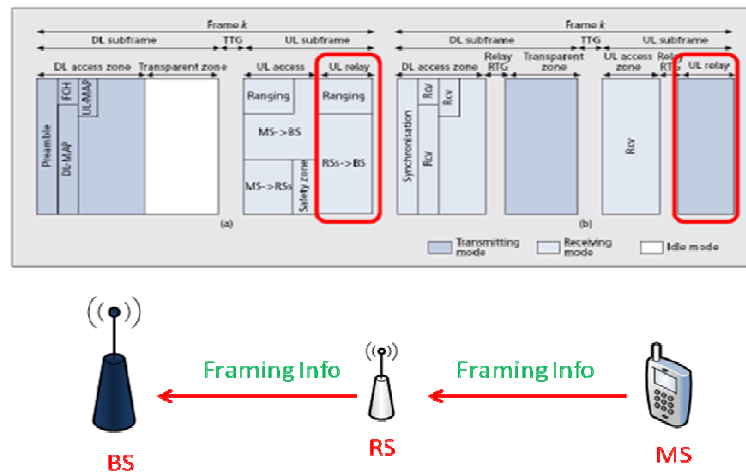


Figure 20 RS initial ranging

RS initial ranging: When the MR-BS receives a ranging code, it waits for RNG-REQ with the same ranging code from its subordinate RSs for T48 timer. Once T48 timer expires, the MR-BS compares measured signal information at each station to decide the most appropriate path to communicate with the code originating MS, according to channel measurement information. Algorithms to select a path are out of the scope of this document.

When the ranging status at the selected path is continuous, the MR-BS transmits an RNG-RSP to the MS directly with initial ranging CID. The RNG-RSP contains adjustment information measured at the RS on the selected path. If the ranging code has been successfully received at the access RS on the selected path and the MR-BS decides to apply uplink and downlink relaying to the MS, the RS receives and relays an RNG-

REQ message transmitted on a burst specified with CDMA_Allocation-IE in UL-MAP after decoding the UL-MAP or optionally R-MAP in the same frame.

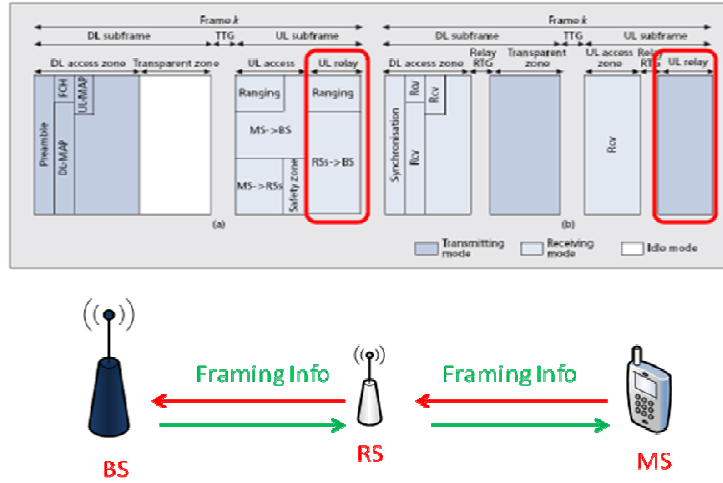


Figure 21 RS network entry

RS network entry: After the initial ranging, authentication, and registration processes, the BS may request the RS to determine the signal strength of each of its neighboring RSs and forward it to the BS. The BS can then determine the most suitable access station with which to associate the RS based on traffic load, signal strength, and so on. The final stage of network entry is then the configuration of the RS parameters, including its operation mode (e.g. transparent or non transparent) and scheduling mode.

When the RS receives an RNG-REQ containing MS MAC address with initial ranging CID, it forwards the message to the MR-BS with the RS basic CID, so that the MR-BS can identify the RS the MS connects to. Receiving the RNG-REQ, the MR-BS assigns basic and primary CIDs to the MS and sends the RNG-RSP, which just contains the MS's assigned CIDs to the MS directly with the initial ranging CID. After assigning the basic and primary CID to the MS, the MS and the MR-BS continue the network entry process as described in the MS initial ranging procedure.

The final stage of network entry is then the configuration of the RS parameters, including its operation mode and scheduling mode.

3.6 The Link Capacity in Multihop Networks

The basic theorem of capacity in wireless networks can be found in many academic papers and books [50],[6]. Those information sources are defined in term of traditional one-hop communication even between BS and MS or point-to point networks. The implementations of single link wireless networks are different based on the particular purposes of network providers. There are alternative formulas to calculate points of interest, channel model method, channel condition and so on.

In this thesis, we consider our network as a fixed wireless network and communication between BS→SS and BS→RS-SS scenarios.

3.6.1 Link Capacity in PMP-Mode

To calculate the area covered by each modulation scheme, we must determine the maximal distance R_i between Base Station (BS) and users using a corresponding modulation. This distance is determined using the maximal SNR a user should receive without data loss. Different values of received SNR for different modulation/coding schemes have been calculated according to modulation schemes in PHY layer section

and we shall now use these to calculate R_i . The path loss for the free space model is given by [13].

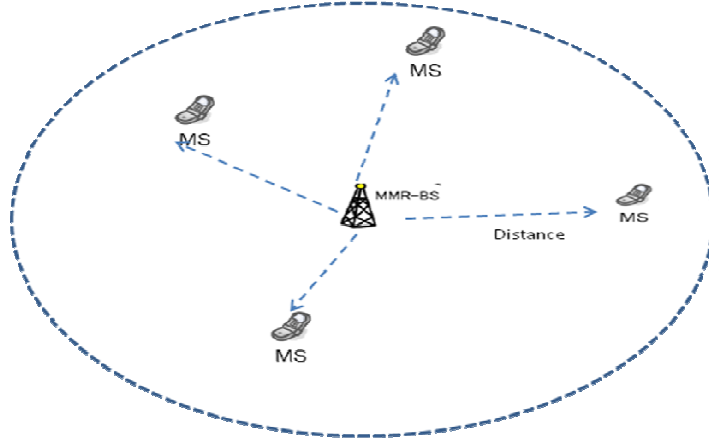


Figure 22. Link in PMP-Mode

$$PL_i[dB] = -10 \log \left[G_E G_R \left(\frac{\lambda}{4\pi R_i} \right)^2 \right]$$

$$= -10 \log G_E - 10 \log G_R + 20 \log \left(\frac{4\pi R_i}{\lambda} \right)$$

Where G_E is the emitter antenna gain, G_R is the receiver antenna gain, R_i is the distance between the emitter and the receiver and λ is the wavelength. This path loss is also equal to:

$$PL_i[dB] = P_E[dBm] - SNR[dB] - N[dBm]$$

Where P_E is the emitted power and N is the thermal noise (in decibel units), equal to:

$$N[dBm] = 10 \log(\tau T W)$$

T : $1.38 \cdot 10^{-23}$ watt/KHz is the Boltzmann constant,

T is the temperature in degrees Kelvin ($T = 290$) and W is the Transmission bandwidth in Hz.

Using the above equations, we can calculate the relationship between the distance and the SNR as follows:

$$R_i = \frac{\lambda * 10^{\frac{P_E(dBm) + 10 \log(G_E)(dB) + 10 \log(G_R)(dB) + 10 \log(bB) + 10 \log(Gb)(bB) - SNR(bB) - N(dBm)}{20}}}{4\pi}$$

Recall that Shannon capacity of an ideal, band-limited, AWGN channel is

$$C = W \log_2 \left(1 + \frac{S}{WN_0} \right)$$

Where S and W are transmitted power and channel bandwidth, respectively N_0 is the power spectral density of noise.

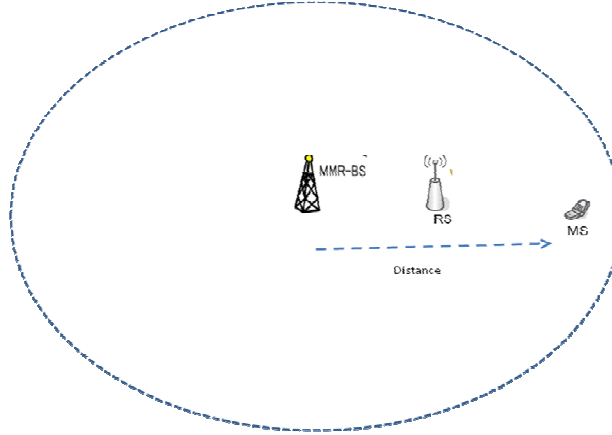


Figure 23: Link in RS-Transparent Mode

As we can see when MS is moving far away from BS, the WiMAX base station will use adaptive modulation to select the modulation scheme based on the channel condition or SNR, in other words depending on the transmitted power of the BS to MS. From the different modulation schemes, the link capacity at different distances between BS and MS are also different, i.e. the longer the R_i , the lower the link capacity. In the example above, we consider only one link but in PMP-mode of operation there are more links between BS and MSs. The analysis still has the same concept but each MS will be assigned link bandwidth in different values depending on its network entry challenge to get bandwidth request.

3.6.2 Link Capacity in RS-Transparent Mode

In an OFDMA based relay system, with a sufficiently large number of n sub-channels, the link capacity can be classified in two stages:

A: The capacity at the hop between source and relay for n -th sub-carrier is:

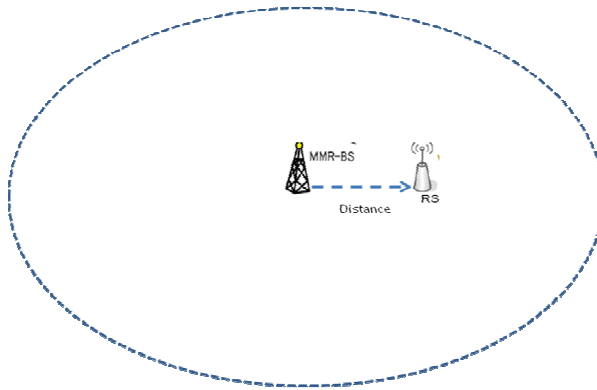


Figure 24: BS \rightarrow RS link

$$C_{1,n} = \frac{W}{N} \log_2 \left(1 + \frac{S_n}{WN_o / N} |a_{sb,n}|^2 \right)$$

Where $a_{sb,n}$ denotes the channel coefficient between source and the best relay for the n -th sub-carrier. Similarly, S_n is the power allocated to the n -th sub-carrier.

B: the capacity at the hop between relay and destination for the n -th sub-carrier is:

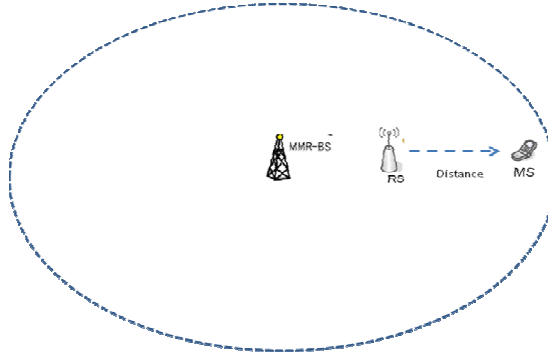


Figure 25: RS→SS link

$$C_{1,n} = \frac{W}{N} \log_2 \left(1 + \frac{S_n}{WN_o / N} |a_{bd,n}|^2 \right)$$

For regenerative relaying channels, the end-to-end capacity C_n is determined by the smallest single-hop capacity [9],

$$\begin{aligned} C_n &= \min(C_{1,n}, C_{2,n}) \\ &= \frac{W}{N} \log_2 \left[1 + \frac{S_n}{WN_o / N} \min \left\{ |a_{sb,n}|^2, |a_{bd,n}|^2 \right\} \right] \\ &= \frac{W}{N} \log_2 \left[\left(1 + \frac{S_n}{WN_o / N} \max(h_{1,n}) \right) \right] \end{aligned}$$

Finally, the total capacity of the channel is the sum of Ergodic capacity of all sub-carriers,

$$C = \frac{W}{N} \sum_{n=1}^N E \left[\log_2 \left(1 + \frac{S_n}{WN_o / N} \gamma_n \right) \right]$$

where $\lambda_n = \max(h_{1,n})$.

On the assumption that all sub-carriers are i.i.d (independently and identically distributed), the best power allocation scheme that maximizes the capacity is $S_1 \rightarrow S_n$

$=S/N$. This conclusion can be easily proved by using the Lagrange multiplier method. Therefore, C can be written as:

$$C = WE[\log 2(1 + SNR\gamma_n)]$$

where $SNR=S/NoW$

Finally we can prove that the capacity of MS in $RS \rightarrow MS$ link will be higher than $BS \rightarrow MS$ direct link because C directly depends on the SNR or S , transmitted signal of RS which is better than BS for MS because of the distance.

CHAPTER 4

NETWORK SIMULATORS

Network simulation is an important tool in developing, testing and evaluating network protocols. Simulation can be used without the target physical hardware, making it economical and practical for almost any scale of network topology and setup. It is possible to simulate a link of any bandwidth and delay, even if such a link is currently impossible in the real world. With simulation, it is possible to set each simulated node to use any desired software. This means that deploying software is not an issue. Results are also easier to obtain and analyze, because extracting information from important points in the simulated network is done by simply parsing the generated trace files. Simulation is only of use if the results are accurate, an inaccurate simulator is not useful at all. Most network simulators use abstractions of network protocols, rather than the real thing, making their results less convincing. OPNET uses a simplified finite state machine to model complex TCP protocol processing. NS-2 uses a model based on BSD TCP, it is implemented as a set of classes using inheritance and NCTUns uses a novel kernel-reentering simulation methodology.

4.1 NS-2 Network Simulator

The original development of ns-2 started as early as 1989 as REAL simulator. The first release of ns-2 was available in 1996. The main drawbacks of ns-2 turned out to be the lack of wireless transmission modeling and detailed channel models.

Network Simulator Version 2, also known as NS-2 [37]. NS-2 is an event driven packet level network simulator developed as part of the VINT project (Virtual Internet Testbed). This was a collaboration of many institutes including UC Berkeley, AT&T, XEROX PARC and ETH. Version 1 of NS was developed in 1995 and version 2 released in 1996. Version 2 included a scripting language called Object oriented Tcl (OTcl). It is an open source software package available for both Windows 32 and Linux platforms.

NS-2 has many and expanding uses including:

- To evaluate the performance of existing network protocols.
- To evaluate new network protocols before use.
- To run large scale experiments not possible in real experiments.
- To simulate a variety of IP networks

4.1.1 NS-2 directory structure

As shown in Figure 24, the C++ classes of ns-2 network components and protocols are implemented in the “ns-2.*” subdirectory and the TCL library (corresponding to configurations of these C++ instances) in the “tcl” subdirectory.

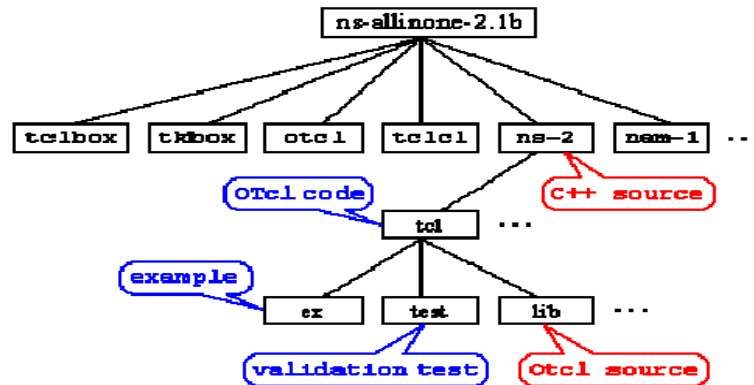


Figure 26: NS2 Network Components [17]

4.1.2 Network Components

Network components are Node, Link, Queue, etc. Some of them are simple components, that is, they correspond to a single C++ object; The others are compound components, that is, they combine multiple simple components, e.g. a Link component is composed of a Delay component (emulating propagation delay) and a Queue component. In general, all network components are created, plugged and configured by some TCL scripts (`./ns-allinone-2.*/tcl/`) when ns-2 is initialized. More detailed information about NS2 can be found at www.isi.edu/nsnam/ns/.

4.2 NCTUns Network Simulator

NCTUns is a software tool that integrates user-level processes, operating system kernel, and the user-level simulation engine into a cooperative network simulation system. This manual aims to provide knowledge about NCTUns to help researchers develop their own protocol modules on top of NCTUns. The formats of various simulation-related files are explained in this document. These simulation-related files are used to specify and describe a complete simulation case. Normally, these files are automatically generated by the GUI program of NCTUns without the user having to create them manually. However, it may sometimes be necessary (or useful) for a developer to create or modify these files manually. The NCTUns network simulator and emulator (NCTUns) are high-fidelity and extensible network simulators capable of simulating various devices and protocols used in both wired and wireless networks. Its core technology is based on the kernel-reentering simulation methodology invented by Prof. S.Y. Wang at Harvard University in 1999 when Wang was pursuing his Ph.D. degree. Due to this novel methodology, NCTUns provides many unique advantages that cannot be easily achieved by traditional network simulators such as OPNET Modeler and ns-2. NCTUns was first released to the networking community on November 1, 2002, according to the download user database, 15,049 people from 133 countries have registered at the web site and downloaded it, and these numbers are still growing.

Initially, NCTUns was developed for the FreeBSD operating system. As the Linux operating system has become popular, NCTUns now only supports the Linux operating system. Specifically, the version of Linux distribution that NCTUns 6.0 currently supports is Red Hat's Fedora 11 with kernel version 2.6.28.9. Although officially NCTUns only supports Fedora distribution, it is possible to port it to other Linux distributions such as Debian or Ubuntu. This is because all Linux distributions use the same Linux kernel but users have to configure and set their system differently to Fedora system configurations and settings. More detail can be found at <http://NSL.csie.nctu.edu.tw/nctuns.html>

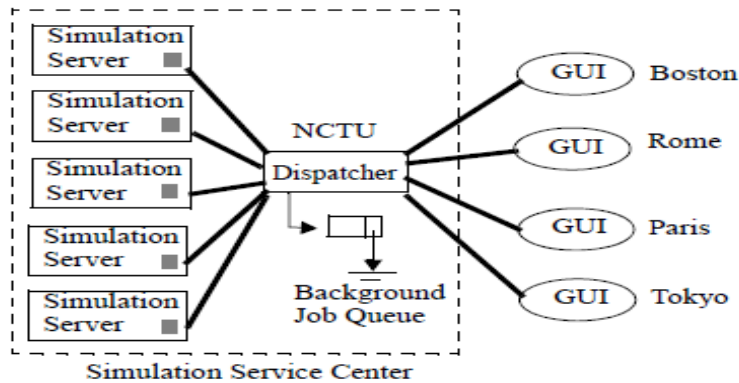


Figure 27 NCTUns Network Components [53]

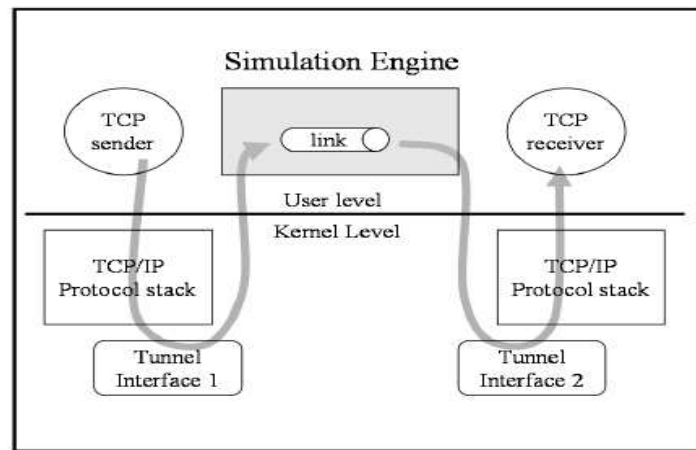


Figure 28: NCTUns Simulation Engine [53]

4.3 OPNET Network Simulator

There is another simulator, OPNET, which requires a license. Table 5 compares the wireless physical models used in the three simulators. Whereas ns-2 and OMNeT++ are freely available. OPNET is a commercial tool. While higher ISO/OSI layers (above layer 2) are the focus of these tools, the lower layers and especially the physical layer and the transmission characteristics are modeled very simply. The support for wireless communication systems in terms of detailed interference modeling, new channel models (e.g. for MIMO), node mobility, different receiver models (e.g. for different multiple access schemes) is very limited. The IEEE 802.11 model supports amendments a,b,e and g. There is also a community supported IEEE 802.11n model available. OPNET has founded a “WiMAX Model Development Consortium” which had several internal releases from September 2005 to July 2008. These releases are only available to the consortium members. OPNET states that this model supports IEEE 802.16-2004 and IEEE 802.16e-2005 [25]. Updated information on OPNET can be found at www.opnet.com.

4.4 QualNet/GloMoSim Network Simulator

GloMoSim [37] is another open-source network simulator based on parallel programming. Hopefully, it can emulate the real world more accurately. However, it may be hard to debug parallel programs. Although GloMoSim currently solely supports wireless networks, it provides more physical-layer models than ns-2.

QualNet is the next generation of the scalable GloMoSim (Global Mobile Information Systems Simulator) [GloMoSim] simulator. GloMoSim was designed to simulate large-scale wireless networks with thousands of mobile nodes, each of which may have different communication capabilities via multi-hop terrestrial, airborne, and satellite media [37]. QualNet has extended GloMoSim's capabilities to wired networks as well as mixed wired and wireless networks. Like its predecessor, QualNet uses the parallel simulation kernel provided by the PARSEC discrete-event simulation language. As a result, QualNet is among the few simulators for wireless and wired networks that have been implemented on sequential and parallel architectures. Examples of parallel platforms include an 8-processor DELL™ Power Edge 6100 running Windows NT®, a 24-processor Sun® Enterprise 5000 running Solaris™, a 28-processor SGI™ 2000 running IRIX®, and a dual-processor Intel Xeon® machine running Red Hat.

QualNet includes detailed models of commonly used protocols at each of the primary layers of the protocol stack. These range from commonly used applications like file transfer (ftp) and web browsing (http) to transport, routing, and MAC layer protocols. In each case, commonly used protocols in both wired and wireless networks have been modeled. For instance, routing protocols like OSPF and RIP that are common in wired networks have been modeled, as well as AODV and DSR for wireless networks. Protocols for GSM cellular and Wi-Fi networks have also been developed. The current list of protocol models is available in QualNet version 3.6.

At this time, QualNet and GloMoSim are not free software. Users need to pay for a license. <http://www.scalable-networks.com>

4.5 OMNeT++ Network Simulator

OMNeT++ has been developed by Andres Varga and is a discrete event driven simulation environment with a number of additional models (e.g., for TCP/IP, peer-to-peer networks and LAN protocols) being available. Modeling of the physical and link layer is mainly provided by the Mobility Framework of OMNeT++ [48]. Currently, OMNeT++ support for IEEE 802.11 and sensor networks. Support to model long-term or short-term fading, are available through the MiXiM framework . www.omnetpp.org/

There are other network simulators such as GTNet, SSFNet, JiST, and there may be more but at this time, we have not discovered any others and these are not continuing development.

Table 6 Physical layer and propagation models available in network simulators

Simulator	NCTUns	Ns-2	OPNET	GloMoSim
License fee	no	no	yes	yes
Noise (SNR) calculation	cumulative	Comparison of two signals	cumulative	cumulative
Signal reception	SNRT based VER based	SNRT based	VER based	SNRT based VER based
Fading	Reyleigh Ricen	Not included	Not included	Reyleigh Ricen
Path loss	Up to 33 models	Free space Two ray	Free space	Free space Two ray, etc.

Source [37]

As we can see, NCTUns and ns-2 are open software and there is no fee or charge, moreover they let users modify the protocol module freely. NCTUns gives more simulation options and more advanced methodology; and it is easier for users to implement (GUI) than ns-2. On the other hand, to use OPNET and GloMoSim, users have to pay for a license which may be very costly and they users are not allowed to modify the protocol module.

CHAPTER 5

PERFORMANCE ANALYSIS AND SIMULATION

5.1 Design and Implementation of IEEE 802.16j Transparent Mode Networks over NCTUns-6.0

In this section, we will describe the NCTUns module-based platform and implementation of IEEE 802.16j on both PMP and RS-transparent mode networks over NCTUns-6.0.

5.1.1) NCTUns-6.0 Installation and Setup

As the NCTUns website indicates that it works more conveniently with Linux RED-HAT than other operating systems, we used this operating system for our work. After successfully installing RED-HAT version 12, we could download NCTUns-6.0 from <http://nsl.csie.nctu.edu.tw/nctuns.html> and follow the GUIManual.pdf

5.1.2). NCTUns-6.0 Module-based Platform

NCTUns version 6.0 is a module-based platform simulator which means that the user can easily insert his/her new module into NCTUns and replace the default module with his/her new module in the protocol stack.

Figure 27 shows an example of protocol module combinations in NCTUns and illustrates how a packet traverses the modules from Host1 to Host2 through Switch.

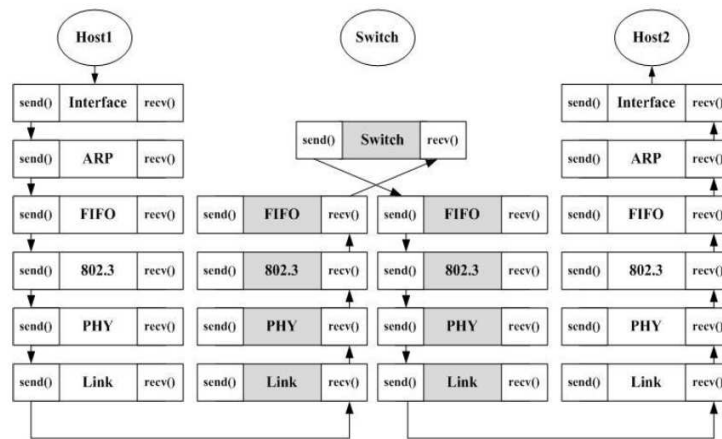


Figure 29: NCTUns Protocol Module

For more detail on how each module works, we would invite anyone interested to refer to NCTUns-6.0 Protocol manual in [62].

5.1.3) Supported IEEE 802.16j Transparent Mode Network Topologies in NCTUns-6.0

As mentioned before, NCTUns-6.0 version supports the new standard of IEEE802.16j both in transparent and non-transparent modes. In this project we focus

only on transparent mode. To create a transparent mode network we need three network components: (1) the Transparent Mobile Relay Base Station (TMR-BS), (2) the Transparent-Relay Station (T-RS), and (3) the Transparent-Mobile Station (T-MS). The Relay Base Station functions with IEEE802.16e base Station compatibility. The Transparent Relay Station (T-RS) is located between BS and MS. It simply forwards incoming data to its subordinate MSs and leaves the scheduling of these data to the TMR-BS. Finally, the MS or end-user terminal is similar to any other user terminal to communicate with BS through RS or directly in the case of transparent mode.

5.1.4) Protocol Stacks of IEEE 802.16j Transparent Mode Networks in NCTUns-6.0

This section indicates the protocol stack of those network components in more detail.



Figure 30: TMR-BS Protocol [53]

5.1.4.1) IEEE 802.16j TMR-BS Node

The TMR-BS provides services for T-MSs and connects with a backbone network. It has two interfaces: one is an IEEE 802.3 Ethernet interface for connecting to the backbone network and the other is an IEEE 802.16j radio interface for communicating with T-RSs and T-MSs. Its IEEE 802.3 Ethernet interface must have enough bandwidth to support the entire IEEE 802.16j network. This IEEE 802.3 Ethernet interface uses the IEEE 802.3 protocol stack, comprising the Interface, ARP, FIFO, MAC8023, and PHY modules. The IEEE 802.16 radio interface needs to work in accordance with the IEEE 802.16j standard. In NCTUns implementation, an IEEE 802.16j interface has the following modules: an Interface module, a MAC802_16J_PMPBS module, an OFDMA_PMPBS_MR module, a CM module, and a LINK module.

The main modules in the protocol stack of the TMR-BS are the MAC802_16J_PMPBS module and the OFDMA_PMPBS_MR module. The MAC802_16J_PMPBS module performs the functions of the MAC layer of a TMR-BS and the OFDMA_PMPBS_MR module performs the physical-layer functions, which use the OFDMA technology. The Channel Model (CM) module simulates various channel conditions such as signal power attenuation, shadowing, and multi-path fading effects.

5.1.4.2) IEEE 802.16j T-RS Node.

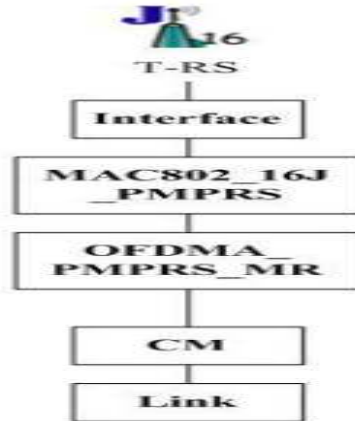


Figure 31: TMR-RS Protocol(source reference [2])

The protocol stack of a Relay station acts similarly to T-MS because it is seen like T-MS from BS. In transparent mode operation RS does not transmit any framing messages such as preamble and DL-MAP. Furthermore, T-MSs will not notice the existence of a T-RS. The RS has only one interface, an IEEE 802.16j wireless interface, which is used to communicate with the TMR-BS and T-MS. The protocol stack of an RS is composed of an Interface module, an MAC802_16J_PMPRS module, an OFDMA_PMPRS_MR module, a CM module, and a Link module. The MAC802_16J_PMPRS module performs the functions of the MAC layer of a T-RS, which includes exchanging the messages and relaying the data between a TMR-BS and a T-RS. The OFDMA_PMPRS_MR module performs the physical-layer function, encoding and decoding the data transferred to TMR-BS and T-MS. Similarly, the Channel Model (CM) module is added into the protocol stack of a TMR-RS to simulate various channel conditions.

5.1.4.3) IEEE 802.16j T-MS Node

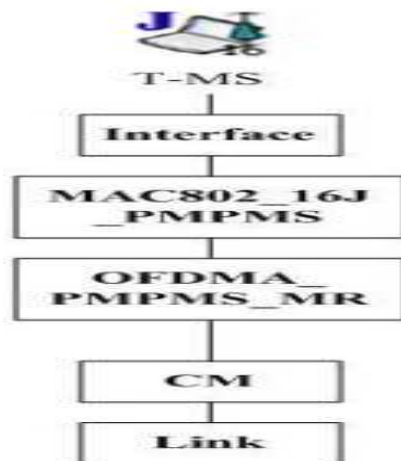


Figure 32: T-MS Protocol [53]

The T-MS has one interface, which is an IEEE 802.16j wireless interface, to communicate with the TMR-BS and T-RS. The protocol stack of the T-MS is composed of an Interface module, an MAC802_16J_PMPMS module, an OFDMA_PMPMS_MR module, a CM module, and a Link module. The MAC802_16J_PMPMS module performs the functions of the MAC layer of a T-MS. These functions include

receiving/transmitting messages from/to its TMR-BS and T-RS. The OFDMA_PMPMS_MR module performs physical-layer functions.

5.1.5) Protocol Stacks of IEEE 802.16j PMP-Mode Networks in NCTUns-6.0

In PMP operation mode, the network protocol stack of BS and SSs is similar to BS and SSs of RS-transparent mode. The only thing different is there is no RS.

5.1.6) Construction of IEEE 802.16j Network in NCTUns-6.0

To study the capacity of network with different distances between BS and SS both in PMP-mode and RS-Mode. The following table gives some common parameters used in simulation both PMP and RS-transparent modes.

Table 7: System parameters for PMP and RS-Transparent Modes

OFDMA parameters	value
FFT-size	1024
# of sub-carriers	840
DL sub-carrier allocation	30
UL sub-carrier allocation	35
Bandwidth	10 MHz
Sampling factor	28/25
Sampling Frequency	11.2 MHz
CP ratio	1/8
CP time(T_g)	11.425 μ s
Symbol time(T_s)	102.825 μ s
Frame duration	5 ms
Physical slot	0.357143 μ s
TTG	90 ps
RTG	90 ps

5.1.6.1) PMP-Mode Network Construction

Table 8: PMP-Mode System Model

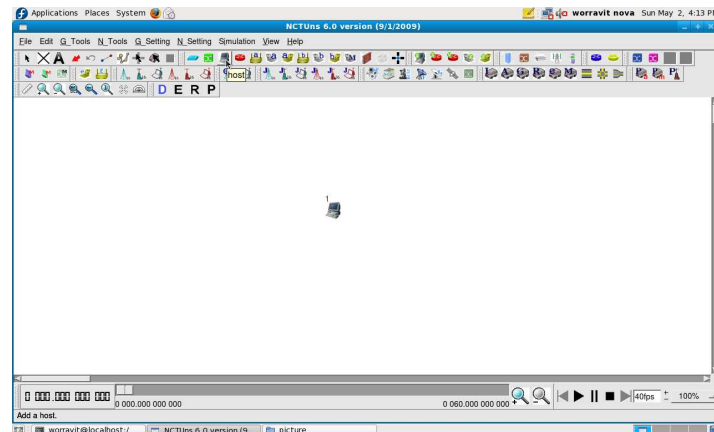
BS Cell Radius	600 m	
Transmitting power	BS	43 dbm
	SS	35 dbm
Antenna height	BS	30 m
	SS	1.5 m
Channel model	Cost_231_Hata	
Distances	BS \rightarrow SS1	184 m
	BS \rightarrow SS2	382 m
	BS \rightarrow SS3	422 m
	BS \rightarrow SS4	482 m
	BS \rightarrow SS5	522 m

Base station Node

After successfully running nctunsclient, in the working area we needed one host to link with Base Station for control section. Use mount select host symbol and place it in the working area. There are two phases for network creation, network drawing and component editing.

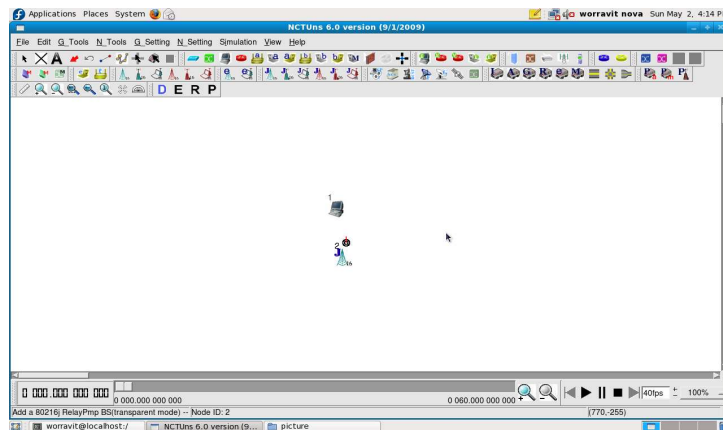
- Network Drawing

Step 1 Host Drawing



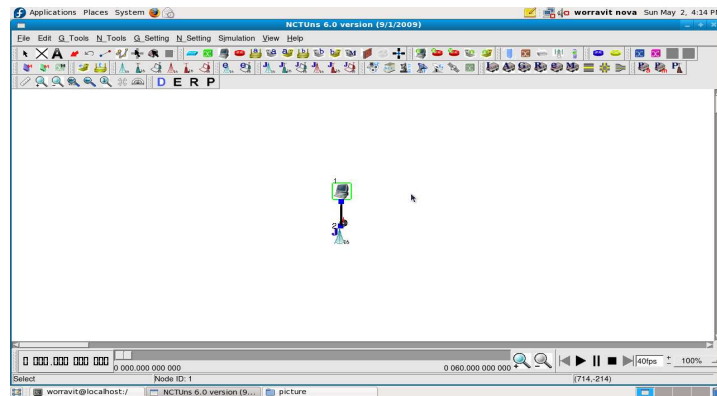
The first step is to specify the desired network topology in the GUI environment. As shown in Figure, there are several node icons on the GUI's tool bar at the top. In this case, we choose to create one host (Node 1).

Step 2 BS Drawing



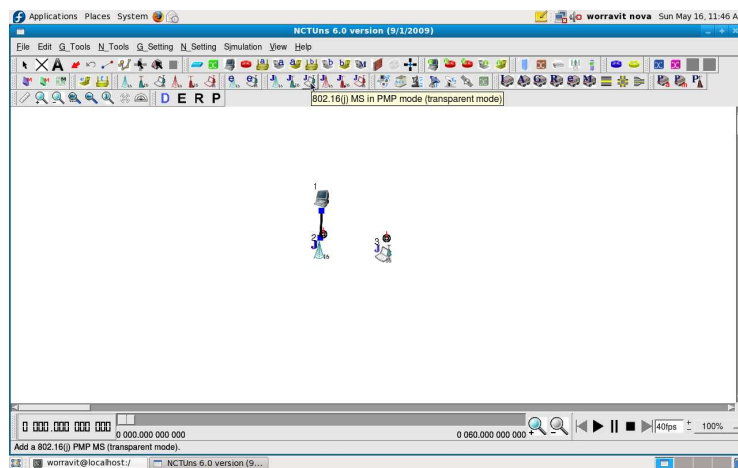
In BS case, we choose to create one BS (Node2).

Step 3 Host and BS linking



The TMR-BS connects with the host (on the backhaul network) through a wired link and it communicates with other nodes in this topology through an IEEE 802.16j wireless interface.

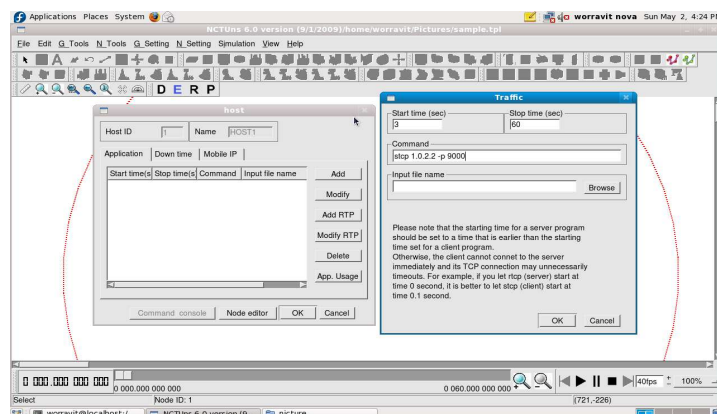
Step 4 T-MS drawing



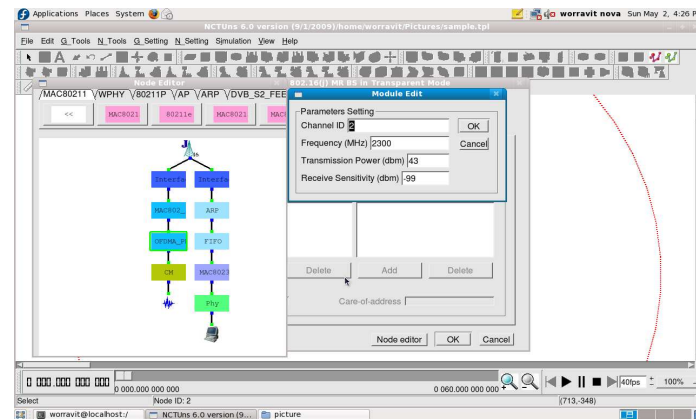
For SS creating, we choose SS icon in the tool bar to create one SS (Node 3).

-Component editing

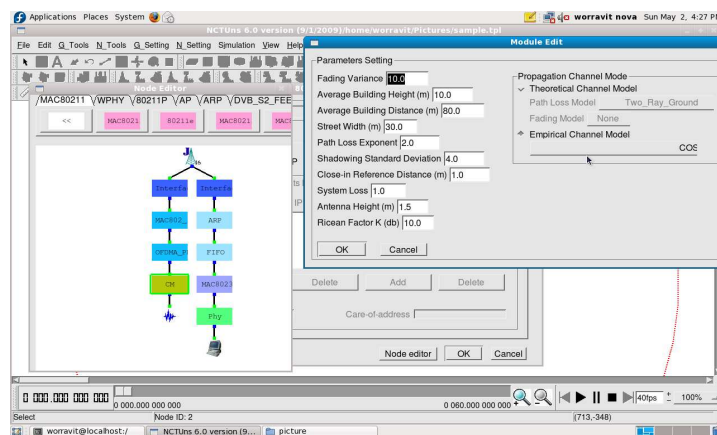
BS-Host editing



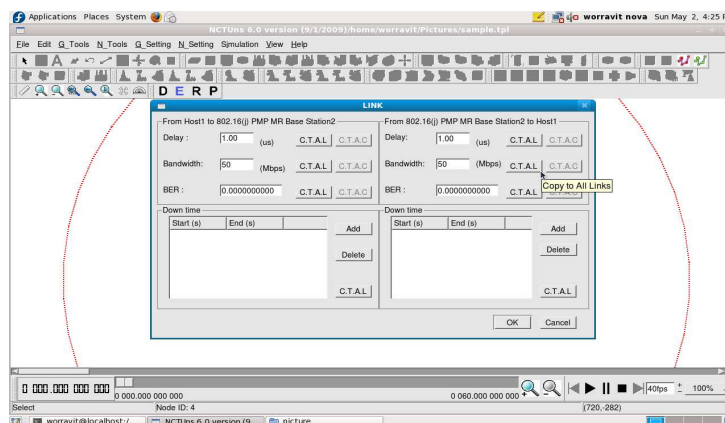
At the Host, most information concerns how BS communicates with users, including sending, receiving, setting time, port numbering used for communication. These can be set in “Application block” of Host as can be seen in the figure.



Inside “Application block” we can set channel ID, operating frequency and transmitting power, receiving sensitivity.



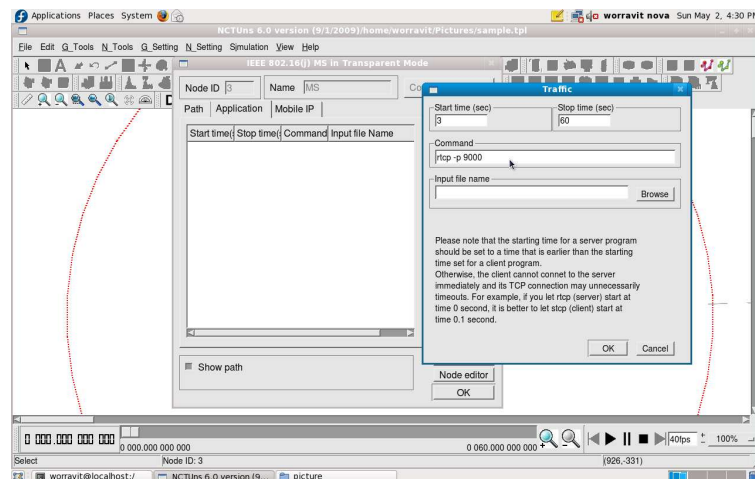
In OFDMA block and in “CM” block, there are various parameters that we can set but usually we need only, BS-antenna height and propagation channel mode. The rest of them can be let for default.



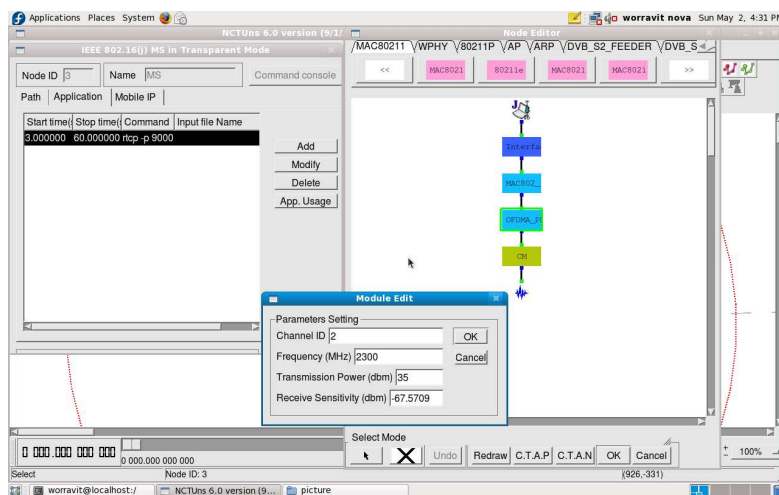
Finally, we link BS with Host with wired cable and set its bandwidth to 50 Mbps in this case.

T-MS editing

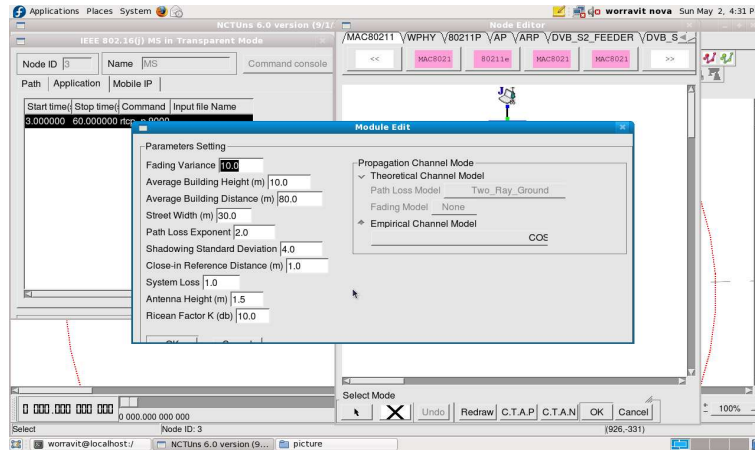
In the T-MS, we need to set time of start/stop sending, receiving, port number and these must be the same as the settings in Host to let T-MS communicate correctly by using the node edit icon as in the figure below.



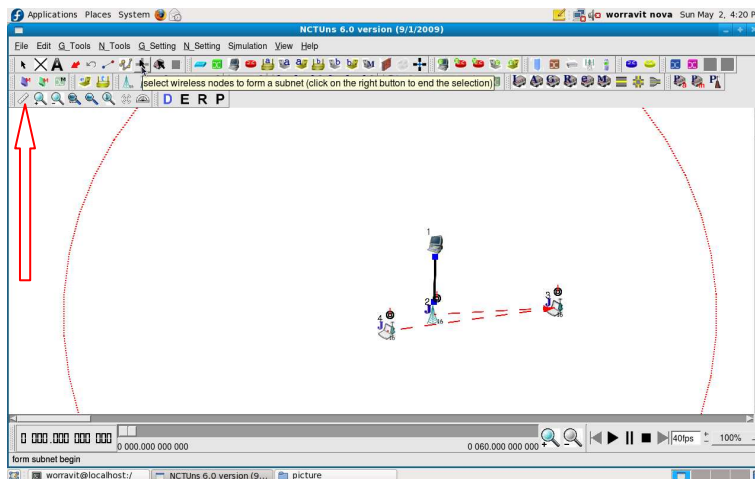
In “Edit” icon of SS, we can set the start/stop sending time.



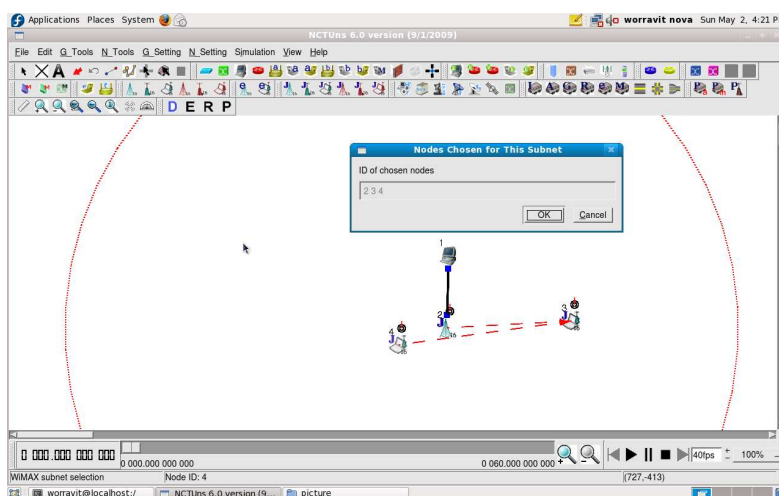
And also we need to set the channel ID and operating frequency to be the same as in the BS setting. For Tx power and receive sensitivity, we can set different values from the BS depending on simulation purpose but it is very important that both the BS and the T-MS can see each other.



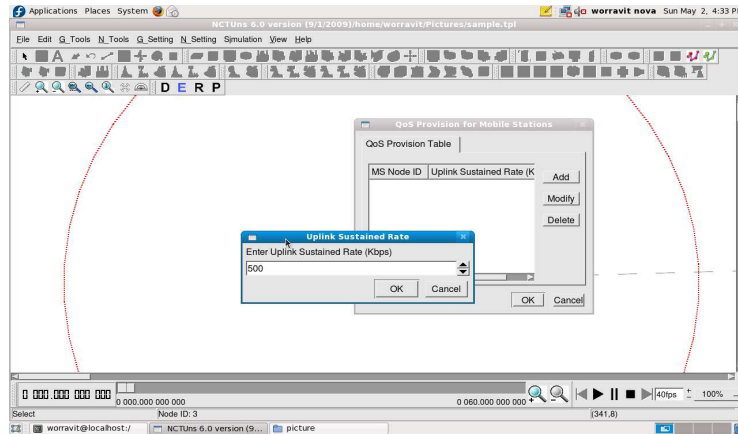
Also in the T-MS edit module, we can set propagation Channel Mode which is Cost 231 in our case, and must be the same in BS setting. The SS's antenna height is set to 1.5 m and the rest of parameters can be left at the default values.



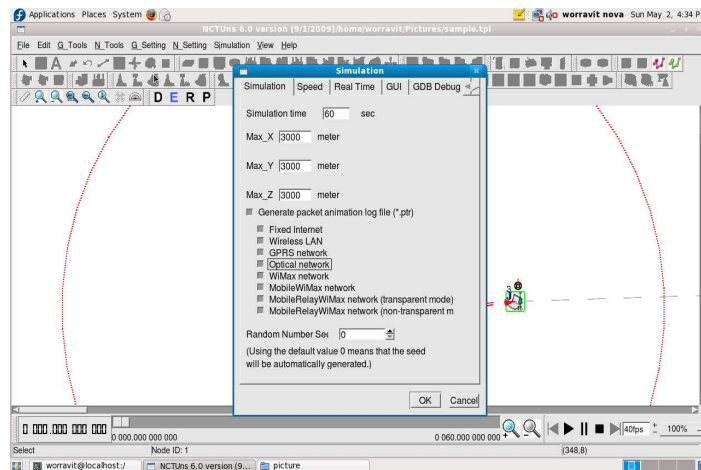
The distance between each piece of equipment (BS-SS, SS-SS) can be measured by using the rule icon.



Where there are more than one T-MSs, we need to group the T-MSs sub-mark for GUI default. This step is very important because if T-MSs get different sub-settings it means they can not see the BS. Sub-network settings can be set using the icon in the figure.

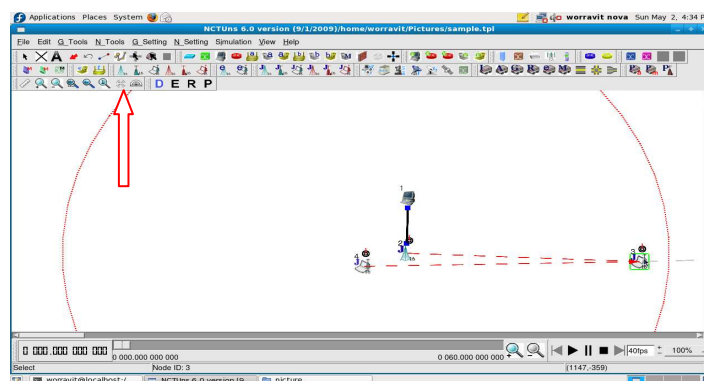


We also need to set the uplink sustained rate for all T-MSs to avoid the problem of bandwidth fairness.

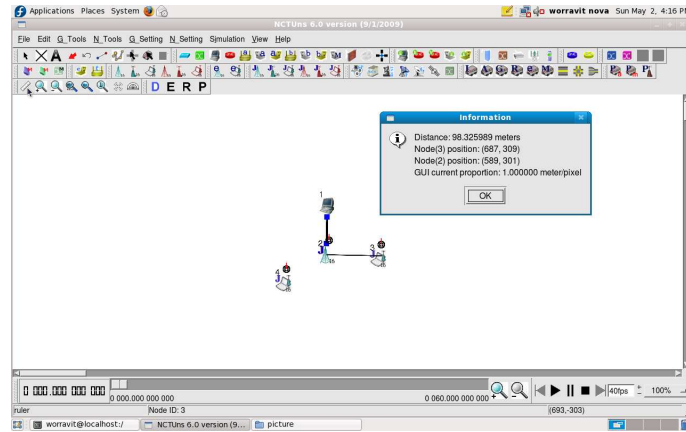


Finally before the simulation can be done correctly, we must set simulation time as indicated in Host and T-MS set-up and some animation options in the simulation item and follow-up details in the figure.

Base Station Coverage Range Setting



In real simulations, we may need to know BS coverage. To do this we can use the physical layer and channel model tool bar to see the BS coverage range as shown in the figure.



As our simulation will concern the distance between BS and T-MSs, we need to know the distances between BS-SS in each simulation by using the Specify physical layer icon.

5.1.6.2) RS-Mode

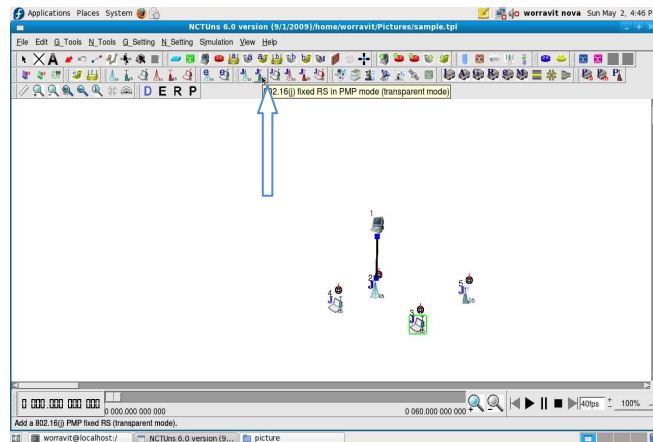
Table 9: Rs-Transparent Mode System Model

BS Cell Radius	600 m	
Transmitting power	BS	43 dbm
	RS	43 dbm
	SS	35 dbm
Antenna height	BS	30 m
	RS	20 m
	SS	1.5 m
Channel model	Cost_231_Hata	
Distances	BS → RS	300 m
	BS → SS1	184 m
	BS → SS2	382 m
	BS → SS3	422 m
	BS → SS4	482 m
	BS → SS5	522 m

Most of the steps in RS-Mode for drawing and editing are similar to PMP-mode described in the previous section. The only new step added is RS by just choosing the RS icon in the tool bar menu and placing it between BS and T-MS.

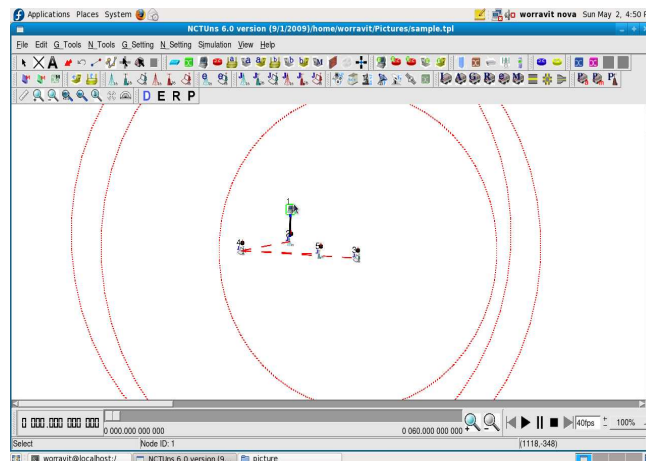
RS Drawing

Step 1 RS insertion



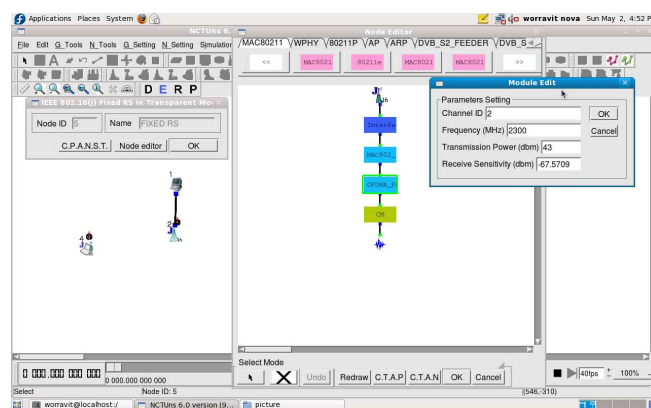
From the tool bar menu, select and place RS between BS-SS link.

Step 2 RS coverage range



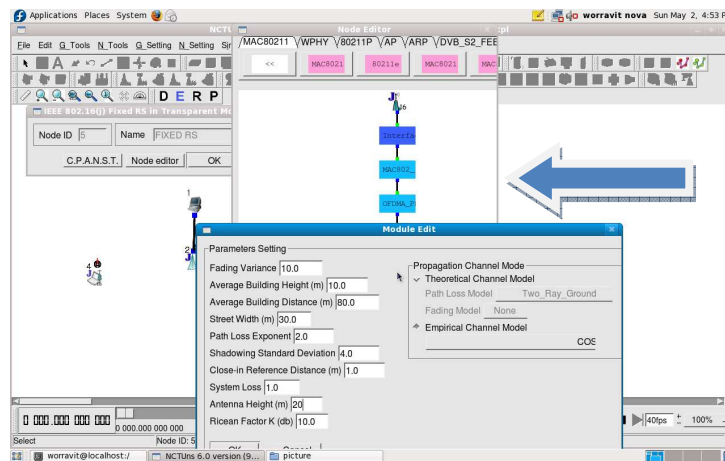
Make sure RS is located in the BS range because we are in RS-Transparent mode.

Step 3 RS editing



Once the above cases are set, we can now set the RS parameters such as channel ID, operating frequency, transmit/receive power.

Step 4 common parameter settings



RS uses same the operating parameters as BS. The only difference is the antenna height of RS is set to 20 m while BS is set to 30 in our case.

5.1.6.2.1) MS path selection in RS-Mode:

To decide the access station for a T-MS, NCTUns implements a path selection algorithm proposed in [8]. The TMR-BS decides T-MS's access station according to the weight of the link between the T-MS and T-RS and the weight of the link between the T-RS and TMR-BS. The weight of a link corresponds to the modulation and coding rate used on that link. The TMR-BS will choose to use the T-RS as the T-MS's access station if the following condition is met:

Ws: the corresponding weight of T-MS to TMR-BS's uplink

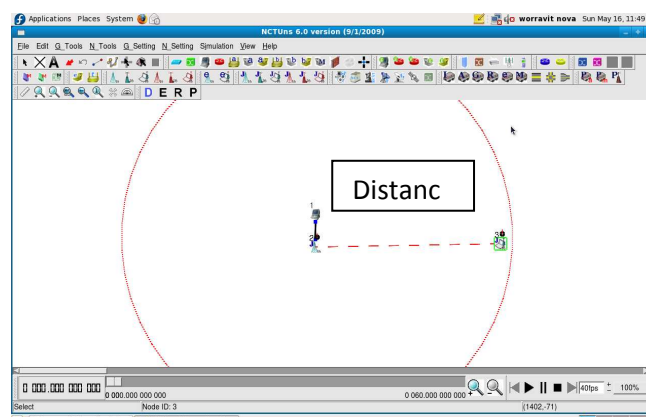
Wr: the corresponding weight of T-MS to T-RS's uplink

Wp: the corresponding weight of T-RS to TMR-BS's uplink

$Wr + Wp < Ws$; otherwise MS connects directly to BS

5.2) Network Scenarios

5.2.1) . PMP-mode with different distances between BS and T-MS

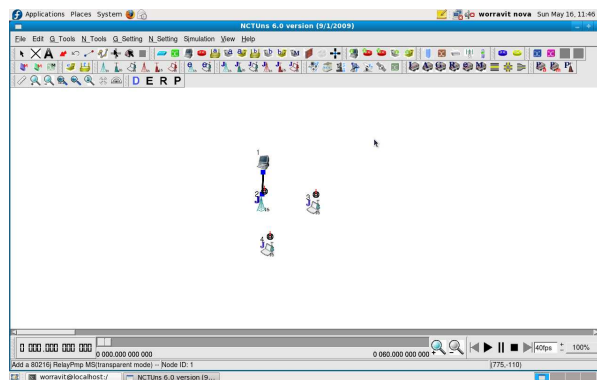


In PMP-Mode, our simulation purpose is to study the network performance behavior while increasing the distances between BS and SS from the nearest to the longest as indicated in Table 7.

5.2.2). PMP-mode with different numbers of SSs

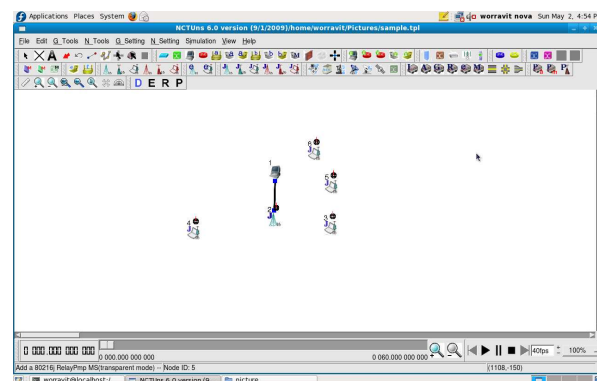
We also tried to study the network performance with an increasing number of users on the network. As shown in the figure, we started increasing the number of SS from 1 to 2.

Case. SS=2



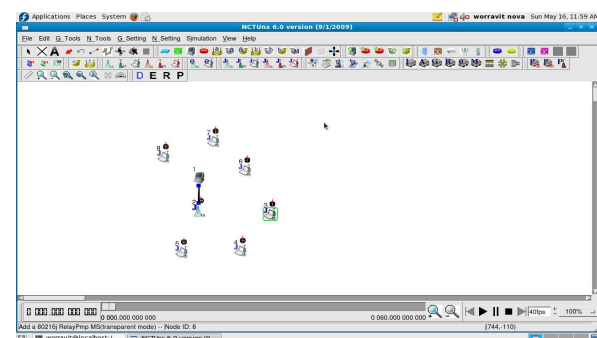
SSs increased from 1 to 2

Case. SS=4



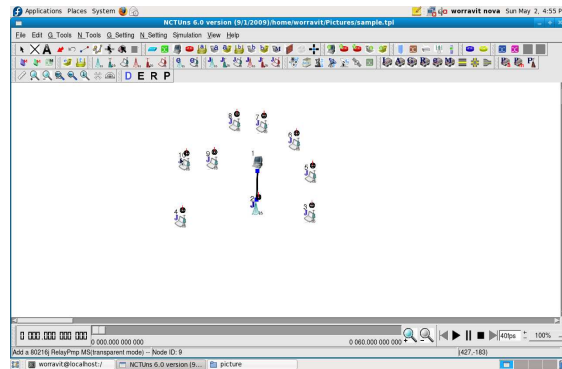
SSs increased from 2 to 4.

Case. SS=6



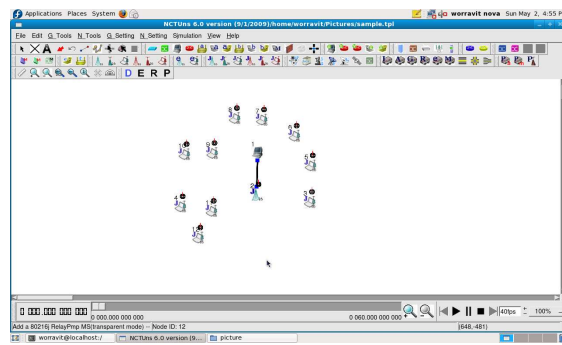
SSs increased from 4 to 6.

Case. SS=8



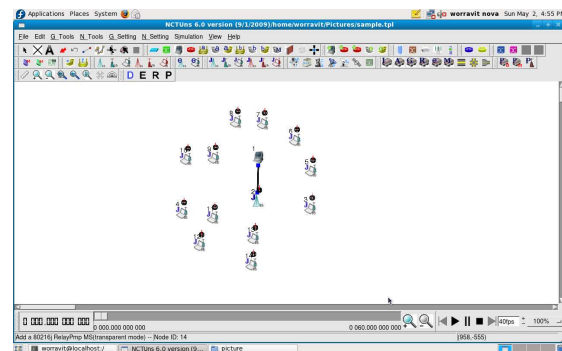
SSs increased from 6 to 8.

Case. SS=10



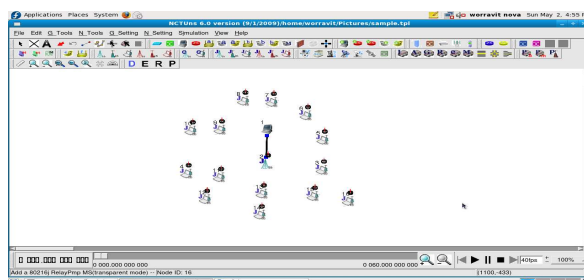
SSs increased from 8 to 10.

Case. SS=12



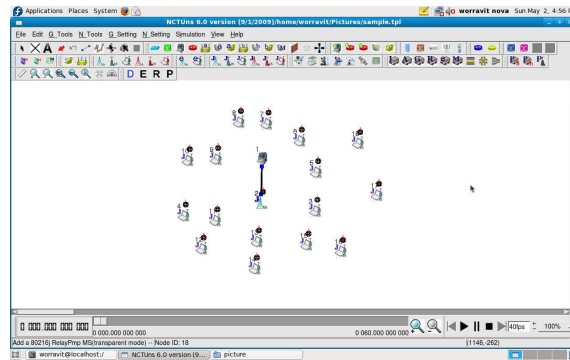
SSs increased from 10 to 12.

Case. SS=14



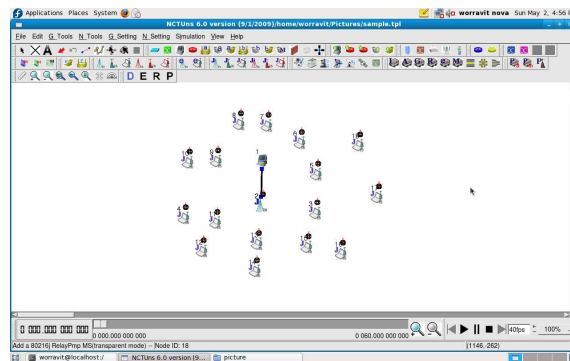
SSs increased from 12 to 14.

Case. SS=16



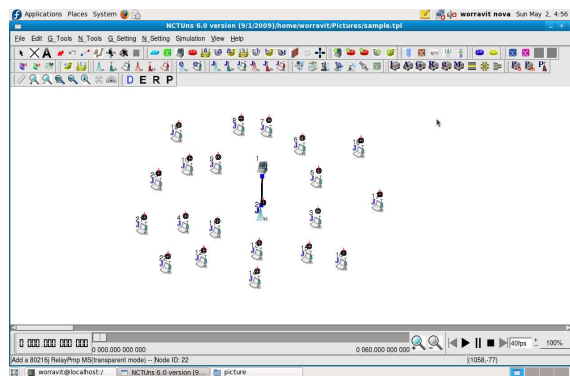
SSs increased from 14 to 16.

Case. SS=18



SSs increased from 16 to 18.

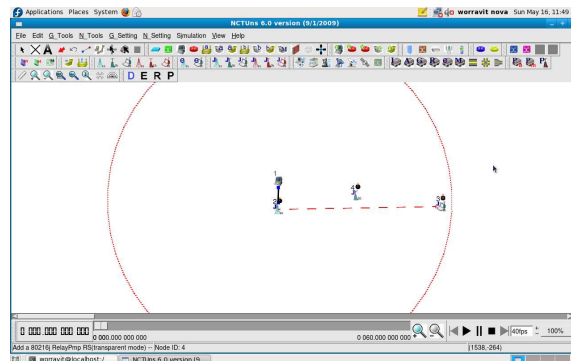
Case. SS=20



SSs increased from 18 to 20

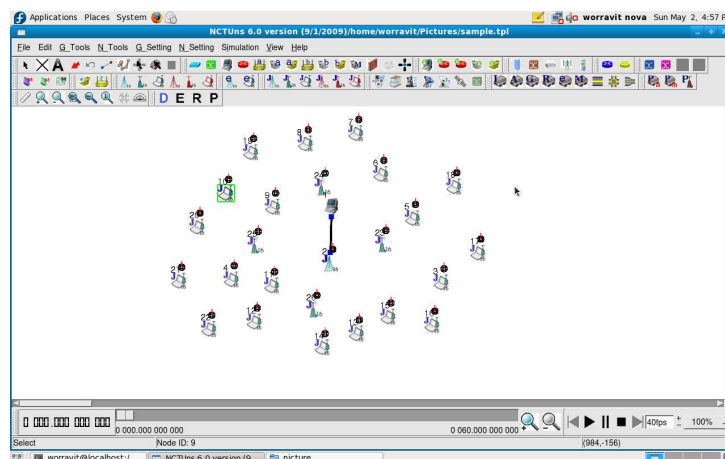
5.2.2). RS-mode with Different Distances between BS →SS and RS→SS

Case A BS→SS varying distance with RS located in the middle



The above figure shows the simulation topology of RS-Transparent mode by varying distances between BS→SS while the RS is inserted between them at a fixed location. The distance-varying method is same as in PMP-mode.

Case B 4 RSs in Big Network



In this case, we want to study how RS numbers affect system performance by setting 4 RSs in a 20-user network. We try to set four equilibrium directions to locate RS around BS.

5.3) DESIGN AND IMPLEMENTATION OF IEEE 802.16j NETWORKS OVER ns-2

5.3.1) WiMAX (IEEE 802.16j) patch

There are many simulators provide IEEE 802.16 simulation module but it is quite difficult to find IEEE 802.16J patch as it is a recently released standard. With the well-known commercial software, OPNET, QualNet, researchers would not know the detailed and currently supported functionalities until the expensive source code has been

purchased. For the most popular network simulators ns-2 [17], many researchers designed and released their own IEEE 802.16 module for free. However, the modules provided by NIST, NDSL and IRC [60] do not support QoS OFDMA and multi-hop relay functionalities.

5.3.2 Light WiMAX Simulator (LWX) Patch for IEEE 802.16 and IEEE 802.16j Networks

In this thesis, we design and implement an IEEE 802.16j network with a light-weight software architecture, named Light WiMAX simulator (LWX), which provides flexible and robust functionalities to evaluate the performance of IEEE 802.16j network capacity in both PMP-mode and RS-Transparent mode. It has been based on ns2 version 2.33 with RED-HAT Fedora 12 core. The light-weight design of LWX is inherited from the original classes in ns2 to simplify simulator software architecture, accelerate the understanding of the operations and workflows of LWX, and cooperate with other network protocol components of ns2. LWX supports QoS, OFDMA, multi-hop relay specified in the standard [24]. As the development of LWX is based on an object-oriented approach, we can only change the settings of the simulation script without recompiling the simulator to observe what performance the IEEE 802.16j network systems can achieve.

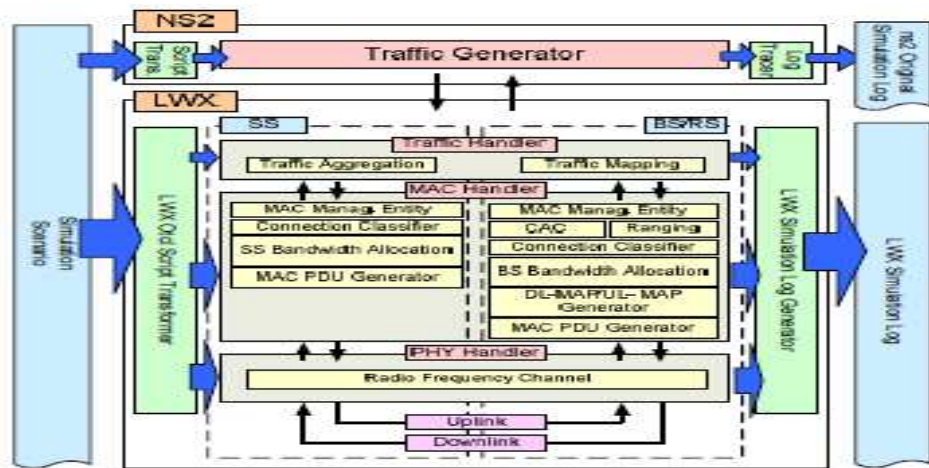
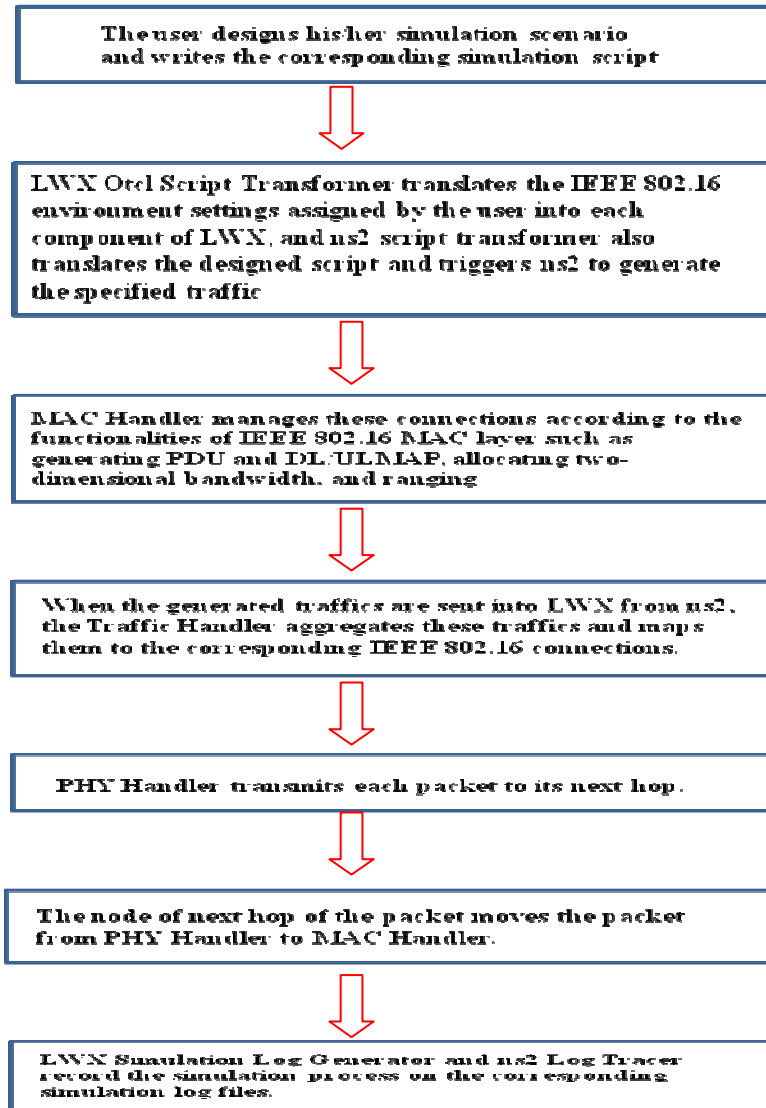


Figure 33: The Software Architecture and Workflow of LWX Patch [60]

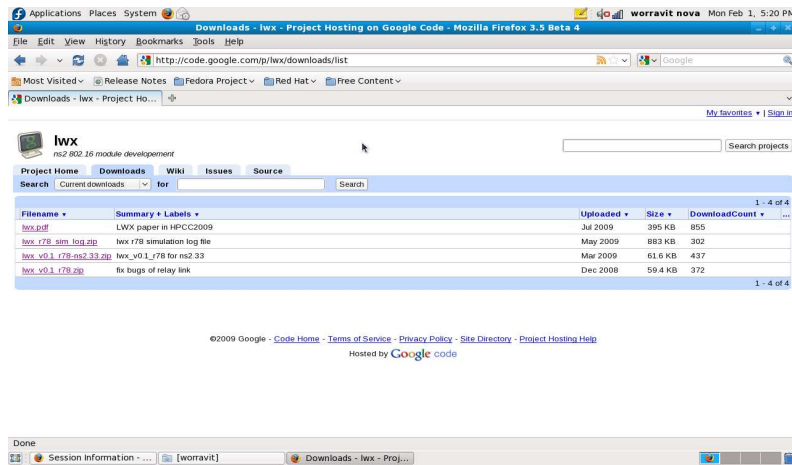
The software architecture of LWX and the relation between LWX and the original ns2 system are shown in Figure 38. Within LWX, all components including Traffic Handler, MAC Handler, PHY Handler, LWX Otcl Script Transformer, and LWX Simulation Log Generator, are designed by object-oriented programming language C++ and grouped into several classes. Traffic Handler addresses the aggregation and mapping of the traffic from application layer of ns2 or from MAC Handler of LWX. MAC Handler deals with the tasks of IEEE 802.16 MAC layer including ranging, packet data unit (PDU) generation, call admission control (CAC), bandwidth allocation, et al. PHY Handler handles the functionalities of IEEE 802.16 wireless signal transmission such as modulation and signal coding. LWX Otcl Script Transformer is designed to translate the designed simulation script settings into each component within LWX. LWX Simulation Log Generator is used to record the simulation process for some special designs of IEEE 802.16 standard such as the

content of DL/UL-MAP message and the structure of each allocated burst that the original ns2 simulation log tracer does not support.

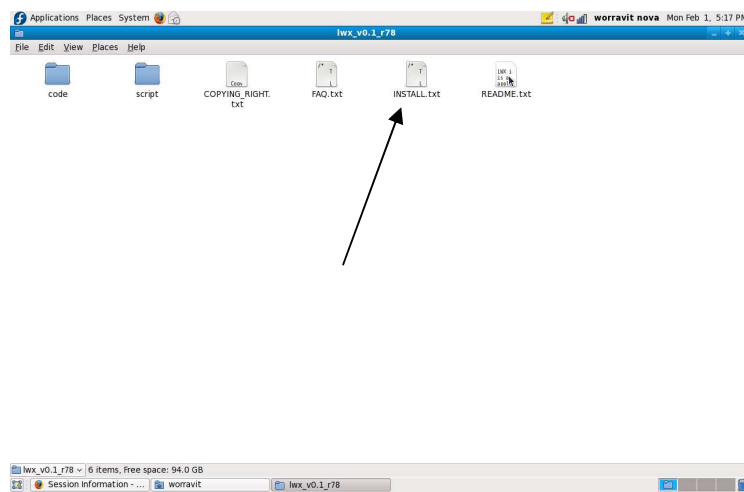
5.3.3) LWN Working flow



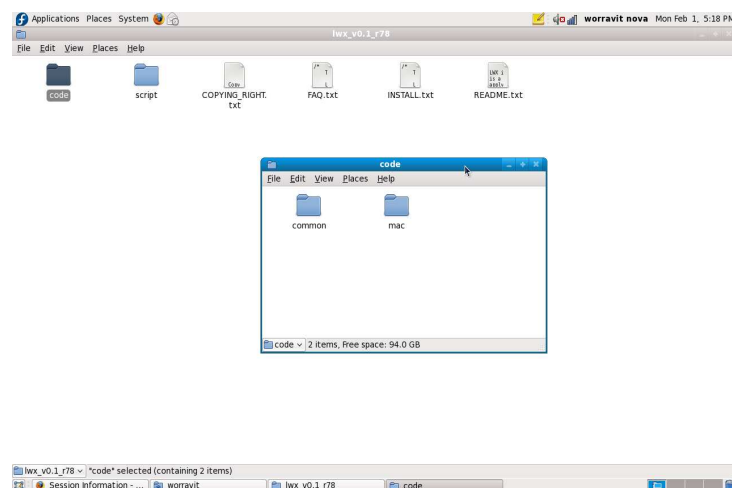
5.3.4) LWX Patch Setting



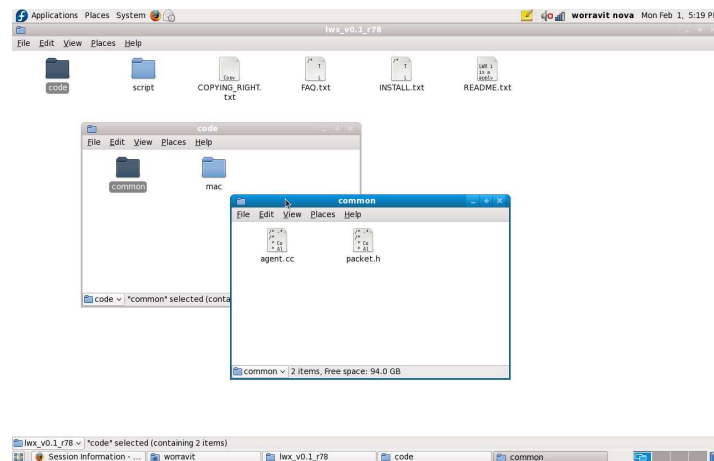
- 1) Download LWX-Patch from web site and use the ns2 version to be simulated (ns-allinone-2.33 for this case).



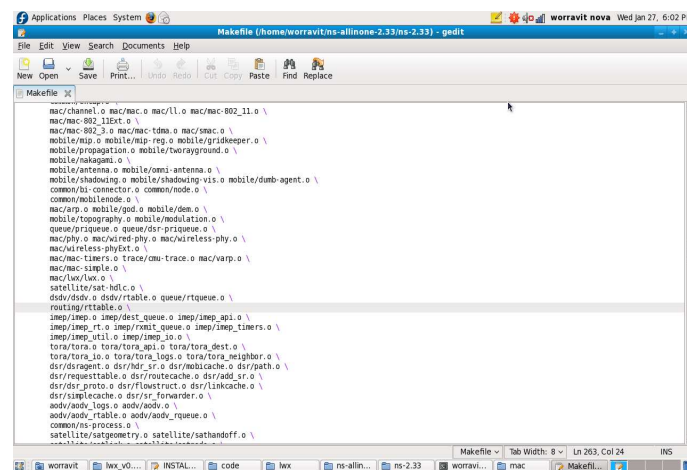
- 2) Open and read the instruction for installing step-by-step in install.txt file



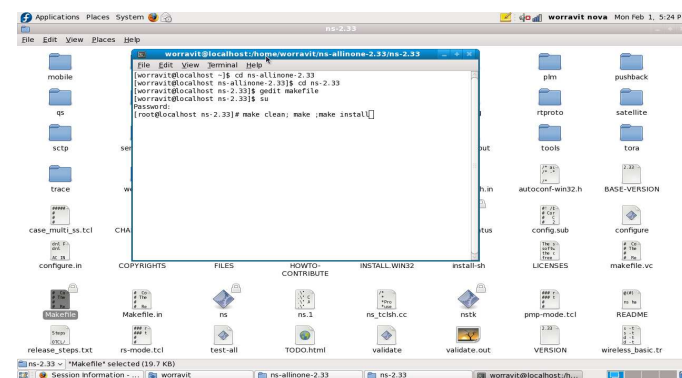
3) Copy all files in code directory of LWX patch to MAC file directory of ns-2



4) Add all common files in common directory of LWX to common file directory of ns-2.



5) Modify some Make files of ns2 as indicated in install.txt file



6) RE-run Make from Linux command window. At this step if there are no problems, the pop-up message will show make success.

5.4) IEEE 802.16j Topology Building with NS-2

Table 9 Parameters used in LWX simulation

Name	Value
System bandwidth	20 MHz
OFDMA frame duration	5 ms
OFDMA symbol time	100.94 μ s
# of sub-carriers for downlink/uplink Data transmission	1680
Num. of sub-channels for downlink	60
# of sub-channel for uplink	70
Slot size of downlink(subch x symbol)	1x2
Slot size of uplink(subch x symbol)	1x3
Downlink/uplink bandwidth ratio	3:1
Access/relay bandwidth ratio	1:1

A) PMP-Mode

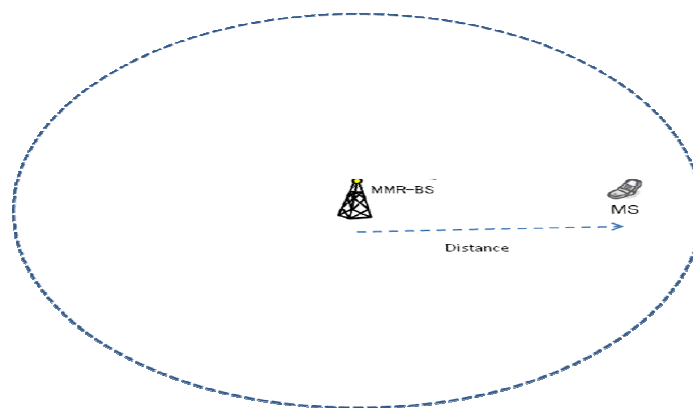


Figure 34: PMP-Mode for ns2

Topology building in NS2 can be done using any editor to write the script. The main part of the network will be explained below.

1) Specify Basic Parameters for the Simulation

```
# =====
# Default Script Options
# =====
set opt(chan) Channel/WirelessChannel ;#Channel Type
set opt(prop) Propagation/TwRayGround ;# radio-propagation model
set opt(macif) Phy/WirelessPhy ;# network interface type
set opt(mac) Eac/LUX ;# MAC type
set opt(lfq) Queue/DropTail/PriQueue ;# interface queue type
set opt(ll) LL ;# link layer type
set opt(ant) Antenna/OmniAntenna ;# antenna model
set opt(lfqlen) 50 ;# max packet in lfq
set opt(nm) 3 ;# number of wclenodes
set opt(rp) AODV ;# routing protocol. DSDV, DSR, AODV.
set opt(x) 250 ;# Topology size
set opt(y) 250 ;# Topology size
set opt(trace) wireless_basic.tr ;# trace file
#set opt(nam.tr) wireless_basic.nam ;# the nam trace file
```

Some basic parameters of the system can be set in this part of tcl script, for example, channel, MAC type, link layer, topology, network interface, etc.

2) Create a simulator object

```
set ns [new Simulator]
# This command should be called before the universal trace command $ns trace-all
$ns use-newtrace
#set namtrace [open $opt(nam.tr) w] ;# for nam
#$ns namtrace-all-wireless $namtrace $opt(x) $opt(y) ;# for nam
set tracefd [open $opt(trace) w]
$ns trace-all $tracefd
```

Simulator object needing to be set for each new simulation script is written.

3) Trace file setting

```
proc finish { } { ;# new a procedure finish
    global ns namtrace tracefd opt ;# set global variable
    $ns flush-trace
    $close $namtrace ;# for nam
    close $tracefd ;# close file
    # exec nam $opt(nam.tr) & ;# for nam
    exit 0
}
```

Define trace file to record all simulation data.

4) Initial Location of nodes and create routing table (god)

```
# set up topology object
set topo [new Topography]
$topo load_flatgrid $opt(x) $opt(y)
# Create God
create-god $opt(nm)
# create channel
set chan [new $opt(chan)]
```

GOD is the routing table setting for the network.

5). Configure node

```
# configure node, please note the change below.
$ns node-configure -adhocRouting $pr(rr) \
    -llType $opt(ll) \
    -macType $opt(mac) \
    -ifqType $opt(ifq) \
    -ifqlen $opt(ifqlen) \
    -antType $opt(ant) \
    -propType $opt(prop) \
    -phyType $opt(phy) \
    -topoInstance $topo \
    -agentTrace $tr \
    -routerTrace $tr \
    -macTrace $tr \
    -movementTrace $tr \
    -channel $chan_
```

Node configuration is set to tell ns-2 to recognize and store simulation data for each node.

6) Create the connection between nodes

```
# -----
# adding nodes
# =====
set node_id(0) 0
set node(0) [$ns node]
$nsdc(0) random-motion 0
$ns initial_node_pos $node(0) 20
$nsdc(0) set X_ 15.0
$nsdc(0) set Y_ 15.0
$nsdc(0) set Z_ 0.0
$nsdc(0) nodeName $node_id(0)
Mac/LWZ env add_bs node_id $node_id(0)
set node_id(1) 101
set node(1) [$ns node]
$nsdc(1) random-motion 0
$ns initial_node_pos $node(1) 20
$nsdc(1) set X_ 17.0
$nsdc(1) set Y_ 17.0
$nsdc(1) set Z_ 0.0
$nsdc(1) nodeName $node_id(1)
Mac/LWZ env add_ss node_id $node_id(1) bs_node_id $node_id(0)
set node_id(2) 102
set node(2) [$ns node]
$nsdc(2) random-motion 0
$ns initial_node_pos $node(2) 20
$nsdc(2) set X_ 18.0
$nsdc(2) set Y_ 18.0
$nsdc(2) set Z_ 0.0
$nsdc(2) nodeName $node_id(2)
Mac/LWZ env add_ws node_id $node_id(2) bs_node_id $node_id(0)
```

Connect nodes together by setting the node ID in the MAC command. The MS distance from BS can also be set here by changing the X,Y coordinate values.

7) Set MAC command

```
# add flow
# Mac/LWZ env add_flow <type> $src_nid $from_nid $to_nid $flow_info
# type: bs_to_ss, ss_to_bs, rs_to_bs, rs_to_ss
Mac/LWZ env add_flow bs_to_ss $src_nid $from_nid $to_nid $flow_info
# set flow attribute
# Mac/LWZ env set_flow $src_nid $from_nid $to_nid $flow_info <type> <value>
# type: rate(byte), qos_class {1-5}, Rmin(kbps), Rmax(kbps), Load(pct), Jitter(ms)
Mac/LWZ env set_flow $src_nid $from_nid $to_nid $flow_info rate 6
Mac/LWZ env set_flow $src_nid $from_nid $to_nid $flow_info qos_class 2
Mac/LWZ env set_flow $src_nid $from_nid $to_nid $flow_info Rmin 1000000
Mac/LWZ env set_flow $src_nid $from_nid $to_nid $flow_info Rmax 2000000
Mac/LWZ env set_flow $src_nid $from_nid $to_nid $flow_info Load 60
Mac/LWZ env set_flow $src_nid $from_nid $to_nid $flow_info Jitter 45
$ns at 1.00 "$chr_0 start"
$ns at 3.00 "$chr_0 stop"
```

The MAC command setting is a very important part because it provides network control of link and packet. All of the values in MAC are defined by a patch designer based on IEEE 802.16j standard.

8) Stop Simulation

```
# Tell nodes when the simulation ends
#
for (set i 0) {$i < $npt($ns) } {incr i} {
    $ns at 10.0 "$node($i) reset";
}
$ns at 10.0 "finish"
$ns at 10.01 "puts 'NS EXITING...'; $ns halt"
puts "Stopping Simulation..."
$ns run
```

Finally, we need to tell ns-2 about start and stop of simulation time at the end of the tcl script.

B) RS-Mode

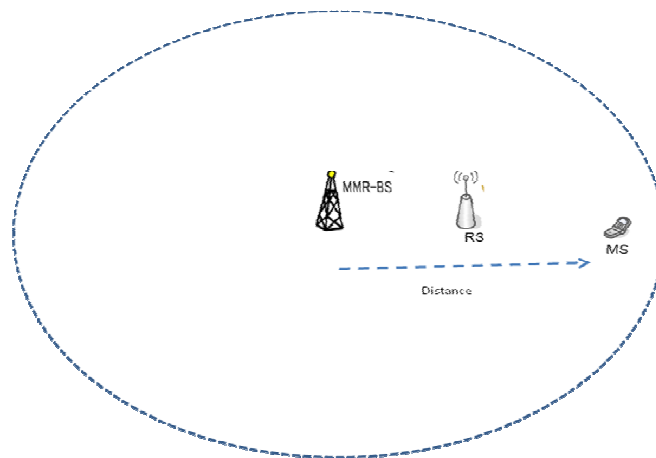


Figure 35: RS-Transparent Mode for ns2 simulation

```
# =====
# adding nodes
# =====
set node_id(0) 0
set node(0) [$ns node]
$node(0) random-motion 0
$ns initial_node_pos $node(0) 20
$node(0) set X_ 15.0
$node(0) set Y_ 15.0
$node(0) set Z_ 0.0
$node(0) nodeid $node_id(0)
Mac/LWK env add_bs node_id $node_id(0)
set node_id(1) 1
set node(1) [$ns node]
$node(1) random-motion 0
$ns initial_node_pos $node(1) 20
$node(1) set X_ 16.0
$node(1) set Y_ 16.0
$node(1) set Z_ 0.0
$node(1) nodeid $node_id(1)
Mac/LWK env add_rs node_id $node_id(1) bs_node_id $node_id(0)
set node_id(2) 101
set node(2) [$ns node]
$node(2) random-motion 0
$ns initial_node_pos $node(2) 20
$node(2) set X_ 17.0
$node(2) set Y_ 17.0
$node(2) set Z_ 0.0
$node(2) nodeid $node_id(2)
Mac/LWK env add_ms node_id $node_id(2) bs_node_id $node_id(0)
```

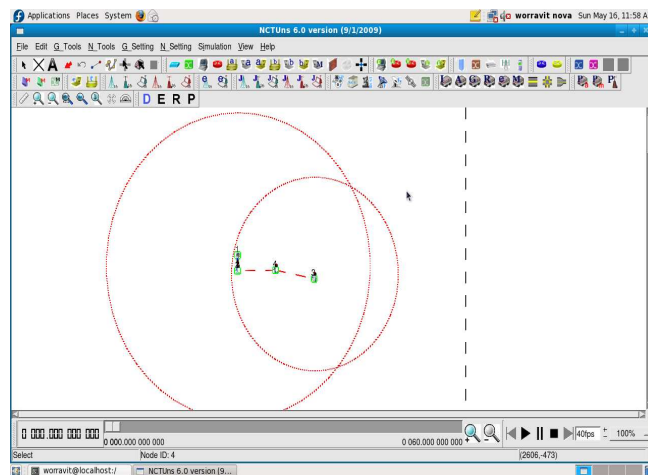
In the case of RS-mode in ns-2, most parameters will be same as PMP-mode. The only modified script is adding RS-node to the node setting part of PMP-mode (in red).

5.5 DESIGN AND IMPLEMENTATION OF IEEE 802.16J NETWORK WITH DIRECTIONAL ANTENNAS IN NCTUns-6.0

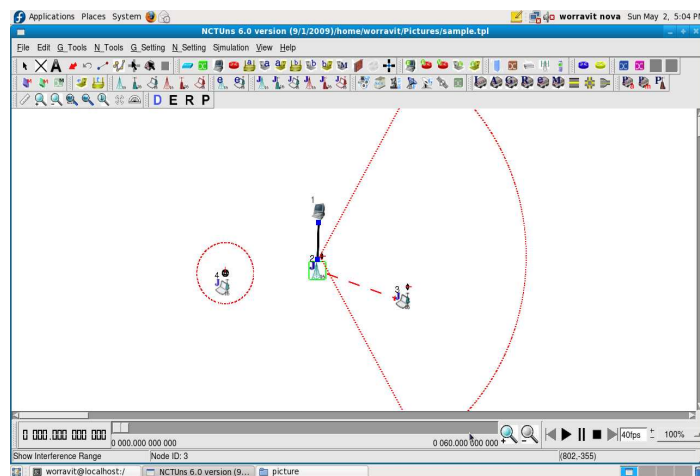
Unlike Omi-directional antennas, directional antennas focus the RF energy in a particular direction. As the gain of a directional antenna increases, the coverage distance increases. For directional antennas, the lobes are pushed in a certain direction and little energy is there on the back side of the antenna as compared with an Omni-directional antenna.

It is very important to consider that in our network we focus our simulation only in fixed network not mobile ones so that we can ignore the problem of BS cannot see SSs due to the angular coverage is less. In NCTUns-6.0, we can set the antenna patterns as following.

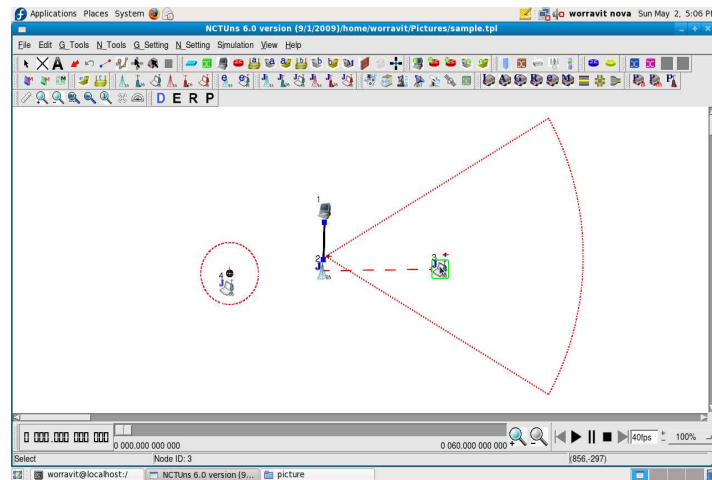
1) Omnidirectional Antenna Pattern



2) 120 Degree Directional Antenna Pattern



3) 60 Degree Directional Antenna Pattern



5.6) Simulation Results

In NCTUns-6 Network Simulator

Generally, there are two options for tracing results in NCTUns-6.0 simulation. First, using the command setting in MAC set up to record all simulation events in a file but this method needs unit conversion so it is necessary to understand what this means in terms of format. Another method is to monitor from the coordinator window (as in this case) and save it to file when the simulation finishes. The following shows the output of some simulation from the coordinator window.

```
***MS(4) Ranging code relay from RS(3)>>>(u_mstors = 7, u_rstobs =
7, u_mstobs = 7)<<<, >>>(d_bstors = 6, drstoms = 0, d_bstoms =
6)<<<*** Time:873346610***MS(4)==>BS(2), Relay Weight = 0.440000 >
Direct Weight = 0.220000 Current Time:      88.00 sec      Event#:
<Insert:19156, Dequeue:19156, Rest:372> 2992      88      2873
Kbyte/sec ==> 22.448812 Mbit/sec
```



In NS-2 Simulator

It is important to note that there are many methods to trace result from an ASCII file, using awk or perl scripting language to interpret the trace file and then display it by NAM. In our case, we use basic Linux commands like grep and its options. Using awk or perl scripting methods would cause many problems as we use Fedora RED-HAT Linux distribution which needs modification of many points and requires programming skills. Therefore we leave this out to avoid these problems. When tracing into an output ASCII file, the trace is organized in 12 fields as follows.

Event	Time	From node	To node	Pkt type	Pkt size	Flags	Fid	Src addr	Dst addr	Seq num	Pkt id
1	2	3	4	5	6	7	8	9	10	11	12

- 1→event type
 - r →receive
 - + →enqueued
 - “-“ →dequeued
 - d →dropped
- 2→occurred time
 3→input node
 4→output node
 5→packet type(CBR,TCP)
 6→packet size
 7→some flags
 8→flow id
 9→source address
 10→destination address
 11→packet sequence number
 12→id of packet

Example of output trace file from simulation

```
r -t 4.885125825 -Hs 1 -Hd 1 -Ni 1 -Nx 190.00 -Ny 190.00 -Nz 0.00 -
Ne -1.000000 -Nl AGT -Nw --- -Ma 0 -Md 0 -Ms 8 -Mt 0 -Is 0.1 -Id
1.1 -It tcp -Il 1060 -If 0 -Ii 9099 -Iv 30 -Pn tcp -Ps 480 -Pa 0 -
Pf 0 -Po 0
```

Where tcp packet size =1060 and its unit has to do with the definition of MAC in program.

5.7 Simulation Result Analysis and Comparisons

5.7.1) Graph 1 for PMP-Mode and RS-Mode at Different Distances

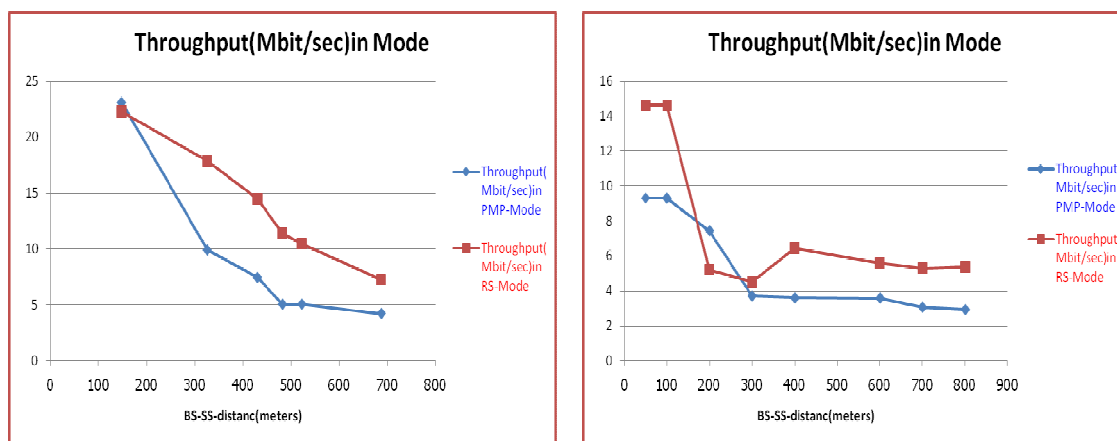


Figure 36: Graph of PMP and RS-Transparent Modes at Different Distances

The graph in figure 36 gives information about throughput of system versus distances between BS and SS in both PMP-mode and RS-Transparent mode.

In PMP-mode

We can see that the throughput in NCTUns-6.0 (about 23 Mbits) starts at a higher level than ns-2 (15 Mbits). This is because if we look inside both simulator engines, there are different methods implemented. NCTUns-6.0 uses a tunnel interface which requires more system memory, while ns-2 uses a discrete-event time-stepped approach requiring less system memory at simulation start. When the distance has been increased, throughput of ns-2 decreases moderately while the throughput of NCTUns-6.0 on the other hand decreases only slightly. Two parameters are involved in this phenomenon:

Firstly, because each simulator implements its MAC functionalities differently according to the previous section, things such as slot size of sub-channel for downlink/uplink or OFDMA symbol time directly affect packet transmission on the system.

Secondly, the propagation model which most affects system throughput because it concerns receiving signals at the receiver. NCTUns-6.0 is set to cost 231 (referenced to IEEE 802.16j standard recommendation) which is an empirical model widely used to study cellular systems and based on extensive measurements with reasonable accuracy within 1 dB for distances ranging from 1 to 20 km. Moreover, it adopts the Rayleigh distribution which is based on a well-studied distribution with special properties that affect the performance of a wireless network. NS-2 on the other hand is set to the Two Ray propagation model because it cannot support cost 231 and its model also considers the simulation field as a flat landscape. Two Ray is too optimistic and at times too conservative and signal power starts out with an R^2 falloff rate and then transitions to a R^4 falloff rate at greater ranges.

In RS-Transparent-mode

The graph for this mode shows that the throughput of NS-2 falls sharply in the first step of increasing distance and remains quite stable till the end while NCTUns-6.0 throughput continually decreases until the end. These can be explained by using path selection in both simulators.

On the one hand, NCTUns-6.0 uses the weight of links to select access link for SS so that, as the distance increases, the signal between BS and SS will decrease until the SS moves nearly to RS and switches its link to RS according to the value of weight as indicated in NCTUns-6.0 simulator section. On the other hand, ns-2 uses matrix vector of node_ID and flow_ID to select the link based on location of node not weight. This means that SS will switch its link from BS to RS if its matrix vector value is higher than RS, i.e. it can only do this if located further from BS than from RS.

Finally, we can prove that networks with RS can improve system throughput better than PMP-mode. This is because RS amplifies the signal between BS→SS links and re-sends it to SS so that SS still receives a better signal even when the distance increases compared to PMP-mode.

5.7.2) PMP-Mode with Increasing the number of SSs(max SSs=20 in this case)

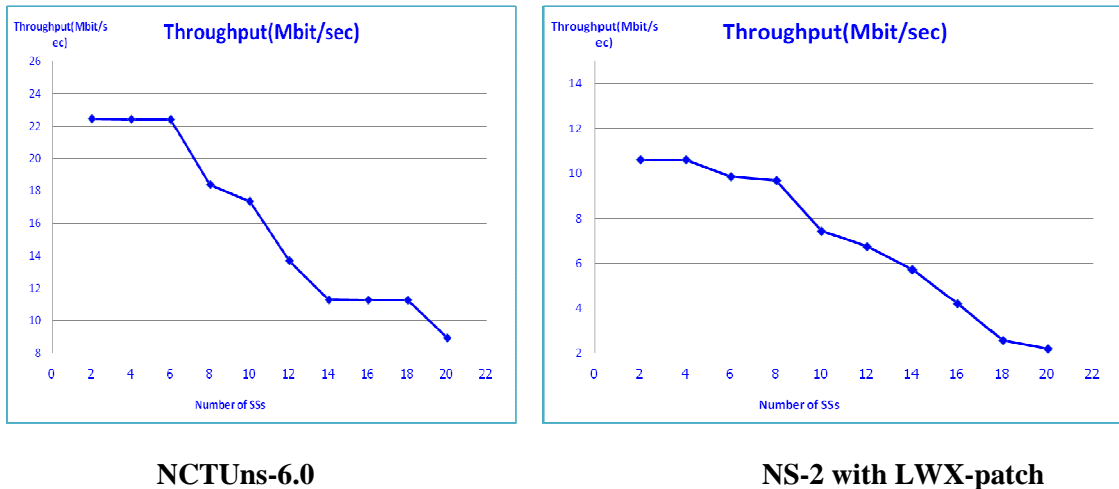


Figure 37: Graph of PMP-mode with increasing numbers of SSs

In figure 37, we try to increase the number of users in PMP-mode and plot the system performance between both simulators. As we can see in the graph, both their performances continue to decrease as the number of SSs increases but ns-2 gives better performance than NCTUns-6.0, because of different algorithms for flow queue implementation. NS-2 has been implemented by round-robin scheduling which has a separate queue for every data flow, so a data flow can be identified by its source and destination address. The algorithm lets every active data flow (that has data packets in the queue) to take turns at transferring packets over a shared channel in a periodically repeated order and simple functions embedded in ns-2 are used to generate artificial traffic. Furthermore, only fake data is used. In contrast, NCTUns-6.0 uses real-life protocol stacks which are directly executed to generate realistic traffic and real data payloads are carried in each transmission so packets need to be read out of the kernel and then written into the kernel, i.e. a lot of system calls need to be made. From these explanations, one can understand the tendency in the graph of NCTUns-6.0 to perform a little bit lower than ns-2 as the number of SSs increases.

5.7.3) RS-Mode with increasing number of RS while network size SSs=20

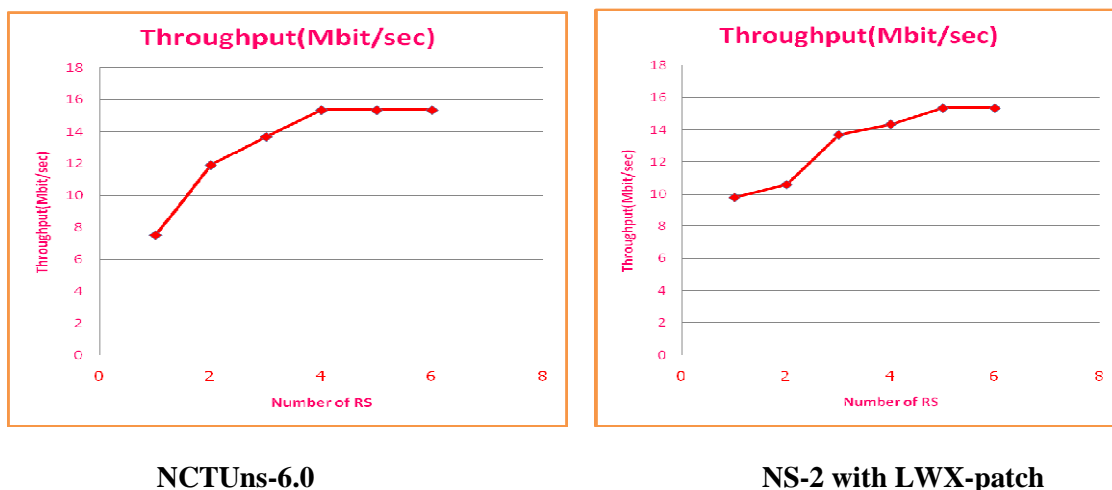


Figure 38: Graph of RS-Mode with increasing numbers of RSs

In figure 38, we want to study the effect of RS numbers in a large system so we use 20 SSs and insert 6 RS-Transparent into the network (see network topology in network creation section). The graph shows that RS increase system throughput both in ns-2 and NCTUns-6.0 but when the number reaches 5 RSs, the throughput is quite stable. This can be explained as follows: when the number of RSs increases to a certain number the system throughput will not improve because an increasing number of RSs on the network also increases the signals, causing interference on the system. Consequently, it reduces overall system performance. In the ns-2 simulator, the increase in throughput is less than in NCTUns-6.0 this because ns-2 uses a Round Robin algorithm, making the system have more packets in its queue while NCTUns-6.0 uses the weight value to select paths for users so RS will serve groups of user separately based on their weights.

5.7.4) SNR of Different Directional Antenna Implementations

When using directional antennas in the network, the transmission/receiving direction of the antenna should be properly set to obtain the best gain, so that a better communication quality can be achieved.

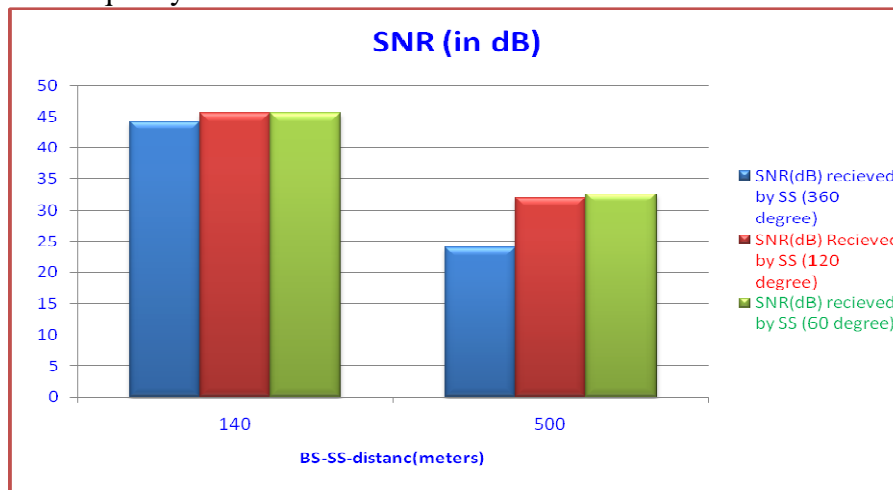


Figure 39: Graph of PMP-Mode with different Antenna Types

Figure 39 shows that when the distance between BS and SS is shortest (140 m in this simulation), all antennas give very similar SNR but once SSs move further away from BS (at 500 m), 60- and 120-degree directional antennas give better SNR than a 360-degree omni-directional antenna. The gain is a little higher with a 60-degree directional antenna than 120-degree directional antenna because of greater concentration of radiation in a certain direction and reduced interference from unwanted sources.

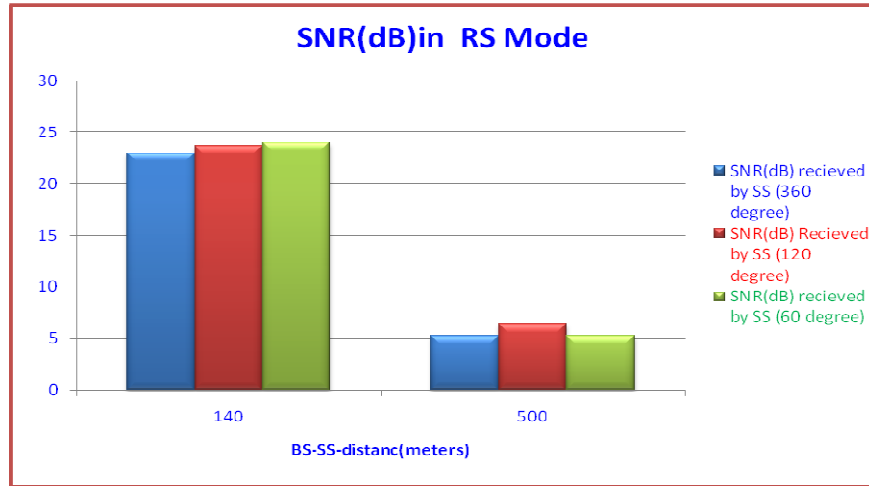


Figure 40: Graph of RS-Mode with Different Antenna Types

In RS-mode, when we applied directional antennas to RS-Transparent mode and monitored their SNR at different BS→SS distances, at a distance of 140 m most directional antennas gave very similar SNR values, only slightly increased from omni-directional: about 23, 24 and 24.5 for omni-directional, 120 degree and 60 degree directional antennas respectively. On the other hand, at a longer distance (500 m) the 120 degree directional antenna gave a little bit higher than the rest, possibly implying that the scanning angle of the 120 degree antenna is wider than the 60 degree one at a higher range. Unlike in PMP-Mode, at 500 m, SNR values of RS-Transparent mode significantly decrease because of the interference and the front-to-back ratio between BS →RS→SS depending on the radiation pattern of the energy left behind the antenna or wasted. The higher the gain of the antenna, the higher the front-to-back ratio. This problem is also very important for network design in order to install and measure to avoid this problem in RS-mode but it is out of the scope of this thesis.

CHAPTER 6

AN EXAMPLE OF COMPARISON AND COST ANALYSIS BETWEEN MULTIHOP RELAY AND SINGLE HOP WIMAX

In the previous section, it has been shown that incorporation of relay into the WiMAX network improves coverage and throughput performance. However, from the operator perspective, the economic cost associated with the utilization of relays needs to be analyzed. This is the aim of this section.

6.1) Cost Analysis Methodology

As the cost of network building depends on the network scenarios, we present two network scenarios for our cost analysis and compare them with a conventional network building method. The different stages of cost analysis can be explained by presenting the factors in the flow diagram below.

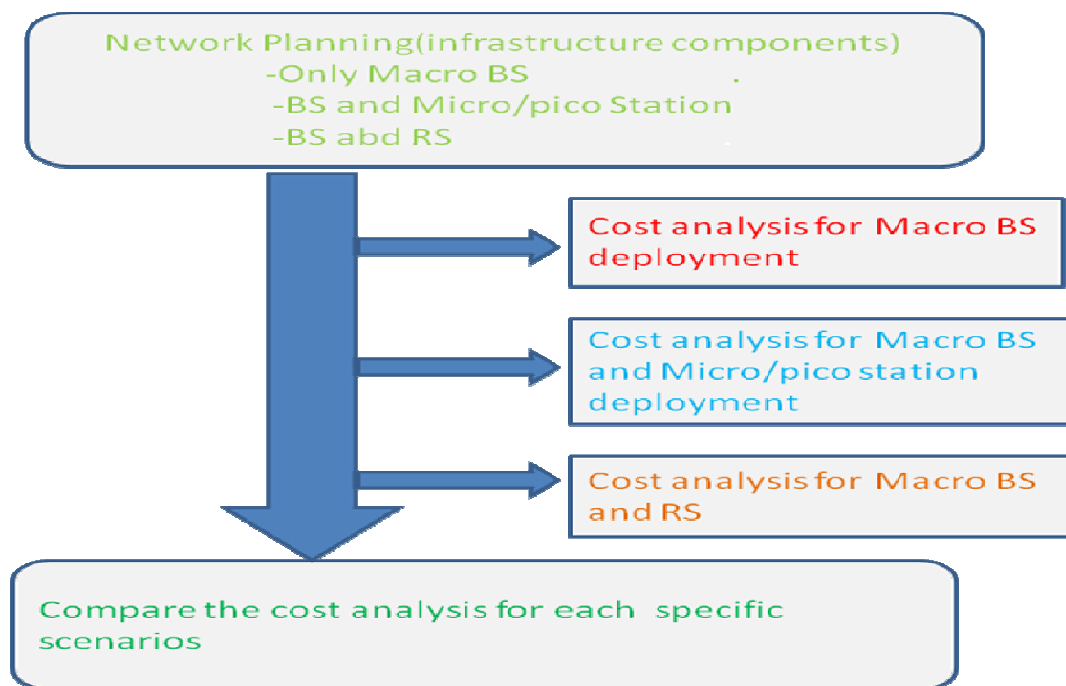


Figure 41: Cost Analysis Methodology Diagram

6.2) Cost Components of Network

Each component of the network has a different cost. Generally, in terms of network planning and dimensioning, these can be evaluated in two groups.

- 1) CAPEX (the one-off costs that have to be paid at the time of deployment)
- 2) OPEX (the costs that occur periodically)

Both CAPEX and OPEX include payments for spectrum access, network deployment, operation and maintenance. For the same deployment scenario CAPEX

and OPEX will vary based on different clutter categories (Dense Urban, Urban, sub Urban or Rural) and will also vary from region to region depending on the economics of the country.

With the knowledge of the absolute cost associated with each of the CAPEX and OPEX elements for any infrastructure deployment, the total cost of network deployment can be calculated.

Table 11 Example CAPEX cost elements for scenarios

Cost element	Unit cost (k€)	Assumptions / Remarks
Macro BS equipment	50	Three sectors, air conditioning, batteries, container, antennas, cables, etc.
Micro BS equipment	5	Omni-directional, small footprint, low transmit power (no cooling)
RS	7	Fixed decode-and-forward RS with own RRM and scheduling, more expensive than Micro BS due to technological innovation required. No wired backhaul connection. Otherwise, similar hardware characteristics as micro BS.
Macro BS site acquisition and deployment	58	Identification of site, initial fees and taxes, and required structural changes
Micro BS site acquisition and deployment	6	Small footprint, outdoor installation
RS site acquisition and deployment	4	Small footprint, no backhaul
Gateway	100	RAN interface to core network, can serve a large number of BSs
Centralized RRM servers	100	One central RRM server per RAN, distributed RRM functions reside in BSs
Macro fixed line connections	0.15	Connection to fiber optic access network
Micro fixed line connections	0.05	Connection to mass-market ADSL line
Initial radio planning and network optimization	1.6	per macro or micro BS
Total CAPEX		
Macro Base Station	Micro Base Station	Relay Base Station
€ 309,100	€ 12,750	€ 11,000

Table 12 Example OPEX cost elements for scenarios

Cost element	Periodic cost (k€/yr)	Total cost (k€) ^a in 10 years	Assumptions / Remarks
Macro BS site rent, maintenance, power and operation	17	132	Includes software upgrades
Micro BS site rent, maintenance, power and operation	3	23.2	Small footprint, no cooling or back-up batteries
RS site rent, maintenance, power and operation	2	15.6	Small footprint, no cooling or back-up batteries
Macro BS fixed line connections	20	156	Professional high-capacity failsafe backhaul line
Micro BS fixed line connections	0.8	6.3	Mass-market DSL

a. The total OPEX costs are represented by their net present values, assuming a lifetime of 10 years and a discount rate of 6%.

Total OPEX					
Macro Base Station		Micro Base Station		Relay Base Station	
€ 37,000	Over 100 years € 288,000	€ 3,800	Over 10 years 29,500	2,000	Over 10 years 15,600

reference [32]

Backhaul expenses present a significant part of operators' cost of ownership. Any possibilities that eliminate wired backhaul will ultimately enable operators to lower costs without compromising on service quality or performance.

6.3) An Example Network Scenario for cost analysis and Design

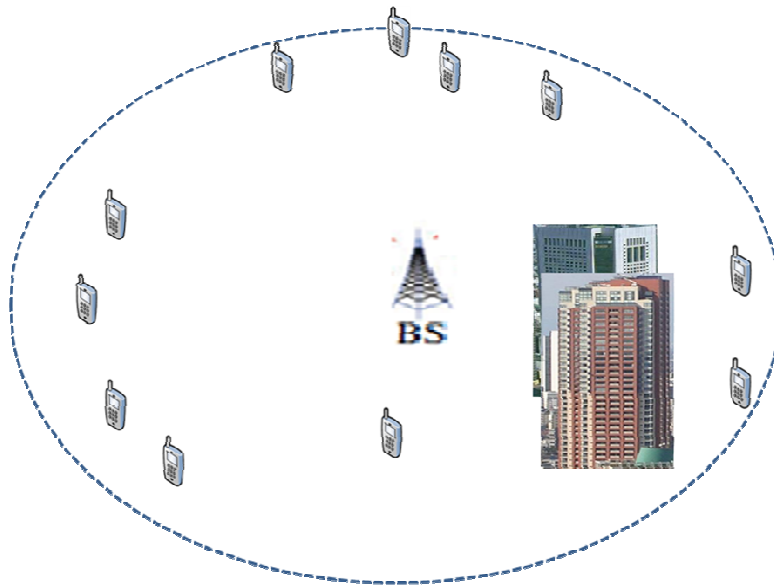


Figure 42: An Example Network Scenario for cost analysis and Design

Assumptions:

- 1) From network scenario above, network operator “A” wants to operate and service its customers from the beginning.
- 2) No operated networks have existed previously because we want to show the pure differential cost (if there had been an earlier wireless network, then the implementation could be modified or some parts of the network could be upgraded which is not our purpose).
- 3). Operator “A” is a WiMAX network operator.

Customer Requests:

- 1). All customers want to connect to high speed broadband Internet so operator “A” cannot build a 2G network; it must therefore be 3G.
- 3). As low a cost as possible.

Alternative Problem Solutions:

Generally, depending on the network scenario, telecommunications engineers have 3 methods to meet this requirement.

Solution 1:

Using the network topology shown below but this does not look like a good solution because with 3 BSs the cost will be very high, according to the CAPEX and OPEX data. Moreover, it may cause interferences between base stations that will decrease signal quality.

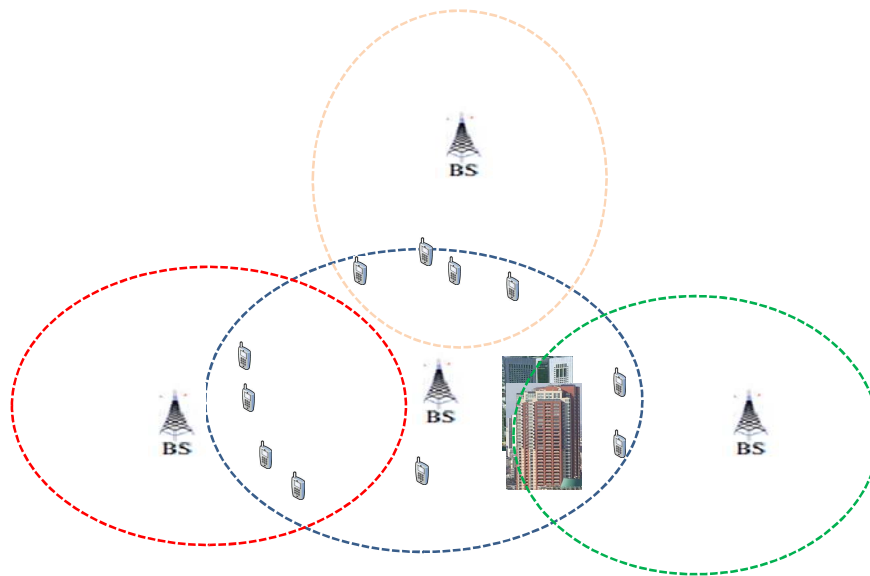


Figure 43: Solution 1 for cost analysis and Design

Cost Calculation:

As we need 3 BSs, referring to the BS price in terms of CAPEX and OPEX, the total cost = $3 \times 344,100 = \text{€}1,032,300$ and $3 \times 288,000 = \text{€ } 864,000$ over 10 years.

Solution 2:

Using one base station and about 6 Micro Base Stations for shadowing zone and coverage hole to increase link bandwidth. This method is in quite common use in 2G networks but the cost of some equipment, leasing, and backhaul is still high.

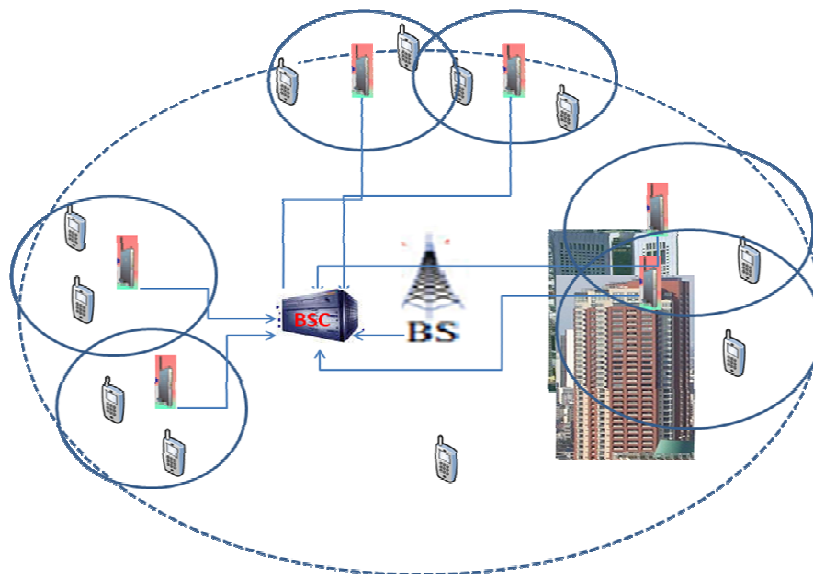


Figure 44: Solution 2 for cost analysis and Design

Cost Calculation:

Total Cost = 1BS+6MBS = (€ 344,100 + 6 x € 16,550)= **€ 443,400** and 177,000 x 6 + 288,000 = **€ 1,062,000** over 10 years.

Solution 3:

Using multihop relay network (IEEE 802.16j), this method will be lower cost than above methods because of the advantages of RS over Pico Cell in CAPEX and OPEX data as indicated before.

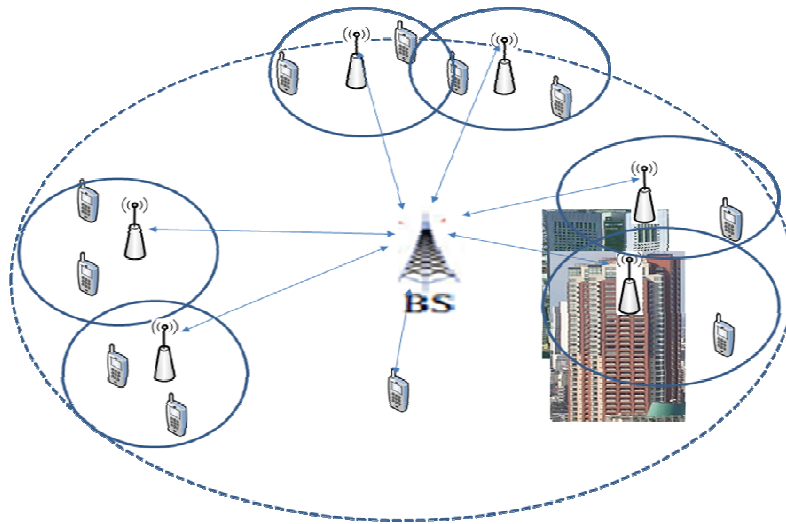


Figure 45: Solution 3 for cost analysis and Design

Cost Calculation:

Total Cost = 1BS+6RS = (€ 344,100 +6 x 13,000) =**€ 351,900** and 15,600 x 6 = 93,600 + 288,000 = **€ 381,600** over 10 years.

Conclusion:

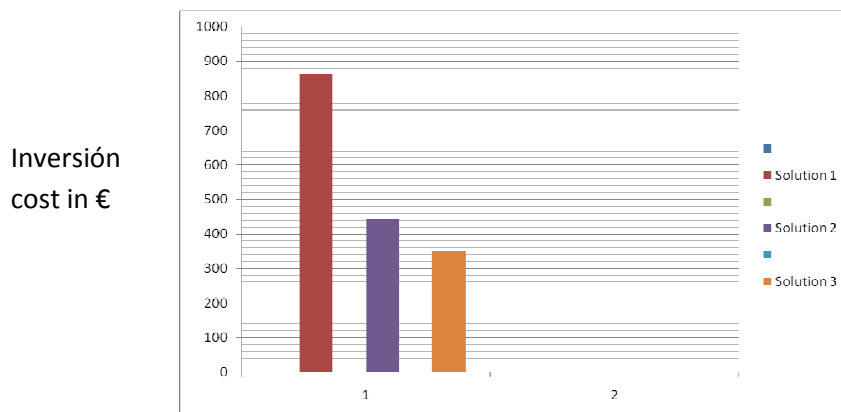


Figure 46: Cost comparison for 3 solutions

We have provided very simple examples because we wanted to see the cost difference between using RS and Micro Base Station, but it is based on standard

methods. In practical design terms, there may be some extra constraints to be considered and slightly increased cost calculation.

We can see from these three methods that the multihop relay for WiMAX IEEE 802.16j is attractive for the operator because it has many advantages over the traditional network planning and design: faster to build, higher quality network and lower cost for example.

With great application potential, relay technologies have been actively studied and considered in the standardization process of next-generation mobile communication systems, such as 3GPP LTE-Advanced and IEEE 802.16j (multihop relays for WiMAX standards).

CHAPTER 7

CONCLUSION AND FUTURE WORK

Conclusion

Standard IEEE 802.16, supported by the WiMAX forum, is a promising radio technology that offers fixed and mobile BWA. WiMAX promises high performance similar to that of wired systems and it allows coverage of large geographic regions. One key feature of WiMAX is the support of multihop communication between base station and subscribers (IEEE 802.16j). The results presented in this thesis motivated the IEEE 802.16j network to increase capacity in base station area by simulating various network scenarios on different network simulators.

The thesis describes a comprehensive system concept to compare fully the differences of capacity in different modes of operation in the WiMAX system. Unlike traditional mode of operation (PMP-mode), RS affects a large portion of the IEEE 802.16j system: multihop communication is required in the PHY layer to form new framing through the new PHY layer specified in this IEEE 802.16j. Simulated models are used to evaluate the DL of the OFDMA based IEEE 802.16j system in terms of cellular coverage and throughput. It compares single-hop and multi-hop scenarios and illustrates the advantages of multi-hop operation. The network simulators comprise all aspects of the capacity in WiMAX systems affected by RS-mode of operation.

The performance evaluation results gained by means of computer simulation show the potential gains from multihop technologies in terms of throughput, and capacity of the RS enhanced in a WiMAX system. The major parameters that influence the system performance are identified and evaluated.

Future Work

WiMAX is seen by the current 3G mobile operators as a competitor. Most of these service providers have remained focused on current services and are not participating in WiMAX trials or deployments. The 3GPP/3GPP2 mobile industry has responded to development of WiMAX and other moves for open access by accelerating 3GPP-LTE. LTE has been positioned as the evolution of 3G to universal terrestrial radio (UTRAN), while to opponents WiMAX is known as a broadband wireless access system. WiMAX and LTE are converging upon 4G technology that includes seamless handover, QoS, security, and higher-level compatibility such as user authentication and billing across still dissimilar low-level interface networks. The greatest advantage of WiMAX over other competitor technologies is the timing. At the moment, Mobile WiMAX is ready to be deployed and to start serving the insatiable demand for wireless broadband, while LTE is at least 2 years away. Although most traditional cellular mobile operators are not backing WiMAX, there are a considerable number of global service providers such as; *Clear wire, Sprint and Vodafone, etc*, and reputable companies such as; *Intel, Dell, Nokia, Siemens, Motorola, NEC and Samsung, etc*, who support WiMAX policies.

As Multihop WiMAX is a novel standard, not many certified products are available on the market and there are not many trials and deployments under way; it can be seen as a topic that has huge research potential. Many specialists believe that the future 4G platform will be formed as a combination of LTE and WiMAX standards. So

the most controversy would focus on the global market share for each of these mobile broadband technologies. Therefore, each innovative service provider is competing to include state-of-the-art technologies in their supporting standard as soon as they appear.

Advanced releases of Broadband WiMAX will implement a considerable number of innovative technologies such as; SIMO, MIMO, AAS and beam forming. Utilization of each of these techniques can affect the capacity by increasing the total throughput and resource efficiency, via different signaling procedures. On the other hand, new modifications such as support for higher speeds (IEEE 802.16m) are an example of applications that will restrict the system's actual throughput. Therefore, enhancing the capacity of the system presented in this thesis based on these additional features can be seen as an interesting future work. Furthermore, the scheduling process and mobility handling procedures will be updated constantly to meet the QoS demanded by WiMAX applications. Therefore, I am also interested in the traffic modeling scheme presented as it may be the beginning of further developments to guarantee subscribers' data-rates and this would be an area of great interest for my doctoral thesis.

APRENDICE: A

10/350	9.69379418	11/349	9.62671561
12/348	9.55322571	13/347	9.47331814
14/346	9.38698596	15/345	9.29422163
16/344	9.19501698	17/343	9.08936326
18/342	8.97725106	19/341	8.85867035
20/340	8.73361046	21/339	8.60206008
22/338	8.46400726	23/337	8.31943940
24/336	8.16834327	25/335	8.01070498
26/334	7.84651005	27/333	7.67574336
28/332	7.49838921	29/331	7.31443136
30/330	7.12385298	31/329	6.92663681
32/328	6.72276509	33/327	6.51221970
34/326	6.29498217	35/325	6.07103380
36/324	5.84035573	37/323	5.60292903
38/322	5.35873486	39/321	5.10775455
40/320	4.84996979	41/319	4.58536278
42/318	4.31391642	43/317	4.03561454
44/316	3.75044209	45/315	3.45838540
46/314	3.15943247	47/313	2.85357323
48/312	2.54079984	49/311	2.22110704
50/310	1.89449243	51/309	1.56095682
52/308	1.22050454	53/307	0.87314373

The Gain Pattern of the 60-degree Directional Antenna Provided by NCTUns

Degree	Gain (dBi)	Degree	Gain (dBi)
0	10.01294452	1/359	10.00975522
2/358	10.00018706	3/357	9.98423924
4/356	9.96191042	5/355	9.93319875
6/354	9.89810182	7/353	9.85661667
8/352	9.80873981	9/351	9.75446718

54/306	0.51888660	55/305	0.15774961
56/304	-0.21024640	57/303	-0.58507627
58/302	-0.96671075	59/301	-1.35511688
60/300	-1.75025882	61/299	-2.15209902
62/298	-2.56059997	63/297	-2.97572664
64/296	-3.39744986	65/295	-3.82575085
66/294	-4.26062725	67/293	-4.70210113
68/292	-5.15022937	69/291	-5.60511737
70/290	-6.06693667	71/289	-6.53594808
72/288	-7.01253175	73/287	-7.49722645
74/286	-7.99078140	75/285	-8.49422510
76/284	-9.00895785	77/283	-9.53687808
78/282	-10.08055809	79/281	-10.64349440
80/280	-11.23047450	81/279	-11.84813303
82/278	-12.50583056	83/277	-13.21711414

84/276	-14.00230068	85/275	-14.89342343
86/274	-15.94475128	87/273	-17.25871164
88/272	-19.06608410	89/271	-22.10439603
90/270	-166.66272129	91/269	-52.10439603
92/268	-49.06608410	93/267	-47.25871164
94/266	-45.94475128	95/265	-44.89342343
96/264	-44.00230068	97/263	-43.21711414
98/262	-42.50583056	99/261	-41.84813303
100/260	-41.23047450	101/259	-40.64349440
102/258	-40.08055809	103/257	-39.53687808
104/256	-39.00895785	105/255	-38.49422510
106/254	-37.99078140	107/253	-37.49722645
108/252	-37.01253175	109/251	-36.53594808
110/250	-36.06693667	111/249	-35.60511737

112/248	-35.15022937	113/247	-34.70210113
114/246	-34.26062725	115/245	-33.82575085
116/244	-33.39744986	117/243	-32.97572664
118/242	-32.56059997	119/241	-32.15209902
120/240	-31.75025882	121/239	-31.35511688
122/238	-30.96671075	123/237	-30.58507627
124/236	-30.21024640	125/235	-29.84225039
126/234	-29.48111340	127/233	-29.12685627
128/232	-28.77949546	129/231	-28.43904318
130/230	-28.10550757	131/229	-27.77889296
132/228	-27.45920016	133/227	-27.14642677
134/226	-26.84056753	135/225	-26.54161460
136/224	-26.24955791	137/223	-25.96438546
138/222	-25.68608358	139/221	-25.41463722
140/220	-25.15003021	141/219	-24.89224545
142/218	-24.64126514	143/217	-24.39707097
144/216	-24.15964427	145/215	-23.92896620
146/214	-23.70501783	147/213	-23.48778030
148/212	-23.27723491	149/211	-23.07336319
150/210	-22.87614702	151/209	-22.68556864
152/208	-22.50161079	153/207	-22.32425664
154/206	-22.15348995	155/205	-21.98929502
156/204	-21.83165673	157/203	-21.68056060

158/202	-21.53599274	159/201	-21.39793992
160/200	-21.26638954	161/199	-21.14132965
162/198	-21.02274894	163/197	-20.91063674
164/196	-20.80498302	165/195	-20.70577837
166/194	-20.61301404	167/193	-20.52668186
168/192	-20.44677429	169/191	-20.37328439
170/190	-20.30620582	171/189	-20.24553282
172/188	-20.19126019	173/187	-20.14338333
174/186	-20.10189818	175/185	-20.06680125
176/184	-20.03808958	177/183	-20.01576076
178/182	-19.99981294	179/181	-19.99024478
180	-19.98705548		

The Gain Pattern of the 120-degree Directional Antenna Provided by NCTUns

Degree	Gain (dBi)	Degree	Gain (dBi)
0	5.88539066	1/359	5.88472915
2/358	5.88274425	3/357	5.87943472
4/356	5.87479855	5/355	5.86883292
6/354	5.86153415	7/353	5.85289775
8/352	5.84291841	9/351	5.83158993
10/350	5.81890525	11/349	5.80485642
12/348	5.78943460	13/347	5.77262998
14/346	5.75443184	15/345	5.73482844
16/344	5.71380703	17/343	5.69135381
18/342	5.66745391	19/341	5.64209131
20/340	5.61524882	21/339	5.58690803
22/338	5.55704926	23/337	5.52565148
24/336	5.49269228	25/335	5.45814777
26/334	5.42199253	27/333	5.38419950
28/332	5.34473993	29/331	5.30358324
30/330	5.26069697	31/329	5.21604661
32/328	5.16959549	33/327	5.12130468
34/326	5.07113279	35/325	5.01903585
36/324	4.96496710	37/323	4.90887682
38/322	4.85071210	39/321	4.79041660

40/320	4.72793032	41/319	4.66318929
42/318	4.59612524	43/317	4.52666529
44/316	4.45473156	45/315	4.38024068
46/314	4.30310339	47/313	4.22322396
48/312	4.14049961	49/311	4.05481982
50/310	3.96606562	51/309	3.87410869
52/308	3.77881044	53/307	3.68002091
54/306	3.57757751	55/305	3.47130367
56/304	3.36100717	57/303	3.24647830

58/302	3.12748773	59/301	3.00378402
60/300	2.87509070	61/299	2.74110295
62/298	2.60148357	63/297	2.45585830
64/296	2.30381027	65/295	2.14487325
66/294	1.97852366	67/293	1.80417077
68/292	1.62114483	69/291	1.42868227
70/290	1.22590750	71/289	1.01180983
72/288	0.78521430	73/287	0.54474406
74/286	0.28877141	75/285	0.01535296
76/284	-0.27785758	77/283	-0.59372901
78/282	-0.93582024	79/281	-1.30862089
80/280	-1.71790704	81/279	-2.17128493
82/278	-2.67905630	83/277	-3.25566463
84/276	-3.92226369	85/275	-4.71164926
86/274	-5.67876416	87/273	-6.92660771
88/272	-8.68641770	89/271	-11.69605616
90/270	-156.24480078	91/269	-26.69605616
92/268	-23.68641770	93/267	-21.92660771
94/266	-20.67876416	95/265	-19.71164926
96/264	-18.92226369	97/263	-18.25566463
98/262	-17.67905630	99/261	-17.17128493
100/260	-16.71790704	101/259	-16.30862089
102/258	-15.93582024	103/257	-15.59372901
104/256	-15.27785758	105/255	-14.98464704
106/254	-14.71122859	107/253	-14.45525594
108/252	-14.21478570	109/251	-13.98819017
110/250	-13.77409250	111/249	-13.57131773
112/248	-13.37885517	113/247	-13.19582923

114/246	-13.02147634	115/245	-12.85512675
116/244	-12.69618973	117/243	-12.54414170
118/242	-12.39851643	119/241	-12.25889705
120/240	-12.12490930	121/239	-11.99621598
122/238	-11.87251227	123/237	-11.75352170
124/236	-11.63899283	125/235	-11.52869633
126/234	-11.42242249	127/233	-11.31997909
128/232	-11.22118956	129/231	-11.12589131
130/230	-11.03393438	131/229	-10.94518018
132/228	-10.85950039	133/227	-10.77677604
134/226	-10.69689661	135/225	-10.61975932
136/224	-10.54526844	137/223	-10.47333471
138/222	-10.40387476	139/221	-10.33681071
140/220	-10.27206968	141/219	-10.20958340
142/218	-10.14928790	143/217	-10.09112318
144/216	-10.03503290	145/215	-9.98096415
146/214	-9.92886721	147/213	-9.87869532
148/212	-9.83040451	149/211	-9.78395339
150/210	-9.73930303	151/209	-9.69641676
152/208	-9.65526007	153/207	-9.61580050
154/206	-9.57800747	155/205	-9.54185223
156/204	-9.50730772	157/203	-9.47434852
158/202	-9.44295074	159/201	-9.41309197
160/200	-9.38475118	161/199	-9.35790869
162/198	-9.33254609	163/197	-9.30864619
164/196	-9.28619297	165/195	-9.26517156
166/194	-9.24556816	167/193	-9.22737002
168/192	-9.21056540	169/191	-9.19514358
170/190	-9.18109475	171/189	-9.16841007
172/188	-9.15708159	173/187	-9.14710225
174/186	-9.13846585	175/185	-9.13116708
176/184	-9.12520145	177/183	-9.12056528
178/182	-9.11725575	179/181	-9.11527085
180	-9.11460934		

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