KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI, GHANA

LINK LEVEL PERFORMANCE EVALUATION OF RELAY-BASED WIMAX NETWORK

By

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Declaration

I hereby declare that, except for specific references which have been duly acknowledged, this work is the result of my research towards the MSc. Telecommunication Engineering, and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been submitted either part or whole for any other degree elsewhere.

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Dedication

To my dear wife, Joyce Ayinbono Anafo.

Abstract

The recent demand for higher data rate services from wireless network users is overwhelming. Social media influx as well as the proliferation of smart-phones, tablet computers and other newly improved wireless devices has erupted a new trend in wireless network traffic where average capacity and speed is no longer appreciable. In order to cope with this trend in traffic requirement, wireless network operators are considering a gradual rollover of an existing third generation (3G) network to a fourth generation (4G) network with orthogonal frequency division multiple access (OFDMA) based technologies such as

Fourth Generation Long Term Evolution (4G LTE) and Worldwide Interoperability for Microwave Access (WiMAX). Relay technology promises appreciable network throughput and coverage enhancement which is required for these systems to function to their optimum performance. This thesis is focused on analyzing the link-level performance of a relay-based WiMAX network under varying conditions. The study involves a hypothetical view as well as MATLAB simulations with results generated which are used to judge the benefit of relay deployment. This is aimed at solving pertinent issues such as coverage holes and cell edge problems which are associated with classical non-relay based cellular networks. We evaluated the performance of relay and direct link communication in terms of BER (Bit Error Rate), spectral efficiency and capacity. We investigated the effect of multipath fading on link performance. We also investigated the effect of user speed on performance. Our results however indicate improved performance in terms of BER, spectral efficiency and capacity in the downlink when relays are used.

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Chapter 1

Introduction

1.1 Background and Research Motivation

Wireless communication has experienced enormous growth in the Telecommunication industry over the past decades. Presently, there are over six billion eight hundred million mobile cellular subscribers globally according to the 2014 International Telecommunication Union (ITU) report. This has mobile-broadband subscriptions approaching two billion three hundred million in 2014 with 55percent in developing countries. [1][2].

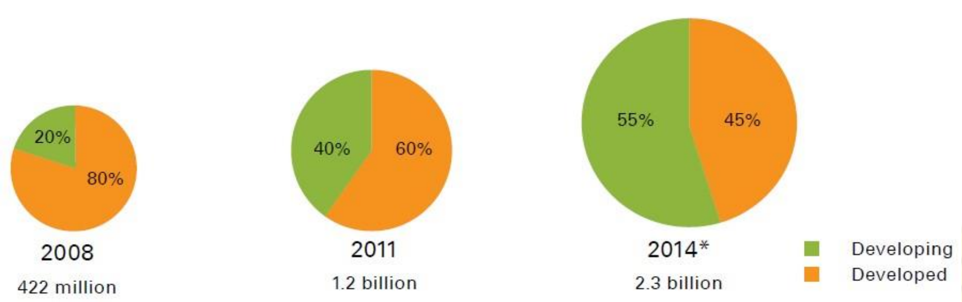


Figure 1.1 Growth charts Mobile-broadband subscription
Source: ITU World Telecommunication/ICT Indicator database

This phenomenal trend in growth poses great engineering challenge that only requires efficient and reliable wireless design.

Third Generation (3G) wireless network systems have been the most widely deployed in recent years across countries. This has aided entirely new ways of communication, information access, conducting business and entertainment; while liberating users from slow, bulky equipment and immobile points of access. The integration of voice, video and data communication into one network has progressively drifted the demand from wireless voice services to high speed bandwidth intensive data services [3]. From some point of view, 3G has been the right bridge for mobile telephony and the internet. Third Generation (3G) wireless network technologies like HSPA and WCDMA have permitted the making of video calls whiles simultaneously accessing the internet. Also, playing interactive games anywhere anytime has been made possible with nominal data rates of up to 2.05 Mbps for stationery devices, 384 Kbps for slowly moving devices and 128 Kbps for fast moving devices [4][5].

While the potential of 3G is speedily being transformed into reality, efforts are far advanced into research with focus on realising systems that can provide even higher data rates and allin-one connectivity which is more capable beyond 3G expectation.

The progressive development of mobile communication systems over the years and projections are depicted in figure 1.2. This clearly indicates that, mobility and data rates are the main determinants that influence the advancement in wireless systems.

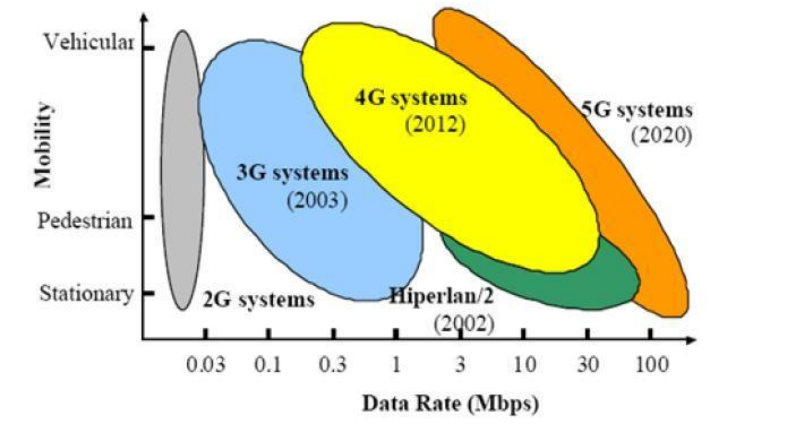


Figure 1.2 Wireless Systems advancement and projections [70]

Before we delve further into the description of the next generation 4G, we first take a snap view of the progression of radio access depicted in figure 1.3. The technology for the first generation was analog permitting only voice communication without data access. The second generation launched in 1995 was based on digital technologies which allowed for data access but with low transmission rate. This was not enough for multimedia services. Multimedia services were accommodated in the third generation mobile system which was launched around 2000 [4].

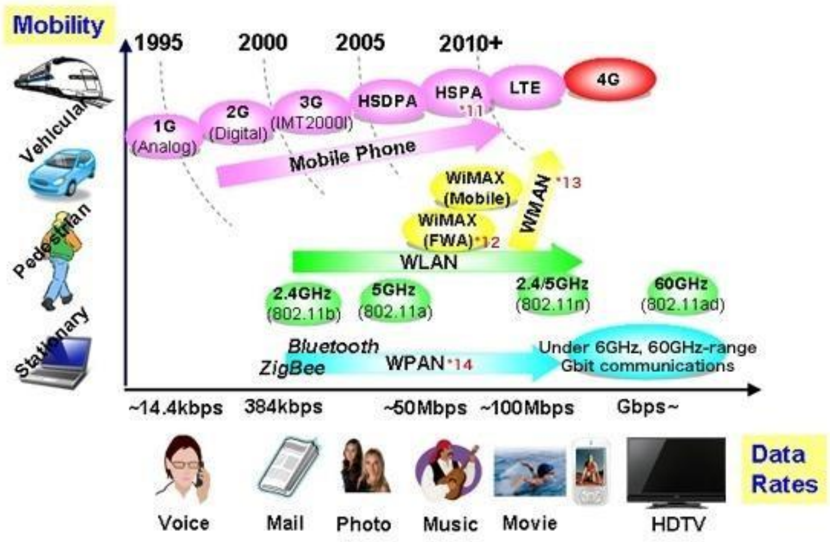


Figure 1.3 Trend of advancement in wireless communication [71]

The recent development of sophisticated mobile devices and the tremendous bandwidth they require for their efficient use is overwhelming. Furthermore, the increased utilization of internet based social media and some bandwidth intensive websites such as Youtube, has ignited the fervent need for even higher speed data networks with higher information bit rates [3][7]. High throughput is a key requirement particularly in the downlink due to the expected increase in volumes of data files downloads from servers and websites.

The convergence of Wireless broadband technologies and 3G is expected to meet these demands of high speed data transmission and has been classified under 4G (Fourth Generation) systems [5]. 4G networks are expected to offer speed of 100 Mbps in macro-cells and 1 Gbps in micro-cellular networks. Broadband systems are the regular option expected to render appreciably high data rates, but it cost network operators so much for the required spectrum [8]. Consequently, in designing a wireless air interface scheme, spectrum efficiency is invariably a significant challenge. Complex receivers are normally required in broadband systems to cater for the significant amount of resolvable multipath in a frequency selective channel [8].

However, 4G seeks to provide optimum connectivity on any device through any network at anytime and anywhere [6]. Commercial deployment of these systems is in progress and is replacing 3G technology with features which extend the capabilities of the existing 3G networks by permitting a wide range of applications with enhanced comprehensive access.

Eventually, 4G networks will incorporate broadband wireless utilities, for example HDTV (High Definition Television) with speed of 4-20 Mbps and computer network applications with speed of 1 - 100 Mbps [7]. Such a feature is to appropriate 4G networks to substitute several utilities of WLAN systems since cost involved for 3G networks to accommodate this application is significantly high. This is due to the relatively too low spectral efficiency of 3G networks which is incapable of supporting high data rates at low cost [3]. As a result, enhanced spectral efficiency is one of the principal emphases of 4G system which has been significantly improved to offer optimum broadband access.

Additionally to high data rates, 4G systems are required to offer higher QoS (Quality of Service) of about 98 – 99.5% which is superior to that of 3G cellular systems which aimed to attain 90 – 95% coverage [5]. This means, the network system is required to be more adaptive and flexible to be able to attain such level of QoS. For instance, some applications require network connectivity to be maintained than achieving a high data rate. Therefore, data rate has to be dropped if transmission path is poor to maintain the link. This might cause data rate to vary from a very low speed of 1kbps in extremely poor transmission path through to as high as 20 Mbps when the path is in good condition [7]. Otherwise, additional resources are allocated to users whose transmission path is poor for applications that require fixed data rates.

The principal summary of 4G is to examine and produce an improved air interface with high capacity capable of accommodating high mobility, high data rates and high QoS. This is achieved within a suit of protocols and technologies summarised as follows:

- High peak data rate operation obtained in a wide frequency band with orthogonal frequency division multiplexing (OFDM).
- Improved spectral efficiency (above 5 bit/s/Hz) with the aid of multiple input multiple output (MIMO) multiplexing and higher-order modulation.
- Improved data rate at the cell edge via low-rate channel coding, Interference coordination/cancellation and Transmitter beam-forming/adaptive array antenna reception.
- Enhanced Multimedia operations with low-delay and highly reliable radio transmission using error control techniques achieved using hybrid automatic repeat request (HARQ).
- Flexible radio resource allocation based on the required transmission rate and QoS with the aid of Orthogonal frequency division multiple access (OFDMA) and Frequency and time domain scheduling.
- Operation conditions support a maximum terminal speed of 300 km/h with advanced channel estimation.

There is a great challenge of transmitting high data rate over a wireless link. This is basically influenced by three limiting factors which are co-channel interference, delay spread and multipath fading [8]. Multi-carrier technique of transmission has been regarded as ever promising and suitable for high data rates as well as providing appreciable spectral efficiency with relatively low implementation cost [5]. Via this scheme of transmission, high rate serial data stream can be divided into several low rate parallel sub-streams of data modulated on parallel subcarriers. Consequently, the effect of inter symbol interference (ISI) and delay spread is reduced significantly on the account that the symbol rate on each subcarrier is considerably less than the initial serial symbol rate [8]. OFDM as a distinctive example of multicarrier modulation has been vastly employed in the field of digital communication over a couple of years [28]. However, the challenge of implementation techniques, algorithms and theory has sustained a persistent interest in the research community. This is manifested in the degree of amount of publications appearing in conferences and journals over the years.

Presently, there exist a significant number of wireless transmission technologies which are allotted over different network categories subject to the network scale ranging through PAN, WLAN, WMAN and WAN. The deployment of wireless networks technology is based on the demand for higher data transmission rates. Technologies that promise to provide higher data rates are rapidly enticing more vendors and operators. One of the most capable prospects of such arising technologies is WiMAX (Worldwide Interoperability for Microwave Access) described by the IEEE 802.16 standard [9].

WiMAX is intended for wireless metropolitan area networks (WMAN) providing broadband wireless access up to 50 Km for fixed stations and 5-15 Km for mobile stations [9][10][11].

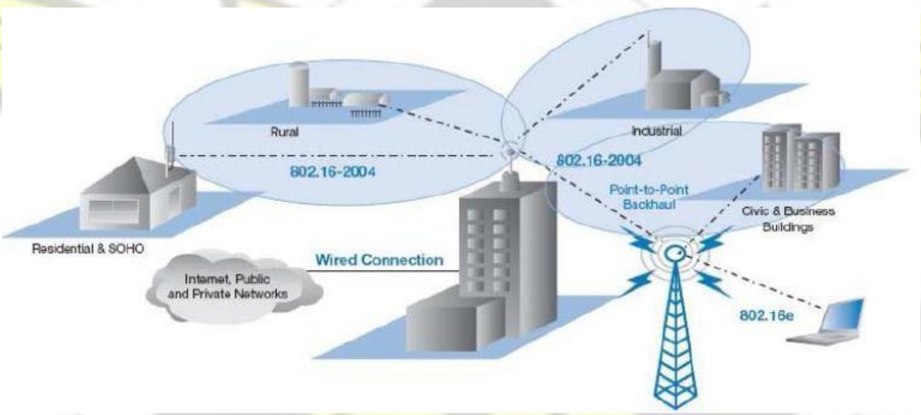


Figure 1.4 WiMAX Network [72]

Many researchers do believe that WiMAX can propel the wireless data transmission concept to a greater magnitude than expected. The development of the IEEE 802.16 (WiMAX) standard is as a result of the increasing high capacity and high speed communication demand for video, voice and multimedia. This impact immensely on the manner people interact or communicate as well as enjoy their entertainment.

WiMAX standards have evolved through the years since its introduction in 2001 with IEEE 802.16 standard which was also known as fixed WiMAX [19]. The Mobile WiMAX system came to existence in February 2006. From many industry sources, some important features of Mobile WiMAX are the utilisation of OFDM, MIMO, AMC, beam-forming and several of other recent protocols which are categorized as 4G features today. System gain was increased and portability and mobility enhanced through handovers [10]. The IEEE 802.16j standard introduced in 2009 sought to enhance coverage, throughput and system capacity by including mobile multi-hop relay stations (MMR) [11].

A traditional WiMAX cellular network earmarks a BS (base station) to offer services within a given radius of coverage. The core limitation of this architecture include low spectral efficiency at cell boundaries as a consequence of low SNR (signal to noise ratio) and coverage holes as a result of shadowing caused by land forms in mountainous areas and obstacles such as high rise buildings in urbanized settings. These impede drastically on transmission resulting in low data rates.

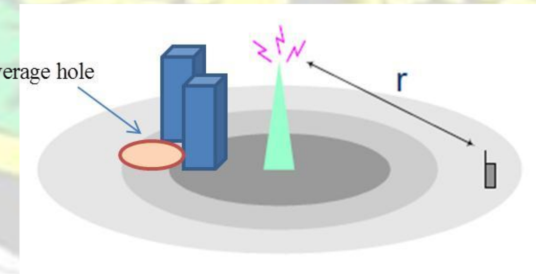


Figure 1.5 Conventional cellular coverage problems

Cellular problems of these nature have received much interests from both academic and industry researchers with some countermeasures proposed in aspects of interference management such as OFDM, MC-CDMA, etc., and also cooperation techniques such as MIMO and smart antennas. However, Spectrum efficiency near the cell edge is still poor as users suffer from enormous path loss and large inter-cell interference. Users require increased transmit power due to low bit energy to noise rate at these regions in order to maintain bit fidelity and good throughput. Coverage holes problem also persist in urban and mountainous areas which deplete coverage to users in shadowed regions [11].

A simple solution to solving these issues is to strategically increase the density of BS within a geographical area which could also extend coverage to far-reached places. This approach is however cost ineffective to network operators and inefficient when few users are to be served. The use of a simple form of a BS called relay is the rapid and cost effective way of deploying the network infrastructure [16]. Relays do not require E1 or T1 backhaul connection to communicate with BS that has link connection with some portion of their air link bandwidth [11]. User information from a nearby mobile station (MS) or user can be forwarded to a base station with the help of the relay station. Signal coverage can be effectively extended while enhancing overall throughput via the use of relay. Figure 1.6 shows a typical relay WiMAX network.

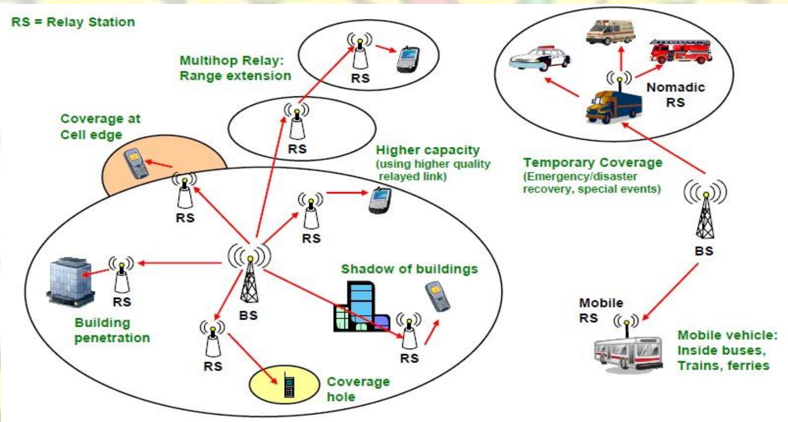


Figure 1.6 Relay WiMAX Network [11]

Types of relays that can be deployed include NT-RS (non-transparent relay station) and T-RS (transparent relay station) [17]. NT-RS are usually deployed to offer coverage at cell edge or beyond coverage of BS. This offer total connectivity interface between the BS and MS where traffic signal together with control signals and preamble are transmitted through relay. The other type; T-RS is deployed within BS coverage area to relay only traffic signal between BS and MS. BS send control information to MS directly in this mode. T-RS are basically used to improve throughput and capacity within the cell [21].

A well-studied relay technique is the cooperative relay techniques. In cooperative approach, data is co-operatively transmitted by multiple RSs to MS in downlink or to the BS in uplink with the aim to enhance system performance [16]. Cooperative technique has enjoyed great deal of interest from researchers in recent time. It is a suitable scheme for system level analysis. In this study however, our focus is on link level analysis, quantifying the performance of a relay link user communicating via a single relay path and examining it against a direct link user performance. We have based our work on non-cooperative relay approach, where a single relay path is used to route data from source to destination. Linklevel performance assessment is used in our study to evaluate the activity of a single communication link while varying link parameters. This result can be used to judge the possible performance of deploying relays to solve the issues of coverage, throughput and capacity of a WiMAX cellular system.

1.2 Problem Statement

Several geographical factors, user location and terrestrial obstacles impede connection between MS and BS hence, making it impossible to achieve the set target of services anywhere, anytime subscribed in the objectives of IEEE 802.16 WiMAX standard.

Traditional architecture of WiMAX cellular system has some resolute drawbacks. These include coverage holes and degraded spectral efficiency due to low SNR at cell boundaries. The characteristic usage of relays is to solve this prevalent problem while extending coverage beyond cell boundaries. However, poor network deployment could cause low performance and wastage of limited resources.

Link-level performance evaluation is significant to the assessment of the behavior of a single communication link under varying condition which could provide essential results necessary to estimate the potential benefit of utilizing relays in solving the issues of coverage holes and reduced spectral efficiency at cell boundaries.

It is worthwhile therefore, to investigate the performance of relay link usage and compare to that of the usage of a direct link. A study in this direction will inform the choice and proper deployment of relays which will enhance coverage and overall cell throughput.

1.3 Motivation

WiMAX is currently one of the most sought after wireless broadband technologies. With the prevailing demand for higher data rate in wireless communication, WiMAX stand as the promising landmark technology that could provide the desired solution for high speed communication. Yet in Ghana, geographical factors and densely packed high rise buildings in populated urban areas contribute immensely to transmission impairment. Relay technology promises a cost effective way of solving this issue.

Relay WiMAX described in the IEEE 802.16j standard offer coverage extension beyond cell borders which is essential in scattered rural settlements. Additionally, OFDM technique has been adopted as basis for the physical layer of the standard which significantly aids in achieving the required spectral efficiency for this objective.

There are a number of contributions from the research community on different aspects of multi-hop relay such as frame structure, routing, optimal relay placement, radio resource management, etc. One aspect which hasn‟t been well studied is link performance; and this has attracted our interest.

1.4 Research Objective

The main objective of this thesis is to investigate the performances of relay and direct link users of mobile relay WiMAX under varying link conditions.

1.4.1 Specific Objectives

The specific objectives of this study include:

1. To study and examine the performance of relay link and direct link usage in Additive White Gaussian Noise (AWGN) by quantifying the bit error rate (BER) and spectral efficiency against signal to noise ratio (SNR).
2. To investigate the effect of fading channels on performance of relay link and direct link usage via multipath Rayleigh and Rician channels.
3. To investigate the effect of user speed on performance.
4. To evaluate and compare the capacities of relay and direct links.

1.5 Thesis organization

The thesis is organized as follows: Chapter two presents the literature review. Chapter three presents the mathematical derivations and system model with parameters necessary for simulation. In chapter four, link-level simulation is performed to investigate link performance calculation of BER, spectral efficiency and capacity. Chapter five summarizes the results of the thesis and informs a potential direction leading to future research.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents the literature review; the background and context which form the basis of the successive chapters. A brief overview of WiMAX and Relay is treated while surveying some existing literature pertinent to this work and ascertaining possible research axis.

2.2 Wireless cellular network generations

The phenomenal growth in the mobile and wireless communication industry in the past decade has warranted significant changes to how networks are designed. Voice traffic being the fundamental focus of the earliest generation of mobile communication framework has now drifted to emphasize more on high data rate service provision. The first generation (1G) mobile phone systems, used in the late 1970s through to the late 1980s could carry voice signal alone between parties in communication [14].

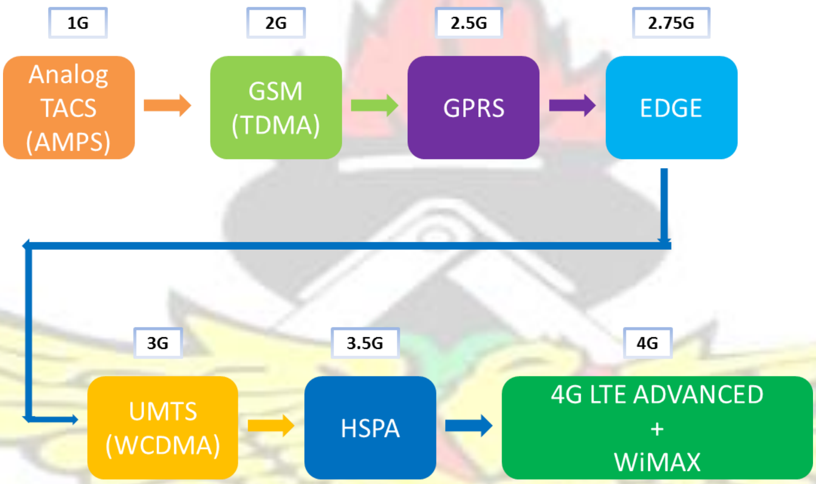


Figure 2.1 Cellular Network Evolutions

In 1991, the second generation (2G) networks which include CDMA, TDMA, GSM, PCS, and iDEN were commercially launched, presenting digital signaling in telecommunication via packet data transmission while introducing services such as SMS (Short Messaging Service), MMS (Multimedia Messaging Service) and email [14]. 2.5G, 2.75G and 3G technologies were subsequently introduced to meet the ever-growing demand on data rate.

With 3G technologies such as WCDMA (Wideband Code Division Multiple Access) and HSPA (High Speed Packet Access) offering speed of 144Kbps to 2+Mbps, services such as video on demand, video conferencing, mobile TV, GPS (Global Position System) and location-based services became attractive and gradually grew into becoming a need than luxury for a greater number of users. However reaching beyond 3G speed, came the 3.5G HSDPA (High-Speed Downlink Packet Access) technology, with speed up to 14.4Mbps to augment 3G performance for web browsing, graphic intensive websites, video conferencing and on-demand video services [14]. Table 2.1 provides a comprehensive summary of the advancement of wireless cellular networks.

Table 2.1 Generations of mobile cellular networks [14][15]

Technology	**1G**	**2G**	**2.5G**	**3G**	**4G**
Year of Implementation	1984	1995	1999	2002	2010
Service	Analog voice	Digital voice, SMS	Higher capacity, packetized data, MMS	Higher capacity, broadband data	Higher capacity, completely IP, multimedia
Standards	AMPS, TACS, Standards NMT	TDMA, CDMA, GSM, PDC	GPRS, EDGE,	WCDMA, CDMA2000	Single standard
Data Bandwidth	1.9 kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	OFDMA, MC-CDMA
Core Network	PSTN	PSTN	PSTN, packet network	packet network	Internet

4G networks technologies such as WiMAX, LTE and UMB which are currently in their early deployment stages can offer speed from 100Mbps to 1Gbps providing enormous data rate for bandwidth intensive services and applications.

2.3 WiMAX Overview

WiMAX is an acronym for World Wide Interoperability for Microwave Access, specified under the IEEE 802.16 standard, with an operating frequency band ranging between 2 GHz to 66 GHz [12]. WiMAX basically offer very low cost wireless internet service to several hundreds of users over a wide geographical area. It describes a metropolitan area networking (MAN) framework offering wireless option to cable DSL (Digital Subscriber Line), T1 level services for last mile broadband access and a backhaul for 802.11 hotspots. WiMAX is duly being adopted in wireless cellular due to its higher data rates [18].

Prior to the introduction of WiMAX, several operators in the Telecommunication industry had wireless broadband equipment that used proprietary technologies which obviously were not interoperable. The WiMAX Forum Network Group (WiMAX NWG) developed the network architecture of WiMAX to guarantee interoperability among diverse vendors and their broadband equipment [19]. Being a scalable digital wireless access 4G technology, WiMAX offer a shared basis for wireless connectivity in fixed, portable, and mobile environment [10]. As a wireless broadband technology, WiMAX perform similar to Wi-Fi (IEEE 802.11) networks providing QoS (Quality of Service) and coverage for fixed and mobile networks. In fixed stations setup (fixed WiMAX), it could cover up to 50kilometers and 5 to 15 kilometers for mobile standard. WiMAX is intended to be a complement or a competitor to cellular technologies such as LTE and UMTS.

2.3.1 The working of WiMAX

Microwave technology is the platform that WiMAX utilises to extend wireless services to wireless enabled devices which are WiMAX compatible such as computers, cell phones, tablets etc. Similar to any wireless cellular network technology, WiMAX uses base stations to establish a wireless communication link [10].

WiMAX operation is comparable to that of Wi-Fi except for coverage range and data rates. WiMAX base stations are mounted high to provide optimum coverage to WiMAX receivers such as chip installed in a tablet PC, dongles, etc., similar to Wi-Fi chip.

The communication process in WiMAX is categorized in two major stages, communication between WiMAX receiver and WiMAX BS as well as communication between BS and internet backbone. Communication between two WiMAX BSs is through point to point line of sight (LOS) microwave link whereas connection between WiMAX BS and the IP backbone network can be via wired connection as depicted in figure 2.2. Subscribers communicate with WiMAX BS through point to multipoint connections [52].

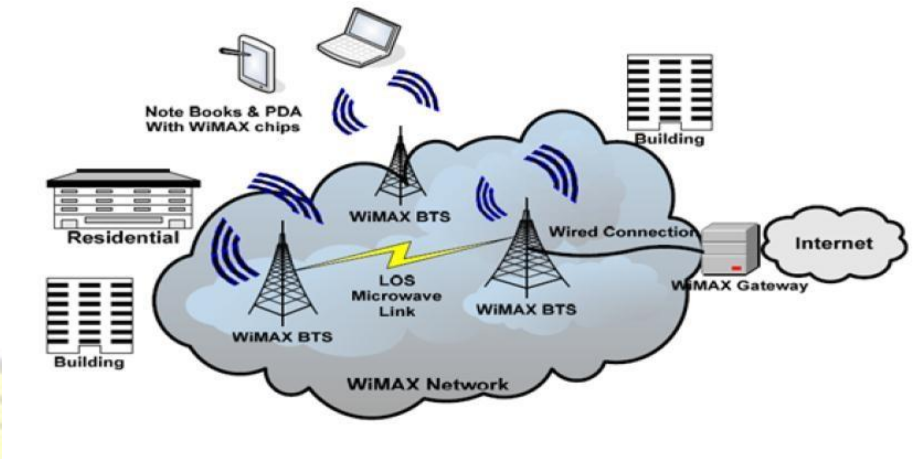


Figure 2.2 WiMAX BS Communications [72]

2.3.2 Evolutions of WiMAX Standards

The development of WiMAX commenced many years back as a means to find an appropriate and easily deployable option for conventional wire-line broadband technology capable of providing wireless internet access to remote and rural areas where wired systems economically appeared not feasible.

IEEE 802.16 Working Group:

In 1998, the IEEE 802.16 working group focused to develop WMAN solution for Line of Sight (LOS) based point to point and point to multipoint wireless broadband systems. The IEEE 802.16 standard known as the fixed WiMAX was first introduced in December 2001 as a technology capable of providing broadband wireless DSL for fixed stations covering a large geographic area, with operating frequency spectrum ranging between 10GHz to 66GHz [19][24]. It was meant to support line-of-site channel condition making use of single carrier physical (PHY) layer with burst Time

Division Multiplexed (TDM) on MAC layer. Using bit rate extending from 32Mbps to 134Mbps in 28MHz channel bandwidth, it supports digital modulation schemes including QPSK, 16QAM and 64QAM with channel bandwidths of 20MHz, 25MHz and 28MHz [18].

IEEE 802.16a:

In January 2003, the working group produced another standard, IEEE 802.16a, after some amendments in the earlier standard including Non-Line of Sight (NLOS) applications in the frequency range of 2 GHz to 11 GHz band. It uses Orthogonal Frequency Division Multiplexing (OFDM) on physical layer with Orthogonal Frequency Division Multiple Access (OFDMA) on the MAC layer [18].

IEEE 802.16-2004:

An improvement of the previous standard resulted in the introduction of the IEEE 802.16d or HiperMAN (High Performance Metropolitan Area Network) in June 2004, developed by ETSI (European Telecommunications Standards Institute) technical committee for Broadband Radio Access Network (BRAN) in cooperation with IEEE 802.16. The air interface of fixed broadband wireless access systems together with some multiple physical layer specification and medium access control layer were revised to provide multiple services. It supports fixed application providing non-line-of-site service with a frequency spectrum below 11GHz which is optimized for packet switched networks. With bit rate up to 75Mbps in 20MHz channel bandwidth, it supports OFDM 256 FFT, QPSK, 16QAM and 64QAM digital modulations with bandwidths ranging from 1.7MHz to 20MHz [18].

IEEE 802.16e -2005:

In 2005, IEEE 802.16e (called mobile WiMAX), an amendment of the previous version without compromising subscriber capabilities was released, to enhance mobility and portability with the introduction of handovers, improved no-line-of-site coverage by means of AAS (Adaptive Antenna System) with MIMO (Multiple Input Multiple Output) technology and increased gain by using denser sub channelization [10]. This enhancement specifies a system that combines fixed and mobile wireless access capable of providing services to users moving at vehicular speed as depicted in figure 2.3. A frequency spectrum below 6GHz licensed band suitable for mobility was adopted with bit rate up to 15 Mbps in 20MHz channel bandwidth. It supports scalable OFDMA, QPSK, 16QAM and 64QAM with channel bandwidth selection within the range of 1.75MHz to 20MHz [18]. However, signal power loss is prevalent along the propagation path for certain frequencies hence leading to limited coverage. Additionally, coverage holes or dead spot and areas of poor reception caused due to fading and blocking further reduce the efficiency of this standard. Conversely, one of the salient efforts to solve this problem has been to deploy relatively more base stations within a geographical area [35]. However, this effort does not seem efficient due interference and high cost of deploying BSs. Alternatively, by using relay approach presents the solution for enhanced coverage and throughput via the IEEE 802.16j standard.

IEEE 802.16j-2009:

IEEE 802.16j (Mobile Multi-hop Relay WiMAX) standard was developed in 2009, fully compatible with IEEE 802.16e with the aim to enhance coverage, throughput, and capacity by adding multi-hop relay capabilities of interoperable relay stations (RS) and base stations (BS)

[17] as depicted in figure 2.3. The mesh mode in previous standards was discarded from the IEEE 802.16j standard while enhancing the MAC and physical layer to supports multihop relay enabled base station (MR_BS) and relay stations (RS) [11]. The standard specify two relay modes dependent on what manner of frame configuration and scheduling information transmitted. These are transparent and non-transparent modes [17].

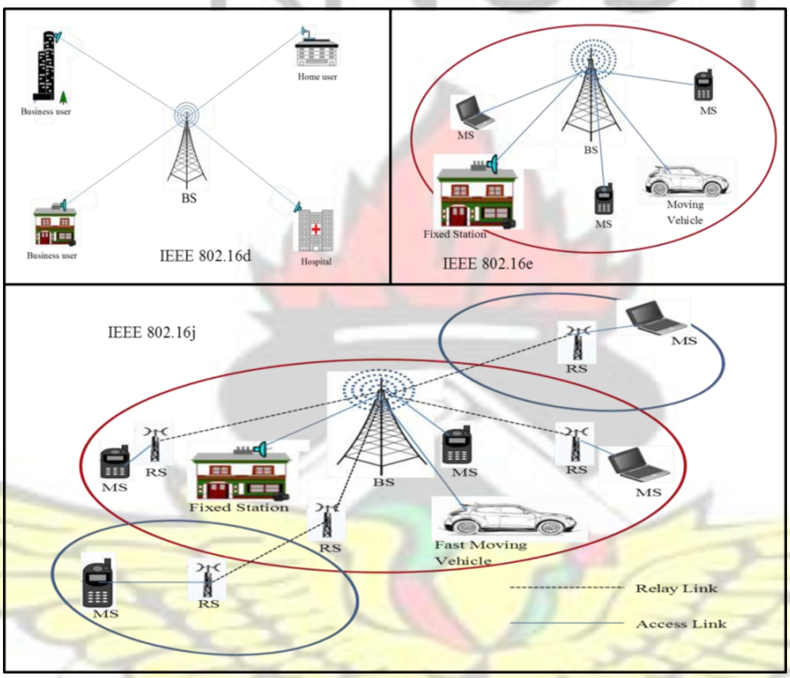


Figure 2.3 IEEE 802.16 WiMAX Standards

Relays shortens the transmission path between BS to MS and enhances network capacity by permitting less vigorous burst profile and higher transmission rate while increasing the coverage of the BS. In this light, IEEE 802.16j is held to be a cost effective option for 4G network deployment [11]. The details of operating frequencies, channel bandwidth, modulation and multiplexing techniques etc. for these standards are given in Table 2.2. **Table 2.2 Summary of WiMAX standards**

PARAMETERS	IEEE 802.16	IEEE 802.16d	IEEE 802.16e	IEEE 802.16j
Completed	December, 2001	June, 2004	December, 2005	May, 2009
Spectrum	10-66 GHz	2 GHz - 11 GHz	2GHz - 6GHz (mobile) 2GHz - 11GHz (Fixed)	< 11 GHz
Channel Condition	Line-of-sight service	Nonline-of-sight service	Nonline-of-sight service	Nonline-of-sight service

Bit Rate	32-134 Mbps in 28 MHz Channel bandwidth	Up to 75 Mbps in 20 MHz Channel bandwidth	Up to 15 Mbps in 20 MHz Channel bandwidth	Up to 15 Mbps in 20 MHz Channel bandwidth
Modulation	QPSK, 16 QAM and 64 QAM	OFDM 256 FFT, QPSK, 16 QAM and 64 QAM	Scalable OFDMA, QPSK, 16 QAM and 64 QAM	Scalable OFDMA, QPSK, 16 QAM and 64 QAM
Mobility	Fixed	Fixed	Nomadic / Mobile	Nomadic / Mobile
Channel Bandwidth	20, 25 and 28 MHz	1.7-20 MHz	1.7-20 MHz	1.7-20 MHz

2.3.3 WiMAX Objectives

WiMAX standardization took into perspective several objectives [24] which include:

Interoperability:

Interoperability is the key objective of WiMAX which ensures that, equipment from different vendors interoperates in the framework without difficulty. International standards do not define boundaries for subscriber module usage.

Wide Coverage:

WiMAX systems is capable of covering large areas due to various modulation schemes adopted such as QPSK, 16 –QAM and 64 – QAM.

High Capacity:

WiMAX is capable of providing enormous capacity for bandwidth intensive applications compared to Universal Mobile Telecommunication System (UMTS) and Global System for Mobile communication (GSM).

High Security:

User integrity, authentication and confidentiality are assured through encryption and authentication protocols such as AES adopted by the WiMAX standard.

Flexible Architecture:

WiMAX allows for numerous system designs including Point-to-Point, Point-to-Multipoint and Permeating coverage

Quality of Service (QoS):

WiMAX provides communication for different traffic including VoIP, multimedia applications and data, whiles ensuring a higher degree of QoS.

Mobility:

Mobility is the key feature of the IEEE 802.16e and IEEE 802.16j standards due to Scalable Orthogonal Frequency Division Multiple Access (SOFDMA) and Multiple Input and Multiple Output (MIMO) techniques adopted at the physical layer [10][17][19].

2.3.4 WiMAX Network Architecture

The WiMAX Network Reference Model (NRM) which is the logical representation of the WiMAX architecture was developed by the Network Working Group of the WiMAX Forum classifying functional entities and the interoperability between them specified by various reference points. The model is segmented into three entities: the Connectivity Service Network (CSN), the Access Service Network (ASN) and the mobile station (MS)

[22][23][24].

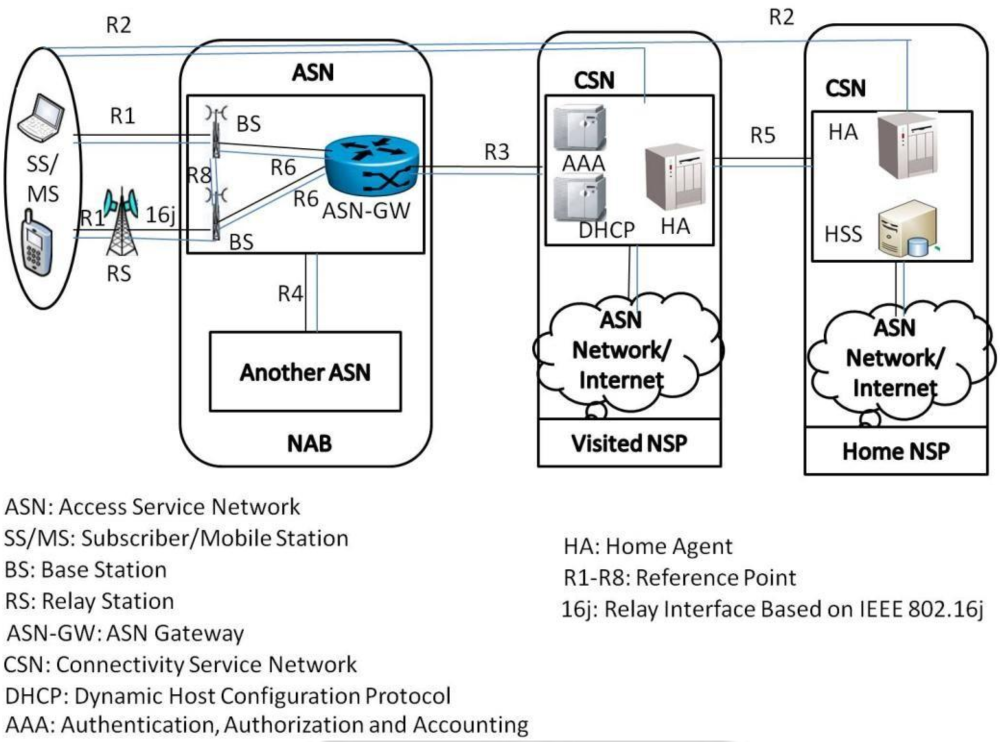


Figure 2.4 Relay WiMAX Network Reference Model

- The Connectivity Service Network (CSN) present IP connectivity services to a WiMAX subscriber and defines the network function associated with infrastructure.
- The Access Service Network (ASN) comprises functions that provide radio network access to the WiMAX subscriber.
- The mobile station (MS) refer to the end user device used to access the radio network. Based on the efficiency and interoperability requirement, the equipment vendors decide the assembly and allotment of functions into physical devices within the functional entities. Every one of these entities; CSN, ASN and MS embody a grouping of functional entities each of which may be recognized in a single physical functional entity or distributed over multiple physical functional entities [22][24].

Specific mapping of functions to network elements defines different profiles. In a single network structure, two network elements (the base station (BS) and the ASN Gateway (ASN-

GW) are mapped onto the functions [23].

The Access Service Network (ASN):

The radio related functions of the ASN (i.e. physical and medium access control (MAC) layers functions) are performed by the base station. Functions associated with subscriber data such as routing, bridging and other control functions are performed by the ASN-GW. The Access Service Network (ASN) Gateway, aggregates traffic from base stations, manages handoff and is responsible in delivering end-to-end QoS for enhanced application performance [22].

The Connectivity Service Network (CSN):

The CSN connects to the Application Service Provider (ASP), the internet and other corporate and public networks. It consists of a variety of functions contained by the core data network that outlines a fundamental component of an end-to-end WiMAX network. Some of the functions the CSN describes include IP services, subscriber services and mobility management. These are field-established methods that offer the scalability, performance, services and capacities necessary. Functions that encompass the CSN environment include: Authentication Authorization and Accounting (AAA) which offer authentication, accounting, authorization, management of users, service profiles of subscribers, DNS/DHCP server which render primary IP Address search for Mobile Stations, Home Agent (HA) which offer Mobile-IP functionality that permits traffic meant for mobile devices to be transparently routed to the ASN Gateway, Policy control server which offer a subscriber‟s access to the network and dynamically configures the service flows [22].

Mobile Stations (MS):

End user terminal devices used by the subscribers to utilize diverse services made available by the WiMAX operators. These terminals may either be fixed or mobile terminals.

Base Stations (BS):

The air interface to the subscriber unit is provided by the base station.

2.3.5 WiMAX OFDM PHY Layer

OFDM transmission technique is the basis of the WiMAX PHY layer which ensures high speed data, video, and multimedia communication.

OFDM as a multichannel modulation technique has currently become the technology trend for most advanced and emerging communication systems worldwide. However, the idea of transmitting parallel-data and FDM (frequency-division multiplexing) could be traced back to the 1950s and 1960s [9] where the US military employed numerous high frequency multichannel modulation military systems, such as KINEPLEX, ANDEFT and KATHRYN [28].

Several applications of OFDM have evolved over the past two decades and have been proposed for a number of wired and wireless usages [34]. The first commercial application was in DAB (Digital Audio Broadcasting) which was developed, standardized and came in usage in 1995 in Sweden and UK [9][27]. OFDM has also been used for the Digital Video Broadcasting [35]. OFDM under the acronym of Discrete Multi-Tone (DMT) has been selected for asymmetric digital subscriber line (ADSL) [36]. The specification for Wireless LAN standard such as IEEE 802.11a/g and ETSI HIPERLAN2 has employed OFDM as their PHY technologies. IEEE 802.16 standard for Fixed/Mobile BWA has also accepted OFDM for PHY technologies.

Multiple-access is also possible in OFDM scheme. This technique is called OFDMA and is implemented by providing each user with a small number of sub-carriers. Even though this technique is similar to FDMA, it avoids the use of large guard bands that are used to prevent adjacent channel interference.

OFDM as a special case of multicarrier parallel transmission technique, scheme employs the transmission of high-rate serial data stream divided into sets of low-rate sub-streams and transmitted over a number of lower-rate SCs (subcarriers). OFDM is seen in the light of being either a multiplexing or a modulation technique. The key benefit in using OFDM system is its increased resilience against narrowband interference or frequency-selective fading. Subcarriers bandwidths made small relative to the channel bandwidth causes flat fading in subcarriers and permits simple equalization impacting an extension of the symbol period of the sub-streams compared to time-dispersive radio channel delay spread. Single-carrier systems offer single interference or fade which has the tendency of causing entire link failure while just a small fraction of erroneous subcarriers is affected in multicarrier systems which can be corrected using error-correction coding [28].

2.3.5.1 Key Benefits of OFDM

Orthogonal as a word, stresses the fact that there is a mathematical clear-cut relation between carriers. In typical FDM, conservative filters and demodulators are used to receive signals in a number of spaced apart carriers in which guard bands are established between these carriers in frequency domain resulting in the reduction of the frequency spectrum efficiency. Conversely as depicted in figure 2.5, in OFDM where carriers are mathematically orthogonal, offer the possibility to arrange the carriers in a manner that there is an overlap of the sidebands of the individual carriers and still ensure that signal received is free from adjacent carrier interference. Figure 2.6 illustrates the spectral efficiency of OFDM system as weighed against that of FDMA. Better bandwidth utilization is accomplished through the overlapping multicarrier technique.

There is a significant distinction between overlapping multicarrier methods such as OFDM and non-overlapping multicarrier methods such as FDMA. Ensuring overlapping transmit spectra of sub-channel waveforms give rise to high spectral efficiency. However, overlapping spectra require orthogonal sub-channels. Orthogonal scheme permits the use of a common channel to transmit and detect signals perfectly without interference. Smearing between the transmitted signals which causes loss of information occurs when orthogonality is lost during transmission.

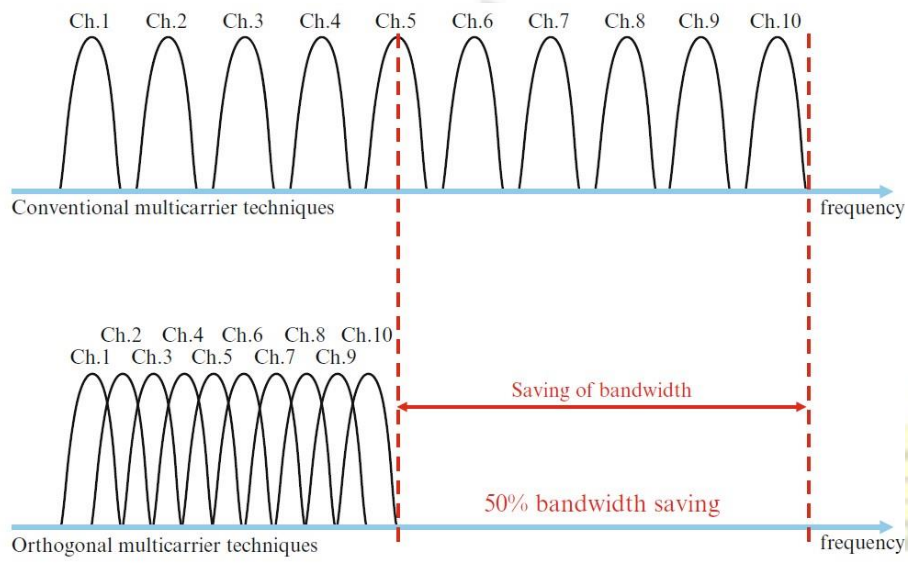


Figure 2.5 OFDM signals [28]

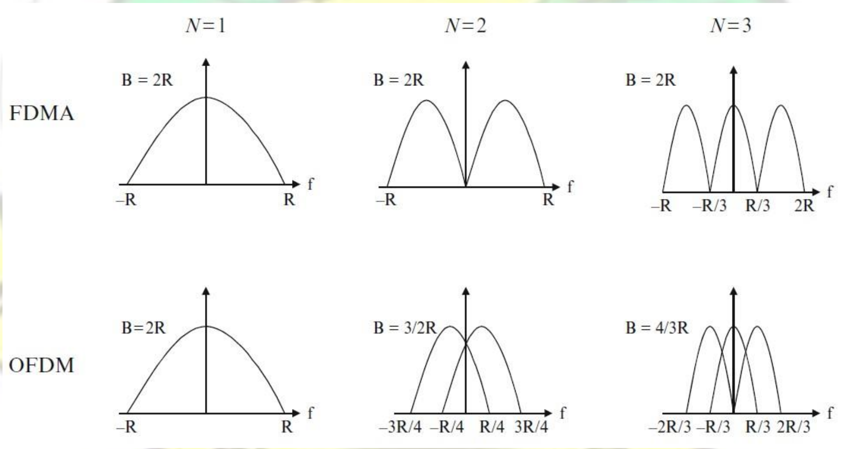


Figure 2.6 OFDM spectrum efficiency weighed against FDMA spectrum [9]

In OFDM transmission, the peak of a sub-carrier must correspond with the nulls of a succeeding sub-carrier as described in figure 2.7. This ensures interference free from neighboring overlapping sub-carrier spectrums at the peak of a required sub-carrier and avoids the wastage of bandwidth commonly found in non-orthogonal carrier scheme.

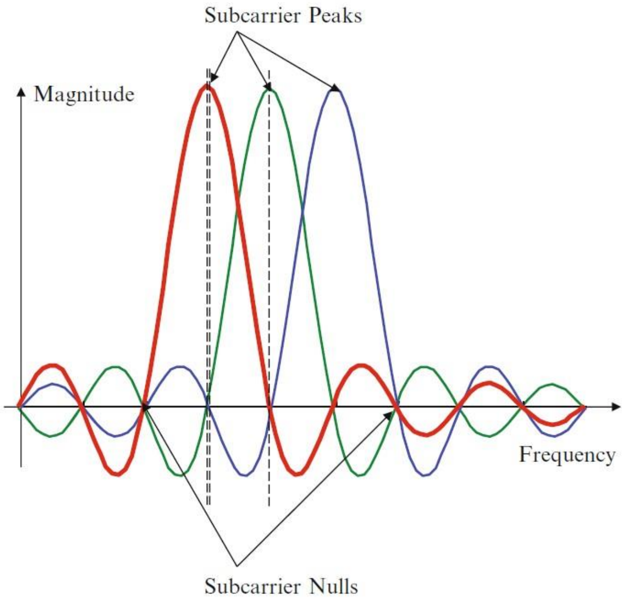


Figure 2.7 OFDM subcarrier signals [28]

2.4 Cellular Relay-based Networks

Relay-based wireless access networks have been the subject of great interest lately and impacting immensely on the commercial cellular world. This is manifested in the increased activities in standardization related to relay and the associated growing product base in the wireless telecom industry particularly in WiMAX and LTE.

Multi-hop Relay technology has been employed in several wireless networks notably sensor networks [25], ad hoc networks [26] and wireless mesh networks [29].

Distinctively, these network types possess characteristics such as mobility, scale, form factor, among others resulting in different system design.

Multi-hop Cellular Networks (MCN) can largely be divided into two relaying architecture; one which utilizes end terminals to relay traffic and one which uses relay stations [30]. The latter is the type in focus here i.e., multi-hop cellular relay-based architecture.

Cellular relay-based networks have in recent years enjoyed significant interest in wireless systems that require low deployment and operational cost as well as QoS. Volumes of recent research works seem to focus extensively on the benefits and issues which relate to this technology.

Particularly, numerous European projects focus on relay-based networks such as FIREWORKS [32], WINNER II [31], REWIND [47] and ROCKET [46]. Additionally, two major recent mobile wireless technologies which are based on this relay architecture are the 802.16j Relay WiMAX systems by IEEE and the LTE-Advanced systems [48]. While we digress further into the description of Relay WiMAX later in this chapter, LTE-Advanced is a mobile communication standard developed by the Third Generation Partnership Project (3GPP) to meet the International Mobile Telecommunication (IMT) Advanced requirements of 4th Generation (4G) systems. Relay solution has been realized by the 3GPP and the IEEE as a feasible way out to increase the capacity of mobile systems at low cost.

2.4.1 Characteristics of Relay-based Networks

Relay-based wireless network is a multi-hop design having a fixed infrastructure in which a Relay Station (RS) forms a different entity besides the BS and its associated Mobile Stations (MSs). Typically, a few low cost relays and their associated BSs form a relay-based system. Relay systems are mostly considered applicable in the network operator contexts as the operator plans and deploys the wireless access network. These settings are typically characterised by a tree-based routing setup in which end user terminals connect to BS via short two to three hops routes. The IEEE 802.16j-2009 Relay WiMAX is a typical example of this architecture. Authors in [53][54] introduced the basic theories and principles of relay WiMAX presenting most of the major modifications in the IEEE802.16j standard. While in [58], authors detailed the specification of IEEE 802.16j-2009.

Authors in [49] and [51] have detailed the key concept and benefits of this new network design providing motivation and features relating to relay-based system design. They particularly indicate throughput enhancement, coverage enhancement and deployment cost as the three main benefits derived from relay-based architecture compared to conventional single-hop system. Each of these key benefits is further detailed below.

Throughput Enhancement:

Relay design is expected to increase the throughput for users at the cell edge of a WiMAX system. Notably, subscribers at cell edges may be required to communicate at reduced rates [79] due to low received signal strength at these regions. In addition, relay-based design is expected to increase system capacity by deploying relays such that it enables more aggressive spatial re-use.

Coverage Extension:

The use of a relay is probable to improve coverage in severely shadowed regions as well as extend the coverage range of a BS. In either case, coverage is improved via the RS transmitting from an advantageous location nearer to a disadvantaged user [80][81].

Cost Reduction:

There is a potential cost gains in relay based networks deployment than single hop wireless systems. Relay stations are relatively cost effective than base stations. However, wider coverage and enhanced throughput can be achieved at low cost by adding relays in a network which is reasonable than deploying only expensive base stations to offer good coverage and enhanced capacity [17]. Relays which have lower complexity compared to BSs are expected with no wired connection to the backhaul [49] which is significant in providing a good cost performance in deploying a cellular network.

Authors in [11][36][37][38][39][40][44] centered their studies on coverage extension while authors of [41][42][43] had their spotlight on throughput enhancement. However, the heart of these two areas of studies has been engrossed to achieve efficient utilization of network resources in a cost effective way. Thus cost effective deployment of network is the core advantage of relay based networks.

2.4.2 Type of Relays

Relays can be classified based on the signal processing techniques they employ. Authors in [71] proposed two main techniques namely, Amplify and Forward (AAF) and Decode and Forward (DAF) which are eminent to process the received signal at the relays. Each technique is described below.

Amplify-and-Forward:

AAF protocol is mostly used in analog repeaters which simply amplifies and forwards the received signal in the downlink and uplink. This method offer an advantage in terms of delay however, certain issues arise including: increase in system noise level, increase in interference level due to lack of specific scheduling and erroneous data is forwarded without correction over multiple links..

Decode-and-Forward Scheme:

In DAF scheme, received signal at the relays are fully decoded and re-encoded before signal is retransmitted which offer some advantages for the management of radio resource. Resource allocations to both relay and access links becomes quite easier making this scheme a worthy candidate for OFDMA-based systems. Additionally, this scheme is appropriate in environment where heterogeneous modulation and coding schemes are used such as in OFDMA systems. However, this scheme define some latency issues as some amount of processing time is required for the signal decoding and re-encoding process.

There has been a substantial work available in literature on relay types many of which are on analytical performance comparison of Amplify and Forward (AAF), Decode and Forward (DAF) and other relay protocols.

In [109], authors considered amplify-and-forward and decode-and-forward relay schemes investigating outdoor-to-indoor relay communication links and quantifying the end-to-end channel capacity. In measuring the links constituting the relay transmission, Real-time sounder was utilized. They established the extent to which capacity is improved when decode and forward relay scheme is used compared to when amplify and forward is utilized. However, they did not establish the effect of latency and resource consumption in their model.

In [103], Decode and Forward Relay is used to allow for opportunistic relay of packets which helped to propagate redundant signals over multiple paths. The authors utilised this approach to combat the channel noise and fading effects. They investigated the use of packet combining in cooperative diversity scenario which exploits the inherent spatial diversity along with the inherent time diversity in Automatic Receive Request (ARQ) retransmissions. Additionally, their approach sought to save resource in their by relaying packets only at instants when direct transmission fails with performance measures in BER and throughput in AWGN and also in multipath fading.

System level performance simulation is employed in [104] with a simple Amplify and forward relay protocol operating in full duplex mode in a multihop environment. The authors investigated bandwidth efficiency and the associated service outage performance for different relay scenarios which aimed at improving carrier-to-interference ratio in heavily shadowed region. The problem with their system is the minimal throughput gain experienced by relays in open space due to co-channel interference from relays in neighbouring cells. Meanwhile, increased system capacity was demonstrated by fully reusing the frequency in all relays while improving the per-user data rate in cell edges and heavily shadowed regions. Authors in [105] investigated the performances for full-duplex in two-way Amplify and Forward relay channel consisting of two source nodes and a single relay node in terms of outage probability and ergodic capacity. They were able to establish better performance in the presence of loop interference in full duplex mode than in two non-orthogonal half duplex channels.

A situation of power allocation at relays was addressed in [106] to increase the transmission rate in a non-orthogonal Amplify and Forward relay network where amplified signals are simultaneously transmitted at the same time and with the same frequency. A unified power allocation in Amplify and Forward approach is presented in [107] in multi-hop OFDM relaying systems. Authors considered a short and long-term individual and total power constraint at the BS and RSs, and formulate decentralized low complexity power allocation algorithms when links are subjected to fading. Two stages were adopted, including a power distribution phase among distinct subcarriers, and a power allocation phase among different relays. In [108], authors derived a closed-form expression of outage probability for Amplifyand-Forward OFDM Relay System with subcarrier mapping over Nakagami-m fading channels. Subcarrier mapping in OFDM relay system has also been shown in their literature as a performance enhancement mechanism.

2.4.3 Relaying Techniques

The relay being a further unit found in the transmission path is responsible for forwarding the different transmissions between the BS and users. Authors in [17] have outlined several conventional relaying techniques which include (1) time domain relaying, (2) frequency domain relaying and (3) hybrid time/frequency domain relaying. An alternate technique which has gained much interest from researchers is the unconventional co-operative relaying.

Time Domain Relaying

Relays forward data in either downlink or uplink operating in a single frequency. This involves accessing the medium in time multiplex where resources are separated in time in the downlink or in uplink permitting transmission and reception of data at the relay. Cost efficiency is the key advantage of this technique as only one transceiver is require at the relay.

Frequency Domain Relaying

Different frequencies are used by relays in their operations allowing for simultaneous transmit and receive of data. However, cost of the relays is increased due to the increased complexity of hardware, addition of transceiver and frequency channel.

Hybrid Time/Frequency Domain Relaying

Relays periodically use different frequency channels for data forwarding enabling switching between two frequencies. This is to permit concurrent transmission of data by BS and RS on separate frequencies. This does not require additional transceiver likened to the Frequency domain scheme. However, hardware complexity is increased to support the need for fast frequency switching.

Cooperative Relaying Techniques

This technique allow for same data to co-operatively be transmitted by multiple RSs to an MS or the BS in downlink or uplink respectively. This scheme considerably enhances overall system performance similar to spatial multiplexing and transmit/receive diversity in MIMO systems [16]. However, the signalling overhead and the complexity of cooperation technique are among pertinent issues that need to be addressed in order to fully assess the merits and demerits of these schemes.

2.4.4 Challenges in Planning of Cellular Relay-based Networks

Network planning is quite a challenging task in rolling out a cellular network. These challenges come in many aspects and the incorporation of relays into the network gives rise to new issues. To ensure that the installed network is enhanced, it is necessary to investigate and determine certain facets in relation to the number of relays to deploy along with their location in addressing the relay selection process while mitigating the interference through frequency re-use.

2.4.4.1 Relay Placement and Transmission

Relay stations (RS) are the nodes found between the BSs and MSs thereby reducing the transmission distance. System performance is sensitive with respect to the number of deployed relays as well as their location. If well placed could enhance system capacity, system reliability as well as throughput per user. The problem related to relay placement has been studied in different wireless multi-hop networks such as in WLANs [84] and sensor networks [83]. The authors in [85] suggested an approach to maximise the overall system capacity by defining an algorithm for relay placement and also determining the number of relays to deploy. They clearly demonstrated significant gains via careful relay deployment. However, their work also demonstrated that no additional gain is achieved above a certain number of relays deployed. Therefore, defining the relay position under certain realistic assumptions is presented and perceived as NP-hard problem and is hence a challenging problem to solve [86]. In [39], the authors planed BS and RS location of two hop network taking into consideration which set of BSs and RSs will accommodate a user demand with the least cost which in practice, seem not applicable since users are nomadic. However, if the MS distribution is assumed to be uniform in an ideal scenario according to [17], system optimization can be achieved by adopting an iterative algorithm in the placement of RS. In practice, non-uniform distributed traffic demand must be considered especially in large geographic areas. In the first stage of network deployment, the BSs locations are first determined followed by the design of the RS location algorithm to locate the RSs [16].

The IEEE 802.16j mobile multi-hop relay network utilizes several transmission schemes for its relays as surveyed by authors in [16][43] captured in the standard [17]. Authors is [57][59][60][61] present some other studies on relay placement which focus on finding the best location for RS in order to improve performance by extending the coverage of a WiMAX system. In [57], the authors established a clear relationship between relay bandwidth reservation and the placement of the relay station. They also recommended an optimisation scheme where relay bandwidth reservation and relay placement are combined.

2.4.4.2 Path Selection

Path selection involves identifying and choosing the most appropriate path to base stations by taking into account limits such as bandwidth available, radio resource, interference, etc. Centralized path routing involves storing path information in the BSs whereas distributed path routing populating path information in RSs. Using source routing mechanism, relay path information is fixed in the data burst by the base stations allowing , RSs to forward data in the given path provided in the received data burst. In the event of inability of the BS to control the entire network, distributed path routing is preferred over centralized path routing for effective use of radio resources. Throughput performance rest on both the bandwidth and loss rate physical-layer, however, routing method should take into account both bandwidth and the link loss rate [17].

Two transmission phases are required for routing through relay with data duplicate over the RS which consequently reduce the system capacity. Packets buffering at the relays may occur due to multi-hop transmission which as a result causes higher latencies. This problem increases with respect to increase in number of hops. Therefore forwarding through an RS should be considered only when necessary to ensure optimum throughput and reduced delay for each link in the network [87]. In making such decisions, measures such as the traffic load at each station, link quality and the system topology should be considered.

2.4.4.3 Frequency Re-use

Radio frequency is a limited, scarce and expensive resource. It is largely improbable for same frequency to be used in adjacent cells. Frequency re-use is a mechanism that promises efficient utilisation of limited radio resource [88]. This technique has attracted the interest of several researchers in the industry. Authors in [89] gave comprehensive overview of the basic mechanism and algorithms involved in frequency planning and re-use processes for singlehop network. In [90], different re-use factors for cellular multi-hop network scenario are investigated and their respective impact on the system capacity. They demonstrated that via the use of directional antennas to limit the interference on the relay links, relay-based systems can offer significant gains over conventional single-hop systems.

The performance enhancement offered by Relay WiMAX systems over Fixed WiMAX systems is influenced by numerous factors including network topology, relay mode, transmit power level at the relays and the type of antennas used. A profound understanding of the relationship between the enhancement of relay based WiMAX systems and the multiple parameters that are necessary to the system design can offer a roadmap for the deployment of relay-based WiMAX systems. The focus of the reviewed work provided is to give a better understanding of the impact of different design options on performance.

2.4.4.4 Routing Management

Routing procedure is a significant aspect of Relay WiMAX which impact immensely on throughput. The path selection is very critical as there is a cost associated with it in terms of throughput and delay which warrant for an intelligent routing algorithm to ensure good performance of the system.

However, several routing algorithms are found in literature with different measures used to analyse the performances of different paths. Authors in [91] introduce a metric which constitutes the bandwidth unit needed to transmit a fixed amount of data by using a specific Modulation and coding scheme. The efficiency of the routed path used to transmit a bit over a medium by their metric does not account for the traffic load at the relay. Authors in [64] presented a routing scheme in multi-hop Relay-based WiMAX. Their proposed path selection maximizes the throughput of the network while minimizing latency. In finding the best route, the authors considered the Signal to Noise Ratio, the number of hops and the available link bandwidth in their decision.

The achievable throughput is considered by authors in [91] and [92] by reckoning the bandwidth at the relay in terms of available free slots. This quite profound in managing the traffic load in QoS oriented wireless system. However, how to determine the available slots at each relay is not discussed. Additionally, defining the amount of resources available at the relay is directly related to the scheduling algorithm and the way the resources are managed; either centralised or distributed mode. Further in their bandwidth-based metric scheme, they did not investigate the impact of the additional signalling overhead associated with their approach. Authors in [65] conducted a system level performance in transparent relay mode demonstrating the fact that, there can only be up to 10% increase in maximum throughput in the downlink. They also argued in the article that throughput enhancement can only benefit a half of the BS coverage. Routing procedures in Relay WiMAX systems differ depending on the manner resources are managed.

Relay WiMAX routing issues seem less complex than in other wireless systems such as wireless mesh networks. However, there exist some pertinent issues in relation to path selection specifically with non-transparent relay systems.

2.4.4.5 Resource Allocation

Relay WiMAX significantly has an increases signalling overhead compared to the conventional single-hop WiMAX system. Therefore, to meet the different QoS requirements of each user require the design of novel scheduling algorithms as well as carefully managed signalling for an efficient resource allocation.

Authors in [93] and [94] analysed the MAC efficiency issues with Relay WiMAX proposing different schemes for the MAC efficiency optimization. A new downlink resource allocation algorithm is proposed in [93] which dynamically allocate resources on the downlink for relay transmission with respect to bandwidth requirement. However, this work did not consider OFDMA and scheduling not covered at all. Authors in [94] sought to reduce system overhead while improving the efficiency of utilisation of the MAC frame by proposing an aggregation scheme. The need for connection and packet aggregation which combat significant overhead was highlighted in this work. But notably, the Relay WiMAX standard different schemes from those described in [94] are defined to aggregate the relay link traffic.

Generally, most resource allocation work evolving through the years which focus on the MAC efficiency optimization does not follow the Relay WiMAX specification. These works significantly rely on system-level performance.

One aspect which is imperative with multiple relays deployment is the possibility to enable concurrent transmission at the relays which is significant for efficient utilisation of available radio resources provided interference is well managed. Resource scheduling in an urban setting under severe shadowing was investigated by the authors in [95]. They assumed in their system 4 directional antennas on both the base station and the relay station which resulted in their simulation highlighting on the advantages of directional antennas over omnidirectional antennas in an urban settings. Notably, system throughput can be increased by 6 or 12 times with the proposed method compared to an omni-directional system. Additionally, this work greatly utilised spatial re-use for throughput enhancement which is further spot on via simulation studies in [96][97]. The authors emphasised the need for distributed scheduling (i.e. scheduling at the BS as well as RSs) which maximises concurrent transmissions while preventing severe interference due to wrong re-use decisions. However, the frame structure considered in these works does not conform to Relay WiMAX

specifications and the relay type considered is not clear.

In [98], authors discussed several publications focusing on the management of radio resource in OFDM relay based systems which can be adapted by Relay WiMAX systems. Various approaches for dynamic resource allocation found in literature were presented.

Several of these proposals on system performance enhancement exhibit some short fall either by their signalling requirements or their complexity in implementation. Distributed scheduling is one solution discussed by authors in [98] which promises a reduced overhead and system complexity.

Largely, this review demonstrates that there is still work needed in the performance enhancement process of OFDM relay systems and hence relay WiMAX systems. Relay WiMAX systems requires a scheduling algorithm design which takes into account the detailed issues with regards to the frame structure in transparent or non-transparent mode, signalling and QoS.

2.4.5 Cooperative Relaying Techniques

In [99][100], authors utilised cooperative relaying approach in relay WiMAX system to yield improvements of over 100% when compared with conventional single hop system. The issue with their work is when it is related to the specification of relay WiMAX standard. The Authors in [66][67] examined and analysed the performance of various cooperative relay diversity schemes which aimed at choosing the best scheme the highest end-to-end throughput. Two hops cooperative relay frame structure in two phases was proposed in which BS transmit data to the RSs in the first phase while in the second phase, BS and RSs send data to the end terminals via a SISO. Notably in this work, BS and MS link condition is not reliable when RS is transmitting which indicates the impact of BS in the cooperative technique.

Cooperative relaying technology is to a large extend still an emerging trend and acquiring great interest from both the academic and industry cycles and this is most likely not expected to reach maturity soon. A lot more work is still needed in several aspects with regards to synchronisation among stations, antenna requirement and the amount of overhead allowable in relation to feedback on channel information.

2.4.6 Performance Evaluation of 802.16j Systems

Many works have been published prior to and after the approval of the IEEE 802.16j-2009 amendment which sought to enhance performance of different facets of relay WiMAX. Several of these works evaluate the PHY layer performance increase that can be offered via deploying relays in practical scenarios.

Authors thoroughly studied the frame structure for multihop relays in [56], proposing a flexible framework for multi-zone which support 802.16j relay-based systems as well as 802.16e mobile stations. The benefits of relay deployment to extend coverage and enhance capacity in a single cell were presented through performance analysis.

Investigative dimensioning methods to both traditional cellular WiMAX and Relay-based WiMAX were introduced by authors in [62][63][55]. Their results clearly showed significant improvement in coverage extension when relays are deployed. However, the issue with these works is demonstration of some inefficient bandwidth usage.

In [101], a downlink performance evaluation of a relay WiMAX system in both transparent and non-transparent mode is carried out. The system generated numerous coverage holes as a result of a frequency reuse of 1 in a sectorised system with 3 relays per sector. The core extract of their result indicate that non-transparent relays performs better transparent relays in terms of capacity increase of conventional single hop scheme. The authors established the fact that it is possible to achieve up to about 40% system capacity increase with nontransparent relays while transparent relays achieve up to about 25% capacity increase. However, one salient aspect not considered in this work is the deployment cost of the two systems. While the distributed scheduling non-transparent mode require two different operating frequency channels, the centralised transparent relays operate on a single frequency channel leading to a major cost disparity between the two systems which the authors did not discuss.

Authors in [102] analysed the uplink capacity performance of IEEE 802.16j relay WiMAX system with focus on centralised scheduling in non-transparent mode. Their analysis and simulations indicate a 40% gain in the uplink. Moreover, a cost analysis is presented where authors per their assumptions emphasis on the viability of non-transparent relays in terms of cost of deployment when relay cost 25% less than the BS.

Noticeably, multiple parameters such as path selection, relay placement, number of deployed relays etc., which are relevant in designing relay WiMAX systems are not considered in both [101][102]. It is noteworthy however, to bring to bear the maximum number of parameters that are relevant to significantly impact on capacity during system design.

Although some clues are offered in these works with respect to achievable throughput gain of relay WiMAX systems, a lot more work is still left aloof and worth considering in terms of the best design practises and performance measures in different scenarios.

2.4.7 Summary

Relay WiMAX offer several gross benefits and solution to some conventional deployment problems of wireless access networks. Coverage enhancement for BSs and increase in capacity in congested areas are both realised by simply associating low cost relays with BSs. However, some relevant aspects in designing such a system have been presented and some existing related literature reviewed with emphasis on prevalent research gaps.

The Relay WiMAX is relatively a new technology with a new architecture which presents several complexities amidst an already thought-provoking wireless environment in a mobile world. Largely, system design becomes difficult due the extensive aggregate of choice available to engineers tied with a general deficiency of understanding of the different design decisions and their impact.

Several issues pertaining to Relay WiMAX remain unanswered as several research works are based on inaccurate assumptions. Hence, the need for much work to be done considering different system configurations which is essential in determining the most practicable scenarios of this technology. It is imperative to note that, transparent and non-transparent systems produce different issues and different approaches are required to solve them. While the reviewed literature in this chapter are essential and complement this thesis naturally, some significant system configuration components that impact on performance are not considered.

Chapter 3

System Design, Modeling and Simulation

In this chapter, we deduced the concepts and derivations that are relevant for simulation in view of developing a system model. We consider a single cell scenario consisting of a central BS and several RSs for the purpose of throughput and capacity enhancement. The MSs are arbitrarily distributed throughout the cell and only N MSs are randomly chosen to be active at a time for each scenario.

3.1 System Model

Several assumptions were made due to system complexity. We considered two hops with two kinds of users, a direct link MS (user), communicating directly with the BS and relay link MS (user), communicating through relay stations to the BS as depicted in figure 3.1. This is due to the fact that more than two-hop relaying without extending coverage reduces the efficiency of using RSs.

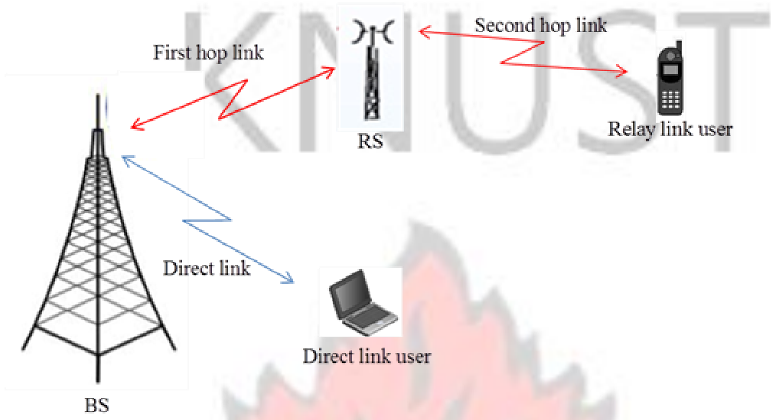


Figure 3.1 System model

The focus is on only the downlink communication whiles considering transparent relay with Amplify and Forward (AAF) relay protocol. Every node has a single omni-directional antenna and operates in half-duplex mode. For multipath fading, Rician fading and Rayleigh fading were considered for BS-RS link and access link respectively. For channel propagation models, SUI channel model and Cost 231 Hata model were used for BS-RS link and access link respectively.

The BS is responsible for allocating resources and is connected to the backhaul network, while the RSs have no backhaul links but are wirelessly connected to the BS. The main responsibility of the RS is to relay data between the BS and MSs. The one-hop links; BS to RS and RS to RS are referred to as *relay links*, and users served through these links are classified as relay link users. Similarly, the links; BS to MS are referred to as *direct links* and users served directly by the BS are considered *direct link users*. We assume that every node in a cell has a single omni-directional antenna and operates in half-duplex mode; hence, no terminal can receive and transmit data simultaneously.

3.2 Channel

In order to model such wireless channels, we can suppose that for each point in the 3dimensional space, the wireless channel is a linear time-varying filter with following impulse response [28]

$$h(t,\tau) = \sum_{k=0}^{N-1} c_k(t)\,\delta(\tau - \tau_k(t))\, e^{j\theta_k(t)} \tag{3.1}$$

where t and τ are the observation time and application time of the impulse, respectively.

N is the number of multipath components, $c_k(t)$, $\tau_k(t)$, $\theta_k(t)$ are the random time - varying amplitude, arrival-time, and phase sequence, respectively, and δ is the delta function. The output of the wireless channel for a given transmitted signal $s(t)$ can be calculated by:

$$y(t) = \int_{-\infty}^{\infty} s(t-\tau)\, h(t,\tau)\, d\tau + n(t) \tag{3.2}$$

where $n(t)$ is the background noise.

3.2.1 Propagation Model

In radio propagation, the general path loss model is given by

$$P_r = \frac{P_t\, g_t\, g_r}{L_p} \tag{3.3}$$

Where P_r and P_t represent the power received and transmitted, g_r and g_t represent the receiver and the transmitter antenna gain while L_p is the end to end path loss. Practically, several factors such as distance between transmitter and receiver, transmitter height, receiver height and terrain influence the propagation path loss immensely. To consider all these factors however, we proposed COST 231 Hata model for our access link and Stanford University Interim (SUI) Channel Model for our link between BS and RS.

3.2.1.1 COST-231 Hata Model

We considered this model for the access links, (i.e. BS-MS link and RS-MS link) in order to vary the velocities of the MS. A model that is widely used for predicting path loss in mobile wireless systems is the COST-231 Hata model. The COST-231 Hata model is designed to be used in the frequency band from 500 MHz to 2 GHz. It also contains corrections for urban, suburban and rural (flat) environments and its simplicity and the availability of correction factors has seen it widely used for path loss prediction at this frequency band [45].

The median path loss L_p is given by:

$$L_p = 46.3 + 33.9\log_{10} f - 13.82\log_{10} h_b + (44.9 - 6.55\log_{10} h_b)\log_{10} d - a(h_m) + C_F \quad (3.4)$$

Where $a(h_m)$ is the antenna correction factor of the MS given by:

$$a(h_m) = (1.11\log_{10} f - 0.7)h_m - (1.56\log_{10} f - 0.8) \quad (3.5)$$

Where h_m represents the transmitter height and h_b represents the receiver height all in meters. d represents the distance between the transmitter and the receiver in *Kilometers* and f is the utilised frequency in *MHz*.

The Jakes Doppler spectrum applies to a mobile receiver with the following assumptions:

- The radio waves propagate horizontally.
- At the receiver, the angles of arrival of the radio waves are uniformly distributed over $[-\pi, \pi]$.
- At the receiver, the antenna is omni directional. [41]

The baseband normalized Jakes Doppler spectrum is given analytically by:

$$S(f) = \frac{1}{\pi f_m \sqrt{1 - \left(\frac{f}{f_m}\right)^2}}, \quad |f| \le f_m \tag{3.6}$$

where f_m is the maximum Doppler shift.

3.2.1.2 Stanford University Interim (SUI) Channel Model

This model can be used for simulations, design, development and testing of technologies suitable for fixed broadband wireless applications [50]. However, we used it for our BS-RS link. The parameters for the model were selected based on some statistical models. This model is based on the Stanford University‟s proposal for broadband wireless access path loss estimation. The goal of the model implementation is to simulate channel coefficients with the specified distribution and spectral power density generated using the method of filtered noise [40]. A set of complex zero mean Gaussian distributed number is generated with a variance of 0.5 for the real and imaginary part for each tap to achieve the total average power of this distribution which is 1. In this way, we get a Rayleigh distribution (equivalent to Rice with $K_{\text{Rice}} = 0$) for the magnitude of the complex coefficients. In case of a Rician distribution ($K_{\text{Rice}} > 0$), a constant path component m has to be added to the Rayleigh set of coefficients. The K-factor specifies the ratio of powers between this constant part and the variable part. The distribution of the power is shown below:

Total power p of each tap:

$$p = |m|^2 + \sigma^2 \tag{3.7}$$

where m is the complex constant and σ^2 the variance of the complex Gaussian set.

$$K_{Rice} = \frac{|m|^2}{\sigma^2} \quad (3.8)$$

From the above two equations, the power of the complex Gaussian:

$$\sigma^2 = p.\frac{1}{K_{Rice}+1} \quad (3.9)$$

and the power of the constant part as:

$$|m|^2 = p.\frac{K_{Rice}}{K_{Rice}+1} \quad (3.10)$$

The SUI channel model address a specific power spectral density (PSD) function for the scatter component channel coefficients which is given by:

$$S(f) = 1 - 1.72 f_0^2 + 0.785 f_0^2 \qquad |f_0| \le 1$$
$$= 0 \qquad |f_0| > 0 \quad (3.11)$$

Where, the function is parameterized by a maximum Doppler frequency f_m and

$$f_0 = \frac{f}{f_m} \quad (3.12)$$

To generate a set of channel coefficients with this PSD function, the original coefficients are correlated with a filter which amplitude frequency response is:

$$H(f) = \sqrt{S(f)} \qquad (3.13)$$

There are no frequency components higher than f_m (for the construction formula of *S(f)* so the channel can be represented with a minimum sampling frequency of $2f_m$ according to the Nyquist theorem. For this reason we chose the sampling frequency equal to $2f_m$.

3.2.2 Multipath Fading Channels

We assume well known fading channels such as the Rayleigh fading for the access links (i.e. BS-MS and RS-MS links) and Rician fading channel for the relay link (i.e. BS-RS link). The Rayleigh fading channel is most applicable when there is no propagation along the line of sight between the transmitter and receiver, while the Rician fading channel is more appropriate when there is a dominant line of sight component at the receiver.

For BS-MS and RS-MS access links, we can precisely model via a Rayleigh distribution the amplitude distribution of the received signal as:

$$p(\alpha) = \frac{\alpha}{\sigma^2}\exp\left(-\frac{\alpha^2}{2\sigma^2}\right), \quad \alpha \geq 0 \qquad (3.14)$$

Where α represent the received signal amplitude and σ^2 represent the local mean power [69]. Now according to the amplitude of the received signal probability density function (pdf) in (3.14), we can derive the received signal power pdf, γ, which has the exponential pdf:

$$p(\gamma) = \frac{1}{\gamma^*}\exp\left(-\frac{\gamma}{\gamma^*}\right), \quad \gamma \geq 0 \qquad (3.15)$$

where γ^* represent the received signal mean power. Similarly, for the relay (BS-RS) link, we can via Rician distribution model the amplitude distribution of the received signal as:

$$p(\rho) = \frac{\rho}{\sigma^2} \exp\left(-\frac{\rho^2 + v^2}{2\sigma^2}\right) I_0\left(\frac{\rho v}{\sigma^2}\right), \rho \geq 0, v \geq 0 \quad (3.16)$$

If $I_n(.)$ represent a modified n^{th} -order Bessel function of the first kind, $\frac{1}{2}v^2$ characterise the power of the LOS component while the power of all other scattered components denoted as σ^2; we can deduce the total mean power of the received signal γ^* as:

$$\gamma^* = \frac{1}{2}v^2 + \sigma^2 \quad (3.17)$$

The Rician K-factor is given as the ratio between the signal power in the dominant component and the local mean scattered power [68], where $K = \frac{v^2}{2\sigma^2}$. The Rician distribution becomes Rayleigh when the K-factor goes to zero; the pdf of γ, (received signal power) from equation (3.13), can be obtained by transforming random variable ρ into γ via the amplitude and power relation of the signal $\gamma = \frac{1}{2}\rho^2$. According to [69] the pdf of received signal power is given by:

$$p(\gamma) = \frac{(1+K)e^{-K}}{\gamma^*} \exp\left(-\frac{(1+K)\gamma}{\gamma^*}\right) I_0\left(\sqrt{\frac{4K(1+K)\gamma}{\gamma^*}}\right), K \geq 0, \gamma \geq 0 \quad (3.18)$$

Where □* is the received signal mean power.

3.3 Relay Strategy

An MS located within BS coverage can either be served directly by BS or via RS. More often than not, the MSs will prefer an RS route only if the achievable relay link data rate (BS-RS-SS) is superior to the direct link data rate (BS-SS). The relay link data rate is influenced by the link capacities and time durations of the linking two hops. The assumption made in our case is that every node has a single antenna and operates in half duplex mode and also, data arriving equals data leaving at the RS node.

For each transmission time interval according to [17], the BS allocates sub-channels to both relay and direct links. Within a segment, if the k_{th} sub-channel represented by $a_{k,m}$ is allocated to a direct link user m then;

$$a_{k,m} = \begin{cases} 1, & \text{subchannel k allocated} \\ o, & \text{otherwise} \end{cases} \quad (3.19)$$

Likewise

$$b_{k,r,m} = \begin{cases} 1, & \text{subchannel k allocated to user using RSr} \\ 0, & \text{otherwise} \end{cases} \quad (3.20)$$

Where $b_{k,r,m}$ represent k_{th} subchannel allocated to user m using RSr (relay station r) using the second hop link [34].

Estimating the capacity of direct link in the first time slot using Shannon‟s formula is given by:

$$C_{k,m} = B_k \log_2 \left(1 + p_{k,m} g_{k,m} / \sigma^2\right) \quad (3.21)$$

With B_k representing the bandwidth of the each channel, $P_{k,m}$ represent the transmit power on the k_{th} subchannel of BS to MS m, $g_{k,m}$ represent the gain of subchannel and σ^2 represent the AWGN power level [33].

Similarly capacity of the relay link is

$$C_{k,r} = B_k \log_2\left(1 + p_{k,r}\, g_{k,r} / \sigma^2\right) \tag{3.22}$$

Where $P_{k,r}$ denotes the transmit power on the k_{th} subchannel of BS to RS r. for m number of users on the relay link, the above equation becomes:

$$C_{k,r,m} = B_k \log_2\left(1 + p_{k,r,m}\, g_{k,r,m} / \sigma^2\right) \tag{3.23}$$

On the direct link, the realistic data rate in the first time slot according to [33] is given by:

$$C_m = \sum_{k=1}^{K} C_{k,m}\, a_{k,m}, \quad m \in \Omega_D \tag{3.24}$$

Where Ω_D represent a set of direct link users.

And on the relay link, in the second time subslot, data rate for user m is given by:

$$C_m^{(2)} = \sum_{k=1}^{K} C_{k,r,m}\, b_{k,r,m}, \quad m \in \Omega_R \tag{3.25}$$

In the first time slot, all relay link users share the data rate of RS r, therefore producing a data rate in the first time subslot for each user in the relay link as:

$$C_m^{(1)} = C_r^{(1)} \cdot C_m^{(2)} \Big/ \sum_{m \in \Omega_{R_r}} C_m^{(2)} \tag{3.26}$$

If $C_r^{(1)}$ denotes data rate of RS r of the first hop link given by:

$$C_r^{(1)} = \sum_{k=1}^{K} C_{k,r}\, a_{k,r} \qquad (3.27)$$

If a single user is considered as in our scenario, then $C_m^1 = C_r^1$.

Now, given that $t_{BS\text{-}RS}$ represent the first time subslot and $t_{RS\text{-}MS}$ represent the second time subslot; the total duration of the downlink subframe transmission should be $t_{BS\text{-}RS} + t_{RS\text{-}MS}$.

The amount of data transfer from BS to RS is equal to that from RS to MS.

$$C_m^1 \cdot t_{BS\text{-}RS} = C_m^2 \cdot t_{RS\text{-}MS} \qquad (3.28)$$

To determine the average data rate of user on the relay link, we divide the amount of data received by the time required to receive it [34].

$$\bar{C}_m = \frac{C_m^1 \cdot t_{BS\text{-}RS}}{t_{BS\text{-}RS} + t_{RS\text{-}MS}} \qquad (3.29)$$

Since RS cannot receive from BS while transmitting to MS. Subsequently, using the relation in [33], we can rewrite the relay data rate of the MS as:

$$\frac{1}{\bar{C}_m} = \frac{1}{C_{m1}} + \frac{1}{C_{m2}} \qquad (3.30)$$

3.4 OFDM Implementation in WiMAX

This is an algorithm for computing discrete Fourier transform as a very efficient way of carrying out parallel processing. In OFDM technique we have large number of carriers and subcarriers which have to be processed simultaneously at the same time [20]. Basically, the structure of an

OFDM symbol is presented in frequency domain which is made up of three forms of subcarriers:

- Data subcarriers which is responsible for data transmission.
- Pilot subcarriers responsible for various estimation purposes.
- Null subcarriers responsible for guard bands and DC carrier.

The number of these subcarriers will determine the required size for the FFT (or IFFT) algorithm. Data is sent in the form of OFDM symbols.

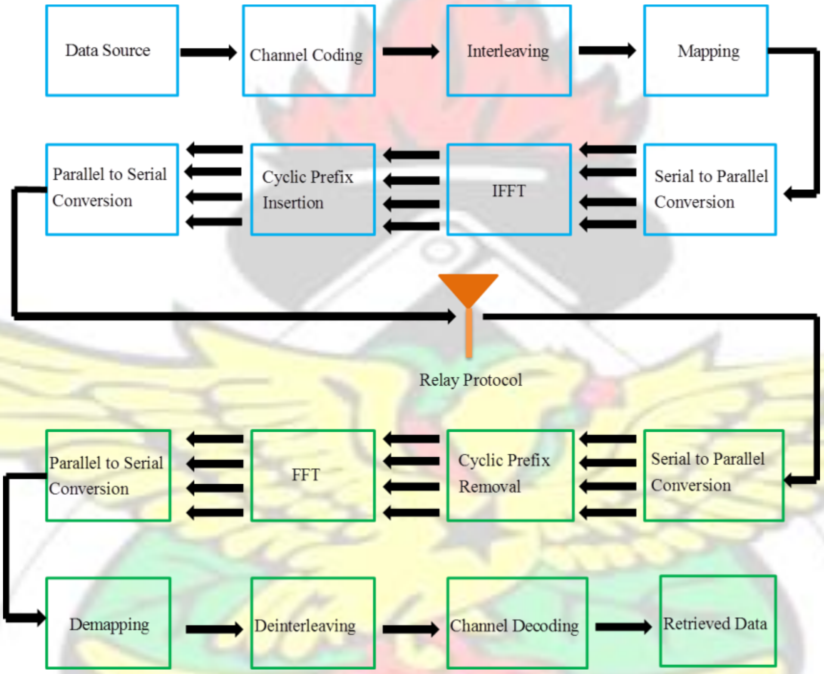


Figure 3.2 System Implementation with Relay

The purpose of the guard bands is to enable the signals to naturally decay and create the FFT „brick wall" shaping [28]. It can also be used for cancelling the Inter-channel interference. The figure 3.3 below shows the OFDM symbol representation in frequency domain. Note that the DC subcarrier is left zero and put in the middle.

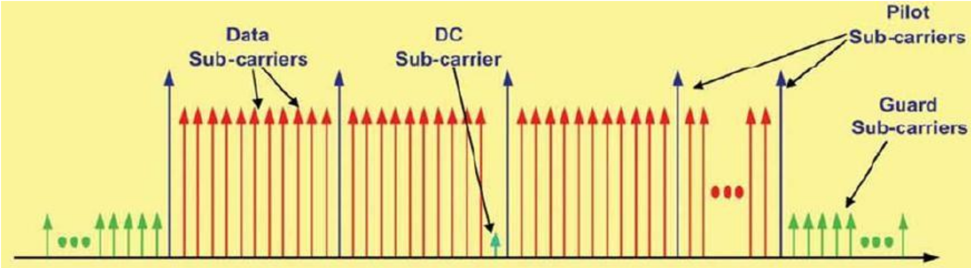


Figure 3.3 OFDM symbol structure in frequency domain [28]

There are basically two categories of OFDM symbol parameters (i.e. primitive and derived) that describes OFDM symbol completely. There exists a stable relation between these two allowing for the derived to be obtained from the primitive. The following are some important definitions of OFDM parameters that are used in our simulation.

N_{data}: Number of data subcarriers that data symbols are apportioned at the transmitter.

N_{pilot}: Number of pilots subcarriers which are used to synchronize the receiver to the transmitter in terms of phase, frequency and timing and to estimate the channel at the receiver.

N_{guard}: Number of guard subcarriers or the outer carriers. These are not used for transmission and are called virtual sub-carriers.

Number of used subcarriers, N_{used}: $N_{used} = N_{data} + N_{pilot}$

N_{FFT} is the FFT size, and it specifies the number of samples for processing and specified as the smallest power of two, and greater than N_{used} and given by:

$$N_{FFT} = 2^{[\log_2 N_{data}]} \quad (3.35)$$

where N_{data} the number of data subcarriers.

Nominal Channel Bandwidth, BW was chosen to be 5 MHz in our simulation because it is widely used.

BW_{used} is the used Channel bandwidth which is physically occupied by the WiMAX signal in frequency domain. The used channel bandwidth is mathematically equal to the product of the number of used subcarriers (N_{used}) and the subcarriers spacing (Δf) in the frequency domain.

BW_{used} must be smaller than the nominal bandwidth given by : $BW_{used} = N_{used}. \Delta f$

F_s denote the sampling frequency which is the primary frequency of the system given according to the WiMAX standard [10] by:

$$F_s = \left\lfloor \frac{n \cdot BW}{8000} \right\rfloor \cdot 8000 \quad (3.36)$$

Where ⌊.⌋ indicates the approximation to the nearest integers towards minus infinity and n is the sampling factor. F_s must always be greater than BW.

The relation given above is inscribed in the WiMAX standard but F_s also be calculated as follows:

$$F_s = \frac{1}{T_s} = \frac{N_c}{T_B}. \quad (3.37)$$

Here, F_s must be chosen to be at least twice the maximum frequency of the signal to prevent the phenomenon of aliasing.

However, for better channel selectivity at the receiver and considering channel interference, a much higher sampling rate is desirable, i.e., $F_s > N_c \backslash T_b$.

3.5 BER Calculations

BER is calculated after channel decoding is implemented with Viterbi decoder following symbol demapping which produce the data bits. This is after channel equalization and parallel to series conversion.

3.6 Spectral Efficiency

The spectral efficiency of a channel is a measure of the number of bits transferred per second for each Hz of bandwidth [3]. We derived the spectral efficiency using the relation [42]:

$$\square\square\ \square(1\ BER)^{n}\ kr \tag{3.38}$$

Where *BER* is the bit error rate, *n* denotes the number of bits in the block, *k* represents the number of bits per symbol and *r* is the overall code rate.

Chapter 4

System Implementation and Testing

4.1 Introduction

In order to evaluate the link performance, we employed MATLAB version R2012a to develop a simulation program to realise our system and to compare the two links under study. This chapter presents the simulation result as well as deduction and interpretations of theories in our system model obtainable in the previous chapter with the aim to render a complete view on a better way of performance.

4.2 Simulation Results and Discussion

In the simulation setup, a WiMAX cell scenario of BS is considered and RS deployed within its coverage. A downlink transmission is considered with a channel bandwidth of 5MHz and a 2.5GHz carrier frequency. The BS is centralised and the RS kept in amplify and forward (AAF) mode.

First, we estimate the link condition in terms of BER between the BS, the RS and the MS as a function of bit energy to noise ratio (E_b/N_0) and subsequently spectral efficiency and capacity are also evaluated. We used the SUI channel model for link between BS-RS and Cost 231 channel model between BS-MS and RS-MS links while specifying the velocity of MS within the Doppler frequency. Initialization parameters and input data form the core of the program.

At the time of initialization, parameters that can be set include the number of subcarriers, the nominal bandwidth, CP length, symbol modulation level and coding rate, range of the bit energy to noise ratio (E_b/N_o) values (from 0 to 40 dB) and channel model parameters for simulation. The input data stream is randomly generated. Output variables are available in MATLAB workspace while bit error rate (BER) values for different E_b/N_o are stored in text files which facilitate to draw plots. In our model, the simulation of the system is repeated and the number of transmitted bits and bit errors are calculated for each simulation. At the end, BER is estimated as the ratio of the total number of observed errors and the total number of transmitted bits.

The performance of the system model is evaluated using varied modulation and coding schemes such as BPSK ½, QPSK ½, QPSK ¾, 16-QAM ½, 16-QAM ¾, 64-QAM 2/3 and 64-QAM ¾ while using SUI-3 channel model for BS-RS link and COST 231 Hata model for BS-MS and RS-MS access links considering several MS velocities.

Our simulations can be summarised into 3 stages:

1. BER and Spectral efficiencies at fixed speed of MS in pure AWGN channel.
2. BER at varied speed of MS in fading channel (i.e. Rayleigh and Rician) compared to that of non-fading pure AWGN channel.
3. Capacities of the two links under study (i.e. relay and direct link).

The next sections present a set of plots to identify trends in signal quality as we change different parameters. These plots include BER vrs. E_b/N_0, spectral efficiency vrs E_b/N_0 and capacity vrs E_b/N_0 plots.

4.2.1. Performance measure of Relay and Direct links in AWGN channel

In this section, we have presented various BER vrs E_b/N_0 and spectral efficiency vrs E_b/N_0 plots for all the mandatory modulation and coding schemes as specified in the IEEE 802.16j standard for both relay and direct link. Figures 4.1 - 4.14 show these plots exhausting BPSK, QPSK, 16-QAM and 64-QAM in pure AWGN using OFDM comparing performances of the two links. For each cited modulation, the BER of relay and direct links are compared as well as their respective spectral efficiencies which are estimated based on equation (3.35).

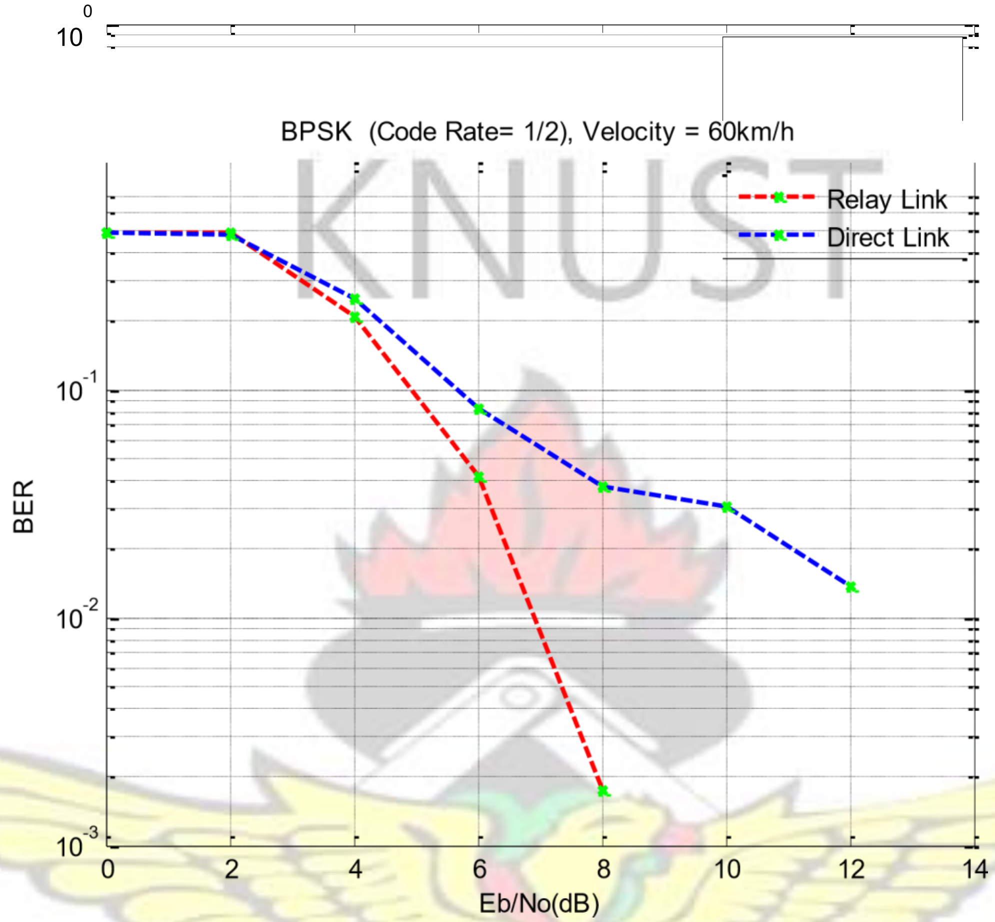
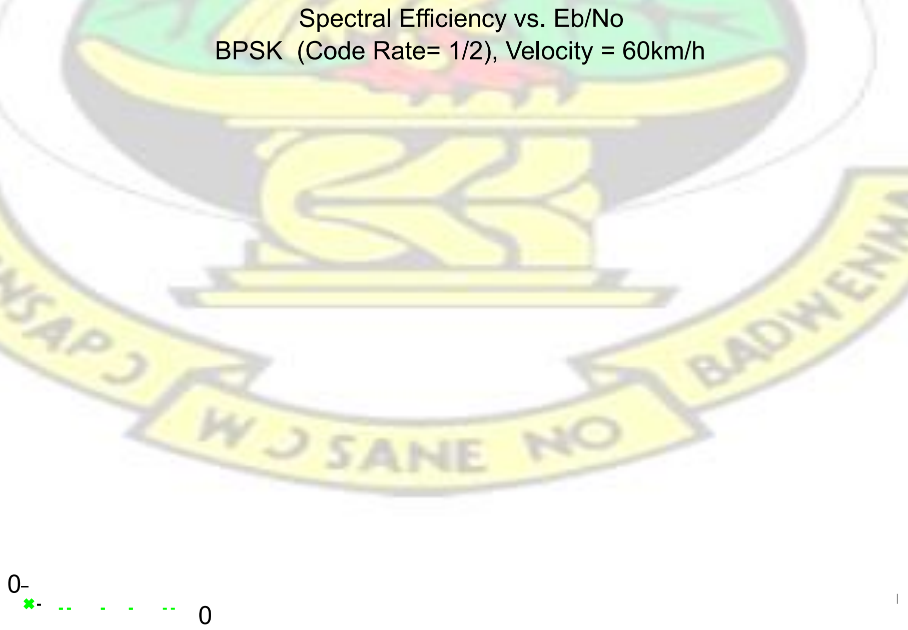


Figure 4.1 Plot of BER against E_b/N_0 for MS at 60km/h via AWGN channel (BPSK-1/2)



Spectral Efficiency against E_b/N_0

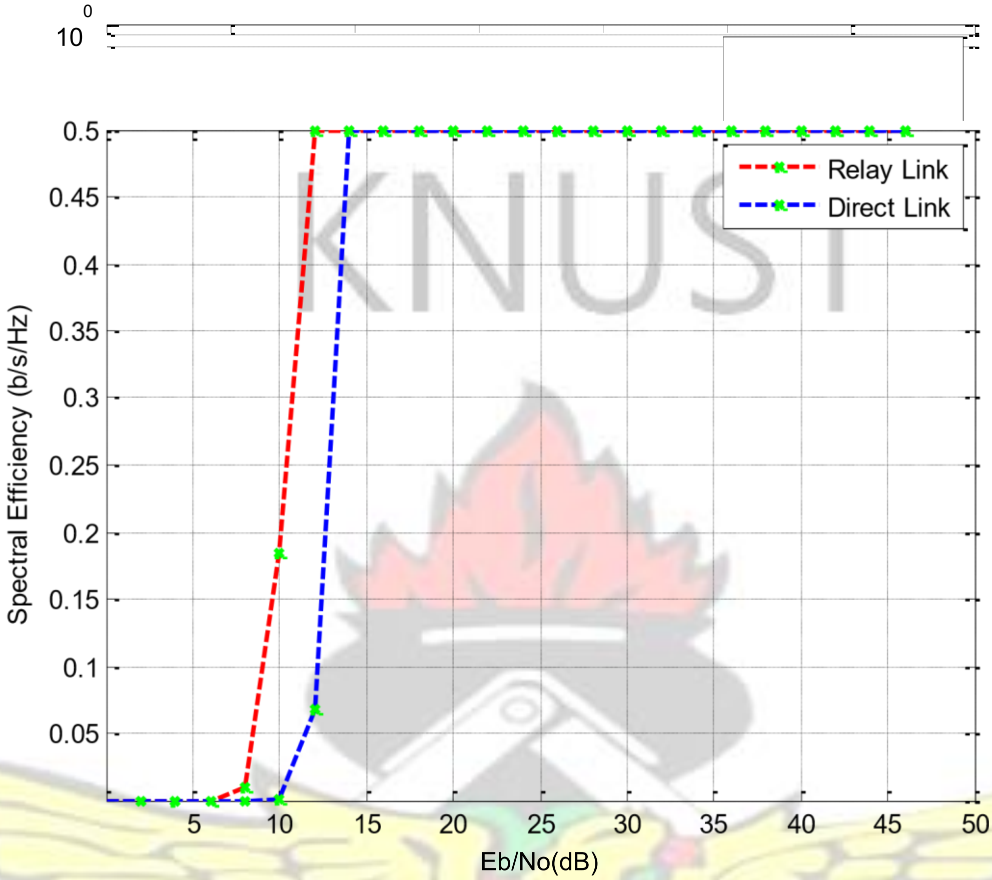
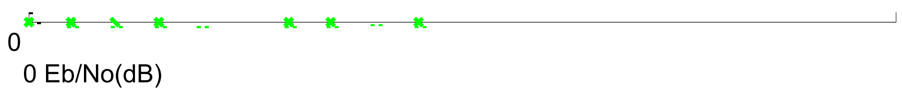


Figure 4.2 for MS at 60km/h via AWGN (BPSK-1/2)



Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (

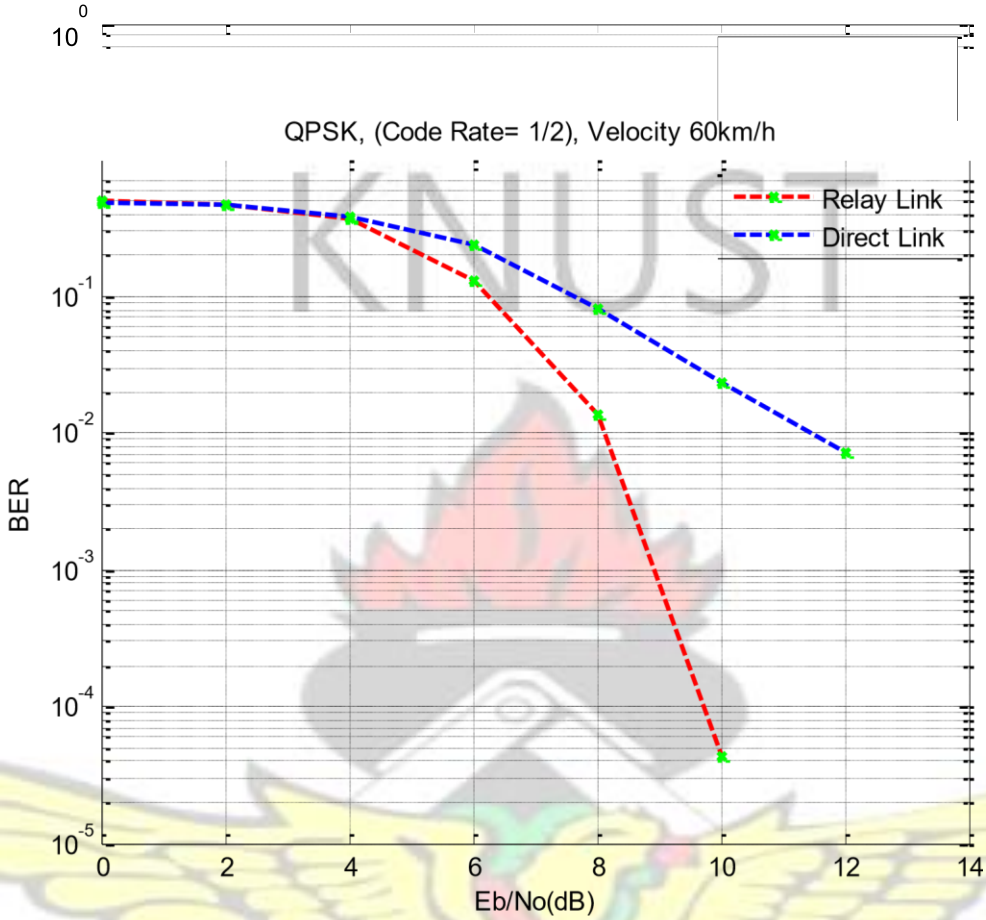
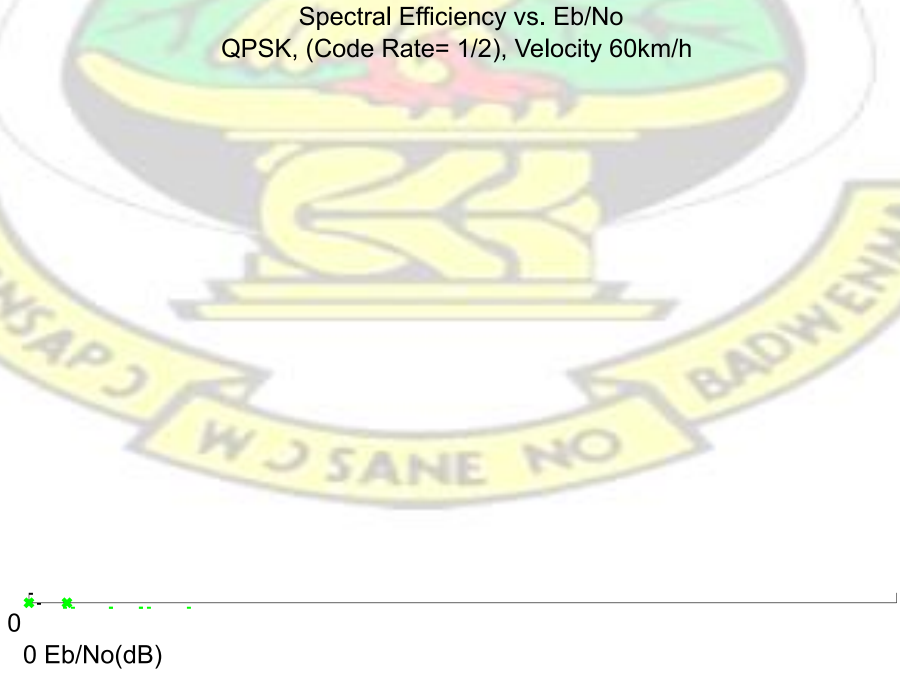


Figure 4.3 Plot of BER against E_b/N_0 for MS at 60km/h via AWGN channel (QPSK-1/2)



Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (

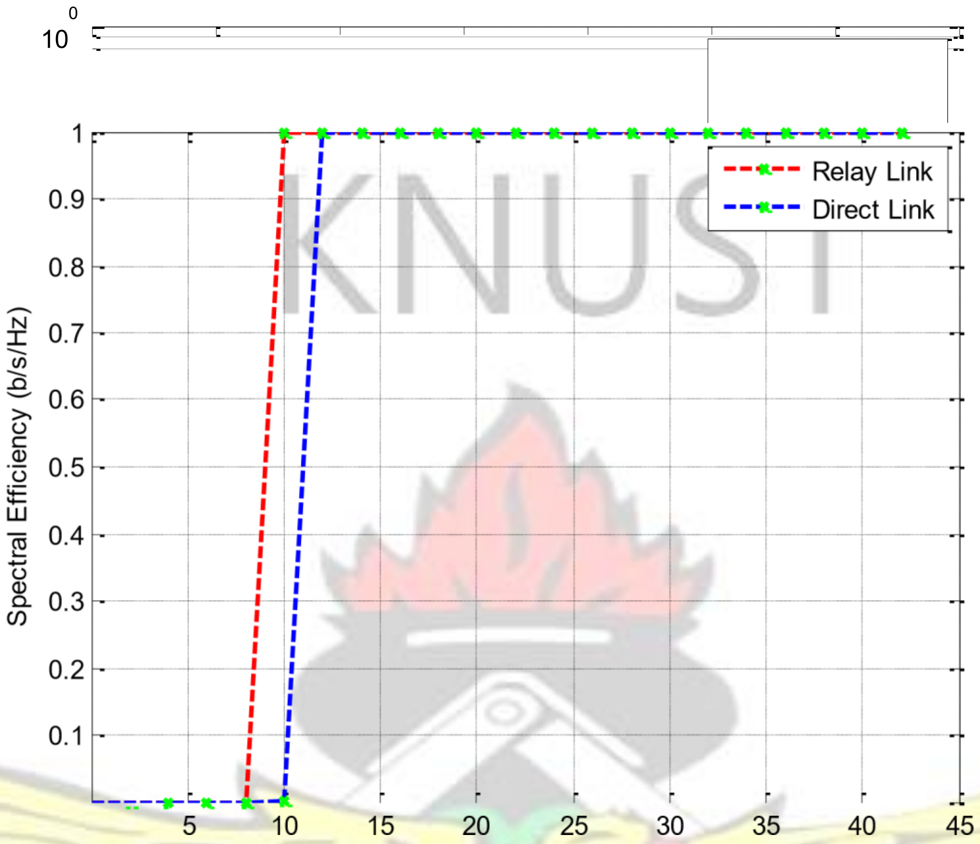


Figure 4.4 QPSK-1/2)

0

0 Eb/No(dB)

Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (

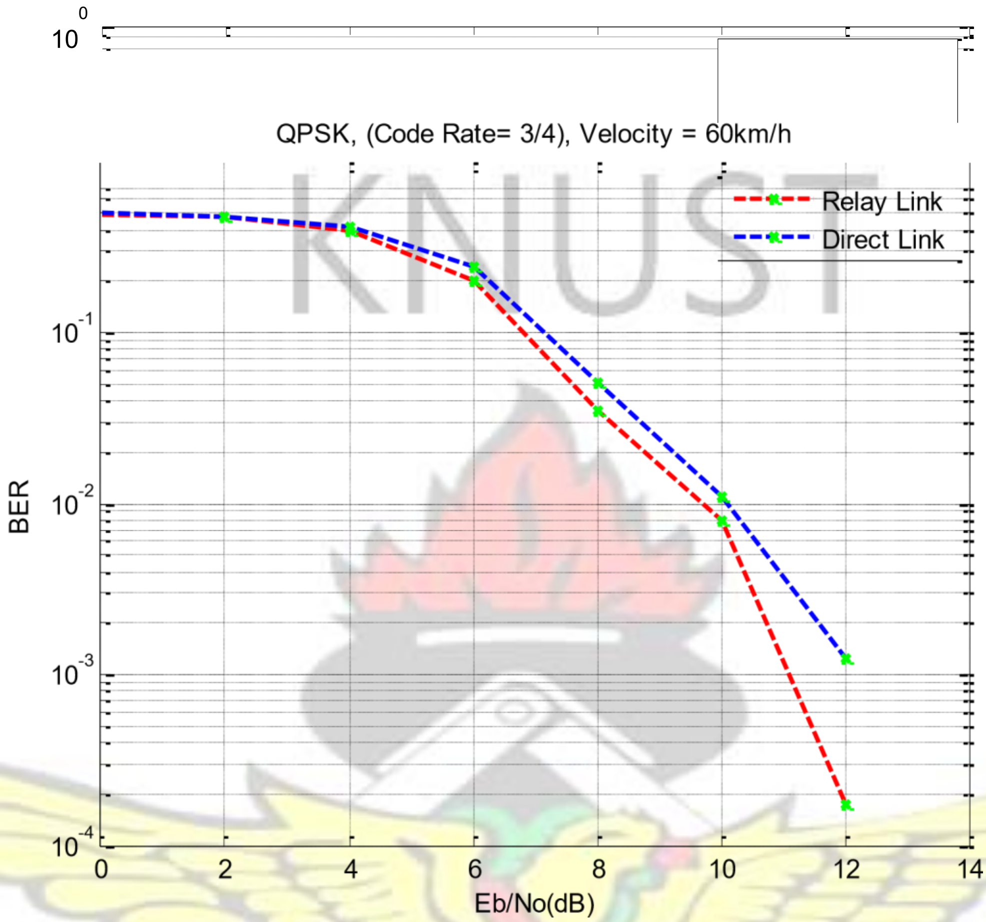
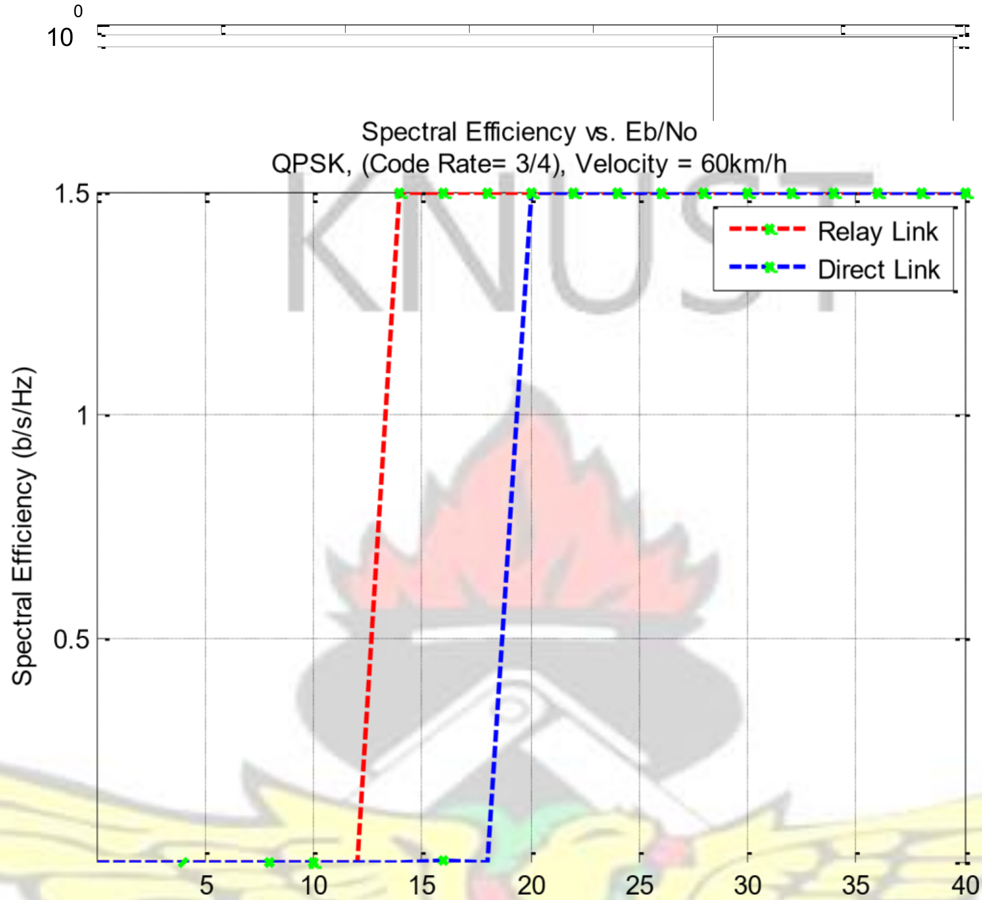


Figure 4.5 Plot of BER against E_b/N_0 for MS at 60km/h via AWGN channel (QPSK-3/4)

Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (



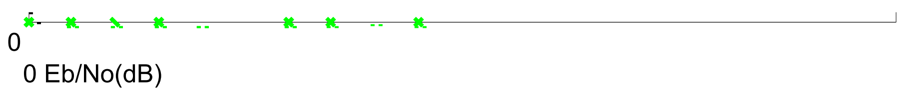


Figure 4.6 Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (QPSK-3/4)

10^{0}

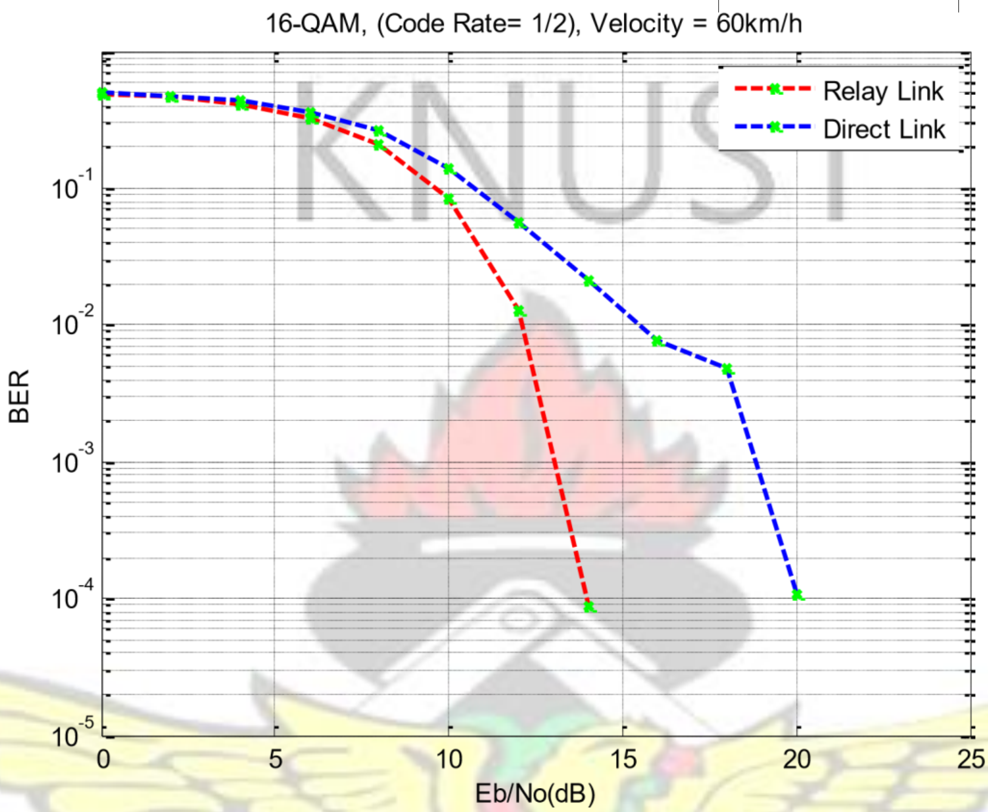


Figure 4.7 Plot of BER against E_b/N_0 for MS at 60km/h via AWGN channel (16QAM-1/2)

Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (

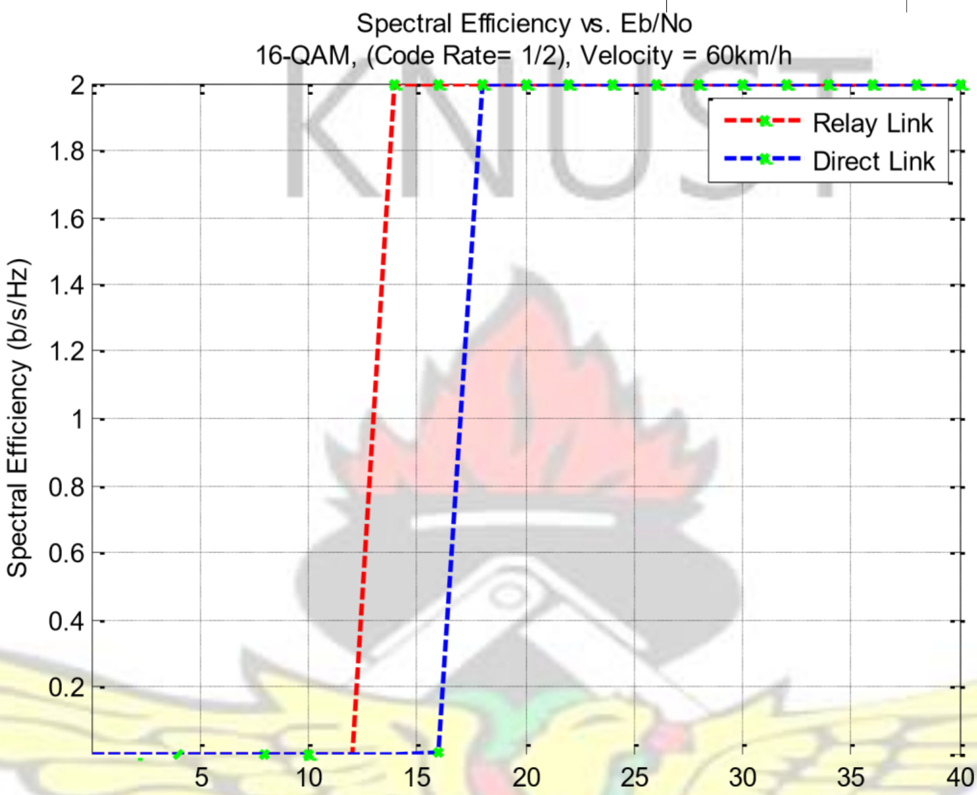


Figure 4.8 Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (16-QAM-1/2)

5 10
15 25
30 35

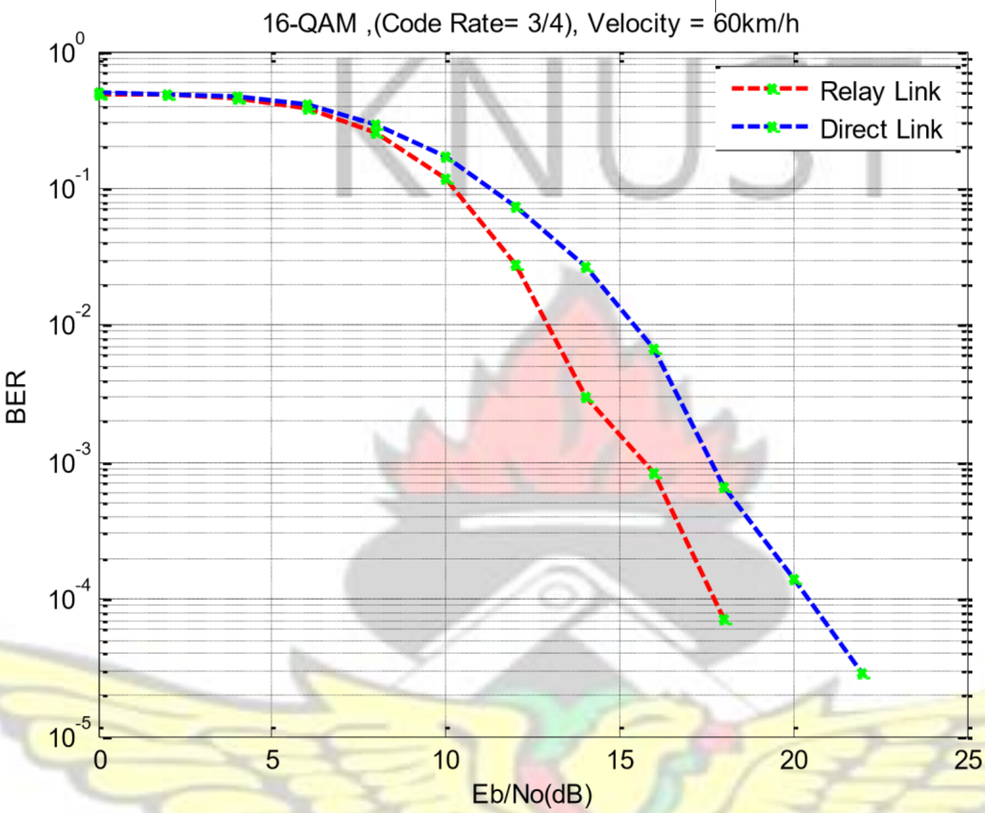


Figure 4.9 Plot of BER against E_b/N_0 for MS at 60km/h via AWGN channel (16QAM-3/4)

Spectral Efficiency vs. Eb/No
16-QAM ,(Code Rate= 3/4), Velocity = 60km/h

5 10
15 25
30 35

Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (

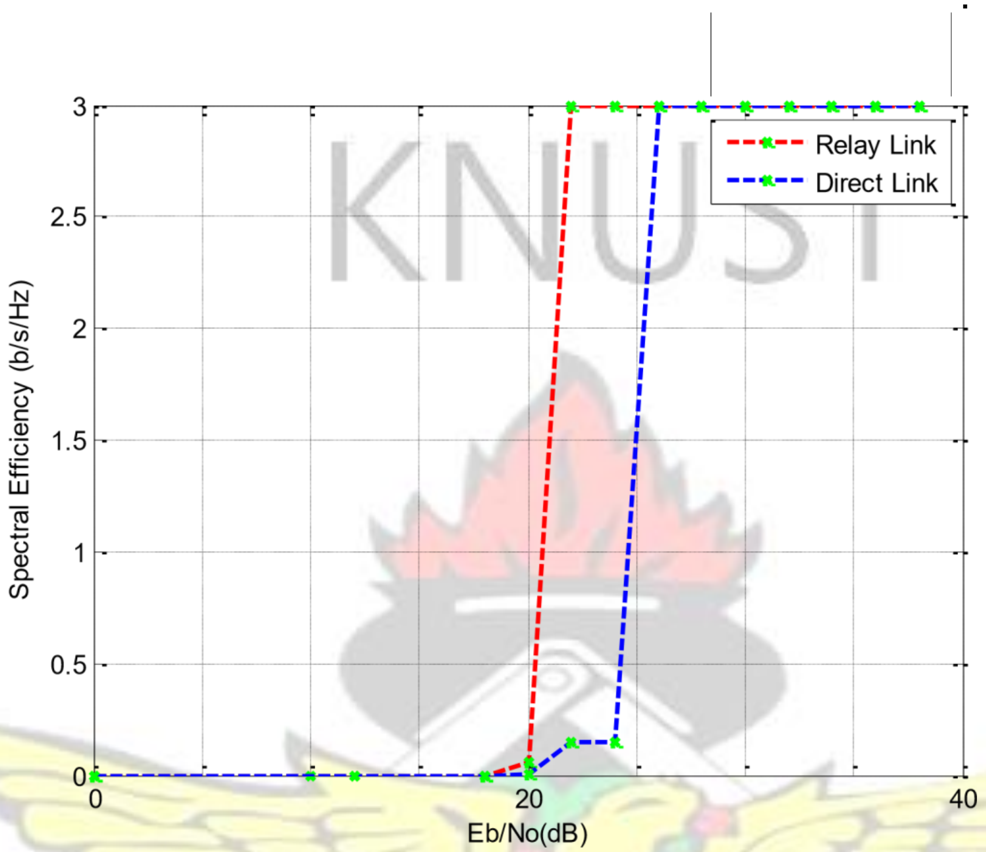


Figure 4.10 16-QAM-3/4)

64-QAM ,(Code Rate= 2/3), Velocity = 60km/h

0

5 10
15 25
30 35

Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (

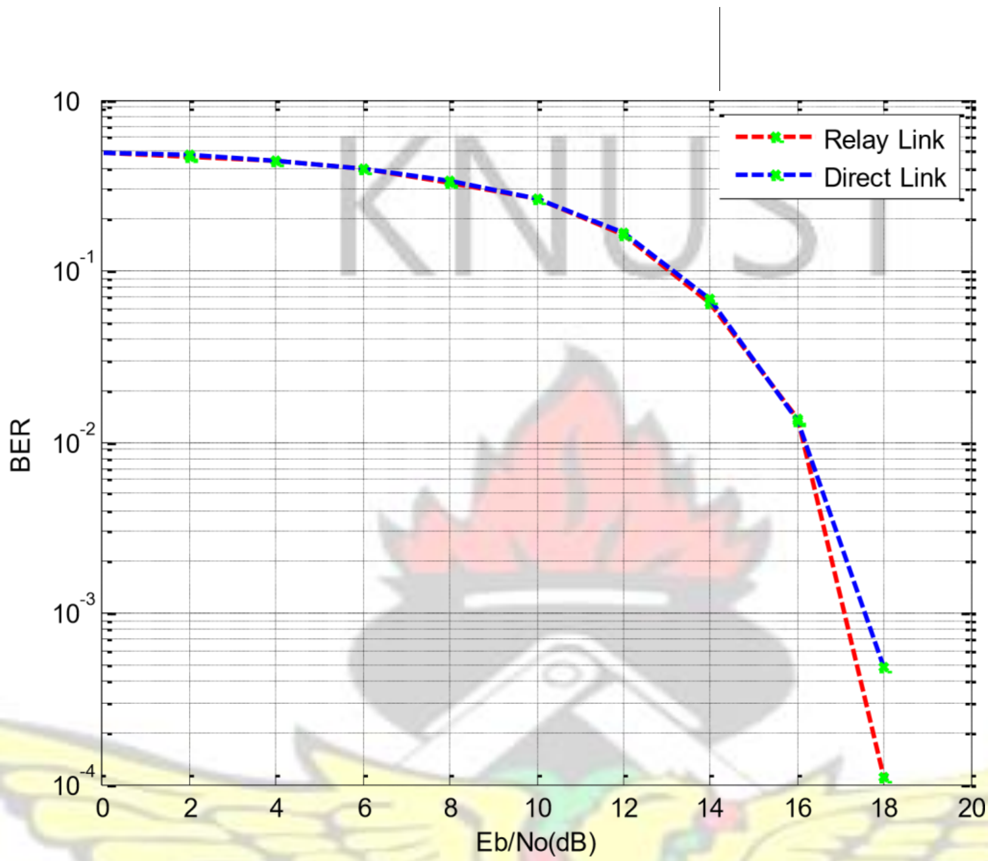


Figure 4.11 Plot of BER against E_b/N_0 for MS at 60km/h via AWGN channel (64QAM-2/3)

Spectral Efficiency vs. Eb/No
64-QAM ,(Code Rate= 2/3), Velocity = 60km/h

5 10
15 25
30 35

Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (

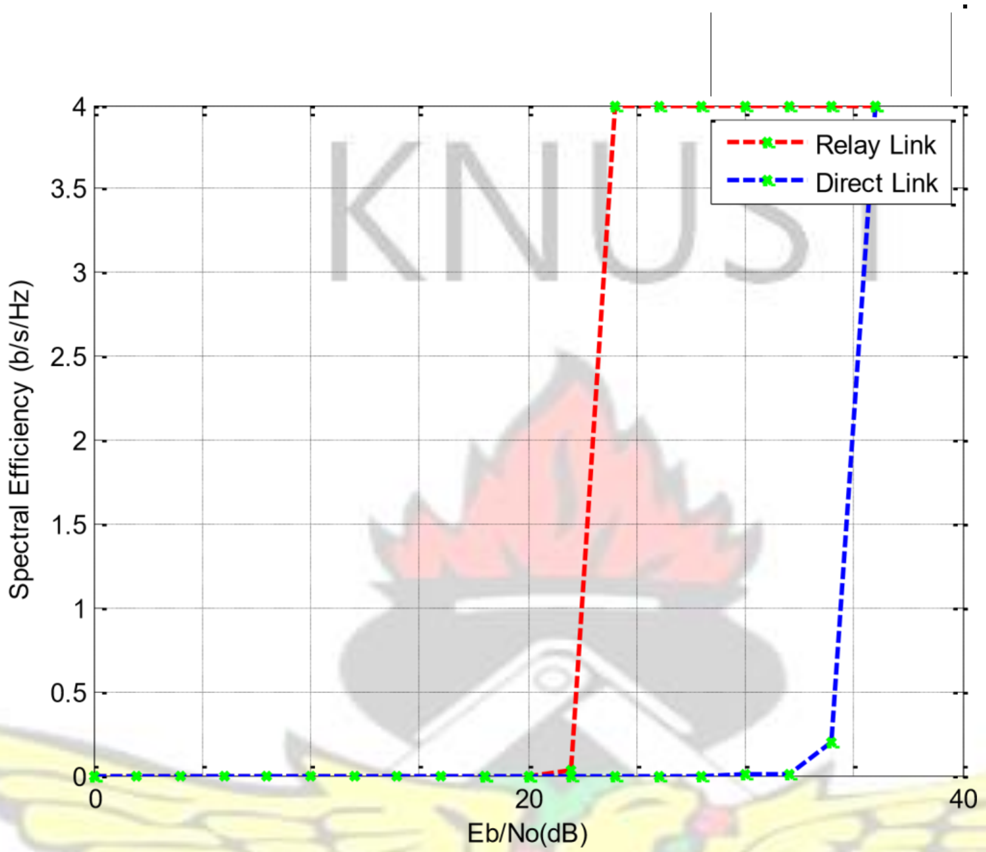


Figure 4.12 64-QAM-2/3)

5 10
15 25
30 35

Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (

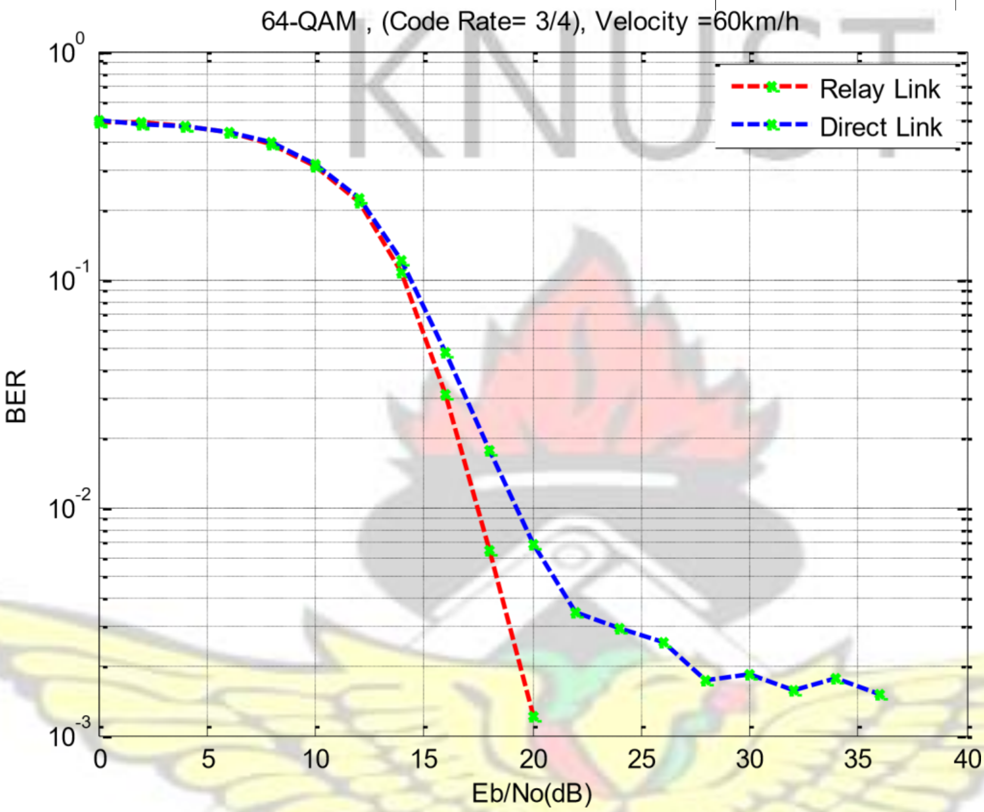


Figure 4.13 Plot of BER against E_b/N_0 for MS at 60km/h via AWGN channel (64-QAM-3/4)

5 10 15
25 30 35

Spectral Efficiency against E_b/N_0 for MS at 60km/h via AWGN (

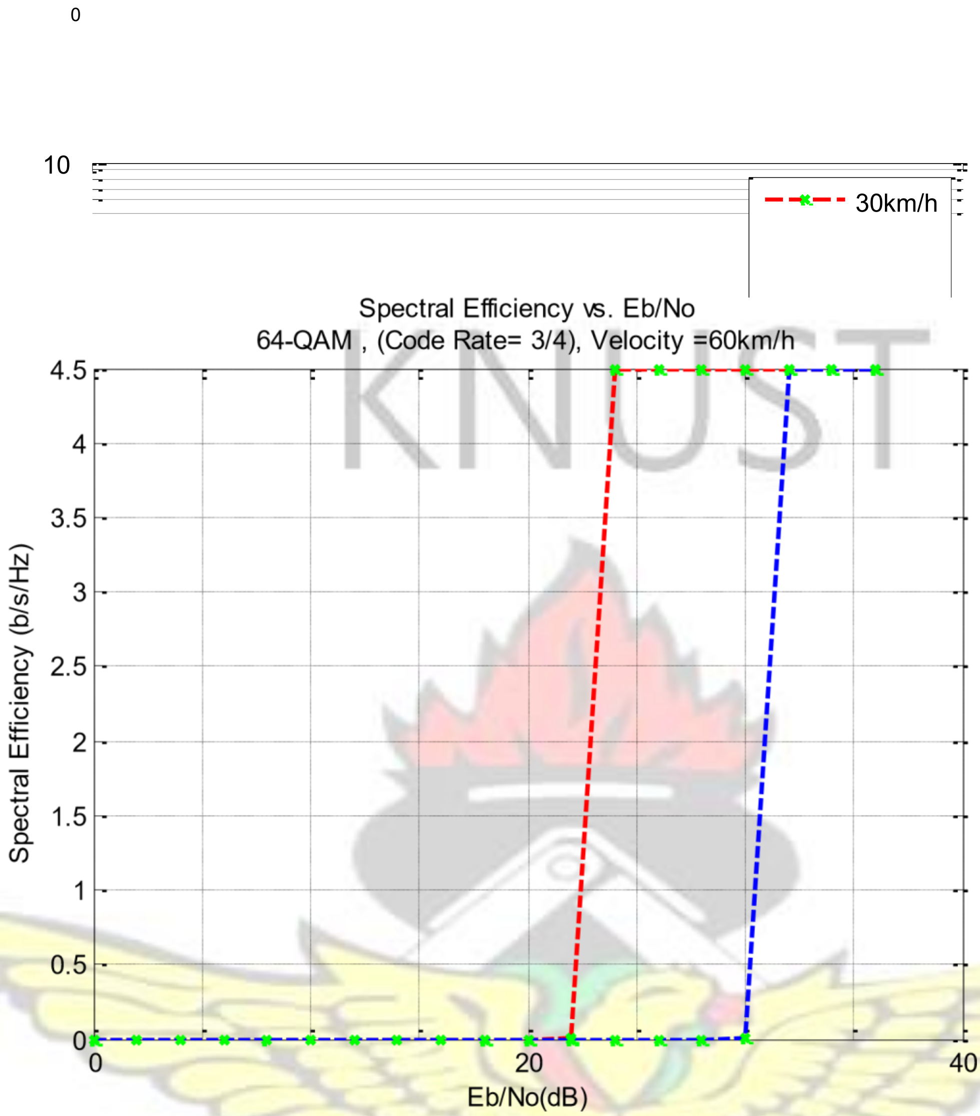


Figure 4.14 64-QAM-3/4) We observed that, the relay link marginally performed better than the direct link at an MS velocity of 60km/h. It was also prominent that BPSK is more power efficient and need less bandwidth amongst all other modulation techniques used in this OFDM adaptive modulation. In case of bandwidth utilization, the 64-QAM modulation requires higher bandwidth and gives an excellent data rates as compared to others while the QPSK and the 16-QAM techniques are in the middle of these two and need higher bandwidth and less power efficient than BPSK. But they required lesser bandwidth and lower data rates than 64-QAM. BPSK has the lowest BER while the 64-QAM has highest BER than others.

BER against E_b/N_0

4.2.2. Effect of speed and fading on Performance

The results presented here are for simulations performed for the MS velocities of 30, 60 and 90 km/h in fading and non-fading pure AWGN channels. The prime purpose of this section is in two folds. The first is to investigate the effect of speed to system performance and the next is to probe into the influence of fading channel to performance. Figures 4.15, 4.17 and 4.19 present the BER curves of QPSK-1/2, 16-QAM-1/2 and 64-QAM-2/3 with varied MS speed of 30, 60 and 90km/h while considering a relay link in pure AWGN channel. Figures 4.16, 4.18 and 4.20 present BER curves with same parameters in multipath fading channel.

It is clearly indicated from the results obtained that fading channels offer degraded performance compared to non-fading channels. On the side of testing, speed has a great impact on performance. It was noted that when low speed of MS performed better than higher MS speed.

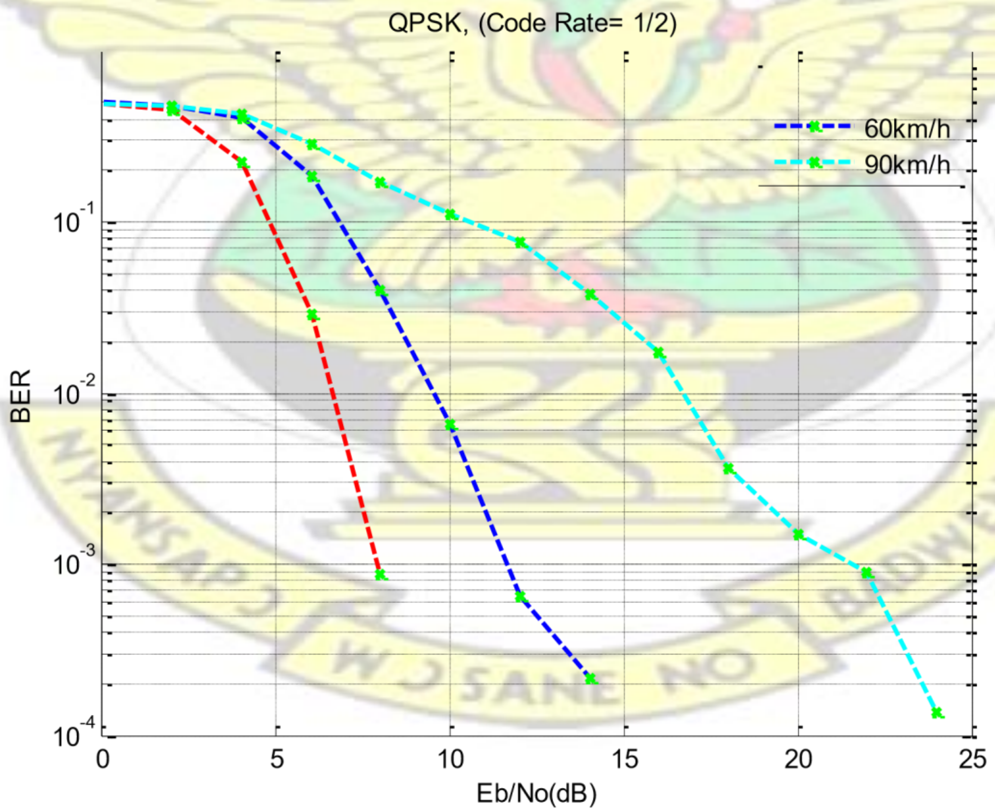


Figure 4.15 BER against E_b/N_0 for QPSK-1/2 in AWGN, V=30,60 and 90 km/h

0

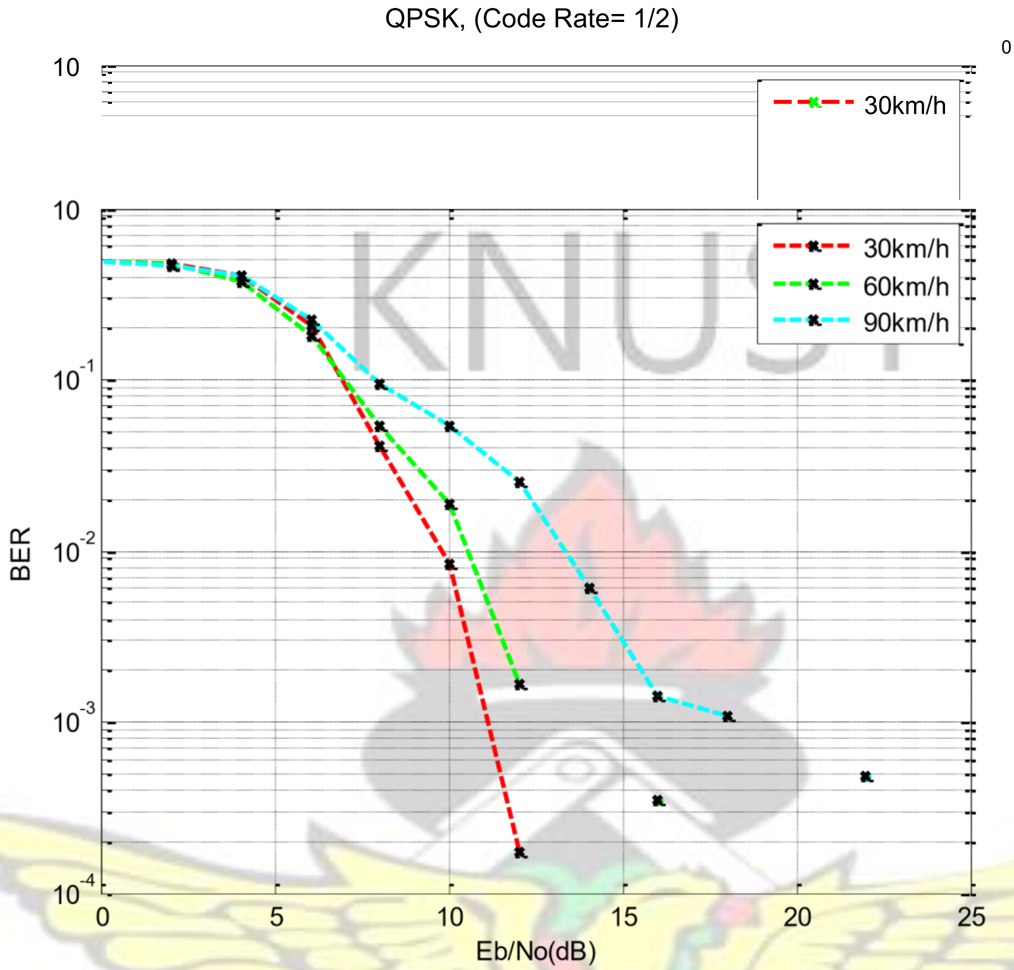


Figure 4.16 for QPSK-1/2 in Fading channel, V=30,60 and 90 km/h

BER against E_b/N_0

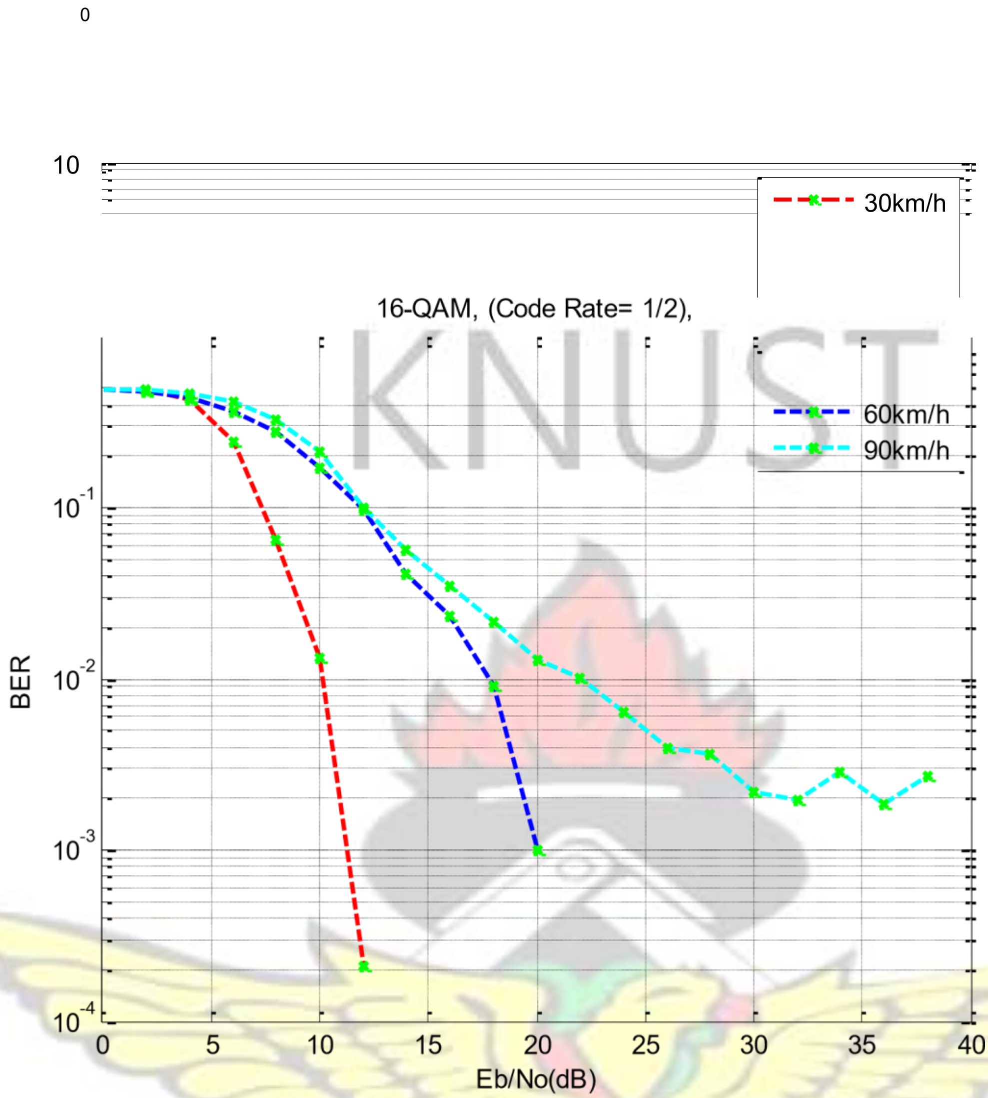


Figure 4.17 BER against E_b/N_0 for 16-QAM-1/2 in AWGN, V=30,60 and 90 km/h

16-QAM, (Code Rate= 1/2),

0

BER against E_b/N_0

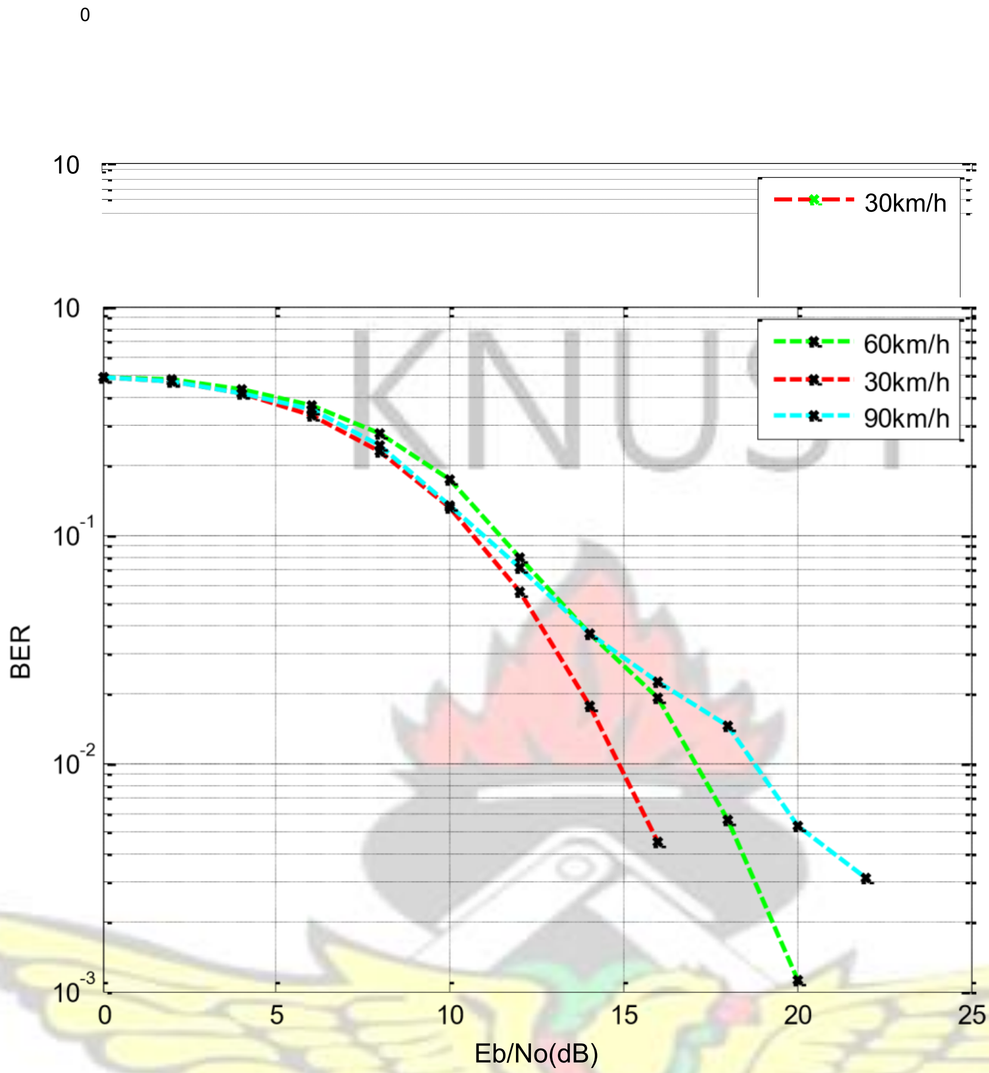


Figure 4.18 for 16-QAM-1/2 in Fading channel, V=30,60 and 90 km/h

BER against E_b/N_0

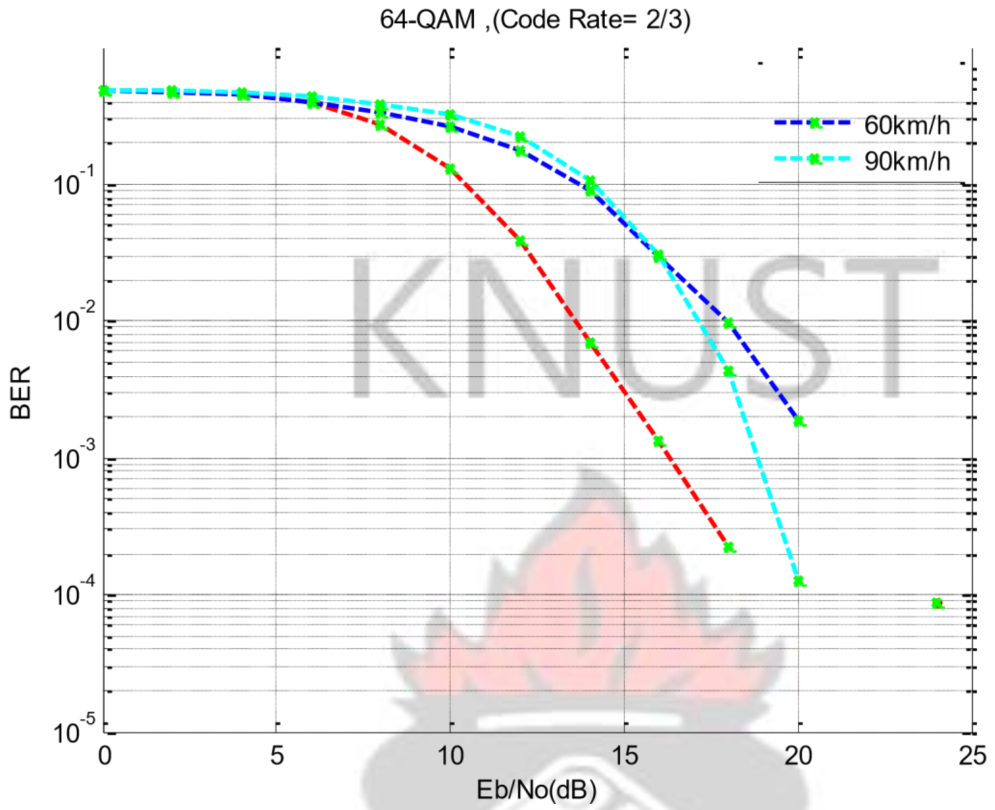
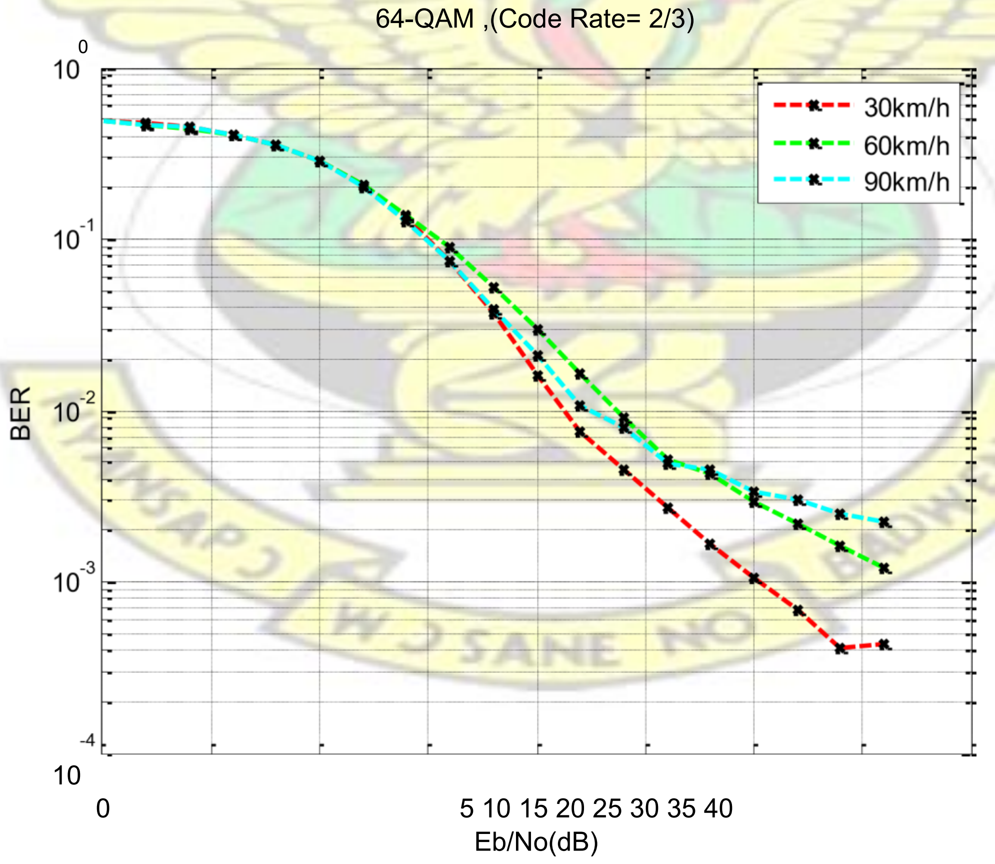
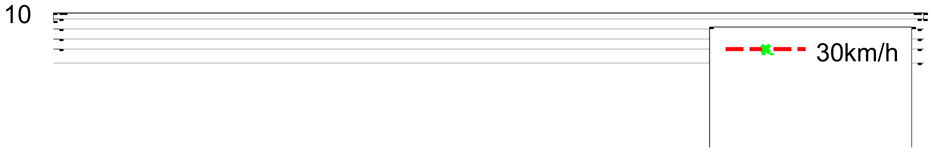


Figure 4.19 BER against E_b/N_0 for 64-QAM-2/3 in AWGN, V=30,60 and 90 km/h



0

Figure 4.20 for 64-QAM-1/2 in Fading channel, V=30,60 and 90 km/h



4.2.3. Capacities of relay and direct links

This section focused on link capacities in AWGN and multipath fading channels. Figure 4.21 presents link capacities of relay and direct links in pure AWGN non-fading channel while figure 4.22 shows the link capacities in multipath fading channel according to equations (3.25) and (3.31). From our results obtained, it was observed that relay links offer higher capacity compared to direct links. However, both link capacities reduce marginally in multipath fading channels.

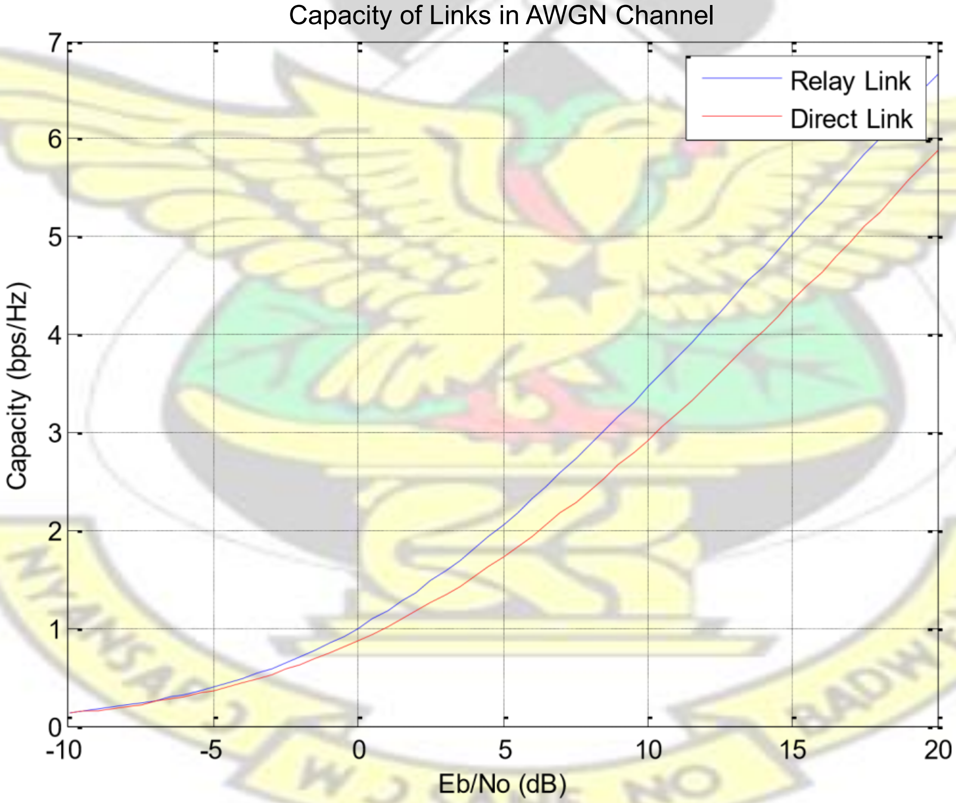


Figure 4.21 Link Capacities of Relay and Direct links against E_b/N_0 in pure AWGN channel

BER against E_b/N_0

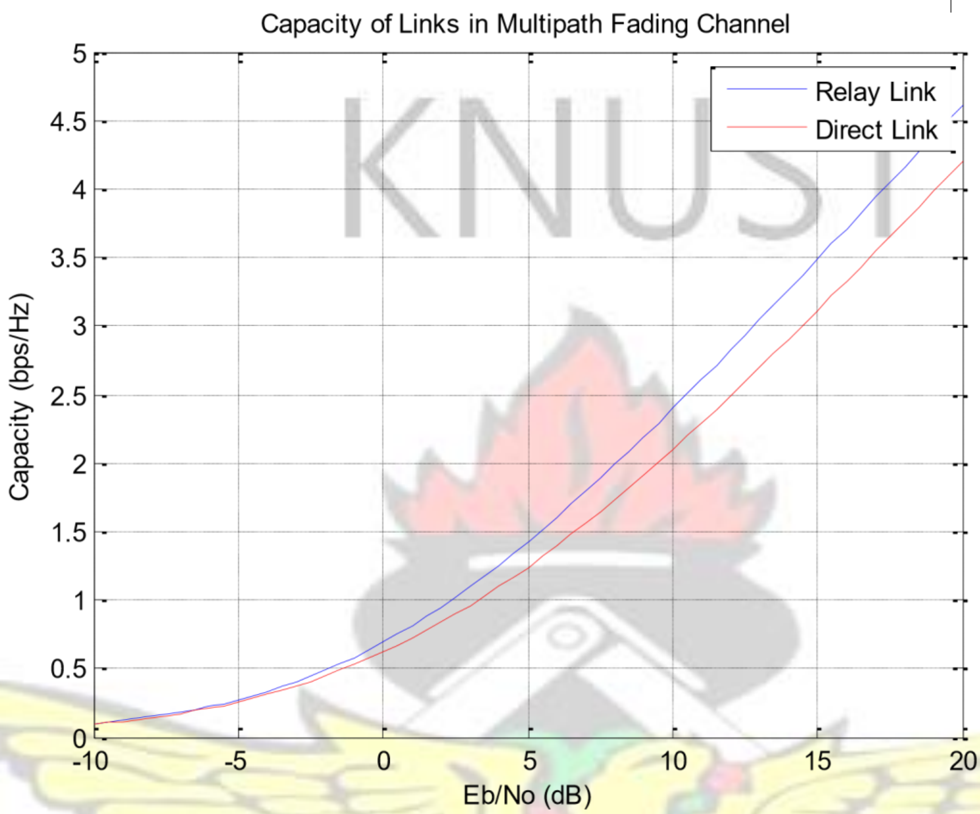


Figure 4.22 Link Capacities of Relay and Direct links against E_b/N_0 in pure Multipath Fading channel

Chapter 5

Conclusion and Recommendations

5.1 Conclusion

For promising wireless networks such as WiMAX, high speed, high capacity and coverage form the nucleus in achieving an excellent user experience. The IEEE 802.16j-2009 multihop relay network standard, an amendment of the previous IEEE 802.16e -2004 standard offer the potential of providing users with an appreciable degree of communication they need.

The core of this thesis is to perform an analytical test and study of the impact of deploying relays to increase throughput and capacity in relay-enhanced WiMAX networks. The simulation is based on three main performance measures which are BER, Spectral efficiency and capacity with two communication links under study; relay and direct links. Our study involves a hypothetical physical layer OFDM mode of transmission over a pure AWGN and fading channels (via Rician and Rayleigh). The modulation techniques used are BPSK, QPSK, 16-QAM and 64-QAM respectively.

The results show how various network parameters such as relay deployment, modulation and coding profiles, multipath fading and speed of users affect link performance. We explored two different scenarios with regards to throughput and capacity enhancement; an MS communicating directly with a BS and an MS communicating with a BS through RS.

In terms of link performance, relay link performed appreciably better than direct link in all performance measures studied (i.e. BER, spectral efficiency and link capacity). This is attributed to an increase in bits energy to noise ratio that relays offer which is essential for high data rate transmission. In terms of multipath fading, it was concluded that fading channels significantly had lower performance compared to non-fading AWGN channel.

Mobile WiMAX is more affected by the channel because of Doppler shift. To study different speeds, we used speeds of 30, 60 and 90 km/h and noted that as the speed increases, the performance of the system decreases.

Latencies on both links were not considered in this work due to a negligible delay difference in the single cell scenario.

In conclusion, the impact of deploying relays was thoroughly evaluated through link level analysis. The analytical framework was presented highlighting on improved performance on BER, Spectral Efficiency and Capacity as a benefit of using relay enhanced network. The results also show how factors such as speed and fading affect performance. The simulation results will serve as a baseline for future work on coverage and cell edge problem in other aspects like cooperative relaying and its countermeasures. Future work may incorporate real world involvement where drive test and optimization tools can be used to achieve a more practical result.

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Appendix A

Main codes

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Link level evaluation for Relay WiMAX % IEEE 802.16j
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% clear
all; clc;
%close %close any open figures
%index:Modulation,Overall Coding rating
%1: BPSK , Code Rate= 1/2
%2: QPSK , Code Rate= 1/2
%3: QPSK , Code Rate= 3/4
%4: 16-QAM , Code Rate= 1/2
%5: 16-QAM , Code Rate= 3/4
%6: 64-QAM , Code Rate= 2/3
%7: 64-QAM , Code Rate= 3/4
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
index=7; % choose index according to the above table
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
switch index case 1
m=1;%m :% Number of bits per symbol M=2^m;
sigconst=qammod(0:M-1,M); % Signal constellation for M-QAM scale =
modnorm(sigconst, 'avpow', 1);%Scaling factor for normalizing
modulation output
TITLE ='BPSK  (Code Rate= 1/2)'
Modulation_Type='BPSK'; %modulation type
N=12; % Codeword length in RS
K=12;% Message length in RS
```

```
T=0;%no. of data bytes which can be corrected in RS enc.
p=1;% Message length in CC q=2;% Codeword length in
CC r=0.5;%overall rate puncpat=[1 1];%puncture
vector in convolution coding case 2 m=2; M=2^m;
sigconst=qammod(0:M-1,M);
scale = modnorm(sigconst, 'avpow', 1);
TITLE ='QPSK, (Code Rate= 1/2) ';
Modulation_Type='QPSK';
N=32;
K=24; T=4; p=2;
q=3; r=0.5;
puncpat=[1 1 0 1];
case 3 m=2;
M=2^m;
sigconst=qammod(0:M-1,M);
scale = modnorm(sigconst, 'avpow', 1);
TITLE ='QPSK, (Code Rate= 3/4), Velocity = 60km/h';
Modulation_Type='QPSK';
N=40;
K=36;
T=2; p=5;
q=6;
r=3/4;
puncpat=[1 1 0 1 1 0 0 1 1 0]; case 4
m=4; M=2^m; sigconst=qammod(0:M-1,M);
scale = modnorm(sigconst, 'avpow', 1);
TITLE ='16-QAM, (Code Rate= 1/2),';
Modulation_Type='16QAM';
N=64;
K=48; T=8; p=2; q=3; r=0.5;
puncpat=[1 1 1 0]; case 5 m=4; M=2^m;
sigconst=qammod(0:M-1,M); scale =
modnorm(sigconst, 'avpow', 1);
TITLE ='16-QAM ,(Code Rate= 3/4), Velocity = 60km/h';
Modulation_Type='16QAM';
N=80;
K=72;
T=4; p=5;
q=6;
r=3/4;
puncpat=[1 1 0 1 1 0 0 1 1 0]; case 6
m=6; M=2^m; sigconst=qammod(0:M-1,M);
scale = modnorm(sigconst, 'avpow', 1);
TITLE ='64-QAM ,(Code Rate= 2/3)';
Modulation_Type='16QAM';
N=108;
K=96; T=6; p=3; q=4; r=2/3;
puncpat=[1 1 0 1 1 0 ]; case 7 m=6;
M=2^m; sigconst=qammod(0:M-1,M);
scale = modnorm(sigconst, 'avpow', 1);
TITLE ='64-QAM , (Code Rate= 3/4), Velocity =60km/h';
Modulation_Type='64QAM';
N=120;
K=108;
T=6; p=5;
q=6;
r=3/4;
puncpat=[
1 1 0 1 1
0 0 1 1
0]; case
```

```
8 m=8;
M=2^m;
sigconst=qammod(0:M-1,M);
scale = modnorm(sigconst, 'avpow', 1);
TITLE ='256-QAM , (Code Rate= 3/4), Velocity = 60km/h';
Modulation_Type='256 QAM';
N=120;
K=108;
T=6; p=5;
q=6;
r=3/4;
puncpat=[1 1 0 1 1 0 0 1 1 0]; end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Subcarreries numbers
Nc=256;Ntotal=Nc;%total no of subcarriers
Ndata=192; %No of data subcrriers
Npilots=8; %No of pilot subcarriers
Nguard=56; %No of guard subcarriers
Nused=Ndata+Npilots;%No of used subcarriers
BW=5; %nominal channel bandwidth in MHz
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%oversampling rate NN=Fs/BW
if (rem(BW,1.75)==0)
NN=8/7; else if
(rem(BW,1.5)==0) NN=86/75;
else if (rem(BW,1.25)==0);
NN=144/125;
else if (rem(BW,2.75)==0) NN=316/275;
else if(rem(BW,2.0)==0)
NN=57/50; else
%otherwise NN=8/7; end
end end end end
BW=BW*1e6; %nominal channel bandwidth in Hz
%%---------------------------------------------------------- %
Derived OFDM Symbol Parameters -
%%----------------------------------------------------------
Nfft=2^ceil(log2(Ndata)); % smallest power of 2 > Nused
Fs=floor((NN*BW)/8000)*8000;% sampling frequency in Hz
delta_f=Fs/Nfft;%subcarrier spacing in Hz Tb=1/(delta_f);%useful
symbol time in seconds
G=1/4; %cyclic prefix (G=Tg/Tb)
Tg=G*Tb; %CP time
Tsym=Tg+Tb; %total symbol time
Ts=1/Fs; %sampling time in seconds
BWused=Nused*delta_f;%used bandwidth Tframe=5e-3;
%Frame period in s.
Ns=Tframe/Tsym; %Number of OFDM symbols per frame.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Multipath CHANNEL Parameters of SUI-3 channel model for relay link
%fd=0.5; %doppler frequency in Hz for relay link
%for direct and access link fd must be calculated as follows
c=3e8; % light speed in m/s fc=2; %carrier frequency in GHz
V= 60 ; % mobile receiver velocity in km/h
fd=fc*1e9*V*1e3/(3600)/c;%Doppler shift, in Hertz P_db=[0
-11 -22]; %paths power in dB
tau=[0 0.4 0.9]*1e-6; %path delay vector in seconds k=[3 0 0];%k-factor of
Rice distribution in db k=10.^(k/10);%k factor of Rice distribution in
linear scale chan = ricianchan(Ts,fd,k,tau,P_db); %construct the
channelobject object chan.DopplerSpectrum=doppler.rounded; %define the
doppler fillter frequency spectrum
```

```
chan.StoreHistory=0;chan.ResetBeforeFiltering=1;%to reset before every
filtering chan.NormalizePathGains=1; %to normalize path gain
D=chan.ChannelFilterDelay; %delay of the channel object
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
BER_T=[];N_errors_T=[];data_T=[];r_s_T=[];  for
ii=1:5;% main loop
%%-------------------------------------------------------
%1:Generate a vector of random data points and randomize it %--------------
----------------------------------------
data=randint(1,Ndata*m*r*K,2);%data generation %--------------------------
----------------------------
% % 2.CHANNEL CODENG -
%-------------------------------------------------------
randomized_data = randomizer(data);%randomization
data_T=[data_T randomized_data];clear data;  %2.1:Reed
solomon encoding---------------
generator=rsgenpoly(255,239,[],0);%RS field and code generator
rs_encoded_data=rsencoder(randomized_data,N,K);%RS endoder
%2.2 : CONVOLUTION ENCODING
trellis=poly2trellis(7,[171 133]);% CC trellis tblen=96; %the traceback
length conv_encoded_data =convenc(rs_encoded_data
,trellis,puncpat);%convolution encoder
%2.3: INTERLEAVER----------------------
Ncb=length(conv_encoded_data);%number of coded bits
Nrows=12;%we will use 12 level interleaver Ncoloums=Ncb/Nrows;
%number of coloums
interleaved_data=matintrlv(conv_encoded_data,Nrows,Ncoloums);%perform the
interleaving
clear     conv_encoded_data;     %3.symbol     constellation     mapper
in_msg=reshape(interleaved_data,m,1/m*length(interleaved_data));%reshape
.  Clear    interleaved_data;  msgs=bi2de(in_msg','left-msb');%%  Bit-to-
Symbol Mapping h=modem.qammod(M); % Construct a qam modulator object.
h.symbolorder='gray'; % Set the 'symbolorder' property of the object to
'gray'. sig=scale*modulate(h,msgs); % Modulate Using M-QAM. clear
msgs;
Ns=length(sig)/Ndata;%Number of OFDM symbols per frame Tframe=Ns*Tsym;
% Frame Time
% -----------------------------------------------------
% - %4.series to parallel
%%-----------------------------------------------------
sigs2p=reshape(sig,Ndata,Ns);
% -----------------------------------------------------
% %5. subcarriers allocation
%------------------------------------------------------
sub_carreres=zeros(Nc,length(sig)/Ndata);
[P_pilots,X_data,G_x]=subchannelization(Ntotal,Ndata,Npilots,Nguard);%subca
rriers locations
sub_carreres(X_data,:)=sigs2p(:,1:end);%allocate data on data-subcarriers
sub_carreres(P_pilots,:)=1;%fill in the pilot subcarriers
Ns=size(sub_carreres,2);%Number of OFDM symbols per frame %the
left subcarriers are guard subcarriers
% ----------------------------------------------------- %
6.ifft (to peforme OFDM modulation)
%------------------------------------------------------
timedomain_symbols=ifft(sub_carreres,Nfft);
% -----------------------------------------------------
% 7.ADD syclic prefix
%------------------------------------------------------
CP_len=G*Nfft;%CP length
```

```
% 8.append the CP at the beginning of time data
timedomain_symbols_CP=[timedomain_symbols(end+1-
CP_len:end,:);timedomain_symbols]; clear
timedomain_symbols;
tx=timedomain_symbols_CP;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% x=tx(:).';%9.parralel
to series to get the time domain vector
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%10. Tx RRCF %%%%%%%%%%%%%%%%%%%%%%
% Define Filter-Related Parameters nsamp = 2; % Oversampling
rate filtorder = 40; % Filter order delay =
filtorder/(nsamp*2); % Group delay(# of input samples)
rolloff = 0.25; % Rolloff factor of the filter
% Create a Square Root Raised Cosine Filter. rrcfilter
= rcosine(1,nsamp,'fir/sqrt',rolloff,delay); %
Upsample and apply square root raised cosine filter.
[ytx t]= rcosflt(x,1,nsamp,'filter',rrcfilter);
ytx=ytx';
%%%%%% 11. RF up-converter %%%%%%%%%%%%%%%%%%%%%%%%%%%%
fc=2.5e9;%carrier frequency in Hz
xin=ytx.*exp(i*2*pi*fc.*t);%RF up-converter
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% if D~=0;
xin=[xin zeros(1,D)];%append zeros to compensate for channel filter delay
end
% -----------------------------------------------------------
y_filtered=filter(chan,xin) ; %12.fading channel
SNR=10*log10(m*r)-10*log10(nsamp):2:40;%Range of SNR values, in dB.
EbNo=SNR-10*log10(m*r)+10*log10(nsamp);% calculate corresponding Eb\No
for n = 1:length(SNR) % 13.Add White Gaussian Noise
y_f=awgn(y_filtered,SNR(n),'measured', [], 'dB'); %-------------------
------------------------------------ if D~=0;
y_f=y_f(1,D+1:end);%remove zero y=y_f.*exp(-
i*2*pi*fc.*t);%14.RF down-converter else
y=y_f.*exp(-i*2*pi*fc.*t);%RF down-converter
end clear y_f;
%%%%%%%%%%%%%%%15.Filter received signal by square root raised cosine
filter. yrx = rcosflt(y,1,nsamp,'Fs/filter',rrcfilter);yrx=yrx'; yrx
= downsample(yrx,nsamp); % Downsample. yrx = yrx(2*delay+1:end-
2*delay); % Account for delay.
y=yrx; clear
yrx;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
rx=reshape(y,size(tx,1),size(tx,2));clear y;%16.series to parallel
%%%%%%%%%%%%%%RECEIVER%%%%%%%%%%%%%%%%%%%%%%%%
symbol_length=size(rx,1); yyy=rx(CP_len+1:symbol_length,:);
%17.remove CP
% -----------------------------------------------------------
% 18.fft (performe IOFDM)
%-----------------------------------------------------------
rc_carriers=fft(yyy,Nc);clear yyy;
% ----------------------------------------------------------- %
19.desubchanelization and exract sub_subcarriers %-----------
------------------------------------------
data_sub=rc_carriers(X_data,:);%exract data subcarriers
pilot_sub_r=rc_carriers(P_pilots,:);%exract pilot sub carriers
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
freq_vector=data_sub(:)';%20.parallel to series
% 21.channel estimation
```

```
f_pilots=P_pilots;%positions of pilots_subcarriers f_data=X_data;%positions
of data subcarrer
H_pilots=pilot_sub_r;%estimate the channel coefficients on pilots_positions
%Using interpolation to estimate the channel coefficients on data
subcarrers_positions
H_i = interp1(f_pilots,H_pilots,f_data,'spline'); %data subchannels
estimation
% -----------------------------------------------------
% 22.equalization
Equalized_data_signal=data_sub./H_i; % Equalize the received signal of
data.
% 23.parrallel to series after equalization
Equalized_data_signal=Equalized_data_signal(:).';
% 24.symbol constellation demapper
g = modem.qamdemod(h); % Create a demodulator object from a modem.qammod
object
g.symbolorder='gray'; %gray encoded demaped_signal =
demodulate(g,Equalized_data_signal./scale);%25.Demodulate signal using M-
QAM with Eq. binary_signal=de2bi(demaped_signal,'left-msb');%Convert the
Integer-Valued Signal to a Binary Signal binary_signal=binary_signal';
bits_vector=binary_signal(:).';%Convert from a matrix to a vector. %
%26.CHANNEL DECODENG -
%deinterlaever%%%%%%%%%%%%%%%%%%%%%%%%
deinterleaved_data=matdeintrlv(bits_vector,Nrows,Ncoloums);clear
bits_vector;%perform the deinterleaving % convolution decoder
%%%%%%%%%%%%%%%%%%%%
convdecod_data=vitdec(deinterleaved_data,trellis,tblen,'trunc' ,'hard',
puncpat);clear deinterleaved_data %decoding % RS
Decoder%%%%%%%%%%%%%%%%%%%%%%%%%%% rsdecoded_data
=rsdecoder(convdecod_data,N,K);clear convdecod_data;
%%%%%%%%%%%%%%%% BER calculations format('short','e');
[N_errors(n),BER(n)]=biterr(rsdecoded_data,randomized_data); end
%for the loop n = 1:length(SNR)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
BER_T=[BER_T; BER];N_errors_T=[N_errors_T; N_errors] ;r_s_T=[r_s_T
rsdecoded_data]; end % end for i=1:5 loop clear rx;
%%%%%%%%data rate calculation%%%%%%%%%%%%%%%%%%
bit_rate = Ndata*m*r/Tsym;% Data rate in bps
symbol_rate=bit_rate/m;% Symbol rate in symbol/s
n_e=sum(N_errors_T);l=length(data_T);ber_t=n_e./l; % error
calculation%%%%%% se=(1-ber_t).^l*m*r;%Spectral
Efficiency %Plot BER results.
semilogy(EbNo,ber_t ,'--mx',...
'LineWidth',1.5,...
'MarkerEdgeColor','k',...
'MarkerFaceColor',[.49 1 .63],...
'MarkerSize',5); grid;
%title({TITLE })
xlabel('Eb/No(dB)'); ylabel('BER');
%figure %%% Plot Spectral Efficiency
plot(EbNo,se,'--rx',...
'LineWidth',1.5,...
'MarkerEdgeColor','g',...
'MarkerFaceColor',[.49 1 .63],...
'MarkerSize',5); grid on; title({'Spectral Efficiency vs.
Eb/No' TITLE } ) xlabel('Eb/No(dB)'); ylabel('Spectral
Efficiency (b/s/Hz)') hold on;
%%%%%%%%%%%End of main Code%%%%%%%%%%%%%%%%%%%%%
```