ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

# LONG DISTANCE POINT-TO-POINT Wi-Fi LINK FOR CONNECTIVITY IN RURAL AREAS OF ETHIOPIA

A Thesis submitted to the School of Electrical and Computer Science in the partial fulfillment of the requirements for a MSc. degree of Communication Engineering

By:
**Talile Miresa Gamtesa**
Advisor:
Dr. -Ing. **Dereje Hailemariam**

**June 8 , 2015**

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**TALILE MIRESA GAMTESA**

**JUNE 2015**

**Approval by Board of Examiners**

Dr.-Ing. Dereje Hailemariam

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Advisor

Signature

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Internal Examiner Signature

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External Examiner Signature

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Chairman, School Dean Signature

# Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been duly acknowledged.

Talile Miresa ______________ ______________
Declared by Signature Date

________________________
Place

## Submission Approval

This thesis entitled **'LONG DISTANCE POINT-TO-POINT Wi-Fi LINK FOR CONNECTIVITY IN THE RURAL AREAS OF ETHIOPIA'** submitted in partial fulfillment of the requirements for the Masters of Science in Communication Engineering to School of Electrical and Computer Science, written by Talile Miresa, has been submitted for examination with my approval as Addis Ababa University advisor.

**Name:** _Dr.-Ing. Dereje Hailemariam

**Signature:** ______________________________

**Date of submission:** ________________________

# Abstract

Internet coverage in rural areas of Ethiopia is extremely limited which, in turn, limits access to knowledge, education, health, commerce and other important services. As rural areas are characterized by low-income, highly scattered and low population density, traditional approaches for backhauling based on telephone, cellular, satellite or fiber is in general expensive, especially, in low population density and low-income regions like Ethiopia. To address this rural area network access problem, this thesis proposes Institute of Electrical and Electronics Engineers (IEEE) 802.11n-based point-point technology as a backhauling solution. The thesis shows that, with careful planning, using high gain antennas and tuning relevant medium access control (MAC) layer parameters, inexpensive, off-the-shelf Wi-Fi radios can be viable solution to rural connectivity problem.

The work started by assessing limitations of IEEE 802.11-based access point in a long-distance point-to-point setup. Due to the long distance, high gain antennas are required. A pair of parabolic reflectors, originally designed for satellite TV reception with their feeders replace with that of Wi-Fi, are used. The standard IEEE802.11 MAC layer performs poorly in a long-distance step; hence, the necessary MAC layer parameters were changed to fit the long distance requirements. Before deploying the system a link budget analysis had to be conducted for selected sites to predict the performance of the system.

To demonstrate the appropriateness of this solution a testbed was built and deployed in the premises of Addis Ababa Institute of Technology (AAiT) over 128 meters. The testbed is built from a pair of Dragino MS14 access points connected to parabolic reflectors of 175 centimeters diameter. Several experiments were conducted on this testbed to evaluate its performance. The measured results indicate that at 128 meters distance a maximum throughput of 32.8 Mega bits per second and received signal power of -72dB was achieved by adjusting antenna height and orientation. Another experiment was conducted using Radiomobile link simulation tool to evaluate the performance of this same system when implemented in a real rural area. The simulation result showed that with extensive link planning, the same antenna can give coverage to rural area about 30 kilometers away a city. The simulation was conducted between Bishoftu city and a rural location called Chaffee Donsa.

# Acknowledgement

First of all I would like thank my advisor Dr.-Ing. Dereje Hailemariam for his support and encouragements throughout thesis work. I would also like to thank Ato Teshome Hambisa for allowing me to use the lab and the resources in the laboratory at any time and for his support during lab work.

I would also like to extend my heartfelt thank you to my family and friends for their input and encouragements. My mother Ilfinesh Mario, my sisters Anane Miressa and Gelane Komo, my brothers Yadessa Miresa and Demeksa Miresa, Tuli Bayissa and Oljira Mekonnen, thank you for always being there for me whenever I needed you. My friends Gelane Raggassa, Selemawit Tesfaye and Girma Gutama thank you for your encouragement and support. Special thanks to my dear friend Nega Gerbaba for pushing me to work harder.

Last but the most important gratitude is to the almighty God for everything.

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# Abbreviations

AAiT – Addis Ababa Institute of Technology
A-MSDU – MAC Service Data Unit Aggregation
A-MPDU – MAC Protocol Data Unit Aggregation
AP – Access Point
CSMA/CA – Carrier Sense Multiple-Access/Collision Avoidance
CCK – Complementary Code Keying
CW – Contention Window
DSL – Digital Subscriber Line
DIFS – DCF Interframe Space
DCF – Distributed coordination function
EDCF – Enhanced DCF
FCC – Federal Communications Commission
FEC – Improved Forward Error Correction
GDP – Gross Domestic Product
HT – High Throughput
ICT – Information and Communication Technology
IFS – Interframe Spacing
IEEE – Institute of Electrical and Electronics Engineers
ISM – Industrial, Scientific and Medical
HCCA – HCF Controlled Access
IEEE – Institute of Electrical and Electronics Engineers
ISM – Industrial, Scientific and Medical
LAN – Local Area Network
LOS – Line of Sight
LTE – Long Term Evolution
MAC – Media Access Protocol
MCS – Modulation and Coding Schemes
MIMO – Multiple Input Multiple Output
NAV – Virtual Carrier Sense by MAC- Network Allocation vector
OFDM – Orthogonal Frequency Division Multiplexing
PC – Point coordinator
PIFS – PCF Interframe Space
PHY – Physical

PPT – Point-to-point
QoS – Quality of Service
RIFS – Reduced Interframe Space
RTS/CTS – Request-to-send/clear-to-send
SIFS – Short Interframe Space
STAs – Stations or clients
TXOP – Transmit Opportunity
TDMA – Time Division Media Access
TIER – Technology Infrastructure for Emerging Regions group
Wi-Fi – Wireless Fidelity
WiLDNet – Wi-Fi-based Long Distance Networks
WiMAX – Worldwide Interoperability for Microwave Access
WMM – Wi-Fi Multimedia

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# 1 Introduction

Information and Communication Technology (ICT) has an enormous impact on economic growth and social change of any country. It enhances development in education, innovation, entrepreneurship, health care, etc. It also facilitates social interactions allowing individuals and businesses to collaborate regardless of their locations. Internet is a means for providing access to ICT services and resources. In fact, according to the World Bank 2009 report, 10 percent increase in broadband Internet correlates to 1.38 percent increase in Gross Domestic Product (GDP) growth [1].

ICT in general and Internet in particular has great significances for rural populations of developing countries like that of Ethiopia, which is the focus of this thesis. It provides them with access to information in sectors such as education, health, market and all other important livelihoods. This information, in turn, will strengthen the efficiency of service delivery in these areas and improve quality of life in the rural livelihood. "According to [2]:"

> "Modern communication technologies, when systematically applied and adapted to conditions in rural areas of developing countries, can be used for rural communication to increase participation, disseminate information and share of knowledge and skills" [2].

The importance of Internet for the rural community can be associated with education, health, commerce and all other sectors as briefed in the next paragraphs.

Education is an essential tool for change and development. More and more people in Ethiopia and all over the world are currently enrolled in universities and colleges to study different programs, on-campus or through distance education to make career improvements or personal changes. Internet is an important tool in the teaching-learning processes. The application of the Internet in education is understood as the usage of Internet technologies to solve various educational tasks, namely, teaching, learning and management of the educational process [3]. The accessibility and quality of education for rural areas can be improved by using Internet and applications such as video conference, for on-line learning; E-library and learning platforms such as moodle or black board for both distance and on-campus students [4]. Hence, the use of Internet in education bridges the recurrent educational gaps of rural communities such as inaccessibility of libraries, information, lecturers, fellow students and other essential educational assets.

The other important application of ICT services in general and that of Internet in particular for the rural community is in health sector. The number of doctors per patient in developing nations like Ethiopia is in general very low; the number is even lower in rural areas of the developing nations [5]. This shortage of health workers can limit access to good health services. This gap can be narrowed by using ICT services such as video aided consultation, emails or chats, so that doctors anywhere in the world can assist doctors and other medical staff working in rural areas. Just as any field, the field of medicine also changes from time to time, and Internet can help medical professionals to update themselves. Hence, Internet has a substantial potential in assisting the provision of efficient health care for rural population by equipping health professional in the area with vital assistance through facilitating on-line support from experts in the field of medicine for different medical databases and on-line medical services.

Most of the rural communities are both farmers and traders. Easy access to daily market information can help such farmers take informed decision about their products. These decisions can help the farmers choose the product they need to produce, the technique they can use, when and where they should sell their products. Internet can thus play a leading role in disseminating such vital information [6].

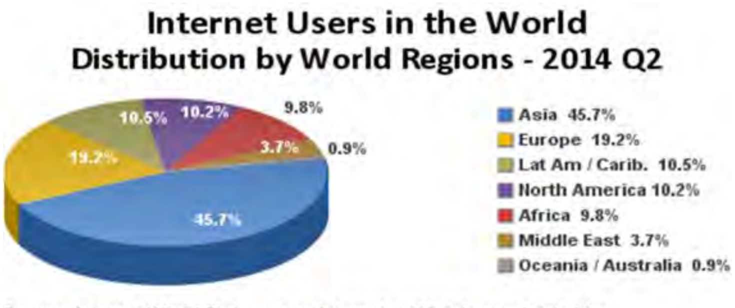
Internet can also improve rural public and private employees' staff retention. Rural areas of developing countries like that of Ethiopian don't usually have most of the infrastructures and services such as good roads, shopping centers, hospitals, collages, etc that large cities enjoy. These factors often discourage individuals from working in these rural areas. But availability of Internet can help retain the employees as it narrows the information gap and improve the delivery of the stated services which in turn contribute to the quality of life in rural areas. In short, in this competitive and dynamic world the need for updating oneself at work, life style, entrepreneurship or any other life aspects is becoming essential for people leaving anywhere.

Access to Internet can give people the opportunity to get information, communicate and collaborate with others. It can positively influence society's perception, culture as well as practices regarding health, education, self-improvement, sophistication and other aspects of life. In nut shell, even if Internet is not the only developmental tool; it is a very crucial tool that influences and encourages development and social changes especially of the unprivileged rural communities of the developing nations like that of Ethiopia which is the special concern of this thesis.

## 1.1 Internet Penetration Gap and Proposed Solution

Even though Internet's contribution to the rural development is significant, the penetration of Internet in developing countries, specifically in Sub-Saharan countries is still limited. According to DALBERG broadband penetration in Sub-Saharan countries is low compared to regions of similar income, more specifically, although 15% of the world’s population lives in Sub-Saharan Africa, only 6% of the world’s Internet users do [7].

According to more recent information by Internet Live Stats, the continent Africa itself, though it is the second largely populated continent in the world, accounts for only 9.8 percent of the world Internet users [8]. (See Figure 1)



Source: Internet World Stats - www.internetworldstats.com/stats.htm
Basis: 3,035,749,340 Internet users on June 30, 2014
Copyright © 2014, Miniwatts Marketing Group

*Figure 1.1 Internet Users in the world distribution by world regions-2014 [41]*

Looking into the case of Ethiopia, the country’s share of the Internet is only 0.6 percent while its population accounts for 1.33% of the worlds’ population placing the country on 103th position out of the 198 countries of the world. This is very insignificant specially compared to the share of other countries like USA, which accounts for 9.58 percent of the world’s Internet users with only 4.45 percent of the world’s population and with even that of Kenya which account for 0.57 Internet users constituting only to 0.63 percent of the world population.

In a closer look, Eighty-four percent of population of Ethiopia lives in rural areas where the coverage of Internet is even lower compared to the urban areas of the country. There are several reasons for these gaps in Internet coverage of the rural areas. The overwhelmingly high cost of the technologies, high energy constraints, poverty, illiteracy, sparse population, topological and geographical environment, are among the few reasons for the limit infrastructure development and implementation of the common telecommunication infrastructures such as fiber optics, satellite or Worldwide Interoperability for Microwave Access (WiMAX) for Internet services in the rural area.

Wireless Fidelity (Wi-Fi) has been found out to be successful and economical for rural areas of developing countries [9] [10] [11]. Wi-Fi is a trademark of the Wi-Fi Alliance, an industry association promoting the standardization and interoperability of wireless local area network (WLAN) connectivity based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11 series of standards. Part of what makes Wi-Fi, also referred to as IEEE802.11; technology attractive includes their mass production, low cost of equipment's and the operation on license free band. In addition, the system can be operated from simple operation centers, can be mounted on natural mountains, operated by people with little or no expertise and owned by the communities, governmental or non-governmental organizations. All these reasons make Wi-Fi a very attractive solution for rural area setups.

However, Wi-Fi is originally designed for short distance Local Area Networks (LAN). Implementation of this system for long distance for rural application needs several modifications and redesigning to make up for the long distance. The focus of thesis is thus, designing and implementing IEEE802.11n-based point-to-point network to be used for long distance rural deployment. In order to prove this concept, a test bed is built using in low cost, off the shelf access points with directional antennas and modified MAC and PHY layer parameters.

## 1.2 Statement of the Problem

Even though Internet play a critical role in the development of a nation, its availability and coverage in rural areas of Ethiopia is extremely limited. The main reasons for the scarcity are the high cost of network implementation and customers' settlement. Customer settlement in rural areas of the country is often characterized by low income, highly scattered and low population density. To address these problems, long distance point-to-point Wi-Fi seems to be one technology solution.

This thesis, thus, is aimed at filling the Internet gap in rural community by designing, implementing and testing a low-cost, easily deployable Internet solution based on IEEE802.11 technologies that can be used for rural Internet provision.

## 1.3 Objective

### 1.3.1 General Objective

The main purpose of this thesis is to implement IEEE802.11n-based wireless solution for long distance point-to-point links to provide Internet service in rural Ethiopia.

### 1.3.2 Specific Objectives

The specific objectives of this thesis work are:

- To study relevant IEEE802.11n Media Access Control (MAC) protocols and investigate how to tune relevant parameters so as to optimize its performance for long distance communication;
- To review antenna design procedures and apply it for the design of high-gain directional parabolic reflector antennas;
- To conduct link budget design, considering potential areas of deployment;
- Based on the designed antennas and tuned MAC protocol parameters, build a testbed and implement the testbed  in the premises of Addis Ababa Institute of Technology (AAiT), take measurements, evaluate the performance and draw recommendations

## 1.4 Scope and Limitation

**Scope**

This thesis is to present IEEE802.11 technology as a technologically viable and economically feasible telecommunication infrastructure for rural areas of Ethiopia. The scope of this thesis is restricted to the design and implementation of IEEE802.11 based long distance point-to-point testbed and testing the system in the university premises.

**Limitation**

There we liming factors in conducting this thesis. The experiments were limited in AAIT premises because there is no regulation in this country allowing a license free band to be used for long distance communication. Another limitation was even though Time Division Media Access (TDMA) was suggested as a better solution in the original proposal, due to the lack of compatible free firmware; it is not included in this thesis.

## 1.5 Related Work

There has been considerable effort in launching projects that implement IEEE802.11 technology for rural area broadband provision. These projects have proven to be effective and found applications in schools, health clinics and various other community services.

The approach used in most of the projects is using directional antennas and changing the carrier sense multiple-access/collision avoidance (CSMA/CA) MAC layer protocol to TDMA MAC to provide effective point-to-point broadband gateway and point-to-multi-point distribution network.

Most of the implementations projects were, directly or indirectly, supported by Technology Infrastructure for Emerging Regions group (TIER) group of the Berkeley University lead by Doctor Eric Brewer [12]. TIER is a research group at the University of Berkeley, California. The project investigates the design and deployment of new technologies for emerging regions. The development and continues improvement of TDMA MAC was one of the projects this group launched.

Wi-Fi-based Long Distance Networks (WiLDNet) is one of the results of this project. WiLDNet explores the use of directional antennas to create a long distance point-to-point link by using TDMA MAC [6]. Another result of the TIER groups' effort is the development of JALDIMAC [8]. JALDIMAC is an open source TDMA MAC driver for Openwrt[15] built for newer open source driver, mac80211 [16]. Regardless the promised IEEE802.11n support and open source code, this software is never thoroughly tested and it is currently abounded.

One outstanding beneficiary of the TIER groups' support is the Venezuela project [17]. The aim of this project was to test the limit of the Wi-Fi technology in a point-to-point setup and they managed to provide coverage at 280kms by using Linksys WRT54G with Openwrt firmware and recycled parabolic dish antennas. They later repeated the procedure with a 30dB commercial antenna and routers with TIERs' TDMA MAC, achieving coverage at 382 km and 6Mbps throughput.

There were several other efforts to develop a TDMA-based MAC for IEEE802.11 in the past. SoftMAC [10] explores the use of the madwifi driver for Atheros-based Wi-Fi radios. Overlay MAC [11] uses the Click modular router [12] and implements TDMA in a configurable module between the MAC layer and the network layer.

Another notable work is FRACTLE MAC by Nirav and Bhaskaran Ashutosh[21]. Their approach involves reprogramming the code of the madwifi driver [22] in order to implement TDMA. Madwifi is a former open source wireless driver for Linux systems. However, this driver is currently replaced with mac80211. As interesting as these open source TDMA MAC software are, unfortunately they have discontinues support.

A more recent solution for Wi-Fi based long distance network with TDMA MAC, are the commercial solutions NETshe[23] and Ubiquiti's AirMAX [24].The Ubiquiti AirMAX series are a one-step solution to sharing broadband Internet connectivity over Point-to-Point (P2P), Point-to-Multi-Point (P2MP) networks. NETshe on the hand is based on the Openwrt and it is free for testing. The problem with this solution is, it is not open source and currently they provide support for only few devices.

There are several research testbed and deployment project examples wireless long distance networks in different corners of the world. Few notable real life deployments include, Digital Gangetic Plains[25] in Uttar Pradesh, India, Aravind Network for Telemedicine[26] in Tamil Nadu, India, Akshaya Network[27] for e-governance in Kerala, India, MIT's Roofnet[28], FRACTEL[29] at IIT Bombay, India, and VillageNet[30] are some of the important network research test beds built for providing support for various envisaged applications particularly real-time applications such as e-learning, e-governance, telemedicine, and telephony.

Most of these earlier researchers use the IEEE 802.11b/g standards. IEEE 802.11b/g standards have highest data rates capped at 54Mbps, their highest observable throughput is relatively low. IEEE802.11n standard has currently dominated the Wi-Fi markets and tests on its capacity in deployments of long distance outdoor Wi-Fi links is worth investigating and likely to give better speeds. For example, Wireless Backhaul Technology (WiBACK)s' project, exploited the capacity gains introduced by the MIMO capabilities using a single cross-polarized antenna[31]. They managed to achieve 170 Mbps 10kms away.

## 1.6 Contribution

The main contribution of this thesis is introducing a low cost IEEE802.11n based long distance Internet technology to Ethiopia.

The testbed built in this thesis, the results collected and the procedures used in implementing the technology can easily be applied to an actual deployment of this technology in a rural setup. The deployment of Internet in rural areas will in turn contribute to development and help improve life in rural areas in general.

To the best of my knowledge, this thesis work is the first experiment based thesis that showed the viability of an inexpensive Wi-Fi technology for rural connectivity in Ethiopia. I believe this thesis inspires further rural connectivity research and implementation projects in our country.

## 1.7 Research Layout

This thesis is organized as follows, giving a clear flow and understanding of the thesis work. Chapter one presents the objectives, scope and limitation and a short introduction of the thesis work. Chapter two presents the theoretical background of the IEEE802.11 standards, antenna fundamentals and design. Chapter three describes the challenges of using IEEE802.11 technology for long distance and introduces the solutions. Chapter four and five presents the design details of a point-to-point network and Chapter six presents the experiments conducted results and conclusions drawn from the results.

# 2 Background

## 2.1 IEEE 802.11 Technology

### 2.1.1 Overview

The IEEE 802.11 technology is a Wireless Local Area Network technologies operating on 2.4, 3.6, 5 and 60GHz Industrial, Scientific and Medical (ISM) license-free bands. IEEE 802.11x family is the most popular and accepted industry standardization for medium access control (MAC) sub-layer of the data link layer and physical (PHY) layers of the Open Systems Interconnection model (OSI) for WLAN. (See Figure 2.1)

The OSI model is a conceptual model that divides network traffic into a number of layers. Each layer is independent of the layers around it, and each builds on the services provided by the layer below while providing new services to the layer above. The OSI model doesn't define the protocols to be used in a particular network; but the abstraction between layers made it easy to design an elaborate and highly reliable protocol stacks, such as the ubiquitous TCP/IP stack.

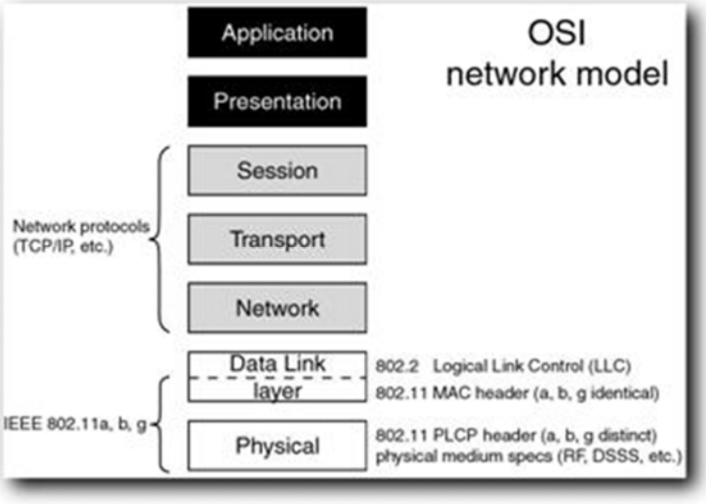


*Figure 2.2 OSI model for IEE802.11 x [32]*

The IEE802.11x PHY layer provides an electrical, mechanical, and procedural interface to the transmission medium. The shapes and properties of the electrical connectors, the operating frequencies, the modulation schemes in use and similar low-level parameters, are specified here. The PHY layer of the IEEE802.11x standard defines three basic transmission techniques; namely, Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), and Diffuse Infrared.

The IEE802.11x MAC sub-layer has several functionalities including framing, scanning, synchronization, authentication, association and disassociation, security, error checking, fragmentation and reassembly, power management and media access control.

All IEEE 802.11x wireless LAN clients use shared channel. In order to use the shared channel properly, there needs to be a protocol to schedule the time to use the channel. As distance increases the so does the time each transmission takes hold of the channel. This makes media access control an important parameter in long distance communication. That why the next section is dedicated to this topic.

### 2.1.2 Media Access Control

The MAC sub-layer architecture defines two primary access methods, namely, distributed coordination function (DCF) and point coordination function (PCF), and their coexistence in an IEEE 802.11x for shared media control. DCF is the fundamental access method of the IEEE 802.11x. The DCF is implemented in all STAs and PCF is defined as an optional access method.

**Distributed coordination function (DCF)**

DCF is a contention-based protocol. It uses a method called a carrier sense multiple-access/collision avoidance (CSMA/CA) functions to sense and resolve state of radio channel. Carrier sense schemes use, physical sensing by physical layer or Virtual Carrier Sense by MAC- Network Allocation vector (NAV).

How DFC works is described in as follows,

- Before transmitting a packet, a client will first sense the medium. If it is idle and remains so for an Interframe Spacing (IFS) period, the packet can be immediately transmitted.
- If the medium was not idle or the transmission fails, the client must defer until the medium is free and in the case of Virtual Carrier Sense, sets its NAV timer and will not sense the state of the channel until the NAV timer has expired.
- After the NAV timer has expired or channel is physically sensed to be no longer busy, the client will calculate a backoff interval, a uniform random number between 0 and the value of the Contention Window (CW). The contention window is initially set to be equal to $CW_{min}$ which is a value defined by the PHY layer.
- Then, it senses the channel for an IFS period. If the channel is idle at the end of this period the client will set a backoff timer equal to the value of the backoff period calculated previously. This timer is periodically decremented while the channel continues to stay idle.

- If the channel becomes busy either during the IFS period or before backoff reaches zero, the client goes into a defer state without changing the value of the backoff timer.
- If the client goes back into a defer state it goes through the same process as before in which the client waits for the medium to become idle by first sensing the medium and then by setting the NAV timer. When the medium returns to an idle state, the client must wait for an additional IFS period before continuing to decrement the backoff counter.
- When the medium has been idle for an IFS period and the backoff counter reaches zero, the client will transmit its data.
- If the client discovers that the transmission has failed then the client must exponentially increase the value of CW. As a result, if the medium is very busy, exponential increases in the maximum backoff delay will occur and the probability of packet collisions will decrease. After increasing CW, the client generates a new value for the backoff interval and re-senses the state of the channel.
- After either of the two transmits states have been completed successfully (by having been properly acknowledged by the receiver using an ACK packet), several things happen. First, the value of CW is reset to CWmin after successful transmission occurs. Second, the client goes through a mandatory backoff interval in which the state of the medium is ignored. The client then goes back to the initial state in which the client waits for data to be ready for transmission.

A problem hidden terminal occurs when a mutual receiver is in range of two transmitters which are not in range of one another. In this case attempting to detect if the medium is free does not necessarily work because the two transmitters cannot detect one another's transmissions. To overcome the problem, the IEEE 802.11 DCF media access scheme utilizes a request-to-send/clear-to-send (RTS/CTS) mechanism which can be exploited optionally prior to MPDU transmission. The RTS and CTS frames include information on how long it will take to deliver the upcoming data frame (in the fragmentation case, it indicates the duration of the first fragment) and the corresponding ACK over the radio link. Stations that receive these control frames set their local NAV timer and will not initiate transmission until the NAV timer expires. DCF is capable of offering only asynchronous data transmission on a best effort basis.

After each frame transmission, IEEE802.11x protocols require an idle period on the medium, called an Interframe space (IFS). There are different IFS time intervals:

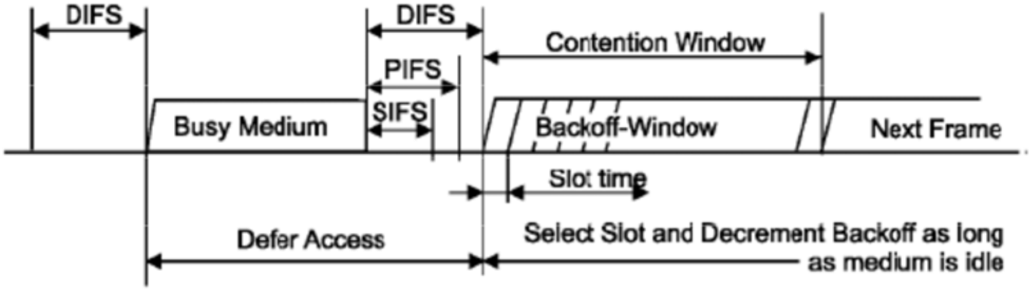


*Figure 2.3 Media Access Control timing diagram [32]*

- ✓ **DCF Interframe Space (DIFS):** When a STA desires to transmit a data frame for the first time within a DCF network, the duration of a DIFS must be observed after the previous frame's completion. The duration of a DIFS is longer than both the SIFS and PIFS.
- ✓ **PCF Interframe Space (PIFS):** PIFS are used by STAs during the contention-free period (CFP) in PCF mode.
- ✓ **Short Interframe Space (SIFS):** SIFS is the shortest of the IFSs and is used prior to ACK as well as the second or subsequent MPDUs of a fragment burst. SIFS is used as a priority interframe space once a frame exchange sequence has begun. It allows the participants of a frame exchange sequence to complete their conversation uninterrupted.
- ✓ **Reduced Interframe Space (RIFS):** RIFS were introduced with 802.11n to improve efficiency for transmissions to the same receiver in which a SIFS-separated response is not required, such as a transmission burst.

### Other Media Access Methods

IEEE 802.11 also defines other media access methods, such as PFC, EDCF and HCCA to support requirements of different users and data types. The IEEE 802.11 PCF function allows time critical or delay sensitive packets to be given priority over regular data transmissions. The PCF offers techniques for prioritized access to the shared radio channel and is centrally coordinated by a point coordinator (PC) station which is typically an AP. PCF is based on a centralized polling scheme for which a point coordinator (PC) provides contention-free services to the associated stations in a polling list.

The IEEE 802.11x standard also defined two new component of the IEEE802.11e MAC called the

Enhanced DCF (EDCF) and HCF Controlled Access (HCCA) in order to support Quality of Service (QoS). The EDCA is required for prioritized contention-based QoS services and provides differentiated channel access to frames of different priorities as labeled by the higher layer.

This allows high priority traffic a better chance to contend for the medium. Each priority level is assigned a different Transmit Opportunity (TXOP), which is the bounded interval during which a station can send as many frames as possible. Wi-Fi Multimedia (WMM) certified APs enable EDCA, while other 802.11e enhancements are optional.

HCF Controlled Access (HCCA) is required for parameterized contention-free QoS services. This method works a lot like PCF, and is considered the most advanced coordination function, allowing QoS to be configured to great precision.

### 2.1.3 IEEE802.11 Architectures and Modes

The IEEE 802.11 standard defines two types of network architectures, namely, Adhoc and Infrastructure. In IEEE 802.11 infrastructure mode, all the wireless devices in the network can communicate with each other or wired networks through an Access Point (AP). An ad-hoc network is self-organized wireless network without any fixed or backbone infrastructure.

IEEE802.11 also defines several modes of operation such as master mode, managed modem monitoring and mesh mode. Master mode also known as AP mode or infrastructure mode that is used to create a service that looks like a traditional access point. Managed mode or client mode that enable clients to join a network created by a master. Monitor mode that is used to passively listen to all radio traffic on a given channel by some tools for analyzing problems on a wireless link or sniffing traffic. Mesh mode, were several APs connected to each other through wireless connection while each AP connects several STAs.

Mesh networks are special implementation of adhoc network and they extend the reach of wireless networks and are ideally suited for many environments such as commercial zones, neighborhood communities and university campuses. Their popularity comes from the fact that they are self-organized, self-configurable and easily adaptable to different traffic requirements and network changes. IEEE802.11s is WLAN Mesh Networking amendment to the 802.11 MAC. Which means it uses the existing PHY layer (802.11a/b/g/n) and integrates mesh networking services and protocols at the MAC Layer. Amendment to IEEE 802.11 includes creating a Wireless Distribution System with automatic topology learning and wireless path configuration. Mesh networks use different routing protocols such as OLRS, BATMAN, BATMAN advanced (BATMAN-ADV) for topology learning and wireless path configuration. OLRS, BATMAN, BATMAN-ADV are layer 3 routing protocols while BATMAN-ADV is the latest and fastest routing protocol because it uses layer 2 routing protocol.

### 2.1.4 Different Versions of IEEE802.11x

The IEEE802.11x family standard has undergone several improvements which are developed into different main and amendments versions. IEEE802.11-1997 was the first Local area wireless networking standard followed by IEEE 802.11b, IEEE 802.11a, IEEE 802.11g, IEEE 802.11n, IEEE 802.11ad and IEEE 802.11ac, in that order. Other standards in the family (IEEE802.11c–f, h, j) are service amendments.

IEEE 802.11b standard operate on 2.4GHz frequency band. IEEE802.11b provides raw data rates up to 11 Mbps, a maximum throughput of about 5.5Mps, using a modulation technique called Complementary Code Keying (CCK). 2.4GHz frequency band is often prone to interference from microwave and other devices operating in this frequency range.

The 802.11a uses a more efficient transmission method called Orthogonal Frequency Division Multiplexing (OFDM) that enables it to deliver raw data rates up to 54 Mbps. IEEE 802.11a uses 5GHz frequency band which has shorter range compared to 2.4GHz band but less prone to interference. IEEE802.11g is uses OFDM modulation and operates on 2.4-GHz frequency band. It can deliver a raw data rates up to 54 Mbps, on the same radio frequency as IEEE802.11b. [33]

IEEE802.11n is the next evolution of this stand that introduced about several changes at physical and MAC layer. IEEE802.11 also incorporated several amendments. This changes enabled it to deliver a maximum data rate of 600Mps and of throughout of around 150Mps.

**IEEE802.11n MAC sub-layer improvements**

**Frame aggregation:** Refers to sending multiple MAC frames in one PHY layer packet to reduce overhead. Legacy 802.11a/g devices can send no more than 2304 payload bytes per frame. But new 802.11n devices have the option of bundling frames together for transmission, increasing payload size to reduce the significance of the fixed overhead caused by inter-frame spacing and preamble. There are two aggregation options:

MAC Service Data Unit Aggregation (A-MSDU): It groups logical link control packets (MSDUs) with the same 802.11e Quality of Service, independent of source or destination. The resulting MAC

frame contains one MAC header, followed by up to 7935 MSDU bytes.
MAC Protocol Data Unit Aggregation (A-MPDU): This occurs later, after MAC headers are added to each MSDU. Complete MAC frames (MPDUs) are then grouped into PHY payloads up to 65535 bytes.

**Block Acknowledgement:** Reduces the number of ACKs that a receiver must send to a transmitter to confirm frame delivery. Legacy 802.11a/g transmitters expect an (almost immediate) ACK for each frame. But 802.11n transmitters also accept Block ACKs which confirm receipt of multiple unicast frames.

**IEEE802.11n Physical improvements**

The 802.11n standard comes with several physical layer enhancements including the introduction of MIMO, better OFDM and the possibility of using wider bandwidth as briefly discussed below.

**Better OFDM:** 802.11n increases the number of sub-carriers in each 20 MHz channel from 48 to 52, enabling it to provide a maximum data rate of 65Mps for a single transmitter, 130Mps for two, and 195Mps for three and 260Mps for four. When using 40 MHz channels, 802.11n increases the number of sub-carriers available to 108. This enables it to provide a maximum data rate of 135 Mbps, 270 Mbps, 405 Mbps, and 540 Mbps for one through four transmitters, respectively.

**Improved Forward Error Correction (FEC):** FEC is a system of error control whereby the sender adds redundant data to allow the receiver to detect and correct errors. The legacy 3/4 coding rate is improved to 5/6 for IEEE802.11n, resulting in a better error control.

**Short guard interval:** 802.11n can also use a short guard interval that is 400 nanoseconds long, instead of 800 nanoseconds, which further increases throughput.

**Channel bonding:** IEEE802.11-1997 and IEEE802.11b use radio channel spacing of 22 MHz wide while IEEE 802.11b/g radios use one of the 11 20 MHz wide channels (three non-overlapping: 1, 6, 11) within the 2.4 GHz ISM frequency band. IEEE802.11n uses both 20 MHz and 40 MHz channels. 40 MHz channel is achieved by bonding two 20MHz channels, 802.11n achieves slightly more than doubling the data rate when moving from 20 MHz to 40 MHz channels [34].

**Multiple-Input and Multiple-Output (MIMO) antennas**

Wireless channels are often characterized by multipath propagation. Multipath occurs when different signals arrive at the receiver at various times, from many directions, with different polarizations. These signals can add destructively and reduce signal quality. In general performance of traditional single radios antennas are negatively affected by multi-path.

Multiple-Input and Multiple-Output is a modern antenna technique that makes use of multiple antennas at both the transmitter and receiver to improve channel capacity, throughput, coverage and reliability. IEEE802.11n defines many "M x N" antenna configurations, ranging from "1 x 1" to "4 x 4". The first number is the maximum number of transmit antennas and the second number is the maximum number of receive antennas.

Each of the receive radios independently decode the arriving signals. Then, each radio's received signal is combined with the signals from the other receive radios. With a lot of complex processing, an improved signal will be achieved.

IEEE802.11n implements one or more of the following MIMO techniques:

**Spatial Multiplexing:** A technique where, multiple streams of data are simultaneously sent transmitted through different antennas and decode with multiple receivers. This technique increases channel capacity. All 802.11n APs must implement at least two spatial streams, up to a maximum of four streams.

**Spatial diversity:** This technique uses redundant data on different paths. The purpose of spatial diversity is to make the transmission more robust. It is typically employed when the number of antennas on the receiving end is higher than the number of streams being transmitted.

**Transmit Beamforming:** Uses physical layer phase delays between antennas to electronically steer transmissions when sending a single spatial stream to non-802.11n clients. When there is more than one transmit antenna, it is possible to coordinate the signal sent from each antenna so that the signal at the receiver is dramatically improved. This technique is generally used when the receiver has only a single antenna and it's an optional 802.11n feature which is not yet widely implemented.

**Space-time block coding:** In this technique, the signal copy is transmitted not only from a different antenna but also at a different time. This is an optional 802.11n feature and it may be used in combination with Spatial Multiplexing, but can only be used when the number of transmit antennas exceeds the number of receive antennas.

Another interesting IEEE802.11 MIMO special feature is MIMO power save. This feature limits power consumption penalty of MIMO by utilization of multiple antennas only on need basis.

### Modulation and Coding Schemes (MCS)

802.11n APs and stations need to negotiate capabilities like the number of spatial streams and channel width. They also must agree upon the type of RF modulation, coding rate, and guard interval to be used. The combination of all these factors determines the actual PHY data rate, ranging from a minimum 6.5 Mbps to a maximum 600 Mbps. MCS index is an integer that defines the combination of these values.

The 802.11n standard allows around 77 possible MCS' some compulsory, some optional MCS selects, the best combination of 8 data rates, bonded channels, multiple spatial streams, different guard intervals and modulation types. It is possible to set MCS value manually, but the real value is based on RF channel conditions and is set by the system automatically.

| **MCS index** | **Spatial streams** | **Modulation type** | **Coding rate** | **Data rate (Mbit/s)** | | | |
|---|---|---|---|---|---|---|---|
| | | | | **20MHz channel** | | | **40MHz channel** |
| | | | | **800ns GI** | **400ns GI** | **800ns GI** | **400ns GI** |
| 0 | 1 | BPSK | ½ | 6.50 | 7.20 | 13.50 | 15.00 |
| 1 | 1 | QPSK | ½ | 13.00 | 14.40 | 27.00 | 50.00 |
| 2 | 1 | QPSK | ¾ | 19.50 | 21.70 | 40.50 | 45.00 |
| 3 | 1 | 16-QAM | ½ | 26.00 | 28.90 | 54.00 | 60.00 |
| 4 | 1 | 16-QAM | ¾ | 39.00 | 43.30 | 81.00 | 90.00 |
| 5 | 1 | 64-QAM | 2/3 | 52.00 | 57.80 | 108.00 | 120.00 |
| 6 | 1 | 64-QAM | ¾ | 58.50 | 65.00 | 121.50 | 135.00 |
| 7 | 1 | 64-QAM | 5/6 | 65.00 | 72.20 | 135.00 | 150.00 |
| 8 | 2 | BPSK | ½ | 13.00 | 14.40 | 27.00 | 30.00 |
| 15 | 2 | 64-QAM | 5/6 | 130.00 | 144.40 | 270.00 | 300.00 |
| 16 | 3 | BPSK | ½ | 19.50 | 21.70 | 40.50 | 45.00 |
| 23 | 3 | 64-QAM | 5/6 | 195.00 | 216.70 | 405.00 | 450.00 |
| 24 | 4 | BPSK | ½ | 26.00 | 28.80 | 54.00 | 60.00 |
| 31 | 4 | 64-QAM | 5/6 | 260.00 | 288.80 | 540.00 | 600.00 |
| 32 | 1 | BPSK | ½ | N/A | N/A | 6.50 | 7.20 |

*Table 2.1 The 802.11n standard some MCS indexes [35]*

## 2.2 Antenna Basics and Link Planning

Antennas are a very important component of communication systems. The IEEE definition of an antenna according to Stutzman et al. is, “That part of a transmitting or receiving system that is designed to radiate or receive electromagnetic waves” [36]. It is the transition between a guiding systems (transmission line or waveguide) and free space, converting the energy of a guided wave into the energy of a free space wave and or vice versa. Antenna is a very important component of any wireless communication system.

### 2.2.1 Antenna Parameters

An antenna is characterized by antenna parameters such as gain, directivity, input impedance, polarization, radiation pattern etc. Antennas demonstrate a property known as reciprocity in that an antenna will maintain the same characteristics regardless if it is transmitting or receiving [37]. In the following, brief descriptions of these basic parameters are presented.

**Directivity**

Directivity is the ability of an antenna to focus energy in a particular direction when transmitting, or to receive energy from a particular direction when receiving. If a wireless link uses fixed locations for both ends, it is possible to use antenna directivity to concentrate the radiation beam in the wanted direction.

The directivity of an antenna is equal to the ratio of the maximum power density P(θ, φ)max (watts/m$^2$ ) to its average value over a sphere as observed in the far field of an antenna. Thus,

$$D = P(\theta, \varphi)_{max}/P(\theta, \varphi)_{av} \tag{2.1}$$

Directivity is also given as the ratio of the area of a sphere (4πsr) to the beam area $\Omega_A$ of the antenna. Thus, the smaller the beam area is, the larger the directivity.

$$D = D = 4\pi/\Omega_A \tag{2.2}$$

*Were*

$\Omega A$ *beam area*

Depending on their directivity antennas can be categorized as isotropic, omni-directional and directional. Isotropic antennas are theoretical antennas that radiate energy in all directions equally. Isotropic antennas don't exist in reality and are used as reference while describing antenna parameters. Omni-directional antennas radiate roughly the same pattern all around the antenna in a complete 360° pattern. It is often used in a point-to-multi-point communication such as dipole used with access points and routers or outdoors arrays antenna used on cellular towers.

Directional antennas are special types of antennas that radiate energy more powerfully in a specific direction more than others. These antennas have high gain since they concentrate the energy in the required direction. They have found very important applications for long distance point-to-point links including satellite communication and long distance Wi-Fi links. Examples of directive antennas include Yagi antenna, biquad, horn, patch antenna, the parabolic dish, and many more.

### Antenna gain

Gain of an antenna is one of the most important parameters in planning a link or determining wireless systems' coverage capacity. Gain of an antenna is a measure of the ability of the antenna to direct the input power into radiation in a particular direction. The gain G of the antenna is defined as product of the directivity, D, and the efficiency, $\xi$.

$$G = \xi . D \qquad (2.3)$$

### Antenna efficiency

Antennas are not perfect lossless radiators and hence not all the power accepted by antenna is actually radiated. Total efficiency ($\xi$) is the product of reflection efficiency ($\xi_r$), conduction-dielectric efficiency ($\xi_{cd}$) and Polarization efficiency ($\xi_p$).

$$\xi = \xi r..\xi cd.\xi p \qquad (2.4)$$

**Conduction-dielectric efficiency ($\xi_{cd}$):** It represents material losses in the antenna structure and transmission line. The conduction-dielectric efficiency is calculated as a ratio of the power delivered to the radiation resistance to the power delivered to radiation resistance and resistance of the load (*See Figure 2.1*)

$$\xi_{cd} = R_r/(R_L + R_r) \qquad (2.5)$$

*Where:*

$R_r$ : *radiation resistance and*

$R_L$: *resistance of the load*

**Reflection efficiency:** This represents reflected power due to poor impedance matching. (See input impedance section below). Reflection efficiency is given by,

$$\xi_r = (1 - (|t|)^2) \tag{2.6}$$

*Where:*

*t: voltage reflection coefficient at the input terminals of the antenna and is given by,*

$$t = (Z_{inp} - Z_0)/(Z_{inp} + Z_0) \tag{2.7}$$

*Where*

$Z_{inp}$ = *antenna input impedance,*

$Z_0$ = *characteristic impedance of the transmission line]*

**Polarization efficiency ($\xi_p$):** This represents how well the transmitter and receiver antenna are aligned, as explained in the next paragraphs.

**Polarization**

Polarization is an important parameter during installation of antenna for proper alignment. Polarization describes the direction of the electrical field vector or the plane in which the electric wave vibrates.

There are three types of polarizations, namely, linear, circular and elliptical polarizations. Linear polarization is when the direction of electric field vector is limited to a given plane along the direction of propagation. When the electric field vector is composed of two plane waves of equal amplitude by differing in phase by 90° it said to be circularly polarized. If two plane waves of differing amplitude are related in phase by 90°, or if the relative phase is other than 90° then the light is said to be elliptically polarized.

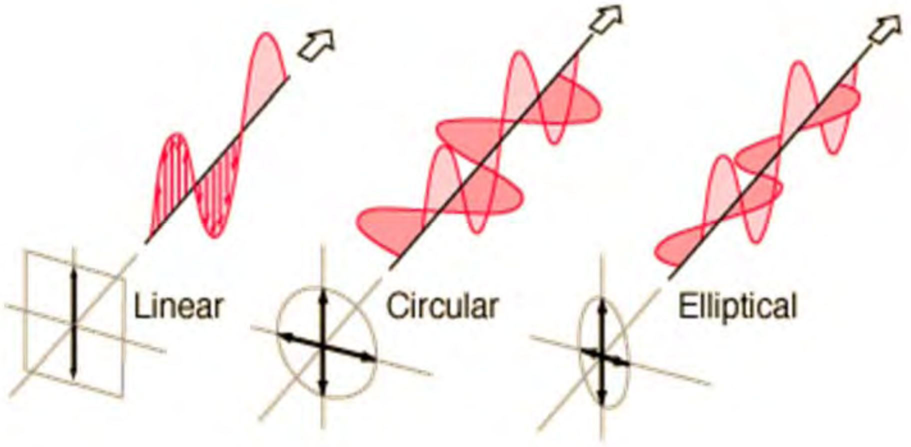


*Figure 2.4 Types of polarization*

Due to the reciprocity theorem, antennas transmit and receive in exactly the same manner. Hence, a vertically polarized antenna transmits and receives vertically polarized fields. Consequently, if a horizontally polarized antenna is trying to communicate with a vertically polarized antenna, there will be no reception.

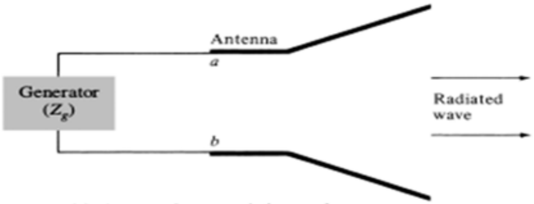
In general, for two linearly polarized antennas that are rotated from each other by an angle, the power loss due to this polarization mismatch will be described by the Polarization Loss Factor (PLF):

$$PLF = cos2\theta \tag{2.8}$$

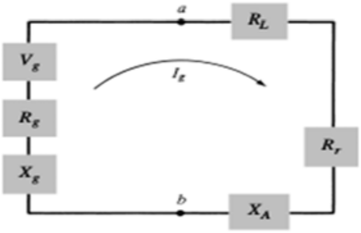
Hence, if both antennas have the same polarization, the angle between their radiated E-fields is zero and there is no power loss due to polarization mismatch. Antennas at both ends of the communication systems must be polarization-matched.

### Input Impedance

The impedance at a given point in the antenna is determined by the ratio of the voltage to the current at that point. It determines how well a transmitter can transfer power into an antenna.



(a) Antenna in transmitting mode



(b) Thevenin equivalent

*Figure 2.5 Antenna equivalent circuit [38]*

For an efficient transfer of energy the impedance of the transceivers, antenna, and transmission cable connecting them must be the same. If the antenna tuning circuit on a transmitter (or receiver) is designed for a 50 ohm load, the antenna should, of course, have impedance near 50 ohms for best results. Transceivers and their transmission lines are typically designed for 50Ω impedance. If the antenna has impedance different than 50Ω, then there is a mismatch and an impedance matching circuit is required. When any of these components are mismatched, transmission efficiency suffers.

### Radiation pattern

Radiation pattern of an antenna is a graphical representation of the relative distribution of the antenna parameters (radiated power, gain, etc) in space. It is usually given by the plot of the directivity (gain) of the antenna as a function of an observation point plotted on spatial co-ordinates specified by the elevation angle (θ) and the azimuth angle (φ). The observation point with respect to the antenna position is usually depicted in terms of an angular position.

It can be plotted as a 3D graph or as a 2D polar or Cartesian slice of this 3D graph. Radiation pattern serves as the signature of an antenna.

## Beamwidth

Beamwidth is the angular separation of the half-power points of the radiated pattern. The most popular is the half power beamwidth (HPBW), which is the measure of the angle over which the radiation intensity of the antenna is at least one-half the value of its maximum value.

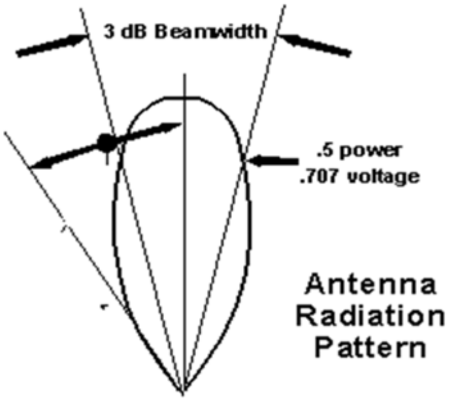


*Figure 2.6 Antenna Beamwidth [39]*

Beamwidth of antenna can be used as a measure of directivity in such a way that the directivity of an antenna increases as its beamwidth is made smaller, that is, as the energy radiated is concentrated into a smaller solid angle.

## Antenna bandwidth

From a transmission line's prospective; an antenna is just impedance. If not well matched, a significant fraction of the transmit/receive power will not be transferred to/from the antenna. The bandwidth of the antenna is defined as the size of the frequency band over which the square magnitude of the reflection coefficient $|\Gamma|^2$ is smaller than a given threshold. Therefore, in order to ensure maximum power radiation, we need antennas with high radiation efficiency and are well matched

There are several different types of antennas. In the following section, some antenna types that are used in this thesis will be discussed next.

### 2.2.2 Antenna types

There are several antenna types designed for different types of applications. These antennas are categorized as omni-directional and directional antennas. Omni-directional antenna includes dipoles, loop antenna and directional antennas include yagi, patch and parabolic antennas. The antennas used in this thesis are described next.

**Parabolic Antennas**

Directional Antennas are often used for a point-to-point Wi-Fi or microwave links in long distance communications. This is because; they have narrow beamwidth and high gain. There are various types of directional antennas including grid and dish parabolic reflectors, patch, panel and different types of modern smart antennas. Parabolic antenna is the topic of discussion because it is the antenna selected for this thesis.

Parabolic antenna comprises of a driven element or feeder and a passive reflector. The driven element can be a wire dipole antenna, biquad, horn or other antenna types. Based on the relative position of the feeder and the reflector, parabolic antennas are categorized into center-fed and offset fed antennas. Center-fed antennas are easy to analyze and construct while offset antennas have in general better efficiency.

For a center-fed parabolic antenna, the feeder must be positioned at the exact focal point of the parabola-shaped reflector to collect all the incoming electromagnetic energy. This is because according to reflector theory, the basic property of a perfect parabolic reflector is that it converts a spherical wave irradiating from a point source placed at the focus into a plane wave. Conversely, all the energy received by the dish from a distant source is reflected to a single point at the focus of the dish, which is fed to the receiver circuit either through a coaxial line feed or the whole receiver system is connected at the focal point of the reflector. (See *Figure 2.6 below*)

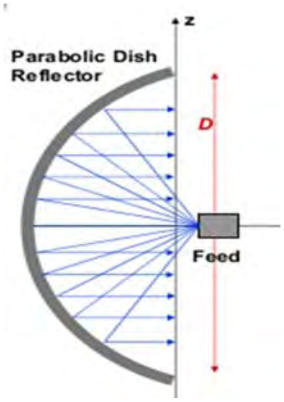


*Figure 2.7 Center-fed parabolic dish*

The position of the focus, or focal length, is given by:

$$f = D^2/16d \qquad (2.9)$$

*Where:*

$D$: *diameter,*

$d$: *depth of the parabola at its center ,*

$f$ : *focal length*

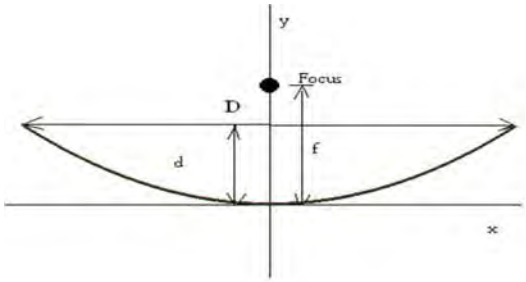


*Figure 2.8 Focal point of a center-fed parabolic dish [40]*

In order to illuminate the dish properly, the beamwidth of the feeder antenna needs to match the f/D ratio of the parabolic reflector with the following formula: [41]

$$f/D = 1/4 * tan(\Theta/2) \qquad (2.10)$$

*Where:*

$\Theta$: *beamwidth of a feeder,*

$D$: *diameter,*

$f$ : *focal length*

The ratio f/D shows whether the dish is shallow or deep. A small f/D means that the dish is deep a broad beamwidth feed is needed to illuminate it properly. But if f/D is higher your dish is rather flat and you will need a narrow beamwidth feed to illuminate it.

The beamwidth is the most important parameter in choosing the feed for a parabolic reflector. If a feed with broader beamwidth than required is chosen, the parabola will be over illuminate and some signal will be lost. On the other hand if the dish is under illuminate by choosing a narrow beamwidth antenna, the dish is not used to its full capacity and the gain will be lower. In both conditions the overall efficiency of the antenna system will be affected.

The gain of parabolic reflector dish is proportional to the size and depends on the frequency and efficiency of the antenna systems, as given by the following formula,

$$G = 10 \log_{10} \eta(\pi D/\lambda)^2 \tag{2.11}$$

*Where:*

$\eta$: *efficiency,*

$\lambda$: *wavelength,*

*D: diameter of the dish*

*G: gain.*

And beamwidth($\Psi$) of the parabolic antenna is given by,

$$\Psi = 70\,\lambda/D \tag{2.12}$$

*Where:*

$\lambda$: *wavelength*

*G: gain*

The efficiency is determined by radiation, reflection and polarization efficiencies. The reflection efficiency can be made close to 1 by matching the input impedances of the antenna structures while polarization efficiency can also be made close to 1 by adjusting the alignment between the transmitter and receiver antennas. Since parabolic reflector is typically metallic with a very high conductivity, ohmic losses due to the reflector is negligible and this efficiency is typically close to 1 and can be neglected. The ohmic losses are often due to the transmission lines, connector or the feed antenna. The overall efficiency of these antennas is often taken to be between 50-70% [42].

There are other factors that affect the efficiency of a parabolic reflector, this factors include,

**Surface Error:** Small deviations in the shape of the reflector degrades performance, especially for high frequencies that have a small wavelength and become scattered by small surface anomalies

**Non-Ideal Feed Phase Center:** The parabolic dish has desirable properties relative to a single focal point. Since the feed antenna will not be a point source, there will be some loss due to a non-perfect phase center for a horn antenna.

### Biquad Antenna

Biquad antenna is a very simple wideband antenna that can be designed to operate a given operating frequency. Biquad antenna consists of two quad antennas and a reflector element. A quad antenna is a wire antenna which is constructed by bending a wire so that the wire forms a square. The length of the quad element is usually chosen to be roughly equal to the operating wavelength. This is because when the length of quad element approaches the wavelength, maximum radiation (directivity) occurs in the directions perpendicular to the quad plane on both sides (Balanis 2005). A reflecting element is added to the biquad to increase directivity by reflects the electromagnetic wave back to the front of the antenna, that is, no radiation to the back of the antenna.

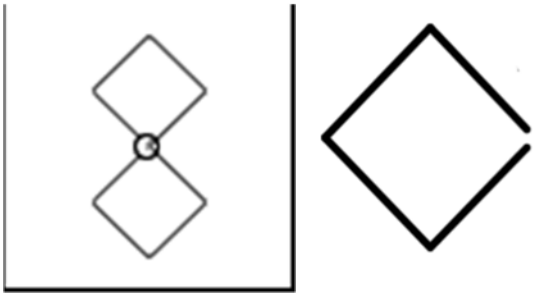


*Figure 2.9 biquad antenna and its quad element*

The input impedance of a reflector antenna can be adjusted not only by varying the dimension of the radiating element (in this case, biquad antenna), but also the displacement of the radiating element above the reflector. Although the biquad antenna is a resonant antenna and its impedance is real (no reactance or imaginary part) at a certain frequency only, the antenna's input impedance very close to 50 Ohms across the WLAN frequency range can still be achieved.

### Dipole Antenna

Dipole antenna is the simplest and most widely used class of antenna in radio and telecommunications. It consists of two identical conductive elements usually bilaterally symmetrical.

Figure 2.10 Dipole antenna

Dipole antenna is an omni-directional antenna. The radiation is the maximum at right angles to the dipole, dropping off to zero on the antenna's axis. Therefore a dipole mounted vertically will be omnidirectional in the horizontal plane. Dipoles mounted horizontally will have gain in two opposing horizontal directions but nodes (directions of zero gain) at 90° from those directions (along the direction of the conductor). (See Figure 2.11)

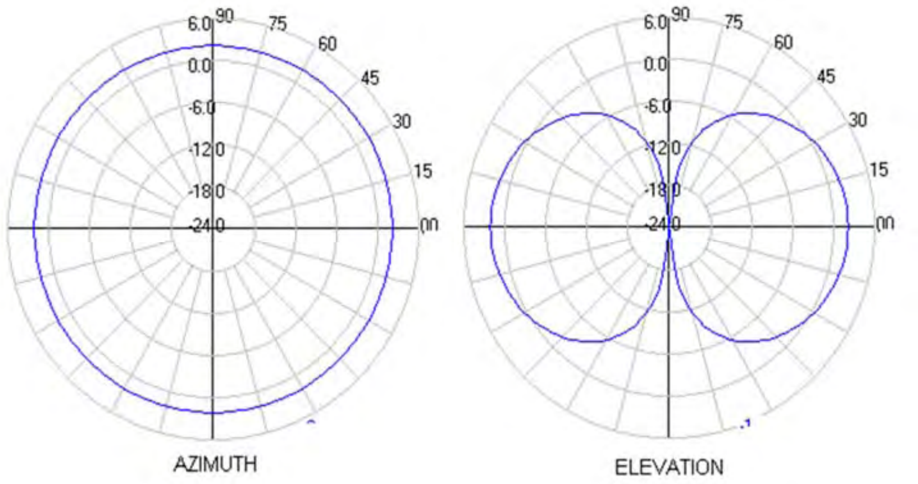


*Figure 2.11 Radiation pattern of dipole antenna*

The most common type of dipole antenna is half-wavelength antenna. The half-wavelength dipole antenna is a simple dipole whose length is half-wavelength of the operation frequency. A folded dipole is a half-wave dipole with an additional wire connecting its two ends. Rubber duck antenna is a type of half-wave dipole antenna. These different antenna types are used in various different applications. The Application of folded dipole antennas are commonly television and VHF FM broadcast. Rubber ducky antennas are the most common antenna type used by Wi-Fi access points and routers.

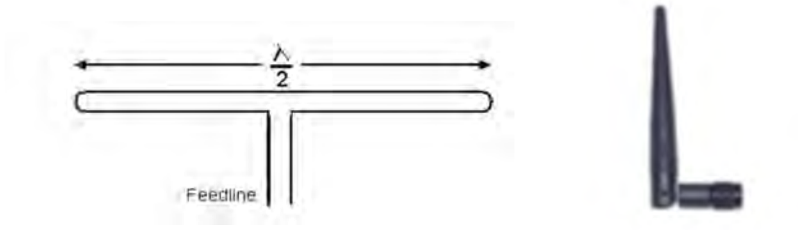


*Figure 2.12 Folded antenna and rubber duck antenna, respectively*

## 2.3 Link Planning

In order to have a communication between a transmitting and receiving communication systems, a certain minimum signal is required to be collected by the receiving antenna. Link budget analysis is a mathematical tool that determines if this minimum signal can be achieved, in other words, if a radio link is feasible. Whether or not signals can be passed between two radios depends on the transmitted power, antenna gains and system losses, environmental losses and the loss as distance increase. The loss due to distance is called path loss. Link budget accounts for all these gains and losses in a transmission system.

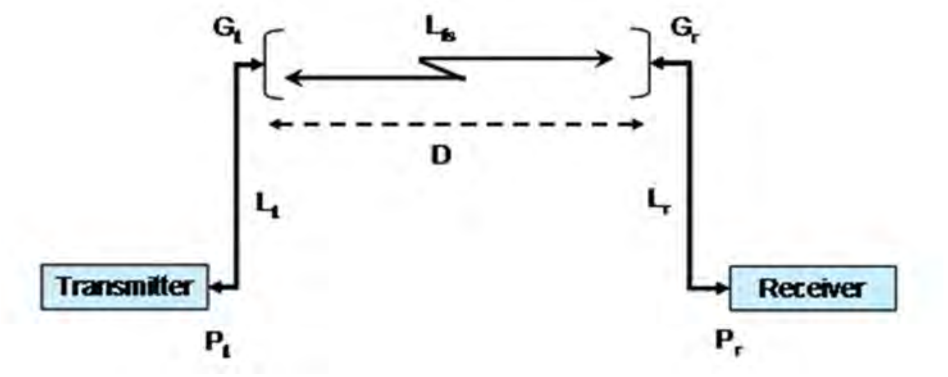


*Figure 2.13 Link budget analysis*

$$P_r(dBm) = P_t(dBm) + G_r(dBm) + G_t(dBm) - L(dB) \qquad (2.13)$$

*Where:*

*Pr: Received power*

*Pt: Transmitted power*

*Gr: Receiver antenna gain*

*Gt: Transmitter antenna gains*

*L: losses*

**Transmitted power:** Input power to the antenna system. The transmitter power information is provided by the manufacturer of the device.

**Receiver and Transmitter Antenna Gains:** Receiver and transmitter antenna gains, calculated depending on the type and characteristics of the antennas used.

**Received Power:** It is the power collected by the receiver. Often times, in link budget analysis, the lowest power of signal the radio can distinguish, called the receiver sensitivity is used. Receiver sensitivity is information is provided by the manufacturer of the device and always expressed as a negative dBm (- dBm).

“The 802.11 standard defines receiver sensitivity as the received signal level required to guarantee BER below $10^{-5}$. This determines the amount of energy per bit required to overcome the noise. As bits/sec increases, more receiver power will be needed to provide the same energy per bit. Receiver sensitivity decreases as the transmitter rate increases so to maintain the same signal-to-noise as the distance increases the throughput diminished. Or for longer distance one should choose lower data rates to compensate for reduction of the signal strength with distance”, WNWD standards [56].

## Losses

**Cable Loss:** Some of the signal's energy is lost in the cables, the connectors and the antenna structures of the transmitter and receiver antennas. The loss depends on the type of materials and length of the cables.

**Free space path loss:** This loss happens because the radiated signal energy expands as a function of the distance from the transmitter. That is, as a signal spreading out from a transmitter, it will move away from the source spreading out in the form of a sphere. As it does so, the surface area of the sphere increases. And according to the law of the conservation of energy, as the surface area of the sphere increases, so the intensity of the signal must decrease. Hence, the signal decreases in a way that is inversely proportional to the square of the distance from the source of the radio signal in free space

$$FSPL = (4\,P.d/\lambda)^2 = (4\,P.d.f/c)^2 \tag{2.14}$$

$$FSPL(dB) = 20log10(d) + 20log10(f) + 32.44 \tag{2.15}$$

*Where:*

*FSPL: Free space path loss*

*d : Distance of the receiver from the transmitter (meters)*

*λ: Signal wavelength (meters)*

*f : Signal frequency (Hertz)*

*c: Speed of light in a vacuum (meters per second)*

**Friis equation**

Friis equation represents the relationship between the transmitted signal power, receiver and transmitter gains, distance, wavelength and the receiver powers for a lossless ideal channel.

$$Pr = PtGtGr/(4\pi d\lambda)^2 \qquad (2.16)$$

$$Pr = Pt + Gr - FSPL - L \qquad (2.17)$$

*Where:*

*L: cable lossless*

If unobstructed, radio waves will travel in a straight line from the transmitter to the receiver and Friis equation can be used to analyze a link.

But in reality, there are environmental losses. Environmental losses happen due to reflection, diffraction, scattering, rain drop, etc. Hence, the total path loss is the sum of free space path loss and other environmental losses.

*Path loss (L) = FSPL + Environmental losses* (2.18)

The link budget has also to be modified as follows:

$$P_r = P_t G_t G_r/(4\pi d\lambda)^2\, L \qquad (2.19)$$

$$Pr = Pt + G_t + G_r - L \qquad (2.20)$$

*Where:*

*L: Cable lossless and Environmental losses*

## Propagation Models

Different communications links in different environments encounter different terrain, path, obstructions, atmospheric conditions and other phenomena; it is not easy to formulate the exact loss for all telecommunication systems. As a result, different propagation models exist for different types of radio links under different conditions. Propagation models are characterization of radio wave propagation as a function of frequency, distance and other conditions. Some of these models are free space model and two ray ground model, models such as Longley Rice model, Okumura model.

**Free Space Model-** This model assumes a single unobstructed path between transmitter & receivers were the received power is a function of transmitted power, antenna gains & distance between transmitter and receiver. This model uses Friis equation.

**Two Ray Ground Model-** Here it is assumed that the total received power at the receiver end is the sum of powers due to two paths, the direct path between transmitter & receiver and the path obtained by one ground reflection between the same transmitter & receiver separated by same distance as in case first. Another important parameter in this model is the height of location of receiver & transmitter with respect to the ground surface. This model uses the following formula.

$$Pathloss = 40log(d) - 10log(G(hr.ht)^2)^2 \qquad (2.21)$$

Where ht and hr are the heights of the transmitter and receive antennas respectively and d is the distance between the transmitter and receiver.

**Longley Rice Model-** This model takes in to consideration terrain profiles, climate, subsoil conditions and ground curvature. Fundamentally; it deploys geometrical optics along with two-ray ground reflection model. One major limitation of the model is that it does not take any account of building & foliage. This model is applicable in case of point to point communications in the frequency range of 40 MHz -100GHz in the range from 1 -2000 km.

**Okumura Model-** An empirical model developed by Japanese radio scientist Okumura. In this models path loss profile is a simple power law relationship, where exponent μ is a function of frequency & antenna height. It is applicable for frequency range from 150 MHz to 1920 MHz deployed for a distance range of 1Km to 100Km. Path loss in Okumura model is expressed as:

$$L50(I)[dB] = LF(I) + AM(f,I) - G(ht) - G(hr) - Garea \qquad (2.22)$$

*Where:*

| | |
|---|---|
| *L50 :* | *50th percentile of path loss or median value.* |
| *LF(I):* | *Free space propagation path loss.* |
| *AM(f,I):* | *Median attenuation relative to free space.* |
| *G(ht):* | *Base station antenna height gain factor.* |
| *G(hr):* | *Mobile station antenna height gain factor.* |
| *Garea:* | *Gain due to type of environment.* |

$G(hr)=20 \log(ht/200)\ 1000m > hr > 30m$

$G(hr)=10 \log(hr/3)\ hr<= 3m$

$G(hr)=20 \log(hr/3)\ 3< hr< 10m$

$ht$ = *transmitter antenna height.*

$hr$ = *receiver antenna height.*

**Fading Margin (FM):** This margin is the amount of signal above the sensitivity of radio that should be received in order to ensure a stable, high quality radio link during bad weather and other atmospheric disturbances. The higher the fade margin, the more reliable the link will be. The required Fade Margin depends on several factors including: Frequency used link distance and reliability requirements. For example, for a 2.4GHz, ISM band radio usually a fading margin of 10 to 20dB is often considered~~.~~ [43].

$$FM = Pr - Prses \tag{2.23}$$

$$Prses(dBm) = Pr(dBm) + Gr(dB) + (dB) - Pcables(dB) - L(dB) + F \tag{2.24}$$

*Where:*

$Prses$: *Receiver Sensitivity*

### Fresnel zone

Fresnel zone is a concept used by propagation theory to calculate the effect of environmental losses due to reflections and diffraction loss between a transmitter and receiver. Fresnel zones are cylindrical ellipses drawn between transmitter and receiver. The size of the ellipse is determined by the frequency of operation and the distance between the two sites. Fresnel zones are numbered and are called 'F1', 'F2', and 'F3' etc. There are an infinite number of Fresnel zones, however, only the first 3 have any real effect on radio propagation. Obstacles in the first Fresnel zone will create signals with a path-length phase shift of 0 to 180 degrees, in the second zone they will be 180 to 360 degrees out of phase, and so on.

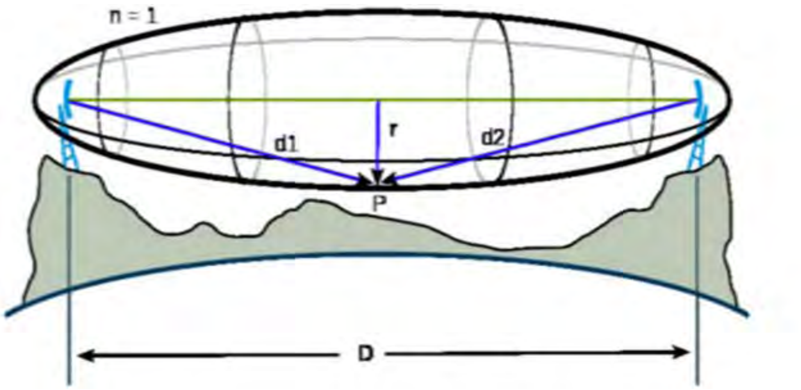


*Figure 2.14 Fresnel zone [63]*

The general equation for calculating the Fresnel zone radius at any point P in between the endpoints of the link is the following:

$$h = 17.32. d_1. d_1/f . (d_1 + d_1) \qquad (2.25)$$

*Where:*

*h: Fresnel radius at a point just above potential obstruction*

*f: frequency in GHz*

*d: distance (km) from transmitting antenna to point just above potential obstruction*

The first zone must be kept largely free from obstructions to avoid interfering with the radio reception. However, some obstruction of the Fresnel zones can often be tolerated. The rule of the thumb with Fresnel considerations is to keep at least 60% of first Fresnel zone unobstructed to achieve acceptable signal strength and tolerable signal attenuation. [44]

The application of this formula is used by link planning software such as RadioMobile. RadioMobile is a link planning software that predicts the performance of a radio link by using information about the equipments, required performance level and a digital map of the area. It automatically builds a profile between two points in the digital map showing the coverage area and first Fresnel zone. RadioMobile calculates the received signal strength, free space loss and loss due to environment such as tree absorption, terrain effects, climate, and even estimating path loss. It also calculates the link length, azimuth, elevation and tilt you should give to the antennas.

# 3 The IEEE802.11 Technology for Long Distance Communication

The default IEEE802.11 technology poses physical and MAC layer challenges in a point-to-point long distance setup. This is because, IEEE802.11 access points often have low gain, as they use omni-directional antennas designed for a small areas such as offices, classrooms, cafeterias, etc. The MAC layer timeouts are also defined for such a short distances. That is the ACK timeout is very short and inter frame spacing of the CSMA/CA process is very short. Hence, in order to use IEEE802.11 technology for long distance communication, among others, there has to be changes at MAC layer and the antenna. These changes target,

- ✓ Achieving higher Signal-to-Noise Ratio (SNR) that satisfies the receiver sensitivity requirement specified by the manufacturer for the distance under consideration ;
- ✓ Achieving a good throughput and lower packet loss ,
- ✓ Achieving an optimal site selection and link planning to overcome environmental losses

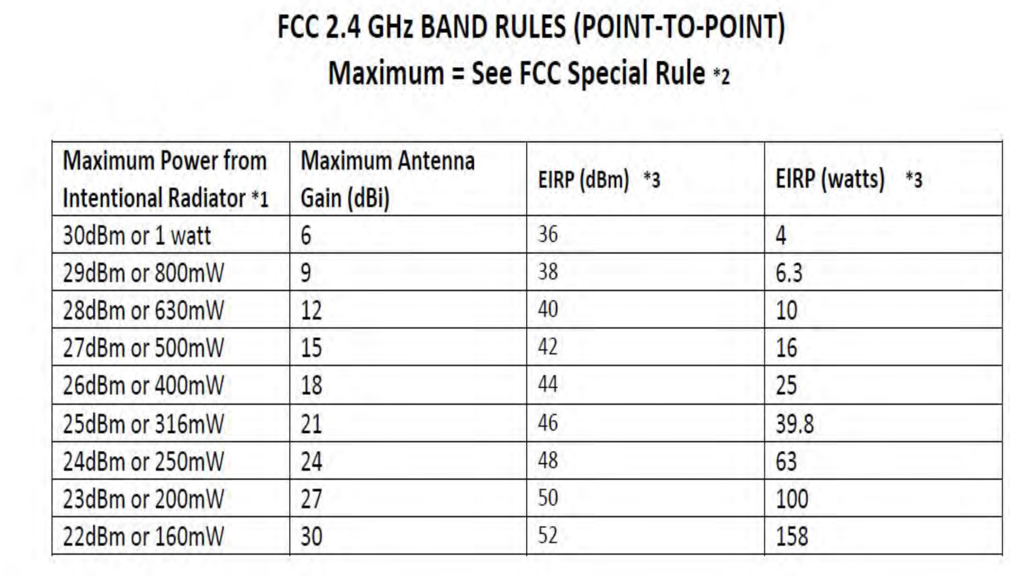
In order to establish communication between the access points, a certain minimum level of signal should reach the receiving antenna and there should be enough time for packets to reach their destination and for acknowledgment and other packets to be received. The physical and MAC layer changes and the necessary link planning procedures to make communication possible at long distance using IEEE802.11 will be discussed in the next sections.

## 3.1 Physical Design Considerations

**Achieving higher SNR**

Long distance communication over a wireless channel needs higher SNR in order to compensate for the path loss as well as the losses due to obstructions, climate conditions and interference. The low gain, Omni-directional antennas and the limited transmitter power of IEEE802.11 technologies will not be able to give coverage for long distance.

One way of achieving higher SNR is by increasing the transmitter power of the access points. However, because of regulations, there is a limit to how much we can increase transmitter power (see table 3.1). A more viable approach is to use high gain antennas at transmitter and receiver. The design of these antennas has to also take interference into account. This is because the license free frequency band IEEE802.11 technologies use is shared by many organization, devices and home appliances. Hence, in addition to the high gain requirement, directionality has to be taken into account.



FCC 2.4 GHz BAND RULES (POINT-TO-POINT)
Maximum = See FCC Special Rule *2

| Maximum Power from Intentional Radiator *1 | Maximum Antenna Gain (dBi) | EIRP (dBm) *3 | EIRP (watts) *3 |
|---|---|---|---|
| 30dBm or 1 watt | 6 | 36 | 4 |
| 29dBm or 800mW | 9 | 38 | 6.3 |
| 28dBm or 630mW | 12 | 40 | 10 |
| 27dBm or 500mW | 15 | 42 | 16 |
| 26dBm or 400mW | 18 | 44 | 25 |
| 25dBm or 316mW | 21 | 46 | 39.8 |
| 24dBm or 250mW | 24 | 48 | 63 |
| 23dBm or 200mW | 27 | 50 | 100 |
| 22dBm or 160mW | 30 | 52 | 158 |

*Figure 3.15 FCC rule for unlicensed wireless equipment operating in ISM band.[50]*

**Link planning**

No matter how much the gain of an antenna is increased, if the wireless link between the transmitter and receiver is highly obstructed it is not possible to get a good SNR. In order to get the best out of a point-to-point long distance communicate system, there should be a good line-of-sight between the transmitter and receivers. Fresnel zone clearance of greater than 60% is often considered acceptable for establishing a reasonable line-of-sight clearance between transmitter and receiver [45]. This is achieved with the help of software such as Radiomobile.

In some environments achieving an acceptable Fresnel zone clearance between transmitter and receiver antennas might need to be mounted on very tall towers. Communication towers are the dominant cost factor in most communication systems [46]. However, the recommendation of thesis is to mount the system on natural towers such as hills to minimize the cost incurred due to expensive towers and it can be said, without loss of generality, that the topology of Ethiopia is favorable for such an implementation.

## 3.2 MAC Layer Design Considerations

As mentioned earlier, CSMA/CA, the de-facto MAC protocol of IEEE802.11 technology, is ill-suited for long distance communications because of MAC layer timeouts.
In the case of IEEE802.11a/b/g, upon successfully receiving a packet the receiver node is required to send an acknowledgment within a tight time bound called ACKTimeout or the sender has to retransmit. This mechanism has few drawbacks, as explained in the following paragraphs.

As the link distance increases, propagation delay increases as well, and the sender waits for a longer time for the ACK to return. If the time it takes for the ACK to return exceeds the ACKTimeout parameter, the sender will retransmit unnecessarily and waste bandwidth. These limits the theoretical ACK timeouts are 744µs (11 km) for 802.11b, and 372µs (55 km) for 802.11g [47].

This parameter is a little bit different for IEEE802.11n, the standard used in this thesis. IEEE802.11n uses block acknowledgement method which means that the receiver only sends ACK after receiving a block of packets, which in effect improves channel utilization, compared to the legacy standards IEEE802.11a/b/g.

The problem of short ACKTimeout can be approach by increasing its value and limiting the retry time for hardware that supports these features. However, limiting the retry value decrease throughput, because there is no guaranty that packets won't fail.

In even the number of nodes contending for the communication channel at a time is two in a point-to-point link, there is the higher probability of collisions at long distance due to the nature of CSMA/CA protocol. With CSMA/CA channel-access mechanism, nodes listen to the medium for a specified time period (DIFS) before transmitting a packet, thus ensuring that the channel is idle before transmission. If the channel is occupied, to prevent all stations transmitting at the same time after the channel is idle, the back-off process starts. The back-off time counter is represented by the randomly generated number, CWmin, which is subsequently decremented as long as the carrier sense functions report an idle medium. If a transmission starts and the channel becomes busy during a back-off decrease, the value is frozen and the process pauses. When the channel becomes idle again for the time of a DIFS, the process is resumed with the frozen value. When the counter reaches zero, the station is allowed to start the transmission in the current slot.

For longer links it is possible for a node to start transmitting a packet unaware of another packet transmission at the other end. As the propagation delay increases, this probability of loss due to collisions increases. Increased value of CWmin or back-off means that the probability of collision is low but it also leads to more idle time on the medium to more delay.

Hence, in trying to optimize these parameters (CWmin and retry) for long distance, a compromise has to be made between throughput, delay and collision. Taking everything into account, the optimal value for number of retries is one (a single chance to retry a frame) and a CWmin value of 7 for longer distances and/or higher MCS [48].

As pointed out in in Section 1.5, most of the earlier projects based on IEEE802.11a/b/g, approached this problem by changing ACKTimeout or changing the whole MAC method from CSMA/CA. Currently, some manufacturers' products such as Mikrotik Nstreme or Ubiquiti Networks AirMAX, offer proprietary TDMA MAC alongside the standard Wi-Fi. These two products offer both the hardware and firmware together. NETshe on the other hand offers firmware that supports TDMA MAC for free. The problem with NETshe is it supports only a few hardwares and the source code is not free.

On the other hand, some firmware such as Openwrt allows the manipulation of MAC layer parameters mentioned above. This combined with the many features IEEE802.11N, gives an interesting method of solving this problem. This is the approach used in this thesis, which will be discussed in Chapters 4 and 5.

# 4 Antenna Design

## 4.1 Point-to-Point long-distance testbed description

The Wi-Fi-based PTP long-distance link has two Wi-Fi radios, transmitter and receiver, each with its own parabolic dish antenna. One of the radios is to be connected to a wired network while the other one on is connected to a distribution network remote site connected.

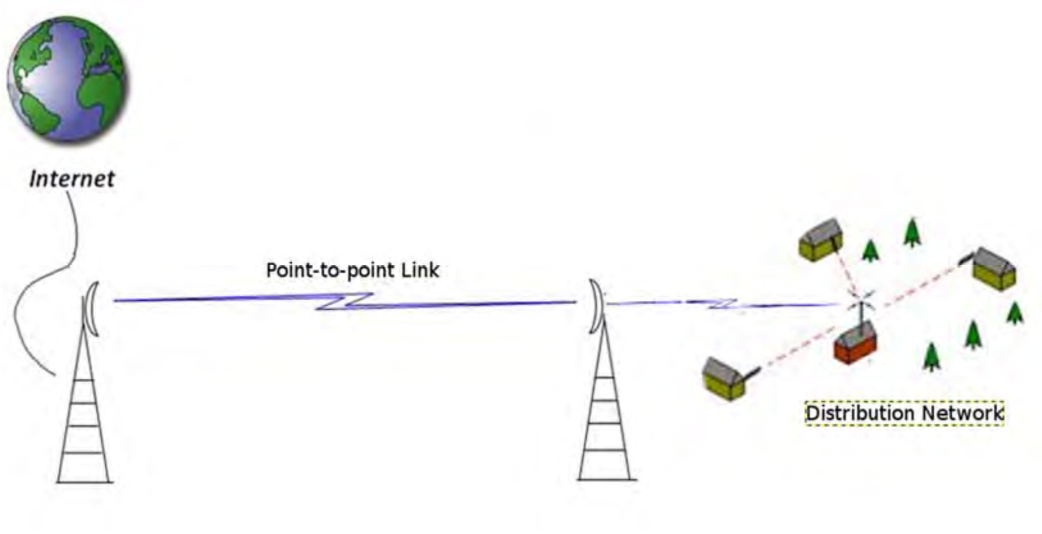


*Figure 4.16 Point-to-point wireless link*

The Wi-Fi radios used to establish a point-to-point link needs physical components such as antenna, power source, cable and firmware for controlling the overall device functionality. The performance of a wireless link also depends on factors like, the proper selection of protocols used by the firmware, the input power, length of cables and antenna parameters.

Wi-Fi radio firmware offer two options for establishing PTP wireless links namely Wireless Distribution System (WDS) mode and mesh mode. WDS is a very simple, non-standard extension to the wireless 802.11x standards where connected network devices share a common broadcast domain and, hence, are in the same local area network. This means there is no need for routing in WDS mode which makes it is simple; however, it lacks the flexibility of configuring different networks and is not compatible with many hardware devices, including dragino MS14, the access point used for this thesis.

The PTP link in this thesis uses mesh protocol to establish a direct link between the two access points. Unlike WDS, with mesh protocol it is possible to create different LANs. IoT mesh firmware with MS14 access point is used for conducting this thesis. Mesh protocol that has an additional advantage of being scalable in case of future expansion to include redundant and multi-hop networks.

The distance covered by a transmitting or receiving antenna depends on input power, losses in the system and environment, and gain of the antenna. The input powers of most communication systems are usually regulated and it is not possible to make big change to this parameter. Losses in an antenna system include losses in the antenna structure, connectors and cables and have to be taken under consideration while designing wireless communication system. The type and parameters of antenna plays a key role in establishing a wireless link between two points, which makes antenna design an important task in designing a wireless communication system. That's why the next section is dedicated to antenna design, specifically, parabolic antenna design.

The environment or the wireless channel for implementation also affects the performance of a wireless system and is going to be discussed in Chapter 5, under link budget analysis and site selection.

## 4.2 Antenna design

An antenna is characterized by several parameters such as gain, directivity, beam-width, efficiency, radiation pattern, etc. Hence, designing an antenna is a process of designing these parameters for a specific requirement.

Directionality is a very important requirement in a point-to-point wireless communication. This is to minimize interference with other devices operating on the same frequency band and focusing the energy in a specific required direction, instead of distributing it in all directions. Directivity and beam-width have an inverse relationship. Measuring the directivity or beam-width of an antenna is not an easy task. However, it is possible to get the beam-width of specific antenna type from its radiation pattern, which can usually be generated using modeling and analysis software such as NEC4 and empire software.

Antenna gain is probably the most important parameter in a long distance communication design. The gain is proportional to the efficiency and directivity of the antenna. For most antenna types the gain of antenna depends on factors like size and shape of the antenna structure. For instance, the gain of a parabolic antenna is proportional to its diameter and efficiency.

The following procedures describe the steps taken in designing and building long distance point-to-point antennas**:**

- ✓ **Determining the required directivity:** For a long distance point-to-point applications antenna with high directivity is needed as opposed to omni-directional antennas. This is because; directional antennas concentrate energy in a specific direction and minimize the possibility of interference.

- ✓ **Determine the required antenna gain:** Link budget analysis is a very important mathematical tool that link parameters such as the required antenna gain. Link Budget analysis employs different types of path loss models in order to determine link parameters. Hence, link budget analysis might be conducted with the use of software or manual calculation in the case of simple path loss models such as free space path loss model.

- ✓ **Determining the antenna type:** Depending on the required gain and directivity, the appropriate antenna type and size is chosen. This decision also took into account factors like availability, cost, easy of design, etc. For instance, parabolic antennas are used for this thesis work. In addition to being high gain, highly direction, their easy of design, availability on local market and feasible cost made parabolic antennas antenna of choice for this thesis.

- ✓ **Feed Selection:** Gain of a parabolic dish antenna depends on its directivity and efficiency. The most important factor that determines the efficiency of a parabolic antenna is how well the parabolic reflector is illuminated by the feed antenna. Hence, feed antenna for parabolic antennas has to be properly selected and mounted. The parabolic reflector has to be properly illuminated by the feed antenna. In order to properly illuminate a center-fed parabolic dish antenna, the beamwidth of the feed antenna has to match with focal length to diameter (f/D) ratio of the parabolic reflector and it has to be mounted at the focal point of the dish.

- ✓ **Making the antenna:** Once the design is complete the antennas and the necessary materials are purchased, the next step is building and assembling the parts.

- ✓ **Analysis:** Antenna characteristics such as gain, directivity and radiation pattern of the antenna is analyzed and verified. Some of the antenna characteristic are not easy to measure and sometimes require expensive laboratory equipments. One way of estimating these values is by building software models of these antennas and taking computer simulated results.

### 4.2.1 Parabolic Antenna Design

Parabolic antenna is selected for its high gain, directionality and reasonable price. In addition, this antenna is easy to redesign for a specific frequency of operation, in this case 2.4GHz. This is because by only changing the feeder the parabolic antenna can function at different frequencies.

In this thesis a maximum of 100km is considered for designing the antennas. This consideration is depending on the observation that most of the rural areas are often a few kilometers to a few tens of kilometers from the suburban or urban areas. Hence, for 100km distance, the link Line-of-Sight (LOS) budget analysis shows that a 30.2dBm gain antenna is needed (see Section 5.2). As indicated by equation 4.1 below, it is possible to achieve this gain with parabolic dish with 175cm in diameter.

Hence, a pair of dish parabolic reflectors of 175cm in diameter and 30cm depth was selected. The efficiency of an amateur built antenna is in general considered between 45-50% [45]. Efficiency of parabolic antenna depends on factors like, the feeding length of coaxial cable, how well the parabolic reflector is illuminated by the feed antenna, how well the two antennas are aligned and whether the impedance of the feed antenna is matched to the coaxial cable. Through careful design these parameters it is possible to maximize the efficiency of a parabolic antenna. Hence taking efficiency to be 50%, the gain of the parabolic dish antenna is given as follows,

$$G = 10 \log_{10} \eta(\pi D/\lambda)^2$$

$$\lambda = 3/2.462 = 0.122\text{m}, \ \eta=0.5, \ D=1.75\text{m}$$

$$G \sim 30.1 \text{ dBi} \qquad (4.1)$$

*Where:*

*G: antenna gain*

*$\lambda$: wavelengths*

*$\eta$: efficiency*

Once the size of the parabolic reflector is decided, the next step is designing the feeder antenna. A reflector is a passive component that helps in concentrating the signal in a desired direction while the feed antenna is physically connected to the transmitter or receiver circuit, sends or receives the signal to or from the reflector at a given frequency.

## 4.2.2 Feed Design

Choice of a feed for parabolic reflector depends on several factors. This includes: how well a feed illuminates a parabolic dish, the need for coaxial cable, length of the coaxial cable, connectors, etc.

How well a feed illuminates a parabolic dish depends on the relationship between the focal length to diameter (f/D) of the dish and the beamwidth of the feed antenna. The f/D ratio determines if the dish is deep or shallow and what kind of a feeder can illuminate the dish properly. A deep dish needs feed with wide beamwidth to illuminate it properly and a shallow dish needs a narrow beamwidth antenna. Hence, the choice of feed, specifically their radiation pattern, affects the efficiency of the parabolic antennas [40].

With a dish of diameter of 1.75m, depth of 0.3m, the F/D ratio is 0.365 as the calculated below:

$$f = D^2/16d = 0.638\text{m} \qquad (4.2)$$

$$F/D = 0.365 \qquad (4.3)$$

*Where:*

*f: focal length*

*D: diameter*

*d: depth*

This shows that the parabolic dish is quite shallow and needs a feed that has wide beamwidth(ϴ), $111.183^0$, as shown below:

$$f/D = 1/4 * tan(\Theta/2)$$

$$\Theta = 4tan^{-1}(f/D) = 111.183 \qquad (4.4)$$

*Where:*

*f: focal length*

*D: diameter*

While the beamwidth of the feeder antenna is a very critical parameter in feed design, other issues that affect the performance of the antenna have to be taken into consideration. Losses in the cables, connectors and the antenna structure and impedance mismatch between the antenna and the connecting cable will affect the overall performance of the system and have to be taken into consideration during design. Loss due to cable length can be reduced by using a short cable or not using any cable at all. Compared to industry manufactured antennas, loss in antenna structure of an amateur antenna can be higher because of inaccurate in measurements, quality of materials and devices used during construction. This problem can be minimized by either using ready made antennas. Impedance mismatch can be avoided or at least minimized by complying to the 50ohm input impedance in designing an antenna for Wi-Fi application.

In an effort to optimize the efficiency of the parabolic antenna, different types of feed antennas were considered and experimented with in this thesis.

**Biquad Feed**

Biquad feed is very popular among amateur communities and it was the first antenna experimented in this thesis. (see chapter 6). The biquad antenna in Figure 4.*2* was built using copper wires and ordinary data cd **.** It has two quad elements made of wire and a back reflector. The quad element is made from copper wire with a diameter of 2.5mm and the back reflector is an ordinary data cd. The size of each side of the quad elements should be close to one fourth of the wavelength of the signal [67]. Hence, for a frequency of 2.462MHZ each side was made 30.5mm.

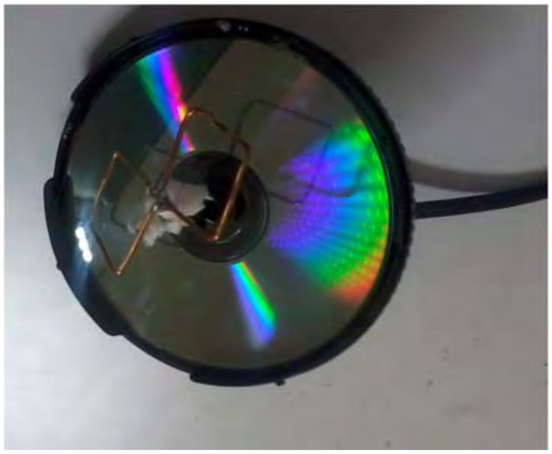


*Figure 4.17 Biquad antenna*

Biquad antenna has a beamwidth between 60 and 70 degrees [49]. The parabolic dish requires $111.183^0$ beamwidth feed (see equation 4.4). Hence, biquad antenna does not illuminate the parabolic reflector fully; hence the reflector is not working to its full capacity which in turn reduces the efficiency of the antenna.

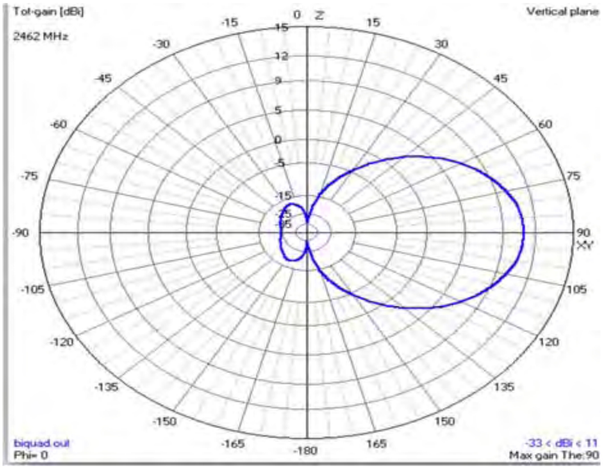


*Figure 4.18 Biquad radiation pattern with 4NEC2 software*

**Dipole Feed**

The dipole antenna used in this design is the coaxial dipole of the access point. Due to the small size of the whole access point compared to the parabolic dish it was possible to hanged it at the focus of the dish and there was no need for using coaxial cable, hence, there is no cable loss. The other advantage is that the input impedance of the antenna conforms to standard and there is no loss due to input impedance mismatch. The standard input impedance for Wi-Fi is 50 ohms [49].

On the other hand, dipole antennas have Omni-directional field pattern, as indicated in Figure 4.4. Hence, there is some spillover loss but that's the design trade-off considering all the advantages listed above.

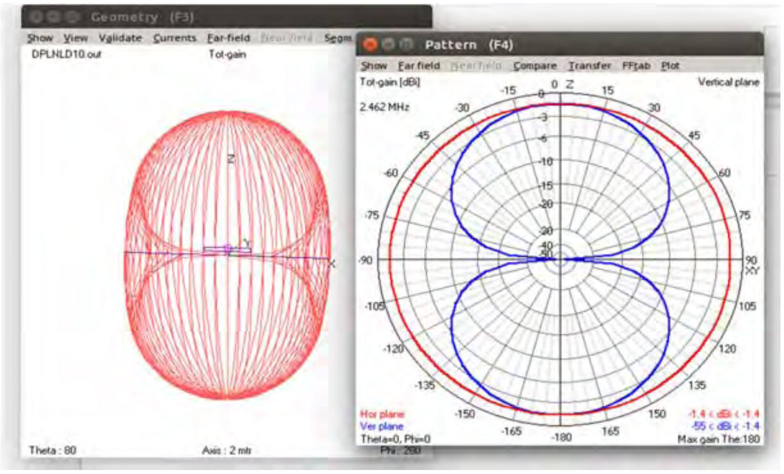


*Figure 4.19 Dipole antenna radiation pattern, generated in 4NEC2 software*

In this thesis IEEE802.11n is used and IEEE802.11n uses MIMO antennas. Hence, MIMO antenna is used as a feed to the parabolic antenna. This means that it is more than one feed mounted on the same dish and some loss due to non-single point feed is expected. One other important consideration in the case of MIMO feed is there is a possibility of skewing of the signal. But by adjusting the azimuth and elevation of the dishes it's possible to get good performance. The experiment conducted has also revealed that the performance is much better than without the reflector.

**Beamwidth of the parabolic dish**

As indicted by Equation *2.12*, it is possible to estimate the beamwidth of an antenna reasonably accurately as follows,

$$\Psi = 70\lambda/D = 14.945 \quad (4.5)$$

*Where:*

$\Psi$: *beamwidth*

$\lambda$: *wavelength*

$D$: *diameter*

This result shows that the selected antenna is a highly directional antenna and satisfies the design requirement. This result is also verified by antenna modeling software called NEC-2. (See Section 4.3)

## 4.3 Antenna Modeling and Analysis

With help of software like NEC-2 and Empire it was possible create a computer model of the feed antennas and analyze their characteristic. This software lets us create computer models of different kinds of antennas and generate their characteristics such as radiation pattern, gain, directivity, etc. This section is dedicated to modeling and analysis of parabolic antennas using software called NEC-2 software.

**NEC-2**

The Numerical Electromagnetic code (NEC-2) is a computer code for analyzing the electromagnetic response of an arbitrary structure consisting of wires and surfaces in free space or over a ground plane. This software lets us build the antenna structure from wires, generate different outputs including: current and charge density, electric or magnetic field in the vicinity of the structure and radiated fields. In addition, NEC-2 is free and very easy to use software. NEC is used to design the parabolic antenna in this thesis. The far field generated by this software clearly shows that the antenna is highly directional.

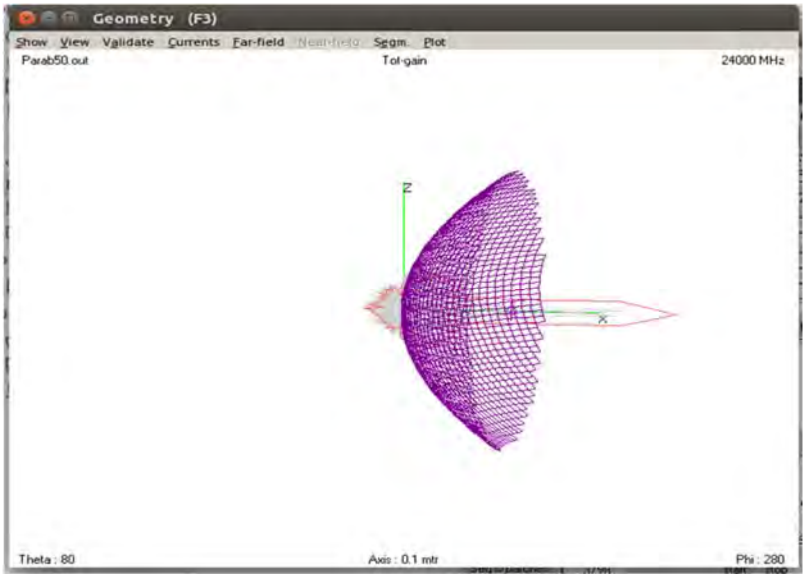


*Figure 4.20 3D parabolic antenna with radiation pattern designed with NEC software*

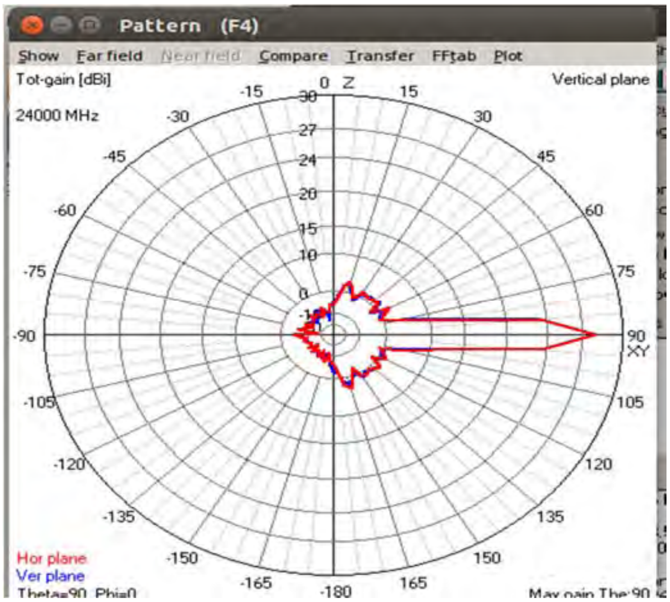


*Figure 4.21 Horizontal and Vertical Radiation pattern of parabolic antenna designed with NEC software*

The following table summarizes the specifications of the designed antenna.

| **Symbols and Equations** | **Description** | **Values** |
|---|---|---|
| C | Speed of light | 3x10$^{8}$m/s |
| F | Frequency | 2.462GHz |
| D | Diameter | 1.75m |
| D | Depth | 30cm |
| $\lambda = C/F$ | Wavelength | 0.122m |
| $f = D^2/16d$ | Focal length | 0.638m |
| $G = 10 \log_{10} \eta(\pi D/\lambda)^2$ | Maximum Gain of parabolic dish | 30.1dBi |
| f/D | Focal length to diameter ratio | 0.365 |
| $\Theta = 4 \tan^{-1} (f/D)$ | Beamwidth of feeder needed to properly illuminate parabolic dish | 111.183 |
| $\Psi=70\lambda/D$ | Beamwidth of parabolic dish | 14.945$^{0}$ |

*Table 4.2 Specification of antenna parameters*

# 5 Link planning and parameters optimizations

## 5.1 Link Budget Analysis

Link budget analysis is a critical tool for the planning and deployment of any wireless communication network. It is the accounting of all gains and losses from the transmitter through the medium to the receiver in a wireless communication system. The performance of a communication link depends on the transmitter power, available bandwidth, receiver sensitivity, and antenna gains, losses in antenna structures and cables and environmental conditions. Link budget can be used to calculate the wireless coverage range that can be achieved by using a given antenna or it help in figuring out the antenna gain required to give coverage at a specific distance.

Link budget analysis of an ideal channel can be conducted using Friis equation. An ideal channel is a channel free of objects that might absorb or reflect radio energy and the only loss is path loss due to distance between transmitter and receiver. An ideal channel is assumed if there is a line-of-sight between the transmitter and receiver.

Link budget analysis of a non line-of-sight link takes into consideration the effects of multi-path and signal fading. The link budget analysis of a non line-of-sight link is often conducted with the help of software such as Radiomobile. Radiomobile software uses both free space path loss and Longley-Rice propagation models for analyzing a link. If a radio path has more than 60% clearance of the First Fresnel zone, only free space loss is considered. But if the there is less than 60% clearance in the signal path, the link is non-line-sight and obstructions add losses are taken into consideration. Radiomobile uses the Longley-Rice propagation model in the case of non-line-of-sight links.

### 5.1.1 Link budget analysis using Friis equation

Friis equation is used to estimate the link performance of a line of sight links. This analysis tool is used to make a rough estimation of the gain of the antenna needed in the initial stage of the design in this thesis. This is because the consideration of this thesis is not designing an antenna for a specific site but a general purpose antenna that can give coverage at a maximum of 100km in an ideal channel. Had it being for a specific site, the site has to be selected first and with the help of Radiomobile the link is analyzed with a more accurate model such as Longley-Rice propagation model that takes that specific tertian profile into consideration. This analysis led to the selection of the type and dimension of the antenna. This design is described in detail the next few paragraphs.

The same antenna is used at transmitter and receiver, i.e, $G_t$=$G_r$=G; Assuming very short cables with negligible loss is used, i.e, $L_t$ = $L_r$ = 0, and the access points are set to operate at data rates of 11Mbps and 54Mbps, i.e, receiver sensitivity, $P_{sen}$s=-84dBm & $P_{sens}$ =-68dBm, respectively(see Table xx) and FM=fading margin= 15dBm,

$$L_{fs} = 20log(r) + 20log(f) + 32.4$$

$$L_{fs} = 20log(100) + 20log(2462) + 32.45 = 140.276dBm \qquad (5.1)$$

$$P_r = P_t - L_{fs} + G_r + G_t - L_t - L_r$$

$$G = -½\left(Pt\text{–} Pr - FM\text{–} Lfs - 0 - 0\right) \qquad (5.2)$$

*Where,*

*Input power: Pt = 27dmb*

*Radius: r = 100km*

*Frequency f = 2.462GHz*

The gain for 11Mpb is ,

$$G = -½\left(27\text{–} (-84) - 15\text{–} 140.276\right) = 22.128dB \qquad (5.3)$$

An the gain for 54Mbp is,

$$G = -½\left(27\text{–} (-68) - 15\text{–} 140.276\right) = 30.138dB \qquad (5.4)$$

This shows that if a clear line of sight is established between transmitter and receiver, an antenna with 30.138dB gain can give coverage at 100kms away.

But in reality loss in a communication system is inevitable and link design has to take these losses into consideration. Calculation of environmental losses needs the prior knowledge of the environment and it is very difficult. With the help of software like Radiomobile it is possible to estimate these losses.

| No | Data Rate (Mbs) | Receiver Sensitivity (dBm) |
|---|---|---|
| 1 | 135 | -65 |
| 2 | 65 | -65 |
| 3 | 54 | -68 |
| 4 | 11 | -84 |
| 5 | 6 | -88 |
| 6 | 1 | -90 |

*Table 5.3 Receiver Sensitivity at different data rates for Dragino ms14 [51]*

### 5.1.2 Link planning using Radiomobile

Link planning is the process of selecting appropriate sites for communication system deployment in for optimal operation. The condition of a wireless channel is a very important factor in determining how well a communication system functions. That is, channel with best line of sight has a better performance than one with a lot of obstructions. Through careful planning and site selection, it is possible to improve the performance a wireless system. Radiomobile software is important software that assists in site selection and performance prediction of a wireless link.

Selecting installation sites for our communication system takes several issues into consideration. From performance perspective, it is better if the link between the two antennas has least 60% Fresnel zone clearance. This type clearance is often achieved at higher altitude. Installing the communication a very high altitude may sometimes be challenging because of inaccessibility of such locations. Hence there should be a trade off in deciding how high the system needs to be mounted and convenience during installation and maintaining.

Once sites are selected, Radiomobile software is used to analyze the link. In order to analyze the link Radiomobile needs geographical data like latitude, longitude and altitude of the sites. This information can be easily generated by using android application called Wi-Fi Analyzer. Wi-Fi analyzer is a mobile application that uses GPS to generate our current locations latitude, longitude and altitude.

Radiomobile is a link planning tool that takes into considerations, terrain and elevation profile, grounding effects of earth’s curvature, tower heights, choice of antenna. Taking these factors into account, this software gives us important information such as,

- the distance between the links
- received signal level
- fading margin
- how the antennas should be pointed in azimuth, inclination and tilt angles

The following is the summary of steps that needs to be taken in selecting sites for installing the Wi-Fi based point-to-point communication system.

1. Select two convenient sites, preferably at higher altitude
2. Use Wi-Fi Analyzer to generate latitude, longitude and altitude of both sites
3. Using Radiomobile analyze the link between this sites
4. If the performance according to Radiomobile is acceptable, proceed to installation. However, if the performance is not acceptable, chose a different location and repeat the above steps, until a satisfactory result is achieved. The criterion for deciding if a link has acceptable performance not is often whether the link has acceptable fading margin or not.

As a prove of concept the link between Bishoftu city and Chaffe Donsa and a rural area called Chaffe Donsa is analysed using Radiomobile. In Bishoftu a location with latitude of $8.75^0$, longitude of $38.9833^0$ and altitude 2393m is selected. And in Chaffe Donsa a location with latitude: $8.75^0$, longitude of $38.9833^0$ and altitude 2406m is selected. The antenna heights at both sites are assumed to be 2m. The antennas used at both sites are taken to be same parabolic antennas designed in this thesis. (See Figure 5.1)

Radiomobile assumes fixed receiver sensitivity of -113.02dB. But the Dragino MS-14 access point used in this thesis has a different receiver sensitive value (see table 5.1 above). Hence, the fading margin has to be recalculated taking this correction as follows.

$$FM = P_t - P_r + G_t + G_r - L_f = 27 - (-68) + 60.2 - 177.32 = -21.12dB \qquad (5.6)$$

*Where:*

Psens=*-68dB,*

*Pt =27dBm,*

*Gt=Gr=30,*

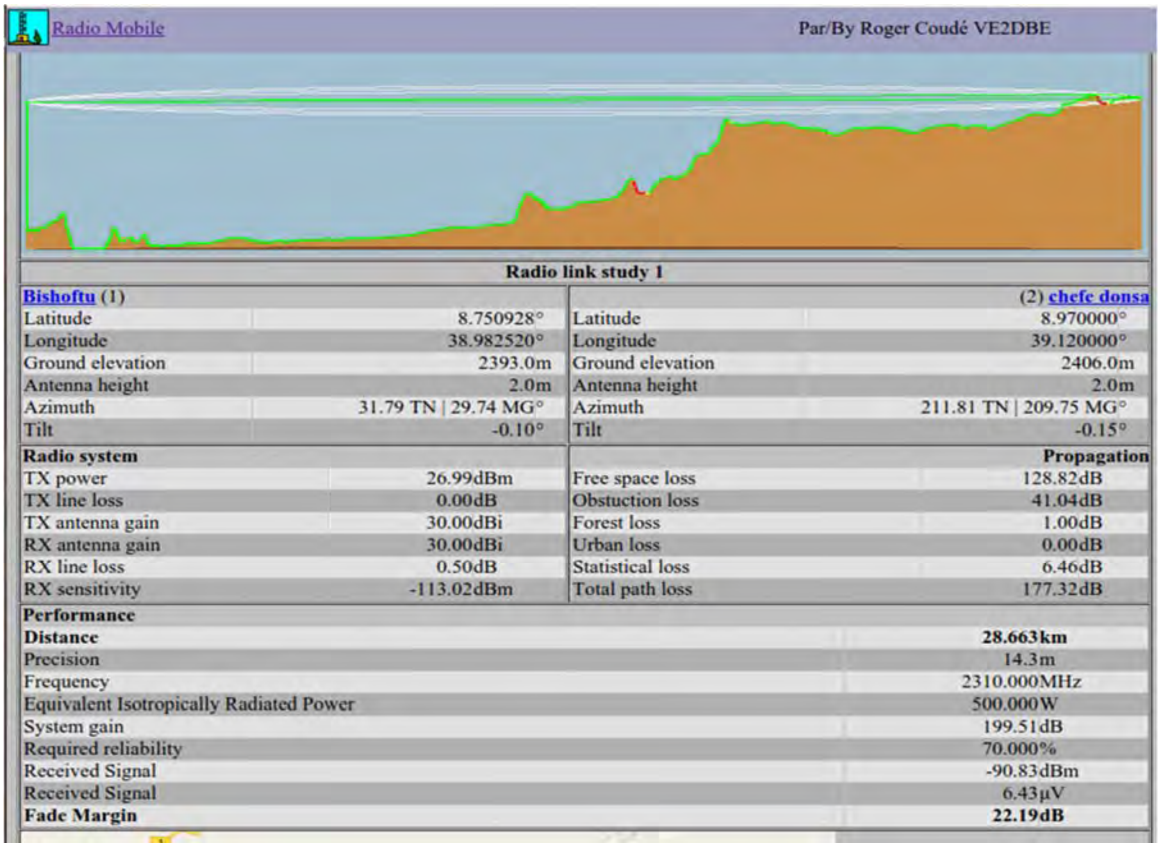
*Lf =177.32dB (from Figure 5.1)*

This result shows that the fading margin is less than minimum fading margin, which is often considered to be 15-20 dB. Hence, different sites should be selected or the height of the antenna should be increased.

In the second step two different sites were selected in both Bishoftu and Chaffe Donsa. In addition. Antenna height of of 5m and 10m are considered at Bishoftu and Chaffe Donsa sites respectively. In Bishoftu a location with latitude of $8.8^0$, longitude of $38.98252^0$ and altitude 2393m and in Chaffe Donsa a location with latitude: $8.97\ ^0$, longitude of $38.12^0$ and altitude 2406m were selected. And for these second sites~~-~~,

$$FM = P_t - P_r + G_t + G_r - L_f = 27 - (-68) + 60.2 - 159.08 = -3.88dB \qquad (5.7)$$

Comparing the two links (in Figure 5.1 and 5.2), it can be observed that the fading margin has improved from -21.12 to -3.88. This improvement is the result of better site selection with better clearance and higher antenna heights. This result can be further improved selecting even better sites. Hence, the decisions of were to install these communication systems needs physical site visit. In addition to selecting sites with better Fresnel zone clearance, site visit also helps to check the feasibility of this site for physical security, accessibly and access to power source.

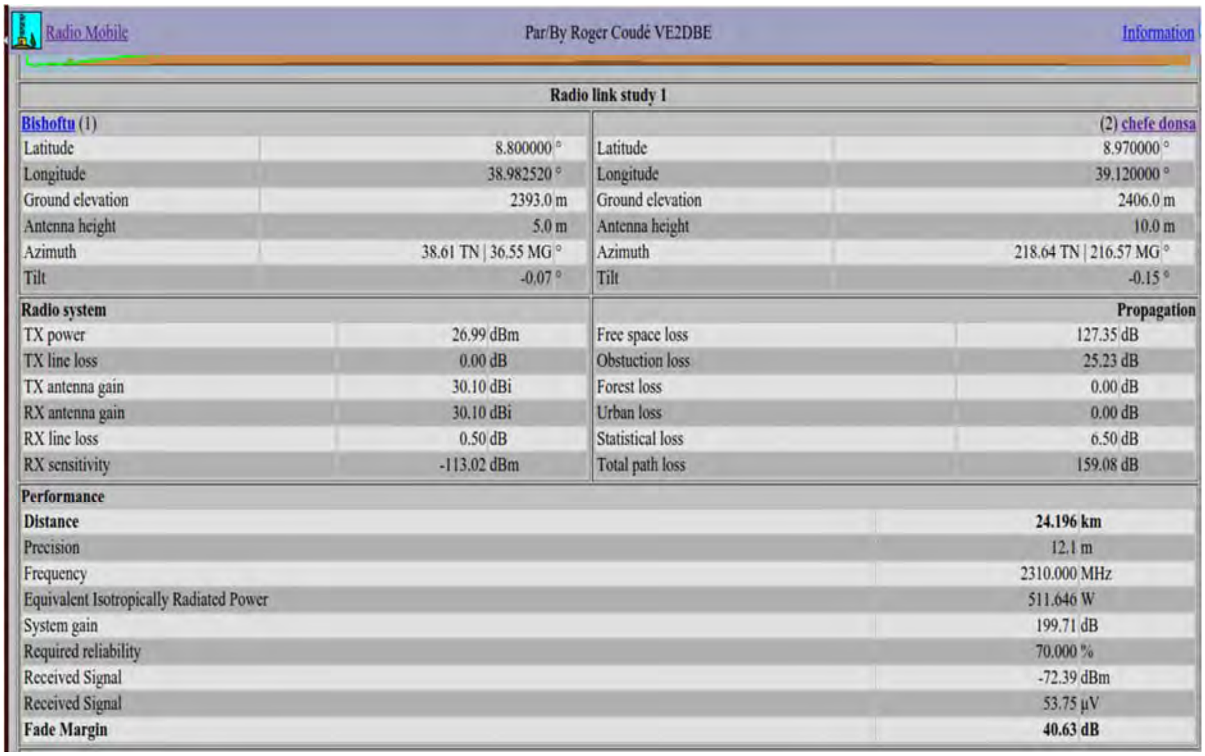


**Radio link study 1**

| **Bishoftu** (1) | | | (2) **chefe donsa** |
|---|---|---|---|
| Latitude | 8.750928° | Latitude | 8.970000° |
| Longitude | 38.982520° | Longitude | 39.120000° |
| Ground elevation | 2393.0m | Ground elevation | 2406.0m |
| Antenna height | 2.0m | Antenna height | 2.0m |
| Azimuth | 31.79 TN \| 29.74 MG° | Azimuth | 211.81 TN \| 209.75 MG° |
| Tilt | -0.10° | Tilt | -0.15° |
| **Radio system** | | | **Propagation** |
| TX power | 26.99dBm | Free space loss | 128.82dB |
| TX line loss | 0.00dB | Obstuction loss | 41.04dB |
| TX antenna gain | 30.00dBi | Forest loss | 1.00dB |
| RX antenna gain | 30.00dBi | Urban loss | 0.00dB |
| RX line loss | 0.50dB | Statistical loss | 6.46dB |
| RX sensitivity | -113.02dBm | Total path loss | 177.32dB |

| **Performance** | |
|---|---|
| **Distance** | **28.663km** |
| Precision | 14.3m |
| Frequency | 2310.000MHz |
| Equivalent Isotropically Radiated Power | 500.000W |
| System gain | 199.51dB |
| Required reliability | 70.000% |
| Received Signal | -90.83dBm |
| Received Signal | 6.43µV |
| **Fade Margin** | **22.19dB** |

Figure 5.1: Radiomobile link between Bishoftu and Chaffe Donsa



**Radio link study 1**

| **Bishoftu** (1) | | (2) **chefe donsa** | |
|---|---|---|---|
| Latitude | 8.800000 ° | Latitude | 8.970000 ° |
| Longitude | 38.982520 ° | Longitude | 39.120000 ° |
| Ground elevation | 2393.0 m | Ground elevation | 2406.0 m |
| Antenna height | 5.0 m | Antenna height | 10.0 m |
| Azimuth | 38.61 TN \| 36.55 MG ° | Azimuth | 218.64 TN \| 216.57 MG ° |
| Tilt | -0.07 ° | Tilt | -0.15 ° |

| **Radio system** | | **Propagation** | |
|---|---|---|---|
| TX power | 26.99 dBm | Free space loss | 127.35 dB |
| TX line loss | 0.00 dB | Obstuction loss | 25.23 dB |
| TX antenna gain | 30.10 dBi | Forest loss | 0.00 dB |
| RX antenna gain | 30.10 dBi | Urban loss | 0.00 dB |
| RX line loss | 0.50 dB | Statistical loss | 6.50 dB |
| RX sensitivity | -113.02 dBm | Total path loss | 159.08 dB |

| **Performance** | |
|---|---|
| **Distance** | **24.196 km** |
| Precision | 12.1 m |
| Frequency | 2310.000 MHz |
| Equivalent Isotropically Radiated Power | 511.646 W |
| System gain | 199.71 dB |
| Required reliability | 70.000 % |
| Received Signal | -72.39 dBm |
| Received Signal | 53.75 µV |
| **Fade Margin** | **40.63 dB** |

*Figure 5.22 Radiomobile link between Bishoftu and Chaffe Donsa, improved antenna height*

## 5.2 Parameter optimization

The MAC layer optimization is a very complex process and after several researches, trying different concepts, software and protocols, it was decided that for the scope of this thesis, to focus on changing the relevant IEEE802.11n parameters. As explained in background IEEE802.11n offers several features that we can use that enhances performance.

**Frequency and Channel width Selection**

The 2.4 GHz frequency band is chosen for this thesis. This is because it can travel longer and penetrate through objects better than the 5 GHz frequency. The interference from devices operating in the same band is kept to minimum because of the narrow beamwidth of the parabolic antenna.

As discussed earlier in section 2.1.4, by using channel bonding, it is possible to achieve slightly more than double the data rate. With 2.4 GHz frequency band one can only use one such channel. Channel 11 is selected for this design. That means the center frequency will be channel 11 and the band ranges from channel 7 to 13.

### Modulation and Coding Scheme (MCS) index

The experiments were conducted by first setting MCS index to 6, which means 64-QAM modulation, 400 guard interval and 135Mps bitrates maximum values are selected. However, depending on the channel condition, the system automatically increases or decreases the MCS index value. MCS index is set for Openwrt with the following command:

$$iwdevwlan0setbitratesmcs - 2.46$$

As seen in Section 3.2 for a very long distance timing parameters of the MAC layer such as CWmin, retry time need to be adjusted. The settings of these parameters followed some recommended values.

**ACKTimeout:** By increasing ACKTimeout, it is possible to reduce the probability of retransmitting of packets. Some hardware and firmware combinations allow changing this parameter. Openwrt allows adjusting ACKTimeout for IEEE802.11b/g protocols but not for IEEE802.11N for atheros devices. Hence, these parameters weren't implemented for the experiments expect with IEEE802.11G.

**Retry times:** Higher retry value for a frame has a positive influence on the throughput, which means no data is left undelivered but it leads to additional delay. But the optimal value is found to be one [47]. For computers, access points and routers with hardware that support it, Linux and Openwrt systems lets the retry value to be changed with the following command:

$$iwconfigwlan0retry1$$

**CWmin value:** Decreasing this value reduce the back-off time and so increasing the collision probability. And the optimal value is found to be 7 for long distance [7]. Openwrt allows the manipulation of this parameter as long as the hardware supports and for the experiments this value was set to the recommended value of 7.

# 6 Results and Conclusion

## 6.1 Experimental Setup

This section presents the different experiments conducted with the Wi-Fi based point-to-point connectivity testbed in order to evaluate, optimize and predict its performance. The testbed uses access points called Dragino MS14 with IoT mesh firmware [69]. IoT mesh firmware is an open source firmware based on OpenWrt. MS14 is based on Open hardware design and it has access point and microcontroller functionalities [69]. MS14 has LAN, WAN ports and 802.11 b/g/n Wi-Fi capabilities. MS14 has two radio paths, 2.5 dB chip antenna and external antenna for higher gain and directional requirement. Hence, the external antenna is replaced with the parabolic dish antenna made according to the design of this thesis.

For all the experiments the following parameters were considered.

- Power of 20dBm
- Center frequency of 2.462GHz (channel 11)

The first experiment was conducted to verify the advantage of using parabolic dishes antenna. This experiment was conducted with a spectrum analyzer and signal generator. The transmitter antenna was powered by signal generator, with a power of 20dBm and at frequency of 2.462GHz and the receiver antenna was connected to the signal generator with center frequency 2.462GHz, span 22MHz and start frequency 2.44 GHz. This experiment was conducted in a lab with the transmitter and receiver antennas 4meters apart.

*6.23 Experiment 1 Lab Setup*

From this experiment, it was possible to observer that by adjusting the antenna directions it was possible to get a received power of -31dBm at a 4m distance, while the theoretical is around -28dBm (see equation 6.1). This experiment is repeated without the parabolic reflectors and resulting in -45dBm received power. This result shows that by using parabolic dish antennas, received signal power has significantly improved, compared to using a dipole antenna.

The second experiment was conducted indoors on a corridor, 30 meters long. The purpose of this experiment is mainly comparison of the different feeders, IEEE802.11 modes and different channel width. This experiment is conducted with the following settings:

- IEEE802.11G mode,
- IEEE802.11N mode with no channel bonding (IEEE802.11N/ HT20),
- IEEE802.11N mode with channel bonding (IEEE802.11N/ HT40) with biquad feed and
- IEEE802.11N mode with channel bonding (IEEE802.11N/ HT40) with dipole feed, as shown in Table 6.1 below.

| **Selection** | **Throughput** | **Average signal** | **Maximum Observed Bitrate** |
|---|---|---|---|
| IEEE802.11G biquad | 18.4 Mps | -50 dBm | 54.0 Mps MCS 7 40Mhz |
| IEEE802.11N/HT40 biquad | 62.8 Mps | - 45 / - 47 dBm | 120 Mps MCS 5 40Mhz |
| IEEE802.11N/HT20 biquad | 43.4 Mps | - 48 dBm | 52.0 Mps MCS 5 |
| IEEE802.11N/HT40 dipole | 69.7-72.9 Mps | -44 / -46 dBm | 150.0 Mps MCS 7 40Mhz |

*Table 6.4 Performance comparison of different feed antennas and different modes*

As summarized in Table 6.1 above, from the measured received signal, throughput, data rate, it was possible to conclude that,

- IEEE802.11N has better performance than IEEE802.11G.
- By enabling channel bonding (HT40), the performance of the system improved significantly.
- Dipole feeders outperformed biquad feeders

Based on this observation, the dipole feeder and IEEE802.11N mode with channel bonding was selected for the rest of the experiments. These results also verified outstanding performance of the IEEE802.11n mode and its channel bonding feature.

The third experiment was conducted outdoors with antennas 128 meters apart, the longest suitable link found in AAIT premises. The purpose of these experiments was to test the effect of site selection and antenna positioning, performance as distances increases and comparison against theoretical and simulated results. At first the experiment was conducted with dipole antennas. Unfortunately, it wasn't possible to receive any signal during this trial. Then it was conducted with the new parabolic dish antenna and the performance of systems was good quite satisfactory during this second trail. By further improving the alignments of the two antennas, it was possible to receiver better received power. (See Table 6.1)

During this third experiment, it was possible to observer that, with the antennas 128 meters apart, at beginning of the experiment it wasn't possible to get any signal because of bad orientation. Then by continuously adjusting the orientation of the two antennas, the received power improved from -81dB to -72dB, while data rate improved from 2.7Mps to 32.8Mps. This result shows that link planning is a big part of long distance Wi-Fi implementation and that antenna height and orientation are very critical to this process.

*Figure 6.24 IEE802.11 long distance point-to-point testbed, AAIT premises*

| Distance(m) | Trails | Throughput (Mps) | Tx Data Rate (Mps) | Rx Data Rate(Mps) | Received Power (dBm) |
|---|---|---|---|---|---|
| 5 | | **77.9** | **150,MCS 7** | **135,MCS 5** | **-38** |
| 28 | | **37.8** | **135,MCS 7** | **120,MCS 5** | **-61** |
| 83 | 1st | 28.7 | 40.5, MCS 2 | 90.0, MCS 4 | -73 |
| | **2nd** | **35.3** | **81,MCS 4** | **120,MCS 5** | **-68** |
| **128** | 1st | 2.7 | 14.4, MCS 1 | 6.5, MCS 0 | -81 |
| | 2nd | 26.6 | 54.0, MCS 3 | 60.0, MCS 3 | -75 |
| | **3rd** | **32.8** | **60,MCS 3** | **60,MCS 3** | **-72** |

*Table 6.5 Summary of outdoor experiment conducted in AAIT premises*

Table 6.2 also shows that, as the signal condition degrades with distance or due to environmental condition, the system automatically sets the MCS value; hence data rate to lower value.

In order to observe the the systems' performance as distance increases, the third experiment is repeated with the antennas at 5, 28, and 83 meters apart .Based on table 6.2, diagram 6.1 was plot to to observe this system performance and distance relationship graphically. It shows the relationship between throughput, received power and Tx and Rx data rates and distance.

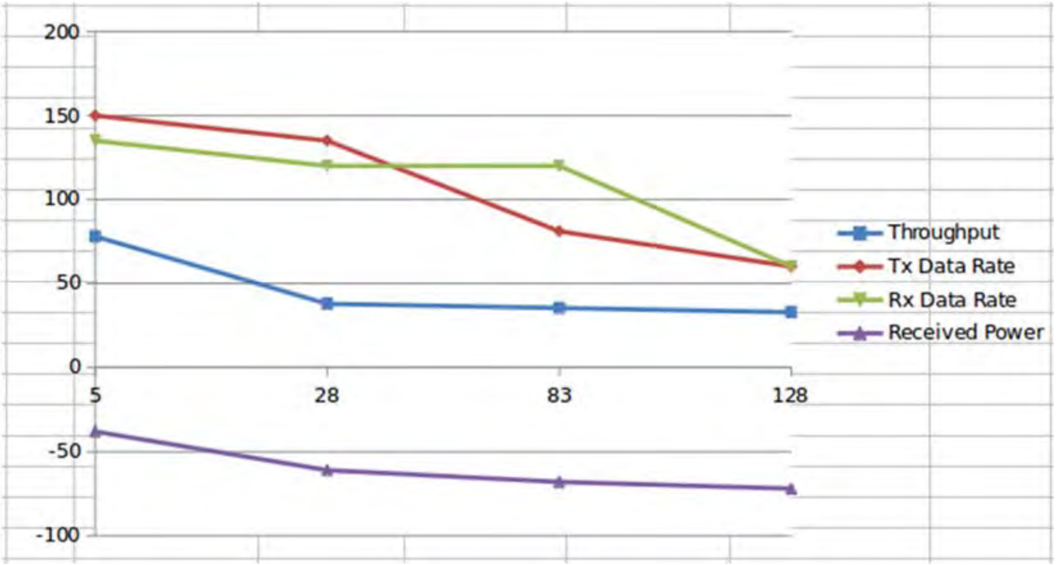


*Diagram 6.1 Throughput, Tx and Rx data rate and Received Signal VS distance plot*

The diagram shows that all throughput, received power and Tx and Rx data rates decrease with distance, which means overall performance of the system decreases with distance. Diagram 6.1 also shows that change in throughput per unit distance is very low as well. The first result, between 5 and 28 is an exception because this experiment was restricted to a less than ideal environment was there were several obstructs beyond 5 meters. That is why the throughput is very good at 5m but dropped very quickly beyond that but they change with distance was very low beyond that point.

This shows that site selection is critical to designing a PTP long distance wireless communication link. That is if there is a Line-of-Sight between the transmitter and receiver antennas, signal power loss due to environment will be minimized. Even though this experiment is limited to a small area with less, the actually rural implementation over large area offers opportunity to select sites with better Fresnel zone clearance. The experiments were limited in AAIT premises because there is yet no regulation in this country allowing a license free band to be used for long distance communication. This regulation issue needs to be dealt with in the future.

## 6.2 Conclusion

The present thesis was conduct on IEEE802.11n-based wireless solution for long distance point-to point links to provide Internet service for rural areas of Ethiopia. Specifically, it is aimed at the design, implementation and evaluation of a testbed based on IEEE802.11n standard. The testbed uses high gain parabolic antenna with MIMO feed. To attain the objectives of the thesis, several experiments were conducted in Addis Ababa Institute of Technology (AAIT) premises. From these experiments, it was possible to observer that by using high gain directional antennas, exploiting the some features of the IEEE802.11n standard and through exhaustive site selection process, IEEE802.11 technologies can be used for long distance point-to-point connectivity.

The work presented in this thesis meets the objectives. A wireless networking technology was designed and built that can be used to provide economical networking connectivity to remote areas. It was started by understanding the constraints imposed by the wireless long-distance, point-to-point communication. Then a pair parabolic dish antenna was designed and built and few MAC layer modifications were made to meet the requirements of long-distance communication. As link planning is a very critical process to the planning and implementation of this Wi-Fi-based point-to-point communication system, besides implementing and conducting several experiments on the testbed, this thesis work also tried to lay groundwork for a real world deployment process. This involves using Radiomobile software to plan the deployment sites and estimate the performance of the system. In conclusion, the work presented in this thesis shows that IEEE802.11 based point-to-point is a technologically viable and economical feasible solution to rural connectivity in Ethiopia.

## 6.3 Future work

The work done in this thesis is the first real approach in implementing long distance point-to-point connectivity testbed for rural areas of Ethiopia. The next logical step toward implementation should be getting the appropriate permission to use license free band. To be able to implement and test this technology at even further distance, it is necessary to change the MAC protocol from CSMA/CA to TDMA MAC. There are few propriety solutions but this approach limits the research opportunity for amateurs and students for they may be expensive and may not be compatible with a lot of devices. An open source solution would be a very good alternative. Hence, programming of a TDMA MAC protocol that works for all hardware and is compatible with open source firmwares like openwrt will be a great step towards the success of such a project.

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