EXTENDING IEEE 802.11 (Wi-Fi) RANGE:

EXPERIMENTAL VALIDATION AND FUNDAMENTAL PERFORMANCE LIMITS DETERMINATION

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2014

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EE300-0010/12

A thesis submitted to Pan African University Institute of Basic Sciences Innovation and Technology in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering.

2014

DECLARATION

This thesis is my original work and has not been submitted for award of a degree in any other university.

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DEDICATION

To my beautiful wife, Anne Sheryl, my lovely kids Teila Togore and Emmanuel Kariis, you inspire me to rise early and pray for you every morning.

To my *mama*, Gladys Muriis, your dreams still linger in my heart. To late *baba*, Moses Muriis, your love for me is still fresh, you put me on your shoulders, and I see where you didn’t see.

ACKNOWLEDGEMENT

This research work could not be done by me alone. There are so many people that made this work a success, and without them, this work would not have materialized. Since I cannot mention each one of them, I acknowledge that, in their unique contributions they became part of this dream that is now turning to a reality, and I thank them much.

In addition, my sincere gratitude goes to my supervisors Professor Vitalice K. Oduol and Dr. Philip K. Langat for their encouragement, insightful comments, hard questions and immense knowledge that enabled me to carry out this research. Their willingness to spare time and discuss my progress is worth my heartfelt appreciation.

I thank my fellow colleagues: Ombati, Hailu, Bereket, Solomon and the entire Electrical class of 2012 for their enthusiasm, corporation and synergy to assist one another complete this course. I will forever be indebted to them. My fellow researchers: Waitara, Karugu, Kamindu, Omondi, Ochieng, Nyangau, Amdany, Munyao, Kinyua and Mwangi, their great dedication, tireless endeavors and commitment to this work, during those freezing and rainy days on mountain tops can never be forgotten. They made this work be and I will forever be grateful.

To the entire PAUISTI fraternity, I owe them this achievement. From the flawless dissemination of research funds, which we so much needed, to great trainings and workshops that you organized to help us finish our research in time, I can only say, God bless them abundantly. Finally, I give glory to the almighty God, without whose strength, I would not have managed to come this far.

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ACRONYMS

3G - third generation of mobile telecommunication technology standard

ASL – Above Sea Level

BPSK – Binary Phase Shift Keying

CRC – Cyclic Redundancy Check

CSMA/CA – Carrier Sense Multiple Access/ Collision Avoidance

DSL – Digital Subscriber Line

DSSS - Direct Sequence Spread Spectrum

EVDO - Enhanced Voice-Data Optimized

IEEE – Institute of Electrical and Electronics Engineers

FHSS - Frequency-Hopping Spread-Spectrum

GI – Guard Interval

IITK – Indian Institute of Technology, Kanpur

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 Scheme

Mbps - Mega Bits per Second

MB/s - Mega Bytes per Second

MHz - Mega Hertz

MIMO - Multiple Input multiple Output

MIT - Massachusetts Institute of Technology

OSI – Open Systems Interconnection

PDAs – Personal Digital Assistant(s)

RTT - Round-Trip Time

SISO – Single Input Single Output

TCP - Transmission Control Protocol

TDMA – Time Division Multiple Access

TFL – Transmitter Feeder Loss

TIER – Technology and Infrastructure for Emerging Regions

UNII – Unlicensed National Information Infrastructure

Wi-Fi - Wireless Fidelity

WiMAX – Worldwide Interoperability for Microwave Access

W-CDMA – Wideband Code Division Multiple Access

WLAN – Wireless Local Area Network

DEFINITION OF TERMS

Digital Gangetic Plains (DGP): is a set of projects based in India that utilizes the Wi-Fi over long distance point-to-point links

DSL: was originally digital subscriber loop but now refers to as Digital Subscriber Line is a family of technologies that provide Internet access by transmitting digital data using a local telephone network which uses the public switched telephone network.

Guard Interval (GI): represents a short pause that separates successive packet transmissions

ISM Band: radio frequency band reserved internationally for the use for industrial, scientific and medical purposes

Last Mile: The final access network that connects to or reaches the customer or end users.

Multiple Input multiple Output – defines an antenna configuration where there are more than one antenna at either end of the radio link

Node: is an Access Point or a client infrastructure, complete with antenna and a Wi-Fi radio used to form one end of a communication link

Round-Trip Time (RTT) - also called round-trip delay, is the time required for a signal pulse or packet to travel from a specific source to a specific destination and back again

Rural Area: Is a large and isolated area of an open country (in reference to open fields and not forests), often with low population density.

Single Input Single Output: defines an antenna configuration where there is only one antenna at either end of the radio link

UNII: radio frequency spectrum between 5.125-5.825GHz reserved for use by IEEE-802.11 devices

Urban Area: Is an area with an increased density of human–created structures and higher population density in comparison to the areas surrounding it. This definition includes cities, municipalities, town councils and urban councils.

ABSTRACT

This thesis demonstrates the use of UNII-3 (Wi-Fi) frequencies, 5.725 - 5.825GHz, in setting up long distance point-to-point links, capable of providing broadband Internet in rural areas. Although this frequency band was initially intended for indoor wireless local area networks (WLAN), its lack of licensing and inexpensive off-shelf networking devices has prompted many researchers and technology enthusiasts to extend its use to outdoor settings. This work seeks to experimentally verify that Wi-Fi radios whose MAC protocol is based on TDMA channel access mechanism overcome the fundamental challenges associated with CSMA based radios when used to implement long distance point-to-point links. A long distance point-to-point test-bed model that uses high-gain directional antennas, which may be replicated to provide broadband Internet access in rural areas particularly in developing countries, is developed. Five such long-distance point-to-point links of varying distances have been set up, the longest distance being 24.3 kilometers.

Performance characteristics of such links are carried out, and their behavior analyzed at varying link parameters. This thesis seeks to determine what the best link parameters (channel width, Modulation and Coding Scheme (MCS), packet size and transmit power) are for links of varying lengths as well as the effect of each on the achievable throughput. Further, the interrelationship of throughput and packet loss is sought.

The results obtained confirm that a TDMA based Wi-Fi radios are able to reliably deliver high throughput in long distance point-to-point links, the only mandatory

requirement being a clear line of sight with at least 60% Fresnel zone clearance. Channel bonding enables utilization of 40MHz wide channels and when tested over long distance point-to-point links it delivers high throughput, as high as 100Mbps. This performance is superior in comparison to the 20MHz-wide channels when used over the same scenario, of long distance point-to-point links.

Higher modulations and coding schemes indices, MCS 13, 14 and 15, deliver the highest throughput in comparison to the lower indices; their performance, however, begin to crumble with increase in distance. MCS 14 and 15 perform abysmally in links of lengths exceeding 10km. It was expected that the links would withstand external Wi-Fi interference, by shifting the channel of use dynamically. However, it is observed that, the link performance in the presence of an interferer is inferior, by far, to when there is no interference.

CHAPTER ONE

1 INTRODUCTION

1.1 Background

In the recent past, the information revolution has experienced accelerated growth particularly as a result of technological advancements. The ease in which communication takes place between individuals and communities in distant localities has resulted in what is commonly known as ‘global village’. Similar trends are evident in Kenya and efforts have been made that are aimed at transforming Kenya into a knowledge-based economy. However, not all regions have equally benefitted from this growth. There is need to provide a high-capacity nationwide broadband network for maximum utilization of the benefits that accrue from such advancement in communication technologies. Kenya has an established strategic blue-print, Vision 2030, which recognizes the empowering role of Information Communication Technologies in both social and economic growth. The Vision 2030 anchors some of its key objectives and aspirations upon the success in rolling out, affordability and ease of access to broadband technologies.

Any community that enjoys the fruits of broadband access has the potential of reaping great social economic benefits. Some of these benefits may be in form of growth in opportunities of investments, ease of accessing government services, improved service delivery to the peoples, improved quality of education, higher capacities of wealth creation among others.

Broadband can be defined as Internet connectivity that is always on and that provides high capacity for data access. The term broadband is often associated with a wide range of technologies that enable high-speed transmission of data. A more definitive meaning of broadband requires the inclusion of technical parameters that can be quantized. For the purposes of this work, speed, quality of service and rate of data flow in the network (often referred to as bandwidth) are considered as the primary parameters used to define broadband. This definition is nonetheless taken in cognizance of the fact that fast-changing rate in which technologies become obsolete may result in review of the minimum threshold values that qualify the term, broadband. The broadband definition in Kenya for the period 2013-2017 is a '… *connectivity that is always-on and that delivers a minimum of 5mbps to homes and businesses for high speed access to voice, data, video and applications for development*.'[1]

Broadband access, on another perspective, has not gone beyond urban population. Most rural areas in the developing countries have not received the full benefits of information revolution that has been embraced by the urban population in both the developing and developed countries. The telecommunication service providers have not served most rural localities with broadband Internet access, due to their uneconomical disadvantages. These areas are therefore in dire need for low-cost connectivity solutions and in particular, broadband Internet access. Presently, only a mere 1.8% of Kenyan geographic space is served with broadband access[2]. The rest of the general public either use the traditional dial-up Internet access, intermittent mobile broadband Internet access, both provided by telecommunication providers or do not access Internet at all. With the growing need for access to Internet, a new approach needs to be advanced to provide ubiquitous and superior broadband services. Provision of quality broadband network within the entire country will evidently improve the way business is transacted, the way people associate and collaborate as well as define completely new ways of learning and living altogether.

Quite a number of technologies exist in which broadband access is provided today; these include fiber, satellite, fixed wireless (WiMAX and Wi-Fi), mobile broadband (occurring in various variants as 3G, W-CDMA, LTE, EVDO, etc) as well as broadband over power lines. Each of these technologies has its own merits, demerits, outlay of setup and running costs, and situations in which it is best suited. Some situations are best served by fiber-optic cables or wired copper lines whereas others are served best by wireless technologies. The former two options work best within cities and urban areas. Remote areas and distant towns often require wireless communication technologies to bridge the digital divide. Recently, there is a rising rush by Internet service providers to tap in the wireless markets.

Table 1-1: Kenya Broadband subscriptions

	Kenya Broadband subscriptions		
Financial Year	**2010/11**	**2011/12**	**2012/13**
Fixed Broadband (DSL, Satellite and Fiber)	6,552	35,265	64,850
Wireless (WIMAX)	5,646	17,282	18,634
Mobile	108,928	674,255	1,315,339
Total	**121,126**	**726,802**	**1,398,823**

The table 1-1 shows that the total broadband subscription, in Kenya, for the period 2012/13 stood at 3.54% compared to 1.84% recorded[1] for the 2011/12 period. The wireless broadband penetration for this period (2012/13) stood at 3.38% which is below the Africa's average penetration that stood at 7.1% during the same period [2].

The highlighted broadband technologies are inadequate to serve the growing demand for broadband access. They are either limited by distance, cost or capacity. Fiber and wired lines provide very high capacity but their setup costs prevail over any profitability that any business

[1] These percentage figures are approximations in comparison to the total population in Kenya of 40Million

may want to pursue. On the contrary, the wireless systems are capable of traversing great distances to remote areas.

It is of the essence that researchers seek to come up with better technologies to serve the broadband Internet access needs, particularly to serve the rural areas. New and better ways of providing broadband Internet to the mass population needs to be sought. An all-encompassing networking solution is required to provide broadband to the under-served populations.

The IEEE-802.11 (Wi-Fi) family of wireless technologies has shown tremendous acceptance as well as growth since its inception. While it was designed for indoor use, short range access and primarily as a last-hop wireless access, its wide acceptance has motivated its use beyond its originally intended use. The typical range of Wi-Fi spans up to a hundred meters from the access point to station. However, it comes with a number of advantages such as open standard and interoperability, which enables it to enjoy competitive mass production and thereby widespread acceptance.

In view of foregoing, IEEE-802.11 (Wi-Fi) has been anticipated as being affordable and acceptable alternative to provide broadband access to rural areas[3]. There is evidence of ongoing research on the feasibility of using Wi-Fi over long distance point-to-point links; the Ashwani, the Ak-shaya, Aravind Eye Care System (www.aravind.org) and Digital Gangetic Plains (DGP) projects, all in India[4][5]. The Wi-Fi links, in 2.4GHz ISM band, are used in the above-mentioned projects to realize long distance point-to-point network deployments ranging up to a hundred kilometers. Figure 1-1 illustrates the envisaged network model intended for providing broadband access in rural areas. This model is not specific on what frequencies must be used. It generally depicts the envisaged scenario of distant villages and public utilities receiving broadband Internet access from a neighboring town using long distance point-to-point links. The performance of this model at UNII-3 frequencies is the subject of this work.

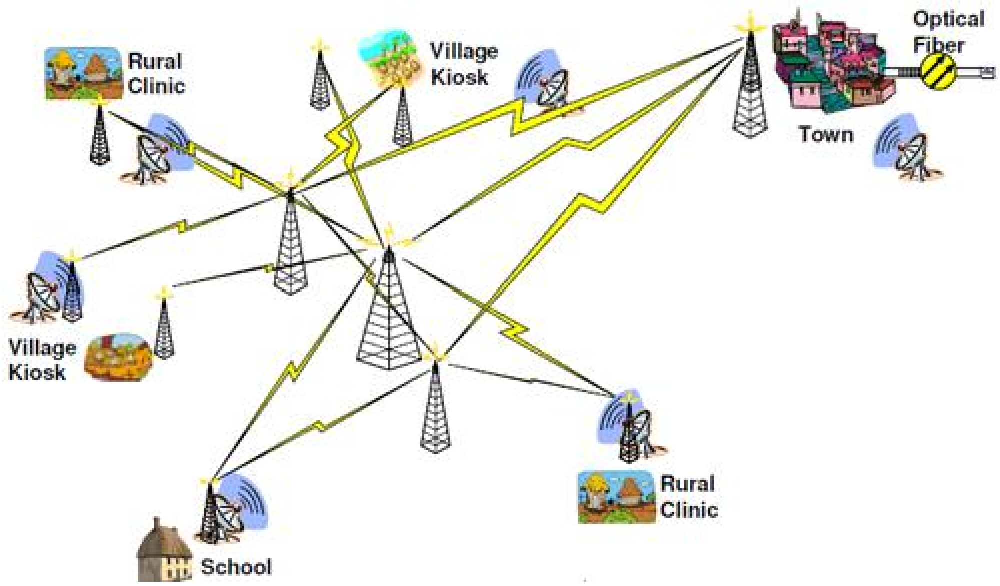

Figure 1-1: The Envisaged Network Model

1.2 Problem statement

Most proprietary Wi-Fi radios come with the 802.11 MAC Protocol that is based on CSMA/CA. This protocol is contention based and employs link-level mechanism which results in poor bandwidth utilization for long distance links as observed by Patra et al.[6]. In long distance point-to-point links, the packets take long to travel and the adjacent nodes are not able to detect the other node is transmitting, and therefore it goes ahead to transmit. When the two nodes transmit at the same time, the collisions occur and this results in throughput degradation. High and variable packet losses are experienced in the long distance Wi-Fi based links due to external Wi-Fi interference[7].

Significant research has been done in an effort to overcome these challenges [6], most of them proposing the replacement of the CSMA/CA with TDMA based MAC protocol, in the Wi-Fi radios for use in the long distance point–to-point communication links. This proposal has motivated a number of manufacturers to design and implement proprietary 802.11 non-standard Wi-Fi devices that implement TDMA-based MAC protocols for use in long distance links. *AirMAX*™ from Ubiquiti Networks and *Nstreme*™ from Mikrotik Inc. are some of the proprietary TDMA MAC protocols implemented on Wi-Fi radios that are intended for long distance networks.

The 802.11 non-standard protocols and equipments, such as TDMA-based MAC protocol, seek to extend the Wi-Fi standard 802.11, by implementing proprietary features. Since they do not strictly adhere to any design specifications or standards, the manufacturers implement them the best way they see how. There is a need to evaluate the performance of the TDMA MAC approach in implementing the long distance point-to-point links particularly when using the Wi-Fi frequencies and standards. Once the performance is observed to have merits, a recommendation to the *IEEE Standards Association* should be made so that an amendment to the 802.11 standard may be initiated to standardize the TDMA approach on the Wi-Fi radios for use in long distance links set-up. Once the standardization is complete, the *Wi-Fi Alliance* will be in a position to certify the Wi-Fi radios from different manufacturers to ensure their conformity to the standards of interoperability and compatibility to the existing 802.11 wireless networking devices.

A few test-beds have been implemented in the 2.4GHz band and reliable links, with TCP throughput as high as 7.6Mbps have been achieved[8]. However, some of these links have experienced high packet losses and network latency as well as persistent high levels of interference because of the crowding in the ISM band[8]. The 5.8GHz range of frequencies, UNII-3 band, is associated with stricter requirement for clear line of sight and very little work has been done to characterize the performance of such links. To the best of author's knowledge, no consistent and scientific study has been done to characterize the performance of TDMA based Wi-Fi radios in the 5.8GHz band. This thesis, attempts to characterize the performance of TDMA based Wi-Fi radios, with an aim of determining its usability in establishing long distance point-to-point links in the UNII-3 frequency band.

1.3 Research questions

1) How and to what extent does varying the link length, packet size, transmission rate, transmit power affect the achievable throughput?

2) To what extent is the external Wi-Fi Interference detrimental to the link quality?

3) Are there identifiable causes of abysmal performance or packet losses that may degrade the achievable throughput on UNII-3 (Wi-Fi) based long distance point-to-point links?

4) Is there any correlation between packet loss and throughput? Is there a set of parameters that maximizes achievable throughput with respect to link distance?

1.4 Objectives

1.4.1 Main Objective

To experimentally validate the usability of the UNII-3 (Wi-Fi) frequencies, 5.725-5.825GHz, in establishing long distance point-to-point links, quantify the links throughput and thereby characterise its variation with respect to different link parameters and varying link lengths.

1.4.2 Specific Objectives

1) To investigate how and to what extent the link length, channel width, packet size, transmission rate, and transmit power affect the achievable throughput.

2) To evaluate the performance of the Wi-Fi based point-to-point in the presence of external Wi-Fi interference.

3) To establish any possible causes of abysmal performance or packet losses that may degrade the achievable throughput on UNII-3 (Wi-Fi) based long distance point-to-point links.

4) To investigate the effect of varying packet size, channel width, transmission rate and transmit power on the observed packet losses and thereby determine a set of parameters that result in maximum throughput.

1.5 Justification

Performance of long distance UNII-3-based links is unknown and no scientific findings are known to exist. Such performance characteristics are necessary in order to guide any possible deployments without repeatedly falling in the same pitfalls. A predictive model is needed, such that expected link performance can be evaluated even before setting up the links, which is by itself an expensive affair, leave alone being time consuming. As already highlighted, UNII-3 frequency band offers a potential of delivering broadband Internet access to rural and under-served areas, by riding on its unlicensed and inexpensive Wi-Fi technology. Therefore, characterizing its performance at different link lengths, conditions and varying parameter settings offer an opportunity to tell what works and what does not.

1.6 Thesis contributions

To the best of the authors' knowledge, no consistent and systematic study has been done in regard to the use of TDMA based Wi-Fi radios, in the UNII-3 frequency band, in establishing long distance point-to-point links. Further, no known performance characteristics are available of such links. While TDMA based Wi-Fi radios are in the market, one cannot tell what to expect their performance to be. No predictive models exist that may guide future deployments of point-to-point links capable of providing broadband Internet access in rural areas. In this regard therefore, the contributions of this thesis are four-fold:

1) It verifies that UNII-3 Wi-Fi frequencies, despite their stringent requirement for line of sight, are capable of delivering high bandwidth, 100+Mbps, point-to-point links in rural areas. It confirms that TDMA based MAC protocol overcomes the challenges of delayed acknowledgements and link level contention based mechanisms, associated with the CSMA/CA based MAC protocol in establishing long distance links.
2) It demonstrates that different parameter settings are required for links of varying lengths. While higher MCS indices are capable of delivering the highest bandwidth links, they perform dismally with increased distances and the lower indices supersede them in these scenario. The lower indices, that is MCS 0,1 and 2 in the lower MCS set and MCS 8, 9, and 10 are least affected by distance, while the higher ones, MCS 6,7 and MCS 14,15 are the most affected. The links follow strictly the link budget requirements and there exists a minimum transmit power below which link cannot be established. Chanel bonding does indeed improve the performance of the long distance links, just as it performs in the indoor settings. However, there is an upper distance limit, when lower channel widths outdo the wider channels.

3) It reveals that the link peak throughput is associated with close to zero packet losses, contrary to the findings of [17] .There is no significant packet losses on the links, as long as the links meet the minimum requirements spelt out in 2) above. High packet losses arise only when the required threshold limits are breached.
4) It reveals that, in the presence of external Wi-Fi interference, these long distance links perform better when they are on a fixed channel than when they are shifting the channels dynamically, contrary to expectations.

1.7 Organization of the Thesis

The works of other researchers in this field is discussed at length in chapter two.An overview of the 802.11 standards is highlighted as well as its advancements. Further, the limitations of the MAC protocol in long distance Wi-Fi application are pointed out. A design scenario is presented in chapter three, creating a picture of the test-bed model and its possible application. An outline of the requirements and consideration that are put in place when setting up long distance Wi-Fi links is discussed in length. A detailed description of the steps followed in the establishment of the long distance Wi-Fi test-beds is then made. The design considerations highlighted in chapter two are described in terms of how well they are met and the extent in which they affect links establishment. Chapter four describes the results and their significance to the study while chapter five presents the conclusions and recommendation.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Background

Point-to-point links may be established on licensed or unlicensed microwave frequencies. The licensing refers to the requirement by a national regulatory authority to get approval before any deployment of a wireless networking infrastructure at a defined frequency bands. The frequency bands that do not require licensing are 900MHz, 2.4GHz, 5.2-5.8GHz, 24GHz and 60GHz. On the other hand, most of the remaining frequency bands are reserved for specified applications and one must get approval, after application and paying requisite licensing fees, to erect wireless communication infrastructure.

The licensing fees, payable annually, posses as a hindrance to most telecommunication service providers in their attempt to provide broadband Internet access to rural areas. This is because; the rural population has a lower purchasing power and their slow uptake of technology renders them as an unprofitable market segment. The end result has been the isolation of the rural population in the service delivery that requires use of Internet access such as government services, Internet banking, and social media among others.

The unlicensed spectra may provide the needed alternative in providing broadband Internet access to rural areas. Since no prior licensing is required, a community may set up a point-to-point microwave links in the unlicensed frequency bands, connecting an Internet-backbone in an urban area to the connection-less rural area.

2.2 The typical design scenario

The envisaged network model uses the unlicensed UNII-3 frequencies to establish long distance point-to-point links. These links are used to extend the Internet ‘hotspot’ from urban localities to the distant rural areas. Most of the rural areas are often a few kilometers (5-30km) from the urban areas, indicating that a broadband Internet access can be tapped from an urban area and channeled to the neighboring rural areas using few point-to-point links and then distributed to the entire area using CSMA/CA Wi-Fi technologies as depicted in figure 2-1 below.

The typical design scenario, in figure 2-1, is represented by the following:

1. Internet Backbone provided by ISP (in an urban area)
2. ISP access point (in an urban area)
3. A high directional antenna to establish point-to-point link (in an urban area)
4. A high directional antenna to establish point-to-point link (in a rural area)

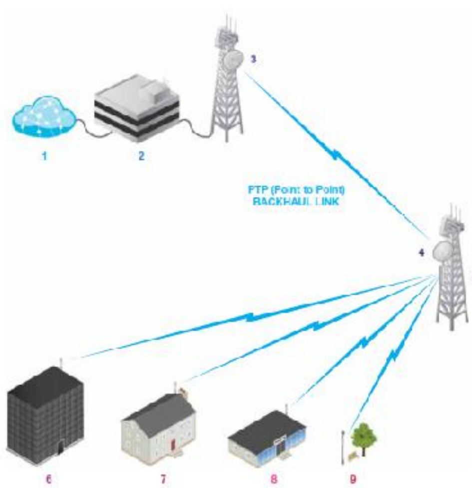

Figure 2-1: Typical point-to-point Broadband access

5. An antenna mast (in a rural/remote area) from which the Internet is distributed as point to multi point broadband access

6. A corporate building (in a remote/rural area)

7. A house (in a remote/rural area)

8. A business (in a remote/rural area)

9. A small village mast with omni-directional antenna acting as a wireless hotspot

There is evidence of ongoing research on the feasibility of using Wi-Fi over long distance point-to-point links; the Ashwani, the Ak-shaya, Aravind Eye Care System (www.aravind.org) and Digital Gangetic Plains (DGP) projects all in India[3][4]. The 2.4GHz band of frequencies has been used extensively in the above-mentioned projects to realize long distance point-to-point network deployments, ranging up to a hundreds of kilometers. Some of these deployments make use of 802.11 Wi-Fi radios whose data link layer has been modified from the CSMA/CA based MAC protocol to the TDMA based protocols. Therefore, the 2.4GHz based long distance point-to-point links has considerable leverage over the 5.8GHz links in terms of the number of experimental studies and documentation of performance characteristics [9][8][6].

Two primary Wi-Fi standards defined in the 2.4GHz frequency band are 802.11b and 802.11g. The 802.11n, which works in both 2.4GHz and 5GHz bands, adds to this list. The deployments, as mentioned above, make use of the 802.11b/g standards which has low transmit speeds capped at 11Mbps when compared to the envisaged 802.11n, 5.8 GHz, network deployment that has as high as 600Mbps raw data rates. The 11Mbps upper limit has substantially constrained the maximum achievable throughput at 7.63Mbps for most of the mentioned, 802.11b/g long distance Wi-Fi deployments.

2.3 Overview of IEEE 802.11 standard

Wi-Fi is an acronym for Wireless Fidelity that is internationally recognized as IEEE 802.11 standard. It is a recent technology that gained significant attention in the late 90’s and early 2000’s. Wi-Fi was initially intended to serve as an extension of local area network (LAN) to cover beyond its fixed locations. It eases connection to LAN because of its lack of cabling requirement. Though its primary goal was to serve the business needs, it has gone beyond offices to homes and public places. Wi-Fi is seen as better alternative to providing broadband Internet access. This is because, most electronic devices such as personal computers, laptops or PDAs come pre-installed with Wi-Fi cards and still their cost remains within reach of many. The fact that Wi-Fi technology operates in the unlicensed spectrum, further favours its widespread adoption.

The 802.11 family is divided into different variants, depending on the modulation techniques employed, the allowable data rates per stream, frequency of operation among others. The original version of IEEE 802.11 standard, from which the new standards inherit their major characteristics, was designed to operate with two basic data rates (1 or 2 Mbps). It spelled out three different PHY (physical) layer technologies: direct sequence spread spectrum (DSSS), frequency-hopping spread-spectrum (FHSS) and infrared (IR). The FHSS and DSSS use the microwave transmission at 2.4GHz whereas the IR uses frequencies in the terahertz range[10].

The internationally accepted and common standards are 802.11a, 802.11b, 802.11g and 802.11n. The 802.11b/g standards are the most popular and they operate over an 80MHz bandwidth at 2.4GHz range of frequencies. The 2.4GHz frequency band is used in innumerable electrical appliances making the 802.11b/g standards to sporadically suffer interference, due to the limited number of non-overlapping channels and overcrowding from microwave ovens, Bluetooth devices among others, as illustrated in figure 2-2. Different approaches are used to control susceptibility to interference on these two standards. The 802.11b uses direct-sequence spread spectrum (DSSS) whereas 802.11g uses the orthogonal frequency-division multiplexing (OFDM) signaling.

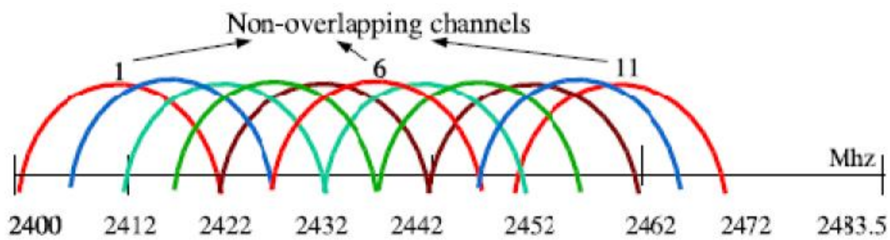

Figure 2-2: Eleven overlapping channels of the 802.11b/g standard

802.11a on the other hand, operates in the UNII band in the 5.470-5.825GHz. It uses the OFDM modulation technique at the physical layer allowing data rates of 1.5-54Mbps. While it has maximum data rate of 54Mbps, the net achievable throughput is approximately 22Mbps[11]. A summary of the 802.11a/b/g variants is shown in the table 2-1.

Table 2-1:IEEE802.11a/b/g features summary

	IEEE 802.11a	IEEE 802.11b	IEEE 802.11g
Raw Data Rates	54 Mbps	11 Mbps	54 Mbps
Average Actual Throughput	4-5 Mbps	27 Mbps	20-25 Mbps
Frequency	5 GHz	2.4 GHz	2.4 GHz
Available Spectrum	300 MHz	83.5 MHz	83.5 MHz
Modulation Encoding	OFDM	DSSS	DSSS
Number of Channels/ non-overlapping	12/8	11/3	11/3

2.4 Advancements in IEEE 802.11n standard

The 802.11n is an improvement of previous standards with many superior features such as the MIMO streaming capability, spatial diversity, spatial multiplexing, a maximum net data rate of 600Mbps and most importantly, its backward compatibility to the original 802.11 specifications.

The data rates in this standard are defined using Modulation and Coding Scheme (MCS) indices, which range between 0 and 15. MCS is a new way, of defining the data rate in addition to other parameters that are absent or constant in the legacy 802.11 standards. These parameters define the number of spatial streams, the coding rate, the modulation type, the number of forward error correction encoders, number of code bits per symbol, guard interval and the number of data sub carriers.

The 802.11n sixteen MCS indices are categorized in two groups, referred to as sets, depending on what MIMO mode they operate on, as shown in table 2-2 below. The lower set, MCS 0-7, exploits the spatial diversity which enables these modes to achieve longer transmission range than Single Input Single Output (SISO) based classic Wi-Fi radios. The higher set, MCS 8-15, sends two simultaneous data streams, a concept called spatial multiplexing. The lower set is therefore more resilient to Cyclic Redundant Check (CRC) errors at the expense of slower data rates. The indicated maximum data rate of any MCS index is not always achievable because of large frame overheads, increased payload redundancy and inhibiting physical characteristics of the links[12]. The lower MCS indices are best suited for longer links with low throughput requirements whereas higher MCS indices work best for short transmission range with relatively high throughput requirements.

The 802.11n standard, officially launched in 2009, defines maximum of four spatial streams. The 802.11ac standard, that is slowly entering the markets, accommodates up to eight spatial streams.

Table 2-2: Modulation and Coding Schemes of IEEE 802.11n standard

802.11n						
HT MCS Index	Spatial Streams	Modulation & Coding rate	Data Rate (GI[2] = 800ns) 20MHz[3]	Data Rate (GI = 400ns) 20MHz	Data Rate (GI = 800ns) 40MHz	Data Rate (GI = 400ns) 40MHz
0	1	BPSK 1/2	6.5	7.2	13.5	15
1	1	QPSK 1/2	13	14.4	27	30
2	1	QPSK 3/4	19.5	21.7	40.5	45
3	1	16-QAM 1/2	26	28.9	54	60
4	1	16-QAM 3/4	39	43.3	81	90
5	1	64-QAM 2/3	52	57.8	108	120
6	1	64-QAM 3/4	58.5	65	121.5	135
7	1	64-QAM 5/6	65	72.2	135	150
8	2	BPSK 1/2	13	14.4	27	30
9	2	QPSK 1/2	26	28.9	54	60
10	2	QPSK 3/4	39	43.3	81	90
11	2	16-QAM 1/2	52	57.8	108	120
12	2	16-QAM 3/4	78	86.7	162	180
13	2	64-QAM 2/3	104	115.6	216	240
14	2	64-QAM 3/4	117	130.3	243	270
15	2	64-QAM 5/6	130	144.4	270	300

The modulation and coding rate defines how data is transmitted over the wireless channel. High data rates may be achieved by use of the higher modulation schemes such as 64-QAM or higher which allows combination of two or more spatial streams. However, these modulation schemes

[2] GI is Guard Interval
[3] Channel Width

demand interference-free and clear line of sight wireless links. The older modulation schemes such as BPSK, on the other hand, have higher error tolerance as well as longer transmission range. The coding rate indicates the percentage of the usable data streams of the MCS. It is expressed as a fraction with the highest value being 5/6 or 83.3%. The Guard Interval (GI) represents a short pause that separates successive packet transmissions. The longer the GI the more reliable the link gets [13].

The channel width defines the range of frequencies over which the data streams spans. The wider channels are capable of supporting higher data rates. While it is tempting to use the wider channels always, their demand of least interference and clear line of sight often poses performance challenges particularly with respect to transmission range and/or achievable throughput[14].

The 802.11n standard accrues many benefits over its predecessors mainly from its use of MIMO, spatial streams and spatial multiplexing. MIMO refers to the number of transmit and receive antennas that are involved in the exchange of signals across a communication link. A 2x2 MIMO for instance refers to two transmitting antennas and two receive antennas which is the bare minimum for the 802.11n standard. Spatial multiplexing is mandatory feature in 802.11n standard and depends on MIMO technology for it to work. It is achieved when multiple antennas send different signal flows of individually encoded data streams (spatial streams) over the communication link. In this case, multiple data streams are transmitted in the same channel but using different antennas and at the receiver end; they are de-multiplexed using MIMO processing[15]. Figure 2-3 depicts a classic transceiver pair where a wireless signal is transmitted from one antenna and received by two antennas that utilize space diversity. Of the two received signals, only the best signal is processed, a feature called space diversity.

The MIMO transceiver, represented in figure 2-4, out-performs the former because the multiple data streams transmitted are all received and processed. The redundancy of the multiple signals translates to superior performance particularly when dealing with scattered, faded signals or signals that undergo multipath propagation. The multiple data streams thus received, delivers double, triple or quadruple data rates depending on the receive antennas in the MIMO architecture used.

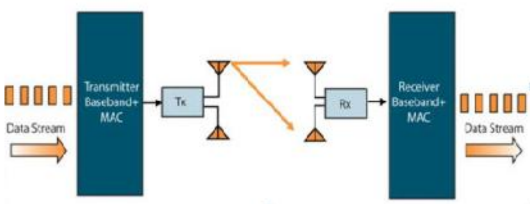

Figure 2-3: Classic 802.11 transmitter

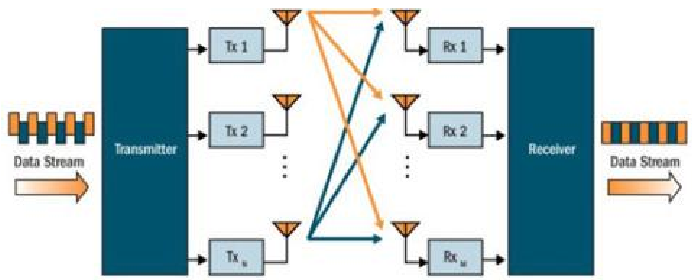

Figure 2-4: MIMO with two spatial Streams

2.5 802.11 MAC protocol limitations

The media access layer in the 802.11 standard provides access control functions to the communication medium in terms of coordination of the media access, addressing, generating the frame check sequences, and ensuring security and authentication mechanisms. MAC protocol limitations of the 802.11 standards when used in long distances scenarios arise from the contention based approach of the CSMA/CA which was initially designed for indoor use. Extending the capability of this standard to long distance introduces inefficiencies particularly in the handling of packet acknowledgments and collisions detection. The CSMA/CA requires that the receiver acknowledges each of the sent packets. When the link length extends beyond the hundred meters range, the responses time out resulting in retransmission being initiated and the vicious cycle recurs over and over until no communication is possible[16]. In addition, the characteristic contention-based approach of CSMA/CA protocol does not perform optimally where there is no arbitrary contention, as is the case with point-to-point links. These two factors mean that the quality of service achievable is abysmal and hence unsuitable for successful long distance applications.

A superior quality MAC protocol is needed to overcome the fundamental CSMA/CA based MAC protocol shortcomings. A modification of the existing MAC protocol to reduce the effects of these limitations was attempted by Raman et al[7]; they called it 2P MAC Protocol. The primary feature of 2P involves loosely synchronizing the operation of the multiple links at a node where they transmit at the same time (SynTx) or receive at the same time (SynRx). The node traverses between the two phases and thereby avoids the contention based approach of CSMA/CA. The observed performance improvement of the 2P MAC over CSMA/CA was two-fold for a single point-to-point link and for larger networks, a factor of 20 was observed[7][17].

2.6 TDMA MAC protocol

There are plenty of research efforts aimed at designing, testing and implementing TDMA-based MAC protocols for use in Wi-Fi based long distance networks such as SRAWAN[18], WiFiRe MAC[16], JaldiMAC[19], WiLDNet[6] among others. Time Division Multiple Access (TDMA) based protocol divides the channel access time to multiple slots and assigns each slot to each node in the link. In this approach, each node transmits in its own time slot which means the collision avoidance mechanism is unnecessary since no collisions are likely to occur. TDMA media access mechanism, therefore, is well suited for long distance point-to-point links, since there is no likelihood of wasted time slots or collisions.

The TDMA based media access affords inherent Quality of Service (QoS) since the maximum time for a station to gain access to the medium is bounded. This level of QoS is superior to the one offered in the CSMA based media access since the latter depends on the independent queuing of different traffic types with shorter inter-frame spacing for high priority traffic packets. This queuing approach does not guarantee maximum latency as provided in the upper bounded maximum time slots offered by TDMA access. The TDMA media access control mechanism is employed by new technologies such as AirMAX™ and Nstreme™, which are incompatible with standard Wi-Fi, to eliminate the needless arbitrary contention, hidden node problem and the huge round-trip-time (RTT) delay in the long distance networks. It provides high Quality of Service for delay intolerant applications such as VoIP and even improves the performance of basic applications as web browsing and file sharing.

2.7 Wi-Fi based long distance network design challenges

Deploying Wi-Fi based long distance point-to-point links requires well thought-out design considerations, described next, in order to avoid many technical and obvious deployment pitfalls.

2.7.1 Line of sight and Fresnel zone clearance

A long distance Wi-Fi based point-to-point link demands clearance of the line of sight failure of which the link experiences attenuation that cause degradation in the received signal strength. The line of sight clearance comes at a cost of erecting antenna towers. To counter this cost, it is preferable to select elevated points or pre-existing tall/storey building on which to mount the antennas.

The line of sight path is divided into different regions, called Fresnel zones that accommodate varying velocities of the transmitted signal. Fresnel zone is an elliptical region surrounding the straight path (LOS) between the transmitting and receiving antennas and is caused by diffraction of the signal at a circular aperture [11] as illustrated in figure 2-5 below.

Radio waves travel in a straight line unless obstructed. When there are reflecting surfaces within an even Fresnel zone, the radio waves reflected from these surfaces arrive out of phase with the line of sight signal causing destructive interference and hence signal degradation. When the reflection off a surface is in an odd Fresnel zone, the interference is constructive leading to improved signal quality[20]. A clear first Fresnel zone allows the transmitted signal to travel with very little attenuation. The first Fresnel zone is 60% clear when at least 0.6 of its midpoint radius is free of obstruction. To achieve best results, the radius of the elliptical shape needs to be calculated in order to determine the height of the antenna towers.

Fresnel losses may be as high as 20dB if large objects and obstructions are present in the line of sight. However, if at least the first 0.6 Fresnel zone is free of such objects, then Fresnel losses of approximately 6dB can be avoided[20]. Whereas attempts may be made to attain clear line of sight by erecting antennas on very high towers, the degradation of microwave frequencies with height, due to ground reflections cancelling out the signal, becomes the drawback that must be contended.

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. A formula to be used in calculating the Fresnel zone radius clearance is shown in equation(2.1)

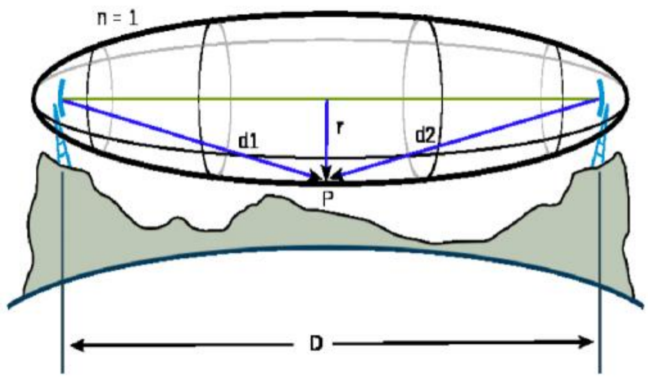

Figure 2-5: Detailed illustration of Fresnel zone and associated dimensions

$$r = 17.32\sqrt{\frac{d_1 d_2}{f(d_1 + d_2)}} \text{ [10]} \qquad (2.1)$$

Where r is the Fresnel radius at a point just above potential obstruction

f is the frequency of the Wi-Fi signal in GHz

d_1 is the distance (km) from transmitting antenna to point just above potential obstruction

d_2 is the distance (km) from receiving antenna to point just above potential obstruction

2.7.2 Effect of earths curvature on antenna heights

When the line of sight distance between the antennas exceeds 16 kilometers, the effect of earth curvature becomes more pronounced and calculations must be made to determine how much the heights of the antenna towers must be adjusted to compensate for its effect[20]. The trees, bushes, buildings and landscape features such as protruding hills along the path must also be taken into account to establish any possible effect they may introduce on the link performance. It can be shown, by Pythagoras theorem, as shown in figure 2-6, that if one moves from point A along its tangent for distance x km to point B, he will be ¢ meters above the ground as given by equation(2.3).

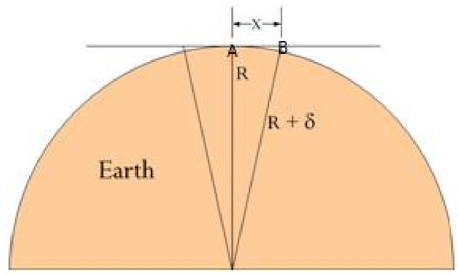

Figure 2-6: Effect of Earths curvature on antenna height

$$\left(R + ¢\right)^2 = R^2 + x^2 \Rightarrow ¢ = \sqrt{R^2 + x^2} - R \tag{2.2}$$

Simplified evaluation of R, using Taylor series, in equation (2.2) above shows that the increase in antenna height ¢ is given by equation(2.3), where R_{eff} is the effective earths radius given by $R_{eff} = {}^4\!/_3 R$

$$¢ = \frac{x^2}{8R_{eff}} \times 1000 Meters \tag{2.3}$$

2.7.3 Application throughput requirements

The link performance requirements need to be identified before the deployment is embarked on. This involves specifying the minimum required network throughput in each link in order to meet the application requirements and users' needs that are to be supported by the link. If a high end application such as a teleconferencing facility is to be set up between patients in a rural hospital and the doctors in the urban locale, then a minimum of 384Kbps must be met in order to facilitate high quality video conferencing[5]. Link distance directly influences the performance particularly because it determines the path loss, the transmit power required on each node as well as the receiver sensitivity, what gain of antennas must be met among others.

2.7.4 Inter-link and external Wi-Fi interference

Inter-link or external Wi-Fi interference may arise from operating links in the overlapping channels. To achieve an interference free network, it is prudent to avoid setting up links in the presence of multiple interfering networks or users. Since the UNII band is unlicensed, there is always a possibility of other persons erecting a network in the preferred channel. Another approach to avoid the link quality degradation caused by the external Wi-Fi interference is to enable channel shifting in the Wi-Fi radios. The shifting of channels helps the radio to switch to a lesser interfered channel.[21]

2.8 Related work

The earliest of works that attempted the use of Wi-Fi beyond its typical range was called Roofnet Project and was carried out by a group of MIT students. It comprised of an unplanned wireless mesh network nodes that served a large area with broadband Internet access[22]. The mesh network comprised of individual outdoor point-to-multipoint links that extended the Wi-Fi range to a few kilometers using omni-directional antennas. Their objectives were limited to the use of omni-directional antennas and multiple hops mechanism to extend the range of the Wi-Fi links. They failed to utilize the capacity of single-hop point-to-point links that have the potential of reducing the routing challenges that accompanies multi-hop settings.

Sheth et al. conducted further experiments on the performance of Wi-Fi based long distance links, using IEEE802.11b/g standards. These links exhibited very high and variable packet losses, resulting in very poor usability of the high throughput along the links [17]. Further tests indicated that when higher transmit power (23dB+) and higher sensitivity Wi-Fi radios were used, longer links in the range of a hundred kilometers could be achieved. These two contradictory results revealed the cause of high packet losses to be the carrier-sensing feature of the 802.11 MAC protocol in long distance links[7][9][3].

Some further work in this field was advanced by TIER group in University of California Berkeley [6]. They used high-gain directional antennas to boost the link length. This allowed them to achieve link distance spanning up to a few tens of kilometers[6]. Flickenger et al. [8] achieved 6Mbps over a 382km link. Their findings were based on a TDMA enhanced MAC protocol modifications on IEEE802.11b/g standard that are necessary for a long distance links, as described by [7][6]. Since the 802.11g standard has data rates capped at 54Mbps, their observed peak throughput was relatively low. The IEEE 802.11n standard, which has superior performance, has since dominated the Wi-Fi markets and tests on its capacity in deployments of long distance outdoor Wi-Fi links, is worth investigating. This justifies the attempts in using of the 5.8 GHz frequencies to establish long-range point-to-point links to provide broadband access to rural areas.

The introduction of TDMA based MAC protocols for use in long distance Wi-Fi links led to increased interest among many technology enthusiasts and manufacturers. Two projects in India used the IEEE 802.11 b/g (Wi-Fi) as a cost-effective technology to provide wireless access to rural areas i.e. Digital Gangetic Plains (DGP), and Ashwani [3]. The DGP project was initiated in 2002 at the Indian Institute of Technology, Kanpur (IITK), Uttar Pradesh, to explore the technical feasibility of establishing long-distance Wi-Fi based links. The Ashwani Project is a network deployment effort by the Byrraju Foundation, to provide broadband access and services to a collection of villages in the West Godavari district of Andhra Pradesh, India. Real time TCP throughput above 364 Kbps was achieved which supported interactive video-based applications such as distance-education and telemedicine, on the network.

CHAPTER THREE

3 METHODOLOGY

3.1 Basic requirements

A basic Wi-Fi based long-distance link requires two pairs of a Wi-Fi radio and a high gain[4] directional antenna; in this work parabolic dish antennas, because of their high directionality and gain, are used. Each pair is located at each of the two nodes, one connected to the wired backhaul broadband access and serving as the access point while the other on the remote site. Two teams are stationed at the two nodes and an additional wireless router is used to extend wireless LAN to unlimited number of computers, at the remote site. A pair of binoculars is used to obtain a general view of either nodes and enable the teams get a general view of the location required to achieve a line-of-sight (LOS). If a clear LOS cannot be established, a repeater may be used in between the nodes to overcome the obstacles, as shown in figure 3-1. A cellular phone for each team is necessary for communication purposes, particularly sharing of the setup link parameters and the link performance testing.

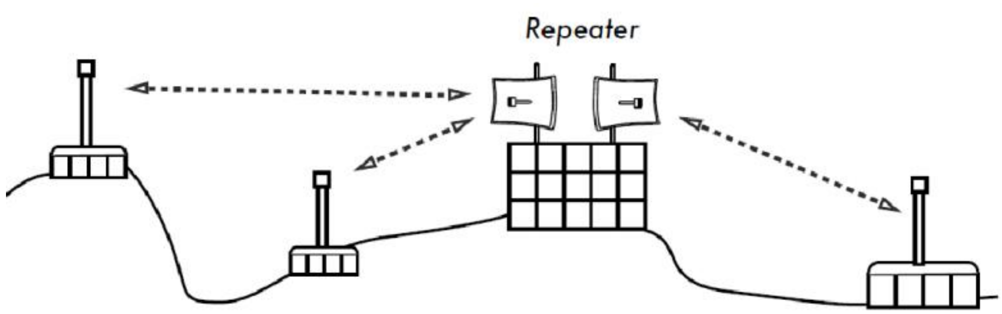

Figure 3-1: The repeater acts as a bridge between nodes that have no clear LOS

[4]The gain required depends on the link budget

Several factors such as site selection, terrain and elevation profile, tower heights, choice of antenna, link budget, Fresnel zone clearance, antenna polarization, earth grounding, and earth's curvature among others are the primary factors that are considered for a successful link establishment.

3.2 Site selection

Topographical software, Google Earth, is employed to determine the best locations that are clear of topographical barriers, obstacles or rugged terrain as required for LOS establishment. Figure 3-2 shows the elevation and terrain profile of a 24.3km link, the longest achieved link distance. It is evident that a very clear line of sight is established, as far as the earths elevation and terrain is concerned. Similar profiles are obtained for five other links defined in table 3-1, all of which has clear line of sight. Two links, which had earlier between cosidered for deployment were disqualified because of their unfavourable terrain, one of which is shown in figure 3-3. Six links were established as shown in the figure 3-4 below

Figure 3-2: Terrain profile of link E-F, a 24.3KM link

Figure 3-3: Terrain Profile: Dedan Kimathi University and Karatina University, Town Campus

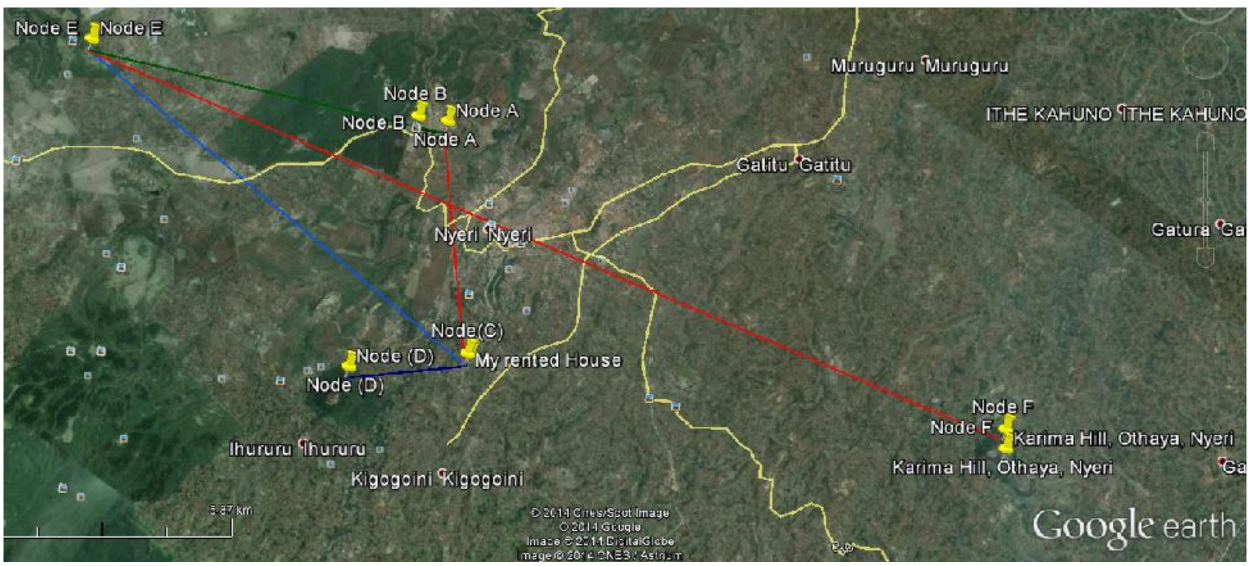

Figure 3-4: Satellite view showing locations of the six nodes used in test-bed setups

3.3 Calculation of the antenna heights

The effect of earth's curvature on elevation of antenna was considered in section 2.7.2 above, where the governing equation was defined as(2.3). Antenna elevation required for a 24.3km link is calculated to be approximately 8.68km, as shown in equation (3.2), considering the effective earth's radius, R_{eff} is given by

$$\mathrm{R}_{eff} = \tfrac{4}{3} R = \tfrac{4}{3} \times 6378km = 8504km \tag{3.1}$$

$$¢ = \frac{24.3^2}{8 \times 8504} \times 1000 = 8.68 \mathit{Meters} \tag{3.2}$$

Table 3-1 summarises the antenna height requirement due to earth's curvature. These heights are calculated, similarly, as that of 24.3km link above. Since elevation requirement may be distributed between the two nodes, it is insignificant in shorter links. Only the link E-F is significantly affected which agrees to the 16km lower limit as described in section 2.7.2

Table 3-1: Link lengths with their associated antenna height requirements due to the earth's curvature

Link code	Link description	LOS Link length	Required elevation
A-C	Dedan Kimathi University (Resource Centre) - Shama Hostels Kamakwa	5.4km	0.43 meters
A-E	Dedan Kimathi University (Resource Centre) – Aberdare country club (hill top)	7.8km	0.89 meters
C-D	Aberdare country club (hill top) – Nyeri Hill	2.4km	0.09 meters
C-E	Shama Hostels Kamakwa - Aberdare country club (hill top)	10.7km	1.68 meters
E-F	Aberdare country club (hill top) –Othaya (Karima Hill)	24.3km	8.68 meters

Antenna height elevation required for the first Fresnel zone clearance is calculated as described in section 2.7.1. Link E-F, of length 24.3km, is used next to demonstrate this calculation. Given the frequency of operation $f = 5.8$ GHz and the distances d_1 and d_2 are assumed to be equal and the highest potential obstacle is located at the midpoint ($d_1 = d_2 = 12.15\text{km}$), then the combined antenna tower heights would be given by equation (2.1)

$$h = 17.32\sqrt{\frac{12.15 \times 12.15}{5.8(24.3)}} = 17.73 Meters \tag{3.3}$$

From these calculations, it is clear that a minimum antenna mast height on each side is at least eight meters, half of 17.15meters. Considering the antenna masts are located at elevated points, as shown in table 3-2, there is the advantage of reduced height requirements. For this work, detachable antenna masts of seven meters are used. Figure 3-2, 3-5, 3-6, 3-7 and 3-8, show the terrain profile the five links which shows that they meet clear line of sight requirement.

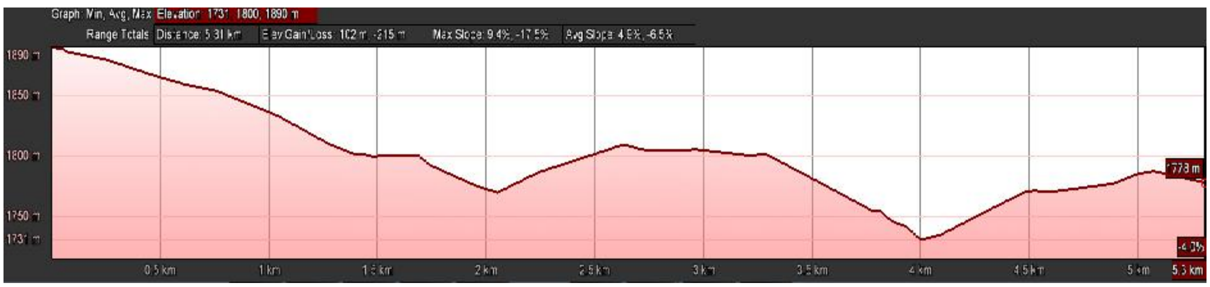

Figure 3-5: Terrain Profile of link A-C

Figure 3-6: Terrain Profile of link A-E

Figure 3-7: Terrain Profile of link C-D

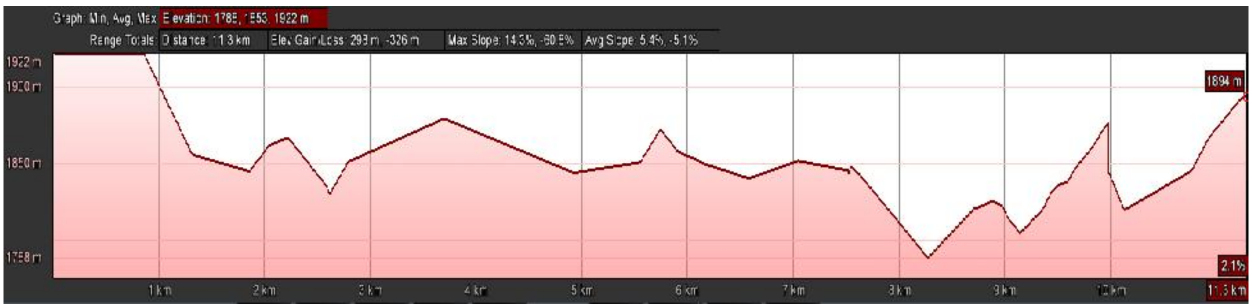

Figure 3-8: Terrain Profile of link C-E

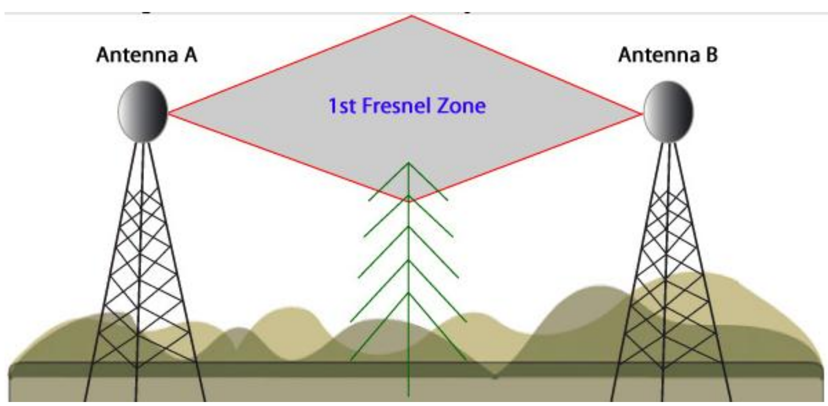

Figure 3-9: Illustration of Fresnel Zone with Obstruction at the midpoint

Looking at the terrain of link E-F, as shown in figure 3-2, node E has an altitude of 2008 meters above sea level (ASL) whereas node F is at 1942 m ASL altitude. The antennas at each node are hosted on a mast of seven meters ASL. Since the highest midpoint is at 1800m altitude, there is

215 meters difference between the midpoint and node E. Similarly, 149m height difference exists between highest midpoint obstacle and node F. To achieve 100% Fresnel zone clearance, the midpoint Fresnel radius of 17.73m, obtained in equation**Error! Reference source not found.**, is required. An additional 8.68m is required to cater for the elevation due to earth's curvature, as obtained in equation(3.2). Assuming that the midpoint has potential obstruction of 15 meters, an approximate average height of a tree, as illustrated in Figure 3-9, the total antenna elevation, for the link E-F, must be greater than or equal to 41.41metres

$$15 + 17.73 + 8.68 = 41.41 Meters \tag{3.4}$$

In comparison to the height difference of 149m between the lowest node, F, and this elevation requirement, then, for this link, a 100% Fresnel clearance was correctly achieved. If by any chance the 100% Fresnel clearance is not achieved, 40% blockage allowance of the Fresnel zone is normally allowed such that the total antenna elevation requirement reduces to 28.85m.

$$0.6 \times (15 + 17.73 + 8.68 = 41.41) = 28.85 meters \tag{3.5}$$

Table 3-2: Node Locations and their corresponding tower location

Site Name	**Notation**	**Tower Location**
Kimathi University (Resource Center)	A	16M building
Kimathi University (Old Admin)	B	18M building
Shama Hostels- Kamakwa	C	17M Building
Nyeri Hill	D	0m, No building
Aberdare country club (hill top)	E	0m, No building
Othaya (Karima Hill)	F	0m, No building

3.4 Link budget considerations

Link budget requirements demand proper calculation of the gain of the antennas used as well as the sensitivity of the Wi-Fi radios to achieve required signal strengths. The overall goal is to ensure that the signal strength at the transmitter meets the threshold required by the sensitivity of the receiver. Several parameters, as listed below, are considered for the threshold to be met.

a) **Effective transmitting power (P_{eff})** is equal to Wi-Fi radio transmit power, P_t (dBm) plus the antenna gain, G_t (dBi) less the cable and transmitter feeder losses, TFL (dB)

$$P_{eff}(dB) = P_t(dBm) + G_t(dBi) - TFL(dB) \tag{3.6}$$

b) **Path loss, *pl* (dB)** is the loss of signal strength along the transmission path

c) **Effective receiving sensibility, S_{eff}** is equal to Receive antenna gain, G_r (dBi) less receiver feeder loss, RFL (dB) and Wi-Fi radio sensitivity, S (dBm)

$$S_{eff}(dB) = G_r(dBi) - TFL(dB) - \mathrm{S}(dBm) \tag{3.7}$$

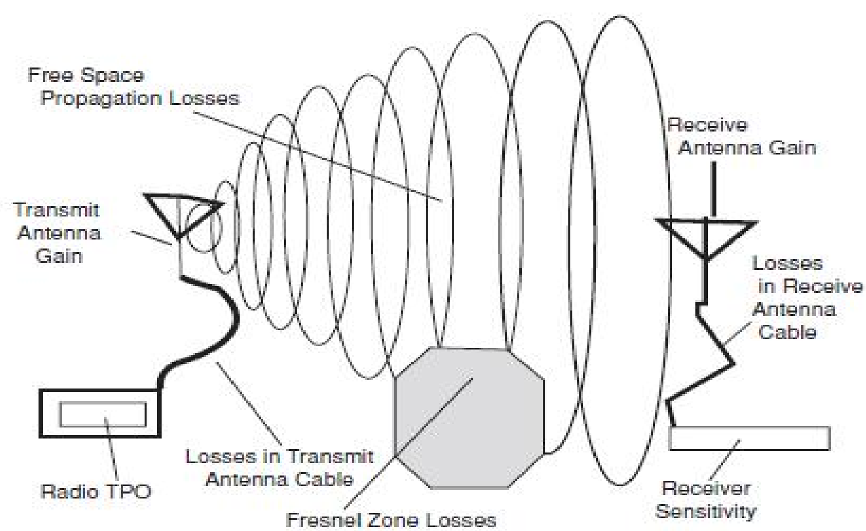

Figure 3-10: Illustration of link budget parameters

The received signal level, often referred to as Received Signal Strength Indication (RSSI), is a crucial criteria when evaluating the quality of a wireless link. Different environments demand varying levels of signal strength depending on how much signal attenuation, scattering, fading and/or multipath propagation that the transmitted signal has gone through.

The manufacturers of different wireless devices and radios define specific pairs of threshold receiver sensitivities and their corresponding data rates. Likewise, Ubiquiti M5 radios come with a technical specification datasheet that defines the data rates with their corresponding transmit power and receiver sensitivity as shown intable 3-3 below. In this table, the data rate is specified in terms of Modulation Coding Scheme (MCS) Indices. The receiver sensitivity is the weakest signal strength received at the receiver side needed to achieve a successful communication link. This means that, specific data rates can only be achieved when their specified receiver sensitivities are met.

Table 3-3: Transmit Power and Receiver Sensitivities for Ubiquiti Rocket M5 radio

IEEE Standard	**Data Rate**	**Avg. TX (dBm)**	**Tolerance (dBm)**	**Sensitivity (dBm)**	**Tolerance (dBm)**
802.11n (5 GHz)	MCS0	27	+/-2dB	-96	+/-2dB
	MCS1	27	+/-2dB	-95	+/-2dB
	MCS2	27	+/-2dB	-92	+/-2dB
	MCS3	27	+/-2dB	-90	+/-2dB
	MCS4	26	+/-2dB	-86	+/-2dB
	MCS5	24	+/-2dB	-83	+/-2dB
	MCS6	22	+/-2dB	-77	+/-2dB
	MCS7	21	+/-2dB	-74	+/-2dB
	MCS8	27	+/-2dB	-95	+/-2dB
	MCS9	27	+/-2dB	-93	+/-2dB

	MCS10	27	+/-2dB	-90	+/-2dB
	MCS11	27	+/-2dB	-87	+/-2dB
	MCS12	26	+/-2dB	-84	+/-2dB
	MCS13	24	+/-2dB	-79	+/-2dB
	MCS14	22	+/-2dB	-78	+/-2dB
	MCS15	21	+/-2dB	-75	+/-2dB

Since the transmit power defines how much data rate and what modulation scheme is usable, the link budget requirements for each link is considered. For illustration purposes, a 24.3km link, E-F, is used. The link has the following parameters: LOS link length, *r,* of 24.3km, the curvature of the earth is 8.68 Meters (as calculated in section 3.3 above), the highest obstacle is estimated to be a 15 meters at midpoint, the frequency of operation, *f*, is 5.8GHz, the Fresnel radius is calculated to be 17.73 meters (with 0% blockage allowance)

The **path loss,** *pl***,** is defined by

$$pl = (\frac{4\pi r}{\lambda})^2 \quad or \quad pl = 10\log(\frac{4\pi r}{\lambda})^2 dB \tag{3.8}$$

Where λ is the wavelength of the transmitted signal in meters obtained from $\lambda = \frac{c}{f}$ with

$c = 3\times10^8 ms^{-1}$ and $f = 5.8GHz$ which gives $\lambda = \frac{3\times10^8}{5.8\times10^9} = 0.052 meters$

Therefore path loss $pl = (\frac{4\pi \times 24.3\times10^3}{0.052})^2 = 3.448\times10^{13}$ which when expressed in decibels becomes $pl = 10\log(3.448\times10^{13}) = 135.4dB$

The data collection for each link required each parameter to be set at a point where throughput is maximized. For the 24.3km link, peak throughputs were achieved when MCS 13 was used at 40MHz channel width. Therefore, as seen in table 3-3 above, the Ubiquiti MIMO Airmax, M5 Wi-Fi radio has transmit power of MCS 13 capped at, $P_t = 24\text{dBm}\ (125\text{mW})$ and receive sensitivity at -79dBm. If the cable and connector losses are approximated to be negligible, then the effective transmit power, P_{eff} can be expressed as

$$P_{eff} = P_t - TFL + G_t = 24dBm - 0 + 30dBi = 54dBm \tag{3.9}$$

Where TFL is the transmitter feeder loss and is assumed to be negligible and G_t is the transmit antenna gain.

The effective receiver sensibility S_{eff} is given by

$$S_{eff} = G_r - RFL - S = 30dBi - 0dB - -79dBm = 109dBm \tag{3.10}$$

Finally the link budget shows that power margin of 27.6dBm is available as calculated in equation (3.11)

$$P_r = P_{eff} + S_{eff} - pl = 54dBm + 109dBm - 135.4dB = 27.6dBm \tag{3.11}$$

A link whose power margin is greater than 0dB has met the link budget requirements [10], and so is the E-F link.

3.5 Choice of antennas

Most microwave systems utilize parabolic dish antennas because of their high gain advantage. This antenna comprises of a driven element and a passive spherical reflector. The driven element, often called the antenna feed, may be a wire dipole antenna. The reflector size is dictated by the wavelength of the signal to be transmitted or received and is usually in the order of several wavelengths. The driven element must be positioned at the exact focal point of the parabola-shaped reflector. At this position, it receives the converged narrow beam of the electromagnetic waves that bounce off the reflector, which is thereafter fed to the Wi-Fi radio either through a coaxial line feed or the radio is connected at the focal point of the reflector.

Figure 3-11: Rocket Dish Antenna (30dBi)

For this work, Ubiquiti Rocket-dish antenna, shown in figure 3-11 and whose specifications are highlighted in table 3-4. The rocket dish antenna works with a MIMO TDMA based, AirMAX, Wi-Fi radios to deliver performance improvements in throughput, scalability and reduced network latency compared to other off-the-shelf Wi-Fi radios.

Table 3-4: Antenna parameters of a Rocket Dish Antenna

Frequency Range	5.1-5.8 GHz
Gain	30 dBi
Horizontal polarization Beam width	5 deg. (3 dB)
Vertical polarization (Beam width)	5 deg. (6 dB)
Front /Back lobe Ratio	-34 dB
Maximum Voltage to standing wave ratio (VSWR)	1.4:1
Dimensions	648 mm diameter
Polarization	Dual Linear
Cross-polarization Isolation	35 dB min

3.6 Intrinsic link impediments

There may arise unaccounted causes of link failure even when there is clear line of sight and Fresnel zone free of obstructions. Technically, the microwave frequencies are unaffected by the ionized layers of the atmosphere because the region of their operations is way below these layers. However, temperature inversion may prove a major setback. When temperatures get high, the hot air rises and is often mixed with moisture. When the microwave signal traverses across this cloud of rising moisture, attenuation of the signal is observed [10].

With expanse network of cellular telephony, which operates in the 1.8-1.9GHz band, it is possible for the long distance Wi-Fi radios to experience broadband noise or interfering harmonics from the high-power collocated base transceiver stations (BTSs)[11]. External Wi-Fi interference, swaying of the antenna tower by wind and fading of the received signal are also likely to be experienced despite a well-designed setup being in place. Finally, there might be other possible causes of degradation of the link due to ground reflections, diffractions at the edges of large objects along the line of sight, transmission ducts along the line of sight or even troposphere scattering which are all intrinsic to the physical characteristics of the microwave signal[10]. For most of these link impediments, establishing a clear line of sight for each of the links mitigates their effects. The swaying of the antenna mast is reduced by providing mast support in form of guy ropes as shown figure 3-14.

3.7 Antenna polarization

Antennas by their design have different polarizations in which they operate. The direction in which the antenna must be aligned depends on which polarization mode it is to operate on. It may be vertical/ horizontal polarization for the grid parabolic dish antennas. The antenna pairs needs to be set on the same polarization, or else up to 20dB loss of signal strength is experienced along the link. It is also possible to reduce the external Wi-Fi interference by operating one link in a different polarization from the neighboring antennas. At microwave frequencies, the horizontal polarization is known [20] to provide less multipath propagation effects as well as provide low path loss in situations where there is an obstructed line of sight.

3.8 Earth grounding

The antenna tower requires proper grounding for lightning protection. It is not uncommon to find inadequately grounded antenna towers or even no grounding at all. This scenario poses great risks to the inhabitants of the building where the antenna is mounted and even the users. The number of grounding rounds and the gauge of grounding copper cables determine how well the setup is protected from any static discharge or lighting that may arise causing destruction of both life and property. Extremely high voltages in static charges develop at the antenna top and a grounding mechanism needs to be robust enough to handle such high risk scenario. Since copper cables have relatively high resistance to sudden increase in electric current during a lightning strike, a least four copper rods are used to ground the antenna masts. Copper ties are finally connected to the network of grounding rods.

3.9 Antenna alignment

While the antenna alignment is an enormous research task by itself [23], way beyond the scope of this research, a simplified approach of antenna alignment is used. Since the link distances are relatively short, the antenna alignment is majorly performed to achieve azimuth plane alignment first and then a little tilting of the antenna masts to achieve elevation plane alignment.

The Ubiquiti antennas have an inbuilt software-based frequency spectrum analyzer that is used to perform antenna alignment. It produces different beep sounds depending on the signal strength received. When the antennas are completely out of alignment, the received signal strength falls below -96dBm or less. As the antenna masts are rotated in the azimuth plane and/or tilted in elevation plane, the received signal strength rises to the best achievable. For most long distance links, the best alignment produces signal strength in the range of -20dBm to -68dBm depending on the link length. Figure 3-12 shows the interface of the software-based spectrum analyzer used in the antenna alignment.

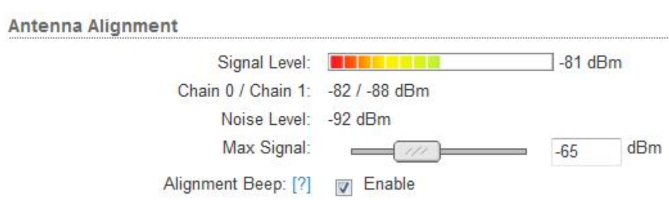

Figure 3-12: Software based Spectrum analyzer

3.10 Power Supply

The sources of power options are either the mains electricity or a DC battery with an inverter for the remote stations; a 12V lead acid battery plus a 300W inverter are sufficient. For the remote nodes that run for extended periods of time, an 80W solar panel with voltage stabilizer may be required to provide uninterrupted power supply. Three nodes, A, B and C, run on mains electricity while the other three, D, E and F, run on 12v battery power. A 300W AC-DC power inverter was used to supply AC power to the node workstations and radios. Since the power requirements of one node is below 100W, a 12V, 75Ah, battery is sufficient to supply one node with eight hours uninterrupted power for three days, which was sufficient for data collection of one link.

3.11 Equipment used

The equipment listed below are used to setup the six links mentioned. The same equipments are used for each link apart from the antenna masts which, because of their bulkiness are used for each node individually. In terms of cost, this test-bed model is much cheaper than the existing microwave links that require annual licensing and approval from the national regulatory authority. The set up costs may escalate if the nodes are located in regions where LOS is hard to achieve and hence the need to setup taller masts, but the running cost is absolutely minimal.

(1) 2 Ubiquiti *Rocket* dish 30dBi antennas

(2) 2 Ubiquiti *Rocket* MIMO AirMAX Wi-Fi radios

(3) 2 Ubiquiti *NanoBeam*^{TM} dish antennas (27dBi) with inbuilt MIMO AirMAX Wi-Fi radios

(4) 2 Ubiquiti *Airgrid*^{TM} dish antennas (17dB) with inbuilt AirMAX Wi-Fi radios

(5) 2 Cisco *Linksys* wireless routers

(6) 6 mini–towers of heights 7m

(7) 200m Cat 5e outdoor tough cable and 20 RJ45 connectors.

(8) Tools: Crimping tool, LAN tester, spanners, screwdrivers, drill, and a 100m power extension cable.

(9) Software: geographical mapping software (Google map)

(10) 2 pairs of 50x10 High magnification binoculars

(11) 2 300W AC-DC power inverters

(12) Movable tables and a chair

(13) Four laptops

3.12 Data collection

Six links are tested for consistency in variability of the achievable throughput. Data collection is done for all the links mentioned, independently of each other. Six independent factors and their effect on the achievable throughput are investigated. These are the channel width, packet size, transmit power, transmit rate (MCS index), external Wi-Fi interference and link distance. The objective is to determine how and to what extent each of these affects achievable throughput and their correlation with link distance.

Data collection involves a series of parameter variation at each node for each link. Once the antenna alignment test is performed and the link is optimally established, default values of MCS, transmit power, channel width and packet size are set. The link performance with respect to each parameter is evaluated while the other parameters remain unaltered.

To start with, different values of channel widths are set and the link performance, in terms of TCP throughput is observed. The TCP throughput is measured in terms of how fast a 1.17GB TCP file transfer succeeds at a given node parameter configuration. When the best value of channel width is determined it becomes the default value of channel width of that link and the next parameter, transmit power, is varied. The minimum value of transmit power is set on each of the radios and a TCP file transfer is initiated. The transmit power is increased steadily, while observing the TCP throughput until the best peak throughput is achieved. The observed TCP throughput is recorded as the characteristic link performance at each parameter. In addition to the throughput and packet reception ratios available from the Wi-Fi radio software interface, the time it takes to complete the file transfer is used to compute the TCP throughput. This is repeated for varying parameters.

Figure 3-13: Antennas mast supported by guy ropes –Node C

Figure 3-14: Pictorial View of the team performing tests at Node E

CHAPTER FOUR

4 RESULTS & DISCUSSION

This thesis confirms that Wi-Fi based long distance point-to-point links, implemented with TDMA based Wi-Fi radios, are capable of delivering broadband Internet access. Since most users in the village require Internet to primarily access web pages, access emails, visit and share in social sites and rarely download one or two files in a day, a peak throughput of 100+Mbps can meet the demands of an entire village. Assuming 256kbps bandwidth may be utilized by 2-5 users at any given time then a single point-to-point link, can serve 1000+ simultaneous users.

The fundamental performance characteristics and limits are analyzed. It is shown that at varying parameter settings (link length, channel width, packet size, transmit rate and transmit power) different throughput and packet losses are achieved. The presence of Wi-Fi interference is significant and does cause degradation in achievable throughput.

4.1 Effect of channel width on throughput

This section seeks to evaluate how channel width and the concept of channel bonding affect the achievable throughput for long distance Wi-Fi based links. Several tests are conducted initially to determine which parameter, among channel width, packet size, transmit rate and transmit power, has the greatest impact on the achievable throughput. It is observed that each of them has a threshold value below or above which the link performance experiences very high degradation.

The effect of channel width is investigated first. For each of the five links, the antenna and radio settings are initially kept at default configurations. The default configuration is a general setting that the off-the-shelf Wi-Fi devices are preset. In this configuration, the Ubiquiti Rocket Dish and radio comes with default channel width of 20MHz, transmit power at maximum (27dBm), packet size at 1500bytes and transmit rate at maximum of MCS 15, equivalent to 300Mbps. The object of this section is to compare the performance of the different link lengths when deliberate changes to the default channel width are made to higher (40MHz) or lower values (10MHz & 5MHz) as illustrated in figure 4-2 and 4-3.

When the tests are conducted, the widest channel width (40MHz) gives the best and very consistent results. An average achievable throughput values in the range of 96Mbps to 106Mbps is recorded for each of the five links when the channel width is set at 40MHz. This is in contrast to the default, 20MHz, channel width. As indicated in the figure 4-1 the four different channel widths have very distinct performance characteristics.

While the three lower channel widths have a trend that predictably decays, in a power series, with link distance, it is apparent that the 40MHz channel width is unaffected by link distance. On the contrary, its average throughput is relatively constrained at 100Mbps mark and does not rise or fall above this value no matter the link distance. It is not circumstantial that the link capacity exceeds the 100Mbps mark, but in fact this limit is caused by the Fast Ethernet Standard maximum data rate. Ethernet cables, category 5e, are used to interconnect the Wi-Fi radio to the laptops at each node.

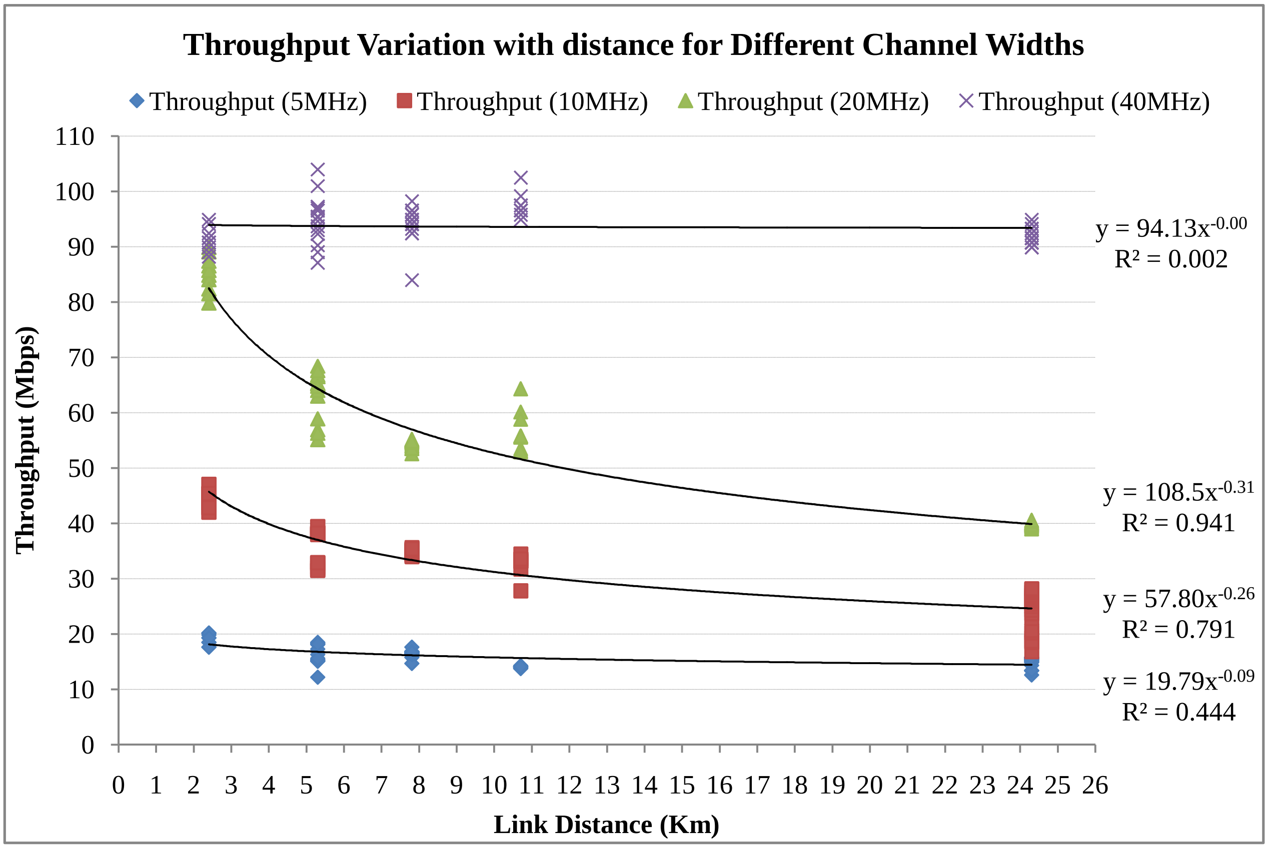

Figure 4-1: Throughput Variation with distance for Different Channel Widths

It is worth noting that channel width has very significant effect on the attainable throughput for any link distance [24]. As observed, there is a negative correlation between achievable throughput and link distance. Short link distances exhibit different peak throughputs at varying channel widths. For long distance links in the range of 1-25km, 40MHz channel width exhibits best performance with peak throughput constrained at 100Mbps range.

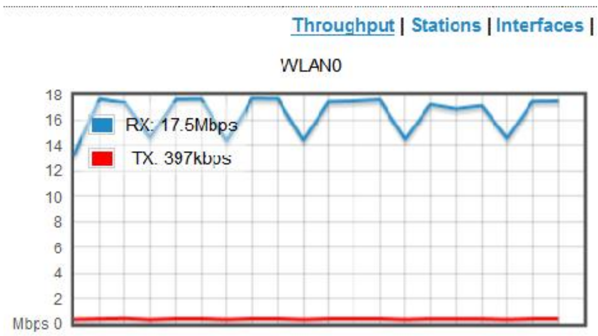

Figure 4-2: TCP throughput on 7.8km link at 5MHz (from the Ubiquiti AirOS interface)

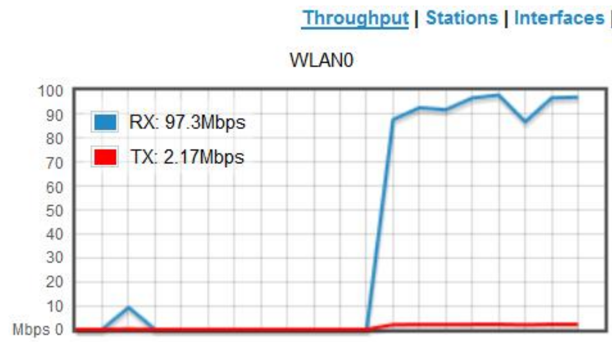

Figure 4-3: TCP throughput observed on 7.8km link at 40MHz

An increase in link distance results in a very consistent decrease in the achievable throughput. An attempt is made to model the interrelationship between achievable throughput and link distance for different channel width using power regression models shown in equations (4.1) - (4.4) for channel widths 40MHz, 20MHz, 10MHz and 5MHz respectively. In equations (4.1) - (4.4), y represents throughput (Mbps) and x represents the link distance in kilometers.

A comparison of these four model equations with their associated R-Squared values shows that the three lower channel widths (5MHz, 10MHz, and 20MHz) have a very consistent trend; a negative correlation of throughput vis-à-vis distance exists. It is further evident, from the coefficient of determination, R^2, that the three lower channel widths have considerably high goodness of fits to equations(4.2),(4.3) and (4.4) with 94%, 79% and 44% throughput variation being explained by each equation respectively. However, the 40MHz channel width shows inconsistency with the proposed power regression model equation since only 0.2% of the variation may be explained by equation(4.1) as indicated by the coefficient of determination, R^2.

$$
\begin{aligned}
y &= 94.13x^{-0.00} \\
R^2 &= 0.002
\end{aligned}
\tag{4.1}
$$

$$
\begin{aligned}
y &= 108.5x^{-0.31} \\
R^2 &= 0.941
\end{aligned}
\tag{4.2}
$$

$$
\begin{aligned}
y &= 57.80x^{-0.26} \\
R^2 &= 0.791
\end{aligned}
\tag{4.3}
$$

$$
\begin{aligned}
y &= 19.79x^{-0.09} \\
R^2 &= 0.444
\end{aligned}
\tag{4.4}
$$

From these observations, there is significance effect of channel width and link distance on the achievable throughput. Wider channels give superior performance for short distance links when compared to narrower channels. As the link distances increase, the achievable throughput decays as a power series whose base is the link distance. The wider channels have larger exponent of decay which indicates that as link distance increase, the narrower channels are preferable. The exact channel width to use depends on the throughput requirements of the link. Since wider channels are affected more by distance than narrower channels, one would prefer to use a narrower channel at a given distance if the throughput requirement is satisfied by the chosen channel width even if a wider channel would offer higher achievable throughput. The effect due to channel width is more pronounced than that of link distance. Justifiably, it is possible to predict the performance of the Wi-Fi based long distance point-to-point links from the graph shown in figure 4-1 and equations (4.1) - (4.4).

The afore mentioned findings validates the usability of the UNII-3 frequencies in establishing long distance point-to-point links capable of providing broadband Internet access in rural areas. A clear outline is drawn and anyone who wishes to install such links needs to follow the empirical graph on figure 4-1 and/or the equations (4.2) - (4.4) to predict the expected throughput for different link distances and/or channel widths. In summary, the general trend of the link performance with respect to varying channel width is illustrated by a group bar chart in figure 4-4.

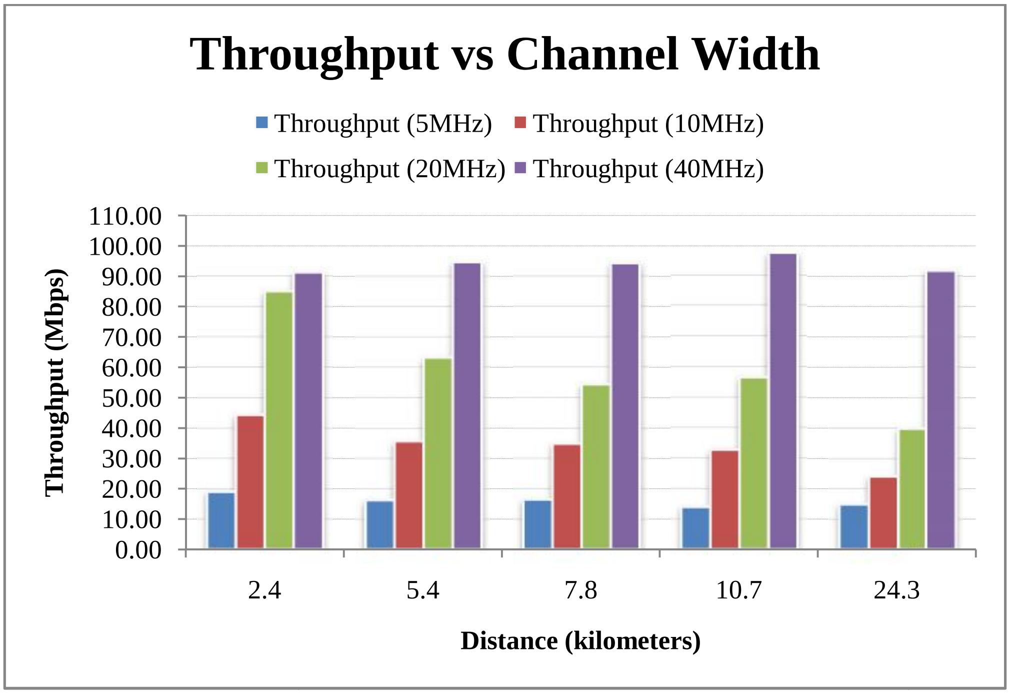

Figure 4-4: A group bar chart showing throughput variation with distance for different channel widths

4.2 The link budget demands and its effect on achievable throughput

The 27.6 dB power margin, for the 24.3km link, obtained in section 3.4, strictly speaking, is a theoretical value with quite a number of assumptions. If a 15dB minimum power margin $M_{reserved}$ is reserved to account for any link uncertainties, then the operating margin, M remains at $27.6 - 15 = 12.6 dBm$. From this realization, the transmit power therefore becomes the parameter which determines what MCS value is used for a given link distance, to deliver maximum peak throughput. Rearranging equation (4.5) to make P_t the subject gives equation(4.7) which dictates the minimum transmit power, when margin $M = 0$, for 24.3km link operating at the MCS 13.

$$\mathrm{M} = P_{eff} + S_{eff} - pl - M_{reserved} \tag{4.5}$$

$$M = (P_t - 0 + 30dBi) + (30 - -79dBm) - 135.4dBm - 15dB = 0dBm \tag{4.6}$$

$$P_t = -30dBi - 109dBm + 135.4dBm + 15dBm = 11.4dB \tag{4.7}$$

This result in equation(4.7) agrees with the experimental analysis as seen in figure 4-5. Throughput for the 24.3km link remains relatively at zero until 12dBm transmit power is exceeded at which point it shoots to approximately 10Mbps and rises speedily to 40Mbps at 15dBm. Comparing this value with similar throughput from 4-13, on page 60, for the same 24.3km link, it is evident that MCS 13 does not reach its maximum potential, 90-100Mbps, but achieves a peak throughput of 40Mbps which is easily reached by MCS 4 or MCS 10. This confirms that transmitting at higher MCS index, without meeting its link budget adequately, renders the link inefficient and makes it unable to achieve its maximum usable data rate. Figure 4-6 and 4-7 illustrate this scenario perfectly well. Figure 4-6 depicts a satisfactory transmit power for a 5.4km link at 27dBm and therefore an average peak throughput above 90Mbps is achieved. On the other hand, at 6dBm transmit power, unreliable throughput with very high variability is shown in 4-7.

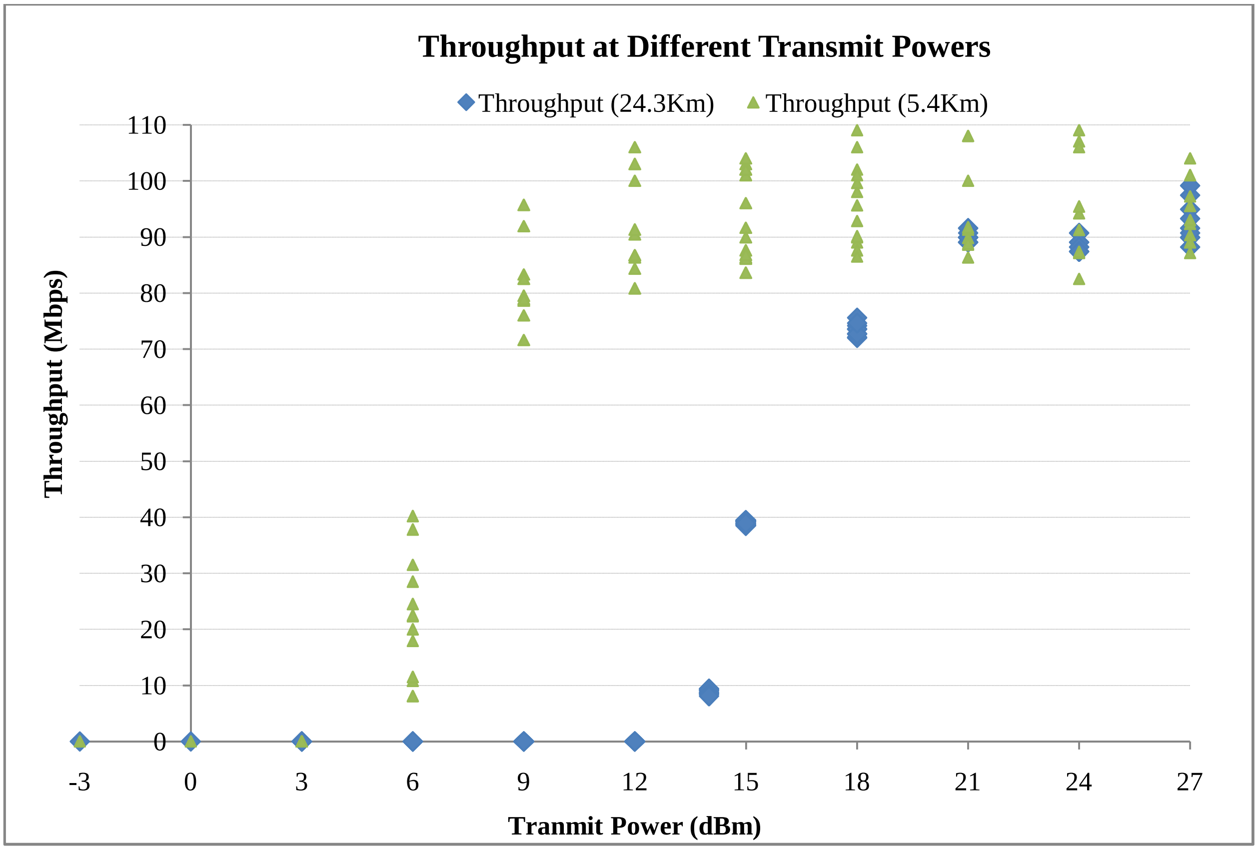

Figure 4-5: Transmit power requirements of 5.4Km and 24.3 Km links and its effect on the achievable throughput at MCS 13

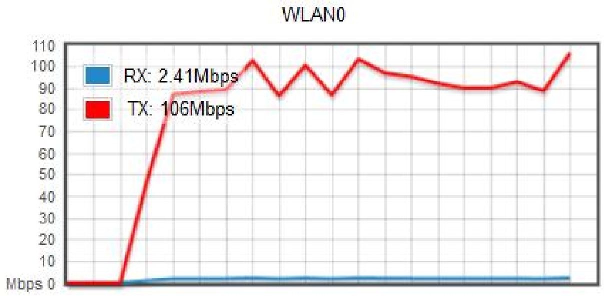

Figure 4-6: TCP throughput observed on 5.4km link at 27dBm at MCS 13

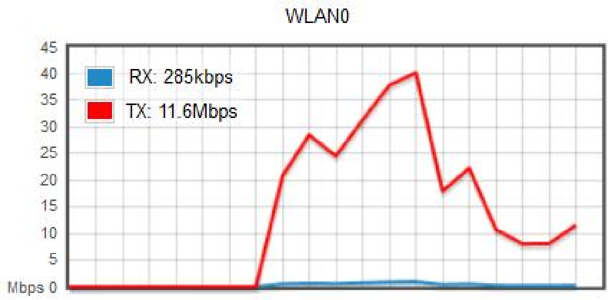

Figure 4-7: Actual throughput observed on 5.4km link at 6dBm at MCS 13

Repeating the transmit power requirements analysis for a 10.7km link as was carried out above, the path loss (*pl*) is obtained to be 128.3dBm, the receiver sensitivity remains at -79dBm for MCS 13 and the new minimum transmit power is found to be 4.3dBm as calculated in equation (4.8) below.

$$P_t = -30dBi - 109dBm + 128.3dBm + 15dBm = 4.3dBm \tag{4.8}$$

Similarly, the 10.7km link follows the analytical link budget requirements as defined in equation(4.8). From 4-8, it is observed that the throughput of the 10.7km link remains at zero until 6dBm transmit power is reached at which point it shoots to approximately 60Mbps. Since the experimental transmit power is in the scale of $\pm 3dBm$, the $M_{reserved}$ is an acceptable approximation and equation(4.5) may be used to define link budget requirements of varying lengths.

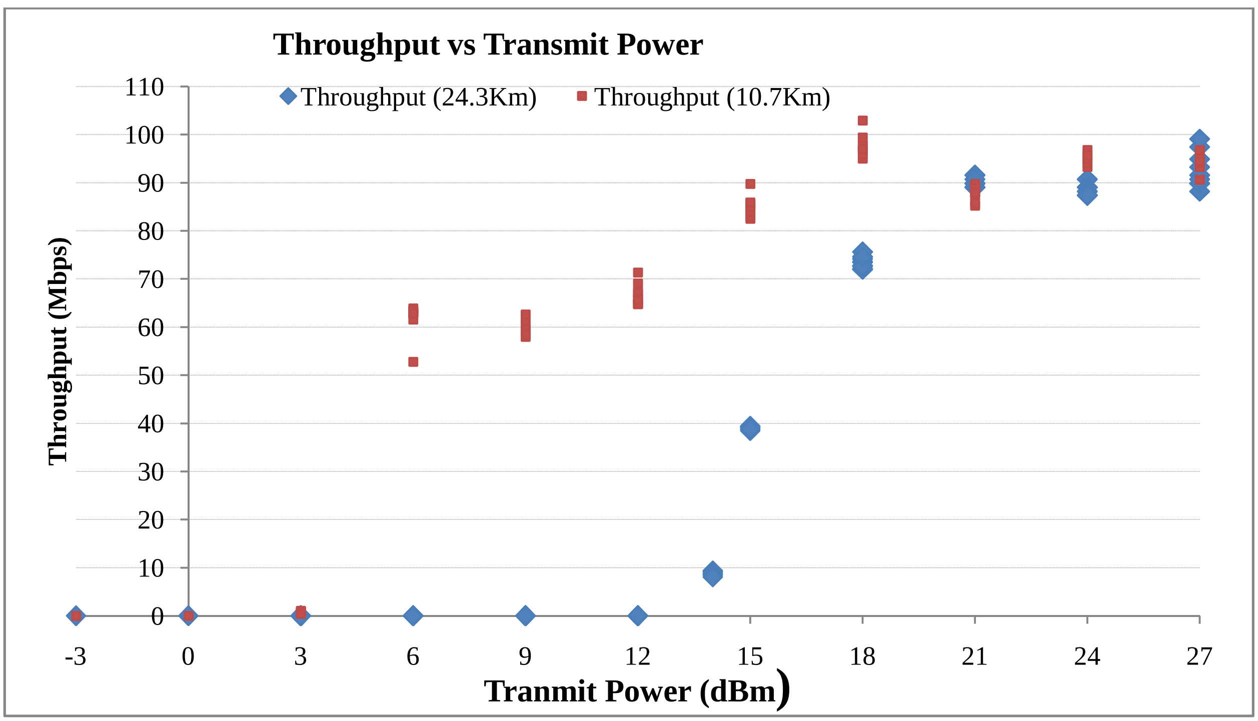

Figure 4-8: Comparison of transmit power requirements of 10.7Km and 24.3 Km links

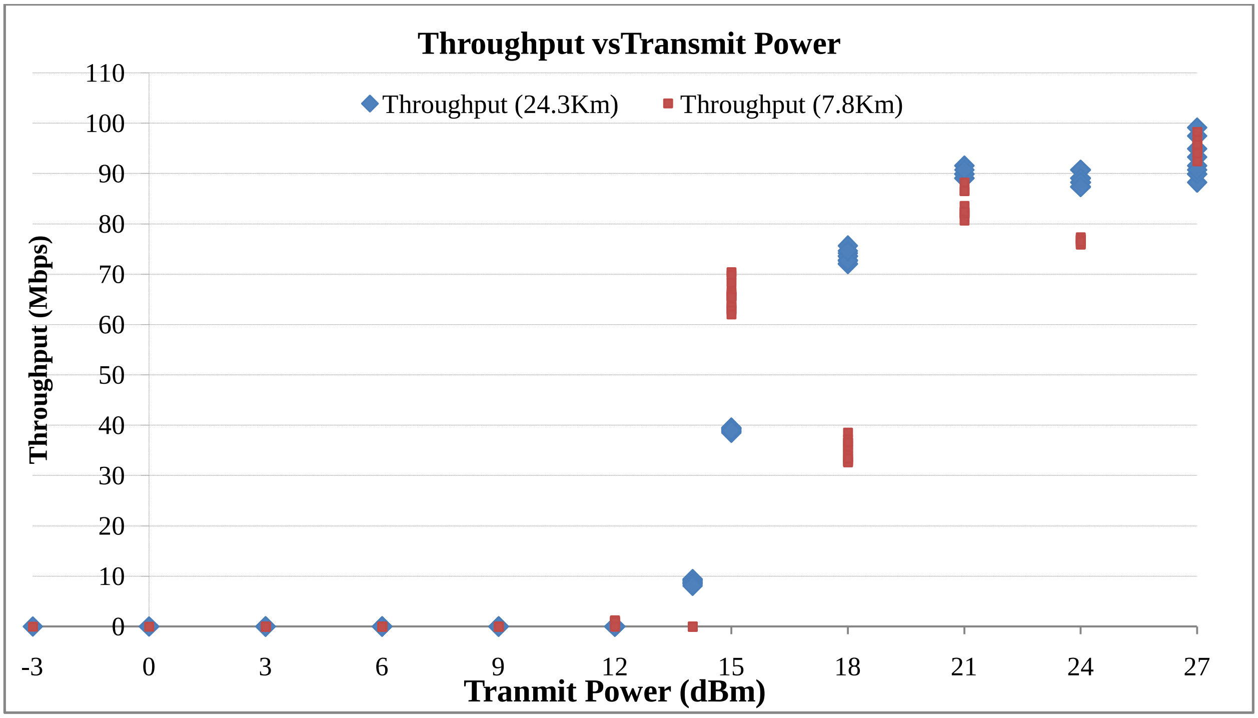

Figure 4-9: A comparison of transmit power requirements of 7.8Km and 24.3 Km links

From the basic theory of link budget requirements and modulation and coding rates schemes, a simple rule of thumb is that the minimum threshold of transmit power must be met for the link to be established[11]. This is observed in all the cases as depicted in figure 4-5, 4-8, 4-9 and 4-10. It is seen that the shorter links (as 2.7km shown in 4-10) requires lower transmit power in order for the link throughput to rise above zero. Since 4-10 compares the longest link and the shortest links tested, it is very clear that the effect of transmit power significantly affects the links throughput. The shorter links require significantly lower transmit power when compared to the longer links in order to achieve the same peak throughput. An analysis on the difference in the amount of transmit power required for these two links in order to attain the equal peak throughput is done by testing the effect of path loss, *pl*, difference between the two links. From equation (3.8) the *pl* for the 2.7km link is obtained as:

$$pl = (\frac{4® r}{\lambda})^2 = (\frac{4® \times 2.7 \times 10^3}{0.052})^2 = 4.257 \times 10^{11} = 10\log(4.257 \times 10^{11}) = 116.3dB \qquad (4.9)$$

Similarly, the *pl* for the 24.3km link is equal to 135.4dB. The *pl* difference, Δfsl is

$$\Delta pl = 135.4dB - 116.3dB = 19.1dB \qquad (4.10)$$

To show that the transmit power requirements of these links is significantly affected by their length, the points at which they attain the peak throughout (100Mbps) should have the transmit power difference equal to 19.1dB as obtained from equation(4.10). Looking at 4-10, the 2.7km link attains peak throughput at the transmit power of 9dBm whereas the 24.3km link at 27dBm, which is a difference of $18 \pm 3dBm$, a very close approximation, which agrees to the above analysis. A group bar chart in figure 4-11 illustrates the general trend of average throughput at different transmit power as a comparison for different link distances.

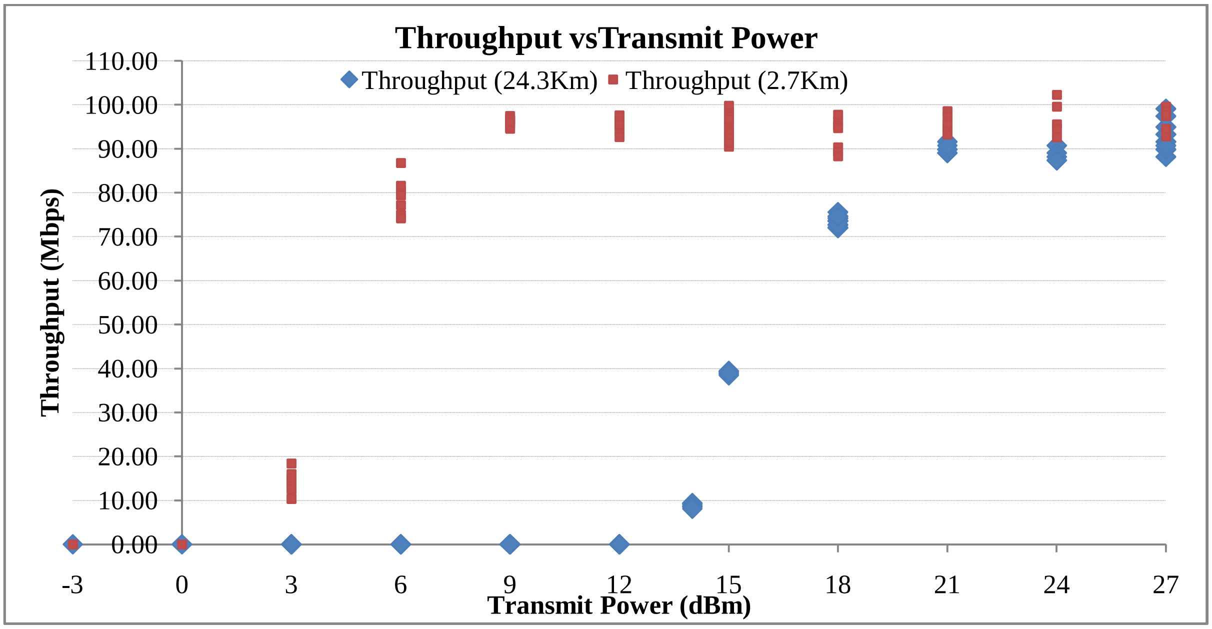

Figure 4-10: A comparison of transmit power requirements of 2.7Km links at MCS 15 and 24.3 Km at MCS 15

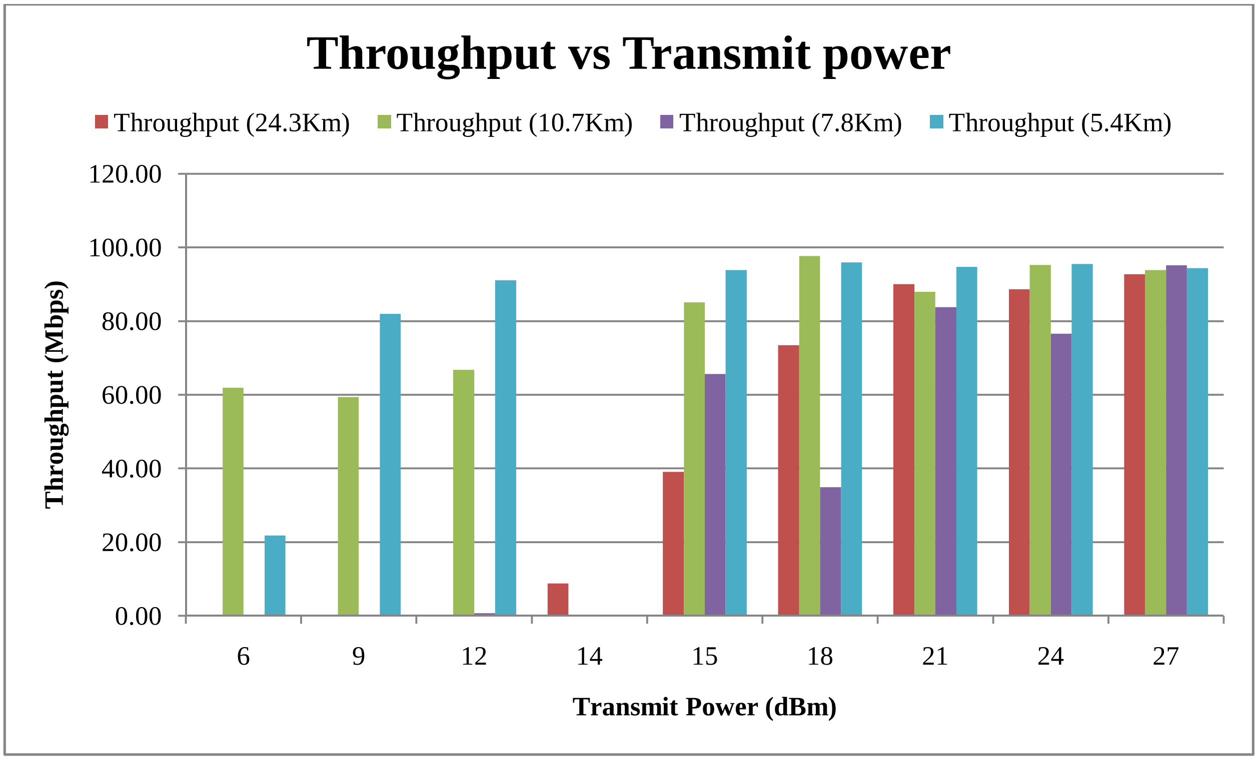

Figure 4-11: A group bar chart showing average throughput for different link lengths and transmit powers

4.3 Choosing the best MCS for different link lengths

The goal of the next set of tests is to determine how the transmit rate affects throughput for different link lengths. The idea is to develop a predictive model that may be used to guide future deployments particularly in selecting what MCS to use for different link lengths. As expected, different link lengths work best with differing MCS indices [25].

Figure 4-12 compares the performance of the shortest, 2.7km, to the longest, 24.3km, links in terms of the achievable throughput. It is observed that, the ideal performance of 802.11n Wi-Fi links, at 5GHz frequencies in a typical indoor setup for which it was designed, is replicated pretty closely when used to establish long distance point-to-point links. For the two links, the throughput increases steadily from the lowest MCS to the highest in the lower set and a similar trend is observed for the higher set of the MCS indices. It is noted that in both links, the peak throughputs for the lower MCS set is smaller than the one achieved by the higher MCS set. This trend agrees in theory on which these two sets of the MCS values are founded. The lower MCS set utilizes spatial diversity, implemented using maximum ratio combining (MRC), to increase the link quality for longer transmission range, whereas the higher set of MCS values exploits spatial multiplexing to transmit two simultaneous data streams over the same channel and thereby achieve higher data rates at the expense of shorter transmission range.

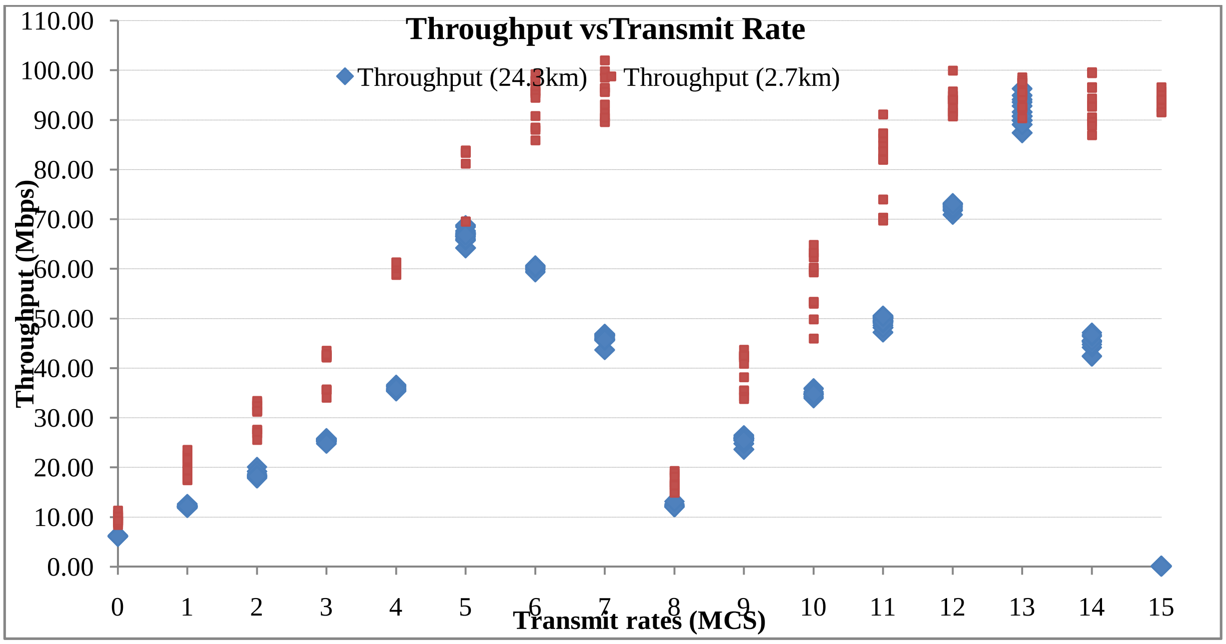

Figure 4-12: A comparison of dependence of throughput on the transmit rate for 24.3Km and 2.7Km links

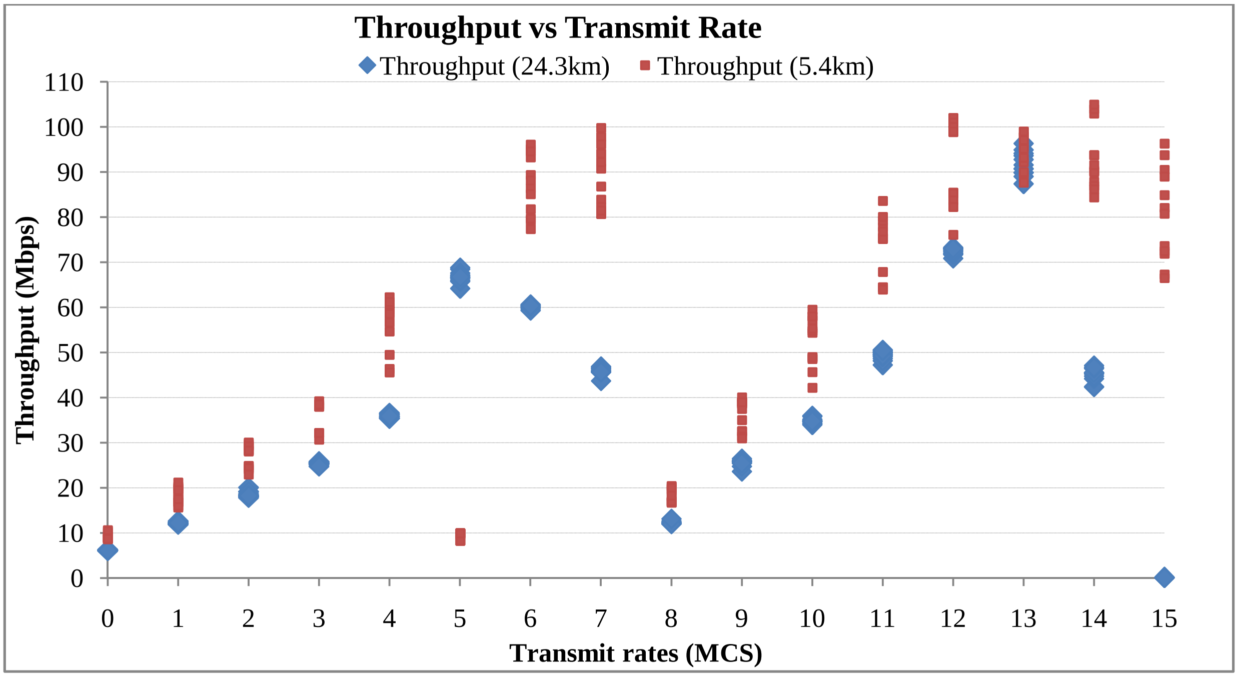

Figure 4-13: The dependence of throughput on the transmit rate for 24.3Km and 5.4Km links

Another common trend, as observed in figure 4-12 and 4-13, is that the higher set of MCS values for the shorter links (2.7km and 5.4km) performs optimally and achieves the peak throughput of 100Mbps without breaking down. However, these same MCS values begin to break down, at MCS 14 and 15, and perform abysmally for the longer links (7.8km, 10.7km and 24.3km), as may be observed in figure 4-14 and 4-15. This is indicative of the distance limit beyond which a given MCS index may no longer be usable [25]. As mentioned earlier, the peak throughput is constrained at 100Mbps, a limit imposed by the category 5e Ethernet cables, whose maximum bandwidth is 100Mbps.

A very consistent finding is that the lowest MCS indices, in both lower and higher MCS sets, are least affected by distance. This is evident from the fact that in both sets, all the link distances have relatively the same throughput values. In all the links, the throughput ranges between 10-20Mbps for MCS 1 and 2 while the MCS 8 and 9 deliver a relatively higher throughput values in the range of 10-40Mbps. Further, the variation of throughput between the shortest and the longest links, at the lower edge of both of the MCS sets is not as pronounced as in the upper edges of these sets. It is observed that with an increment in MCS index in the both sets there is a wider disparity between the observed throughputs.

While the data collected may not satisfactorily be used to develop a comprehensive predictive model, to predict the expected peak throughput for link distances exceeding 25km, the observations made are nonetheless conclusive in the fact that throughput decreases monotonically with distance no matter the MCS used. Higher MCS indices, in each MCS set, are most affected by the link distance. Further, the higher MCS set is more adversely affected by distance in comparison to the lower set. This, however, is in contrast to the achievable throughput for the two sets; the upper indices, of each set, despite delivering superior performance, breaks down faster with distance in comparison to the lower MCS indices. Again, while the lower edge MCS indices are relatively stable with increase in link distance, they do not deliver as high throughput.

There are some inconsistent trends, particularly with the performance of 7.8km and 10.7km links at MCS 14 and 15 in comparison to that of 24.3km link. The two former links exhibits slower or zero throughputs while the latter shows considerably higher capacity, in the range of 40-50Mbps. While it was expected that the two links would perform better in these MCS indices, this failure to agree with the expectation may be explained by the variation of the link environments of the three links. As found out in section 3.3, the 24.3km link achieves 100% the Fresnel zone clearance by far while the former two barely meets this requirement.

The observed trend of the behavior of link throughput with different MCS indices, therefore, acts as a very useful guide for future deployments of Wi-Fi based long distance point-to-point links. Someone wishing to attain a given throughput with a certain degree of reliability is able to choose an optimal MCS depending on the link distance, by using the graphs in figure 4-12 to 4-15.

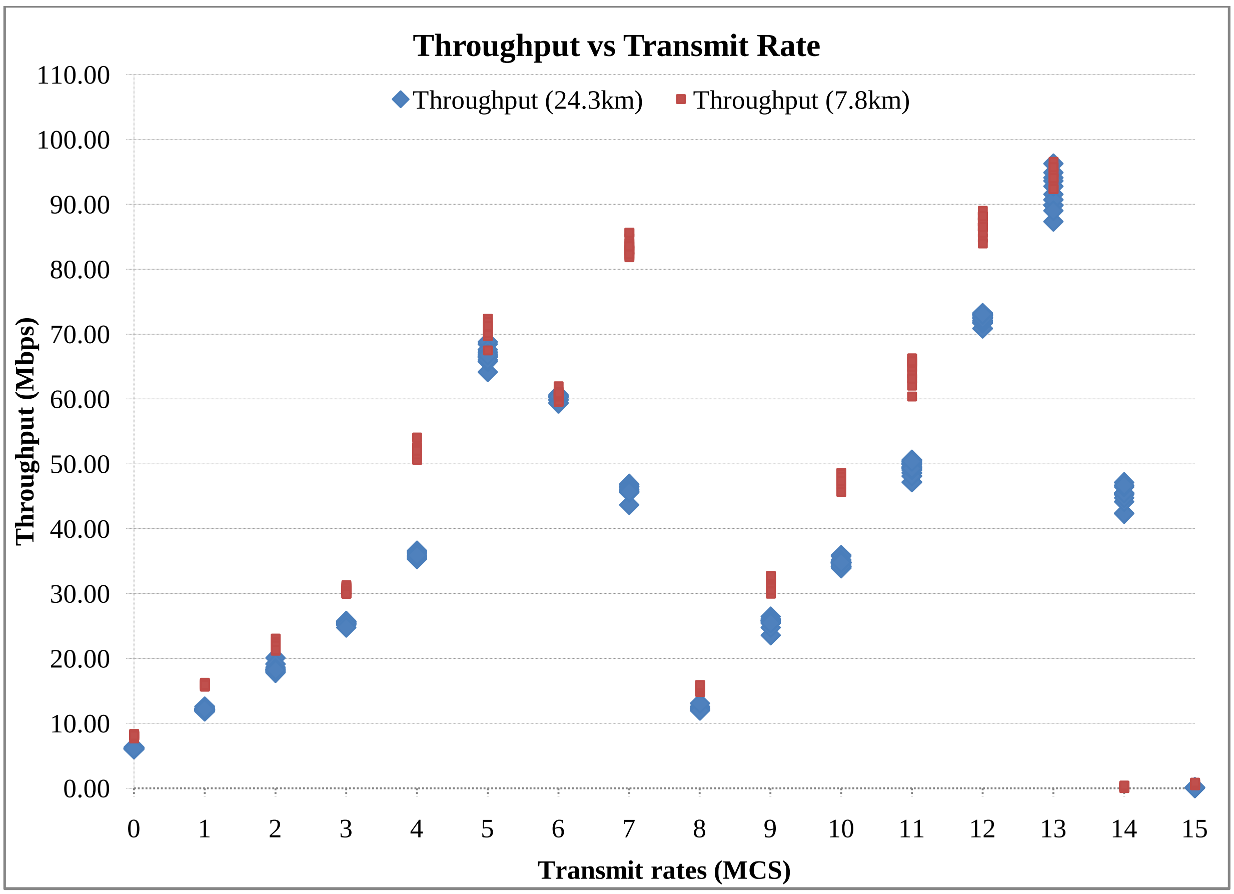

Figure 4-14: Dependence of throughput on the MCS indices for 24.3Km and 7.8Km links

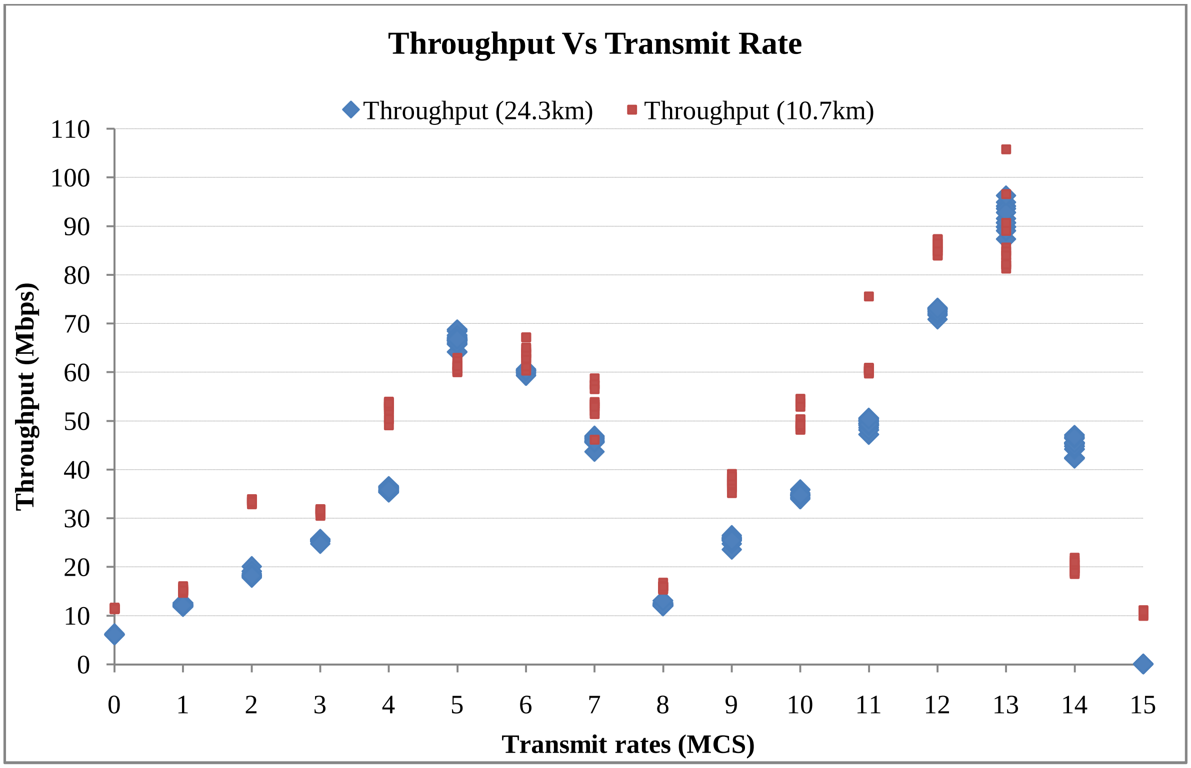

Figure 4-15: Dependence of throughput on the MCS indices for 24.3Km and 10.7Km links

To illustrate the significance of the findings above, the actual TCP throughput observed on the 10.7km link is demonstrated in figure 4-16 to 4-19. At the extreme end of the MCS indices, a very high variability and unreliability is observed as shown in figure 4-17. It is observed that the high variability observed at MCS 15 (in figure 4-17) reduces to a very consistent and reliable trend when a lower MCS index such MCS 12 is used (as shown in 4-19). While the MCS 0 and MCS 6 do not have as high variability, their peak throughput is superseded by the MCS 12 and therefore the later becomes the preferable choice for the 10.7km link. Figure 4-20 summarizes the performance of different MCS indices for different link distances by comparing them in a bar chart.

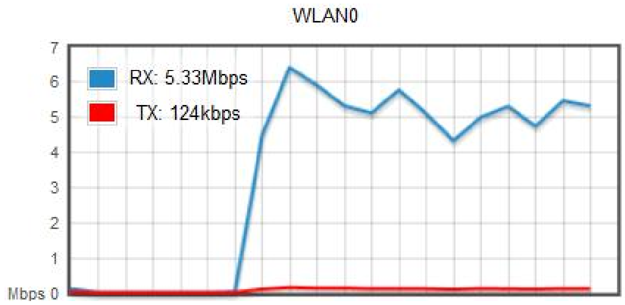

Figure 4-16: TCP Throughput observed on 10.7km link at MCS 0 (Lowest MCS)

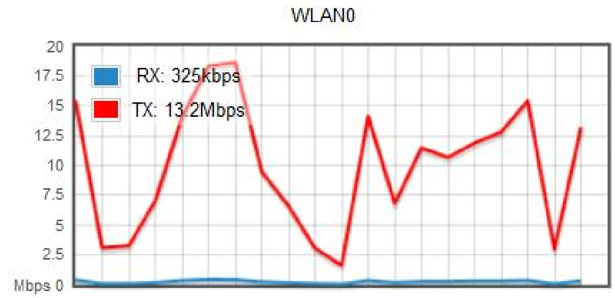

Figure 4-17: TCP Throughput[5] observed on 10.7km link at MCS 15 (Highest MCS with highest variability)

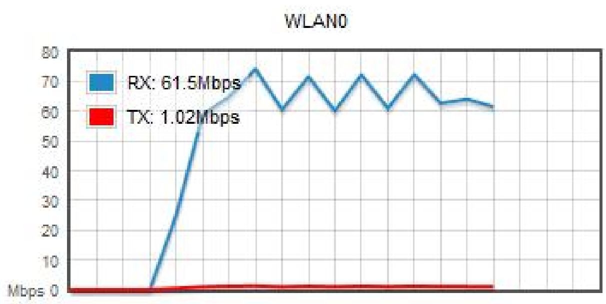

Figure 4-18: TCP Throughput observed on 10.7km link at MCS 6 (low but reliable choice)

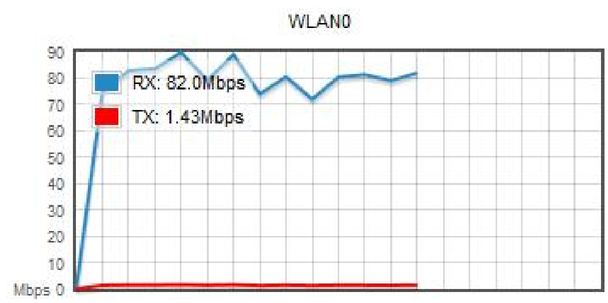

Figure 4-19: TCP Throughput observed on 10.7km link at MCS 12 (best performing MCS)

[5] An upload file transfer is used to capture the TCP throughput in this figure instead of download file transfer which used in the other figures. The difference is, nonetheless, inconsequential.

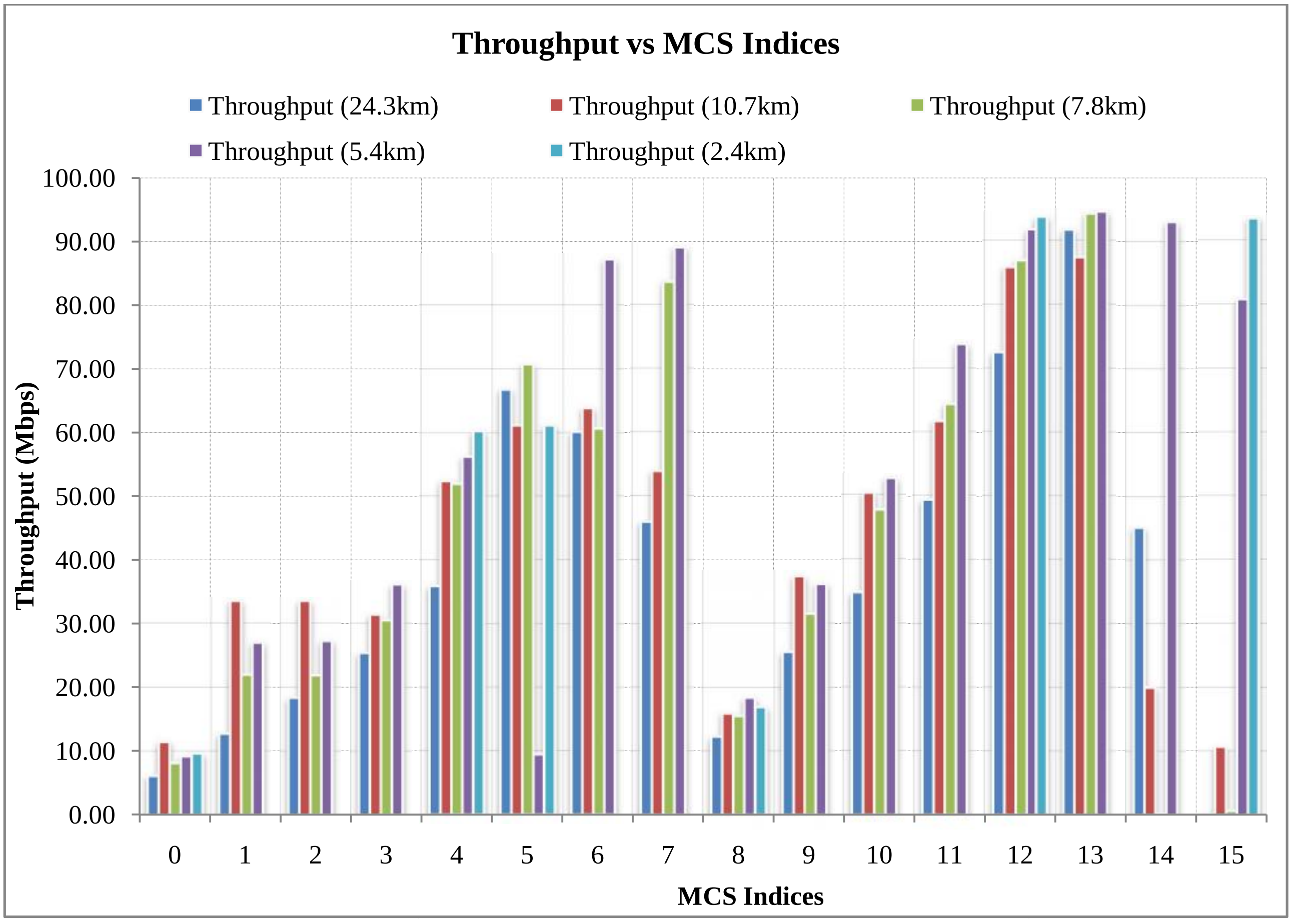

Figure 4-20: A bar chart comparison of throughput dependence on MCS indices

4.4 Non-significance effect of the packet size on link quality

Different packet sizes are sent over each of the five links and different observations are made as shown in figure 4-21. It is noted that there is a minimum packet size below which all the links break down and no communication is possible. 1500 bytes packet size is the minimum set by the manufacturer of the Ubiquity Wi-Fi radios. The tests are therefore limited to packet sizes equal to and greater than 1500 bytes.

Since maximum packet size defined for the 802.11 standards is 2024bytes, variation between these two limits is made and its effect on throughput is observed. It is noted that the effect of packet size on achievable throughput at these limits is not significant and appears to be random and inconsistent. Further, the default packet size, as set by the manufacturer, outperforms larger packets sizes, although there is no very consistent trend to validate this fact as seen in figure 4-21.

In theory, it is expected that larger packet sizes would render high throughputs since it is assumed that each packet would have the same header overhead and therefore accommodate more data in the payload section[26]. However, the observation from figure 4-21 indicates no significant improvement. It is logical to argue that since 802.11n standard does utilize frame aggregation as a means of increasing throughput, by sending larger sizes of frames before expecting acknowledgement, it is possible that increased size of packet, only adds padding in the payload without necessarily increasing data size[24]. Therefore, this means that relatively equal throughput is observed for all the packet sizes within the acceptable range of 1500-2024bytes packet sizes. In this case therefore, the insignificant variation observed in figure 4-21 is better explained by the differences in links varying environments and other intricate properties associated with each link, than by the packet size difference.

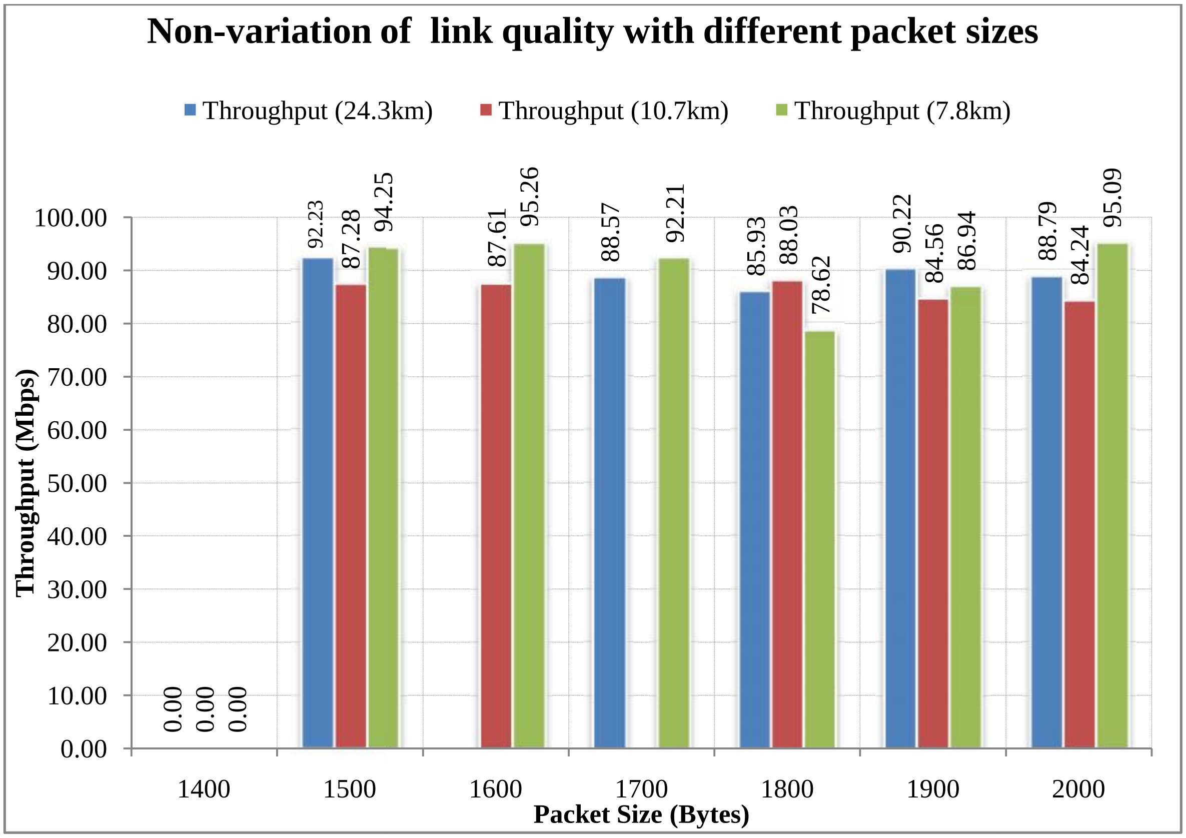

Figure 4-21: a bar chart illustrating the effect of packet size on throughput achievable on links of varying distances

4.5 The detriment of external Wi-Fi interference on the link quality

It is generally accepted that any external Wi-Fi interference to an 802.11 link will cause considerable interference. In this set of tests, the actual extent of external Wi-Fi interference on a point-to-point link is sought to be quantified. Two parallel links of 0.6km in distance are set up, both using different antennas, of different gains and features. Link A, utilizes a pair of 17dBi parabolic dish antennas, Ubiquiti Airgrid™ M5, in a Single Input Single Output (SISO) antenna system configuration. Link B uses a pair of 25dBi parabolic dish antennas, Ubiquiti NanoBeam™ M5, whose radios employ 2x2 MIMO antenna systems.

Before introducing interference, each antenna pairs are tested individually to test their TCP throughput performance. After doing initial antenna alignment as described in section 3.9 TCP throughput performance is tested by initiating TCP file transfer over the link. A 1.17GB file is sent across each link and the speed achieved for each transfer is averaged. The results of these tests are shown in the first-two bar charts in figure 4-22. It is worth noting that these two links have different average throughputs, despite having similar environment and conditions of operation. This is attributed to antenna misalignment in link B, which was observed after the tests were underway. While aligning the antennas could have generated higher average throughput, its significance would have been inconsequential since the comparison was on the influence of the external Wi-Fi inference on the links initial average.

The next step involves running the two parallel links simultaneously while performing the TCP file transfer. A critical decline in the average throughput is observed in both of the links, with link A being the most affected. A 72% decline in throughput is observed in link A in comparison to 46% decline in link B. This shows superior performance of link B whose antennas are built on MIMO technology in relation to a SISO based antennas.

Interference becomes highest pronounced when the Wi-Fi radios operate in the same channels. To curb this scenario, it is recommended that Wi-Fi radios in close proximity operate on channels that are far apart to avoid co-channel interference or channel leakage. Channel shifting is a feature enabled in most 802.11 radios which if enabled changes from the channel in use to the one with least usage and hence lowest interference.

While the first interference tests are conducted with channel shifting disabled in both links, the two subsequent tests have channel shifting enabled in either of the links, while in the other link channel shifting remains disabled. The third and fourth bar charts in figure 4-22, illustrates these observations. It is noted that there is a further decrement in throughput for both of the links. The MIMO based link, link B, performs better when it is shifting the channels and worst when interferer, link A, is shifting channels. This may be attributed to indeterminate nature in which the channel shifting algorithm randomly selects the available, less interfered channels.

Contrary to the expectations, that channel shifting would improve the links tolerance to external Wi-Fi interference, it is noted that working with fixed but separate channels is far much superior to any attempts to apply channel shifting, whether singularly or simultaneously.

The preference to operate links on fixed but separate channels applies to the worst case scenario when two or more interfering links cannot be avoided. The best option, though, is to separate the interferers in terms of distance as far as possible. This is evident as in figure 4-23 which gives a vivid comparison between when a link interference-free, has interference without applying channel shifting and when either interferer applies channel shifting or both.

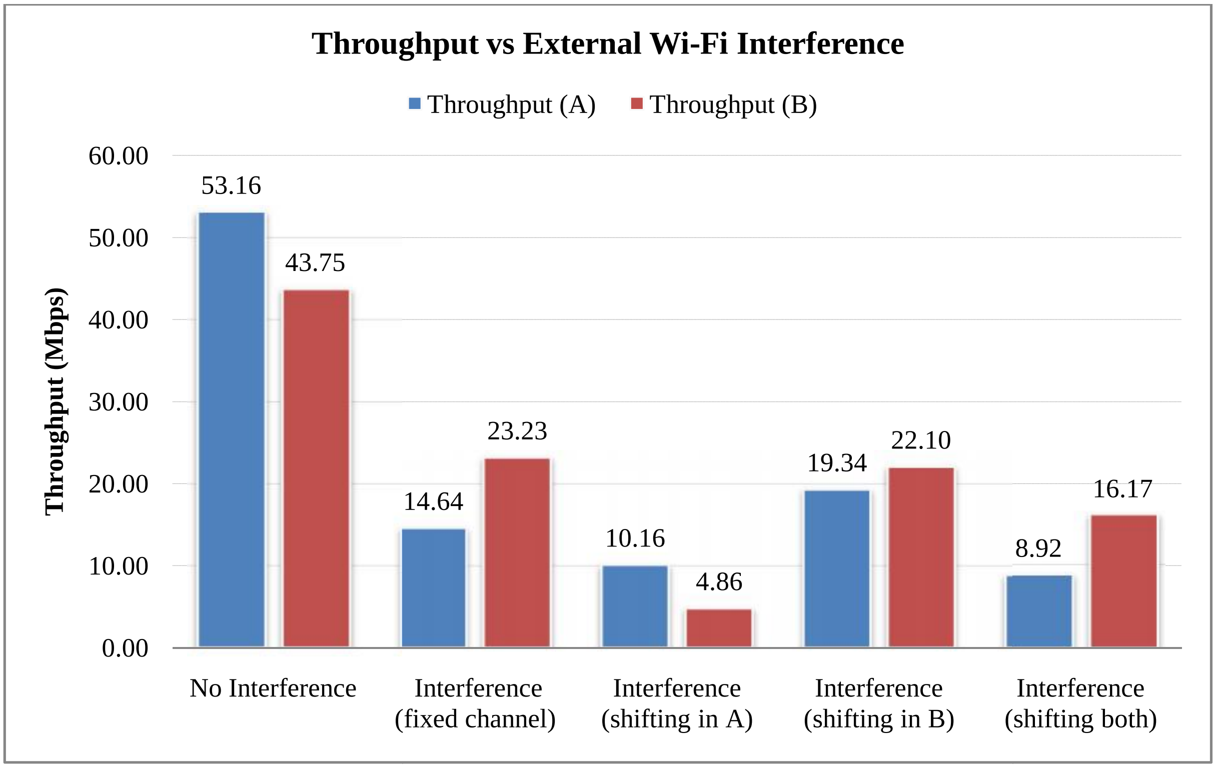

Figure 4-22: Effect of external Wi-Fi interference on average links throughput

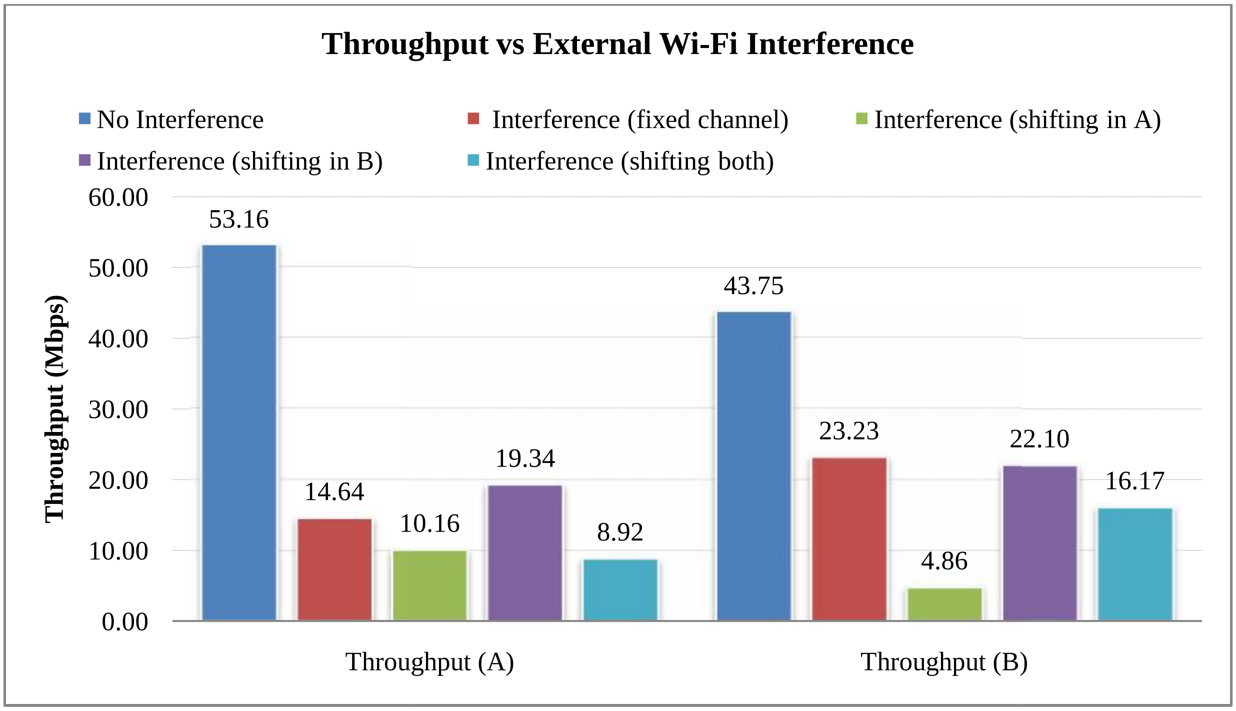

Figure 4-23: A comparison of two links response to external Wi-Fi interference

Figure 4-24, and Figure 4-25 illustrates the comparative performance of links A and B under interference at fixed channels, whereas figure 4-26 and Figure 4-27 illustrates their performance under channel shifting conditions, respectively.

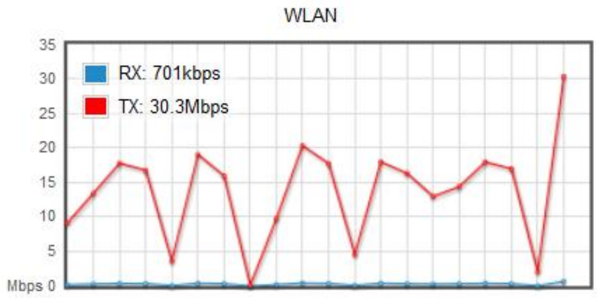

Figure 4-24: TCP Throughput observed on link A with interference at fixed channels

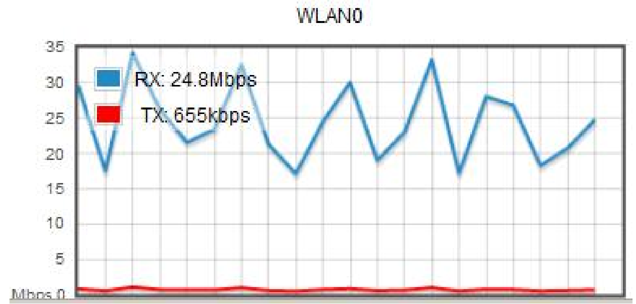

Figure 4-25: TCP Throughput observed on link B with interference at fixed channels

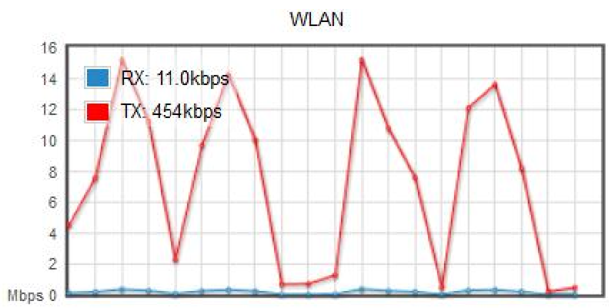

Figure 4-26: TCP Throughput observed on link A with interference (Channel shifting enabled in both link A & B)

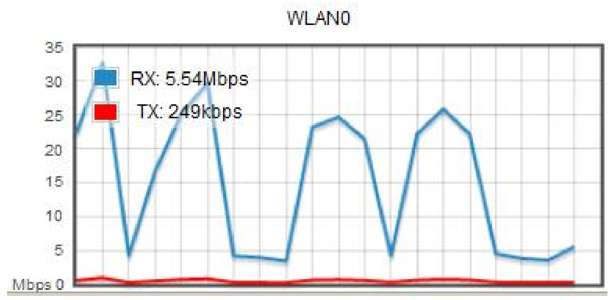

Figure 4-27: TCP Throughput observed on link B with interference (Channel shifting enabled in both link A & B)

4.6 The interrelationship between packet loss and throughput

In each of the observations made for achievable throughput, in all the five links, the related packet losses are also recorded. Ping tests are done, simultaneously with the TCP file transfers. Substantial packet losses are observed when a given parameter is set beyond its acceptable fundamental performance limit as defined in the empirical graphs for the varying link distance. Non-clearance of the line of sight and Fresnel zone severely degrades the performance of the link. For instance, there is significant rise in the packet losses when the nodes are supplied with inadequate transmit power; whenever the transmit power is below the minimum link budget threshold, as described in section 4.2 above, high packet losses rise above 90%.

4-30 shows packet loss at transmit power below the threshold limit of 15dBm and figure 4-31 shows packet loss at transmit power above this threshold. Similarly, as discussed in section 4.3, MCS 14 and 15 experiences significant packet losses, at link distances beyond 7.8km. Figure 4-28 and 4-29 illustrate non-significant packet loss for the 24.3km.

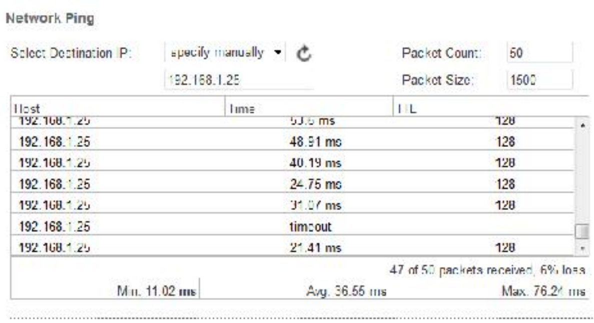

Figure 4-28: Packet Loss at unsuitable MCS 14 for 24.3km Link

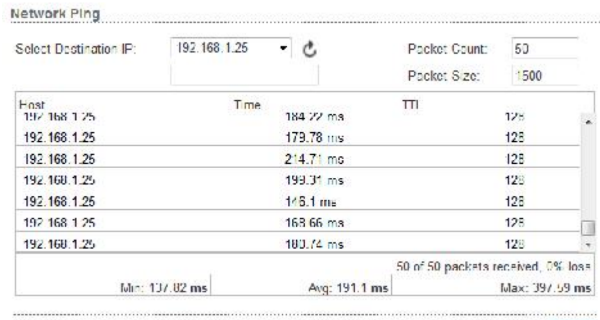

Figure 4-29: Packet Loss at suitable MCS 8 for 24.3km Link

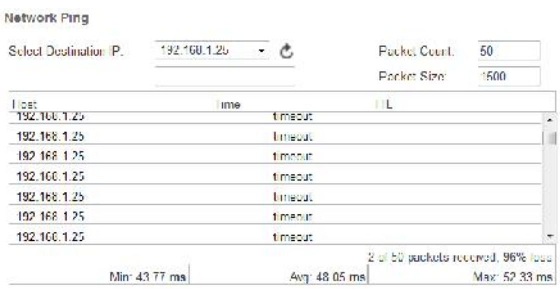

Figure 4-30: Packet Loss at inadequate transmit power 12dBm for 24.3km Link

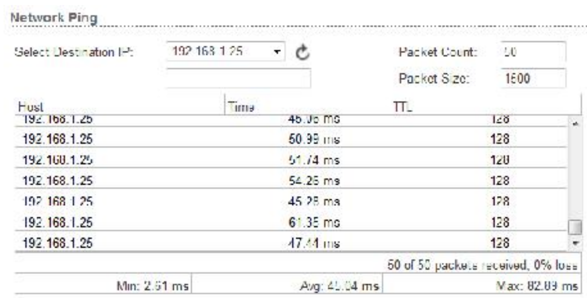

Figure 4-31: Packet Loss at adequate transmit power 27dBm for 24.3km Link[6]

Channel width on the other hand does not affect the observed packet losses. The maximum as well as the minimum channel widths, 40MHz and 5MHz respectively, demonstrates 0% packet losses as can be seen in **Error! Reference source not found.** and **Error! Reference source not found.**

[6] MCS 7 is used in this case, whereas MCS 13 is used in the link shown **Error! Reference source not found.** and Figure 4-33

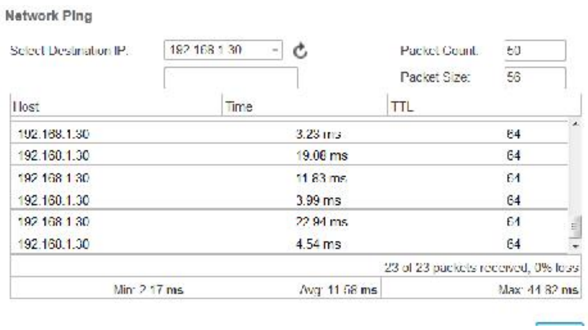

Figure 4-32: Packet Loss at 40MHz channel Width for 10.7km Link

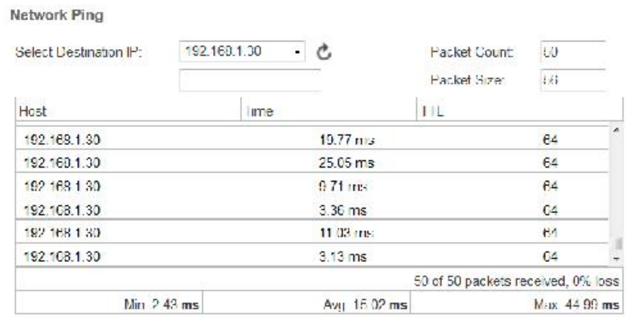

Figure 4-33: Packet Loss at 5MHz channel Width for 10.7km Link

4.7 Summary

The longer the link distances, the poorer the observable throughput for each of the link parameters, that is the channel width, transmit rate (MCS), and transmit power. There is definite length beyond which certain parameters are not usable. There was, however, a notable non-variation of observable throughput with varying channel width for the entire range of tested link distances, between 1 and 25km, as cited earlier, this was attributed to the upper limit, at 100Mbpsthroughput, imposed by the category 5e maximum achievable bandwidth. The size of the packets transmitted is immaterial in regard to the observable peak throughputs.

Inter-link and external Wi-Fi interference degrades the achievable throughput to as low as 72% decline in link throughput. Further, Substantial packet losses are observed when a given parameter is set beyond or below its acceptable fundamental performance limit as defined in the empirical graphs for the varying link distance. For instance, there is significant rise in the packet losses when the nodes are supplied with inadequate transmit power; whenever the transmit power is below the minimum link budget threshold, as described in section 4.2

above, high packet losses rise above 90%. Further, non-clearance of the line of sight and Fresnel zone severely degrades the performance of the link, making the link unfeasible.

1) Is there any correlation between packet loss and throughput? Is there a set of parameters that maximizes achievable throughput with respect to link distance?

90-100% packet losses are associated with 0Mbps throughput. This situation arises when line of sight is not cleared or when a given parameter is set beyond or below its acceptable fundamental performance limit as defined in the empirical graphs for the varying link distance. At any given moment, there exists a set of parameters that delivers maximum throughput. This set is a function of distance; that is, for each given link distance, there is channel width, MCS and transmit power that delivers maximum achievable throughput.

CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This thesis demonstrates a simplified test-bed model of a long distance point-to-point links operating in the UNII-3 Wi-Fi frequencies. The model developed requires use of TDMA based MAC protocol in the data link layer in order to overcome the fundamental shortcomings of per packet acknowledgment and carrier sense detection experienced in the CSMA/CA based off-the shelf Wi-Fi radios. A replicable high-throughput link setup is realized using this model for long distance links, as high as 25km, which is way beyond the typical 100m range of the standard 802.11 links. A consistent and scientific investigation in the performance and reliability of such links is presented. This investigation presents a detailed a cause-effect inter-relationship arising from the variation of link parameters from the worst set of settings to the best settings. Finally, a series of empirical graphs is demonstrated which marks the fundamental performance limits of each link parameter.

The results obtained validate the use of UNII-3 Wi-Fi frequencies in setting up long distance point-to-point links in rural areas. They show that despite the links' stringent requirement for line of sight, they are capable of delivering high bandwidth, 100+Mbps, broadband Internet. Further, it contrasts the superior performance of TDMA based (*AirMAX*™) Wi-Fi radios, to the inferior performance of the off-shelf radios, which are based on CSMA/CA. This therefore confirms that the challenges of delayed acknowledgements and link level contention based mechanisms, associated with the CSMA/CA based MAC protocol in establishing long distance links are easily overcome using the TDMA approach as predicted by Patra et al [6]. This therefore confirms that

TDMA approach of MAC protocol, implemented on Wi-Fi radios, is capable of delivering high throughput internet access in rural areas using point-to-point links at UNII-3 frequencies.

This work shows that in order to use the ordinary off-the shelf Wi-Fi radios in the long distance outdoor settings, only a few amendments are required. Since these devices operate on the 802.11a/b/g/n standards, a change of the CSMA/CA based MAC protocol to the TDMA based MAC layer needs to be effected. This change is necessitated by the fact that the 802.11a/b/g/n standards were originally intended for indoor and short range use, where collisions and media sensing as well as per packet acknowledgments were essential.

Since the Wi-Fi technology has enjoyed mass popularity both in production and adoption, a standardised non-proprietary TDMA MAC protocol is preferable so that manufacturers can implement it, en-mass, on off-the-shelf devices. This standardization will motivate the adoption of the developed model and thereby meet the existing need of serving underserved remote and rural areas with unlicensed and inexpensive broadband Internet access.

5.2 Recommendations

While this work uses and recommends the use of Wi-Fi radios whose MAC protocol is based on the TDMA MAC to implement long distance Wi-Fi based long distance point-to-point links, its actual design and implementation remains non-standardized and unknown. The existing TDMA based MAC protocols, namely: *AirMAX* and *Nstreme*^{TM} are, to say the least, proprietary and their performance metrics can only be assessed as a black box. It is not possible to pinpoint the exact cause of any abnormality in performance of the TDMA radios at a given parameter.

It is preferable that the design and implementation of these TDMA based MAC protocols be made public and accessible to other scholars, technology enthusiasts as well as manufacturers. In this case, any design flaws and performance bottlenecks that may arise will correctly be identifiable and corrected. Further, openness to scrutiny allows other superior designs to developed thereby making the entire approach popular as well as full grown it its capacity to deliver broadband access to the under-served areas.

Further, since these protocols are not inter-operable even amongst themselves, it is desired that a standardized design be published and formalized such that manufacturers may to adhere to them in order to achieve device compatibility. This will in effect reduce the vendor lock-in among the radio users. In this regard, the author recommends the Communication authority of Kenya (CAK) to collaborate with *IEEE Standards Association* in considering a joint initiative such as a Task Group (TG) whose mandate is evaluating the possibility of amending to the 802.11 standard to incorporate the TDMA approach on the UNII-3 based Wi-Fi radios for use in long distance links set-up. Once the standardization is complete, the *Wi-Fi Alliance* will be in a position to certify the long distance Wi-Fi radios from different manufacturers to ensure their conformity to the standards of interoperability and/or compatibility to the existing 802.11 wireless networking devices.

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APPENDICES

APPENDIX A: LIST OF PUBLICATIONS

Warutumo Mureithi, Kibet Langat, and Vitalice Oduol, "Using UNII-3 (Wi-Fi) Frequencies to Establish Long Distance Point-to-Point Links Capable of Providing Broadband Internet Access to Rural Areas: Experimental Validation," *Innovative Systems Design and Engineering*, vol. 5, no. 10, pp. 40-49, November 2014.

Warutumo Mureithi, Kibet Langat, Ciira Maina, and Vitalice Oduol, "Link budget requirements of long distance point-to-point links based on UNII-3 frequencies," in *KSEEE-JSAEM International Engineering Conference*, Mombasa, 2014.

Warutumo Mureithi, Kibet Langat, Ciira Maina, and Vitalice Oduol, "Extending IEEE 802.11 (Wi-Fi) Range: modulation and coding scheme factor," in *International Engineering Conference*, Mombasa, 2014.