UNIVERSITY OF NAIROBI

SCHOOL OF ENGINEERING

PERFORMANCE CHARACTERIZATION OF E-BAND LINKS FOR WIRELESS BACK-HAUL IN BROADBAND NETWORKS: THE CASE FOR KENYA

BY

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F56/68842/2011

A Thesis submitted in partial fulfilment for the Degree of Master of Science in Electrical and Electronic Engineering, in the Department of Electrical and Information Engineering in the University of Nairobi

January 2018

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Dedication

I dedicate this work to my wife Emma and son Sewe for the support and encouragement during my studies.

Acknowledgement

I would like to express my sincere appreciation to my supervisor Prof Vitalis Oduol for the guidance, encouragement and insightful contribution that helped to shape this research topic. Your ability to handle difficult situations has been unrivaled. Thank you so much and may God bless you abundantly.

I would also like to express my gratitude to my second supervisor Dr. Peter Akuon whose energy and keenness to details ensured standards, procedures and best practices were followed to the letter. Thank you for helping us to improve the organization of this work and successful completion.

Further appreciation goes to my employer Safaricom limited and partners NEC Africa and Aviat Networks, through my line manager David Adhiambo and heads of department Robert Mutai and Elly Odera for facilitating this project to successful completion.

To my loving wife Emma, your support has been enormous. I must admit that it's through your understanding, support and loyalty that I have managed to reach this far. God bless you abundantly my best friend.

Abstract

The demand for high data speeds by users of mobile and fixed data services, telecom operators, data service providers and heavy data application institutions has posed a huge challenge of optimum backhaul solutions. To this end, the commercial viability for 71-76/81-86 GHz frequency band commonly referred to as E-band spectrum has attracted a lot of research for the last decade in order to find economic wireless gigabit connectivity that can complement optical fiber cable. Several countries have so far promoted the use of E-band by proposing the licensing model and licensing fee with USA and Australia cited as the countries that have implemented E-band links. Since weather statistics vary from place to place, ITU-R has recommended prediction methods for different regions based on weather statistics for link propagation design. These prediction methods are based on specific climatic and topographical conditions within radio administration territories. Given that Kenya has its own whether patterns it's necessary to carry out practical experiment to validate the literature with a view to opening up E-band for use in Kenya. This research has analyzed the usefulness of E-band point-to-point microwave link in providing wireless backhaul capacities comparable to that of fiber optic cable. In partnership with Safaricom Ltd as the sponsor, practical experiments have been utilized in this study with transceiver equipment from two suppliers: NEC Africa (PTY) Limited and Aviat Networks. In particular, microwave links that utilize the E-band frequencies were set up in three different cities in Kenya i.e. Nairobi (Latitude 01 19 10.41 S, Longitude 036 53 30.95 E), Mombasa (Latitude 04 01 24.10 S, Longitude 039 37 35.10 E) and Kisumu (Latitude 00 05 45.80 S, Longitude 034 45 20.79 E) and validated the acceptable propagation and data performance of E-band links for distances within and above the values given in the existing literature. Daily occurrences of signal losses were compared with the rainfall pattern, and this has been used to further validate the practicality of the experiments. From the experiment it can be concluded that the typical range for E-band should be up to 3km for link availability of 99.999%. It was also noted that E-band link can operate up to 6km under clear whether conditions. Based on the results, it is therefore possible to use E-band link for backhaul solution in broadband networks. The results of this case study will provide practical planning data and information on the acceptable link range, frequency planning, propagation and performance of E-band links.

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List of Acronyms

AMR	Adaptive Modulation Radio
ANSI	American National Standards Institute
BBE	Background block error
BBER	background block errored ratio
CA	Communication Authority of Kenya
CEPT	European Conference for Postal and Telecommunications Administrations
dB	Decibels
ECC	Electronic Communications Committee
EIRP	Effective Isotropic Radiated Power
ES	Errored seconds
ESR	errored second ratio
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FSL	Free Space Loss
FSO	Free Space Optics
IETF	Internet Engineering Task Force
ITU	International Telecommunication Union
ITU-R	Radio Communication sector of International Telecommunication Union
LOS	Line of Sight
MSS	Mobile soft switch
OFC	Optical Fiber Cable
PoE	Power over Ethernet
POP	Point of Presence
QAM	Quadrature Amplitude Modulation
RF BBE	Radio frequency background block error
RF ES	Radio frequency errored seconds
RF OFS	Radio frequency out of frame signal
RF SEP	Radio frequency severely errored packets
RF SES	Radio frequency severely errored seconds
RF UAS	Radio frequency unavailable seconds
RFC	Request for comments
SES	Severely errored seconds
SESR	severely errored second ratio
SLA	Service Level Agreement
SRTM	Shuttle Radar Topography Mission
UAS	Unavailable seconds
WARC	World Administrative Radio Conference

WiMAX Worldwide Interoperability for Microwave Access

List of Symbols

γ_R	specific attenuation due to rain	dB/km
k	frequency coefficient	k_H or k_V
α	polarization coefficient	α_H or α_V
γ_c	specific attenuation due to fog	dB/km
γ_a	specific attenuation due to atmospheric gases	dB/km
γ_o	specific attenuation due to dry air	dB/km
γ_w	specific attenuation due to water vapor	dB/km

Chapter One

Introduction

1.1 Theory of Microwave Radio Link Propagation and Modulation

The E-band spectrum at 71-76/81-86 GHz is of increasing interest to service providers and systems designers because of the wide bandwidth available for high speed data communication. The wide bandwidths enables the design of high capacity wireless backhaul systems that can support applications that require high speed data transmission [1].

Planning and design for the use of E-band spectrum must take into consideration the propagation characteristics of radio signals at this frequency range. While signals at lower frequency bands (6-42 GHz) can propagate for many kilometers and penetrate more easily through light vegetation and difficult atmospheric conditions, E-band wave signals can travel only a few kilometers and would struggle through vegetation and difficult atmospheric conditions, because they possess short wavelengths that can easily be absorbed by larger molecules or scattered easily by objects [1].

However, these characteristics of E-band propagation are not necessarily disadvantageous. The propagation characteristics of E-Band are almost similar to lower frequency bands with just slightly higher free space attenuation, which reduces the link distance capabilities. Firstly, the traditional frequency bands have been depleted due to an increase in the demand for mobile access backhaul; where backhaul which sometimes refers to backbone link is the intermediate link between the core network and the small subnets usually at the edge of the entire network hierarchy. Secondly, the lower bands cannot backhaul significant amount of data due to bandwidth limitations. Presently the Communication Authority, which is the spectrum regulator in Kenya, only licenses a maximum of 28 MHz of bandwidth for 6-42 GHz frequency bands, which is not sufficient to provide gigabit connectivity. In order to achieve higher data speeds with the traditional lower frequency point-to-point microwave links, higher modulation e.g. M-ary quadrature amplitude modulation (MQAM) are employed. However, higher modulation orders also suffer from amplified noise figures which impact on the overall system gain thereby limiting the propagation capability. This is because channel bandwidth limits the number of symbols per second that can be carried over a microwave carrier. With square MQAM modulation scheme, a modulation efficiency of $log_2 m$ bits is realized, which is then coded onto each symbol, where m refers to the modulation index. For example, the modulation efficiency, which is also referred to as bits per M^ary symbol is 1 for BPSK, 2 for QPSK, 3 for 8QAM. Currently the highest modulation scheme achievable by modern digital microwave radio is 1024QAM, which translates to a modulation efficiency of 10 bits per M^ary symbol. In fact, it is well known that the user bit rate is the product of modulation efficiency, bandwidth and coding rate [2]. The microwave capacity increases with higher modulation efficiencies, but this reduces the system gain. Table 1-1 and Figure 1-1 shows how the radio channel capacity and transmit power varies, by changing modulation scheme at a constant bandwidth in the same frequency band for Ericsson Minilink Traffic Node equipment. It can easily be noted that while radio capacity increases by ~170Mbps when moving from 4QAM to 1024QAM, the transmit power reduces by 5 dB resulting in system gain reduction. As result of this, the effect of propagation characteristics also changes. The net effect of this change is that at 4QAM the equipment performance will be better in longer path length/distance link and during bad weather conditions than when operating with a modulation scheme of 1024QAM. It is also worth noting that with a bandwidth of 28 MHz; only 225 Mbps can be achieved [3]. It can therefore be concluded that with cross-polarization interference cancellation (XPIC) solution, only a maximum of 450 Mbps can be achieved with lower frequency band microwave links [3].

Table 1-1: Typical microwave radio capacities and transmit power at different modulation schemes from Ericsson TN equipment [3]

Modulation	**Modulation Efficiency**	**Capacity (Mbps)**	**Bandwidth (MHz)**	**Frequency Band (GHz)**	**Transmit Power (dBm)**
4QAM	2	~46	28	23	24
16QAM	4	~92	28	23	22
32QAM	5	~115	28	23	22
64QAM	6	~137	28	23	21
128QAM	7	~160	28	23	21
256QAM	8	~182	28	23	20
512QAM	9	~204	28	23	20
1024QAM	10	~225	28	23	19

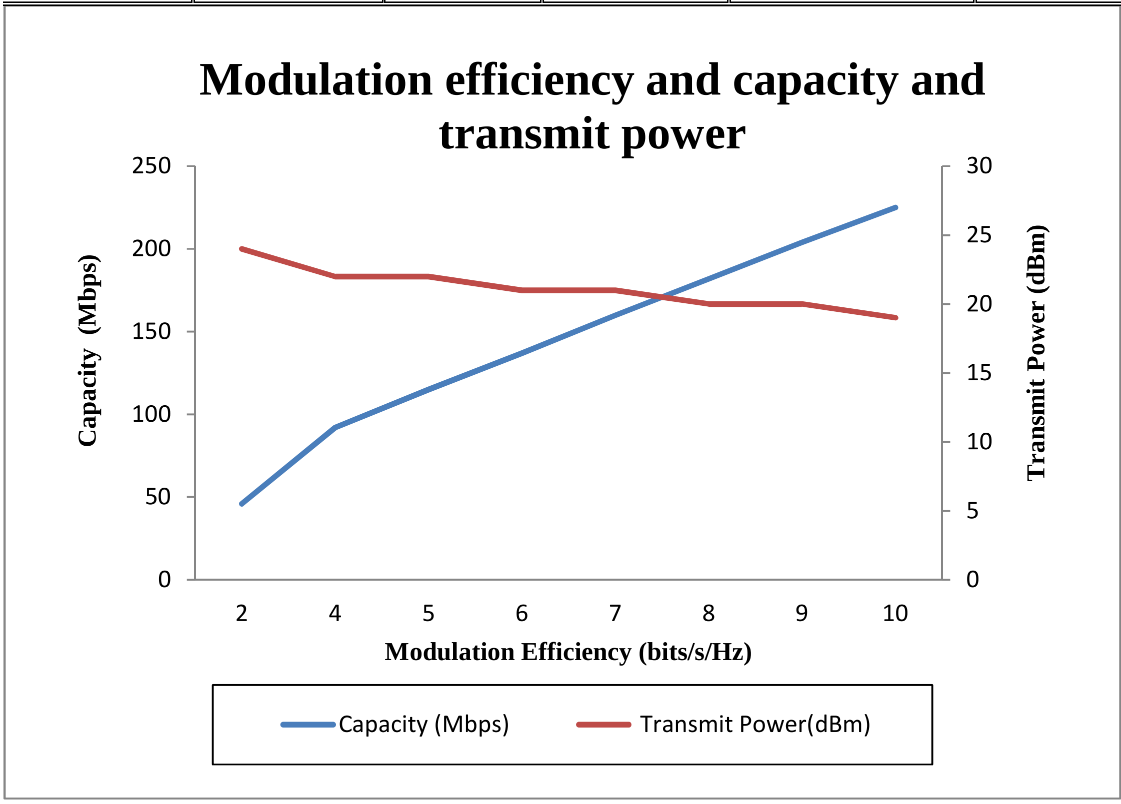

Figure 1-1 Graph of modulation efficiency, capacity and transmit power from Table 1.1 data.

1.2 Advantages of E-band

With 5 GHz bandwidth of spectrum available, E-band enables high speed gigabit per second speeds and greater data rates that cannot be achieved at the bandwidth-limited traditional microwave frequency bands. The following are some of the advantages of E-band:

High capacity E-band microwave link can be implemented at cost of about Kenya shillings 1.8 million which is a fraction of the cost of implementing fiber optic cable alternatives. Additionally E-band links have been proposed to be licensed under light licensing model where operators pay only administrative fee hence low network operational expenditure. Therefore wireless systems have a shorter payback period when compared to the costs and duration of implementing fiber optic cable which currently costs approximately Kenya shillings 1500 per meter for 1.2m depth on soft soil. This is excluding terminal equipment and way leave costs. Installing a high capacity point to point wireless system can be more economical than leasing fiber.

All higher frequency wireless systems i.e. conventional microwave above 10 GHz, 60 GHz, infrared and E-Band are all affected by rainfall attenuation. Unlike infrared, E-band is not affected by fog, dust, air turbulence or any other atmospheric impairment that commonly affect infrared links for several hours regularly. This is because low specific atmospheric attenuation of about 0.5 dB/km occurs in the spectrum around 70-90 GHz and the fact that fog and cloud particles are much smaller than E-band wavelengths.

E-band is a licensed spectrum, therefore all individual links have to be licensed and registered with national communications authorities and coordinated with other links of the same band in the area. This gives links full interference protection from other nearby transmitters using the same frequency band. The licensees are therefore fully protected by the regulator in the event of interference [4]. E-band links are proposed to be licensed under a light license model in the USA, United Kingdom and Australia, whereby licenses are issued to the applied spot frequencies inexpensively. This licensing model provide considerable benefits over traditional link licenses [4]. Table 1-2 provides an example of the annual license fee proposed in countries promoting E-band systems deployment.

Table 1-2: Typical licensing model in countries promoting E-band [4]

Country	**E-band license structure**	**Typical E-Band license fee**
USA	On-line light license	$75 for 10-year license
UK	Light license	£50 per year
Australia	Light license	AU$187 per year

1.3 Potential Applications of E-Band radio

- Radio access network backhaul (2G, 3G & 4G)
- Redundant access for fiber optic cable - Network Diversity
- Wide Area Network (WAN) Access
- Enterprise Fixed Data Connectivity
- Local Area Network (LAN) Extension
- Backbone point of presence (POP) Access

Figure 1-2 illustrates application of E-band for mobile services backhaul where three eNodeB, long term evolution (LTE) radio access network equipment are aggregated into one rack unit (1 U) switch then transported to a two rack unit (2 U) core switch and then into the mobile soft switch (MSS) [5].

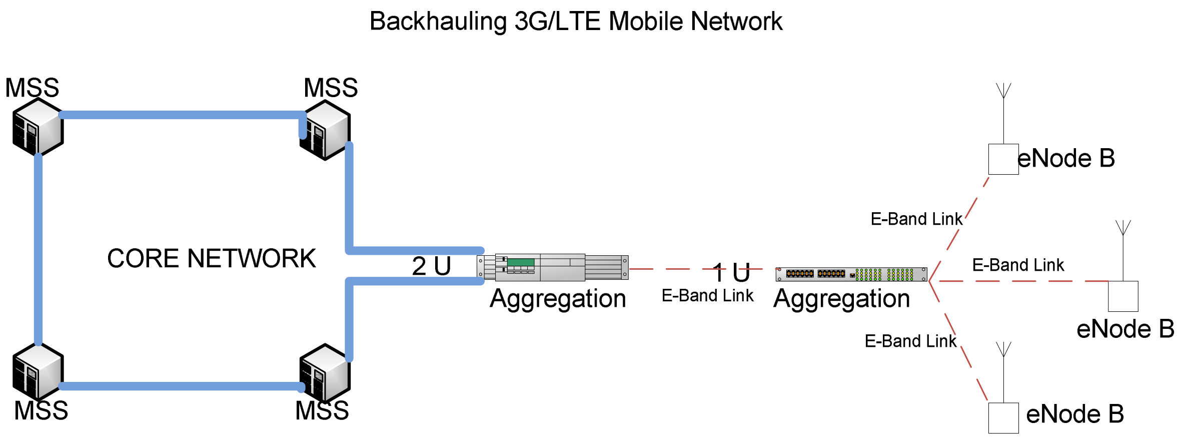

Figure 1-2: Application of E-Band link in 3G/LTE Mobile Network [5]

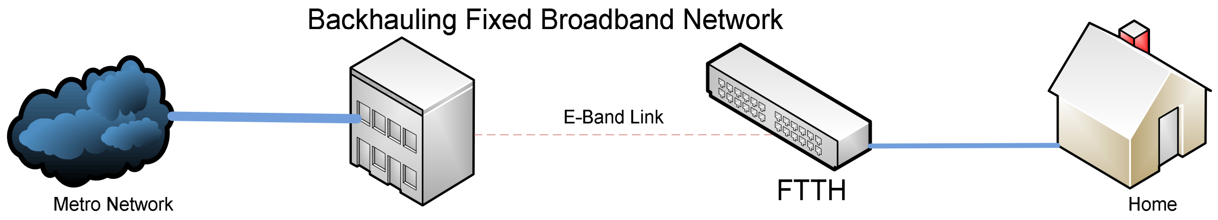

Figure 1-3: Application of E-Band link in Fixed Broadband Network [5]

Figure 1-3 illustrates application of E-band for fiber to the home (FTTH) backhaul by providing connection between two optical line terminals (OLT) facing the internet service provider and customer premises respectively [5].

1.4 Problem Statement

Since weather statistics vary from place to place, ITU-R has recommended prediction methods for different regions based on weather statistics. These prediction methods are based on specific climatic and topographical conditions within radio administration territories. In fact, Recommendation. ITU-R P.837-6 classifies rain attenuation in Kenya as 40-70 (mm/h) exceeded rain rate for 0.01% of the average year, this work is therefore necessary with a view to aiding design engineers with link planning and optimization references; the study explores the experimentation of E-band wireless technology in Kenya with a focus on radio propagation and data performance characterization for future planning and design references and to provide insightful information about E-band solution and its application in the Information and Communication Technology sector. The information presented in this thesis should be useful to frequency managers, system designers, policy makers, and telecommunications service providers and users.

1.5 Research Justification

The current situation in the telecommunication industry in Kenya is such that only optical fiber cable can provide optimal backhaul solution in broadband networks. In cases where optical fiber cable cannot be deployed or redundancy is required to maintain services availability in the event of a fiber cut, then the operators are left with only the choice of deploying bandwidth limited lower frequency microwave links. These links do not have sufficient capacity to provide optimal backhaul in broadband networks.

At E-band frequency segment, the availability of 5 GHz bandwidth provides an opportunity to carry out a trial with a view of characterizing the performance of communication wireless links at this frequency band in order to get a high speed wireless backhaul solution that can be used to compliment optical fiber cable.

So far the information provided in the existing literature gives performance characteristics of links at E-band frequency but none has provided specific field test scenarios to validate the literature. More so, most of the literature provided are based on the temperate regions yet different regions have got different climatic conditions and ITU-R in its multipath modelling predictions classifies different regions based on rainfall intensity and atmospheric refractivity. In fact, Recommendation. ITU-R P.837-6 classifies rain attenuation in Kenya as 40-70 (mm/h) exceeded rain rate for 0.01% of the average year. This work is therefore necessary because weather statistics vary from place to place.

1.6 Research Objective

The main objective of this case study is to provide knowledge and promote the use of E-band in Kenya for wireless backhaul in broadband networks.

The following objectives have been used to characterize propagation and performance of E-band in Kenya.

1. To demonstrate that it is possible to obtain acceptable E-band link performance levels for distances within and above the values reported in the existing literature (inclusive of standards), even in the presence of rain.
2. To correlate the daily rain rate data from the Meteorological Department of Kenya with the links performance levels obtained to further validate the practicality of the experiments.
3. To determine the range (distance) and availability performance of the E-Band links.

1.7 Thesis Organization

Chapter one of this work covers a brief introduction of E-band, advantages and possible applications. It also covers a brief discussion of capacity limitations currently experienced in the lower frequency bands used for point-to-point millimeter wave line-of-sight communications. It also covers the problem statement and research objective.

Chapter two covers the literature review on the emergence of E-band. It also covers detailed point-to-point wireless line-of-sight systems engineering, in terms of propagation path and link budget modeling with a detailed analysis of all factors that affect wireless propagation in free space.

Chapter three covers the aspects of actual link planning and implementation. It covers path profile modeling, link budget simulations, frequency planning and actual link implementation and data collection.

Chapter four gives the results and analysis of E-band links performance based on the data collected from the links and meteorological stations.

Chapter five provides discussions of the observations made.

Chapter six provides conclusions and future work.

The work in this thesis has been published in the following paper:

Sewe Stephen Arato and Oduol Vitalice Kalecha, “Performance Analysis of E-Band 70/80 GHz Frequency Segment for Point to Point Gigabit Connectivity,” *International Journal for Innovation Education and Research,* Vol:-4 No-4, 2016.

Online-ISSN 2411-2933, Print-ISSN 2411-3123

Chapter Two

Literature Review

2.1 Historical Background of E-band

The 71-76 GHz and 81-86 GHz E-band allocations for fixed services were established by the International Telecommunication Union (ITU) at the 1979 WARC-79 World Radio communication Conference [1]. In 1997 Federal Communications Commission (FCC) Office of Engineering and Technology New Technology Development Division published the first research on the usability of millimeter wave bands [6]. The research covered millimeter wave propagation, including free space propagation and the effects of various physical factors on propagation. The research found that propagation ideally suits short range (<20 km) communications and that limited range permits a high degree of frequency reuse. On the other hand the research found this band to have high attenuation in a rain environment and poor foliage penetration [6].The conclusion of the research was that system designers and radio propagation planners could take advantage of the good propagation characteristics manifested at E-band frequencies to develop wireless service applications for short range point-to-point systems such as local area networks.

In July 2000, the FCC Commission held a public forum to address possible new uses of the 92-95 GHz band. Several speakers at the forum indicated that, due to technological developments, new uses of this band were approaching practicality. In addition, in September 2001, Loea Communications Corporation filed a petition requesting the establishment of service rules for the licensed use of the 71-76 GHz and 81-86 GHz bands after experimenting with technology it had developed for use in the these bands [7].

In response to these two developments, the FCC, in June 2002, proposed rules to allow the commercial use of the 71-76 GHz, 81-86 GHz, 92-95 GHz bands (E-band) for a broad range of new fixed and mobile services [7].

In October 2003, the FCC announced the issuance of E-band licenses to both Federal Government and non-Federal Government users (private entities, as well as state and local governments) on a co-primary basis [8]. Licensees were provided with interference protection on a link-by-link basis, with the priority being set based on the date of link registration.

In 2005, the Electronic Communications Committee (ECC) within the European Conference for Postal and Telecommunications Administrations (CEPT) released a first European-wide band plan for E-band similar to the US [9].

In 2006, the European Telecommunications Standards Institute (ETSI) released technical rules for equipment operating in the 71-76 and 81-86 GHz bands [10].

Since then a number of countries have continued to lead the way in opening up the E-band spectrum for high speed point-to-point millimeter wave links with band plan first done by the US. So far a number of system designers, in particular E-band Communication Corporation have developed equipment for use in the E-band which has since been deployed in the US, United Kingdom, Ireland, Australia, Russia and South Africa [4]. There has been very little information published on the actual and real performance of links in this frequency band though. In particular there are no field test data indicating the typical range for E-band for different ITU-R rain regions. Given that climatic conditions and weather statistics vary from place to place, it is necessary to carry out the practical experiment to validate the performances provided in the literature. This research has therefore explored the trial of E-Band wireless technology link in Kenya with a focus on radio propagation and data performance characterization for future planning and design references and to provide insightful information about E-Band solution and its application in the Information and Communication Technology sector.

2.2 Terrestrial Point-to-Point System Engineering

When planning a terrestrial microwave link the objective is to provide enough capacity that meets the customer bandwidth demand and also to meet the desired quality and availability that guarantees the set telecommunication transmission link performance standards. In order to achieve the error performance objective, proper planning and design of terrestrial line-of-sight system must be done by considering several propagation effects and using propagation predictions and data account for losses related to these effects in the link budget [12].

A typical microwave link system comprises radio transceivers, waveguides and duplex channel frequencies and transmit and receive antennas based on line of sight as illustrated in figure 2-1.

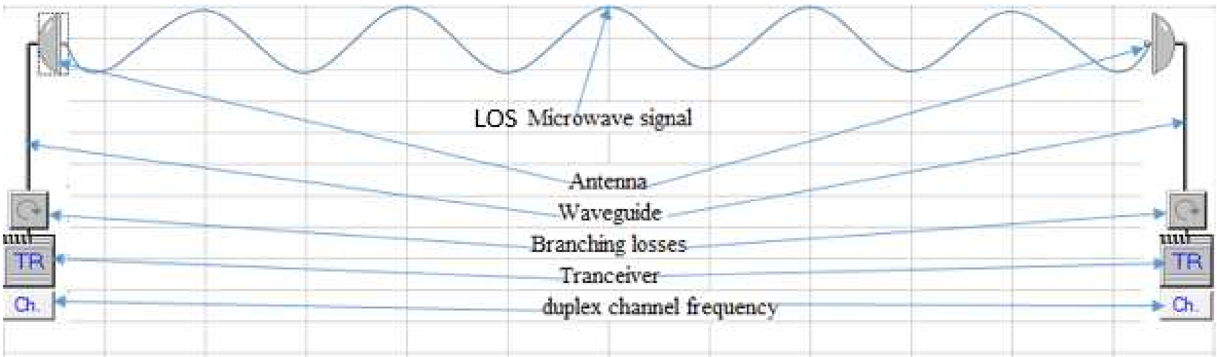

Figure 2-1: Typical terrestrial line-of-sight system

Planning for terrestrial system in figure 2-1 must take into consideration the following fading mechanisms:

Diffraction fading caused by obstruction of the path by man-made obstacles like buildings and terrain obstacles like hills or mountains, rocks and trees.

Attenuation due to atmospheric oxygen and water vapour.

Fading caused by multipath or beam spreading (defocusing) due to refraction and surface reflection.

Attenuation due to the difference in angle of signal arrival at the receiver and angle of signal launch at the transmitter.

Attenuation due to rainfall and dust and fog particles in the atmosphere.

Figure 2-2 illustrates how these fading mechanisms affect the microwave signal propagation. All these fading mechanisms can be modelled and characterized by frequency, path length and geographical area of link propagation [24].

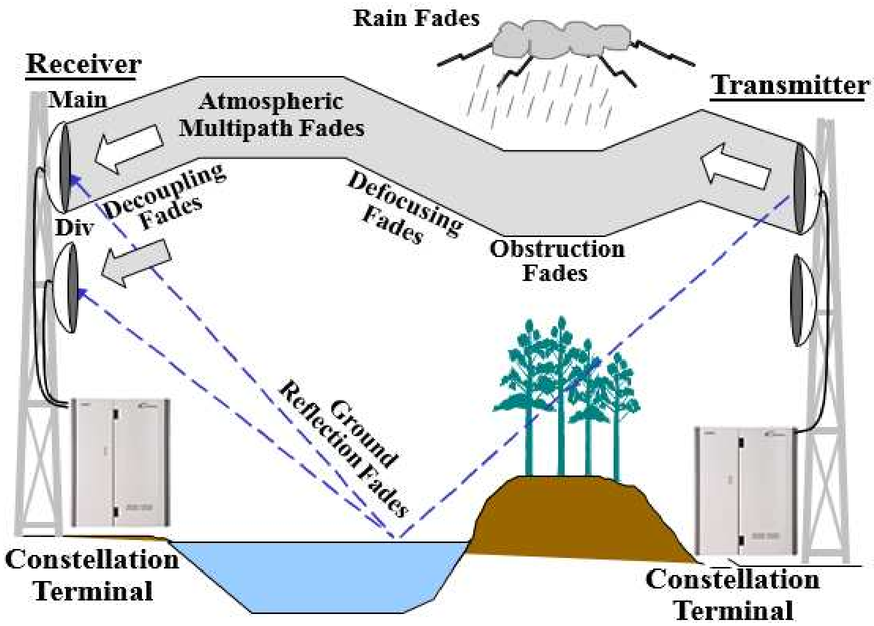

Figure 2-2: A representation of radio link with propagation effects [2]

2.2.1 Diffraction Fading

Microwave link propagation is influenced by refraction, reflection and diffraction [12]. Refraction is majorly caused by atmospheric humidity and the temperature gradient which changes the signal speed and therefore bends downwards (super refraction) or upwards (sub refraction due to large positive values of the gradient of refractive index, low k-factor values) [12]. In particular variations in atmospheric refractive conditions cause changes in k-factor (a model for signal flow in different atmospheric refractive layers) from its median value of approximately 1.33 for a standard atmosphere [12]. Severe super refraction, usually prevalent in humid coastal regions and flat lands with low altitudes can result in antenna defocusing or total signal blackout (ducting) [12]. Direct wave or refracted signal are sometimes obstructed by obstacles such as manmade features like buildings or natural features like hills, rocks and trees causing signal losses due to diffraction. Diffraction fading is therefore the factor that determines the antenna height. It is imperative to carry out proper link path profile engineering to obtain the best antenna heights in order to avoid diffraction and refraction losses otherwise known as multipath fading [24].

Radio propagation path clearance can be modeled based on radio frequency line of sight by Fresnel zones theory where the size of each Fresnel zone varies based on the radio propagation frequency and the path length [23]. The longer microwave paths and lower propagation frequencies have bigger Fresnel zones. A Fresnel zone radius is greatest at the midpoint of a microwave path hence the midpoint requires the most clearance of any other point along the path [23]. Equation (2-1) can be used to calculate the Fresnel zone radius at any point P in between the end points of the link. As a rule of thumb the first Fresnel zone should be clear of any obstacle to ensure no signal loss due path blockage. Figure 6 illustrates a typical Fresnel zone clearance.

$$F_n = \left(\frac{n\lambda d_1 d_2}{d_1 + d_2}\right)^{0.5} \ (m) \tag{2-1}$$

Where:

F_n = nth Fresnel zone radius in meters.

d_1 = the distance of P from one end of the link in meters.

d_2 = the distance of P from the opposite end in meters.

λ = the wavelength of the transmitted signal in meters.

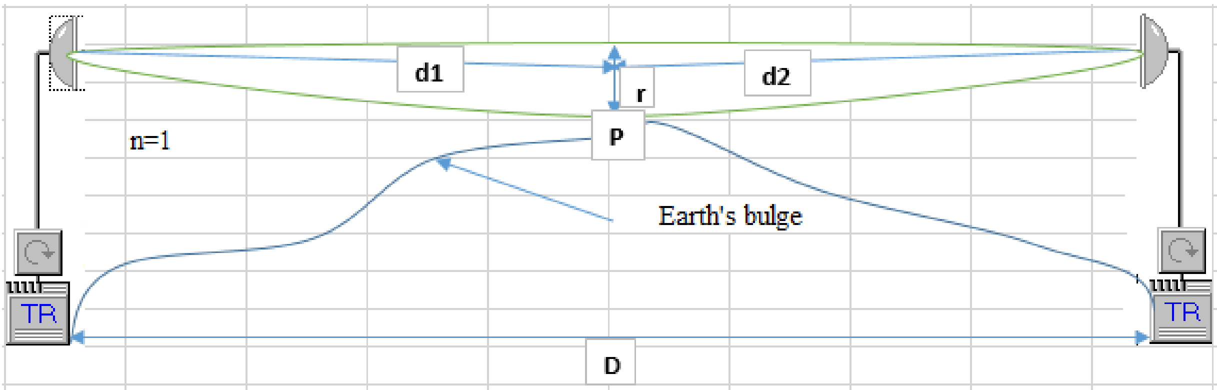

Figure 2-3: Fresnel zone clearance

A Fresnel zone is largest at the midpoint of the link path length where d_1=d_2 and $D = d1 + d2$, if we insert this relation into equation (2-1), we get equation (2-2).

$$r = \frac{1}{2}\sqrt{n\lambda D} \ \ (m) \tag{2-2}$$

Where r = the radius of first Fresnel zone (n=1) at point P.

Diffraction loss due to path clearance depends on the type of terrain and vegetation as well as man-made features like buildings [25]. Diffraction losses over an average terrain can be estimated for losses greater than 15 dB by equation (2-3) as:

$$A_d = -20\frac{h}{F1} + 10\ dB \tag{2-3}$$

Where

h: The height difference (m) between the virtual line-of-sight and the top of the obstacle (h is negative if the top of the obstacle is above the virtual line-of-sight).

$F1$: The radius of the first Fresnel ellipsoid

Diffraction fading can be avoided by installing the transmitter and receiver antennas at high heights such that even a ray that suffers severe bending does not get obstructed by the earth's bulge when k is at its lowest value. According to diffraction theory the direct path between the transmitter and the receiver needs a clearance above ground of at least 60% of the radius of the first Fresnel zone to achieve free-space propagation conditions [24]. Antenna heights are determined using the k-factor value based on the climatic conditions. In the absence of any climatic data, a median value $k = {}^{4}/_{3}$ for inland and temperate climates and 1.0 $F1$ clearance over the highest obstacle can be used [24]. Figure 2-4 illustrates the geometrical description of the height, h in equation (2-3).

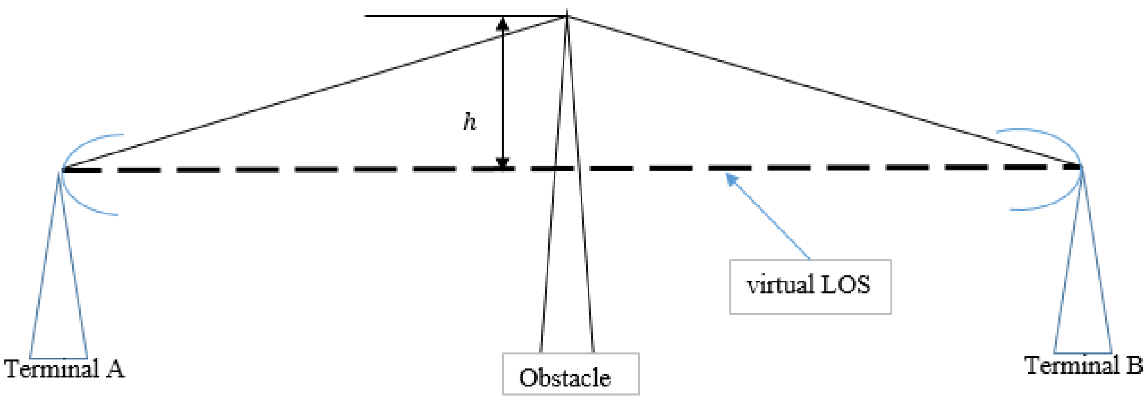

Figure 2-4: Geometrical description of height, h in equation (2-3).

2.2.2 Electromagnetic Wave Propagation

Electromagnetic waves like any other related physical quantities follows the inverse square law. Energy expands during transmission and also reflected on the return, so the inverse means the receiver at the remote end will receive energy according to $1/r^4$ power, where r is the propagation distance [12]. Let the total isotropic power radiated from the point source, be 1W.

The surface area of a sphere is given by

$$A = 4\pi r^2 \qquad (2\text{-}4)$$

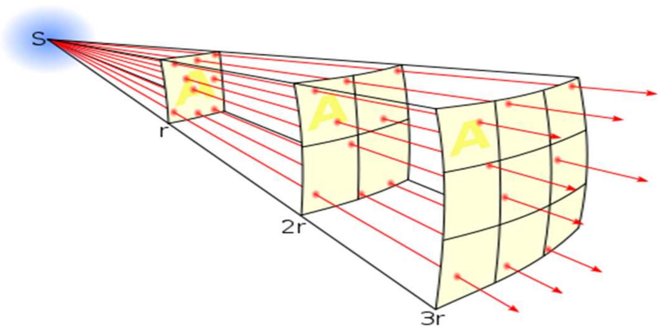

Figure 2-5: Example of electromagnetic radiation from an antenna. S represents an ideal source of electromagnetic radiation and A represents an arbitrary segment of the surface of a sphere of radius r [12].

At the distance r equal to 1 km from the source,

A=12,566,370.61 m^2

The power intensity I, is given by

$$I = \frac{P(W)}{4\pi r^2} \qquad (2\text{-}5)$$

With 1W of isotropic power,

I=7.95775x10^{-8} Wm^{-2}

This when converted into decibels using, $10log_{10}I$

= -71dBW

At 2km, A=50,265,482.44m^2 and the power intensity is 1.98944x10^{-8} Wm^{-2}= -77dBW

From the calculations, it can be seen that at 2km the power intensity is ¼ of that at 1km, the power falls off inversely as the square of the distance as $10log_{10}d^{-2} = -20log_{10}d$. Thus when the distance is doubled, the additional free space loss is 6 dB. Thus power per unit area in the direction of wave propagation varies inversely with the square of the distance from the source. This obeys the general inverse square law as shown in Figure 2-6.

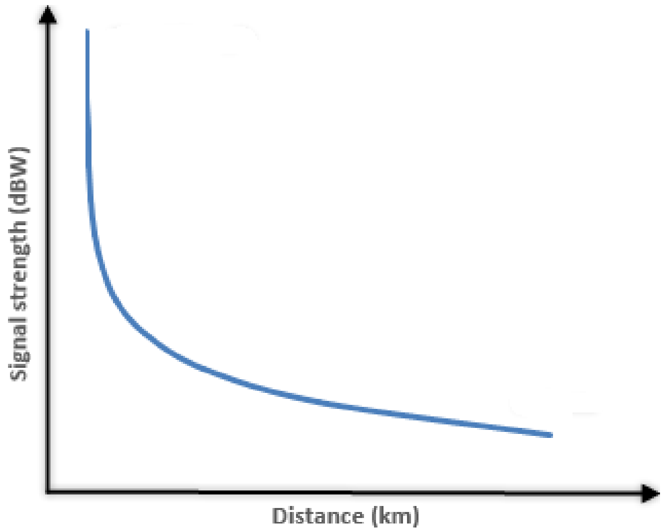

Figure 2-6: Inverse square law curve [12]

2.2.3 Attenuation Due to Atmospheric Gases and Free Space Loss

The main aim of a microwave and millimeter wave signal transmission is to ensure energy transmitted from the source is received by the remote receiver without encountering too much attenuation. Since an electromagnetic signal loses 6 dB of power every time the propagation distance is doubled, it is important to understand the source of such losses, their contribution and how to counter them in order to build reliable transmission systems [12]. Firstly there is specific atmospheric gaseous attenuation where the electromagnetic signal is absorbed by atmospheric oxygen, water molecules and dust particles causing varying losses from 0.1 dB/km to about 25 dB/km across the microwave and millimeter wave frequency spectrum [26]. In order to avoid these losses reliable point to point transmission can be achieved using selected frequency spectral windows with low atmospheric absorption. According to Figure 2-7, traditional microwave frequencies of 6-42 GHz have the lowest specific attenuation due to atmospheric absorption with highest loss experienced in the band between 20-30 GHz, in particular there is a high specific attenuation due to water vapour at 22 GHz while the region from 60 to 70 GHz also known as V-band has high specific attenuation due to both water vapour and dry air. The 70-100 GHz spectrum window has a relatively low specific atmospheric attenuation ranging from 0.2 dB/km to about 0.35 dB/km making it favorable for radio transmission [13]. For this reason, E-Band wireless systems can transmit high data rates signal over many kilometers under clear conditions [13].
Specific atmospheric gaseous attenuation in the frequency range 1-350 GHz comprises of specific attenuation due to dry air, γ_o (dB/km) and water vapor, γ_w (dB/km) [26]. Thus the total specific attenuation due to atmospheric gases, γ_a (dB/km) is given by:

$$\gamma_a = \gamma_o + \gamma_w \quad \text{(dB/km)} \tag{2-6}$$

Figure 2-7 shows the specific attenuation for a frequency range of 1-350 GHz for dry air and water vapour at sea level with a density of 7.5 g/m^3, temperature of 15^{o}C and a pressure of 1013.25hPa.

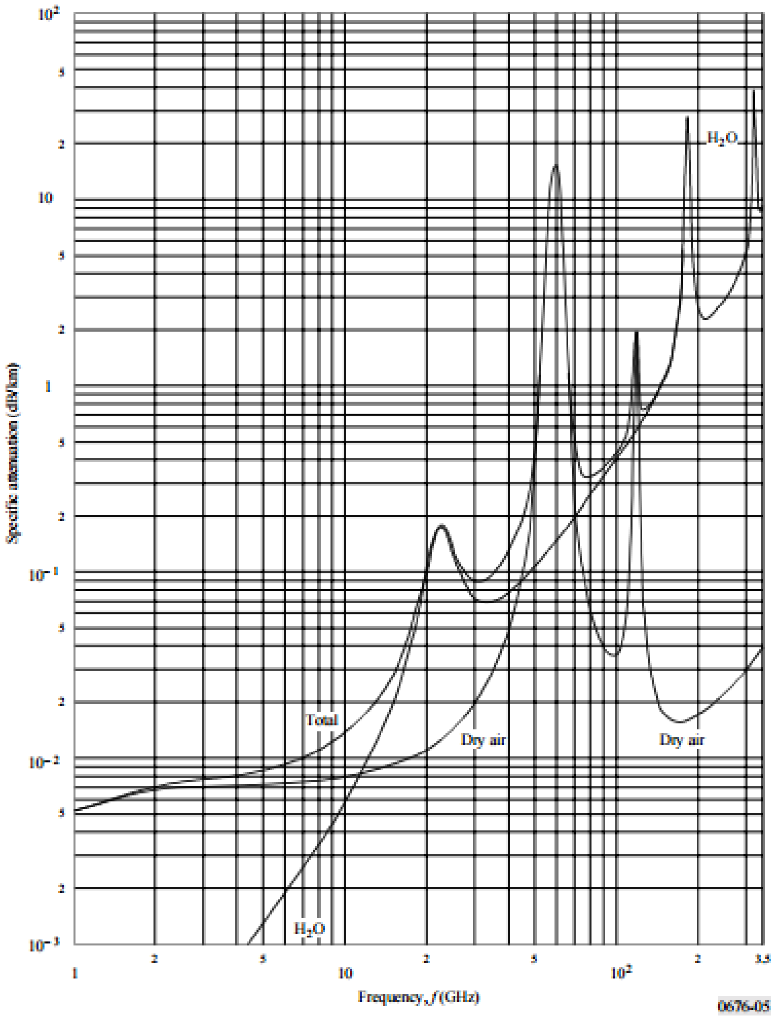

Figure 2-7: Specific attenuation due to atmospheric gases [26]

Attenuation due to atmospheric gases on terrestrial paths from sea level to an altitude of 5000m is thus given by:

$$A_a = \gamma_a d \quad dB \tag{2-7}$$

Where

A_a (dB)= Total attenuation due to atmospheric gases.

γ_a (dB/km)= Specific attenuation due to atmospheric gases.

d (km)= path length

Figure 2-8 shows attenuation due to atmospheric gases, A_a (dB) for 1-350 GHz at sea level.

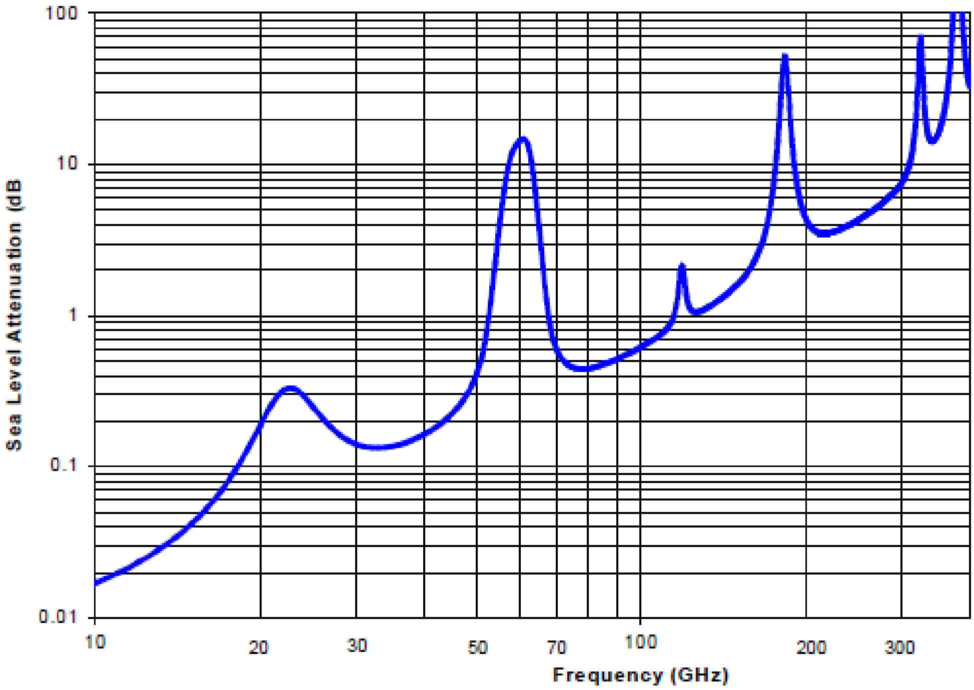

Figure 2-8: Atmospheric and molecular absorption [22]

According to Figure 2-8, attenuation due to atmospheric gases in the E-band spectrum region at sea level is less than 1dB making it viable for terrestrial point to point line of sight communication systems.

The second cause of electromagnetic signal attenuation is the free space loss (FSL). Free space loss is the expected attenuation of an electromagnetic wave signal as it travels away from the source [14]. When a signal radiates from the antenna, it spreads out over an increasingly larger distance. As the area covered increases, the power intensity (the amount of power per unit area) decreases. This effectively weakens the electromagnetic wave signal. When calculating the link budget, it is important to first obtain the free space loss in order to determine the link feasibility. The free space loss is given by:

$$FSL = \left(\frac{4\pi d}{\lambda}\right)^2 \quad (2\text{-}8)$$

$$= \left(\frac{4\pi d f}{c}\right)^2$$

Where:

- f is the transmission frequency in (MHz)
- d is the path length between the transmitting and receiving antennas in (km)
- c is the speed of light, given as 2.99792458 × 10^8 m/s

$$FSL(dB) = 10log_{10}\left(\frac{4\pi df}{c}\right)^2$$

$$= 20log_{10}\left(\frac{4\pi df}{c}\right)$$

$$= 20log_{10}\left(\frac{4\pi}{c}\right) + 20log_{10}d + 20log_{10}f$$

$$= 20log_{10}d + 20log_{10}f + 32.44 \qquad (2\text{-}9)$$

Equation (2-8) complies with ITU-R P.525 [14], free space attenuation calculation for point-to point microwave transmission links in all frequency bands permitted by ITU-R frequency sector. Example of free space loss for 23 GHz and 80 GHz link over a 3km path length will thus be;

For 23GHz

$$FSL(dB) = 20log_{10}d + 20log_{10}f + 32.44$$

$$= 20log_{10}3 + 20log_{10}23000 + 32.44$$

$$= 20 \times 0.4771 + 20 \times 4.3617 + 32.44$$

$$= 9.542 + 87.234 + 32.44$$

$$= 129.216dB \qquad (2\text{-}10)$$

For 80GHz

$$FSL(dB) = 20log_{10}d + 20log_{10}f + 32.44$$

$$= 20log_{10}3 + 20log_{10}80000 + 32.44$$

$$= 20 \times 0.4771 + 20 \times 4.9031 + 32.44$$

$$= 9.542 + 98.062 + 32.44$$

$$= 140.044dB \tag{2-11}$$

From the two values it is evident that at E-band the free space attenuation is higher compared to the lower frequency bands. Thus the lower frequency bands have better radio propagation characteristics than their E-Band counter parts. However, the gain of an antenna increases with frequency [1, 22, 27]. This antenna characteristic compensates for the high free space loss and makes the E-band to have a high effective isotropic radiated power that can enable it to perform considerably better in the same propagations conditions as 23 GHz band.

2.2.4 Attenuation Due to Rainfall (Precipitation)

Rain attenuation greatly affects the performance (availability) of all microwave links above 10 GHz [24]. Specific attenuation due to rain can be estimated by the equation;

$$\gamma_R = kR^{\alpha} \tag{2-12}$$

Where γ_R (dB/km) is the specific rain-related attenuation and R (mm/hour) is the rain rate parameter differentiating the intensity of a rain fall and may be obtained through a set of specified values given in ITU-R Recommendation P.837-1. The coefficients k and α are frequency and polarization (vertical or horizontal) dependent and may be obtained from a set of specified values given in ITU-R Recommendation P.838-1. Figure 2-9 shows specific attenuation due to rain for 1-1000 GHz frequency range. As illustrated in Figure 2-9, heavy downpour at the rate of 25mm/hour will cause an attenuation of about 10 dB/km at E-band frequencies which increases to over 30 dB/km during a tropical storm at the rate of 100mm/hour. ITU-R rain attenuation models (P.530, P.837 and P.838) are available to predict rainfall intensities and annual rainfall at those intensities that are used during link design and planning to determine the desired availability due to rain [18, 19, 20].

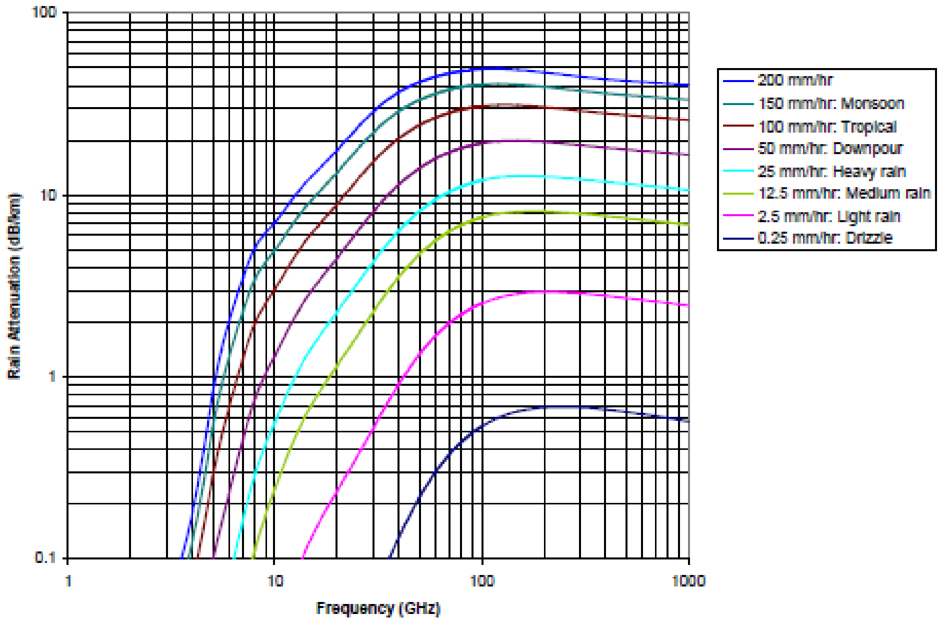

Figure 2-9: Specific rain attenuation at microwave and millimeter wave frequencies [1]

To estimate rain attenuation, the propagation distance is used to account for the distribution of the rain cells. Attenuation due to rain is given by:

$$A = \gamma_R . d \tag{2-13}$$

where, d is the propagation distance

2.2.4.1 Actual Rainfall Attenuation Estimation

In most cases it is assumed that the rain distribution is uniform throughout the propagation distance. However, this is never the true scenario as rain rate distribution tend to vary horizontally thus different sections of the path receive different rain rate especially in the tropical climates that receive convectional type of rainfall [28]. In order to get the actual estimation of rain attenuation, it is imperative to get effective path length in order to take into account the non-uniformity in rain rate distribution [28]. According to ITU-R P.530 Rain Algorithms in Pathloss 5, effective path length, d_{eff} is calculated to account for non-uniform rain rate distribution [18].

In order to get effective path distance, a parameter called path reduction factor, r is used to account for the limited distribution of the rain cells along the propagation distance [28]. According to ITU-R P.530, an estimate of distance factor, r is given by:

$$r = \frac{1}{1 + d/d_0} \tag{2-14}$$

Where, for $R_{0.01} \leq 100$ mm/hour;

$$d_0 = 35e^{-0.015R_{0.01}} \tag{2-15}$$

For $R_{0.01} > 100$ mm/hour, 100 mm/hour is used in place of $R_{0.01}$

The rain attenuation exceeded for 0.01% of the time is therefore given by:

$$A_{0.01} = \gamma_R . d_{eff} = \gamma_R dr \quad dB \tag{2-16}$$

2.2.5 Attenuation Due to Fog and Clouds

According to ITU-R P.840, clouds and fog consist of suspended droplets of water condensed around dust particles with diameters ranging from about 10µm for fog to 100µm for rain clouds. The liquid water density in fog varies from 0.05 g/m^3 for light fog with visibility of about 300m to 0.5 g/m^3 for thick fog with visibility of about 50m [29]. Clouds and fog can cause considerable attenuation to microwave and millimeter wave propagation for frequencies above 10 GHz and may be significant at frequencies over 100 GHz. According to ITU-R P.840, specific attenuation due to cloud or fog can be calculated using the equation:

$$\gamma_c = K_l M \qquad dB/km \tag{2-17}$$

Where

γ_c= Specific attenuation (dB/km) due to cloud or fog.
K_l = Specific attenuation coefficient $((dB/km)/(g/m^3))$
M= Liquid water density in the cloud or fog (g/m^3)

Figure 2-10 shows the values of K_l for frequency range of 5-200 GHz at temperatures between -8° and 20° C.

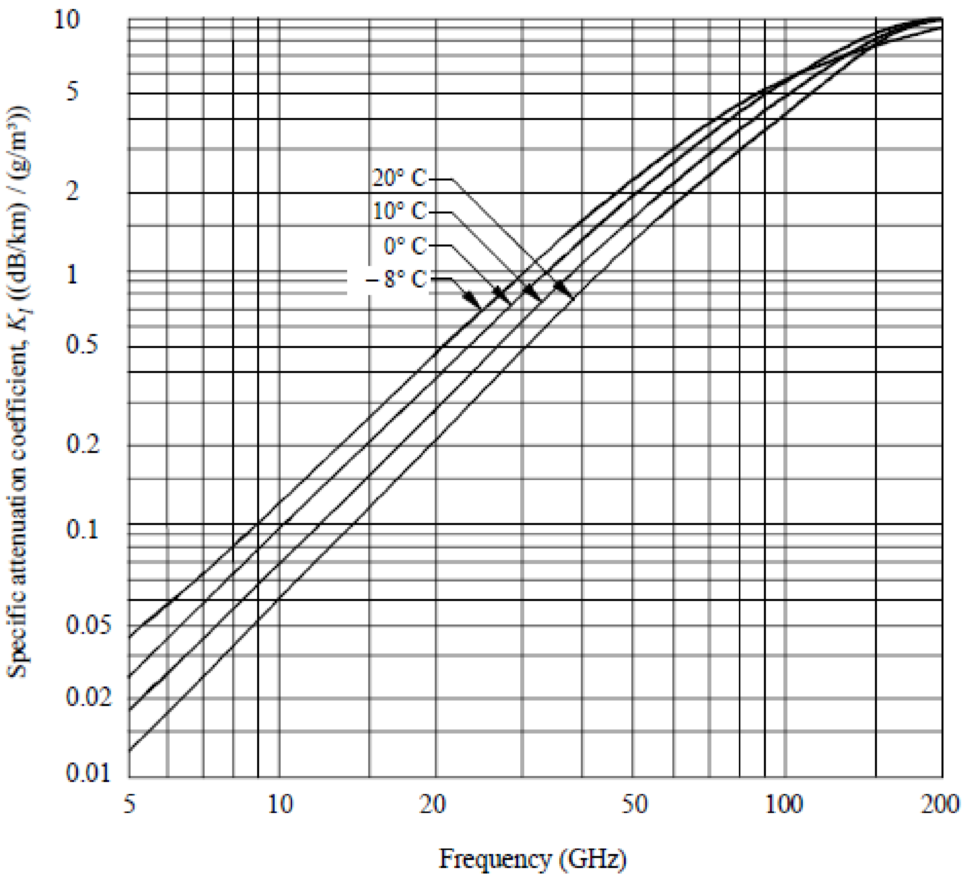

Figure 2-10: Specific attenuation coefficient, K_l $((dB/km)/(g/m^3))$ for 5-200 GHz frequencies [29]

2.2.6 Refraction Fading Due to k-factor Variations

Radio wave signal fading due to refraction can largely be attributed to humidity. Humidity is the amount of water vapour in the atmosphere. Relative humidity is the actual amount of water vapour in the air relative to the total water vapour the air is capable of holding [12]. During the hot weather conditions, the hot air is capable of holding much more moisture compared to the cold air in cold seasons. Thus the outage due to refraction fading is likely to be proportional to the average annual temperature [12]. In most cases the temperature decreases with increase in altitude causing the troposphere to be thermodynamically unstable and in a situation of turbulent mixing which leads to a median part of the refractivity gradient distribution at -40N-units/km or k-factor equals to 4/3 [12]. According to ITU-R P.453, this condition is more prevalent in inland and temperate regions which results in slight downwards wave refraction and normal propagation is experienced at 90-

95%. In some unique conditions where temperature rises with increase in height above the sea level, a stable stratified troposphere can be created which causes refractivity layering with each layer having a different refractive index gradient [12]. This layering might result in signal entrapment between two layers leading to a signal black out hence cannot be received by the receiver antenna. A ducting layer is formed if a layer with a refractivity gradient below -157 N-units/km or k-factor equals ∞ is immersed in a broader region with a smaller refractive index gradient lapse rate [2, 12]. During this phenomenon the wave experiences super refraction and ducting. These conditions are mostly experienced in humid and coastal climates [12]. Ducting can cause signal fading as a result of antenna defocusing and a potential interference because they provide a mechanism for radio wave signals to propagate far beyond their normal line of sight range [30]. Figure 2-11 illustrates refraction fading due to k-factor variations. This kind of fading is more prevalent on system path lengths greater than 40 km where the antennas are on different radio horizons. Some of the mechanisms used to mitigate ducting are through proper establishment of the ducting layer and installing antennas at higher heights, down tilting and up tilting of antennas in order to increase path inclination which helps the signal to penetrate through different atmospheric layers. Space diversity antenna can also be used to reduce fading due to ducting [30]. During cold nights when the sky is clear, the cool air is heavier than warm air. The cool air then descends thus lowering the temperature over a moist, warm ground to the dew point causing steam fog. This causes a steam fog that slows down radio wave signal propagation resulting in a sub refractive atmosphere which refracts the waves upwards and causes fading due to defocusing or antenna decoupling. This type of refraction fading is called atmospheric boundary layer fading (ABL) [12]. ITU-R multipath models are available in recommendations P.530 and P.453 for microwave and millimeter wave line of sight links path engineering.

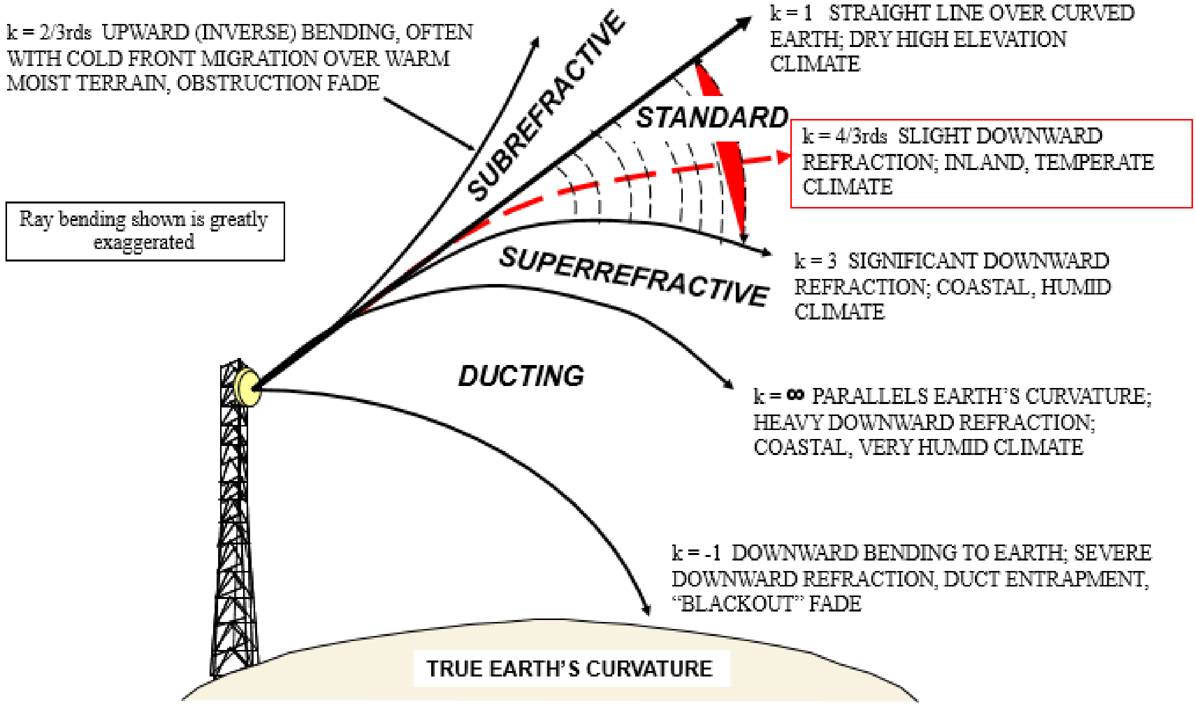

Figure 2-11: Illustrating k-factor fading [2]

2.2.7 Reflection Fading

Reflection fading occurs in very clear paths passing over water or uniform vegetative grounds like sugar cane plantations or paddy fields [24]. The clear paths usually acts like a mirror surface causing reflection of the main signal to form reflected signal. This leads to more than one signal arriving at the receiver antenna with varying arrival time delays. This can result in signal enhancement or multipath fading due to multiple signals cancellations. Reflection fading can be mitigated through reduction of ground surface reflection by up tilting antennas and use of space diversity antennas, increase of path inclination to achieve a geometrically horizontal signal. When designing space diversity solution to mitigate reflection fading, the main antenna signal should be out of phase with the diversity antenna signal around the median k-factor in the refractivity gradient distribution [2]. Figure 2-12 illustrates space diversity in action with direct and reflected signals adding up at the main antenna and cancels out at the diversity antenna at site A.

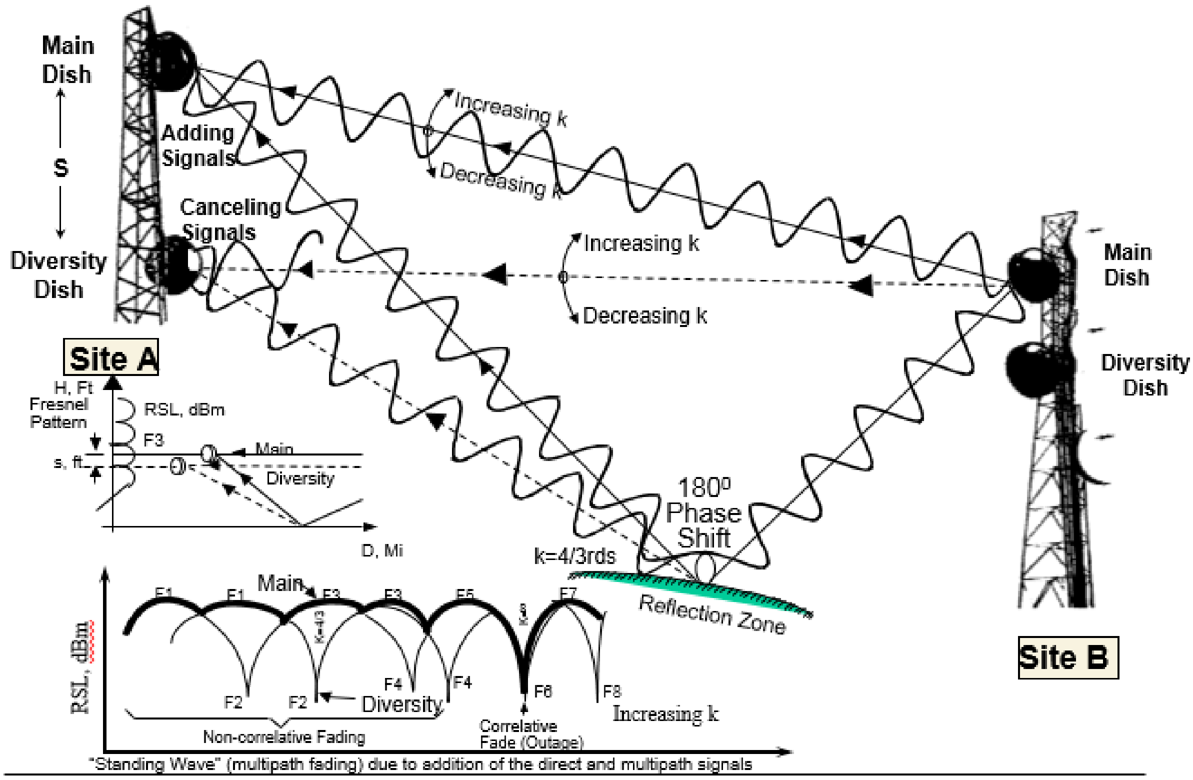

Figure 2-12: Illustration of space diversity solution in reflection fading [2]

2.2.8 Antenna Misalignment Fading

Large antennas and high frequency antennas have got a very thin pencil like beam widths which makes them very difficult to align. The highly directive beam width means the side lobes are highly suppressed and have a difference of at least 20 dB from the main lobe signal [27]. During installation, the antenna must be properly aligned to ensure maximum ray directivity from the main lobe. A misaligned antenna is likely to experience defocusing/decoupling fading. E-band antenna for example has a beam width of 0.9^{o} hence a misalignment will result in a deviation of about 35 dB from the main lobe signal. This kind of deviation would result in a very low received signal level resulting in considerable fading [27]. Figure 2-13 shows antenna alignment sketches to illustrate how antenna alignment should be done during installation to ensure maximum gain and to minimize defocusing/decoupling fading.

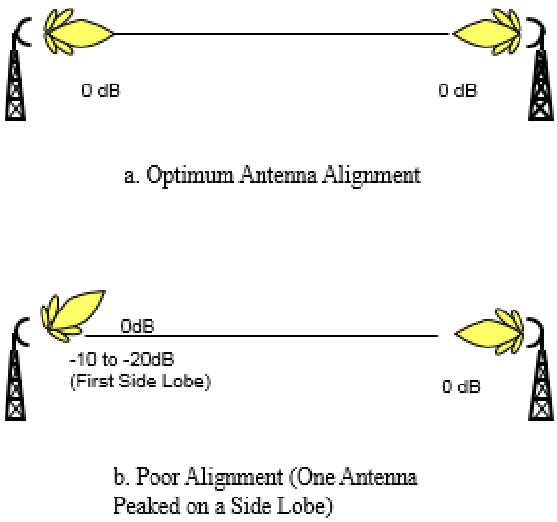

Figure 2-13: Antenna alignment sketches [2]

2.2.9 Error Performance and Availability Events for Link Paths

The principal objective of microwave link engineering is to realize a communication system with good quality and up time (availability) that satisfies the intended end user needs. Link quality refers to the link performance with regards to bit error rate (BER) while link availability refers to the link performance with regards to the operational up time [2]. According to ITU-T recommendation G.826, a microwave link is defined as “unavailable” during a period of unavailable seconds (UAS) which occurs after 10 consecutive events of severely errored seconds (SES) consequently a new period of available time begins after 10 consecutive non-SES events [31]. An errored block (EB) is one in which one or more bits are errored. Errored second (ES) is a one second period with one or more errored blocks or during which a loss of signal (LOS) or alarm indication signal is detected. Severely errored second (SES) occurs if 30% or more of errored block are detected. The bit error ratio during SES is $\geq 1.10^{-3}$ and loss of signal or alarm indication signal are detected. Background block error (BBE) is an errored block not occurring due to SES [24]. Error performance parameters; errored second ratio (ESR), severely errored second ratio (SESR) and background block errored ratio (BBER) should only be evaluated in service paths [31]. Where errored second ratio is the ratio of errored second to total seconds in available time during measurement interval and it is applicable to both path and connections. Severely errored second ratio is the ratio of severely errored second to total seconds in available time during measurement interval and it is applicable to both path and connection. Background block errored ratio is the ratio of background block errors to total blocks in available time during measurement period. The count of total blocks excludes all blocks during severely errored seconds and it is only applicable to the path [31]. Figure 2-14 illustrates the error performance and availability events for microwave link path. The error performance objectives provide a guide to the target system requirements. New technologies must take them into account and a design that overcomes the various attenuation and fading factors discussed must be put in place in order to implement a system the supports the end user demands. Based on the guidelines and previous work done on microwave and millimeter wave link engineering and research on E-band in particular, there are encouraging signs that the technology can be explored further. E-band has a very high free space loss in the region of 100 dB while its rain attenuation is equally high. However, E-band has some encouraging characteristics that still makes it viable for point to point line of sight system. Firstly, the E-band region is not affected greatly by atmospheric gases attenuation and cloud and fog attenuation.

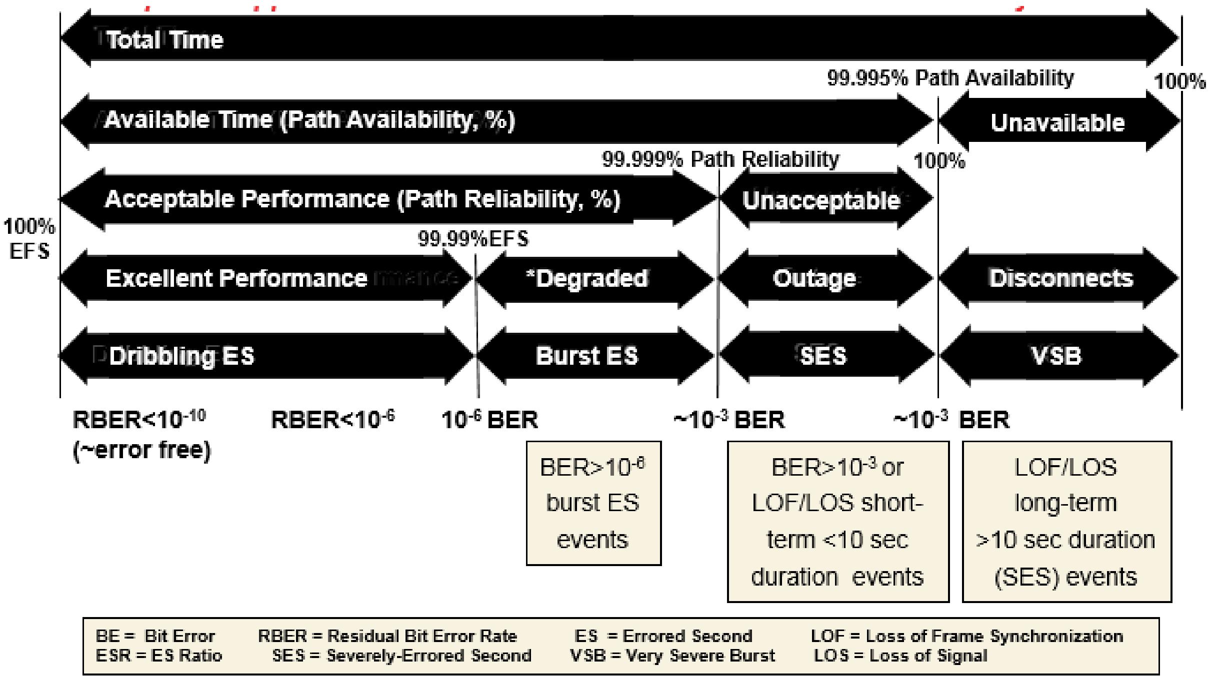

Figure 2-14: Illustration of error performance and availability events [2]

Secondly the Federal Communications Commission (FCC) permits E-band radios to operate with output power of up to 3W [1]. Thirdly, antenna gains tend to increase with increase in frequency due to a highly directive beam width that concentrates the gain into the main lobe. E-band being at 80 GHz is likely to have a high antenna of 45 and 50 dBi for 0.3m and 0.6m diameter antennas respectively. This high antenna gain aided with high radio output power will result in a high system gain that can easily overcome the high free space and rain attenuation to achieve a reasonable fade margin for successful transfer of data [1, 22, 27]. Figure 2-15 illustrates the effect of frequency on antenna gain for a 0.3 m parabolic antenna.

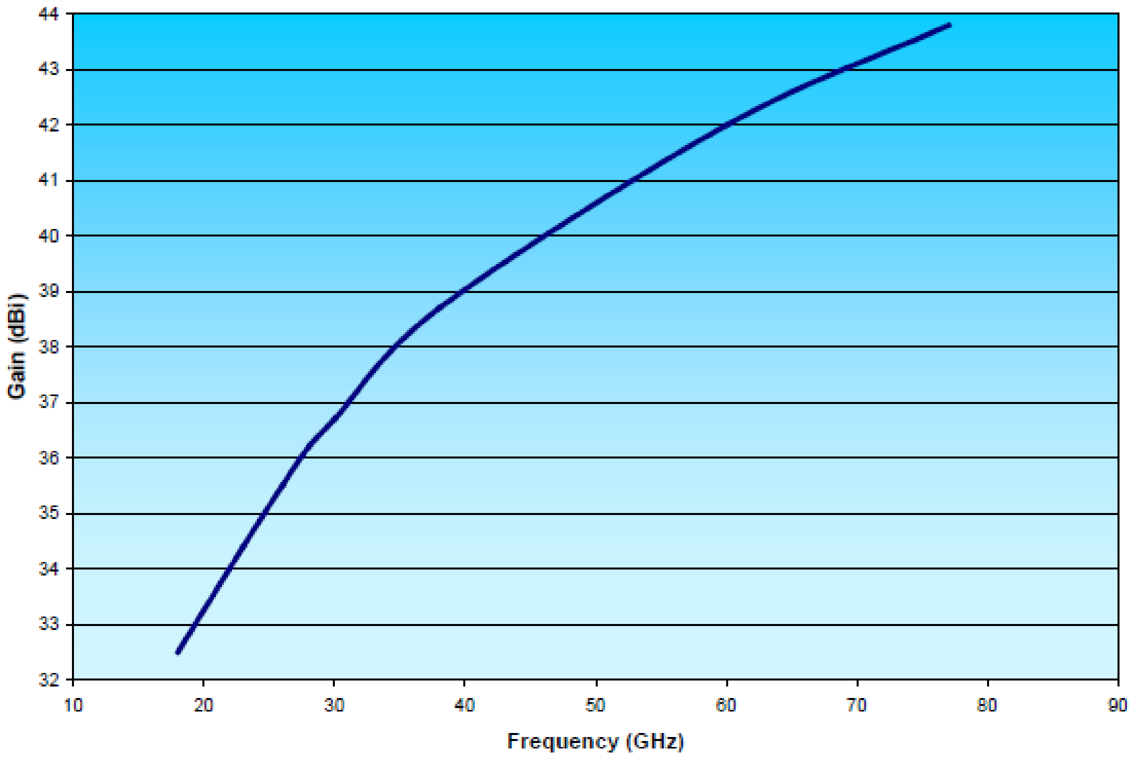

Figure 2-15: The effect of frequency on antenna gain for a 0.3m parabolic antenna [1]

Chapter Three

Methodology

3.1 Experiment Links Setup

In terms of practical implementation, one link was installed in Nairobi, two links in Mombasa using NEC equipment and three links in Kisumu using Aviat equipment with different path lengths. The links were monitored for a period of 3 months and daily performance results recorded. Performance analysis was done based on the data collected over the period for different link path lengths against the expected or planned performance. The following activities were carried out during this stage:

- Link path analysis i.e. maps study, path survey and geometry.
- Link budget simulations
- Frequency planning
- Link installations, tests, measurements and analysis

Figure 3-1 illustrates the links setup that was used to carry out the experiment. The system consists of an integrated radio frequency (RF) unit that has radio frequency processing as well as Ethernet switch carrier class functionalities. The RF unit is connected to the antenna as a direct mount thereby eliminating waveguide cable losses. The RF unit is powered through an indoor Power over Ethernet injector, where the same cable doubles up as data and power carrier. This helps to reduce extra cabling. The data output port for PoE injector is then connected to the cell site router which then distributes data traffic to various equipment at site.

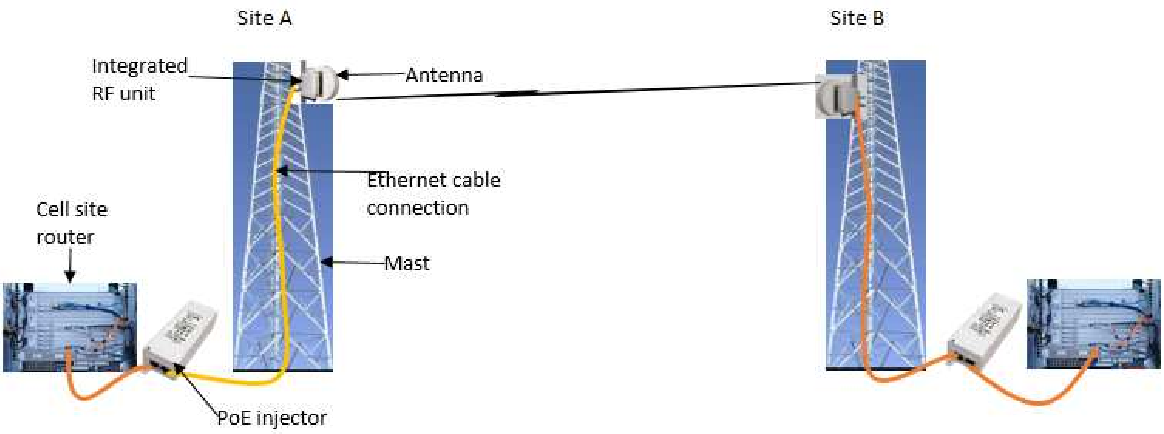

Figure 3-1: A block diagram of the measurement setup

3.2 Path Profile Planning

A path profile is a geometrical representation of the path travelled by the radio signal between the transmitting and receiving antennas. The path profile analysis helps in determining the antenna positions on both ends of the link ensuring the link is free of any obstruction such as trees, hills buildings and other man made features in order to achieve line of sight (LOS). Since an electromagnetic wave signal bends downwards (super refraction) or upwards (sub refraction) during transmission, a radio line of site requires more clearance in order to accommodate the characteristics of microwave signals notably refraction caused by atmospheric water vapor. Thus the path clearance can be modeled by Fresnel zones theory. The size of each Fresnel zone varies based on the radio propagation frequency and the path length. The longer microwave paths and lower propagation frequencies have bigger Fresnel zones. A Fresnel zone radius is greatest at the midpoint of a microwave path hence the midpoint requires the most clearance of any other point along the path. Equation (2-1) can be used to calculate the Fresnel zone radius at any point P in between the end points of the link at 80 GHz frequency as

$$F_n = \left(\frac{3nd_1d_2}{800(d_1+d_2)}\right)^{0.5} (m) \tag{3-1}$$

For maximum Fresnel radius r at the midpoint of the path at 80GHz, we get

$$r = \frac{1}{2}\sqrt{0.00375nD} \quad (m) \tag{3-2}$$

If d is taken to be 2 km for example, then r becomes

$$r = 1.369 \ \ (m)$$

Pathloss 4.0 software for microwave link planning and design was used for path profile analysis after field survey and verifications since it is the universally accepted microwave link engineering tool. Path profiles were plotted from field-verified topographical maps, SRTM (Shuttle Radar Topography Mission) data. The profiles were computer-generated based on topographical details like elevations, lakes, and rivers. The profile obstacles considered were trees, man-made structures e.g. buildings, water tanks and these were modeled as single or range of objects depending on the field survey findings. The signal propagation parameter, used for path clearance criteria was $k = 1.33$ based on ITU-R P.453-9 recommendation used for microwave signal refractivity modeling.

3.3 Link Budget Simulations

A link budget is the calculation of system gains and losses in order to achieve net gain or fade margin. The link budget helps in determining the link feasibility, fade margin and availability. The following two parameters are important in determining link feasibility:

EIRP (Effective Isotropic Radiated Power): This is the antenna transmitted power equal to the radio transmitter output power plus the transmitting antenna gain minus cable (waveguide) loss.

Receiver sensitivity threshold: This is the minimum RF signal power detectable by the receiving antenna. The following formula is used in calculating a link budget.

$$RSL = TX_{out} - C_t + G_t - FSL + G_r - C_r \tag{3-3}$$

Where:

RSL = Received signal level in dBm

TX_{out} =Radio transmitter output power in dBm

C_t =Transmitter cable (waveguide) attenuation in dB

G_t =Transmitting antenna gain in dBi

FSL =Free Space Loss in dB

G_r =Receiving antenna gain in dBi

C_r =Receiver cable (waveguide) attenuation in dB

If the received signal level (RSL) is greater than the receiver sensitivity threshold, then the link is considered to be feasible.

The formula is used to determine the link feasibility but does not take into consideration the long term rain outages prediction, geo climatic factor, space diversity improvement and short term multipath outage predictions. Pathloss 4.0 was used for a detailed link budget design taking into account rainfall and multipath outage predictions. This experiment used ITU-R P.530-7/8 recommendation for rain outage, link availability, maximum path length and required fade margin predictions and ITU-R P.837-1 for rainfall climatic zones.

Attenuation of radio frequency signal is majorly contributed by the free space path loss and the rainfall (precipitation). These two major contributors have an overall effect on the propagation distance that a microwave link can effectively operate.

3.3.1 Free Space Loss at 80 GHz

This is the path loss representing attenuation the signal suffers as it travels through the atmosphere. Using the free space loss equation, Figure 3-2 derived from equation (2-9) shows the effect of free space attenuation on the propagation distance at E-band frequency. An extra fade margin is required to take care of the increase in free space attenuation as the propagation distance increases.

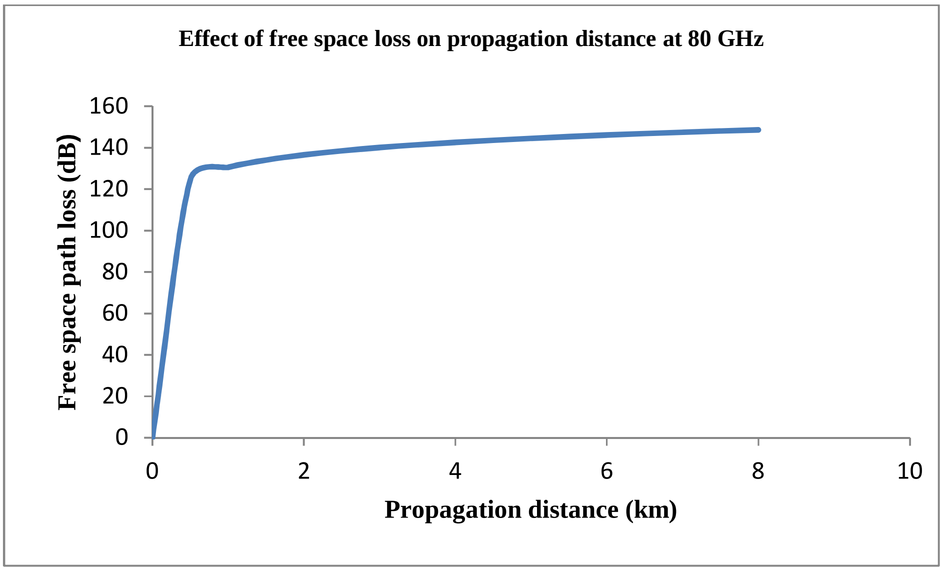

Figure 3-2: Free space path loss as a function of propagation distance at 80 GHz.

3.3.2 Rainfall (Precipitation) Attenuation

When computing path attenuation due to rain, the procedure given in ITU-R recommendation P.530-9 is used; the rain rate $R_{0.01}$ exceeded of 0.01% for the time is obtained from the data given in ITU-R recommendation P.837-1. Specific attenuation, γ_R(dB/km) is computed using equation (2-12) and data provided in ITU-R recommendation P.838-2 for frequency, polarization and rain rate of interest. The distance factor, *r* and attenuation, $A_{0.01}$ are then calculated using equations (2-14) and (2-16) respectively. Using the rain attenuation, ($A_{0.01}$) equation (2-16) and the rain rate ($R_{0.01}$) of 8, 15, 30 and 35 mm/hour, the graph in Figure 3-3 was generate to illustrate the effect of rain attenuation on the propagation distance at 80 GHz with vertical polarization. From the graph, rain attenuation tends to reduce the propagation range of a microwave link. Using Pathloss 4.0 software for microwave link budget modelling, a link budget was simulated at different rain rates, 8mm/hour for a drizzle, and 15mm/hour for light rain and 35mm/hour for heavy rain. In Pathloss simulation, a 0.01% probability that a given rain rate R will be exceeded for a given time was used. Figure 3-4 illustrates the simulated E-band link availability against the link path length.

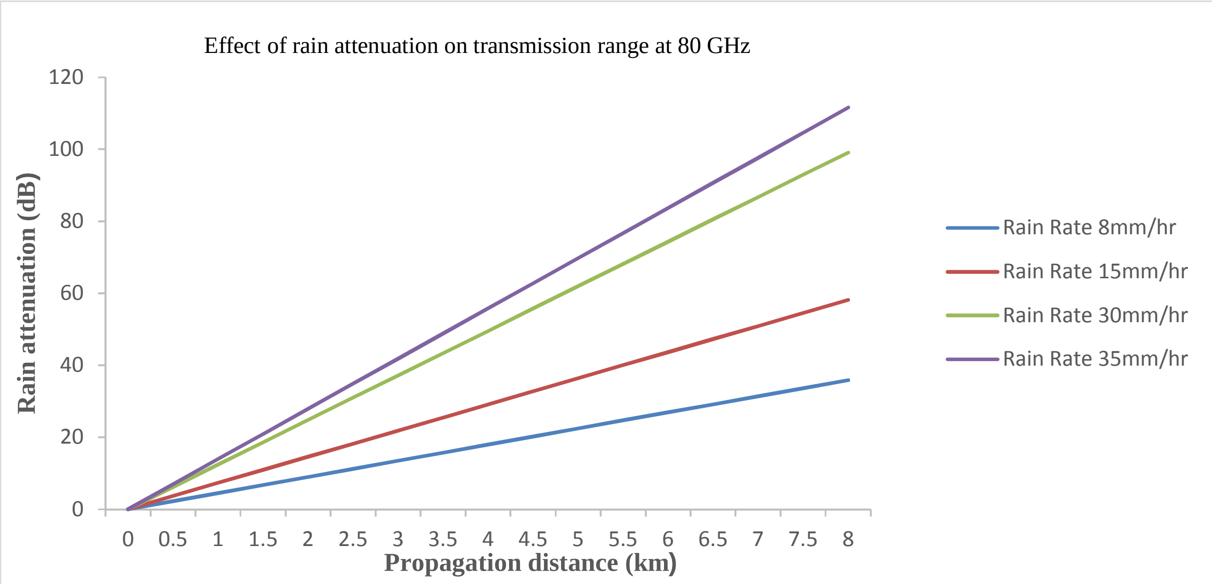

Figure 3-3: Rain attenuation vs propagation distance

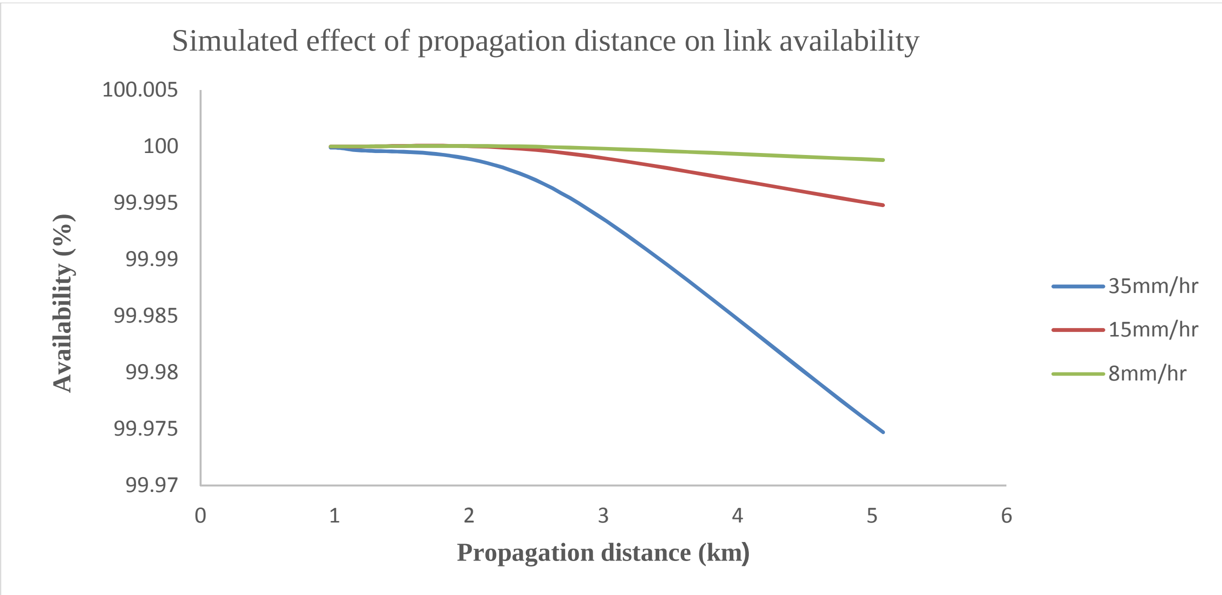

Figure 3-4: Simulated availability vs propagation distance

3.4 Frequency Planning and Management

In accordance with ITU Radio Regulations, the following key procedures were followed.

An equipment type approval certificate was obtained from the CA authorizing its use for telecommunication purposes in Kenya having attained the required ETSI compliance standards.

A trial authorization license was obtained from CA authorizing the use of E-band frequency for transmitting radio signals in Kenya.

In order to achieve FDD communication, the ETSI through ECC/REC (05)07 in annexes 1 and 2 defined the channel arrangement for 71 GHz to 76 GHz and 81 GHz to 86 GHz as lower and upper bands respectively where each 5GHz bandwidth has nineteen 250 MHz channels [9]. The reference frequency of the lower and upper bands are 71000MHz and 81000MHz respectively, with 250MHz as the separation between the lower band edge and the centre frequency of the first channel and separation between centre frequencies of the final channel and the upper band edge. Figure 3-5 shows E-band frequency channel plan with 250MHz channel bandwidth and a duplex separation of 10GHz, where *f* and *f'* represents a frequency pair for FDD communication.

71-76GHz																		
f1	*f2*	*f3*	*f4*	*f5*	*f6*	*f7*	*f8*	*f9*	*f10*	*f11*	*f12*	*f13*	*f14*	*f15*	*f16*	*f17*	*f18*	*f19*
71250	71500	71750	72000	72250	72500	72750	73000	73250	73500	73750	74000	74250	74500	74750	75000	75250	75500	75750
81-86GHz																		
f'1	*f'2*	*f'3*	*f'4*	*f'5*	*f'6*	*f'7*	*f'8*	*f'9*	*f'10*	*f'11*	*f'12*	*f'13*	*f'14*	*f'15*	*f'16*	*f'17*	*f'18*	*f'19*
81250	81500	81750	82000	82250	82500	82750	83000	83250	83500	83750	84000	84250	84500	84750	85000	85250	85500	85750

Figure 3-5: E-Band frequency channel plan with 250MHz channel bandwidth

The 250 MHz channel plan can further be subdivided into 125 MHz and 62.5 MHz channels if need be. Consequently channels of larger size i.e. 500 MHz, 750 MHz or 1 GHz can be obtained through aggregation of individual 250 MHz channels.

In this experiment, a channel spacing of 250 MHz was adopted. Channel bandwidth aggregation can be done to obtain larger bandwidths of 500, 750 and so on when there is a need for higher data rate over a given link.

3.5 RFC 2544 Tests

The following four tests were carried out using an Ethernet test meter ascertain carrier class Ethernet capability of E-band equipment. The frame sizes used during the tests were 64, 128, 256, 512, 768, 1024, 1280, 1518, and 1582 so as to ensure all maximum transmission unit (MTU) sizes are tested. Results for each test was appended in a tabulated format.

Throughput Test: The throughput test defines the maximum number of frames per second that can be transmitted without any error. This test is done to measure the rate-limiting capability of an Ethernet switch as found in carrier Ethernet services. This is done by starting from maximum frame rate and then comparing the number of transmitted and received frames. If there is a frame loss, the transmission rate is reduced by a predefined percentage/rate and the test is repeated until there is no more frame loss. The resultant transmission rate without frame loss is then concluded as the maximum throughput.

Back-to-Back Test: This is a testing for the buffering capability of an Ethernet switch or an equivalent device. It measures the maximum number of frames received at full line rate before a frame is lost. This measurement is used to validate the excess information rate (EIR) when required.

Latency Test: Latency is the total time taken for a frame to travel from source to destination. It is the sum of the processing delays in the network elements (switches/routers) and the propagation delay over the transmission medium (radio/fiber/cable links). The test methodology measures latency at maximum error-free throughput or over an averaged range of specified throughputs (loads). It first establishes a frame rate, and then sends a time-stamped frame within the frame stream. The difference between the send and receive times establishes the latency.

Frame Loss Test: Frame loss is the number of frames that were sent successfully from source but were never received at the destination. It is expressed as a percentage of frames lost against total frames sent. It is used to measure how a network responds to overload conditions, rather than the point at which no frame loss occurs.

Chapter Four

Results and Analysis

The following links were implemented successfully and monitored for a period 120 days. Daily graphical results have been provided for performance analysis. The links Kisumu used 4QAM in order to boost system gain.

Table 4-1 shows E-band links planning and design parameters.

Parameter	**Mombasa**		**Nairobi**	**Kisumu**		
	Link 1	**Link 2**	**Link 1**	**Link 1**	**Link 2**	**Link 3**
Link Path Length	6.12km	0.49km	2.55km	2.91km	5.09km	5.3km
Transmit Frequency (MHz)	81125	81125	81125	83125	82125	82125
Receive Frequency (MHz)	71125	71125	71125	73125	72125	72125
Duplex Spacing (MHz)	10000	10000	10000	10000	10000	10000
RF Channel Spacing	250MHz	250MHz	250MHz	250MHz	250MHz	250MHz
Modulation	16QAM	16QAM	16QAM	4QAM	4QAM	4QAM
Ethernet Bandwidth (Mbps)	799	799	799	370	370	370
Antenna Size (m)	0.6	0.3	0.3	0.6	0.6	0.6
Antenna Gain (dBi)	50.5	43.5	43.5	50.5	50.5	50.5
Transmit Power (dBm)	13	13	13	14	14	14
Receiver sensitivity threshold	-63	-63	-63	-74	-74	-74
RX Level (dBm)	-40.93	-35.57	-39.69	-28.37	-33.1	-33.54
Fade Margin (dBm)	22.07	38.43	23.31	45.63	40.9	40.46
Design Availability (%)	99.867	99.99999	99.978	99.993	99.969	99.966
Equipment Type	NEC	NEC	NEC	AVIAT	AVIAT	AVIAT

The following graphs were plotted and observations were made on links performance based on daily received signal levels.

The 0.49 km path length link in Mombasa did not register any period of ES, SES and UAS for the entire 120 days as shown in figure 4.1. Figure 4.1 shows received signal level from the daily link performance data for 0.5km link in Mombasa. The graph shows maximum received signal level registered was -28 dBm while the minimum received signal level was -70 dBm. The good performance can be attributed to the fact that the link is relatively short hence a higher fade margin due to low free space loss.

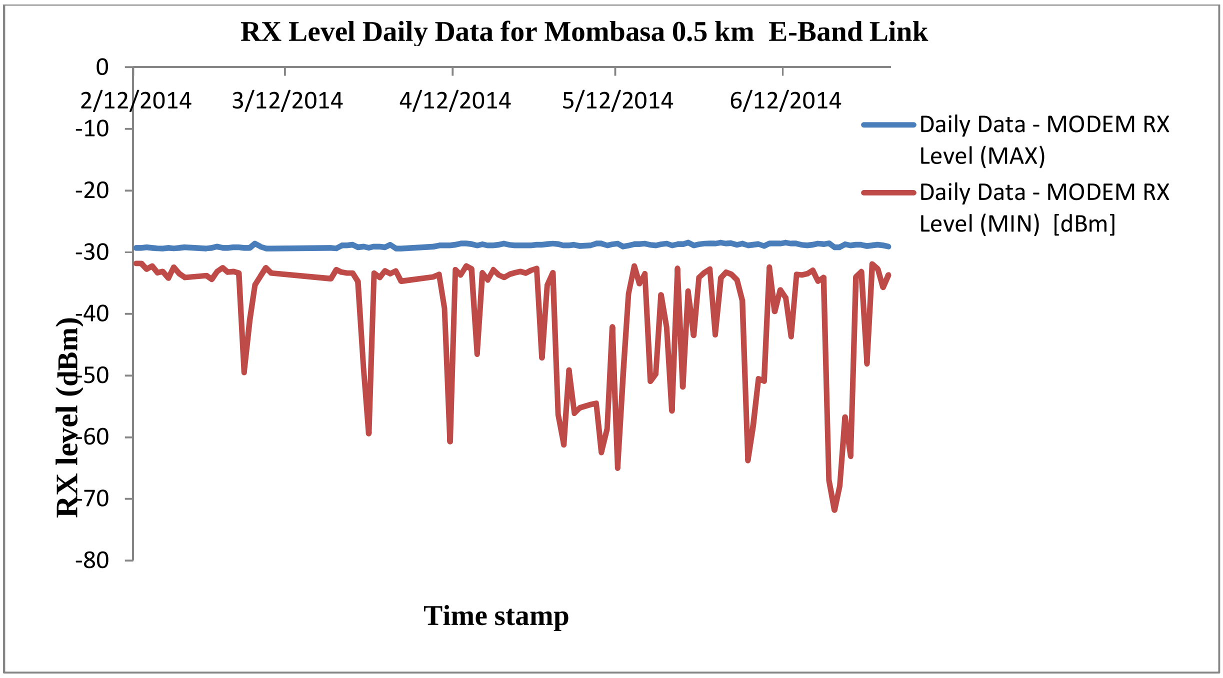

Figure 4-1 Daily maximum and minimum RX levels for link 2 in Mombasa

The link in Nairobi city with a path length of 2.55 km registered periods of errored seconds (ES) in 12 out of 120 days. However, only 10 out of the 12 days had periods of unavailable seconds (UAS) as shown in Table 4-2 and Figure 4-2.

Table 4-2: Periods of Errored seconds, severely errored seconds and unavailable seconds for link in Nairobi

Time Stamp	RF BBE	RF ES	RF SES	RF SEP	RF UAS	RF OFS	RX Level (MIN) [dBm]
6/23/2014	683954	209	26	5	164	2	-74
6/19/2014	147912	46	11	1	0	0	-70.7
6/6/2014	160576	46	6	2	524	266	-82.6
6/5/2014	125500	249	0	0	3302	1113	-89.4
5/10/2014	606528	215	29	2	399	126	-77.7
5/2/2014	11	4	0	0	0	0	-68.7
4/24/2014	77250	31	4	1	9015	175	-90
4/19/2014	39321	12	1	0	133	92	-77.2
4/17/2014	286145	104	19	3	60	0	-72.4
4/14/2014	59745	23	2	0	362	83	-88.6
4/6/2014	106065	38	5	0	285	70	-86.6
2/17/2014	268013	223	9	1	379	63	-88.1

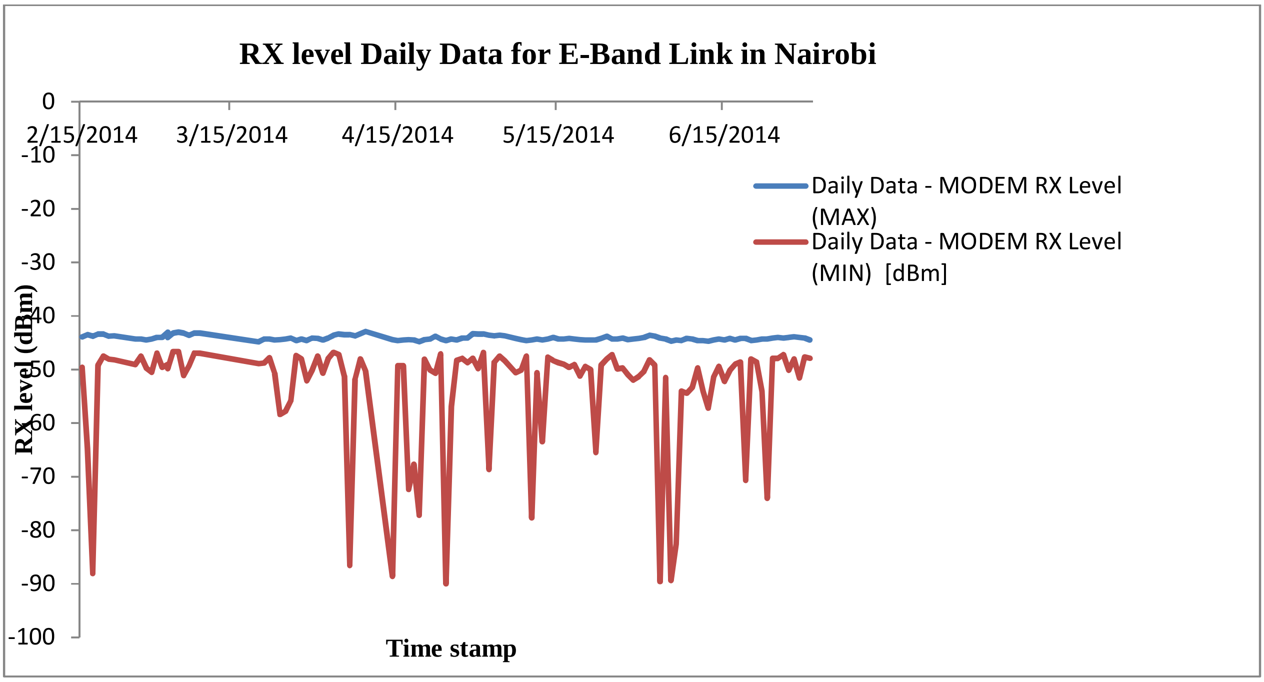

Figure 4-2 Daily maximum and minimum RX levels for the link 1 in Nairobi

Figure 4-2 shows the graph of daily received signal level for the E-band link installed in Nairobi. The link registered a maximum received signal of -42 dBm and a minimum of -89 dBm over the test period. The link registered periods of errored seconds (ES) in 12 out of 120 days. However, only 10 out of the 12 days had periods of unavailable seconds (UAS) as shown in Table 4-2 over the test period. The results shows that the link performed well but fell short of the required fade margin to overcome the higher free space loss. To correct this, an antenna size of 0.6m diameter should be introduced in this case to boost the system gain. The modulation scheme can also be lowered to 4QAM to increase transmit power and receiver sensitivity. A 0.6m antenna will contribute additional 14 dB to the link budget while the modulation scheme at 4QAM will provide additional 5 dBm to the link budget and increase the receiver sensitivity to -74 dBm. These corrective actions will bring up the minimum RSL to about -70 dBm thus link outage will not be experienced.

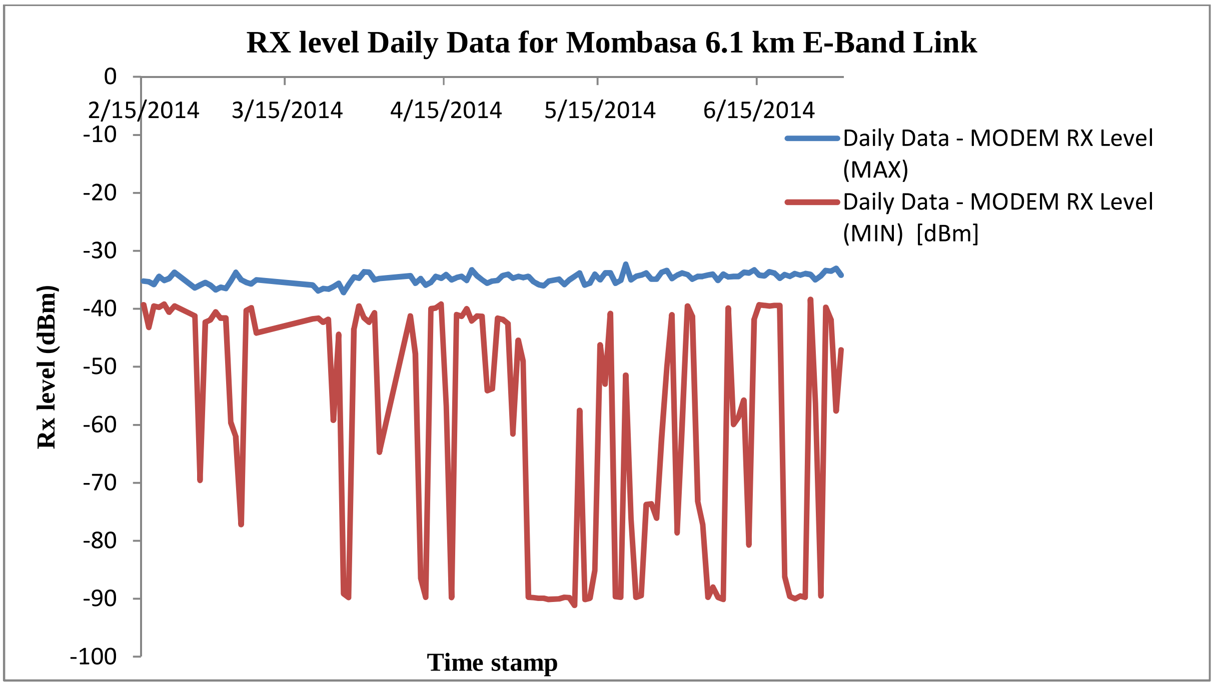

Figure 4-3 Daily maximum and minimum RX levels for link 1 in Mombasa

The link in Mombasa city with a path length of 6.1 km registered periods of errored seconds (ES) in 41 out of 120 days with 40 experiencing periods of unavailable seconds (UAS) as shown in Table 4-3 and Figure 4-3.

Figure 4-3 shows the graph of daily received signal level for the 6.1km E-band link installed in Mombasa. The link registered a maximum received signal of -35 dBm and a minimum of -89 dBm over the test period. The link registered periods of errored seconds (ES) in 41 out of 120 days with 40 experiencing periods of unavailable seconds (UAS) as shown in Table 4-3 over the test period. The results shows that the link performed well but fell short of the required fade margin to overcome the higher free space loss. To correct this, a larger antenna size should be introduced in this case to boost the system gain but this is not possible since currently there is no larger antenna than 0.6m for E-band. The modulation scheme can be reduced to 4QAM to increase transmit power and receiver sensitivity. When the link modulation is reduced to 4QAM additional 5 dBm will be added to the link budget but this is not enough to boost the system gain. The recommendation in this case is to break the link into two. Though this option is expensive, it will provide acceptable link availability.

Figure 4-4 shows daily maximum RSL for the two links in Mombasa while Figure 4-5 shows the daily minimum RSL. From the graphs performance of 0.5km link is better than that of 6.1km because it has lower free space loss given the short distance.

Table 4-3 Periods of Errored seconds, severely errored seconds and unavailable seconds for link 1 in Mombasa

Time Stamp	RF BBE	RF ES	RF SES	RF SEP	RF UAS	RF OFS	RX Level (MIN) [dBm]
6/27/2014	111215	32	4	0	252	39	-89.5
6/24/2014	168841	70	12	2	3567	357	-89.7
6/23/2014	444497	233	12	2	2884	719	-89.5
6/22/2014	644391	177	6	0	1985	485	-90
6/21/2014	321581	158	13	2	3798	809	-89.6
6/20/2014	146573	27	3	1	65	31	-86.2
6/13/2014	59915	23	1	0	103	49	-80.7
6/8/2014	165790	66	9	1	1123	433	-90.1
6/7/2014	872687	381	42	6	2590	884	-89.7
6/6/2014	45037	15	0	0	151	69	-88
6/5/2014	279337	117	7	1	2082	407	-89.7
6/4/2014	25934	12	1	0	32	23	-77.2
6/3/2014	128330	49	6	1	17	0	-73.1
5/30/2014	73292	20	2	0	31	17	-78.6
5/26/2014	991658	310	19	4	917	155	-76.1
5/25/2014	346598	118	28	4	106	0	-73.6
5/24/2014	195426	57	9	2	25	0	-73.7
5/23/2014	259734	87	22	3	120	26	-89.4
5/22/2014	219579	123	2	0	1780	401	-89.7
5/21/2014	191995	74	10	2	136	45	-76.2
5/19/2014	810486	260	46	6	2860	509	-89.7
5/18/2014	940381	352	49	5	1175	423	-89.6
5/14/2014	276606	100	15	1	538	161	-85.1
5/13/2014	279440	77	13	1	733	127	-89.9
5/12/2014	1421871	517	49	6	10753	2092	-90.1
5/10/2014	389310	98	6	1	1107	337	-91.1
5/9/2014	581582	238	20	2	5660	748	-89.8
5/8/2014	805839	222	35	4	2446	597	-89.7
5/7/2014	234455	88	6	0	1935	239	-90
5/5/2014	357206	107	19	3	1022	300	-90.1
5/4/2014	88786	53	8	1	2206	78	-89.9
5/3/2014	1073306	388	30	2	5865	1237	-89.9
5/2/2014	425191	204	39	5	3479	582	-89.8
5/1/2014	131809	58	4	1	534	114	-89.7
4/16/2014	159707	66	2	0	2175	279	-89.8
4/11/2014	768406	261	38	1	3849	859	-89.7
4/10/2014	48543	22	3	0	109	57	-86.4
3/27/2014	88357	36	4	0	477	75	-89.8
3/26/2014	1557241	468	104	8	2153	298	-89.1
3/6/2014	1376563	488	62	6	729	107	-77.2
2/26/2014	3684	26	0	0	0	0	-69.6

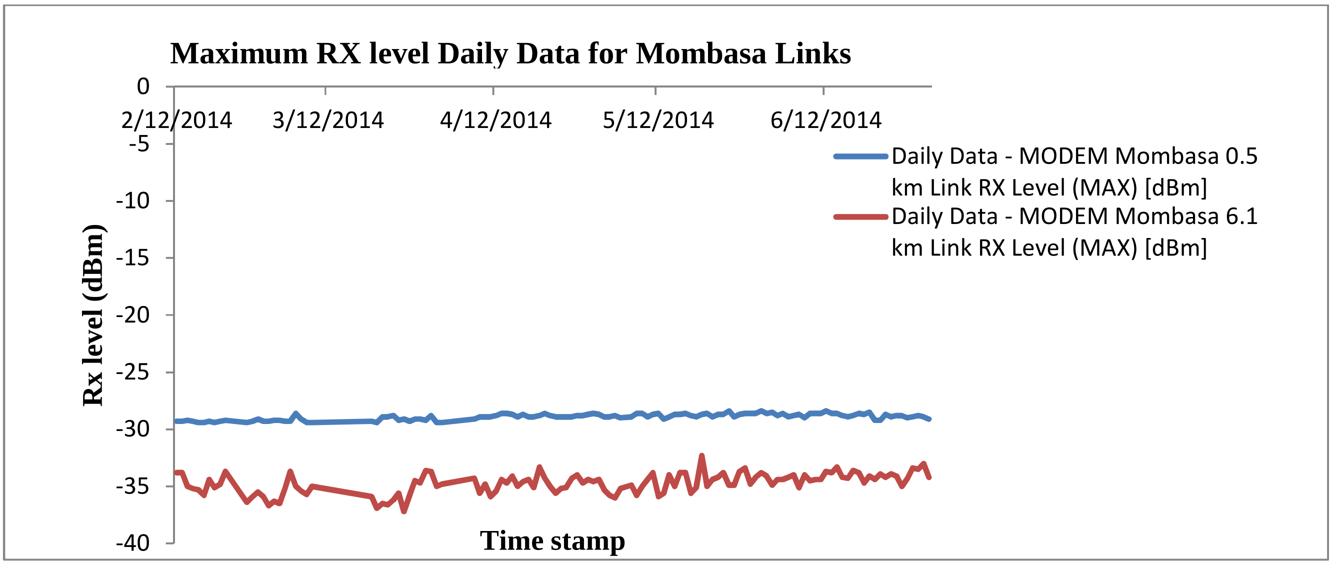

Figure 4-4 Comparison of maximum RX levels for links 1 and 2 in Mombasa

Comparing the maximum and minimum received signal levels, the link with a path length of 0.5 km showed better performances than the one with a path length of 6.1 km as shown in Figures 4-4 and 4-5 respectively.

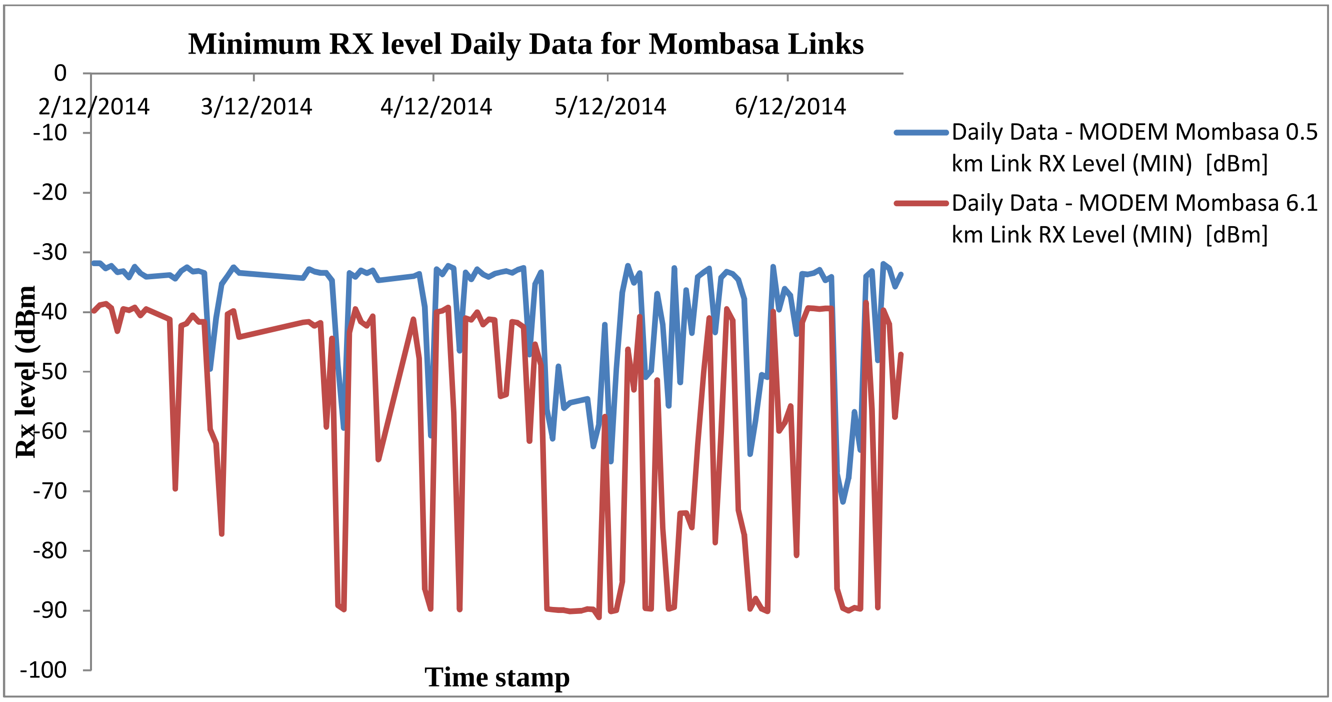

Figure 4-5 Comparison of minimum RX levels for links 1 and 2 in Mombasa

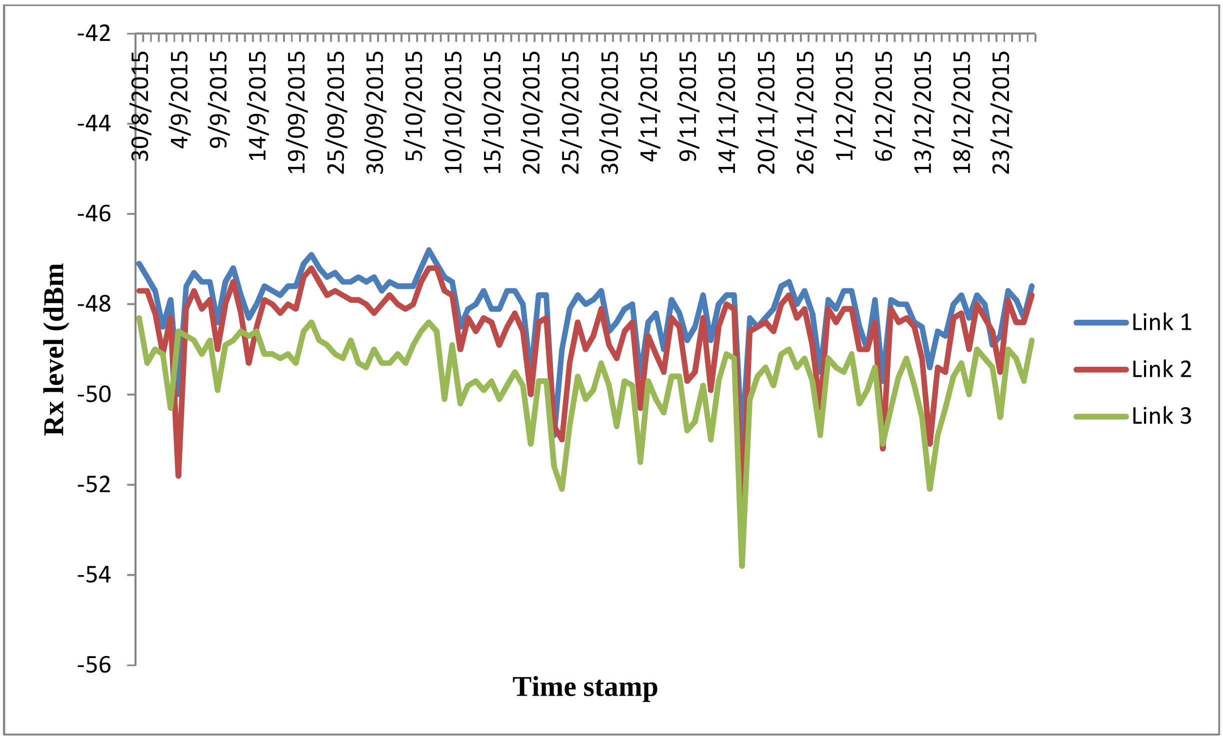

Figure 4-6 Comparison of RX levels for links 1, 2 and link 3 in Kisumu

Link 1 which is the shortest hop of 2.91km in Kisumu performed better than the other hops which are all more than 5km as shown in Figure 4-6. Figure 4-6 is a plot of the daily receive signal levels for the three links in Kisumu. The receive signal levels are good and that translates into a good fade margin for information transmission. However, the links performance in Kisumu are not as good as the links in Mombasa and Nairobi. This can be attributed to differences in weather patterns.

The following graphs were plotted and observations made on link performances in comparison to daily rainfall data obtained from the meteorological department of Kenya. Data from Jomo Kenyatta International Airport Meteorological Station was used for Nairobi link performance analysis while data from Mombasa Port Reitz Airport Station was used for Mombasa links' performance analysis. The rainfall data used for Kisumu links' performance analysis were extracted from Kisumu Meteorological Station located at Kisumu International Airport.

The link of 0.5km path length in Mombasa had 100% availability throughout the 120 days period even with the presence of rainfall as shown in Figures 4-7 and 4-8.

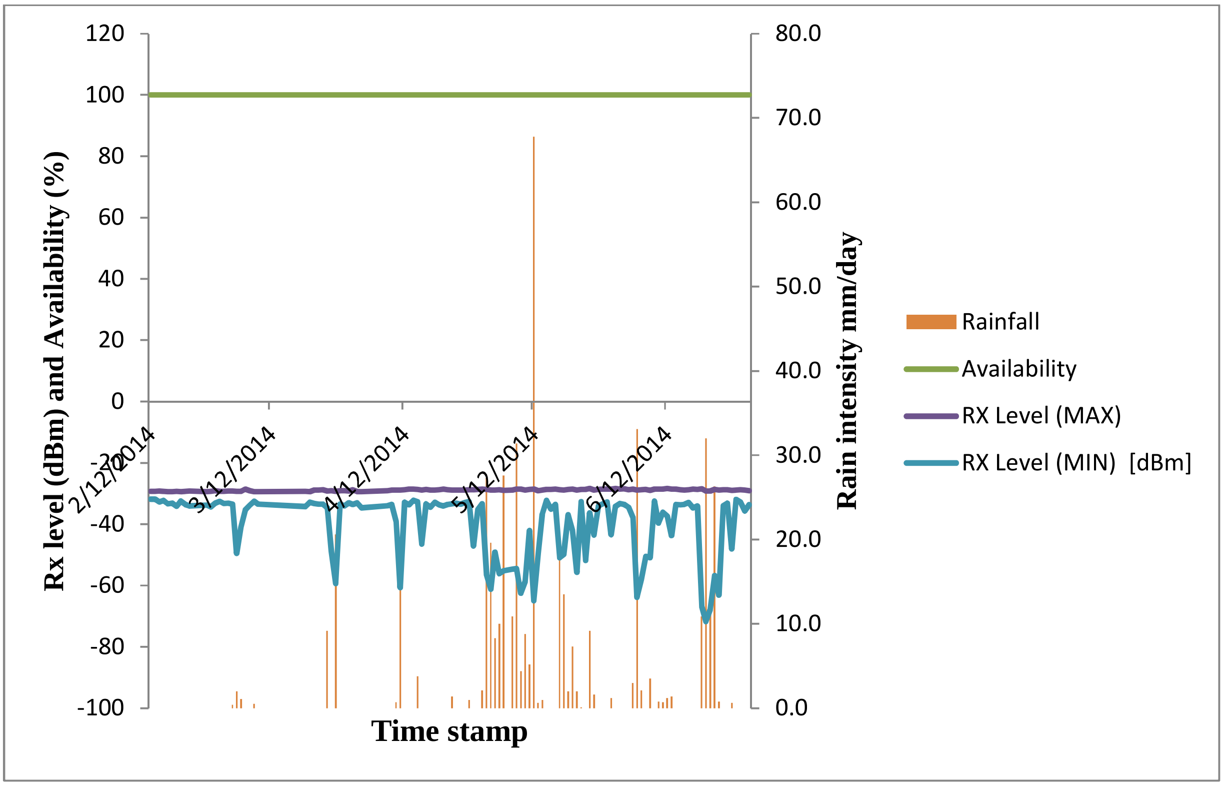

Figure 4-7 Comparison of RX levels and Availability with daily rainfall data for link 2 in Mombasa

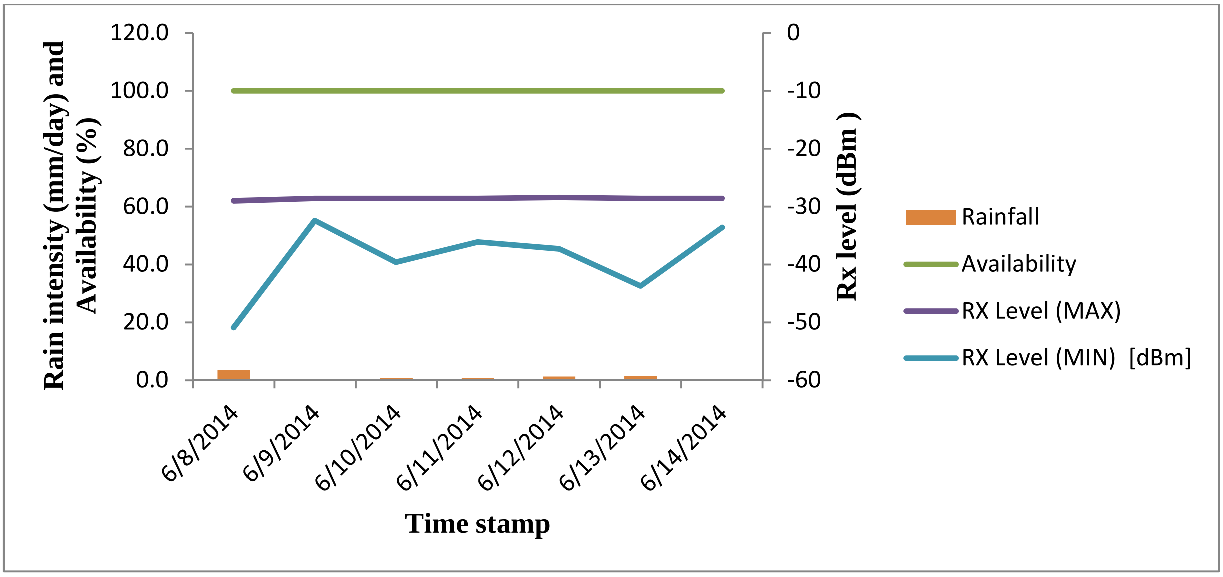

Figure 4-8 One week comparison of RX levels and Availability with daily rainfall data for link 2 in Mombasa

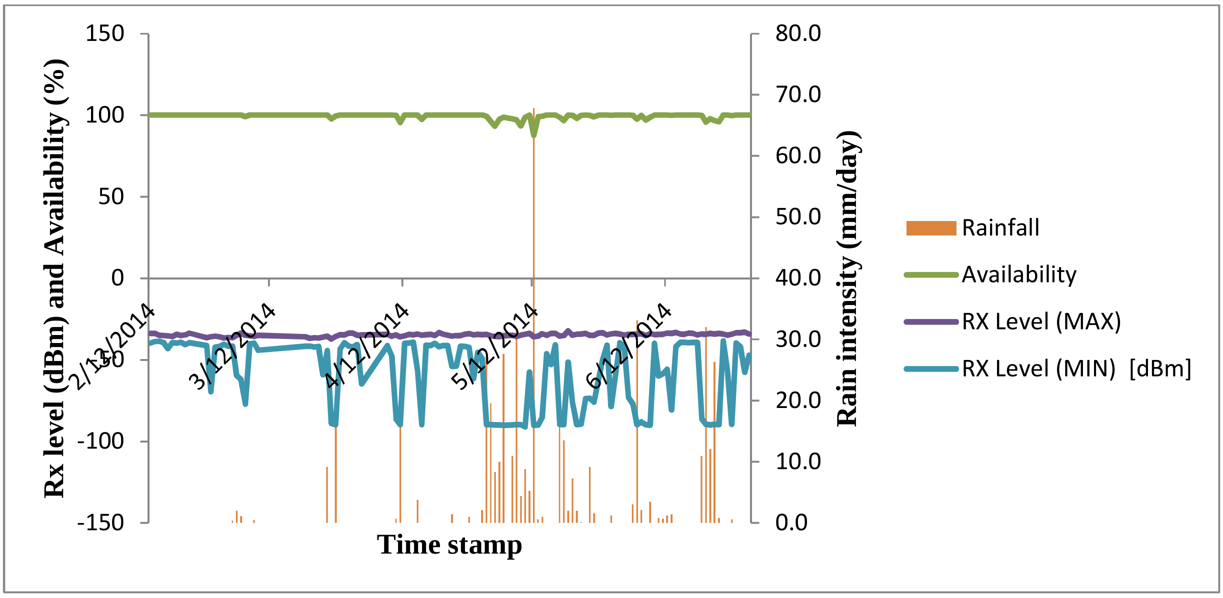

Figure 4-9 Comparison of RX levels and Availability with daily rainfall data for link 1 in Mombasa

Links in Mombasa and Nairobi with 6.12 km and 2.55 km respectively, registered periods of unavailability due to rainfall as shown in Figures 4-7 to 4-12.

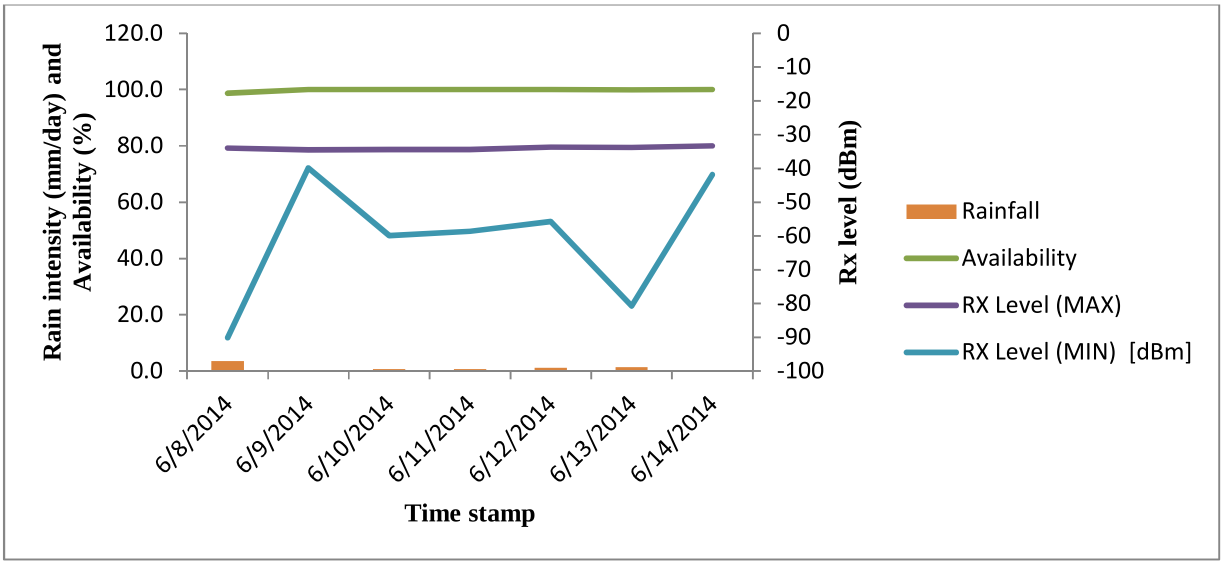

Figure 4-10 One week comparison of RX levels and Availability with daily rainfall data for link 1 in Mombasa

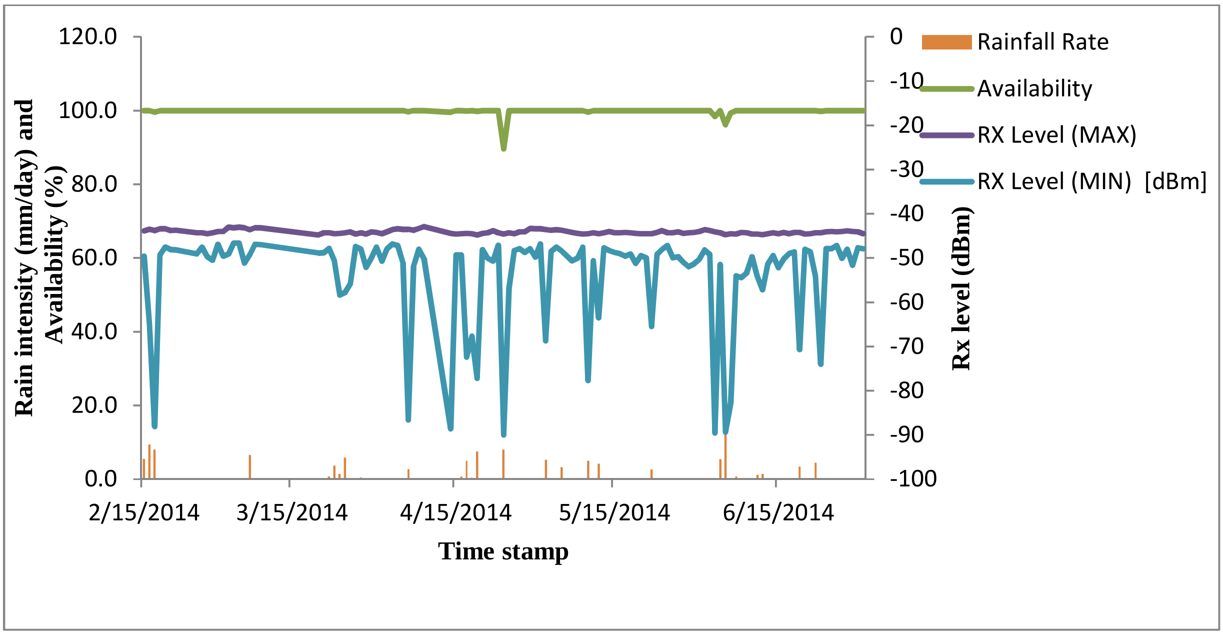

Figure 4-11 Comparison of RX levels and Availability with daily rainfall data for link 1 in Nairobi

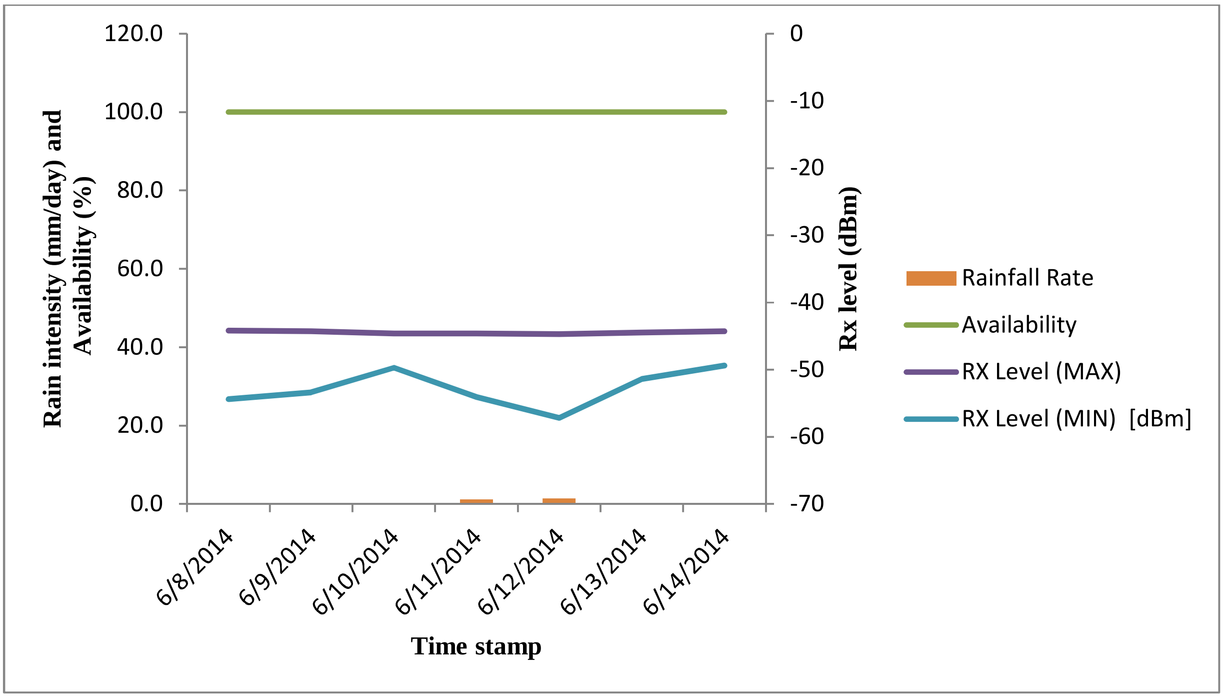

Figure 4-12 One week comparison of RX levels and Availability with daily rainfall data for link 1 in Nairobi

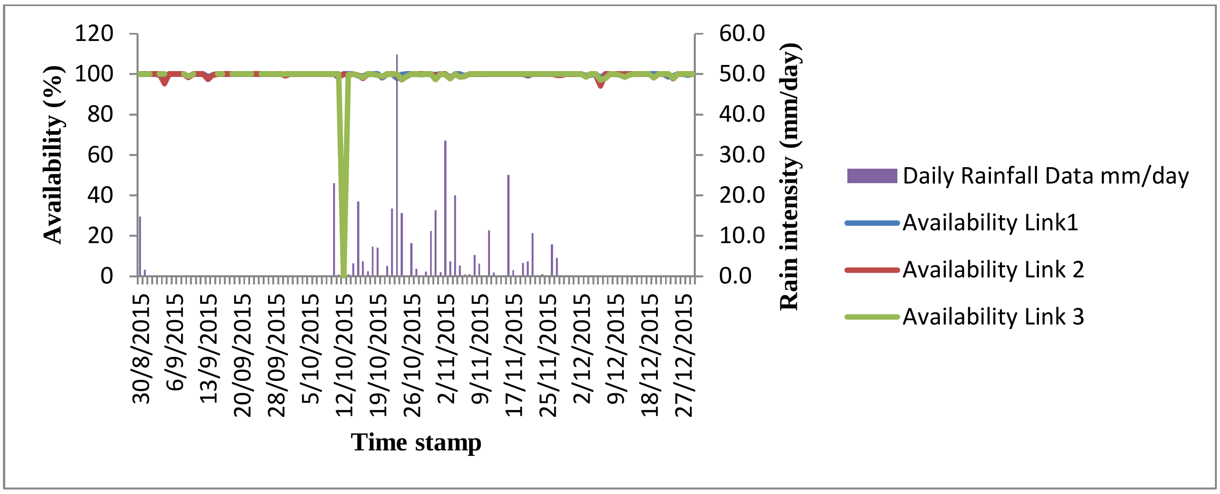

Figure 4-13 Comparison of RX levels and Availability with daily rainfall data for links 1, 2 and 3 in Kisumu

There were big discrepancies in rainfall data versus links performance in Kisumu as shown in Figures 4-13 to 4-14. A couple of cases are observed where the links availability are 100% even in the presence of rain and cases where there is a dip in availability yet there was no rainfall recorded on such date. This could be due to the fact that the rainfall data used were extracted from the Airport station which is located some miles away from the locations where the links are installed and this could have been caused by differences in distribution of rain cells. The September and December rainfall data were not available.

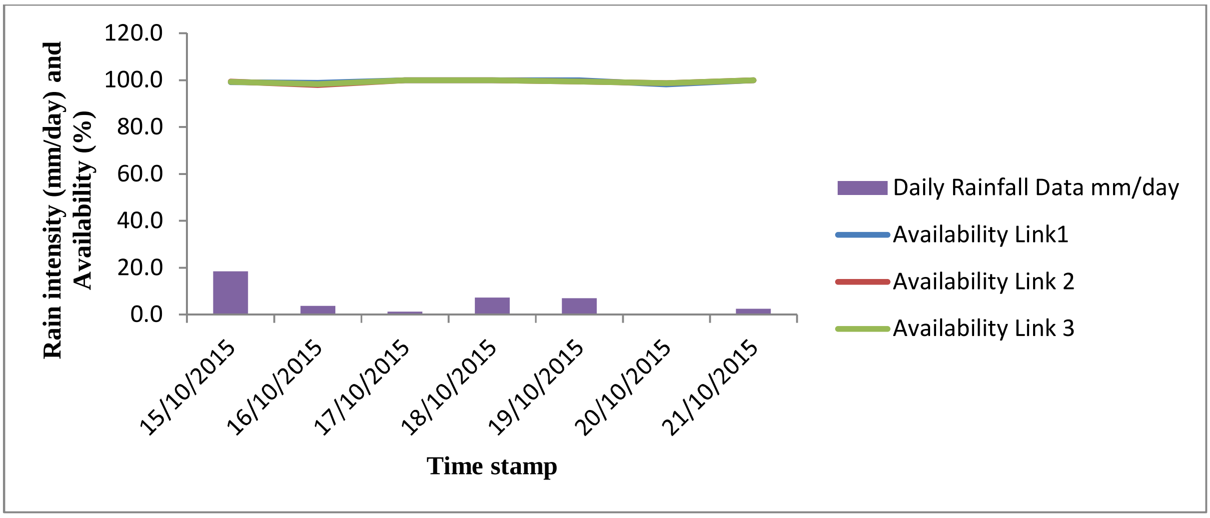

Figure 4-14 One week comparison of RX levels and Availability with daily rainfall data for links 1, 2 and 3 in Kisumu

Figures 4-7 to 4-12 gives a comparison of received signal levels and availability against rainfall data. This comparison is necessary in order to understand the behavior of E-band links in the presence of rain. In fact it is well known that rainfall attenuation affects all microwave links above 10 GHz but the extent of this depends on the rainfall attenuation coefficient for specific frequency band. From the Figure 4-7 and 4-8 it is can be seen that the link with 0.5km did not register any period of unavailability during rain periods. However, the RSL dipped to -70 dBm indicating it experienced rainfall attenuation but it have enough fade margin to counter this owing to its short path length. Figure 4-9 and 4-10 shows that the 6.1km link in Mombasa experienced outages during rainy periods. During these periods the received signal levels dropped to -90 dBm a sign that the link suffered significantly due to rain attenuation because of its longer path length. To correct this, a larger antenna size should be introduced in this case to boost the system gain but this is not possible since currently there is no larger antenna than 0.6m for E-band. The modulation scheme can be reduced to 4QAM to increase transmit power and receiver sensitivity. When the link modulation is reduced to 4QAM, additional 4 dBm will be added to the link budget but this is not enough to boost the system gain. The recommendation in this case is to break the link into two. Figures 4-11 and 4-12 shows that the 2.55km link in Nairobi experienced outages during rainy periods. During these periods the received signal levels dropped to -89 dBm a sign that the link suffered significantly due to rain attenuation because of its long length. Again to correct this, a larger antenna with a higher gain should be introduced to boost the system gain in order to counter rainfall attenuation. Since this link was designed with a 0.3m antenna it is possible to upgrade to a 0.6m antenna which is available. The modulation scheme can also be reduced to 4QAM in order to increase transmit power and increase the receiver sensitivity. A 0.6m antenna will contribute additional 14 dB to the link budget while a modulation scheme at 4QAM will provide additional 5 dBm to the link budget and increase the receiver sensitivity to -74 dBm. These corrective actions will bring up the minimum RSL to about -70 dBm thus link outage will not be experienced.

A sample RFC 2544 test on the longest hop of 6 km resulted with the maximum throughput of 790 Mbps with a modulation of 16QAM, 250MHz bandwidth and the longest transmission delay of 672.6 µs as shown in Table 4-4.

Table 4-4 RFC 2544 Tests Results for link 1 in Mombasa

RFC 2544 TEST RESULTS FOR THE 6 KM LINK				
Frame size(Bytes)	Throughput (Mbps)	Frame Lost	Latency (**μs**)	Burst Size
1582	790	0	672.6	2
1518	789	0	681.6	2
1280	787	0	680.8	2
1024	784	0	665.2	2
768	779	0	661.6	2
512	769	0	651.5	2
256	742	0	526.6	2
128	691	0	147.2	2
64	609	0	143.4	2

Chapter Five

Discussions

One would wonder whether a microwave link can operate at these extra high frequencies. The answer is yes, this study has proved it is possible. So how does it work? The maximum equipment transmit power at 16 dBm for QPSK is more or less the same as that of the equipment used in lower frequencies. In order to overcome the high FSL and to achieve the fade margin required, the E-band Andrews antennas are designed with very low side lobes, but very directive main lobe to maximize on the gain. The high directivity of the E-band antennas requires special installation skills and high precision/accuracy during link alignment in order to achieve the desired signal levels. Figures 5-1 and 5-2 illustrates E-band antenna radiation pattern envelope for E-band 0.6m and 0.3m diameter respectively. Antenna radiation pattern envelope illustrates the antenna's discrimination and directivity as a function of angle. Where discrimination property determines the antenna's capability to discriminate against unwanted frequencies while directivity determines the gain and sensitivity of the antenna. The discrimination property of an antenna is important when planning a microwave link in an area congested with microwave links of the same frequency band. Antennas with good discrimination capability in this case helps to reduce co-channel interference and enhance frequency re-use. The directivity property of an antenna gain is important when more power is required to boost the link fade margin. Antennas with small beam widths enhances the directivity resulting in high gain and sensitivity. The E-band antenna of 0.6m diameter with 0.5^0 beam width has a higher gain of 50.5 dBi compared to 0.3m diameter antenna with 0.9^0 beam width and a gain of 43.5 dBi.

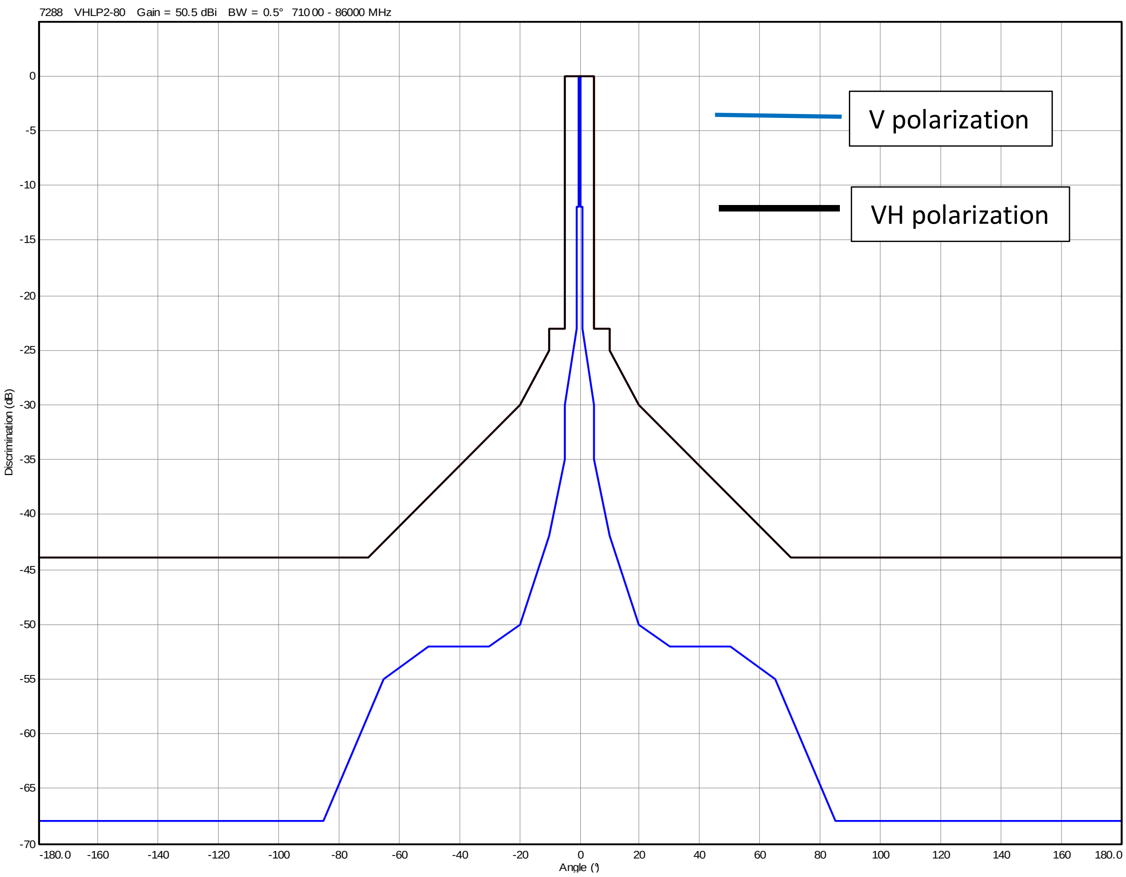

Figure 5-1 Radiation Pattern envelope of a 0.6 m E-band antenna

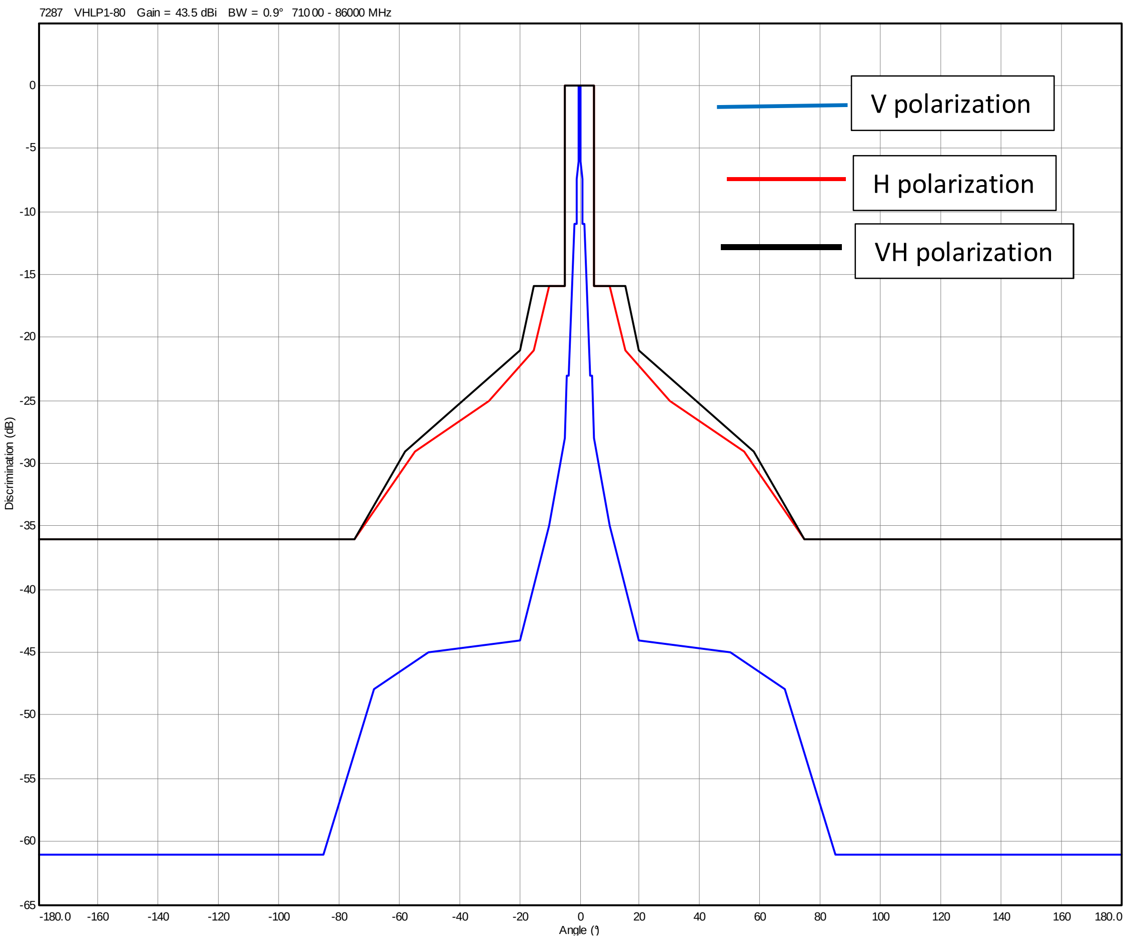

Figure 5-2 Radiation pattern envelope of a 0.3 m E-band antenna

Another factor that has contributed to the success and good performance of the E-Band is the highly sensitive receiver. While the equipment design receiver threshold is -63 dBm, the results obtained in the field proved to be far much better than this by about 8 dB. From the data collected it was noted that none of the links registered even a single errored second (ES) at a received signal level of -70 dBm. All the links operated well without effects on the customer traffic while operating at received signal levels of between -63 and -70 dBm.

The relatively short path length for the 0.5km link in Mombasa is a testimony to the ability of the link's EIRP to effectively overcome the free space loss and other forms of atmospheric and rain attenuation. The notable difference in the maximum received signal levels for the two links in Mombasa shows the effect of propagation distance on free space loss. As the link propagation distance increases the free space loss increases as well. Thus in as much as the longer link had a bigger antenna and gain, the additional 7 dBi gain was not enough to compensate for the 22 dB free space loss difference. The free space loss equation at 80GHz shows that there is a 22 dB increase in free space attenuation when the link distance is increased from 0.5 km to 6 km. The result also obeys the inverse square law where power decreases inversely as the square of the distance.

The fade margin of a link is expected to take care of the atmospheric attenuation that a link is likely to encounter during propagation. When the FSL is too big, a huge proportion of the fade margin is eaten up leaving the link vulnerable to rain and atmospheric attenuation. When comparing the minimum received signal levels for the links in Mombasa, the shorter link did not suffer any ES or UAS caused by rainfall attenuation while the longer link seemed to have suffered periods of ES and UAS in 40 out of 120 days. Rainfall attenuation is a function of frequency and distance of propagation. Thus an increase in the path length coupled with high frequencies results in high rain attenuation that affects the availability of a microwave link.

In order to improve the link performance to encounter rainfall attenuation, various methods of design can be used. Increase of an antenna size would be ideal in cases where a smaller antenna has been used. E-band has only two antenna sizes 0.3 m and 0.6 m with the difference of 7 dBi gain between them. Thus when replacing a 0.3 m dish with a 0.6 m, the system gain will be boosted by 14 dB.

Another way to improve the link performance is by use of adaptive and coding modulation technology. We know that the lower modulation schemes have higher transmit power, but lower capacity compared to the higher modulation schemes with relatively lower transmit power but with higher capacity . With this technology, system designers can plan a link to operate with higher modulation and higher capacity during good propagation conditions but drops step by step to the lowest modulation when the conditions are bad. In this case part of the customer traffic is lost. Usually a priority policy is implemented such that critical services classified as EF (expedited forwarding) and AF (assured forwarding) are not lost. So far E-band equipment can only operate up to 64 QAM as the highest modulation scheme, thus adaptive modulation would work from 64QAM, 32QAM, 16QAM and QPSK. Considering the link in Nairobi which had some periods of ES and UAS, the first thing would be to implement adaptive modulation. Because the link was implemented with 16QAM and TX power of 13 dBm, QPSK with TX power of 16 dBm will give a boost in system gain by 3 dB, which can comfortably encounter the effects of light rainfall. Because the results showed that receive signal levels could dip up to -90 dBm, an increase of antenna size to a 0.6 m dish would therefore be appropriate as well. This would boost the system gain by additional 14 dB, thus tackling the rainfall effect completely. The link can as well remain as it is if only meant to provide redundancy to an optical fiber cable link. In this case only adaptive modulation would be recommended in order to control the additional cost that comes with antenna replacement.

For the case of the 6.1 km link, adaptive modulation would be recommended in order to boost the performance during the bad weather conditions otherwise the path length needs to be broken into two if it is a critical link providing critical services.

ITU-T Recommendation G.114 specifies 250ms with a tolerance of up to 400ms for voice services as the general limits for one-way transmission delay. With a delay of 672µs, E-band link has proved to be within the desired limits and a carrier class Ethernet carrier device. From the throughput results it is also evident that if the channel bandwidth is expanded to 500MHz for example, then a data rate of 1.5Gbps is achievable with modulation maintained at 16QAM. If the hop length is short then a higher modulation of 64QAM can be used as an alternative way of achieving a higher data rate without having to increase the bandwidth.

Chapter Six

Conclusion and Future Work

6.1 Conclusion

The main purpose of this case study was to demonstrate the possibility of obtaining acceptable and sustainable performance of E-Band links in Kenya with an aim to open up high spectrum opportunities in this frequency band for alternative high data rate backhaul solutions. It has been proved that E-Band link can perform well in path lengths of up to 3km and beyond this range under clear weather conditions.

The good receiver sensitivity of E-Band equipment has seen the links work under very low received signal levels. This together with the high antenna gain has made it possible for equipment in this frequency band to be able to operate on higher path lengths of up to 6km or even more under clear weather conditions.

Though the 6 km path length link seemed to be suffering a lot from rainy weather conditions, this can be improved by using QPSK and wider channel bandwidth so that the link performance is improved without compromising the desired data rate. With proper link planning and design, E-Band can perform well enough just like the traditional frequencies bands above 10GHz. The typical range should be up to 3km for link availability of 99.999%. However, route redundancy is recommended for E-Band path lengths greater than 3km to avoid interruption of customer traffic during rainy weather conditions. The capability of E-Band equipment as Ethernet carrier device has also been confirmed through RFC 2544 tests that have given good throughput and latencies that are well within the general limits of ITU-T recommendation G.114. In this era of high data demand, E-Band will work well to compliment optical fiber cables but also to provide an alternative backhaul solutions for short and last mile solutions. This is expected to be good news to data players in Kenya since E-Band regulatory frequency fee is expected to be cheaper by virtue of light licensing due to its low propagation capabilities compared to lower frequency bands below 10GHz. E-Band link can therefore be celebrated as a reality in Kenya.

6.2 Future Work

In conclusion, the research found that E-band links can perform typical well for path length of 3km and up to 6km under clear weather conditions. It was noted that in order to improve the performance an increase in antenna size provides a boost to the link budget and therefore increased fade margin. However, E-band antennas presently available have the largest antenna size of 0.6m hence it was not possible to explore this option to improve the performance of 6km path length E-band link during rainy periods. In order to improve the future performance of E-band links beyond 3km and up to 6km as this study has found out, it is recommended that further research work should be carried out towards the development of 1.2m diameter E-band antenna.

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Appendices

Appendix A

Equipment specifications

NEC iPASOLINK EX

NEC iPASOLINK EX technical specifications

NEC iPASOLINK EX	
Frequency Band	71-76GHz/81-86GHz FDD
Modulation	QPSK/16/32QAM (Hitless AMR)
Channel Separation	250MHz (ETSI/ANSI)
Interfaces	2 x GbE (Electrical or Optical)
QoS	8 classes queue strict priority/DWRR
Synchronization	Synchronous Ethernet
Ethernet OAM	IEEE802.1ag/ITU-T G.1731/IEEE802.3ah
Radio Configuration	1 + 0 or 2 + 0
Antenna	Direct mount (0.3-0.6m dia.)
Ambient Temperature	-33 to +50°C
Power Line Voltage	-40.5 to 57VDC or PoE
Power Consumption	50W typ.
Dimensions(mm) and Weight	270(W) x 270(H) x 100(D) < 5.5kg

Aviat WTM 3300

Aviat WTM 3300 technical specifications

Aviat WTM 3300	
Frequency Band	71-76GHz/81-86GHz FDD
Modulation	QPSK/16/64QAM
Channel Separation	250MHz (ETSI/ANSI)
Interfaces	RJ45 or RJ45 PoE (100/1000 BaseT)
QoS	8 classes queue strict priority/WRR
Radio Configuration	1 + 0
Antenna	Direct mount (0.3 and 0.6m dia.)
Ambient Temperature	-33 to +55°C
Power Line Voltage	-48VDC or PoE
Power Consumption	36W
Dimensions(mm) and Weight	280(W) x 280(H) x 84(D)/3.5kg

Appendix B

Meteorological rainfall data

KENYA METEORLOGICAL DEPARTMENT-DAILY RAINFALL DATA IN MM

Station_ID	Station_Name	Year	Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
9136164	DAGORETTI CORNER MET. STATION	2014	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9136164	DAGORETTI CORNER MET. STATION	2014	2	0.0	0.0	0.0	0.0	0.0	0.0	13.5	5.6	1.2	22.6	0.0	0.0	0.0	0.6	16.6	8.7	0.0	0.0	0.0	9.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
9136164	DAGORETTI CORNER MET. STATION	2014	3	0.0	0.0	0.0	0.0	0.0	6.6	0.0	0.0	0.0	0.0	0.0	5.8	18.5	50.1	0.0	15.0	0.1	0.0	0.2	0.0	0.0	1.1	3.0	0.0	4.3	0.2	0.0	0.7	0.0	16.1	0.0
9136164	DAGORETTI CORNER MET. STATION	2014	4	0.0	0.0	0.0	0.0	0.0	4.7	0.0	0.0	0.0	5.7	8.8	6.2	0.0	0.0	0.0	0.7	0.5	9.9	8.9	0.0	0.0	0.0	7.9	2.4	0.0	0.0	0.0	0.0	0.0	0.0	
9136164	DAGORETTI CORNER MET. STATION	2014	5	0.0	9.7	0.0	0.0	0.9	30.4	0.0	0.0	0.0	6.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	2.6	0.0	5.4	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0
9136164	DAGORETTI CORNER MET. STATION	2014	6	0.0	0.0	0.0	11.4	0.1	0.3	15.6	0.1	0.0	0.5	0.7	2.1	0.1	0.0	0.0	0.0	0.0	0.0	11.4	1.1	0.0	5.9	0.0	0.0	0.0	0.2	0.5	0.0	0.0	0.0	
9136164	DAGORETTI CORNER MET. STATION	2014	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3	3.4	0.0	0.0	4.3	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.1	0.0
9439021	MOMBASA PORT REITZ AIRPORT	2014	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9439021	MOMBASA PORT REITZ AIRPORT	2014	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
9439021	MOMBASA PORT REITZ AIRPORT	2014	3	0.0	0.0	0.4	2.0	1.1	0.0	0.0	0.5	0.0	0.0	0.0	0.0	2.8	33.8	6.9	0.0	0.0	0.5	2.0	0.0	0.0	0.0	0.0	0.0	9.2	0.0	20.6		0.0	0.0	0.0
9439021	MOMBASA PORT REITZ AIRPORT	2014	4	0.0	0.0	0.0	1.7	0.2	2.8	0.0	0.0	0.0	0.7	19.2	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	1.0	0.0	0.0	2.1	
9439021	MOMBASA PORT REITZ AIRPORT	2014	5	27.3	19.6	8.3	10.0	27.6	12.8	10.9	31.4	4.4	8.8	5.2	67.8	0.6	1.0	0.0	0.0	0.0	20.6	13.5	2.0	7.3	2.0	0.1	0.0	9.2	1.6	0.0	0.0	0.0	1.2	0.0
9439021	MOMBASA PORT REITZ AIRPORT	2014	6	0.0	0.0	0.0	3.0	33.1	2.1	0.0	3.5	0.0	0.8	0.7	1.2	1.4	0.0	0.0	0.0	0.0	0.0	0.0	10.9	32.0	12.1	26.3	0.8	0.0	0.0	0.6	0.0		0.0	
9439021	MOMBASA PORT REITZ AIRPORT	2014	7	0.0	0.0	0.0	0.0	0.0	3.4	1.0	0.0	0.0	0.0	1.8	1.5	0.0	0.0	0.0	4.1	1.9	0.0	2.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	1.2	0.0	17.0	21.0	2.7
9034025	KISUMU METEOROLOGICAL STATION	2015	8	0.0	1.4	0.0	0.5	0.0	0.0	1.9	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	3.8	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	14.8	1.6
9034025	KISUMU METEOROLOGICAL STATION	2015	9																															
9034025	KISUMU METEOROLOGICAL STATION	2015	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.0	0.4	5.1	0.4	3.2	18.5	3.7	1.2	7.3	7.1	0.3	2.6	16.8	54.9	15.6	0.0	8.2	1.9	0.0	1.1	11.2	16.3
9034025	KISUMU METEOROLOGICAL STATION	2015	11	1.0	33.5	3.7	20.0	2.7	0.4	0.5	5.3	3.1	0.2	11.4	0.9	0.0	0.0	0.0	25.1	1.5	0.0	3.3	3.7	10.7	0.0	0.0	0.5	0.0	7.9	4.5	0.0	0.3	0.1	
9034025	KISUMU METEOROLOGICAL STATION	2015	12																															
9136168	J.K.I.A. METEOROLOGICAL STATION	2014	2	0.0	0.0	0.0	0.0	0.0	0.0	13.0	2.3	1.5	32.5	1.0	0.0	0.0	5.5	9.4	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
9136168	J.K.I.A. METEOROLOGICAL STATION	2014	3	0.0	0.0	0.0	0.0	0.0	6.6	0.0	0.0	0.0	0.0	0.0	3.5	24.1	30.2	0.0	0.0	1.2	0.0	4.2	0.0	0.0	0.8	3.7	1.4	5.8	0.0	0.0	0.5	0.0	0.0	0.0
9136168	J.K.I.A. METEOROLOGICAL STATION	2014	4	0.0	0.0	0.0	0.0	0.0	2.7	0.0	0.0	0.0	5.8	0.0	6.2	0.0	0.0	0.0	0.8	5.0	0.4	7.5	0.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	
9136168	J.K.I.A. METEOROLOGICAL STATION	2014	5	0.0	5.2	0.0	0.0	3.2	1.7	0.0	0.0	0.0	5.0	0.0	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9136168	J.K.I.A. METEOROLOGICAL STATION	2014	6	0.0	0.0	0.0	5.4	26.5	0.0	0.8	0.0	0.0	0.0	1.2	1.4	0.0	0.0	0.0	0.0	0.0	0.0	3.5	0.0	0.0	4.5	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	
9136168	J.K.I.A. METEOROLOGICAL STATION	2014	7	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.6	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Appendix C

Sample Pathloss 4.0 Link Budget Simulations

	Imara Daima	Embakasi
Elevation (m)	1627.64	1623.00
Latitude	01 19 10.41 S	01 18 29.30 S
Longitude	036 53 30.95 E	036 54 42.70 E
True azimuth (°)	60.35	240.35
Vertical angle (°)	-0.11	0.10
Antenna model	VHLP2-80	VHLP2-80
Antenna height (m)	0.00	0.00
Antenna gain (dBi)	47.40	47.40
Radome loss (dB)	0.00	0.00
Frequency (MHz)	80000.00	
Polarization	Vertical	
Path length (km)	2.55	
Free space loss (dB)	138.67	
Atmospheric absorption loss (dB)	1.03	
Net path loss (dB)	44.89	44.89
Radio model	iPASOLINK EX 80G 16Q 25	iPASOLINK EX 80G 16Q 25
TX power (watts)	0.02	0.02
TX power (dBm)	13.00	13.00
EIRP (dBm)	60.40	60.40
Emission designator	250M00G7W	250M00G7W
RX threshold criteria	BER 10-6	BER 10-6
RX threshold level (dBm)	-63.00	-63.00
Maximum receive signal (dBm)	-10.00	-10.00
RX signal (dBm)	-31.89	-31.89
Thermal fade margin (dB)	31.11	31.11
Geoclimatic factor	3.14E-06	
Path inclination (mr)	1.82	
Fade occurrence factor (Po)	1.06E-05	
Average annual temperature (°C)	22.00	
Worst month - multipath (%)	100.00000	100.00000
(sec)	0.02	0.02
Annual - multipath (%)	100.00000	100.00000
(sec)	0.09	0.09
(% - sec)	100.00000 - 0.19	
Rain region	ITU Region A	
0.01% rain rate (mm/hr)	8.00	
Flat fade margin - rain (dB)	31.11	
Rain rate (mm/hr)	30.74	
Rain attenuation (dB)	31.11	
Annual rain (%-sec)	99.99970 - 94.98	
Annual multipath + rain (%-sec)	99.99970 - 95.17	

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Reliability Method - ITU-R P.530-7/8
Rain - ITU-R P530-7

	Changamwe	Nyali
Elevation (m)	53.70	23.08
Latitude	04 01 24.10 S	04 02 16.01 S
Longitude	039 37 35.10 E	039 40 46.76 E
True azimuth (°)	105.10	285.09
Vertical angle (°)	-0.31	0.27
Antenna model	VHLP2-80	VHLP2-80
Antenna height (m)	35.00	35.00
Antenna gain (dBi)	47.40	47.40
Radome loss (dB)	0.00	0.00
Frequency (MHz)	80000.00	
Polarization	Vertical	
Path length (km)	6.12	
Free space loss (dB)	146.27	
Atmospheric absorption loss (dB)	2.46	
Net path loss (dB)	53.93	53.93
Radio model	iPASOLINK EX 80G 16Q 25	iPASOLINK EX 80G 16Q 25
TX power (watts)	0.02	0.02
TX power (dBm)	13.00	13.00
EIRP (dBm)	60.40	60.40
Emission designator	250M00G7W	250M00G7W
TX Channels	1H 81125.0000V	1L 71125.0000V
RX threshold criteria	BER 10-6	BER 10-6
RX threshold level (dBm)	-63.00	-63.00
Maximum receive signal (dBm)	-10.00	-10.00
RX signal (dBm)	-40.93	-40.93
Thermal fade margin (dB)	22.07	22.07
Geoclimatic factor	1.12E-05	
Path inclination (mr)	5.00	
Fade occurrence factor (Po)	3.05E-04	
Average annual temperature (°C)	22.00	
Worst month - multipath (%)	99.99981	99.99981
(sec)	5.04	5.04
Annual - multipath (%)	99.99993	99.99993
(sec)	21.64	21.64
(% - sec)	99.99986 - 43.27	
Rain region	ITU Region J	
0.01% rain rate (mm/hr)	35.00	
Flat fade margin - rain (dB)	22.07	
Rain rate (mm/hr)	18.19	
Rain attenuation (dB)	22.07	
Annual rain (%-sec)	99.86714 - 41898.92	
Annual multipath + rain (%-sec)	99.86700 - 41942.20	

Mon, Oct 06 2014
2460-2510-E-Band.pl4
Reliability Method - ITU-R P.530-7/8
Rain - ITU-R P530-7

	Changamwe B	Changamwe A
Elevation (m)	55.98	53.70
Latitude	04 01 16.31 S	04 01 24.10 S
Longitude	039 37 21.16 E	039 37 35.10 E
True azimuth (°)	119.08	299.08
Vertical angle (°)	-0.27	0.26
Antenna model	VHLP1-80	VHLP1-80
Antenna height (m)	25.00	25.00
Antenna gain (dBi)	43.50	43.50
Radome loss (dB)	0.00	0.00
Frequency (MHz)	80000.00	
Polarization	Vertical	
Path length (km)	0.49	
Free space loss (dB)	124.37	
Atmospheric absorption loss (dB)	0.20	
Net path loss (dB)	37.57	37.57
Radio model	iPASOLINK EX 80G 16Q 25	iPASOLINK EX 80G 16Q 25
TX power (watts)	0.02	0.02
TX power (dBm)	13.00	13.00
EIRP (dBm)	56.50	56.50
Emission designator	250M00G7W	250M00G7W
RX threshold criteria	BER 10-6	BER 10-6
RX threshold level (dBm)	-63.00	-63.00
Maximum receive signal (dBm)	-10.00	-10.00
RX signal (dBm)	-24.57	-24.57
Thermal fade margin (dB)	38.43	38.43
Geoclimatic factor	1.77E-06	
Path inclination (mr)	4.64	
Fade occurrence factor (Po)	6.04E-09	
Average annual temperature (℃)	22.00	
Worst month - multipath (%)	100.00000	100.00000
(sec)	2.30e-06	2.30e-06
Annual - multipath (%)	100.00000	100.00000
(sec)	9.87e-06	9.87e-06
(% - sec)	100.00000 - 0.00	
Rain region	ITU Region A	
0.01% rain rate (mm/hr)	8.00	
Flat fade margin - rain (dB)	38.43	
Rain rate (mm/hr)	852.90	
Rain attenuation (dB)	38.43	
Annual rain (%-sec)	100.00000 - 0.00	
Annual multipath + rain (%-sec)	100.00000 - 0.00	

Mon, Oct 06 2014
2028-2460-E-Band.pl4
Reliability Method - ITU-R P.530-7/8
Rain - ITU-R P530-7

	1502	WN0420
Elevation (m)	1175.03	1202.63
Latitude	00 05 45.80 S	00 03 29.02 S
Longitude	034 45 20.79 E	034 47 05.08 E
True azimuth (°)	37.51	217.51
Vertical angle (°)	0.06	-0.10
Antenna model	VHLP2-80	VHLP2-80
Antenna height (m)	45.00	25.00
Antenna gain (dBi)	50.50	50.50
TX line type	Integrated	Integrated
TX line length (m)	0.00	0.00
TX line unit loss (dB /100 m)	3.00	3.00
TX line loss (dB)	0.00	0.00
Miscellaneous loss (dB)	0.70	0.70
Frequency (MHz)	80000.00	
Polarization	Vertical	
Path length (km)	5.30	
Free space loss (dB)	145.01	
Atmospheric absorption loss (dB)	2.13	
Net path loss (dB)	47.54	47.54
Radio model	W33-83G5-365Mb-4Q-250M	W33-83G5-365Mb-4Q-250M
TX power (watts)	0.03	0.03
TX power (dBm)	14.00	14.00
EIRP (dBm)	63.80	63.80
Emission designator	250MD2W	250MD2W
TX Channels	5L 72125.0000V	5H 82125.0000V
RX threshold criteria	BER 10-3	BER 10-3
RX threshold level (dBm)	-74.00	-74.00
Maximum receive signal (dBm)	-20.00	-20.00
RX signal (dBm)	-33.54	-33.54
Thermal fade margin (dB)	40.46	40.46
Dispersive fade margin (dB)	100.00	100.00
Dispersive fade occurrence factor	1.00	
Effective fade margin (dB)	40.46	40.46
Geoclimatic factor	1.77E-06	
Path inclination (mr)	1.43	
Fade occurrence factor (Po)	1.02E-04	
Average annual temperature (°C)	22.00	
Worst month - multipath (%)	100.00000	100.00000
(sec)	0.02	0.02
Annual - multipath (%)	100.00000	100.00000
(sec)	0.10	0.10
(% - sec)	100.00000 - 0.21	
Rain region	ITU Region K	
0.01% rain rate (mm/hr)	42.00	
Flat fade margin - rain (dB)	40.46	
Rain rate (mm/hr)	21.76	
Rain attenuation (dB)	40.46	
Annual rain (%-sec)	99.96562 - 10841.15	
Annual multipath + rain (%-sec)	99.96562 - 10841.36	

Sat, Mar 05 2016
1502-WN0420-E-Band.pl4
Reliability Method - ITU-R P.530-7/8
Rain - ITU-R P530-7

	1502	4038
Elevation (m)	1175.03	1401.86
Latitude	00 05 45.80 S	00 03 00.32 S
Longitude	034 45 20.79 E	034 45 14.59 E
True azimuth (°)	357.84	177.84
Vertical angle (°)	2.54	-2.57
Antenna model	VHLP2-80	VHLP2-80
Antenna height (m)	25.00	25.00
Antenna gain (dBi)	50.50	50.50
TX line type	Integrated	Integrated
TX line length (m)	0.00	0.00
TX line unit loss (dB /100 m)	3.00	3.00
TX line loss (dB)	0.00	0.00
Miscellaneous loss (dB)	0.70	0.70
Frequency (MHz)	80000.00	
Polarization	Vertical	
Path length (km)	5.09	
Free space loss (dB)	144.66	
Atmospheric absorption loss (dB)	2.05	
Net path loss (dB)	47.10	47.10
Radio model	W33-83G5-365Mb-4Q-250M	W33-83G5-365Mb-4Q-250M
TX power (watts)	0.03	0.03
TX power (dBm)	14.00	14.00
EIRP (dBm)	63.80	63.80
Emission designator	250MD2W	250MD2W
TX Channels	5L 72125.0000V	5H 82125.0000V
RX threshold criteria	BER 10-3	BER 10-3
RX threshold level (dBm)	-74.00	-74.00
Maximum receive signal (dBm)	-20.00	-20.00
RX signal (dBm)	-33.10	-33.10
Thermal fade margin (dB)	40.90	40.90
Dispersive fade margin (dB)	100.00	100.00
Dispersive fade occurrence factor	5.00	
Effective fade margin (dB)	40.90	40.90
Geoclimatic factor	2.80E-06	
Path inclination (mr)	44.57	
Fade occurrence factor (Po)	2.30E-06	
Average annual temperature (℃)	22.00	
Worst month - multipath (%)	100.00000	100.00000
(sec)	4.92e-04	4.92e-04
Annual - multipath (%)	100.00000	100.00000
(sec)	2.11e-03	2.11e-03
(% - sec)	100.00000 - 0.00	
Rain region	ITU Region K	
0.01% rain rate (mm/hr)	42.00	
Flat fade margin - rain (dB)	40.90	
Rain rate (mm/hr)	22.68	
Rain attenuation (dB)	40.90	
Annual rain (%-sec)	99.96893 - 9798.07	
Annual multipath + rain (%-sec)	99.96893 - 9798.08	

Sat, Mar 05 2016
1502-4038-E-Band.pl4
Reliability Method - ITU-R P.530-7/8
Rain - ITU-R P530-7

	4038	1515
Elevation (m)	1401.86	1545.58
Latitude	00 03 00.32 S	00 01 32.02 S
Longitude	034 45 14.59 E	034 44 40.79 E
True azimuth (°)	338.92	158.92
Vertical angle (°)	3.21	-3.23
Antenna model	VHLP2-80	VHLP2-80
Antenna height (m)	26.00	46.00
Antenna gain (dBi)	50.50	50.50
TX line type	Integrated	Integrated
TX line length (m)	0.00	0.00
TX line unit loss (dB /100 m)	3.00	3.00
TX line loss (dB)	0.00	0.00
Miscellaneous loss (dB)	0.70	0.70
Frequency (MHz)	80000.00	
Polarization	Vertical	
Path length (km)	2.91	
Free space loss (dB)	139.80	
Atmospheric absorption loss (dB)	1.17	
Field margin (dB)	1.00	
Net path loss (dB)	42.37	42.37
Radio model	W33-83G5-365Mb-4Q-250M	W33-83G5-365Mb-4Q-250M
TX power (watts)	0.03	0.03
TX power (dBm)	14.00	14.00
EIRP (dBm)	63.80	63.80
Emission designator	250MD2W	250MD2W
TX Channels	9H 83125.0000V	9L 73125.0000V
RX threshold criteria	BER 10-3	BER 10-3
RX threshold level (dBm)	-74.00	-74.00
Maximum receive signal (dBm)	-20.00	-20.00
RX signal (dBm)	-28.37	-28.37
Thermal fade margin (dB)	45.63	45.63
Dispersive fade margin (dB)	100.00	100.00
Dispersive fade occurrence factor	5.00	
Effective fade margin (dB)	45.63	45.63
Geoclimatic factor	2.80E-06	
Path inclination (mr)	56.27	
Fade occurrence factor (Po)	2.23E-07	
Average annual temperature (°C)	22.00	
Worst month - multipath (%)	100.00000	100.00000
(sec)	1.60e-05	1.60e-05
Annual - multipath (%)	100.00000	100.00000
(sec)	6.88e-05	6.88e-05
(% - sec)	100.00000 - 0.00	
Rain region	ITU Region K	
0.01% rain rate (mm/hr)	42.00	
Flat fade margin - rain (dB)	45.63	
Rain rate (mm/hr)	49.90	
Rain attenuation (dB)	45.63	
Annual rain (%-sec)	99.99288 - 2244.91	
Annual multipath + rain (%-sec)	99.99288 - 2244.91	

Sat, Mar 05 2016
4038-1515-E-Band.pl4
Reliability Method - ITU-R P.530-7/8
Rain - ITU-R P530-7

Appendix D

Daily Links Performance Data

NEC Links Performance Data

Daily Data - MODEM								
Time Stamp	RF BBE	RF ES	RF SES	RF SEP	RF UAS	RF OFS	RX Level (MAX)	RX Level (MIN) [dBm]
7/1/2014	0	0	0	0	0	0	-29.1	-33.7
6/30/2014	0	0	0	0	0	0	-28.9	-35.7
6/29/2014	0	0	0	0	0	0	-28.8	-32.7
6/28/2014	0	0	0	0	0	0	-28.9	-31.9
6/27/2014	0	0	0	0	0	0	-29	-48.1
6/26/2014	0	0	0	0	0	0	-28.8	-33.1
6/25/2014	0	0	0	0	0	0	-28.8	-34
6/24/2014	0	0	0	0	0	0	-28.9	-63.1
6/23/2014	0	0	0	0	0	0	-28.7	-56.7
6/22/2014	0	0	0	0	0	0	-29.2	-67.9
6/21/2014	0	0	0	0	0	0	-29.2	-71.8
6/20/2014	0	0	0	0	0	0	-28.5	-66.9
6/19/2014	0	0	0	0	0	0	-28.7	-34.1
6/18/2014	0	0	0	0	0	0	-28.6	-34.7
6/17/2014	0	0	0	0	0	0	-28.8	-32.9
6/16/2014	0	0	0	0	0	0	-28.9	-33.5
6/15/2014	0	0	0	0	0	0	-28.8	-33.7
6/14/2014	0	0	0	0	0	0	-28.6	-33.6
6/13/2014	0	0	0	0	0	0	-28.6	-43.7
6/12/2014	0	0	0	0	0	0	-28.4	-37.3
6/11/2014	0	0	0	0	0	0	-28.6	-36.1
6/10/2014	0	0	0	0	0	0	-28.6	-39.6
6/9/2014	0	0	0	0	0	0	-28.6	-32.4
6/8/2014	0	0	0	0	0	0	-29	-50.9
6/7/2014	0	0	0	0	0	0	-28.7	-50.5
6/6/2014	0	0	0	0	0	0	-28.8	-58.1
6/5/2014	0	0	0	0	0	0	-28.9	-63.8
6/4/2014	0	0	0	0	0	0	-28.6	-37.7
6/3/2014	*0	*0	*0	*0	*19	*0	*-28.8	*-34.5
6/2/2014	0	0	0	0	0	0	-28.5	-33.6
6/1/2014	0	0	0	0	0	0	-28.6	-33.2
5/31/2014	0	0	0	0	0	0	-28.4	-34.2
5/30/2014	0	0	0	0	0	0	-28.6	-43.4
5/29/2014	0	0	0	0	0	0	-28.6	-32.7
5/28/2014	0	0	0	0	0	0	-28.6	-33.3
5/27/2014	0	0	0	0	0	0	-28.7	-34.1
5/26/2014	0	0	0	0	0	0	-28.9	-43.5
5/25/2014	0	0	0	0	0	0	-28.4	-36.3
5/24/2014	0	0	0	0	0	0	-28.7	-51.8
5/23/2014	0	0	0	0	0	0	-28.7	-32.6
5/22/2014	0	0	0	0	0	0	-28.9	-55.7
5/21/2014	0	0	0	0	0	0	-28.6	-42.1
5/20/2014	0	0	0	0	0	0	-28.7	-36.9
5/19/2014	0	0	0	0	0	0	-28.9	-49.8
5/18/2014	0	0	0	0	0	0	-28.8	-50.9
5/17/2014	0	0	0	0	0	0	-28.6	-33.5
5/16/2014	0	0	0	0	0	0	-28.7	-35.1
5/15/2014	0	0	0	0	0	0	-28.7	-32.2
5/14/2014	0	0	0	0	0	0	-28.9	-36.7
5/13/2014	0	0	0	0	0	0	-29.1	-49.5
5/12/2014	0	0	0	0	0	0	-28.6	-65
5/11/2014	0	0	0	0	0	0	-28.7	-42.1
5/10/2014	0	0	0	0	0	0	-28.9	-58.7
5/9/2014	0	0	0	0	0	0	-28.6	-62.5
5/8/2014	0	0	0	0	0	0	-28.6	-54.5
5/7/2014	0	0	0	0	0	0	-28.9	-54.7

5/5/2014	0	0	0	0	0	0	-29	-55.2
5/4/2014	0	0	0	0	0	0	-28.8	-56.1
5/3/2014	0	0	0	0	0	0	-28.9	-49.1
5/2/2014	0	0	0	0	0	0	-28.9	-61.2
5/1/2014	0	0	0	0	0	0	-28.7	-56.3
4/30/2014	0	0	0	0	0	0	-28.6	-33.3
4/29/2014	0	0	0	0	0	0	-28.7	-35.3
4/28/2014	0	0	0	0	0	0	-28.8	-47.1
4/27/2014	0	0	0	0	0	0	-28.8	-32.6
4/26/2014	0	0	0	0	0	0	-28.9	-32.9
4/25/2014	0	0	0	0	0	0	-28.9	-33.4
4/24/2014	0	0	0	0	0	0	-28.9	-33.1
4/23/2014	0	0	0	0	0	0	-28.9	-33.3
4/22/2014	0	0	0	0	0	0	-28.8	-33.6
4/21/2014	0	0	0	0	0	0	-28.6	-34.1
4/20/2014	0	0	0	0	0	0	-28.8	-33.7
4/19/2014	0	0	0	0	0	0	-28.9	-32.8
4/18/2014	0	0	0	0	0	0	-28.9	-34.5
4/17/2014	0	0	0	0	0	0	-28.7	-33.3
4/16/2014	0	0	0	0	0	0	-28.9	-46.5
4/15/2014	0	0	0	0	0	0	-28.7	-32.7
4/14/2014	0	0	0	0	0	0	-28.6	-32.2
4/13/2014	0	0	0	0	0	0	-28.6	-33.7
4/12/2014	0	0	0	0	0	0	-28.8	-32.8
4/11/2014	0	0	0	0	0	0	-28.9	-60.7
4/10/2014	0	0	0	0	0	0	-28.9	-39.1
4/9/2014	0	0	0	0	0	0	-28.9	-33.6
4/8/2014	0	0	0	0	0	0	-29.1	-34
4/2/2014	0	0	0	0	0	0	-29.4	-34.7
4/1/2014	0	0	0	0	0	0	-29.4	-33
3/31/2014	0	0	0	0	0	0	-28.8	-33.5
3/30/2014	0	0	0	0	0	0	-29.2	-33
3/29/2014	0	0	0	0	0	0	-29.1	-34.1
3/28/2014	0	0	0	0	0	0	-29.1	-33.4
3/27/2014	0	0	0	0	0	0	-29.3	-59.4
3/26/2014	0	0	0	0	0	0	-29.1	-48.8
3/25/2014	0	0	0	0	0	0	-29.2	-34.7
3/24/2014	0	0	0	0	0	0	-28.8	-33.4
3/23/2014	0	0	0	0	0	0	-28.9	-33.4
3/22/2014	0	0	0	0	0	0	-28.9	-33.2
3/21/2014	0	0	0	0	0	0	-29.4	-32.8
3/20/2014	0	0	0	0	0	0	-29.3	-34.3
3/9/2014	0	0	0	0	0	0	-29.4	-33.4
3/8/2014	0	0	0	0	0	0	-29.4	-32.5
3/7/2014	0	0	0	0	0	0	-29.1	-33.9
3/6/2014	0	0	0	0	0	0	-28.6	-35.3
3/5/2014	0	0	0	0	0	0	-29.3	-41
3/4/2014	0	0	0	0	0	0	-29.3	-49.5
3/3/2014	0	0	0	0	0	0	-29.2	-33.4
3/2/2014	0	0	0	0	0	0	-29.2	-33.1
3/1/2014	0	0	0	0	0	0	-29.3	-33.2
2/28/2014	0	0	0	0	0	0	-29.3	-32.5
2/27/2014	0	0	0	0	0	0	-29.1	-33.1
2/26/2014	0	0	0	0	0	0	-29.3	-34.4
2/25/2014	0	0	0	0	0	0	-29.4	-33.8
2/21/2014	0	0	0	0	0	0	-29.2	-34.1
2/20/2014	0	0	0	0	0	0	-29.3	-33.5
2/19/2014	0	0	0	0	0	0	-29.4	-32.4
2/18/2014	0	0	0	0	0	0	-29.3	-34.2
2/17/2014	0	0	0	0	0	0	-29.4	-33.1
2/16/2014	0	0	0	0	0	0	-29.4	-33.3
2/15/2014	0	0	0	0	0	0	-29.3	-32.2
2/14/2014	0	0	0	0	0	0	-29.2	-32.7

2/13/2014	0	0	0	0	0	0	-29.3	-31.8
2/12/2014	0	0	0	0	0	0	-29.3	-31.8
Daily Data - MODEM								
Time Stamp	RF BBE	RF ES	RF SES	RF SEP	RF UAS	RF OFS	RX Level (MAX)	RX Level (MIN) [dBm]
7/1/2014	0	0	0	0	0	0	-34.2	-47.1
6/30/2014	0	0	0	0	0	0	-33	-57.6
6/29/2014	0	0	0	0	0	0	-33.5	-42
6/28/2014	0	0	0	0	0	0	-33.4	-39.7
6/27/2014	111215	32	4	0	252	39	-34.3	-89.5
6/26/2014	0	0	0	0	0	0	-35	-56.3
6/25/2014	0	0	0	0	0	0	-34.1	-38.4
6/24/2014	168841	70	12	2	3567	357	-33.9	-89.7
6/23/2014	444497	233	12	2	2884	719	-34.2	-89.5
6/22/2014	644391	177	6	0	1985	485	-33.9	-90
6/21/2014	321581	158	13	2	3798	809	-34.4	-89.6
6/20/2014	146573	27	3	1	65	31	-34.1	-86.2
6/19/2014	0	0	0	0	0	0	-34.7	-39.4
6/18/2014	0	0	0	0	0	0	-33.8	-39.4
6/17/2014	0	0	0	0	0	0	-33.6	-39.5
6/16/2014	0	0	0	0	0	0	-34.3	-39.4
6/15/2014	0	0	0	0	0	0	-34.2	-39.3
6/14/2014	0	0	0	0	0	0	-33.3	-41.8
6/13/2014	59915	23	1	0	103	49	-33.8	-80.7
6/12/2014	0	0	0	0	0	0	-33.7	-55.7
6/11/2014	0	0	0	0	0	0	-34.4	-58.6
6/10/2014	0	0	0	0	0	0	-34.4	-59.9
6/9/2014	0	0	0	0	0	0	-34.5	-39.9
6/8/2014	165790	66	9	1	1123	433	-34	-90.1
6/7/2014	872687	381	42	6	2590	884	-35.1	-89.7
6/6/2014	45037	15	0	0	151	69	-34	-88
6/5/2014	279337	117	7	1	2082	407	-34.2	-89.7
6/4/2014	25934	12	1	0	32	23	-34.4	-77.2
6/3/2014	128330	49	6	1	17	0	-34.4	-73.1
6/2/2014	0	0	0	0	0	0	-34.9	-41.3
6/1/2014	0	0	0	0	0	0	-34.1	-39.5
5/31/2014	0	0	0	0	0	0	-33.8	-60
5/30/2014	73292	20	2	0	31	17	-34.2	-78.6
5/29/2014	0	0	0	0	0	0	-34.8	-41
5/28/2014	0	0	0	0	0	0	-33.4	-50
5/27/2014	0	0	0	0	0	0	-33.7	-62.3
5/26/2014	991658	310	19	4	917	155	-34.9	-76.1
5/25/2014	346598	118	28	4	106	0	-34.9	-73.6
5/24/2014	195426	57	9	2	25	0	-33.8	-73.7
5/23/2014	259734	87	22	3	120	26	-34.2	-89.4
5/22/2014	219579	123	2	0	1780	401	-34.4	-89.7
5/21/2014	191995	74	10	2	136	45	-35	-76.2
5/20/2014	0	0	0	0	0	0	-32.3	-51.4
5/19/2014	810486	260	46	6	2860	509	-35.1	-89.7
5/18/2014	940381	352	49	5	1175	423	-35.6	-89.6
5/17/2014	0	0	0	0	0	0	-33.8	-40.8
5/16/2014	0	0	0	0	0	0	-33.8	-53
5/15/2014	0	0	0	0	0	0	-35	-46.2
5/14/2014	276606	100	15	1	538	161	-34	-85.1
5/13/2014	279440	77	13	1	733	127	-35.6	-89.9
5/12/2014	1421871	517	49	6	10753	2092	-35.9	-90.1
5/11/2014	0	0	0	0	0	0	-33.8	-57.5
5/10/2014	389310	98	6	1	1107	337	-34.4	-91.1
5/9/2014	581582	238	20	2	5660	748	-35	-89.8
5/8/2014	805839	222	35	4	2446	597	-35.8	-89.7
5/7/2014	234455	88	6	0	1935	239	-34.9	-90
5/5/2014	357206	107	19	3	1022	300	-35.2	-90.1
5/4/2014	88786	53	8	1	2206	78	-36	-89.9
5/3/2014	1073306	388	30	2	5865	1237	-35.8	-89.9

5/2/2014	425191	204	39	5	3479	582	-35.3	-89.8
5/1/2014	131809	58	4	1	534	114	-34.4	-89.7
4/30/2014	0	0	0	0	0	0	-34.6	-49
4/29/2014	0	0	0	0	0	0	-34.4	-45.4
4/28/2014	0	0	0	0	0	0	-34.7	-61.6
4/27/2014	0	0	0	0	0	0	-34	-42.5
4/26/2014	0	0	0	0	0	0	-34.3	-41.8
4/25/2014	0	0	0	0	0	0	-35.1	-41.6
4/24/2014	0	0	0	0	0	0	-35.2	-53.8
4/23/2014	0	0	0	0	0	0	-35.6	-54.1
4/22/2014	0	0	0	0	0	0	-35	-41.3
4/21/2014	0	0	0	0	0	0	-34.3	-41.2
4/20/2014	0	0	0	0	0	0	-33.3	-42.1
4/19/2014	0	0	0	0	0	0	-35.1	-40
4/18/2014	0	0	0	0	0	0	-34.4	-41.3
4/17/2014	0	0	0	0	0	0	-34.6	-41
4/16/2014	159707	66	2	0	2175	279	-35	-89.8
4/15/2014	0	0	0	0	0	0	-34.1	-56.8
4/14/2014	0	0	0	0	0	0	-34.7	-39.2
4/13/2014	0	0	0	0	0	0	-34.4	-39.8
4/12/2014	0	0	0	0	0	0	-35.4	-40
4/11/2014	768406	261	38	1	3849	859	-35.9	-89.7
4/10/2014	48543	22	3	0	109	57	-34.8	-86.4
4/9/2014	0	0	0	0	0	0	-35.6	-47.8
4/8/2014	0	0	0	0	0	0	-34.3	-41.2
4/2/2014	0	0	0	0	0	0	-34.8	-64.7
4/1/2014	0	0	0	0	0	0	-35	-40.7
3/31/2014	0	0	0	0	0	0	-33.7	-42.3
3/30/2014	0	0	0	0	0	0	-33.6	-41.6
3/29/2014	0	0	0	0	0	0	-34.7	-39.5
3/28/2014	0	0	0	0	0	0	-34.5	-43.4
3/27/2014	88357	36	4	0	477	75	-35.8	-89.8
3/26/2014	1557241	468	104	8	2153	298	-37.2	-89.1
3/25/2014	0	0	0	0	0	0	-35.6	-44.4
3/24/2014	0	0	0	0	0	0	-36.2	-59.2
3/23/2014	0	0	0	0	0	0	-36.6	-41.8
3/22/2014	0	0	0	0	0	0	-36.5	-42.3
3/21/2014	0	0	0	0	0	0	-36.9	-41.6
3/20/2014	0	0	0	0	0	0	-35.9	-41.7
3/9/2014	0	0	0	0	0	0	-35	-44.2
3/8/2014	0	0	0	0	0	0	-35.7	-39.8
3/7/2014	0	0	0	0	0	0	-35.4	-40.3
3/6/2014	1376563	488	62	6	729	107	-35	-77.2
3/5/2014	0	0	0	0	0	0	-33.7	-62
3/4/2014	0	0	0	0	0	0	-35.2	-59.6
3/3/2014	0	0	0	0	0	0	-36.5	-41.6
3/2/2014	0	0	0	0	0	0	-36.3	-41.6
3/1/2014	0	0	0	0	0	0	-36.7	-40.5
2/28/2014	0	0	0	0	0	0	-35.9	-41.9
2/27/2014	0	0	0	0	0	0	-35.5	-42.3
2/26/2014	3684	26	0	0	0	0	-35.9	-69.6
2/25/2014	0	0	0	0	0	0	-36.4	-41.2
2/21/2014	0	0	0	0	0	0	-33.7	-39.5
2/20/2014	0	0	0	0	0	0	-34.8	-40.6
2/19/2014	0	0	0	0	0	0	-35.1	-39.2
2/18/2014	0	0	0	0	0	0	-34.4	-39.7
2/17/2014	0	0	0	0	0	0	-35.8	-39.5
2/16/2014	0	0	0	0	0	0	-35.3	-43.2
2/15/2014	0	0	0	0	0	0	-35.2	-39.3
2/14/2014	0	0	0	0	0	0	-35	-38.6
2/13/2014	0	0	0	0	0	0	-33.8	-38.8
2/12/2014	0	0	0	0	0	0	-33.8	-39.8
Daily Data - MODEM								

Time Stamp	RF BBE	RF ES	RF SES	RF SEP	RF UAS	RF OFS	RX Level (MAX)	RX Level (MIN) [dBm]
7/1/2014	0	0	0	0	0	0	-44.5	-47.9
6/30/2014	0	0	0	0	0	0	-44.1	-47.7
6/29/2014	0	0	0	0	0	0	-44	-51.6
6/28/2014	0	0	0	0	0	0	-43.9	-48
6/27/2014	0	0	0	0	0	0	-44	-50.1
6/26/2014	0	0	0	0	0	0	-44.1	-47.2
6/25/2014	0	0	0	0	0	0	-44	-47.9
6/24/2014	0	0	0	0	0	0	-44.1	-47.9
6/23/2014	683954	209	26	5	164	2	-44.3	-74
6/22/2014	0	0	0	0	0	0	-44.3	-54.1
6/21/2014	0	0	0	0	0	0	-44.5	-48.6
6/20/2014	0	0	0	0	0	0	-44.6	-48
6/19/2014	147912	46	11	1	0	0	-44.2	-70.7
6/18/2014	0	0	0	0	0	0	-44.2	-48.6
6/17/2014	0	0	0	0	0	0	-44.5	-49
6/16/2014	0	0	0	0	0	0	-44.2	-50.2
6/15/2014	0	0	0	0	0	0	-44.5	-52.2
6/14/2014	0	0	0	0	0	0	-44.3	-49.4
6/13/2014	0	0	0	0	0	0	-44.5	-51.4
6/12/2014	0	0	0	0	0	0	-44.7	-57.2
6/11/2014	0	0	0	0	0	0	-44.6	-54.1
6/10/2014	0	0	0	0	0	0	-44.6	-49.7
6/9/2014	0	0	0	0	0	0	-44.3	-53.4
6/8/2014	0	0	0	0	0	0	-44.2	-54.4
6/7/2014	0	0	0	0	0	0	-44.6	-54
6/6/2014	160576	46	6	2	524	266	-44.5	-82.6
6/5/2014	125500	249	0	0	3302	1113	-44.7	-89.4
6/4/2014	0	0	0	0	0	0	-44.3	-51.5
6/3/2014	0	0	0	0	1401	1	-44.1	-89.6
6/2/2014	0	0	0	0	0	0	-43.8	-49.2
6/1/2014	0	0	0	0	0	0	-43.6	-48.2
5/31/2014	0	0	0	0	0	0	-44	-50.3
5/30/2014	0	0	0	0	0	0	-44.2	-51.3
5/29/2014	0	0	0	0	0	0	-44.3	-52
5/28/2014	0	0	0	0	0	0	-44.4	-51
5/27/2014	0	0	0	0	0	0	-44.1	-49.7
5/26/2014	0	0	0	0	0	0	-44.3	-49.9
5/25/2014	0	0	0	0	0	0	-44.3	-47.2
5/24/2014	0	0	0	0	0	0	-43.8	-48
5/23/2014	0	0	0	0	0	0	-44.2	-49.2
5/22/2014	0	0	0	0	0	0	-44.5	-65.5
5/21/2014	0	0	0	0	0	0	-44.5	-50
5/20/2014	0	0	0	0	0	0	-44.5	-49.4
5/19/2014	0	0	0	0	0	0	-44.4	-51.2
5/18/2014	0	0	0	0	0	0	-44.3	-49.1
5/17/2014	0	0	0	0	0	0	-44.2	-49.6
5/16/2014	0	0	0	0	0	0	-44.3	-49
5/15/2014	0	0	0	0	0	0	-44.3	-48.7
5/14/2014	0	0	0	0	0	0	-44	-48.3
5/13/2014	0	0	0	0	0	0	-44.3	-47.7
5/12/2014	0	0	0	0	0	0	-44.5	-63.5
5/11/2014	0	0	0	0	0	0	-44.3	-50.6
5/10/2014	606528	215	29	2	399	126	-44.5	-77.7
5/9/2014	0	0	0	0	0	0	-44.6	-47.5
5/8/2014	0	0	0	0	0	0	-44.4	-50.1
5/7/2014	0	0	0	0	0	0	-44.2	-50.6
5/5/2014	0	0	0	0	0	0	-43.7	-48.4
5/4/2014	0	0	0	0	0	0	-43.6	-47.5
5/3/2014	0	0	0	0	0	0	-43.7	-48.6
5/2/2014	11	4	0	0	0	0	-43.6	-68.7
5/1/2014	0	0	0	0	0	0	-43.4	-46.8
4/30/2014	0	0	0	0	0	0	-43.4	-49.8

4/29/2014	0	0	0	0	0	0	-43.3	-47.9
4/28/2014	0	0	0	0	0	0	-44.1	-48.7
4/27/2014	0	0	0	0	0	0	-44.1	-47.9
4/26/2014	0	0	0	0	0	0	-44.5	-48.3
4/25/2014	0	0	0	0	0	0	-44.3	-56.9
4/24/2014	77250	31	4	1	9015	175	-44.6	-90
4/23/2014	0	0	0	0	0	0	-44.3	-47.1
4/22/2014	0	0	0	0	0	0	-43.8	-50.7
4/21/2014	0	0	0	0	0	0	-44.3	-50.1
4/20/2014	0	0	0	0	0	0	-44.4	-48.1
4/19/2014	39321	12	1	0	133	92	-44.8	-77.2
4/18/2014	0	0	0	0	0	0	-44.5	-67.7
4/17/2014	286145	104	19	3	60	0	-44.4	-72.4
4/16/2014	0	0	0	0	0	0	-44.5	-49.3
4/15/2014	0	0	0	0	0	0	-44.6	-49.3
4/14/2014	59745	23	2	0	362	83	-44.4	-88.6
4/9/2014	0	0	0	0	0	0	-42.9	-50.3
4/8/2014	0	0	0	0	0	0	-43.3	-48
4/7/2014	0	0	0	0	0	0	-43.7	-51.8
4/6/2014	106065	38	5	0	285	70	-43.5	-86.6
4/5/2014	0	0	0	0	0	0	-43.5	-51.2
4/4/2014	0	0	0	0	0	0	-43.4	-47.2
4/3/2014	0	0	0	0	0	0	-43.6	-46.8
4/2/2014	0	0	0	0	0	0	-44.1	-47.9
4/1/2014	0	0	0	0	0	0	-44.5	-50.7
3/31/2014	0	0	0	0	0	0	-44.2	-47.5
3/30/2014	0	0	0	0	0	0	-44.1	-50.1
3/29/2014	0	0	0	0	0	0	-44.6	-52.1
3/28/2014	0	0	0	0	0	0	-44.3	-48
3/27/2014	0	0	0	0	0	0	-44.6	-47.4
3/26/2014	0	0	0	0	0	0	-44.1	-55.8
3/25/2014	0	0	0	0	0	0	-44.3	-57.8
3/24/2014	0	0	0	0	0	0	-44.4	-58.4
3/23/2014	0	0	0	0	0	0	-44.5	-50.7
3/22/2014	0	0	0	0	0	0	-44.3	-47.8
3/21/2014	0	0	0	0	0	0	-44.3	-48.8
3/20/2014	0	0	0	0	0	0	-44.8	-48.9
3/9/2014	0	0	0	0	0	0	-43.2	-47
3/8/2014	0	0	0	0	0	0	-43.2	-46.9
3/7/2014	0	0	0	0	0	0	-43.6	-49.3
3/6/2014	0	0	0	0	0	0	-43.2	-51.1
3/5/2014	0	0	0	0	0	0	-43	-46.6
3/4/2014	0	0	0	0	0	0	-43.2	-46.6
3/3/2014	0	0	0	0	0	0	-43	-49.1
3/3/2014	0	0	0	0	0	0	-44	-49.8
3/2/2014	0	0	0	0	0	0	-44	-49.6
3/1/2014	0	0	0	0	0	0	-44	-46.9
2/28/2014	0	0	0	0	0	0	-44.3	-50.5
2/27/2014	0	0	0	0	0	0	-44.5	-49.7
2/26/2014	0	0	0	0	0	0	-44.3	-47.5
2/25/2014	0	0	0	0	0	0	-44.3	-49.1
2/21/2014	0	0	0	0	0	0	-43.7	-48.2
2/20/2014	0	0	0	0	0	0	-43.8	-48.1
2/19/2014	0	0	0	0	0	0	-43.4	-47.5
2/18/2014	0	0	0	0	0	0	-43.4	-49.2
2/17/2014	268013	223	9	1	379	63	-43.8	-88.1
2/16/2014	0	0	0	0	0	0	-43.5	-64.7
2/15/2014	0	0	0	0	0	0	-43.9	-49.6

Aviat Links Performance Data

	RSL			Availability		
Date	Link 1	Link 2	Link 3	Link 1	Link 2	Link 3
30/8/2015	-47.1	-47.7	-48.3	100	100	100
31/8/2015	-47.4	-47.7	-49.3	100	100	99.86
1/9/2015	-47.7	-48.2	-49	100	100	100
2/9/2015	-48.5	-49.1	-49.1	100	100	
3/9/2015	-47.9	-48.3	-50.3	99.52	100	99.97
4/9/2015	-50	-51.8	-48.6	97.65	95.21	99.97
5/9/2015	-47.6	-48.1	-48.7	100	100	
6/9/2015	-47.3	-47.7	-48.8	100	100	99.97
7/9/2015	-47.5	-48.1	-49.1	100	100	
8/9/2015	-47.5	-47.9	-48.8	100	100	99.97
9/9/2015	-48.4	-49	-49.9	98.62	98.28	98.9
10/9/2015	-47.5	-48	-48.9	100	100	100
11/9/2015	-47.2	-47.5	-48.8	100	100	
12/9/2015	-47.8	-48.2	-48.6	100	100	
13/9/2015	-48.3	-49.3	-48.7	98.62	97.44	99.97
14/9/2015	-48	-48.5	-48.6	99.45	99.61	
15/9/2015	-47.6	-47.9	-49.1	100	100	99.97
16/9/2015	-47.7	-48	-49.1	100	100	100
17/09/2015	-47.8	-48.2	-49.2	100	100	
18/09/2015	-47.6	-48	-49.1	100	100	99.97
19/09/2015	-47.6	-48.1	-49.3	100	100	100
20/09/2015	-47.1	-47.4	-48.6	100	100	100
21/09/2015	-46.9	-47.2	-48.4	100	100	100
22/09/2015	-47.2	-47.5	-48.8	100	100	100
23/09/2015	-47.4	-47.8	-48.9	100	100	
25/09/2015	-47.3	-47.7	-49.1	100	100	99.97
26/09/2015	-47.5	-47.8	-49.2	100	100	100
27/09/2015	-47.5	-47.9	-48.8	100	100	99.97
28/09/2015	-47.4	-47.9	-49.3	100	100	99.97
29/09/2015	-47.5	-48	-49.4	100	100	99.8
30/09/2015	-47.4	-48.2	-49	99.59	99.06	100
1/10/2015	-47.7	-48	-49.3	100	100	100
2/10/2015	-47.5	-47.8	-49.3	100	100	100
3/10/2015	-47.6	-48	-49.1	100	100	100
4/10/2015	-47.6	-48.1	-49.3	100	100	100
5/10/2015	-47.6	-48	-48.9	100	100	100
6/10/2015	-47.2	-47.5	-48.6	100	100	100
7/10/2015	-46.8	-47.2	-48.4	100	100	100

8/10/2015	-47.1	-47.2	-48.6	100	100	100
9/10/2015	-47.4	-47.7	-50.1	100	100	99.97
10/10/2015	-47.5	-47.8	-48.9	100	100	99.97
11/10/2015	-48.5	-49	-50.2	98.32	98.51	99.97
12/10/2015	-48.1	-48.3	-49.8	100	100	--
13/10/2015	-48	-48.6	-49.7	99.98	99.35	99.58
14/10/2015	-47.7	-48.3	-49.9	100	100	99.97
15/10/2015	-48.1	-48.4	-49.7	99.11	99.42	99.25
16/10/2015	-48.1	-48.9	-50.1	98.89	97.91	98.41
17/10/2015	-47.7	-48.5	-49.8	100	100	100
18/10/2015	-47.7	-48.2	-49.5	100	100	100
19/10/2015	-48	-48.6	-49.8	100	99.42	99.38
20/10/2015	-49.6	-50	-51.1	98.2	98.71	98.81
21/10/2015	-47.8	-48.4	-49.7	100	100	100
22/10/2015	-47.8	-48.3	-49.7	100	100	99.87
23/10/2015	-50.9	-50.7	-51.6	97.88	99.63	100
24/10/2015	-49	-51	-52.1	99.79	97.26	97.47
25/10/2015	-48.1	-49.3	-50.7	100	98.73	98.81
26/10/2015	-47.8	-48.4	-49.6	100	100	100
27/10/2015	-48	-49	-50.1	100	100	100
28/10/2015	-47.9	-48.7	-49.9	100	100	99.74
29/10/2015	-47.7	-48.1	-49.3	100	100	100
30/10/2015	-48.6	-48.9	-49.8	99.84	100	100
31/10/2015	-48.4	-49.2	-50.7	99.5	99.45	97.28
1/11/2015	-48.1	-48.6	-49.7	100	100	100
2/11/2015	-48	-48.4	-49.8	100	100	99.69
3/11/2015	-49.6	-50.3	-51.5	98.28	97.88	97.72
4/11/2015	-48.4	-48.7	-49.7	100	100	100
5/11/2015	-48.2	-49.1	-50.1	100	98.57	98.47
6/11/2015	-49	-49.5	-50.4	99.11	98.89	98.94
7/11/2015	-47.9	-48.3	-49.6	100	100	100
8/11/2015	-48.2	-48.5	-49.6	99.92	100	100
9/11/2015	-48.8	-49.7	-50.8	100	100	100
10/11/2015	-48.5	-49.5	-50.6	99.89	100	100
11/11/2015	-47.8	-48.3	-49.8	100	100	100
12/11/2015	-48.8	-49.9	-51	100	100	100
13/11/2015	-48	-48.5	-49.7	100	100	100
14/11/2015	-47.8	-48	-49.1	100	100	100
16/11/2015	-47.8	-48.1	-49.2	100	100	100
17/11/2015	-51.1	-52.8	-53.8	100	100	100
18/11/2015	-48.3	-48.6	-50.1	100	100	100

19/11/2015	-48.5	-48.5	-49.6	99.91	100	100
20/11/2015	-48.3	-48.4	-49.4	99.1	99.56	100
21/11/2015	-48.1	-48.6	-49.8	100	100	100
23/11/2015	-47.6	-48	-49.1	100	100	100
24/11/2015	-47.5	-47.8	-49	100	100	100
25/11/2015	-48	-48.3	-49.4	100	100	100
26/11/2015	-47.7	-48.1	-49.2	100	100	100
27/11/2015	-48.2	-48.9	-49.7	100	99.46	100
28/11/2015	-49.5	-50.3	-50.9	100	99.39	100
29/11/2015	-47.9	-48.1	-49.2	100	100	100
30/11/2015	-48.1	-48.4	-49.4	100	99.88	100
1/12/2015	-47.7	-48.1	-49.5	100	100	100
2/12/2015	-47.7	-48.1	-49.1	100	100	100
3/12/2015	-48.5	-49	-50.2	99.3	98.71	98.67
4/12/2015	-49	-49	-49.9	99.6	100	100
5/12/2015	-47.9	-48.4	-49.4	100	100	100
6/12/2015	-49.7	-51.2	-51.1	98.32	94.18	97.14
7/12/2015	-47.9	-48.1	-50.3	100	100	97.89
8/12/2015	-48	-48.4	-49.6	100	100	100
9/12/2015	-48	-48.3	-49.2	100	100	100
12/12/2015	-48.4	-48.5	-49.8	99.69	100	99.48
13/12/2015	-48.5	-49.2	-50.5	100	99.83	98.52
14/12/2015	-49.4	-51.1	-52.1	100	100	99.57
15/12/2015	-48.6	-49.4	-50.9	100	100	100
16/12/2015	-48.7	-49.5	-50.3	100	100	100
17/12/2015	-48	-48.3	-49.6	100	100	100
18/12/2015	-47.8	-48.2	-49.3	100	100	100
19/12/2015	-48.3	-49	-50	100	98.34	98.17
20/12/2015	-47.8	-48	-49	100	100	100
21/12/2015	-48	-48.3	-49.2	100	100	100
22/12/2015	-48.9	-48.6	-49.4	98.63	100	100
23/12/2015	-48.7	-49.5	-50.5	99.18	97.72	97.98
24/12/2015	-47.7	-47.9	-49	100	100	100
27/12/2015	-47.9	-48.4	-49.2	100	100	100
28/12/2015	-48.3	-48.4	-49.7	99.35	100	100
1/1/2016	-47.6	-47.8	-48.8	100	100	99.97

Appendix E

Project cost and schedule

Project Cost			
Microwave link Installation, commissioning and accepatance			
Link Name	**Configuration**	**Antenna size in diameter (m)**	**Unit Price (KES)**
Mombasa Link 1	1+0	0.6	187,500.00
Mombasa Link 2	1+0	0.3	187,500.00
Nairobi Link 1	1+0	0.3	187,500.00
Kisumu Link 1	1+0	0.6	187,500.00
Kisumu Link 2	1+0	0.6	187,500.00
Kisumu Link 3	1+0	0.6	187,500.00
			1,125,000.00
Transport			
Town	**Distance (km)**	**Unit Price (KES)**	**Total Amount**
Kisumu	500	45	22500
Mombasa	500	45	22500
Nairobi	20	45	900
			45900
Equipment purchase and shipment			9,000,000.00
Project management and quality assurance			200,000
Acquisition of meteorological data			20000
Stationary and printing			30000
Publication			12000
			9,262,000.00
		SUB TOTAL	10,432,900.00
		Add 16% VAT	1669264
		GRAND TOTAL	12,102,164.00

Project Schedule	
Activity	**Projected duration**
Equipment manufacturing and shipment	
NEC links	01/11/2013-31/12/2013
Aviat links	01/05/2015-30/06/2015
Link planning, design and installation site preparations	
NEC links	01/11/2013-31/12/2013
Aviat links	01/05/2015-30/06/2015
Equipment installation and commissioning	
NEC links	01/01/2014-31/01/2014
Aviat links	01/07/2015-31/07/2015
Results and data collection	
NEC links	February 2014-July 2014
Aviat links	August 2015-January 2016
Data analysis and thesis completion	February 2016-August 2016

Appendix F

Publication resulting from the research.

International Journal for Innovation Education and Research www.ijier.net Vol:-4 No-4, 2016

Performance Analysis of E-Band 70/80 GHz Frequency Segment for Point to Point Gigabit Connectivity

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Abstract

The commercial viability for E-Band spectrum has attracted a lot of research for the last decade in order to find economic wireless gigabit connectivity that can complement fiber optic cable. This paper has analyzed the usefulness of E-Band point-to-point microwave link in providing wireless backhaul capacities comparable to that of fiber optic cable. In particular, microwave links that utilize the E-band frequencies were set up in three different cities in Kenya i.e. Mombasa (Latitude 04 01 24.10 S, Longitude 039 37 35.10 E) and validated the acceptable propagation and performance of millimeter wave links at E-Band frequencies for distances within and well above the promised limits in the existing literature. Daily occurrences of signal losses closely match the rainfall pattern, and this has been used to further validate the practicality of the experiments. These experiments were successful in verifying that E-Band can be used in Kenya for short range backhaul connectivity and in slightly over stretched path lengths of 3-6 km under clear atmospheric conditions.