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Hybrid Microwave and Free Space Optics Network for Mobile Backhaul Capacity and Availability Improvement

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Declaration

I hereby declare that this thesis is a presentation of my own work and that any material used from other sources has been clearly identified and properly acknowledged and referenced.

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Dedication

This thesis is dedicated to my newborn son, Nolawi.

Abstract

With the growing demand for high speed mobile data and the increasing use of smart devices, the existing microwave (MW) or radio frequency (RF) backhaul network is going to be a bottleneck for end users data volume requirements. Additionally, the performance of the MW link is significantly degraded by bad weather conditions, such as rain. To mitigate these limitations, free space optics (FSO) becomes a promising backhaul technology due to its large bandwidth and use of a different carrier frequency that is not impacted by rain. However, FSO is exposed to link loss or failure under foggy weather conditions, whereas MW links are prone to fog. Having this complementary advantage of FSO and RF, using hybrid FSO/RF networks is a preferred solution to improve the availability of the link and the capacity of backhaul networks.

In this paper, an adaptive switching hybrid FSO/RF system is used to improve the performance of the hard switching scheme, which is exposed to link flapping due to short-term changes in weather conditions. The switching threshold of the FSO and RF links and multi-rate switching on each link are determined, and the availability and capacity performance of the hybrid system are investigated based on received signal-to-noise ratio (SNR) values. To meet the objective, the methodology followed includes data collection, system and channel modeling, and RF, FSO, and hybrid performance comparison. The system used gamma gamma distribution for the FSO channel and the Rician model for the RF channel model.

Simulation results are obtained using the Matlab tool. The effects of rain and fog on the RF and FSO links are simulated and discussed, respectively. The availability of the system in terms of outage probability shows that the hybrid system significantly reduces the SNR value to 14 dB to achieve 99.99% link availability, which is not achieved by an RF-only or FSO-only link. The result also shows that adaptive switching mode has a better bit error rate (BER) than hard switching mode since the switching of links between FSO and RF and switching between multi rates on each link is based on maintaining target BER. To maintain good quality of service (QoS), the target BER of the system is set, and the system gradually lowers its modulation order to the maximum possible data rate based on received SNR values.

Keywords: ***FSO, RF, Hybrid FSO/RF, Adaptive Switching, Backhaul Network, Outage Probability, BER, Rician distribution, Gamma Gamma distribution***

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First, praise and thanks be to the Almighty God with his mother Saint Virgin Mary for his showers of blessings throughout my life.

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God Bless.

Table of Contents

List of Figures

List of Tables

List of Acronyms

APD	Avalanche Photodiode
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
DD	Direct Detection
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
FSO	Free Space Optics
FSPL	Free Space Path Loss
IDU	Indoor Unit
IM	Intensity Modulation
IoT	Internet of Things
ITU-R	International Telecommunication Union Radio communication
LED	Light Emitting Diode
LOS	Line of Sight
LPDC	Low Parity Density Code
MW	Microwave communication
NLOS	Non line of sight
NMIE	National Metrology Institute of Technology
ODU	Outdoor Unit
PIN	P-i-N Diode
RF	Radio Frequency
RMS	Root Mean Square
SNR	Signal to Noise Ratio

Chapter One

Introduction

1.1. Overview of Mobile Backhaul

Cellular networks are undergoing continues improvement to accommodate the exponentially growing data traffic, resulting from growth in the internet traffic, web-based activities and multimedia services. Supporting this traffic, in turn, demands backhaul networks which are capable of transmitting data at higher rate [1]. As a result, connecting last mile base stations (BSs) through reliable backhaul network is a critical component in network planning [2]. The most common and widely used mobile backhaul networks are RF links. This links are operated using the frequency range of 1 GHZ - 100 GHZ keeping line of site (LOS). It is used to aggregate cellular services from access to the main core network. However, due to its limited bandwidth and spectrum range, it becomes a bottleneck to the current demand of bandwidth [3]. It is also predictable that the existing RF frequency range is inadequate to answer the backhaul bandwidth requirement of latest mobile generation like 5G and beyond [1].

On the other hand, FSO is a high-speed point-to-point optical wireless technology that uses light as transmission medium between transceivers [4]. FSO link is very easy to deploy and can be used as an alternative backhaul network for wireless communication which in addition fits to the current low interference to electromagnetic radiation and high bandwidth requirement.

1.2. FSO Communication

FSO communication is the transmission of data at frequency above 300 GHz without cables or any form of guided media. Since FSO system was invented, it was used in military applications with little commercial use. This technology was not expanding as expected because of the following reason: demand of the time was addressed by existing communication technology, shortage of cost effective FSO technology and impact of weather condition such as heavy fog on the performance of FSO technology [5].

The market statistics predicted that the expected investments in FSO equipment will exceed $300 million in 2029 [6]. Currently, there are numbers of commercially viable FSO products in the market that offer up to 30 Gbps in an ideal weather condition [7, 8, 9, 10, 11, 12].

In summary, the basic features of FSO system are described as below.

- High data rate – theoretically, the FSO technology can offer up to hundreds of Gbps which is beyond the maximum data transmission of RF link [13].

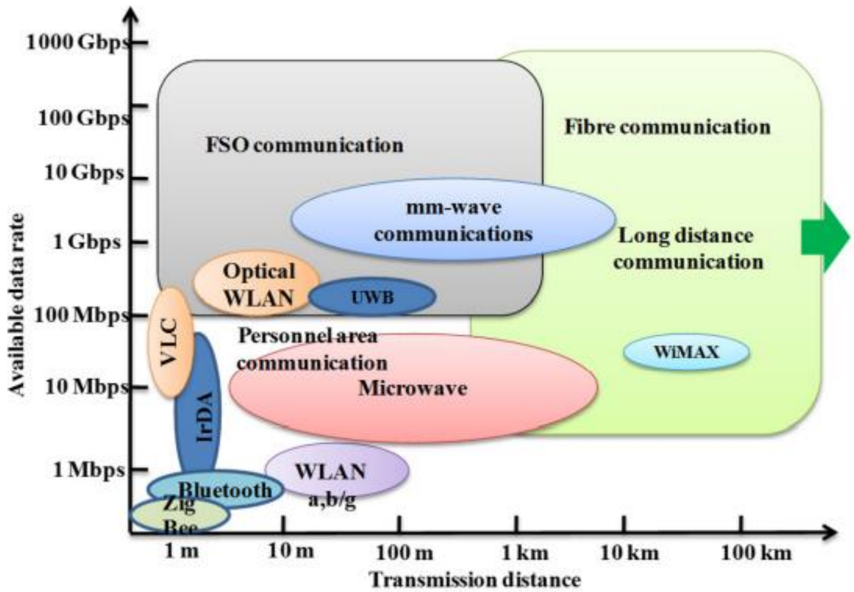

Fig-1.1. Comparison of RF and Optical technology in terms of data rate and link coverage [14].

- License free spectrum - FSO spectrum has an abundance of license free bandwidth (700 - 1500nm range of wavelength) [15]

- High security – Unlike RF signal which exhibit broadcast radiation, FSO spectrum has narrow beam profile and require high directionality. This make it highly secured technology.

1.3. Hybrid Link Implementation

Despites its bandwidth, FSO is subjected to high attenuation due to atmospheric turbulence like fog, snow, haze, etc. Presence of fog is the main cause for the attenuation of optical signal [5]. FSO signal is also absorbed and scattered due to suspended tiny particle present in the atmosphere [16] and hence, its performance will be limited. As a result, reliability becomes an essential aspect to answer the design and deployment of FSO-based backhaul network [2]. Additionally, one reason FSO cannot replace microwave communication is that its requirement for optical signal to keep the LOS [17]. It exhibit narrow beam profile and hence a very small deviation of LOS will degrade the services quality.

Despites the LOS requirement of FSO, its optical path is relatively insensitive to rain. In contrast, RF is not affected by fog and haze due to their difference in carrier frequency [18]. Using this complementary nature of FSO and RF links, hybrid RF/FSO system can improve reliability of mobile backhaul. Different switching scheme is discussed in the literature on the operation of hybrid FSO/RF network. Hard switching is one of the switching scheme in which the system transmit data using one link at a time. If the optical channel is degraded, the data transmission carried on using RF link [19]. One drawback in the switching scheme is that the frequent link flapping can degrade system performance. The alternative approach to overcome frequent switching is soft switching. In this switching scheme both link transmit data simultaneously using same data rate [3]. This switching method leads to limitation of FSO link capacity by RF link when there is a possibility to transmit maximum data rat using FSO link only.

1.4. Statement of the Problem

To address the availability and capacity of mobile backhaul using hybrid MW and FSO network different switching is discussed in the literature. The hard switching scheme is based on fixed transmission rate, which is exposed to frequent link flapping due to atmospheric turbulence [19]. To improve the performance of the system, adaptive based hybrid switching system is preferable option [20]. In this method transmission rate of FSO channel gradually degrade and switches to RF at its worst-case scenario. In RF link the transmission rate also varied according to the RF channel.

However, the switching threshold value between FSO and RF link and adaptive rate on each link are not discussed. Determining the SNR threshold value for link switching and data rate switching on each link is important to investigate the performance of adaptive hybrid FSO/RF. In this paper, we determine the switching threshold of the FSO and RF links and investigate the availability and capacity performance of adaptive hybrid FSO/RF. The receiver SNR value is the deciding factor of link and data rate switching. FSO link is considered as a primary link for transmission of data. In clear weather condition the transmitter adaptive controller transmit with maximum possible modulation order and enjoying high data rate. When the receiver SNR value lowered to certain threshold, the transmitter adaptively lower its modulation order and hence its data rate to which it fits the range of SNR values. If receiving SNR values continuously degrading, the transmitter keep lowering FSO modulation order till its worst case, lowest modulation order. When the receiver SNR of FSO link is read below lowest threshold, the transmitter switch the link to the RF link. The transmitter adaptive controller is then check the range of receiving SNR value and map to the possible modulation order of RF link. The RF link adaptively transmit the data until the lowest possible modulation order of RF link is reached. If the receiving SNR read below threshold value of RF link the system goes outage. The hybrid FSO/RF system assure the availability of the link and adaptively maintain the data rates under given weather condition.

1.5. Literature Review

Performance evaluation of a selection combining scheme for the hybrid FSO/RF System is presented in [3]. This article investigates the performance of hybrid FSO/RF using receiver diversity combining scheme. Parallel transmission on both FSO and RF link with the same data rate is modelled in this article and uses gamma-gamma and Rayleigh fading channel to model atmospheric turbulent channel. Using the MATLAB tool, the result demonstrates that the system is robust to all atmospheric conditions when compared with FSO only link. The limitation with this paper is parallel transmission of FSO and RF which leads to power wastage and unnecessary interference in the RF. Additionally, the FSO data rate is limited to RF link.

The author in [20], analysis of adaptive multi-rate FSO/RF multi rate system using Malaga distribution model in turbulent channel was discussed. The paper tried to improve performance of hard switching scheme of hybrid FSO/RF by employing the system with adaptive characteristics. The M-distribution channel model is used to analyses the performance of hybrid FSO/RF. The probability of outage, average goodput and mode probability quantitative measure are used to compare the results of simulation. The gap observed in this paper is that the switching threshold of FSO and RF link is not set.

Motivated by poor switching scheme of past works in terms of power efficiency, [13] come up with a new switching scheme for hybrid FSO/RF communication in the presence of strong atmospheric turbulence. The paper aimed to implement new switching scheme for hybrid FSO/RF, obtain a better BER, and enhance power efficiency. The proposed model of this paper provides two threshold level for FSO link and single threshold level for RF link. Negative exponential and Rayleigh fading channel are used for FSO and RF link, respectively. Using MATLAB tool probability of outage, BER and average power is simulated. However, RF limits FSO data rate when the second threshold level is used.

Performance analysis of hard switching based hybrid FSO/RF system over turbulence channels is analyzed in [19]. The paper assumes that at a time only one link is activated with RF link is in standby mode and FSO link has priority. FSO channel follows Gamma Gamma distribution whereas RF channel follows Rayleigh distribution. The analytical expression is derived for different hybrid FSO/RF metrics such as probability of outage, bit error rate and ergodic capacity. Additionally, numerical comparison between hybrid FSO/RF and single FSO is done. Single threshold hybrid FSO/RF system is sensitive to short term changes under atmospheric turbulence. The frequent link flapping leads to services degradation.

In above works, the capacity of FSO link is limited by RF link due to parallel transmission of RF and FSO link to address atmospheric factors. The power efficiency of the system is also poor. Hybrid FSO/RF system which based on single threshold switching scheme is lead to service degradation due to frequent link flapping under atmospheric turbulence. This paper improves performance of hard switching hybrid FSO/RF scheme using adaptive switching scheme and also reduce power wastage while favored link is working.

1.6. Objectives

i. General Objective

The main objective of this thesis is to determine the switching threshold of the FSO and RF links and investigate the availability and capacity performance of adaptive based hybrid FSO/RF.

ii. Specific Objectives

- Examine essential properties of terrestrial FSO and comprehend the properties of atmospheric channel and its challenge on system performance;
- Review the channel fading models caused by atmospheric turbulence and select an appropriate fading model based on their limitation and range of validity;
- Asses hybrid RF/FSO switching methods and identify best possible switching method for the system model;
- Investigate link performance of an FSO and RF system in terms of link range, data rate and outage probability, BER and channel capacity

- Investigate performance comparison of hard and adaptive switching of hybrid FSO/RF system in terms BER and channel capacity.

1.7. Methodology

The methodology followed in this thesis contains reading past journals and articles about FSO, RF and hybrid technology, data collection, channel characteristics and modelling, geometric loss, effects of atmospheric turbulence on FSO and RF link, the probability of outage, BER, channel capacity hybrid FSO/RF and their performance comparison.

The literature review work was focused on literature papers that related to performance of hybrid FSO/RF technology under turbulent environment. Articles, academic journals, research work, dissertations and conference papers were reviewed to support this thesis. The data are collected from NMIE which includes rainfall and wind speed for five successive years.

Analytical expression of fog and rain attenuation of FSO and RF subsystem is discussed and simulated. Then system and channel model of the system is done. Regarding channel model, RF subsystem follows the Rician distribution, whereas FSO subsystem follows Gamma Gamma distribution to analyze their performance under different turbulent regime. The performance comparison of RF subsystem, FSO subsystem and hybrid FSO/RF were carried out using metrics such as probability of outage, BER and channel capacity. The simulation tool used in this thesis is MATLAB. Finally, conclusion and future work are done based on the result obtained and possible expansion of the thesis.

1.8. Contributions of the Thesis

In doing this study, the thesis,

- Tried to analyze the improvement of mobile backhaul network in terms of availability and capacity using hybrid FSO/RF communication system
- Help telecom operators to consider while designing mobile backhaul especially where rainfall and/or fog weather condition are critical.
- Help operators to identify which type of backhaul network should be used to address the availability and capacity of the network where optical fiber cable installation is not possible.

- Intend to include the study of free space optics to the institute so that it will be used as a reference and improvement area of studies for future development

1.9. Thesis Organization

The rest chapter of this thesis is organized as below. Chapter two deals with basics of FSO, RF and Hybrid RF/FSO and different switching technics adapted in hybrid RF/FSO. Chapter three will present system and channel model of hybrid RF/FSO, fading types and mathematical expression involving the system model. In Chapter four, we will discuss performance analysis of FSO, RF and hybrid FSO/RF system. FSO and RF performance under the different turbulent channel, adaptive hybrid RF/FSO performance with respect to outage probability, BER and channel capacity. Finally, conclusion and future work will be discussed in Chapter five.

Chapter 2

Basics of FSO, RF and Hybrid FSO/RF

2.1. Introduction

In this chapter, we will discuss the basics of FSO and RF technologies. For each technology, the system block diagram and its detail description will be explained. Environmental weather condition and atmospheric channel dependence of FSO and RF technologies are discussed. The effect of fog on FSO link and rain on RF link is also seen in detail. Additionally, switching techniques of hybrid FSO/RF hybrid mode is mentioned.

2.2. FSO Concept

FSO is a line of sight technology that involves the use of laser technology to offer optical connections and allow wireless data to travel via atmosphere for telecommunication purpose. This day, commercially viable FSO technology is capable of transmitting up to 30Gbit/s of data, voice and video services via air, without the demand of optical fiber cable or using licensed spectrum [16].

The FSO system block diagram is illustrated below in Figure 2.1 comprises of three parts: Transmitter, medium and receiver.

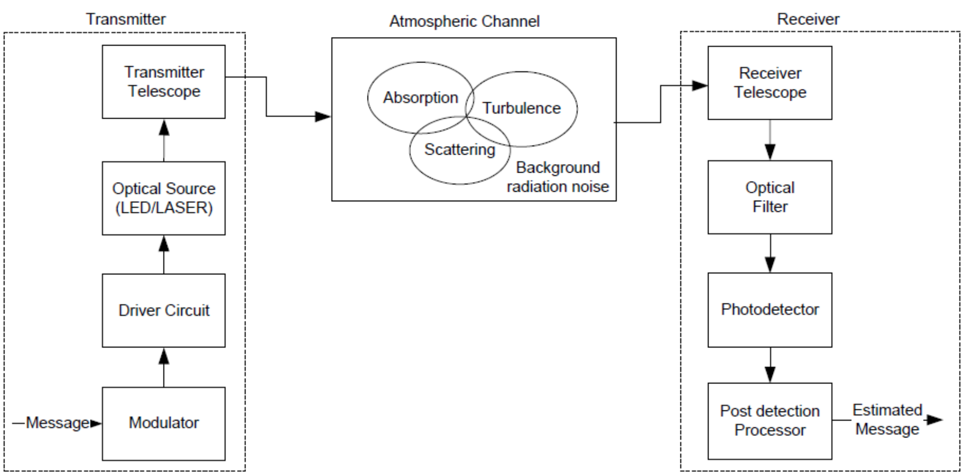

Fig-2.1. FSO system block diagram [5].

2.2.1. Transmitter

The transmitter block consists of the modulator, driver circuit, optical source (LED/LASER) and transmit optics. The incoming source data are modulated into optical carrier using laser or LED and propagated via atmosphere to the desired receiver direction. The size of the transmitter aperture, the power and beam quality are the essential factor in the optical transmitter system since laser intensity and beam divergence depend on these parameters [21]. In most of the past work, FSO link modulation type is intensity modulation and direct detection (IM/DD) [22, 24, 25]. IM/DD modulation type is when the information bits without requirement of phase information directly modulates the power of light from laser/LED. That means there is no need of using local oscillator like in the heterodyne coherent modulation system. Coherent modulation experiences higher data rate than direct detection. In contrast, it has nonlinear response and economically high cost.

FSO system operates in the wavelength range of 750-1600nm where the optical attenuation power in this window is less than 2dB/Km. In 750-850nm wavelength range, relatively cheap, low reliability, low power and short span FSO products are available. Whereas in the 1520 - 1600nm wavelength range, high quality transmission, detection and low attenuation is experienced. This wavelength window has a high data rate when compared with 750-850nm. Additionally, it is compatible with Erbium Doped Fiber Amplifier (EDFA) and suitable for dense wavelength division multiplexing (DWDM) technology. The later wavelength range applicable for long distance fiber span [5, 25]. 1550nm wavelength window has low solar background and scattering in light, which is a major factor for fiber attenuation. One of the drawbacks of this window is its low sensitivity in detection and hardware cost.

2.2.2. Atmospheric Channel

Atmosphere is a layer of gases that surrounds the planet. It consists of different composition of gas molecules as depicted below in Table 2.1. Due to the effect of gravity, these gases are held together on the earth’s surfaces. The composition of particles depends on altitude from the earth. The highest concentration of these particles are exist near the earth and decrease as we go up [26].

Table 2.1. The gaseous content of the atmosphere [26].

Gas	**Volume (%)**
Nitrogen	78.08
Oxygen	20.95
Argon	0.93
Water vapor	0–4
Carbon dioxide	0.041
Neon	0.0018
Helium	0.0005
Methane	0.00018
Nitrous oxide	0.00003
Ozone	0.000004

There are other particles in the atmosphere, which are important in FSO communication [16]. These are: Aerosols, dust, smoke and atmospheric turbulence. Aerosol is a suspension of fine solid or liquid in the air. The size of aerosol particle ranges from 0.01-10µm. Fog is considered as a main challenge in FSO communication since it causes a significant amount of FSO signal attenuation. Fog is a dense cloud of small water droplet suspended in the air around the earth's surface that significantly reduces visibility. The fog effect in FSO system discussed in detail in Section 2.2. Another important atmospheric particle in FSO communication is dust. It is powder of small pieces of earth's particle or sand where as smoke is suspension of carbon and other particle that are emitted from the burning substance. As the light propagate in the air, due to the interaction with molecules in the medium the intensity of optical radiation decreases. The molecules absorb the photon energy and converted to different form of internal energy. This phenomenon is called absorption. The atmospheric turbulence is fluctuation of refractive index due to pressure, temperature and wind speed in space and time along the channel's optical propagation. It causes distortion of the optical transmitted signal called Scintillation [27]. The modelling of FSO systems in turbulent atmosphere will be discussed in detail in chapter Three.

2.2.3. Receiver

The receiver is where the incident signal is collected to retrieve the original data. The receiver has the following blocks [5]:

- Receiver telescope: where the sum total of incoming optical signal is collected and focused on photo detector. The larger the aperture area of telescope the larger the radiation is collected, but there will be more radiation background.
- Optical filter: filter unwanted signal so as to reduce background solar radiation
- Photo detector: Converts optical signal to electrical signal and vice versa. The most well known photodetectors are P-i-N diode (PIN) and the avalanche photodiode (APD) diodes.

2.3. FSO Attenuation

Transmitted optical signal faces different attenuation while propagating in the atmosphere.

2.3.1. Geometric attenuation (A_{geo})

Geometric attenuation is attenuation due to FSO system configuration. FSO link geometric path loss depends on path length, area of aperture, beam width of optical transmitter and area of transmitter aperture [28]. This loss is fixed loss that means it does not vary with time. Geometric loss is a ratio of receiver aperture surface area to the transmitter beam at the receiver [16].

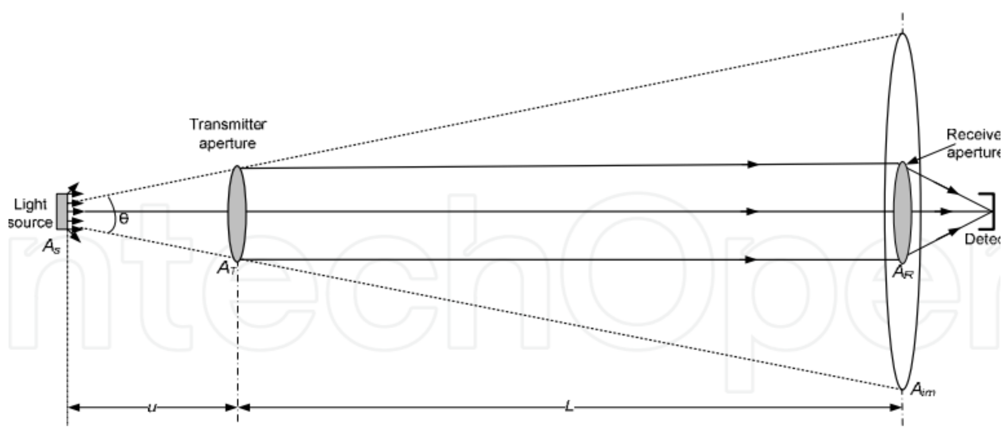

Fig 2.2. Beam divergence in FSO [29].

The mathematical expression of geometric loss is given by [29].

$$A_{geo} = \frac{d_2^2}{[d_1 + L.\theta]^2} \quad \ldots\ldots (1)$$

The geometric loss in dB is thus,

$$L_{geo} = -20\log(\frac{d_2}{d_1 + L.\theta}) \quad \text{...} (2)$$

Where d_2 is diameter of reciever aperture (m), d_1 is diameter of transmitter aperture (m), L is link range (m) and θ is beam divergence (mrad).

To investigate the effect of geometric configuration of FSO performance, lets compare two FSO product with different transmitter and receiver aperture diameter.

Table 2.2. Parameters of different FSO product.

Parameter	**Diameter of Transmitter Aperture**	**Diameter of Receiver Aperture**
Parameter 1	8 cm	10 cm
Parameter 2	3.5 cm	15 m

i. **Geometric loss versus Link distance**

Geometric loss of FSO system with varying link length is observed under two parameters in table 2.2. The simulation is carried using MATLAB tool. The Fig. 2.3 shows the geometric loss against link range using divergence angle 0.02 mrad. The link range used is 1 Km to 3Km and the simulation show that the geometric loss is proportional to the link range. As demonstrated in Fig 2.3 below, for a 2 Km link range the geometric loss of parameter 1 is 3.64dB and that of parameter 2 is 1.38dB

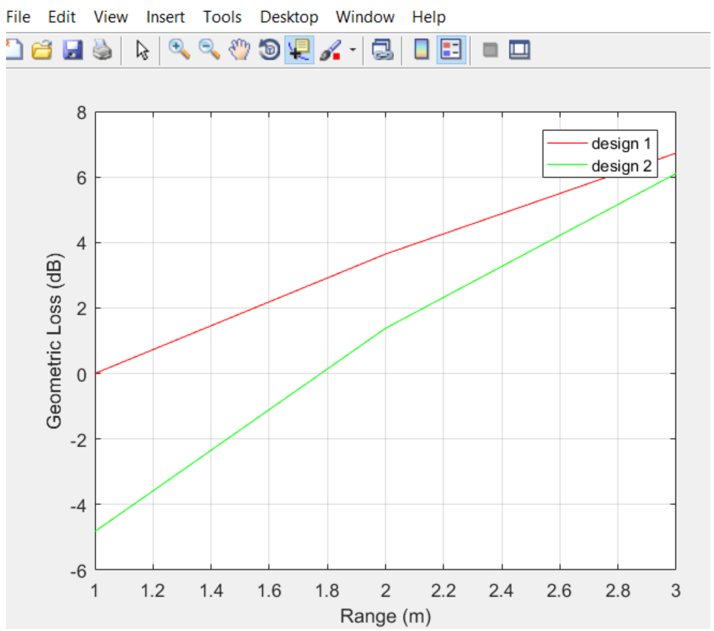

Fig 2.3. Geometric loss versus link range.

ii. Geometric Loss versus Divergence Angle

Geometric loss of FSO system against the link length is observed under different beam divergences. The geometric loss is proportional to divergence angle that is as divergence angle increases, the geometric loss is also increases. According to the given parameter for 2 Km link range, the geometric loss of 2 mrad, the beam divergence loss is 1.38 dB, for 4 mrad the loss is 10 dB and 16 dB for 6 mrad. The demonstrated result shows that small divergence angle of laser beam in FSO system could minimize the effect of geometric loss as shown in Figure 2.4 below. Generally, in configuring internal geometric parameter of FSO communication the transmitter aperture is recommended to be less than 5cm whereas receiver aperture should be larger than 15cm [29].

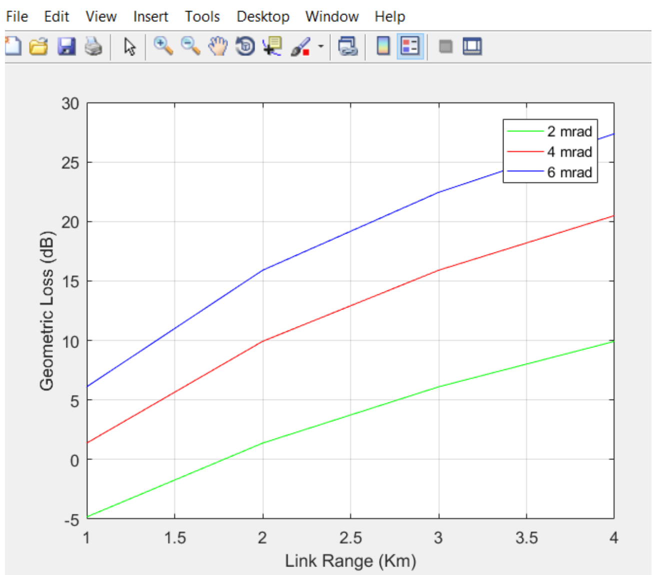

Fig 2.4. Geometric loss for different beam divergence angle.

2.3.2. Atmospheric Attenuation (A_{atm})

The atmospheric attenuation is the loss of optical radiation while the signal is traversing the atmosphere. This loss could be due to absorption or scattering. The optical power loss is estimated by the Beer-Lambert law [30]

$$\tau = \frac{P_r}{P_t} = e^{(-\beta L)} \quad \text{.......... (3)}$$

Where τ is atmospheric attenuation, P_r is received power, P_t is transmitted power, L=transmission distance between transmitter and receiver, β= total attenuation coefficient and is given by

$$\beta_{tot} = \beta_{abs} * \beta_{scat} \quad \text{.......... (4)}$$

Where β_{abs} *and* β_{scat} are attenuation coefficient due to absorption and scattering respectively.

2.3.3. Fog Attenuation

FSO communication has extremely depend on local whether condition that affects the transmitted signal. Fog and snowfall are among the most weather conditions that attenuates FSO transmission [31]. The reason is that fog consists of fine water droplets suspended in the air with diameters less than 100 µm. The particle's size is comparable with a wavelength of FSO signal and hence it causes blockage of photons. Mostly, in the design of FSO, empirical models are obtained depending on visibility data. Visibility is the distance required to reduce the intensity of light source to 5 % or 2% of its original [32]. The density of the fog (dense, moderate and thin) has different effects on optical signal. The maximum intensity of the solar spectrum, 550nm, is used to measure visibility. There are different models used to predict the effect of fog in wireless optical communication. This paper discusses three well-known models that predict fog attenuation based on visibility: Kruse, Kim and Al-Naboulsi models [31, 32, 33, 34].

i. Kruse Model

Since 1962, Kruse model is a unique model for predicting attenuation from given visibility data

$$A = \frac{13}{V}\left(\frac{\lambda}{0.55}\right)^{-q} \quad dB/Km \ \dots\dots (5)$$

Where ***q*** is a coefficient that depend on particle size distribution and **V** is visibility in Km and λ is operating frequency. The coefficient *q* has different expression for different visibility range.

$$q = \begin{cases} 1.6 & V > 50Km \\ 1.3 & 6 < V < 50Km \\ 0.585V^{-1/3} & V < 6Km \end{cases} \dots\dots (6)$$

The main drawback of Kruse model is the model cannot precisely estimate specific attenuation when visibility is less than 1 km and it estimates less optical attenuation for longer wavelengths. Fog attenuation that has a larger particle size was not directly considered in this model.

ii. Kim Model

Review and amend Kruse model for visibility parameter less than 500 m. The coefficient q, in Kruse model is modified as below,

$$q = \begin{cases} 1.6 & V > 50Km \\ 1.3 & 6Km < V < 50Km \\ 0.16V + 0.34 & 1Km < V < 6Km \\ V - 0.5 & 0.5Km < V < 1Km \\ 0 & V < 0.5Km \end{cases} \dots\dots (7)$$

Kim model suggests that for visibility less than 500m meter, the attenuation level will be same under all wavelength range i.e. wavelength independent. Comparing the fog attenuation models, Kim model has better estimate fog attenuation under all visibility ranges and modify some drawbacks of other models [33].

iii. Al-Naboulsi Model

Al-Naboulsi model separates characteristics of advection and radiation fog and suggest distinct model for each. When warm and wet masses of air raise up above the colder on marine surface, advection fog in created whereas radiation fog is due to radiation over continental surfaces.

According to Al-Naboulsi advection fog model is

$$\alpha_{ad}(\lambda) = \frac{0.11478\lambda + 3.8367}{V} \quad \ldots\ldots (8)$$

and radiation fog is

$$\alpha_{rad}(\lambda) = \frac{0.18126\lambda^2 + 0.13709\lambda + 3.7502}{V} \quad \ldots\ldots (9)$$

For both model the attenuation is expressed as

$$A\left(\frac{dB}{Km}\right) = \frac{10}{ln10}\,\alpha(\lambda) \quad \ldots\ldots (10)$$

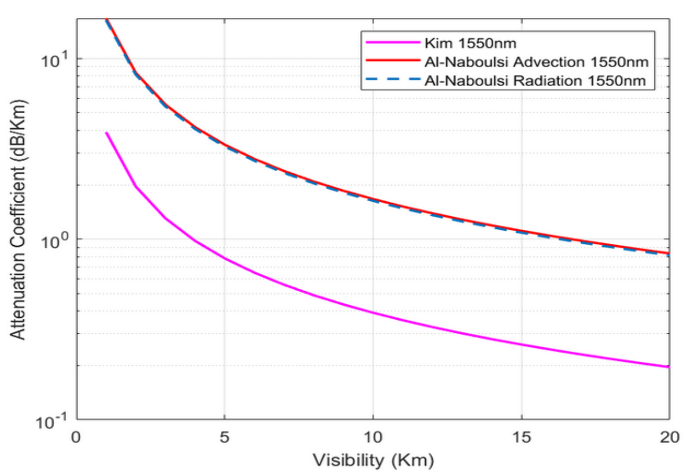

Fig- 2.5. Comparison of different fog attenuation model against visibility for Lambda 1550nm.

2.4. Radio Frequency (RF)

2.4.1. Microwave link network

Microwave spectrum operates at a frequency range of 3-30 GHZ and it supports high data rate at distances up to 100 Km [27, 35]. Microwave network is point-to-point radio communication system that operates in duplex mode, pair of transmitter and receiver frequency. It contains a radio unit and unidirectional antenna, commonly parabolic reflector antennas transmitting a radio signal from one location to another [35, 36].

Figure 2.6 below depicts a general block diagram of RF communication systems. In the RF indoor unit the digital baseband signal modulated to intermediate frequency and in the outdoor unit the intermediate frequency up-converted to the analog radio frequency which is fed the antenna via waveguide. The RF signal is then propagated as electromagnetic wave in the air. At the receiver, the antenna collects the transmitted signal and the outdoor unit down-convert the incoming RF signal back to an intermediate frequency. Finally, at the indoor unit, the intermediate frequency is demodulated and the original baseband signal is retrieved.

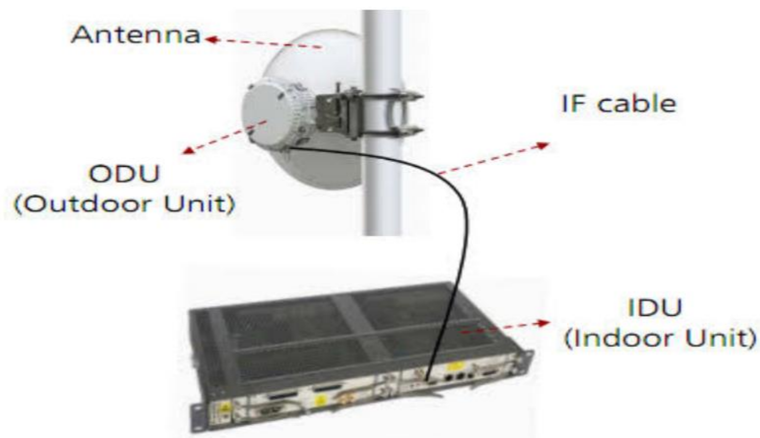

Fig. 2.6 - Element of microwave link network [37].

2.4.2. Millimeter wave Link network

Millimeter wave operate in 30-300 GHz frequency band. Due to its wide bandwidth and capable of transmitting high transmission data rate, service providers are increasing their interest in this frequency band. When we come to the propagation characteristics of millimeter wave, it is highly scattered and absorbed by gaseous particle and rainfall [40]. For frequency band greater than 10GHz, attenuation due to rainfall become the great limitation of reliable wireless communication system.

Like FSO link, MW link has also experienced power attenuation as it propagates through the atmosphere.

A. **Free Space Path loss:** this loss of MW link is the reduction of power strength as a link distance increases, analog as to geometric loss in FSO. The free space path loss of RF signal is gives as

$$\text{FSPL}=20log\frac{4\pi L}{\boldsymbol{\lambda}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (11)$$

L is link distance and λ is RF wavelength

B. **Rain Attenuation:** the size of a raindrop is comparably same size as the RF signal wavelength, which causes scattering of RF signal. This loss is significant in RF communication and need to be considered while designing, and deploying RF communication systems. Rain is measured by the accumulation of a raindrop in mm in a given time called rain rate, mm/hr. According to International telecommunication Union for Radio communication (ITU-R) recommendation a specific rain attenuation is given by [39]:

A (dB/Km) = aR^b , where **R** is rain rate (mm/hr)………..…………(12)

A is specific rain attenuation, **a** and **b** are function of polarization and frequency which have been derived from scattering calculation and they are given by

a = 4.21*$10^{-5}f^{2.42}$ (for 2.9 GHz ≤ f≤ 54 GHz)

a = 4.09*$10^{-10}f^{0.069}$ (for 54 GHz ≤ f≤ 180 GHz)

b = 1.41$f^{-0.0779}$ (for 8.5 GHz ≤ f ≤ 25 GHz)

b = 2063$f^{-0.272}$ (for 25 GHz ≤ f ≤ 164 GHz

Using Equation (12), attenuation of rainfall (dB/Km) with respect to frequency range is plotted for different rain rate using MATLAB as depicted below in Figure 2.7. From the plot, it is clear that the rainfall attenuation will get higher as rain rate increases. As the frequency increases and at high rain rate the rainfall attenuation keep increasing and become maximum at about 100GHz. The rain attenuation experiences slight decrement or steady as frequency increases further.

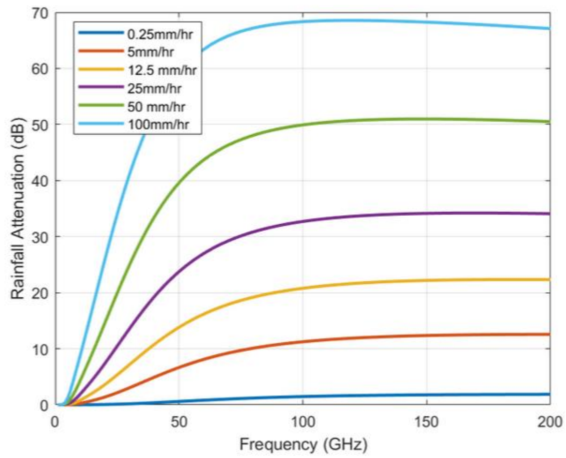

Fig 2.7- Specific rainfall attenuation using ITU-T standard

2.5. Hybrid FSO/RF

2.5.1. Introduction

As mentioned in chapter 1, FSO is a promising technology due its benefit of wide bandwidth, immune to security, license free, high data rate. Despite these advantages, FSO link is unfavorable to weather conditions like fog, scintillation (atmospheric turbulence) and smoke. In contrast, the RF signal is prone to rain than fog. Due to this complementary advantage of FSO and RF link, hybridizing this technology is one of the vital solution to overcome the weather barriers. Hybrid FSO/RF system will provide connection, availability and reliability under any type of severe weather conditions. The fundamental point here is how does both subsystem work together to transport the services at its optimal data rate.

2.5.2. Switching Techniques

Hybrid technology uses switching techniques to work with either link depending on suitable weather conditions for the link selections. This section deal with hybrid concept and switching techniques adopted. To keep link availability and reliability, there are number switching techniques between FSO and RF are adopted.

A. Redundant RF

As shown in the figure below, the FSO and RF link are always active and simultaneously transmitting at the same data rate over both links. This technique has advantages of ensuring 100% link availability and reliability irrespective of the weather condition. This system does not require channel state information at the transmitter. However, since the data rate of the system is limited by RF link, we cannot entertain the bandwidth of FSO link. That means we are using hybrid network even at lower data rate. Additionally, using a redundant RF link in clear weather or in rainy weather condition leads to wastage of power and generating unnecessary interference.

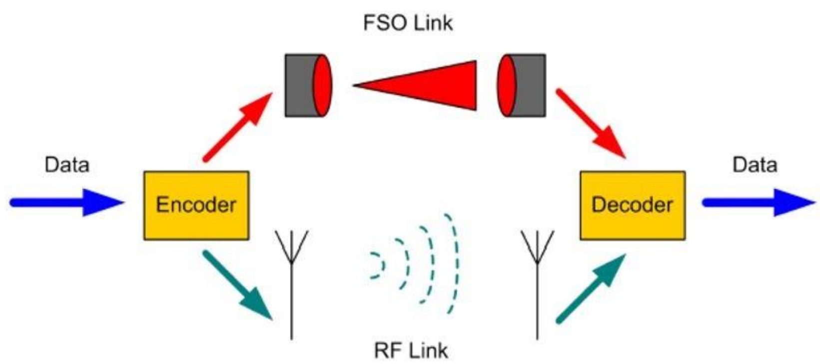

Fig 2.7 - Hybrid FSO/RF system with redundant RF link [38].

B. Hard switching

In hard switching data is transmitted on either of the links at a time. Primary transmission link is selected to be a FSO link. Based on the feedback signal from the receiver the link would switched to RF link if FSO link is affected due to weather condition. When FSO signal is acceptable, again the link switchover to FSO link. The disadvantage of hard switching is that there might be frequent link flapping between FSO and RF links due to uncertain atmospheric turbulence. This frequent switching between the two links might lead degradation of system performance.

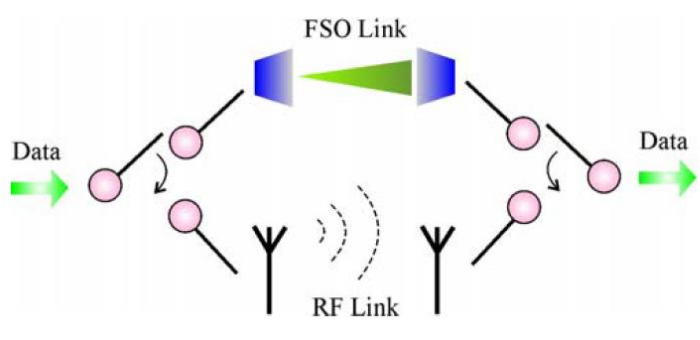

Fig 2.8 - Hybrid FSO/RF system with hard switching [39].

C. Soft Switching

In soft switching the hybrid system uses channel coding on both links. The data are encoded using Low Parity Density Code (LPDC). The incoming data are copied to FSO and RF link and decide the rate of transmission according to channel condition. Where as in raptor code, there is no need to know the channel state information. The transmitted data rate between FSO and RF is automatically adjusted based on single bit feedback channel. The data are transmitted over FSO link with higher data rate than RF link [5, 41, 42]. Soft switching increases the system complexity and addition of hardwares.

Chapter Three

Hybrid FSO/RF System and Channel Model

3.1. Introduction

In this chapter, we will discuss the adaptive switching hybrid FSO/RF system and its channel model. We will revise some known channel model used in FSO and RF link and select the appropriate channel model best suited for system model. The FSO and RF subsystem model is also discussed in this chapter. The overall system model and its working principle, link switching scenario and adaptive transmission rate selection are explained in detail.

3.2. FSO and RF Channel Model

3.2.1. Turbulent Channel

Due to random variation of temperature, pressure and wind speed in the atmosphere, there will be a fluctuation in the beam of lights' refractive index known as atmospheric turbulence [5, 43]. This random variation, called eddies, causes random fluctuations of refractive index and it in turns causes distortion and bending of laser beam. The phase of the laser beam will be shifted due to this distortion and as a result, there will be intensity fluctuation, which is called scintillation [43]. The turbulent eddies are categorized as small scale (scattering) and largest (refraction) eddies [5]

3.2.2. FSO Channel Modeling

To analyze the effect of atmosphere on the system we have to model the channel of FSO link which is atmosphere. At the receiver, the incoming signal is combination of transmitted signals, geometric loss, impulse response of atmospheric channel and signal distortion due to turbulent channel [43]. The impulse response characterized the effect of atmospheric channel. Let's revise some common channel model of FSO link as follows

A. Lognormal Distribution

Lognormal modeling is commonly used in weak atmospheric channel. In moderate and strong channel this model lead to inaccurate performance result [43, 44]. According to [45] the probability density function (pdf) of the log normal distribution is expressed as

$$p(I) = \frac{1}{I\sqrt{2\pi\sigma_i^2}} \exp\left(\frac{-(\ln I + \frac{\sigma_i^2}{2})^2}{2\sigma_i^2}\right) \ldots\ldots (3.1)$$

Where σ_i^2 is Rytov variance, measured in terms of variance of beam amplitude

$$\sigma_i^2 = 1.23 C_n^2 K^{7/6} L^{11/6} \ldots\ldots (3.2)$$

And $K = 2\pi/\lambda$ is wave number which describe inverse relation between variance and wavelength, C_n^2 is altitude and wind speed dependent refractive index structure which determine the condition of atmospheric turbulence i.e. weak, moderate or strong. L is FSO link distance between transmitter and receiver station. The drawback of this model is it obey with the experimental result only in weak turbulent region [5].

B. Gamma Gamma Distribution

This model assumed that the atmosphere consists of large and small eddies turbulence which causes the fluctuation of signal intensity [5]. The gamma gamma model agrees with the experimental data for the range of weak to strong atmospheric turbulences [44]. The pdf of the gamma gamma distribution is given as [46]

$$f(I) = \frac{2(\alpha\beta)^{\frac{\alpha\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}} K_{\alpha-\beta}(2\sqrt{\alpha\beta.I}) \ldots\ldots (3.3)$$

Where I is normalized irradiance, α *and* β are small and large eddies respectively. $\Gamma(.)$

is gamma function and $K_{\alpha-\beta}(.)$ is modified Bessel function of second order. The expression of small and large eddies is given as [43, 44, 45]:

$$\alpha = \{\exp\left(\frac{0.49 * \sigma_i^2}{\left(1+1.11\sigma_i^{12/5}\right)^{7/6}}\right) - 1\}^{-1} \ldots\ldots (3.4)$$

$$\beta = \{\exp\left(\frac{0.51*\sigma_i^2}{\left(1+0.69\sigma_i^{12/5}\right)^{7/6}}\right) - 1\}^{-1} \text{.............................} (3.5)$$

The Rytov variance σ_i^2 is given in Equation (3.2).

when $\alpha \gg 1$ *and* $\beta \gg 1$, the atmospheric condition is in weak regime. As α *and* β decreases, irradiance fluctuation increases. As β close to unity, saturation region, the gamma gamma distribution approximated to negative exponential distribution [46].

C. Negative exponential distribution

The Negative exponential distribution is suitably used in strong turbulence region. In strong atmospheric condition, the scattering particle larger than FSO wavelength and negative exponential model is used in this case [43, 47]. The pdf of the negative exponential distribution is expressed as [47]:

$$f = \frac{1}{I_0}\exp\left(\frac{-I}{I_0}\right), \quad I > 0 \text{...} (3.6)$$

Where I is irradiance at receiver and I_0 mean radiance

In this paper FSO channel is modelled using gamma gamma distribution since this model is widely used in turbulent under all regime. The pdf of gamma gamma function is plotted using MATLAB tool as shown in Figure 3.1 below

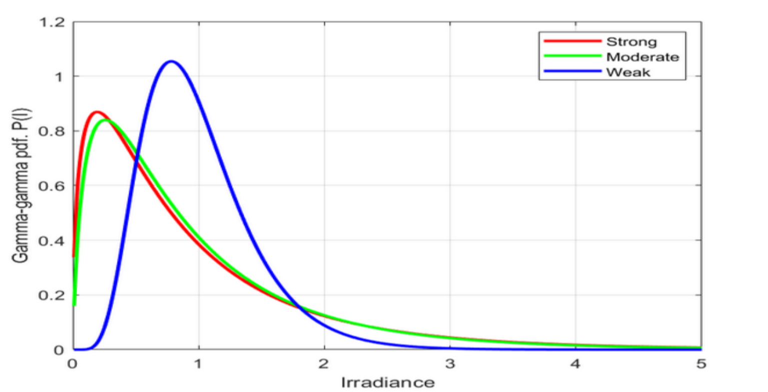

Fig 3.1. PDF of gamma gamma function against irradiance

As shown in the figure above for the same irradiance different pdf is obtained for different turbulence condition. For example, for the value of I =1, the pdf value is 0.896, 0.397, 0.387 for weak, moderate and strong regime respectively. In weak turbulent condition, it behaves like lognormal distribution and in strong turbulence it behaves like negative exponential distribution. As seen from the graph as the atmospheric turbulence increases the gamma-gamma distribution spread out more. The small and large scale eddies are large in weak turbulence and gets smaller in strong turbulence as the irradiance fluctuation increases

3.2.3. RF channel modeling

Radio signal experience free space loss and rapid fluctuation while propagating through the air. The multipath fading is due to nonstop change of time varying environmental condition (scattering, diffraction, reflection). At the receiver the sum total of signals received may follow certain statistical behavior. Some of the well-known RF channels modelling are discussed below

A. Rician Distribution

Rician distribution model used mostly in sub-urban areas and where line of sites exists between transmitter and receiver. The pdf of Rician distribution is given by [45]

$$f(I) = \frac{1}{\sigma_R^2} \exp\left\{-\frac{I^2+K_R^2}{2\sigma_R^2}\right\} I_0[\frac{IK_r}{\sigma_R^2}], \quad I > 0 \ldots\ldots (3.7)$$

Where I represent irradiance at the receiver, I_0 is Bessel function of the first kind and order zero and $K = \frac{K_r}{\sigma_R^2}$ is Rician factor i.e. the ratio of dominant transmitted power to the scattered power in dB.

B. Nakagami-m Distribution

Nakagami-m distribution channel used in of LOS and non-line of sight (NLOS) fading channels. Rayleigh and Rician model can be expressed well with Nakagam-m distribution model by varying the m, a shaping parameter which is used to control the shape of the distribution. If we make $m = 1$, Nakagami model approximate to Rayleigh model and if $m < 1$ it well describe Rician distribution [45, 45, 47]. The pdf of Nakagami-m distribution is expressed as [45]:

$$f(x; m, w) = \frac{2m^m}{\Gamma(m)w^m} x^{2m-1} \exp\left(-\frac{m}{w} x^2\right) \ldots\ldots (3.8)$$

Where m is shape parameter and w is scale parameter.

The below Figure 3.2 shows probability density function of Nakagami-m distribution against irradiance with parameter of m and w.

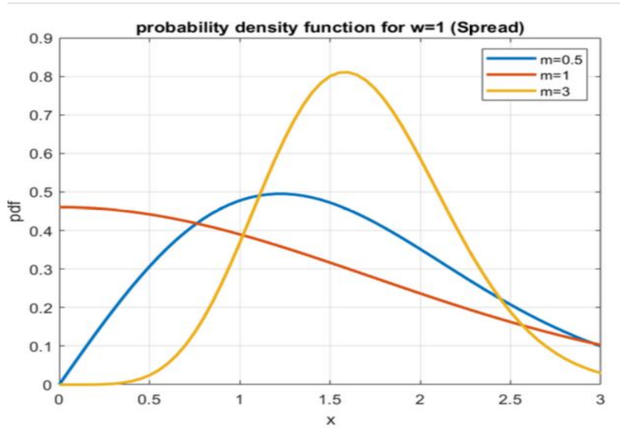

Figure 3.2: PDF of Nakagami-m function against irradiance.

C. Rayleigh Distribution

RF propagation follows multipath, use different path while travelling from transmitter to receiver. To model this statistical behavior of RF signal Rayleigh distribution channel model is suitable. It is used when there is NLOS component exists. The pdf of Rayleigh fading is given by [47]

$$f_h(h) = \frac{h}{\sigma^2}\exp(-\frac{h^2}{2\sigma^2}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3.9)$$

Where h is fading gain and σ^2 is variance.

The RF channel model in this paper is Rician distribution channel. Since FSO link necessarily needs direct line of sight, following that RF signal propagation experience direct line of sight.

3.2.4. FSO and RF System Model

At the transmitter of FSO subsystem, the data stream is modulated using Pulse Amplitude Modulation (N-PAM) and fed to FSO transmission link. PAM is a spectrally efficient modulation scheme. It also enhances Peak-to-Average Power Ratio (PAPR), bandwidth capacity and data throughput. The FSO subsystem assumes intensity modulation and direct detection (IM/DD). At the receiver the photodiode converts the incident optical power to equivalent electrical signal. The received signal of the FSO subsystem is given by [48]

$$R_{fso} = \eta . I . x + n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.13)$$

Where η is receiver conversion efficiency, I is intensity, complex random variable that varies as given channel model, x is modulated information signal and n is additive white Gaussian noise.

In RF subsystem, Quadrature Amplitude Modulation (M-QAM) is used at the transmitter. QAM modulation is spectrally efficient and widely used modulation type in existing microwave network. The RF received the signal at the receiver is given by [49]

$$R_{rf} = h.x + n \qquad (3.14)$$

Where h is Rician fading channel and x is M-QAM transmitted signal information. n is Additive White Gaussian Noise (AWGN).

We consider hybrid FSO/RF as shown in Figure 3.3. It operates based on switching between FSO and RF link and adaptive transmission rate on each link. The system model consists of two forward links: FSO link and RF link and one feedback link. The switching scheme adopts multi rate based threshold for both links. The FSO data transmission rate is controlled by the FSO subsystem whereas the RF data transmission is controlled solely by RF subsystem.

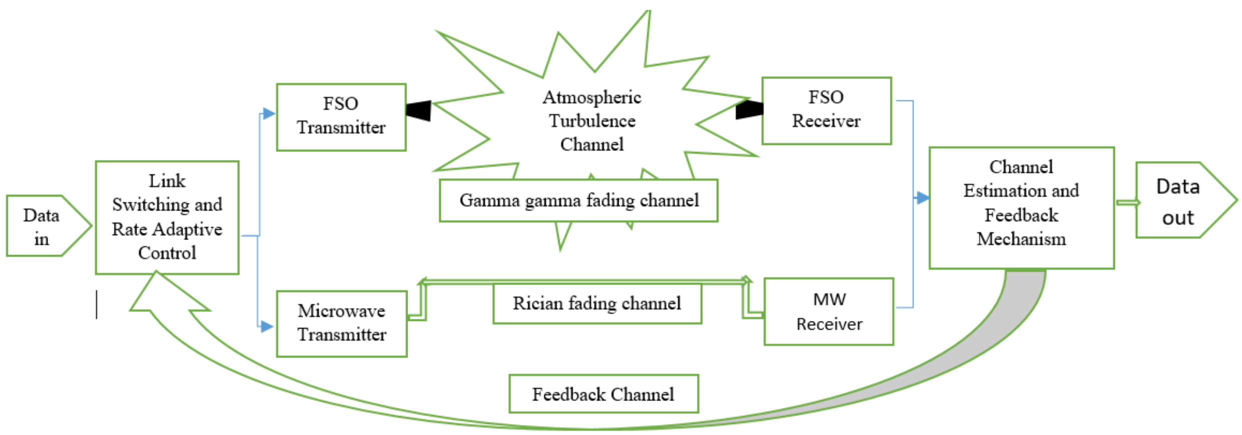

Figure 3.3: Hybrid FSO/RF system model.

Assuming that our primary link is FSO link with the highest available modulation order. When the received signal strength via primary link degrades, FSO system gradually lowers its modulation order in a discrete manner and corresponding transmission data rate until its worst scenario. If the received SNR is no more acceptable within all possible FSO threshold value, the transmission link switched to RF link with the possible maximum modulation order and data rate. The RF link, like FSO link, adaptively transmit the data based on feedback channel information.

Figure 3.4. shows the working principle of hybrid FSO/RF system. Let us assume that the there is a clear weather condition. Our primary transmission mode is FSO link with the maximum possible modulation order. Whenever FSO signals deteriorate the system switch to lower possible modulation order based on the feedback channel information. If the channel quality does not change or gets better than before the FSO link remain active and the system keeps operating on the current modulation order or switch back to high order respectively. The same scenario happened on RF subsystem. As the FSO link becomes no longer available due to strong environmental condition the system switched to RF link and the RF subsystem adaptively transmitted the data. When the received signal is lower than the RF minimum threshold SNR value, the system goes to complete outage. At this point, the system transmitted only pilot signals which check if the channel quality gets better.

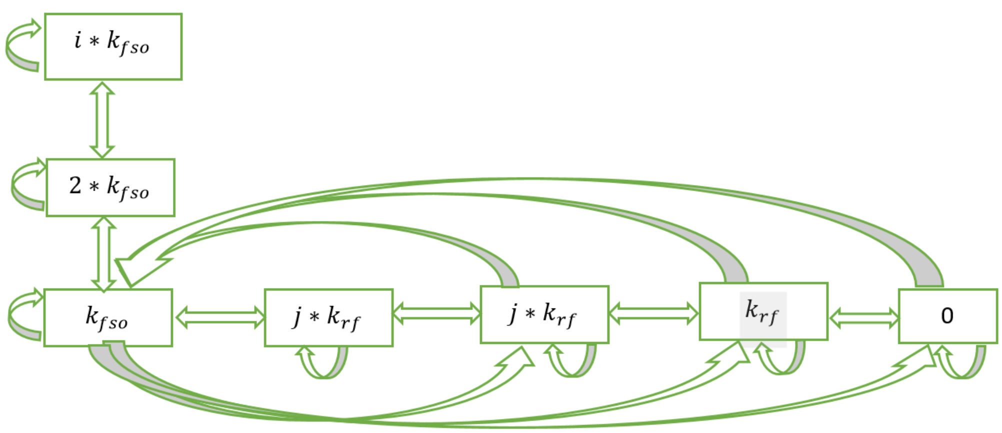

Figure 3.4: Adaptive hybrid FSO/RF working principle.

3.2.4.1. Link Switching and rate adaptive control

Based on the channel state information the link switching operate between FSO and RF link. Let say SNR_{th} is threshold SNR value of FSO link and SNR_{rf} threshold SNR values of RF link. At any given time *t*, the system use one of the following link transmission link, D_l:

$$D_l = \begin{cases} FSO \quad if\ SNR_{thfso} < SNR_{fso} < infinity \\ RF \qquad if\ SNR_{thrf} < SNR_{rf} < SNR_{thfso} \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.10)$$

Transmission Adaptive rate

We assume that FSO deploy N-ary, N-PAM and M-ary, M-QAM for RF link.

$N = 2^i$, i=1, 2, … n with symbol rate, K_{fso}

$M = 2^j$, j=1, 2, … n with symbol rate, K_{rf}

The transmission rate of FSO and RF link is given by:

$$K = K_{fso} Log_2^N, \quad \text{if} \quad SNR_{fso(i)} < SNR_{fso} < SNR_{fso(i+1)} \quad \ldots\ldots (3.11)$$

$$K = \begin{cases} K_{rf} Log_2^M & if \quad SNR_{thfso} < SNR_{fso} < infinity \\ 0 & if \quad SNR_{rf} < SNR_{rf1} \end{cases} \quad \ldots\ldots (3.12)$$

Channel estimation and Feedback Mechanism

At the receiver, the incoming signal is distorted, phase shifted and attenuated due to nature of atmospheric channel. After the receiver detects the signal, the system estimate the received signal by correlating with the reference signal. The result is fed to the transmitter via feedback channel so that the transmitter transmits the signal based on received channel state information on either of the link with adaptive transmission rate.

The adaptive switching mode at the transmitter is merely depend on the received optical SNR. This paper assumed that the channel state information received by transmitter via feedback channel is error free and not lead to an incorrect switching decision. In reference to preset threshold SNR values and respective data rate, knowing the received optical and RF SNR at the receiver is adequate information for switching decision.

Chapter 4

Performance Analysis of FSO, RF and Hybrid FSO/RF System

4.1. Introduction

This chapter will discuss about the performance analysis of FSO, RF and hybrid FSO/RF system. The specific rain attenuation of RF link due to rainfall is simulated for both vertical and horizontal polarization. For FSO link, the power received under different link range and receiver aperture diameter is discussed. The availability of RF link, FSO link and hybrid FSO/RF link in terms of outage probability is also discussed in detail. The BER and channel capacity of the two link and hybrid system is also simulated and discussed in this chapter.

4.2. RF Link Analysis

Rain is a primary cause for the degradation of RF signal and leads to link outages. In tropical climate, the observable rain attenuation is for the propagation frequency greater than 10 GHz [50]. Rain significantly deteriorates RF signal due comparable size of rain drop and wavelength which is scattered the RF signals [50,51]. To estimate rainfall rate at location of interest, the distribution of rain at 1-min integration time has to be available [53]. From NMIE data 15-min rain rate (mm/hr) of central Addis Ababa city is obtained for 5 years (2015-2020). However, it is not advised to design communication system with longer integration time because it misses the high intensity rainfall which stays for short duration [52]. Therefore, 15-min rainfall rate should be converted to 1 min integration time. To do this, ITU-R P837.7 provide the conversion steps of 15-min to 1-min integration time. The annual rainfall rate exceeded for 0.01% (99.99%) availability, $R_{0.01}$(mm/hr) is determined. From the collected data, the 1-min integration time of central Addis Ababa city is 152.84 mm/hr [53].

To find the specific rain attenuation of RF signal due to rainfall, ITU-R P.838-3 recommend the power law relationship. The specific attenuation $A(\frac{dB}{Km})$ is determined from the rain rate $R_{0.01}$(mm/hr) is expressed as.

$$A\left(\frac{dB}{Km}\right) = k_{hv} * R_{0.01}{}^{ahv} \quad \ldots\ldots (4.1)$$

Where the coefficient k_{hv} and a_{hv} are function of frequency and polarization and given by ITU-R P.838-3 [54].

$$log_{10}^{k_{hv}} = \sum_{j=1}^{4}(a_j \exp(-[\frac{(log_{10}^{f} - b_j)}{c_j}]^2)) + m_k log_{10}^{f} + c_k \ldots\ldots (4.2)$$

$$a_{hv} = \sum_{j=1}^{5}(a_j \exp(-[\frac{(log_{10}^{f} - b_j)}{c_j}]^2)) + m_a log_{10}^{f} + c_a \ldots\ldots (4.3)$$

Where f is propagation frequency in GHz, k_{hv} and a_{hv} are given in [54]. The coefficients a_j,b_j,c_k,$m_k$and m_a are constants defined in ITU-R P.838-3 for horizontal and vertical polarizations.

The specific rain attenuation under vertically and horizontally polarized signals is depicted below in Figure 4.1 for range of frequencies. The simulation shows that the attenuation is steeply increases as frequency increases and reach maximum at 100 GHz. After this frequency, the attenuation is no more dependent on operating frequency and starts decreasing slightly. Additionally, the horizontally polarized signal is attenuated more than vertically polarized signal due to non-spherical shape with base straightened raindrop shapes.

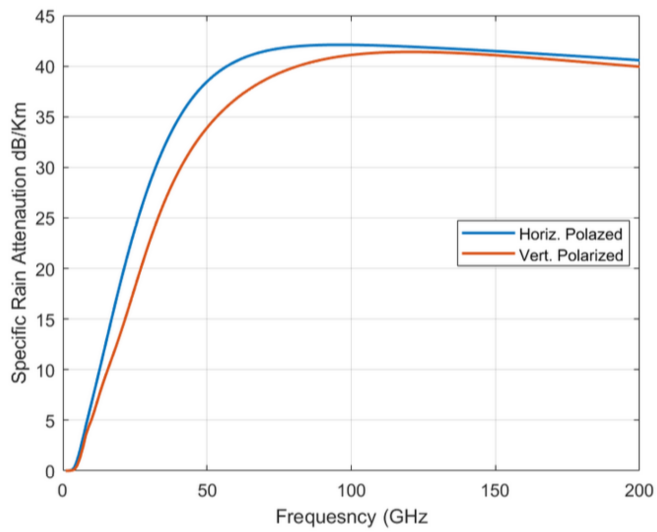

Figure 4.1: Specific rain attenuation of vertically and horizontally polarized signal under range of frequencies

4.3. FSO Link Analysis

Considering the laser transmitted power P_{tx} at a wavelength, the received signal P_{rx} at the receiver detector is given by [53].

$$P_{rx} = P_{tx}(\frac{D}{\emptyset_{div}L})^2 \,.\, 10^{-0.1\beta L}\partial_{tx}\partial_{tx} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

Where D is receiver aperture diameter, $\emptyset_{div}$ is divergence angle, β is attenuation factor, L is link distance between transmitter and receiver and $\partial_{tx}, \partial_{tx}$ are transmitter and receiver optical efficiency. The FSO data rate is given by [54].

$$R = \frac{4*P_{rx}}{\pi*E_p*N_b}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.5)$$

Where E_p is a photon energy at a given wavelength given by E_p = h*c/λ, h is planks constant and c is speed of light and N_b is receiver sensitivity in photon/bit.

Simulation Result

The weather effect on FSO link is simulated using MATLAB and FSO link performance: received power and data rate is evaluated with respect to receiver diameter aperture and link range. The parameters used in FSO and RF link are listed below in Table 4.1.

Table 4.1: FSO link parameters under different fog condition and atmospheric turbulences

Operating parameter	value
Wavelength	1550nm
Transmitter power	50mw
Transmitter divergence angle	2.5cm
Transmitter efficiency	0.9
Receiver efficiency	0.9
Receiver sensitivity	-20dBm
Receiver diameter	0.15 cm
Range	1000 m
FSO attenuation	0.6 dB/km
(ITU-R P.1817.1)	18 dB/km
	29 dB/km
Atmospheric turbulence	Weak $\alpha = 10.10$, β=11.60
	Moderate $\alpha = 5.4181$, β=4.0821
	Strong $\alpha = 3.994$, β=2.1223
Receiver diameter	0.15 cm
Altitude	2388 m
Wind speed	9 m/s

The increase of receiver aperture diameter will increase the received signal strength since more photons are collected at the receiver as its diameter is getting high.

The received optical power, as shown in Figure 4.2., is directly proportional to the receiver aperture diameter. This implies that the receiver diameter should be large enough to collect transmitted signal and detect it. On the other hand, received signal strength against link range is simulated. Any propagated signal attenuated by many factors as the link distance increases. In FSO link analysis, as it is observed from the plot, a fog is a critical factor that cause a significant signal loss.

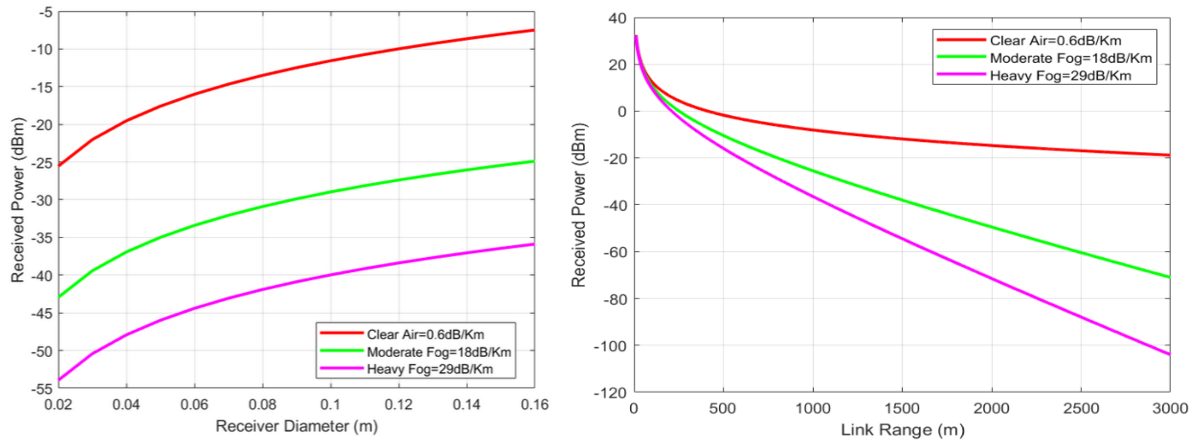

Figure 4.2: Received optical power with respect to receiver aperture diameter and link range

4.4. Outage Probability

Probability of outage is one of the essential metrics in wireless communication. We say the system in outage when the received signal is below lowest SNR threshold level or acceptable limit. The error of information received with this SNR value is greater than the preset acceptable BER. The system quite transmitting data at this point. We assume that the system keep transmitting a pilot signal to check if the received signal is in acceptable range.

4.4.1. Switching Threshold

The key objective of adaptive transmission rate is to deliver highest possible data rate while maintaining the required QoS. For both FSO and RF link target BER is regarded as common level of services quality requirement. The target BER, BER_0 is set to be 10^{-4}. The switching threshold SNR level for FSO and RF link is determined from the following equation [20].

$$SNR_{fso(i)} = \frac{2(2^i-1)(2^{i+1}-1}{3}[erfc^{-1}(\frac{2^i * i * BER_0}{2^i-1})]^2 \quad (4.6)$$

$$SNR_{rf}(j)=\frac{2}{3}\left(2^{j}-1\right)\ln\left(\frac{1}{5*BER_0}\right) \ldots\ldots \text{(4.7)}$$

Where $i = j = 2, 3, 4$ ...

Using MATLAB simulation tool the SNR threshold value is determined as shown in the table 4.2 below.

Table 4.2. Switching threshold of adaptive hybrid FSO/RF with N-PAM and M-QAM

Receiver SNR threshold range	FSO (dB)	(31, ∞)	(28,31)	(25, 28)	(0, 25)			
	RF (dB)	Not considered			(23,25)	(19,22)	(14,18)	(0,14)
Modulation Order		16-PAM	8-PAM	4-PAM	16-QAM	8-QAM	4-QAM	Outage

4.4.2. Outage Probability of RF Link

The outage probability of RF link is when the received SNR of radio link is less than the threshold SNR.

$$P_{OutRF} = P\left(SNR_{RF} < SNR_{thRF}\right) = F\left(SNR_{thRF}\right) \ldots\ldots \text{(4.8)}$$

Where F(.) is the cumulative distribution function.

The RF subsystem follows line-of-sight (LOS) link and use M-ary QAM. Using Rician distribution the pdf of RF link is given by [55]:

$$f_{SNR}\,(SNR) = \frac{K+1}{SNR_{avg}} \exp\left(-(K+1)\frac{SNR}{SNR_{avg}} - K\right) * I_o\left(2\sqrt{K(K+1)\frac{SNR}{SNR_{avg}}}\right) \ldots\ldots \text{(4.9)}$$

Where K is the Rician factor, 9dB used in this thesis. $I_o(.)$ is zero order modified Bessel function of the first kind, SNR_{avg} is average SNR and SNR is instantaneous received SNR. The simplified cumulative distribution function (CDF) is expressed as [55]:

$$F_{SNR}\,(SNR_{th}) = 1 - Q\left(\sqrt{2K}, \left(\sqrt{2(K+1)\frac{SNR}{SNR_{avg}}}\right)\right) \ldots\ldots \text{(4.10)}$$

Where and Q(.) first order Marcum Q-function.

4.4.3. Outage Probability of FSO link

The outage probability of FSO link is when the received SNR of FSO link is less than the threshold SNR.

$$P_{OutFSO} = \text{P}\,(SNR_{FSO} < SNR_{thFSO}) = F(SNR_{thFSO}) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.11)$$

The FSO subsystem follows Gamma-Gamma distribution and use N-ary PAM. By integrating Eq. (3.3), the CDF of Gamma-Gamma FSO link is given as [56].

$$F_{SNR}\,(SNR_{th}) = \frac{(\alpha*\beta)^{\frac{(\alpha+\beta)}{2}}}{\Gamma(\alpha)*\Gamma(\beta)}\left(\frac{SNR_{th}}{SNR_{avg}}\right)^{\frac{(\alpha+\beta)}{2}} G_{1,3}^{2,1}\left\{\alpha\beta\sqrt{\frac{SNR_{th}}{SNR_{avg}}}\,\middle|\,\left(\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta-\alpha}{2},\frac{-(\alpha+\beta)}{2}\end{matrix}\right)\right\} \ldots (4.12)$$

Where α *and* β small and large eddies expressed in Equation (3.4) and (3.5). Where $G_{1,3}^{2,1}$ is MeijerG-function which estimate as a combination of hypergeometric series.

4.4.4. Outage probability of Hybrid FSO/RF

The outage of the system is when the received SNR of two respective subsystems are below their threshold. Assuming the FSO link and RF link are statistically independent, the outage probability of hybrid system is given by:

$$P_{outHybrid} = P_{OutFSO} * P_{OutRF} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.13)$$

Substituting Equations (4.8) and (4.10) in Equation (4.11) the outage probability of hybrid system is expressed as

$$P_{outHybrid} = (1 - \text{Q}\,(\sqrt{2K}, \left(\sqrt{2(K+1)\frac{SNR}{SNR_{avg}}}\right)) * \frac{(\alpha*\beta)^{\frac{(\alpha+\beta)}{2}}}{\Gamma(\alpha)*\Gamma(\beta)}\left(\frac{SNR_{th}}{SNR_{avg}}\right)^{\frac{(\alpha+\beta)}{2}} G_{1,3}^{2,1}\{\alpha\beta\sqrt{\frac{SNR_{th}}{SNR_{avg}}}\,\middle|\,(\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta-\alpha}{2},\frac{-(\alpha+\beta)}{2}\end{matrix})\} \ldots\ldots (4.14)$$

The outage probability of RF, FSO and Hybrid FSO/RF link is simulated using MATLAB R2018a and their performance is observed under different turbulent regime. The regime depend on FSO C_n^2 (Equation 3.2) which is function of wind speed and altitude and given by [57].

$$C_n^2 = 0.00594(\frac{v}{27})^2 * (10^{-5}(h+a)^{10} * exp^{\frac{-(h+a)}{1000}} + 2.7 * 10^{-16} * exp^{\frac{-(h+a)}{1500}} + 1.7 * 10^{-14} m^{\frac{-2}{3}} * (\frac{a_o}{a})^{\frac{-4}{3}} \ldots (4.15)$$

Where $v(\frac{m}{s})$ root mean square (RMS) wind speed, $h(m)$ is height of ground above sea level, $a\ (m)$ is height of first transceiver above the ground and a_o is the height difference between transceiver. From NMIE wind speed data of central Addis Ababa city, the maximum RMS wind speed v is $6.4\ \frac{m}{s}$.

In this thesis $v = 9\ \frac{m}{s}, 10 < a\ (m) < 35, a_o = 10\ m$ is used to compute C_n^2. Accordingly using Equations (3.4) and (3.5), α and β is calculated and obtained as seen in Table 4.1 for different turbulent regime.

The outage probability of RF, FSO and hybrid link is simulated and depicted below in Fig 4.3. from the simulation it is observed that as SNR value increase the probability of outage decrease under all turbulent regime as expected. The adaptive hybrid system goes in complete outage if the SNR value read below 14dB. At this SNR value as seen from the Fig. 4.3., the hybrid network perform better availability than that of RF only and FSO only link. The outage probability $1.1*10^{-5}$, $1.15*10^{-5}, 1*10^{-5}$, $0.95*10^{-5}$ is achieved at 35 dB, 36 dB, 45 dB and 65 dB for RF link, FSO link under weak, moderate and strong turbulence respectively. $1.02*10^{-5}$ outage probability is achieved at SNR of 24 dB for hybrid FSO link under weak turbulence and RF link. This implies that the outage probability is significantly improved when the system operates under hybrid condition when compare with individual performance of FSO and RF subsystems. The carrier class availability (99.999%) of link achieved under RF signal is at 35 dB and for FSO weak turbulence regime it is achieved at 36dB. However, by using hybrid RF/FSO system the carrier class availability is achieved at 24 dB under FSO weak turbulence, which is 10 dB better than RF only link and significantly improve outage of FSO link subsystem.

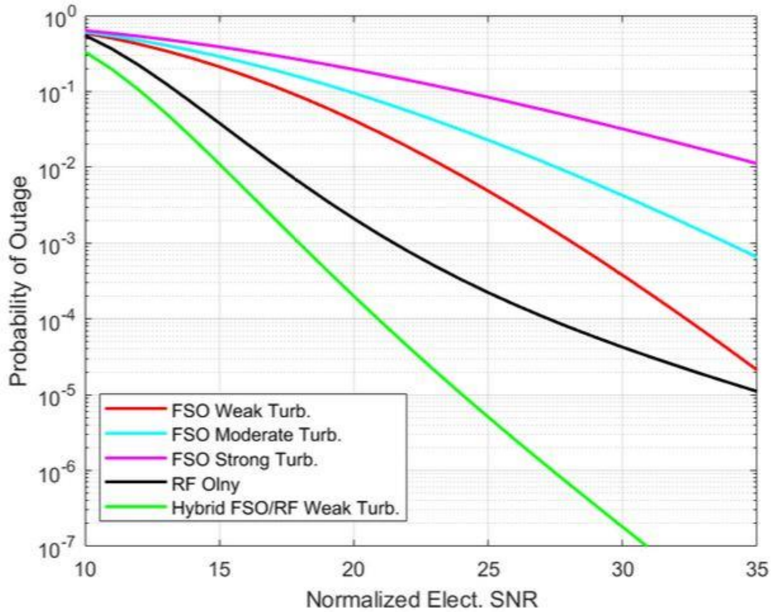

Figure 4.3. The outage probability of RF link, FSO link under weak, moderate and strong atmospheric turbulence and hybrid link

4.5. Bit Error Rate

Bit error rate is the average number of received bit that are in error divided by the total number of bit transmitted.

4.5.1. BER of RF Link

According [58], the BER of RF link for Rician fading and M-ary QAM modulation is given below. For the value of 0<K<∞ and M>4 the BER of RF link is given by:

$$BER = \frac{0.2*(1+K)*(M-1)log2^{M}}{(1+K)*(M-1)+1.5*SNR_{avg}} \exp[\frac{-1.5*SNR_{avg}*K}{(1+K)*(M-1)+1.5*SNR_{avg}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.16)$$

4.5.2. BER FSO Link

The average BER of N-ary PAM modulation FSO sub system is given as in [59]:

$$P_{BER} = \frac{2*(M-1)}{M*log2^{M}} * \frac{2^{(\alpha+\beta-3)}}{\pi^{1.5}*\Gamma(\alpha)*\Gamma(\beta)} G_{5,2}^{2,4}\{\frac{4*SNR}{(a*b)^2}\Big|^{\frac{1-\alpha}{2},\frac{2-\alpha}{2},\frac{1-\beta}{2},\frac{2-\beta}{2},1}_{0,\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.17)$$

4.5.3. BER of Hybrid FSO/RF link

The bit error rate of hybrid RF/FSO using M-QAM modulation of RF and N-ary PAM FSO link is developed. This paper assume that the system operate in adaptive hard switch mode where RF is used as stand by link while FSO link is active path as long as SNR value of the link is above threshold. If the SNR of FSO link is below minimum value of required SNR, the system switch to possible mode of M-QAM RF link where the range of SNR value met. The hybrid FSO/RF system will be in outage if the received signal at the receiver is low than the RF threshold value. Using [60], the BER of hard switching hybrid FSO/RF system is expressed as:

$$P_{hyb,BER} = \frac{(1-P_{out,FSO})P_{BER,FSO}+P_{out,FSO}(1-P_{out,RF})P_{BER,RF}}{1-P_{out,RF}*P_{out,FSO}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4.18)$$

Where $P_{out,FSO}$ and $P_{out,RF}$ outage probability of FSO link and RF link whereas $P_{BER,FSO}$ and $P_{BER,RF}$ are BER of FSO and RF link respectively.

The BER of adaptive switching mode is the sum of the each BER given under preset range SNR threshold value as shown on Table 4.2. and expressed as [13].

$$P_{Adapt,BER} = BER_{(4-QAM)} + BER_{8-QAM} + BER_{16-QAM} + BER_{4-PAM} + BER_{8-PAM}BER_{16-PAM} \quad \ldots\ldots\ldots (4.19)$$

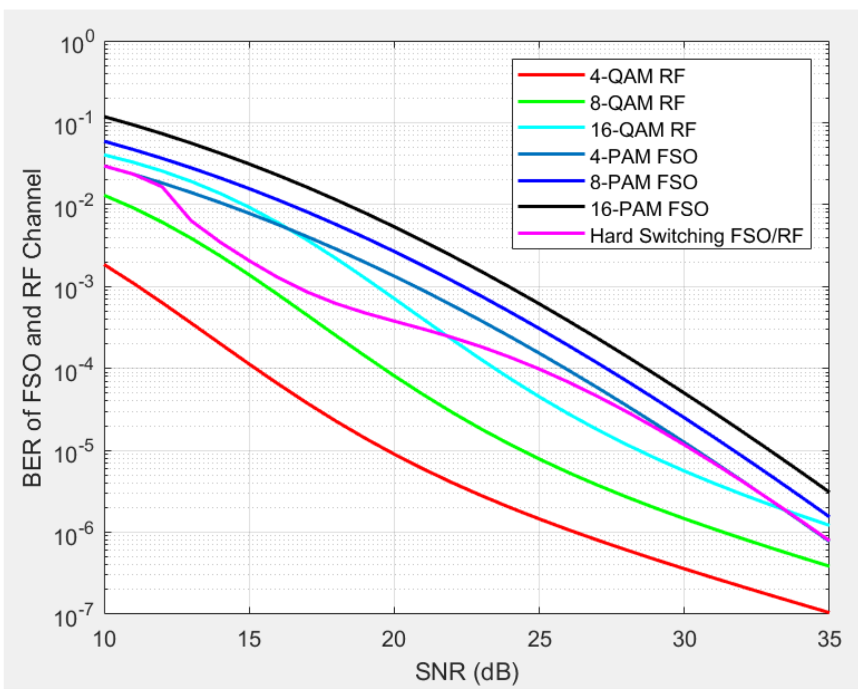

Fig. 4.4 The BER of different modulation order of RF and FSO channel and hard switching under Rician and gamma gamma fading channel

In hard switching scheme, the system transmitting with fixed data rate using RF and FSO link. For low SNR the performance of hybrid mode is better than that of FSO-only link. At low SNR the good quality of service is insured by RF link. As SNR value increases the BER of hybrid link asymptotically approach and finally converges to FSO link.

To keep the good QoS the target BER under fading channel has to be met. At lower SNR the system operate using lowest modulation order of RF link, 4-QAM. As the SNR value increases and read greater than 19dB, the system switches to higher modulation order of RF link, 8-QAM. If the SNR value keep increasing and read above 26dB, the system switch to FSO link and start transmitting with 4-PAM modulation order. In clear weather condition, the system entertain high data rate using 16-PAM modulation order. On the other hand, as the atmospheric turbulent increasing the system adaptively lowering its modulation order and hence transmission rate in accordance with the range of reading of SNR values. Due to this reason the adaptive switching mode improve short term link flapping problem observed in hard switching and deliver the services with keeping good QoS.

4.6. Channel Capacity

Average channel capacity is one of the essential parameter to evaluate the performance of FSO and RF channel. Channel capacity is the maximum possible information transmitted in bit per second.

4.6.1. Channel Capacity of RF Link

For Rician fading the channel capacity of RF subsystem is given by [58]

$$C_{rf} = \int_0^\infty B_{rf} log_2(1 + SNR)p(I)dI \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.20)$$

where $p(I)$ is pdf of specified distribution model

After complex mathematical derivation the channel capacity of RF under Rician fading channel is expressed as in [61].

$$C_{rf} = log_2(1 + \frac{K.SNR}{1+K}) + \frac{1}{\ln(2)}.\frac{SNR\,(1+K)}{(1+K+K.SNR)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.21)$$

4.6.2. Channel Capacity of FSO Link

For FSO communication under atmospheric turbulence condition, the ergodic capacity averaged over distribution of I is given by [50, 59].

$$C_{fso} = \int_0^\infty B_{fso} log_2(1 + SNR)p(I)dI \text{ .... } (4.22)$$

where $p(I)$ is pdf of specified distribution model.

According to the average channel capacity of FSO system under gamma-gamma distribution is expressed mathematically as [59].

$$C_{fso} = \frac{B*2^{(\alpha+\beta-2)}}{pi*\ln(2)*\Gamma(\alpha)*\Gamma(\beta)} G_{6,2}^{1,6}\ \frac{16SNR}{(\alpha*\beta)^2} \left| \begin{matrix} 1,1,\frac{1-\alpha}{2},\frac{2-\alpha}{2}\frac{1-\beta}{2}\frac{2-\beta}{2} \\ 1,0 \end{matrix} \right. \text{ .... } (4.23)$$

4.6.3. Channel Capacity of hybrid FSO/RF Link

As expressed in Eq. 4.22 and 4.23 the channel capacity of FSO link and RF link is depend on the SNR value not on the modulation order of RF and FSO systems. Therefore, the normalized channel capacity of adaptive and hard switching hybrid system is the same and expressed as [56]:

$$C_{hyb} = C_{fso}(SNR_{thFSO}) * P_{fso}(SNR \geq SNR_{th}))+P_{fso}(SNR < SNR_{th})*C_{rf}(SNR_{thRF}) \text{.......... } (4.23)$$

Where $C_{fso}(SNR_{thFSO})$ and $C_{rf}(SNR_{thRF})$ are the capacity of the system when only FSO or RF link when on of them is active at a given time. Channel capacity of hybrid system is the sum of the capacity of FSO link provided that the link is available i.e. $SNR \geq SNR_{th}$ and capacity of RF link provided that the FSO link is unavailable or receiving SNR of FSO link is below threshold.

$$C_{hyb} = C_{fso}(SNR_{thFSO}) * (1 - P_{outfso}(SNR_{th})+P_{outfso}(SNR_{th})* C_{rf}(SNR_{thRF}) \text{... } (4.24)$$

The below Fig. 4.5 shows the channel capacity of FSO link, adaptive hybrid FSO/RF link. The result shows that the adaptive hybrid system has improvement in ergodic capacity when compared with FSO only link. The improvement is specially observed at lower SNR where the capacity of FSO only subsystem is far less than that of hybrid system. However, as SNR of the system increases the channel capacity of hybrid RF/FSO approach to the curve of channel capacity of FSO link only and finally converges. This clearly shows that the system is operating on FSO link only at higher SNR value instead of activating RF link. The hybrid system achieves better capacity at low SNR region due to switch over to RF link.

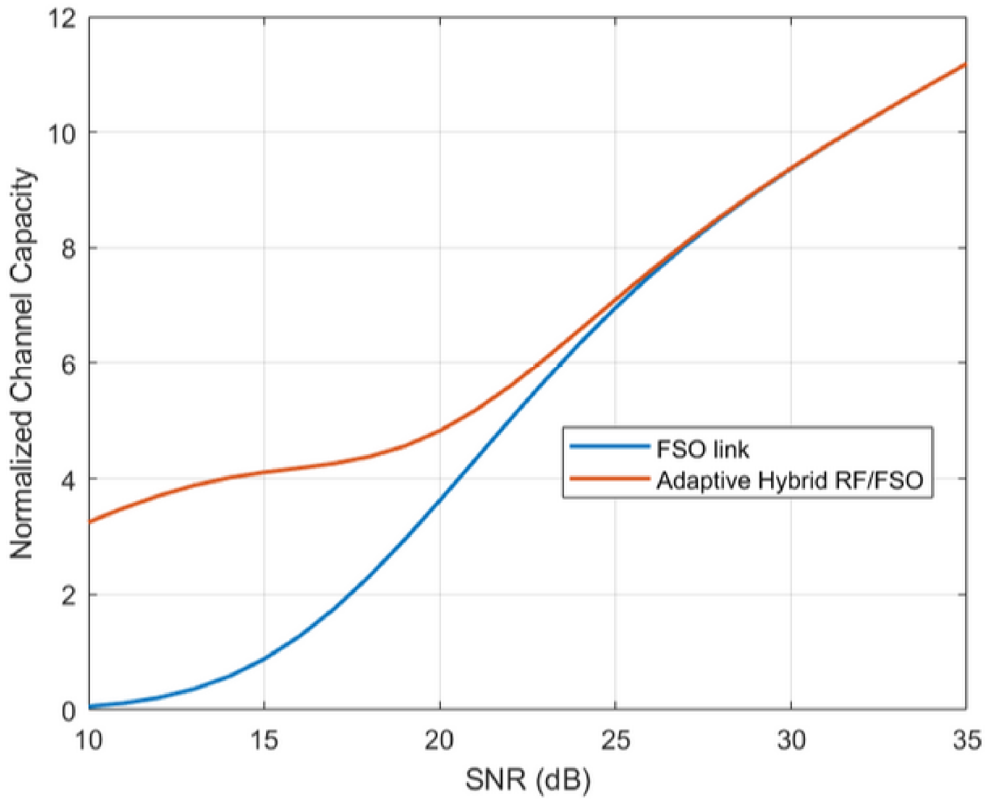

Figure 4.5 - The channel capacity of FSO-only and hybrid FSO/RF link

Chapter 5

Conclusions and Future Work

5.1. Conclusions

The focus of this thesis is to determine the switching threshold of the FSO, RF links and adaptive multi rate switching on each link and investigate the availability and capacity performance of hybrid FSO/RF. The hard switching scheme is based on fixed transmission rate and exposed to short term link flapping. It instantly switched from higher data rate of FSO link to lower data of RF link and vice versa under atmospheric weather condition like fog and rain. Adaptive based hybrid switching system is preferable option to improve system performance observed in hard switching. The switching threshold value between FSO and RF link and adaptive rate on each link are not discussed in past works. This paper determine the switching threshold of the FSO and RF links and investigate the availability, BER and capacity performance of adaptive hybrid FSO/RF. The receiver SNR value is the deciding factor of link and data rate switching.

The system model consists of link switching and rate adaptive control at the transmitter, which the link between FSO and RF is first selected and possible data rate is then transmitted based on the received SNR value. The receiver SNR value information is fed to transmitter via feedback channel. At the receiver, there is channel estimation and feedback mechanism, where the electrical SNR value is measured and the decision is made. The channel model used in FSO system is selected to be a gamma gamma distribution due to its versatility models in weak, moderate and strong turbulent condition whereas Rician distribution used to model RF channel due to existence of LOS component path.

The FSO link performance due to different fog attenuation and RF link performance due to rain rate is simulated and analyzed. The outage probability of adaptive hybrid FSO/RF link is demonstrated and compared with the outage performance of the FSO - link and RF-link only. Since the outage probability measure the availability of FSO and RF link, adaptive and hard switching of hybrid link have same SNR threshold value. At 14 dB the hybrid link achieved 99.99% availability under weak turbulent condition of FSO link and RF link. The availability of RF and FSO only link at this threshold value is far less than this.

The BER performance of adaptive switching mode shows that the system gradually lowering or increasing its modulation order based on the received SNR value to keep good QoS by maintaining target BER. This way adaptive switching mode perform better than hard switching mode. The channel capacity of hybrid system improvement is specially observed at lower SNR where the capacity of FSO only subsystem is far less than that of hybrid system. At lower SNR the good QoS is assured by RF link.

5.2. Future Scope

To meet the current and future bandwidth demand and reliability of mobile backhaul, the network may require an alternative form of wireless backhaul network. Hybrid FSO/RF network has been a promising candidate used to address these challenges. The ideas proposed in this thesis can be expanded by considering the following points;

1. Hybrid FSO/RF performance with pointing errors: - pointing error or misalignment fading is due to misalignment of the FSO transmitter laser and receiver photodiode. Since FSO link is always need exact LOS, small deviation may cause high power loss at the receiver. Pointing error is caused by vibration of transmitter and receiver station. Taking the misalignment fading into consideration the performance of hybrid FSO/RF link could be studied.
2. Effect of incorrect feedback channel hybrid FSO/RF: - this thesis assumes that there is a perfect channel state information feedback received by the transmitter. However, considering the feedback channel under fading conditions would lead to an erroneous in switching between FSO and RF link. This will degrade system performance. So, this paper can be expanded in studying the effect of the feedback channel under fading conditions.

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