



Faculty of Engineering

**A New Modulation Technique Using Double Transmission In Free Space
Optical Communication for Access Network**

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A New Modulation Technique Using Double Transmission In Free Space
Optical Communication for Access Network

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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ABSTRACT

In FSO communication links, the atmospheric turbulence has a significant impact on the quality of a laser beam where turbulence results in intensity scintillation, which can severely impair the operation of target designation and FSO communications systems. This research proposed the Double Transmission Balance Receiver (DTBR), a new approach for modulation technique in free-space optical communication. By utilise the Gaussian atmospheric channel analysis is the first step method. This factor will determine the trajectory of the research study and will restrict this strategy to implementing the calculations-related research. The second method is a mathematical derivation development where the new modulation technique is compared to conventional modulation techniques. The performance evaluation will investigate signal strength, signal threshold, signal-to-noise ratio, and bit error rate. In the meantime, the third method simulates the DTBR method using the OptiSystem software. This allows for an analysis close to actual FSO conditions, which can be validated with the theoretical portion. From the result shows that analysis from effective power, in strong turbulence condition the DTBR can improve approximately 50% of power received. For bit rate analysis, it can operate at higher bit rate of 10 Gbps (STM64) with the BER is approximately at 5.91×10^{-11} as compared to conventional ASK only at 2.77×10^{-4} . This gives percentage improvement about 175%. Meanwhile in distance analysis, the DTBR manage to achieve BER approximately 5.51×10^{-17} while conventional only 4.89×10^{-4} . Thus, contribute improvement of 13 magnitude of BER or equivalent of 325%. Therefore, via the presented analysis the new proposed is have the better performance as compare to conventional ASK technique with new threshold at level zero '0'.

Keywords: *Free space optical, modulation, conventional ASK, BER, signal noise*

Teknik Modulasi Baharu Menggunakan Penghantaran Berganda Dalam Komunikasi Optik Ruang Bebas untuk Rangkaian Capaian

ABSTRAK

Dalam komunikasi FSO, pergolakan atmosfera mempunyai kesan yang ketara ke atas kualiti pancaran laser di mana pergolakan menghasilkan kilauan intensiti, yang boleh menjejaskan operasi penetapan sasaran dan sistem komunikasi FSO dengan teruk. Penyelidikan ini mencadangkan Penerima Baki Penghantaran Berganda (DTBR), pendekatan baru untuk teknik modulasi dalam komunikasi optik ruang bebas. Dengan menggunakan analisis saluran atmosfera Gaussian adalah kaedah langkah pertama. Faktor ini akan menentukan trajektori kajian penyelidikan dan akan menyekat strategi ini untuk melaksanakan penyelidikan berkaitan pengiraan. Kaedah kedua ialah pembangunan terbitan matematik di mana teknik modulasi baru dibandingkan dengan teknik modulasi konvensional. Penilaian prestasi akan menyiasat kekuatan isyarat, ambang isyarat, nisbah isyarat kepada hingar, dan kadar ralat bit. Sementara itu, kaedah ketiga mensimulasikan kaedah DTBR menggunakan perisian OptiSystem. Ini membolehkan analisis hampir dengan keadaan FSO sebenar, yang boleh disahkan dengan bahagian teori. Daripada keputusan menunjukkan bahawa analisis daripada kuasa berkesan, dalam keadaan turbulensi yang kuat DTBR boleh meningkatkan kira-kira 50% kuasa yang diterima. Untuk analisis kadar bit, ia boleh beroperasi pada kadar bit yang lebih tinggi iaitu 10 Gbps (STM64) dengan BER adalah lebih kurang pada 5.91×10^{-11} berbanding ASK konvensional hanya pada 2.77×10^{-4} . Ini memberikan peratusan peningkatan kira-kira 175%. Manakala dalam analisis jarak jauh, DTBR berjaya mencapai BER kira-kira 5.51×10^{-17} manakala konvensional hanya 4.89×10^{-4} . Oleh itu, menyumbang peningkatan sebanyak 13 magnitud BER atau bersamaan dengan 325%. Oleh itu, melalui analisis yang dibentangkan, cadangan baharu mempunyai

prestasi yang lebih baik berbanding teknik ASK konvensional dengan ambang baharu pada tahap sifar '0'.

Kata kunci: *Ruang bebas optik, modulasi, ASK konvensional, BER, bunyi isyarat*

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LIST OF ABBREVIATIONS

APD	Avalanche photodiode
ASK	Amplitude Shift Keying
BER	Bit Error Rate
DTBR	Double Transmission Balance Receiver
ERF	Error Function
FCC	Federal Communications Commission
FEC	Forward Error Control
FSO	Free Space Optic
Gpbs	Giga bit per seconds
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light Emitting Diode
Mbps	Megabits per seconds
OOK	On Off Keying
PIN	p-i-n diode
Rx	Receiver
SNR	Signal to Noise Ratio
Tx	Transmitter

CHAPTER 1

INTRODUCTION

1.1 Study Background

The Light Amplification by Stimulated Emission of Radiation technology was successfully created by scientists in the 1960s, and it was later used in the optical communication industry (Jahid et al., 2022). The term "Free Space Optics," or FSO for short, refers to an optical communication method that transmits data between two sites using light, which typically comes from a laser as its source, and which travels across free space (Free Space Optic, 2020). Alexander Graham Bell, who was the first person to discover it in the late nineteenth century with his experiment to convert voice sounds into telephone signals and transmit them between receivers through free air space along a beam of light for a distance of approximately 600 feet, is credited with making this discovery (Fu, 2019). This technology has the same characteristics as fibre optic communications, and the only difference is in the medium through which the signal is sent. Whereas the data in an optical fibre connection are sent via the cable using laser light that has been modified, the data in a FSO communication are sent as a narrow beam across the atmosphere. As a result of the fact that light travels through air at a quicker rate than it does through glass, it is reasonable to refer to FSO as optical communications that occur at the speed of light. The fog, haze, scintillation, and heat of the atmosphere all have a significant role in determining the quality of the connection as well as its degree of stability. The maximum range that terrestrial networks can provide is restricted (less than 10 km). In today's world, the FSO communication systems are being looked at more and more as a potentially lucrative choice for the speedy provisioning of multi-gigabit per second networks (Carbonneau and Wisely, (1998), Harjeevan and Nitin, (2022), Nosov et al., (2022)).

During the last several years, there has been a meteoric rise in the usage of FSO technology, mainly for applications pertaining to the "last mile." This is due to the fact that FSO lines offer the transmission capacity necessary to circumvent information bottlenecks (Fei, 2019). This high-speed data application is able to convey audio, video conferencing, and real-time picture transmission, and it also makes communication more inexpensive for everyone and every area (Hamed, 2002). A FSO system may be used for a wide variety of applications in today's world, including high-bandwidth internet access in the last mile, temporary high-bandwidth data communications, mobile phone backhaul (3G), satellite links, and other applications in which optical fibres cannot be used. The communication skills make it possible not only for humans to communicate and make contact with one another but also for humans to engage with machines and machines to interact with one another. Our sight, hearing, and sense of touch will all be able to make contact with a virtual three-dimensional presence to the connection (Anuranjana, 2019).

1.2 Problem Statement

The purpose of the FSO's communication is to alleviate the effects of any meteorological events. Atmospheric attenuation and air turbulence are two main atmospheric phenomena that might impact the quality of the FSO signal, as documented in Laialy & Natan (2020). Atmospheric attenuation, as reported by Marko (2021) and Wang et al., (2021), may lead to signal scattering and absorption. It may be necessary to adjust the layout of a FSO system so that it can transfer more power without jeopardising user safety or shortening the propagation connection. Atmospheric scintillation is attributed to temperature inhomogeneity, as reported by Li et al. (2003) and Shreesh (2020). When the optical beam travels through the atmosphere, it encounters both constructive and destructive interference, which may weaken the signal (Shrouk,

2021). When the distance between transmitter and receiver is more than 1 km, scintillation may drastically reduce FSO connection availability and performance (Tomoko et al., 2021).

The typical ASK - OOK modulation method is a common basic modulation technique that is now employed in commercially available terrestrial FSO systems (Ebrahim & Bedir, 2020). Nevertheless, the main issue with traditional ASK - OOK is the threshold signal level. The decision circuitry's threshold level/point for distinguishing between bits zero and one is always positioned halfway between the predicted values of data bits one and zero (Won et al., 2021). This will result in the best possible error performance in non-fading channels. Nevertheless, when turbulence is present, the received signal level fluctuates, and the threshold detector must watch this variation in order to find the best decision point (Yamamoto & Ohtsuki, 2003). As a consequence, a considerable design challenge will be required, since channel noise and fading will need to be continuously monitored for the OOK in FSO to work ideally. Ignoring the signal fluctuation and allowing the OOK FSO system to function with a constant threshold level will result in an increase in detection inaccuracy (Lee & Chan, 2004).

Because of the background noise, dark current dominates the detection of weak signals in FSO transmission. FSO is encountering significant hurdles in limiting the presence of undesired signal noise in the receiver. This is because the laser beam is transmitted straight through the air, with varying contributions from atmospheric effects (Androutsos et al., 2021). As a result, the optimum receiver design must condense the presence of noise.

1.2 Objectives

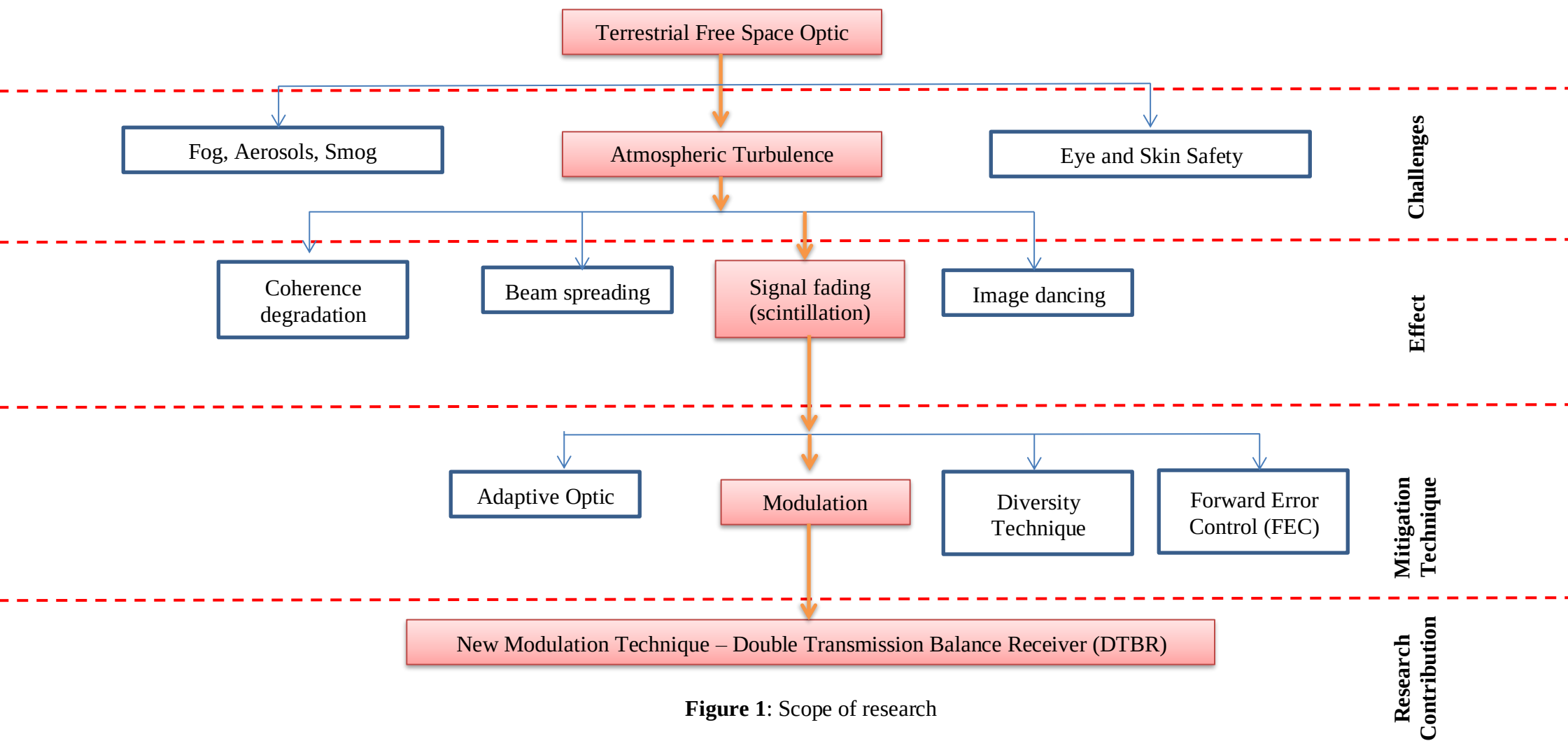
The realisation of FSO technology's potential inspired the development of a brand-new DTBR method. Understanding the impact of air turbulence on signal transmission is essential to evolving this system into a robust communications technology. Because of this, the following are the study's primary aims:

- a) To examine the restriction of traditional ASK in open space optical communication systems due to atmospheric effects.
- b) To develop a new Double Transmission Balance Receiver (DTBR) technique using Optisystem.
- c) To compare and validate the performance between conventional ASK-OOK and DTBR

1.3 Scope Research

The research effort is carried out under the terrestrial FSO, which may be divided into three basic problems. The impact of absorption and dispersion is the first issue (fog, aerosol, and smog). However, the effects of air turbulence and eye and skin safety are the second and third obstacles. The current primarily focuses on the atmospheric turbulence effects that are particular to the scintillation effect, which causes signal fading in the FSO. There are four approaches that may be used to reduce the scintillation effect. The first is adaptive optics, which does not need wavefront measurements, which are difficult to get under high scintillation circumstances, which are common in many communication situations. It works by directly optimising a performance quality parameter, such as

communication signal strength. The second technique is forward error control (FEC), which seeks to keep bound error variability under predefined bounds in order to enhance connection dependability. The third approach is diversity, which is separated into two parts: a) spatial domain technique and b) temporal domain technique. The modulation strategy is used in the fourth method.



1.5 Thesis Organization

Thesis divided by 6 main chapter as follows. For the Chapter 1 will discuss the direction of research which contains of overview, problem statement, objective, scope research, thesis organization, research significance and research gap. The second is Chapter 2, which discuss background of free space optic. It will focus on the three major effects that are atmospheric turbulence effect, atmospheric attenuation effect and lastly precaution of laser. Under this chapter is to discuss the details of the related on previous researchers in the FSO field and a solution that has been proposed to mitigate the effect of atmospheric turbulence. The effect of FSO can split into five categories because of turbulence that are coherence degradation, beam spreading, image dancing, and signal fading. Apart from that, this chapter also discuss the fundamental of FSO for advantage and disadvantage in our current technology.

Meanwhile, for Chapter 3 discuss detail the flow of method that has been used carried out in research. It can be divided in to two main part that is theoretical and simulation. The theoretical method will explain on the related formula and development of derivation of the proposed DTBR. The other part is the simulation method which targets to verify and compare between theory and simulation. It also enables the new proposed DTBR technique running test performance closed to real condition in order to improve the conventional design.

In Chapter 4 is mainly focus the details on how structure development of DTBR technique. It will be divided into two main parts, theoretical and simulation. The theoretical basis for mathematical derivation will involve the element of signal power, SNR and BER.

Then the simulation part is focused on designing DTBR and fit into FSO communication system. The software that used for simulation is Optisystem. Among the important component used to design DTBR are laser power, bit sequence, modulation format, modulator, FSO channel, inverter, photodetector, subtractor, combine, and filter. The next chapter that involve is Chapter 5. It focuses on the overall performance of the DTBR technique in the presence and without presence of turbulence. In order to measure the how far ability of DTBR in poor condition the performance FSO communication system is concentrate on strong turbulence effect. Both results in theoretical and simulation also will be presented, include comparison as well. The final chapter is Chapter 6. It discuss the summary achievement of aim and important finding. As further action related to research, it will also include the sub topic recommendation and future work.

1.6 Research Significance

FSO communication is always hampered by the atmospheric effect, which causes beam signal fluctuations and a rise in unwanted signal. An unique modulation DTBR approach will improve the threshold issue in traditional ASK and lessen the influence of noise at the receiver. The conceptual design development included two important enhancements. Initially, the mono signal is converted to a double signal to create bipolar magnitude. As seen in Figure 2.16, the standard amplitude signal for ASK OOK will typically set the threshold at the middle amplitude level of around 0.5. At a new threshold, the amplitude of the double signal, however, might decrease to zero. This will result in a more reliable and concrete optical communication system performance. The second is an improvement in noise compression by integrating a balance detection design approach at the receiver. In general, two balanced photodetectors receive light from the two outputs of the

beam splitter where the signal beam and the reference beam are overlaid. The difference between the photocurrents provides the desired interferometric signal while reducing the light source's intensity noise. Balanced detection enables the utilisation of the whole incoming signal strength for detection, while discarding photons that carry no relevant information. Balanced detection gives a larger optical power dynamic range and longer reaches than single-ended detection.

1.7 Research Gap

In the past, substantial research on optical communication in free space has been conducted in optical technology. Compared to other mediums, such as microwave, radio frequency, and others, this technology is particularly alluring and promising. As end-user demand for wireless communication increases in terms of speed, data capacity, and number of users, the free space optical system is the optimal solution. Nonetheless, there is still need for improvement in order to create a reliable and efficient performance system.

Table 1.1: Prior researcher related with research

Researcher	Title	Method	Weakness
Abhishek Kumar and Prabu Krishnan (2022),	RoFSO system based on BCH and RS coded BPSK OFDM for 5G applications in smart cities,	Hybrid system using radio frequency and free space optical communication. The system embedded with OFDM coded.	Complicated system and involve very complex development if convert in real implementation.

Laialy Darwesh and Natan S. Kopeika (2020),	Deep Learning (DL) for Improving Performance of OOK Modulation Over FSO Turbulent Channels,	Using different models of DL over different strength FSO turbulent channels, without the need for prior knowledge of the parameters of the channel.	It requires very large amount of data in order to perform better than other techniques. It is extremely expensive to train due to complex data models. Moreover deep learning requires expensive GPUs and hundreds of machines. This increases cost to the users
Ebrahim E. Elsayed and Bedir B. Yousif (2020),	Performance evaluation and enhancement of the modified OOK based IM/DD techniques for hybrid fiber/FSO communication	The system uses the modified OOK based on IM/DD to implement adaptive and electrical SNRs detection thresholds	Involve complex process and it is computational expensive. Therefore, is not appropriate for real-time applications

	over WDM-PON systems		
Lun Li, Ting Bu, Yi Li, Sixiao Wei, Alan Harris, Zhijiang Chen, Ken Foo, Dan Shen and Genshe Chen (2021).	Machine Learning Based Tool Chain Solution for Free Space Optical Communication (FSOC) Propagation Modeling.	Develop a novel machine learning (ML) based prediction model.	Machine Learning is autonomous but highly susceptible to errors.
Marko Smilic, Dejan Milic and Zorica Nikolic (2021),	Adaptive transmission algorithms and diversity techniques for improving performance in communication systems,	Implement adaptive method combine with multi receiver/transmitter	Threshold not stable when fluctuation signal and high presence of noise at receiver.

Based on prior researcher work linked to this study, it discovered that no research in ASK for OOK employing dual carrier with subtraction signal at receiver to establish an unique threshold level set to 0 amplitude has been undertaken. It can regulate and compress the presence of noise by integrating the balancing receiver. It was anticipated that a simple and

inexpensive procedure capable of increasing received power, receiver sensitivity, and decreasing bit error rate would be used.

1.8 Summary

In this chapter, the brief of development concept of DTBR has been explained. Problem of statement and objectives research also discussed. The entire research work can illustrated in Figure 1 which divides into challenges, effect, mitigation technique and research contribution. The next chapter summarizes the literature review relevant to the research area work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides an overview of recent research, theories, and principles of FSO systems as they pertain to the primary research focus. It will include an overview of terrestrial free space optical, the influence of an atmospheric channel, including atmospheric attenuation, atmospheric turbulence, and laser safety. In this chapter, also briefly examine the mitigation approaches for reducing the fading impact caused by turbulence. Figure 2.1 illustrates the flow of Chapter 2.

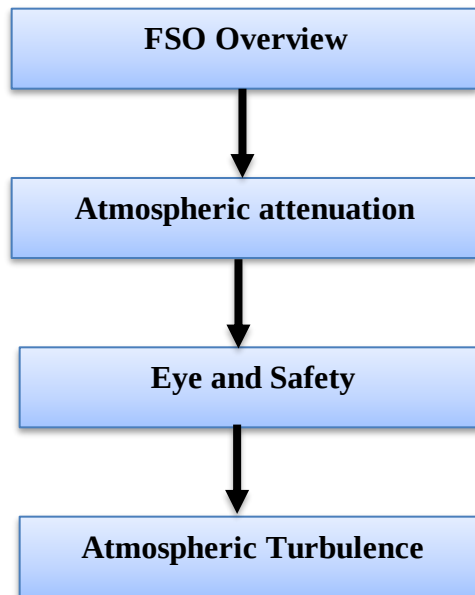


Figure 2.1: Flow of Literature Review

2.2 Overview

For broadband communications, the terrestrial FSO communication is a line-of-sight (LOS) technique that delivers a modulated beam of visible or infrared light across the atmosphere. FSO employs Light-Emitting Diode (LED) or laser (Light Amplification by Stimulated Emission of Radiation) point sources of data transfer in a way similar to fibre optic communication. The fundamentals of FSO communication are shown in Figure 2.2 as a block diagram.

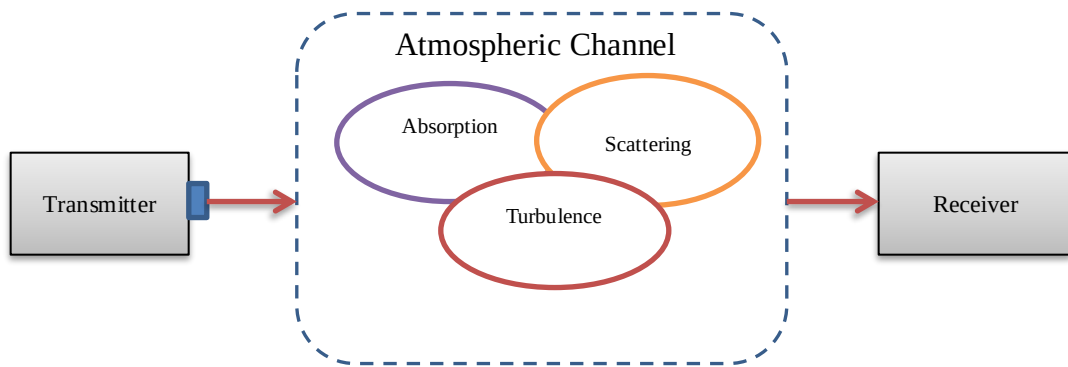


Figure 2.2: Element FSO communication

The FSO communication may be broken down into three primary parts: the transmitter, the atmospheric channel, and the receiver (Bouchet et al., 2005). The transmitter is primarily responsible for modulating the source data onto the optical carrier, which is subsequently propagated through the atmosphere to the receiver. The most common kind of modulation is Intensity Modulation (IM), in which the source data is modified according to the intensity of the optical radiation. There are three basic impacts in the atmospheric channel component. First is absorption, which happens predominantly in reaction to water particles and is also

influenced by gases, but to a much lesser extent than water absorption (Mohammed et al., 2020). This effect diminishes the FSO beam's power density and has a direct impact on the system's availability. Yet, the usage of electricity depending on atmospheric conditions and the use of geographical diversity assist to maintain the appropriate degree of network availability (Swaminathan et al., 2021). Second, scattering occurs when a wavelength collides with a dispersed wavelength. The scattering does not result in energy loss, but a directional redistribution of energy may result in a considerable decrease in beam intensity at greater distances (Zyambo et al., 2001). The last consequence is turbulence, which occurs when solar radiation contacts the Earth. Part of the radiation is absorbed by the Earth's surface, which in turn warms the air mass near the surface. This bulk of warmer and lighter air will turbulently combine with the surrounding quantity of colder air, causing fluctuations in signal transmission (Varun et al., 2019).

In terms of advantages of FSO technology communication over fiber communication, the FSO is not requiring the licensing from the Federal Communications Commission (FCC). Unlike the RF, communication need the licensing for frequency allocation because of RF uses the frequency that is less than 300 GHz (Abhishek & Prabu, 2022). Apart from that, the FSO can support the capacity up to 2.5Gbps if compare to RF limited to 622Mbps. The further study has successfully tested 160Gbps in laboratories and speed might reach Terabit range (Wu et al. 2022). The FSO also has an attractive alternative to the excessively high cost of digging the street to lay the fiber and requiring permission from authorities for installation. This technology transmission only needs a place on a roof or behind a window to set up a transceiver. The duration of installation can be made over within a few hours or one day (Kolka et al., 2007).

Behind the advanced of this technology, the obvious limitation in FSO is vulnerable to weather condition. This led to this technology not applicable for long distance in terrestrial FSO. This technology also needs a line of sight (LOS) transmission to operate. Any blocking over the laser light will cause the receiver not received the signal and drag to loss of communication data. For instance, the flying bird across the laser beam propagation is most normal cases that block the laser light. The building movement also can impair the link performance. This is because of the arising of pointing error in FSO system (Dhiraj & Abhilash, 2022).

2.2.1 Fundamental of FSO System

There are several fundamentals of FSO technology that differ from other wireless communication system.

- a) **Narrow beam size** - Laser beams have a diffraction restricted divergence of 0.01–0.1 mrad (Dennis, 2002). This means that the transmitted power is focused in a restricted region, enabling an FSO connection with sufficient spatial isolation from possible interferers. The tight spatial confinement enables the laser beams to operate essentially independently, offering virtually infinite frequency reuse in many situations and making data interception by unintentional users impossible. Narrow beams demand tighter alignment.

- b) **Weather dependent** – The state of the atmosphere has a direct influence on how well terrestrial FSO performs. High attenuation may be caused by fog, which is one of the most difficult weather conditions to deal with in FSO.
- c) **Unlicensed spectrum** – Interference from neighbouring carriers is a serious concern for wireless RF communication due to the crowded RF band. To reduce this interference, regulatory bodies, such as the Federal Communications Commission (FCC) in the United States and the Office of Communications (Ofcom) in the United Kingdom, have implemented rigorous rules. So, receiving a portion of the RF spectrum demands a hefty cost and months of red tape. Currently, optical frequencies are not affected by any of these factors. As a result of the lack of a licencing fee and accompanying bureaucratic time delay, the return on investments in FSO technology accrues much more rapidly, since the initial setup cost is cheaper and the deployment period is shorter.
- d) **Large bandwidth capacity** – The quantity of data sent in any communication system transported is directly related to the capacity of the modulated carrier. The allowable data capacity can be up to 20% of the carrier frequency. Using an optical carrier whose frequency ranges from 10^{12} to 10^{16} Hz could thus permit up to 2000 THz data capacity. Optical communication therefore guarantees an increased in information capacity compared to radio frequency-based communication systems. This is simply because, on the electromagnetic spectrum, the optical carrier frequency, which includes infrared, visible, and ultraviolet frequencies, is far greater than the radio frequency. The usable frequency capacity in RF range is comparatively lower by a factor of 105.

- e) **Fast installation** – The length of time needed for a FSO connection to reach full functionality, starting from installation down to link alignment, could be as low as four hours. The key requirement is the establishment of an unimpeded line of sight between the transmitter and the receiver. It can also be taken down and redeployed to another location easily.
- f) **Cost effectiveness** – FSO deployment is less expensive than RF with antenna a comparable data rate. FSO can deliver the same capacity as optical fibre but without the extra cost of right of way and trenching. Based on recent findings by fSONA, an FSO company based in Canada, the cost per Mbps per month based on FSO is about half that of RF-based systems (Wu et al. 2022).

2.2.2 Main Element in FSO system

Figure 2.2 also depicts the block diagram of a typical terrestrial FSO connection. An FSO system, like any other communication technology, is made up of three major components: transmitter, channel, and receiver.

2.2.2.1 Transceiver

Its initial component's principal function is to modulate the source data onto the optical carrier, which is subsequently transmitted through the atmosphere to the receiver. The most common kind of FSO modulation is intensity modulation (IM), in which the source data is modified to the intensity of the optical radiation. To achieve the modulation, the driving

current of the optical source may be varied directly in sympathy with the data to be conveyed or through an external modulator, such as the symmetric Mach-Zehnder interferometer. The external modulator is a critical component of the transmitter. As compared to direct modulation, it allows for a larger data rate. Yet, the external modulator's weakness has a nonlinear response. Additional features of the emitted optical field, including as phase, frequency, and polarisation state, may also be manipulated with data using an external modulator. The signal will then be sent to the transmitter telescope through the modulator. This is the last section of the transmitter before the signal enters the transmission channel. It collects, collimates, and directs optical radiation towards the receiver telescope at the opposite end of the channel.

The selection of an optical wavelength light source is another key criterion in the transmitter section. Each wavelength range has a distinct ability. The commercially available FSO systems operate at wavelengths ranging from 750 nm to 1600 nm, with one or two systems being designed to work at 10,000 nm. Several wavelengths are seeing substantial absorption in this range. Absorption happens predominantly in reaction to water particles such as moisture, which are an intrinsic element of the environment even in clear weather (Mohammad et al., 2019). Since gas-specific absorption coefficients are extremely minor when compared to water absorption, the contribution of gas absorption to the total absorption coefficient is not discussed here. Nevertheless, gas absorption may dominate the absorption qualities of the atmosphere in the longer wavelength range over 2000 nm. The general optical wavelength in FSO as following.

a) Wavelength range 780 to 850 nm

Higher power laser sources are available in this range, and these wavelengths have seen extensive application in commercial FSO operation. While inexpensive lasers may provide the required 780 nm wavelength, their short average lifetimes are sometimes a problem. At the same time, at the 850 nm laser wavelength, dependable, low-cost, high-performance transmitter and detector components are widely utilised in network and transmission gear (Bloom et al., 2003). This wavelength is compatible with state-of-the-art vertical-cavity surface-emitting laser (VCSEL) technology and highly sensitive silicon (Si) avalanche photodiode (APD) detector technology.

b) Wavelength range 1520 nm to 1600 nm

Although this wavelength is optimal for interplanetary communication, it has recently been adapted for use on Earth, where high-performance transmitter and detector components are easily accessible for FSO. Low attenuation and abundant components at this wavelength make WDM FSO system development feasible. As compared with 850 nm Si APD detectors, the components are more costly and the receiver surface area is lower. In addition, the superior performance of these wavelengths has made them the preferred choice of many businesses for use in long-haul fibre networks. Important for systems requiring a power output of more than 500 mW and a data throughput of more than 2.5 Gbps, these wavelengths are also compatible with erbium-doped fibre amplifier (EDFA) technology. As a conclusion, due to the limited transmission of the human eye at these wavelengths (780-850 nm), about 50 times as much power may be transferred at 1520 nm-1600 nm as can be transmitted at 780-850 nm (Bloom et al., 2003).

c) Wavelength range 10,000 nm

This wavelength is new to the commercial FSO arena and is being developed due to better performance under the fog transmission. However, there is some considerable debate regarding these characteristic which claim dependent upon fog type and duration. Only a few components are available at 10 μm which is the reason it is not widely used in telecommunications equipment. At this wavelength, it does not penetrate glass and making this component not suitable to deploy behind the window. However, the poor glass penetration will cause not to be concentrated by optical aids and enables for eminent power operation in unrestricted environments (Bloom et al., 2003).

2.2.2.2 Receiver

Its primary role is to aid in data recovery by using the incident optical field to reconstruct the sent signal. The receiver has a number of major components on the inside that work together to process incoming information. The process starts with a receiver telescope, whose job is to gather and concentrate the incoming optical radiation onto the photodetector. The larger the aperture of the receiver telescope, the more independent radiations it can gather and average before shining them on the photodetector. This is known as "aperture averaging," however with a larger aperture comes with an increase in ambient noise. Then, thereafter, you should use an optical band-pass filter to cut down on the ambient noise. After it happens, the signal may reach the photodetector. In order to transform the optical signal into an electrical one, photodetectors like the p-i-n diode (PIN) and the avalanche photodiode (APD) are used. The signal from a photodetector is sent to a post-detection processor, also

known as a decision circuit. Amplification, filtering, and signal processing will all be part of this procedure. This allows for the production of data recovery with a high degree of accuracy.

There are two distinct types of receiver detection. Optical radiation's intensity on the photodetector is measured by a direct detection receiver. Depending on how strong the incident field is, the photodetector will provide different results. It is best used in intensity-modulated optical systems and has a fairly simple implementation (Zhu et al., 2021). The second is a receiver that uses coherent detection. The photo-mixing effect will be used for detection of this kind. The photodetector's surface combines the incoming optical field with one created locally. Different types of coherent receivers exist, including homodyne and heterodyne receivers. Unlike heterodyne detection, in which the incoming radiation and the local (optical) oscillator have different frequencies (Safi et al., 2020), homodyne receivers have a frequency/wavelength that is identical to that of the incoming radiation (Zhu et al., 2021).

2.2.3 FSO Current Technology

Among the areas of application of terrestrial FSO can be listed:

- a) **Last mile access** – Last mile congestion between users and the backbone is eliminated using FSO. Data speeds from 1 Mbps to 10 Gbps may be found on a variety of commercially accessible links spanning from 50 m to a few kilometres in distance (Abhishek & Prabu, 2022).

- b) **Multi-campus communication network** –FSO is useful for bridging the gap between different networks on a campus and for creating redundant connections at either Fast-Ethernet or Gigabit-Ethernet speeds (Antonios et al., 2021).
- c) **High definition television** – Because to the high bandwidth demands of HD cameras and TV transmissions, FSO is becoming more used in the broadcast business for transmitting live signals from HD cameras in distant locations to a master control room (Li et al., 2021).
- d) **Optical fibre back up link** –When the primary optical fibre connection is damaged or unavailable, this backup system is activated to prevent any data loss or communication breakdown (Hailay et al., 2021).
- e) **Difficult terrains** –In situations when acquiring the right of way would be too costly or impossible, such as when crossing a river, a particularly busy roadway, or rail lines, FSO provides an appealing alternative.
- f) **Cellular communication back-haul** – Transport IS-95 code division multiple access (CDMA) signals from macro and micro-cell sites to the base stations and back-haul traffic between base stations and switching centres in 3G and 4G networks (Willebrand & Ghuman, 2002).
- g) **Disaster recovery/Temporary links** – The technique is useful in situations when just a short-term connection is required, such as during a conference or in the case of an emergency that causes an existing communication network to fail (Majumdar & Ricklin, 2008).

2.3 Atmospheric Attenuation

A parallel beam of energy loses intensity as it travels from its source due to air absorption and scattering; this phenomenon is known as atmospheric attenuation (Flecker et al., (2006) and Lamia & Ali, (2022)). Absorptive attenuation and scattering attenuation are the two primary types.

2.3.1 Absorption

Absorption happens when photons are extinguished by suspended water molecules in the terrestrial atmosphere. It has resulted in the attenuation over signal during the propagation transmission. As the increase of the humidity in the environment, the absorption will increase and causes the attenuation to rise high (Mohammed et al., 2021).

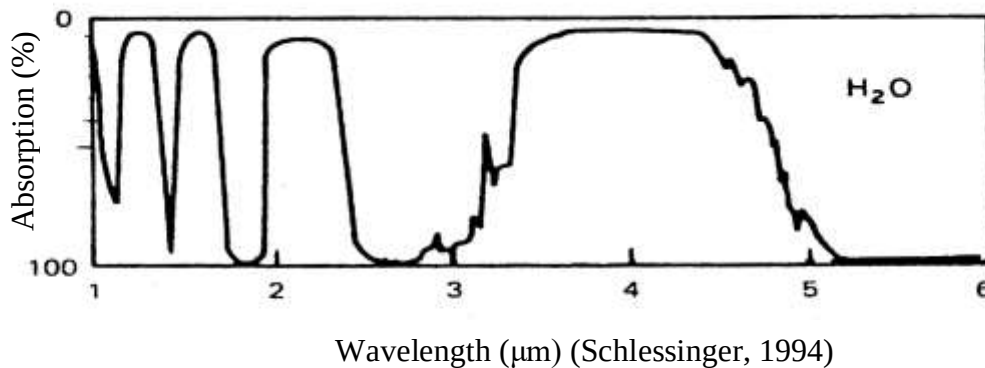


Figure 2.3: Absorption rate for H₂O

The water vapor (H₂O) and carbon dioxide (CO₂) handle most of the absorption of radiant energy by earth's atmosphere, as shown in Figure 2.3 and Figure 2.4. These gases have absorption bands on the infrared spectrum (Willebrand & Ghuman, 2002). From Figure 2.3 shows that the strong absorption of H₂O occurs near the region of 2.7 m and 4.3 m.

Meanwhile the Figure 2.4 shows the absorption of CO₂ occur in the wavelength region 1.4, 1.9, 2.7 and 6.3m (Schlessinger, 1994).

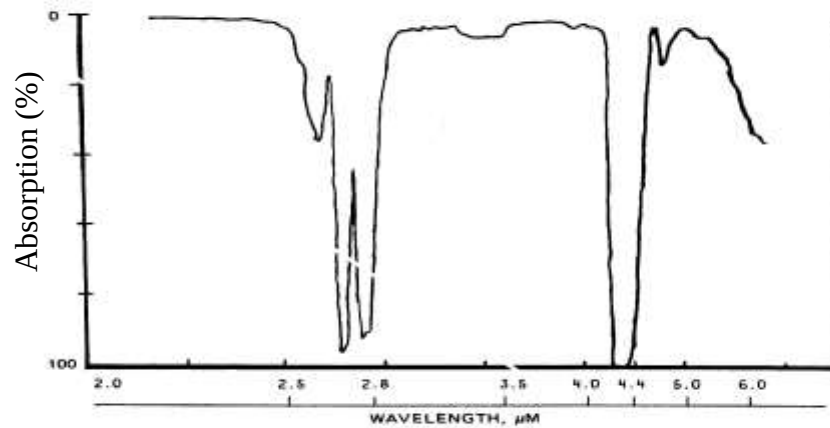


Figure 2.4: Absorption rate for CO₂ (Schlessinger, 1994)

2.3.2 Scattering

When a laser beam collides with particles or molecules of varying sizes and shapes, this is known as scattering, and it results in the loss of energy. This will result in a weaker transmitted signal. Because of this, laser power is diminished in the air. Scattering is caused by microscopic particles in the air, such dust or droplets of water vapour. Scattering may also be caused by imperfections on the surface from which the light is entering. It's not only that dispersion is more powerful than absorption.

General behaviour of Rayleigh, Mie, and Non-Selective scattering in the atmosphere was shown in Figure 2.5.

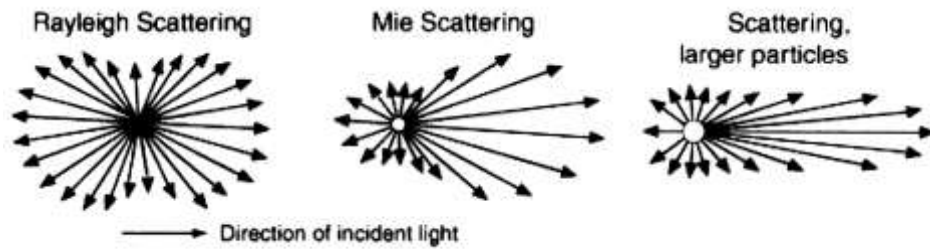


Figure 2.5: Category of scattering (Magidi & Pondani, 2022)

There are essentially three distinct kinds of dispersion. Rayleigh scattering is the first kind. When the particle size is significantly smaller than the incoming wavelength, this phenomenon happens. Light scattering is very sensitive to wavelength, much like absorption. Rayleigh scattering, with its symmetric angular distribution, is caused by particles with sizes comparable to the wavelength, such as air molecules and haze. Rayleigh scattering is very noticeable in the UV and VIS range, but it is negligible at longer wavelengths (Magidi & Pondani, 2022).

The Mie scattering is the second form of scattering, and it happens when the wavelength of the incoming light is the same as or larger than the wavelength of the tiny particles or molecules. To a larger extent, Mie scattering is caused by atmospheric particles like fog and aerosols. The third kind of scattering happens when the particle size is significantly greater than the incident wavelength and is known as non-selective scattering. Raindrops and other water droplets disperse in this area. Indeed, geometrical optics may be used to characterise this kind of scattering as well. This scattering, in contrast to Rayleigh scattering, is more focused in the forward direction.

Sometimes, the effects of molecular absorption and scattering are added together, and this is represented by a single attenuation coefficient, which may be written as

$$\alpha(\lambda) = \alpha_A(\lambda) + \alpha_S(\lambda) \quad \text{Equation 2.1}$$

where α_A and α_S describe the processes of molecule absorption and scattering with the coefficients. Attenuation coefficient α is linked to laser radiation's transmittance after travelling a distance L , as defined by

$$\tau = \exp[-\alpha(\lambda)L] \quad \text{Equation 2.2}$$

where αL is the result referred to as the optical depth. Absorption and scattering are both well-understood, predictable phenomena whose outcomes may be anticipated under certain circumstances.

2.4 Eye and Skin Safety

Both the skin and the eye may be injured by the optical beams, but the damage to the eye is far more severe due to the eye's capacity to focus and concentrate optical energy. There is no risk to anyone's eyes from the communications beam in the laser systems, hence they are widely used. When comparing the 1550nm system to the 850nm and 780nm systems, the 1550nm system is safer to use with higher-powered lasers. Eye injury may occur when light with wavelengths shorter than 1400nm passes through the cornea and lens and focuses on the retina. The wavelengths at which the human eye is able to absorb light are shown in Figure 2.6.

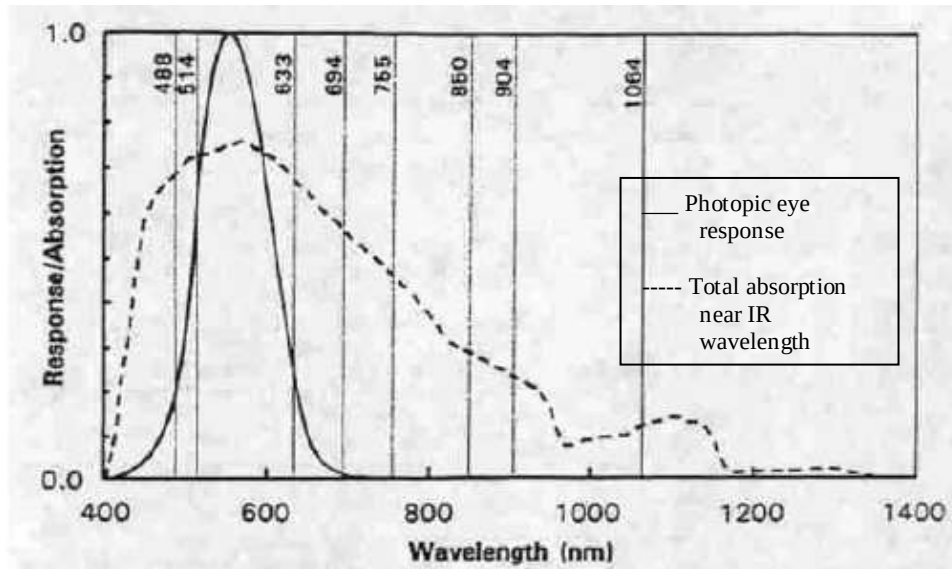


Figure 2.6: Effect of wavelength over human eye (Djordjevic et al., 2007)

When it comes to the security of optical beams, one of the worldwide standard-setting organisations that might be looked to for guidance is the International Electrotechnical Commission (IEC). Several worldwide standards applicable to all forms of electrical equipment, including lasers and laser equipment, have been published by this organisation (IEC60825-1). The IEC's categorizations for laser standards are shown in Figure 2.5.

Table 2.1: Comparison wavelength limit

Wavelength	850nm	1550nm
Maximum Permissible Exposure (MPE)	$2.0\text{mW}/\text{cm}^2$	$100\text{mW}/\text{cm}^2$

Table 2.1 shows the MPE for wavelength 850nm and 1550nm, respectively. As we can see, the shorter wavelength (850nm) only permissible $2\text{mW}/\text{cm}^2$ but the longer wavelength (1550) nm can support up to $100\text{mW}/\text{cm}^2$. As a practical matter, the maximum safe laser power is around 50 times greater at 1550nm than it is at 850nm. In order to accommodate faster data rates and propagate farther distances, a factor of 50 may give up to 17dB of extra margin. The maximum

throughput of commercial 850nm systems is 622Mbps, whereas 1550nm systems can achieve 2.5Gbps.

In order to safeguard the eyes and skin of anybody who could come into touch with laser equipment's radiation, standard-setting bodies have mandated MPE limits. Maximum safe radiation exposure is the amount of radiation, expressed as a power per unit area (W/cm² or J/cm²), over which there is no reasonable expectation of harm. It can determine the MPE for a given wavelength and exposure period by measuring the effect on the cornea of the eye or on the skin. In ideal circumstances, it is only around 10% of the dosage that might cause harm (Djordjevic et al., 2007).

Class 1 lasers are the best option for use in optical wireless communication systems since their radiation is completely safe. There is no need for cautionary labelling or other safety measures while using a Class 1 laser. See Table 2.2 for further explanation.

Table 2.2: Standard for categorising lasers, IEC 60825-1

Category	Description
Class 1	A very low-powered source of radiation between 302.5 to 4000 nanometers. Despite its technological design, the device poses no risk to the user under any realistic scenario of use, including direct visual inspection (binoculars, microscope, monocular)
Class 1M	Similar to Class 1, but might be harmful if looked at via a telescope, binoculars, or other optical device. Beams from a Class 1M laser have a very wide diameter, or they diverge.
Class 2	In the visible spectrum (400-700 nm), low-power devices produce light. Defense reflexes, such as the palpebral reflex, often provide eye protection (closing of the eyelid). The palpebral reflex effectively protects under all foreseen situations of use,

	including vision with optical equipment (binoculars, microscope, monocular).
Class 2M	Device generating visible light at low power (in the range of 400 to 700 nm). The palpebral reflex and other defence mechanisms generally keep your eyes safe (closing of the eyelid). Except for when employing optical devices for seeing, the palpebral reflex is an efficient kind of defence.
Class 3R	Device with an average power output, radiating in the range of 302.5 to 4000 nm. Having a clear view of anything might be harmful.
Class 3B	Device with an average power output in the 302.5-4,000 nm wavelength range. In all cases, it is risky to look directly into the beam. Before installation or maintenance takes place, it undergoes medical exams and receives the necessary training.
Class 4	There is always a risk of fire and damage to the eyes and skin when using a high-powered equipment. A key switch and safety interlock are required features. Installation and upkeep are preceded by medical examinations and any necessary training.

2.5 Atmospheric Turbulence

Atmospheric turbulence is a significant obstacle for FSO. There are three ways in which a beam of light inside the channel is affected by atmospheric turbulence. The intensity of the optical signal fluctuates because, first, the wavefront is warped by the change due to the scintillation index. The second reason of beam straying is diffraction, which occurs when the laser beam's diameter is less than or equal to the size of the eddies. Finally, the laser beam expands over the diffraction limit due to air turbulence. Scintillation is a major issue that may significantly lower connection BER performance.

Temporary pockets of air with slightly differing indices of refraction are created when the atmosphere experiences turbulence. The whole laser beam will bend if the turbulence cells are greater than the beam diameter. Figure 2.7 shows this effect in action. Variation in the spatial intensity distribution of the laser beam, brought on by atmospheric turbulence, is responsible for laser beam wandering and laser beam spreading (Arka et al., 2019). Turbulence in a laser beam may be attributed to minute, dynamic changes in the atmosphere's index of refraction.

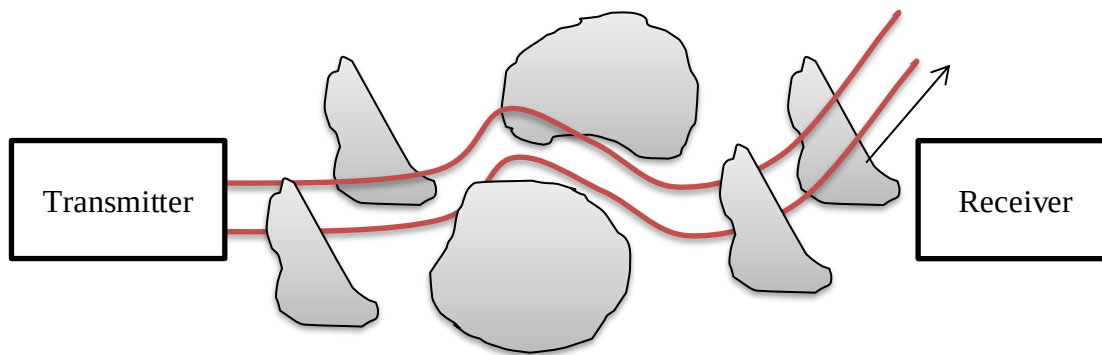


Figure 2.7: Phenomenon laser beam wanders due to larger turbulence cells (Manor & Arnon, 2003)

As the turbulence cell sizes are often lower than the beam width, the laser beam is inevitably deformed as it sways and bends through the turbulent air. Temporal fluctuations in the laser beam's intensity at the receiver are caused by constructive and destructive interference, which arises from minute differences in the arrival times of different components of the beam wave front. Figure 2.8 provides a graphical analysis of this event.

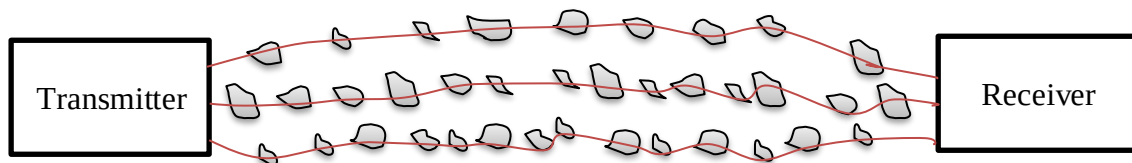


Figure 2.8: Phenomenon scintillation at the receiver when turbulence cells are smaller than the beam diameter (Manor & Arnon, 2003)

Many methods exist for reducing air turbulence, including:-

- 1) Adaptive Optics
- 2) Forward Error Correction (FEC)
- 3) Diversity Technique
- 4) Modulation Technique

2.5.1 Mitigate Effect 1: Adaptive Optics

Signal fading on a millisecond time period is caused by air turbulence-induced wavefront aberrations in open space optical communication. The bit error rate (BER) is the most important metric of communication quality, and it is affected by both transient mistakes caused by electronic-circuit-related noise and persistent random interruptions in data transit caused by atmospheric fading due to turbulence. Adaptive optics (AO) may be used to lessen the impact of this (Fried, 1998).

The primary benefit of AO is not data recovery but rather the proactive avoidance of long-term data loss. This might be achieved by reducing the wave front distortions caused by air turbulence (Tyson et al., 2005). Nevertheless, controlling the active/adaptive optical components included into the receiver or transmitter optics in real time to reduce the likelihood of fading in the transmission signal is difficult.

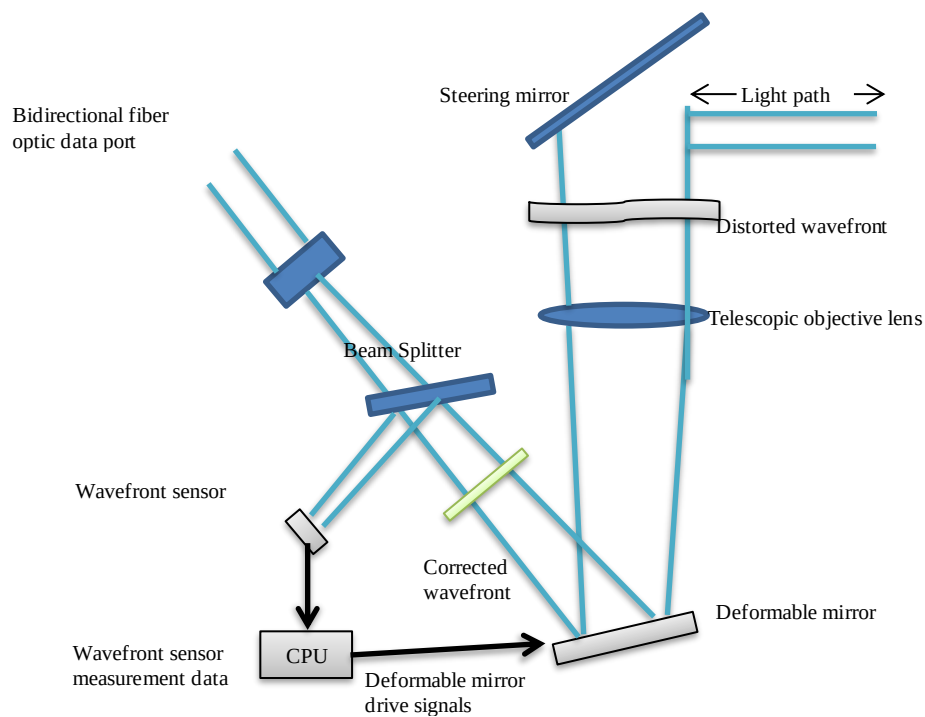


Figure 2.9: Noise reduction using adaptive optics systems (Grave & Drenker, 2002)

There are two general approaches for AO technique:

- a) Conventional adaptive approach- based on wavefront sensing and reconstruction (Tyson, 2002). It is necessary to aim a portion of the received beam towards a wavefront sensor.
- b) Blind optimization approach- implemented a feedback system based on the communication signal's low-pass filtered reception

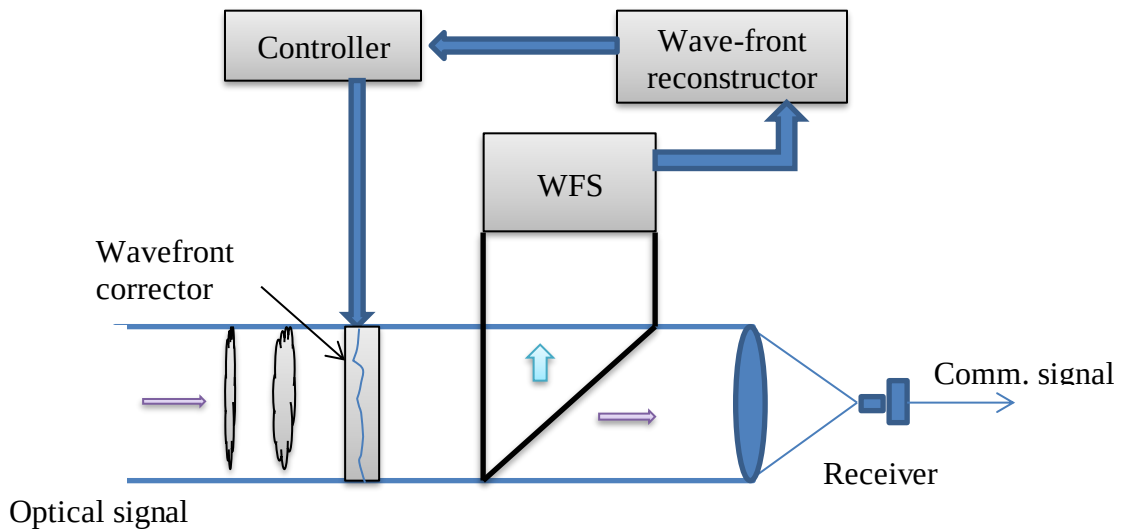


Figure 2.10: Wavefront sensor (WFS) and wave front reconstruction in adaptive optics approach (Majumdar & Ricklin, 2007)

Stochastic parallel gradient descent (SPGD) is one of the newer AO technologies (Ricklin and Davidson, (2002) and Ricklin et al., (2004)). With the development of high-capacity wave front phase controllers and the advent of parallel processing hardware based on VLSI micro-electronics, a new generation of AO methods has become possible (Willebrand & Ghuman, 2002)

The SPGD can be divided into four techniques.

- 1) Feeding back the intensity of the signal (J)
- 2) In order to mitigate the effects of turbulence on transmitter-generated beam spreading, adaptive transmitters are used (TX). The feedback signal is derived from the receiver's (Rx2) measured signal strength (J_2).
- 3) In an adaptive transceiver, the same adaptive optical components are used for both the received and sent optical signals.

- 4) The complexity of an adaptive transceiver's FSO configuration is reduced when fibre optics components are used.

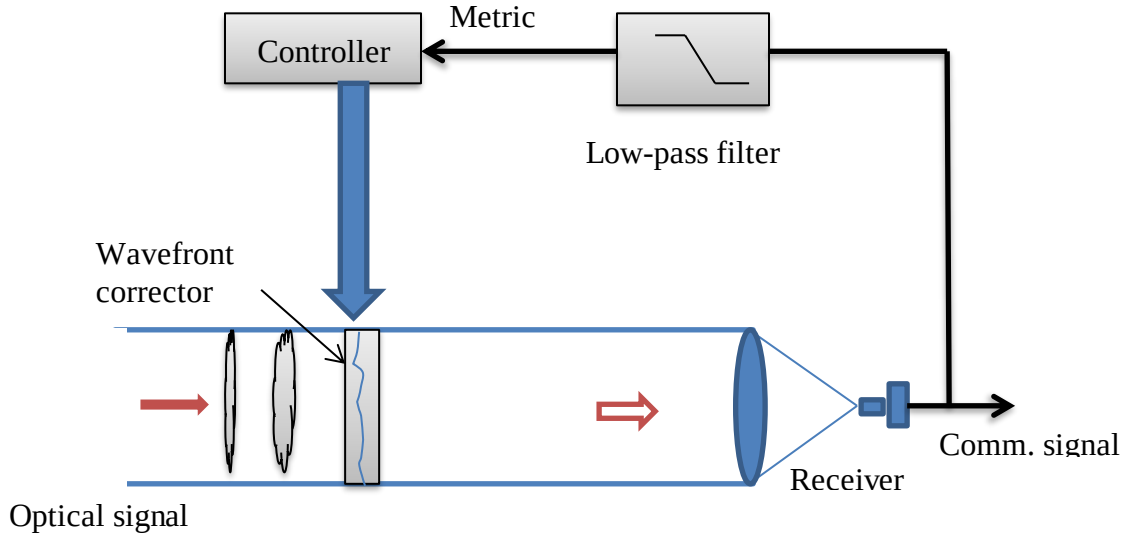


Figure 2.11: Blind optimization performance for wavefront distortion compensation (Majumdar & Ricklin, 2007)

2.5.2 Mitigate Effect 2: Forward Error Correction (FEC)

Across unstable or noisy communication networks, the forward error correction method is used to limit the effects of data transmission faults (Zhu et al., 2021). Errors may be recognised and fixed at the receiver with the help of an error-correcting code if enough redundancy was added to the information bits before transmission (ECC). Because to the redundancy, the receiver is able to catch and fix minor faults that may have occurred anywhere in the message without having to resend it. Although FEC prevents the receiver from requesting data retransmission via the reverse channel, it comes at the cost of a permanently increased forward channel capacity (Rajan & Jagjit, 2019).

Hence, FEC is used in contexts where retransmissions are either impossible or very costly, such as one-way communication lines and multicast broadcasts to numerous recipients. In order to aid in the restoration of damaged data, FEC data is often included in mass storage devices and is widely used in modems.

The theoretical error performance of coded systems across time-varying channels has been studied for a long time (Sonali et al, 2021). Researchers have shown that the FEC increases the noise and pulse distortion margins in long-distance optically amplified transmission systems (Yamamoto & Ohtsuki, 2003). The following are only some of the proposed forward error correction (FEC) schemes:

- a) Reed-Solomon (RS) codes (Ricklin et al., 2004)
- b) Convolutional codes (Ricklin & Davidson, 2002)
- c) Turbo codes (Li et al, 2021a)
- d) Trellis-coded modulation (Li et al., 2021b)

2.5.3 Mitigate Effect 3: Diversity Technique

These strategies are suitable to the domain where the receiver aperture is less than the fading's correlation length and the observation interval is shorter than the fading's correlation duration. It is assumed that the receiver is oblivious of the current fading situation. Similarly, this strategy depends on the statistical properties of fading as a function of both temporal and geographical coordinates in order to work correctly.

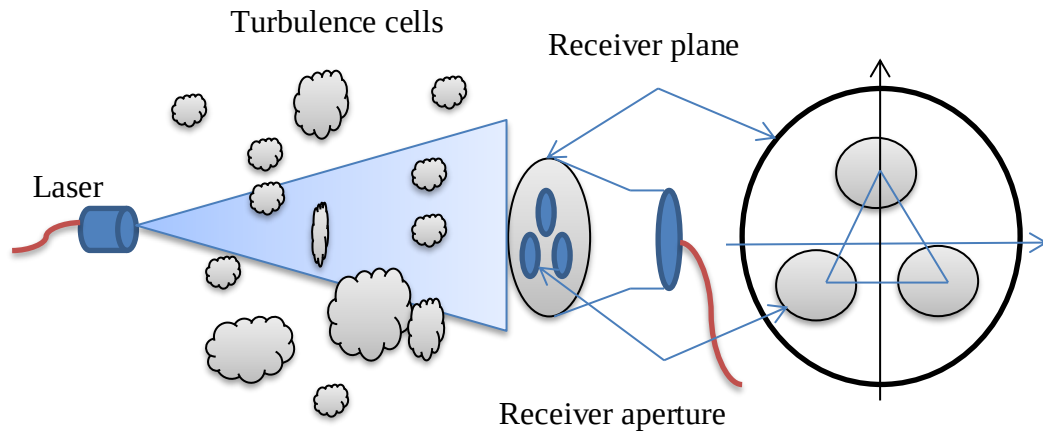


Figure 2.12: Diagram of triple-aperture receiver (Qian et al., 2021)

The investigation of the diversity approach has been carried out by a great number of scholars, as described in (Qian et al. 2021). Among the several types of diversity, the spatial variety is particularly appealing due to the fact that it is less complicated (Trisno et al., 2005).

Given that the optical wave front coherence length in the atmosphere is on the order of centimetres, it is simple for FSO systems to include spatial variety into their designs. As a result, numerous transmitters need to be spaced no farther than a few millimetres apart in order to experience independent fading channels (Navidpour et al., 2007). In addition to its use as a tool for reducing the effects of fading, a structure with several apertures makes it less likely that the laser beam will be temporarily obscured by impediments (Lee & Chan, 2004).

In general, this method may be broken down into two distinct groups, which are:

- a) Temporal diversity approach - one must deploy a single receiver. When the receiver only has access to a marginal statistic of the fading, a symbol-by-symbol ML detector may be utilised to achieve peak performance. If the receiver has knowledge of the fading's temporal correlation, then it may use Maximum-likelihood Sequence detection (MLSD). Although while this leads to improved performance, the resulting complexity is quite high.
- b) The spatial diversity approach requires the use of at least two receivers, which must be placed in various locations or oriented in different directions in order to gather the signal light. It is possible to combat turbulence-induced fading by employing the reception strategy of spatial diversity, which makes use of several receivers. When it is not feasible to place the receivers sufficiently far away from one another, the fading at the various receivers is correlated, which reduces the diversity benefit. The diversity gain cost that was brought on by fading correlation can be alleviated by the utilisation of maximum-likelihood (ML) detection.

2.5.4 Mitigate Effect 4: Modulation

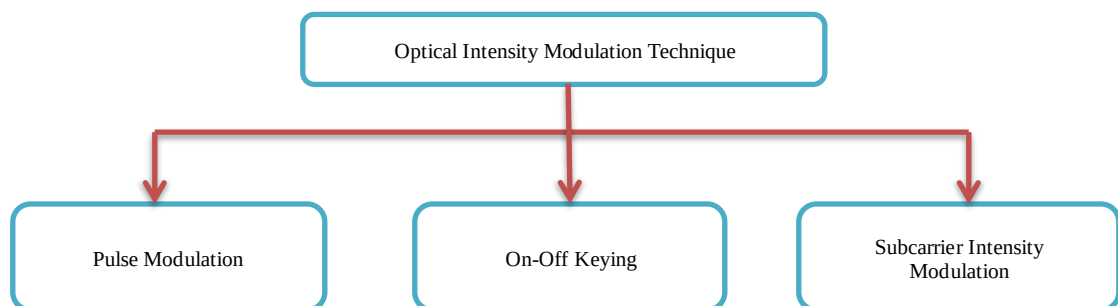


Figure 2.13: Type digital modulation technique

It is also possible to enhance the performance of the FSO link that is caused by the turbulence effect by using an appropriate modulation scheme that strikes a suitable balance between the level of complexity and the level of performance. Figure 2.13, which depicts the category of digital modulation, can be used as a guide to understanding the modulation tree. In general, digital modulation may be broken down into three primary approaches, which are as follows:

- (a) Pulse Modulation
- (b) Subcarrier Intensity Modulation (SIM)
- (c) On-Off Keying (OOK)

2.5.4.1 Type Modulation 1: Pulse Modulation

The pulse modulation can be defined as the process of transmitting signals in the form of pulses by using special techniques. Among the technique in pulse modulation are:-

- (a) Pulse amplitude modulation (PAM)
- (b) Pulse width modulation (PWM)
- (c) Pulse position modulation (PPM)
- (d) Pulse code modulation (PCM)

One of the most well-known types of pulse modulation is called pulse position modulation, or PPM for short. This method has the distinct benefit of being significantly more energy efficient on average than its counterparts (Zheng et al., 2018). The PPM modulation technique is superior to OOK in terms of its power efficiency; however, this improvement comes at the price of a necessity for a higher bandwidth and an increase in

complexity. In the earlier study on Q-ary PPM, a straightforward way of soft remapping with a minimal level of complexity was presented. One of the biggest obstacles to creating a terrestrial FSO system is the complexity of the receiver. Synchronization between the slot and the symbol is required for the PPM receiver to demodulate the information stored on the pulse position. When it comes to optical wireless communication systems, PPM is a fascinating modulation method owing to its increased power efficiency. This is especially true for applications involving distant space laser transmission (Hemmati, 2007).

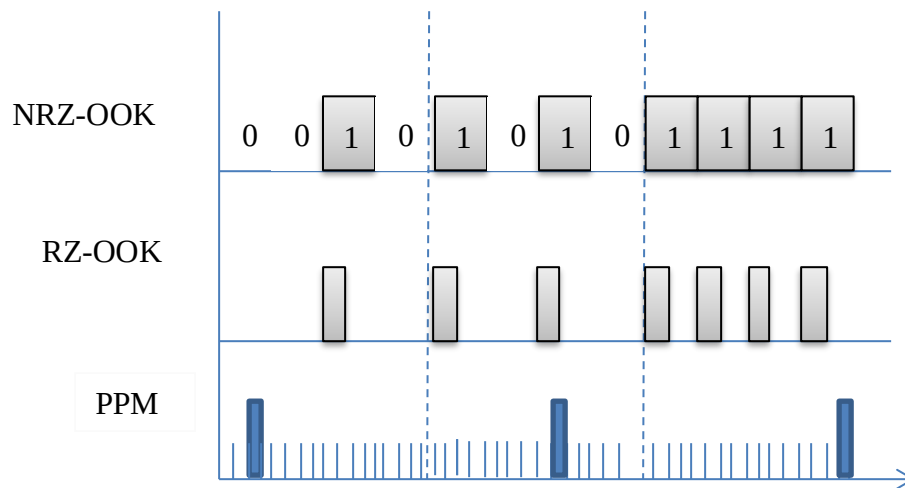


Figure 2.14: Comparison time waveforms for NRZ, RZ and PPM OOK (Samir et al., 2021)

2.5.4.2 Type Modulation 2: Subcarrier Intensity Modulation (SIM)

Because multiple carrier radio frequency (RF) communications have proven to be so effective, subcarrier intensity modulation has been adapted from this method. There have been many different software implementations, including (Hailay et al., 2021);

- a) Digital television
- b) Local area networks (LANs)

- c) Asymmetric digital subscriber line (ADSL)
- d) 4G communication systems
- e) Optical fiber communications

For instance, the commercial use of sub carrier modulation methods has occurred during the transmission of cable television signals and in combination with wavelength division multiplexing in optical fibre communication networks (Shakir, 2019). Nevertheless, there are a number of challenges that must be dealt with before SIM can be implemented. The following are some examples:

- a) Reasonably high average transmitted power as a result of:
 - i. The optical source stays ON during the transmission of both the binary digit "1" and the binary digit "0," as opposed to the OOK protocol in which the source remains ON just during the transmission of bit "1."
 - ii. Multiple subcarrier composite electrical signals, which are the sum of modulated sinusoidal, need a DC bias for optimum operation. The composite electrical signal, which will eventually alter the laser's intensity, must never be in a negative condition. Since the composite electrical signal's minimum value decreases (becomes more negative) as the number of subcarriers increases, the average transmitted power rises. This is because the required DC bias increases as a direct result of this modification (Shakir., 2019). This factor leads to wasteful power consumption and limits the number of sub carriers that can be maintained when several SIM cards are used.

- b) The likelihood of signal distortions as a result of intrinsic laser non-linearity and signal clipping as a result of over-modulation.
- c) Particularly stringent criteria for synchronization on the receiver side.

According to (Sidorovich et al., 2002), the SIM performance can be improved over air turbulence by the use of the Moment Generating Function (MGF) technique. This improvement can be measured in terms of BER and SNR. It utilised non-coherent and differentially coherent subcarrier modulation in order to provide a high accurate series of BER and SER solution, which was particularly useful for big SNR analysis. An investigation of the spectral efficiency of SIM was carried out with the help of the adaptive subcarrier PSK intensity approach (Salem et al., 2003).

2.5.4.3 Type Modulation 3: On-Off Keying (OOK)

In commercial terrestrial wireless optical communications systems, the OOK signalling is the predominate modulation technique that is used. This is largely as a result of its straight forward design, which makes it resistant to the inherent nonlinearities of both the laser and the external modulator (Kim et al., 1999). Nevertheless, in order for the OOK method to work at its absolute best in the atmospheric turbulence channels, an adaptive threshold is required (Fei et al., 2019).

Utilizing the bit error probabilities derived from on-off keying (OOK) modulated FSO systems for all turbulence regimes, the performance of FSO systems on turbulence atmospheric channels can be evaluated. When the connection is operating at a data rate of several gigabits per second, it is possible to lose up to 109 consecutive bits. This has a

catastrophic impact on the network's throughput owing to interactions with higher layer protocols. The typical scintillation fades last between one microsecond and one hundred microseconds (Won & Sang, 2019). Therefore, the fading duration and strength that was caused by the turbulence has to be minimized. In order to lessen the amount of signal fading, the forward error controls, often known as FEC, have been proposed as a technique (Zhu & Khan, 2002).

However, a paper published in Razavi & Shapiro (2005), reveals that implementation error control coding is responsible for substantial processing delays and a reduction in efficiency as a result of the amount of redundant bits that will be required. Some of the researchers additionally recommend making use of an array receiver, as discussed in (Qian, et al., 2021), in order to reduce the channel fading that is caused by air turbulence. In order to lessen the impact of the turbulence, a number of people have suggested using semiconductor amplifiers that work in saturation mode (Abtahi et al., 2006). The investigative study of adaptive optics to correct the wavefront deformation produced by air turbulence has been carried out, however this technology is highly expensive and hard to execute on terrestrial FSO systems. Adaptive optics has been investigated to correct the wavefront deformation (Grave & Dranker, 2002).

Direct detection and coherent detection are the two primary types of photo detection that may be utilized in the OOK modulation process. Photo detection is a method that aims to recover information that was communicated by converting an optical signal into an electrical signal. This process may be stated as a definition. Starting with the transmitter, the information can be encoded in the frequency, phase, or intensity of the radiation coming

from an optical source like an LED or a laser. After that, the encoded radiation is sent along through the free-space channel until it reaches the receiver. The front-end mechanisms at the receiver concentrate the filtered radiation such that it is focused onto the photo detecting surface in the focal plane.

The basic feature of OOK modulation can be described as

- a) Simple to implement and easy detection
- b) The common technique for intensity modulation/direct detection
- c) Due to the issue of time-varying fading, a threshold is needed to make the best choice.
- d) A return-to-zero (RZ) pulse that only uses a portion of the duration bit
- e) Transmission of a non-return-to-zero (NRZ) pulse with a duration of one bit.

2.5.4.3.1 Direct Detection

This detection method is the most basic form of optical receiver since it just reacts to the instantaneous power of the gathered field. As a result, it is the most efficient at measuring the signal strength. The local oscillator is not required to retrieve the encoded information in the direct detection approach since it is simply connected with the intensity fluctuation of the transmitted field (Sorensen & Gagliardi, 1979; & Karp et al., 1970). Because of this, the detection method in question is also known as envelope detection. Figure 2.15 provides an illustration of the fundamentals of the direct detection approach.

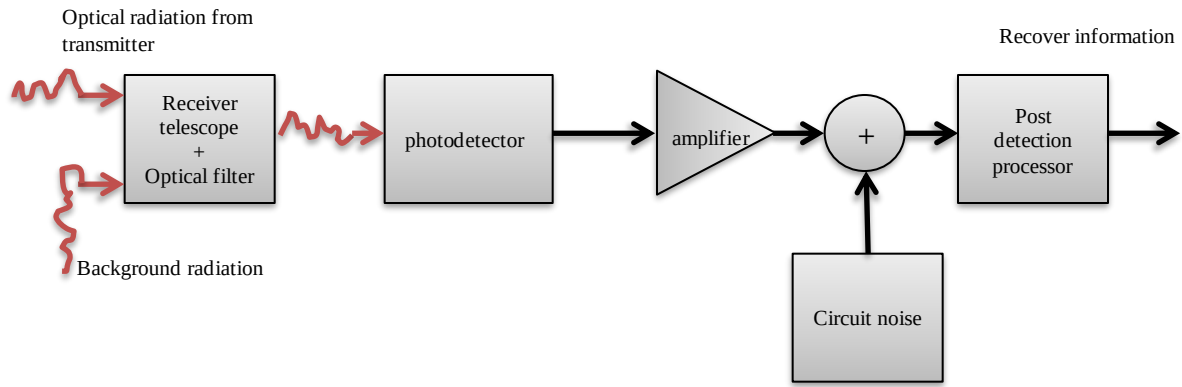


Figure 2.15: Signal process in direct detection approach (Samir et al., 2021)

Sadly, the optical field will always be able to identify the existence of extra sources and disturbances at the receiver (Mphuthi et al., 2019). The sounds that arise during the process of detecting, such as shot noise, dark current noise, background noise, and thermal noise which generate from the circuit system itself. Examples of these noises include, all of these things have the potential to contaminate the signal that is being received. The existence of turbulence, in particular when associated with the threshold signal level, will make this situation significantly worse.

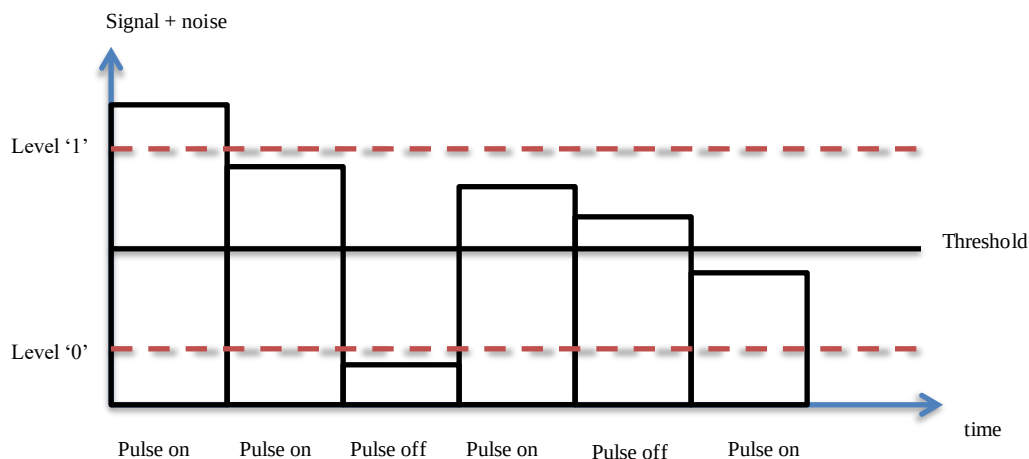


Figure 2.16: On Off Keying detection process (Majumdar & Ricklin, 2007)

The Figure 2.16 shows the behavior of OOK level for digital signal. The level '1' is indicating the pulse on condition whereas the level '0' is indicates pulse off condition. It can be summarized as shows in Table 2.3.

Table 2.3: OOK scheme signalling status

Pulse condition	Threshold	Description
Pulse On	Above	Signal presence
	Below	Miss detection
Pulse Off	Above	False alarm
	Below	No signal

The scenario known as "miss detection" takes place when the signal is being sent, but its strength does not exceed the threshold level. The occurrence of false alarms, on the other hand, takes place when the noise level alone surpasses the threshold level and is consequently regarded as a signal (Andrews & Phillip, 2000). Figure 2.17 illustrates this circumstance and provides a description of it.

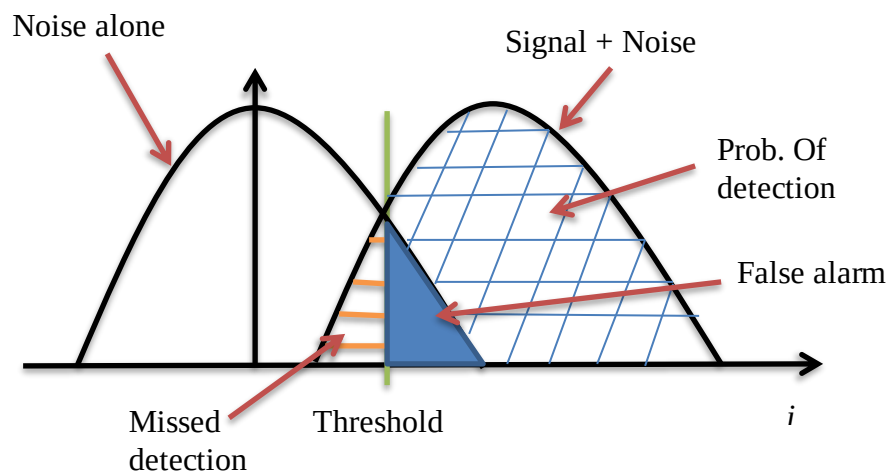


Figure 2.17: Miss detection and false alarm in signal processing (Andrews & Phillip, 2005)

According to what was said in (Zhu et al., 2021), the most significant obstacle OOK faces is the requirement of an adaptive threshold in order to operate effectively in conditions

of air turbulence. This fact, along with a few others, is one of the factors that has contributed to the rise in interest in the study of SIM in FSO systems (Samir et al. 2021). As a result, the fact that the majority of the work that has been described in the literature (Uysal et al., 2004) is based on this signalling approach should not come as a surprise to anybody.

2.5.4.3.2 Coherent Detection

Here, an optical local oscillator is employed to produce optical radiation at a specific wavelength/frequency (Zhu & Khan, 2003a). The frequency of the local oscillator is not required to match that of the incoming radiation carrying information. This possibility explains the two versions of coherent detection explained further down. Figure 2.18 illustrates the block diagram for a coherent receiver. It is important to note that coherent detection in optical detection is distinct from coherent detection in radio frequency (RF) terminology. Unlike to RF coherent detection, optical coherent detection does not require the output of the local oscillator to have the same phase as the incoming radiation.

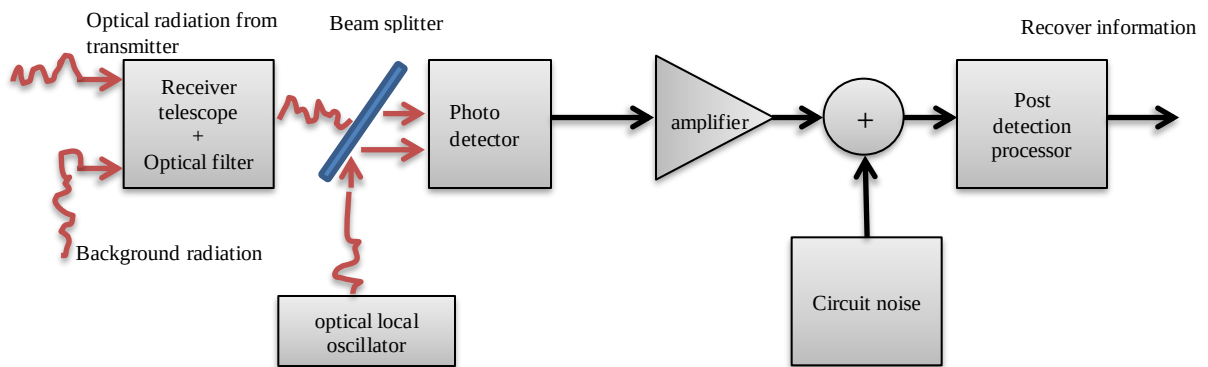


Figure 2.18: Example of coherent detection in FSO communication system for (Qian et al., 2021)

2.5.5 Effect of Atmospheric Turbulence

The implementation of FSO communication that is most appropriate to real-world circumstances is the use of an intensity modulation/direct detection (IM/DD) system. The transmitted data is on-off keying (OOK) intensity modulated, and it is given to the recipient through an atmospheric channel.

Receiving optical signals and focussing them onto a photodetector is the responsibility of the receiver aperture. The photodetector is responsible for turning the immediate optical power into an electrical current for the detecting process. When there is atmospheric turbulence between the transmitter and the receiver, there will be random fluctuations in the received signal's intensity.

The instantaneous received signal power P_R , expressed as a mathematical equation, represents a random quantity. The quantity being monitored is the average or mean received signal strength, indicated by the symbol $\langle P_R \rangle$ which is provided by

$$\langle P_R \rangle \cong \frac{\pi}{8} D^2 \langle I(0, L) \rangle = \frac{P_R}{1 + 1.33 \sigma^2 \Lambda^{5/6}} \quad \text{Equation 2.3}$$

In addition, the average signal current can be calculated as $\langle i_s \rangle = \Re \langle P_R \rangle$, where $\Re$ is the photodetector's sensitivity. The detector's $i = i_s + i_N$ output current is a random variable with mean value $\langle i_s \rangle$ and variance $\sigma_i^2 = \sigma_s^2 + \sigma_N^2$, where σ_s^2 indicates fluctuations in the signal that add to the detector noise and are proportional to the normalised intensity variance σ_I^2 by.

$$\sigma_s^2 = \langle i_s^2 \rangle - \langle i_s \rangle^2 = \langle i_s \rangle^2 \sigma_I^2 \quad \text{Equation 2.4}$$

Applying the relationships presented in Equation 2.3 and Equation 2.4, the averaged SNR $\langle \Gamma_0 \rangle$ at the detector's output has the form

$$\langle \Gamma_0 \rangle = \frac{\langle i_s \rangle^2}{\sigma_i^2} = \frac{\Gamma_0}{(1+1.33\sigma_I^2\Lambda^{5/6})^2 + \Gamma_0\sigma_I^2} \quad \text{Equation 2.5}$$

The BER can be expressed as

$$P_r(e)_{OOK} = \frac{1}{2} \operatorname{erfc} \left(\frac{i_s}{2\sqrt{2}\sigma_N} \right) = \frac{1}{2} \operatorname{erfc} \left(\frac{1}{2\sqrt{2}} \sqrt{\Gamma_0} \right) \quad \text{Equation 2.6}$$

Equation 2.6 must be changed to account for signal fluctuations when optical turbulence is present. In this instance, the threshold level is now set to half the average signal corresponding to a received pulse, ($i_T = \langle i_s \rangle / 2$).

The probability of false alarm, P_f is independent of the randomness of the received signal and can be expressed as

$$P_f = P_R|1|0 = \frac{1}{2} \operatorname{erfc} \left(\frac{1}{2\sqrt{2}} \sqrt{\Gamma_0} \right) \quad \text{Equation 2.7}$$

However the miss probability, p_m is now

$$P_m = P_R|0|1 = \frac{1}{2} \operatorname{erfc} \left(\left[\frac{2i_s}{\langle i_s \rangle} - 1 \right] \frac{1}{2\sqrt{2}} \sqrt{\Gamma_0} \right) \quad \text{Equation 2.8}$$

in which i_s is the signal from a random detector that represents the instantaneous received strength. These questions require averaging over the intensity fluctuation spectrum in order to calculate the average $\langle P_R(e) \rangle$. In turn, this allows

$$\langle P_r(e) \rangle = \frac{1}{4} \left\{ \operatorname{erfc} \left(\frac{1}{2\sqrt{2}} \sqrt{T_0} \right) + \int_0^\infty P_I(i_s) \left(\left[\frac{2i_s}{\langle i_s \rangle} - 1 \right] \frac{1}{2\sqrt{2}} \sqrt{T_0} \right) di_s \right\} \quad \text{Equation 2.9}$$

where $P_I(i)$ is the PDF of the intensity fluctuations.

Assuming the threshold level is dynamically set at half of the instantaneous received signal level i_t , which leads to expression, it can attain the limiting performance of average BER.

$$\langle P_r(e) \rangle_L = \frac{1}{2} \int_0^\infty P_I(i_s) \operatorname{erfc} \left(\frac{i_s}{2\sqrt{2}\langle i_s \rangle} \sqrt{\langle T_0 \rangle} \right) di_s \quad \text{Equation 2.10}$$

This shows that the turbulence will deteriorate the signal performance FSO and the most problem OOK signaling is relating threshold ability as discussed further in Chapter 4. In Chapter 4 also will discuss the probability of error for DTBR technique.

2.6 Summary

This chapter offers a general introduction to terrestrial FSO communication. The most significant difficulties associated with FSO may be broken down into three categories: atmospheric attenuation, atmospheric turbulence, and skin and laser safety. It has been demonstrated that the traditional ASK-OOK approach has a number of flaws, and its limitations have been outlined. Therefore, the primary objective of this research is to enhance the standard ASK-OOK performance in terms of signal received, signal-to-noise ratio (SNR), and bit error rate (BER), particularly in the presence of significant turbulence.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This section provides an outline of the development of the DTBR technique's development. It consists of a description of the parameters, an approach to the simulation, and a study of noise. The next subtopic provides an explanation of the general research technique in a nutshell. Figure 3.1 shows the flow of Chapter 3.

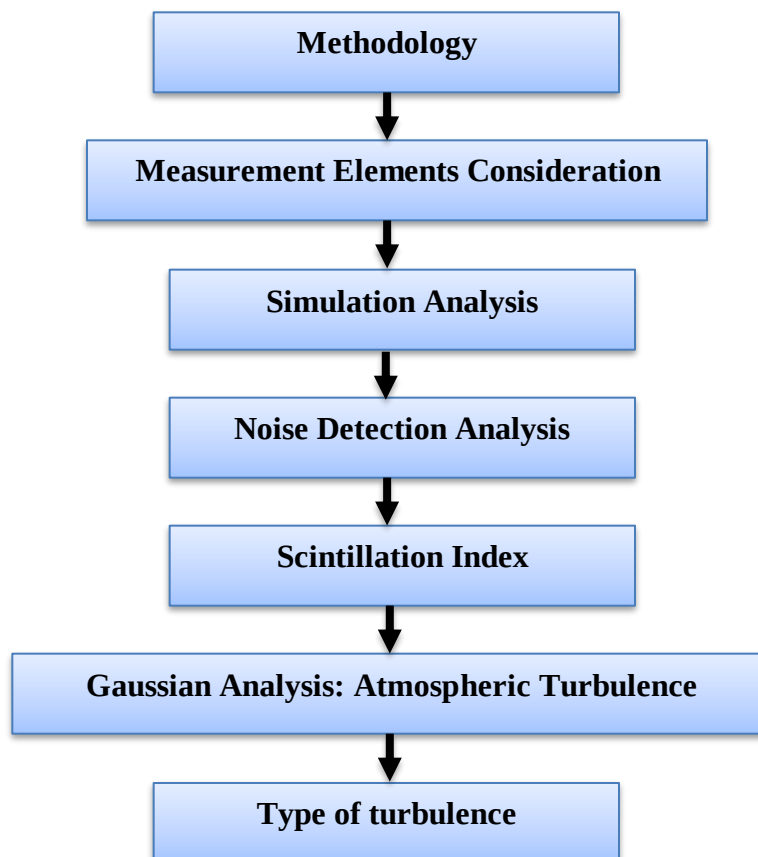


Figure 3.1: Flow of Methodology

3.2 Methodology

The creation of the new approach being proposed will take place over two primary stages. Deriving the basic idea behind the DTBR system is the first step in the process. Constructing mathematical models that are connected to signal power, signal to noise ratio (SNR), and bit error rate will be a part of it (BER). This step is highly significant since it ensures that the design idea will match the evolution of the derivation. This component is given in in Section 4.2 in Chapter 4. The mathematical derivation of the new approach will be described in terms of two requirements that relate to signal-to-noise ratio and bit error rate (BER). The first requirement is taken into consideration when there is no turbulence in the atmosphere, while the second condition is taken into consideration when there is turbulence in the atmosphere. After finishing the mathematical derivation, the performance of this modulation is studied and compared to the performance of the traditional ASK in order to determine whether or not the DTBR has been improved.

The second part is to assess the new DTBR technology utilising optical simulator from Optiwave product that is Optisystem software. This will help further investigate the findings, which are set up to be as near as possible to the actual FSO state. The theoretical conclusions that were reported in earlier work may now also be validated by this step of the process. Aside from that, the simulations make it possible for the modulation design to function in an FSO system network in the most effective way. This is due to the fact that the implementation in simulator takes into account the practical elements such as scintillation index, attenuation impact, and geometrical loss, all of which play a vital part in the performance evaluation of the FSO. Figure 3.2 provides a visual representation of the study technique as a whole.

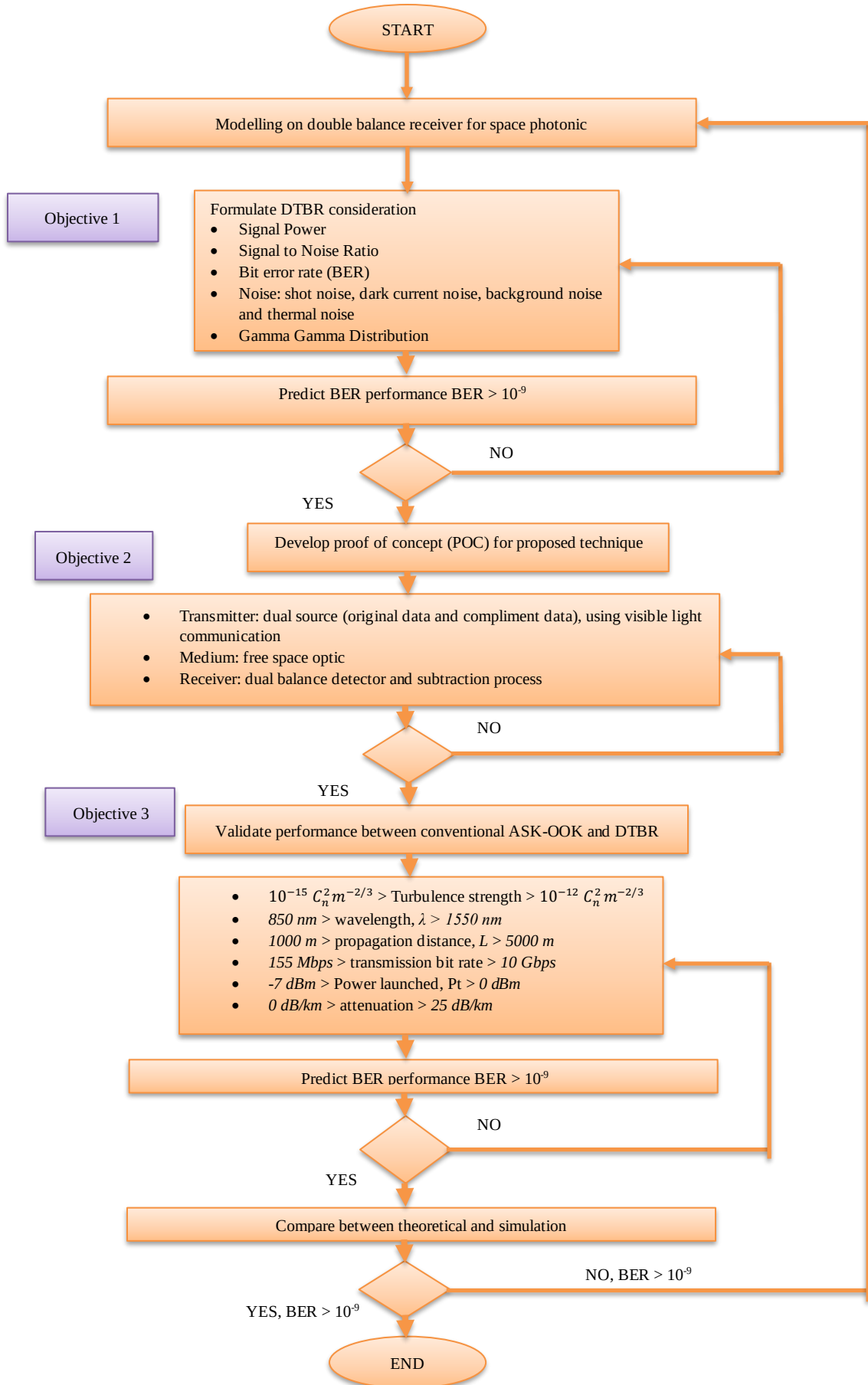


Figure 3.2: Overall flowchart of work process DTBR technique

3.3 Measurement Elements Consideration

The design parameter is one of the key aspects in order to measure the effectiveness of the new modulation approach. It offers the designer the opportunity to alter the parameters or make them flexible so that they may conduct an analysis of the capabilities of the new system. In the course of this work study, the following are the design parameters that will be utilized:

- a) **Receiver Aperture** - This design parameter may have some connection to the impact of averaging the aperture, and it may also have some bearing on the amount of coverage added to the process of collecting intensity signals. Due to the fact that the receiver aperture might change in value, the effective signal strength will likewise be subject to variation. When taking into account this parameter, there are two primary consequences, the first of which is a reduction in the scintillation index, and the second is an increase in the effective signal power.
- b) **Propagation distance** - when it comes to terrestrial FSO communication, the propagation distance plays a significant role in determining the level of performance that may be expected. The relatively short distance for FSO is becoming increasingly popular in the industry at the moment. Strong as ever is the influence of the atmospheric channel, which is one of the primary factors. The ever-increasing needs of FSO, on the other hand, require that this technology be able to work across greater distances. As a consequence of this, it is possible for this technology to become cost viable without the requirement of a router or regenerator for long distance transmission. The case study conducts a comparison of the propagation distance up to three kilometres.

- c) **Bit rate** - the term "bit rate" refers to the speed at which one bit of data is sent. To put it another way, it may be described as the speed at which the system is capable of transmitting one bit of data through the channel. In general, a greater bit rate will result in an increased amount of bit error; nonetheless, the fact that a system is able to function at a high bit rate confers a significant competitive advantage over another system. In today's world, commercial FSO networks are readily capable of operating at 2.5 Gbps; however, recent findings from ongoing research conducted by scientists indicate that technological advancements can enable data rates of up to 10 Gbps and even higher. This is one of the primary benefits of FSO if comparing other mode communication technologies such as fibre and radio frequency which normally restrict to 622Mbps for best performance. In this study, four primary bit rates STM-1 (155 Mbps), STM-4 (622 Mbps), STM-16 (2.5 Gbps), STM-64 (10 Gbps) are employed, according to the Synchronous Digital Hierarchy (SDH) standard, generally used for metro applications.
- d) **Signal power** - when it comes to selecting the signal with the greatest possible quality, the effective power in FSO is an essential factor. The performance of the system is affected by the signal power coming from the transmitter as well as the receiver power at the receiver. Because of this, determining the effective power in FSO, which is generally measured in terms of dBm, is extremely crucial. The effective power is primarily defined in this work by the signal power that is associated with the signal-to-noise ratio (SNR), and the signal power is connected to the power received at the receiver, which is related to the power sent at the transmitter. The comparison for the transmit power is made between three different levels of power, beginning with -5 dBm, then moving on to 0 dBm, and lastly ending with 5 dBm. This change in power

transmissions is being done in order to investigate how well a newly developed modulation method may function with a low amount of transmitted power. In the meanwhile, the range for the amount of power received is set to be between -50 dBm and 0 dBm.

3.3.1 Signal to Noise Ratio (SNR)

To put it simply, the signal-to-noise ratio (SNR) is the proportion of signal power to total power. Its primary use is to compare the decibel level of a wanted signal to the amount of background noise (dB). For a given FSO system, the signal-to-noise ratio (SNR) is determined by comparing the power received over the presence noises, which can include things like shot noise, background noise, dark current noise, and thermal noise.

3.3.2 Bit Error Rate (BER)

The chance of the decision circuit in a digital communication system making an inaccurate identification of a bit is the thing that makes up the BER of that system. When it comes to FSO communication, the objective is to send the largest number of bits per second across the greatest feasible distance while making as few mistakes as possible. Calculating the bit error rate (BER) of the system, which is dependent on the modulation format and the signal-to-noise ratio (SNR), allows one to make predictions about the performance of FSO. In terms of modulation, an example of this would be if an OOK transmitter were to send a pulse of light into a channel to represent a "1," but it would not send any light if it were representing a "0." There are two different ways that an error might arise when there is a signal as well as noise present at the input of the receiver. The first type of mistake is an

error "1," which occurs when the recipient chooses "0," but "1" was actually communicated. The second cause of mistakes for '0' is when the receiver interprets the data as '1' when it was actually '0' that was transmitted.

Due to the fluctuation of the signal in the presence of turbulence, the SNR is considered to be an average, and as a result, the BER will also consider an average to include the factor of the probability distribution of irradiance or intensity. Both of these effects are caused by the presence of turbulence. The majority of FSO communications have decided that a minimum of 10^{-9} should be used as the benchmark for BER; this number will also be used in this research and study to represent the worst-case scenario. It is possible to declare as a single fault that can only be allowed once per one billion bits is sent.

3.4 Simulation Analysis

This approach can also become the preliminary stage before being implemented in real-world conditions. In order to perform validations and optimization analyses, the usage of simulation software may be used to its full potential. For the purposes of this study, the simulation software tool known as Optisystem Version 7 was employed. The simulation makes it possible for each of the design modulation sequence systems to be tested using varying particular sets of designing parameters including scintillation index, power transmits, receiver aperture, propagation distance, and bit rate. This can be done using the simulation. In terms of performance, the most important metrics to look at are the bit error rate (BER), effective power, eye diagram shape, and oscilloscope pattern.

3.4.1 Simulation Setup

The complete setup for DTBR in optisystem is shown in Figure 5.11. It comprises three main part that are transmitter, medium/channel and receiver. Meanwhile the details component description can be found in Subtopic 4.2 Chapter 4. The Table 3.1 and 3.2 shows the main component and analyser setup respectively.

Table 3.1: Main component setup

Component	Setup description (*DS = default setting), (RFM – range for measurement)
Transmitter	
Continuos Wave (CW) Laser	1. Frequency = 193.1Terahertz (DS) - 1550nm and 850nm (RFM) 2. Power = 0dBm (DS) - -10dBm – 10dBm (RFM) 3. Linewidth= 10Mhz (DS) 4. Initial Phase= 0deg (DS)
Pseudorandom Bit Sequence Generator	Mark Probability = 0.5 (DS)
NRZ (Non Return Zero) Generator	1. Ractangular shape (DS) 2. Amplitude and Bias = (1,0) (DS) 3. Fall and Rise time = 0.05 bit (DS)
Electrical Not	1. Threshold = 0.5 (DS) 2. High level output and low level output = 1,0 (DS)
Fork (1 x 2)	DS
Mark Zhender Modulator	1. Extinction ratio = 30dB (DS) 2. Symmetry factor = -1 (DS)
Medium	
Free Space Optic	1. Range = 1-5km (RFM) 2. Attenuation = 0 – 30dB/km (RFM) 3. Geometrical Loss = (DS) - Transmitter aperture (5cm) - Receiver aperture (20cm) - Beam divergence (2mrad)
Receiver	
PIN Photodetector	1. Responsivity = 1A/W (DS) 2. Dark current = 10nA (DS)
Low Pass Bessel Filter	1. Cutoff requency = 0.75*bit rate (DS) 2. Depth = 100dB (DS)
3R Regenerator	DS
Combiner	Loss = 0dB (DS)
Electrical subtractor	DS

(default setting = all the value has been set by developer software based on current commercial product/equipment/component in optical market)

Table 3.2: Analyzer component setup

Additional component setting analyzer result measurement	
Component	Setup description
Oscilloscope Analyzer	Placing both at transmitter and receiver - Transmitter – tap at output NRZ pulse generator - Receiver – tap at output electrical subtractor
Electrical Power Meter	
BER (Bit Error Rate) Analyzer	Only at receiver and tap at output 3R Regenerator

3.5 Noise Detection Analysis

In the world of FSO communication, there are many different noise sources. The performance of the signal is decreased as a direct result of all of this noise. The photodetectors capacity to detect the incoming signal will be hindered as a result of these sounds. If the strength of the signal is lower than the power of the noise, it will not be possible to differentiate between the signals in a clear manner. The shot noise that is produced as a result of the stochastic character of the photon-to-electron conversion process and the thermal noise that is linked with the amplifier circuitry are the two primary factors that contribute to the overall level of noise in the optical receiver. These many sources of noise are invariably present with the optical signal. Dark current noise and background illumination noise are two further types of noise that are involved in the detection of optical radiation. Both of these types of noise have the potential to have negative impacts on FSO communication systems.

3.5.1 Shot Noise

The only kind of noise that has a substantial impact on its performance is the kind that is linked with the quantum nature of light itself. Quantum noise, sometimes known as shot noise, is the most significant type of noise produced by a photodetector. At the output of a photodetector, two current components are produced during the measurement of an unmodulated lightwave employing the device. The first one is a DC current, and the second one is the shot noise signal, which is something that should not be there. When an optical signal is incident on a photodetector, there is a phenomenon known as shot noise that occurs as a result of the stochastic character of the creation and collecting of discrete photoelectrons. It has a constant power density over the whole frequency range. If the electrical circuit that comes after the photodetector is only capable of handling the frequency bandwidth f , then the mean-square current amplitude of the shot noise may be calculated as follows:

$$i_{shot}^2 = 2e\Re(i_s)B \quad \text{Equation 3.1}$$

where e represents the electron charge, $\Re$ represents the receptivity, and B represents the bandwidth. In addition to the primary source of shot noise for an APD, there is a noise figure related with the additional noise produced by the random avalanche process. This noise figure $F(M)$ is defined as the ratio of the actual noise generated in an avalanche photodiode to the noise that would exist if all carrier pairs were multiplied by exactly M and is given by $F(M) = \frac{\langle m^2 \rangle}{M^2}$, where $\langle m^2 \rangle$ is the mean square gain and can be approximated as M^{2+x} , with x varying from 0 to 1 based on the material and structure. Hence, the meansquare current amplitude of the shot noise for APD $\langle i_{SN}^2 \rangle_{APD}$ is given by $\langle i_{SN}^2 \rangle_{APD} = 2qi_s M^2 F(M) \Delta =$

$2q_M\Delta f$, where i_s is the average value of total multiplied output current, i_M is the average unmultiplied photocurrent, and M is the APD factor.

.

3.5.2 Dark Current Noise

The photocurrent that is created by the photodetector even when there is no photon falling on it is called the dark current. The black current is the current that continues to flow through the bias circuit of the device even when there is no light incident on the photodiode. In the p-n junction of the photodiode, it is caused by electrons and/or holes that are created as a result of thermal activity. The operating temperature, the bias voltage, and the kind of semiconductor all have a significant impact on the dark current. Their values can range anywhere from 100 pA for silicon all the way down to 100 nA for germanium, depending on the material.

$$i_{dark}^2 = 2e(i_d)B \quad \text{Equation 3.2}$$

3.5.3 Background Noise

The detection of photons produced by the surrounding environment is the source of this particular sort of noise. Noise in the background illumination is created by light that is present but is not a component of the transmitted signals. One example of this is ambient light. It is impossible to prevent the emergence of this noise if the photodetector is not shielded from the radiation that is present in the background. These noise sources are comparable to the shot noise as a result of the discreteness and unpredictability that is shared

by both the dark current and the background radiation. Background radiation noise comes from a variety of sources, the most prominent of which being the sun and the atmosphere.

$$i_{background}^2 = 2e\Re\langle i_{sky} + i_{sun} \rangle B \quad \text{Equation 3.3}$$

where, $i_{sky} = \frac{N(\lambda)\Delta\lambda\pi\Omega_{FOV}^2}{4}$ and $i_{sun} = W(\lambda)\Delta\lambda$. The $N(\lambda)$ is spectral radiance of sky $W(\lambda)$ = spectral radiant emittance of sun, $\Delta\lambda$ = bandwidth of an optical bandpass filter (OBPF) and Ω_{FOV}^2 = photodetector field of view angle (FOV) in radians.

3.5.4 Thermal Noise

Thermal noise also called Johnson noise or Nyquist noise. This is the noise caused by the thermal fluctuation of electrons in any receiver circuit of equivalent resistance R_L , and temperature T_n .

Heat-related background noise, often known as Johnson or Nyquist noise. In a receiver circuit with equivalent resistance R_L and temperature T_n , this is the noise induced by the thermal fluctuation of electrons.

$$i_{thermal}^2 = \frac{4k_b T_n B}{R_L} \quad \text{Equation 3.4}$$

where B is the electrical equivalent noise bandwidth of the receiver, T_n is the temperature of receiver noise, R_L is the load resistance, and k_b is the Boltzman's constant. The thermal energy of the charge carriers in any resistor causes variations in local charge densities above absolute zero. These varying charges produce regional voltage gradients that may result in a commensurate current flowing across the remainder of the circuit.

3.6 Scintillation Index

The scintillation index in the weak turbulence regime was determined in (Andrews & Phillips, 2003).

$$\sigma_B^2 = 3.86\sigma_I^2 \left\{ \begin{array}{l} 0.4[(1 + 2\theta_{ed})^2 + 4(\Lambda_{ed})^2]^{5/12} \\ X \left(\cos \left[\frac{5}{6} \tan^{-1} \left(\frac{1+2\theta_{ed}}{2\Lambda_{ed}} \right) \right] \right) \\ - \left(\frac{11}{6} (\Lambda_{ed})^{5/6} \right) \end{array} \right\} \quad \text{Equation 3.5}$$

where σ_I^2 is the Rytov variance that can be written as

$$\sigma_I^2 = 1.23C_n^2 k^{7/6} L^{11/6} \quad \text{Equation 3.6}$$

Meanwhile, for strong turbulence, the Andrews & Philips (2005) developed strong fluctuation theory may use the scintillation index.

$$\sigma_{strong}^2 = \exp \left[\frac{0.49\sigma_B^2}{(1+0.56\sigma_B^{12/5})^{7/6}} + \frac{0.51\sigma_B^2}{(1+0.69\sigma_B^{12/5})^{5/6}} \right] - 1 \quad \text{Equation 3.7}$$

which σ_B^2 is given in Equation 3.21.

3.6.1 Flux Variance

According to Andrews (1998), the flux variance of the intensity variations at the detector plane derived for the collecting lens with normalised radius Ω_G is valid for all atmospheric conditions:

$$\sigma_{flux}^2(L + L_f, \Omega_G) = \exp[\sigma_{inx}^2(L + L_f, \Omega_G) + \sigma_{iny}^2(L + L_f, \Omega_G)] - 1 \quad \text{Equation 3.8}$$

where $\sigma_{\ln x}^2$ represents the flux variance related to large-scale fluctuations (Andrews et al., 1997).

When the receiving aperture is bigger than the spatial scale size that creates intensity fluctuations, the receiver will average the fluctuations across the aperture, resulting in a lesser scintillation than when measured with a point receiver. This is the impact of aperture averaging, and it may be explained as follows: when the receiving aperture is bigger than the spatial scale size that causes intensity variations, the receiver will average the intensity fluctuations across the aperture (Vetelino et al., (2007). It has been established that averaging across a larger aperture shifts the relative spatial frequency content of the intensity spectrum towards lower frequencies. This is due to the fact that the most rapid variations caused by small-scale sizes tend to average out (Mahon, et al., 2008). The scintillation consequently measured by a receiving aperture is produced by scale sizes larger than the aperture. The accumulation of more light is the most visible advantage of increasing the aperture size. A process known as aperture averaging causes the scintillation index to drop when the aperture size is extended to a point where it exceeds several multiples of the light's coherence length (Kerr & James, 1973).

When sufficient turbulence is present, the intensity flux variance obtained by a small receiving aperture exhibits a two-scale characteristic. Following the coherence scale, ρ_o , there is a levelling effect, followed by a second drop in the intensity flux variance when the aperture is larger than the scattering disk $L/\kappa\rho_o$. A dramatic reduction in scintillation is noticed as aperture size increases until the coherence scale is attained (Churnside, 1991). Due to the ineffectiveness of medium-sized particles in producing scintillation under strong

turbulence, the levelling effect is produced. If the receiving aperture is greater than 0, the small-scale scintillation will be substantially averaged out in the presence of strong turbulence. The probability density function (PDF) of the intensity fluctuations should be affected by the fact that the current models, which were developed for point receivers, are formed by modifying the small and large scale distributions. So, throughout this dissertation, we use the Gamma Gamma distribution, which is applicable to all fluctuation regimes (Al-Habash et al., 2001). In Chapter 4, the Gamma Gamma distribution function is deconstructed in detail to analyse BER performance in the presence of air turbulence.

The large-scale eddies' log intensity is represented as ;

$$\sigma_{\ln x}^2(L + L_f, \Omega_G) = 0.49\sigma_R^2 \left(\frac{\Omega_G - \Lambda_e}{\Omega_G + \Lambda_e} \right)^2 XR \left[\frac{\eta_x}{1 + 0.4\eta_x \frac{(1 + \theta_e)}{(\Lambda_e + \Omega_G)}} \right]^{7/6} \quad \text{Equation 3.9}$$

where $R = \frac{1}{3} - \left(\frac{1}{2}\right)(1 - \theta_e) + \left(\frac{1}{5}\right)(1 - \theta_e)^2$. Equation 4.2 quantity η_x represents the normalised large-scale cutoff frequency as defined by the behaviour of $\sigma_{\ln x}^2$ as it asymptotically approaches zero in the saturation regime and mild turbulence. (Andrews et al., 2001):

$$\eta_x = \frac{R^{-6/7} \left(\frac{\sigma_B}{\sigma_R} \right)^{12/7}}{1 + 0.56\sigma_B^{12/5}} \quad \text{Equation 3.10}$$

Meanwhile log intensity due to small scale eddies is given as;

$$\sigma_{\ln y}^2(L + L_f, \Omega_G) = \frac{1.27\sigma_R^2\eta_y^{-5/6}}{1 + 0.4\frac{\eta_y}{(\Lambda_1 + \Omega_G)}} \quad \text{Equation 3.11}$$

where the corresponding cutoff frequency is

$$\eta_y = 3 \left(\frac{\sigma_R}{\sigma_B} \right)^{12/5} (1 + 0.69 \sigma_B^{12/5}) \quad \text{Equation 3.12}$$

3.7 Gaussian Analysis: Atmospheric Turbulence

In this particular piece of research, the study is performed using the Gaussian atmospheric optical channel. Poisson analysis and Gaussian analysis are the two primary types of statistical examination that may be performed. a) Poisson analysis and b) Gaussian analysis (Alda, 2003). The photoelectron count is a part of the Poisson analysis, but the Gaussian analysis may be utilized to construct the signal current probability distribution when large signal photoelectron counts are taken into consideration together with the detection thermal noise, as was discussed in Section 3.5. If there is no loss of generality, the receiver area may be normalised to unity, which is represented by the optical intensity, I . This would not have any bearing on the generality of the assertion. The formula for determining the received signal in an OOK system is as follows, assuming R to be the photodetector's sensitivity:

$$i(t) = \Re I + n(t) \quad \text{Equation 3.13}$$

$n(t) = N(0, \sigma^2)$ represents additive white Gaussian noise (AWGN), $[g(t - jT)]$ is the pulse shaping function, and $dj = [-1, 0]$.

At the receiver, a threshold detector compares the incoming signal to a predetermined threshold level. If the receiver decides a binary '1', the received signal is over the threshold

level; otherwise, a binary '0' is determined. Hence, the likelihood of probability error is given as:

$$P_e = P(1) \int_{-\infty}^{i_{th}} P(0|1) dI + P(0) \int_{i_{th}}^{\infty} P(1|0) di \quad \text{Equation 3.14}$$

where i^{th} is the threshold signal level and the marginal probability given as :

$$P(i|0) = \frac{1}{\sigma^2 \sqrt{2\pi}} \exp(-i^2/2\sigma^2) \quad \text{Equation 3.15}$$

$$P(i|1) = \frac{1}{\sigma^2 \sqrt{2\pi}} \exp\left[-\frac{(i - \Re I)^2}{2\sigma^2}\right] \quad \text{Equation 3.16}$$

For symbols with equal probabilities, $p(0) = p(1) = 0.5$, hence the optimal threshold point is $i_{th} = 0.5\Re I$, and the conditional probability of error is reduced to::

$$P_{ec} = Q\left(\frac{i_{th}}{\sigma}\right) \quad \text{Equation 3.17}$$

where $Q(x) = 0.5\text{erfc}(x/\sqrt{2})$.

3.8 Type of Turbulence (ToT)

The previous article demonstrates that there are a few different turbulence models that have been utilised in FSO studies that pertain to atmospheric channel research for communication. When attempting to describe the atmospheric turbulence-induced

scintillation, the log-normal model is the one that is most frequently cited as having been used (Shrivastava et al., 2019). This model is only applicable in conditions with low levels of air turbulence. If the level of turbulence is increased, then numerous scattering effects which the log-normal model does not take into account will need to be taken into consideration. After the weak turbulence domain, the gamma-gamma and negative exponential models may be utilised to describe the signal fluctuation under a wide variety of atmospheric turbulence conditions. This is because both of these models are nonlinear (Shakir (2019) and Uysal et al. (2006)).

As was covered in Chapter 2, the turbulence in the atmosphere is responsible for the thermal inhomogeneities that exist along the path. These inhomogeneities are what cause the variations that result from the conversion of solar energy (Wasiczko et al., 2004). The solar power warms the atmosphere irregularly with a variety of cells, which is the first step in the process that results in turbulence. This causes there to be a range of temperatures throughout the atmosphere, as well as changes in the index of refraction of the atmosphere. The oscillations in the amplitude of the received optical signal are the direct result of the light source FSO, as stated in the research conducted by (Yue et al., 2019). Calculating the scintillation index, which is connected to the mean and standard deviation of the intensity distribution, is one way to quantify the impacts of air turbulence. This index may be defined as the mean intensity divided by the standard deviation which report in K. Pang et el. (2018) the intensity distribution which can defined by (Andrews & Phillips, 2005):

$$\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1 \quad \text{Equation 3.18}$$

Generally the atmospheric turbulence is divided into three main regimes which depend on the turbulence strength (Rasouli & Tavassoly; 2006). Table 3.3 shows the categories atmospheric turbulence where basically varies from 10^{-15} to $10^{-13} \text{ m}^{-2/3}$.

Table 3.3: Range turbulence regime

Atmospheric turbulence regime	Turbulence strength $C_n^2 \text{ m}^{-2/3}$
Weak	10^{-15}
Moderate	10^{-13}
Strong	10^{-12}

Using the probability density function (PDF) of the arbitrarily decaying intensity signal, the efficacy of an FSO system with an atmospheric turbulence channel can be evaluated mathematically (Zheng et al., 2018). Several PDF models, including K distribution, log normal distribution, and gamma-gamma distribution, have been proposed to cope with more general intensity fluctuation conditions (Churnside & Clifford (1987) and Al- Habash et al. (2021)).

3.8.1 ToT 1: Log Normal Distribution

The distribution of intensity is lognormal for weak turbulence. The probability density function (PDF) valid for $I > 0$ is denoted by (Andrews et al., 2001).

$$p(I) = \frac{1}{\sqrt{2\pi\sigma_I^2}} \frac{1}{I} \exp\left\{-\frac{(\ln(I/I_0) - E[l])^2}{2\sigma_I^2}\right\} \quad I \geq 0 \quad \text{Equation 3.19}$$

3.8.2 ToT 2: Gamma-Gamma Distribution

It is recommended to use the Gamma Gamma Distribution when dealing with a weak to strong regime. It was achieved through a modulation that took place between the intensity on a small scale (y) and the intensity on a large scale (x) (Andrews et al., 2001):

$$I = xy \quad \text{Equation 3.20}$$

where x and y are presumed to be statistically independent and gamma-distributed. The conditional probability density function (PDF) for the intensity is determined by the small-scale intensity, which is assumed to have a fluctuating mean that is dispersed or modulated by the distribution of the large-scale fluctuations. The unconditional PDF for the intensity is a doubly stochastic process obtained by taking the expected value of the unconditional PDF, which yields the GG distribution (Al-Habash et al., 2001):

$$p_I(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{(\alpha+\beta)}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}) \text{ For } I>0 \quad \text{Equation 3.21}$$

where I stands for the standardised intensity, $\Gamma(x)$ for the gamma function, and $K_\mu(x)$ for the second-kind modified Bessel function. The values of the PDF, α and β , denote the corresponding effective counts of large- and small-scale scatterers. By determining the second instant of the Gamma Gamma dispersed intensity, they are connected to the scintillation index (Al-Habash, 2001):

$$\langle I^2 \rangle = \left(1 + \frac{1}{\alpha}\right) \left(1 + \frac{1}{\beta}\right) \quad \text{Equation 3.22}$$

In this particular piece of work, the computation utilizes the PDF Gamma-Gamma. The example calculations of the Gamma Gamma probability density function and the determination of the values alpha and beta are shown in Appendices A and B, respectively.

3.8.3 ToT 3: The Exponential Distribution

This PDF will use in case for the limit of strong intensity turbulence which usually the number of scattering is large (Goodwin, 1970). The exponential distribution sometime also known as a fully developed speckle regime. This saturation regime is obey the Rayleigh distribution that using the negative exponential statistic (Guiomar et al., 2022).

$$p(I) = \frac{1}{I_0} \exp\left(-\frac{I}{I_0}\right) \quad I_0 > 0 \quad \text{Equation 3.23}$$

where $E[I] = I_0$ is the mean received intensity. The value of the scintillation index, $S.I = 1$ when under this saturation regime.

$$\sigma_{flux}^2(L + L_f, \Omega_G) = \exp[\sigma_{lnx}^2(L + L_f, \Omega_G) + \sigma_{lny}^2(L + L_f, \Omega_G)] - 1$$

3.9 Summary

It has been stated that there are two primary stages involved in putting the research technique into practice. The evaluation of noise, which served to signal the existence of FSO, was also provided. Shot noise, background noise, dark current noise, and thermal noise are

some of the several types of noise that are taken into consideration. The Gaussian atmospheric channel, more precisely the Gamma – Gamma distribution type, is utilized for the purpose of computation and analysis.

CHAPTER 4

DEVELOPMENT OF DOUBLE TRANSMISSION BALANCE RECEIVER (DTBR) MODULATION TECHNIQUE

4.1 Introduction

This chapter provided a detailed explanation of the evolution of the Double Transmission Balance Receiver (DTBR) method. In Section 4.2, will go through the model of this new approach, which revolves around the components of the light source, inverter, balance receiver photodetector, and subtractor respectively. Section 4.4 will focus on conducting a comparative study of the DTBR approach and the more traditional ASK (OOK) methodology in order to facilitate an examination of the aforementioned new method. In terms of signal power, data bit rate transmission, route link range, and bit error rate, the comparative study will be utilizing four major indicators of performance. Figure 4.1 illustrate the flow of Chapter 4 in devopment of DTBR.

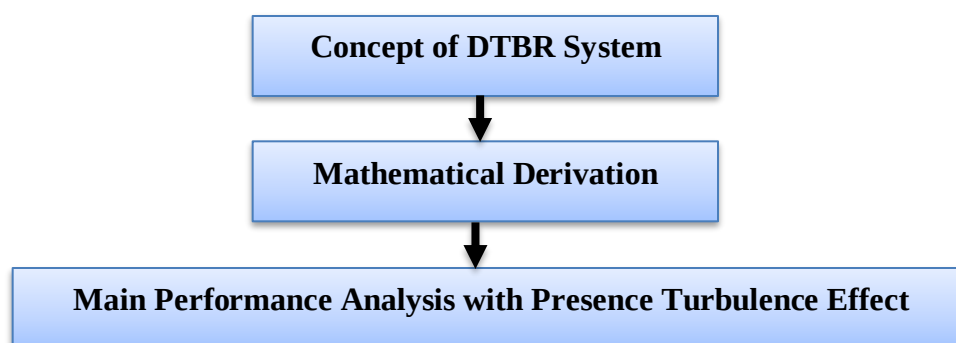


Figure 4.1: Flow of development DTBR technique

4.2 Concept of DTBR System

The development of DTBR, which is based on changing ordinary ASK for OOK, consists of two components. One of these sections modifies conventional ASK. The first portion is sent, and within this section there are three primary components that may be listed: the laser source, the original data, and the inverter data. The balance receiver photodetector and the subtractor make up the two primary components that make up the receiver, which is the second element of the system.

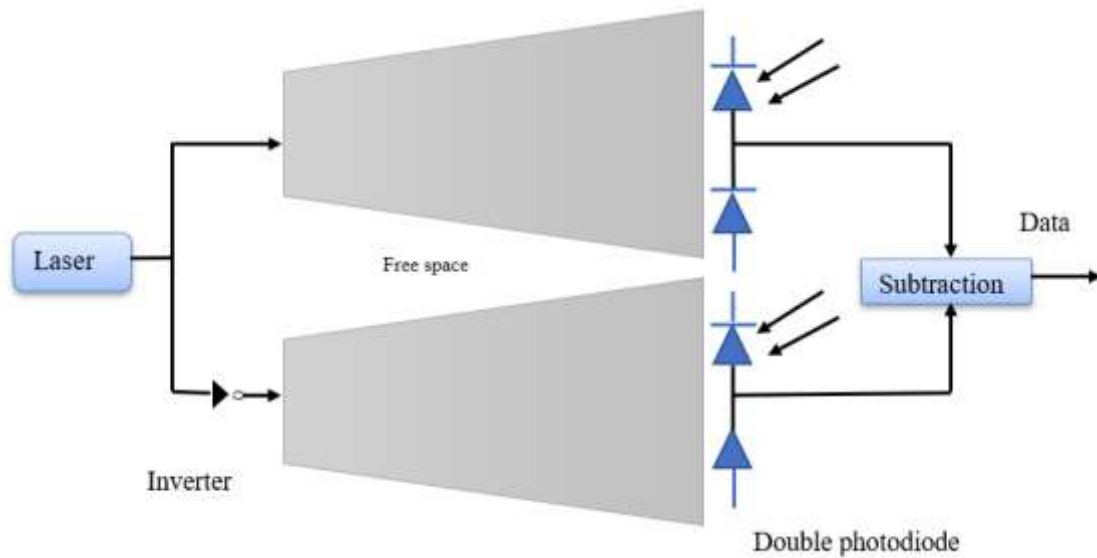


Figure 4.2: Proposed setup for Double Transmission Balance Receiver modulation (DTBR) technique

The recommended configuration for the new DTBR method may be seen in Figure 4.2. This innovative method, in its most basic form, makes use of two transmitters and two receivers. The data from the original source will be transmitted by the first transmitter, while the data complement will be transmitted by the second transmitter. After that, the photodiode is installed in the balance receiver at the receiver. After that, the output from the balanced

receiver is going to be subtracted with the signal that has been inverted to generate the final data.

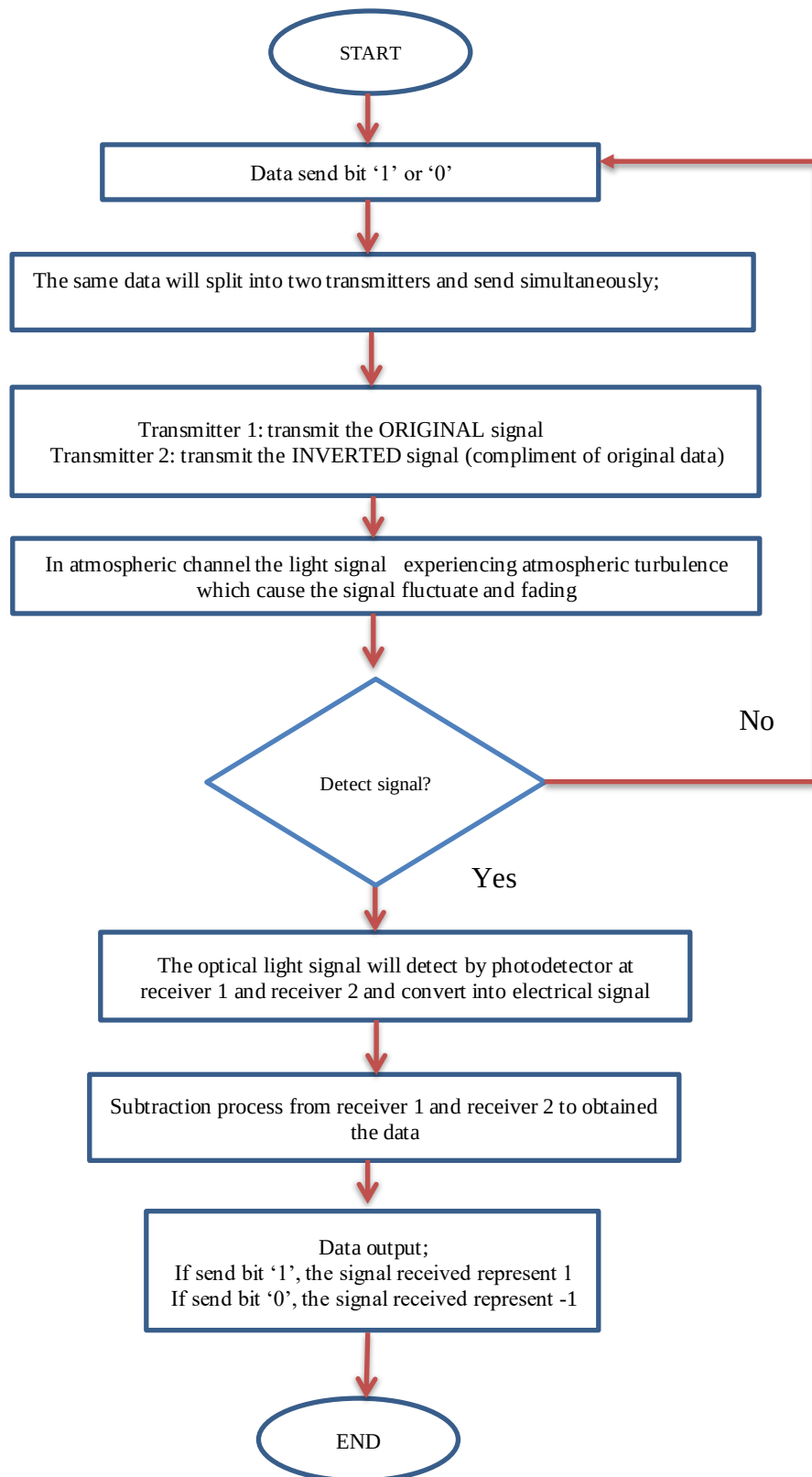


Figure 4.3: Flowchart of a DTBR technique for FSO communication

The signal that was received will make its way to the balance receivers 1 and 2, which are located in the receiver section. Every single balancing receiver has a pair of photodetectors built into it. Before going through the process of subtraction, the output of balance receiver 1 is the carry for the original data, and the output of balance receiver 2 is the inverted data accordingly. It is assumed that the subtractor is an ideal subtractor, meaning that there are no current losses caused by the implementation of the subtraction signal. Figure 4.3 provides a flowchart representation of the DTBR signal processing procedure.

4.2.1 Component 1: Light Source (LS)

The modulated light source, which is typically a laser or light-emitting diode (LED), provides the optical signal that is transferred and is responsible for determining all of the system's capabilities in terms of transmission. This signal is what determines whether or not the system is capable of transferring data. The sensitivity of the detector is the sole element that makes a substantial contribution to the system's overall performance, although there are many others.

4.2.1.1 LS Type 1: Light Emmitting Diode (LED)

LEDs, which stand for light-emitting diodes, are light-emitting structures made of semiconductors. LEDs are often utilized in applications that need moderate bandwidth requirements up to 155 Mbps because of their comparatively low transmission power. These

applications typically take place over shorter distances. LEDs are able to function in a variety of wavelength ranges, which are determined by the material system. LEDs offer a much expanded spectrum range of operation in comparison to narrow band or single wavelength laser transmission sources. The output of a sample LED is displayed in Figure 4.3, which is taken from the optical spectrum. Around the designated center wavelength of operation, a typical full width half maximum (FWHM) emission spectrum has a range of between 20 and 100 nm in its maximum and minimum values. LEDs that emit infrared light are sometimes utilized as transmission sources in remote controls for home appliances. LED sources provide a number of benefits, including a very low cost as well as an incredibly long life. In recent years, the Light Emitting Diode (LED) has been investigated for use as a light source in aircraft cabins in order to facilitate short-range FSO communication within the aircraft. Free-space optical (FSO) communication seems to be one of the finest alternatives for reducing weight and power as the aircraft cabin provides the bigger number of nodes to interconnect. This is the case since the aircraft cabin shows the larger number of nodes. In addition, the operation of FSO communication systems is safer than that of radio frequency solutions since these systems do not interact or have any effect on the communication equipment that is already on board. Following this, a presentation on high-throughput point-to-multipoint free-space optical links will be given. A description of the conceptual architecture, as well as its primary performances and limits, are contrasted with avionics needs and standards.

4.2.1.2 LS Type 2: Light Amplification by Stimulated Emission of Radiation (LASER)

Only lasers that are able to be modulated at 20 Mbps to 2.5 Gbps are capable of meeting the needs of the present market in the industry that is commonly known as telecommunications. When choosing a device, it is essential to consider both the manner in which the device is modulated and the quantity of power that is generated by the modulation. Figure 4.4 presents a sample of the output from the laser.

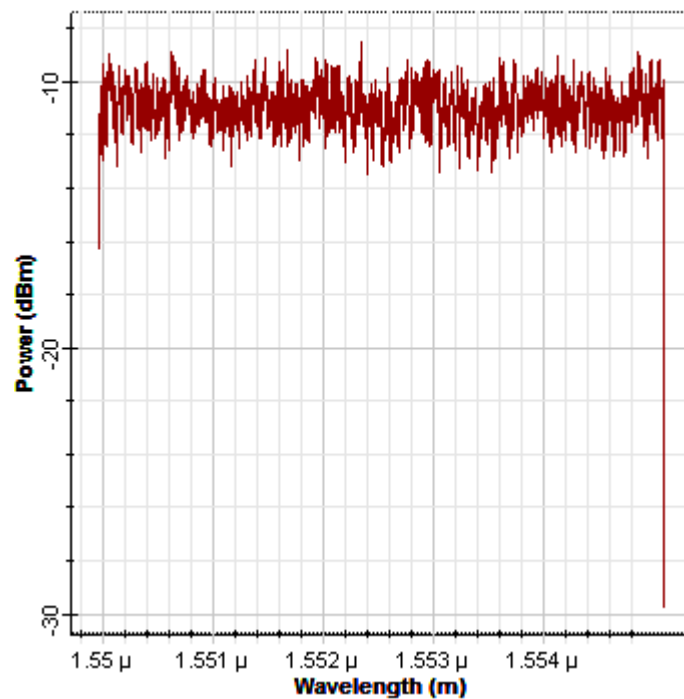


Figure 4.4: Example LED output

Among the familiar laser for range wavelength 850 nm to 1550nm

- The VCSEL 850nm wavelength is an offshoot of the development of fiber communications and possesses a great deal of desirable characteristics. The market for transmission components was completely transformed by VCSELs as a result of the significant cost and performance benefits that they offered in comparison to earlier technologies. Most notably, VCSELs offer high reliability values for MTBF and a tolerable, nominal average power level of several milli watts of output when operating at high speeds. This is the most notable aspect of VCSELs. The link margin is determined not by the peak power but rather by the average power. Because operation speeds for off-the-shelf devices are often less than 1 Gbps, 850-nm products have a stronghold on the low-price FSO market. This is due to the fact that the 850-nm VCSEL is significantly more affordable than many of its rivals. Because of the great efficiency of VCSELs, power dissipation is not often a concern for these light-emitting diodes, and hence, active cooling is not necessary. Moreover, the light produced by VCSELs has a circular beam form as opposed to an elliptical beam. The round shape of the beam pattern, which perfectly matches the round core of an optical fibre, makes coupling simpler and more effective. Due to the enormous success of VCSEL technology, numerous VCSEL manufacturers can now create 850 nm laser structures with shorter wavelengths and direct modulation rates of more than 3 Gbps (Bloom et al., 2002).
- Due to the low attenuation properties of optical fibre in this wavelength range, Fabry-Perot (FP) and Distributed-Feedback Lasers (DFB) lasers based on InGaAs/InP semiconductor technology were created particularly for fibre optic communications systems. About 1550 nm is the working wavelength of these lasers. These lower-

power laser sources were developed at the same time as high modulation speed, wavelength stability, reliability, and long lifetimes. Today's lower-power 1550 nm DFB lasers have shown excellent lifetime performance, which meets the stringent requirements of the telecommunications industry. DFB lasers may operate in environments with strict environmental regulations and power fibre networks with 1–40 Gbps of modulation (Willebrand et al., 2003).

In this thesis, we choose the continuous wave laser (CW) as show in Figure 4.5 with a wavelength selection at 1550nm for the case research study. This is because at 1550nm wavelength the FSO systems should able to:

- a) Function at greater power levels, which is crucial for longer-distance FSO systems
- b) Enable fast modulation in FSO systems
- c) Generate with a limited environmental impact and little energy use
- d) Operates across a broad temperature range without significantly degrading performance, particularly for outdoor systems

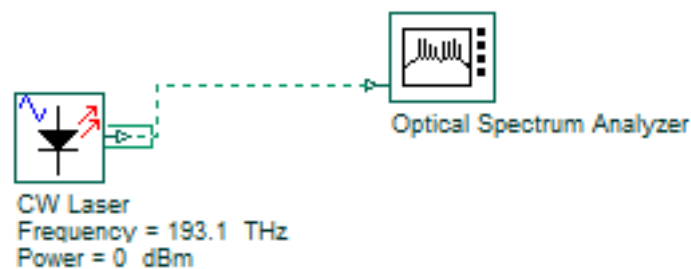


Figure 4.5: CW laser setup

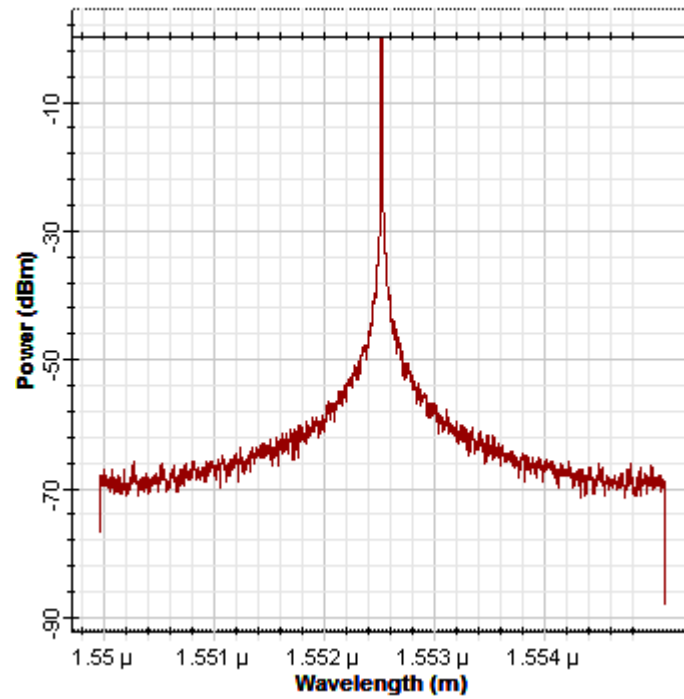


Figure 4.6: Example output LASER

4.2.2 Component 2: Inverter Functionality

An inverter is a type of logic gate that flips the state of the input signal such that it becomes the opposite of the output signal. When the input is correct, the result is always false, and the opposite is also true. The NOT operation in Boolean logic can be carried out via an inverter. As shown in Figure 4.7, the inverter is a component of the FSO communication system that is responsible for converting the electrical signal that was previously produced by the pulse generator.

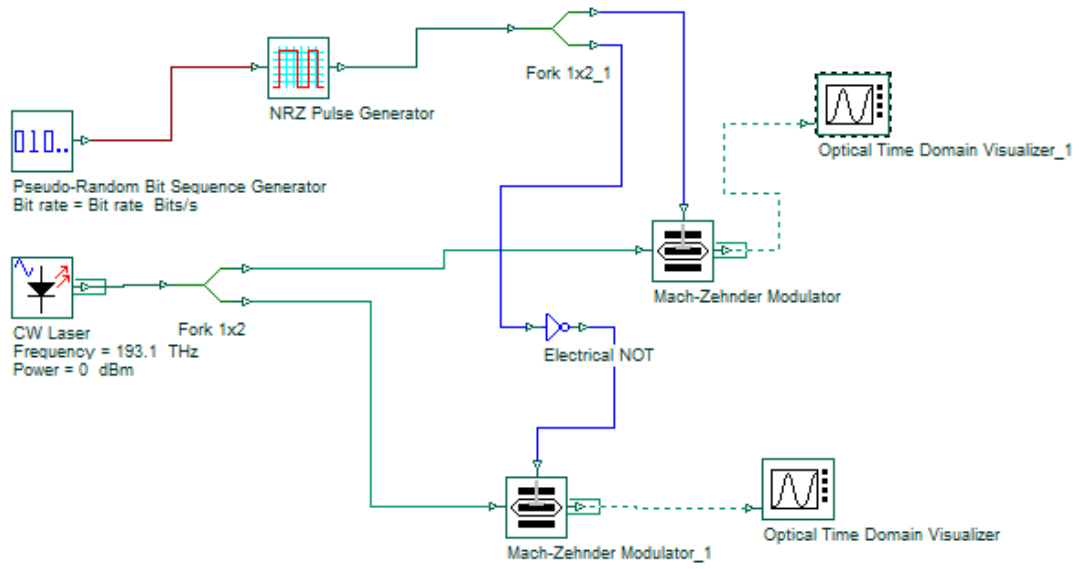


Figure 4.7: Signal complement using inverter for DTBR technique

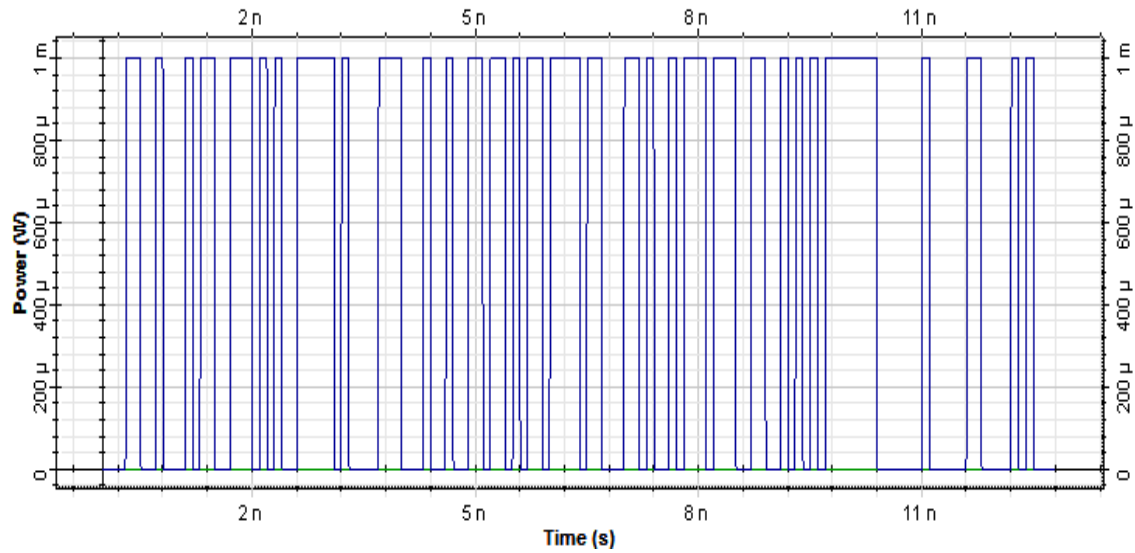


Figure 4.8: Example output original data signal

The Figure 4.8 and Figure 4.9 shows the output signal for condition with and without inverter effect respectively.

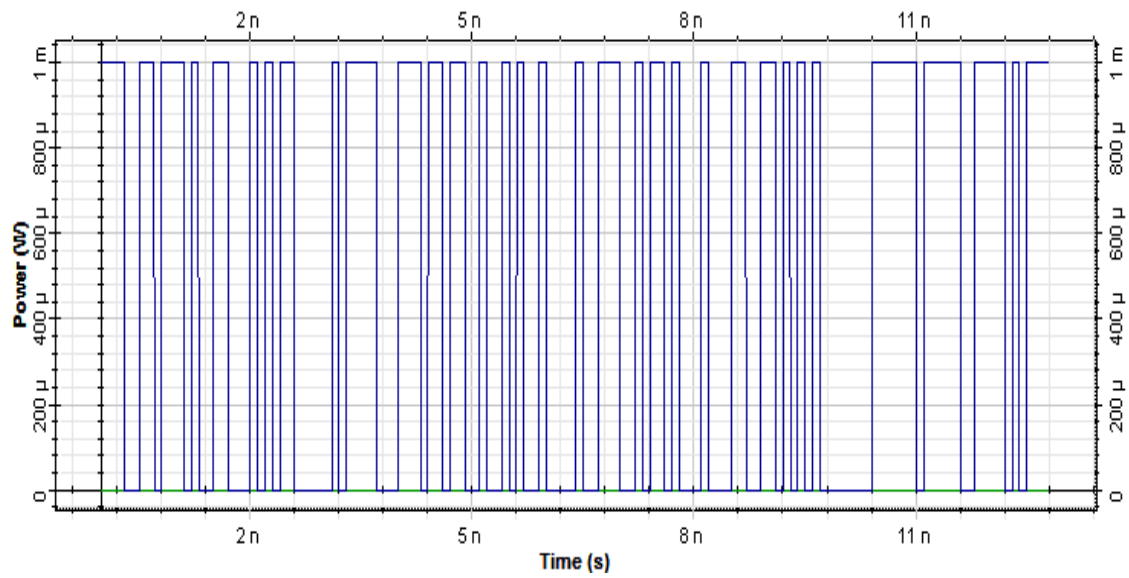


Figure 4.9: Example compliment of original data signal due to inverter effect

4.2.3 Component 3: Balance Receiver

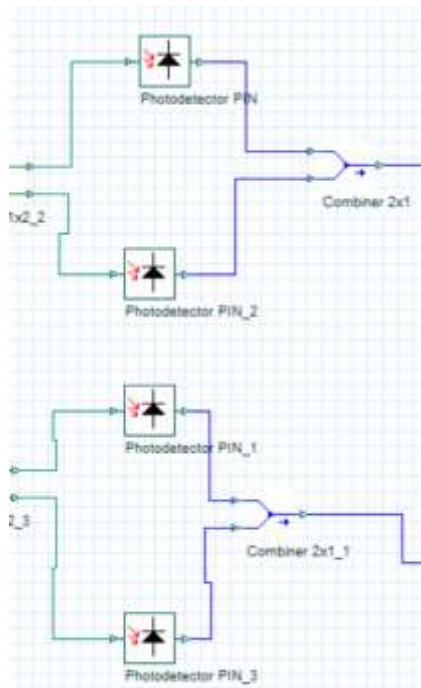


Figure 4.10: Balance receiver 1 and 2 setup

The configuration for the balancing receiver is depicted in Figure 4.10. It consists of two photodetectors for each component of the receiver. For the purpose of this investigation and analysis, a PIN type photodetector is being employed. In common, the balanced receivers, which are made up of anti-parallel photodiodes, are able to suppress both the amplified spontaneous emission noise (ASE) from erbium-doped fibre amplifiers and the laser relative intensity noise (RIN). Therefore, it is possible to attain performance that is shot noise-limited at high optical powers, which considerably enhances the link gain, spurious-free dynamic range, and noise figure.

4.2.4 Component 4: Photodetector

A semiconductor's essential component is either photo resistance, a current generator, or a voltage generator. The value of the photodetector's resistance, current, or voltage depends on the radiant power that has been incident upon it when it is illuminated. In the FSO system, the photodetectors received images of the transmitter's near fields after they had travelled along paths, optical beams through the atmosphere, and certain optics components (Sorensen & Gagliardi, 1979). PIN photodetectors and APD photodetectors are the two most common types of photodetectors used in current technologies.

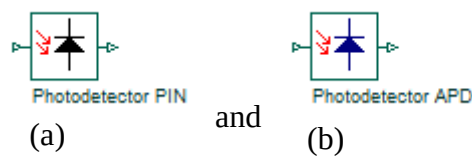


Figure 4.11: Type for PIN and APD light detector

PIN photodiode's 'p' and 'n' regions are separated by an inherent I region that is very weakly doped with n. During typical operation, a large amount of reverse bias voltage is applied across the device to guarantee that the intrinsic area is totally depleted. When an incoming photon has a higher energy than the bandgap energy of the material, an electron may be stimulated from the valence band to the conduction band. This permits the photon to release a portion of its energy. The electron-hole pairs that are liberated as a consequence of this action called photocarriers. The PIN photodetector is designed to create the bulk of photocarriers in the depletion zone, which is the region where the great majority of incoming light is absorbed (Abou, 2019). Because to the high electric field present in the depletion zone, photocarriers may separate and be collected on the other side of the junction with the inverted bias. This causes a current to flow through an external circuit, and for each photocarrier generated, one electron flows through the circuit. Photocurrent refers to the flow of electric current.

Before the principal signal photocurrent enters the input circuitry of the subsequent amplifier, it is first multiplied on the inside of the Avalanche Photodiode (APD), which is an acronym for avalanche photodiode. Due to the fact that the photocurrent is quadrupled in this process before coming into contact with the thermal noise that is linked with the receiver circuit, the sensitivity of the receiver is increased. Because the n^+-p junction is so shallow in this architecture, photocarriers are generated initially almost entirely in the weakly p -doped intrinsic layer that is referred to as a p -layer. When there is an enough voltage difference between the p and n layers, photocarriers are able to quickly drift over the p layer. As a consequence of this, an enormous field gradient is produced at the n^+-p junction close to the positive electrode, which results in the successful avalanche multiplication of charges. The avalanche mechanism is a function of the bias voltage in addition to being a function of

itself. Si APD is normally operated with a value of M equal to 100 for practical applications. The voltage for the reverse bias might be anywhere from 10 to 100 V. When the bias voltage is too high, the photodiode runs the risk of producing a self-sustaining avalanche current even when it is not being excited by light, which results in an increase in the amount of noise produced by the photodiode (Alathwary & Altubaishi, 2019).

A pin photodiode's sensitivity can't compare to that of an APD due to the latter's significantly higher gain. It's possible that the increased sensitivity will be somewhere in the range of 4 to 7 dB. However, in addition to their benefits, they come with a number of significant drawbacks, including the following: a high operating voltage is necessary in order to generate a robust electric field; the multiplication factor is highly temperature dependent; and additional noise results from saturation effects when applied to high doses of radiation (Amirabadi & Vakili (2019) and Amirabadi & Vakili (2021)). Although solutions to these problems can be found and compensation can be provided, the overall cost will grow. A pin photodiode followed by an electronic amplifier, on the other hand, might potentially give good sensitivity margin, but at the penalty of a longer reaction time. Due to the lower cost, the design consisting of a pin photodetector and electronic amplifier could be more beneficial than the APD setup for data transfer at rates lower than one gigabit per second.

4.2.5 Component 5: Subtractor

Figure 4.11 depicts an electrical subtractor as a function that subtracts the electrical signal from the output of photodetectors 1 and 2. To simplify the computation, it is assumed that the ideal electrical subtractor has no current loss throughout the subtraction operation.

$$\text{subtractor o/p} = (\text{balance receiver 1}) - (\text{balance receiver 2}) \quad \text{Equation 4.1}$$

where the output from the subtractor is in electrical signal form. Consequently the signal output of DTBR technique results the double magnitude of power at receiver as shows in Figure 4.12.

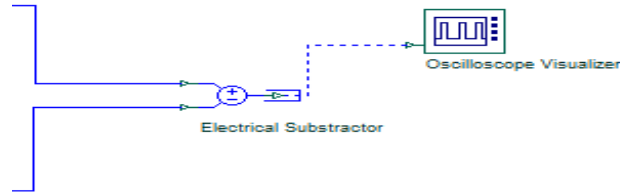


Figure 4.12: Subtraction process configuration

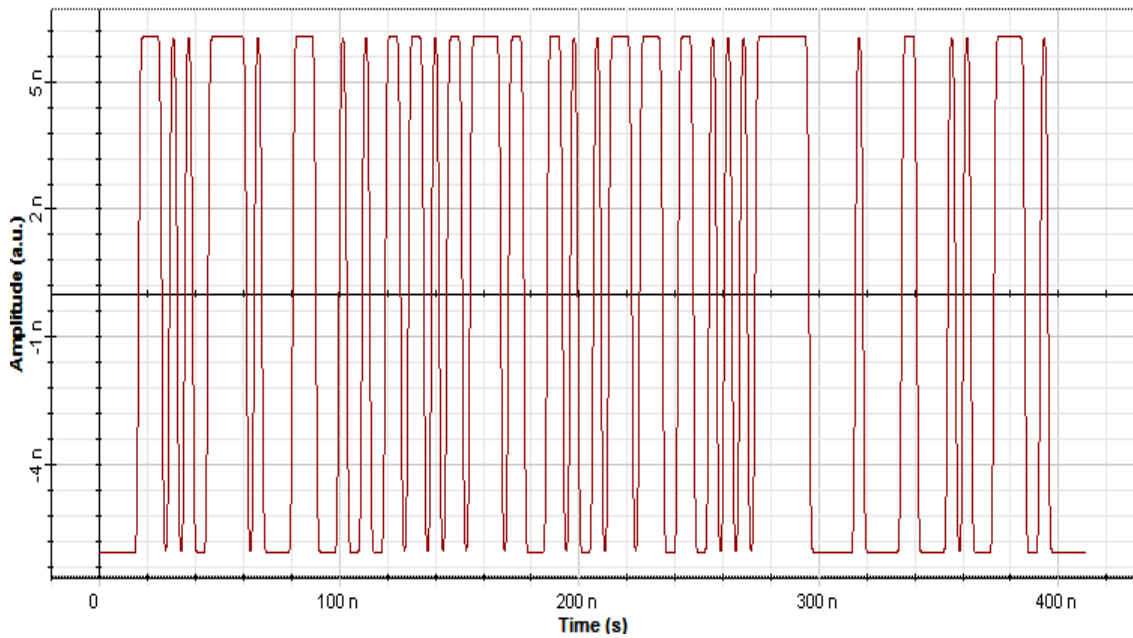


Figure 4.13: Example output after subtraction process

In Figure 4.13 show the increment of the amplitude level as compared with conventional OOK signaling in Figure 4.8 and Figure 4.9. Now, every bit of data has the full

cycle wave pattern from 1 to -1 for bit '1' and bit '0'. The next chapter will discuss in detail the analytical performance of DTBR and conventional ASK.

4.3 Mathematical Derivation

In the event that there is no turbulence, the process of developing the DTBR concept using a theoretical method will entail the signal power, threshold detection, signal-to-noise ratio, and bit error rate. After that, it will analyse the results of the comparison between the theoretical and the traditional ASK approach.

4.3.1 Signal power

The square of the optical field's amplitude may be used to determine the optical beam's intensity (Andrews et al., 2000). The intensity may be expressed as when taking into account the radial distance r from the optical axis.

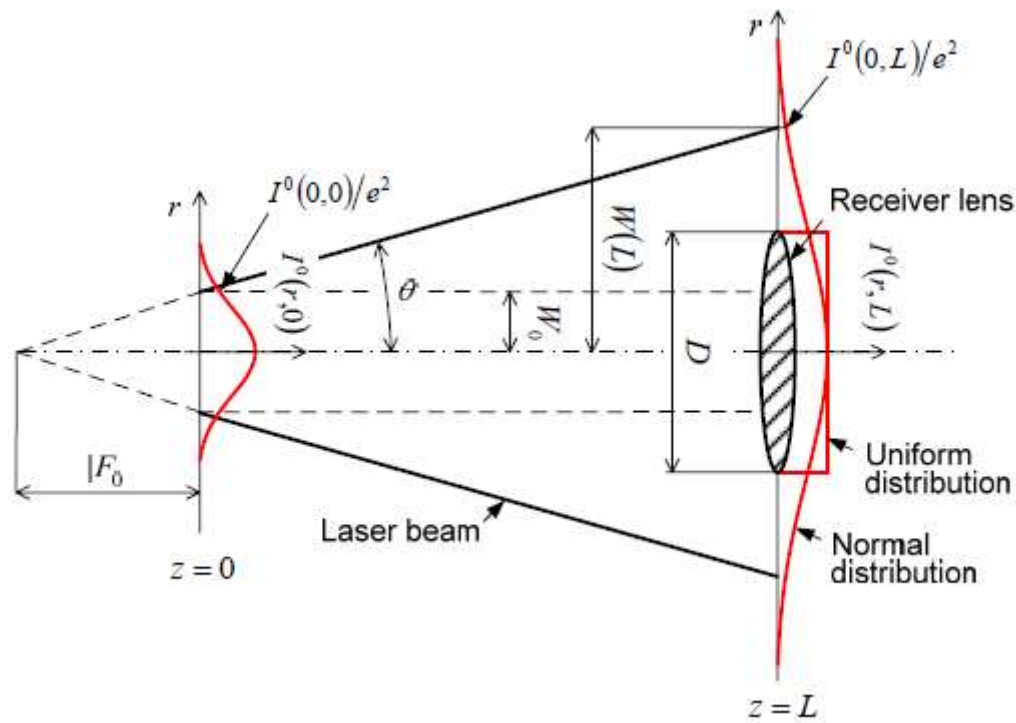
$$I^o(r, L) = I_o \left[\frac{W_o}{W(L)} \right]^2 \exp \left[-\frac{2r^2}{W^2(L)} \right] \quad \text{Equation 4.2}$$

where $I^o = (0,0)$ is the transmitter output intensity at the centre line of the beam, $W(L)$ is the beam spot radius, and 'o' symbol signifies the intensity in free space absent turbulence. The relationship between the intensity of an optical beam and its total power for $r = 0$ as stated by (Saleh & Teich, 1991).

$$I^o(0, L) = I_o \frac{W_o^2}{W^2(L)} = \frac{2P_o}{\pi W^2(L)} \quad \text{Equation 4.3}$$

where P_o is the beam's total transmitted power. The power P incident on the circular receiver lens with aperture diameter D and distance L may be expressed as follows:

$$P(D, L) = P_o \left[1 - \exp \left(-\frac{D^2}{2W^2(L)} \right) \right] \quad \text{Equation 4.4}$$



4.3.1.1 Conventional ASK-OOK Scheme

The total signal power at the receiver for IM/DD is described in SNR as

$$SNR_0 = \frac{\text{Total signal power}}{\text{Total noises}} \quad \text{Equation 4.6}$$

$$= \frac{i_s^2}{\sigma_N^2}$$

where (i_s^2) is total signal power and (σ_N^2) is the total signal noises.

$$i_s = \Re P_r \quad \text{Equation 4.7}$$

where the poor represent the power received and then $\Re$ represent the responsivity which can be written as

$$\Re = \frac{\eta e \lambda}{hc} \quad \text{Equation 4.8}$$

Therefore, λ is the wavelength transmission, η is the detector quantum efficiency in electrons/photon, e is an electric charge in coulombs, h is Plank's constant, and c is the speed of light. Remember that the Gaussian model for intensity profile may be used to explain the free space propagation of a laser beam as

$$P_r = \int_0^{2\pi} \int_0^\infty I(O, L) r dr d\theta$$

$$= \Re \left(\frac{\pi D^2}{8} I(0, L) \right) \quad \text{Equation 4.9}$$

where $I(0, L)$ can be obtained in Equation 4.3.

4.3.1.2 Double Transmission Balance Receiver Scheme

The total signal power at the receiver for DTBR after through the subtraction process at the receiver can described as

$$\begin{aligned}
i_s &= i_{s1} - i_{s2} \\
&= i_{s1} - (-\overline{i_{s1}})
\end{aligned}
\tag{Equation 4.10}$$

where i_{s2} is complimentary of i_{s1}

Recall that free space propagation of a laser beam in the Gaussian model for intensity profile as described as

$$P_r = \int_0^{2\pi} \int_0^\infty I(O, L) r dr d\theta \tag{Equation 4.11}$$

Therefore,

$$\begin{aligned}
i_s &= 2\Re \int_0^{2\pi} \int_0^\infty I(O, L) r dr d\theta - (-2\Re \int_0^{2\pi} \int_0^\infty I(O, L) r dr d\theta) \\
&= 2\Re\left(\frac{\pi D^2}{8} I(0, L)\right) - (-2\Re\left(\frac{\pi D^2}{8} I(0, L)\right)) \\
&= 4\Re\left(\frac{\pi D^2}{8} I(0, L)\right)
\end{aligned}
\tag{Equation 4.12}$$

Thus, the total signal power of DTBR can be written as,

$$i_s = 4\Re P_r \tag{Equation 4.13}$$

4.3.2 Threshold detection in DTBR Technique

Figure 4.15 provides an illustration of the threshold detection signal that is produced by the receiver component. The signal that was received from the subtractor is sent into the balance receiver 1 and the signal that was received from the balance receiver 2 accordingly. In addition to this, we are going to presume that the received signal is completely synchronous at the receiver and that there is no delay condition.

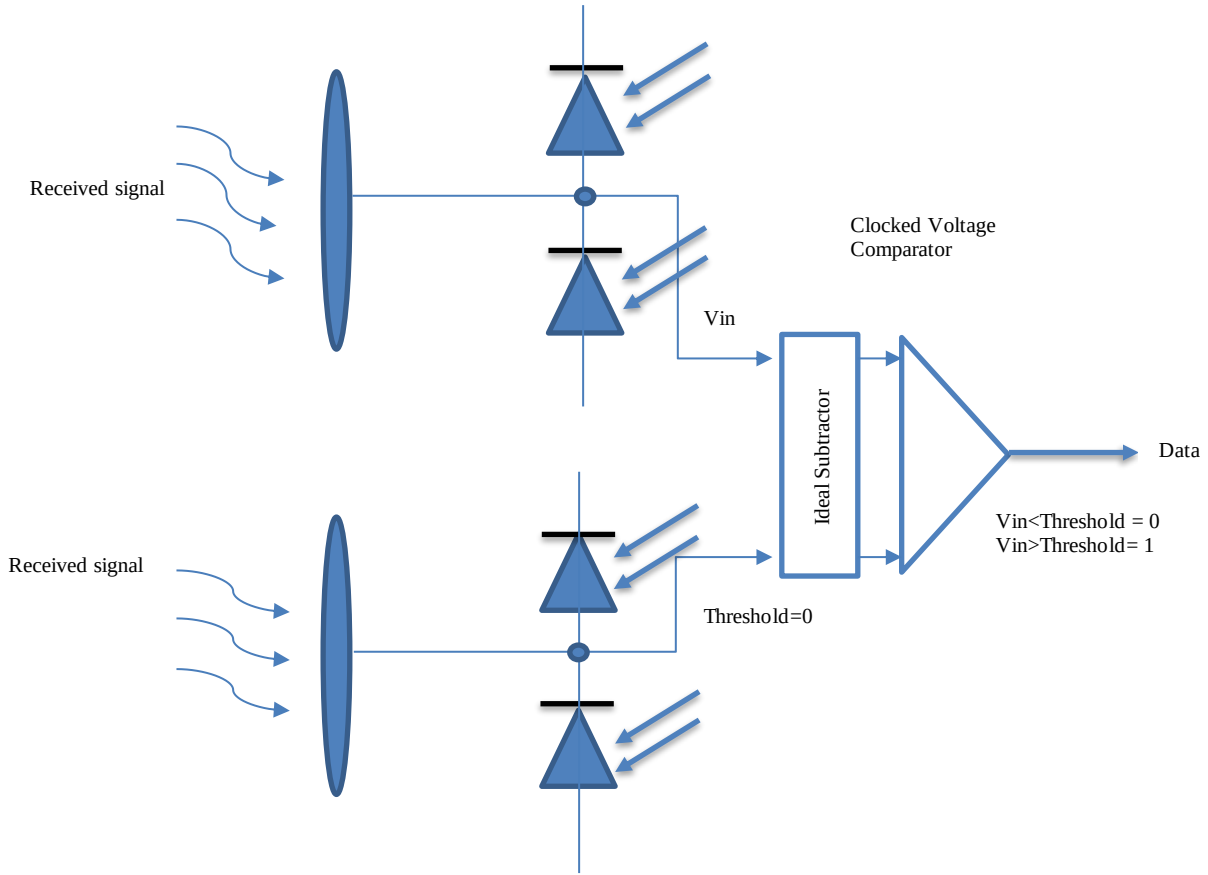


Figure 4.15: Threshold detection concept at receiver for DTBR technique

The channel is considered to be a zero-mean wide-sense stationary Gaussian process in the conventional ASK approach, and all receiver processing circuits aside from the threshold device are assumed to be linear. Together with the notion that the threshold device is linear, these two presumptions are made. A binary signal and noise may be present at the input of the linear-processing receiver circuit in this scenario, and the sample output may be denoted as

$$r_o = x_o + n_o \quad \text{Equation 4.14}$$

where r_o is the received signal, x_o is a signal being sent whether bit '1' or '0' and n_o is represent Addictive White Gaussian Noise (AWGN) with zero mean Gaussian random variable ($\mu = 0, \sigma_N^2 = \frac{N}{2}$).

Nevertheless, the received signal for DTBR technique from photodetector 1 and photodetector 2 respectively as shown in Figure 4.16 which can be denoted as:

$$r_1 = x_1 + n_1 \quad \text{Equation 4.15}$$

and

$$r_2 = x_2 + n_2 = \bar{s}_1 + n_2 \quad \text{Equation 4.16}$$

where $s_2 = \bar{s}_1$ which $\bar{s}_1$ mean complements of s_1 , the x_1 and x_2 are the signal transmitted and n_1 and n_2 are zero mean Gaussian random variable. r_o is an output signal after via the subtraction. The output after subtraction can be derived as:

$$r_o = r_1 + r_2 \quad \text{Equation 4.17}$$

Substitute the Equation 4.15 and Equation 4.16 into Equation 4.17 will produce the output

$$r_o = (x_1 + n_1) - (\bar{x}_1 + n_2)$$

$$r_o = x_1 - \bar{x}_1 + n_1 - n_2$$

$$r_o = x + n \quad \text{Equation 4.18}$$

where the $x = x_1 - \bar{x}_1$ and $n = n_1 - n_2$

The overall process of binary detection for DTBR technique can be denoted in Table 4.1.

Table 4.1: Bit detection for DTBR technique at receiver

Transmitter (T _x)		FSO CHALLENGES	Receiver (R _x)		Subtraction process	
Sending bit		Atmospheric turbulence	Received bit		R _{x1} -R _{x2}	
T _{x1}	1		R _{x1}	1	Bit '1'	1
	0			0		
T _{x2}	0		R _{x2}	0	Bit '0'	-1
(Compliment)	1			1		

The signal is in the polar signalling format, commonly known as the anti-podal signal. The method assumes that n is also a Gaussian RV with zero mean and variance $2\sigma_o^2$, since n_1 and n_2 are Gaussian RVs with zero mean and variance σ_o^2 , respectively.

4.3.3 SNR Without Presence of Turbulence

4.3.3.1 Conventional ASK – OOK Technique

The ratio of signal power (i_s^2) over the presence of signal noises (σ_N^2), as shown in Equation 4.6, may be used to calculate the output SNR in the absence of optical turbulence. Meanwhile for the total noise power (σ_N^2), we only consider the shot noise and thermal noise for the simplicity calculation purpose.

$$\sigma_N^2 = i_{shot}^2 + i_{thermal}^2 \quad \text{Equation 4.19}$$

The shot noise for conventional ASK can be rewritten,

$$\begin{aligned}
i_{shot}^2 &= 2e(i_s)B \\
&= 2e(\Re P_r)B \\
&= 2e\Re\left(\left(\frac{\pi D^2}{8}\right)\left(\frac{2P_o}{\pi W^2(L)}\right)\right)B,
\end{aligned}
\tag{Equation 4.20}$$

and for the thermal noise,

$$i_{thermal}^2 = \frac{4k_b T_n B}{R_L} \tag{Equation 4.21}$$

Therefore, SNR without presence of turbulence can be written as,

$$SNR_o = \frac{\Re^2\left(\left(\frac{\pi D^2}{8}\right)\left(\frac{2P_o}{\pi W^2(L)}\right)\right)^2}{2e\Re\left(\left(\frac{\pi D^2}{8}\right)\left(\frac{2P_o}{\pi W^2(L)}\right)\right)B + \frac{4k_b T_n B}{R_L}} \tag{Equation 4.22}$$

4.3.3.2 Double Transmission Balance Receiver Modulation Technique

The shot noise for DTBR can be re-written and become,

$$\begin{aligned}
i_{shot}^2 &= 2e(i_s)B \\
&= 2e(2\Re P_r)B \\
&= 4e\Re\left(\left(\frac{\pi D^2}{8}\right)\left(\frac{2P_o}{\pi W^2(L)}\right)\right)B,
\end{aligned}
\tag{Equation 4.23}$$

and for the thermal noise same as the Equation 4.21.

Thus, SNR without presence of turbulence can be written as,

$$SNR_o = \frac{4^2 \Re^2\left(\left(\frac{\pi D^2}{8}\right)\left(\frac{2P_o}{\pi W^2(L)}\right)\right)^2}{8e\Re\left(\left(\frac{\pi D^2}{8}\right)\left(\frac{2P_o}{\pi W^2(L)}\right)\right)B + \frac{4k_b T_n B}{R_L}} \tag{Equation 4.24}$$

4.3.4 Bit Error Rate (BER)

The bit error probability may be considered of as an estimate of the bit error rate, often known as BER. This estimate remains accurate over a sizable period of time and in the

face of large amounts of bit mistakes. The number of bit errors in a digital transmission may be defined as the number of received bits in a data stream that have been altered because of noise, interference, distortion, or problems with bit synchronisation. As a data stream is transferred via a communication channel, certain kinds of errors may happen. By dividing the total number of bit transfers by the number of bit errors that happened during the investigational period, one may get the bit error rate, also known as the bit error ratio (BER). The BER is a performance statistic that is often expressed as a percentage and has no units. The anticipated value of the BER, also known as the bit error probability P_e , may be expressed as follows: The bit error probability of any binary transmission may be calculated using the following general equation (Andrews et al., 2005):

$$P_e = P(1) \int_{-\infty}^{V_T} P(0|1)dI + P(0) \int_{V_T}^{\infty} P(1|0)dI \quad \text{Equation 4.25}$$

Therefore the BER characteristic can be is defined as

- 1) The percentage of incorrect bits compared to all bits.
- 2) The theoretically anticipated expected BER is the probability of error.
- 3) The more the signal is distorted, the more erroneous bits there are.
- 4) The basic description of the performance criteria for a digital communication system is the BER.
- 5) As it is a key sign of the system's health, it is a crucial idea to comprehend in any digital transmission system.

4.3.4.1 Conventional ASK – OOK Scheme

The conventional ASK are using the bit ‘1’ and ‘0’ to indicate the signal data. Therefore, it will involve two possibility the incoming signal whether decide signal ‘1’ or signal ‘0’. The

probability of the received signal, x conditioned "0" and "1," given a Gaussian additive noise, is as follows:

- μ_1 = mean of x when bit '1' is transmitted
- μ_0 = mean of x when bit '0' is transmitted
- σ_1^2 = variance of x when bit '1' is transmitted
- σ_0^2 = variance of x when bit '0' is transmitted

In order to determine the bit '1' and bit '0', it need the threshold to decide. The rule is:

- If $x > \text{"Threshold"}$, will choose bit '1' was sent
- If $x < \text{"Threshold"}$, will choose the bit '0' was sent

Thus the two conditional probability density function (PDF) for can be written as

$$P(0|1) = \frac{1}{\sigma_1\sqrt{2\pi}} \int_{-\infty}^{I_D} \exp\left(-\frac{(I-I_1)^2}{2\sigma_1^2}\right) dI = \frac{1}{2} \operatorname{erfc}\left(\frac{I_1-I_D}{\sigma_1\sqrt{2}}\right) \quad \text{Equation 4.26}$$

$$P(1|0) = \frac{1}{\sigma_0\sqrt{2\pi}} \int_{I_D}^{\infty} \exp\left(-\frac{(I-I_0)^2}{2\sigma_0^2}\right) dI = \frac{1}{2} \operatorname{erfc}\left(\frac{I_D-I_0}{\sigma_0\sqrt{2}}\right) \quad \text{Equation 4.27}$$

where complementary error function $\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-y^2) dy$ and I_D is the threshold value.

The $P(0|1)$ is represent the conditional error of the system will occur if the receiver decided the incoming signal as '0' but indeed the transmitter sent the bit '1'. Meanwhile for $P(1|0)$ is indicate that the receiver decide the incoming signal as bit '1' but indeed the transmitter sent the bit '0'. Therefore BER can be written as

$$BER = \frac{1}{4} \left[\operatorname{erfc} \left(\frac{I_1 - I_D}{\sigma_1 \sqrt{2}} \right) + \operatorname{erfc} \left(\frac{I_D - I_0}{\sigma_0 \sqrt{2}} \right) \right] = \frac{1}{2} \operatorname{erfc} \left(\frac{Q}{\sqrt{2}} \right) \quad \text{Equation 4.28}$$

$$= \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{SNR}{2}} \right)$$

where the $Q(x)$ is Gaussian Q-function with $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}} dt$

4.3.4.2 Double Transmission Balance Receiver Scheme

As can be seen in Table 4.2, the DTBR method still makes use of the basic bits that are the same as traditional ASK-OOK signalling, which are bit '1' and bit '0'. However, the received signal that is intended to be received differs. In the event that the transmitter transmitted bit "1" the receiver ought to have received signal "1" and in the event that the transmitter sent bit "0" the receiver ought to have received signal "-1". The term "bipolar signalling" might be used to describe this phenomenon. It is possible at this point to write the two conditional PDFs for the DTBR approach as

$$P(0|1) = \frac{1}{\sigma_1 2\sqrt{2\pi}} e^{-\frac{(I-I_1)^2}{4\sigma_1^2}} \quad \text{Equation 4.29}$$

$$P(1|0) = \frac{1}{\sigma_0 2\sqrt{2\pi}} e^{-\frac{(I-I_0)^2}{4\sigma_0^2}} \quad \text{Equation 4.30}$$

By considering equally likely condition, we obtain the BER in absence atmospheric turbulence

$$P(0|1) = P(1|0) = Q \left(\sqrt{\frac{2E_b}{N_o}} \right) \cong \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{E_b}{N_o}} \right) \quad \text{Equation 4.31}$$

$$= \frac{1}{2} \operatorname{erfc}(\sqrt{SNR})$$

In terms of E_b and N_o and $\frac{E_b}{N_o} = SNR_o$ can be obtained in Equation 4.22.

4.4 Main Performance Analysis With Presence of Turbulence: Comparison evaluation DTBR Versus Conventional ASK-OOK

The signal-to-noise ratio and bit error rate are the two most important aspects of performance that need to be evaluated. The SNR will indicate the amount of noise that is present on top of the signal, and the BER will define the maximum number of bit errors that can occur (Nistazakis et al., 2009).

4.4.1 Signal to Noise Ratio (SNR)

In the presence of atmospheric turbulence, the received signal exhibits additional power losses (refraction, diffraction) and random turbulence fluctuations. The SNR will determine as a mean SNR. In this case it will consider the SNR without presence of turbulence and also the flux variance as shown in Equation 4.32 The mean SNR can be written as

$$\langle SNRP \rangle = \frac{SNR_0}{\sqrt{\left(\frac{P_{SO}}{\langle P_S \rangle}\right) + \sigma_{flux}^2(L+L_f, \Omega_G) SNR_0^2}} \quad \text{Equation 4.32}$$

where the $\sigma_{flux}^2(L+L_f, \Omega_G)$ and SNR_0 can be obtained in Equation 3.8 and Equation 4.24.

$$\langle SNRP \rangle = \frac{SNR_0}{\sqrt{1 + q_c \Lambda_1 + 1.63 \sigma_I^{12/5} \Lambda_1 + \sigma_{flux}^2(L+L_f, \Omega_G) SNR_0^2}} \quad \text{Equation 4.33}$$

where P_{SO} is the signal power in the absence of atmospheric effects and $\sigma_I^2(L + L_f, \Omega_G)$ is the intensity flux variance on the photo detector. Angle bracket $\langle \rangle$ represents the mean.

The power ratio $\frac{P_{SO}}{\langle P_S \rangle}$ provides a measure of SNR deterioration caused by atmospheric induced beam spreading given by

$$\frac{P_{so}}{\langle P_S \rangle} = 1 + 1.63 \sigma_R^{\frac{12}{5}} \Lambda_1 \quad \text{Equation 4.34}$$

4.4.2 Probability of Error, P_e

When determining the BER performance when the turbulence effect is active, it is necessary to take into account the complete error probability. Since the signal to noise ratio is calculated using the mean value, as demonstrated in Equation 4.33, this method will require the integral representation of BER in order to determine the mean of BER. The probability error of DTBR performance when turbulence is present and the Gamma-Gamma distribution is being used may be stated as:

$$Pr(E) = \langle BER \rangle = \frac{1}{2} \int_0^\infty p_I(I) \operatorname{erfc} \left(\sqrt{\left\langle \frac{E_b}{N_o} \right\rangle} I \right) dI \quad \text{Equation 4.35}$$

where $p_I(I)$ is a gamma-gamma distribution as shown in Equation 3.21 and the $\left\langle \frac{E_b}{N_o} \right\rangle = \langle SNRP \rangle$. When aperture averaging effects are considered, parameters α and β of the gamma-gamma PDF are defined as

$$\alpha = \frac{1}{\exp[\sigma_{\ln x}^2(L + L_f, \Omega_G)] - 1} \quad \text{Equation 4.36}$$

$$\beta = \frac{1}{\exp[\sigma_{\ln y}^2(L + L_f, \Omega_G)] - 1} \quad \text{Equation 4.37}$$

where $\sigma_{\ln x}^2(L + L_f, \Omega_G)$ and $\sigma_{\ln y}^2(L + L_f, \Omega_G)$ are relate to large and small scale log intensity variances obtained in Equation 4.21 and Equation 4.23 respectively. The Appendix C shows the example calculation using the MATLAB code to obtain probability of error with some calculation value has been made early using excel. This because there is no simple

mathematical form for complex integral gamma gamma and error function as shown in Equation 4.35.

4.5 Summary

The evolution of the DTBR method has been explored, to summarise this topic. New mathematical formulas for SNR and BER, applicable to the recently suggested method, have been successfully obtained for the scenario where there is no turbulence present. The essential points are summed up in Table 4.2 below. The existence of turbulence and the results of the study will be discussed in greater detail in the following chapter, which is Chapter 5.

Table 4.2: Summary of DTBR derivation

	Conventional ASK-OOK	DTBR
Signal Power	$i_s = \Re(\frac{\pi D^2}{8} I(0, L))$	$i_s = 4\Re(\frac{\pi D^2}{8} I(0, L))$
Bit detection	Bit '1' = 1 Bit '0' = 0	Bit '1' = 1 Bit '0' = -1
SNR	$\frac{\Re^2((\frac{\pi D^2}{8})(\frac{2P_o}{\pi W^2(L)}))^2}{2e\Re\left(\left(\frac{\pi D^2}{8}\right)\left(\frac{2P_o}{\pi W^2(L)}\right)\right)B + \frac{4k_b T_n B}{R_L}}$	$\frac{4^2\Re^2((\frac{\pi D^2}{8})(\frac{2P_o}{\pi W^2(L)}))^2}{8e\Re\left(\left(\frac{\pi D^2}{8}\right)\left(\frac{2P_o}{\pi W^2(L)}\right)\right)B + \frac{4k_b T_n B}{R_L}}$
BER	$\frac{1}{2} \operatorname{erfc}\left(\sqrt{\frac{SNR}{2}}\right)$	$\frac{1}{2} \operatorname{erfc}(\sqrt{SNR})$

CHAPTER 5

PERFORMANCE ANALYSIS OF DOUBLE TRANSMISSION BALANCE RECEIVER (DTBR) IN FSO SYSTEM

5.1 Introduction

The purpose of this chapter is to explore the performance analysis of DTBR in free space optical communication while taking into account the influence of turbulence. We will also discuss about how to derive the signal to noise ratio (commonly known as SNR) and the bit error rate (also known as BER). The performance of DTBR will be examined and comparison with conventional ASK. The findings provided came from theoretical study which from derivation of SNR and BER and also result created through simulation. For this research studies is employing the Optisystem software simulation tool. Therefore, this chapter will divide into two main section that is theoretical performance and simulation performance which will evaluate three element effect on signal power, bit rate and distance transmission.

5.2 Theoretical Performance

In the theoretical analysis, the primary conditions that will be looked at are as follows: The first method is called condition over power signal, and it involves determining the strength of the signal as it is going through turbulent conditions. The stronger the signal, the higher the quality of the signal. The second prerequisite is to conduct an analysis of the bit error rate. Due to the high scintillation index, the BER has the potential to rapidly grow when intense turbulence is present. A lower BER will suggest that the system is performing

more effectively. In the meantime, the third criteria is the performance of the propagation distance. This is one of the most important aspects of the FSO communication that relates to the range link. The further that an FSO system is able to transmit a signal, the more of a benefit it will be to the system's ability to function efficiently across a long range link. The standard ASK method and the DTBR approach are going to have their respective analytic performances compared to one another. As another method of determining whether or not the system has been improved, the study will make use of the percentage of progress made. Table 5.1 shows the typical parameters to analyze the performance of the DTBR under strong turbulence condition.

Table 5.1: Parameters for DTBR technique performance under strong turbulence

Parameters	Symbols	Value
Wavelength	λ	1550 nm 1300nm 850nm
Distance	L	1000 m
Photodetector efficiency	η	0.7
Power transmitt	P_o	0 dBm
Collecting lens	W_G	0.01 m
Radius of curvature	F_o	∞
Spot beam at transmitter (z=0)	W_o	0.025 m
Bit rate	B	STM-1;155Mbps STM-4;622Mbps STM-16; 2.5Gbps STM-64; 10Gbps
Attenuation	dB/km	7dBkm

5.2.1 Analysis 1: Power

Figure 5.1 compares the effectiveness of received power under light turbulence for DTBR and traditional ASK. Equation 4.35 output is used to study how the curve gap improvement of the DTBR approach may be used to achieve BER performance lower than the BER 10^{-9} , which is considered to be the lowest acceptable BER. According to the graph, the conventional ASK and DTBR are approximately at -21 dBm and -27 dBm, respectively, under the weak turbulence impact. The permissible bit error transmission threshold, shown as a dotted red line, is 10^{-9} . It shows that DTBR can boost performance by roughly 28%.

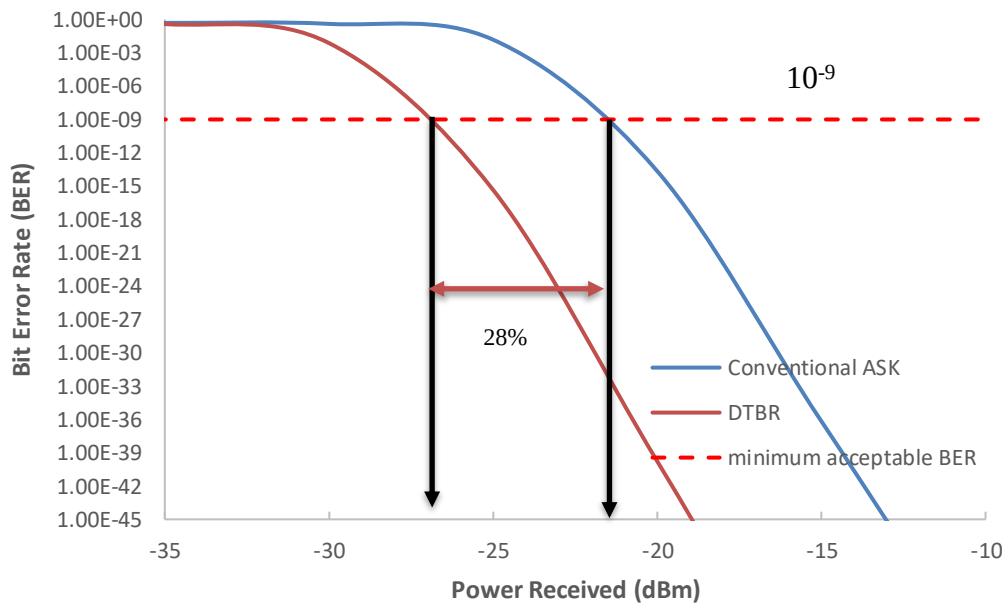


Figure 5.1: Comparison DTBR and Conventional ASK for effective power received under weak turbulence

Meanwhile, Figure 5.2 compares DTBR with traditional ASK for the influence of power received under high turbulence conditions. As a consequence, the BER performance is -19 dBm and -12 dBm, respectively. In general, the BER performance degrades as the quantity of turbulence increases. However, as compared to the usual approach, the DTBR

may boost the power received by around 58%. Indeed, the advancement has provided an advantage over FSO transmission since significant turbulence can cause signal drop to poor quality beam propagation. This allows the DTBR to function more robustly under adverse weather conditions..

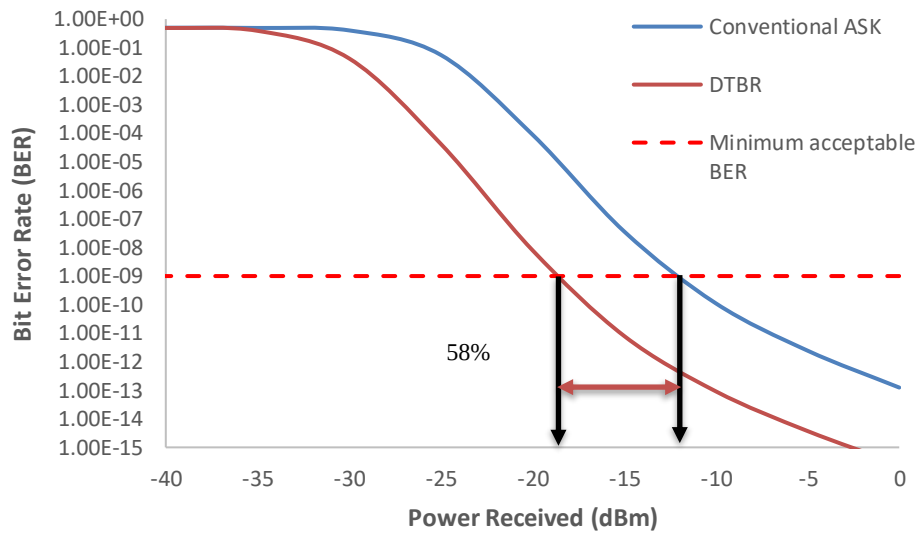


Figure 5.2: Comparison DTBR and Conventional ASK for effective power received under strong turbulence

In Figure 5.3 shows the performance analysis of BER for different power transmits when operate in strong turbulence. This graph is mainly to investigate the ability of the system manage to use the lowest minimum power to operate. As notice in the graph, the conventional method require higher power which approximately 4 dBm for minimum acceptable BER 10^{-9} . However, the DTBR technique can reduce the minimum requirement power which able to operate approximately only -4 dBm. This indicates that the new proposed technique able running under heavy turbulence with small power transmit. In other word if

only small power needed to transmit, the FSOC can reduce the cost and at the same time can maintain the high power received at the receiver.

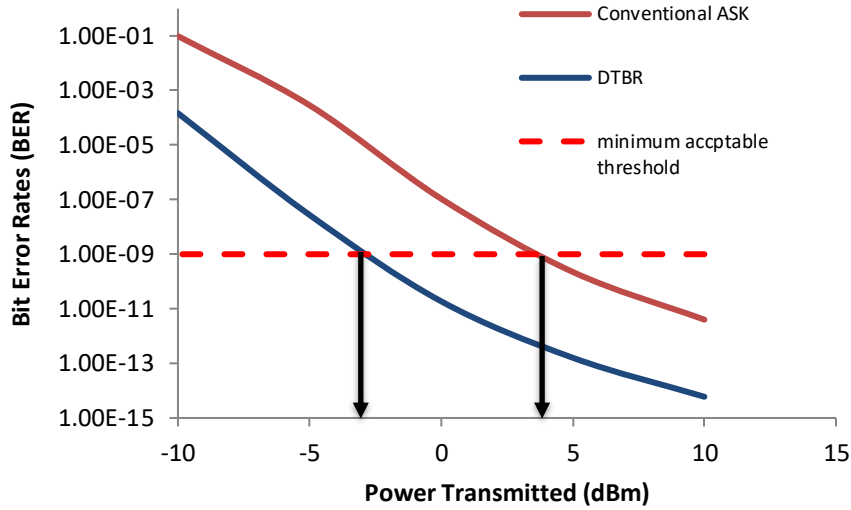
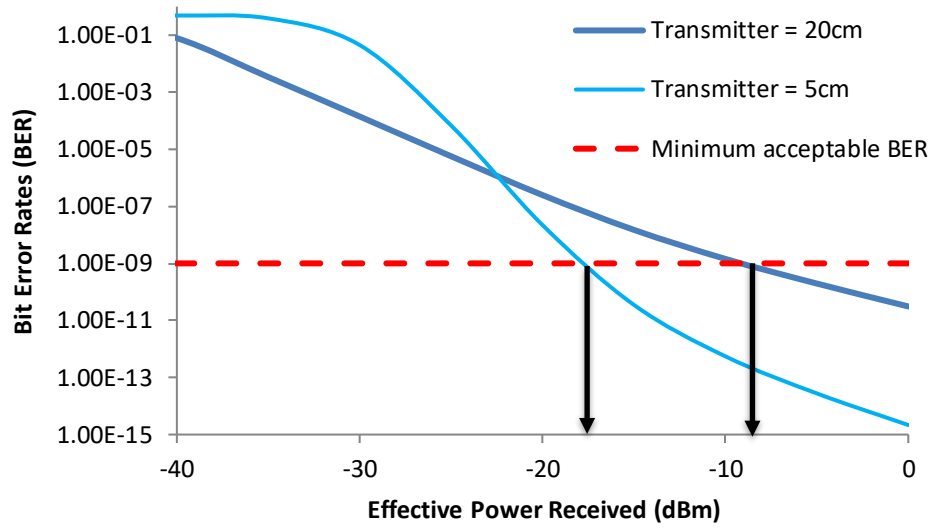


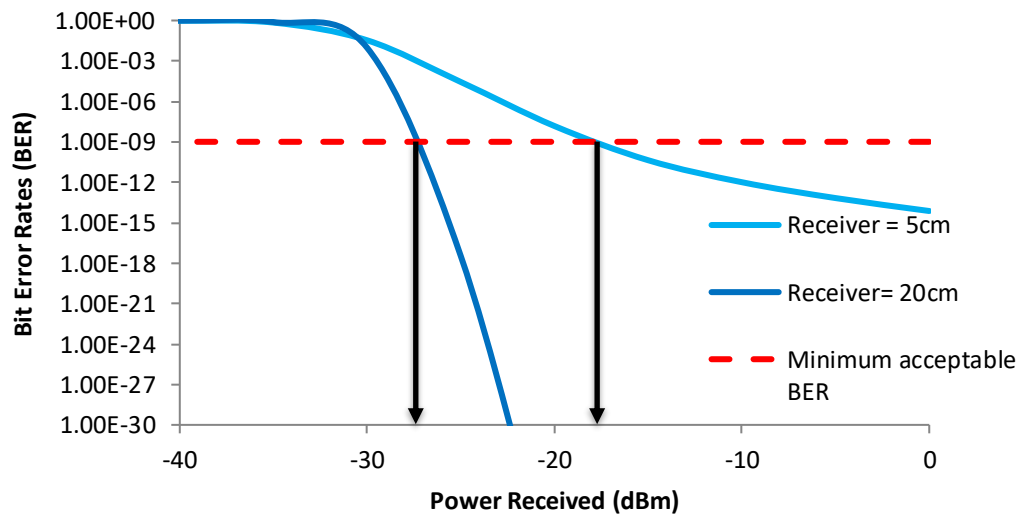
Figure 5.3: Minimum power requirement at transmitter for minimum acceptable BER 10^{-9}

In Figure 5.4 (a) and (b) shows the performance of DTBR transmitter and receiver effect with various aperture size. For the transmit performance in Figure 5.4 (a) is compare with to size 5cm (small) and 20cm (wide) aperture. The results of power received for both size is approximately at -9 dBm and -18 dBm respectively. It shows that the small aperture size of transmitter is better as compare to wide aperture transmitter. The smaller power received means the better system able to detect small light at receiver. The reason is due to small aperture transmitter will produce high intensity power and reduce power loss during transmission. However, it is different scenario in receiver part of FSO system. As we can see in Figure 5.4 (b), the small and wide aperture receiver is approximately at -18 dBm and -28 dBm respectively. The wide receiver aperture is better performance as compare to small receiver. As opposite to transmitter, the wide aperture is more favorable to enhance the receiver effectiveness in order to collect more light. Therefore, it can be conclude to improve

further the DTBR method is using combination small transmitter and wide receiver aperture size.



(a)



(b)

Figure 5.4 (a) and (b): Effect of transmitter and receiver aperture size of DTBR over power received

5.4.2 Analysis 2: Bit Rate

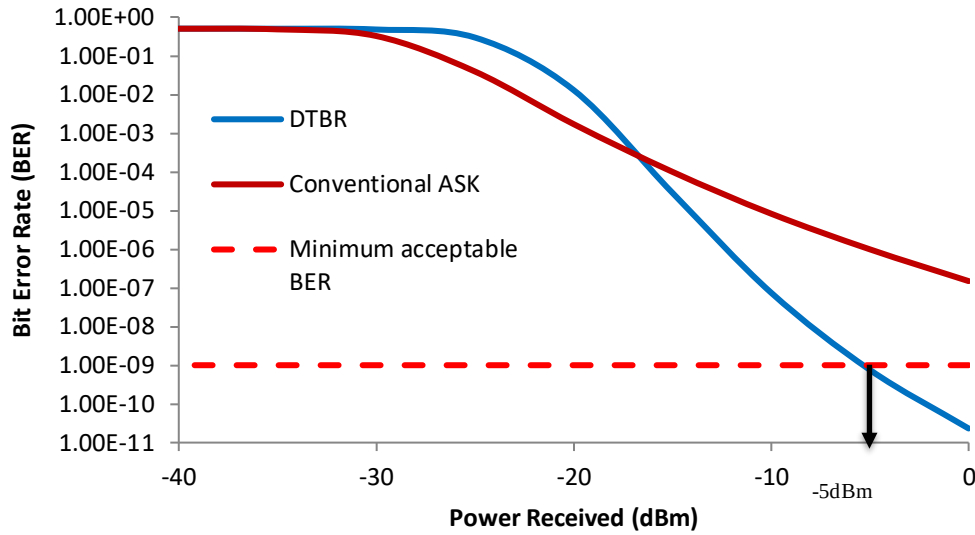


Figure 5.5: Comparison performance received power BER at 10Gbps data rate

Figure 5.5 displays the bit-rate analysis results for DTBR and traditional ASK at large data transmission rates (10 Gbps). This finding helps us learn more about the transmission speeds that both approaches are capable of supporting. Compared to other channels of communication, such as radio frequency and microwave, optical technology is widely used to function at giga bit or tera bit data transfer rates. It is therefore crucial to create an FSO system that can function normally at a high data bit rate. Clearly, only DTBR is able to function with a received signal strength of around -5 dBm, which is the minimum permissible BER. However, in order to enable data transmission rates of 10Gbps using traditional methods, a very large amount of power must be supplied by the transmitter. As a result, the signal quality may be kept high when the suggested new approach is in operation.

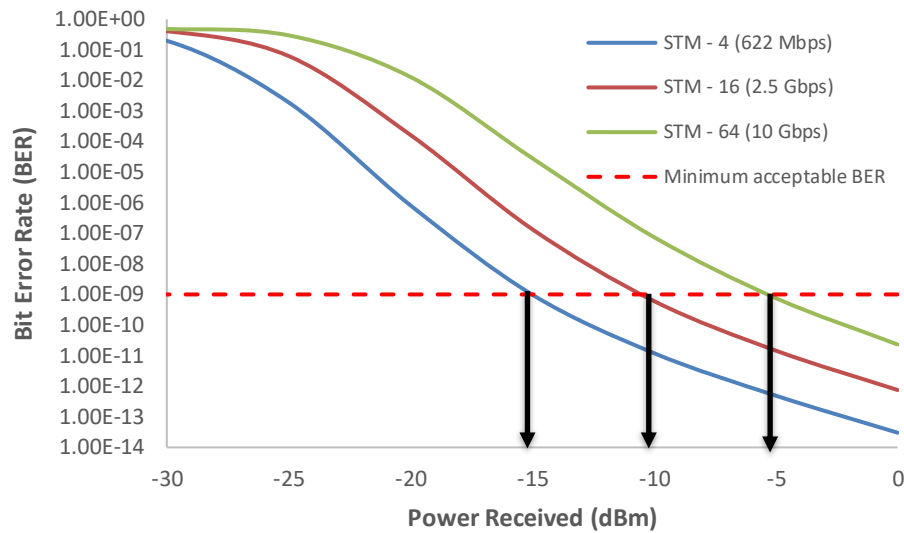


Figure 5.6: DTBR performance BER for different of STM level

Transmission rates of STM-4 (622 Mbps), STM-16 (2.5Gbps), and STM-64 (64 Gbps) are depicted in Figure 5.6, together with the corresponding power received (10Gbps). These days, fibre optic communications often use a data rate known as Synchronous Digital Hierarchy (SDH), abbreviated as STM. Using the graph as a reference, we may estimate that STM4, STM16, and STM64 all have received powers of around -15 dBm, -10 dBm, and -5 dBm, respectively. The graph pattern shows that the level bit rate is decreasing with rising bit rate. Having more data bit errors when running at fast speeds is a bad sign. The most important takeaway is that DTBR can work with very high data rates without compromising signal quality. Because it can provide service at speeds of up to a terabit per second (Tbs), this component is crucial to optical communication.

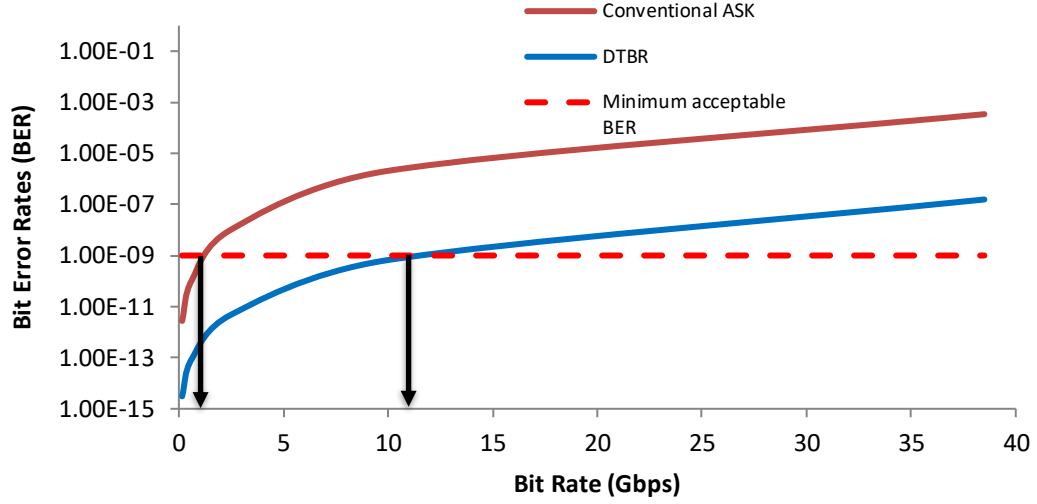


Figure 5.7 : Performance under strong turbulence condition

The investigation of the performance system's response to extreme turbulence is another crucial finding. Figure 5.7 depicts a comparison of the BER under varying transmission bit rates. If we look at the graph, we can see that the minimum bit rate that DTBR can handle is around 11 Gbps, whereas the conventional method can only support around 1 Gbps. Because of this, DTBR can close the gap by around 10 Gbps. In spite of significant turbulence along the path of transmission, this effect is crucial to the successful propagation of FSO beams. In addition, the DTBR approach may strengthen the overall FSO performance to run in any sort of weather impact, not simply turbulence.

5.2.3 Analysis 3: Distance Propagation

Due to the limited range of the widely used FSO technology, analysis of the link propagation is a crucial component. The only similarity is the medium of transmission, which sets this apart from optical fibre optical communication. Measurements of FSO performance have shown that, in general, shorter distances can result in higher quality signal

transmission than longer propagation distances. However, in practise, FSO must have high-quality transmission in order to increase coverage area.

The Figure 5.8 shows the BER versus the various propagation distances strong turbulence condition. As we can see from the graph, as increasing of distance propagation the BER will increase as well. At minimum acceptable BER, the distance of DTBR can support up to approximately 2.2 km and conventional only at 1.2 km. This give improvement about 1km or equivalent to 83% increment of distance. This improvement is important to enable FSO can extent the coverage of path link. This result is expected can increase more FSO distance if set at standard power transmit such as like laserbit equipment 70 dBm. For this analysis on set at 0 dBm power to investigate at low power behaviour.

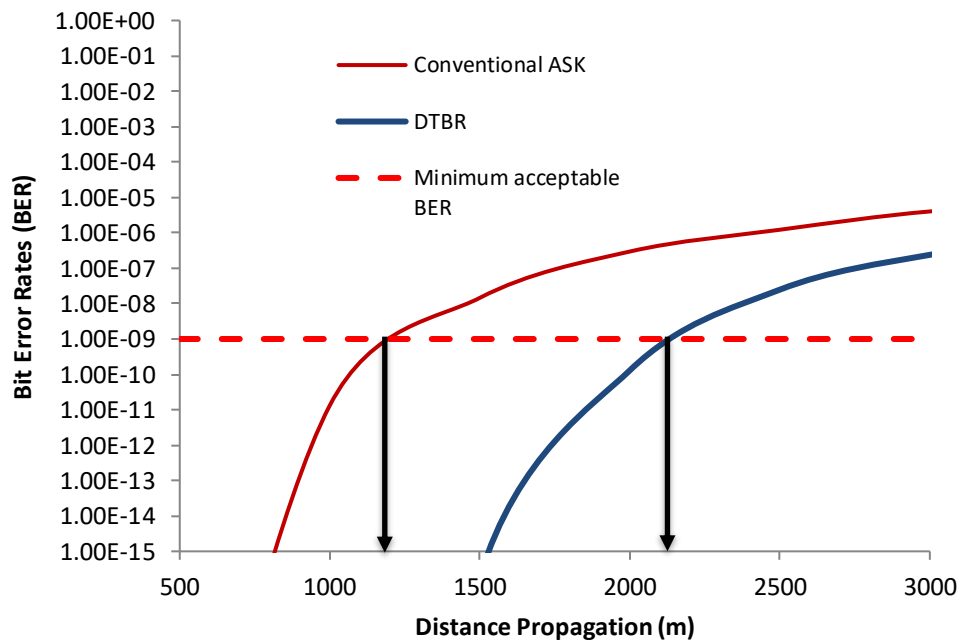


Figure 5.8 : Comparison DTBR and Conventional ASK varying distance under strong turbulence

In Figure 5.9 shows the performance of comparison shorter and longer over DTBR method. This comparison is purposely to analyze the ability of wavelength to operate at high quality signal in strong turbulence and how far distance can support. Each of the wavelength will response differently which depend on condition. As we can see from the graph, for minimum acceptable BER the shorter wavelength only able to operate approximately at 1.7 km distance. However, DTBR manage to increase distance up to 2.2 km. This contribute about 30% improvement of distance. Above 2.5 km, both of technique cannot operate. As discuss in previous graph (Figure 5.8), the gap of different distance can be increase if used standard power transmit which expected can reach up to 5 to 6 km.

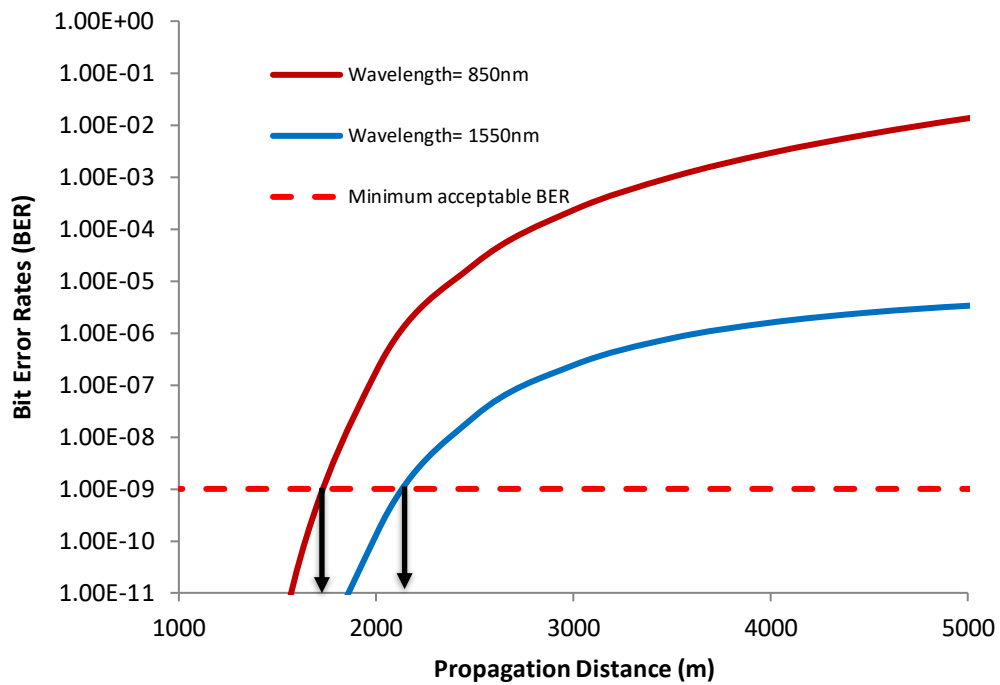


Figure 5.9 : Comparison 780nm and 1550nm wavelength performance

Meanwhile for Figure 5.10 shows the performance of power received for different path link distances. The result is measured for three level of range that is 1 km, 2 km and 3

km. This analysis is purposely to investigate effect of power received and far it drop with 1km different between second and third range. It is important to investigate to study the pattern of power of ability DTBR technique. From the graph, at minimum acceptable BER for 1 km the power received is approximately at -17 dBm. As increases to 2 km distance the received power drop to -24 dBm which contribute gap 40%. When distance at 3 km, the received power drop another 10% which is approximately at -27 dBm. From the result, it can conclude the drop of power received is not contribute bigger different which is good for FSO performance. If too much different cause the overall propagation beam in poor transmission.

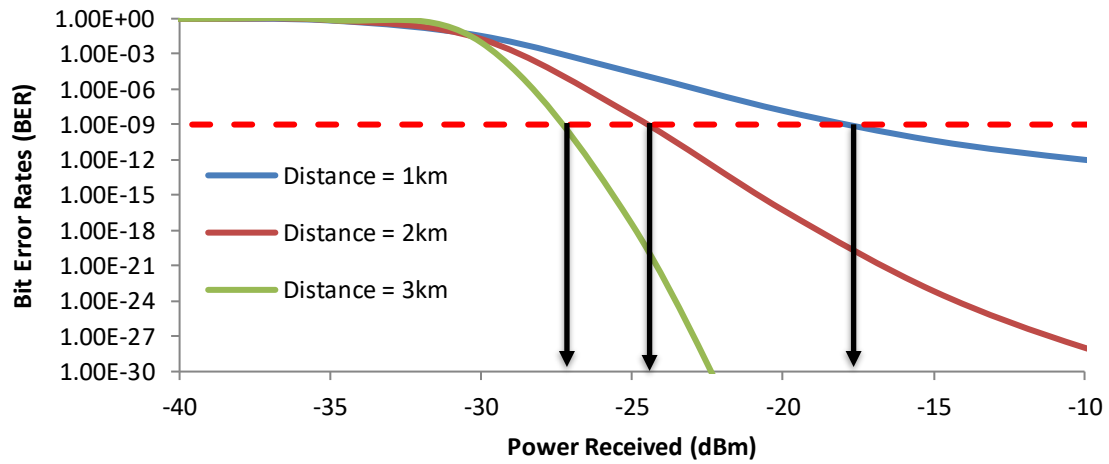


Figure 5.10: Comparison DTBR performance for 1km, 2km and 3km range of transmission

5.3 Simulation Performance

The Optisystem software was used to simulate the performance of the DTBR approach. The topology of the DTBR setup for simulation analysis is depicted in Figure 5.11. The laser source employed at the transmitter is a Continuous Wave (CW) laser with a transmit power of 0 dBm. The wavelength of 1550nm was chosen because it performs better than 850nm. Pseudo-Random Bit Sequence (PRBS) with Non-Return Zero (NRZ) as a modulation format was used to generate the data. The electrical signal will then be modulated into an optical signal by an external modulator, the Mach-Zehnder Modulator (MZM), prior to transmission. There will be two transmitters used: one for original data and one for inverting data.

In medium part, the FSO component will be used. The propagation range is set at 1 km and the attenuation of atmospheric is set to 0 dB/km for condition without presence of turbulence. If presence of turbulence, the attenuation will set in various value according to calculation via theoretical. For the intensity scintillation is set at $100 \times 10^{-15} \text{ m}^{-2/3}$ for strong turbulence condition and for weak turbulence $1 \times 10^{-15} \text{ m}^{-2/3}$. Under geometrical loss factors, the transmitter aperture and receiver aperture are set 2.5cm and 8cm respectively. Meanwhile the beam divergence is pick at 1 mrad and other parameters such as transmitter loss, receiver loss, additional loss and propagation delay are remaining in default value. The noise that generated at receiver were set at random and the dark current value at 10nA with responsivity 1 A/W and thermal noise $100 \times 10^{-24} \text{ W/Hz}$. The performance of the system can be evaluated through BER analyzer, oscilloscope visualizer and eye patterns.

At the receiver, it is assumed that none of the signals that were received had any delay before being detected by the balance receivers 1 and 2. Both of the receivers' balances

are equipped with two photodetectors each. It is anticipated that the noise will be compressed by the balancing receiver, and the photodetector will transform signals from optical to electrical. The signal from the filter will be applied to the output of the balance receiver, and the data will then be sent to the subtraction component section. Output from subtraction procedure is the ultimate output of the DTBR technology.

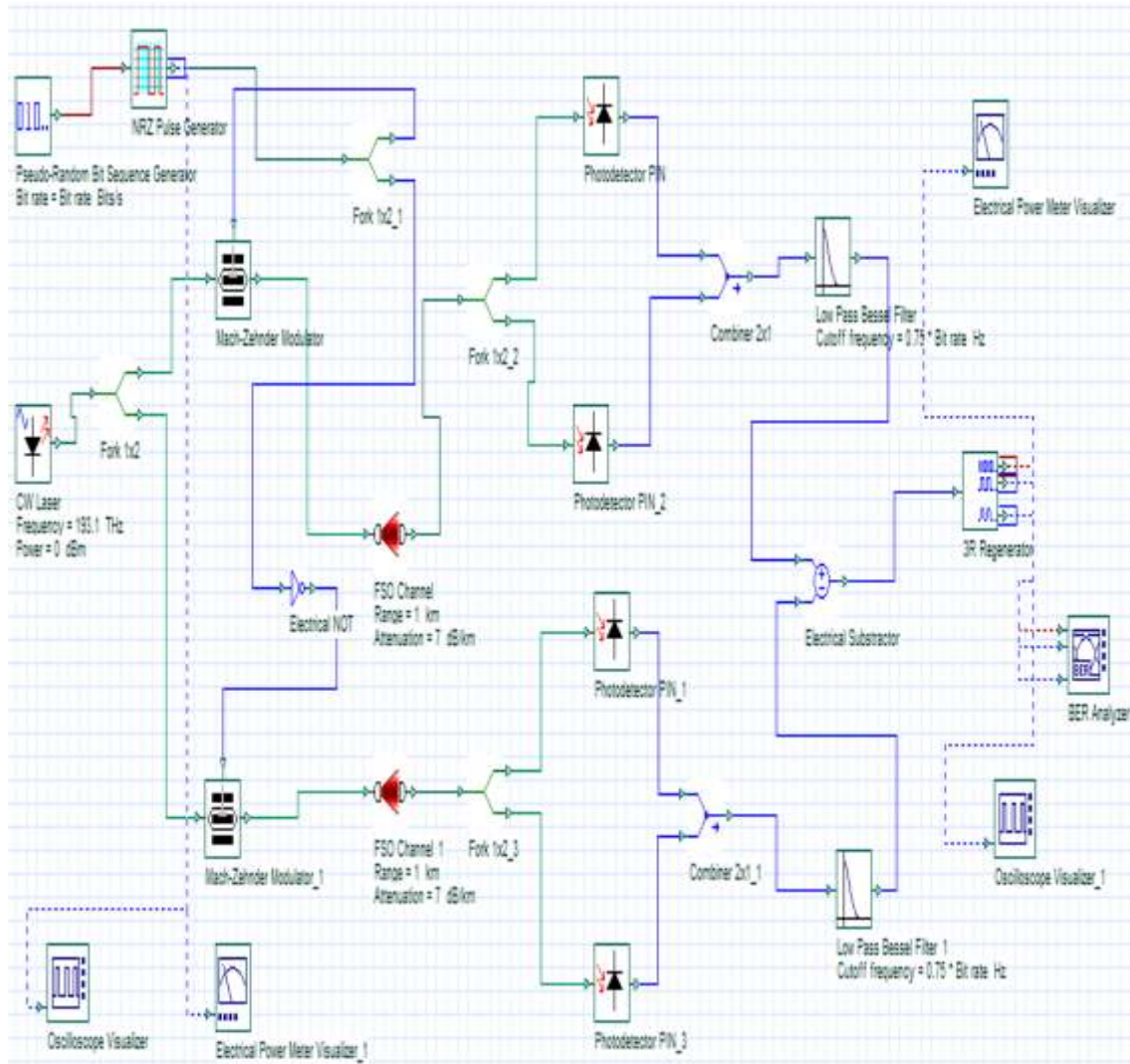


Figure 5.11 : Setup simulation for DTBR technique with parameter $L = 1\text{ km}$, data rate = 622Mbps, $\theta = 1\text{ mrad}$ and attenuation at 7 dB/km

5.3.1 Analysis 1: Power

A comparison of the BER minimum power signal for the DTBR approach and the conventional ASK technique may be seen in Figure 5.12. The received power for conventional ASK and DTBR is -0.2 dBm and -3 dBm correspondingly while operating at an acceptable minimum BER of 10^{-9} . This results in roughly 3 dBm of signal power for the gap. This contributes around a 50 per cent improvement to the minimal power required for the FSO system to operate. This demonstrates that the DTBR technique is capable of operating with a lower minimum power when compared to the conventional approach. This will boost the system's capability to sustain sufficient power even when severe heavy air conditions are present.

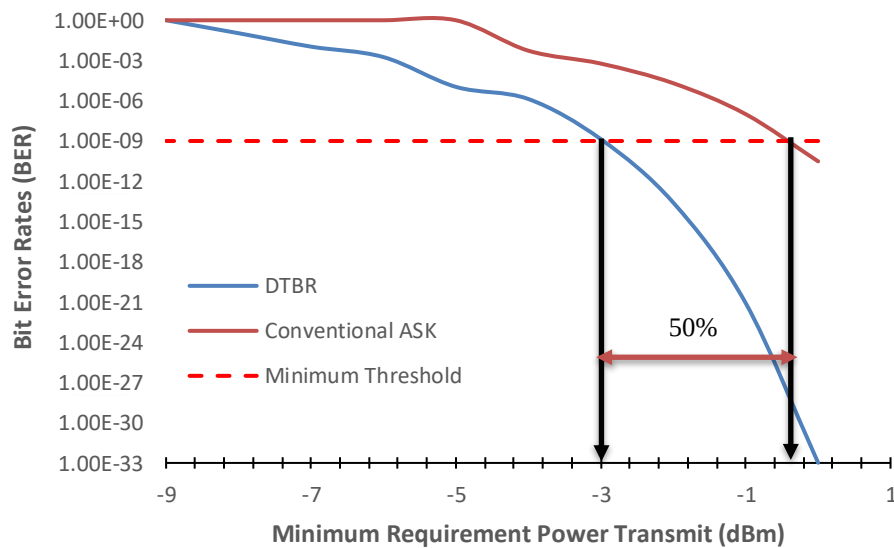


Figure 5.12: Minimum power required to operate FSO system

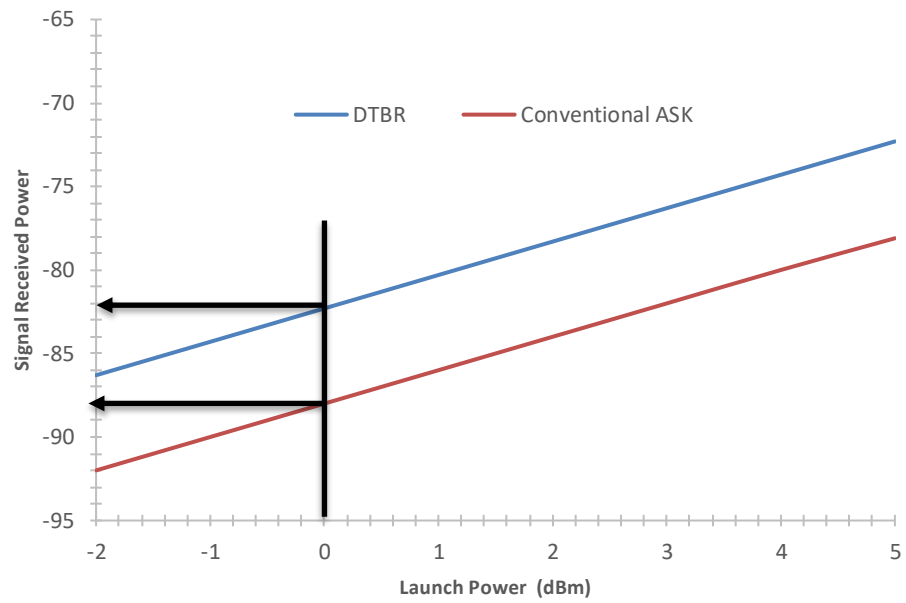


Figure 5.13: Comparison performance of received power operate at low power 0 dBm

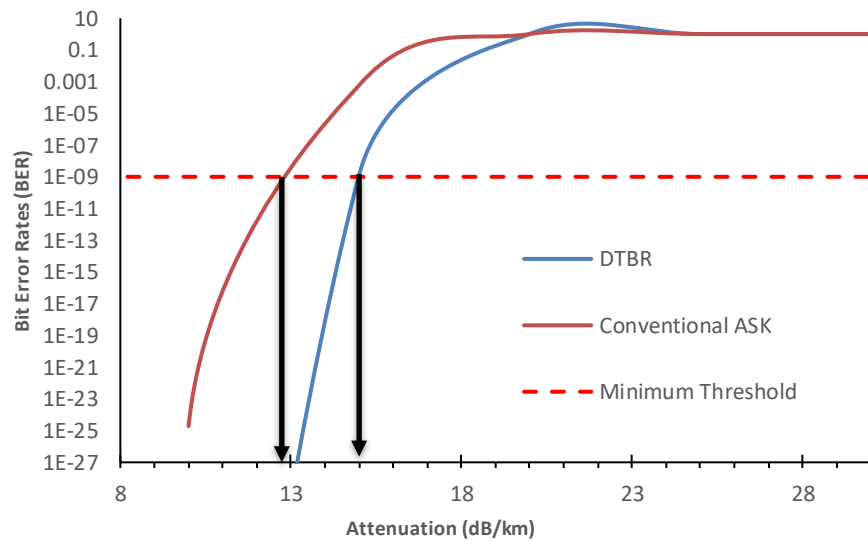


Figure 5.14: Comparison performance BER versus increment of attenuation (dB/km)

The Figure 5.13 shows the comparison performance received power that operate at 0 dBm. It shows that DTBR has better received power with -82dBm and conventional

approach only -88dBm. This analysis is to investigate the ability of new proposed system able to running with minimal power. If the system can able to operate in low consumption of energy it can reduce the cost and life span of the FSO system. From the graph the gap is almost 6dBm with percentage of improvement is 7%. Meanwhile for the Figure 5.14 shows the performance of the system when having increment of attenuation. It is important to know the limit of the system how far can withstand. Since the presence of atmospheric turbulence is unpredictable it very crucial if can have very robust system able function even at very poor weather. From the graph, at minimum acceptable BER 10^{-9} the DTBR is able to operate in higher attenuation where conventional approach only at 12 dB/km and DTBR is at 16 dB/km. This condition will assist FSO to maintain operate in high quality power signal.

Figure 5.15 shows the performance of noise power for both DTBR and conventional approach. The attenuation is set fix at 5dB/km for low atmospheric turbulence presence. The proposed of new system have the ability to reduce the noise signal at receiver. It due to filter from balance receiver which suppress the noise presence at receiver. From the graph, the DTBR have lower noise power which at -68 dBm as compare to and -75 dBm for conventional approach. This indicate that, the new proposed system can perform better to suppress the noise at receiver. Approximately 12 % of improvement. Meanwhile in Figure 5.16 shows the performance of the system for received power if at acceptable minimum BER 10^{-9} . From the graph, DTBR can achieved received signal approximately at -88 dBm and conventional approach -90 dBm. This slight improvement is significant to indicate that the DTBR can improve the quality received signal at receiver.

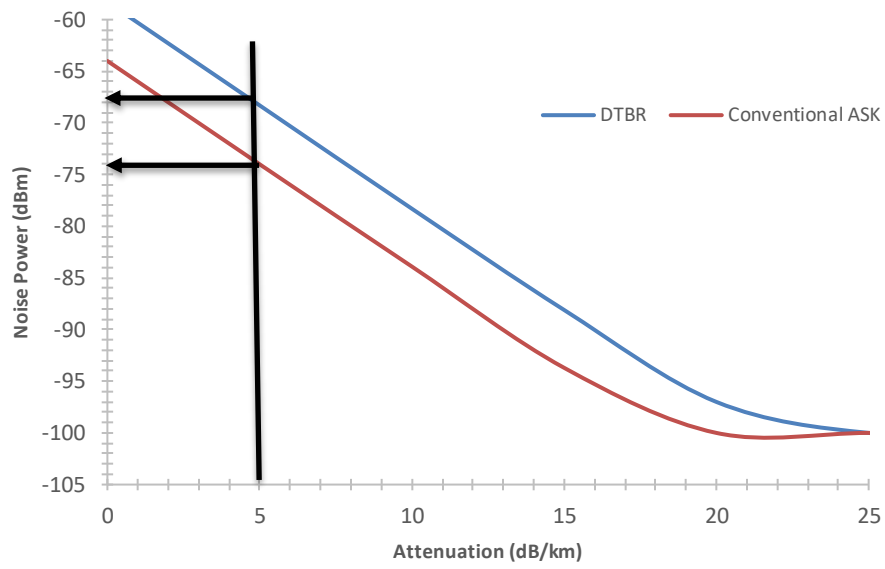


Figure 5.15 : Comparison performance of noise power for both DTBR and conventional approach

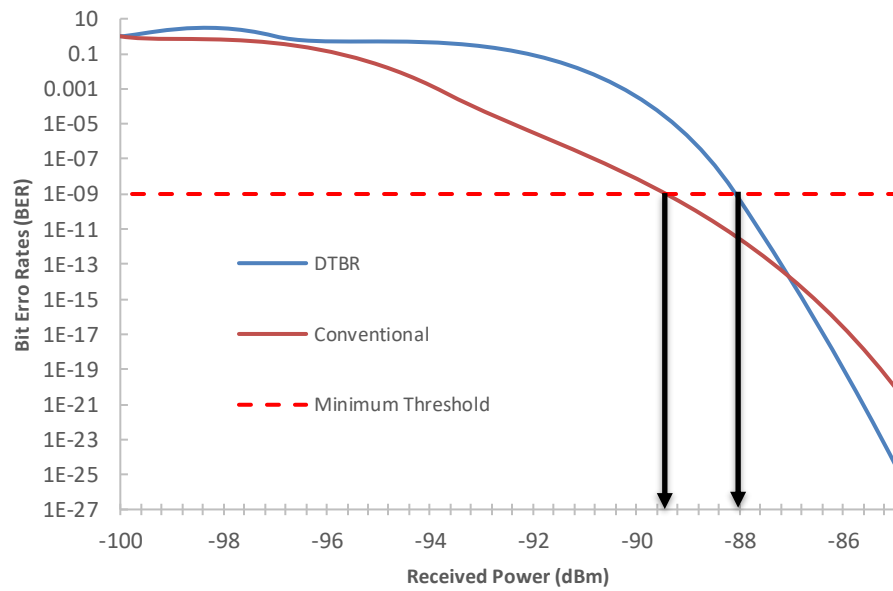
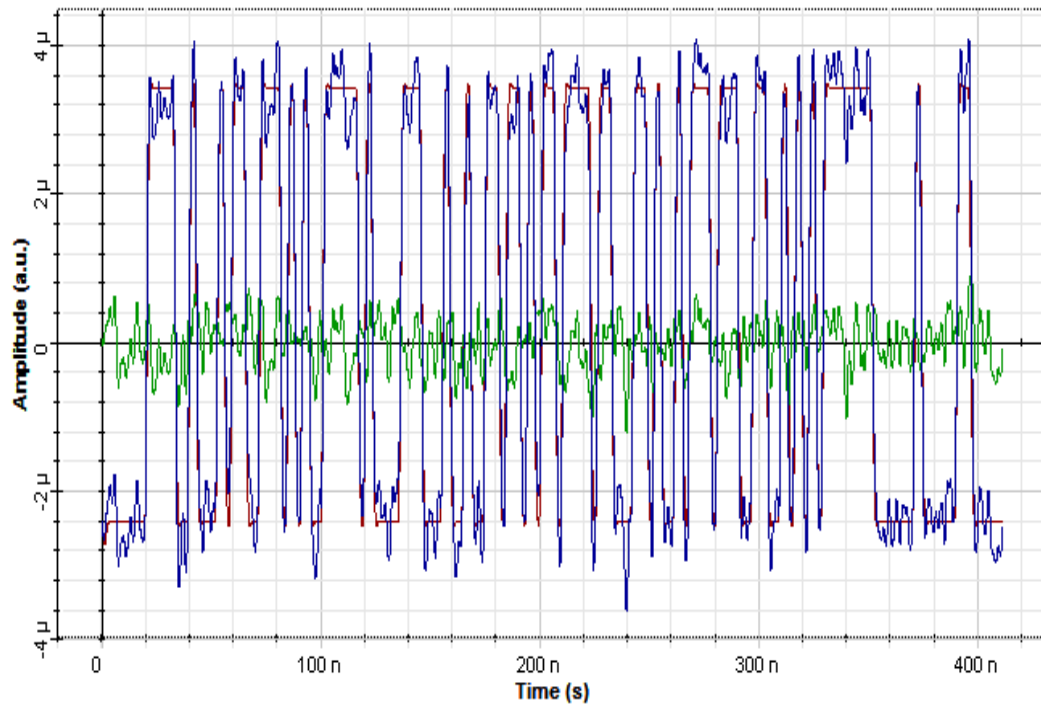


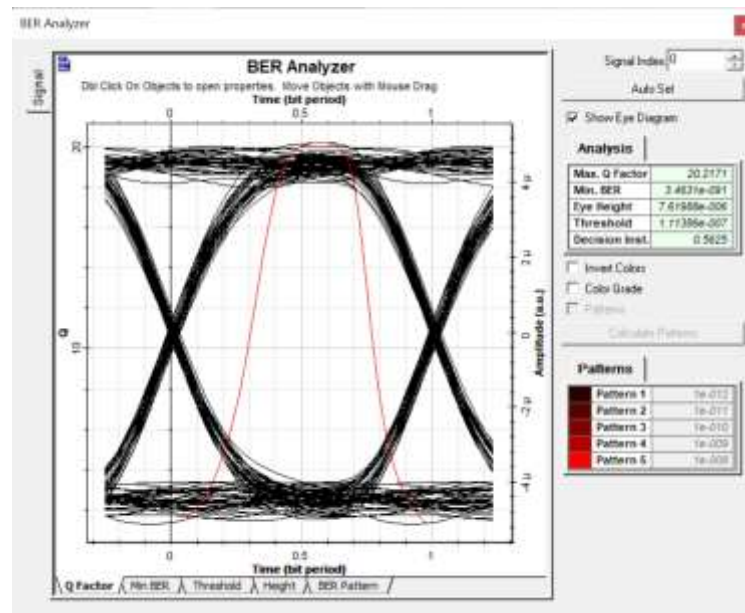
Figure 5.16 :Comparison received power at minimum acceptable BER 10^{-9}

In order to analyze more further the performance of DTBR due to the influence of averaging effect, the results are visualized through eye patterns and oscilloscope analyzer. The Figure 5.17 (a) and (b) shows the performance of eye pattern and oscilloscope result without presence of turbulence. The opening of eye pattern is high it indicates the performance of the system a good and the minimum BER usually below than 10^{-9} . Otherwise, if the opening of eye pattern is low indicate that the system turns to poor performance and in worst condition there is no shape of eye pattern which represent the signal is totally loss. Meanwhile for oscilloscope result, generally shows the three patterns of signal which is consist of signal and noise power. The blue line represents the signal plus noise power meanwhile the red line represents the only signal power and the green line represent only noise power. The opening of eye pattern is high which indicate the performance of system is good and this condition can be viewed effectively in oscilloscope result where the signal power (red line) is high if compare with the noise power (green line). This shows that the level of noise power is still low and allow the detector to receive the signal power with high rate.

From the result, BER is at 3.46×10^{-91} with the max Q factor 20.21, eye hight 7.619×10^{-9} and threshold 1.13×10^{-7} . As no presence of turbulence the data error (BER) is less and system function at best condition. That shows as well in oscilloscope result (Figure 5.17 (b)) where signal received (red ine) is higher as compare to noise signal (green line). However this condition will be change as presence of turbulence as shown in Figure 5.18 and Figure 5.19.



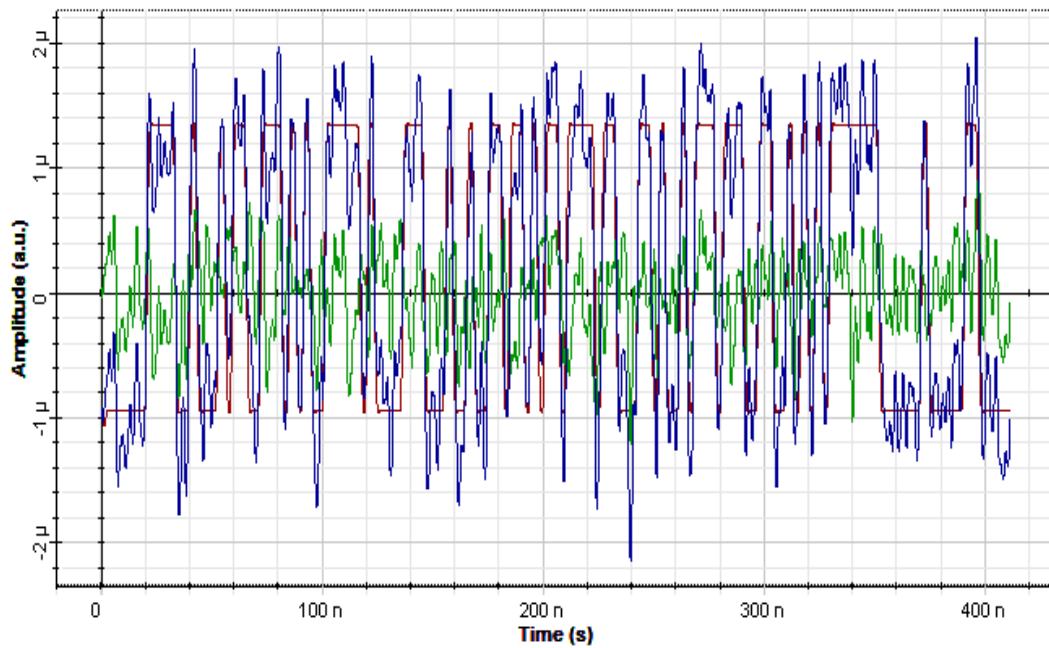
(a)



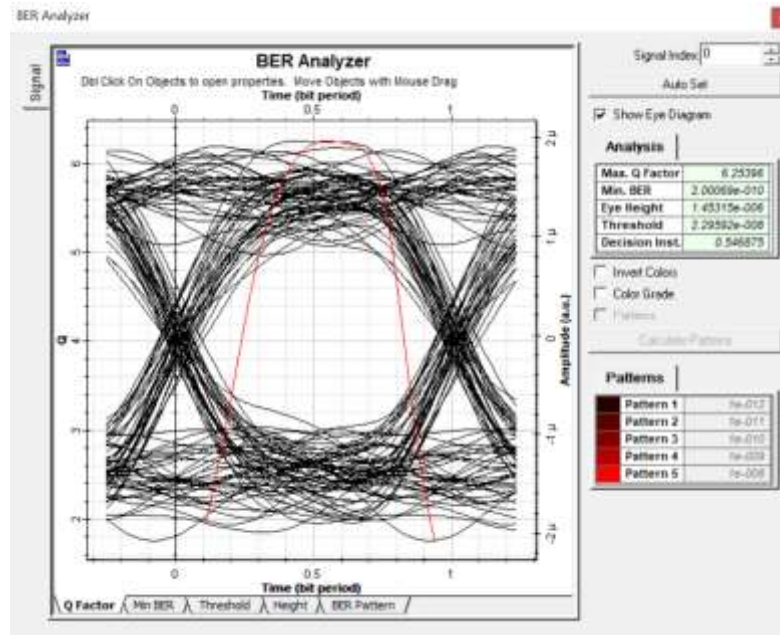
(b)

Figure 5.17 (a) and (b): Figure 5.17 (a) and (b): Performance of eye diagram for noise (green color lines) and signal power (blue color lines) without presence of turbulence

Figure 5.18 (a) and (b) shows the performance of eye pattern and oscilloscope result due to presence of turbulence at $C_n^2=1 \times 10^{-15} \text{ m}^{-2/3}$. The eye opening seems to close with the eye height drop. Meanwhile in oscilloscope result pattern the gap between signal power and noise power are becoming close. This indicates the performance is deteriorating where the noise power is increased but the signal power is decreasing. This indicates that when presence of turbulence the error will increase where drop to 2×10^{-10} as compare to previous condition without turbulence BER at 3.46×10^{-91} . It is a huge difference where increment of magnitude is 81. This is why FSO system is vulnerable with changing of atmospheric condition. This also can be seen in effect of received signal and noise signal as shown in Figure 5.18 (a). In this state, the noise signal is in verge of dominating the overall signal. If that happens, the quality signal will drop and having poor transmission.



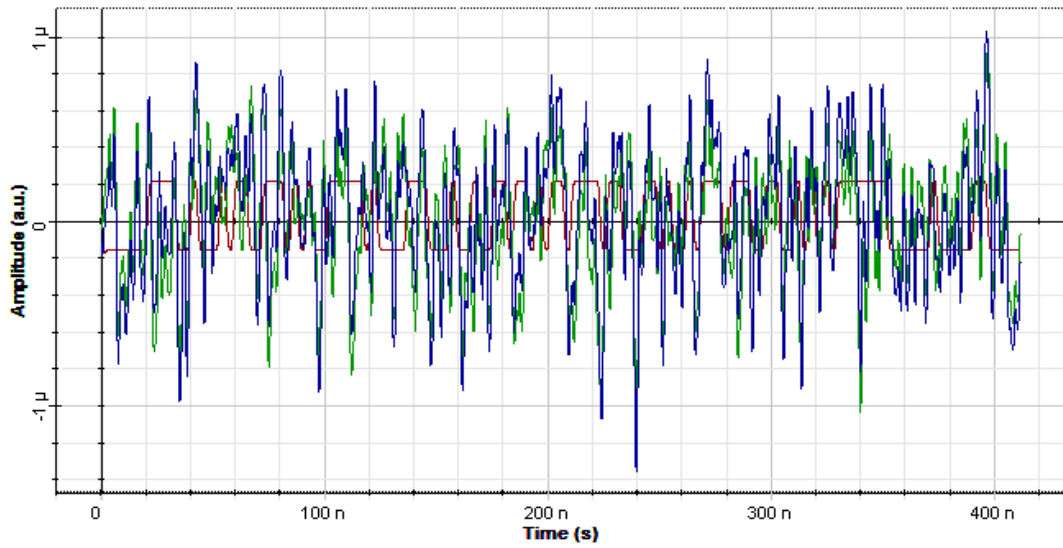
(a)



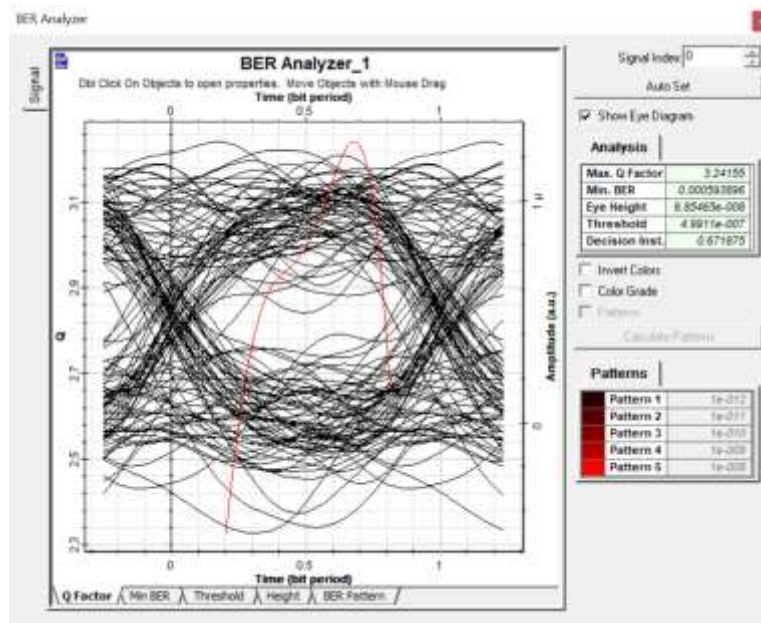
(b)

Figure 5.18 (a) and (b): Figure 5.18 (a) and (b): Performance of eye diagram for noise (green color line) and signal power (blue color line) with presence of turbulence at $Cn^2=1 \times 10^{-13} \text{ m}^{-2/3}$ (Moderate turbulence)

For the worst condition as shown in Figure 5.19 (a) and (b) for the heavy turbulence at $Cn^2 = 100 \times 10^{-12} \text{ m}^{-2/3}$. At this stage there is no eye-opening pattern and usually the minimum BER is at value 1 which represent the high error. For the noise power pattern of oscilloscope results show that the it surpasses the signal power. This indicates that the level of the signal power is very weak and the noise power dominates the overall signal. Here also show that at this point the signal plus noise (blue line) shape pattern turn to similar to noise power.



(a)



(b)

Figure 5.19 (a) and (b): Performance of eye diagram for noise (green color line) and signal power (blue color line) with presence of turbulence at $C_n^2=1 \times 10^{-12} \text{ m}^{-2/3}$ (Strong turbulence)

5.3.2 Analysis 2: Bit Rate

In bit rate analysis, we simulated the data bit rate from 155Mbps until 10Gbps. Here we fix the diameter lens at $D= 8\text{cm}$ with beam divergence value 1mrad . The turbulence is set at $1 \times 10^{-13} \text{ m}^{-2/3}$ under strong turbulence region. Figure 5.20 shows the simulation result for BER versus bit rate under strong turbulence condition. The comparison is between conventional ASK and DTBR along with eye pattern performance. At higher bit rate of 10 Gbps, it can be seen that DTBR can support the transmission where the BER is at 5.91×10^{-11} as compare to conventional ASK surpass the minimum acceptable BER where at 2.77×10^{-4} . This can indicate as well in eye diagram shape where the opening eye for conventional ASK is lower. In other word the DTBR system can improve the error bit and at same time can support the high speed data rate transmission. With this, FSO technology can fulfill the high demand of nowadays consumer which want the more faster technology in data transmission.

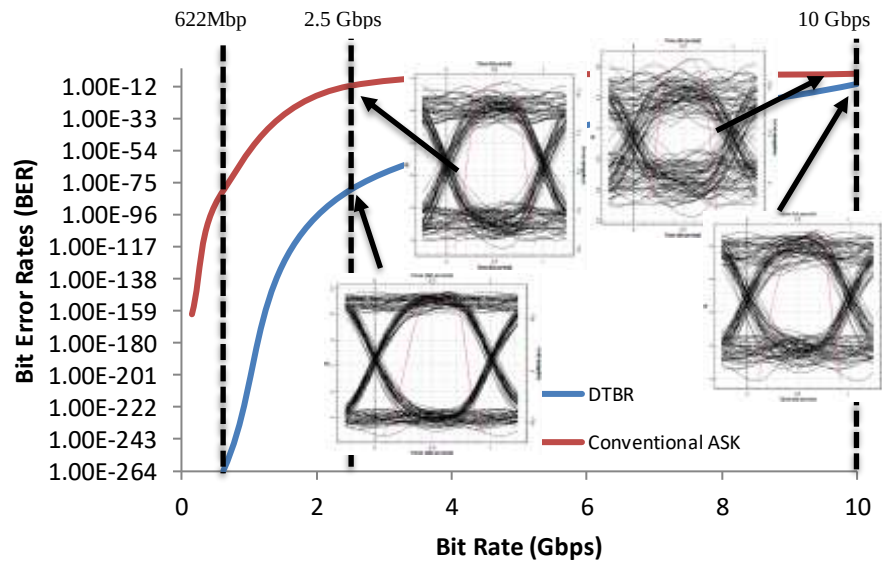


Figure 5.20 : Performance of BER for varying data bit rate under strong turbulence effect

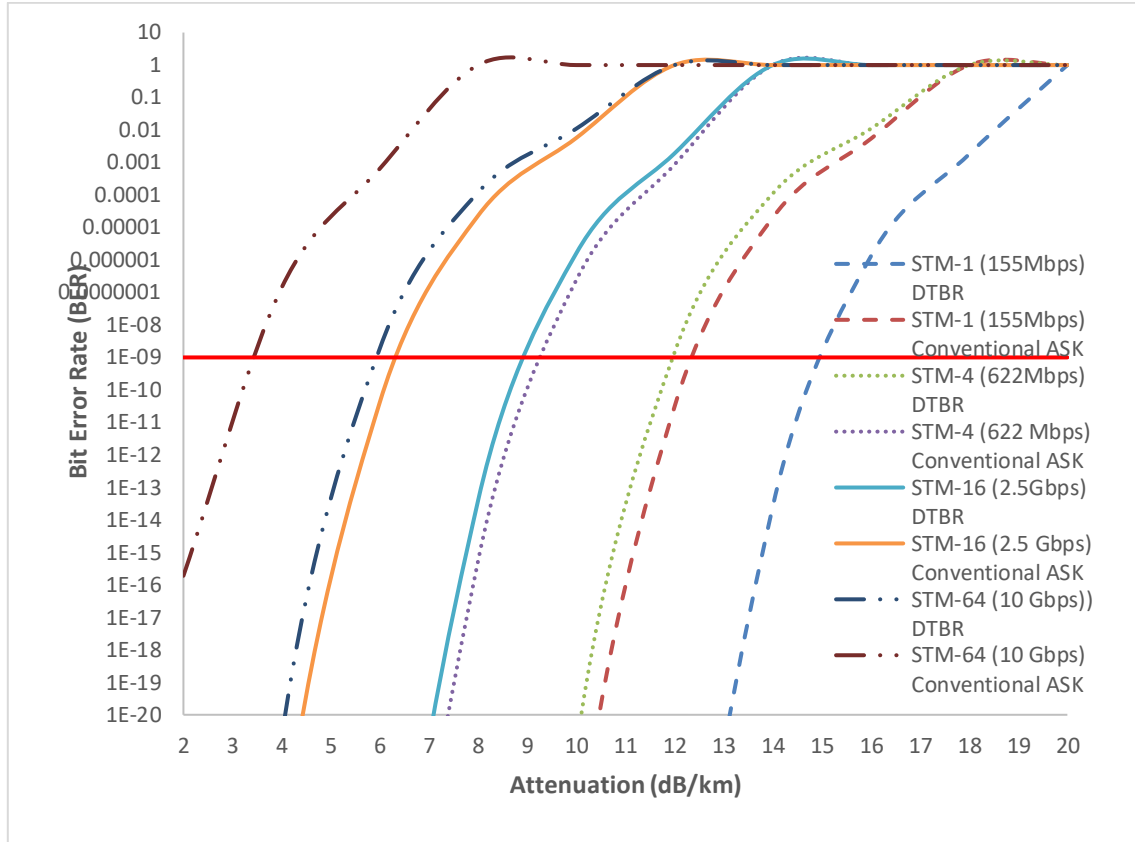


Figure 5.21 :Comparison performance DTBR and conventional ASK for different STM level (STM1, STM4, STM16 & STM64)

Figure 5.21 shows the simulation result for comparison BER versus different STM level bit rate. The Synchronous Transport Module (STM) is a fiber optic network standard for SDH (Synchronous Digital Hierarchy). From the result, at minimum acceptance BER (straight red line) the lowest bit rate which is STM-1 (155Mbps) shows the performance better at higher attenuation which is approximately at 15 dB/km. Meanwhile conventional ASK only able to reach 12 dB/km. At higher bit rate which is STM-16(2.5Gbps), the DTBR can support attenuation closed to 6 dB/km but conventional ASK only at 3 dB/km. Both of these result shows that improvement of DTBR about 25% as compare to conventional ASK. It indicates that this new approach can perform well either at low bit and higher bit rate.

5.3.3 Analysis 3: Distance Propagation

The analysis for effective range was simulated from the range from 1km to 3km. Figure 2.22 shows the BER versus the propagation distance under strong atmospheric turbulence. In the short propagation distance of 1km both of the performance BER for conventional ASK and DTBR is excellent where 1.1×10^{-80} and 4.36×10^{-268} respectively. When increasing of distance up to 3km, the BER is going to decrease due to increment of attenuation as well in transmission as link keep further. This will cause the BER performance will drop as well. From the eye diagram the conventional manage to have BER 4.89×10^{-4} which is below the minimum acceptable BER that is 10^{-9} . However the DTBR still manages to perform better with the BER 5.51×10^{-17} . This show the improvement with 13 magnitude of BER.

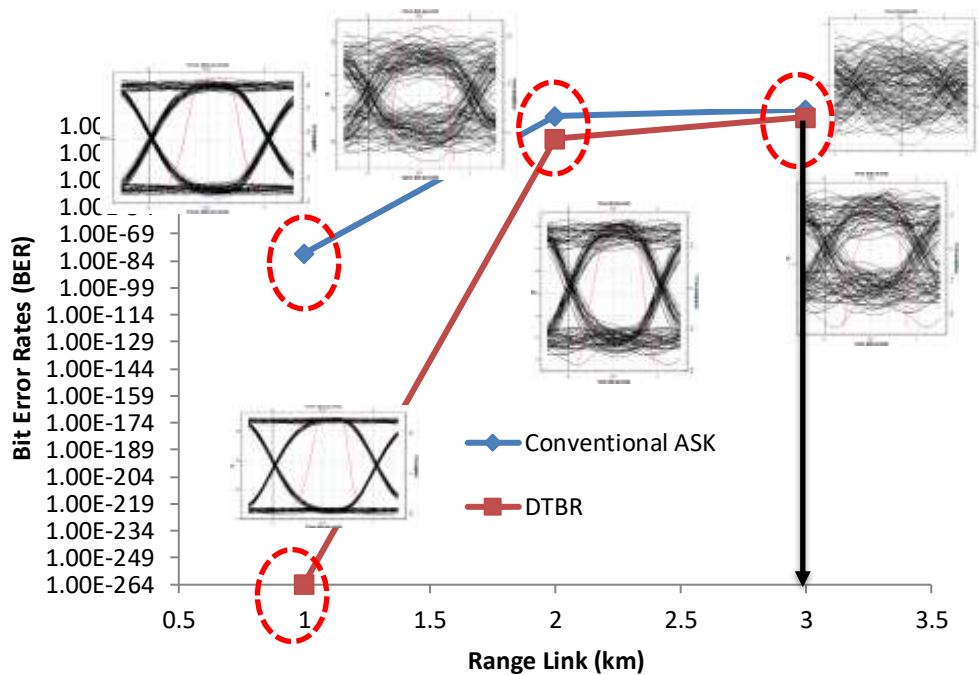


Figure 5.22: Performance of BER for varying distance transmission under strong turbulence effect

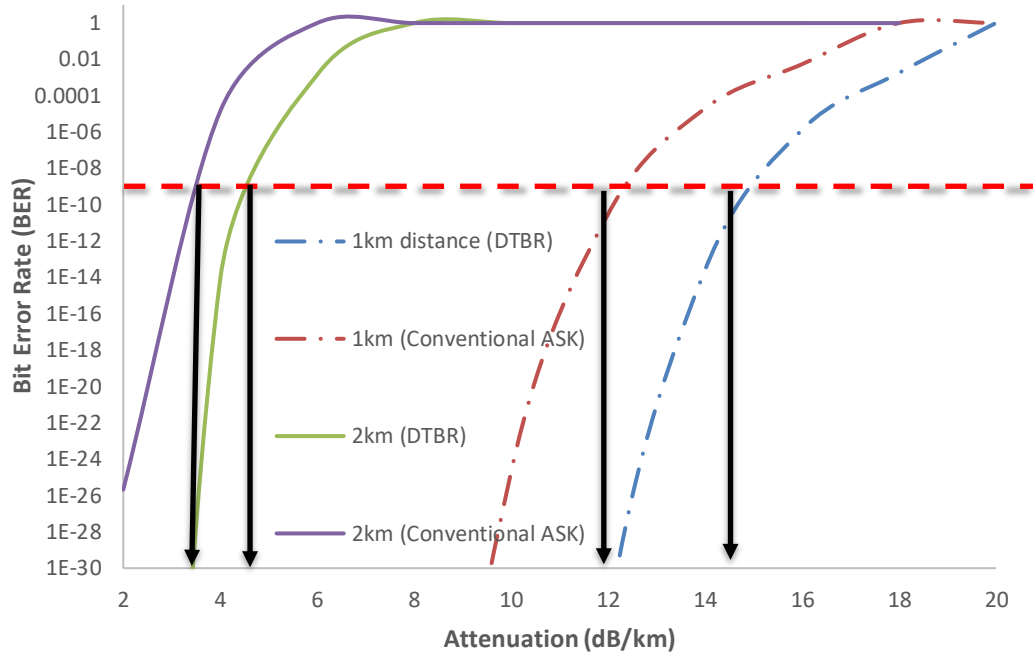


Figure 5.23: Comparison BER versus attenuation for different range propagation

Figure 5.23 shows the comparison BER when having increment of attenuation under strong atmospheric turbulence. Two range will be analysed for comparison performance that is 1km and 2km. In the short distance propagation for 1km, the performance BER at minimum acceptable 10^{-9} shows both approaches are able to support attenuation above 10 dB/km where DTBR and conventional ASK at 15dB/km and 12 dB/km respectively. This gives improvement approximately 25%. However, at long distance for 2km, both approaches are at 5dB/km and 3 dB/km respectively which still DTBR performs better. From this finding, it shows that the ability of DTBR can offer FSO system to transmit more distance coverage with the ability to perform well at high attenuation effect.

5.4 Summary

In this chapter have studied the performance of DTBR under the turbulence condition. From the result analysis on effective power, in strong turbulence condition the DTBR can improve approximately 50% of power received. For bit rate analysis, it can operate at higher bit rate of 10 Gbps (STM64) with the BER is approximately at 5.91×10^{-11} as compare to convetional ASK only at 2.77×10^{-4} . This give percentage improvement about 175%. Meanwhile in distance analysis, the DTBR manage to achieve BER approximately 5.51×10^{-17} while conventional only 4.89×10^{-4} . Thus, contribute improvement of 13 manitude of BER or equivalent of 325%. Therefore, via the presented analysis the new proposed is have the better performance as compare to conventional ASK technique.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The findings of the research will be presented and discussed in this last chapter. It first discusses the contribution of the research, and then moves on to a summary of the conclusions. This chapter will also include some recommendations for more study and research, which can be expanded upon in a variety of ways depending on the extent of the research. Figure 6.1 illustrate the flow of Conclusion chapter.

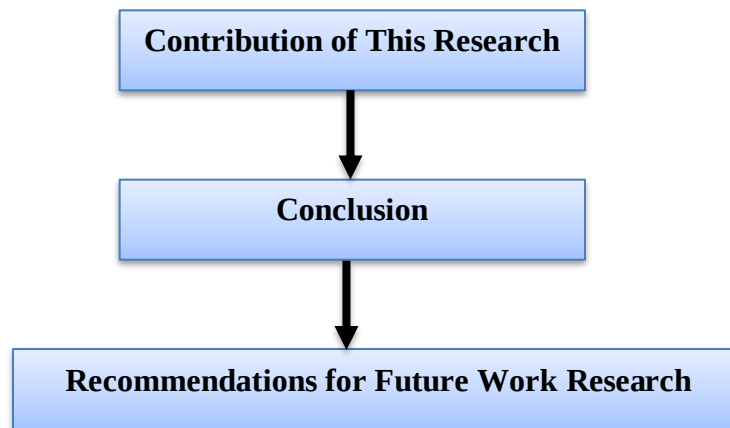


Figure 6.1: Flow of Conclusion

6.2 Contribution of This Research

The major contributions of this thesis could be summarized as:

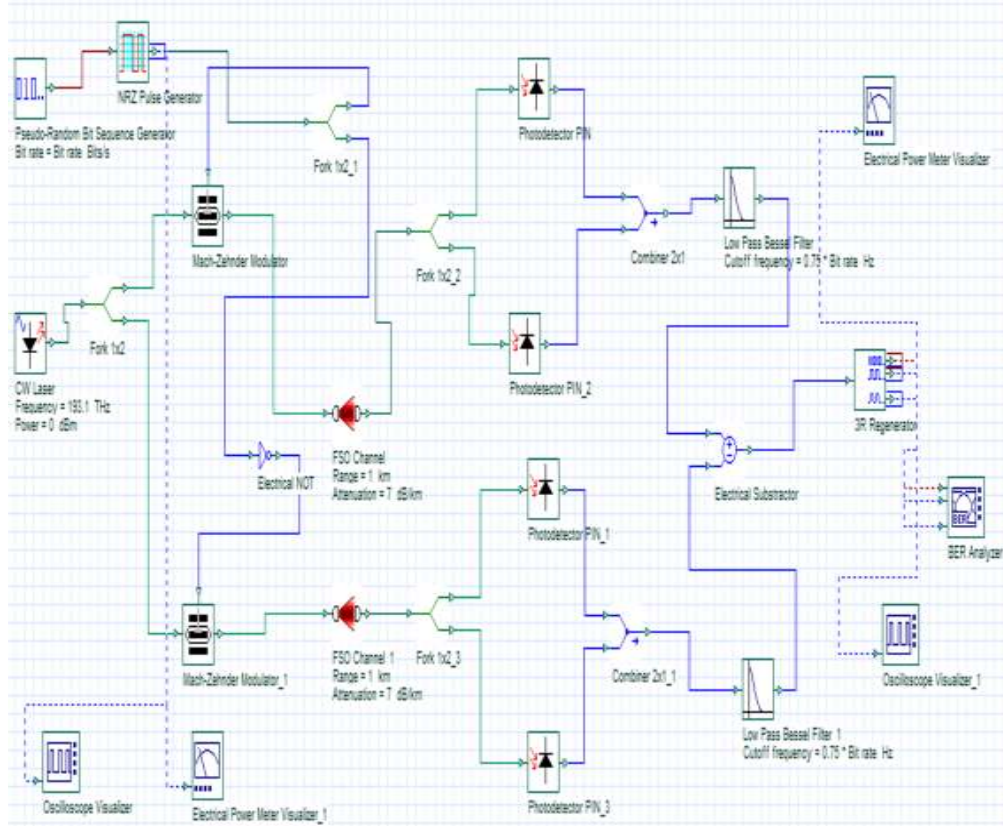
- i. The development of DTBR technique, has improve the performance of conventional technique in term of power received, data bit rate and range link transmission as discussed details in Chapter 5. This new technique overcome the

weakness of conventional ASK modulation and reduce the noise presence at receiver.

- ii. A new mathematical model has been developed for the SNR and BER that used to analyze the result performance.

	DTBR
Signal Power	$i_s = 4\Re\left(\frac{\pi D^2}{8} I(0, L)\right)$
Bit detection	Bit '1' = 1 Bit '0' = -1
SNR	$\frac{4^2 \Re^2\left(\left(\frac{\pi D^2}{8}\right)\left(\frac{2P_o}{\pi W^2(L)}\right)\right)^2}{8e\Re\left(\left(\frac{\pi D^2}{8}\right)\left(\frac{2P_o}{\pi W^2(L)}\right)\right)B + \frac{4k_b T_n B}{R_L}}$
BER	$\frac{1}{2} \operatorname{erfc}(\sqrt{SNR})$

- iii. A new design of DTBR technique using the Optisystem simulation tool has been developed to verify the theoretical analysis.



6.3 Conclusions

In this thesis, the new Double Transmission Balance Receiver technique has been successfully developed as fullfill the first objective. The investigation weakness of the intensity modulation direct detection (IM/DD) was reveal and presented the consequence when experiencing atmospheric effect in free pace optical communication system. The achievable of this objective is proposed concept new technique which consist of two transmitter and receiver, inverter, balance receiver and subtraction process. The fundamental concept idea for DTBR technique consist of two important elements which make this technique can become as a compromising future technology in FSO communication. The firstly is DTBR has overcome the threshold level problem in conventional ASK for OOK modulation where can solve limitation of threshold signal level. The secondly is compress the noise presence at receive. It is important to have minimal noise at receiver in order to

ensure signal power dominate the noise signal. Otherwise, signal will turn to poor quality which as general FSO is vulnerable with atmospheric effect that can trigger high noise signal at receiver. With the ability to suppress the noise this new technique improve the conventional technique which suffer as well of high unwanted signal.

The second objective also has been successfully achieved using two approach. The first approach is theoretical approach which mainly via mathematical derivation. The new formula of power received signal, signal to noise ratio (SNR) and bit error rate (BER) to compare with conventional technique. For tubulence effect is using the Gamma – Gamma distribution in this research. The second approach is via development in simulation environment. The design is developed using Optisystem simulator which enable to test and analyze closed to real environment scenario. Thru simulation as well it can verify the theoretical analysis which is proof that mathematical derivation is correct according to initial concept design.

For the third objective which is to analyse the performance of DTBR also has been successfully achieved. All the result and findings is discussed details in Chapter 5. The analysis generally split two section that is theoretical and simulation. From the result analysis on effective power, in strong turbulence condition the DTBR can improve approximately 50% of power received. For bit rate analysis, it can operate at higher bit rate of 10 Gbps (STM64) with the BER is approximately at 5.91×10^{-11} as compare to convetional ASK only at 2.77×10^{-4} . This give percentage improvement about 175%. Meanwhile in distance analysis, the DTBR manage to achieve BER approximately 5.51×10^{-17} while conventional only 4.89×10^{-4} . Thus, contribute improvement of 13 manitude of BER or equivalent of 325%. Therefore, via the presented analysis the new proposed is have the better performance as compare to conventional ASK technique.

Therefore, as conclusion all objectives is achieved along supported with explanation in this thesis.

6.4 Recommendations for Future Work Research

In order to broaden the scope of the task being researched, a number of different areas might be investigated further. Even though the goals of this thesis have been accomplished, the work that has been done has never been sufficient to cover all of the study areas that pertain to optical wireless communications. As a result, the following set of recommendations may be implemented to make the next work study more comprehensive:

- a) Apart of atmospheric turbulence (scintillation effect) this reseach can be investigate in atmospheric attenuation condition such rain which is it occur throughout year in local weather. It can examined extensive research with different level of rain especially heavy rain and thunderstorms.
- b) Investigate using low power consumption optic source that is LED can be crucial research. The current research investigate laser optic source which is well-known can support for long distance wireless. However, if the design FSO system using LED can able to transmit long distance would be very impactful and very interesting to study.
- c) The hybrid radio over FSO (RoFSO) can also be researched to evaluate the mitigating impact of air turbulence. This study, which was founded on the notion of a multiple subcarrier system, can further demonstrate the potential of subcarrier modulated FSO as a tool for boosting the capacity of communication systems.

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- 1 Kram, A. R., **Kwang Thai, S. A.**, Tamrin, K. F. & Sahari, S. K. (2022). Subtraction dual wavelength for enhanced transmission performance of free-space optical communication over turbulence effect. *IET Electronics Letter*, 58(4), <https://doi.org/10.1049/ell2.12387> [Published]
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APPENDIX A

Gamma-Gamma probability density function (pdf) using MATLAB

```
clear
clc
x=4.2;           % alpha value
alpha=x;
y=1.4;           % beta value
beta=y;
k=(x+y)/2;
k1=alpha*beta;
G=2*(k1^k)/(gamma(alpha)*gamma(beta));
l=0.01:0.01:5;   % intensity
K1=l.^(k-1);
Z=2*sqrt(k1*l);
GammaGamma=G.*K1.*besselk((alpha-beta),Z); % Gamma gamma pdf
Plot (l, GammaGamma)
Xlabel ('Intensity, l')
Ylabel ('Gamma gamma pdf, GammaGamma(l)')
```

APPENDIX B

Generate the value of alpha ' α ' and beta 'b' under different turbulence regimes using MATLAB

```
clear
```

```
clc
```

```
L=0:0.05:80;
```

```
for i=1:length(L)
```

```
    x=L(i);
```

```
    A=(0.49*x) / (1+1.11*x^(6/5))^(7/6);
```

```
    B=(0.51*x) / (1+0.69*x^(6/5))^(7/6);
```

```
    Sci_ind(i) = exp(A+B) - 1;
```

```
    alpha(i) = (exp(A) - 1)^-1;
```

```
    beta(i) = (exp(B) - 1)^-1;
```

```
end
```

```
semilogx(L, alpha, L, beta)           %plot function
```

```
xlabel('Log intensity variance  $\sigma_1^2$ ')
```

```
ylabel('Parameters:  $\alpha$ , beta')
```

APPENDIX C

Calculate the probability of error (BER) using MATLAB and excel calculation input

```
clear
```

```
clc
```

```
syms x
```

```
alpha=2.417;      %calculate using excel then insert in MATLAB
```

```
a=alpha;
```

```
beta=4.813;      %calculate using excel then inser in MATLAB
```

```
b=beta;
```

```

k=(a+b)/2;
k1=a*b;
K=(k1.^k)/(gamma(a).*gamma(b))

%Calculate the Probability of BER in presence of atmospheric turbulence
SNRP=0.007835225;      % SNR effect calculate using excel
fun=@(x)(((erfc((SNRP.*x)/(2.*sqrt(2))))).*(x.^(k-1))).*(besselk((a-
b),2.*sqrt(k1.*x)));
q=integral(fun,0,inf)
p=K*q

```