

# Beam Divergence Loss Mitigation in Free Space Optical Communication Channel Using Field of View Technique

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## Abstract

*A rapid advancement in the electronics and telecommunications industries has been observed. As a result, Communication gadgets are becoming more powerful and are more widely adopted. The demand for high data rate transmission is increasing. This has led to spectrum scarcity in Radio Frequency (RF) systems. Consequently, it is necessary to explore other technical means to meet the increasing demand for higher data rates. Free Space Optical Communication (FSOC) is a promising technology that offers one of such means. However, the major technical challenge in the FSOC systems is that, their performance is limited by atmospheric impairments such as: absorption, scattering and turbulence caused by rain, cloud, snow, wind, dust, aerosol, and fog. This research is aimed to address beam divergence challenge due to fog and raindrop in a tropical climate using wider field of view technique (FoV). The result showed that, for the fog measurement using mini solar panel at the receiver, the system achieved higher SNR of 60 dB at corresponding BER of  $10^{-4}$ . While, with the photodiode, the system achieved an SNR of 38 dB at same BER. For the rain measurement the same procedure was adopted and the system achieved higher SNR of 90 dB and 58 dB at same BER utilizing both solar panel and photodiode respectively. The result showed that, the fog impairment attenuates optical signal more than of rain by 34 % averagely.*

**Keywords:** fog, rain, beam divergence, BER, and NSR

## 1. Introduction

Global devices and connections are increasing faster than the population growth. This is due to recent rapid advancement achieved in the electronics and telecommunications industries. As a result, a remarkable growth in information and communication technologies has been observed (Kaushal, 2016). Similarly, technological advancement achieved in IoT that allows many devices to be networked and the upcoming 5G and 6G networks requirements further improved the telecommunication sector. This emergence of new services increased the need of very high-speed internet, E-conferencing, and live streaming, etc. More than 70% of the Global population will become internet users by the year 2023, whereby the subscription is expected to increase from 3.9 billion (66 %) by 2018 to 5.3 billion (71%) in 2023 (Cisco, 2020). Consequently, the demand for higher bandwidth increased drastically. The typical figure of Worldwide devices and internet connectivity per capita predicted from 2018 to 2023 (Cisco, 2022). as shown in Figure 1.

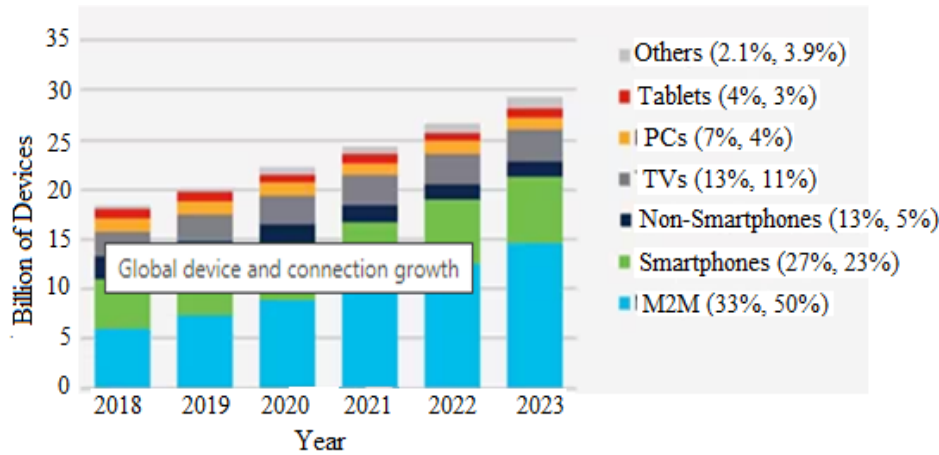


Figure 1: Global Devices and Internet Connection Growth (Yau *et al.*, 2022a)

Figure 1 illustrates how new devices in diverse forms with improved proficiencies and intelligence are presented and accepted in the market yearly. An increased number of appliances, such as smart measuring devices, surveillance system, healthcare facilities, transport, and tracking equipment, are playing a major part to the increased of devices and network connections. By the year 2023, machine to machine (M2M) connections will be almost half of the entire devices and network connections. M2M connectivity expected to be the fastest-growing device and network connections class (Yau, 2021).

### 1.1 Nigerian Internet Subscription Forecast

In the Nigerian context, the Nigerian Communications Commission (NCC) has earmarked the present broadband penetration in the Nigeria at 33% in the year 2018 (NCC, 2018). Similarly, there are approximately 4.5 billion internet users globally as at the second quarter of 2020, this represents a higher growth rate between the years 2000 to 2021 (NCC, 2020). Another research revealed how the broadband internet penetration will increase relative to the Nigerian population from 2015 to 2025 (Clement, 2020). It has been reported that in 2022, the internet users in Nigerian reach 104 million and forecasted to rise up to 150 million users by 2027 (Sasu, 2022). Furthermore, internet penetration is amounted to 48 % of the Nigerian population in 2022 (Sasu, 2022) as illustrated in Figure 2

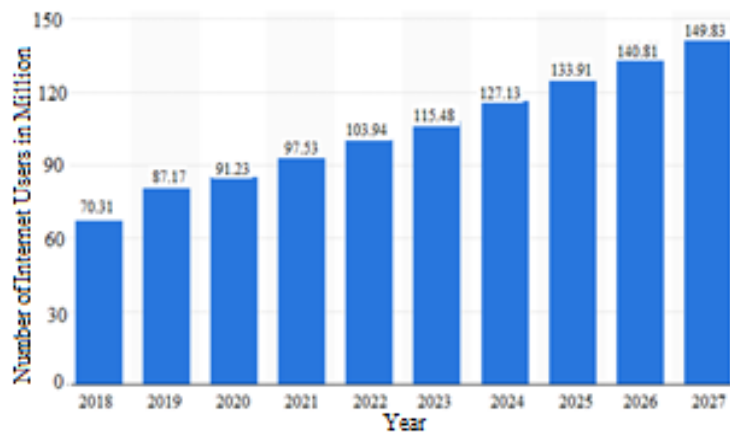


Figure 2: Internet Subscribers in Nigeria (Sasu, 2022)

This ever-growing demand for bandwidth and new emerging applications coupled with the spectrum regulation are the major contributors to the scarcity of traditional Radio Frequency (RF) spectrum. Consequently, the need arose to explore alternatives that would help overcome the RF spectrum constraint. Amongst the few alternatives (massive MIMO, cognitive radio network, etc.) to address the inherent challenge of the traditional RF is the Free-Space Optical

Communication (FSOC). This technology utilizes optical carriers (beam) to send and received information from one point to another over an unguided channel such as atmosphere or free space. Currently, FSOC has the potential to provide large bandwidth capable of providing high speed data, voice, and video communications through the atmosphere (Mingjian *et al.*, 2018). These excellent features qualify FSOC to be among the best candidates that can play a vital role in achieving the goals of 5G and IoT networks. This will determine a new spectrum that caters for the exponentially growing demand for bandwidth (Chowdhury *et al.*, 2019). Light moves faster in air than it does through glass, so it is fair to classify or considered FSOC as optical communications at the speed of light (Ghassemlooy *et al.*, 2019). However, the atmospheric channel is very complex and dynamic in nature, which can affect the characteristics of the optical beam, which in turn results in optical losses due to the cloud, rain, smoke, gases, scintillation, fog, aerosol, and dust (Chan, 2006). This propagation scenario is illustrated in Figure 3. Naturally, the properties of the atmospheric channel are not deterministic in nature, therefore, its effects can be characterized by statistical means (Chan, 2006).

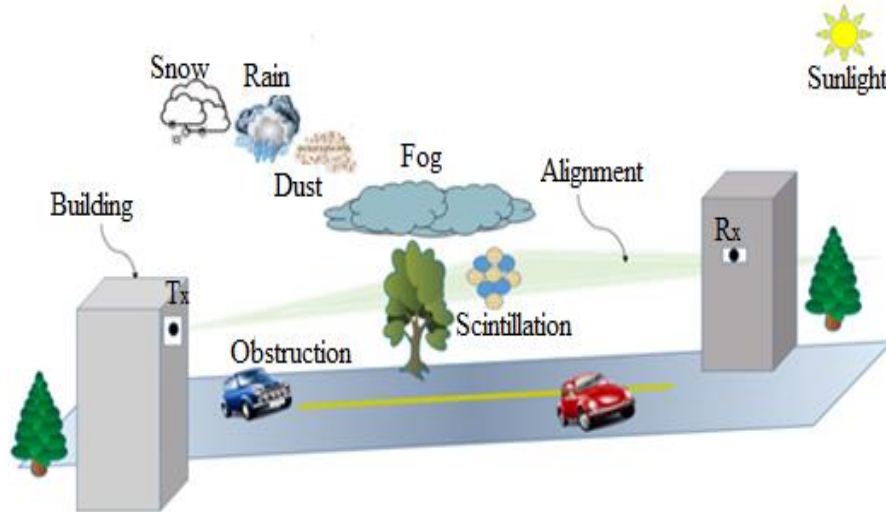


Figure 3: Atmospheric Effects on an FSOC System (Alheadary, 2018)

Figure 3 illustrates some of the existing natural unpredicted factors that caused technical challenge (s) on the optical propagated signal. These technical challenges are the key factors constituting signal degradation on the FSOC channel, which includes: Absorption and scattering loss, Atmospheric turbulence, Beam divergence loss, Background noise and sky radiance, etc. (Henniger and Wilfert, 2010). In order to take full advantage of the potentials of the FSOC technology, a proper investigation on different atmospheric effects is highly needed on the stated technical challenge. Equally, a meaningful interpretation of the field measurements in such adverse conditions is also required for possible mitigation of this purposes. This is to explore the existing gap due to different climatic environmental factors such as rain, dust, and fog, especially in the tropical climate scenario like Nigeria.

## 2. Technical Challenges

Despite the major advantages of FSOC, its extensive deployment is stalled by many issues such as absorption, scattering and distortion. FSOC system utilizes atmospheric channel as a transmission medium whose characteristics are random functions of space and the time. This makes FSOC a random phenomenon and its dependent on atmosphere and geographical position as illustrated in Figure 4 (Kedar and Arnon, 2004).

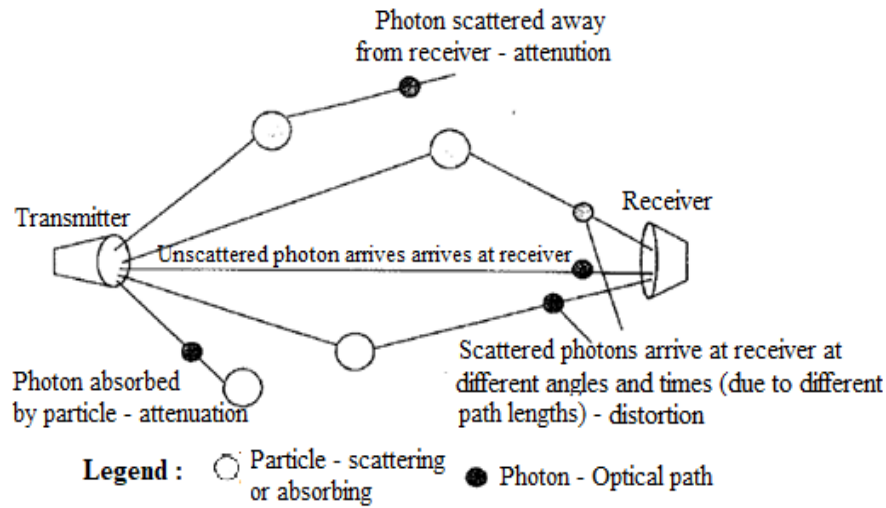


Figure 4: Spatial and Angular Spreading and Variation in Photon Path Length (Kedar and Arnon, 2004).

The spatial and angular spreading and variation in the photon path length may result in scattering and absorption of photon particles due to variation channel impairments as shown in Figure 4. These may also cause serious attenuation. Hence, the need to combat attenuation due to adverse weather conditions and the requirement to maintain power levels within the eye safety limits as standardized by regulatory bodies, such as the American National Standards Institute (ANSI) 2-136 series and the IEC 825 series. These impairments and attenuation of the optical signal constitute the main challenges in FSO technology. Therefore, increasing power to improve transmission efficiency is severely constrained (Kedar and Arnon, 2004).

### 2.1 Absorption and Scattering

The atmospheric channel loss is largely due to scattering and absorption procedures. At visible and infrared (IR) wavelengths, the primary atmospheric absorbers comprise of water molecules, carbon dioxide (CO<sub>2</sub>), and ozone (Kaushal and Kaddoum, 2016). The optical light signal attenuation in the atmosphere is calculated by considering the optical depth  $\tau$  which associated with the power at the receiver  $P_R$  and that of the transmitter  $P_T$  (Ijaz *et al.*, 2013) as,

$$P_R = P_T \exp(-\tau) \tag{1}$$

where  $\tau$  is the optical depth. The ration of the received signal power to that of transmitted signal power in the optical link which is known as atmospheric transmittance, given by (Kaushal *et al.*, 2017),

$$T_a = \frac{P_R}{P_T} = \exp(-\tau) \tag{2}$$

The atmospheric transmittance  $T_a$  and the optical depth  $\tau$  are related to the atmospheric attenuation coefficient  $\gamma$  and the transmission range  $R$  (Kaushal *et al.*, 2017) as:

$$(\lambda, R) = P_R/P_T \exp [-\gamma_t(\lambda)R] \tag{3}$$

where  $\gamma_t(\lambda)$  is the total attenuation coefficient per unit length and  $T_a(\lambda, R)$  is the transmittance of the atmosphere at a given wavelength.

$$\gamma_t(\lambda) = \alpha_{ml}(\lambda) + \alpha_{al}(\lambda) + \beta_{ml}(\lambda) + \beta_{al}(\lambda) \tag{4}$$

where  $\alpha_{ml}$  and  $\alpha_{al}$  represent the absorption coefficient for the molecular and aerosol and  $\beta_{ml}$  and  $\beta_{al}$  Represent the scattering coefficients for the molecular and aerosol.

The loss (dB) experiences by the beam of light during propagation through the atmosphere can be expressed by the following relation:

$$LOSS_{prop} = -10\log_{10} T_a \tag{5}$$

Fang *et al.*, (2018) developed a mitigation technique called partially corrected fading by employing two effective techniques such as multiple-input multiple-output (MIMO) scheme and Forward Error Correction (FEC) scheme to deal with absorption and scattering effects.

### 2.2 Atmospheric Turbulence

FSOC links (distances) are also affected by atmospheric condition (temperature) that changes in both spatial and temporal domains. This variation of temperature in the FSOC channel is due to atmospheric pressure and speed. The effect which is commonly known as optical turbulence or scintillation effect resulted in power fading at the received signal due to the variation of temperature along the propagation path (Kashani, *et al.*, 2015) as:

$$R_e = \mathbf{V}l_f / \nu_k \tag{6}$$

where,  $\mathbf{V}$  is the characteristic velocity (m/s),  $l_f$  is the length of flow (m), and  $\nu_k$  is the kinematic viscosity (m<sup>2</sup>/s).

Ren *et al.*, (2016) proposed spatial diversity in combination with MIMO equalization technique to address both the weak and robust turbulence distortions. The technique provides capacity gains relative to the traditional single aperture systems and has been shown the capability to increase the link robustness for FSOC.

### 2.3 Beam Divergence

When the optical beam of light propagates over the atmosphere, it spreads wider due to diffraction effect. This may be resulted in a condition that the receiver aperture (size) may not be able to accommodate a portion of the transmitted beam. This resulted in beam divergence loss as illustrated in Figure 5. FSOC receiver has a narrow Field of View (FoV) which is not capable of gathering all the transmitted power, resulting in the loss of energy (Kaushal *et al.*, 2017).

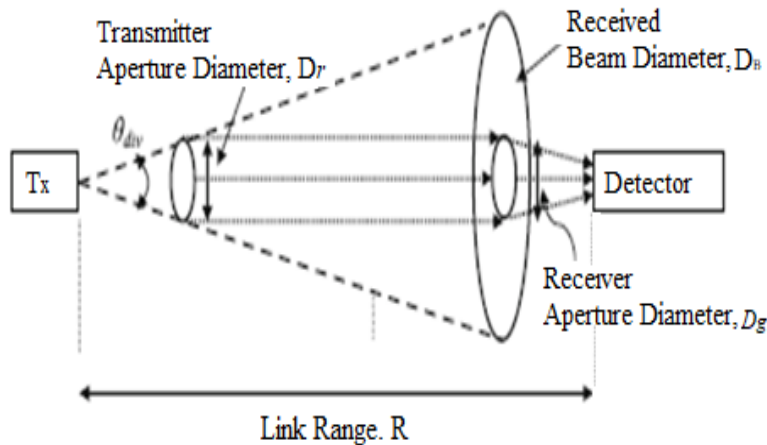


Figure 5: Loss due to Beam Divergence (Kaushal *et al.*, 2017).

Kaushal *et al.*, (2016) observed that, the beam divergence increased with the link length unless the size of the receiver collection aperture was increased or receiver diversity was employed. Generally, the optical source with a smaller or narrow beam divergence is preferable. Figure 5 illustrates the beam divergence loss whereby the receiver is only able to collect a small percentage of the transmitted beam. The optical signal power received by the receiver is expressed as (Kaushal *et al.*, 2017):

$$P_R = P_T G_T G_R L_P \tag{7}$$

where,  $P_T$  presents the transmitted power,  $L_P$  denotes the free space path loss, and  $G_T$  and  $G_R$  are the effective antenna gains of the transmitter and the receiver, respectively.

### 2.4 Background Noise and Sky Radiance

Atmospheric scattering impairment is not only affecting the propagated signal beam within the atmosphere, but also one of the primary sources of sky radiance that introduces channel noise during the daylight communication (Tohsing *et al.*, 2017). Sky radiance is due to the scattering of solar photons along the atmospheric propagation route and it also contributes to the rise of unwanted background noise that reduces the SNR value at the receiver end (Tohsing, *et al.*, 2016). Figure 6 illustrates the scattering process for the different layered model within the atmosphere.

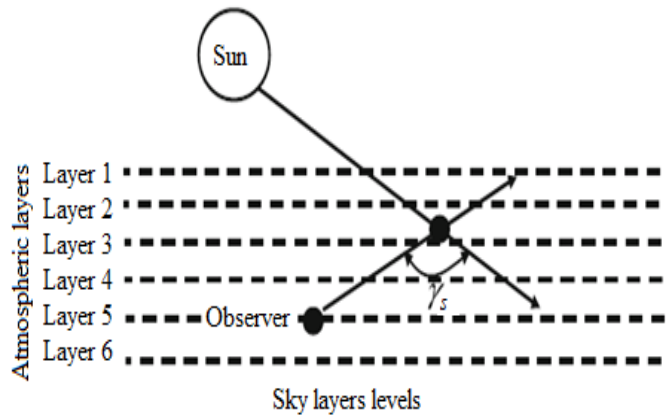


Figure 6: Sky Radiance due to Scattering (Tohsinga, *et al.*, 2016).

The atmosphere is been designed as multiple layers with each layer containing of similar mixture of gases and aerosols. The scattering angle ( $\gamma_s$ ) is the angle designed between the forward direction of the Sun radiation after striking a layer and the point of observation before striking the same layer. It is evident that high concentration of the scatterers, yield lager sky radiance (Tohsing *et al.*, 2017). The application of adaptive optics has been explored to address the effects of sky radiance and background noise using an optical deep-space receiver. This is to improve the superiority of the channel under turbulent atmospheric conditions.

### 3. Method

This part of the research illustrates the step-by-step procedure on how the main aim will be achieved. The main aim of this research is to mitigate the effect of beam divergence in the FSOC channel using a standard test-bed.

#### 3.1 Experimental Validation Setup

The schematic diagram shown in Figure 7 explains the proposed experimental procedure for the developed system characterization and validation.

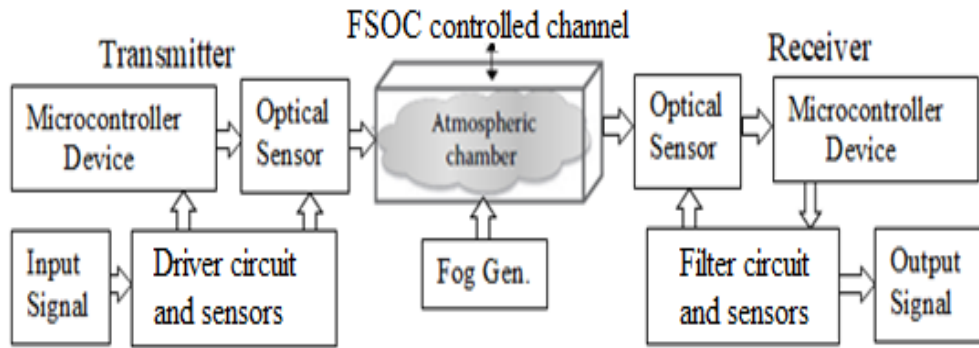


Figure7: Block Diagram of the Experimental Procedure

Figure 7 shows the developed artificial atmospheric chamber. A fog generator is used as a source to generate the fog inside the chamber. The temperature within the chamber is also controlled with the help of heating elements as well as cooling fans. The voltage, current, and ultra-sonic sensors were used to sense, measure and store the values voltage, current and distance into the SD card during each experiment procedure.

**3.2 Testbed Design and Implementation**

This section of the research discussed the designed and the implementation of the developed test-bed. The test-bed is made up of three components such as: Optical transmitter, controlled transmission chamber and optical receiver as shown in Figure 8 and Figure 9 (a & b). This is to facilitate the measurements and allows for the analyses of bit error rate (BER) and signal to noise ratio (SNR).

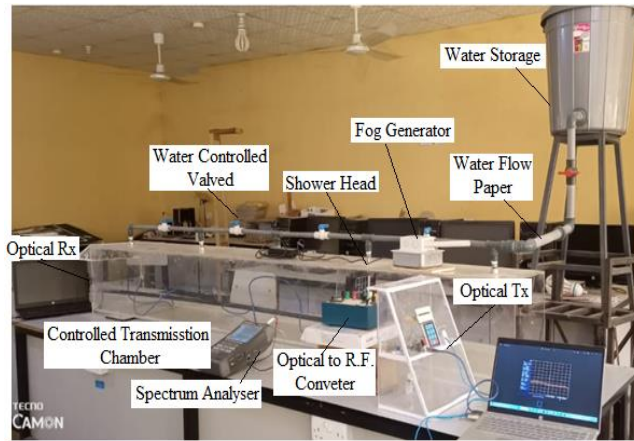


Figure 8: Constructed Test-bed Illustration



(a)



(b)

Figure 9 (a & b): Optical Transmitter Side and Optical Receiver Side

### 3.3 Optical Transmitter

The transmitter accepts the electrical signal at its input, processes the signal and then converts it into optical signal. An opto-electronic device, such as an LED or laser diode are been used to produce an optical signal suitable for transmission via an optical transmission medium. Figure 10 shows the optical transmitter circuit diagram consists of Liquid Crystal Display, (LCD) Arduino microcontroller board, keypad, laser diode, current, and voltage sensors.

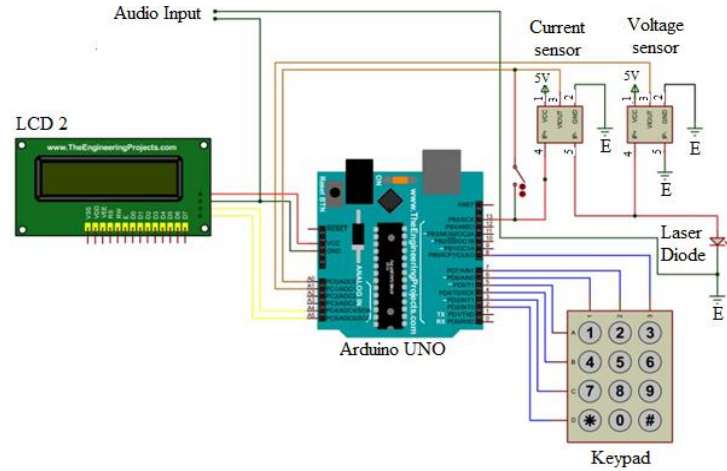


Figure 10: Optical Transmitter Circuit

### 3.4 Controlled Transmission Channel

The controlled channel is made of a transparent plastic material (porcelain) of a size 5.5 cm × 30cm × 30 cm (Ijaz, 2013). This consist of an optical transmitter at one end and optical receiver at the other end. In between the two devices is the controlled transmission channel as shown in Figure 11.

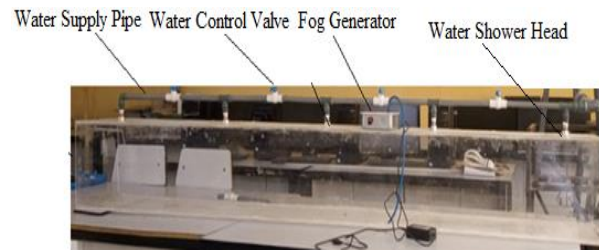


Figure 11: Controlled Transmission Chamber

The artificial fog is generated using the fog generator within the channel to imitate the real fog. The signal is sent from the optical transmitter and is received by the optical receiver placed at different positions away from the transmitter. The received signal (audio, text, or data) is recorded. Also, the voltage, current, and distances are measured using voltage, current and ultrasonic sensors respectively and saved the data in to the SD Card. This procedure is repeated severally by changing the position of the receiver while keeping the transmitter fixed. The transmitter voltage and current are always served as the reference parameters.

### 3.5 Optical Receiver

Photodiode is conventionally used by the optical receivers to detect the sent signal from the transmitter. However, photodiode has narrow receiver aperture which results in a serious optical signal lost due to beam divergence. To mitigate this challenge, a mini-solar panel with a wider aperture compared to that of the photodiode was introduced and served as a receiver. The key function of the receiver is to convert the optical data signal back to its original or electrical signal. Figure 12 shown the optical receiver circuit diagram consisting of LCD, Arduino microcontroller board, ultrasonic sensor, photo diode, mini solar panel, amplifier circuit as well as current, and voltage sensors.



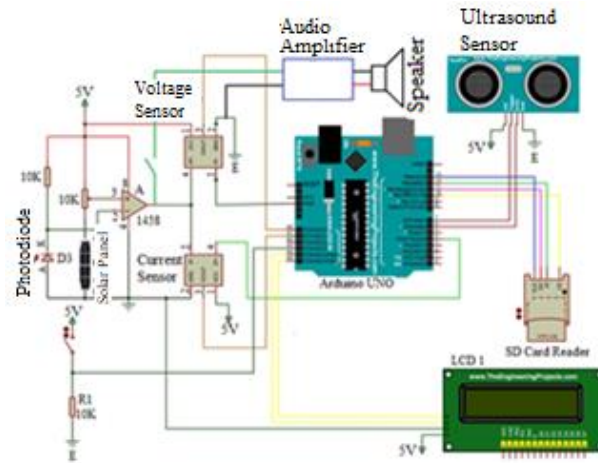


Figure 12: Optical Receiver Circuit

### 3.6 Mini-Solar Panel Receiver

At the receiving end, it is also advantageous to use a mini-solar panel to collect as much of the transmitted power as possible. Consequently, this is to mitigate the effect of beam divergence lost and background ambient light, which introduces noise and thus decreases the performance of the link. Figure 13 is the mini solar panel connection at optical receiver.



Figure 13: Mini Solar Panel Connection

### 3.7 Measurement and Evaluation

The testbed was developed and the measurement was conducted under both fog and rain conditions respectively. The bit error rate (BER) at both transmission and receiving ends were evaluated using equation (8). The BER values were used to evaluate Signal to Noise Ratio (SNR) using equation (10). The test-bed was operated for thorough investigation and analysis of optical attenuation at a transmission window of 550 nm and 1550 nm wavelengths under fog and rain conditions.

### 3.8 Bit Error Rate (BER)

Bit Error Rate (BER) is a parameter used to determine the rate at which errors occur during the signal transmission. This can be simply defined as the number of errors in the bits received to the total number of bits transmitted as defined by Chan, (2016):

$$BER = \frac{\text{No. of bit in Error}}{\text{Total transmitted bits}} \quad (8)$$

### 3.9 Signal-to-Noise Ratio (SNR)

The Signal to Noise Ratio (SNR) is a parameter used to analyze the channel performance. The higher the SNR the better will be the channel performance, then the bit error rate (BER) will become very small or probably insignificant and have no evident effect on the whole signal transmission as defined by Chan, (2016):

$$\text{SNR (dB)} = 10 \log_{10} \left( \frac{\text{Signal power}}{\text{Noise power}} \right) \tag{9}$$

$$\text{BER} = \frac{1}{2} \left( 1 - \sqrt{\frac{\text{SNR}}{2+\text{SNR}}} \right) \tag{10}$$

Equation (10) shows the relationship between SNR and BER whereby the detection of noise in the channel has direct effect on the BER, and this is one of the main reasons for the degradation of a data along the channel.

BER can be obtained by measuring the signal as well as the noise power or by determining the bits of the transmitted signal and that of the received signal using the experimental setup as in Figure 8.

### 3.10 Field of View Diversity (FoV) Technique

This technique is to be adopted to increase the receiver aperture area by means of (i) using multiple number of photodiodes which are to be arranged in parallel or (ii) replacing the receiver photodiode with micro solar panel. This is to mitigating the beam divergence loss caused by scattering effect in the transmission channel. Both measured results will be analyzed and then compared.

## 4. Result and Discussion

This section presents the results analysis of measured values using the developed testbed.

### 4.1 BER versus SNR for Fog Measurement

Signal-to-Noise Ratio (SNR) is typically considered as one of the performance metrics used to measure the quality of the communication signal. SNR is always considered as the measure of the ratio of signal power to noise power. When the value of SNR is higher, it means the quality of the useful signal received at the output is higher than that of the noise signal. The measurements are carried out using the test bed under the artificial fog condition at various distance. Both photodiode and micro solar panel are considered as the optical receiver for the measurements separately. The data obtained was used to simulate the relationship between BER and SNR for both solar and photodiode using equation (10). Figure 14 is the plot of BER against SNR.

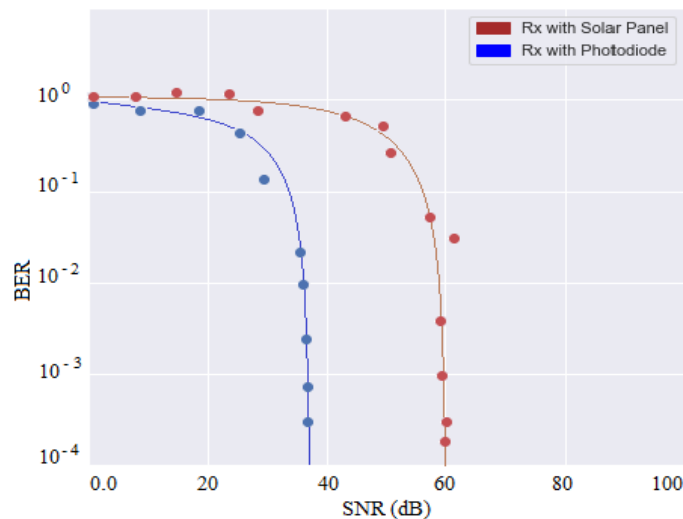


Figure 14: BER Against SNR for Fog Measurements

Figure 14 shows the relationship between the system’s BER and SNR, the result depicts that the higher the SNR, the lower the corresponding BER. Consequently, Figure 14 shows that with the solar panel at the receiver the system achieved higher SNR and lower BER. With the solar panel at the receiver the system achieved higher SNR value of 60 dB at corresponding lower BER value of  $10^{-4}$ . Similarly, with the photodiode at receiver the system achieved low SNR of 38 dB at same corresponding value BER. The result shows that, the photodiode performed poorly due beam divergent loss as a result of its narrow field of view. Table 1 shows the values of BER against its corresponding SNR values achieved by the system under fog measurements.

Table 1: BER against SNR for Fog Measurements

SN	BER	SNR (dB)	
		Photodiode	Solar Panel
1	$10^0$	0.0	0.0
2	$10^{-1}$	37.0	58.0
3	$10^{-2}$	37.5	59.0
4	$10^{-3}$	38.0	59.5
5	$10^{-4}$	38.8	60.0

**4.2 BER versus SNR for Rain Measurement**

Similar procedures as in the case of fog measurements were repeated using the generated artificial rain as shown and explained in the test bet setup. The data obtained are used to plot the relationship between the BER and SNR as shown in Figure 15.

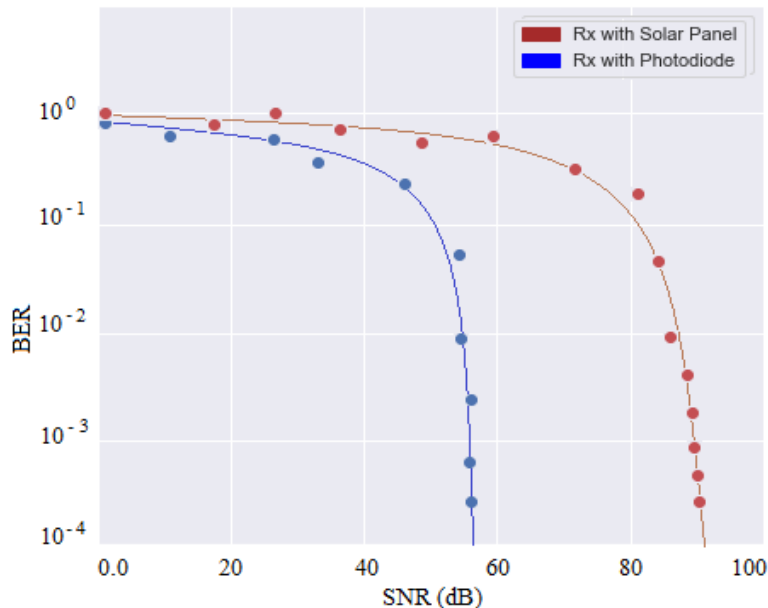


Figure 15: BER against SNR for Rain Measurements

It is observed from the Figure 15 with the photodiode at receiver the system achieved higher SNR value of 58 dB at corresponding BER of  $10^{-4}$ . Correspondingly, same procedure is conducted with the solar panel at the optical receiver where SNR value of 90 dB at corresponding BER value of  $10^{-4}$  are achieved. Table 2 shows the values of BER against its corresponding SNR values achieved by the system under rain measurements.

Table 2: BER against SNR for Rain Measurements

SN	BER	SNR (dB) Photodiode	SNR (dB) Solar Panel
1	10 <sup>0</sup>	0.0	0.0
2	10 <sup>-1</sup>	56.0	80.2
3	10 <sup>-2</sup>	57.0	87.0
4	10 <sup>-3</sup>	57.6	88.0
5	10 <sup>-4</sup>	58.0	90.0

### 4.3 SNR and BER Analysis for Fog and Rain Measurements

This analysis is to evaluate one of the stated objectives of this study. Furthermore, SNR and BER are amongst the performance metrics considered. The percentage increase under both fog and rain conditions are evaluated using the obtained values from Figure 14 and 15 as follows:

- i) The first scenario, is to consider SNR achieved under both conditions (fog and rain) at same BER value using solar panel at the optical receiver.

$$SNR_{Solar} = \frac{SNR_{Rain} - SNR_{Fog}}{SNR_{Rain}} \times 100 \tag{11}$$

$$SNR_{Solar} = \frac{90 - 60}{90} \times 100 = 33.33\%$$

This is to show that, with solar panel, the SNR value achieved under rain condition is greater than that of fog by 33.33 %.

- ii) The second scenario, is to consider SNR achieved under both conditions (fog and rain) with photodiode at the optical receiver

$$SNR_{Phot} = \frac{SNR_{Rain} - SNR_{Fog}}{SNR_{Rain}} \times 100 \tag{12}$$

This is also to show that, with photodiode, the SNR value achieved under rain condition is greater than that of fog by 34.5%.

The average of the two results is

$$Average = \frac{33.33 + 34.50}{2} = 34 \%$$

The measurements are conducted under both fog and rain conditions using photodiode and solar panel at the optical receiver. In both conditions (fog and rain) the SNR achieved while using solar panel is higher than that of photodiode. This indicates that the system is more efficient while using solar panel than photodiode. This is because the higher the SNR value the better for the system performance. Hence, the effect of beam divergence loss is mitigated by means of mini solar panel due to its wider field of view related to photodiode. Furthermore, this shows that fog attenuation affects optical signal more than that of rain attenuation by 34 % averagely.

### 5. Conclusion

The measured results were simulated and the performance metrics of the system were analyzed in terms of BER and SNR. The result showed that, for the fog measurement using mini solar panel at receiver, the system achieved

higher SNR of 60 dB at corresponding BER of  $10^{-4}$ . While with the photodiode, the system achieved an SNR of 38 dB at same BER value of  $10^{-4}$ . Similarly, for the rain measurement using mini solar panel at the optical receiver, the system achieved higher SNR of 90 dB at the corresponding BER of  $10^{-4}$ . While with the photodiode, the system achieved higher SNR of 58 dB at same point BER of  $10^{-4}$ . Hence, it was shown that the effect of beam divergent loss was mitigated with the use of mini solar panel due to its wider field of view compared with that of photodiode. It was also observed that fog impairment attenuates optical signal more than that of rain impairment 34 % averagely.

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