Performance Analysis of Free Space Optics Communication System in Challenging Environments Based on OOK Modulation & MIMO

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***Abstract*— Free-space optical communication (FSO) is an innovative technology that uses light rays to transmit data over the air, providing a wireless alternative to traditional cables. However, the performance of this system is greatly affected by severe weather conditions such as fog, rain, humidity, and atmospheric turbulence, which degrade the quality of communication and pose challenges that require precise solutions. This paper aims to analyze the impact of these environmental factors on the performance of the FSO system using three main criteria: the bit error rate (BER) to evaluate the accuracy of data transmission, the signal-to-noise ratio (SNR) to assess the quality of communication, and the total attenuation induced by each atmospheric condition to quantify its effect on signal degradation. The On-Off Keying (OOK) modulation technique was adopted due to its simplicity and widespread use in optical communication systems. Using MATLAB, simulation models representing different weather scenarios were employed to analyze the performance of the FSO system under varying environmental conditions. The effects of atmospheric changes on system behavior are studied and evaluated to gain a deeper understanding of its operation and limitations. Also, in this paper a further enhancement is introduced to the system by integrating Multiple-Input Multiple-Output (MIMO) technology to improve its performance under challenging conditions as a solution.**

Keywords*— *FSO, OOK, BER, SNR, MATLAB, MIMO, Optical Communication.

I. INTRODUCTION

In recent years, the exponential growth in digital communication services has placed unprecedented pressure on existing transmission infrastructures. Traditional technologies such as Radio Frequency (RF) communication and optical fiber networks though widely adopted are facing increasing limitations. RF systems suffer from spectrum scarcity, interference, and strict licensing regulations, while optical fiber, despite offering high capacity and speed, remains costly and difficult to deploy. As a result, the need for alternative communication methods has become more pressing. One promising solution is Free Space Optics a line-of-sight (LOS) wireless communication technology that transmits data by propagating light through free space. It typically operates within the near-infrared region of the electromagnetic spectrum. An FSO system consists of three essential components: a transmitter, a free-space channel, and a receiver. The transmitter uses a laser source to convert electrical signals into optical pulses that are directed through the atmosphere. These pulses traverse the free-space channel, where their integrity may be significantly affected by environmental factors. Finally, the receiver collects the incoming light and converts it back into electrical signals for processing. Typical FSO links range between 300 meters and 5 kilometers, depending on the type of application and environmental conditions.[1]

This paper when compared to previous studies, it aims to evaluate their overall performance under a range of real-world impairments, giving the ability to predict an accuracy of practical results of the system when affected by severe weather conditions by evaluating the accuracy of data transmission, the quality of communication and the effect on signal degradation. Each environmental factor such as fog, rain, and humidity were modeled separately using appropriate mathematical representations to isolate its impact on signal transmission. Atmospheric turbulence was simulated using the log-normal distribution, while background and internal noise sources were represented through the Additive White Gaussian Noise (AWGN) model. Moreover, integrating the system by (MIMO) technology as a solution to maintain more improvement in system performance. [2, 3,7,11,15]

II. METHODOLOGY

The investigation of the performance of an FSO communication system under various atmospheric attenuation conditions, including fog, rain, humidity, and geometric path losses. To quantify the impact of these environmental factors, several attenuation models are used to represent the physical mechanisms that degrade the optical signal during propagation through the atmosphere. These models describe how different weather conditions affect the received signal power and are essential for realistic performance evaluation of FSO systems.

Atmospheric attenuation in FSO systems results from the interaction between the laser beam and atmospheric molecules and aerosols. The beam power decays exponentially with propagation distance. The optical transmittance τ(λ,L), defined as the ratio of received power Pr to transmitted power Pt over a link distance L, follows the Beer-Lambert law [3, 7]:

$$\tau\,(\lambda, L) = \tau_s + \tau_a = \frac{P_r}{P_t} = e^{-\gamma L} \quad (1)$$

Where: ($\boldsymbol{\gamma}$) is the overall attenuation coefficient, $\boldsymbol{\tau_s}$ is the scattering transmittance and $\boldsymbol{\tau_a}$ is the absorptive transmittance, **L** is the distance between transmitter and receiver (unit: *km*). Based on this model, and by analysing different types of attenuation (fog, rain, humidity, and geometric loss) using the following models:

A. Fog Attenuation

Fog is a major contributor to photon scattering in FSO systems, as the droplet size is comparable to the operating wavelength range (0.5–2 µm), leading to Mie scattering dominance[4]. This causes absorption, scattering, and reflection of the optical beam, degrading signal quality. Fog-induced attenuation is wavelength-dependent, with lower attenuation observed at 1550 nm [5]. It also varies with visibility, affecting transmission performance. The attenuation due to fog follows the Beer–Lambert law [6, 7]:

$$\boldsymbol{\gamma_{fog}} = \frac{\mathbf{3.91}}{\mathbf{V_{is}}}\left(\frac{\boldsymbol{\lambda}}{\mathbf{550nm}}\right)^{-\boldsymbol{\delta}} \quad (2)$$

According to Kim model $\boldsymbol{\delta}$ is given as:

$$\delta = \begin{cases} 1.6 & V > 50km \\ 1.3 & 6km < V < 50km \\ 0.16V + 0.34 & 1km < V < 6km \\ V - 0.5 & 0.5km < V < 1km \\ 0 & V < 0.5km \end{cases}$$

To calculate the attenuation due to fog weather, the given equation is used:

$$\tau_s = e^{-\gamma_{fog} L} \quad (3)$$

B. Rain Attenuation

The rain affects the performance of free space optical communication link. Rain is considered to be the major hurdle for free space optical communication and it degrades the system's performance. The attenuation caused by rain depends upon the size of drops of rain [2] Specific rain attenuation can be calculated using following relationship [2, 7]:

$$\gamma_{rain} = a\, R_{rain}{}^{b} \quad (4)$$

Where: $\boldsymbol{\gamma_{rain}}$ - is the rain specific attenuation in (*dB/km*), $\boldsymbol{R_{rain}}$- the rainfall rate in *mm/hr*, and a, b are parameters depending on frequency, droplet size, and temperature. Assuming spherical drops makes a, b polarization-independent. The Carbonneau model is preferred over the Marshal model due to its basis on physical measurements. a and b for the Carbonneau model equal to 1.076 and 0.67 respectively. Total rain attenuation is given by Beer's law [2, 3, 6]:

$$\text{Rain Attenuation} = e^{-\gamma L} \quad (5)$$

C. Humidity Attenuation

The molecular absorption results from water, carbon dioxide (CO_2) and ozone molecules. The aerosol absorption results from the finely dispersed solid and liquid particles in the atmosphere. To calculate absorption, assumes that variations in the transmission are caused by changes in the water content of the atmosphere. The perceptible water, (in millimeters) is given by [3, 4]:

$$\omega = 10^3 . \rho . \ell \quad (6)$$

where ($\boldsymbol{\rho}$) is the absolute humidity in (*g/m³*). This value can be related with the water vapor pressure ($\boldsymbol{\rho w}$) and with the temperature (*T*) in degrees Celsius illustrated in:

$$\rho = 2.16679 . \rho w / T$$

where the water vapor pressure (ρw) is given by:

$$\rho w = A . 10^{\left(\frac{m.T}{T+T_n}\right)} . \frac{RH}{100} \% \quad (7)$$

where **RH** is relative humidity percentage, **A**, **m** and $\boldsymbol{T_n}$ are constants equal to 6.116441, 7.591386 and 240.7263 respectively [8]. The "Humidity attenuation" or in other words " The absorptive transmittance " can be calculated using the following equations:

$$\tau a = e^{-Ai.w^{1/2}}, \; w < wi \quad (8)$$

$$\tau a = ki . \left(\frac{wi}{w}\right)^{\beta i}, \; w > wi \quad (9)$$

The typical values of the constants Ai, ki, βi and wi are equal to 0.211, 0.802, 0.111 and 1.1 respectively for 1550 nm wavelength.

D. Geometrical loss

Geometric path loss arises due to beam divergence over distance. It depends mainly on the divergence angle (θ), the propagation distance (L), and the receiver aperture area (Ar). This attenuation, caused by beam divergence, reduces received power with distance and is given by[9]:

$$Geometric\ loss = \frac{(d_r)^2}{[d_t + (L\theta)]^2} \quad (10)$$

where, $\boldsymbol{d_r}$ is the diameter receiver aperture (unit: *m*), $\boldsymbol{d_t}$ is the diameter transmitter aperture (unit: *m*), **θ** is the beam divergence (unit: *mrad*), and **L** is the link range (unit: *m*). Geometrical losses are considered constant losses because all internal design parameters remain constant. The total attenuation is the sum of the several partial attenuation factors[2].

In this Paper the environmental factors such as temperature, rainfall intensity, and visibility affect the attenuation in a FSO communication system are investigated. The BER, and the received SNR will be measured under varying rain rates. The attenuation due to humidity will also be measured by gradually varying the temperature from 20 °C to 50 °C, and the effect of visibility changes within a range of 1 *km* to 10 *km*. All these measurements will be carried out over three different transmission distances between the transmitter and receiver: 1 *km*, 2 *km*, and 3 *km*. In addition, the effect of transmitter and receiver aperture diameters on the geometric loss in the FSO system will be studied. Also, the impact of increasing the transmission distance on the performance of the received signal in the FSO system will be studied, and the environmental factor with the greatest impact will be determined.

Performance metrics: The received signal-to-noise ratio (SNR), attenuation, and Bit Error Rate (BER) are considered to evaluate the performance of the FSO system.

1) Received signal to noise ratio for FSO

In communication systems, a higher SNR is desirable, as it reflects better signal quality and improved system performance. For a FSO communication link, the received SNR is given by:

$$SNR = \frac{P_r}{P_{noise}} \tag{11}$$

Where the received power of the signal P_r is given by[2, 9]:

$$P_r = P_t \frac{D^2}{\theta_{div}{}^2 L^2} 10^{-\frac{\gamma L}{10}} \tau_{trans}\tau_{rec} \tag{12}$$

Where $\boldsymbol{P_t}$ is the transmitted power, $\boldsymbol{L}$ is the link distance, $\boldsymbol{D}$ is the receiver diameter, $\boldsymbol{\theta}_{div}$ is the full divergence angle, $\boldsymbol{\gamma}$ is the total attenuation factor (*dB/km*) and $\boldsymbol{\tau}_{trans}$ and $\boldsymbol{\tau}_{rec}$ are the transmitter and receiver optical efficiency respectively, the total noise power P_{noise} is given by [10]:

$$P_{noise} = NEP\sqrt{BW} + \frac{2q\eta G^2 BW}{R_{load}}(P_{bg} + P_r) \tag{13}$$

Where $\boldsymbol{NEP}$ is noise equivalent power of the receiver, $\boldsymbol{BW}$ is the signal bandwidth, $\boldsymbol{q}$ is the electron charge, $\boldsymbol{G}$ and $\boldsymbol{\eta}$ are gain, and responsivity, $\boldsymbol{R}_{load}$ is load resistance, $\boldsymbol{P}_{bg}$ is the background illumination power.

2) Received bit error rate

BER is the number of error bits divided by the total transmitted bits for a studied time period. In order to determine the number of error bits, the transmitted and received bits is compared. The definition of bit error rate can be translated into a simple formula:

$$BER = \frac{Number\ of\ error\ bits}{Total\ number\ of\ transmitted\ bits} \tag{14}$$

III. CHANNEL MODELLING

Atmospheric turbulence is one of the most influential factors contributing to fading in optical wireless communication systems. By causing the received optical signal to vary randomly thus giving rise to signal fading. The fading strength depends on the link length, the wavelength of the optical radiation and the refractive index structure parameter of the C_n^2 channel. The Log-Normal distribution is a popular statistical model for modelling the fading effects of turbulence-induced scintillation of laser beam in FSO communication systems, especially under weak turbulence conditions. This model is mathematically tractable and it is characterized by the Rytov variance σ_x^2 witch can be calculated as [9, 10] :

$$\sigma_x^2 = 1.23\, C_n^2\, K^{7/6}\, L^{11/6} \tag{15}$$

Where: $\boldsymbol{C_n^2}$is the refractive index structure, **K**=2π/λ is the wave number (*an expression suggests that longer wavelengths experience a smaller variance*), MATLAB was used to consider an FSO system that consists of a transmitter, an FSO channel and receiver [5]. As shown in Figure 1.

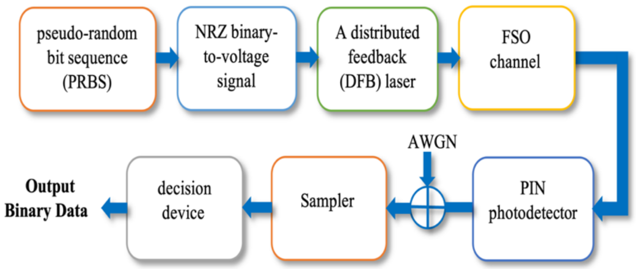


Fig.1. Block diagram of the simulation procedure

The transmitter is represented by a pseudo-random bit sequence (PRBS) generator that produces the binary data. This data is passed to an NRZ binary-to-voltage signal converter, which transforms the binary data into an electrical signal, the electrical signal is converted into the optical domain by a distributed feedback (DFB) laser, which is commonly used for operation at 1550 *nm* [11]. The optical signal is passed through a telescope over the air through the FSO channel [12] toward the receiver. The receiver intercepts the signal and detects it using a PIN photodetector, which converts the optical signal to an electrical signal. This Additive White Gaussian Noise (AWGN) is then added to the electrical signal to model the presence of unavoidable noise in practical FSO systems, including shot noise, background radiation noise, and noise equivalent power (NEP) at the receiver. The sampler and decision device are used to determine the output binary bits from the electrical signal [13].

IV. SIMULATION & CALCULATIONS

Simulation of the FSO system under fog, rain, and humidity effects, incorporating realistic channel modeling (geometric, atmospheric, and turbulence loss), signal modulation/demodulation, and performance metrics like BER and SNR is illustrated in Figure 2. Which is implemented using MATLAB and the results for each of the proposed scenarios is discussed and analyzed in detail as a case.

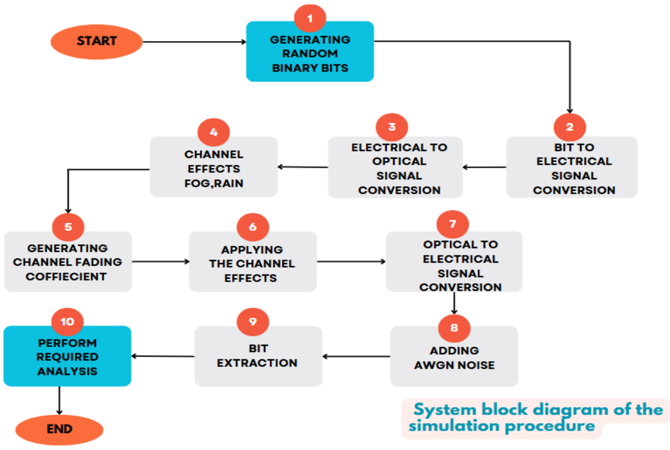


Fig. 2. Block diagram of the simulation procedure

By Generating Random Binary Bits to simulate a pseudorandom binary sequence (*PRBS*) that represents the input to the FSO communication system. The MATLAB function (*randi)* is utilized to create a sequence of bits with values of 0 and 1. While the bit to electrical signal conversion, the bit is expanded using the (*rectpulse)* function to form a non-return-to-zero (NRZ) format suitable for intensity modulation. And the number of samples per bit is determined by the variable (*nsample*). As for electrical to optical signal conversion, by knowing the average output optical power P_{avg} and extinction ratio ε, the following equations are used to calculate the high and low powers corresponding to bits 1 and 0 when implementing OOK modulation [14,1]:

$$P1 = \frac{2\, p_{avg}}{1+\frac{1}{\varepsilon}} \quad (16)$$

$$\mathrm{P0} = \frac{2\, \mathrm{P_{avg}}}{1+\varepsilon} \quad (17)$$

$$\Delta P = P1 - P0 \quad (18)$$

By multiplying the generated electrical signal S_{elec} from step 2 by ΔP and adding the required optical power offset to accommodate the optical power average value, the optical signal at the transmitter side is equal to ($\Delta P \times S_{elec} + P_{avg}$).

V. RESULTS AND DISCUSSION

The results can be divided into six scenarios interim of the different cases, shown as:

A. *Case 1: Geometric loss for different Tx, Rx Aperture Diameters*

The geometric loss analysis for different transmitter \ receiver aperture diameters is done by assuming the link range is 1*km* and the beam divergence is 0.25*mrad* in two different designs. Which are considered as particular design specifications shown in Table 1 and Table 2.

TABLE .1. Design Specifications for different transmitter aperture diameters

Design	Diameter of transmitter aperture	Range of the receiver aperture diameter
design 1	10 cm	5 cm to 20 cm
design 2	5 cm	5 cm to 20 cm

TABLE. 2. Design Specifications for different receiver aperture diameters

Design	Range of the transmitter aperture diameter	Diameter of receiver aperture
design 1	5 cm to 20 cm	15cm
design 2	5 cm to 20 cm	7cm

The geometric losses versus receiver aperture diameter range using the values presented in Table 1 is shown in Figure 3, which it can be seen that the receiver aperture diameter is in the range of 5cm to 20cm**.** For receiver aperture diameter of 5cm, the geometric loss is about 16.9dB for design 1 and 15.5dB for design 2. For the receiver aperture diameter of 20cm, the geometric loss is about 4.8dB for design 1 and 3.5 dB for design 2. It can be seen clearly from the figure that, increasing the receiver aperture diameter directly leads to a reduction in the loss. This phenomenon occurs because as an optical beam propagates, especially over long distances, it undergoes divergence. Only a fraction of the total optical power emitted by the transmitter might intercept the receiver's collection area. A larger receiver aperture can capture a greater portion of the diverging beam, thereby minimizing the power lost due to spatial spreading.

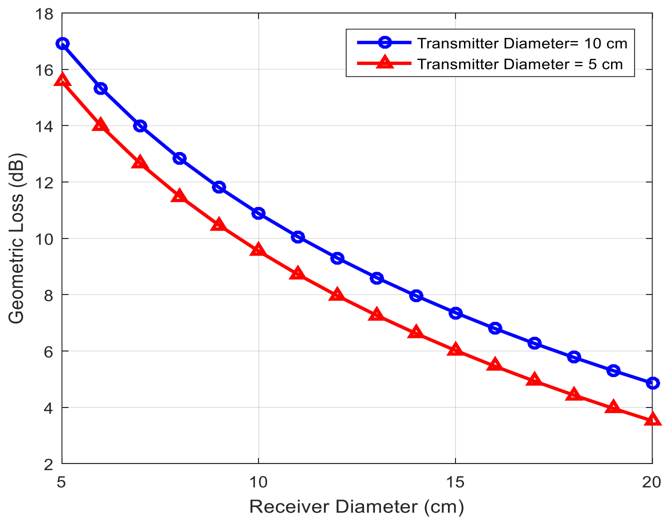


Fig. 3. Geometric loss (dB) versus receiver aperture diameter (m).

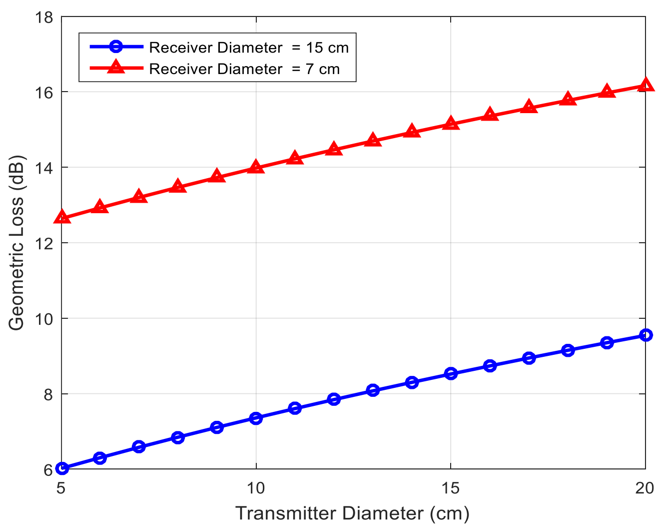


Fig 4:. Geometric loss (dB) versus transmitter aperture diameter (m).

The geometric losses versus transmitter aperture diameter range using the values presented in Table 2 is shown in Figure 4, which it can be seen that the transmitter aperture diameter is in the range of 5cm to 20cm**,** the geometric loss rises with the increase of the transmitter aperture diameter. For transmitter aperture diameter of 5cm, the geometric loss is about 6dB for design 1 and 12.6 dB for design 2. For the transmitter aperture diameter of 20cm, the geometric loss is about 9.5dB for design 1 and 16.1dB for design 2. That means the small transmitter aperture diameter generally leads to higher geometric loss. This is because a larger transmitter diameter means a wider beam footprint at the receiver leading to a larger proportion of the beam being lost.

B. Case 2: Results and discussion of Total Fog Attenuation Analysis for Different Link Distances Under Varying Visibility Conditions

Fog attenuation is primarily dependent on the visibility range, measured in kilometers. In this scenario the visibility range is assumed to vary from 0.5km to 5km with increments of 0.5km. The total fog-induced attenuation was evaluated for different link distances of 1 km, 2km, and 3km to analyze the effect of varying transmission lengths under different visibility conditions. The fog attenuation verses the visibility range for different link distances (1km, 2km, and 3km) is illustrated in Figure 5, which it can be observed that the fog attenuation significantly decreases as visibility increases. For poor visibility conditions (0.5km), the attenuation is relatively high: approximately **7**.8dB, 15.6 dB, and 23.4dB for link distances of 1km, 2km, and 3 km, respectively. As the visibility improves to values greater than 5km, the attenuation becomes minimal and tends to stabilize at lower values (less than 1dB) for all link distances, suggesting that higher visibility significantly reduces the effects of total fog attenuation on FSO performance.

C. Case 3: Results and discussion of Rain Rate

In this scenario, specific values were selected for the main parameters to evaluate system performance under varying rain conditions. Assuming rain rates ranging from 0 to 50 mm/hr, in increments of 5 mm/hr. The main parameters of this scenario are summarized in Table 3.

BER Analysis for different rain rates in *mm/hr* using the values presented in table 3 is shown in figure 6, it can be seen that at a rain rate of approximately 5 *mm/hr*, a BER of around 10^{-5} is achieved, indicating that the system maintains acceptable performance under light rain conditions. As rain rates increase beyond 10 *mm/hr*, the BER begins to rise significantly, reflecting a clear degradation in link quality due to the increasing attenuation caused by heavier rain. This trend highlights the system's sensitivity to rain, where higher precipitation rates lead to more pronounced signal degradation.

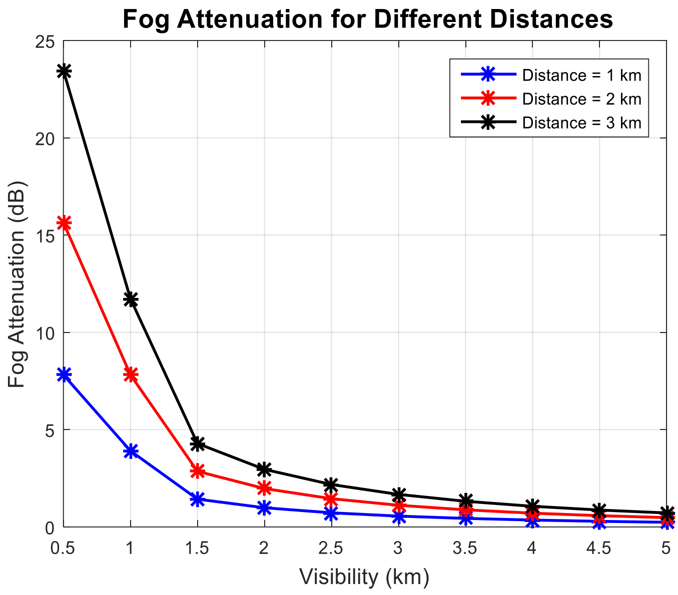


Fig. 5. Fog Attenuation for Different Distance.

TABLE .3. Main Parameters Used in case 3.

Operating Parameter	Value	Operating Parameter	Value
Average Transmitted Power (Pavg)	10 mw	Relative Humidity (RH)	10 %
Laser Beam Divergence Angle (θ_{div})	0.25mrad	Background Light Power (P-background)	0.01Mw
Wavelength (λ)	1550nm	Photodetector Responsivity (PD-Resp)	0.5 A/W
Operating Parameter	Value	Photodetector Gain (PD-Gain)	1 V/A
Transmitter Aperture Diameter (dt)	8cm	Receiver Load Resistance (PD-RL)	50 Ω
Receiver Aperture Diameter (dr)	15cm	Electrical Bandwidth (BW)	0.5GHz
Link Length (L)	500m	electron charge(q)	1.60217662× 10^{-19}
Temperature (T)	20℃	Noise equivalent power (NEP)	$1 \times 10^{-14}\, w/\sqrt{Hz}$
Visibility (Vis)	50Km		

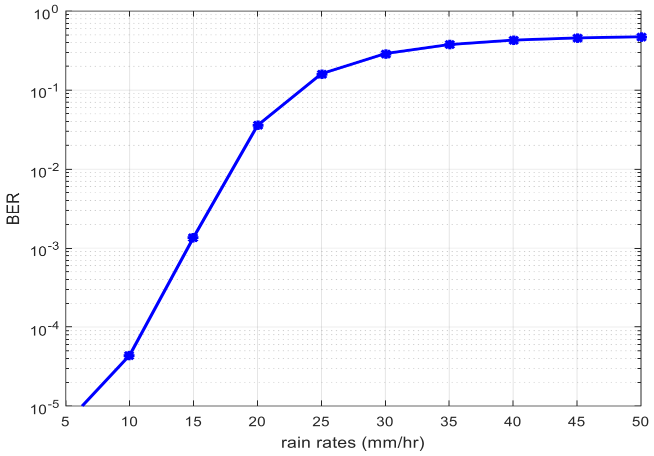


Fig. 6. BER versus rainfall rate (mm/hr) showing the effect of increasing rain intensity on BER.

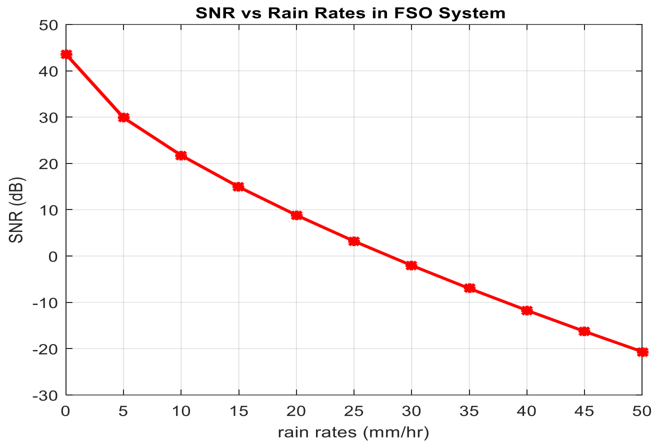


Fig. 7. SNR (dB) versus Rainfall Rate (mm/hr) showing the effect of increasing rain intensity on SNR.

SNR Analysis for different rain rates using the values presented in Table 3 is demonstrated in Figure 7, the SNR decreases significantly as rain rate rises. Specifically, at a rain rate of approximately 5mm/hr, the obtained SNR is around 30dB, reflecting excellent signal quality. However, as the rain rate increases to around 10mm/hr, the SNR drops. This decline continues with increasing rain intensity, and at 50mm/hr, the SNR approaches -20dB, indicating severe signal impairment and near-total signal loss caused by extreme rain conditions.

D. Case 4: Results and discussion of humidity Attenuation Analysis Under Varying Temperature Conditions

The attenuation analysis is primarily dependent on temperature, relative humidity (RH), and transmission distance. In this scenario, the temperature range is assumed to vary from 20°C to 50°C with increments of 5°C, and the relative humidity is fixed at 70%.

The total attenuation due to humidity, was evaluated for different transmission distances of 1km, 2 km, and 3km to analyze the effect of varying link lengths under different temperature conditions. The constants A, m, T_n used for the humidity model are 6.116,7.591,240.726 respectively.

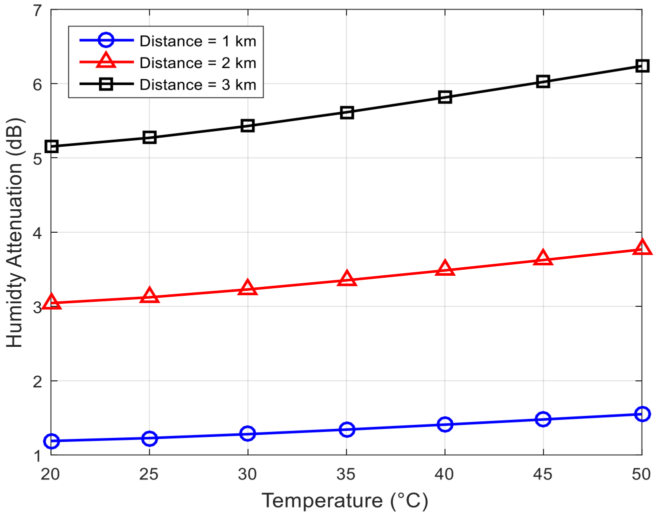


Fig. 8: Humidity Attenuation (dB) versus Temperature (°C)

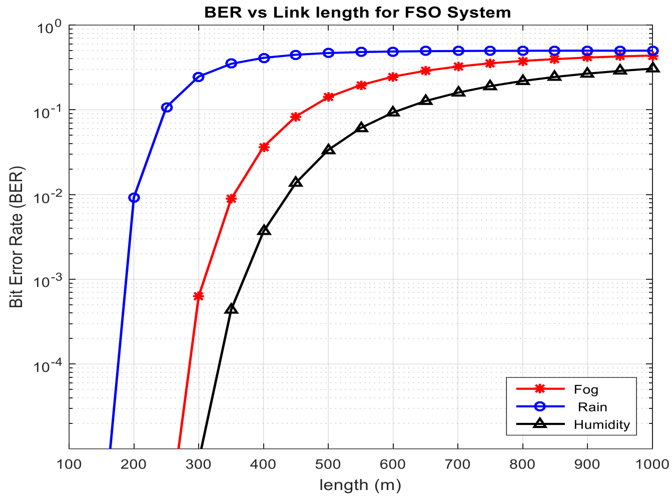
The variation of humidity attenuation (dB) with temperature (°C) for different link distances is shown in Figure 10, it is observed that the humidity attenuation increases with both temperature and distance. For the 1km link, attenuation remains relatively low (around 1.1–1.5dB). For the 2km link, attenuation is higher (around 3.0–3.7dB). At 3km, the system experiences the highest attenuation (from approximately 5.1 dB to above 6.2 dB), with a clear upward trend across the entire temperature range.

E. Case 5: Results and Discussion on the Effects of Fog, Rain, and Humidity on the Performance of the System

This scenario represents the "primary" scenario in this paper, as it takes into account all atmospheric factors affecting the system, including fog, rain, humidity. The system's performance is evaluated by measuring the BER, SNR, and total attenuation. In order to simulate realistic atmospheric conditions, several key parameters were selected based on actual climate data specific to Tripoli, Libya. These parameters include relative humidity, temperature, and rain rate, based on the Climate & Weather Averages in Tripoli, Libya. The key parameters used in this scenario are presented in the Table 4.

TABLE .4. Main Parameters Used in Case 6

Operating Parameter	Value
Average Transmitted Power (Pavg)	10 mw
Laser Beam Divergence Angle (θ_{div})	1 mrad
Wavelength (λ)	1550nm
Transmitter Aperture Diameter (dt)	10 cm
Receiver Aperture Diameter (dr)	15cm
Link Length (L)	1km
Rain Rate (R)	15 mm/hr
Visibility (Vis)	1.5 Km
Relative Humidity (RH)	60 %
Temperature (T)	21℃
Refractive index (C_n^2)	5×10^{-17}
Background Light Power (P-background)	0.01Mw
Photodetector Responsivity (PD-Resp)	0.5 A/W
Photodetector Gain (PD-Gain)	1 V/A
Receiver Load Resistance (PD-RL)	50 Ω
Electrical Bandwidth (BW)	0.5GHz
electron charge (q)	$1.60217662 \times 10^{-19}$
Noise equivalent power (NEP)	$1 \times 10^{-14}\ w/\sqrt{Hz}$



Fig, 9. The BER vs the link length in m.

1. BER Analysis under Atmospheric Conditions: Fog, Rain, and Humidity

In Figure 9, a demonstration of the relationship between the BER and the link length in meters (m) under three different atmospheric conditions. From the obtained BER results, it is evident that at short transmission distances, the system is capable of achieving very low BER), reaching values in the order of 10^{-5}. However, as the transmission distance increases, the BER degrades significantly, depending on the prevailing atmospheric condition.

Under rain conditions, the acceptable BER (10^{-5}) is only achieved up to a distance of approximately 160 meters, beyond which the BER increases. This clearly indicates that FSO systems under rain suffer from severe performance limitations and are only viable for very short-range applications.

In the case of fog, the system maintains an acceptable BER up to around 270 meters, after which the performance begins to deteriorate progressively. This suggests that fog imposes a moderate attenuation effect, allowing for a slightly extended operational range compared to rain.

Under humidity conditions, the system shows the least sensitivity, with the acceptable BER achieved at distances up to 300 meters. This indicates that water vapor has a relatively mild impact on the FSO signal, allowing for more stable performance over longer distances.

2. SNR Analysis under three Conditions: Fog, Rain & Humidity

As for Figure 10, it shows the relationship between the SNR in decibels (dB) and the link length in meters (m) under three different atmospheric conditions. The analysis of the SNR performance under varying atmospheric conditions reveals that while the initial SNR at zero distance is approximately 40dB in All cases, the degree of degradation with increasing distance is highly dependent on the specific weather condition.

In rain conditions, the SNR degrades rapidly, limiting the system's ability to maintain reliable communication over extended distances. At the point where an acceptable (BER = 10^{-5}) is achieved, the corresponding SNR is approximately 17dB.

Under foggy conditions, although the attenuation is less severe compared to rain, it still significantly impacts the signal quality over distance. The required SNR to achieve the acceptable BER is around 14dB.

Humidity, on the other hand, introduces the least degradation among the three weather scenarios. The system is able to achieve an acceptable BER while maintaining an SNR of approximately 15.7dB.

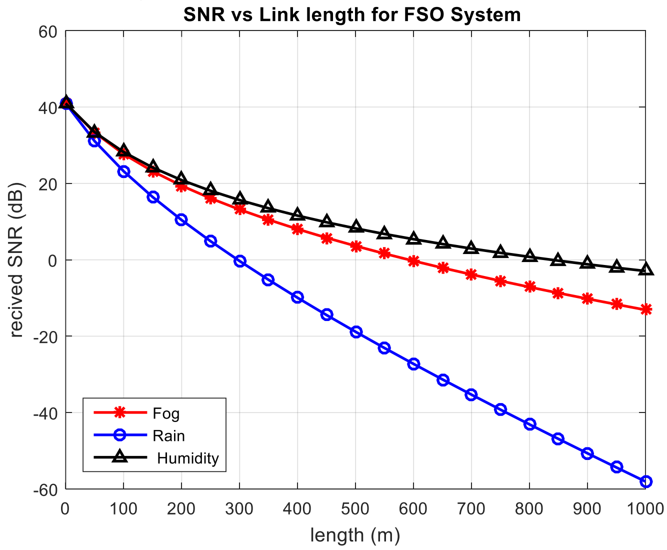


Fig.10. The received SNR (dB) vs the link length in meters relationship between the SNR in decibels (dB) and the link length in meters (m) under three different atmospheric conditions

3. Attenuation Comparison Analysis for each atmospheric condition

In Figure 11, which illustrates the relationship between the total attenuation (in dB) and the link length (in meters) under three different atmospheric conditions. At zero distance, all conditions naturally start at zero attenuation. As the transmission distance increases, the attenuation rises across all conditions, but with markedly distinct rates of increase.

The rain condition, exhibits the steepest and most pronounced growth in attenuation. Specifically, attenuation rises almost linearly, reaching approximately 6.6dB at 1000m. The linear trend suggests a consistent degradation rate per unit distance, highlighting rain as the most dominant factor limiting link performance in outdoor deployments.

In contrast, **the fog condition** shows a much gentler increase in attenuation, reaching around 1.4dB at 1000m. Although fog also induces scattering, its effect is substantially lower compared to rain, especially over longer ranges.

Humidity exhibits the least attenuation increase, barely surpassing 1.1dB at the maximum measured distance. This observation confirms that high atmospheric moisture, in the absence of (rain or fog), has a minor impact on signal loss over distance.

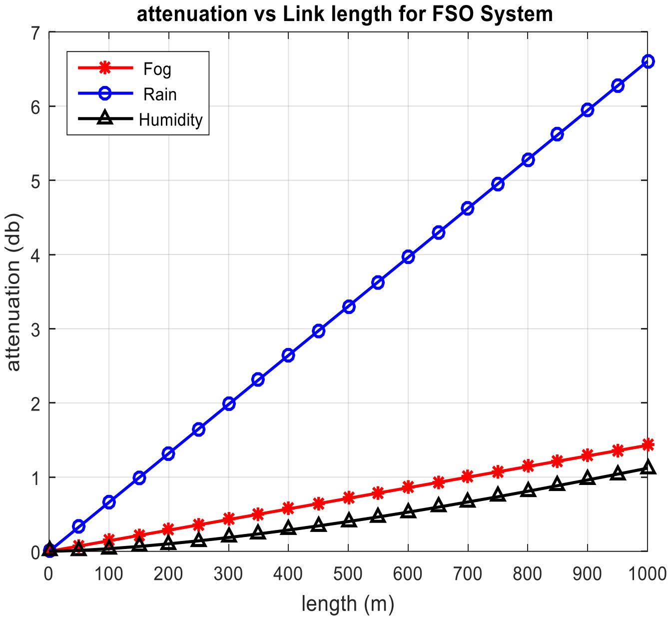


Fig.11. The Attenuation vs the link length in meters showing relationship between the total attenuation (in dB) and the link length (in meters) under three different atmospheric conditions.

F. *Case 6: Enhancing Free-Space Optical (FSO) Communication Using MIMO Techniques*

This scenario represents a "suggested solution" scenario in this paper, aiming to enhance FSO communication performance using MIMO technique. It evaluates the system's ability to maintain low BER and high SNR over extended distances by leveraging spatial diversity. To simulate this configuration, key transmission parameters were chosen. The specific parameters applied in this scenario are summarized in Table 5.

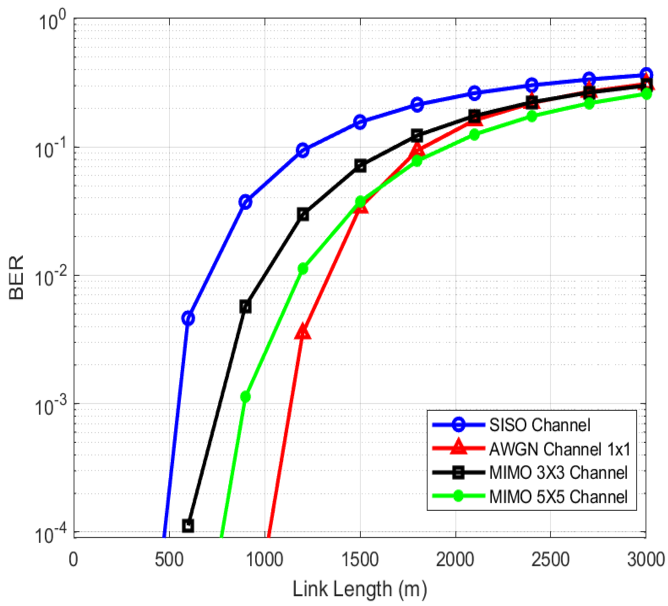
1. BER Analysis for different channels

From Figure 12, which illustrates the performance of the BER over different transmission distances using three communication techniques: SISO, AWGN, and MIMO, the results indicate that SISO consistently exhibits the highest error rates across all ranges, achieving a BER close to 10^{-4} only at a short distance of approximately 490m. In contrast, the AWGN channel unaffected by fading performs significantly better, reaching the same BER level at a much longer distance of around 1050m. When using MIMO technology, a clear improvement is observed. The 3×3 MIMO configuration achieves comparable BER at about 600m, outperforming SISO. The 5×5 MIMO setup further extends this range to 800m.

TABLE .5. Main Parameters Used in MIMO Scenario.

Operating Parameter	Value
Average Transmitted Power (Pavg)	10 mw
Laser Beam Divergence Angle ($\boldsymbol{\theta_{div}}$)	0.25 mrad
Wavelength (λ)	1550nm
Transmitter Aperture Diameter (dt)	8 cm
Receiver Aperture Diameter (dr)	10cm
Link Length (L)	3 km
Rain Rate(R)	2 mm/hr
Visibility (Vis)	60 Km
Relative Humidity (RH)	10 %
Refractive index ($\mathbf{C_n^2}$)	8×10^{-15}
Photodetector Responsivity (PD-Resp)	0.5 A/W
Photodetector Gain (PD-Gain)	1 V/A
Receiver Load Resistance (PD-RL)	50 Ω
Ele	0.5GHz
electron charge(q)	$1.60217662\times 10^{-19}$
Noise equivalent power (NEP)	1×10^{-14} w/√Hz
Temperature (T)	20℃

Fig. 12. Bit Error Rate (BER) vs link length for SISO, MIMO 3×3, MIMO5×5, AWGN channels.



2. SNR Analysis for different channels

An illustration of the relationship between the received SNR and the link length (distance) for three different communication techniques: SISO, 3×3 MIMO, and 5×5 MIMO is shown in Figure 13, also shows the result at a fixed distance of 1500m, the SNR values for SISO, 3×3 MIMO, and 5×5 MIMO were approximately 10dB, 15dB, and 18dB respectively, showing a clear enhancement in signal strength due to spatial diversity.

In the case of the distances at which each system achieved good BER performance, the results show the following: At a distance of 490m, the SISO system achieved an SNR value of approximately 23dB. For the 3×3 MIMO system, the SNR at a distance of 600m was approximately 26dB. In the case of the 5×5 MIMO system, the SNR at a distance of 800 m was approximately 25dB.

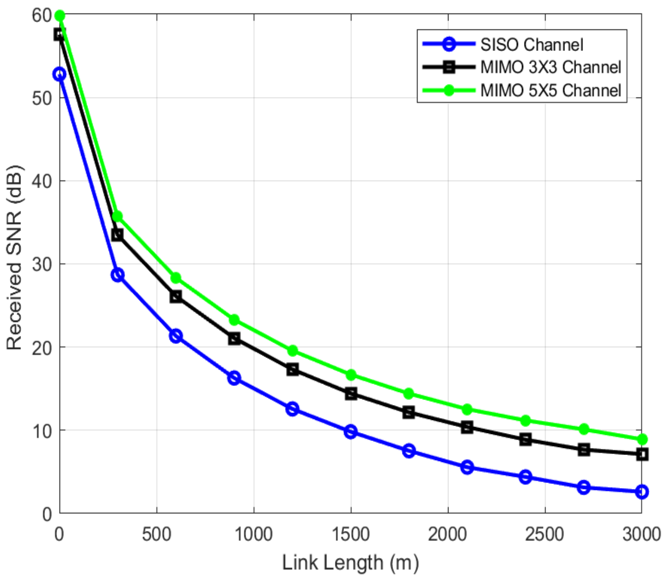


Fig.13. Received Signal-to-Noise Ratio (SNR) vs link length for SISO, 3×3 MIMO, 5×5 MIMO channels

VI. Conclusion

The performance of an FSO communication system was investigated under various atmospheric conditions, including humidity, fog, and rain, with key performance indicators such as SNR and BER and total attenuation used for evaluation based on OOK modulation. The system was configured with a transmission range of 1km and operated at a wavelength of 1550nm, selected for its lower sensitivity to atmospheric attenuation, as well as its eye safety.

A laser source was used for transmission due to its ability to direct optical beams precisely. On the receiver side, a PIN photodetector was utilized, known for its effective optical signal detection and conversion to electrical signals.

The results demonstrated that both transmitter and receiver aperture sizes directly influence geometric loss. Specifically, increasing the transmitter aperture resulted in higher divergence and greater geometric loss, while a larger receiver aperture mitigated this effect by capturing more of the transmitted signal. Additionally, geometric loss attenuation increases with longer link distances.

Regarding weather-induced impairments, rain was identified as the most limiting factor. The results confirmed that the FSO system is unable to maintain operational efficiency under high rain rates, restricting its use to very short transmission distances. Fog was the second most impactful factor; it was observed that attenuation increases significantly as visibility decreases. In humidity-affected conditions, attenuation rose with increasing temperature; however, humidity exhibited the least impact on BER compared to the other conditions.

The integration of a 5×5 MIMO configuration led to a substantial enhancement in system performance by leveraging spatial diversity. Experimental results demonstrated that this configuration successfully extended the transmission range, resulting in approximately 63% greater coverage compared to the conventional (SISO) system as in previous studies.

Overall, the paper shows that the analysis confirms that atmospheric variability has a significant influence on FSO system performance. These findings emphasize that FSO systems are best suited for short-range applications. Moreover, the integration of MIMO technology demonstrates a promising approach to overcoming some of the limitations imposed by environmental factors. This is clearly evident when compared to previous studies and makes it distinct from them in the accuracy of the results and the demonstration of greater reliability of the system when exposed in an environment to different climatic conditions.

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