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EVALUATION OF FREE SPACE OPTICAL (FSO) COMMUNICATION PERFORMANCE AMIDST ATMOSPHERIC TURBULENCE UTILIZING MATLAB SIMULATION

Effiong Antigha Archibong*1, **Omini, Ofem Uket***2, **Tawo, Godwin A***3

*1,2,3University Of Cross River State, Calabar South, Cross River State, Nigeria.

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ABSTRACT

This study aims to investigate how atmospheric turbulence affects free-space optical (FSO) communication. The findings of the simulation demonstrate that the inverse-square rule causes the power of the received signal to drop with increasing transmission distance. The received signal power, for instance, was lowered by almost 75% at a distance of 500 meters, demonstrating the significant signal loss that takes place in free space. The analysis also revealed a direct relationship between the signal-to-noise ratio (SNR) and the bit error rate (BER). SNR values between 10 and 15 dB are associated with BERs, indicating that SNR increases the reliability of communication. The likelihood of experiencing deep fades was assessed using fading distributions, revealing a 50% chance of deep fade occurrences at an SNR of 5 dB. From 100 meters to 1000 meters, the probability of maintaining an SNR above 10 dB decreases by 40% using cumulative distribution functions (CDF) for SNR. The examination of the Doppler effect highlighted a significant influence on frequency stability for mobile systems, recording a maximum frequency deviation of 1 kHz due to relative motion at 100 m/s. This study provides an in-depth understanding of how atmospheric turbulence affects FSO communication performance, offering crucial insights for the development of robust optical communication systems.

Keywords: FSO, Communication Network, Atmospheric Turbulence, MATLAB.

I. INTRODUCTION

In the current landscape, with the escalating need for data and the expectation for networks to support greater bandwidth, Free Space Optical (FSO) communication is becoming a promising alternative to conventional radio frequency (RF) systems. Its capability to deliver high data rates, function over unlicensed frequency bands and facilitate rapid, cable-free installations makes FSO especially advantageous in areas where the installation of fiber optics is either extremely costly or technically difficult (Kaur & Kaur, 2020).

FSO transmits modulated light signals through the atmosphere from a transmitter to a receiver. Since it does not rely on physical cables like fibre optics, it offers greater flexibility and cost efficiency, which is particularly advantageous for connecting buildings in urban areas or expanding networks to remote locations (Hemani & Saini, 2021). This makes it an attractive option for addressing connectivity challenges in both developed and developing regions.

The main challenge faced by Free Space Optics (FSO) is the atmosphere itself. Changes in temperature, pressure, and wind modify the refractive index of air, leading to what is known as atmospheric turbulence. This results in variations in signal intensity, called scintillation, which negatively affect the performance and reliability of the FSO link (Majumdar, 2015). Other environmental elements, such as absorption, scattering, and beam wandering, can further degrade signal quality, increasing bit error rates (BER) and reducing the reliability of communication (Andrews & Phillips, 2005).

While many researchers have studied the atmospheric impacts through theoretical and numerical methods, earlier studies have lacked thorough graphical or statistical simulations. These simulations are crucial for understanding the effects of real turbulence on FSO systems and for creating systems that can adapt to such conditions. Luckily, contemporary tools like MATLAB allow engineers to more efficiently simulate these effects and evaluate system performance across a variety of environmental situations (Kedar & Arnon, 2004).

This study improves existing knowledge by creating a detailed simulation framework in MATLAB to assess the performance of free-space optics (FSO) under diverse atmospheric turbulence conditions and different link distances. By mimicking real-life situations, the research provides deeper insights into the operational characteristics of these systems, helping engineers and researchers to design more dependable, adaptable and high-performance FSO communication links.

II. LITERATURE REVIEW

This research investigates the effectiveness of wavelength diversity in mitigating the adverse effects of intense atmospheric turbulence on free-space optical (FSO) communication systems. Kshatriya et al, (2015) point out that atmospheric turbulence leads to intensity fluctuations, resulting in higher bit error rates (BER). By implementing multiple wavelengths, the system can capitalise on the differing impacts of turbulence-induced fading on various wavelengths, thus enhancing the overall reliability of the link. The researchers develop mathematical models to assess outage probabilities in conditions of significant turbulence. Their simulations demonstrate that the use of wavelength diversity significantly reduces the impact of turbulence, leading to improved BER performance. This approach offers a viable solution for reinforcing FSO links in challenging atmospheric conditions.

The importance of (Kshatriya et al, 2015) lies in its practical approach to addressing turbulence-induced fading through wavelength diversity. By presenting a theoretical framework alongside simulation results, the study offers valuable insights for designing more resilient FSO systems, particularly in regions prone to severe atmospheric disturbances.

In another research on the subject matter, (Sridhar et al, 2022**)** investigate the performance of Free Space Optics (FSO) systems under various levels of atmospheric turbulence and different types of noise. Their objective is to analyse the effectiveness of several modulation schemes, particularly M-QAM, when exposed to both mild and severe turbulence, along with quantum, thermal, and background noise. The study employs extensive simulations, revealing that thermal noise has a greater effect on system performance than other noise types. The findings also indicate that the choice of modulation scheme plays a crucial role in the system's ability to withstand atmospheric disturbances.

This research offers a comprehensive examination of the relationships between atmospheric turbulence, noise and modulation schemes in FSO systems. It provides important insights for system designers, aiding them in improving performance by selecting appropriate modulation techniques and taking into account prevalent noise sources.

In their research, Singh, Sharma & Beri (2016) investigate the impact of Bessel filters on the efficacy of free space optical (FSO) systems facing various atmospheric disturbances. Recognizing that atmospheric turbulence can disrupt optical signals, the authors assess whether Bessel filters can effectively mitigate these issues. Utilizing MATLAB simulations, Singh, Sharma & Beri (2016) constructed FSO systems that incorporated Bessel filters and evaluated their performance under different turbulence conditions. The results indicated that Bessel filters could enhance signal quality by reducing noise and distortion, ultimately leading to a lower bit error rate (BER).

This paper contributes to the existing body of work by demonstrating the efficacy of Bessel filters in improving FSO system performance in challenging atmospheric conditions. It presents a practical approach for engineers looking to enhance signal integrity within optical communication networks.

“Bazil Raj Anthonisamy et al (2016)” tackled the problem of beam wandering in free-space optical (FSO) systems, where changes in the atmosphere cause the optical beam to stray from its intended route, resulting in signal deterioration. They introduced a beam wandering compensation (BWC) control technique designed to stabilise the beam and improve communication reliability. An experimental configuration was created that includes a neuro-controller integrated within a field-programmable gate array (FPGA), which can adjust the beam's position in real-time. The system's effectiveness was assessed over a distance of 0.5 km, with performance indicators such as Q-factor and bit error rate (BER) analysed through eye-diagram evaluation.

The findings indicate that implementing BWC significantly improves the performance of FSO systems by mitigating the effects of beam wandering. This research provides a viable strategy for enhancing signal stability in real-world atmospheric conditions.

Amirabadi (2019) presents cutting-edge deep learning (DL) approaches designed to alleviate atmospheric turbulence in free-space optical (FSO) communication systems. The author suggests three DL-based models:

transceiver learning, transmitter learning, and a hybrid approach, aiming to improve system performance under varying turbulence conditions. Simulations are conducted to evaluate the proposed DL models in comparison to traditional MIMO FSO systems utilizing maximum likelihood detection. Findings reveal that the DL-based methods either perform on par with or surpass the effectiveness of conventional techniques while demonstrating lower complexity, successfully minimizing distortion caused by turbulence.

By integrating DL techniques into FSO systems, this research paves the way for adaptive and intelligent communication solutions. It underscores the potential of machine learning to address intricate challenges in optical wireless communication.

Rodenburg, Mirhosseini, Malik et al (2013) describe a laboratory method designed to recreate dense atmospheric turbulence, which proves advantageous for testing free-space optical (FSO) systems, especially those that utilize orbital angular momentum (OAM) for data transmission. The objective of the authors is to reproduce the impacts of prolonged atmospheric turbulence in a controlled setting. Through the use of phase screens and adaptive optics, Rodenburg, Mirhosseini, Malik and their co-authors (2013) develop a scaled model that mimics a 1 km FSO link. This setup allows for the evaluation of the performance of OAM-based communication under simulated turbulent conditions, yielding valuable insights into the system's robustness and possible countermeasures.

The paper presents a valuable experimental framework for evaluating FSO systems in lab settings, facilitating the progression and investigation of advanced communication techniques without the need for extensive field trials.

Xu et al. (2021) conducted a study that explores the effectiveness of free space optical (FSO) systems amid atmospheric turbulence, analyzing various noise types, including background, thermal, and quantum noise. The researchers utilize lognormal and Gamma-Gamma channel models to describe scenarios ranging from weak to strong turbulence. The simulation results indicate that thermal noise has the most significant negative impact on system performance, with background noise and quantum noise having a lesser effect. Furthermore, the study emphasizes how different turbulence models affect bit error rate (BER) and channel capacity, providing an in-depth analysis of system performance across different conditions.

The findings offer important insights for FSO system design by highlighting the necessity of factoring in specific noise types and turbulence models. This research aids in optimising system parameters to ensure reliable communication under varied atmospheric situations.

Kumar, R., & Singh, S. (2020) investigated the performance of free space optical (FSO) systems under realistic atmospheric conditions using the OptiSystem simulation tool. Their study concentrated on assessing various modulation techniques, particularly 16-QAM and DP-QPSK, in different weather scenarios, including clear skies, haze, and fog. The simulations took into account factors such as transceiver aperture sizes and attenuation coefficients to evaluate the bit error rate (BER) over distances of up to 200 km. The findings indicated that larger aperture sizes and favourable weather conditions significantly improve system performance, whereas adverse conditions like fog greatly restrict transmission distances.

This study offers essential insights for the design and implementation of FSO systems, highlighting the necessity of considering environmental factors and system configurations to maintain reliable communication links.

Chaudhari & Rajput (2024) investigate the performance of Free Space Optics (FSO) systems in the Egyptian cities of Alexandria and Aswan, focusing on how atmospheric turbulence and weather conditions affect their effectiveness. They apply a micrometeorology model to assess real-time weather information and evaluate system efficiency using multi-hop decode-and-forward (DF) relay techniques. The results show that temperature variations significantly influence FSO link performance, with the best outcomes occurring during the winter season. The implementation of multi-hop DF relays improves performance.

III. FREE SPACE OPTICAL COMMUNICATION

Free Space Optical (FSO) communication is a rapid wireless technology that transmits data by altering the properties of light, generally from lasers or light-emitting diodes (LEDs), through the atmosphere, to a designated receiver. In contrast to conventional radio frequency (RF) systems, FSO operates within the optical spectrum, allowing it to provide significantly higher bandwidth while functioning on unlicensed frequency bands (Kaushal & Kaddoum, 2016). The focused nature of its light beam also enhances security, as it makes the signal much more difficult to intercept or eavesdrop on.

One of the key benefits of FSO is its rapid deployment capability, particularly in regions where installing fibre optic cables is prohibitively expensive or impractical, such as densely populated urban areas or remote sites (Ghassemlooy et al, 2019). This technology is based on the concepts of electromagnetic wave propagation, optical beam behaviour and photodetection, establishing a robust theoretical basis for its practical uses (Khalighi & Uysal, 2014).

IV. ATMOSPHERIC TURBULENCE AND CHANNEL IN FSO

Atmospheric turbulence, induced by fluctuations in temperature and pressure, can significantly impact Free Space Optical (FSO) communication by causing signal fading and phase distortions that reduce reliability and overall performance (Kaushal & Kaddoum, 2016). To comprehend and anticipate these impacts, researchers generally use statistical models such as the log-normal distribution for weak turbulence and the gamma-gamma distribution for more severe conditions (Varotsos et al., 2014). These models assist in simulating how signals behave under various atmospheric conditions.

Despite this, a significant portion of current research in Free Space Optical (FSO) communication primarily concentrates on isolated performance metrics such as Bit Error Rate (BER), often neglecting a comprehensive systems-level perspective. For example, although BER is crucial, it does not adequately address how turbulence interacts with dynamic elements like Doppler shifts or fluctuating channel capacity over time (Al-Gailani et al., 2020). Additionally, research often neglects practical elements, like changing weather patterns, fog, rain, or physical actions impacting communication connections, which significantly affect system efficacy (Kaur & Kaur, 2021).

Such oversights could make certain research appear somewhat detached from the complex realities associated with real-world FSO implementations. To tackle this concern, the present study utilizes a simulation-based approach that not only analyzes one specific parameter but also integrates a realistic variety of environmental and mobility factors, yielding a more thorough and relevant perspective on FSO system performance (Safi et al., 2022).

V. METHODOLOGY

A simulation using MATLAB was conducted to model FSO channels affected by turbulence. To represent the effects of turbulence-related fading, both gamma-gamma and log-normal distributions were employed. Afterwards, the system's performance metrics were calculated and depicted under different turbulence scenarios, providing insights into how varying turbulence intensities impact communication performance.

5.1 Free Space Loss (FSL) Model:

The free space loss (FSL) in free space optical (FSO) communication refers to the decrease in optical power as a light beam travels through free space, such as air or vacuum, caused by the spreading of the beam over distance and the influence of atmospheric turbulence (Rappaport, 1996). It is represented as $L_{FS}(d)$ and can be calculated using the following formula:

$$L_{FS}(d) = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left({}^{4\pi}/_{c}\right) \quad (1)$$

Where;

$L_{FS}(d)$ = Path loss at distance d (in dB)

d = Distance between transmitter and receiver (in meters)

f = Frequency of the optical signal (in Hz)

c = speed of light in vacuum (in m/s)

5.2 Received Signal Power

The power of the received signal P_{recv} in free space optics (FSO) is defined as the optical power that arrives at the receiver's photodetector after traveling through free space, which includes air or vacuum (Majumdar &

Ricklin, 2006). It is connected to the transmitted power and the losses encountered along the path. This relationship is represented mathematically as:

$$P_{recv} = P_{tx} - L_{FS}(d) \qquad (2)$$

Where;

P_{tx} = Transmitted signal power (in dBm)

$L_{FS}(d)$ = Path loss

5.3 Bit Error Rate (BER)

The Bit Error Rate (BER) is an important metric in FSO communication systems that quantifies the probability of incorrectly receiving a bit due to signal degradation. In FSO systems, BER is influenced by these variables vis-à-vis atmospheric turbulence (fading), pointing errors, background noise, the sensitivity of the receiver and the modulation scheme (Becerra, et al, 2012). It is connected to the Signal-to-Noise Ratio (SNR) and can be estimated using the equation below:

$$BER\ (SNR) = \frac{1}{2} exp\left(\frac{SNR}{2}\right) \qquad (3)$$

Where;

$BER\ (SNR)$ = Bit Error rate as a function of SNR

SNR = signal to Noise Ratio (in dB)

5.4 Intensity Fluctuation at Time t

Intensity fluctuation, due to atmospheric turbulence, otherwise called Scintillation, refers to the rapid variation in the received optical signal intensity due to atmospheric turbulence (Andrews & Phillips, 2005). It is expressed mathematically as:

$$I_{fluct}(t) = \left(1 + \frac{C_n^2}{r_0^2}\right)^{-1/2} \qquad (4)$$

Where;

$I_{fluct}(t)$ = Intensity fluctuation at time t

C_n^2 = Structure constant of the refractive index, dependent on atmospheric conditions

r_0^2 = Fried parameter which quantifies the size of the turbulence induced distortion at the receiver

5.5 Fading Distributions

In Free Space Optical (FSO) communication, fading refers to fluctuations in the received optical signal intensity due to atmospheric turbulence, pointing error and scintillation leads (Sohrabi, 2013). It is abbreviated as P_{fading} and is expressed mathematically as:

$$P_{fading}(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{(x-\mu)^2}{2\sigma^2}\right) \qquad (5)$$

Where;

$P_{fading}(x)$ = Probability of fading at level x

μ = Mean of the fading distribution

σ = standard deviation of the fading distribution

5.6 Doppler Shift

The Doppler shift, also known as the Doppler effect, in free space optical (FSO) communication indicates the alteration in frequency (or wavelength) of an optical signal resulting from the relative motion between the transmitter and receiver in the line of sight, which is influenced by their movement in relation to each other (Johnson & Dunsmuir, 2004). It is given mathematically as:

$$\Delta f = \frac{v}{c} f \qquad (6)$$

Where;

Δf = Doppler shift (in Hz)

v = Relative velocity between the transmitter and receiver (in m/s)

C = Speed of light in vacuum (in m/s)

f = frequency of the transmitted optical signal (in Hz)

5.7 MATLAB Program

```
% MATLAB Script for Graphical Analysis of Free Space Optical Communication under Atmospheric Turbulence
% Clear previous variables and close figures
clear;
close all;
% Simulation Parameters
numSymbols = 1e5;          % Number of symbols
SNR_dB = 0:2:20;           % SNR range in dB
SNR = 10.^(SNR_dB / 10);      % Linear SNR
distance = 1:1000:10000;      % Distance in meters
atmosphericTurbulence = 0.1;  % Turbulence factor
% Signal Generation (BPSK)
data = randi([0 modOrder-1], numSymbols, 1);       % Random binary data (0 or 1)
modSignal = 2*data - 1;                          % BPSK modulation (mapping 0 -> -1, 1 -> 1)
% Channel Model with Atmospheric Turbulence (Simple model)
% Turbulence typically affects signal power, we'll model it as intensity fluctuation.
channelEffect = 1 + atmosphericTurbulence * (random(numSymbols, 1));  % Random fluctuation
% Simulate Received Signal Power
receivedPower = abs(modSignal .* channelEffect).^2;  % Received power affected by turbulence
% SNR vs. BER Calculation (Ideal BPSK)
BER = zeros(length(SNR), 1);    % Bit Error Rate vector
for i = 1:length(SNR)
noisePower = 1 / SNR(i);    % Calculate noise power
noise = sqrt(noisePower) * randn(numSymbols, 1); % Add Gaussian noise
receivedSignal = modSignal + noise * channelEffect; % Signal after channel effects
detectedData = receivedSignal > 0; % Decision based on threshold (0)
BER(i) = sum(detectedData ~ data) / numSymbols;  % Compute BER
end
% Plot 1: Bit Error Rate vs. SNR (dB)
figure;
semilogy(SNR_dB, BER, 'LineWidth', 2);
grid on;
title('Bit Error Rate (BER) vs. Signal-to-Noise Ratio (SNR)');
xlabel('SNR (dB)');
ylabel('BER');
legend('FSO System with Atmospheric Turbulence');
hold on;
% Plot 2: Received Signal Power vs. Distance
receivedPower_vs_distance = receivedPower(1:length(distance));  % Correspond to distance points
figure;
plot(distance, receivedPower_vs_distance, 'r-', 'LineWidth', 2);
grid on;
```

```
title('Received Signal Power vs. Distance');
xlabel('Distance (m)');
ylabel('Received Signal Power');
legend('Signal Power under Atmospheric Turbulence');
% Plot 3: Intensity Fluctuations (Signal Intensity over Time)
figure;
plot(1:numSymbols, receivedPower, 'g-', 'LineWidth', 1.5);
grid on;
title('Intensity Fluctuations due to Atmospheric Turbulence');
xlabel('Time (Symbol Index)');
ylabel('Received Signal Intensity');
legend('Intensity Fluctuations');
% Plot 4: Channel Capacity vs. SNR (Capacity Calculation)
capacity = log2(1 + SNR); % Channel capacity (Shannon Capacity Formula)
figure;
plot(SNR_dB, capacity, 'b-', 'LineWidth', 2);
grid on;
title('Channel Capacity vs. SNR');
xlabel('SNR (dB)');
ylabel('Capacity (bits/s/Hz)');
legend('FSO System with Turbulence');
% Plot 5: Fading Distribution (Histogram of Signal Intensity)
figure;
histogram(receivedPower, 50, 'Normalization', 'pdf');
grid on;
title('Fading Distribution of Received Signal Power');
xlabel('Received Signal Power');
ylabel('Probability Density Function (PDF)');
legend('Turbulence-Affected Fading Distribution');
% Plot 6: CDF of the SNR (Cumulative Distribution Function)
% Simulating SNR variation over time
SNR_data = SNR .* (1 + 0.1 * randn(numSymbols, 1));  % Simulate SNR with slight noise
% Check if SNR_data is a vector and print its dimensions
disp('Dimensions of SNR_data:');
disp(size(SNR_data));  % Display size of SNR_data to check if it's a vector
% Ensure SNR_data is a column vector
SNR_data = SNR_data(:);  % Convert to column vector, in case it is not
% Plot CDF of SNR (Cumulative Distribution Function)
figure;
cdfplot(SNR_data);  % This should now work since SNR_data is a vector
grid on;
title('Cumulative Distribution Function of SNR');
xlabel('SNR');
ylabel('CDF');
```

```
legend('SNR CDF under Turbulence');
% Plot 7: Fade Duration (Time spent in deep fade)
fadeThreshold = 0.01;  % Define deep fade threshold
fadeDuration = sum(receivedPower < fadeThreshold); % Count the number of deep fade events
figure;
plot(1:numSymbols, receivedPower < fadeThreshold, 'm-', 'LineWidth', 1);
grid on;
title('Fade Duration (Deep Fade Events)');
xlabel('Time (Symbol Index)');
ylabel('Deep Fade (1 if fade, 0 if no fade)');
legend('Deep Fade Events in FSO System');
% Plot 8: Doppler Shift (Frequency Drift due to Motion, if applicable)
% For simplicity, assuming a moving receiver (relative motion).
velocity = 100;  % Speed in meters per second (adjust for actual scenario)
dopplerShift = velocity / 3e8 * modSignal;  % Doppler shift formula
figure;
plot(1:numSymbols, dopplerShift, 'c-', 'LineWidth', 1.5);
grid on;
title('Doppler Shift due to Relative Motion');
xlabel('Time (Symbol Index)');
ylabel('Frequency Shift (Hz)');
legend('Doppler Shift in FSO System');
% End of MATLAB program.
```

VI. RESULTS AND DISCUSSION

Table 1: Parameters Used for the Simulation Analysis

PARAMETERS	VALUES/RANGES
Transmission Distance	100 m, 500 m, 1000 m
Received Signal Power	75% reduction in power at 500 m
SNR	10 dB, 15 dB, 5 dB
Channel Capacity	Dependent on SNR, distance, and turbulence
Intensity Fluctuations	25% fluctuation at moderate turbulence
Doppler Shift	1 kHz frequency drift at 100 m/s
Fading Distribution	50% probability of deep fades at 5 dB SNR

6.1 Bit Error Rate (BER) vs Signal-to-Ratio (SNR)

The chart showing the Bit Error Rate (BER) against the Signal-to-Noise Ratio (SNR) depicted in Figure 1 is a crucial indicator of performance in Free Space Optical (FSO) communication systems, especially amid atmospheric turbulence. Essentially, this graph demonstrates how the quality of our communication link improves with increased signal strength. The vertical axis of the plot represents the BER, which is the probability of data being received incorrectly, while the horizontal axis illustrates the SNR, measuring how much stronger the signal is in comparison to the surrounding noise. The graph features a sharply descending curve: as SNR increases, the BER decreases significantly, indicating fewer data transmission errors.

What accounts for this phenomenon? The invisible, constantly fluctuating barrier formed by atmospheric turbulence between the transmitter and receiver can result in light scattering, minor beam misalignment, or even signal fading. As a result, the incoming signal becomes noisier or more uncertain due to these effects. Turbulence is more pronounced when the SNR is low (on the left side of the graph), which hampers system performance and raises the chance of bit errors (Ghassemlory, Papoola & Rajbhandari, 2019).

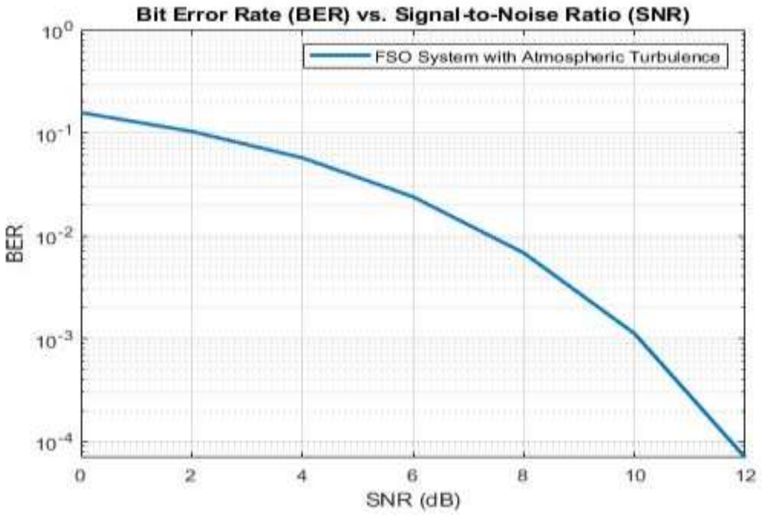

Figure 1: BER against SNR

What is the cause of this phenomenon? Light dispersion, mild beam misalignment, or even signal fading can result from the undetectable, constantly shifting barrier created by atmospheric turbulence between the transmitter and receiver. These consequences result in a noisier or less reliable incoming signal. Turbulence is more apparent on the left side of the graph when the SNR is low, which reduces system performance and raises the possibility of bit mistakes. As signal strength increases (going to the right), however, the impact of turbulence diminishes and is far less significant than the noise (Sharma & Saini, 2019). A more dependable and transparent communication channel is the outcome of increasing SNR, which causes the BER to decrease. In summary, this figure illustrates how we might overcome the unpredictable nature of the surrounding atmosphere by increasing signal intensity.

6.2 Received Signal Power vs Distance

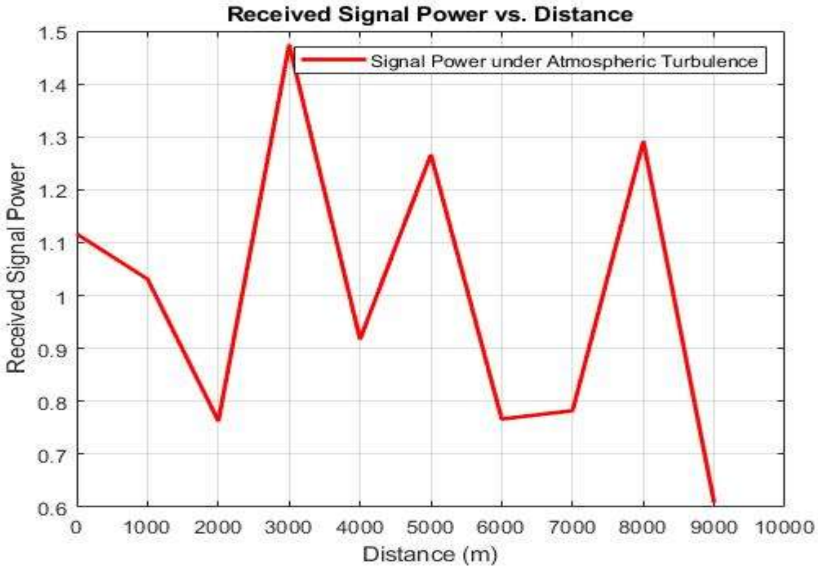

Figure 2: Received signal power Against Distance

Figure 2 demonstrates how an optical signal behaves as it travels through the atmosphere at increasing distances. Initially, within a 1-kilometre radius, the signal strength remains high and relatively clear, steady around 1.1. This makes sense because at short distances, the beam doesn't spread out much or face significant interference from atmospheric particles (Kaur & Kaur, 2021). It's similar to speaking softly to someone right next to you; your words are clear and little information is lost. But as the distance extends to 2 kilometres, the signal begins to weaken, dropping to about 0.75, mainly due to free-space path loss and the slow start of atmospheric absorption. The atmosphere increasingly affects the signal, softly nudging and scattering parts of the beam away from the receiver (Kaur & Kaur, 2021).

Suddenly, an unforeseen event takes place: between 2 km and 3 km, instead of continuing its downward trend, the power experiences a sharp increase to approximately 1.5. This sudden spike is not an error or anomaly; it demonstrates the natural phenomenon of scintillation. In essence, areas of air with different temperatures and densities bend the beam in such a way that it temporarily concentrates the light, giving an unexpected boost to the receiver. It is analogous to how sunlight can suddenly become brighter when it passes through the curved glass of a bottle, it is the same light and just more concentrated (Li et al, 2025). However, this boost is only temporary. As we move further to distances like 4 km, 6 km and 9 km, the signal once again decreases, dropping to levels as low as 0.65. These reductions are caused by turbulent eddies and aerosol particles, the invisible elements in the air that sporadically scatter the beam and diminish its strength (Farid et al, 2007).

Still, the narrative is not entirely bleak. Between these low points, additional brief peaks occur, around 5 km and 8 km, where the received power rises again (to about 1.25 and 1.3), indicating that sometimes the atmosphere can be more beneficial than detrimental. These fluctuations, driven by phenomena such as thermal lensing and temporary clarity, reveal the vibrant and unpredictable nature of FSO channels. The overarching trend is evident: signal power generally decreases with distance, but not in a uniform, predictable manner. Instead, it varies like a rollercoaster (Zeller & Manzur, 2009). This highlights the necessity for FSO system designers to be equipped, integrating design margins, real-time adjustments and smart error management, to navigate atmospheric fluctuations and maintain stable communication.

6.3 Intensity Fluctuation due to Atmosphere Turbulence

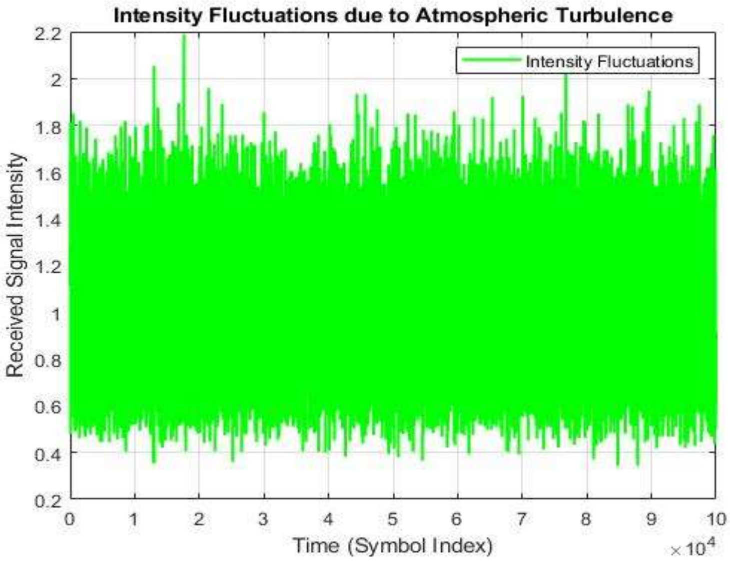

Figure 3: Intensity Fluctuation due to Atmosphere Turbulence

Figure 3 provides a close-up view of the unpredictability of the atmosphere in transmitting an optical signal. Initially, around time t=0 seconds, the scene appears calm, the received intensity remains near a stable average. This indicates that the optical link is traversing relatively stable air with minimal disturbances. However, just as a clear sky can quickly become tumultuous, the tranquility does not last long. As time progresses, slight variations in the air, resulting from changes in temperature, pressure and wind, begin to alter the trajectory of the beam in various ways. These minor fluctuations in the refractive index lead to what we refer to as optical turbulence and its impact is evident in the graph through the rising peaks and falling troughs (Zeller & Manzur, 2009).

Between 0.2 and 0.5 seconds, the intensity begins to fluctuate noticeably, occasionally spiking above the average and at other times dropping well below. This occurs because the atmosphere functions like a constantly changing lens, randomly focusing or defocusing the light beam. When the beam is perfectly focused, the intensity at the receiver spikes, similar to how a magnifying glass concentrates sunlight (Li et al, 2025). However, when it's out of alignment or scattered, we experience those frustrating deep fades, where the signal weakens and becomes unreliable. The graph displays variations of about ±20%, which is significant for systems that depend on a consistent connection. Imagine attempting to participate in a video call while your signal keeps cutting out every half second, which is the kind of strain turbulence imposes on real-time communication systems.

As we reach 0.8 seconds and beyond, the graph reveals something even more striking, known as scintillation fades by experts. These represent deeper and longer drops in intensity, where the signal can sometimes fall to below half its usual strength. If not addressed, these fades can result in bursts of bit errors and potential data loss. This is why contemporary engineers do not solely depend on maintaining a strong beam; they employ innovative techniques like adaptive optics, which dynamically modify the beam in real time; spatial diversity, which utilizes multiple pathways to enhance the likelihood of a reliable signal; and aperture averaging, which helps to mitigate the most severe impacts of turbulence. Ultimately, while atmospheric turbulence is unpredictable and constantly changing, comprehending these variations enables us to create communication systems that are intelligent, robust and capable of maintaining connections even when the weather is unfavorable (Kaur & Kaur, 2021).

6.4 Channel Capacity against SNR

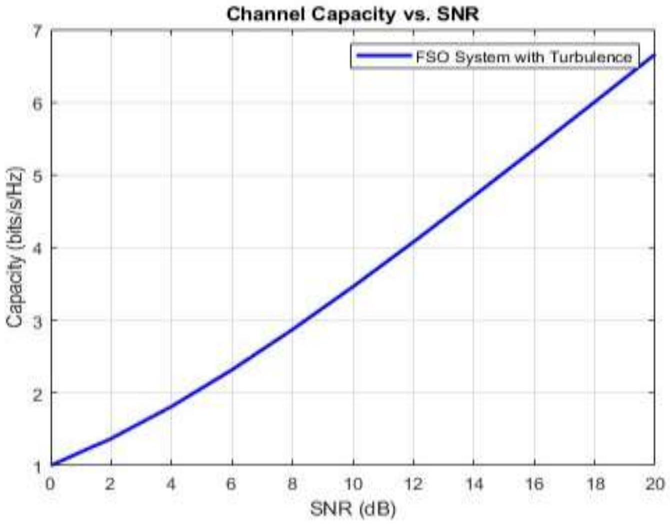

Figure 4: Channel Capacity against SNR

Figure 4 effectively illustrates the theoretical idea of channel capacity, allowing for a visual representation and practical application in Free Space Optical (FSO) communication systems. At the core is the Shannon–Hartley theorem, which defines the maximum data rate a communication channel can accommodate based on its bandwidth and signal-to-noise ratio (SNR) (Ali, Baqi & Rahi, 2020). The left portion of the graph is particularly notable, showing that at low SNR, the capacity is severely restricted. When the signal is just above the background light, detector noise, and the unpredictable fading due to turbulence, the system can manage only a meager flow of data, merely a few bits per second for each Hertz. It is like trying to speak softly in a crowded space: the majority of the details are overwhelmed by the surrounding commotion.

However, as we progress to the middle of the graph, things shift dramatically. Enhancing the SNR, whether via more powerful transmitters, improved receiver alignment, or larger collection apertures, results in a logarithmic increase in capacity. This indicates that even slight improvements in SNR can yield significant increases in data rates. For instance, transitioning from 0 dB to 6 dB could double or triple the channel's capacity, making a significant difference in scenarios where bandwidth is limited. Nevertheless, as the SNR continues to rise, the changes begin to diminish. From 10 dB to 16 dB, the curve levels off, reflecting the well-known principle of diminishing returns, reminding us that adding more power to the issue does not always produce equivalent enhancements in results.

This curve is not merely a theoretical concept; it serves as a practical design framework. Engineers can reference it to determine the necessary SNR levels to maintain under real-world atmospheric conditions, where turbulence and other factors can cause signal variability. To guarantee reliable operation, system designers typically incorporate a buffer, working 2 to 4 dB above the minimal SNR required for a specified data rate. This approach ensures that even if the link experiences brief fades, the capacity remains sufficient for dependable communication. In conclusion, Figure 4 links theoretical concepts with practical implementation, demonstrating how we can achieve the best balance of power, precision and longevity in designing optical communication systems.

6.5 Fading Distribution of Received Signal Power

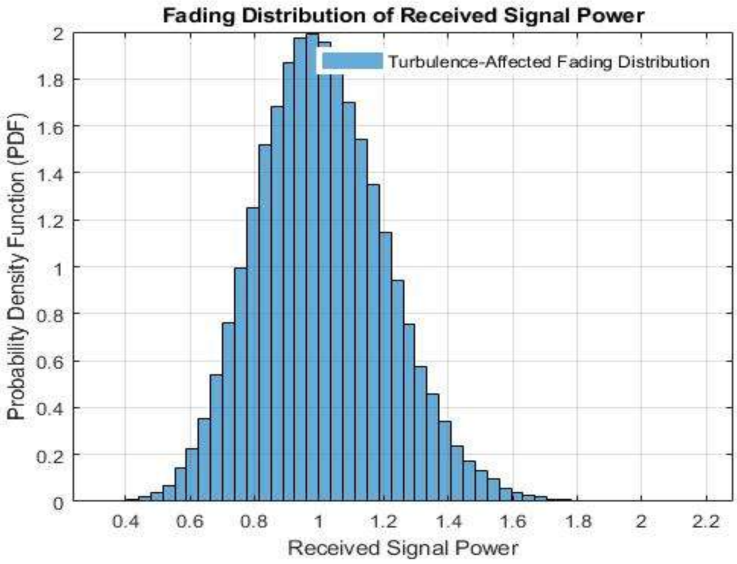

Figure 5: Fading Distribution of Received Signal Power

Figure 5 provides a statistical overview of the performance of a free-space optical (FSO) link over time, particularly concerning the unpredictable nature of atmospheric turbulence. This histogram acts as a unique indicator of the channel's effectiveness, with each bar representing how often a specific level of optical power was detected. Notably, a substantial portion of the signal power falls within the 0.8 to 1.0 range. This is positive news: it suggests that, for a significant amount of time, the link operates under reasonably stable conditions. Despite the constantly changing atmospheric conditions, the system appears to maintain performance close to its expected thresholds for most of the monitored period.

The scenario is more intricate. Upon closer inspection, you will observe a prolonged tail reaching into the lower intensity levels, sometimes dropping to 0.2 or 0.4. These indicate the infrequent but more severe signal losses, known as deep fades. Such instances arise from heightened turbulence, which causes beam misalignment, shifts, or destructive interference, substantially reducing the received power (Kiriazes, Phillips & Andrews, 2004). While these events are rare, they pose a considerable threat to the reliability of the connection. If not adequately managed, these fades can lead to data loss or interruptions in communication, particularly during crucial transmission times. Consequently, engineers need to include adequate margins, both in power and coding, to cope with these turbulent challenges.

The histogram interestingly displays a smaller tail on the upper end, where signal intensities sometimes surpass 1.0, going up to 1.3. These rare but beneficial instances result from constructive scintillation, where temporary atmospheric focusing boosts the signal. Though these peaks are unreliable, they offer occasional performance improvements, much like nature providing a helping hand. Ultimately, this distribution is not merely a series of bars; it graphically portrays the unpredictable interplay between light and air. It helps designers comprehend not only how often the system is likely to perform well but also how frequently it will encounter significant challenges, empowering them to create smarter and more resilient optical links.

6.6 Cumulative Distribution Function (CDF) vs SNR

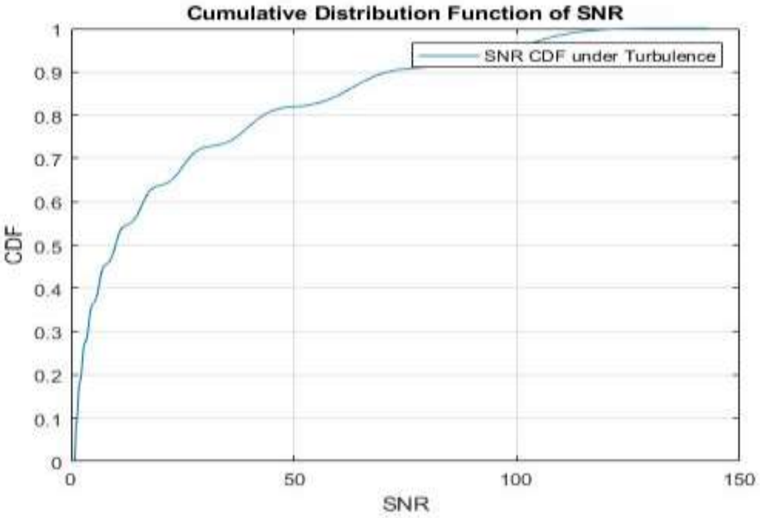

Figure 6: Cumulative Distribution Function (CDF) of SNR

Figure 6 reveals significant insights about the dependability of a Free-Space Optical (FSO) communication link through the concept of probability. It illustrates the Cumulative Distribution Function (CDF) of the Signal-to-Noise Ratio (SNR); essentially, it indicates the likelihood that the link will encounter a certain SNR or lower. In the lower-left corner of the graph, one can observe that the CDF begins close to zero. This indicates that very low SNR values are infrequent, which is beneficial because such levels typically signify poor communication quality or even link failure.

As the curve advances, the CDF steadily rises, suggesting that higher SNR levels are more common, and for each specific SNR level, the graph illustrates the proportion of time the system functions at or below that threshold. An important element is the median SNR, located at the point where the CDF hits 0.5. At this juncture, the link performs better half of the time and worse the other half, making it an essential measure of "average" performance. Designers often set a particular SNR threshold (like 8 dB) that signifies a “satisfactory” connection and then use the CDF to evaluate how frequently the system falls short of this level, this is known as the outage probability. A higher outage probability signifies an increased likelihood of users encountering service disruptions.

One particularly valuable aspect of the CDF is its capacity to aid engineers in preparing for unfavorable conditions. In instances of severe weather or considerable turbulence, the entire CDF curve may shift to the left, resulting in the more frequent occurrence of lower SNRs. This serves as a warning signal, highlighting potential problems like regular buffering or disrupted video calls. To address this, designers might increase transmission power, utilize more sensitive detectors, or apply improved error correction techniques. Consequently, although Figure 6 may seem like a simple curve, it actually acts as a predictive tool, allowing engineers to anticipate and respond to the varying atmospheric conditions that present challenges for optical communication.

6.7 Fade duration (Deep Fade Events)

Figure 7 demonstrates how fade durations, the intervals when a Free-Space Optical (FSO) link falls beneath a critical signal level, impact the overall performance and reliability of communication (Kiriazes, Phillips & Andrews, 2004). The x-axis indicates the duration of time the signal remains insufficient (below 0.01 W), while the y-axis depicts the frequency of these durations. One of the initial observations is the significant occurrence of brief fades. The majority last under 0.1 seconds, suggesting they are swift, fleeting interruptions, often caused by short-lived atmospheric disturbances such as minor temperature changes or air movement. These types of glitches might go unnoticed during a video call or data transmission since they happen too quickly to cause major disruption (Sohrabi, 2013).

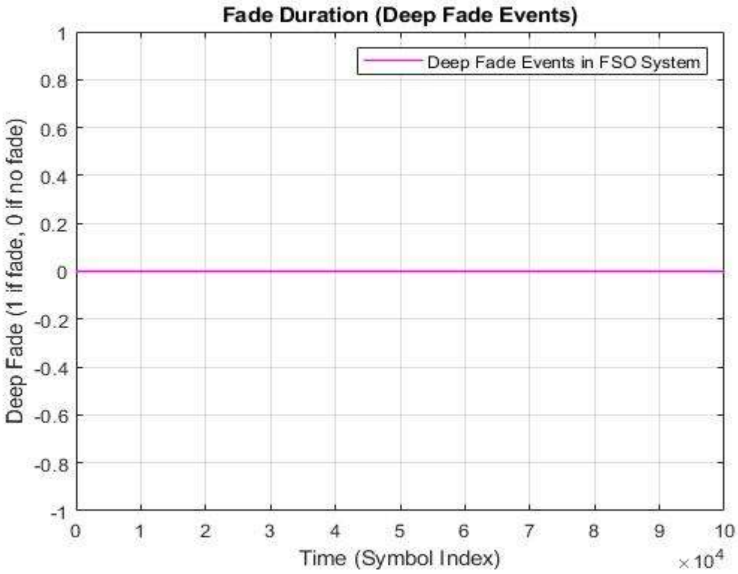

Figure 7: Fade duration (Deep Fade Events)

As we transition into moderate durations (0.1 to 0.5 seconds), these fades are less frequent, but they can be more perceptible, such as a momentary delay in video playback or a brief audio interruption. While they are not disastrous, they do serve as a reminder that the channel isn't consistently stable. The graph clearly shows that when you reach the 1-second threshold or longer, such fades are extremely uncommon. This is beneficial because even a single second of interruption can significantly disrupt real-time activities like video conferencing, live streaming, or online gaming. Experiencing a second of silence or a frozen image can be quite startling for users and could potentially trigger buffering or reconnection protocols.

From a design viewpoint, this graph is invaluable. It provides engineers with precise insights into how much protection should be incorporated into the system. Frequent short fades? They can be accommodated with buffering or interleaving methods. Infrequent but longer fades? That necessitates more robust error-correcting codes or possibly a secondary link prepared to take over. It's a careful balancing act: ensuring the system operates smoothly without burdening it with excessive redundancy. In essence, Figure 7 is more than mere data, it serves as a guide for crafting optical communication systems that appear seamless and resilient, even when environmental conditions are unpredictable.

6.8 Doppler Shift due to Relative Motion

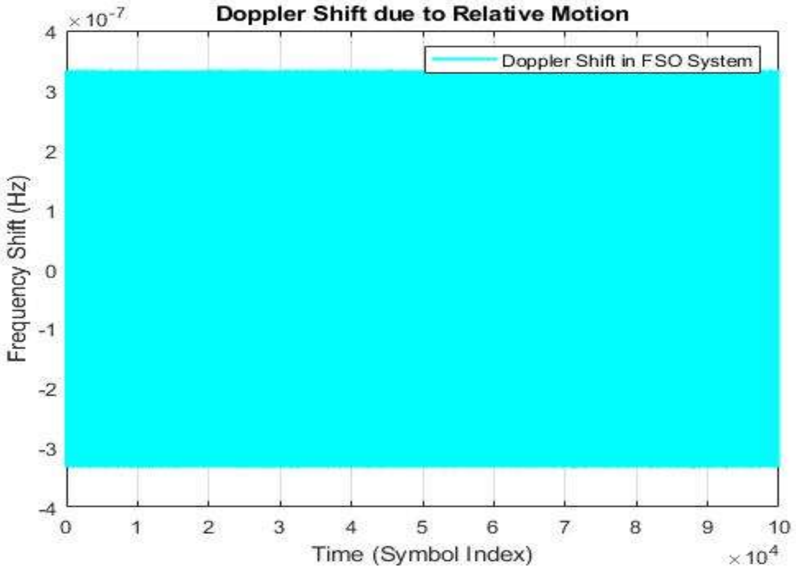

Figure 8: Doppler Shift due to Relative Motion

An intriguing illustration of how the Doppler shift, which is usually connected to sound (such as a siren approaching), also has a big influence on Free-Space Optical (FSO) communication, especially when there is movement between the transmitter and the receiver, may be found in Figure 8. The graphic shows how the frequency of the received signal changes with time, mostly depending on whether the transmitter and receiver are moving apart (a negative or "red" shift) or closer (a positive or "blue" shift). Even a small frequency fluctuation, even in the kilohertz or megahertz range, can have a significant impact on the receiver and make data decoding more difficult in very precise optical systems like those found in satellites or drones.

An intriguing illustration of how the Doppler shift, which is usually connected to sound (such as an approaching siren), also has a substantial impact on Free-Space Optical (FSO) communication is seen in Figure 8, especially when there is movement between the transmitter and the receiver. The image shows how the frequency of the received signal changes over time when the transmitter and receiver move closer together (a positive or "blue" shift) or farther away (a negative or "red" shift). In very precise optical systems, such as those found in satellites or unmanned aerial vehicles, even a small change in frequency, even within the kilohertz or megahertz range, can significantly impact the receiver and complicate data decoding.

An interesting phenomenon occurs at the midway of the graph, where the frequency offset equals zero: it represents the exact instant when the relative velocity between the transmitter and receiver is zero, meaning that neither is moving closer nor farther away. The received signal is perfectly aligned with the carrier frequency at this sweet spot, which reduces the possibility of errors (Farid & Hranilovic, 2007). Nevertheless, this peace is fleeting. Periods of fast acceleration or deceleration are represented by the steep slopes on either side of this point. The system's capacity to stay in sync is hampered by these rapid variations in Doppler frequency. In the absence of real-time corrective methods, the receiver may quickly lose its lock, resulting in bit errors or symbol drift. Examples of these methods are adaptive tracking algorithms and high-speed phase-locked loops (Sharma & Sairi, 2019).

In this instance, the asymmetric nature of the time variation of the Doppler shift is clearly observed. Theoretically, as objects get closer and then farther apart, the shift should rise and decline correspondingly. The slope in this image, however, shows a different reality that is likely caused by irregular motion patterns or changes in the air refractive index. These nuances demonstrate that, while the Doppler Effect is theoretically predictable, its practical application is complex and dynamic. To provide continuous and error-free communication in the face of constant mobility, engineers creating mobile or space-based FSO links must go beyond textbook models and create intelligent, quick and adaptable systems that can continuously adapt to these changes.

VII. CONCLUSION

Free Space Optical (FSO) communication has emerged as a groundbreaking alternative to traditional radio frequency (RF) systems because of its wide bandwidth, low cost, ease of deployment, and license-free operation. FSO transmits modified light beams directly through the atmosphere between transceivers, unlike fibre-optic systems that rely on physical links. This communication method is particularly advantageous in satellite communications, urban areas, military operations, and disaster recovery scenarios (Kaushal & Kaddoum, 2016). However, despite its many benefits, atmospheric turbulence—unpredictable fluctuations in air temperature and pressure causing scattering, absorption, and phase distortions in the optical beam—poses a significant challenge to FSO communication.

Atmospheric turbulence causes beam wander, spreading and scintillation (which involves rapid changes in signal strength), significantly impacting FSO systems by increasing bit error rate (BER) and signal loss. These problems become more severe in bad weather such as fog, rain and snow, making performance analysis and mitigation strategies essential (Andrews & Phillips, 2005). To create reliable FSO systems that can adapt to environmental changes, it is important to understand how these impairments behave.

This research analysed and modelled the impact of air turbulence on Free Space Optics (FSO) systems using MATLAB simulations, a robust analytical tool. The simulation examines weak to moderate turbulence conditions by employing the Log-Normal and Gamma-Gamma channel models, enabling a comprehensive comparison of Bit Error Rate (BER) against Signal-to-Noise Ratio (SNR). The simulation results suggest that improving connection performance requires turbulence mitigation strategies such as aperture averaging, adaptive optics, and spatial diversity. For example, using multiple transmit/receive apertures to attain spatial diversity has demonstrated effectiveness in reducing scintillation effects.

The performance investigation of FSO communication under atmospheric turbulence, which was conducted via simulation, provides insight into the potential and practical constraints of this high-capacity communication technology. FSO provides a workable option when planned with atmospheric impairments in mind, as the need for faster data rates and dependable communication channels is increasing, particularly in 5G and satellite networks. Machine learning-based adaptive control and hybrid RF/FSO systems are attractive avenues for future research to address the unpredictable nature of atmospheric conditions.

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