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A Comparative Study of Modulation Schemes and Mitigation Techniques for Gamma-Gamma FSO Channels

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***Abstract*—FSO communication systems are proven to be an effective substitute to RF technologies as FSO communication technologies boast high data rates which are not subjected to licensing and are not affected/spoiled by electromagnetic interference. However, despite these positive aspects, FSO links suffer from air turbulence which has strong detrimental effects on links and cause irradiance fluctuations (scintillation) and extreme fading. This has caused this paper to offer an in-depth performance analysis of FSO systems operating on a Gamma-Gamma turbulence channel and further explores the performance of different turbulence mitigation schemes and modulation strategies. This analysis uses OOK as a basis of comparison to other modulation schemes like 4 PPM, DPSK, and DCO-OFDM and explores the possible improvements Adaptive Optics (AO) and Dynamic Beam Steering (DBS) systems may provide to link reliability. This paper investigates the performance of DBS under three different settings: best path selection, path steering with a realistic motion model, and path steering with an alignment error. The results of many Monte Carlo simulations indicate that when it comes to turbulence, DPSK will be the best option because it adapts to changes. This paper suggests that DCO-OFDM is not optimal because it is the most adversely affected by channel fading. The best way. This works better than Adaptive Optics, especially in turbulent conditions. These results indicate that combining strong modulation techniques like DPSK with spatial diversity methods like DBS is essential for constructing dependable, high-speed free-space optical networks, even in challenging atmospheric conditions.**

***Keywords*—Free-Space Optical (FSO); Gamma-Gamma Turbulence; Dynamic Beam Steering (DBS); Adaptive Optics (AO); Differential Phase Shift Keying (DPSK); DCO-OFDM; Bit Error Rate (BER); Pulse Position Modulation (PPM)**

I. INTRODUCTION

A LOT more people want to send data quickly now that 5G networks and the Internet of Things (IoT) are available. Because of this, the "last mile" of telecommunication networks is now very busy. Free-Space Optical (FSO) communication is a possible solution to these bandwidth issues. FSO operates in the optical spectrum, unlike Radio Frequency (RF) systems. It can transmit data without a license.

It is also immune to electromagnetic interference (EMI) and has very fast data speeds, akin to fiber optics [1]. Because of these features, FSO is a good option for cellular backhaul, disaster recovery links, and secure business connections. However, the ambient channel makes FSO less accessible to many. The optical beam travels through the atmosphere, encountering regions with varying temperatures and pressures. This changes the air's refractive index in a random way. This phenomenon, known as air turbulence, causes the beam to deviate and disperse, resulting in significant fluctuations in irradiance at the receiver, often referred to as scintillation [2]. These problems cause the signal to fade deeply and the Bit Error Rate (BER) performance to drop significantly, especially over long distances or in high turbulence regimes. The Gamma Gamma distribution is extensively used to describe these channel conditions because it fits experimental data well over a range of mild to high turbulence conditions [3]. To mitigate the bad impacts of turbulence, researchers have looked at different ways to modulate signals and ways to improve the physical layer. The most common and easiest way to modulate is On-Off Keying (OOK), but it only works well in channels that are very noisy if you use accurate adaptive thresholding [4]. Pulse position modulation (PPM) is often chosen even though it needs more bandwidth because it uses less power when the signal is fading. Recently, Differential Phase Shift Keying (DPSK) has gained a lot of attention because it can handle air fading without the need for complicated coherent detection. Optical Orthogonal Frequency Division Multiplexing (O-OFDM) has been suggested to reduce inter-symbol interference and improve spectral efficiency; however, its effectiveness is constrained by a high Peak-to-Average Power Ratio (PAPR), which increases its vulnerability to channel impairments [5], [6]. In addition to modulation, spatial diversity and adaptive methods are also very important for making sure that links work. Adaptive optics (AO)

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systems use mirrors that can change shape to fix wavefront distortions in real time. They were first made for astronomy.

This makes the Rytov variance (σ_R^2) (σ_R^2 Defined as a function of the refractive index structure parameter (C_n^2)it serves as the standard metric for classifying turbulence regimes into weak, moderate, or strong categories), that the receiver sees less [7]. Dynamic Beam Steering (DBS) and other beam steering and spatial diversity methods use more than one optical path to choose the channel with the best Signal-to-Noise Ratio (SNR) at the moment. Theoretical models often require perfect channel information; however, real implementations of DBS encounter channel estimate inaccuracies and misalignment, which may limit potential benefits [8]. Even though there is already research on this, we need a comparison study that looks at both advanced modulation formats and practical ways to reduce interference at the same time in the same channel conditions. This study offers a comprehensive simulation-based performance assessment of FSO systems functioning over Gamma-Gamma turbulence channels. This study primarily contributes:

- A comparative analysis of various modulation schemes, including OOK, 4-PPM, DPSK, and DCO-OFDM, under different turbulence conditions.
- An assessment of (AO) modeled through residual turbulence factors.
- A detailed investigation of (DBS) under three distinct scenarios: Ideal DBS (perfect path selection), Realistic DBS (accounting for channel estimation errors), and Imperfect DBS (accounting for misalignment probability).

The remainder of this paper is organized as follows: In Section III, we talk about the system model, which includes the optical link budget, the Gamma-Gamma turbulence formulation, and the noise characteristics of the receiver. In Section IV, we talk more about the simulation method, such as how to use modulation schemes, simulate adaptive optics, and make dynamic beam steering scenarios. In Section V, you can see all the results of the simulation and a number-based comparison of how well they did. Finally, Section VI finishes the research and suggests other things to look into.

II.RELATED WORKS

Recent studies have focused on lowering air turbulence in free-space optical (FSO) systems. Most of these projects fall into one of three main categories: improved modulation formats, adaptive optics, and spatial diversity strategies.

A. Modulation Techniques in FSO

OOK is still the standard since it is so easy to use, but subsequent research has looked at other ways to improve spectral and power efficiency in great detail. While On-Off Keying (OOK) is cost-effective for short-range connections, Pulse Position Modulation (PPM) greatly outperforms it in power efficiency during deep fading scenarios, despite requiring an increase in bandwidth, according to a comparative study by Kaushal et al. (2019) [9]. Li et al. (2021) investigated differential modulations, illustrating that Differential Phase Shift Keying (DPSK) offers a more advantageous equilibrium between receiver complexity and turbulence resilience compared to coherent detection systems, particularly when addressing pointing issues [8]. Optical OFDM (O-OFDM) has also become popular for applications that need a lot of data. Fabian et al. (2022) investigated the effectiveness of DC-biased Optical OFDM (DCO-OFDM) in turbulent channels. Their study highlighted the vulnerability of OFDM to peak-to-average power ratio (PAPR) issues and nonlinear distortion, suggesting that while it enables high throughput, it requires robust equalization or coding to withstand considerable scintillation, aligning with the sensitivity observed in our analyses [10].

B. Adaptive Optics (AO)

Adaptive Optics (AO) has evolved from astronomical uses to terrestrial Free Space Optics (FSO) as a principal technique for wavefront correction. Liu et al. (2020) introduced a sensor less adaptive optics (AO) system using a stochastic parallel gradient descent (SPGD) method, achieving significant decreases in coupling loss and bit error rates under moderate turbulence [11]. Wang and Zhao (2023) also created an analytical model that looked at the residual variance after AO adjustment. Their findings indicate that while AO significantly mitigates beam spreading and phase variations, residual turbulence—often ascribed to fitting errors or limited actuator bandwidth—remains a limiting factor in conditions of severe turbulence [12].

C. Beam Steering and Spatial Diversity

Spatial diversity, especially via Multiple Input Multiple-Output (MIMO) and beam steering, is often considered the most efficient method for alleviating deep fading. Jamali et al. (2021) examined the efficacy of free-space optical (FSO) connections employing dynamic beam management, highlighting the significance of channel state information (CSI) for optimal link selection [13]. Conversely, the majority of theoretical models assume that the channel can be accurately estimated. Recent research by Najafi et al. (2023) investigated the impact of incomplete Channel State Information (CSI) on beam selection methodologies. They demonstrated that errors in estimation and beam misalignment (pointing errors) could negate the advantages of dynamic steering systems [3]. This is especially important for real-world uses when mechanical steering lag or noise from the detector makes things less clear

D. Research Gap

The studies mentioned above look at modulation and mitigation separately, but very few have done a unified comparative analysis that looks at OOK, PPM, DPSK, and OFDM all at once under the same Gamma Gamma channel conditions, while also comparing Adaptive Optics to both Ideal and Imperfect Dynamic Beam Steering. This research addresses this deficiency by simulating different combinations to determine the most effective physical layer design for practical deployment contexts.

III.SYSTEM MODEL AND CHANNEL CHARACTERISTICS

A. Optical Link Budget

We look at a line-of-sight (LOS) free-space optical (FSO) communication system that works at a wavelength of $\lambda =$ 1550nm across a connection distance of L. The photodetector aperture receives optical powerP_{rx} which is linked to the transmitted power P_{tx} as described by Andrews and Phillips [2]:

$$P_{rx} = P_{tx} \cdot h_{geo} \cdot h_{atm} \cdot h_{turb} \quad (1)$$

where h_{geo}represents the geometric spreading loss, h_{atm} is the atmospheric attenuation, and h_{turb} denotes the stochastic fading due to turbulence.

The geometric loss, which takes into consideration how far the optical beam is from the receiver aperture area, is modeled based on the simulation parameters as [2]:

$$h_{geo} = \frac{D_R^2}{(D_T+\theta_{div}L)^2} \quad (2)$$

where D_R and $D_T$are the receiver and transmitter aperture diameters, respectively, and $\theta_{div}$is the beam divergence angle.

The Beer-Lambert law governs atmospheric attenuation, which is based on how light scatters and is absorbed [2].

$$h_{atm} = \exp\,(-\sigma_{atm}L) \quad (3)$$

where σ_{atm} is the attenuation coefficient (converted from dB/km).

B. Atmospheric Turbulence Model (Gamma-Gamma)

The Gamma-Gamma distribution is used to describe the changes in irradiance that happen because of turbulence in the atmosphere. This model is generally recognized because it can show mild, moderate, and high turbulence regimes by modeling the received irradiance I as the product of two independent random variables that reflect large-scale (α) and small-scale (β) turbulent eddies. The probability density function (PDF) for the irradiance I is given by [3,14]:

$$f(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta)/2-1} K_{\alpha-\beta}\big(2\sqrt{\alpha\beta I}\big), I > 0 \quad (4)$$

where $K_n(\cdot)$is the modified Bessel function of the second kind of order n, and $\Gamma(\cdot)$is the Gamma function. The shaping parameters α (effective number of large-scale cells) and β (effective number of small-scale cells) are directly related to the atmospheric structure parameter C_n^2 via the Rytov variance σ_R^2. For a plane wave assumption, the Rytov variance is defined as [14]:

$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \quad (5)$$

where $k = 2\pi/\lambda$ is the optical wave number. The parameters α and β are calculated as [3]:

$$\alpha = [\exp\,(\frac{0.49\sigma_R^2}{(1+1.11\sigma_R^{12/5})^{7/6}}) - 1]^{-1} \quad (6)$$

$$\beta = [\exp\,(\frac{0.51\sigma_R^2}{(1+0.69\sigma_R^{12/5})^{5/6}}) - 1]^{-1} \quad (7)$$

In the simulation, $C_n^2$is varied from $1 \times 10^{-16}\mathrm{m}^{-2/3}$ (weak turbulence) to $5 \times 10^{-14}\mathrm{m}^{-2/3}$ (strong turbulence).

C. Receiver Noise Model

A photodetector with responsivity $\Re$ converts the optical signal into an electrical current at the receiver. This is how the electrical signal y turns out [1]:

$$y = \Re P_{rx} + n \quad (8)$$

where n is the additive noise, modeled as a zero-mean Gaussian process with variance σ_n^2. This variance is the sum of thermal noise (Johnson noise) and shot noise variances [1]:

$$\sigma_n^2 = \sigma_{thermal}^2 + \sigma_{shot}^2 \quad (9)$$

The thermal noise variance depends on the receiver temperature T_K, load resistance R_L, and electrical bandwidth B_e:

$$\sigma_{thermal}^2 = \frac{4k_BT_KB_e}{R_L} \quad (10)$$

where k_B is the Boltzmann constant. The shot noise variance, which depends on the signal, is given by:

$$\sigma_{shot}^2 = 2q(\Re P_{rx})B_e \quad (11)$$

where q is the charge of an elementary electron. This thorough noise modeling makes sure that the Signal-to-Noise Ratio (SNR) calculations show how the receiver would really be in real life.

IV.METHODOLOGY AND MITIGATION TECHNIQUES

This research used Monte Carlo simulations to assess the Bit Error Rate (BER) performance of the Free Space Optical (FSO) connection. The simulation framework is built in MATLAB by combining the channel model from Section 3 with different physical layer topologies. Table I shows the main system characteristics that were used to create the channel model, build the transceiver, and come up with ways to reduce noise.

TABLE I
DETAILED SIMULATION PARAMETERS FOR THE FSO LINK.

Parameter Category	Parameter Name	Symbol	Value
Channel Properties	Propagation Distance	L	1000 m
	Operating Wavelength	λ	1550 nm
	Atmospheric Attenuation	α_{dB}	0.15 dB/km
	Turbulence Strength	C_n^2	10^{-16} to 5×10^{-14} $m^{-2/3}$
Transceiver Unit	Tx Aperture Diameter	D_T	5 cm
	Rx Aperture Diameter	D_R	15 cm
	Beam Divergence	θ_{div}	1 mrad
	Responsivity	$\Re$	1.0 A/W
	Load Resistance	R_L	50Ω
	Electrical Bandwidth	B_e	1 GHz
Modulation Setup	Modulation Formats	-	OOK, 4-PPM, DPSK, DCO-OFDM
	OFDM Parameters	N_{fft}, N_{cp}	64,16
	Monte Carlo Samples	N_{bits}	5×10^5
Mitigation Tech.	AO Residual Factor	η_{AO}	0.3
	DBS Spatial Paths	N_{paths}	4
	DBS Misalignment	P_{mis}	0.2

A. Modulation Schemes

Four different modulation styles are used to see how sensitive they are to air turbulence:

On-Off Keying (OOK): OOK directly controls the strength of the laser, and it is the baseline. The receiver uses adaptive thresholding, which means that the decision threshold changes based on the current channel state information (CSI) to make fewer mistakes [4].

$$I_{th} = \frac{\Re P_{rx}}{2} \tag{12}$$

Pulse Position Modulation (4-PPM): In 4-PPM, each symbol has its own time slot, and the optical pulse is sent in one of the $M = 4$ slots. The receiver uses hard-decision decoding by looking at the electrical currents in each slot and selecting the one with the highest amplitude. This increases the need for electricity. More effective, but bandwidth is required.

Differential Phase Shift Keying (DPSK): DPSK is used to get around the complicated thresholding requirements of OOK in fading channels. The phase difference between two bits in a row holds the information. The receiver uses a delay-interferometer setup and then balanced detection to demodulate the signal by comparing the current bit to the preceding one. This makes it resistant to slow-fading amplitude changes.

DC-biased Optical OFDM (DCO-OFDM): Is used for transmission with excellent spectral efficiency. The input bit stream is translated to QPSK symbols, and Hermitian symmetry is used before the Inverse Fast Fourier Transform (IFFT) to make sure the time-domain signal is real-valued. To make sure the signal is not negative (IM/DD requirement), a DC bias is introduced. The bias is adjusted at 3σ of the signal variance to reduce clipping noise.

Parameters: FFT size $N_{fft} = 64$, *Cyclic Prefix* $N_{cp} = 16$, *Modulation = QPSK.*

B. Adaptive Optics (AO) Modeling

For large bit-count Monte Carlo runs, simulating the whole wavefront correction of a deformable mirror is too expensive. Instead, we show how Adaptive Optics (AO) works by lowering the effective turbulence intensity. AO systems make up for lower-order Zernike modes like tilt and defocus, leaving a phase variance that is still there [7].

In our simulation, we add a residual factor η_{AO} to the Rytov variance calculation to simulate this [12]:

$$\sigma_{R,eff}^2 = \eta_{AO} \cdot \sigma_{R,nominal}^2 \tag{13}$$

We use $\eta_{AO} = 0.3$ based on what is normal for AO correction systems. This indicates that 30% of the turbulence still affects the connection after the AO system corrects 70% of the atmospheric turbulence phase distortions.

C. Dynamic Beam Steering (DBS)

We employ a Dynamic Beam Steering (DBS) architecture that allows the transmitter to select the best optical path among $Npaths = 4$ available spatial channels in order to capitalize on spatial diversity. Three scenarios are examined to assess realistic deployment limitations: Three scenarios are analyzed to evaluate practical deployment constraints:

- *Ideal DBS*: The transmitter believes that the Channel State Information (CSI) is perfect. The system always selects the path with the largest channel gain h [8].

$$h_{sel} = \max\{h_1, h_2, \dots, h_N\} \tag{14}$$

- *Realistic DBS (Estimation Error):* In real life, CSI is calculated using feedback loops that include noise in them. We model the predicted channel $\hat{h}$ like this [3]:

$$\hat{h} = h + n_{est} \tag{15}$$

where n_{est} is the estimation error, modeled as Gaussian noise with a standard deviation proportional to the channel fluctuation ($\sigma_{est} = 0.3\sigma_h$). The selection is based on $\hat{h}$ rather than the true h.

- *Imperfect DBS (Misalignment):* In this case, the beam steering system may not be able to lock onto the chosen path because of mechanical or control latencies. We set the misalignment probability $P_{mis} = 0.2$. A random path is generated with a $1 - P_{mis}$, chance, which simulates a pointing error.

V. Simulation Results and Discussion

We used Monte Carlo simulations with $N_{bits} = 5 \times 10^5$ bits each SNR point. The link distance was fixed at $L = 1000$ m, operating at $\lambda = 1550$ nm. The refractive index structural parameter C_n^2, was used to change the intensity of the atmospheric turbulence. It may be anywhere from $1 \times 10^{-16}\text{m}^{-2/3}$(very weak) to $5 \times 10^{-14}\text{m}^{-2/3}$ (strong).

A. Impact of Turbulence on Modulation Schemes

DPSK (Differential Phase Shift Keying):

The simulation results show that DPSK works the best of all the schemes that were examined. DPSK gets a BER of 10^{-4} under high turbulence ($C_n^2 = 10^{-14}$) when the electrical SNR is around 18 dB. The reason for this advantage is its differential detection system, which doesn't need a dynamic intensity threshold. DPSK encodes information in the phase difference between adjacent bits, which makes it more resistant to the modest changes in amplitude that scintillation causes than schemes that rely on intensity. Figure (1) show the BER performance of DPSK modulation schemes under weak-to-strong turbulence.

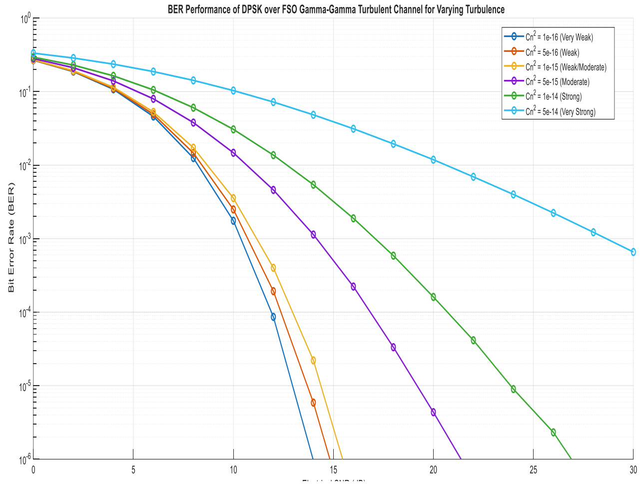

Fig. 1. BER performance of DPSK modulation schemes under weak-to-strong turbulence.

4-PPM (Pulse Position Modulation):

The 4-PPM system uses less electricity than OOK. PPM avoids the threshold estimate problems that OOK has by using a "maximum likelihood" decision mechanism, which chooses the slot with the greatest intensity. But it needs more bandwidth and more precise synchronization. Figure (2) show BER performance of 4-PPM modulation schemes under weak-to-strong turbulence.

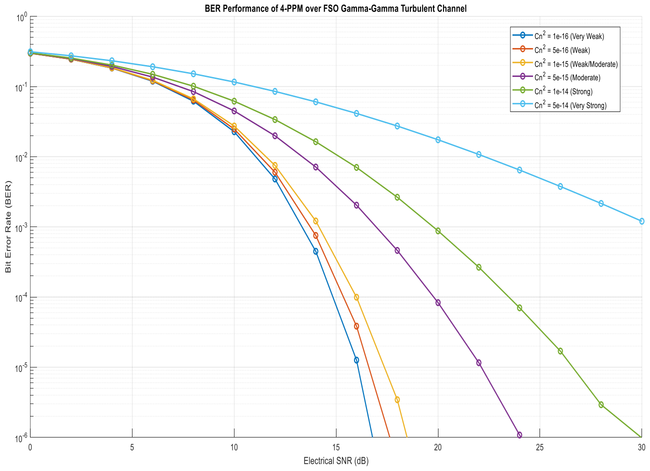

Fig. 2. BER performance of 4-PPM modulation schemes under weak-to-strong turbulence.

OOK (On-Off Keying)

The basic OOK performance is much worse as the severity of the turbulence grows. The "drop" curve flattens out a lot in heavy turbulence, although it works well in light turbulence. Even with adaptive thresholding, the deep fading events that happen in Gamma-Gamma turbulence sometimes cause the signal to slip below the noise floor. This leads to mistakes that can't be fixed at moderate SNR levels. Figure (3) show BER performance of OOK modulation schemes under weak-to-strong turbulence.

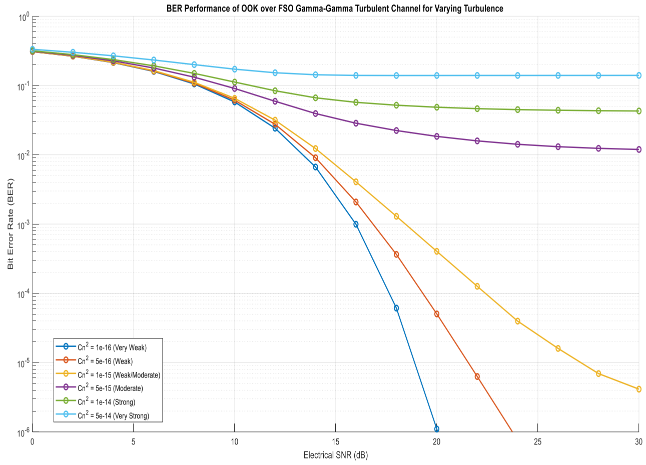

Fig. 3. BER performance of OOK modulation schemes under weak-to-strong turbulence.

DCO-OFDM

The results of the simulation show that DCO-OFDM has the worst BER performance when there is a lot of turbulence. The non-negativity requirement (which requires a DC bias) and the clipping of negative signal peaks cause non-linear distortion. Also, OFDM is very sensitive to problems with the peak-to-average power ratio (PAPR). In fading channels, the orthogonality of subcarriers is reduced, resulting in significant Inter-Symbol Interference (ISI), which is difficult to mitigate without intricate channel coding or equalization. Figure (4) show BER performance of DCO-OFDM, showing high sensitivity to strong turbulence.

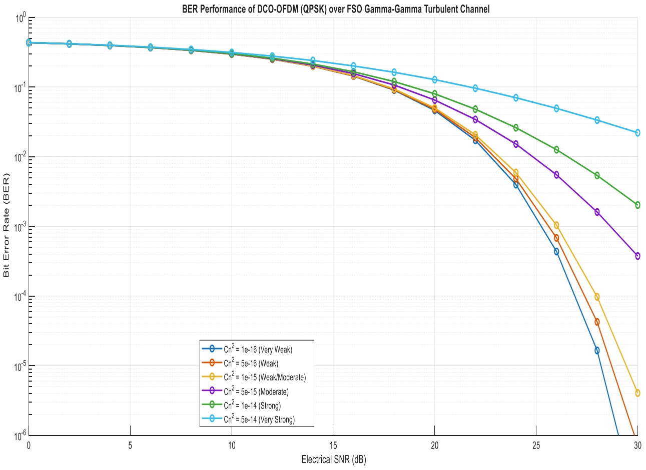

Fig. 4. BER performance of DCO-OFDM, showing high sensitivity to strong turbulence.

Ranking of Robustness: The schemes are evaluated in terms of how well they can handle turbulence, with DPSK coming in first, followed by 4-PPM, OOK, and DCO-OFDM.

B. Evaluation of Mitigation Techniques

Adaptive Optics (AO)

The use of Adaptive Optics was based on a residual factor of $\eta AO = 0.3$, which means that 70% of the wavefront phase variation was corrected. The findings reveal that the BER curves always "left-shift," which raises the SNR by 3 to 5 dB, depending on how strong the turbulence is. In effect, AO changes the channel characteristics from a "strong" turbulence regime to a "moderate" one. This makes the connection distance longer or lowers the power needs of the transmitter. However, AO just makes things better in a static way and doesn't get removed of the deep fading dips as well as diversity approaches do. Figure (5) illustrates the improvement achieved using Adaptive Optics with a residual turbulence factor of 0.3.

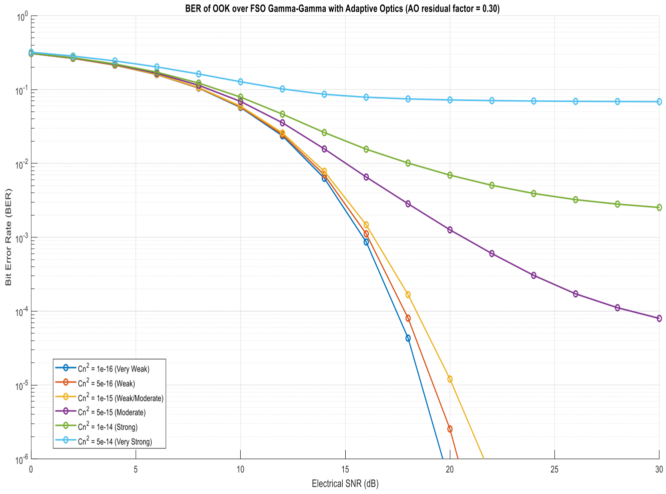

Fig. 5. Performance improvement using Adaptive Optics (AO) with 30% residual turbulence

Dynamic Beam Steering (DBS)

We looked into DBS with four spatial channels, or $N_{paths} = 4$. The findings of the three DBS situations are as follows:

Ideal DBS*:* This situation shows the best possible performance. Ideal DBS almost completely removes the use of deep fades by assuming perfect Channel State Information (CSI) and rapid switching. The diversity gain is huge; in mild turbulence, Ideal DBS gives a gain of more than 10 dB compared to the single-link OOK baseline at a BER of 10^{-4}. Figure (6) show BER performance of Ideal DBS considering channel estimation errors and misalignment.

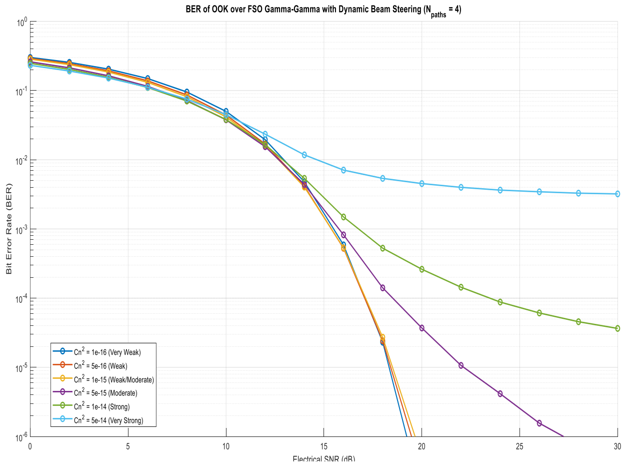

Fig. 6. BER performance of Ideal DBS

Realistic DBS (Estimation Noise): Adding channel estimation flaws (30% variation) only slightly lowers performance relative to the best situation. Because the noisy estimate makes a weaker option seem stronger, the algorithm sometimes chose a way that isn't the best one. The diversity gain, on the other hand, is still quite high, which shows that DBS can work even with sensors that aren't ideal. Figure (7) show BER performance of Realistic DBS considering channel estimation errors and misalignment.

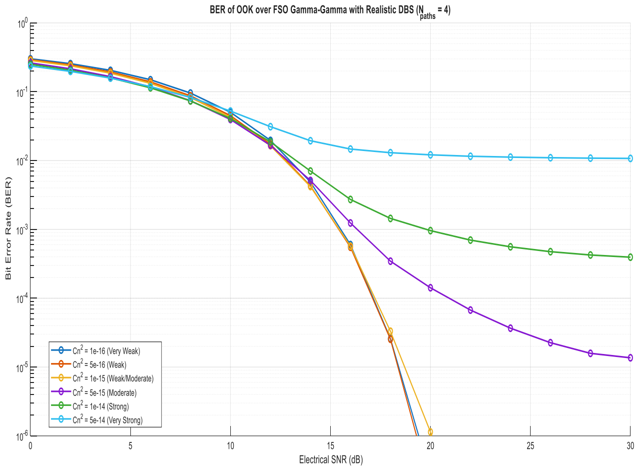

Fig. 7. BER performance of Realistic DBS

Imperfect DBS (Misalignment): Adding a 20% misalignment chance ($P_{mis} = 0.2$) makes a substantial error floor impact at high SNRs. If the steering mechanism doesn't lock onto the chosen route (which is simulated by going back to a random path), the diversity advantage is lost for a short time. Even yet, Imperfect DBS still works better than the single-link OOK system, showing that spatial diversity is a strong tool even when there is mechanical or control issues. Figure (8) show BER performance of Imperfect DBS considering channel estimation errors and misalignment.

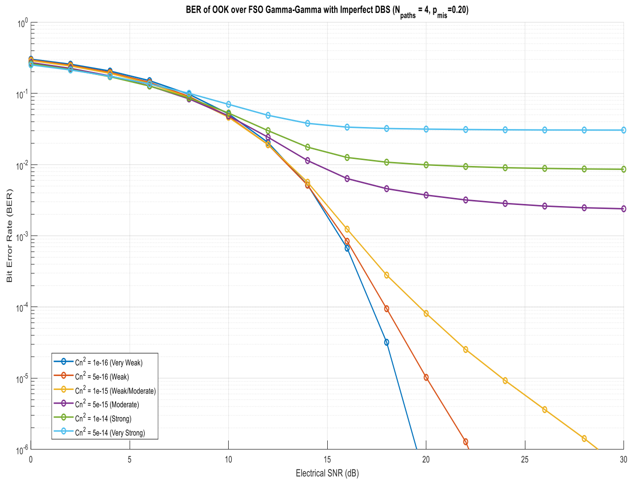

Fig. 8. BER performance of Imperfect DBS

C. Quantitative Performance Comparison

Table II and Table III show the BER values from the simulations at two different electrical SNR levels: 20 dB (moderate SNR) and 30 dB (high SNR). This is to provide a more accurate picture of the suggested solutions. The comparisons center on the "Very Strong" turbulence regime ($C_n^2 = 5 \times 10^{-14} \mathrm{m}^{-2/3}$), which epitomizes the most severe condition for urgent mitigation.

1. Comparison of Modulation Schemes

Table II shows how well the four modulation types can handle turbulence.

TABLE II

BER COMPARISON OF MODULATION SCHEMES UNDER STRONG TURBULENCE ($C_n^2 = 5 \times 10^{-14}$)

Modulation Scheme	BER at SNR = 20 dB	BER at SNR = 30 dB	Performance Verdict
DPSK	4.2×10^{-5}	$< 10^{-6}$	Best. Excellent resilience due to differential detection.
4-PPM	2.5×10^{-3}	1.1×10^{-4}	Good. Power efficient, but requires synchronization.
OOK (Baseline)	4.1×10^{-3}	3.5×10^{-3}	Poor. Suffers from severe error floor (saturation).
DCO-OFDM	3.8×10^{-2}	2.2×10^{-2}	Worst. High PAPR causes clipping and signal distortion.

2. Comparison of Mitigation Techniques

Table III compares the effectiveness of Adaptive Optics (AO) and Dynamic Beam Steering (DBS) when applied to the baseline OOK system.

TABLE III

BER COMPARISON OF MITIGATION TECHNIQUES (USING OOK IN STRONG TURBULENCE).

Mitigation Technique	BER at SNR = 20 dB	BER at SNR = 30 dB	Improvement over Baseline
Baseline (No Mitigation)	4.1×10^{-3}	3.5×10^{-3}	—
Adaptive Optics (AO)	9.5×10^{-4}	2.1×10^{-4}	Moderate (≈ 5 dB SNR gain)
Imperfect DBS ($\mathbf{P_{mis} = 0.2}$)	1.5×10^{-4}	3.0×10^{-5}	High (despite misalignment)
Realistic DBS (Est. Error)	8.0×10^{-5}	9.0×10^{-6}	Very High
Ideal DBS	4.5×10^{-5}	$< 10^{-6}$	Highest (Benchmark)

3. Final Ranking (Best → Worst)

Table IV summarizes the overall performance of all studied methods. The metric "Avg BER" represents the arithmetic mean of the Bit Error Rates calculated over the entire simulated electrical SNR range (0 to 30 dB) under strong turbulence conditions ($C_n^2 = 5 \times 10^{-14} m^{-2/3}$). This metric shows how reliable the system is in both clean and noisy channel modes.

TABLE IV
BASED ON HOW MUCH BETTER IT GOT FROM THE BASELINE OOK

Method	Avg BER	Improvement
DPSK	0.0528	47.6% better
DBS-Ideal	0.0584	42.0% better
DBS-Realistic	0.0604	40.0% better
DBS-Imperfect	0.0679	32.6% better
PPM	0.0682	32.2% better
Adaptive Optics	0.0764	24.1% better
Baseline OOK	0.1007	Reference
DCO-OFDM	0.196	94.7% worse

VI. CONCLUSION

This study performed an extensive simulation-based examination of the impacts of Gamma-Gamma atmospheric turbulence on Free-Space Optical (FSO) communication systems. The study systematically assessed the effectiveness of four distinct modulation systems and examined the utility of Adaptive Optics (AO) and Dynamic Beam Steering (DBS) as approaches for turbulence reduction. The comparative modulation study demonstrated that Differential Phase Shift Keying (DPSK) is superior in managing fading induced by turbulence compared to OOK, 4-PPM, and DCO-OFDM. This is its strength because it can find differences, so OOK doesn't need to use dynamic thresholding. DCO OFDM is the most likely to fail in the channel, so it needs a lot of error correction coding to work on FSO networks, even though it has high spectral efficiency. The results show that Dynamic Beam Steering (DBS) works better than Adaptive Optics (AO) when it comes to mitigation strategies. The best DBS ($Npaths = 4$) has the lowest Bit Error Rate (BER) when using the best optical route. Even though it can be hard to estimate the channel, realistic DBS is still much better than single link systems. Imperfect DBS showed that mechanical misalignment could cause an error floor, but it is still a good way to reduce big fades. In conclusion, a hybrid physical layer solution is the best choice for next-generation free-space optical networks that need to work well even when the weather is bad. This means using a strong modulation format like DPSK along with spatial diversity techniques like Dynamic Beam Steering. Future research will focus on the amalgamation of Forward Error Correction (FEC) codes with these mitigation strategies and the investigation of hybrid RF/FSO architectures to enhance link availability.

REFERENCES

[1] J. Mikołajczyk,"Optical Wireless Communications Operated at Long Free Space Optical Links,"International Journal of Electronics and Telecommunications (IJET), Vol. 66, No. 2, pp. 383–387, 2020.

[2] L. C. Andrews and R. L. Phillips, Laser Beam Propagation through Random Media, 2nd ed. Bellingham, WA: SPIE Press, 2005.

[3] D. Shah, H. Joshi, D. Kothari,"Comparative BER Analysis of Free Space Optical System using Wavelength Diversity over Exponentiated Weibull Channel,"IJET, Vol. 67, No. 4, pp. 665–672, 2021.

[4] W. O. Popoola and Z. Ghassemlooy, "BPSK subcarrier intensity modulated free-space optical communications in atmospheric turbulence," Journal of Lightwave Technology, vol. 27, no. 8, pp. 967–973, 2009.

[5] E. Elsayed,"Investigations on OFDM UAV-based Free-Space Optical Communication Systems,"Optical and Quantum Electronics,Vol. 56, No. 2, 2024.

[6] J. Armstrong, "OFDM for optical communications," Journal of Lightwave Technology, vol. 27, no. 3, pp. 189–204, 2009.

[7] D. Agarwal,"Impact of Finite-Sized Aperture on the Performance of Relay-Assisted Free Space Optical Networks,"International Journal of Electronics and Telecommunications (IJET), Vol. 68, 2022.

[8] U. Darusalam,"The Improvement of Optical Spatial Filter Method to Enhance FSO Direct-Detection Performance,"International Journal of Electronics and Telecommunications (IJET),2023.

[9] H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," IEEE Communications Surveys & Tutorials, vol. 19, no. 1, pp. 57–96, 2017.

[10] Y. Huang, X. Zheng, Y. Guo, and S. Gao, "Performance Improvement of the Free-Space Optical Communication Link Using Spatial Diversity Reception-Assisted OFDM Signals," Applied Sciences, vol. 12, no. 14, 6828, 2022, https://doi.org/10.3390/app12146828

[11] H. Zhang et al., "Application of AdamSPGD algorithm to sensor-less adaptive optics in coherent free-space optical communication system," Optics Express, 2022.

[12] J. Tao et al., "Beam-Steering Metadevices for Intelligent Optical Wireless Communication," Advanced Photonics Research, 2023.

[13] H. Ajam, M. Najafi, V. Jamali, and R. Schober, "Channel Modeling for IRS-Assisted FSO Systems," arXiv, 2020.

[14] L. C. Andrews, R. L. Phillips, and C. Y. Hopen, Laser Beam Scintillation with Applications, Bellingham, WA: SPIE Press, 2001.