International Journal of Research in Interdisciplinary Studies
Volume 3, Issue 10, October 2025
https://www.ijris.com | ISSN (Online): 2584-1017

Impact of Raman Amplifiers in the Mitigation of Turbulence in Free Space Optical Communication by Adaptive Optics

Onyambu Edwin Nyambati[1*], Kiragu Henry Macharia[2], Livingstone M. H. Ngoo[3]
[1]*Transmission Engineer, Network Operations, Nairobi, Kenya*
[2]*Lecturer, Faculty of Engineering and Technology, Multimedia University of Kenya, Nairobi, Kenya*
[3]*DVC - Academic Affairs, Research & Innovation, Multimedia University of Kenya, Nairobi, Kenya*

Abstract—Free-space optical communication (FSOC) presents a potent solution for next-generation networks, offering fiber-like bandwidth without the physical infrastructure. However, its performance is severely constrained by atmospheric turbulence, which induces signal scintillation and fading. This paper characterizes the atmospheric channel using the Gamma-Gamma (G-G) turbulence model, defined by the refractive index structure parameter (C_n^2). The study develops a comprehensive MATLAB simulation platform to emulate FSOC system performance under various turbulence strengths and link distances. The mitigation strategy used; integrates adaptive optics (AO) for wavefront correction and distributed Raman amplification for signal gain. Results demonstrate that this hybrid approach significantly improves the system's resilience. Observing marked reduction in Bit Error Rate (BER) and an enhancement in Signal-to-Noise Ratio (SNR), effectively extending the viable operational range of FSOC systems. This enhanced reliability directly contributes to the practical deployment of FSOC as a cost-effective solution for bridging the digital divide in underserved and remote regions.

***Index Terms*—Adaptive optics, Atmospheric turbulence, Bit error rate, Digital divide, Free-space optical communication, Gamma-Gamma model, Raman amplifier, Signal to Noise Ratio.**

1. Introduction

The digital divide remains a critical global challenge. According to the International Telecommunication Union, 2.9 billion people—over a third of the world's population—have never used the internet. While policy often focuses on physical access, the cost and affordability of ICT are significant barriers, as highlighted by UN-Habitat. Emerging digital inclusion strategies now emphasize not only infrastructure provision but also digital literacy and usage opportunities (UNhabitat, 2021). The post-COVID-19 era has underscored the urgency for "step-change" improvements in connectivity, requiring radically new solutions (Alimi I. A., 2024).

Free-Space Optical Communication (FSOC) is a promising technology that uses laser beams to transmit data through the atmosphere, offering high bandwidth, enhanced security, and rapid deployment. Its potential to deliver high-capacity links over long distances makes it ideal for scenarios where laying fiber is impractical or cost-prohibitive, such as across difficult terrains urban areas, rivers crossings and islands (Phuchortham, 2025). For instance, the Taara project by Alphabet, in partnership with Liquid Intelligent Technologies, successfully bridged a 4.8 km gap across the Congo River between Brazzaville and Kinshasa—a link that would otherwise require a 400 km fiber route, reducing connectivity costs fivefold (Erkmen, 2021).

Despite its merits, FSOC is highly susceptible to atmospheric turbulence, which causes random fluctuations in the received signal's intensity and phase (scintillation) (Alimi I. e., 2017). Traditional mitigation techniques like spatial diversity and adaptive modulation offer limited relief under moderate-to-strong turbulence conditions (Andrews, 2021).This motivates the need for more robust, advanced mitigation strategies (Kshatriya, 2016).

This study investigates a novel, dual-layer mitigation approach combining Adaptive Optics (AO) for real-time wavefront correction and distributed Raman amplification for optical signal gain. We model the channel using the Gamma-Gamma distribution to represent a wide range of turbulence conditions. The novelty of this work lies in the joint simulation and performance analysis of these techniques, evaluating their synergistic effect on key metrics BER and SNR over varying distances and turbulence strengths.

In (Ucuk Darusalam, 2023), the implementation of optical amplifiers (OAs) in cascaded configuration, namely, erbium-doped fiber amplifiers, semiconductor OAs, and Raman amplifiers (RAs), are investigated through simulation. The study aimed to search for the maximum link distance of an optical propagation and enhance the FSO performance caused by each configuration of OAs. The optical relaying network consisted of three nodes, with each node designed with a space of several kilometers under the influence of atmospheric turbulence the work concentrated on relay distance extension. While (Tan, 2022) shows different designs of distributed Raman amplifiers proposed to minimize the signal power profile asymmetry in mid-link optical phase conjugation systems. Demonstrating how the symmetrical signal power profiles along the fiber achieved using various distributed

*Corresponding author: enonyambu@yahoo.com

Raman amplification techniques in the single-span and more realistic multi-span circumstances. (Quatresooz, 2025) Work provides important insights into optical turbulence model selection, enabling accurate site characterization that informed optical terminal design. While the simulation work of this study is as per (Li, 2024) for free-space optical (FSO) communication

The organization of the remainder of this paper as follows: Section III details the system and channel model. Section IV describes the simulation methodology. Section V presents and discusses the results. Finally, Section VI concludes the paper and suggests future research directions.

A. System and Channel Model

1) Atmospheric Turbulence Modelling

Atmospheric turbulence, caused by variations in temperature and pressure, leads to random refractive index fluctuations. Quantified by the refractive index structure parameter, C_n^2, which ranges from 10^{-17} $m^{-2/3}$ for weak turbulence to 10^{-13} $m^{-2/3}$ for strong turbulence. The Rytov variance, σ_R^2, is a common metric for defining turbulence strength (Li, 2024).

For a plane wave:

$$\sigma\_R^2 = 1.23\, C_n^2\, k\text{^}(7/6)\, L\text{^}(11/6) \quad (1)$$

Where,

k = 2π/λ is the wave number and L is the propagation distance.

Turbulence is classified as weak ($\sigma\_R^2 << 1$), moderate ($\sigma\_R^2 \approx 1$), strong ($\sigma\_R^2 > 1$), or extremely strong ($\sigma\_R^2 >> 1$).

Several statistical models describe the intensity fluctuations. This work employs the Gamma-Gamma model for its accuracy across all turbulence regimes. The probability density function (PDF) of the received irradiance I is given by as eqn 2 (communication, 2023) (Salazar, 2022):

$$f(I) = \Gamma(\alpha)\Gamma(\beta)2(\alpha\beta)(\alpha+\beta)/2I(2\alpha+\beta-1)K\alpha-\beta\,(2\alpha\beta I), I > 0 \quad (2)$$

Where,

I represents the normalized irradiance, α and β are parameters of the distribution representing the effective number of large-scale and small-scale eddies, Γ (·) is the Gamma function

$Kv(\cdot)$ is the modified Bessel function of the second kind of order v. The term (αβ)^(α+β)/2(*αβ*)(*α*+*β*)/2 normalizes the distribution. The exponent I (α+β2−1) *I*(2*α*+*β*−1) controls the shape of the distribution

The Bessel function term Kα−β(2αβI)*Kα*−*β*(2*αβI*) captures the correlation between large and small scale fluctuations

2) Phase Power Spectral Density (PSD)

The Kolmogorov model describes the statistics of turbulence. The PSD of phase aberrations is:

$$\Phi\phi(\kappa) = 0.023\, r0 - \frac{5}{3}\kappa - 11/3 \quad (3)$$

B. System Model Method

The research method integrates two key technologies as follows.

1) Adaptive Optics (AO)

The AO subsystem uses a Shack-Hartmann wavefront sensor to measure distortions and a Deformable Mirror (DM) to apply corrective phase shifts in real-time, compensating for wavefront aberrations and reducing beam wander and scintillation (Carrizo, 2019) .

2) Distributed Raman Amplification

A backward-pumped Raman amplifier modelled along the transmission path. It provides distributed gain, compensating for atmospheric attenuation and mitigating deep fades caused by turbulence. The pump wavelength set lower than the signal wavelength (1450 nm pump for a 1550 nm signal) (Binh, 2009) (Tan, 2022) (Saktioto, 2019).

The degradation of the signal-to-noise ratio (SNR). A lower NF is better.

$$NF = SNR_{out}/SNR_{in} \quad (4)$$

a) EDFA Gain

$$GEDFA = exp[(\sigma eN2 - \sigma aN1)L] \quad (5)$$

Where σe and σa are the emission and absorption cross-sections, $N2$ and $N1$ are the populations of the excited and ground states, and L is the length of the doped fiber.

b) Raman Amplifier Gain

The on-off Raman gain for a counter-pumped configuration.

$$GRaman = exp(gR.Pp.Leff/Aeff) \quad (6)$$

Where,

gR - Raman gain coefficient (depending on the pump and signal wavelengths)

Pp - the pump power,

Aeff - effective area of the fiber mode,

Leff = 1−exp(−αpL)/ αp is the effective interaction length,

αp - the fiber attenuation at the pump wavelength

Amplified Spontaneous Emission (ASE) Noise Power For both EDFA and Raman amplifiers, the ASE noise power in a bandwidth Δv is critical.

$$PASE = 2nsphv(G-1)\Delta v \quad (7)$$

Where,

$n$sp - spontaneous emission factor (≥1),

h - Planck's constant,

v - Optical frequency, and

G - Amplifier gain. The factor of 2 accounts for two polarization states.

The spontaneous emission factor $n$sp is typically higher for Raman amplifiers than for EDFAs, which leads to a higher *noise figure* for Raman amps, especially at lower gains. However, the distributed nature of Raman amplification leads to a better overall OSNR in a long-haul system.

2. Link Budget and Performance Metrics

Link Margin /Fade Margin quantifies the system's robustness. The amount of excess power available to overcome unexpected signal attenuation (fading) while maintaining a target performance level. Calculated as:

$$Mlink = Prx - Psens[dB] \tag{8}$$

Where,

Mlink - the Link Margin (dB),

Prx - total received power (dBm),

Psens - the receiver sensitivity (dBm), the minimum received power required to achieve a pre-determined target Bit Error Rate (BER), typically BER target=10−12BERtarget=10−12 for high-reliability systems.

The system's performance

Fundamentally evaluated using two key metrics: SNR and BER.

Bit Error Rate (BER)

The BER is the probability that a transmitted bit is received incorrectly. For a system dominated by additive white Gaussian noise (AWGN), the BER for a simple On-Off Keying (OOK) modulation scheme given by:

$$BER = \frac{1}{2}erfc(\surd SNR/2) \tag{9}$$

where erfc(·) is the complementary error function. The BER expressed in terms of the Q-factor:

$$BER = \frac{1}{2}\ erfc(Q/\surd 2) \tag{10}$$

Signal-to-Noise Ratio (SNR)

The SNR is the ratio of the power of the desired signal to the power of the corrupting noise. It is the primary determinant of the BER. Expressed as a linear ratio or in decibels (dB).

$$SNR(dB)\ =\ 10\ log_{10}(P\_signal\ /\ P\_noise)$$

The total noise power Pnoise is the sum of all noise contributions, including shot noise (σ^2shot), thermal noise (σ^2thermal), and amplified spontaneous emission (ASE) noise from optical amplifiers (σ^2ase):

$$Pnoise = \sigma^{\wedge}2shot + \sigma^{\wedge}2thermal + \sigma^{\wedge}2ase \tag{11}$$

SNR measures the quality of the received optical signal relative to the background noise. A higher SNR means the signal is stronger compared to the noise, which usually leads to better communication performance (lower BER).

The Q function is in the performance analysis of free-space optical (FSO) communication systems to describe the probability of error in the system, particularly when noise and fading affect the signal. The signal quality can degrade due to various factors like atmospheric turbulence, weather conditions, and pointing errors. The Q function models the probability of bit errors in these conditions.

Denoted as (x) defined mathematically as:

$$Q(x) = \frac{1}{\sqrt{2\Pi}}\int_{x}^{\infty}\ e^{i-\frac{t^{\wedge}2}{2}}\delta t \tag{12}$$

This function gives the tail probability of the Gaussian (normal) distribution and is related to the bit error rate (BER) in FSO systems, which measures the fraction of bits transmitted incorrectly.

The Q function used in tandem with a fading distribution, such as the log-normal or Gamma-Gamma distribution, which models the effect of atmospheric turbulence on the received signal. By combining the Q function with these fading models, the BER under different turbulence levels computed, giving insight into system performance under various atmospheric conditions.

3. Methodology

The research approach based on design and simulation using MATLAB. The FSOC system model consists of a transmitter, a channel and receiver as noted figure 1.

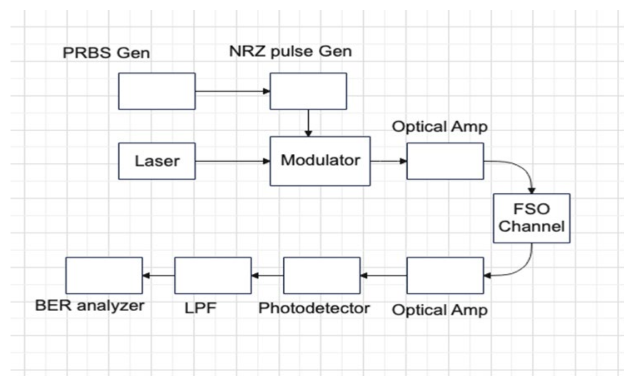

Fig. 1. Block diagram of an FSOC system by function

The Transmitter: includes A Pseudo-Random Bit Sequence (PRBS) generator, NRZ pulse generator, a Continuous Wave (CW) laser at 1550 nm, and a Mach-Zehnder Modulator (MZM).

The Channel: A free-space channel modelled with Gamma-Gamma turbulence and attenuation (0.43 dB/km). The Raman amplifier modelled with a pump power of 0.1 W at 1450 nm and an attenuation of 0.2 dB/km.

Receiver: An Avalanche Photodiode (APD) detector, a Low-Pass Bessel Filter, and a BER analyzer.

The simulation iterates over a range of turbulence strengths (C_n^2 values) and link distances (*L*). For each iteration, the BER and SNR are calculated with and without the hybrid mitigation scheme to quantify the performance improvement.

The study employs a comprehensive numerical simulation to evaluate the performance of Adaptive Optics (AO) combined with Raman optical amplifiers for mitigating atmospheric turbulence in free-space optical communication. The key simulation parameters summarized in table 1. The simulation propagates a Gaussian beam through phase screens using wave-optics, implements AO correction, applies amplifier models, and evaluates performance metrics across multiple turbulence realizations for statistical significance.

Table 1
Simulation parameters

Parameter	Value
Data Rate	5 Gbps
Wavelength (Signal)	1550 nm
Wavelength (Pump)	1450 nm
Transmitter Power	10 dBm
Pump Power	0.1 W (20 dBm)
APD Responsivity	1 A/W
Atmospheric Attenuation	0.43 dB/km
Target BER	10^{-12}

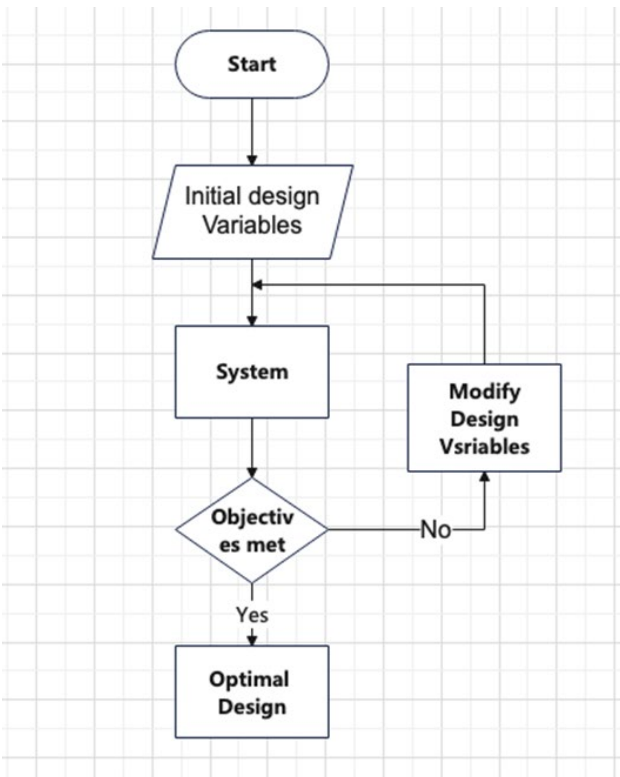

Fig. 2. Simulation flow chat

4. Results and Discussion

MATLAB code models the performance of a Free-Space Optical Communication (FSOC) system under turbulence-induced fading, considering adaptive optics (AO) and two amplifier types: Raman and EDFA (Erbium-Doped Fiber Amplifier). The analysis evaluates irradiance probability density functions (PDFs), signal-to-noise ratio (SNR), and bit error rate (BER) across different turbulence regimes and link distances.

A. Numerical Result

Simulations were conducted for link distances from 1 km to 5 km and C_n^2 values from 10^{-15} $m^{-2/3}$ to 10^{-13} $m^{-2/3}$.

The matlab plots, PDF shows how the received optical signal intensity (irradiance) distributes due to atmospheric turbulence. Turbulence causes fading; stronger turbulence spreads the PDF more and shifts it toward lower irradiance (more signal degradation). Adaptive optics (AO) mitigates turbulence, and Raman amplification boosts the signal.

Comparison plot of wavefront distortion versus distance for a free-space optical link, showing how adaptive optics (AO) improves performance.

This figure shows that as distance increases, turbulence causes higher wavefront error. Adaptive optics (green line) reduces the error significantly compared to the no-AO case (red line). Qualitative demonstration of AO effectiveness).

Shorter distances yield high SNR and ultra-low BER. Longer distances lead to degraded SNR and increased BER.The AO and Raman combo helps maintain acceptable BER even at moderate turbulence.

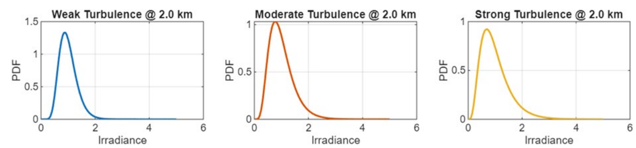

Fig. 3. Pdf plot of signal at 2KM

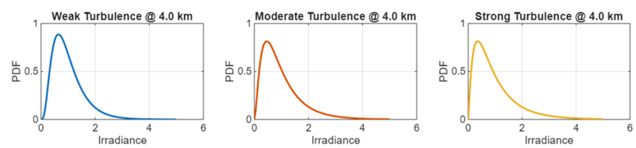

Fig. 4. Pdf plot of signal at 4KM

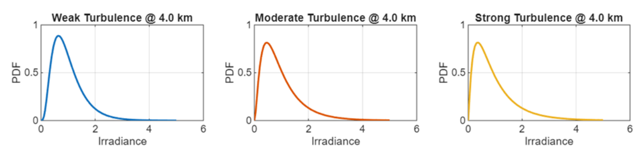

Fig. 5. Pdf plot of signal at 6km

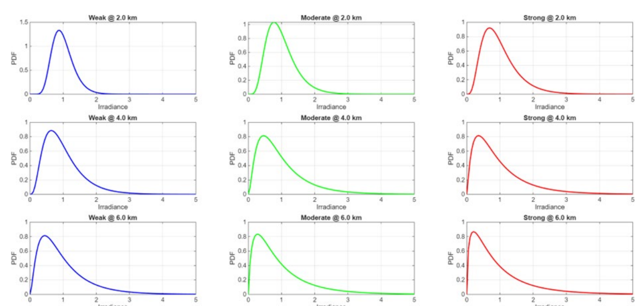

Fig. 6. Summary of irradiance plots

Table 2
Simulation procedure

Component	Purpose
Generate PDF()	Computes probability density under Gamma Gamma turbulence conditions
AO factor	Reduces turbulence effects (σ^2) via a multiplication factor
Raman gain	Amplifies received signal after turbulence, affecting SNR/BER only
Irradiance range	Defines intensity samples over which the PDFs are evaluated
BER/SNR plot	Indicates link reliability after signal processing/amplification

Table 3
Summary on outcomes of graphs

Metric	Before AO + Raman	After AO + Raman	Improvement
SNR (dB)	Lower (degrades with distance)	Higher SNR retained over longer ranges	Better signal integrity and robustness
BER	Higher (e.g., 1e-4 or worse at long range)	Significantly lower (1e-7 or better)	Reduced bit errors, improved reliability
PDF Shape	Broader, more scattered under strong turbulence	More peaked (narrower) after AO and Raman	Better power concentration at receiver
Irradiance Distribution	Shifted due to turbulence	Corrected & amplified	Enables consistent photodetector response

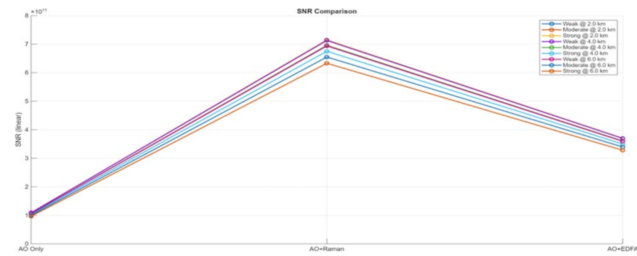

Fig. 7. Illustrates comparison of AO only, A0+EDFA and AO+ Raman

The curve shifts and narrows, suggesting mitigation of turbulence effects.

AO reduces the variance, and Raman gain amplifies the received signal. As distance increases, all turbulence effects worsen (PDFs become broader), but AO + Raman helps to restore the received irradiance distribution.

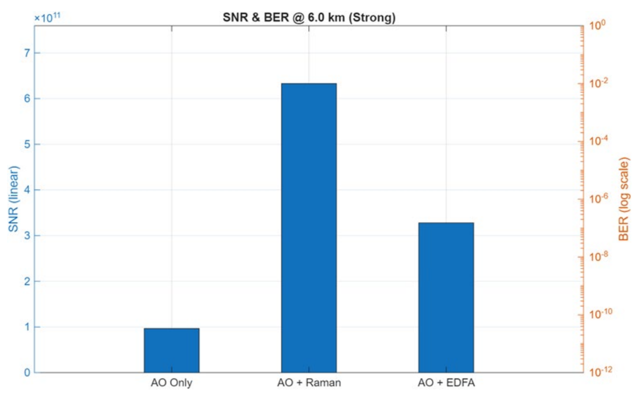

Fig. 8. SNR bar graph

Best SNR realised on AO+BER. At distance of 4 km under strong turbulence ($C_n^2 = 5\times10^{-14}$ $m^{-2/3}$), the standalone system might exceed a BER of 10^{-3}, rendering it unusable for high-speed data. In contrast, the proposed hybrid system could maintains BER below 10^{-9}, well within acceptable limits. The Raman amplifier effectively boosts the signal power, countering attenuation, while the AO system sharpens the focus at the receiver, reducing geometric loss and scintillation. Their combined effect is synergistic, enabling a longer, more reliable link.

This extended range and improved reliability are the key factors that make FSOC a viable "last-mile" or "backhaul" solution for connecting remote communities, directly addressing the economic and geographic challenges at the heart of the digital divide.

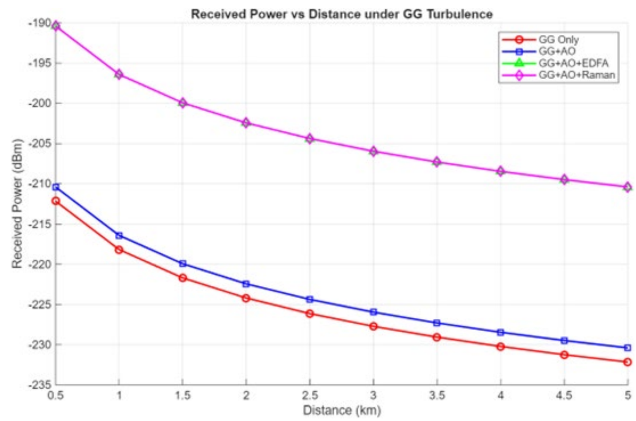

Fig. 9. Plot of power received over distance unmitigated, Mitigated with AO + EDFA or Raman

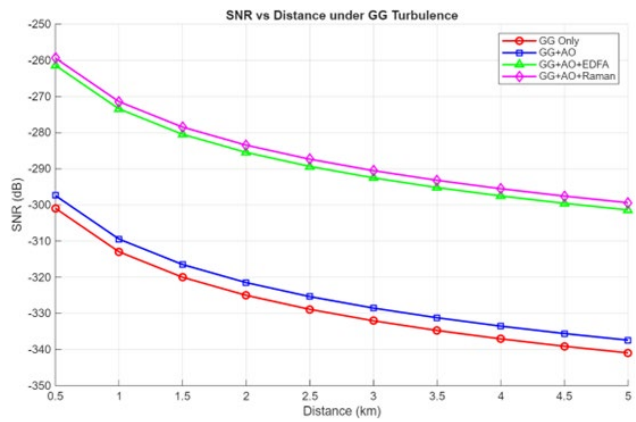

Fig. 10. Plot of SNR resulting over distance unmitigated, Mitigated with AO + EDFA or Raman

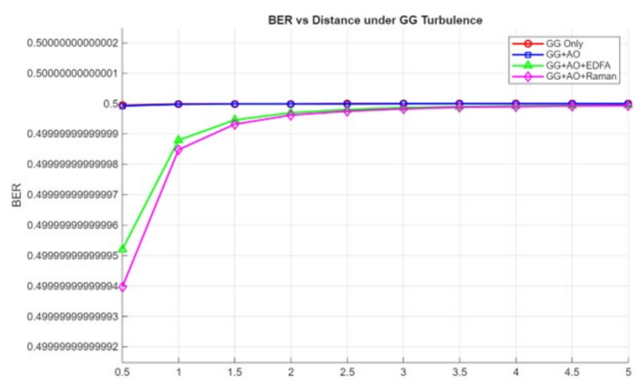

Fig. 11. Plot of BER performance over distance unmitigated, Mitigated with AO + EDFA or Raman

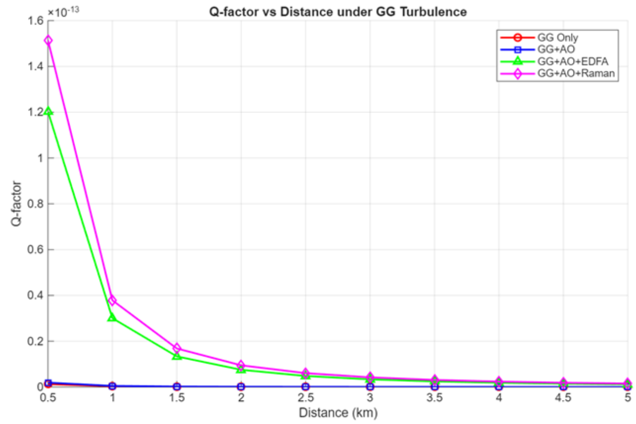

Fig. 12. Plot of BER performance over distance unmitigated, Mitigated with AO + EDFA or Raman

5. Conclusion

This research demonstrates that the detrimental effects of atmospheric turbulence on FSOC links is mitigated through a hybrid approach combining adaptive optics and Raman amplification. By significantly improving BER and SNR performance over practical distances, this strategy enhances the reliability and operational range of FSOC systems.

The implication for global connectivity is profound. Technologies like FSOC can provide a cost-effective, high-capacity alternative to traditional fiber, capable of bridging stubborn connectivity gaps in geographically challenging regions, as exemplified by the Taara project. By sacrificing a minimal amount of absolute signal reliability for a massive gain in deploy ability and cost, FSOC can indeed connect millions more people to faster, cheaper internet.

Future work recommendation are to focus on integrating intelligent, predictive systems using machine learning to dynamically optimize AO correction parameters and pump laser power in real-time based on weather forecasts and channel state information. Further investigation into the scalability of these systems for multi-hop networks and their integration with emerging 6G infrastructure will be crucial for realizing their full potential in bridging the digital divide.

References

[1] Alimi, I. A. (2024). Revolutionizing Free-Space Optics: A Survey of Enabling Technologies, Challenges, Trends, and Prospects of Beyond 5G Free-Space Optical (FSO) Communication Systems.

[2] Alimi, I. E. (2017). Challenges and Opportunities of Optical Wireless Communication Technologies. Optical Communication Technology.

[3] Andrews, L. B. (2021). Adaptive optics model characterizing turbulence mitigation for free space optical communications link budgets. Optical Society of America.

[4] Binh, L. N. (2009). MATLAB Simulink modeling of Raman hybrid amplification for long-distance hut-skipped undersea optical fiber transmission systems. Optical Engineering.

[5] Carrizo, C. E. (2019). Advanced adaptive compensation system for free-space optical communications.

[6] A. N. Khan, M. Zubair and Usman Younis, "Modeling of optical wave propagation through turbulent atmosphere using fractional approach for FSO wireless communication," in *Journal of Physics Communications*, vol. 7, no. 1, 2023.

[7] Erkmen, B. (2021). Beaming Broadband Across the Congo River. alphabet.

[8] Kshatriya. (2016). Investigation on the performance and improvement of free space optical link in atmospheric turbulence. Gujarat Technological University.

[9] Li, L. (2024). Design and Experimental Demonstration of an Atmospheric Turbulence Simulation System for Free-Space Optical Communication. Photonics.

[10] Phuchortham, S. A. (2025). A Survey on Free-Space Optical Communication with RF Backup: Models, Simulations, Experience, Machine Learning, Challenges and Future Directions. sensors.

[11] Quatresooz, F. a. (2025). C2n Modeling for Free-Space Optical Communications: A Review. IEEE Access.

[12] Saktioto, T. (2019). Raman amplifier performance in pre-amplifier use for optical fiber communication systems. Telkomnika (Telecommunication Computing Electronics and Control).

[13] Salazar, F., (2022). Simulating Atmospheric Turbulence: Code Development and Educational Applications.

[14] Tan, M., (2022). Distributed Raman Amplification for Fiber Nonlinearity Compensation in a Mid-Link Optical Phase Conjugation System. Sensors.

[15] Ucuk Darusalam, (2023). The Relaying Network in Free-Space Optical Communications using Optical Amplifiers in Cascaded Configuration. Makara Journal of Technology.

[16] UN. (n.d.).

[17] UNhabitat. (2021). Digital Divide Addressing the Taking action towards digital inclusion. UNhabitat.