Evaluation of Relay Turbulence Protocols in Free Space Optical Communication Systems

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***Abstract*— In this paper, we present relay-assisted transmission technique which is a powerful fading mitigation method utilized in improving the free space optical (FSO) communications link capabilities operating in different atmospheric turbulence conditions. This method implicitly reduces the transmission distance and exploits distance-dependent fading variance of turbulence. The performance of the link is observed on the basis of bit error rate analysis of a 10-Gbps relay-assisted FSO system by employing the amplify and forward (AF) and decode and-forward (DF) relaying modes The free space optical link is modeled on the basis of Gamma-Gamma channel distribution under different atmospheric turbulence regimes. The results show that the relay-assisted FSO system offers an excellent improvement for weak-to-strong turbulence regimes, even without knowledge of the channel state information. Since fading variance is distance-dependent in FSO, relay-assisted transmission takes advantage of the resulting shorter hops and yields significant performance improvements. Under strong turbulence and accumulation of amplifier noise, the range of the link can only be extended by employing an optical regenerator.**

Keywords—All-Free Space optics (FSO), optical relaying, atmospheric turbulence, Amplify-and-forward (AF) and decode-and-forward (DF), bit error rate (BER), relay-assisted FSO

I. INTRODUCTION

Fifth-generation (5G) mobile communication is the probable solution to fulfill the demand of high speed data rate multimedia applications. It will offer services with high capacity, negligible end-to-end delays and energy consumption. 5G communication will be comprise of heterogeneous dense networks with 1000 times more mobile data per unit area and 100 times more interconnected mobile devices compared to existing wireless networks In spite of this, existing radio frequency spectrum is insufficient to meet the demands of future high-data rate 5G services. The electromagnetic spectrum, below 10 GHz has almost been exhausted. The huge demand of future mobile data traffic will not be met by existing wireless technologies[6][12].

The service providers must address the bandwidth bottleneck issues at both the backhaul and last mile access networks in order to increase the network capacity. Technologies including microwave and optical fibers will continue to retain their importance as backhaul bearer[15].

The ultra-wide range of unregulated optical spectrum is considered as a promising solution for the development of future high-density and high-capacity networks for both indoor and outdoor application known as Free Space Optical Communication (FSO). In comparison with RF-based networks, FSO system used in line of sight (LOS) applications thereby offers similar capabilities as optical fiber communication with high-data-rate, inherent security, low maintenance cost and immunity to electromagnetic nterference. FSO system can perform well both for indoor and outdoor services and operate at data rates upto 10Gn/s over a range of few kilometers and upto 1.6Gb/s over a range of 80 m for a single outdoor link However, FSO systems suffer sensitivity issues due to obstacles blockage and to their limited transmitted power. Therefore, the coexistence of FSO and RF systems may provide an effective solution for the huge demands of upcoming 5G and beyond communication systems[19].

Researchers already demonstrated upto 100 Gb/s data rate through FSO for the distances range from several nm to more than 10000 km. FSO can be used to increase bandwidth and capacity without any reduced transmission coverage and at much reduced cost compared to RF based schemes[12].

An effective FSO system should have the following subsequent characteristics[6][19]

- FSO systems should work at higher power levels for extended distance.
- For high speed FSO systems, high speed modulation is vital.
- An overall FSO system design should have small footprint and low power consumption due to its maintenance.
- FSO system should have the power to work over wide temperature range and therefore the performance degradation would be less for outdoor systems.
- Mean time between failures (MTBF) of system should be quite 10 years.

FSO has a wide range of applications from industry, healthcare, railway stations, transportation, homes, shopping malls, underwater, and space. For these application different types of communication, like device-to-device, machine to-

Machine, chip-to-chip; device/machine-to-user, user-to-device/machine, vehicle-to-infrastructure, vehicle to vehicle, and infrastructure to vehicle point-to point; multipoint-to-point; and point-to-multipoint, can be performed using FSO technologies[15].

II. LIMITATION OF FFREE SPACE OPTICAL SYSTEM

Since the medium of the transmission for FSO is troposphere therefore when the light passes through, it faces some environmental challenges which are unavoidable. The effect of those limitations over the troposphere is shown in Fig 1. A number of these limitations are briefly described below[17].

A. Physical obstructions

Tall bbuildings, sign boards, flying object and trees can block optical signal, when it appears in line of sight (LOS) of transmission of FSO system.

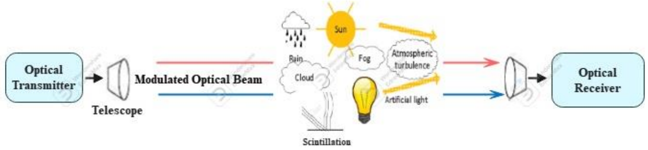


Fig 1: Physical and weather condition effects on FSO link

B. Scintillation

Temperature fluctuations among different air packets can cause in amplitude variation of the optical beam which produces “image dancing” at the receiving side of FSO system. The effect of scintillation is addressed by Light Pointe’s unique multi-beam system[13].

C. Geometric losses

Geometric losses which may be called optical beam attenuation are induced due to the spreading of beam and hence reduce the strength of signal from transmission end to receiver end [4].

D. Absorption

Absorption is caused by the suspended water molecules and CO_2 particles within the terrestrial atmosphere. The photons power would be absorbed by these molecules hence the flux density of the optical beam is decreased.

E. Atmospheric turbulence

The atmospheric disturbance happens because of weather and environment structure. It’s caused by wind and convection which mixed the air parcels at different temperatures. This causes fluctuations within the density of air and it results in the change within the air index of refraction [5].

F. Atmospheric attenuation

It is the result of fog and haze which also depends upon dust and rain. It’s supposed that atmospheric attenuation is wavelength dependent but this is often not true. Haze is wavelength dependent. Attenuation at 1550 nm is a smaller amount than other wavelengths in haze weather. Attenuation in fog weather is wavelength independent [6].

G. Scattering

Scattering takes place when the optical beam and scatterer collide. It’s wavelength dependent phenomenon where energy of optical beam has not changed [12].

III. ATMOSPHERIC TURBULENCE INDUCED FADING

Solar radiation absorbed by the Earth’s surface causes air round the earth’s surface to be warmer compare that at higher altitude. This less dense warmer air rises to combine turbulently with the encompassing cooler air and hence temperature of the air fluctuates randomly.Inhomogeneities turbulence are often seen as discrete cells, or eddies of various temperature, acting like different size of refractive prisms with different refractive indices. The interaction of transmitted optical beam with the turbulent medium leads to fading channel and random variation in phase and amplitude of the received signal [8][9]. The turbulence is characterized by the following parameters:

i. Cn_2: Turbulence strength.
ii. L_o: Large scale eddies
iii. l_o: Small scale eddies or cells

IV. ATMOSPHERIC WEATHER CONDITIONS

The transmission medium of a FSO link is an atmosphere in which signal attenuation depends upon several weather conditions. For instance, fog and heavy snow are the two-primary weather conditions in temperate regions while heavy rain and haze are two main weather conditions in tropical regions and have major effect on link establishment Few weather conditions are described here.

- ***Fog:*** Sun radiation are absorbed, scattered, and reflected by the hindrance caused by fog. Scattering caused by fog is also referred to as Mie scattering, is essentially a matter of boosting the transmitted power [11].
- ***Rain:*** Rain attenuation is a wavelength dependent attenuation and also known as nonselective scattering Rain can fluctuation effects in transmitted optical beam. The visibility of FSO system depends upon the strength of the rain, droplets size and its composition. It can completely modify the characteristics or restrict the passage of optical beam by absorption, scattering, and reflection [9].
- ***Haze:*** Suspended haze particles can stay for longer duration within the air and cause the atmospheric attenuation. So, attenuation values depend on the visibility level at that point. We can check the performance of FSO system either by installing it temporary at the location or, by using Kim and Kruse model [21].
- ***Smoke:*** By the combustion of various substances like carbon, household emission smoke is produced. This will affect the visibility of transmission medium [23].
- ***Sandstorms:*** It is the problem in outdoor link communication. It is characterized by the dimensions of the wind particles that depend on the soil texture and, by the necessary wind speed so to blow the particles during a minimum period of time [11].
- ***Clouds:*** Cloud layers are main a part of earth atmosphere and are formed by the condensation or deposition of water above earth’s surface. This can block the fractions of optical power transmitted from earth to the space[8].
- ***Snow:*** Snow has larger particles which will causes geometric scattering similar to Rayleigh scattering [8].

V. RELAY CHANNEL MODEL AND PROTOCOLS

In cooperative communications, the paths which are independent between the user and the base station are generated via a relay channel as illustrated in Fig 2. The relay channel is a subsidiary channel to the direct channel which is between the source and destination. A key point of cooperative communication process is that the processing of the signal received from the source node will be done by the relay [7].

Cooperative communications protocols can be categorized into two- fixed relaying schemes and adaptive relaying schemes. The paper mainly concentrates on fixed relaying in which the channel resources are divided between the source and the relay in a fixed or deterministic fashion. At the relay processing differs according to the employed protocol. In fixed amplify-and-forward (AF) relaying protocol, the relay scales the received version and transmits an amplified version of it to the destination in addition with the with channel noise. Another processing at the relay node is for the relay to decode the received signal, re-encode it and then retransmit it to the receiver. This type of relaying is known as fixed decode-and-forward (DF) relaying protocol [3][24].

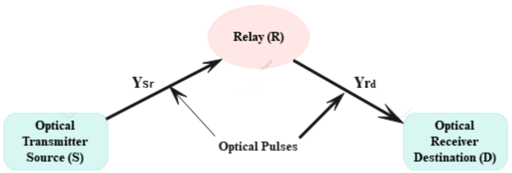


Fig 2: Dual hoe FSO Configuration

DF AND AF PROTOCOLS

a. Decode and Forward (DF) Protocols-:

As shown in fig 2 in a Decode and Forward (DF) cooperation protocol, if the relay is able to decode the transmitted symbol correctly, then the relay forwards the decoded symbol to the destination, otherwise the relay does not send or remains idle. Received signal from source to relay is represented by[2][5]

$$Ysr = \sqrt{E_b} h_1 s + n \tag{1}$$

Where $\sqrt{E_b}$ = signal power

h_1 = signal received at relay from source

s = transmitted symbol with the help of ASK modulation

n = additive white Gaussian noise

For s =1, $Ysr = \sqrt{E_b} h_1 + n$ (2)

$s = 0$ $Ysr = n$ (3)

To detect the signal received at relay we will use the concept of maximum likelihood (ML) ratio detector. For that there are two possible condition.

For first condition

$$(Ysr)^2 > (\mathrm{Ysr} - \sqrt{E_b} h_1)^2$$

For the decoded signal $\hat{s}$ = 1, means signal is not error free.

For second condition

$$(Ysr)^2 < (\mathrm{Ysr} - \sqrt{E_b} h_1)^2$$

If the decoded signal $\hat{s}$ =0, means signal is error free.

Received signal from relay to destination:-

$$Yrd = h_2 \hat{s} + n \tag{4}$$

To detect the signal at receiver we consider two possible conditions.

For first condition

For $\vec{s}$ =1 $(Yrd)^2 > (\mathrm{Yrd} - \sqrt{E_b}\, \mathrm{h}_2)^2$

For second condition

For $\vec{s}$ =0 $(Yrd)^2 < (\mathrm{Yrd} - \sqrt{E_b}\, \mathrm{h}_2)^2$

In this paper, we have mainly focussed on decode and forward protocol as shown by below equation which consists of only multiplicative and AWGN terms [4]

$$Yrd = h_2 \hat{s} + n \tag{5}$$

Calculation of signal to noise ratio (SNR):-

$$Ysr = \sqrt{E_b} h_1 s + n_{sr} \tag{6}$$

$$Ysr = (\sqrt{E_b} \mid h_1 \mid^2) / \sigma^2 \tag{7}$$

Where Ysr = SNR obtained from source to relay

E_b = received energy per bit

σ^2 = noise power

h_1 = signal received from source to relay.

$$Yrd = \sqrt{E_b} h_2 \hat{s} + n_{rd} \tag{8}$$

$$Yrd = \sqrt{E_b} \mid h_2 \mid^2 + \sigma^2{}_{rd} \tag{9}$$

Where Yrd = SNR obtained from relay to destination

E_b = received energy per bit

σ^2 = noise power

h_2 = signal received from relay to destination.

Overall SNR of DF relaying:-

$$\gamma = \min(\gamma_{sr}, \gamma_{rd})$$

BER Calculation:-

$$\int_0^{\circ} Q\left(\frac{\sqrt{z}}{2}\right) f_z(\mathrm{z})\, \mathrm{dz} \tag{10}$$

Where z is the instantaneous SNR and f_z(z) is the pdf of the given function.

$$Z = h_1^2 \sqrt{\bar{\gamma}}$$

Where $\bar{\gamma}$ is the average SNR.

b. Amplifying and Forward (AF) Protocol:-

In amplify and forward relaying scheme, relay channel amplifies the signal with noise that means signal received at destination has multiplicative noise factor G as well as additive white Gaussian noise (AWGN) n which makes the performance analysis difficult [16][17].

$$\begin{aligned} \gamma_{sr} &= h_{sr} s + n \\ Yrd &= G h_{rd} dY_{sr} + n \\ Yrd &= G h_{rd} (\mathrm{h}_{sr} \mathrm{s} + \mathrm{n}) + n \\ Yrd &= \mathrm{G h}_{rd} \mathrm{h}_{sr} \mathrm{s} + \mathrm{G h}_{rd}\, n + n \end{aligned} \tag{11}$$

VI. Atmoshpheric Turbulance Maodel

The surface around the earth becomes less dense and warmer by the absorption of solar radiation which causes air temperature to fluctuate randomly. In-homogeneities that are caused by air turbulence can be seen as a discrete cells of different temperatures acting like refractive prisms of different size. When interaction takes place between optical signal and turbulent medium it will result in random variation and scintillation of optical beam carrying information and that leads to system performance degradation. Atmospheric turbulence is differentiated in terms of regimes that depends on the magnitude of index of refraction variation and in-homogeneities. These regimes are the function of distance travelled by the optical signal via atmosphere and hence classified as weak, moderate, strong and saturation turbulences. This will result in optical signal fading and system performance degradation [18][23].

In our proposed FSO system as shown in fig 3, we uses intensity modulation/direct detection (IM/DD). The laser beam travels along a horizontal path via a turbulence channel with additive white Gaussian noise (AWGN). The channel is assumed to be memoryless, stationary and ergodic, with independent and identically distributed (IID) intensity fading statics [13][18]

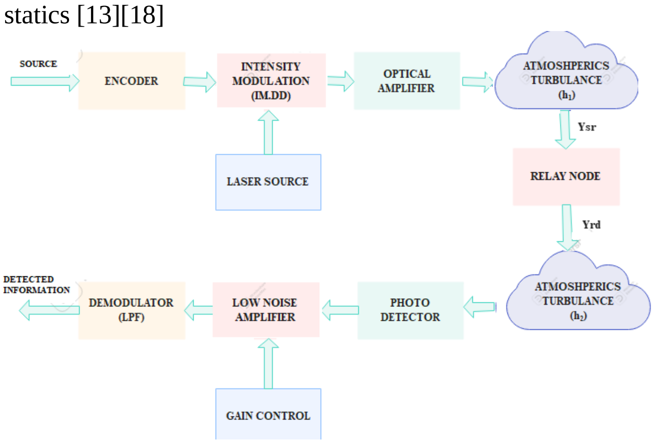


Fig 3: Proposed Block Diagram of Relay Assisted FSO System

The statistical channel model is given by:

$$y = sx + n \qquad (12)$$

Where, y = signal at the receiver

x = modulated signal

s = OOK modulated transmitted symbol

n = AWGN with zero mean and variance $N_0/2$

A. *Log-Normal Turbulence Model*

This model is widely used in calculations of for Probability Density Function (PDF) and hence applicable to weak turbulence conditions and for propagation distance less than 100 meter. In this model, the irradiance fluctuation statistic obeys the log-normal distribution. This model is characterized by a single scattering event and is best suited for weak turbulence regime. The PDF for this model is given by [1][6]

$$f(I) = \frac{1}{I\sqrt{2\pi\sigma_I^2}} e^{\left\{-\left[\frac{\ln(\frac{I}{I_o}) - E(I)\right]^2}{2\sigma_I^2}\right\}} \qquad (13)$$

Where $I > 0$ and

σ_I^2 = Rytov variance,

I = Field irradiance in turbulence medium

I_o = Intensity in free space

$E(I)$ = Mean log intensity.

B. *Gamma-Gamma Turbulence Model*

As we know Gamma-Gamma Model has weak to strong turbulence condition so that PDF of its intensity I is product of two gamma random variables which represents fluctuations from small and large turbulence. For the two random variables are X and Y respectively the received intensity I is given by [8][15]

$$I = XY \qquad (14)$$

The PDF of I is given by

$$f(I) = \frac{2(ab)^{\frac{a+b}{2}} I^{\frac{a+b}{2}-1} K_{a-b}(2\sqrt{abI})}{\Gamma(a)\Gamma(b)} \qquad (15)$$

Where $I > 0$ and

a = no. of large cells

b = no. of small cells

I = Irradiance

Γ(.) = Gamma Function

K (a, b) = Bessel function of Second Order a and b given by equations

$$a = \left[\exp\left(\frac{0.49\sigma_I^2}{(1+1.11\sigma_I^{2.4})^{\frac{7}{6}}}\right) - 1\right]^{-1}$$

$$b = \left[\exp\left(\frac{0.51\sigma_I^2}{(1+0.69\sigma_I^{2.4})^{\frac{5}{6}}}\right) - 1\right]^{-1} \qquad (16)$$

The gamma-gamma turbulence model is valid for all turbulence scenarios from moderate to strong.

C. *Negative Exponential Turbulence Model*

In this, the number of scattering which are independent is high and it can support for saturation regime. Therefore, the irradiance fluctuation will follow the Rayleigh distribution. The negative exponential PDF can be given as [20][21][14]:

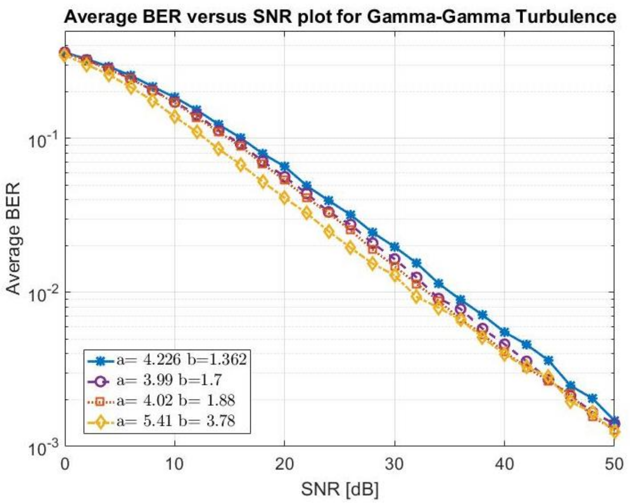
$$f(I) = \frac{I}{I_o}\exp\left(-\frac{I}{I_o}\right), \text{ where } I_o > 0 \qquad (17)$$

Where, E[I] = I_0 is the mean received irradiance.

VII. Results and Conclusion

Implementing AF and DF relaying techniques in our proposed FSO System, it can be observed that signal to noise ratio (SNR) and bit error rate(BER) for decode forward(DF) relaying technique are better than that of Amplify and forward technique..

Applying the same above techniques with negative exponentials distribution gives the worst case scenario



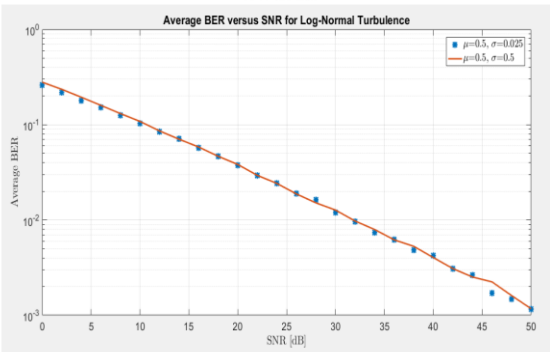


Fig 4: SNR vs BER plot for log-normal turbulence

The graph shown in Fig 4 is for different values of log-irradiance variance. As the value of irradiance variance increases, the distribution becomes more skewed in the infinity direction with longer tails. This denotes the limit of fluctuation of the irradiance as the inhomogeneity of the channel increases.

Fig 5: SNR vs BER plot for gamma-gamma turbulence

The graph shown in Fig 5 represents that as size of the large- and small-scale eddies increases the performance of FSO degrades.

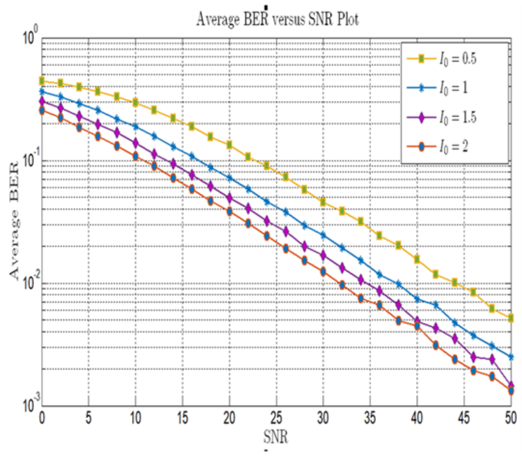


Fig 6: SNR v/s BER relationship plot for negative exponential

The graph shown in Fig 6 is of negative exponential. It comes under very strong turbulence. So, this graph represents that as we increase the expected value of irradiance i.e., I_O the performance degrades eventually.

The SNR versus Average BER plot shown in Fig 7 is for negative exponential fading with I_0=1. The blue line indicates the plot obtained through MONTE CARLO simulation. The red marker plot is obtained by plotting mathematical expression as obtained in Equation As it can be clearly seen that the simulated and analytical plots overlap with each other. This shows that the simulated code and the derived expression give same result.

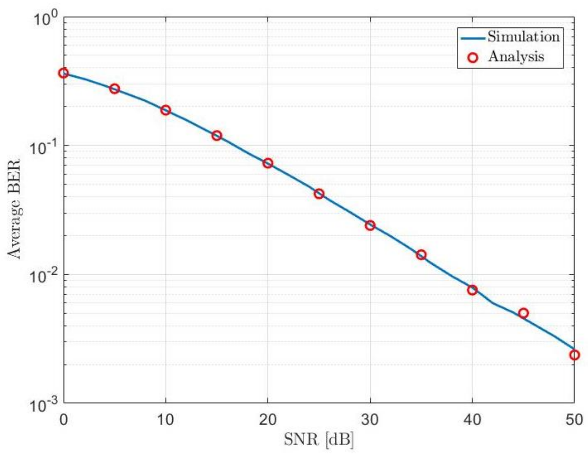


Fig 7. The SNR vss Average BER plot for Io=1

REFERENCES

[1] J. Mirza, A.J. Aljohani, A. Raza, S. Iqbal, S. Ghafoor, "A multi-hop free space optical link based on a regenerative relay, "Alexandria Engineering Journal, vol. 61, Issue 2, pp. 1459-1467, 2022,

[2] R. Miglani, J. S. Malhotra, A. K. Majumdar, F. Tubbal and R. Raad, "Multi-Hop Relay Based Free Space Optical Communication Link for Delivering Medical Services in Remote Areas," in IEEE Photonics Journal, vol. 12, no. 4, pp. 1-21, Aug. 2020.

[3] M. Q. Vu, T. V. Pham, N. T. Dang and A. T. Pham, "Design and Performance of Relay-Assisted Satellite Free-Space Optical Quantum

Key Distribution Systems," in *IEEE Access*, vol. 8, pp. 122498-122510, 2020

[4] Taher, M.A, Abaza, M, Fedawy, M, Aly, M.H., "Relay Selection Schemes for FSO Communications over Turbulent Channels, " Appl. Sci. vol. 9, no. 1281, 2019.

[5] Norhanis Aida Mohd Nor, Matěj Komanec, Jan Bohata, Zabih Ghassemlooy, Manav R. Bhatnagar, and Stanislav Zvánovec, “Experimental all-optical relay-assisted FSO link with regeneration and forward scheme for ultra-short pulse transmission,’ Opt. Express ,vol. 27, Issue 16,pp. 22127-22137, 2019

[6] M. Z. Chowdhury, M. T. Hossan, A. Islam and Y. M. Jang, "A Comparative Survey of Optical Wireless Technologies: Architectures and Applications," in IEEE Access, vol. 6, pp. 9819-9840, 2018,

[7] Nikolaos I. Miridakis, Dimitrios D. Vergados, Angelos Michalas “All-Optical FSO Relaying Under Mixture-Gamma Fading Channels and Pointing Errors” vol 2,, pp. 771-781,Wireless Personal Communications,2018.

[8] Krishnasamy, P. & Kumar D.S., "Polarization shift keying based relay-assisted free space optical communication over strong turbulence with misalignment,"in Optics & Laser Technology, vol. 76,pp. 58–63.2016.

[9] S. Rajbhandari, Z. Ghassemlooy, P. A.Haigh, T. Kanesan, and X. Tang, “Experimental error performance of modulation schemes under a controlled laboratory turbulence FSO channel,” J. Light. Technol., vol. 33, no. 1, pp. 244–250, 2015.

[10] J. Libich, M. Komanec, S. Zvanovec, P. Pesek, W. O. Popoola, and Z. Ghassemlooy, “Experimental verification of all-optical dual hop 10 Gbit/s FSO link under turbulence regimes,” Opt. Lett., vol. 40, no. 3, pp. 391–394, 2015.

[11] L. Yang, X. Gao, and M. Alouini, “Performance analysis of relay-assisted all-optical FSO networks over strong atmospheric turbulence,” J. Light. Technol., vol. 32, no. 23, pp. 4011–4018, 2014.

[12] M. A. Khalighi, M. Uysal, C. Marseille, and E. Engineering, “Survey on free space optical communication: A communication theory perspective,” IEEE Commun. Surv. Tutorials, vol. PP, no. 99, 2014.

[13] J. Y. Wang, J. B. Wang, M. Chen, and X. Song, “Performance analysis for free-space optical communications using parallel all-optical relays over composite channels,” IET Commun., vol. 8, no. 9, pp. 1437–1446, Jun. 2014.

[14] M. Hulea, Z. Ghassemlooy, S. Rajbhandari, and X. Tang, “Compensating for optical beam scattering and wandering in FSO communications,” J. Light. Technol., vol. 37, no. 7, pp. 1323–1328, 2014.

[15] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, Optical wireless communications: System and channel modelling with MATLAB. United Kingdom: CRC Press Taylor and Francis Group, 2013.

[16] M. A. Kashani, M. Safari, and M. Uysal, “Optimal relay placement and diversity analysis of relay-assisted free-space optical communication systems,” Opt. Commun. Netw., vol. 5, no. 1, pp. 37–47, 2013.

[17] V. Sharma and G. Kaur, “High speed, long reach OFDM-FSO transmission link incorporating OSSB and OTSB schemes,” Optik, vol. 124, no. 23, pp. 6111–6114, 2013.

[18] E. Bayaki, D. S. Michalopoulos, and R. Schober, “EDFA-based all-optical relaying in free-space optical systems,” IEEE Trans. Commun., vol. 60, no. 12, pp. 3797–3807, Dec. 2012.

[19] J. Kaufmann, “Free space optical communications: an overview of applications and technologies,” in Proceedings of the Boston IEEE Communications Society Meeting, 2011.

[20] S. Kazemlou, S. Hranilovic, and S. Kumar, “All-optical multihop free-space optical communication systems,” J. Light. Technol., vol. 29, no. 18, pp. 2663–2669, Sep. 2011.

[21] T. A. Tsiftsis, H. G. Sandalidis, G. K. Karagiannidis, and S. Member, “Optical wireless links with spatial diversity over strong atmospheric turbulence channels,” IEEE Trans. Wirel. Commun., vol. 8, no. 2, pp. 951–957, 2009.

[22] L. B. Stotts, L. C. Andrews, P. C. Cherry, J. J. Foshee, P. J. Kolodzy, W. K. McIntire, M. Northcott, R. L. Phillips, H. A. Pike, B. Stadler, and D. W. Young, “Hybrid optical RF airborne communications.” Proc. IEEE, vol. 97, no. 6, pp. 1109–1127, 2009.

[23] M. Safari and M. Uysal, "Relay-assisted free-space optical communication," in IEEE Transactions on Wireless Communications, vol. 7, no. 12, pp. 5441-5449, December 2008,

[24] K. J. R. Liu, A. K. Sadek, W. Su, and A. Kwasinski, Cooperative communications and networking. New York: Cambridge University Press, 2008.