



## Mitigation of Scintillation Effect in Wave Division Multiplexed Free Space Optical Communication using Modified Multibeam Technique

Muhammad A., Tekanyi A.M.S, and Sani S.M  
*Electronics and Telecommunications Engineering Department,  
Ahmadu Bello University, Zaria, Nigeria.*

### ABSTRACT

*Radio Frequency (RF) technology is licensed, bandwidth limited, expensive and congested due to surge in data rate demand. Finding an alternative technology led to the evolution of the Free Space Optical (FSO) communication. The FSO communication has the capability to overcome the challenges of RF technology but not without limitations. The atmosphere is the main channel for FSO communication and it suffers from atmospheric effects including Scintillation. This study mitigated the effect of scintillation in wave a division multiplexed Multi Input Multi Output (MIMO) FSO system. The input data was encoded using Binary Phase Shift Keying (BPSK) and modulated with Mack Zehnder modulator. The Modulated signal was sent through four independent FSO channels in order to improve link reliability and received power. The Equal Gain Combination (EGC) technique was used to combine the data at the receiver. The study achieved 8.35km increase in achievable link distance with acceptable quality factor of 5.9 compared to [4], a 52% increase in received power at a link distance of 4.5km and 50% reduction in BER compared to [4].*

### ARTICLE INFO

#### Article History

Received: November, 2019

Received in revised form: January, 2019

Accepted: January, 2019

Published online: March, 2020

### KEYWORDS

BPSK, Free space optical communication, FSO, Mitigation of Scintillation, Multibeam Technique, Scintillation, and Turbulence induced fading.

### INTRODUCTION

There is a long-standing interest in finding alternative technology to the bandwidth limited congested RF technology. The FSO, which uses the atmosphere as the main channel for communication has demonstrated capability to mitigate the challenges encountered by the RF technology. In terms of speed, security and reliability, FSO is often the candidate of choice and considered as part of the next generation high-speed network [3]. FSO network is also considered the solution to the challenges of the last mile metro network as well as military systems due to its high data rate, mobility, security, and ease of deployment. In spite of the numerous

advantages of the FSO system, its performance is greatly hampered by many challenges, some of which include atmospheric disturbances, pointing error, physical obstructions, geometric losses, and background noise [3]. Atmospheric turbulences are the major impairments in FSO systems with scintillation being the most prevalent. Scintillation is caused as a result of variation in the refractive index that occurs randomly in the air as a result of inhomogeneities in the temperature and pressure of air at the interface of cold and hot air [3]. A number of researchers proposed advanced modulation techniques for mitigating scintillation in the FSO system and others proposed the multi beam



technique. While many of these techniques have addressed the problem of scintillation and maintained acceptable power efficiency, spectral efficiency has remained a challenge in the FSO system.

#### RELATED WORKS

In [8], the author explored the use to MIMO technique to mitigate the effect of scintillation and analysed the outage probability of a MIMO Gaussian FSO channel using the orthogonal PPM modulation with a non-ideal photo detector. The Signal-to-Noise Ratio (SNR) for log-normal, exponential and gamma-gamma distributed scintillation was derived. By assuming a Channel State Information (CSI) at the transmitter, the author demonstrated high gain in the SNR. The expression which related required number of apertures to a given code rate and the number of code word to eliminate outage was also provided. Despite the result achieved by the author CSI assumption could have led to many erroneous calculations of SNR which could have made the realization of MIMO FSO impossible.

The authors in [5] provided a practical demonstration of the comparison of different modulation schemes used in FSO. A chamber filled with hot and cold air was adopted to represent the real life FSO environment and mimic the effect of scintillation while the temperature profile was consistently measured in order to characterize the channel. The channel was characterized as a weak turbulence channel as a result of the scintillation index measured. The result showed that On-off Keying (OOK) offered the worse performance while PPM offered the best performance followed by a combination of PPM with BPSK. The authors limited the work to only weak turbulence due to practical limitation of the test bed, consequently, the extent of signal

degradation in moderate and strong turbulence might have not been accurately interpolated. Thus, a robust modulation technique capable of improving the BER performance in both weak and moderate turbulence is required.

The authors in [11] compared the performance of four modulation schemes namely: BPSK, Differential Phase Shift Keying (DPSK), and Quadrature Phase Shift Keying (QPSK) as well as the famous On-off keying (OOK) in mitigating the effect of scintillation using BER as the performance metric and the gamma-gamma distribution channel as the atmosphere. The BPSK and the QPSK were found to have the same BER performance in both weak and strong turbulence. The QPSK was found to have a very high spectral efficiency – almost doubling the three other techniques, while QPSK and BPSK were found to have the least power requirement. The transmission bandwidth of QPSK was found to be half that of BPSK for the same BER. The author preferred the BPSK to all other techniques for FSO systems as this technique is highly robust against noise but was only able to modulate at 1 bit/symbol which renders it unsuitable for high data rate application.

The authors in [7] proposed a hybrid technique to mitigate the effect of scintillation. A combination of PPM and subcarrier intensity modulated BPSK was proposed in the presence of receive diversity to mitigate scintillation and improve the BER performance. The scheme employed the Equal Gain Combining (EGC) and Maximal Ratio Combining (MRC) to achieve receive diversity combination. The BER with respect to different parameters such as SNR, link distance at various weather conditions was simulated. The results showed that the hybrid modulation scheme (PPM-BPSK-SIM) had significant improvement when compared to PPM or BPSK-SIM. The proposed hybrid technique had good performance in mitigating the effect of turbulence, however, the modulation technique was very complex and this



increased the complexity and cost of the system thereby making its implementation difficult.

In [2], the author investigated the effect of turbulence-induced scintillation on the FSO system based on measurement. An FSO link with data rate of 100Gbps was designed and simulated in the Optisystem environment. The impact of the turbulence-induced scintillation evaluation was based on the BER. A Digital Signal Processing (DSP) receiver was also designed to mitigate the effect of the turbulence induced scintillation. The results showed an improvement in mitigating the effect of scintillation. Although to a certain extent, the study has mitigated the effect of scintillation, it did not consider the amount of power that would be required to transmit the signal for the DSP embedded receiver to be able to detect the signal, cost-effectiveness had been traded for fidelity which is often not the best engineering solution.

The authors in [4] attempted the mitigation of scintillation in WDM FSO using the multi beam technique that employs multiple transmitters for transmission, where the input data is encoded using the Non-Return to Zero (NRZ) encoding technique with Selection Combining (SC) at the receiver. The system successfully mitigated the effect of scintillation up to a link distance of a 4.2km and established the superiority of the multibeam technique over the single beam system. Although the technique achieved tremendous success, the selection combining at the receiver, where the least attenuated signal is selected may not perform optimally at long distances when the signal loses more power. The advantage of diversity is not fully utilized since only one signal is used at a time, thus reducing the efficiency of the technique.

The authors in [9] developed a mathematical model to evaluate the error performance of FSO links under strong

turbulence in a gamma-gamma channel. The study shows that BPSK and Differential Phase Shift Keying (DPSK) outperformed other modulation techniques. The author reduced the effect of scintillation using a combination of transmit diversity and BPSK, however the transmit diversity has an inherent problem of increasing the combining time at the receiver, this can cause delay in signal reception and bits slip is possible in such scenario, thus a more robust technique must be researched.

In [10], the authors examined the effect of atmospheric turbulence combined with pointing error and phase noise on the performance of the FSO system for both Single Input Single Output (SISO) and Single Input Multiple Output (SIMO) systems. The expression for the Average Symbol Error Probability (ASEP) was derived for both systems and simulated for validation. The work demonstrated that the combined effect of these turbulences could be reduced through spatial diversity by increasing the number of receivers in the system combined with any phase shift keying modulation. Although the technique had achieved significant improvement, Optimal Combining (OC) - also known as maximal ratio combining- at the receiver used by the author is a very complex method of diversity combining and often difficult to implement. The OC had high performance at the expense of simplicity and cost which made it a less desirable solution and informed the need to develop a system with a balance between simplicity and performance.

The author in [6], analysed the performance of NRZ, RZ, and Carrier Suppressed Return to Zero (CSRZ) encoding technique in a MIMO FSO. The impact of various parameters such as range, transmit power, and attenuation factor were assessed in terms of the Q-factor and BER. Although NRZ achieved a higher received signal level, the study preferred RZ as the best encoding technique for mitigating atmospheric turbulence in MIMO FSO due

to superior signal quality as indicated by the BER and the eye diagram. The spectral and power efficiency of any FSO modulation scheme are key factors challenging the feasibility of the system and must be taken into consideration at all times, which the authors failed to do.

In [1], the authors analysed the effect of coding schemes used in mitigating scintillation effect in FSO. The two coding schemes considered were NRZ and RZ in both lognormal and gamma-gamma distribution channel using Q-factor and BER as performance metrics. The study preferred NRZ coding in a lognormal

channel with low refraction index for long range FSO transmission. The Lognormal channel is only suitable for describing weak turbulence and could not have been used to generalize the reality of turbulence in the FSO system, thus using the result of NRZ coded FSO system in a lognormal channel to describe the degradation in signal quality would not give an accurate estimation

### SYSTEM MODEL

Figure 1 shows the multibeam techniques used in the work of [4]. It consists of a Pseudo Random Bits Sequence

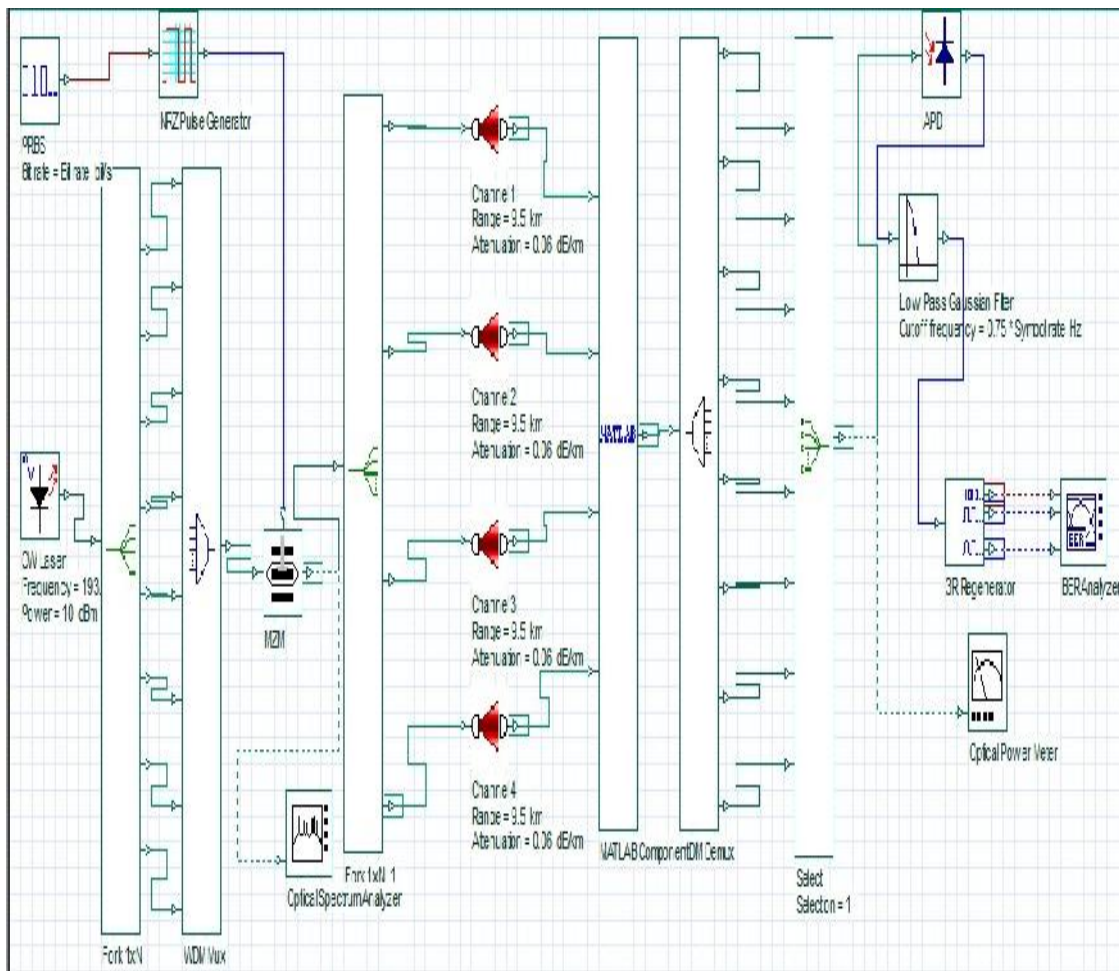
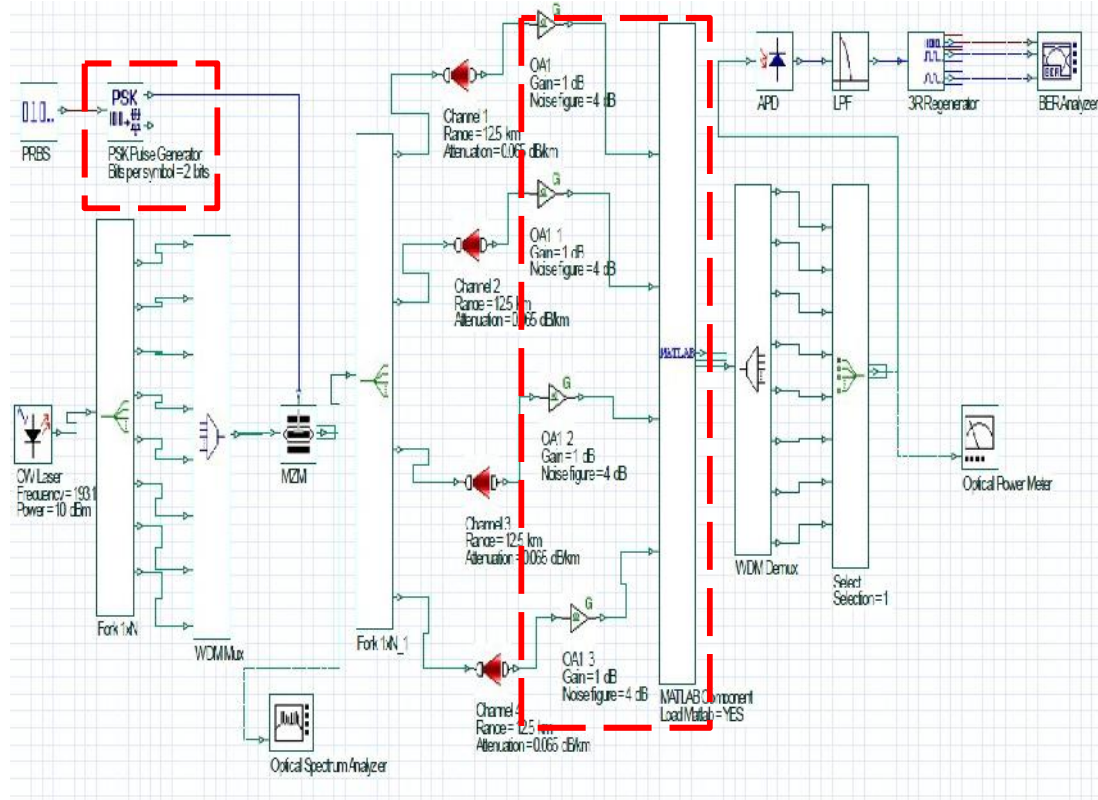


Figure 1: Multibeam Technique (Grover et al., 2017).



**Figure 2:** Modified Multibeam Technique.

RBS generator which generates random combinations of 1's and 0's which are converted into electrical pulses by the NRZ pulse generator. The light energy is generated by a Continuous Wave (CW) laser with a power of 10dBm and a frequency of 193.1THz. The fork duplicates the optical signal into 8 channels with different wavelength to mimic a Wave Division Multiplexed (WDM) system and the resulting signal is passed to the WDM multiplexer. The output of the NRZ pulse generator drives the Mach Zehnder modulator which modulates the optical signal. The fork further divides the modulated signal into four and transmits each signal through an independent FSO channel. The signal arrives at the MATLAB component which selects the signal with the

highest power. The Signal power is measured by the optical meter in the simulation setup of Figure 1.

The resultant output is demultiplexed by the WDM demux and one output branch and is selected and passed to the avalanche photodiode which converts the optical signal to electrical. The signal is filtered, regenerated, and passed to the BER analyser which provides the BER, Q-factor, and eye diagram.

Figure 2 shows the modified multibeam technique, which is similar to Figure 1. The NRZ pulse generator is replaced with PSK pulse generator, and the optical carrier's phase is modulated. Each signal output from the FSO channel is given an optical gain of 1dB before arriving at the MATLAB component, which



act as the equal gain combiner. The EGC combiner then combines the signals coherently using the MATLAB component which results in more signal power and quality.

The FSO channel used in the modified multibeam technique is based on the gamma-gamma-distribution model. A scintillation index of  $10^{-15} m^{-2}$  for Channel 4, for Channel 3,

$$10^{-14} m^{-2}$$

$$10^{-16} m^{-2}$$

for Channel 2 and for Channel 1 was used throughout the simulation of both multibeam and modified multibeam technique. An attenuation of 0.065dB/km was assumed for all channels and a link distance of zero (0) to fourteen (14) kilometres was considered. The transmitter and receiver aperture diameters are 5cm and 20cm respectively, while the beam divergence is kept at 2mrad. The weather is summed to be clear sky – free of rain, fog, snow, or other turbulences except scintillation only.

The systems in Figure 1 and 2 were designed and simulated in Opt system 16.0. The performance of the two techniques were compared in terms of achievable link distance, received optical signal power, Quality factor (Q-factor), and Bit Error Rate (BER).

### RESULTS OBTAINED

The link distance for each FSO channel in the simulation setup in Figure 1 and 2 was varied from 0km to 14km and the results from the simulation setup have been shown in Figure 3 and 4 for both Q-factor and received power respectively. The results have been divided into two; results at link distance of zero and distances other than zero. Simulated received optical power and Q-factor were zero at a distance of 0km which is illogical as power is expected to be maximum at its source. Thus, the value of received optical power was obtained through calculations while the values of Q-

factor, eye height and BER were simulated at link distance very close to zero ( $L \approx 0.01m$ ) which can give approximate value of the parameters at the source.

### RESULTS AT LINK DISTANCE OF ZERO

Simulated values of received optical power, Q factor, BER and eye height were zero at link distance of 0km. These values seem illogical since maximum power is expected at the source of power. Thus, these values were calculated from formulae or simulated at link distances close to zero. Received optical power is given by [19] as

$$(1)$$

Where,  $P_t$  is the transmitted power, while  $D_1$  and  $D_2$  transmitter and receiver aperture diameter are expressed as  $D_1$  and  $D_2$ , respectively.  $\theta_t$  is the transmitting divergence angle, L denotes the link length, and  $\alpha$  is the atmospheric attenuation factor in dB/km

When L is zero, the received optical power becomes dependent on  $D_1$  and  $D_2$ , thus equation (1) reduces to:

$$P_r = P_t \left( \frac{D_2^2}{D_1^2} \right) \quad (2)$$

Since the system transmitted power is 10dBm, the aperture diameters of transmitter and receiver are respectively 0.05m and 0.2m. The received power at a link distance of zero evaluates to **8dBm** for both systems. The values of Q factor, BER and eye height when L is zero are obtained through simulations when L is tending to zero ( $L \approx 0.01m$ ).

### RESULTS AT LINK DISTANCE GREATER THAN ZERO

The simulation results (Q-factor and received power) obtained from the

simulation setup in Figure 1 and 2 are graphically shown in Figure 3 and 4. The link distance of the channel was continuously varied from 0 to 14km and

the corresponding values of received optical power, Q-factor, and BER from the analyser were recorded.

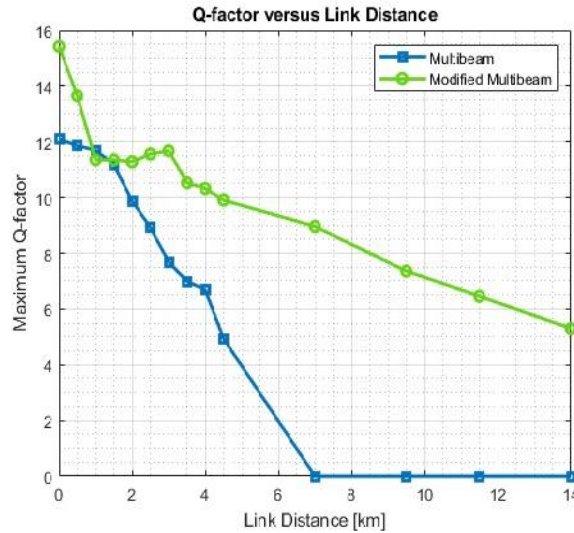


Figure 3: Maximum Q-factor obtained versus Link Distance.

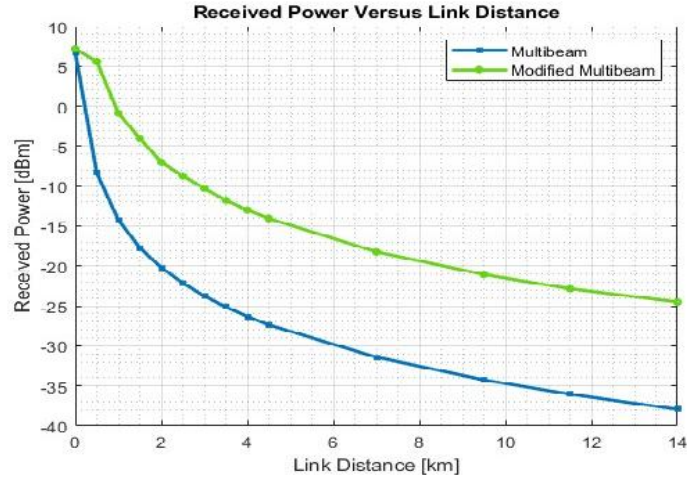
The graphical results in Figure 4 shows that the multibeam technique has a Q-factor of 5.9 up to 4.2km with a BER of  $1.05 \times 10^{-9}$  while the modified multibeam maintained a Q-factor of 5.9 up to 12.5km with a BER of  $4.95 \times 10^{-9}$ . The Q-factor is a measure of the quality of the signal received, and the modified multibeam has achieved a higher Q-factor which is due to the combining power of the EGC as compared to the SC used by [4]. The EGC gives each FSO branch a unity gain and then combines the signal coherently which result in high quality signal with higher received power.

At a distance of 7km, the Q-factor of the multibeam technique hit zero value while that of the multibeam technique remains at a high value of 9 with a BER of  $1.23 \times 10^{-19}$ . The modified multibeam maintained a Q-factor of 5.9 up

to 12.5km with a BER of  $4.95 \times 10^{-9}$ . This increase in the link distance with acceptable Q-factor shows that the quality of the received signal in the modified multibeam technique is superior to that of the multibeam. The undulation in the plot of the modified multibeam technique in Figure 3 is due to the random nature of atmospheric attenuation as attenuation is not only dependent on distance, but also on the state of the channel and the level of scintillation

The two techniques were also compared in terms of optical power received as show in Figure 4. At a link distance of 4.5km. The multibeam technique has a received power of -27.37dBm while the modified multibeam records a received power of -14.05dBm, which translate to 52% increment in the received power. The same increment was recorded throughout the simulation from 0.5km to 14km. The increase in the received power resulted in an

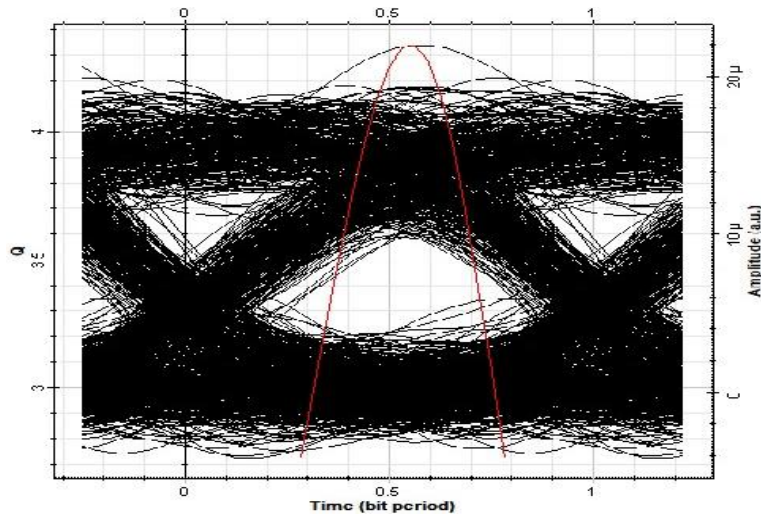
increased tolerance to scintillation and other atmospheric turbulence.



**Figure 4:** Optical received Power versus Link Distance.

The eye diagrams for the two techniques at a link distance of 4.2km were also obtained from the BER analyser of the simulation setup in Figure 1 and 2 and

shown in Figure 5 and 6 respectively. The techniques are compared in terms of the eye opening and eye height which pictorially show the quality of the received signal.



**Figure 5:** Eye diagram of Multibeam Technique at 4.2km



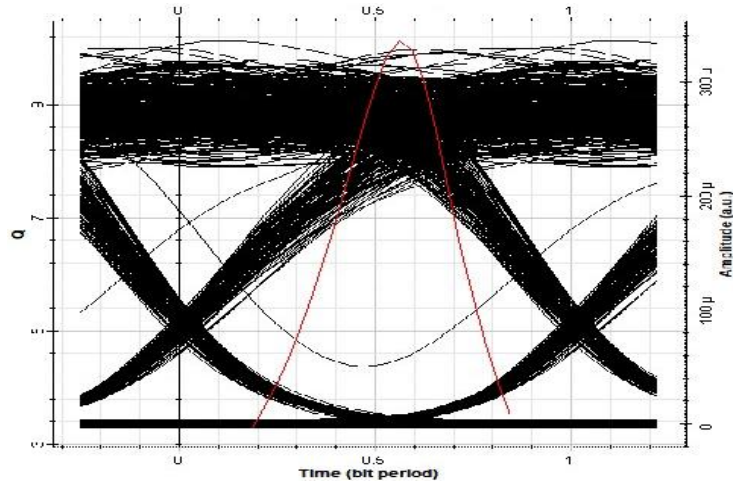


Figure 6: Eye diagram of Modified Multibeam at 4.2km.

From the eye diagram in Figure 5 and 6, it is observed that the opening of the eye for modified multibeam technique in Figure 6 is wider compared to the multibeam in Figure 5. The eye height which is a major determinant of the quality of a signal is  $339 \mu\text{m}$  and  $22.9 \mu\text{m}$  for the modified multibeam and the multibeam technique respectively which represent a  $316.1 \mu\text{m}$  increment. The BER for both systems were also considered and at every link distance, the BER of the modified multibeam was lower compared to the multibeam by 50%.

The spectral efficiency of the two systems which is given as the ratio of bitrate to bandwidth is also considered. For the system used by [4], the bit rate was  $10 \times 10^9$  bits/s while the bandwidth is the channel spacing in the WDM system which was obtained as  $100 \times 10^9$  Hz. This gave a spectral efficiency of 0.1 bits/s/Hz. The same bit rate of  $10 \times 10^9$  bit/s was used in the BPSK based modified multibeam technique, the bandwidth of BPSK system is equal to the bit rate which gives a bandwidth of 10GHz. Therefore, the spectral efficiency is 1bits/s/Hz. It is

observed that the number of bits transmitted in BPSK based multibeam is 10 times more than the number of bits conveyed by the NRZ based multibeam technique for the same SNR. The spectral efficiency of BPSK increases with the increase in the bandwidth of the system, this allows the BPSK to send higher number of bits compared to the RZ and NRZ and this will translate to higher SNR for the BPSK based multibeam technique.

#### VALIDATION

The result obtained were compared to the work of Grover et al., (2017) and ITU standards (ITU-R F.2106-1) for free space optical links. The transmit power was in compliance with the ITU recommended power of 10dBm due to safety considerations and the BER obtained was less than the ITU recommended threshold of  $10^{-6}$  as the highest BER obtained for the modified multibeam at a distance of 14km was  $5.61 \times 10^{-8}$ . The laser used in the system is a class 1 laser which is not harmful whether optical tools (lenses and binoculars) are used or not. The respective frequency and wavelength of the system which are 193.1THz and 1550 nm are less than the ITU



maximum threshold of 200THz and 1550nm, this frequency and wavelength windows have the least attenuation to optical signals. The general improvement in the performance of the modified multibeam technique demonstrate the effectiveness of the technique in mitigating the effect of scintillation while maintaining acceptable level of spectral efficiency in the WDM FSO system

### CONCLUSION

This study combined encoding and MIMO technique to mitigate the effect of scintillation. In this approach, the input bits were encoded using the Binary Phase Shift Keying (BPSK) and sent through four independent FSO channel and combined using the EGC. In the modified multibeam technique, the achievable link distance with acceptable Q- factor of 5.9 had been increased to 12.5km from the 4.2km achieved by the multibeam technique in the work of [4]. The received power achieved by the modified multibeam technique at every link distance was increased by 52% without any increase in the transmit power of the system. The BER of the modified multibeam technique was reduced at every link distance by 50%.

### REFERENCES

- [1] Ahmed, A., Gupta, S., Luthra, Y., Gupta, K., & Kaur, S. (2019). Analysing the Effect of Scintillation on Free Space Optics Using Different Scintillation Models. 2019 6th International Conference on Signal Processing and Integrated Networks (SPIN), 799–804.
- [2] Famoriji, O. J., Fadamiro, A., & Lin, F. (2018). Impact study of turbulence-induced scintillation on FSO link design. 2017 IEEE International Conference on Microwaves, Antennas, Communications and Electronic Systems, COMCAS 2017, 2017- November (February 2018), 1–4. <https://doi.org/10.1109/COMCAS.2017.8244730>
- [3] Farooq, E., Sahu, A., & Gupta, S. K. (2018). Survey on FSO Communication system— limitations and enhancement techniques. Lecture Notes in Electrical Engineering, 472, 255–264. [https://doi.org/10.1007/978-981-10-7395-3\\_29](https://doi.org/10.1007/978-981-10-7395-3_29)
- [4] Grover, M., Singh, P., & Kaur, P. (2017). Mitigation of scintillation effects in WDM FSO system using multibeam technique. Journal of Telecommunications and Information Technology, 2017(2), 69–74. <https://doi.org/10.26636/jtit.2017.11917>
- [5] Ijaz, M., Harris, G., Adebisi, B., Rajbhandari, S., & Popoola, W. (2018). Experimental study of the beam wander mitigation in free space optical communications using single input multiple output system. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, 2017-October (October), 1–5. <https://doi.org/10.1109/PIMRC.2017.8292601>
- [6] Israr, A., Israr, A., Khan, F., & Khan, F. (2019). Optimal Modulation Technique for MIMO FSO Link. Wireless Personal Communications, (0123456789). <https://doi.org/10.1007/s11277-019-06586-6>
- [7] Kumar Giri, R., & Patnaik, B. (2017). Bit Error Rate Performance Analysis of Hybrid Subcarrier Intensity Modulation-Based FSO with Spatial Diversity in Various Weather Conditions. Journal of Optical Communications, 0(0).



- <https://doi.org/10.1515/joc-2017-0073>
- [8] Letzepis, N., Guillén, A., & Member, S. (2009). Outage Probability of the Gaussian MIMO Free- Space Optical Channel with PPM. 57(12), 3682–3690.
- [9] Miglani, R., & Malhotra, J. S. (2018). Statistical Analysis of FSO Links Employing Multiple Transmitter / Receiver Strategy over Double- Generalized and Gamma – Gamma Fading Channel Using Different Modulation Techniques.
- [10] Varotsos, G. K., Nistazakis, H. E., Gappmair, W., Sandalidis, H. G., & George, S. (2019). SIMO subcarrier PSK FSO links with phase noise and non- zero boresight pointing errors over turbulence channels. 831–836. <https://doi.org/10.1049/iet-com.2018.5608>
- [11] Zhang, C., Zhang, H., Tang, X., Lin, B., Zhou, Z., & Lin, C. (2019). Performance Analysis of FSO System with Different Modulation Schemes over Gamma - Gamma Turbulence Channel.
- [12] Smithson G. (2019). Introduction to Digital Modulation for Plextex Ltd, London Road, Great Chesterford. Essex
- [13] Allen J. Bard, Gyorgy Inzelt, Fritz Scholz (2012). Electrochemical Dictionary. Springer Science & Business
- [14] Mr Umesh G B, Syahriar, Prof. M. N Shanmukha Swamy (2017). Survey on Different Types of Channel Estimation Techniques in MIMO-OFDM Communication Systems. International Journal of Engineering Technology, Management and Applied Sciences, 5(1), ISSN 2349-4476
- [15] Hiroyuki Yomo; Elisabeth De Carvalho (2007). A CSI Estimation Method for Wireless Relay Network. IEEE Communications Letters (Volume: 11, Issue: 6, June 2007), doi: 10.1109/lcomm.2007.070160
- [16] Taissir Y. Elganimi (2013). Studying the BER Performance, Power- and Bandwidth- Efficiency for FSO Communication Systems under Various Modulation Schemes. IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT),
- [17] Prabu, K. (2019). Analysis of FSO Systems with SISO and MIMO Techniques. Wireless Personal Communication (2019) 105:1133. <https://doi.org/10.1007/s11277-019-06139-x>
- [18] Paula-Maria Castro-Castro. (2009). Design of Limited Feedback for Robust MMSE Preceding in Multiuser MISO Systems. <https://www.researchgate.net/publication/262688705>
- [19] N. H. M. Noor, A. W. Naji and W. Al-Khateeb (2011) Theoretical analysis of multiple transmitters/receivers on the performance of Free Space Optics (FSO) link, Proceeding of the 2011 IEEE International Conference on Space Science and Communication (IconSpace), Penang, 2011, pp. 291-295. doi: 10.1109/IConSpace.2011.6015903