INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 17 No. 2 (2025) 279-289
https://publisher.uthm.edu.my/ojs/index.php/ijie

Comparison of Advanced Modulation Techniques of Free Space Optical Link for Ground-to-Train Communication

Intan Najihah Hyder Ali Tajuddin[1], Maisara Othman[1]*, Mariyam Jamilah Homam[1], Ansar Jamil[1], Lukman Hanif M. Audah[1], Mohammad Faiz Liew Abdullah[1], Mohd Helmy Abd Wahab[1], Shaharil Mohd Shah[1], Zuhairiah Zainal Abidin[1]

[1] *Advanced Telecommunication Research Center, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, MALAYSIA*

*Corresponding Author: maisara@uthm.edu.my
DOI: https://doi.org/10.30880/ijie.2025.17.02.023

Article Info

Received: 23 October 2024
Accepted: 14 July 2025
Available online: 28 July 2025

Keywords

Free space optical (FSO), G2T communication, non-return-zero (NRZ), OFDM 4-QAM, OFDM 4-QPSK

Abstract

Nowadays, mundane tasks are becoming more 'on-the-go', leading to the increasing popularity of public transport like high-speed trains. Internet access for these trains has increased, requiring the deployment of free space optical (FSO) communications in ground-to-train (G2T) communication. However, there is a lack of research on FSO links for railway communications. Single tracks mathematical models have been applied to address this need. Multiple attenuation intensities were tested for various weather conditions (clear, drizzle, strong rain, rainstorm and light fog), and three modulation techniques which are NRZ, OFDM 4-QAM, and OFDM 4-QPSK at 10 Gbps were implemented to improve link performance. Geometric parameters were optimized, and models were assessed for transmission distance and received optical power. The performance of the modulation techniques has been evaluated at BER of $1x10^{-9}$ for NRZ and BER of $2.8x10^{-3}$ for OFDM 4-QAM and OFDM 4-QPSK using the Optisystem®. Simulation results show that with a slightly lower BER, in strong rain condition for 4-QPSK have a higher ROP of -2.7 dBm compared to -3.7 dBm for 4-QAM. However, a few improvements can be made in future research, such as using multi transmitter concepts such as Multiple Input Single Output (MISO) to improve G2T-FSO performance and extend transmission distance coverage.

1. Introduction

People nowadays are familiar with the phrase 'on-the-go' in order to supplement the hectic schedules of one's own daily life. Transportation choice is crucial for individuals to avoid traffic and rush to their destinations, with high-speed railways (HSR) being one of the primary solutions. People using HSR prioritize completing work quickly but may face challenges if they lack good internet access [1]. The exponential growth of handheld devices and high-speed internet connections in transportation, such as trains, ships, and buses, make internet access essential for efficient work.

In order to offer flawless services for passengers on moving trains, high-speed data transfer between train and base stations is required. Train operators currently provide a limited RF-based wireless network with low data speed, despite the growing demand for high-speed wireless networks [2]. Radio-over-fiber (RoF) systems, which combine RF wireless and optical systems, offer broadband wireless access in high-speed trains [3].

However, constant band switching and intricate optical routing, which reduce base station coverage, pose key challenges for RoF technology. Although RF-based communication is promising for fixed wireless local area networks (WLAN), its efficacy at high speeds is restricted [4]. Free space optic (FSO) technology has an infinite bandwidth at optical wavelengths, making it an excellent choice for high-speed communication [5]. FSO is a viable alternative for ground-to-train (G2T) communications because optical transmitters such as lasers and LEDs can handle large data rates [6].

According to the simulation results from a study done by using NRZ and RZ modulation techniques found that NRZ transmitters achieved better link margins at long coverage lengths and lower BER performance compared to RZ transmitters. They are suitable for extended coverage ranges with fewer base stations. The NRZ modulation technique can cause signal waveform droop due to low frequencies and lack of error correction. Additionally, long strings of ones and zeros can cause loss of synchronization between transmitter and receiver clocks, necessitating the use of a separate clock line.

Thus, a study research using G2T-FSO with various modulation techniques, including non-return-zero (NRZ), Orthogonal Frequency Division Multiplexing (OFDM) for 4-Quadrature Amplitude Modulation (4-QAM) and 4-Quadrature Phase-Shift Keying (4-QPSK), have been conducted using OptiSystem software. The results of the system performances have been analyzed using the bit error rate regarding the transmission distance and the received optical power (ROP) against the bit error rate (BER).

2. Methodology

This section describes the project approach and steps, ensuring that they follow the correct flow to accomplish the goal. It explains the research method and the stages involved in the case study in detail.

2.1 Framework of Study

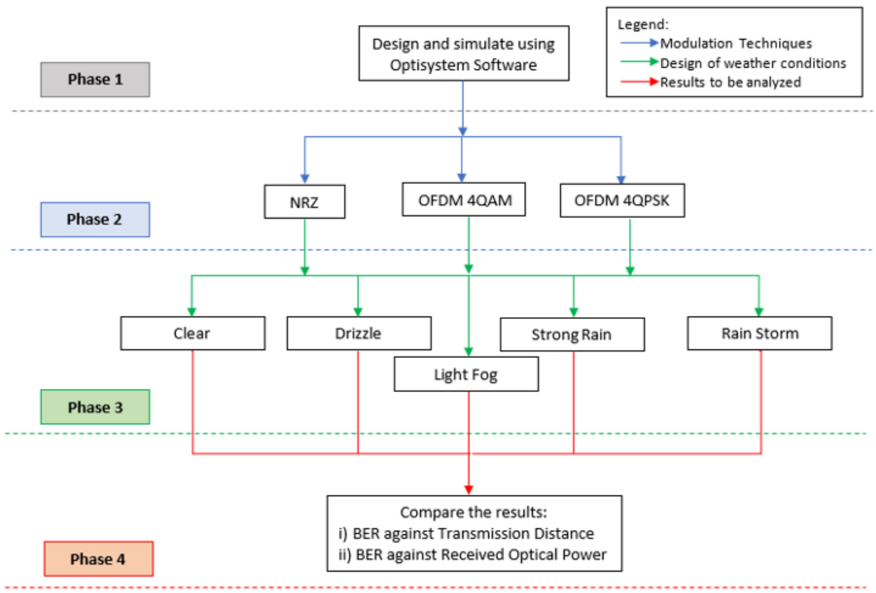


Fig. 1 *Block diagram of the methodology*

The study was carried out using the OptiSystem Software, and three distinct modulation schemes, as illustrated in Fig. 1, were used: NRZ, OFDM 4-QAM, and OFDM 4-QPSK. The modulation approaches were then adjusted using five various designs of weather conditions: clear, drizzle, strong rain, rainstorm, and light fog. The obtained findings were then compared to two comparisons: bit error rate (BER) versus transmission distance and bit error rate (BER) versus received optical power (ROP).

2.2 Phase 1: G2T-FSO Modelling & Simulation

2.2.1 FSO Communication Link Model OptiSystem Simulation

The FSO communication link as depicted in Fig. 2 in OptiSystem is made up of three parts: the FSO transmitter, the FSO channel, and the FSO receiver. The transmitter block employs a laser diode as an optical source, an electrical signal data source, and a Mach Zehnder modulator as an external modulator to externally modulate a

CW laser to convert electrical signal data into optical pulses [7]. The Non-Return-to-Zero On-Off Keying (NRZ-OOK) is used for its simplicity and resistance to attenuation [8].

An electrical binary data signal and an optical laser beam are transformed by the transmitter block into a pulsed modulated signal that transmits over the FSO channel. Additionally, laser beam propagation is subject to a number of atmospheric circumstances on the channel side, including geometrical, system, and atmospheric losses. In order to assess the channel's performance, atmospheric losses in [dB/km] were fed into it. Geometrical loss, fog and rain meteorological conditions were the classifications given to them.

The optical signal is transformed into an electric signal at the receiver side by an avalanche photodetector, which is followed by demodulation [9]. Before receiving bit regeneration, the photodetector signal is then sent into a low pass. The three basic sub-stages of signal regeneration are amplification, retiming, and reshaping. In order to visualise, assess, and analyse the signal at the receiver side, the regenerated signal is then delivered to BER analyser and power metre. Whereas for OFDM 4-QAM and OFDM 4-QPSK, the process of analysing the signal at the receiver have been conducted by BER Test Set.

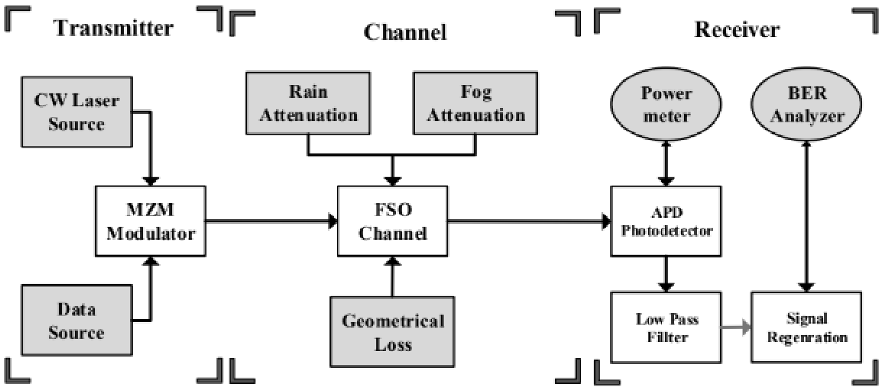


Fig. 2 *Block diagram of the methodology*

2.2.2 G2T-FSO Models

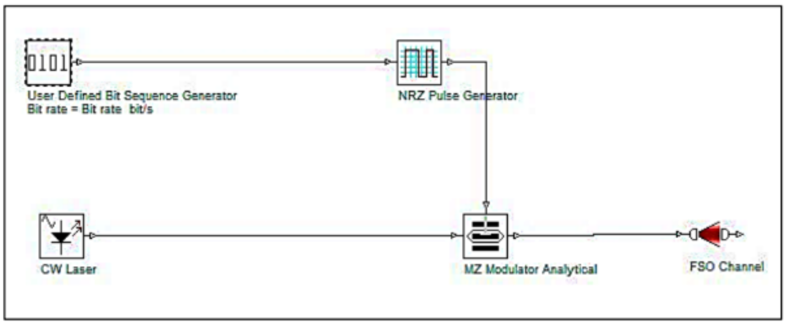


Fig. 3 *G2T-FSO OOK NRZ transmitter block diagram*

For the G2T-FSO model, it been utilizing the NRZ-OOK which is an On-Off-Keying FSO transmitter with a non-return-zero Mach-Zehnder modulator, CW laser supply, bit sequence generator, and NRZ pulse generator like shown in Fig. 3. The bit sequence generates a random binary series of bits coded by an NRZ pulse generator, producing rectangular electrical pulses. These pulses are sent to an MZ modulator, linked to a continuous wave laser source, which in this study, it produces a 1550 nm and 20 mW beam. By switching between On and Off for 1 and 0 bits at a time, the CW intensity was adjusted by the electrical pulse.

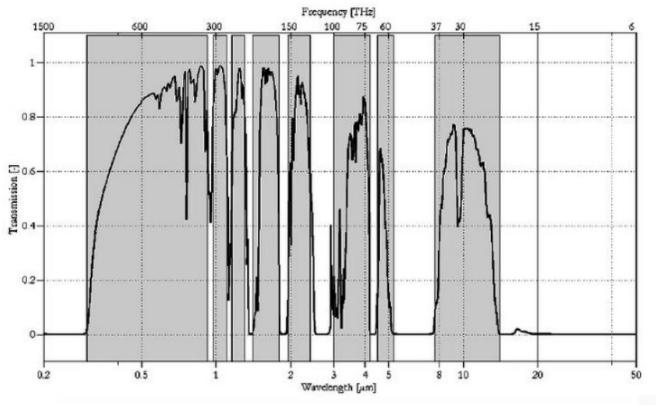


Fig. 4 *G2T-FSO wavelength and transmission*

FSO communication links require specific wavelengths to establish a connection, as transmitted power may be absorbed through the atmosphere. Fig. 4 shows G2T-FSO wavelength and transmission, with grey areas incompatible with free space optics. The thesis design utilizes 1550nm for transmission windows.

2.2.3 Channel Modeling

The earth's atmosphere is used as a medium for optical communications in FSO links, although photon absorption and scattering restrict beam transmission. Photons are absorbed or disappear when they contact with air molecules and atoms [10]. Additionally, when a component of the beam interacts with atoms or molecules, beam redistribution and scattering occur [11]. When creating an FSO link, several parameters are taken into account.

The research used meteorological data and model structure to measure rain attenuation. To accommodate for attenuations caused by rain and fog, the FSO channel was classed using ITU-R code [12]. From 2013 to 2015, the Malaysian Meteorological Department supplied meteorological records from the Batu Pahat Station. Hourly visibility and rain were measured in meters per hour and millimeters per hour.

2.2.3.1 Rain Attenuation

Collisions between raindrops and photons change the refraction index, altering propagation. Light beams bend and reflect away from the receiver's path as a result. Rain attenuation is calculated using Carbonneau's model and rain rate R. The writer calculated maximal rain attenuation rates using meteorological data from 2013 and 2015. To categories data, ITU-R codes were used, resulting in Table 1, which shows suitable values for rain attenuation scenarios.

Table 1 *Rain attenuation simulation parameters*

Rain Intensity and Attenuation			
NO.	**Parameter**	**Value**	**Unit**
1	Max Rain Intensity	65.2	mm/hr
2	Min Rain Attenuation	10.3384	dB/km
3	Average Rain Attenuation	13.2	dB/km
4	Max Rain Attenuation	19.344	dB/km
Simulation Cases Parameters			
NO.	**Precipitation Type**	**Precipitation Rate (mm/hr)**	**Attenuation (dB/km)**
1	Max Rain Intensity	0.25	2.5
2	Min Rain Attenuation	25	6.9
3	Average Rain Attenuation	55	19.3

2.2.3.2 Fog Attenuation

To ensure optimal FSO link functionality, the LOS between transceivers must be unobstructed, requiring a clear path. Fog molecules, which are photon-absorbing components in the atmosphere, are equivalent to transmission

Int. Journal of Integrated Engineering Vol. 17 No. 2 (2025) p. 279-289

wavelength windows due to their fine size [13]. Fog attenuation is calculated using Mie scattering theory and air transparency data, known as visibility [14]. Global visibility codes are used to classify fog and rain attenuation. The values and parameters used for the G2T-FSO OptiSystem simulation are shown in Table 2.

Table 2 *Fog attenuation simulation parameters*

Fog Visibilities			
NO.	**Parameter**	**Value**	**Unit**
1	Min Visibility	65.2	m
2	Average Visibility	10.3384	m
3	Max Visibility	70,000	m
Simulation Cases Parameters			
NO.	**Weather Condition**	**Precipitation Rate (mm/hr)**	**Attenuation (dB/km)**
1	Clear Air	2000	-0.6
2	Light Fog	770	-18.3

2.2.3.3 G2T-FSO Links OptiSystem Simulation Parameters

For each point track along the railway, the system was modelled in OptiSystem utilizing characteristics such as beam divergence and connection range. Iterations were done to determine the train's position on the track using commercially available products and the given transmission window and wavelength. The laser used has a wavelength of 1550 nm. Table 3 summarizes all of the ideal settings for G2T-FSO connections.

Table 3 *Parameters for OptiSystem G2T-FSO link simulation*

Fog Visibilities			
NO.	**Parameter**	**Value**	**Unit**
1	Wavelength	1550	nm
2	Bitrate	10	Gbps
3	Symbol Rate	5	Gbps
4	Transmitter Optical Power	$P_{T_{NRZ}}$=13 $P_{T_{4QAM}}$= -4 $P_{T_{4QPSK}}$= -4	dBm dBm dBm
5	Transmitter aperture diameter	5	cm
6	Receiver aperture diameter	20	cm
7	ADP Responsivity	0.62	A/W
8	Receiver Gain	10	dB
9	Receiver Sensitivity	-46	dBm
10	Dark Current	10	nA
11	Receiver Loss	-1.5	dB
12	Transmitter Loss	-1.5	dB

2.3 Phase 2: Modulation Techniques

In phase 2, the modulation techniques used in the models were manipulated. In all, three modulation schemes were used: NRZ, OFDM 4-QAM, and OFDM 4-QPSK. This phase was carried out so that the G2T-FSO models could be compared to evaluate which modulation approach performed better.

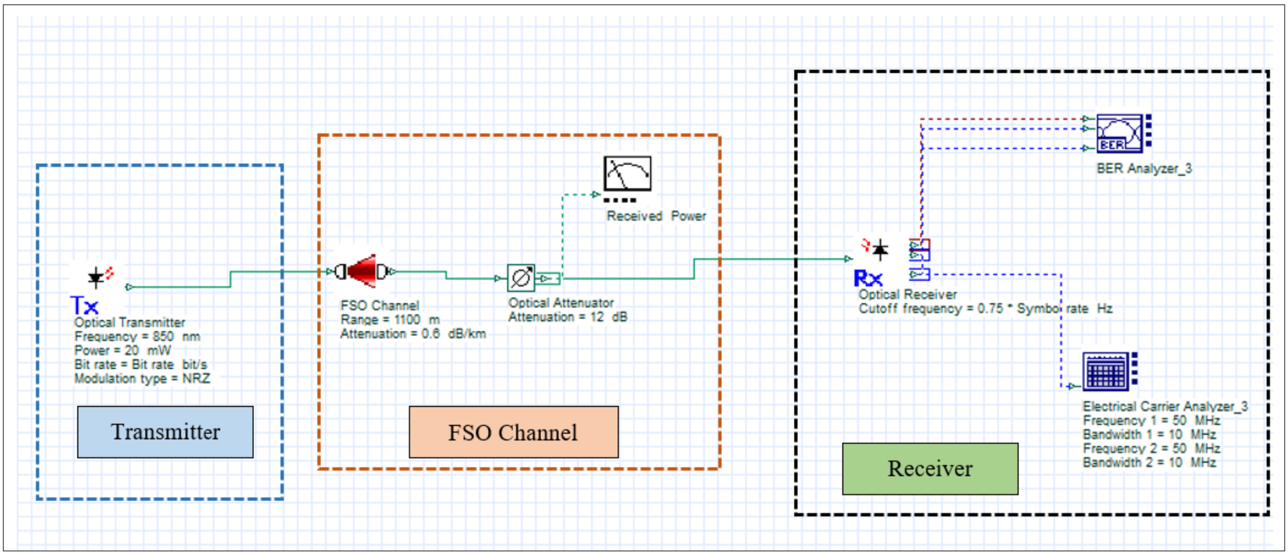


Fig. 5 *G2T-FSO OOK NRZ transmission block diagram*

Fig. 5 displays the NRZ G2T-FSO transmitter OptiSystem model with -0.6 dB/km attenuation. During BER versus range simulation, the optical attenuator was ignored. The range was set to 1100 m for BER against ROP simulation, and the attenuator was iterated from 0 dB to 12 dB.

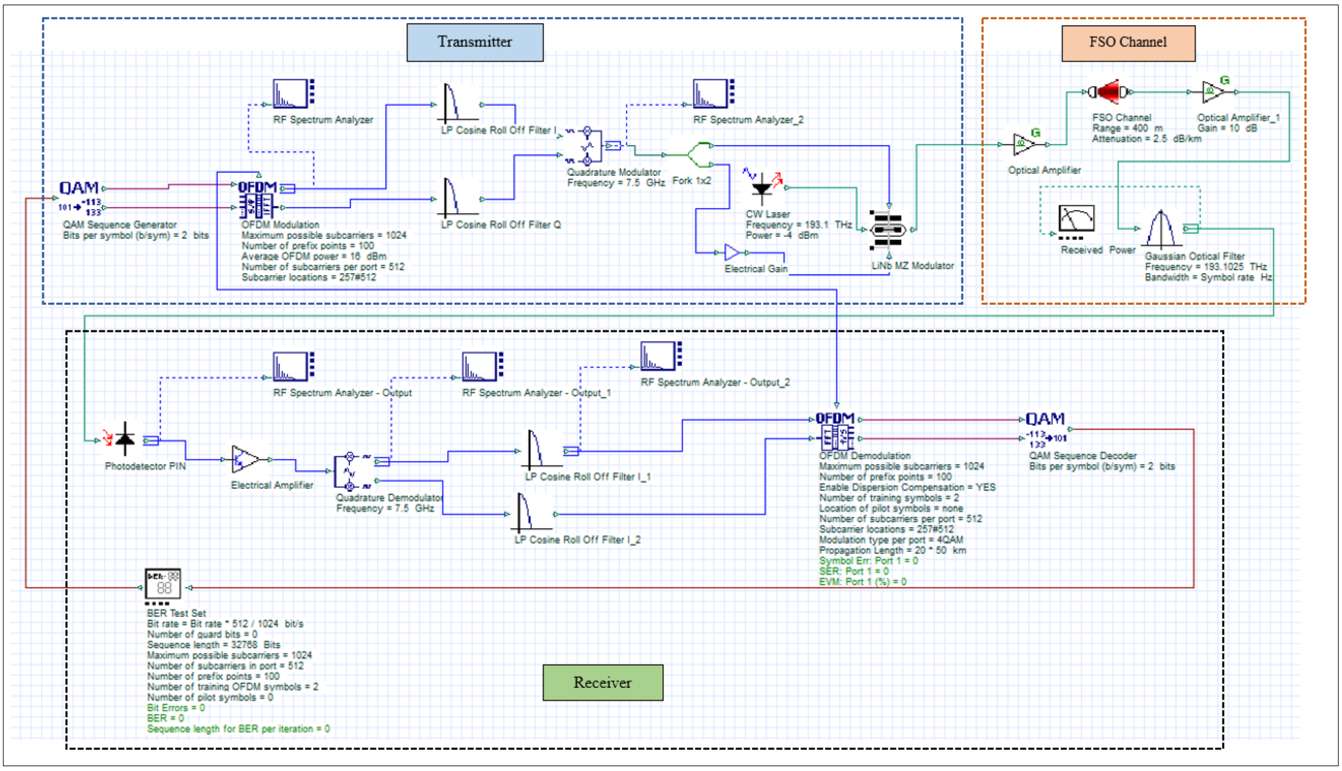


Fig. 6 *OFDM 4QAM G2T-FSO transmitter OptiSystem model*

The OFDM 4-QAM G2T-FSO transmitter OptiSystem model utilizes a complex connectivity compared to the NRZ G2T-FSO model as shown in Fig. 6. It utilizes QAM Sequence Generator and OFDM modulation for QAM modulation, an optical amplifier and Gaussian Optical Filter in the FSO channel, and a BER Test Set is used to calculate the BER reading because it complies with the more advanced and complicated connectivity of the modulation. For instances, QAM and OFDM are advanced modulation methods that can incorporate sophisticated signal processing and encoding strategies. By using a BER test set, it makes testing easier by measuring raw bit error rates without decoding and analyzing these schemes with an emphasis on raw bit error rates.

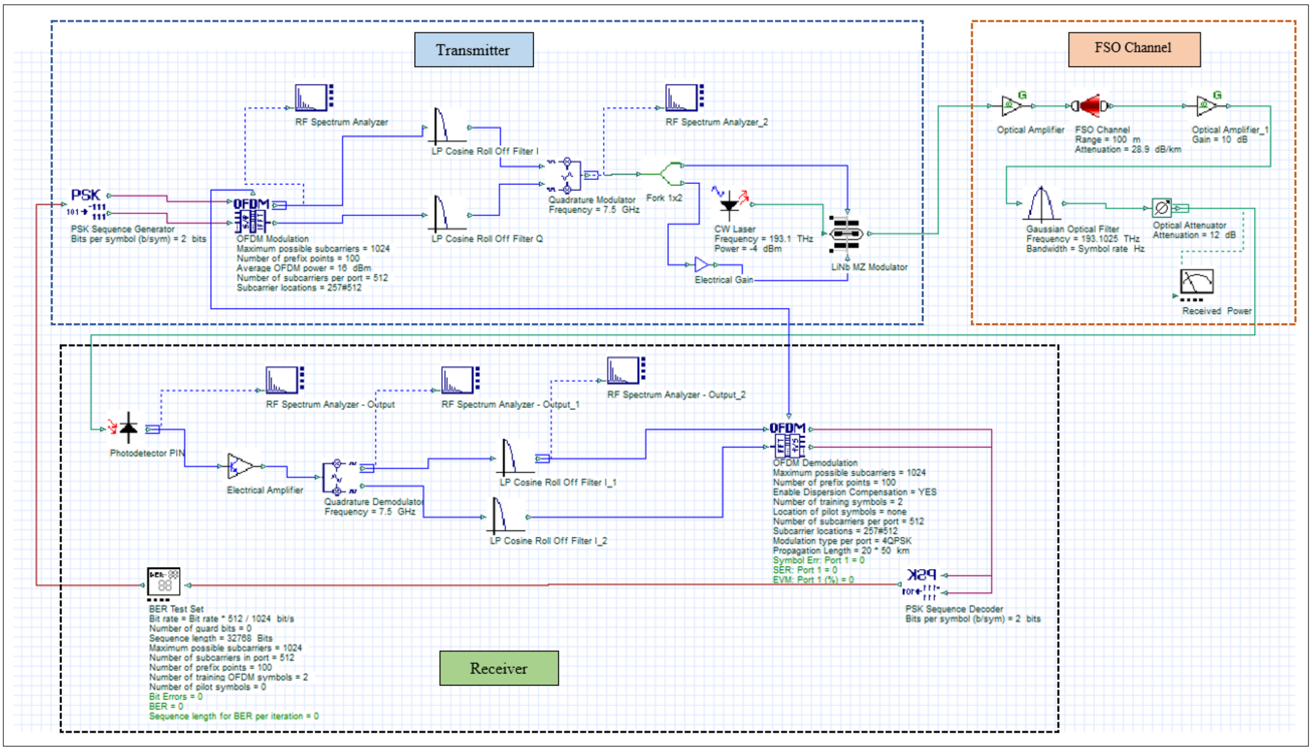


Fig. 7 *OFDM 4QPSK G2T-FSO transmitter OptiSystem model*

Whereas Fig. 7 shows the OFDM 4-QPSK G2T-FSO transmitter OptiSystem model shares connectivity with the OFDM 4-QPSK G2T-FSO transmitter model but differs by using PSK Sequence Generator and PSK Sequence Decoder. Both models use the same parameters for performance assessment.

2.4 Phase 3: Multiple Weather Conditions

In the next phase, modifications were made to improve rain and fog attenuation. Clear, drizzle, heavy rain, and storms affected rain attenuation, while fog attenuation was limited to light conditions. Measurements were taken at Batu Pahat station, and G2T-FSO connection performance was simulated using Tables 1 and 2, verifying accordance with the OptiSystem G2T-FSO connections parameter settings stated in Table 3.

2.5 Phase 4: Results Analysis

In phase four, the system's performance was evaluated in terms of transmission distance and ROP against BER. Data was tabulated to ease the graph plotting process. Findings were compared to bit error rate (BER) against transmission distance and BER versus received optical power (ROP).

3. Results and Discussion

This thesis used three modulation techniques: NRZ, OFDM 4-QAM, and OFDM 4-QPSK, and simulations for rain and fog attenuation. It simulated five weather conditions: clear, drizzle, strong rain, rainstorm, and light fog. Results were compared to transmission distance and received optical power (ROP) were discussed in this section.

3.1 BER Against Transmission Distance

Fig. 8 depicts the BER performance values for the NRZ modulation model, separating data points as feasible or infeasible. As the ideal range for BER in FSO transmission is from $1x10^{-9}$ to $1x10^{-12}$, the feasible zone begins at $1x10^{-9}$. The possible region with the maximum practicable transmission distance is traversed by clear and drizzle. Clear and drizzle have optimal practical distances of 4500 m and 2750 m, respectively. The NRZ G2T-FSO model achieves the shortest transmission distances at 1750m in strong rain (BER of $7.16x10^{-9}$), and distance 1000 m for both rainstorms (BER of $1.08x10^{-5}$), and light fog (BER of $2.09x10^{-6}$). Clear weather performs better than other weather situations.

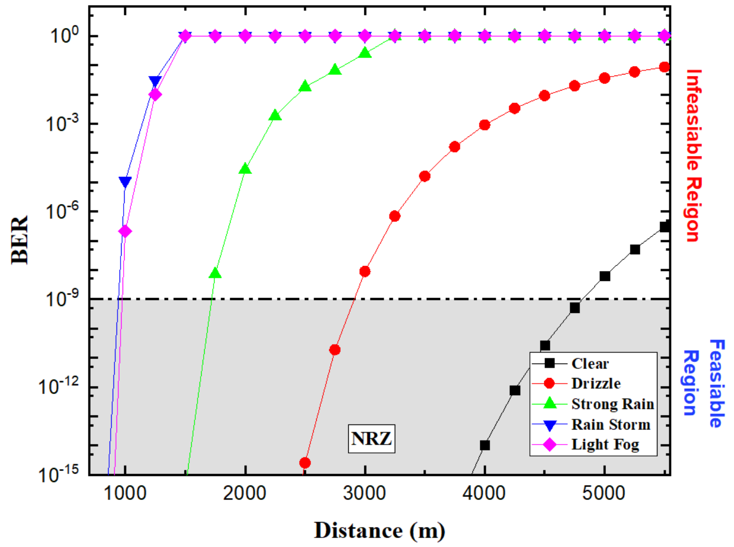
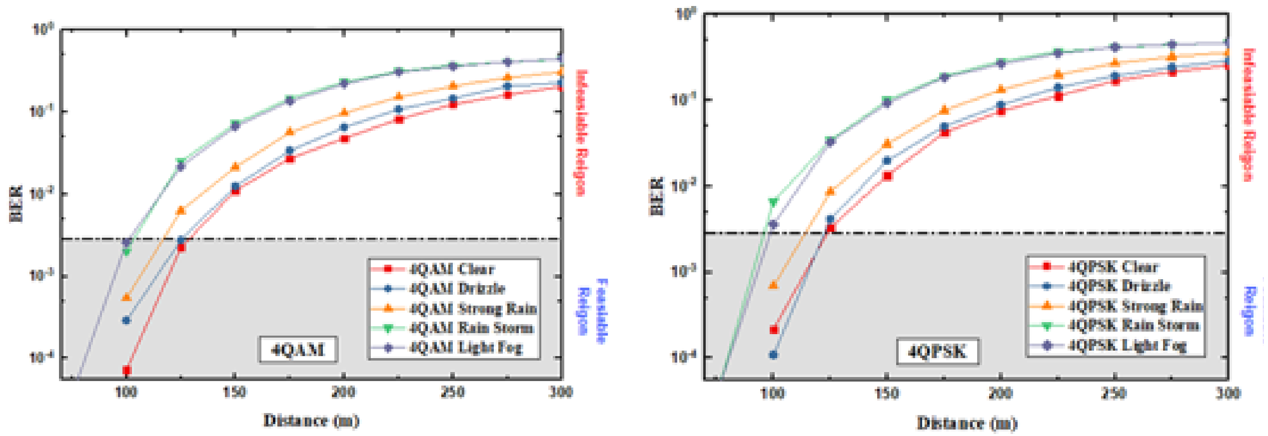
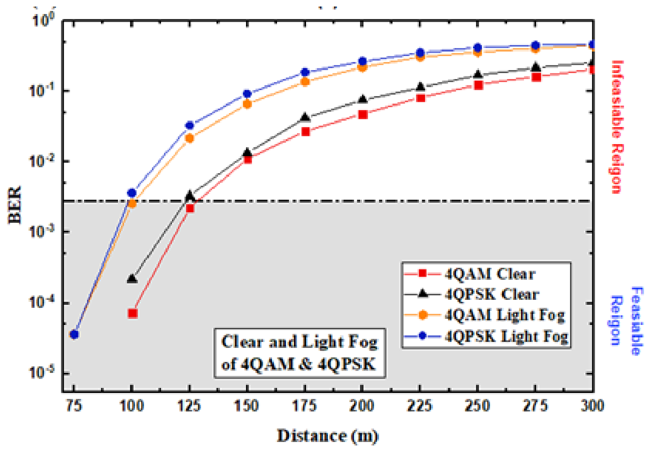


Fig. 8 *BER against transmission distance of NRZ modulation model*

Fig. 9 displays the BER performance values for OFDM 4-QAM and 4-QPSK, with feasible and infeasible regions starting at 2.8x10^{-3}. Forwardly, the transmission quality is assessed using receiver sensitivity at a BER of 2.8 x10^{-3}. Forward error correction (FEC) can be used to achieve error-free transmission with 7% FEC overhead has become the reason why the transmission quality is assessed using receiver sensitivity at a BER of 2.8x10^{-3} [15]. However, most BER measurements are above 2.8 x10^{-3}, indicating that most transmissions do not achieve the optimum BER range for FSO communication. Under clear weather of 125 m, it has been observed the OFDM 4-QPSK have slightly better BER of 3.29x10^{-3} compared to the OFDM 4-QAM with BER of 2.24x10^{-3} at the same transmission distance. The best feasible distances for OFDM 4-QPSK and 4-QAM at light fog weather condition with BER of 3.62x10^{-3} and 2.57x10^{-3} respectively at distance of 100 m. Figure 9 (c) explains 4-QPSK's superior performance compared to 4-QAM by having a lower BER value at the same distance.



(a) **(b)**



(c)

Fig. 9 *BER against transmission distance of (a) 4-QAM; (b) 4-QPSK; (c) Clear and Light fog of 4-QAM & 4-QPSK*

3.2 BER Against Received Optical Power

Shown in Fig. 10, the simulation used a constant range value of 1100 m and an attenuator value of 0 dB to 14 dB to investigate the performance of the G2T-FSO link transmitter model in terms of BER versus ROP for NRZ G2T-FSO model. At 1×10^{-9} a dotted line divided the graph into two pieces dubbed the feasible and infeasible areas. For clear, drizzle, and strong rain, the achievable optimal ROP value that were closest to the feasible line obtained were -28.3 dBm, -28.4 dBm, and -29.2 dBm, respectively. Meanwhile, the light fog and rainstorm do not fall inside the possible region because of it has a higher BER value.

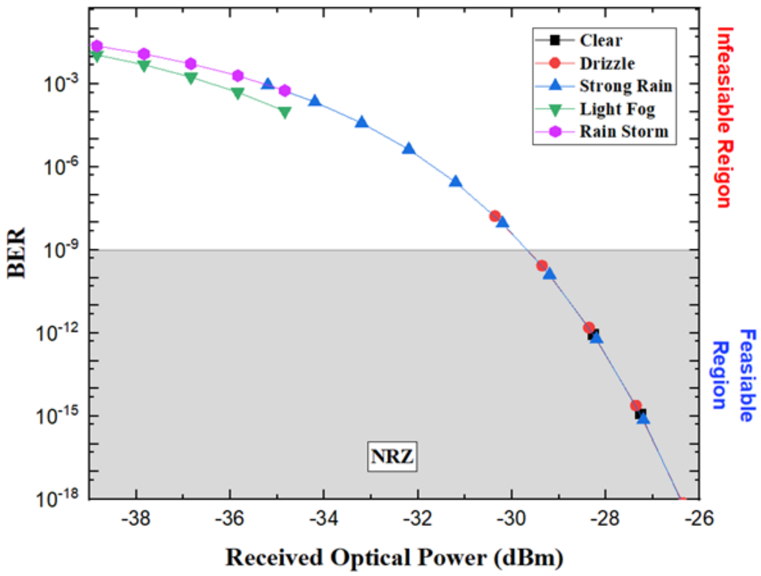


Fig. 10 *Received optical power of NRZ*

The performance of OFDM 4-QAM and OFDM 4-QPSK was assessed using five weather scenarios, with a constant range of 100 m and varying attenuator values. The OFDM case had a reference line of feasible regions at 2.8×10^{-3}. Fig. 11 shows that 4-QPSK received higher optical power than 4-QAM. Performance optimization decreased with weather conditions, with clear, drizzle, strong rain, light fog, and rainstorm conditions being the worst for 4QPSK modulation followed by the same arrangement for 4-QAM. Furthermore, by referring to Fig. 11 (c), with a slightly lower BER, in strong rain condition for 4-QPSK have a higher ROP of -2.7 dBm compared to -3.7 dBm for 4-QAM, indicating that 4-QPSK outperforms 4-QAM. At same distance, 4-QPSK performs better transmission than 4-QAM.

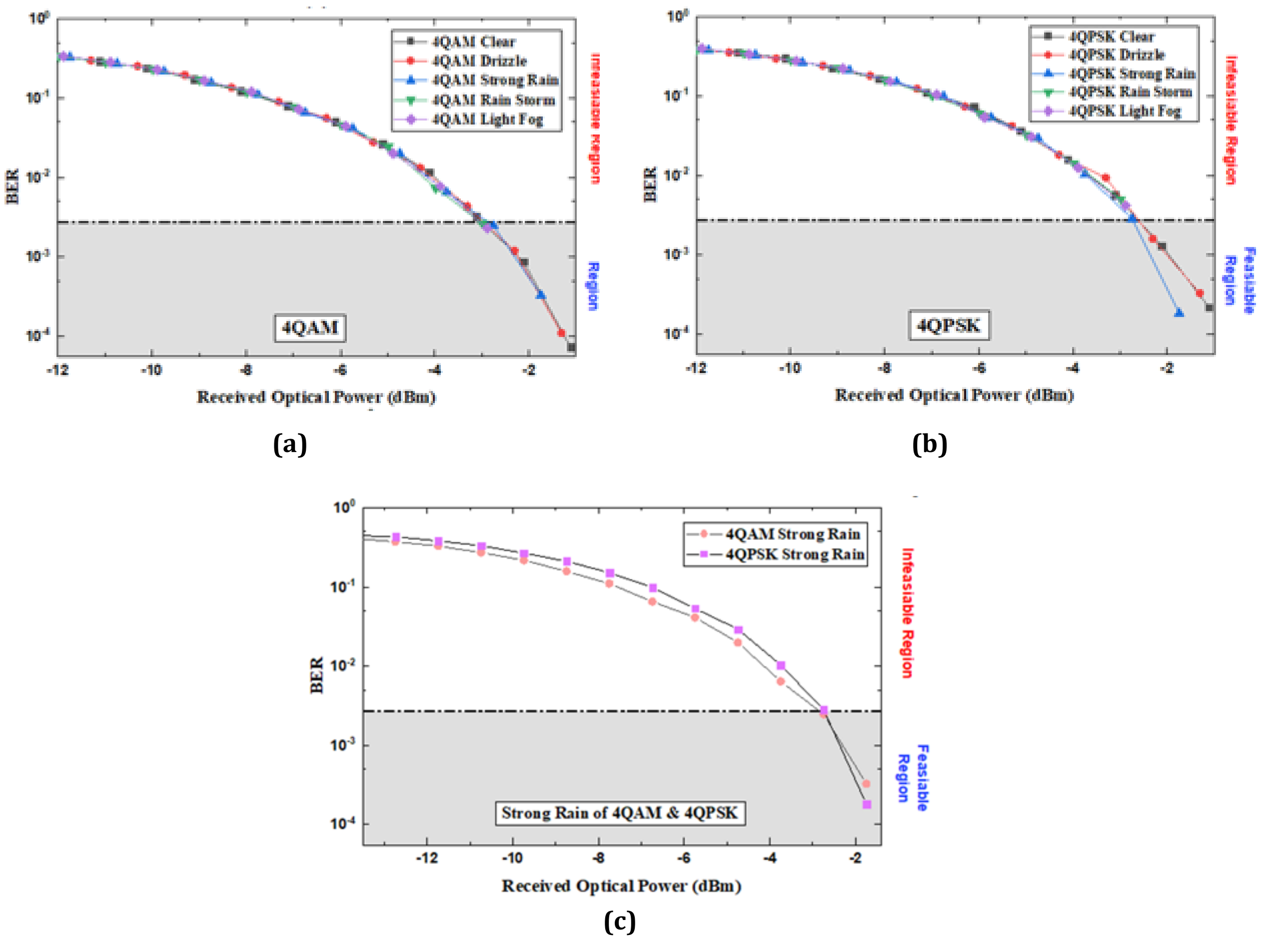


Fig. 11 *Received optical power of (a) 4QAM; (b) 4QPSK; and (c) Strong rain of 4QAM & 4QPSK*

4. Conclusion

With the demand for both HSR transportation and constant internet availability to meet the users' needs, a solution by using FSO technology has been made. The benefits such as its wide, unrestricted, license-free transmission bandwidth spectrum make researchers and developers work hard to explore more about it. Even though the power required is minimum, there is still room for improvement in the performance and reliability of FSO lines due to atmospheric attenuation limits. The tremendous rise in demand for easy internet access while traveling at high speeds made the fusion of FSO technology and high-speed rail unavoidable.

The research achieved its objectives, revealing that the NRZ modulation technique outperforms other advanced G2T-FSO models in transmission distance but has a drawback in received optical power. The OFDM 4-QPSK and OFDM 4-QAM have a similar behavior against the different weather condition. modulation technique outperforms other G2T-FSO models for overall research. If we want to strengthen G2T-FSO communication, we need to investigate different level of the modulation technique to see which of the modulation techniques can applied and suits into the G2T-FSO communication. Besides, a few improvements can be made in future research, such as using multi transmitter concepts such as Multiple Input Single Output (MISO) to improve G2T-FSO performance and extend transmission distance coverage. We believe this investigation of advanced modulation technique can improve the performance of G2T communication in the future.

Acknowledgement

This work was supported by Universiti Tun Hussein Onn Malaysia through Tier 1 (Vot Q126).

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

References

[1] B. Chen, Z. Zhong, B. Ai, K. Guan, R. He, and D. G. Michelson, “Channel characteristics in high-speed railway: A survey of channel propagation properties,” IEEE Veh. Technol. Mag., vol. 10, no. 2, pp. 67–78, 2015. https://doi.org/10.1109/MVT.2015.2411031

[2] G. S. D. Gordon, M. J. Crisp, R. V Penty, T. D. Wilkinson, and I. H. White, “Feasibility Demonstration of a Mode-Division Distributed Antenna System,” J. Light. Technol., vol. 32, no. 20, pp. 3521–3528, 2014. https://doi.org/10.1109/JLT.2014.2313649

[3] M. Taheri, N. Ansari, J. Feng, R. Rojas-cessa, and M. Zhou, “Provisioning internet Access Using Fso in HigH-sPeed rAil networks,” IEEE Netw., vol. 31, no. August, pp. 96–101, 2017. https://doi.org/10.1109/MNET.2017.1600167NM

[4] E. Leitgeb, T. Plank, P. Pezzei, D. Kraus, and J. Poliak, “Integration of FSO in local area networks - Combination of Optical Wireless with WLAN and DVB-T for last mile internet connections,” 2014 19th Eur. Conf. Networks Opt.Commun. NOC 2014, pp. 120–125, 2014. https://doi.org/10.1109/NOC.2014.6996839

[5] I. K. Son and S. Mao, “A survey of free space optical networks,” Digit. Commun. Networks, vol. 3, no. 2, pp. 67–77, 2017. https://doi.org/10.1016/j.dcan.2016.11.002

[6] K. Nakamura et al., “Development of Broadband Telecommunications System for Railways Using Laser Technology,” Electr. Eng. Japan (English Transl. Denki Gakkai Ronbunshi), vol. 190, no. 3, pp. 45–56, 2015. https://doi.org/10.1002/eej.22445

[7] R. Talib, M. F. L. Abdullah, A. Malekmohammadi, and M. K. Abdullah, “A new multi-slot and multi-level coding technique for high capacity communication system,” in 2010 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE), 2010, pp. 1–5. https://doi.org/10.1109/APACE.2010.5719766

[8] R. Talib, M. F. L. Abdullah, A. Malekmohammadi, and M. K. Abdullah, “Multi-slot and multi-level coding technique over amplitude-shift keying modulation for optical communication links,” 2011 16th Eur. Conf. Networks Opt. Commun., pp. 161–164, 2011. https://doi.org/10.1049/iet-com.2018.6113

[9] P. Goyal, A. Kumar, and V. Nath, “Mitigation of atmospheric turbulence in free space optics: A review,” Int. Conf. Adv. Comput. Commun. Technol. ACCT, vol. 2015-April, pp. 634–640, 2015. https://doi.org/10.1109/ACCT.2015.60

[10] M. F. L. Abdullah and S. W. Bong, “Adaptive differential amplitude pulse-position modulation technique for optical wireless communication channels based on fuzzy logic,” IET Commun., vol. 8, no. 4, pp. 427–432, Mar. 2014. https://doi.org/10.1049/iet-com.2013.0443

[11] F. Duerr and H. Thienpont, “Refractive laser beam shaping by means of a functional differential equation based design approach,” Opt. Express, vol. 22, no. 7, p. 8001, 2014. https://doi.org/10.1364/OE.22.008001

[12] W. Li, Z. Qian, and H. Li, “Interpretation and Classification of P-Series Recommendations in ITU-R,” Int. J. Commun. Netw. Syst. Sci., vol. 09, no. 05, pp. 117–125, 2016. https://doi.org/10.4236/ijcns.2016.95010

[13] M. Achour, “Simulating Atmospheric Free-Space Optical Propagation; Part II: Haze, Fog, and Low Clouds Attenuations,” ITCom 2002 Converg. ..., vol. 4873, pp. 1–12, 2002. https://doi.org/10.1117/12.458571

[14] H. Kaushal and G. Kaddoum, “Optical Communication in Space: Challenges and Mitigation Techniques,” IEEE Commun. Surv. Tutorials, vol. 19, no. 1, pp. 57–96, 2017. https://doi.org/10.1109/COMST.2016.2603518

[15] M. B. Othman, T. T. Pham, X. Zhang, L. Deng, J. B. Jensen and I. T. Monroy, "Comparison of carrierless amplitude-phase (CAP) and discrete multitone (DMT) modulation," 2014 IEEE 5th International Conference on Photonics (ICP), Kuala Lumpur, Malaysia, 2014, pp. 214-216. https://doi.org/10.1109/ICP.2014.7002359