

Investigation of Multiple Configuration Transmitter of FSO link for Ground to Train Communication in Straight Track Model

Maisara Othman¹, Mariyam Jamilah Homam¹, Mohammad Faiz Liew Abdullah^{1*}, Wafi Adam Bakhit Mabrouk¹

¹ Department of Electronic Engineering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, Johor, 86400, MALAYSIA

*Corresponding Author: faiz@uthm.edu.my

DOI: <https://doi.org/10.30880/ijie.2024.16.03.020>

Article Info

Received: 5 July 2024

Accepted: 27 October 2024

Available online: 9 November 2024

Keywords

Free space optic, ground to train communication, modulation

Abstract

There is an increasing demand for high-speed train (HSR) services. Consequently, onboard high-speed internet access needs to increase as passengers travel to and from work. This sudden surge in demand introduced new challenges in delivering a seamless internet connection onboard fast-moving trains. Free Space Optical (FSO) Communications technology has a promising future for a variety of applications due to its cost-effectiveness, ease of deployment, and vast unregulated bandwidth, giving it an advantage over current technologies. However, major research into FSO links for railway communications is limited. This research proposes a straight track for FSO Ground-to-Train (G2T-FSO) links to address this issue and meet rising demand. G2T-FSO links use base stations next to the track to provide a line-of-sight (LOS) link for traveling trains. However, significant research on FSO links for railway communications is limited. This paper proposes a straight-track model design for G2T-FSO links to address this issue and meet rising demand. G2T-FSO links use base stations next to the track to provide a LOS link for traveling trains. In this study, FSO links are made up of intensity-modulated transmitters with direct detection receivers that use return zero (RZ) and non-return zero (NRZ) on-off keying (OOK) modulation formats at 2.5 Gbps. The multiple transmitters concept has been used to improve link performance, with single, dual, triple, and quad transmitters. Furthermore, track geometry characteristics have been optimized to provide the best link performance. Meteorological data from the Department of Meteorology Malaysia have been used to simulate rain and fog weather attenuations for Malaysia's environment. The G2T-FSO's performance was evaluated in terms of BER at various distances and received power under various weather conditions using the Optisystem®. The results reveal that moderate rain and fog weather circumstances have a reasonable performance evaluation of the G2T-FSO communications link for the straight track model.

1. Introduction

Applications of free space optic (FSO) communications on mobile terminals are interesting but very challenging due to the nature of the narrow field-of-view (FOV) of the system, which is bounded by the limited transmit power [1]. Traffic light and car-to-car communications are under development and testing, whereas high-mobility ground-to-train FSO (G2T-FSO) communications are emerging as an exciting but very challenging topic. Various studies have demonstrated that there is a demand for the usage of high-bandwidth applications in a moving train, which necessitates a high-speed data connection [2 - 4].

Passengers aboard a moving train currently expect data connection service of comparable quality to that found at home or work. The majority of business travelers work on trains and would use wireless broadband if it were available [5]. As a result, high-speed data transmission between trains and base stations (BS) is required to ensure that all passengers receive smooth digital services [6]. Several efforts have been made to create flawless wireless internet connections in a fast-moving train [6].

Current high-speed rail (HSR) communication technologies face numerous obstacles when establishing dependable wireless communication links in the HSR environment [7]. This is due to a variety of factors resulting from the complex structure of the HSR environment, including high voltage electromagnetic interference, high vibrations, and temperature variations around the train [8]. In addition, the train carriage structure functions as a Faraday cage, blocking incoming signals. High travel speeds, on the other hand, limit wireless propagation in RF systems due to the Doppler effect, resulting in patchy links, penetration losses, and high call drop rates. In addition, there are many HSR track situations, including open regions, slopes, cuttings, viaducts, and station platforms. These circumstances influence wireless channel propagation characteristics, complicating the establishment of a trustworthy link [8]. There is insufficient study on G2T-FSO communication models.

According to the literature review, earlier researchers provided theoretical models for G2T-FSO systems that focused primarily on single-track regular train systems rather than high-speed trains [9 - 14]. End consumers are increasingly demanding access to high-speed wireless networks. When the train is in motion, current operators provide a restricted RF-based wireless network with a data throughput of less than 50 Mbps [15]. Alternatively, radio-over-fiber (RoF) systems have been reported to provide broadband wireless access in high-speed trains by combining RF wireless and optical technologies [16].

The main issue with the RoF technology is the frequent band switching and complex optical routing, which limit the BS coverage distance. In practice, the attainable data rate in trains is substantially lower than the theoretical data rate because the bandwidth is shared by multiple users. Therefore, it is not sufficient to meet the demands of the end-users. Although RF-based communication is a viable technology for fixed wireless local area networks (WLAN), its effectiveness is reduced when nodes move at high speeds, which has sparked interest in employing FSO as a feasible mode of communication for HSR [17]. FSO technology can be used for high-speed communications because of the limitless bandwidth accessible at optical wavelengths [18]. Furthermore, optical transmitters such as lasers and LEDs can handle a high data rate, hence research into ground-to-train communications utilizing FSO has revealed significant promise that has yet to be explored [19]. The G2T-FSO straight track model's system design is improved in this study by employing Optisystem. The system design integrates various transmitter concepts to provide high-performance connectivity and faster data speeds.

The remainder of this paper is organized as follows: Section 2 includes the simulation configuration of the FSO communication link model using Optisystem, as well as the parameter values employed. The results and analysis of multiple configuration transmitters of Non-Return-to-Zero (NRZ) and Return-to-Zero (RZ) modulation for the straight track at various distances and different weather are presented in Section 3. Finally, Section 4 concludes this study of G2T-FSO for straight track.

2. Simulation Configuration of FSO Communication Link Model Using Optisystem

Figure 1 depicts the FSO communication link block diagram implementation in Optisystem. The communication connection is made up of three basic blocks: transmitter, FSO channel, and receiver. The transmitter block consists of an optical source (laser diode), an electrical signal data source, and an external modulator. A Mach-Zehnder modulator is used to externally modulate a Continuous Wave (CW) laser, converting electrical signal data into optical pulses [20]. NRZ and RZ modulation formats are used because they are simple and resistant to attenuation [21]. These modulation methods are critical for high-speed rail communications because they ensure data transmission dependability and integrity over long distances and under variable situations. The NRZ format

optimizes bandwidth consumption and is less prone to timing faults, making it ideal for maintaining high data rates. On the other hand, the RZ format performs better in noisy situations because it includes a return to zero voltage level between bits, which can aid in minimizing inter-symbol interference. These features make NRZ and RZ modulation formats especially useful for FSO communication systems deployed in high-speed train scenarios, where maintaining a stable and resilient link is critical despite the dynamic and difficult operational conditions [22].

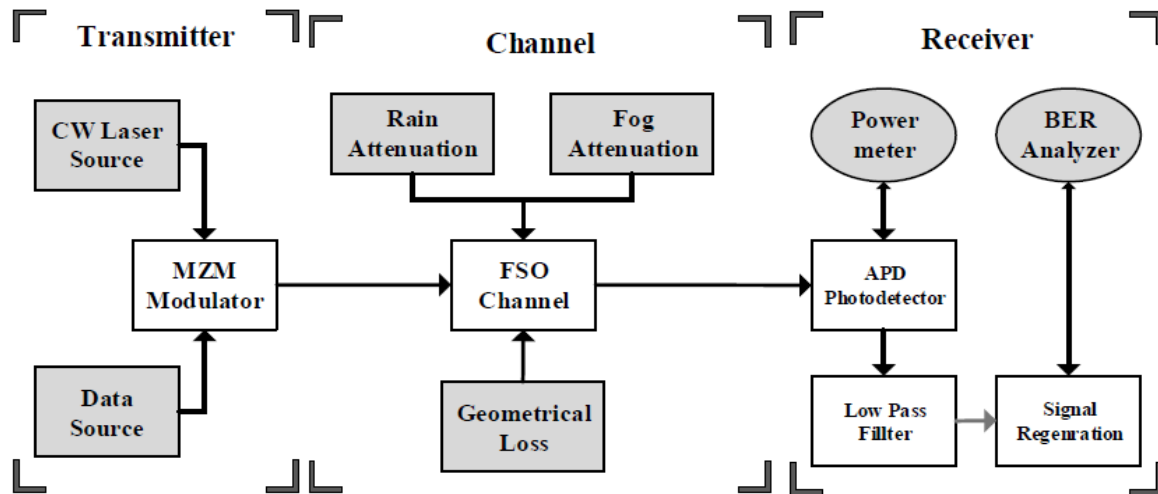


Fig. 1 FSO link block diagram in Optisystem

The transmitter block of an FSO communication system converts electrical binary data into an optical pulsed modulated signal. This signal is generated by modulating a CW laser beam with binary data, yielding a pulsed optical signal that travels over the FSO channel. The channel adds numerous forms of losses during signal propagation, which are classified as geometrical losses, system losses, and atmospheric losses. Atmospheric losses, measured in decibels per kilometer, are crucial for evaluating channel performance and are influenced by elements such as rain and fog. On the FSO channel side, the laser beam is subjected to air losses, which reduce signal quality and range. Geometrical losses result from the spreading of the optical beam over distance, while rain and fog contribute additional attenuation that degrades the signal.

On the receiver side, an avalanche photodetector (APD) is used to transform the incoming optical signal into an electrical pulse [23]. This electrical signal is then routed via a low-pass filter to reduce high-frequency noise and assure signal integrity prior to bit regeneration. The signal regeneration process is divided into three basic stages: amplification, retiming, and reshaping. Amplification increases signal power; retiming corrects synchronization difficulties; and reshaping refines the signal waveform to recover its original form. After the regeneration, the signal is transmitted to a bit error rate (BER) analyzer and power meters. The BER analyzer determines the quality of the received signal by comparing it to the original transmission data, whereas the power meters measure the signal intensity. This comprehensive evaluation allows for visualization and analysis of the signal's performance at the receiver end.

2.1 G2T-FSO links Optisystem Simulation Parameters

To simulate the system in Optisystem, beam divergence for each point track and link range were evaluated using scattering classes such as Mie scattering, Rayleigh scattering, and geometrical scattering [24]. Weather conditions such as rain attenuation and fog attenuation are also calculated and applied to the simulation model. It was done in multiple iterations, each representing a geometrical coordinate of a train's position on the track. Table 1 shows detailed optimal values for the straight G2T-FSO track model. The straight-track G2T-FSO model has fixed values for tilt, coverage, and receiver FOV, as well as link LOS.

The Straight Track G2T-FSO model has fixed values for tilt, coverage, and receiver FOV, as well as link LOS. However, as the train approaches the base station, the link range steadily reduces from 1000 m to 0 m, and the divergence angle varies within a range of $19.5^\circ - 0^\circ$. Furthermore, vertical and horizontal distances are designed to be 5 m and 15 m, respectively. The speed of travel along the straight track was neglected because it does not affect the geometrical configuration of the G2T-FSO link.

Table 1 Straight track G2T-FSO geometrical parameters and straight track model

G2T-FSO link geometrical parameters		
Parameter	Symbol	Value
Tilt angle	γ	2.25°
Coverage angle	δ	0.65°
Receiver FOV	ψ	5.15
Straight Track G2T-FSO Model		
Divergence angle	θ_s	0° -19.5°
Vertical distance	d_{VS}	5 m
Horizontal distance	d_{HS}	15 m
Coverage distance	L_S	1 km
Link range	Z_S	0 – 1000 m

2.2 Multiple Transmitters Approach

The multiple transmitters approach is based on multiple transmitter concepts for the FSO link shown in Fig. 2 [25 - 26]. It uses multiple laser sources that are connected to a single on-off keying (OOK) modulator to generate multiple beams that propagate along the link range. In addition, multiple transmitters and a single receiver were implemented for design simplicity. The total transmitted power of multiple FSO transmitters is defined as the sum of individual transmitters as follows [25]:

$$P_{Total} = (P_{T(mW)} \times N_{TX}) \tag{1}$$

where $P_{T(mW)}$ is power in mW and N_{TX} is the number of transmitters. Alternatively, in dBm, it is defined as follows:

$$P_{Total} = \left[10 \log_{10} \left[\frac{P_{T(mW)}}{1mW} \right] + 10 \log_{10}(N_{TX}) \right] \tag{2}$$

The simulation parameters for different numbers of transmitters were set according to the values tabulated in Table 2. In the simulation design, four cases of different configurations of the multiple transmitters were considered namely, single: 1 transmitter and 1 receiver (1Tx/1Rx), dual: 2 transmitters and 1 receiver (2Tx/1Rx), triple: 3 transmitters and 1 receiver (3Tx/1Rx) and quad: 4 transmitters and 1 receiver (4Tx/1Rx). The notation 1 receiver (1Rx) is for a single FSO receiver which is mounted on the roof of the train.

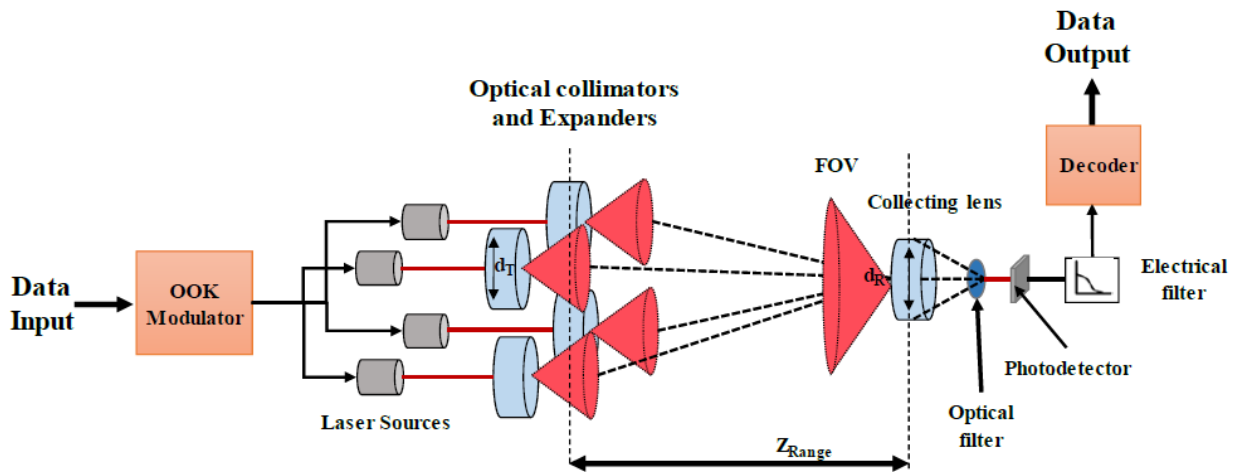
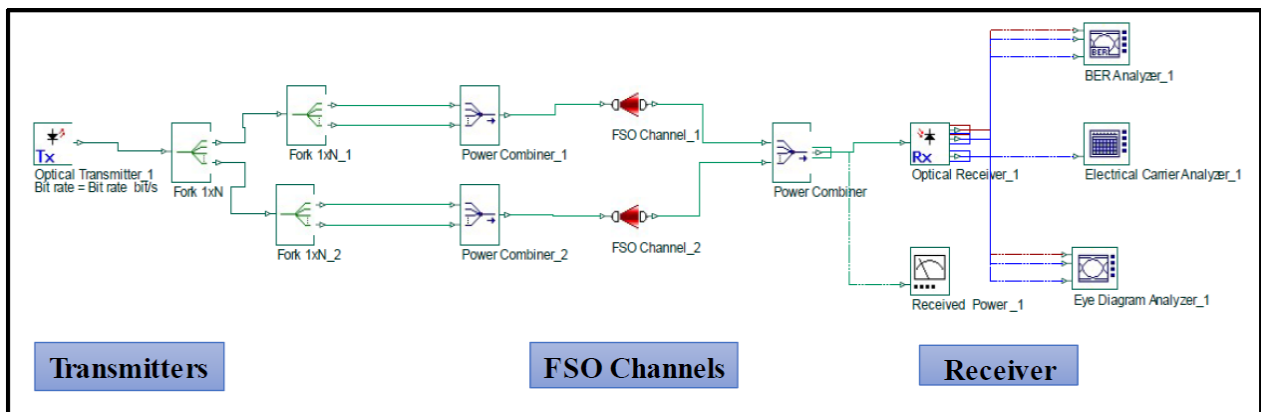


Fig. 2 Multiple transmitters configuration

Table 2 OptiSystem G2T-FSO link simulation parameters

G2T-FSO link parameters		
Parameter	Symbol	Value
Laser wavelength	λ	850 nm
Bit rate	B_r	2.5 Gbps
Transmitter optical power CW	P_T	20 mW
Transmitter optical power NRZ	$P_{TNRZ1TX}$	10.39 mW
	$P_{TNRZ2TX}$	20.55 mW
	$P_{TNRZ3TX}$	31.78 mW
	$P_{TNRZ4TX}$	41.56 mW
Transmitter optical power RZ	P_{TRZ1TX}	6.66 mW
	P_{TRZ2TX}	13.90 mW
	P_{TRZ3TX}	20.85 mW
	P_{TRZ4TX}	27.80 mW
Transmitter aperture diameter	d_R	8 cm
Receiver aperture diameter	d_T	5 cm
APD responsivity	\mathfrak{R}	0.62 A/W
Receiver gain	G_R	10 dB
Dark current	i_{dark}	10 nA
Receiver sensitivity	S_r	-46 dBm
Transmitter loss	L_{Tx}	-1.5 dB
Receiver loss	L_{Rx}	-1.5dB

Fig. 3 shows an example of 2Tx/1Rx implementation of multiple transmitters in OptiSystem. The power was equally distributed to the optical output of the FSO transmitter. Then the power was combined by a power combiner before it was sent through the FSO channel. Pointing losses of -1.5 dB at the transmitter and the receiver were assumed for G2T-FSO communications.

**Fig. 3** Dual G2T-FSO transmitters OptiSystem model (2Tx/1Rx)

2.3 FSO Channel Attenuation Link Parameter

FSO links utilize the earth's atmosphere as a medium to establish an optical link. In this simulation design, the measured meteorological data and empirical models of fog and rain were used to evaluate specific fog and rain attenuation levels. Meteorological records were obtained from the The Malaysian Meteorological Department (Jabatan Meteorologi Malaysia) provided the 33 meteorological records. The three years from January 1, 2013, to December 31, 2015, were used as the data. The measurements were taken at the Batu Pahat Station, which is

located at latitude 1°52'N and longitude 102°59'E. The data includes hourly measurements of visibility and rainfall in meters per hour (m/h) and millimeters per hour (mm/h).

2.4 Rain Attenuation

Transparent raindrops that collide with moving photons change the path's refraction index and have an impact on the propagation path. As a result, light beams are bent and refracted away from the direction of the receiver. Carbonneau's approach, based on rain rate R (mm/h), is commonly used to compute rain attenuation:

$$\gamma_{Rain} \left[\frac{dB}{km} \right] = k \cdot R^\alpha \left[\frac{mm}{hr} \right] \tag{3}$$

where α and k are constants that depend on measured values.

Maximum rain attenuation rates throughout 2013 and 2015 were approximated using recorded meteorological data. ITU-R codes were utilized to group the data into suitable situations in classifying the rain attenuation data. As a result, Table 3 contains the applied values for the rain attenuation conditions.

Table 3 Rain attenuation simulation parameters

No	Precipitation Type	Precipitation Rate (mm/hr)	Attenuation (dB/km)
1.	Drizzle	0.20	2.5
2.	Strong Rain	25	6.9
3.	Rain Storm	55	19.3

2.5 Fog Attenuation

Fog reduces the LOS range by altering link transparency. It is an important aspect to consider when developing an FSO link because attenuation levels can reach 300 dB/km. The Mie scattering hypothesis, which is extensively used to calculate fog attenuation, is based on observations of atmospheric transparency, also known as visibility [22]. Finally, the attenuation of fog and rain was characterized using global visibility codes [23]. Table 4 displays the quantities and levels of fog and rain attenuation employed in the Optisystem simulation for the G2T-FSO.

Table 4 Fog attenuation simulation parameters

No	Weather Condition	Visibility (km)	Attenuation (dB/km)
1.	Clear Air	2000	-0.6
2.	Light Fog	770	-18.3
3.	Moderate Fog	500	-28.9
4.	Thick Fog	200	-70

3. Performance of Straight Track G2T-FSO

The results were obtained from simulations conducted using the OptiSystem simulator, focusing on a straight-track model. The simulation incorporated two modulation techniques: NRZ and RZ. It also took into account various weather conditions that affect attenuation, including clear weather, rain, and fog. The results are presented with a dotted line dividing the data into two distinct regions: feasible and infeasible regions. The feasible region is defined based on the BER results, with performance evaluated at a BER of 10^{-9} . This threshold indicates the level of communication quality and reliability achieved under different conditions.

The feasible region represents the scenarios where the system's performance meets the required BER of 10^{-9} , ensuring reliable data transmission. Conversely, the infeasible region includes cases where the BER exceeds 10^{-9} , indicating suboptimal performance. This division allows for a clear assessment of the system's performance across different modulation techniques and weather conditions, highlighting the effectiveness and limitations of the NRZ and RZ modulation formats in various atmospheric scenarios.

3.1 Straight Track NRZ Modulated Link Bit Error Rate Against Distance

Figure 4 shows the achieved BER performance values for various transmitter configurations, which are divided into feasible and infeasible regions based on their performance metrics. The BER measurements remain below

10^{-9} , indicating high-quality communication. Under clear conditions, the greatest practical ranges for the 1Tx, 2Tx, 3Tx, and 4Tx configurations are 160 m, 340 m, 500 m, and 680 m, respectively, while maintaining a BER of 10^{-9} . These data indicate the system's effective range capabilities under ideal weather circumstances. In moderate rain, the achievable ranges reduce somewhat, with the 1Tx, 2Tx, 3Tx, and 4Tx configurations reaching 140 m, 260 m, 380 m, and 460 m, respectively. Despite the reduction in range due to rain-induced attenuation, the system still has an acceptable BER of 10^{-9} .

Under moderate fog conditions, the achievable ranges are further reduced to 100 m, 120 m, 240 m, and 260 m for the same transmitter configurations. Although the performance is impacted by fog attenuation, the system remains within the acceptable BER range, ensuring reliable communication over these shorter distances. This analysis illustrates how weather conditions affect the performance of FSO communication systems. Clear weather allows for the longest effective communication ranges, while moderate rain and fog reduce the achievable ranges. Despite these reductions, the system remains capable of providing high-quality communication with a BER below 10^{-9} , highlighting the importance of transmitter configuration in maintaining system reliability across varying environmental conditions.

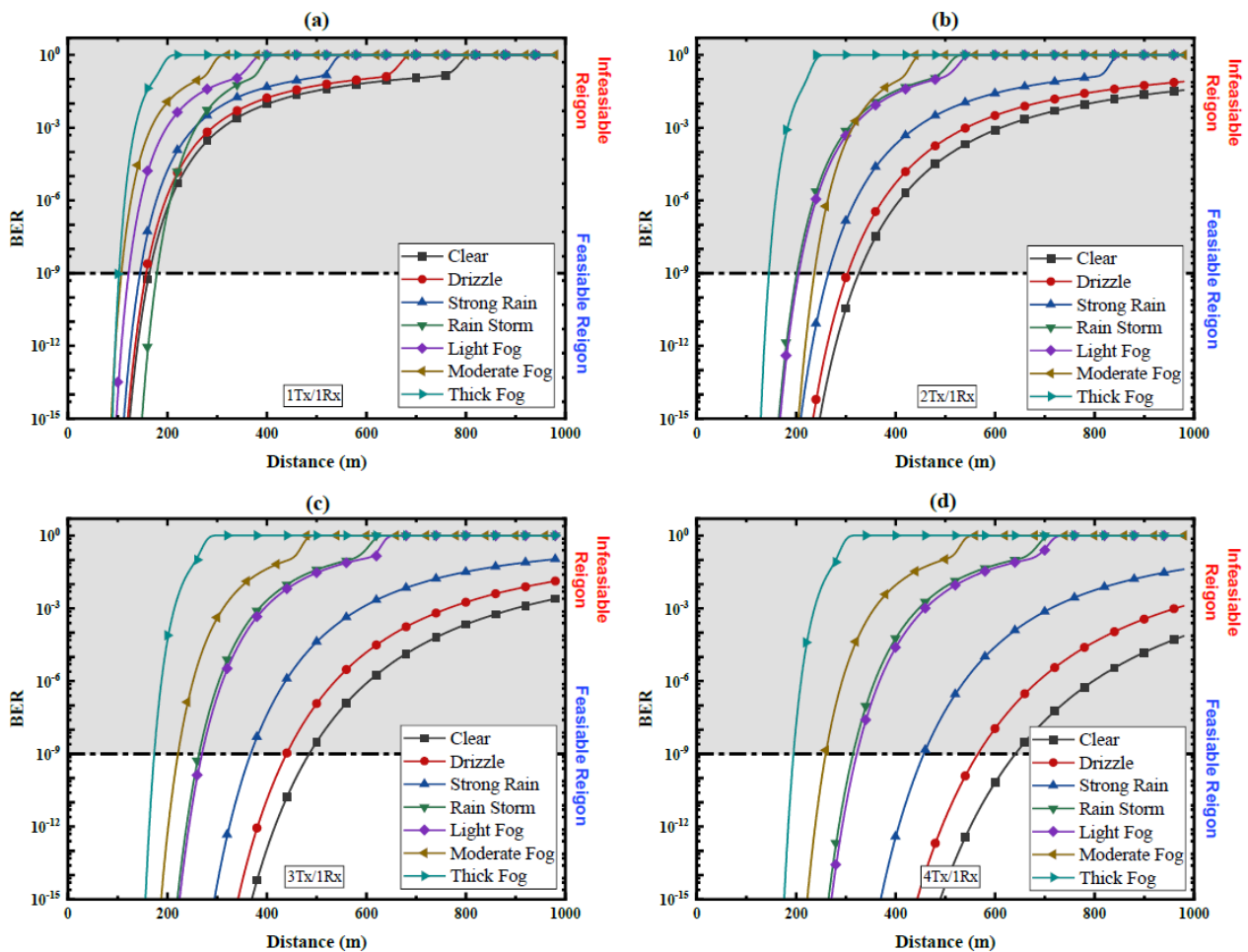


Fig. 4 BER of (a) 1Tx/1Rx; (b) 2Tx/1Rx; (c) 3Tx/1Rx; and (d) 4Tx/1Rx transmitters for NRZ modulated G2T-FSO straight track link

3.2 Straight Track RZ Modulated Link Bit Error Rate Against Distance

Figure 5 depicts the achieved BER for several RZ transmitter designs under varied weather situations. Under clear weather, the system achieved excellent BER values of 10^{-70} at distances of 100 m, 200 m, 300 m, and 400 m for single, double, triple, and quad transmitters (1Tx, 2Tx, 3Tx, and 4Tx), respectively. This demonstrates the effectiveness of the RZ modulation format in maintaining high-quality communication over longer distances. However, under moderate rain conditions, the link range decreases significantly. The achievable distances are

reduced to 80 m, 180 m, 200 m, and 320 m for 1Tx, 2Tx, 3Tx, and 4Tx configurations, respectively. Despite this reduction in range, the system still maintains acceptable BER levels, indicating that the use of multiple transmitters helps to mitigate the effects of rain-induced attenuation.

In the case of thick fog, the link ranges further decrease to 80 m, 120 m, 160 m, and 200 m for the same transmitter configurations. Even under these challenging conditions, acceptable BER levels are achievable. Notably, for the single transmitter configuration, an exceptionally low bit error rate of 1.08×10^{-53} was achieved, highlighting the system's potential for maintaining data integrity even in severe attenuation scenarios. These results underscore the significant impact of weather conditions on the performance of FSO communication systems. The data demonstrates that while clear weather allows for extended link ranges with very low BER, moderate rain, and thick fog reduce the effective range, though multiple transmitters continue to provide reliable communication. The findings emphasize the value of using multiple RZ transmitters to enhance the robustness and reliability of FSO systems, especially in varying and adverse weather conditions.

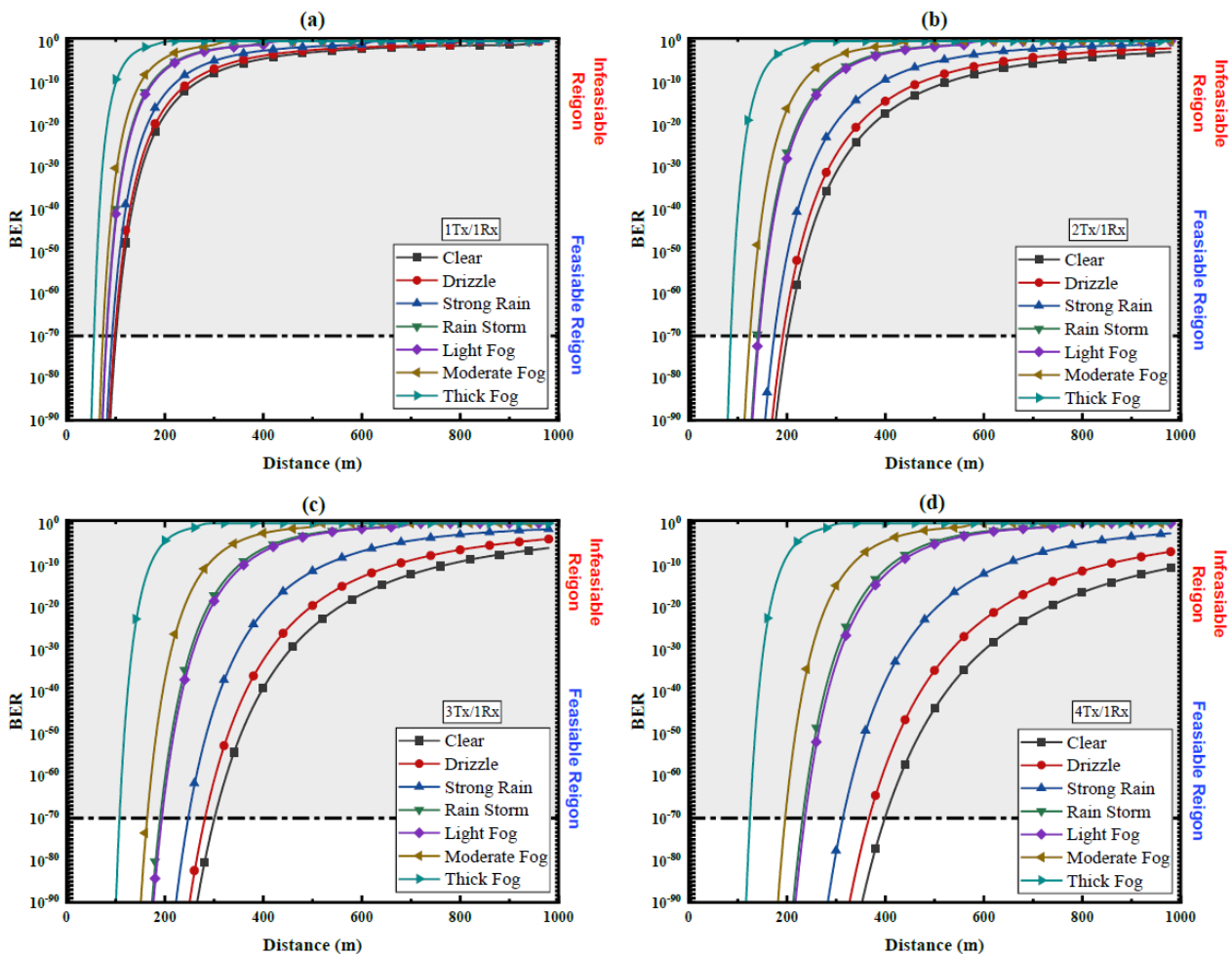


Fig. 5 BER of (a) 1Tx/1Rx; (b) 2Tx/1Rx; (c) 3Tx/1Rx; and (d) 4Tx/1Rx transmitters for RZ modulated G2T-FSO straight track link

3.3 Straight Track NRZ Modulated Link Received Power Against Distance

The performance of the received power under various FSO transmitter configurations is depicted in Fig. 6. G2T-FSO receives power levels exceeding -29.5 dBm, resulting in BER levels above 10^{-9} . In contrast, for levels below -29.5 dBm, the link performance is suboptimal. First, in clear weather conditions, the received power levels of -29.5 dBm are reported at distances of 160 m, 340 m, 500 m, and 680 m for single, double, triple, and quad transmitters, respectively. Under strong rain conditions, with an atmospheric attenuation of 6.9 dB/km, the G2T-FSO link range decreases slightly to 140 m, 260 m, 380 m, and 460 m for 1Tx, 2Tx, 3Tx, and 4Tx, respectively.

Furthermore, under moderate fog conditions with an attenuation of 28.9 dB/km, the link range is drastically reduced to 100 m, 120 m, 240 m, and 260 m for single, double, triple, and quad G2T-FSO transmitters, respectively.

Low weather attenuation results in a slight decrease in the distance range. However, under extreme weather conditions such as rainstorms and thick fog, the link range decreases sharply. Although the decline in performance is significant, the frequency of occurrence of such extreme weather conditions is relatively low. Secondly, considering the average power decrease due to weather effects, compared to clear weather conditions, received power levels drop by -3.24 dBm and -14.55 dBm under strong rain and moderate fog, respectively. This results in an average power shift of 7.9% and 30.7% for each case. This analysis underscores the impact of weather conditions on the performance of FSO links and highlights the necessity for robust transmitter configurations to ensure reliable communication in varying environmental conditions.

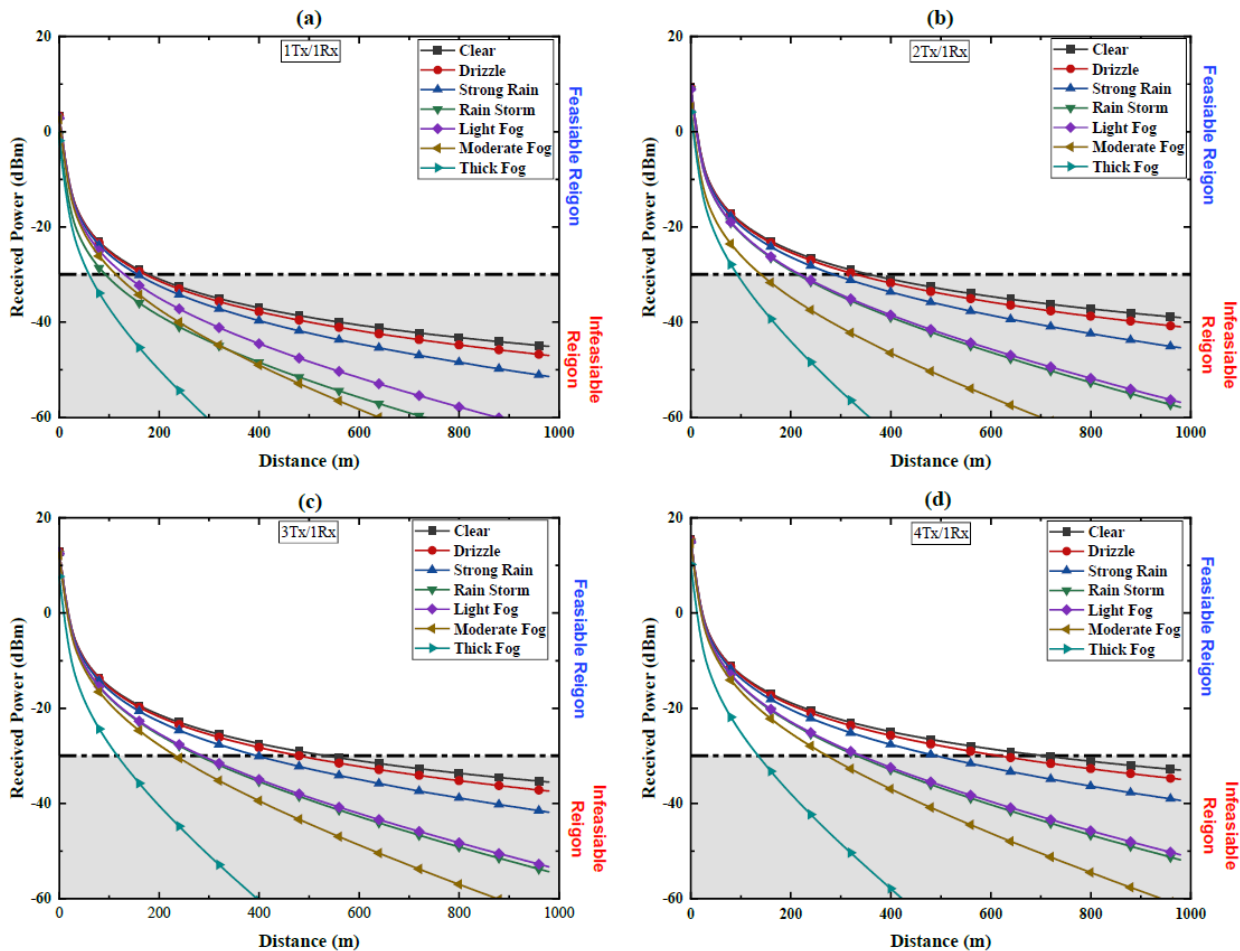


Fig. 6 Received power of (a) 1Tx/1Rx; (b) 2Tx/1Rx; (c) 3Tx/1Rx; and (d) 4Tx/1Rx transmitters for NRZ modulated G2T-FSO straight track link

3.4 Straight Track NRZ Modulated Link Received Power Against Distance

Fig. 7 shows the received power for a G2T-FSO RZ modulated link using single, double, triple, and quad transmitters under various atmospheric conditions, including clear weather, moderate rain, and fog attenuation. Under clear weather conditions, the system covers distances of 100 m, 200 m, 300 m, and 400 m for 1Tx, 2Tx, 3Tx, and 4Tx, respectively, with received power levels of -28.49 dBm, -28.38 dBm, -28.39 dBm, and -28.42 dBm, respectively. In moderate rain, with an attenuation level of -6.9 dB/km, the system performs optimally at ranges of 80 m, 110 m, 180 m, and 220 m for 1Tx, 2Tx, 3Tx, and 4Tx, respectively. Under moderate fog conditions, the link distance decreases significantly, with single and dual transmitters achieving only 80 m and 120 m, respectively, while triple and quad transmitters achieve 160 m and 200 m, respectively. Moderate rain causes a slight average power decline of -3.25 dBm, corresponding to a transmitted power drop of 10.05%, 9.26%, 8.36%,

and 8.64% for the 1Tx, 2Tx, 3Tx, and 4Tx cases, respectively. In contrast, moderate fog results in a higher average power reduction of -14.55 dBm, equating to 37.63%, 35.04%, 32.22%, and 30.87% average power decreases for the 1Tx, 2Tx, 3Tx, and 4Tx cases, respectively. This analysis highlights the varying performance of FSO links in different weather conditions, emphasizing the importance of multiple transmitters in maintaining reliable communication, especially in adverse weather conditions.

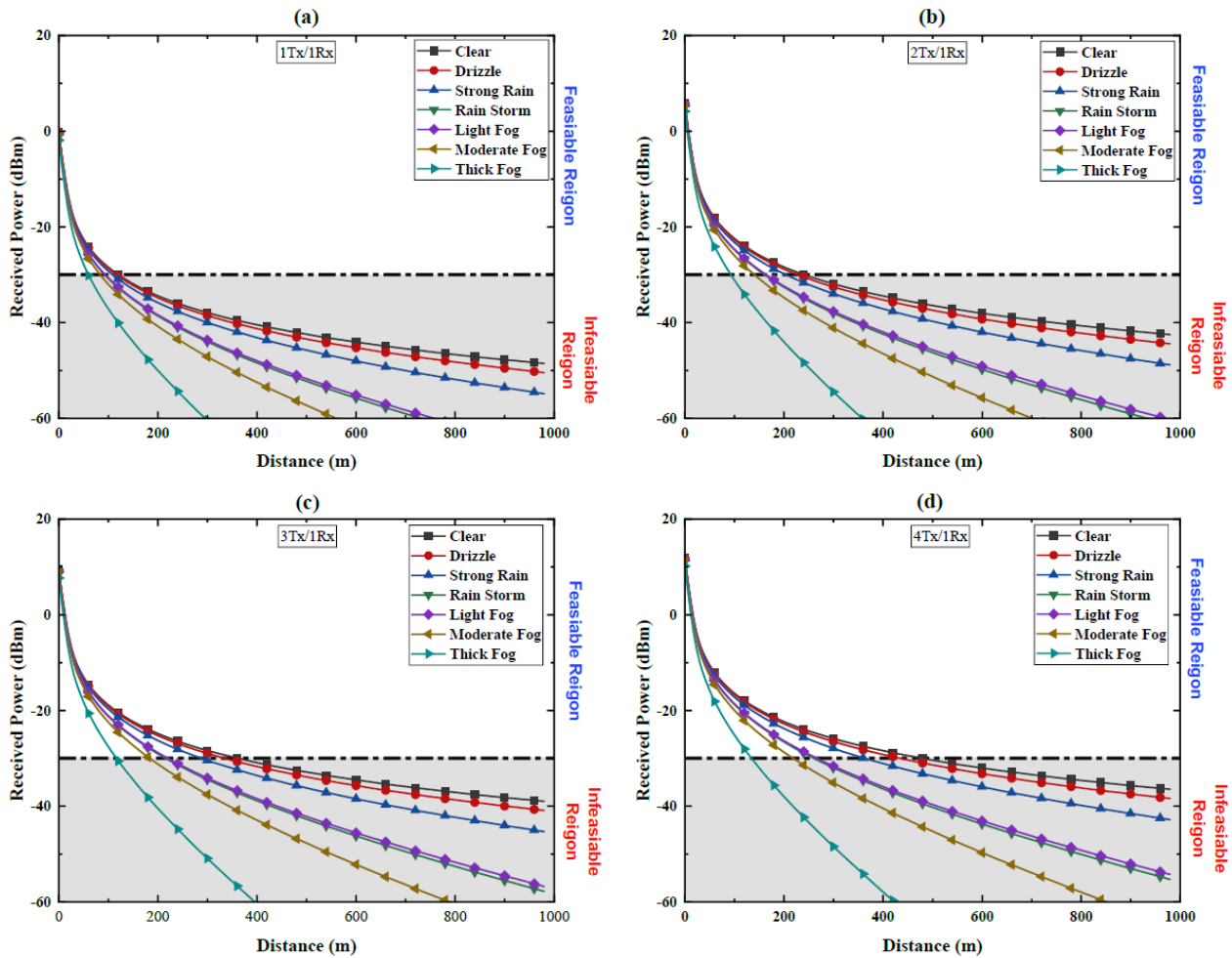


Fig. 7 Received power of (a) 1Tx/1Rx; (b) 2Tx/1Rx; (c) 3Tx/1Rx; and (d) 4Tx/1Rx transmitters for RZ modulated G2T-FSO straight track link

4. Conclusions

The NRZ 4Tx transmitters attained a maximum link range of 680 m in clear weather, demonstrating their capability for long-distance communication. However, under thick fog conditions, the coverage length is reduced to a minimum of 120 m. In comparison, 4Tx RZ transmitters achieved a maximum range of 400 m under clear weather and a minimum link range of 80 m under thick fog conditions. The substantial impact of thick fog on the G2T-FSO link performance is evident, although the likelihood of thick fog occurrence is less than 1%. Therefore, analyzing the effects of moderate rain and fog provides a more practical performance evaluation of the G2T-FSO communications link.

Additionally, increasing the number of FSO transmitters enhances the link range, received power, and mitigation of weather-induced attenuation. The average improvement in received power translates into an extended link range, which increases the system's tolerance to weather-related attenuation and expands the acceptable communication range along the track. This improvement underscores the effectiveness of using multiple transmitters to counteract the impact of adverse weather conditions.

In conclusion, this paper successfully simulated and optimized the G2T-FSO straight-track model across various weather scenarios. The findings highlight that while thick fog poses significant challenges, the use of

multiple transmitters and appropriate modulation formats can significantly enhance the performance and reliability of FSO communication systems, ensuring effective data transmission in diverse environmental conditions.

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 confirm contribution to the paper as follows: **study conception and design:** Wafi Adam Bakhit Mabrouk, Mohammad Faiz Liew Abdullah; **data collection:** Wafi Adam Bakhit Mabrouk; **analysis and interpretation of results:** Wafi Adam Bakhit Mabrouk; **draft manuscript preparation:** Maisara Othman, Mariyam Jamilah Homam, Mohammad Faiz Liew Abdullah, Wafi Adam Bakhit Mabrouk. All authors reviewed the results and approved the final version of the manuscript.*

References

- [1] Tang, X., Ghassemlooy, Z., Rajbhandari, S., Popoola, W. O. & Lee, C. G. (2011). Coherent Polarization Shift Keying Modulated Free Space Optical Links Over a Gamma-Gamma Turbulence Channel. *American Journal of Engineering and Applied Sciences*, 4(4), 520-530. <https://doi.org/10.3844/ajeassp.2011.520.530>
- [2] Ai, B., Guan, K., Rupp, M., Kurner, T., Cheng, X., Yin, X.-F., Wang, Q., Ma, G.-Y., Li, Y., Xiong, L., & Ding, J.-W. (2015). Future railway services-Oriented Mobile Communications Network. *IEEE Communications Magazine*, 53(10), 78–85. <https://doi.org/10.1109/mcom.2015.7295467>
- [3] He, R., Ai, B., Wang, G., Guan, K., Zhong, Z., Molisch, A. F., Briso-Rodriguez, C., & Oestges, C. P. (2016). High-speed railway communications: From GSM-R to LTE-R. *IEEE Vehicular Technology Magazine*, 11(3), 49–58. <https://doi.org/10.1109/mvt.2016.2564446>
- [4] A. Chauhan, R. Verma, A. Joshi and R. Sharma, "Design and Performance Analysis for Underground Trains using Optisystem," *2021 International Conference on Intelligent Technologies (CONIT)*, Hubli, India, 2021, pp. 1-4. <https://doi.org/10.1109/CONIT51480.2021.9498461>
- [5] Al-Gailani, S. A., Mohammad, A. B., Shaddad, R. Q., & Jamaludin, M. Y. (2013). Single and multiple transceiver simulation modules for free-space optical channel in tropical Malaysian weather. *2013 IEEE Business Engineering and Industrial Applications Colloquium (BEIAC)*. <https://doi.org/10.1109/beiac.2013.6560203>
- [6] Xu, S., Zhu, G., Ai, B., & Zhong, Z. (2016). A survey on high-speed railway communications: A Radio Resource Management Perspective. *Computer Communications*, 86, 12–28. <https://doi.org/10.1016/j.comcom.2016.04.003>
- [7] Binghao Chen, Zhangdui Zhong, Bo Ai, Ke Guan, Ruisi He, & Michelson, D. G. (2015). Channel characteristics in high-speed railway: A survey of channel Propagation Properties. *IEEE Vehicular Technology Magazine*, 10(2), 67–78. <https://doi.org/10.1109/mvt.2015.2411031>
- [8] Liu, Y., Ghazal, A., Wang, C.-X., Ge, X., Yang, Y., & Zhang, Y. (2017). Channel measurements and models for high-speed train wireless communication systems in tunnel scenarios: A survey. *Science China Information Sciences*, 60(10). <https://doi.org/10.1007/s11432-016-9014-3>
- [9] Paudel, Rupak, Le Minh, Hoa, Ghassemlooy, Zabih and Rajbhandari, Sujun (2010) High speed short range optical wireless ground-to-train communications. In: *The 11th Annual Postgraduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting (PGNet)*, 21-22 June 2010, Liverpool John Moores University, Liverpool.
- [10] Saini, E., Bhatia, R., & Prakash, S. (2016). High Speed Broadband communication system for moving trains using Free Space Optics. *2016 International Conference on Computational Techniques in Information and Communication Technologies (ICCTICT)*. <https://doi.org/10.1109/icctict.2016.7514550>
- [11] Kotake, H., Haruyama, S., Nakagawa, M., & Seki, K. (2007). BER characteristic of ground-to-train communication system using free-space optics technology. *2007 9th International Conference on Transparent Optical Networks*. <https://doi.org/10.1109/icton.2007.4296271>

- [12] Fathi-Kazerooni, S., Kaymak, Y., Rojas-Cessa, R., Feng, J., Ansari, N., Zhou, M., & Zhang, T. (2018). Optimal positioning of ground base stations in free-space optical communications for high-speed trains. *IEEE Transactions on Intelligent Transportation Systems*, 19(6), 1940–1949. <https://doi.org/10.1109/tits.2017.2741999>
- [13] Kaymak, Y., Rojas-Cessa, R., Feng, J., Ansari, N., & Zhou, M. (2017). On divergence-angle efficiency of a laser beam in free-space optical communications for high-speed trains. *IEEE Transactions on Vehicular Technology*, 66(9), 7677–7687. <https://doi.org/10.1109/tvt.2017.2686818>
- [14] Fan, Q., Taheri, M., Ansari, N., Feng, J., Rojas-Cessa, R., Zhou, M., & Zhang, T. (2018). Reducing the impact of handovers in ground-to-train free space optical communications. *IEEE Transactions on Vehicular Technology*, 67(2), 1292–1301. <https://doi.org/10.1109/tvt.2017.2754960>
- [15] Gordon, G. S., Crisp, M. J., Penty, R. V., Wilkinson, T. D., & White, I. H. (2014). Feasibility demonstration of a mode-division multiplexed MIMO-enabled Radio-Over-Fiber Distributed Antenna System. *Journal of Lightwave Technology*, 32(20), 3521–3528. <https://doi.org/10.1109/jlt.2014.2313649>
- [16] Taheri, M., Ansari, N., Feng, J., Rojas-Cessa, R., & Zhou, M. (2017). Provisioning internet access using FSO in high-speed rail networks. *IEEE Network*, 31(4), 96–101. <https://doi.org/10.1109/mnet.2017.1600167nm>
- [17] Leitgeb, E., Plank, T., Pezzeri, P., Kraus, D., & Poliak, J. (2014). Integration of FSO in local area networks - combination of optical wireless with WLAN and DVB-T for last mile internet connections. 2014 19th European Conference on Networks and Optical Communications - (NOC). <https://doi.org/10.1109/noc.2014.6996839>
- [18] Son, I. K., & Mao, S. (2017). A survey of Free Space Optical Networks. *Digital Communications and Networks*, 3(2), 67–77. <https://doi.org/10.1016/j.dcan.2016.11.002>
- [19] Nakamura, K., Nakagawa, S., Matsubara, H., Tatsui, D., Seki, K., Haruyama, S., & Teraoka, F. (2014). Development of Broadband Telecommunications System for Railways using Laser Technology. *Electrical Engineering in Japan*, 190(3), 45–56. <https://doi.org/10.1002/eej.22445>
- [20] Talib, R., Abdullah, M. F., Malekmohammadi, A., & Abdullah, M. K. (2010). A new multi-slot and multi-level coding technique for high capacity communication system. 2010 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE). <https://doi.org/10.1109/apace.2010.5719766>
- [21] 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 European Conference on Networks and Optical Communications, Newcastle upon Tyne, UK, 2011, pp. 161-164.
- [22] A. Kaur, N. Sharma and J. Singh, "Performance Analysis of Free Space Optical Communication Systems for High-Speed Trains," 2019 10th International Conference on Computing, Communication and Networking Technologies (ICCCNT), Kanpur, India, 2019, pp. 1-6. <https://doi.org/10.1109/ICCCNT45670.2019.8944665>.
- [23] Abdullah, M. F., & Bong, S. W. (2014). Adaptive differential amplitude pulse-position modulation technique for optical wireless communication channels based on Fuzzy Logic. *IET Communications*, 8(4), 427–432. <https://doi.org/10.1049/iet-com.2013.0443>
- [24] W. A. Mabrouk, M. F. L. Abdullah and M. S. M. Gismalla, "Geometric Loss Analysis for Single Curve Track FSO Ground to Train Communications Link," 2021 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE), Penang, Malaysia, 2021, pp. 1-4, <https://doi.org/10.1109/APACE53143.2021.9760629>
- [25] Bilgi, M., & Yuksel, M. (2010). Multi-transceiver simulation modules for free-space optical mobile ad hoc networks. *SPIE Proceedings*. <https://doi.org/10.1117/12.851756>
- [26] Noor, N. H., Naji, A. W., & Al-Khateeb, W. (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)*. <https://doi.org/10.1109/iconspace.2011.6015903>