ASIAN JOURNAL OF ELECTRICAL AND ELECTRONIC ENGINEERING
Vol. 2 No. 2 2022
E-ISSN: 2785-8189

Performance Analysis of a Hybrid Free Space Optics/ Visible Light Communication Systems

Siti Hajar Ab Aziz [1,3]*, Norhanis Aida M. Nor[2], M. Shahnan Zainal Abidin[3]

[1]*Communication Technology Section,*
Universiti Kuala Lumpur British Malaysian Institute, Kuala Lumpur, Malaysia
[2]*Dept. of Science in Engineering, Faculty of Engineering,*
International Islamic University Malaysia, Kuala Lumpur, Malaysia
[3]*Dept of Electrical and Computer Engineering, Faculty of Engineering,*
International Islamic University Malaysia, Kuala Lumpur, Malaysia

*Corresponding author: hajaraziz@unikl.edu.my

(Received: 14th August 2022; Accepted: 26th August 2022)

Abstract— A hybrid free space optical (FSO)/visible light communication (VLC) system is a remarkable wireless technology for overcoming the last mile gap and for future broadband wireless communication. In detail, this research examines the hybrid FSO/VLC system performance using Optisystem 19 software. The system performance of the wireless hybrid FSO/VLC is evaluated using the bit error rate, quality factor, and eye diagram for weak and strong turbulence regimes referring to the Gamma-Gamma atmospheric turbulence channel. At BER of 10^{-9} the maximum attainable distances are 1.3 km and 1.8 km for 0 dBm and 5 dBm transmitted power in clear weather, respectively. However, when the transmit power reduces to -5 dBm, the measured BER drops to 8×10^{-3} with a distance of 1 km link range. Moreover, when the power increases from 0 dBm to 5 dBm, the distance of the connection between Tx and Rx can be extended from 1.1 km and 1.9 km under weak turbulence conditions at the target BER of 10^{-9}. In contrast, at the same target of BER, only 5 dBm of transmitted power managed to capture the signal at a distance of 1.7 km for strong turbulence conditions. This result can be the benchmark research to investigate and identify the best strategies for validating future experimentation difficulties.

Keywords: *Free space optics (FSO), Visible light communications (VLC), Atmospheric turbulence, and Hybrid FSO/VLC.*

1. INTRODUCTION

The growth of wireless devices and technologies is swift and dynamic due to the high demand for reliable, seamless, and high-speed connectivity. Cisco Annual Internet Report forecasted in [1] that the world will have 5.3 billion cybercitizens, 14.7 billion machine-to-machine (M2M) applications, 29.3 billion networked devices, and 628 million public Wi-Fi hotspots in 2023. This increment is due to greater access to smart devices such as smartphones and deployed wearable devices. Most of the available wireless technologies/devices, such as Wi-Fi, cellular and Bluetooth, are based on radio frequency (RF) transmission technology, which cannot satisfy the demand for data transfer, backhaul issues and transmission interruption [2]. This will lead to fine-grained traffic and spectrum crunch, specifically at the "last-mile" and "last meter" access linkages. Even though there are various advancements in RF technology, the accessible RF spectrum is significantly congested [3]. Optical wireless communication (OWC) is one possible solution, complementary to RF wireless systems, which enables the fastest and most reliable data exchange in specific applications indoors and outdoors, mainly to alleviate the pressure on the RF spectrum crisis. The applications include very short-range (mm range), outdoor intra-building linkages (a few km range), and inter-satellite communication (4500 km range). OWC are classified into three main categories based on their operating wavelength: ultraviolet light (100 nm – 400 nm), visible light (380 nm – 780 nm), and infrared light (IR) (800 nm – 2500 nm) [2].

Well known as one of the matured OWC technology, the free space optics (FSO) communications system is commonly utilized for outdoor communications links. It has frequently been employed in various applications, including the resolution of the last-mile bottleneck issue, backhaul for cellular systems, inter-building connections, broadband access in remote locations, and wireless metropolitan area network extensions [3], [4]. This is because of the unique features offered by FSO systems, which include a high data rate with almost unlimited bandwidth, a superior level of security against eavesdropping, low cost of deployment, and resilience to RF-induced electromagnetic interference. Regardless of the benefits, the FSO link is impacted by atmospheric phenomena, including snow, fog, smog, rain and turbulence. In clear weather, air turbulence becomes the main challenge as it generates random variations in the phase and intensity of the light signal, which ultimately results in system performance degradation [5], [6]. There are various number of mitigation schemes to mitigate the impact of atmospheric conditions, including*(i)* coding; *(ii)* aperture averaging; *(iii)* relay-assisted; *(iv)* complex modulation; *(v)* diversity; and *(vi)* adaptive threshold detection [3], [7].

Therefore, this research investigates the performance of hybrid FSO/VLC systems for interconnection between outdoor and indoor environments under weak and strong turbulence conditions using the Optisystem 19 software. The maximum distance under turbulence conditions is investigated based on the transmitted optical power of 0 dBm and 5 dBm. Then, the system's performance is analyzed and evaluated in weak and strong turbulence conditions as specified by the *Q*-factor, bit error rate (BER), and eye diagrams.

The remainder of this paper is presented as follows: Section 2 explains a hybrid FSO/VLC system under turbulence conditions. The findings are presented concisely in Section 3, along with the effects of various laser optical power approaches. Lastly, the conclusion is presented in Section 4.

2. THE HYBRID FSO/VLC LINK

2.1 Overview of the hybrid FSO/VLC system

The benefits of OWC, mainly FSO and VLC technologies, enable the possibility of merging them into a hybrid optical wireless network [8]. The optical-optical wireless hybrid approach is a feasible alternative for enhancing seamless connectivity and fulfilling user quality of service (QoS) requirements for high wireless data rates. The authors [3], [10], [12] claimed that both FSO and VLC technologies are strong enough to endure bandwidth bottleneck issues in the interconnection of outdoor to indoor networks, particularly in highly dense urban areas with a high number of access points. The first demonstration of the hybrid FSO/VLC was done by [13], specifically for tomorrow's indoor wireless broadband access by integrating the outside FSO and the inside VLC system through a single-mode fibre (SMF). The author achieved bit rates up to 300 Mbit/s utilizing 16- quadrature amplitude modulation (QAM) or 32 -QAM- single carrier with frequency domain equalization (QAM-SC-FDE) modulation [13]. Next, a hybrid FSO/VLC heterogeneous interconnection was demonstrated to overcome the wireless network reliability issue and electromagnetic interference levels in a hybrid RF/FSO system [3], [8]. Recently, a lower-cost and portable hybrid RF/VLC/FSO system for indoor communication was demonstrated in [10]. The results showed a data rate of 1 kbps at a 4 cm transmission link. They suggested FSO as a backbone network solution in the last mile access linkage located at the various lighting points in multiple users' enclosed rooms within a building.

To the best author's knowledge, there is still a lack of investigation on FSO/VLC hybrid systems in the literature, with just five experimentally based publications. In addition, the system's performances under turbulence conditions have not been investigated using any simulation tool. This work is a preliminary study investigating and identifying the best strategies for validating future experimentation difficulties.

2.2 Atmospheric Turbulence Influence

Atmospheric turbulence is a random occurrence resulting from atmospheric variations in pressure and temperature, which produce variations in the atmosphere's refractive index and transmission medium [5]. Due to the redistribution of signal energy, this occurrence will lead to fluctuations in the received signal's strength and phase. This inhomogeneity of the two factors creates a turbulent cell that either constructively or destructively interferes with the propagating beam. The parameter $C_n^2$of the refractive index structure measures the turbulence intensity and is acquired from [5], [7], [14]:

$$C_n^2 = (86 \times 10^{-16} \times \frac{P}{T^2})^2 C_T^2 \,, \tag{1}$$

where C_T^2 denotes the temperature structure constant based on the general 2/3 power temperature law, and *P* denotes the atmospheric pressure in millibar. *T* denotes the absolute temperature in Kelvin. Furthermore, the Rytov variance, $\boldsymbol{\sigma_R^2}$ characterizes the turbulence regime, which is derived from [5], [7], [14].

$$\sigma_R^2 = 1.23\, C_n^2 k^{\frac{7}{6}} L^{\frac{11}{6}}, \tag{2}$$

where *L* denotes the propagation path length, and *k* represents the optical wave. Derived from (2), C_n^2 computes the refractive index fluctuation of strong turbulence (10^{-12} $m^{-2/3}$) and weak turbulence(10^{-16} $m^{-2/3}$).

2.3 Simulation Design and Setup Analysis

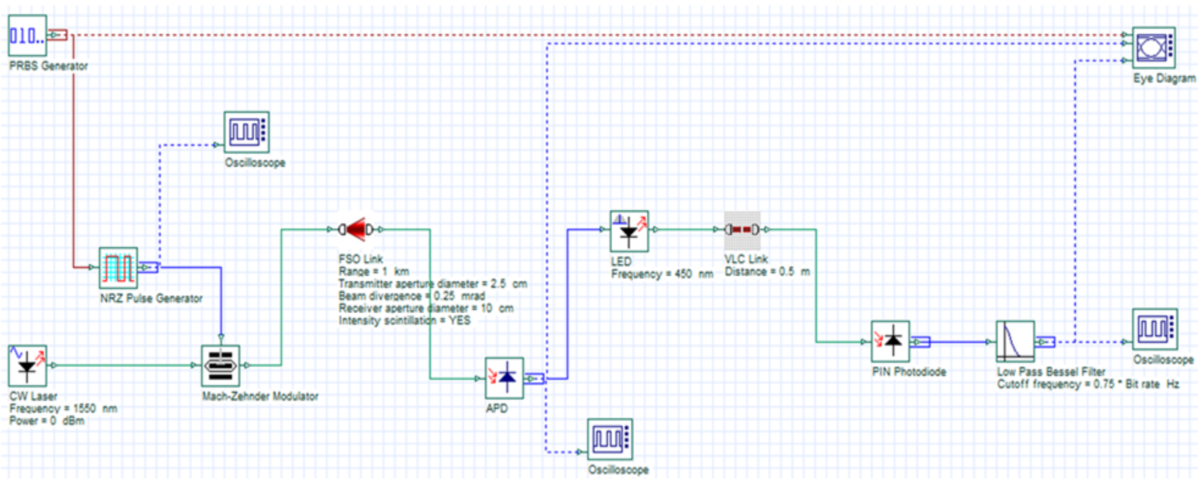

Fig. 1. The hybrid FSO/VLC link

The proposed hybrid FSO/VLC system is illustrated in Fig. 1. The links consist of 2 sections: the FSO link and the VLC link, which are interconnected with SMF fibre. At the transmitter (Tx) side, a BER tester with a 1 Gbps data rate was modulated using the non-return-to-zero on-off keying (NRZ-OOK) format to generate the electrical signal. The electrical signal and the optical source were modulated in the Mach-Zehnder (MZ) modulator, functioning 1550 nm with 0 dBm output power. Then, the modulated optical input signal is transmitted to the FSO channel of the linkspan of 1 km.

At the FSO channel, the optical Tx and receiver (Rx) aperture diameters were set to 2.5 cm and 10.0 cm, respectively. The beam divergence value was 0.25 mrad, consistent with most FSO commercial systems. Next, an avalanche photodiode (APD) was used at the Rx to detect and demodulate the light signal before being coupled with the direct current (DC) signal and applied to the white LED.

The Tx and Rx of the VLC system are in a line of sight (LOS) condition to optimize the light signal quality without considering the reflected light or ambient light from surrounding walls. At the VLC link, a single LED was considered the Tx, operated at the peak wavelength of 450 nm and biased at ~350 mA following the commercial parameters [15]. The gap between the LED and the detector was 0.5 m. The silicon biased detector ranging from 350 to 1100 nm was used for signal detection and demodulation before it was passed to the low-pass Bessel filter with a 0.75 GHz cut-off frequency for signal filtering.

Lastly, the demodulated signal was passed to the eye diagram analyzer for system investigation and evaluation. In order to investigate the robustness of the proposed system over turbulence, the turbulence regime was considered at the FSO channel, classified as a weak condition ($C_n^2 = 5 \times 10^{-15} m^{-2/3}$) and a strong condition ($C_n^2 = 5 \times 10^{-12}\, m^{-2/3}$). The hybrid FSO/VLC link system was constructed according to the link parameters of a typically practical and commercial FSO system, depicted in Table 1.

Table 1: The hybrid FSO/VLC system parameters

Parameters	*Value*
Data rate	*1 Gbps*
Continuous Wave (CW) Laser	
Operating wavelength	*1550nm*
Power	*0 dBm*
FSO Link	
Range	*1km*
Transmitter aperture diameter	*2.5cm*
Beam divergence angle	*0.25mrad*
Receiver aperture diameter	*10cm*
APD photodiode	
Gain	*3*
Responsivity	*1A/W*
Dark current	*10 nA*
LED	
Wavelength	*450nm*
Electron lifetime	*1 ps*
RC constant	*1 ps*
VLC	
Distance	*0.5m*
Transmitter half (1/2)-angle	*60°*
Irradiance half (1/2)-angle	*20°*
Incidence half (1/2-angle	*20°*
PIN photodiode	
Responsivity	*1A/W*
Dark current	*10nA*

3. RESULTS AND DISCUSSIONS

The hybrid FSO/VLC system is evaluated using the quality metric (*Q*-factor), BER and eye diagram. Typically, it is used to evaluate the performance of optical fibre communication (OFC) and optical wireless communication (OWC), also related to the electrical signal-to-noise ratio (SNR) and BER. Additionally, Q-factor represents the SNR for digital optical communication. Remarkably, the greater the *Q*-factor, the better the quality of the signal. The *Q*-factor from BER is based on [16]:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right), \quad (3)$$

where *erfc* represents the complementary error function, the *Q*-factor is calculated by [4] :

$$Q = \frac{V_H - V_L}{\sigma_H - \sigma_L}, \quad (4)$$

where V_L and V_H represent the mean value of the low and high voltages received, σ_H represents high standard deviation and σ_L is a low standard deviation.

The eye diagrams and Q - factors at the aforementioned values of no turbulence, weak turbulence and strong turbulence are depicted in Fig. 2. Typically, the quality of the hybrid system deteriorates according to the turbulence strength. Under a clear atmospheric condition, the *Q*-factors are 2.41, 7.17 and 13.29 for -5 dBm, 0 dBm and 5 dBm transmitted power. We introduced the turbulence to the FSO channel with the same range of transmitted power. For $C_n^2 = 5 \times 10^{-15} m^{-2/3}$(weak turbulence), the *Q*-factors are 3.0, 6.92, and 12.76 for transmitting power of -5 dBm, 0 dBm, and 5 dBm, correspondingly. Concurrently, the eye-opening and *Q*-factor significantly degraded as the C_n^2 increases to $5.0 \times 10^{-12} m^{-2/3}$, which is classified under strong turbulence. The figure shows that the eye diagram is completely shut at -5 dBm transmit power. In order to capture the signal, the transmit power should be increased to at least 0 dBm with a *Q*-factor of 3.28. Moreover, the *Q*-factor and eye-opening will be much better as the transmit power increases. These results show that the propagating optical wave suffers more intensity variations at higher degrees of turbulence resulting in a significantly broader and random optical beam pattern at higher intensity levels[17]. Based on the results, signal distortion increases as the Q-factor decreases, resulting in a narrower eye-opening.

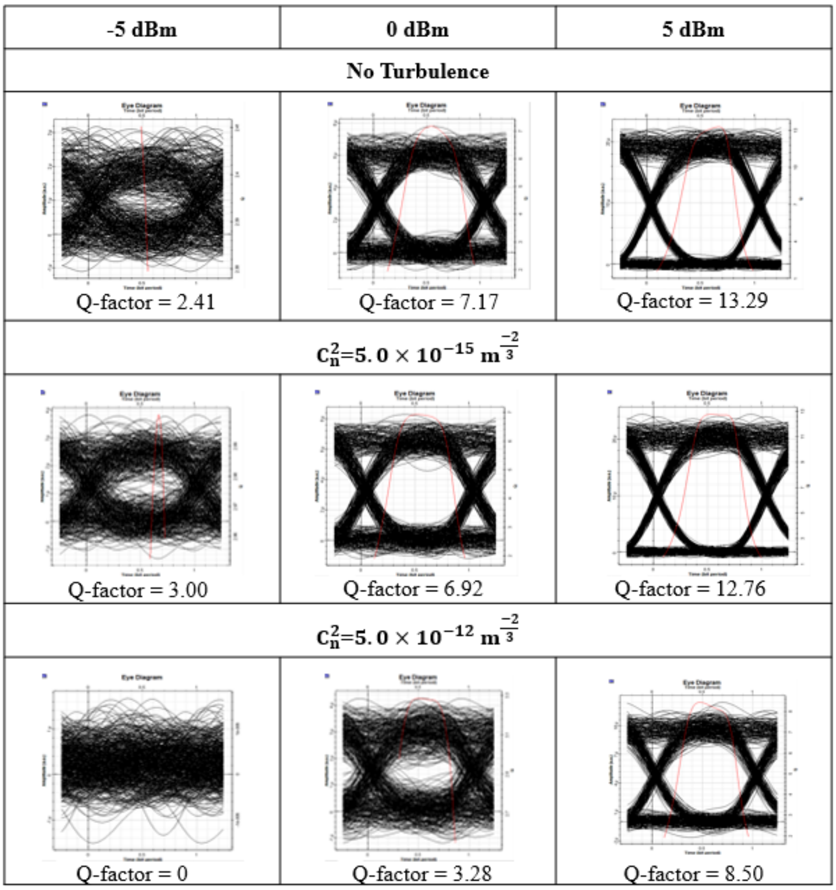

Fig. 2. Eye diagrams and the *Q*- factor at different atmospheric conditions

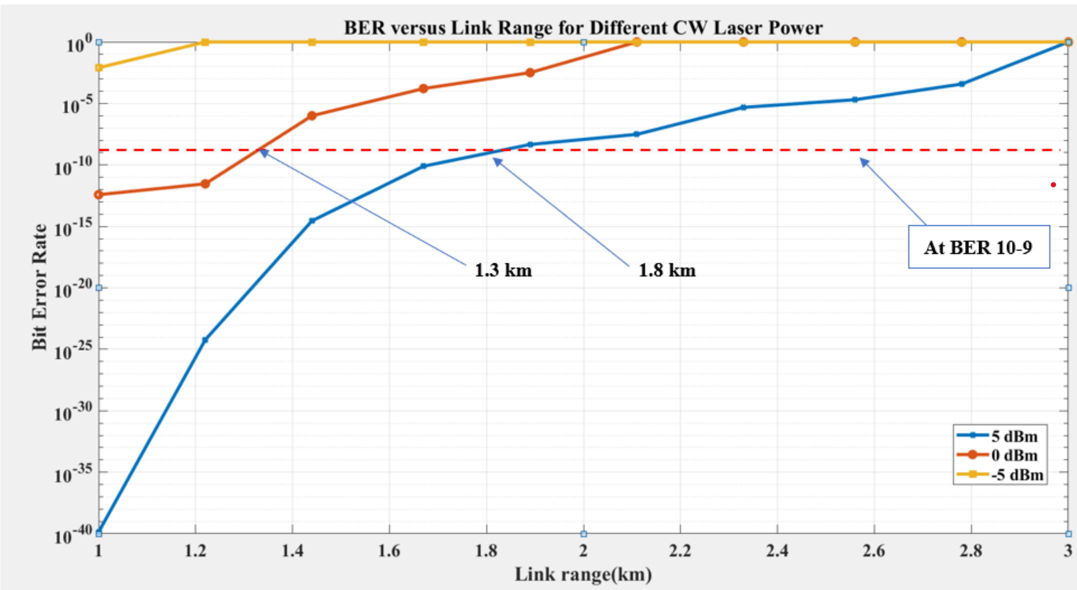

Fig. 3. The BER performance in a clear atmosphere

Then, we analyzed the result of transmitting optical power over the link distance. Fig. 3 compares the transmitted optical power for BER performance against the link distance, ranging from 1 km to 3 km in a clear atmosphere. The minimum required BER for telecommunication applications is 10^{-9}. As shown in Fig. 3, at a BER of 10^{-9}, the signal can be transmitted up to distances of 1.3 km and 1.8 km for 0 dBm and 5 dBm transmitted power, respectively. Despite, when we used -5 dBm transmitted power, no signal was detected at the Rx when the link range was more significant than 1 km. For 5 dBm transmit power, the links can be extended up to 2.8 km with a BER of ~10^{-3}. This result proves that the BER performance increases as the transmitted power increases, which yields to increases in the linkspan.

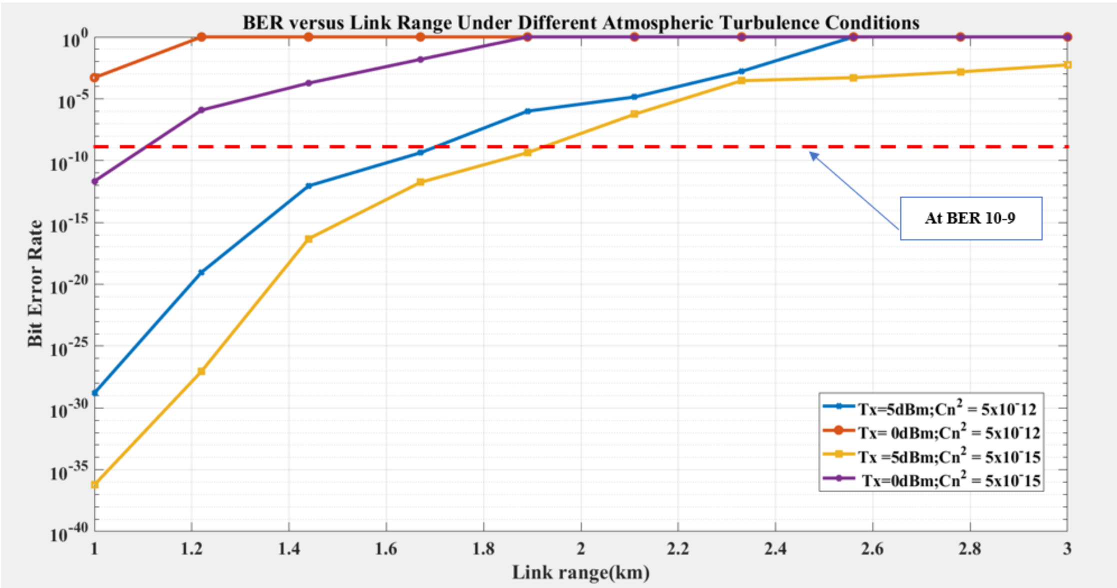

Fig. 4. The BER under turbulence influences

Next, we analyzed the system performance under weak and strong turbulence for 0 dBm and 5 dBm transmitted power to examine the maximum achievable distances at the FSO link. Fig. 4 shows the effect of BER against the link range under weak ($C_n^2 = 5\times 10^{-15} m^{-2/3}$) and strong ($C_n^2 = 5 \times 10^{-12} m^{-\frac{2}{3}}$) turbulence regimes. Theoretically, the link range between the Tx and the Rx will be lengthened as the power increases. In Fig. 4, we prove that as the power increases from 0 dBm to 5 dBm, the distance increases from 1.1 km to ~1.9 km at BER of 10^{-9} in weak turbulence form. Under strong turbulence, at BER of 10^{-9}, the signal can only be captured when the transmit power is 5 dBm, with the link distance is 1.7 km. As illustrated in the figure, only the FSO link under weak turbulence with 5 dBm power managed to obtain 3 km linkspan with BER of 10^{-3}. It can be concluded that by increasing the transmitted optical power, there is an improvement in the BER result and link distance for all weather conditions, thus enhancing overall system performance. However, the penalty increases in cost as the power increases. In addition, the average BER decreases as the scintillation index increases. Hence, a mitigation strategy is vital to increase the transmission range.

4. CONCLUSION

This work presented a performance analysis of hybrid optical wireless systems, particularly FSO/ VLC systems, in the presence of atmospheric turbulences. The impact of transmitted optical power in clear atmospheric, weak, and strong turbulence conditions was carried out to assess the hybrid system's performance. The performance was quantified using the Q-factor, BER and eye diagram. In clear weather, the achievable distances were 1.3 km and 1.8 km for 0 dBm and 5 dBm transmitted optical power at a BER of 10 -9. However, with -5 dBm transmitted power, the BER was reduced to 8×10 -3 for a 1 km range. Moreover, when Tx transmits 5 dBm power, the BER is 10^{-37} for weak turbulence and 10^{-29} for strong turbulence in 1 km range. At 3 km, only the FSO link under weak turbulence with 5 dBm power was managed to obtain the result. Therefore, we need to address an effective technique to enhance the hybrid FSO/VLC systems, considering both FSO and VLC links limitations.

ACKNOWLEDGMENT

This work has been sponsored by the Ministry of Higher Education Malaysia (MOHE) under the Fundamental Research Grant Scheme (FRGS) RACER/1/2019/TK04/UIAM//3 and Universiti Kuala Lumpur British Malaysian Institute.

REFERENCES

[1] Cisco, "Cisco: 2020 Annual Internet Report," Computer Fraud & Security, 2020.

[2] M. Z. Chowdhury, M. K. Hasan, M. Shahjalal, M. T. Hossan, and Y. M. Jang, "Optical Wireless Hybrid Networks: Trends, Opportunities, Challenges, and Research Directions," IEEE Communications Surveys and Tutorials, pp. 930–966, Apr. 2020.

[3] P. Pesek, S. Zvanovec, P. Chvojka, Z. Ghassemlooy, and P. A. Haigh, "Demonstration of a hybrid FSO/VLC link for the last mile and last meter networks," IEEE Photonics Journal, 2019.

[4] N. A. and S. Siti Hajar Ab Aziz, "Performance Analysis of Free Space Optics Link Under the Effect of Rain Attenuation," 2021.

[5] L. Cang, H. K. Zhao, and G. X. Zheng, "The Impact of Atmospheric Turbulence on Terahertz Communication," IEEE Access, vol. 7, pp. 88685–88692, 2019.

[6] N. A. M. Nor, et al., "Experimental all-optical relay-assisted FSO link with regeneration and forward scheme for ultra-short pulse transmission," Optics Express,p. 22127, 2019.

[7] N. A. M. Nor et al., "Experimental investigation of all-optical relay-assisted 10Gb/s FSO link over the atmospheric turbulence channel," Journal of Lightwave Technology, pp. 45–53, Jan. 2017.

[8] Z. Huang et al., "Hybrid optical wireless network for future SAGO-integrated communication based on FSO/VLC heterogeneous interconnection," IEEE Photonics Journal, pp. 1–10, 2017.

[9] X. Li, Z. Ghassemlooy, S. Zvanovec, R. Perez-Jimenez, and P. A. Haigh, "Should Analogue Pre-Equalizers be Avoided in VLC Systems?," IEEE Photonics Journal, pp. 1–14, 2020.

[10] I. E. Lee et al., "Design of a hybrid free space optical and visible light communication system for indoor wireless data broadcasting," Journal of Physics: Conference Series, vol. 1432, no. 1, 2020.

[11] S. R. Teli, S. Zvanovec, and Z. Ghassemlooy, "Optical internet of things within 5g: Applications and challenges," Proceedings - 2018 IEEE International Conference on Internet of Things and Intelligence System, IOTAIS 2018, pp. 40–45, 2019.

[12] B. G. Guzman et al., "Reflection-based relaying techniques in visible light communications: Will it work?," IEEE Access, pp. 80922–80935, 2020.

[13] Z. Zheng, L. Liu, T. Chen, and W. Hu, "Integrated system of free-space optical and visible light communication for indoor wireless broadband access," Electronics Letters, pp. 1943–1944, 2015.

[14] N. S. Sadzali, N. A. M. Nor, and S. H. B. A. Aziz, "Performance Analysis of FSO Systems using Different Modulation Techniques under the Influence of Atmospheric Turbulence," pp. 397–400, 2021.

[15] O. O. Semiconductors, "Golden DRAGON Datasheet Version," pp. 1–21, 2016.

[16] S. Burdah et al., "Performance analysis of Q factor optical communication in free space optics and single mode fiber," Universal Journal of Electrical and Electronic Engineering, pp. 167–175, 2019.

[17] N. A. M. Nor et al., "10 Gbps all-optical relay-assisted FSO system over a turbulence channel," 2015 4th International Workshop on Optical Wireless Communications, IWOW 2015, no. September, pp. 69–72, 2015.