Performance Analysis and Evaluation of Inter-Satellite Optical Wireless Communication System (IsOWC) from GEO to LEO at Range 45000 km

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***Abstract*—The importance of free-space optical (FSO) communication has increased during the last decade, introducing its unique features such as its high data rate, license-free spectrum, ease of deployability, and low power consumption. In the future, communication between low earth orbit (LEO) and geostationary earth orbit (GEO) satellites will be commonly established by using inter-satellite optical wireless communication (IsOWC) systems. That enables GEO satellites to relay information to and from LEO satellites and fixed Earth stations that otherwise cannot transmit/receive data permanently. IsOWC systems are the most effective application of the FSO, and they will be favorited shortly because of their features. In this work, we established an IsOWC between GEO and LEO satellites at a distance of 45000 km to achieve a target bit error rate (BER) equal to 10^{-6}. Furthermore, we proposed an IsOWC system with suitable operating wavelengths. Physical techniques such as the multi-input multi-output (MIMO) technique and a wave division multiplexing (WDM) technique are employed.**

***Index Terms*—Free-space optical communication, inter-satellite optical wireless communication, multi-input multi-output, Q factor, wave division multiplexing.**

I. Introduction

FOR a long time ago, the need for transferring messages between two points with a reliable, secure, and fast method of transmitting messages was on top of importance. Later on, the Ancients realized that the quickest way of conveying information was the light. Consequently, Ancient Greece created a network of light towers at the peak of mountains to establish communications. Semiconductor devices, e.g., laser diode, were among the most significant innovations in science and technology, producing a narrow beam of light in invisible bands (1280–1620 nm) or visible spectrum (400-700 nm). Many optical carrier frequencies have been specified and standardized in the band of 200 THz (1550 nm) and 350 THz (850 nm) as transmission bands for optical communications [1]. Unlike radio frequency (RF) bands, these frequency bands are free of any license requirements around the globe also cannot interfere with satellite or other RF equipment. These bands became commercially available today in FSO systems that operate in the near-infrared (IR) wavelength range between roughly 750 nm and 1600 nm [2]. Optical wireless communication (OWC) is one of the essential applications of communications based on the laser. Hence, OWC can be implemented in deep space as an optical link due to the absence of atmospheric turbulence.

Moreover, several satellite-to-satellite communication experiments have been performed by the European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), German Space Agency (DLR), and National Aeronautics Space Agency (NASA) [3]. For example, in 2001, IsOWC was performed between the satellites ARTEMIS and SPOT four at a rate of 50 Mbps placed in GEO and LEO, respectively [4]. Another IsOWC demonstration campaign was held by the end of 2014 to prove the European Data Relay Satellites (EDRS) system project concept. In November 2014, the first data transmission was performed between Sentinel 1A Satellite at the LEO and Alphasat satellite at the GEO. Then in December 2014, the campaign was finished with link performances that exceeding expectations [5]. By the end of 2016, EDRS started to offer LEO to GEO services for about 40 optical links daily. Today in 2021, more than 15000 links were successfully implemented [6], [7].

The effect of several parameters on IsOWC like Tx/Rx aperture size, transmitted power, data rate, and different wavelengths up to the communication range 6000 km was studied by Kripa Vimal and Shanthi Prince [8]. In the IsOWC system design, the transmitter side consists of a continuous wave (CW) laser used as the optical source, pseudo-random bit sequence generator, and return to zero (RZ) or non-return to zero (NRZ) pulse generator is used to give modulating electrical signal input. However, all the simulation models in this paper use the NRZ encoding scheme to obtain a maximum distance of up to 45000 km [13]. NRZ is a type of on-off Keying (OOK) binary level modulation that represents light is by sending logic “1”. The absence of light is by sending logic “0”. Although the energy of OOK is not highly efficient, it is the most common intensity modulation technique

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used in coherent FSO systems due to its implementation simplicity, low power requirements, and reasonable cost. However, FSO coherent systems still need digital signal processing with high speed and complex circuits [9]. One of the benchmarks that shows the quality of the communication system is the signal to noise ratio (SNR), the relation between the OOK in the case of NRZ and the SNR can be represented as follows [10]:

$$OOK - NRZ = \frac{1}{2}\, erfc\left(\frac{1}{2\sqrt{2}}\sqrt{SNR}\right) \tag{1}$$

The error probability is given as [11], [12]

$$P_e = p(0)\int_{i_{th}}^{\infty} p(i/0)di + p(1)\int_{0}^{i_{th}} p(1)di \tag{2}$$

p(0) and *p(1)* are probabilities of "1" and "0". The margin probabilities are defined as:

$$p(i/0) = \frac{1}{2\pi\sigma^2}\exp\left(\frac{-i^2}{2\sigma^2}\right) \tag{3}$$

$$p(i/1) = \frac{1}{2\pi\sigma^2}\exp\left(\frac{-(i-I_p)^2}{2\sigma^2}\right) \tag{4}$$

Assuming probability of $p(0) = p(1) = 0.5$; hence, the point of optimum threshould is 0.5 $\sqrt{E_b}$, then the conditional error probability will be

$$P_e = Q\left(\frac{0.5\sqrt{E_b}}{2\sigma}\right) \tag{5}$$

Where Q(.) is the Marcum's Q-function, that is, the area under the Gaussian Curve. The Additive white Gaussian noise (AWGN) input has double-sided PSD, $\sigma^2 = {N_0}/{2}$

Therefore by substituting the standard deviation σ in (4) gives

$$P_{e\_bit\_OOK} = Q\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{6}$$

Modulation scheme mach-zehnder modulator (MZM) is used as an external and alternative optical modulator since it is difficult to modulate laser directly, MZM output is connected to transmission aperture. The modulated signal is sent through an optical wireless channel. At the receiver side, an avalanche photodetector (APD) is utilized. Since APD gives a better Q factor than positive-intrinsic-negative (PIN) photodetector [13], [14].

Multiple input multiple output techniques (MIMO) is a method that utilizes a set of antennas for transmitting and receiving signals at each end of an optical link for multiplying the capacity, using multiple transmission and reception to exploit multipath propagation. It is one of the Diversity techniques utilized in wireless communication systems to enhance performance and increase resilience, reliability, and data rate over wireless channels [15]. Optical MIMO and Radio Frequency (RF) MIMO systems almost have equivalent performance. It increases the channel capacity of the system linearly with the number of transmitting antennas. Many copies of the transmitted signal are received using multiple communication channels [16], [17].

Wave Division Multiplexing (WDM) is a way to increase signal carrying capacity such that multiple optical signal carriers at several wavelengths are aggregated to enhance the data rate. Every carrier is modulated separately using electrical bit sequence streams to be transmitted utilizing the same optical link. Most wavelength division multiplexers (WDMs) employ one of several technologies: arrayed waveguide grating (AWG), Y-junction couplers, micro-ring resonators, multimode interference (MMI) couplers, two-mode interference (TMI) couplers, and filters-based four-channel wavelength division multiplexer to increase data rate [18], [19].

In 2017 a research was held to show data transfer between two satellites via the optical link up to 5000 km by utilizing a dense wavelength division multiplexing (DWDM) scheme [20]. Then followed by contribution showed data transportation of 16 different wavelengths using WDM up to communication range 25000 km [21].

In this paper, to enhance the IsOWC Q factor between GEO and LEO satellites at the maximum achievable distance of 45000 km [22], we selected suitable parameters to achieve the best IsOWC performance. Furthermore, we implemented the MIMO technique to understand its effect on the IsOWC. Moreover, the WDM technique is employed to enhance the IsOWC Q factor.

II. System Model

This paper simulates IsOWC between GEO and LEO satellites at a range of 45000 km. Section A presents the effect of different wavelengths on IsOWC; then, the 4X4 MIMO technique is investigated in section B. Finally, the WDM technique is studied in section C. The aim is to enhance the IsOWC performance in terms of Q factor and Bit error rate and achieve a data rate higher than the data rate of 1.8 Gbps achieved in the EDRS-C satellite launched in late 2019 by ESA and Airbus [23]. At the high altitude of the satellites being above the atmospheric layers, no turbulence may affect the wireless channel due to atmospheric effects [24]; therefore, free space loss is considered to be 0 dB/km in our models. Hence the alignment between the transmitter and receiver might not be perfect in IsOWC links. So we assumed the pointing error angles value to be 0.75 μrad, the transmitter and the receiver efficiency equal to 90%, and apertures diameter equal to 30 cm (1/10 of the aperture size required in case of RF signal) to improve Q factor and BER at 45000 km distance [8], [14]. The mathematical representation of IsOWC is as follows [12]:

$$\mathrm{P_r{=}P_t}\eta_t\eta_r(\lambda/4\pi \mathrm{Z})^2\mathrm{G_tG_rL_tL_r} \tag{7}$$

Where P_r is the received power, P_t is the optical power of the transmitter, η_t is the efficiency of the optical transmitter, η_r is the efficiency of the optical receiver, λ is the wavelength, *Z* the propagation distance, G_t is the aperture gain of the transmitter, G_r is the aperture gain of the receiver, L_t pointing loss factor of the transmitter, L_r pointing loss factor of the receiver. While the term $(\lambda/4\pi R)^2$ expresses the free space path loss, other losses like scintillation can be neglected due to the absence of the atmosphere. Moreover, other equations clarify the relation between the aperture diameter of the transmitter and the receiver

TABLE II
PARAMETERS USED IN SIMULATION [8], [14], [20]

Parameter	Value
Aperture diameter Tx	30 cm
Aperture diameter Rx	30 cm
Input power	2.2 watt
Wavelength	850 nm, 1550 nm
Data Rate	2 Gbps
Sequence Length	32 bits
Samples Per bit	64
Transmitter pointing error angle	0.75 µrad
Receiver pointing error angle	0.75 µrad
Transmitter optical efficiency equal	90 %
Receiver optical efficiency equal	90 %

D_t, D_r and the aperture gain of both transmitter and receiver G_t, G_r [25].

$$Gt = \left(\frac{\pi D_t}{\lambda}\right)^2, Gt = \left(\frac{\pi D_r}{\lambda}\right)^2 \tag{8}$$

By substituting (7) in (6) yields

$$\mathrm{P_r}{=}\mathrm{P_t}(D_t D_r/2\pi\lambda \mathrm{Z})^2 \eta_t \eta_r \mathrm{L_t} \mathrm{L_r} \tag{9}$$

Equation (9) clarifies that the received power is inversely proportional to the employed wavelength. Thus when the received power increases, it means that signal to noise ratio increases, enhancing the Q factor.

Since the IsOWC performance between satellites is analyzed in terms of the Q factor and the bit error rate. Therefore, the relationship can be modeled as [8]:

$$BER = \frac{1}{2}\, erfc\left(Q\middle/\sqrt{2}\right) \tag{10}$$

A. Effect of Different Operating Wavelength On IsOWC System

The simulation of IsOWC between GEO and LEO satellites is using the parameters shown in Table I. The laser diodes operating at 850 nm and 1550 nm are chosen because of their features. The 850 nm wavelength has low power density, is highly reliable, requires low operating current, is cheap, and is available in the market. In comparison, the 1550 nm wavelength has a significant advantage: the eye safety since its power density is 50 times higher than that of the 850 nm wavelength, which gives an extra margin up of to 17 dB additional; moreover, its components have a longer lifetime and commonly available parts [25]. An optical transmitter telescope and an optical receiver telescope are assumed to be ideal with gains of 0 dB, and optical efficiency is equal to 1 at each end. Accordingly, an APD photodiode is used as a photodetector at the receiver side, converting the optical signal to an electrical signal. Ordinarily, unwanted frequencies are filtered out using a low-pass Bessel filter [26]. The electrical signal of the bit sequence is regenerated using the 3R regenerator, and the modulated electrical is seen on Eye diagram analysis. BER analyzer is used to analyze the received signal, as shown in Fig. 1.

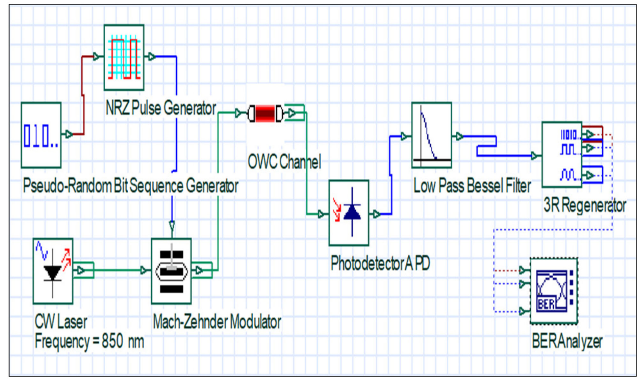


Fig. 1. IsOWC system design using OptiSystem.

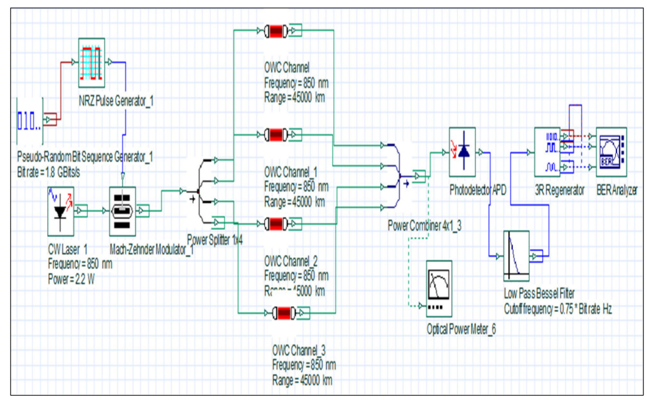


Fig. 2. IsOWC using 4 channels MIMO technique.

B. MIMO Technique Performance in IsOWC

The proposed model uses the same parameters listed in Table 1. Utilizing the same CW laser source at a wavelength of 850 nm in the four wireless channels to investigate the spatial diversity effect in the space between satellites, the output of MZM goes to (1:4) power splitter to divide the input power equally among the four optical wireless channels. Consequently, a (4:1) power combiner at the receiver side to aggregate received power is shown in Fig. 2.

C. WDM Technique Effect in IsOWC

A wavelength, division multiplexing scheme is proposed here, as shown in Fig 3. Conventional WDM was implemented at the transmitter side using four distinct CW laser sources emitting wavelengths 800 nm, 830 nm, 860 nm, and 900 nm, with an input power of 2.2 watt divided 0.55 watt each, multiplexed with 10 GHz of channel spacing. These four wavelengths are multiplexed via (4:1) multiplexer. Input data streams are generated from a 2 Gbps pseudo-random bit sequence generator compared to 1.8 Gbps achieved in the EDRS-C satellite launched in late 2019 by ESA and Airbus [23]. This binary information is converted into an electrical domain using an NRZ line encoder. Each distinct wavelength modulates an independent 2 Gbps information channel using MZM with a 30 dB extinction ratio operating in a push-pull state [27].

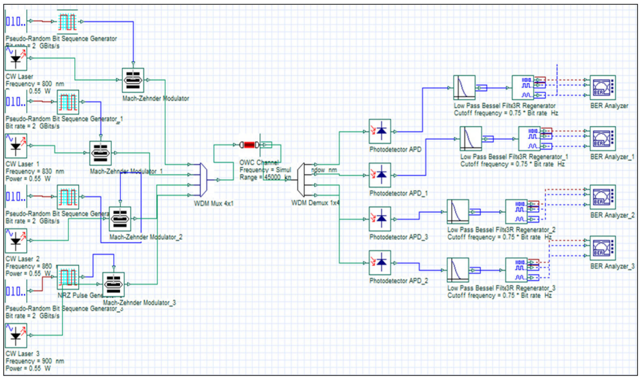


Fig. 3. IsOWC using the WDM technique.

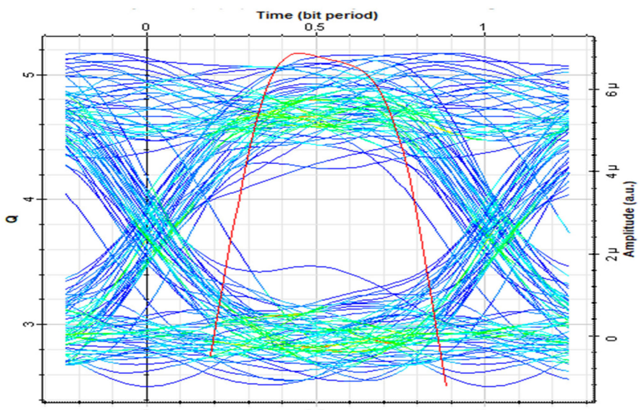


Fig. 4. Eye diagram of IsOWC at the wavelength of 850 nm.

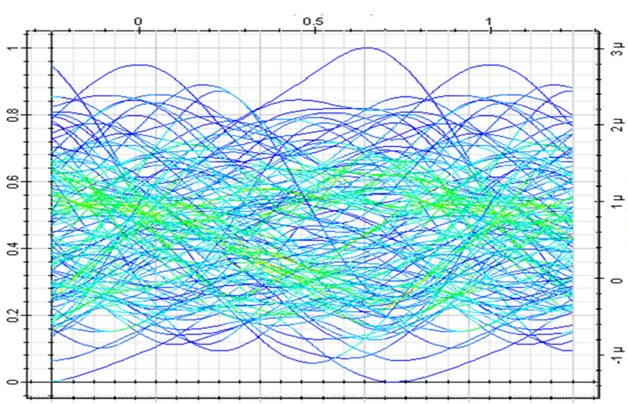


Fig. 5. Eye diagram of IsOWC at the wavelength of 1550 nm

III. Numerical Results

A. 850 nm Vs 1550 nm Wavelengths Effect on IsOWC

Using a wavelength of 850 nm resulted in a received signal with a Q factor equal to 4.3825, BER equal to 5.864×10^{-06}, and an eye diagram of height 1.3833×10^{-06} as shown in Fig. 4. By changing the simulation wavelength from 850 nm to 1550 nm and keeping the rest of the parameters constant as the wavelength increases, the quality factor, and total signal power decrease, as mentioned earlier and clarified in Fig. 5. BER and jitter of the IsOWC system increase gradually at the receiver side at 45000 km, and the Q factor is diminished. From this simulation, the outcome shows that the system has a better Q factor and the total signal power in the case of shorter wavelengths like in the 850 nm wavelength rather than 1550 nm wavelength at a range of 45000 km.

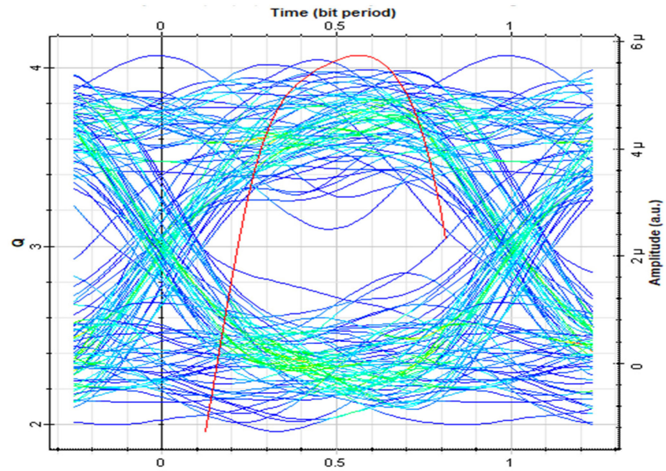


Fig. 6. Eye diagram of Four MIMO channels at wavelength 850 nm.

TABLE II
WDM Technique Results

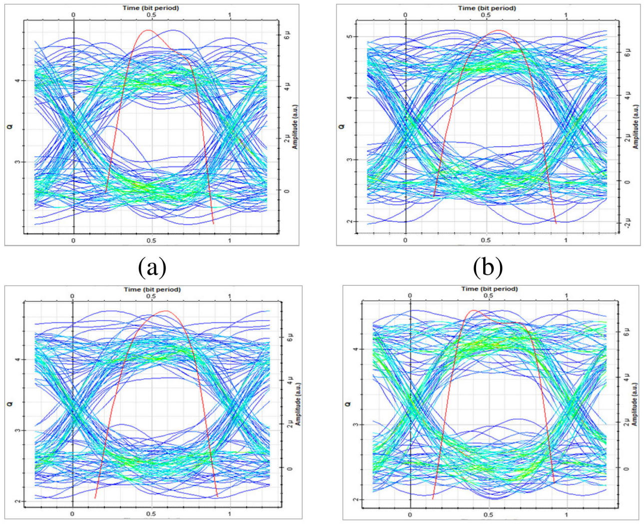
Wavelength (nm)	Q factor	BER	Eye Height
800	4.74494	1.0421×10^{-06}	1.866×10^{-06}
830	4.67306	1.4754×10^{-06}	1.872×10^{-06}
860	4.27279	9.6521×10^{-06}	1.455×10^{-06}
900	4.14466	1.6970×10^{-05}	1.347×10^{-06}

B. Four MIMO Technique Performance in IsOWC

Fig. 6 shows the results of the proposed model by applying the same parameters and utilizing four wireless optical channels that have the exact specifications. The eye diagram of the simulation showed a Q factor of 4.1803, BER 1.45315×10^{-05}, and the eye diagram has a height of 1.29825×10^{-06}. However, the simulation utilized four diverse wireless channels. Therefore, there is no enhancement in the received signal since the spatial diversity feature of the MIMO technique was not helpful here to overcome the channel impairments that result from the turbulence that exists in atmospheric layers since the medium in space is the vacuum.

C. WDM Technique Effect in IsOWC

WDM technique resulted in a better Q factor, less BER, and enhanced the IsOWC link in the range of 800–900 nm, as shown in Table II. Fig. 7 shows the BER analyzer at the receiver side indicates the eye diagram of each wavelength with improved Q factor and reasonable BER. Fig. 8(a) shows the results of the WDM technique using a wavelength range of 800–1600 nm versus Q factor. The figure indicates that shorter wavelengths



(a) (b) (c) (d)

Fig. 7. An eye diagram of the WDM IsWOC system (a) at wavelength 800 nm, (b) at wavelength 830 nm, (c) at wavelength 860 nm, (d) at wavelength 900 nm.

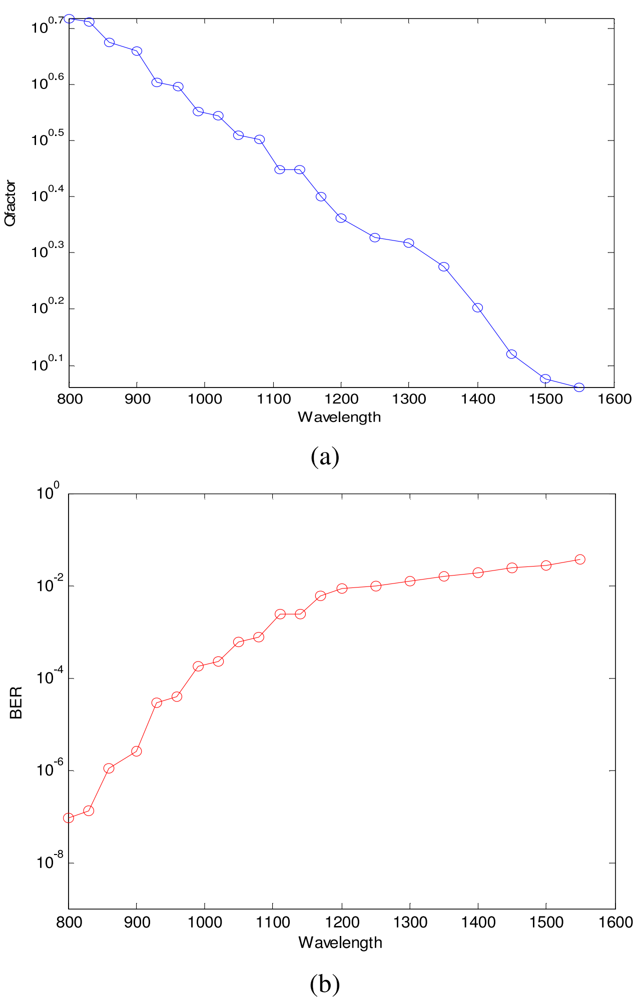


Fig. 8. (a) Wavelength Vs Q Factor in the range of 800–1600 nm, (b) wavelength Vs BER curve in the range of 800–1600 nm.

TABLE III
AGGREGATED RESULTS

Experiment	The wavelength used (nm)	Q factor
Different Wavelength Effect	850	4.3825
	1550	0
MIMO	850	4.1803
WDM	800	4.74494
	830	4.67306
	860	4.27279
	900	4.14466

TABLE IV
ISOWC RESULTS

IsOWC type	IsOWC Distance km	Q factor	BER
LEO – LEO	2000	607	Zero
LEO – MEO	20000	20.5	9.4×10^{-94}
LEO - GEO	45000	4.3825	5.864×10^{-06}
LEO - GEO	46000	4.20531	1.3035×10^{-05}

have a better Q factor than longer wavelengths at long distances between satellites, moreover, Fig 8(b) shows the same range of wavelengths versus BER, and it is evident that BER increase as wavelength increase. Both curves confirm that the optimum operable wavelength range is from 800 nm to 900 nm for long-haul communication links between satellites.

To make it easier for the reader to compare the results, Table III summarizes the results of the three experiments performed in terms of the Q factor at a distance of 45000 km.

Several iterations have been carried out to illustrate IsOWC performance between satellites in different orbits using the exact parameters in Table I. Table IV shows that the maximum achievable distance between satellites with an acceptable Q factor and BER with the given parameters is 45000 km.

IV. CONCLUSION

In our work, an IsOWC system was established between GEO and LEO satellites over a distance of 45000 Km and at a data rate equal to 2 Gbps. Several techniques are applied to achieve a Maximum Q factor and a target of BER equal to 10^{-6}. As a result, it is concluded that the system has a better Q factor and the total signal power in the case of 850 nm wavelength is equal to 4.3825. On the other hand, it is also concluded that the MIMO technique resulted in a Q factor equal to 4.1803, which does not improve the performance due to the absence of atmospheric turbulence effects. Last but not least, WDM showed noticeable enhancements that reached the Q factor up to 4.74494 as a maximum value of the IsOWC system.

REFERENCES

[1] M. Zaki, H. Fayed, A. Aziz, and M. Aly, "The influence of varying the optical wavelength on ISL performance recognizing high bit rates," *IOSR J. Electron. Commun. Eng.*, vol. 9, pp. 64–70, 2014.

[2] S. Bloom, E. Korevaar, J. Schuster, and H. Willebrand, "Understanding the performance of free-space optics," *J. Opt. Netw.*, vol. 2, pp. 178–200, May 2003.

[3] F. Heine, H. Kämpfner, R. Lange, R. Czichy, R. Meyer, and M. Lutzer, "Optical inter-satellite communication operational," in *Proc. MILCOM Mil. Commun. Conf.*, San Jose, CA, USA, 2010, pp. 1583–1587.

[4] P. S. B. Patnaik, "Inter-satellite optical wireless communication system design and simulation," *IET Commun.*, vol. 6, pp. 2561–2567, Nov. 2012.

[5] T. D. E.Benzi, M. J. I.Shurmer, M. Lutzer, and S. Kuhlmann, "Optical inter-satellite communication: The alphasat and sentinel-1A in-orbit experience," in *Proc. 14th Int. Conf. Space Operations*, Daejeon, Korea, 16-20, pp. 1–13, May 2016.

[6] M. Motzigemba, H. Zech, and P. Biller, "Optical inter satellite links for broadband networks," in *Proc. 9th Int. Conf. Recent Adv. Space Technol. (RAST)*, Istanbul, Turkey, Jun. 2019, pp. 509–512.

[7] European Space Agency, EDRS Applications, Jul. 2020. [Online] Available: https://www.esa.int/Applications/Telecommunications_Integrated_Applications/EDRS

[8] K. Vimal and S. Prince, "System analysis for optimizing various parameters to mitigate the effects of satellite vibration on inter-satellite optical wireless communication," in *Proc. IEEE Int. Conf. Signal Process., Inform., Commun., Energy Syst.*, Kozhikode, India, 2015, pp. 1–4.

[9] M.A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *J. IEEE Commun. Surv. Tut.*, vol. 16, pp. 2231–2258, Jun. 26, 2014. [Online]. Available: https://doi.prg/10.1109/COMST.2014.2329501

[10] M. I. Basudewa, Z. Bagaskara, Sa Damita, and D.A. Routra, "Bit error rate performance analysis for free space optic communication," in *Proc. IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 850, 2020, Art. no. 012056.

[11] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling with MATLAB*, 2nd ed. Boca Raton, Florida, USA: CRC Press, 2018.

[12] P. P. sahu. and M. Singh, "Multichannel frequency hopping spread spectrum signaling using code M-ary frequency shift keying," *Comput. Elect. Eng. J.*, vol. 34, no. 4, pp. 338–345, 2008.

[13] P. G. J. Singh and B. Shah, "Performance Evaluation of 32×40 Gbps (1.28 Tbps) FSO Link using RZ and NRZ Line Codes," *Int. J. Comput. Appl.*, vol. 85, no. 4, Jan. 2014.

[14] S. Arora, M. Singh, and Rajveer, "Performance comparison between PIN and APD photodiodes for use in free space optical communication link," *Int. J. Innov. Res. Adv. Eng.*, vol. 2, no. 8, pp. 25–27, Aug. 2015.

[15] S. G. Dev and S. A. Thomas, "Performance analysis of intersatellite optical wireless link using multiple TX/RX and CO-OFDM techniques," *Int. J. Sci. Eng. Res.*, vol. 6, no. 10, pp. 935–939, Oct. 2015.

[16] H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," *IEEE Commun. Surv. Tut.*, vol. 19, no. 1, pp. 57–96, Jan.–Mar. 2017.

[17] A. Mansour, M. Ali Raed, and M. Abaza, "New challenges in wireless & free space optical communications," *Opt. Lasers Eng.*, vol. 89, pp. 95–108, May 2016.

[18] .P. P. Sahu, "A compact optical multiplexer using silicon nano-waveguides," *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 5, pp. 1537–1541, Sep./Oct. 2009.

[19] Z. Yu, F. Luo, L. Zong, and Q. Tao, "A new design of WDM-based optical inter-satellite links in modern small satellite constellations," in *Proc. SPIE 7279, Photon. Optoelectron. Meetings (POEM)*, 2008, pp. 1–6.

[20] S. Chaudhary, N. Chaudhary, S. Sharma, and B.C. Choudhary, "High-Speed inter-satellite communication system by incorporating hybrid polarization- wavelength division multiplexing scheme," *J. Opt. Commun.*, vol. 39, no. 1, pp. 87–92, 2016.

[21] M. Singh and J. Malhotra, "A high-speed long-haul wavelength division multiplexing–based inter-satellite optical wireless communication link using spectral-efficient 2-D orthogonal modulation scheme," *Int. J. Commun. Syst.*, vol. 33, no. 6, Apr. 2020.

[22] H. Zech *et al.*, "LCTS on ALPHASAT and Sentinel 1a: in orbit status of the LEO to geo data relay system," in *Proc. Int. Conf. Space Optics*, 2014, doi: 10.1117/12.2304149.

[23] M. G K. Böhmer, H. K F. Heine, R. R. Lange, M. Lutzer, and R. Meyer, "Laser communication terminals for the european data relay system," in *Proc. SPIE - Int. Soc. for Opt. Eng.*, 2012, pp. 1–3.

[24] A. Alkholidi, "Free space optical communications theory and practices," *Contemporary Issues Wireless Commun.*, vol. 5, pp. 168–174, Nov. 2014, doi 10.5772/58884.

[25] V. K. Jain, H. Kaushal, and A. Vats, "Free space optical communication: laser sources, modulation schemes and detection techniques," *International Conference on Telecommunication and Networking*, Amity University, Noida, 2013.

[26] A.H. Hashim, "Modeling and performance study of inter-satellite optical wireless communication system," in *Proc. Int. Conf. Photon.*, 2010, pp. 1–4.

[27] A. Grover and A. Sheetal, "T1 - A 2×40 Gbps mode division multiplexing based inter-satellite optical wireless communication (IsOWC) system," *J. Wireless Pers. Commun.*, vol. 114, no. 3, pp. 2–3, 2020.