Performance Improvement of an Optical Inter-Satellite Link over Low Earth Orbit

Mohamed I. Shehata, Asmaa Zaki M., Heba A. Fayed, Ahmed Abd El Aziz, Moustafa H. Aly

Electronics and Communications Engineering Department, College of Engineering and Technology
Arab Academy for Science, Technology and Maritime Transport
Alexandria, Egypt
m.ismail34@yahoo.com, eng_asmaa_85@yahoo.com, hebam@aast.edu, ahmedabdelazizyoussef@gmail.com, mosaly@aast.edu

Abstract— Space communication systems are often designed using satellite-to-satellite links based on microwave. It has been found that the future of satellite systems can be improved to operate more efficiently and reliably through the utilization of optical links between satellites (ISL). This work examines the system performance of an optical ISL that is proposed among low-Earth orbit (LEO) satellites. In this study, the proposed link is simulated to to achieve the utmost permitted rate of data and minimum bit error rate over different distances. The system performance is improved by investigating its dependency on the photodetector type, operating wavelength, transmitted optical power, RZ and NRZ schemes.

Keywords—Inter Satellite Link (ISL), Low Earth Orbit (LOE), Visible Light Band (VLB).

I. INTRODUCTION

Recently, laser links have been advancing technologies rapidly and have had many applications in many fields, including optical networks and free-space optical links (FSO) both indoor and outdoor. The outdoor FSO correlation can appear from Earth to Earth, from satellite to Earth or in deep space. However, FSO has become a more promising technique for satellite interfaces (ISLs) due to its advantages such as low transmitted power, size, weight, high speed, immunity and the use of a wide range of operating wavelengths (AH Hashim et al. 2010) addition to its efficiency and reliability if it is compared with microwave links (Arnon. 1998). In addition, communication systems rely on space laser that work in a short frequency range because they have many advantages such as high transmission bit-rate in range of several gigabits per second (G. Muehlnikel et al. 2012), high bandwidth, narrow field of view, narrow laser beam, efficient energy and high precision (K. Shantha lakshmi et al. 2008). For these reasons, WOC technology has attracted attention as a key role for the next generation of FSO communications networks, which depend mainly on the use of satellites (G. Muehlnikel et al. 2012; Hemani et al. 2018).

However, many FSO challenges have arisen, limiting their spread in telecommunications. The reason is due to the impact of these challenges on the connection of communication between senders, regardless of the type of link, whether mobile or fixed, which leads to the separation of the link or weaken. The challenges for mobile FSO links are their ability to vary both the receiver packet beam of the FSO link and the optical power received due to the ever-changing separation distance of the transmitter receiver.

FSO fixed links are currently more reliable than portable ones due to the lack of continuous traceability and alignment requirements to maintain Line of Sight (LOS) (M. K. Al-Akkoumi et al. 2009). LOS also offers many advantages for both telecommunications users and providers, acquiring high bit rates outnumber many Gbps through multiple wavelengths, and that's has been executed in many operational systems for over 30 years (R. J. Daddato et al. 2011). It is worth noting the presence of ISL between different orbits in the SILEX program by ESA and JAXA (G. Muehlnikel et al. 2012; Hemani et al. 2018). These orbits are called by low earth orbit (LEO), medium earth orbit (MEO) and geosynchronous orbit (GEO) and are classified according to their distances as shown in Table I.(I.K. Son, et al. 2017; A. H. Hashim et al. 2010).

Table I Different distances between ISLs.

Orbit Name	Range between orbits (km)
LEO - LEO	600 – 5860
LEO - MEO	Up to 18460
GEO	Up to 45000

Furthermore, Artemis satellite was positioned in the GEO however SPOT 4 satellite was in LEO at altitude of 832 km (Neo 2003). In December 2005, bidirectional communication between Artemis and Kirari was carried out to verify the existence of an ISL (B. Patnaik et al. 2012).

According to the mentioned previously, the majority of communication systems links were simple. Similarly, in this work the proposed link will be simplex as well. This paper investigates the impact of the modulation scheme, detector type, and propagating wavelength on the ISL performance.

Firstly, general information about the proposed ISL visual system is displayed in Sec. 2. Afterwards, the choice between various optical wavelengths with their stipulations and considerations are discussed and recorded in Sec. 3, which is used for earth as well as near-earth and precisely for deep space links. All over simulation, no vibrations are assumed and therefore, the difference in both the FSO link receive beam and the received optical power is ignored (M. K. Al-Akkoumi et al. 2009). Then, Sec. 4 presents the results from the simulated model for the ISL. It includes the link performance extending system parameters concentrating on sent bit rate between LEO satellites at bit error rate (BER) ranging between 10^{-6} to10^{-9} (T. S. Hanzra 2012; B. Smutny et al. 2008) and placing APD detector and NRZ modulation at wavelengths improving the performance of the system. This is followed by main conclusions in Sec. 5.

II. OPTICAL ISL SYSTEM

A. Introduction

The optical ISL system, like any regular communication system, consists of two transceivers linking between emitting and receiving optical signals. In free space channel, lasers are utilized as a signal holder, as well as facilitating wireless communication between the transmitter and receiver sides as shown in Fig. 1. FSO channel is considered a main technology for acquiring high-speed communication systems, which distinguishes them for the transmission of information over long distances.

The laser beam is created based on collimation lenses and its emission based an optical antenna. In order to determine the value of optical path loss, there are two parameters namely range between transmitting and receiving side in addition to laser wavelength (K. Shantha lakshmi et al. 2008).

It is found that the process is reversed at the receiving side and the optical signal is transferred into a bit stream, and is basically composed of a photodetector (PIN or APD), a decoder and a lens to gather the receiving modulated signal, which was modulated using RZ or NRZ with different modulation techniques especially pulse position modulation (PPM).

The proposed model is simulated based on NRZ and RZ modulation, due to its highest quality schemes for achieving maximum coverage distance of the link (B. Patnaik et al. 2012). We will choose the better scheme, which gives adequate system performance. Since it is very hard to modify the laser directly, subsequently, a Mach Zehnder modulator (MZM) is utilized as an external and alternative optical modulator in the transmitter side as seen in Fig. 1.

In exulting the performance of ISL system, it is vital to take into our consideration multiple system requirements, which considered affecting parameters. These parameters can split into two types: internal and external parameters. The internal parameters that have a great impact on ISL design involve optical power, wavelength, transmission bandwidth, transmitter's various laser types, divergence angle, and optical loss on the sending side. Besides the previously mentioned parameters, there are other influences concerning receiving side such as sensitivity, BER, lens diameter, field of view (FOV), and detector (Nazmi A. et al. 2012). While, the external parameters are belonged to the environmental conditions in which the system must run and comprise the following: visibility, atmospheric attenuation, scintillation, deployment distance, window loss, and pointing loss (S. Bloom et al. 2003).

Here, our work concentrates on some internal parameters neglecting the external ones because there are no disturbing environmental effects in deep space.

B. Wavelength Consideration

B.1 Selected Wavelengths Spectrum

Recently, several transmission bands for optical communication have been defined and standardized. Optical carrier frequencies that ranged between 350 THz (850 nm) and 200 THz (1550 nm) have been found to be free from any licensing requirements worldwide and as a result there is no possibility Interference between these frequencies with satellites or other radio frequency equipment (RF). Therefore, these bands are now commercially available for FSO systems, that are in the near infrared (IR) ranged between 750 and 1600 nm wavelength.

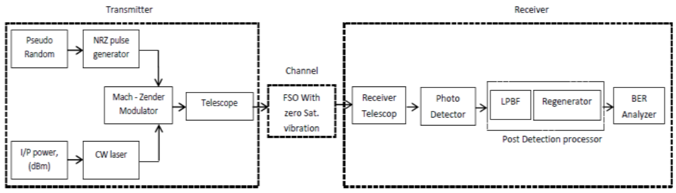

Fig.1 ISL system.

FSO systems that are working near IR range can be utilized for communication through glass (M. Gebhart et al. 2004) in order to achieve rapid installation ease. Unfortunately, optical devices operating at 800 nm spectral range above 2.5 Gbps were not possible due to energy constraints on eye safety. To overcome this problem, especially with regard to energy constraints, a 1550 nm wavelength is chosen for the new high-speed FSO systems (K. Kazaura 2007).

B.2 Wavelength Selection

The choice of the optical wavelength of FSO systems, especially ISL, depends mainly on several key factors such as optical transport windows, eye safety, expenses and wheather effects, addition to the possibility of providing the required components for transmissions and receivers as well as the applications required (T. Plank et al. 2011; M. Czaputa et al. 2011).

Because this paper primarily talks about ISL as an optical correlation, it may be possible to use wavelengths ranging from 750 to 850 nm, because eye safety precautions in space are supposed to be zero. Therefore, these wavelengths are appropriate for FSO operation, as many vendors provide high power laser sources operating in this area.

These wavelengths are based on commercially available detectors, where the detector technology fits into two types. However, each type operates according to specific wavelengths as in visible and IR. Visible wavelengths are typically maintained by silicon APD technology, like at 850 nm wavelength, that has an authoritative transmitter that is characterized by its high cost, outstanding performance and easy availability and therefore its use of transmission network and equipment is widespread (S. Bloom et al 2003; Hemani et al. 2018). Infrared wavelengths are reached either through InGaAs APDs or more recently by connecting individual photon detectors (J. Bourgoin et al. 2013). In the current work, both types are studied and compared. An evaluation is performed between the performance of the ISL and the system parameters in order to acquire the maximum

ISSN: 2692-5079

allowable bit rate in different bands with a maximum BER ranging from 10^{-6} to 10^{-9}.

III. RESULTS AND DISCUSSION

The proposed system shown in Fig. 1 is simulated based on Optisystem ver. 7 as illustrated in Fig. 2. The simulated ISL is supported by different parameters as presented in Table II, like the input power of 12 dBm, this supplies transport between satellites at a distance of tens of thousands of kilometers (I. Google 2015).

Table II Simulation parameters of ISL system.

Parameter	Type or Value
Wireless channel	LOS
Transmit power	12 dBm
Modulation	NRZ or RZ
MZM extinction ratio	26 dB
Transmitter aperture diameter	15 cm
Receiver aperture diameter	15cm
Detector type	APD or PIN
Responsivity	1 A/W
Dark current	10 nA
Propagation distance	1000 - 3000 km
Wavelength	850 nm
Bit rate	2.5 – 40 Gbps for the 1000 km 15 Mbps – 5.6 Gbps for the 3000 km

In first scenario, the simulation is carried out utilizing APD or PIN at various data rates based on each orbit. It is noteworthy to mention that the used data rate at LEO nd MEO orbits is 2.5 - 40 Gbps and 30-100 Mbps respectively. Moreover, we will concentrate on bit rate conveyed between the LEO links.

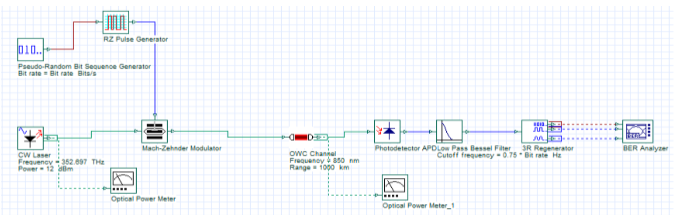

Fig.2 Designed ISL.

Figure. 3 displays the system performance according to the bit error rate (BER) and the Q-factor which is a dimensionless parameter that describes how an under-damped oscillator is. Referring to Fig. 3, the best value of Q- factor is approximately 40 ,which gives coverage of 600 km for LEO orbit in case of APD with very minimized BER. The best Q-factor is less in case of PIN. Likewise, enlargement the space in case of utilizing PIN, the Q-factor will decay to be zero that provides a deprived indication for system performance.

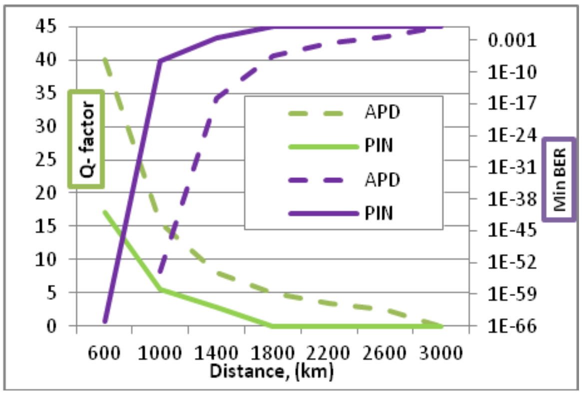

Fig.3 System performance based on Q-factor and BER utilizing different photodiodes.

The eye diagram is illustrated in Figs. 4 and 5 for the APD and PIN photodiodes, respectively, at the same bit rate. It is noticed that, the Q- factor of the system in case of PIN is too small as compared to APD. Since deploying PIN detector reduces the size of eye opening, this will raise the possible occurrence for data errors and jitter as well. In addition, the eye-opening using APD is wider which gives an improvement in system performance. Therefore, it is preferable to employ APD instead of PIN photodiode.

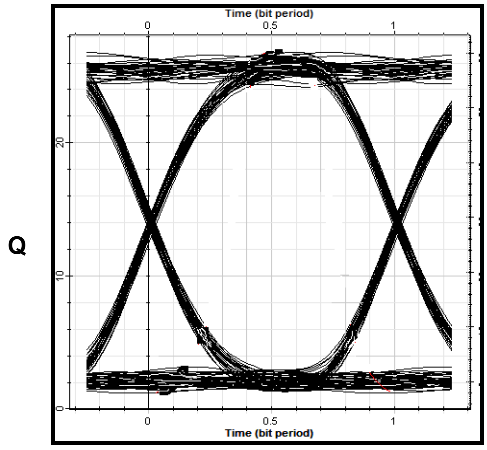

Fig.4 Receiving side eye diagram and Q-factor with data rate 5.6 Gbps at 600 km-LEO utilizing APD photodiode.

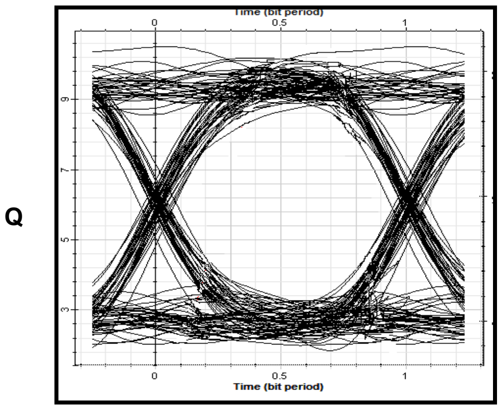

Fig. 5 Receiving side eye diagram and Q- factor with data rate 5.6 Gbps at 600 km - LEO utilizing PIN photodiode.

Although the proposed design can success with different modulation schemes, only NRZ and RZ implementation schemes will be used due to their simplicity. According to the discussion of Figs. 4 and 5, it is interesting to compare the system quality at both schemes using the APD photodiode as shown in Table II.

Table III System performance at different modulation schemes at 600 km in LEO orbit.

Item	Bit rate (Gbps)	NRZ	RZ
Q-factor	2.5	40.1219	34.1866
	10	20.0617	17.1531

From Table III, it is clear that the NRZ scheme is better than NR. This is used in simulation of Fig. 6, where wider eye-opening is noticed leading to a jitter decrease which reduces the potential occurrence for data errors and gives a better system performance.

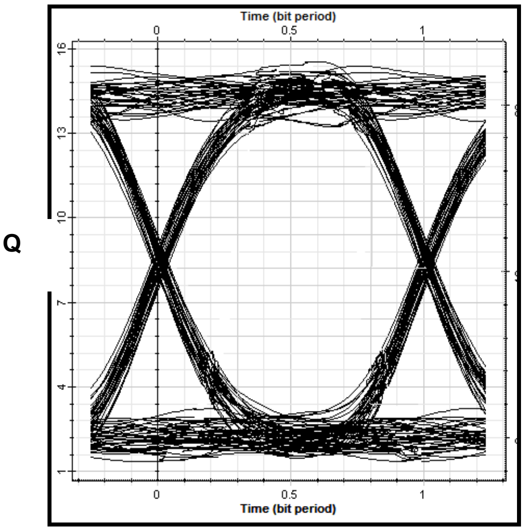

Fig. 6 Eye diagram showing minimum BER for wider eye opening at 2.5 Gbps at 1000 km in LEO orbit based on NRZ scheme.

Now, the wavelength impact will be considered. A range between 2.5 and 40 Gbps is taken into our consideration, which gives a high-speed transmission. In FSO, there is a necessity for a malleable system that can give a capacity equivalent to optical fiber (K. Kazaura 2007). So, for the LEO orbit, a fixed distance of 1000 km has been chosen with a bit rate 2.5 - 40 Gbps, and 3000 km with a bit rate 15 Mbps - 5.6 Gbps. The variation in wavelength will be depending on the optical bands as in O, E, S, C and L bands.

Employing the best suitable wavelength for FSO systems, 1550 nm, (C-band), simulation yields a maximum bit rate of 3 Gbps that could be sent over 1000 km, with a Q-factor ~ 4.5 and 10^{-6} BER as seen in Fig. 7. If higher values of wavelengths are used, like L-band, the system performance decreases as shown in Fig. 8 (wider eye opening).

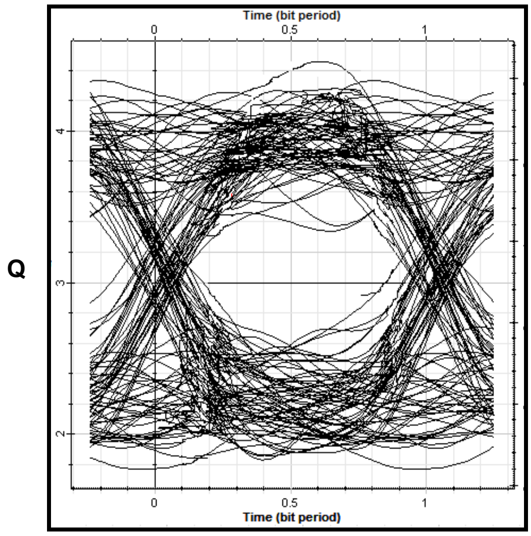

Fig. 7 Q-factor and Eye diagram for 3 Gbps at C-band over 1000 km.

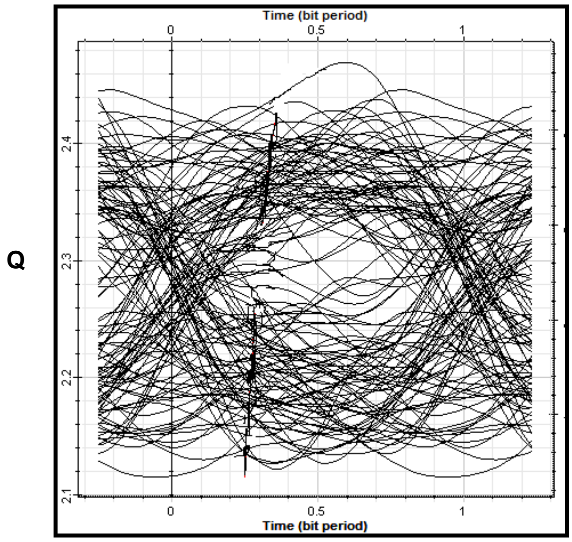

Fig. 8 Q-factor and Eye diagram for 3 Gbps at L- band over 1000 km.

It is also noted that reducing the wavelength to the E band produces better system performance than the higher bands. However, when sending higher bit rates, system quality decreased for the same band.

On the other hand, when lower bands are used, like the O-band (e.g. 1300 nm), a system improvement is noticed at 2.5 Gbps with an improved Q-factor and 10^{-12} BER as displayed in Fig. 9. Thus, if the wavelength is lower than previously mentioned, the system performance will be improved due to reduction of BER with increasing of Q-factor as well.

ISSN: 2692-5079

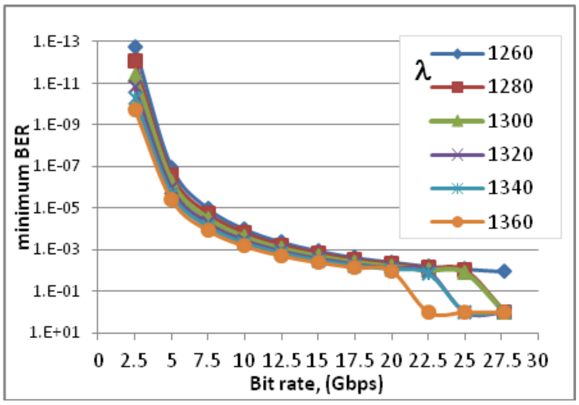

Fig. 9 Variation of minimum BER with bit rate at various O-band wavelengths, λ(nm).

Finally, we investigate the system performance when are used. It is the obvious choice of wavelength in space, because the system's Q factor is about 60 as shown in Fig. 10.

In the end, we check the system performance when utilizing the visible near visible light bands. It is considered the outstanding choice of wavelength in space, due to value of system's Q factor that is approximately about 60 as exhibited in Fig. 10. This value is very appropriate to optimize the system performance giving a best value for the minimum BER as shown in Fig. 11.

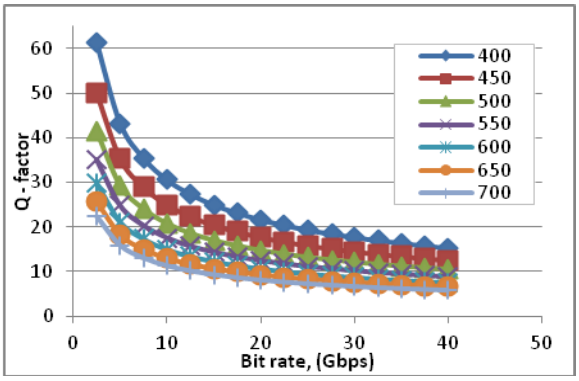

Fig. 10 Variation of the Q-factor with bit rate in the visible light band wavelengths, λ(nm).

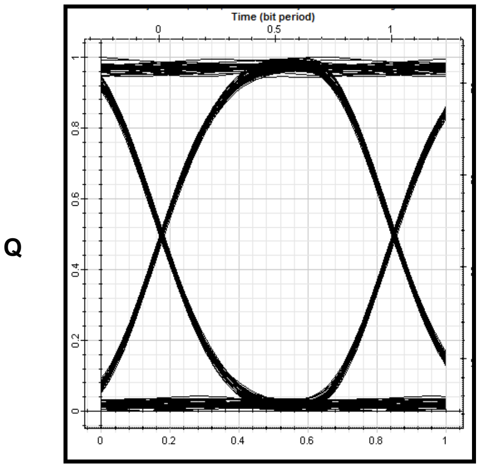

Fig. 11 Eye diagram for minimum BER using visible light band at 2.5 Gbps.

Moreover, after studying the simulated link performance, the admissible transmitted bit rate over a distance of more than 1000 km and 3000 km in various bands has been estimated against the maximum BER extends from 10^{-9} to 10^{-6} and is recorded in Table IV.

Table IV Comparison between admissible transmitted bit rate over various LEO distances.

λ(nm)	Bit rate at BER 10^{-9}		Bit rate at BER 10^{-6}	
	1000 km	3000 km	1000 km	3000 km
500	*40 Gbps	2 Gbps	*40 Gbps	3 Gbps
860	18 Gbps	225 Mbps	33 Gbps	420 Mbps
1300	3.7 Gbps	45 Mbps	6.5 Gbps	81 Mbps
1440	2.25 Gbps	30 Mbps	4 Gbps	53 Mbps
1500	2 Gbps	26 Mbps	3.5 Gbps	46 Mbps
1550	1.75 Gbps	22.5 Mbps	3 Gbps	40 Mbps
1615	1.5 Gbps	19.5 Mbps	2.75 Gbps	34 Mbps

* This value is the actual value that can be transmitted over this distance while the theoretical value is 250 Gbps but cannot be transmitted due to the maximum MZM value to be converted to 40 Gbps.

Its notable the possibility of transmitting 3 Gbps bit rate over various bands acquiring BER of 10^{-6}. Then, it is found that if it is necessary to transmit 3 Gbps at a distance of 3000 km in applications with eye safety restrictions, the C-band may be utilized. On the other hand, as in this work, by ignoring the eye safety requirements, the visible light (VIS) band could be utilized. Likewise, 2 Gbps could be sent inquiring 10^{-9} BER at several bands.

Thus, the choice of 850 nm as one of the new3w3ear Field Visible Light (NVIS) band assures why many vendors are available to operate in the region that has become common in several FSO applications in space. Therefore, as mentioned earlier, there is no regard in the choice of VIS or NVIS bands in space because there is no risk to eye safety. Using the proposed ISL, the received optical power is determined from simulation. It is found constant, in all bands, irrespective of the value of the bit rate. An example is illustrated in Fig. 12 for the O-band.

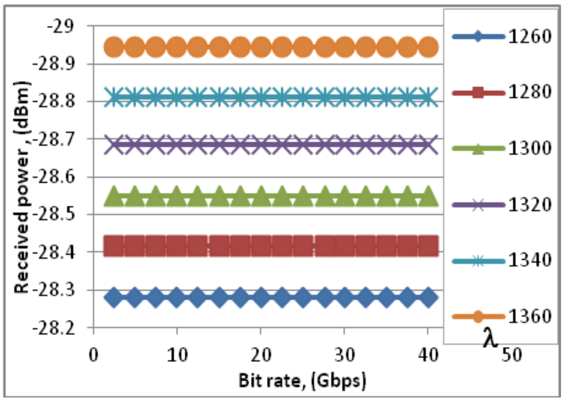

Fig.12 Received power against bit rate at different wavelengths in the O-band wavelengths, λ(nm).

The obtained values of the received optical power at wavelengths for different bands are summarized in Table V.

Table V Received power at various bands at any sent bit rate.

Band	Selected wavelength (nm)	Received power (dBm)	
		1000 km	3000km
Visible light 400-700	500	-20.252	-29.794
Near Visible 800- 920	860	-24.962	-34.505
O – band 1260-1360	1300	-28.551	-38.094
E – band 1360- 1460	1440	-29.44	-38.983
S – band 1460-1530	1500	-29.794	-39.337
C – band 1530 –1565	1550	-30.097	-39.621
L – band 1565- 1625	1615	-30.436	-39.978

The system performance is investigated concerning the variation in transmitted optical power from 0 to 60 dBm, achieving optimum Q-factor with extremely small BER at different wavelengths. This is displayed in Fig. 13.

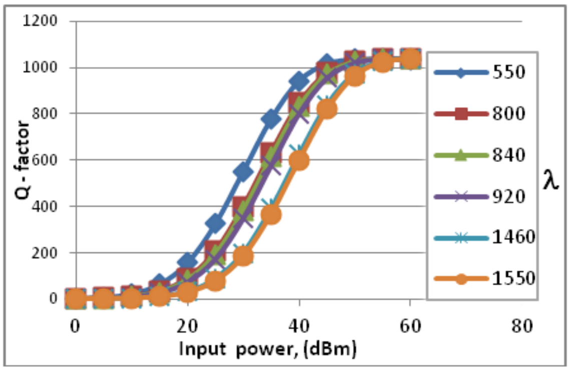

Fig. 13 Q-factor against input power at different wavelengths at 2.5 Gbps over different bands wavelengths, λ(nm).

As expected, the system performance (Q-factor) increases with the input power to a certain limit, then reaches saturation. However, in this research there is no limitation in increasing the power because of no eye safety precautions in space.

As mentioned before, the VIS band was best selection of optical bands, so, the quality of the system through this band is considered the optimum value at 2.5 Gbps giving near zero BER as shown in Fig. 14.

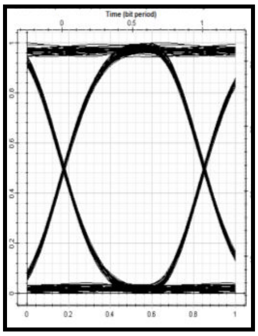

Fig. 14 Eye diagram at 15 dBm input power transmitting 2.5 Gbps in VIS band.

IV. CONCLUSION

This paper investigates the impact of different internal parameters on the proposed system comprising and ISL between two satellites network at LEO orbit. It is found that, the use of APD photodiode and the NRZ scheme is adequate comparing with PIN photodiode and RZ scheme, resulting in a better Q-factor and minimum BER. In addition, the superior optical bands are VIS or NVIS bands instead of using the most commonly band namely C-band. These bands have been to be utilized in FSO systems in order to realize the optimum system. It is noteworthy to mention that, the received optical power is fixed at each band for any sent bit rate.

V. REFERENCES

[1] A. H. Hashim, F. D. Mahad, S. M. Idrus, A. Sahmah, M. Supa, and P. T. Centre (2010) Modeling and Performance Study of Inter Satellite Optical Wireless Communication System. In Proceedings of IEEE Conference on Photonics (ICP), Paper 64.

[2] S. Arnon (1998) Use of Satellite Natural Vibrations to Improve Performance of Free-Space Satellite Laser Communication. Appl. Opt. 37(21), 5031- 5036.

[3] G. Muehlnikel, H. Kämpfner, F. Heine, H. Zech, D. Troendle, T. Spacecom, R. Meyer, and S. Philipp-may (2012) The Alphasat GEO Laser Communication Terminal Flight Acceptance Tests. In Proceedings of International Conference on Space Optical Systems and Applications (ICSOS), vol. 12, pp. 9-12.

[4] K. Shantha lakshmi, M. P. Senthil kumar, and K. V. N. Kavitha (2008) Inter-Satellite Laser Communication System. In Procedding of the International Conference in Computer and Communication Engineering, pp. 522-527.

[5] M. K. Al-Akkoumi, A. Harris, R. C. Huck, and J. J. Sluss (2009) Challenges facing mobile free-space optical communications. In Proceedings of SPIE, vol. 7324, p. 73240L(1-11).

[6] R. J. Daddato, K.J. Schulz and I. Zayer (2011) Deep Space Science Downlinks via Optical Communication. In Proceedings of International Conference on Space Optical Systems and Applications, pp. 8-13.

[7] S. D. Neo (December, 2003) Free Space Optics Communication For Mobile Military Platforms. M.Sc. Thesis, NAVAL Postgraduate School, Monterey, California, USA.

[8] B. Patnaik and P. K. Sahu (2012) Inter-satellite optical wireless communication system design and simulation. IET Communication 6, 2561-2567.

[9] T. S. Hanzra (2012) Performance of Free Space Optical Communication System with BPSK and QPSK Modulation. IOSR J. Electron. Commun. 38-43.

[10] B. Smutny, R. Lange, H. Kämpfner, D. Dallmann, G. Mühlnikel, M. Reinhardt, K. Saucke, U. Sterr, B. Wandernoth and R. Czichy (2008) In-Orbit Verification of Optical Inter-Satellite Communication Links Based on Homodyne BPSK. SPIE 6877, 687702-687706.

[11] B. Patnaik and P. K. Sahu (2012) Inter-Satellite Optical Wireless Communication System Design and Simulation. IET Commun. 6, 2561-2567.

ISSN: 2692-5079

[12] Nazmi A. Mohammed, Amr S. El-Wakeel and Moustafa H. Aly (2012) Pointing Error in FSO Link under Different Weather Conditions. International Journal of Video & Image Processing and Network Security 12, 6-9.

[13] S. Bloom, E. Korevaar and J. Schuster (2003) Understanding the Performance of Free-Space Optics. Journal Optical Society of America 2, 178-200.

[14] M. Gebhart, P. Schrotter, U. Birnbacher, E. Leitgeb, and A. S. C. Satcom (2004) Satellite Communications , Free Space Optics and Wireless LAN combined : Worldwide broadband wireless access independent of terrestrial infrastructure. In Procedings of IEEE MELECON Conference, pp. 449-452.

[15] K. Kazaura (2007) studies on Performance of Ultra High Speed Free-Space Optical Communication Systems. M.Sc. Thesis, Graduate School og Global Information and Telecommunication Studies, Waseda University, China.

[16] T. Plank, E. Leitgeb, and M. Loeschnigg (2007) Recent developments on free space optical links and wavelength analysis. Communication," in Proceedings of International Conference on Space Optical Systems and Applications, pp. 14-20.

[17] T. Plank, M. Czaputa, E. Leitgeb, S. S. Muhammad, N. Djaja, B. Hillbrand, P. Mandl, and M. Schönhuber (2011) Wavelength Selection On FSO-Links," in Proceedings of the 5th European Conference on Antennas and Propagation (EuCap), pp. 2508-2512.

[18] J. Bourgoin, B. L. Higgins, B. Helou, R. Girard, R. Laflamme, and T. Jennewein (2013) A comprehensive design and performance analysis of LEO satellite quantum communication," New Journal of Physics, 1-33.

[19] I. Google (Accessed: 09 Dec 2015) Wavelength Range Of Optical Radiation," Available: http://www.light-measurement.com/wavelength-range/.

[20] H Kaushal1, G Kaddoum and Haryana (2016) Optical Communication in Space: Challenges and Mitigation Techniques. IEEE Communications Surveys & Tutorials, 1553-877X

[21] I. K. Sonb and S. Mao (2017) A survey of free space optical networks. Digital Communications and Networks. 3, 67–77.