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Analysis of inter-satellite free-space optical link performance considering different system parameters

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ABSTRACT

The welcome and adaptation of optical wireless technology by the modern era has brought forward the concept of an inter-satellite free-space optical communication system. In the present work, I study the combined effect of selection of different operating wavelengths and detector types along with the pointing errors at the transmitter and receiver side on the performance of an inter-satellite free-space optical link. The link performance has been optimized by measuring and analyzing the bit error rate and quality-factor of received signal under different scenarios. Performance of the inter-satellite link has also been investigated considering different modulation formats and data rates for LEO and MEO distances.

1. Introduction

Free-space optical communication turns out to be an efficient and promising technique for transmission of information at high data rates [1]. This technology has the potential to revolutionize the way in which data can be transferred through different optical links such as from satellite to ground, satellite to satellite and other indoor and outdoor wireless channels [2]. Free space optics (FSO) systems offer many advantages over the radio frequency (RF) satellite systems used conventionally as a result of their unique features such as high data-rate and security, unrestricted spectrum, low power consumption, easy deployable and large bandwidth capability [3,4].

Inter-satellite links (ISL) play a significant role in global coverage network considered as the captivating target of the next generation wireless communication. Several satellite-to-satellite communication experiments have been performed by European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), German Space Agency, and National Aeronautics Space Agency (NASA) [5–7].

In 2001, the first inter-satellite optical links (ISOL) have been performed between ARTEMIS and SPOT 4 satellites at a rate of 50Mb/s placed in geostationary orbit and low earth orbit, respectively [6]. In 2006, JAXA has established a bidirectional inter-satellite optical link between its OICETS satellite and ARTEMIS satellite at receive and transmit data rate of 2 Mb/s and50 Mb/s, respectively. German Space Agency (DLR) established its first inter-satellite communication link in 2008, using coherent modulation techniques (BPSK) between TerraSAR-X and NFIRE satellites [8].

Study of terrestrial FSO links is more emphasized in the existing literature. Further, the performance of optical inter-satellite communications' links are mainly investigated for a given modulation format and detection scheme. In Ref. 9 an inter-satellite optical communication link was proposed at an operating wavelength of 1550 nm using non return-to-zero (NRZ) modulation technique at a data rate of 1 Mbps. Use of BPSK modulation technique has been considered in Ref. 8 to improve system performance.

In Ref. 10, two different types of detection schemes, i.e, homodyne and intradyne detection have been compared for an inter-satellite optical communication link considering higher order modulation techniques. Inter-satellite optical communication links are affected as a result of satellite vibration. The effects and ways to mitigate them have been studied in Ref. 11. The performance of an optical ISL using space and polarization diversity techniques is investigated in Ref. 12.

In the present work, I study the combined effect of selection of different operating wavelengths and detector types along with the pointing errors at the transmitter and receiver side on the performance of an inter-satellite free-space optical link. Performance of the link is investigated using different modulation formats and data rates for low earth orbit (LEO) and medium earth orbit (MEO) distances.

The remaining part of the paper is organized as follows. System parameter validation for the enhancement of the ISL link per-

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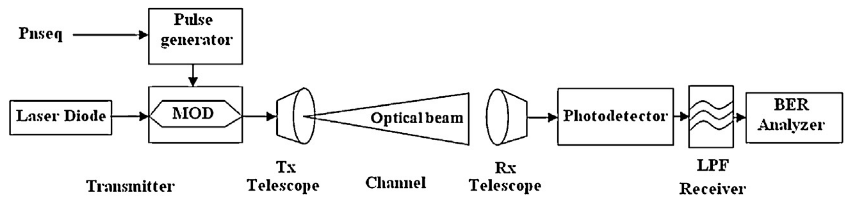

Fig. 1. Schematic configuration of a free space inter-satellite optical link.

formance has been presented in Sect. 2. Section 3 describes the numerical results and discussions which is followed by concluding remarks in Sect. 4.

2. System parameters validation for enhancement of link performance

Several internal and external parameters of the system are required to be taken into consideration while examining the performance of an ISOL.

Internal parameters are system-specific parameters which include optical power, transmission bandwidth, wavelength, optical loss, types of lasers used in the transmitters, receiver field of view (FOV), receiver sensitivity and receive lens diameter. Losses due to atmospheric attenuation, scintillation effects and window and pointing error losses along with deployment distance fall in the category of external parameters and depend upon the weather conditions or environment under which the system must be required to operate. In this work I mainly consider some of the internal parameters as in the deep space there is no requirement of analyzing effects of turbulence or environmental conditions that cause different types of atmospheric path losses.

A typical ISL optical link like any other communication system is depicted in Fig. 1. Laser diode is a continuous wave (CW) laser with FWHM as10 MHz and 10 dBm power. Pnseq generates the pseudorandom binary sequence (PRBS) at a high data rate with period of 2^7-1. Input data signal is externally modulated by a modulator to form return-to-zero (RZ) or non return-to-zero PRBS signals. A telescope or a lens can be used as an irradiation device in the transmitter.

The signal propagates through the optical wireless channel (OWC) in the form of narrow electromagnetic beam and is received by the receiver at the other side of the link.

The receiver subsystem consists of a low-pass filter (LPF), an optical detector, and a bit error rate (BER) analyzer. Photo detector output is directed towards a low-pass bessel filter for removing any high-frequency components present in the signal thus improving signal to noise ratio of the received signal. BER analyzer has been used to observe the performance of the signal at the receiver.

The functional parameters of inter-satellite communication system can be analyzed by Friis transmission equation. Received optical signal is thus expressed as [13]:

$$P_R = P_T G_T \eta_T \, \eta_R G_R L_T L_R (\lambda/4\pi Z)^2, \quad (1)$$

where P_T - transmitted power,

G_T & G_R - gains of the telescopes at transmitter and receiver side, respectively,

η_T & η_R - transmitter and receiver optics efficiencies, respectively,

L_T&L_R - transmitter and receiver pointing loss factors, respectively,

λ - transmission wavelength, and

Z - transmission range.

As seen in Eq. (1), there is a dependency of system parameters on each other. Hence, for the proper functioning of the system, care must be taken while selecting the system parameters so that sufficient signal strength is received at the receiver with negligible error.

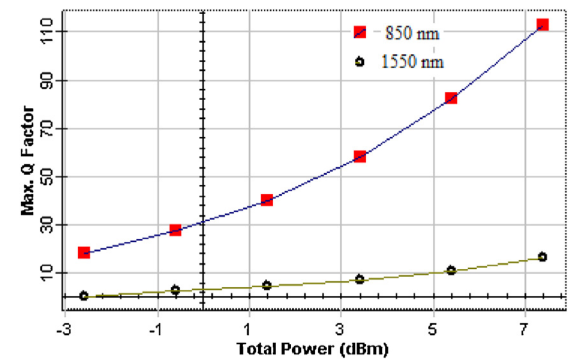

Fig. 2. Q-factor *vs.* total transmitted power considering different wavelengths.

The choice of operating wavelength is a one of the significant design parameters for space based optical communication applications. There is a number of factors that influence the choice of wavelengths in the design process of an FSO system. It determines the performance of the link, as well as detector sensitivity of the system [14].

Eye and skin safety remains as one of the criteria as certain wavelengths may cause potential damage to the retina [15]. Trade-off between pointing bias as a result of thermal variations across the surface of the Earth and receiver sensitivity is another factor determining the choice of wavelengths [3]. Further, cost and availability of transmitter and detector technology, also deeply impact the wavelength selection.

Lasers presently being used for ISL communication applications operate mainly in the near-IR region lying roughly between 750 and 1600 nm.

Operation at lower operating wavelengths results in lesser antenna gain requirement. On the other hand, higher operating wavelengths result in lower pointing-induced signal fades, as well as provide better link quality [16].

As the gain of the antenna decreases with the increase in the wavelength of operation, hence it will be advantageous to use lower operating wavelengths. On the other hand use of higher values of operating wavelength may provide better quality of the link and reduce the pointing-induced fading of the received signal [16].

Thus, for achieving a better performance of the system, a careful optimization of the operating wavelength is required in the design of an inter-satellite optical link.

Figure 2 presents the variation of a quality-factor (Q-factor) with input power at the operating wavelengths of 850 nm and 1550 nm, respectively. It is revealed from the figure that an improvement of up to 100 in the value of Q-factor of the output signal is achieved after passing through ISOL with a span of 200 km at a data rate of 1.25 Gbps when the operating wavelength has been chosen as 850 nm as compared to 1550 nm.

The selection of 850 nm wavelength thus has been considered as a fixed parameter for the rest of the analysis as its use provides better performance and there is an availability of several vendors which can provide laser sources with higher power operating in this

Table 1
Fixed parameters used in simulation.

Parameter	Value
Aperture diameter Tx	10 cm
Aperture diameter Rx	10 cm
Optics efficiency Tx/Rx	0.8
Modulation scheme	NRZ, RZ
Gain (APD)	3
Responsivity	1 A/W
Dark current	10 nA
Receiver filter type	Bessel filter
Receiver sensitivity	−31dBm
MZ modulator with Extinction ratio	30 dB
Line-width	10 MHz
Wavelength	850 nm

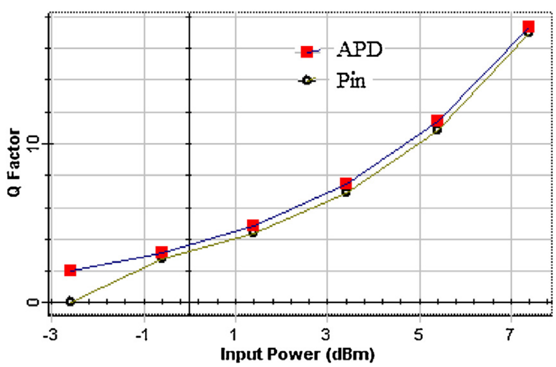

Fig. 3. Q-factor *vs*. total transmitted power considering different detectors.

Table 2
Q-factor and BER of PIN and APD photo detector.

Input Power (dBm)	PIN		APD	
	BER	Q-factor	BER	Q factor
−3	1	0	0.02	2
−1	2×10^{-3}	2.75	8×10^{-4}	3.12
1	6.2×10^{-6}	4.3	7.4×10^{-7}	4.8
3	2×10^{-12}	6.97	4×10^{-14}	7.41
5	8×10^{-28}	10.86	2×10^{-30}	11.3
7	7×10^{-65}	16.9	7.5×10^{-68}	17.3

wavelength region [14]. Table 1 shows some of the fixed parameters used in this simulation. Additional losses due to variation in atmospheric effects and attenuation are ideally assumed to be zero.

3. Numerical results and discussion

The performance of the ISL optical link has been optimized in terms of BER and Q-factor of the received signal by varying the detector type considering avalanche photodiode (APD) and PIN detector and using the simulation parameters as mentioned in Table 1. Maximum possible bit rate that can be sent over LEO and MEO orbits giving adequate system performance is also investigated. Link performance has been further analyzed by varying the transmitter and receiver pointing errors and using different modulation schemes.

Referring to the simulation results depicted in Fig. 3 and Table 2, respectively, it is observed that in case of PIN photo-detector the Q-factor of the received signal remains small as compared to the case with APD for different values of input power. As a result of gain factor, the performance of the APD receiver comes out to be better than that of corresponding PIN photo detector. Since use of the PIN detector will reduce opening of the eye-diagram that may result in the increase of the potential occurrences of data errors and timing jitter, therefore it is preferable to use APD instead of

Table 3
Different orbit ranges.

Type of Orbit	Range between orbits, (km)
LEO - LEO	200 – 1,200
MEO - MEO	5000 – 15,000
GEO	36,000

PIN photo diode at the receiver side to improve the quality of the system. APD receivers are also considered more suitable as satellite communication involves longer distances which imply lesser value of the received signal power.

As a result of the remaining analysis this paper involves the use of APD photo detector and operation at 850 nm wavelength. The satellite orbits can be categorized into different types based on their location or distance from the Earth. The orbits are chosen so that the satellites may not get damaged as a result of the high energy charged particles which exist in the two Van Allen belts.

ESA and JAXA has demonstrated ISL between satellites in different orbits [4]. These are named as LEO-LEO, medium E arth orbit (MEO-MEO) and GEO-GEO, respectively depending upon the distance between the orbits as shown in Table 3.

As a result of extensive transmission time lag and heavy propagation loss, GEO-GEO satellite links remains ineligible for inter-satellite optical communication applications. The LEO and MEO satellites links are extremely desirable for the globular link and communication function [4]. For globular link and communication function, LEO-LEO and MEO-MEO satellite links have been extremely desirable.

The link performance is further analyzed considering different data rates at LEO and MEO distances. It has been noticed from Fig. 4 that transmission of the signal at the same bit rate but at different increasing distances results in decrease of the Q–factor at the receiver. Each distance has also its own maximum bit rate for example for 800 km LEO distance, maximum data rate is 5 Gbps and the information at this rate cannot be transmitted for longer than 1000 Km as it results in the decrease in the Q-factor to an unacceptable value.

Likewise the maximum allowable bit rates for corresponding MEO distances giving adequate system performance in terms of Q-factor and BER≈10^{-6} have been listed in Table 4.

The narrow transmitted laser beam allows for secure and efficient transmission as this results in a significant portion of the transmitted power being captured by the receiver. On the other hand, it is not always that the beam transmitted in an FSO system will have the mentioned characteristics. Typically, the beam width of optical beam will be relatively wide (2–10 mrad) divergence. The transmitter and receiver pointing errors may cause further divergence of the received signal. For permissible error free trans-

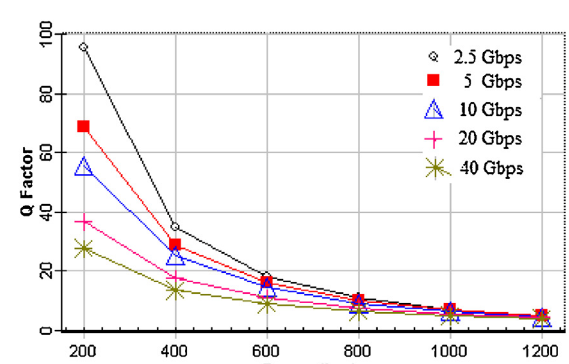

Fig. 4. System performance in terms of Q-factor considering different data rates at LEO distances.

Table 4
Performance of the system using different data rates at LEO and MEO distances.

Orbit	Range (km)	Data rate	Q- factor
LEO	600	20 Gbps	12
	600	40 Gbps	10
	1000	10 Gbps	8.5
	1000	20 Gbps	7
MEO	5000	30 Mbps	4.31
	5000	35 Mbps	4.2
	10000	10 Mbps	3.9
	10000	5 Mbps	4

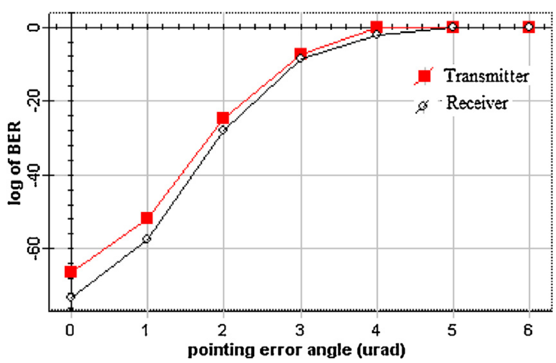

Fig. 5. BER *vs.* Transmitter and Receiver pointing errors.

mission, the typical value of pointing error allowed is around 1 µrad. The SNR degrades and thus BER increases with the increase in the pointing error up to 5 µrad shown in the Fig. 5. Transmitter pointing error angel has more effect on signal degradation as compared to the effect caused by error at the receiver side.

Modulation technique can be selected considering transmission range and applications of the communication system. RZ modulation format offers increased bit-rates and is considered to be more robust against distortion effects. Whereas NRZ provides better performance with regard to a bandwidth utilization for long haul communication applications.

Although the proposed model is able to accommodate different modulation formats, in this paper, RZ and NRZ modulation types have been considered as they are simple to implement. These are also referred to as on-off keying (OOK).

It would be interesting to compare the performance of ISOL in terms of Q–factor achieved at the output of the photodetector with the use of different modulation schemes. The use of RZ modulation scheme has resulted in decreased system performance compared to the NRZ one.

Figure 6 depicts the results of comparison showing that the use of RZ modulation scheme results in the reduced value of Q–factor

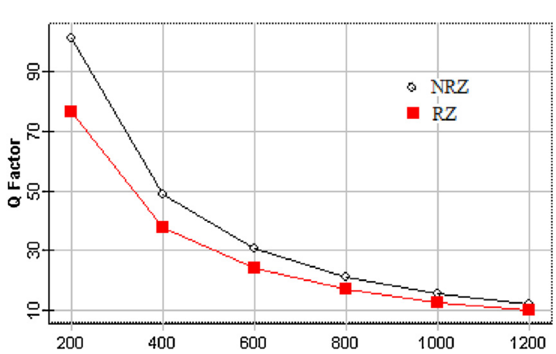

Fig. 6. Q-factor *vs.* transmission range considering RZ and NRZ modulation formats–LEO distances.

for a given transmission range up to 1,200 km as compared to NRZ scheme. Thus, it will be better to employ the NRZ scheme rather than the RZ one for having reduced number of potential errors in data and for achieving better performance of the system.

Thus, for the same reasons as discussed previously and as expressed in other research works and experimental trials, the ISOL will provide an optimized performance at 850 nm using NRZ modulation scheme and APD photodetectors.

4. Conclusions

In this paper, the performance of an inter satellite optical link is optimized in terms of BER and Q-factor which are affected by variation of different internal parameters of the system such as operating wavelengths, pointing errors, detector type and modulation scheme. Impact of using APD photodetector and 850 nm as operating wavelength on the quality of the ISOL has been studied.

It has been observed that the transmitter pointing error angel causes more effect on signal degradation as compared to the effect caused by error at the receiver side. Performance of the link has also been investigated to determine the maximum possible bit rate that may be transmitted over ISOL giving adequate performance of the system for LEO and MEO distances.

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