Research Article

Aqeel Madhag* and Haidar Zaeer Dhaam

Satellite vibration effects on communication quality of OISN system

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Abstract: Over space optical communications are considered as the critical technology for high-bandwidth, high-speed, and large-capacity communications. Indeed, the laser wavelength's narrow beam divergence requires a precise beam pointing at both ends of the optical link. The precise beam pointing makes the laser beam pointing to or from a moving object is one of the most challenging processes for optical space communications. In this work, the effect of the pointing error due to satellite platform vibration over the performance of the laser communication link of the optical inter satellite network (OISN) system in terms of the quality factor is investigated. Indeed, an optical communication system has been built using the OptiSystem program to simulate the link between satellites in space for the OISN system. In addition, the proposed system shows by simulation the optimal parameters' values required for the design of the optical communication link between satellites of the OISN system. Moreover, the effect of pointing error due to the platform vibration on the performance of the OISN system is investigated for different scenarios of the pointing error (i.e., no pointing error; one side of the link with pointing error, and two sides of the link with pointing error). The simulation shows that, first, the optimal parameters that can be used for the optical communication link between satellites of the OISN system in terms of the laser wavelength; laser power; optical modulation scheme; optical telescope aperture diameter; and telescope optical efficiency. In addition, the simulation shows that existing pointing error due to vibration at one side of the optical link leads to degradation of the performance of the OISN system in terms of the quality factor for different laser beam power; distances between satellites; telescope diameters; and telescope efficiencies. Moreover, existing pointing errors at the two sides of the optical link lead to rapid degradation of the considered OISN system performance even with the increase of the laser power or telescope diameter, which tend to compensate for its effect initially and then quit.

Keywords: optical communication, satellite vibration, pointing error, optisystem

1 Introduction

Communication between individuals and/or communities has been an essential life requirement from the beginning of history. Humans succeeded in sending an electromagnetic signal (i.e., wireless signal) for the first time at the end of the 19th century; from that date, such type of communication gained attention. In the last decades, communication technologies have been developed, and the Internet has been invented and separated over all continents, where the rapidly growing use of such services creates congestion in the communications networks [1–3]. That is, there is an exponential growth in telecommunication traffic [4,5]. In a consequence, there is a great demand for large communication bandwidth, as the numbers of new data and multimedia services and applications are overgrowing [6–8]. In fact, the communication networks (i.e., Internet, mobile, information, and multimedia services, etc.) required to cover large parts of the earth majorly used ground-to-satellite and satellite-to-satellite networks. Actually, wireless communication over a space has some limitations, such as wireless beams spread by a squared factor as the distance between the transmitter and the receiver is increased [9].

On the other hand, over a space, optical communications are considered as the key technology for high-speed and large-capacity (i.e., multi-gigabit-per-second) communications. Indeed, laser, as a part of the electromagnetic spectrum, has been invested in communication

* **Corresponding author: Aqeel Madhag,** Department of Laser and Optoelectronics Techniques Engineering, Engineering Technical College/Najaf, Al-Furat Al-Awsat Technical University, Al-Najaf 31001, Iraq, e-mail: madhagaq@atu.edu.iq
Haidar Zaeer Dhaam: Department of Laser and Optoelectronics Techniques Engineering, Engineering Technical College/Najaf, Al-Furat Al-Awsat Technical University, Al-Najaf 31001, Iraq, e-mail: haidar.dhaam @atu.edu.iq

since the sixties of the last century, whereas laser light can be used as a signal that carries information and data with a line-of-sight, high-bandwidth between remote sites. In fact, optical communication networks have provided a reasonable solution for such requirements due to the high-speed and data rate transmission for longer distances. Such kind of communication was done using optical fiber or free space optical communication [10]. Due to the landscape difficulties come across the laying of the fiber cable and the huge installation cost of such a network using optical fiber to cover large and rural areas of the earth. An optical inter satellite network (OISN) system provides a good solution for such an issue. Actually, the OISN system has many advantages such as colossal bandwidth, low power consumption, no need for licensing or tariffs requirements for such utilization, lightweight, high level of security [11], overcoming the security issue of wireless communication, compact size, considerably low priced, and radiation-free effects, where such features made it a substitute to the existing microwave satellite system [12]. So then, OISN provides a fascinating alternative to microwave links between satellites for many applications. On the other hand, the OISN system has some disadvantages such as precise alignment is required, a narrow point of view, and sensitivity to vibration of the satellite platform.

In fact, the laser wavelength's narrow beam divergence requires a precise beam pointing at both ends of the optical link. The precise beam pointing makes the laser beam pointing to or from a moving object (e.g., a satellite moving in orbit) is one of the most challenging processes for optical space communications. That is, one of the crucial points is to have an accurate alignment between transmitter and receiver for the free-space optical communication system. Indeed, the laser beam has a narrow beam width than the microwave one. In other words, in comparison to the microwave link, the OISN has a divergence angle, and the receiver field of view is very narrow. Working with such a narrow beamwidth coupled with a significant communication distance between satellites for the OISN system, the line-of-sight alignment is necessary, and transmitter-receiver alignment error (i.e., pointing error) may have a severe impact on the performance of the OISN system. A significant pointing error can ultimately reduce the power level of the received signal at the receiver and result in a significant bit of error. There are many sources of the pointing error, mainly the frictional and bearing noise, attitude uncertainty, satellite base frame mechanical vibration, and rotational disturbances of the satellite platform inherited by the satellite structure. In addition, the uncertainty in laser beam pointing between satellites depends on the tracking sensor noise, signal timing errors, and computational errors.

The performance of laser satellite communication systems has been studied in many literature, for instance, refs [13–21]. Ref. [13] studied the effect of pointing errors on the average bit error probability of inter-satellite laser communications. In ref. [14], evaluated the performance of inter-satellite optical wireless communication considering multiple wavelengths and diverse modulation formats. Ref. [15] studied the spectral-efficient large-speed single-channel IsOWC system using a polarization division multiplexed quadrature phase shift keying scheme. Ref. [16] studied the performance of two independent channels, each having a unique mode to carry nonreturn zero encoded data of 10 Gbps each on inter satellite optical wireless communication network. Ref. [17] presented the performance enhancement of the system by using multiple antennas and advanced modulation techniques. Ref. [18] studied the influence of satellite vibration on the radio over an inter-satellite optical wireless communication system with an optical booster amplifier and an optical pre-amplifier. Ref. [19] presented a mathematical model to minimize transmitter power and optimize transmitter gain as a function of the building-sway statistics, the communication system parameters, and the required bit-error probability. Ref. [21] stated the connection between the main parameters of the tracking and pointing and communication subsystems. Ref. [20], a high-speed communication system considered a hybrid wavelength-division multiplexing and polarization interleaving schemes under the influence of pointing error was analyzed. Indeed, due to the space limitation, more literature is eliminated.

In contrast to the existing literature, in this article, the pointing error effect on the quality of optical communication between satellites in the OISN system has been investigated using the most recent parsers, which is an OptiSystem program. This work contributes in many folds by providing a simulation study using the most recent programming (i.e., OptiSystem) to realize the effect of satellite mechanical vibration on the optical communication between satellites in the OISN system. That is, the effect of the pointing error due to satellite platform vibration over the performance of the laser communication link of the OISN system in terms of the quality factor is investigated. Indeed, an optical communication system has been built using the OptiSystem program to simulate the link between satellites in space for the OISN system. In addition, the proposed system shows by simulation the optimal parameters' values required for the design of the optical communication link between satellites of the OISN system. Moreover, the effect of pointing error due to the platform vibration on the performance of the OISN system is investigated for different scenarios of the pointing error (i.e., no pointing error; one side of the link with pointing error, and two sides of the link with pointing error).

This article is organized as follows. Section 2 expresses the model of the considered system. Section 3 demonstrates the simulation results and their comments. Conclusions are listed in Section 4.

2 Model configuration

2.1 Transmitter model

The transmitter part of the OISN system has the rule of preparing the information to be transmitted optically using a laser beam. Mainly the optical transmitter in the OISN system includes a laser source, for example, a laser diode. Then, the information to be transmitted is modulated on the laser beam using a Mach-Zehnder modulator, which is an electro-optic device that invests the electric fields in changing the laser path lengths and creates a phase modulation to the emitted laser signal. Finally, the OISN transmitter telescope collimates and aligns the laser beam that carries the transmitted information.

As shown in Figure 1, the whole electro-optical components hold by mechanical joints. That is, the electro-optical components, such as the telescope optical components, sun shutter, tracking unit, optical interface unit between transmitter and receiver, and steering mirrors all are contained in the two-axis gimbals' structure (azimuth and elevation), while other electronic units are located off-gimbals. Consequently, due to the

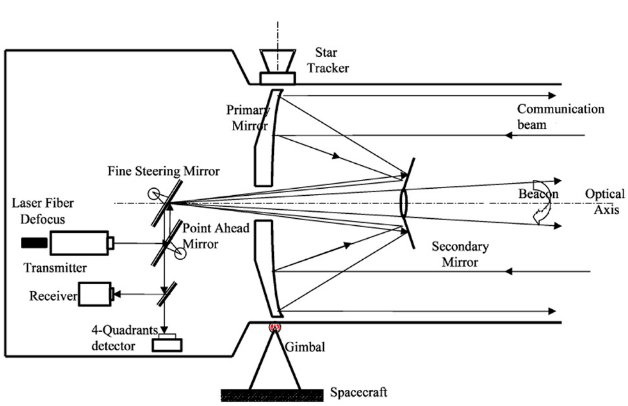

Figure 1: Transceiver diagram of the optical and mechanical structure [22].

angular movement of the satellite (i.e., spinning around its body center and orbiting in its orbit), the slight vibration will be amplified by the small joints, and it has a considerable effect on the transmitted laser beam. Moreover, combined with the long communication distance the laser propagates between satellites, the resultant pointing error of the transmitted laser beam will be amplified. Mathematically, the pointing error due to the mechanical vibration presents as two-axis errors (i.e., elevation and azimuth errors angles). Indeed, the angle of the elevation pointing error is assumed to have a Gaussian distribution, such as refs [9,23,24]:

$$\mathfrak{p}(\theta_{\text{elevation}}) = \frac{1}{\sqrt{2\pi\varrho_{\text{elevation}}}} \times \exp\left[-\left(\frac{\theta_{\text{elevation}} - \Gamma_{\text{elevation}}}{2\varrho^2_{\text{elevation}}}\right)\right], \tag{1}$$

where $\theta_{\text{elevation}}$ is angle of the elevation pointing error; $\Gamma_{\text{elevation}}$ its mean; and $\varrho^2_{\text{elevation}}$ is its variance.

Similarly, the angle of the azimuth pointing error distribution [9,23,24]:

$$\mathfrak{p}(\theta_{\text{azimuth}}) = \frac{1}{\sqrt{2\pi\varrho_{\text{azimuth}}}} \times \exp\left[-\left(\frac{\theta_{\text{azimuth}} - \Gamma_{\text{azimuth}}}{2\varrho^2_{\text{azimuth}}}\right)\right]. \tag{2}$$

It is worth mentioning that the aforementioned distributions do not have a biased term since the calibration of the transmitted laser beam optical axis will be done continuously over time. So then, considering the Cartesian geometry transformation, the angle of the radial pointing error will be:

$$\theta_r = \sqrt{\theta_{\text{azimuth}} + \theta_{\text{elevation}}}. \tag{3}$$

Moreover,

$$\varrho^2_{\theta_r} = \varrho^2_{\text{azimuth}} = \varrho^2_{\text{elevatoin}}. \tag{4}$$

The majority of the literature assumes the independency and identicality of the elevation and azimuth distributions. Therefore, the radial pointing error angle has the following distribution function:

$$\mathfrak{p}(\theta_{ri}) = \frac{\theta_{ri}}{\varrho^2_{\text{azimuth}}} \times \exp\left[-\left(\frac{\theta^2_{ri}}{2\varrho^2_{ri}}\right)\right], \tag{5}$$

where all the aforementioned parameters are the same as the ones listed earlier but related to radial pointing error angle; subscript $i \in \{T_x, R_x\}$ indicates the identity either to be transmitter or receiver; T_x denotes transmitter; and R_x denotes receiver.

2.2 OISN channel

The OISN system uses the laser beam as an optical signal to carry information between satellites over space as a communication medium, whereas space is considered a vacuum medium. Therefore, the environmental processes, such as absorption, scattering, shimmering, fading, and multi-path, affect the received signal's quality will be dominated by the effect of uncertainty or error in the line of sight (i.e., error in pointing angle). Specifically, the space losses (i.e., the loss in signal strength as it travels through free space) can be given as refs [9,23–27]:

$$\text{losses}_{\text{free spsce}} = \mho_{R_x} \times \mho_{T_x} \times \left(\frac{\lambda}{4\pi L_{\text{TR}}}\right)^2, \tag{6}$$

where λ is the laser beam wavelength; L_{TR} is the distance between the transmitter and receiver telescopes; and $\mho_{R_x}$ and $\mho_{T_x}$ are the receiver and transmitter directivity, respectively, that measures the degree to which the radiation emitted is concentrated in a single direction (i.e., directivity measures the power density the antenna radiates in the direction of its strongest emission, versus the power density radiated uniformly in all directions). The directivity is given as ref. [28]:

$$\mho_i = \frac{4\pi}{\Phi_i}, \tag{7}$$

where $i \in \{T_x, R_x\}$; T_x denotes transmitter; R_x denotes receiver; and Φ_i is the solid angle of the transmitter or the receiver, which is given by ref. [28]:

$$\Phi_i = \frac{\lambda^2}{\omega_o^2}, \tag{8}$$

where $i \in \{T_x, R_x\}$ and ω_o is the laser beam waist radius. Indeed, data are send over the light speed to a long distance using a narrower laser beam width than the radio frequency (RF) system. The RF system wavelength is much longer than lasers; hence, it requires a highly accurate alignment to ensure satellites' connection with the line of sight. Consequently, working with a narrow beam-width laser between satellites over thousands of kilometers becomes more sensitive, especially in the presence of relative motion and satellite vibration, where such noise sources may be optical sensor noise, friction, and bearing noise, and/or satellite base-frame vibration noise.

2.3 Receiver model

The receiver of the OISN system gets the signal traveled over the distance of the optical link from the transmitter, where the effect of vibration at the transmitter has a significant contribution to the received signal pointing error. Therefore, the optical signal gain at the receiver (R_x) is given by:

$$\begin{aligned}
\text{gain}_{\text{overall}} &= \frac{P_{R_x}}{P_{T_x}},\\
P_{R_x} &= \text{gain}_{\text{overall}} \times P_{T_x},\\
P_{R_x} &= P_{T_x} \times \text{gain}_{T_x} \times \text{effeciency}_{T_x}\\
&\quad \times \text{channel}_{\text{losses}} \times \text{losses}_{T_x}\\
&\quad \times \text{gain}_{R_x} \times \text{effeciency}_{R_x} \times \text{losses}_{R_x},\\
P_{R_x} &= P_{T_x} \times \Psi_{T_x} \times \eta_{T_x} \times \mho_{T_x}\left(\frac{\lambda}{4\pi L_{\text{TR}}}\right)^2\\
&\quad \times \mho_{R_x} \times \Upsilon_{T_x} \times \Psi_{R_x} \times \eta_{R_x} \times \Upsilon_{R_x},
\end{aligned} \tag{9}$$

where P_{T_x} denotes the transmitted power; Ψ_{T_x} and Ψ_{R_x} denote the telescope gain at the transmitter and receiver satellites, respectively; η_{T_x} and η_{R_x} are the efficiency of the optical system at the transmitter and receiver satellites, respectively; Υ_{T_x} and Υ_{R_x} are the laser beam pointing error losses of the transmitter and the receiver, respectively; and other parameters are defined in equation (6). The satellite telescope optics efficiency is given by ref. [29]:

$$\eta_i = \frac{\mathcal{T}_i}{\mathfrak{A}_i}, \tag{10}$$

where $i \in \{Tx, Rx\}$; $\mathcal{T}_i$ denotes the light acquisition time; and $\mathfrak{A}_i$ is the telescope availability, which are given by, respectively, [29]:

$$\mathcal{T}_i = \tau^i_{\text{calib}} + \tau^i_{\text{acquir}}, \tag{11}$$

$$\mathfrak{A}_i = \tau^i_{\text{schedul}} + \tau^i_{\text{reconf}} + \mathcal{T}_i + \tau^i_{\text{fail}} + \tau^i_{\text{conti}}, \tag{12}$$

where τ_{calib} is the calibration time; τ_{acquir} is the acquiring time; τ_{schedul} is the scheduling observation time; τ_{reconf} is the telescope system reconfiguration time; τ_{conti} is the time that space contamination prevent observations; and τ_{fail} is the telescope fault/inability time. The transmitter and receiver telescope gain are given by ref. [9,23,24]:

$$\Psi_{T_x} = \left(\frac{\pi d_{T_x}}{\lambda}\right)^2, \tag{13}$$

$$\Psi_{R_x} = \left(\frac{\pi d_{R_x}}{\lambda}\right)^2, \tag{14}$$

receptively, where d_{T_x} and d_{R_x} are the satellite telescope diameter. Note that the telescope gain at the transmitter and receiver may be the same or not, depending on the manufacturer of the satellite. The laser beam pointing error losses for transmitter and receiver, respectively, are given as follows:

$$\Upsilon_{T_x} = \exp^{-(\Psi_{T_x} \times \theta_{rT_x})}, \tag{15}$$

$$\Upsilon_{R_x} = \exp^{-(\Psi_{R_x}\times\theta_{rR_x})}, \tag{16}$$

where θ_{rT_x} and θ_{rR_x} are defined in equation (3); and all parameters have been defined earlier. Plugging equations (13)–(16) into equation (9) result in:

$$\begin{aligned}
P_{R_x} &= P_{T_x} \times \left(\frac{\pi d_{T_x}}{\lambda}\right)^2 \times \eta_{T_x} \times \mho_{T_x} \times \left(\frac{\lambda}{4\pi L_{\mathrm{TR}}}\right)^2 \\
&\quad \times \mho_{R_x} \times \exp^{-(\Psi_{T_x}\times\theta_{rT_x})} \times \left(\frac{\pi d_{R_x}}{\lambda}\right)^2 \times \eta_{R_x} \\
&\quad \times \exp^{-(\Psi_{R_x}\times\theta_{rR_x})}, \\
&= P_{T_x} \times \eta_{T_x} \times \mho_{T_x} \times \mho_{R_x} \times \eta_{R_x} \times \left(\frac{\lambda}{4\pi L_{\mathrm{TR}}}\right)^2 \left(\frac{\pi d_{T_x}}{\lambda}\right)^2 \\
&\quad \times \left(\frac{\pi d_{R_x}}{\lambda}\right)^2 \times \exp^{-(\Psi_{T_x}\times\theta_{rT_x})} \times \exp^{-(\Psi_{R_x}\times\theta_{rR_x})}, \\
&= P_{T_x} \times \frac{\mathcal{T}_{T_x}}{\mathfrak{A}_{T_x}} \times \mho_{T_x} \times \mho_{R_x} \times \frac{\mathcal{T}_{R_x}}{\mathfrak{A}_{R_x}} \times \left(\frac{\pi\ d_{T_x}\ d_{R_x}}{4\ \lambda\ L_{\mathrm{TR}}}\right)^2 \\
&\quad \times \exp^{-\left[\left(\left(\frac{\pi d_{T_x}}{\lambda}\right)^2\times\theta_{rT_x}\right)+\left(\left(\frac{\pi d_{R_x}}{\lambda}\right)^2\times\theta_{rR_x}\right)\right]}, \\
&= P_{T_x} \times \frac{\mathcal{T}_{T_x}}{\mathfrak{A}_{T_x}} \times \frac{4\pi\omega_o^2}{\Lambda^2} \times \frac{4\pi\omega_o^2}{\Lambda^2} \times \frac{\mathcal{T}_{R_x}}{\mathfrak{A}_{R_x}} \times \left(\frac{\pi\ d_{T_x}\ d_{R_x}}{4\ \lambda\ L_{\mathrm{TR}}}\right)^2 \\
&\quad \times \exp^{-\left[\left(\left(\frac{\pi d_{T_x}}{\lambda}\right)^2\times\theta_{rT_x}\right)+\left(\left(\frac{\pi d_{R_x}}{\lambda}\right)^2\times\theta_{rR_x}\right)\right]}, \\
&= P_{T_x} \times \frac{\mathcal{T}_{T_x}}{\mathfrak{A}_{T_x}} \times \left(\frac{2\pi\omega_o}{\lambda}\right)^2 \times \frac{\mathcal{T}_{R_x}}{\mathfrak{A}_{R_x}} \\
&\quad \times \left(\frac{\pi\ d_{T_x}\ d_{R_x}}{4\ \lambda\ L_{\mathrm{TR}}}\right)^2 \times \exp^{-\left[\left(\left(\frac{\pi d_{T_x}}{\lambda}\right)^2\times\theta_{rT_x}\right)+\left(\left(\frac{\pi d_{R_x}}{\lambda}\right)^2\times\theta_{rR_x}\right)\right]}, \\
&= P_{T_x} \times \frac{\mathcal{T}_{T_x}}{\mathfrak{A}_{T_x}} \times \frac{\mathcal{T}_{R_x}}{\mathfrak{A}_{R_x}} \times \left(\frac{\pi^2\ \omega_o\ d_{T_x}\ d_{R_x}}{2\ \lambda^2\ L_{\mathrm{TR}}}\right)^2 \\
&\quad \times \exp^{-\left[\left(\left(\frac{\pi d_{T_x}}{\lambda}\right)^2\times\theta_{rT}\right)+\left(\left(\frac{\pi d_{R_x}}{\lambda}\right)^2\times\theta_{rR_x}\right)\right]},
\end{aligned} \tag{17}$$

where P_{T_x} denotes the transmitted power; $\mathcal{T}_{T_x}$ and $\mathcal{T}_{R_x}$ denote the light acquisition of the transmitter and receiver, respectively; $\mathfrak{A}_{T_x}$ and $\mathfrak{A}_{R_x}$ denote the telescope availability of the transmitter and receiver, respectively; d_{T_x} and d_{R_x} denote the satellite telescope diameter of the transmitter and receiver, respectively; ω_o denotes the laser beam waist radius; λ denotes the laser wavelength; L_{TR} denotes the distance between satellites; and θ_{rT_x} and θ_{rR_x} denote the angle of the radial pointing error. There are two possible signal levels for the optical signal, which lead to two signal-to-noise ratios (SNRs). Considering that there can be two power levels at the receiver, then there is a probability of making an erroneous decision in the receiver. The quality factor gives a measure of overall system quality by combining both SNRs. That is, the quality factor is a measure of how the optical signal is noisy for optical communication, and it facilitates the system performance analysis. The quality factor can be given by ref. [30]:

$$Q_{\mathrm{factor}} = \frac{P_{HR_x} - P_{LR_x}}{\sigma_H - \sigma_L}, \tag{18}$$

where P_{HR_x} and P_{LR_x} are the optical power at the high and low levels, respectively; σ_H and σ_L are the standard deviations of the noise at the high and low levels, respectively. For more details of equation (18); see ref. [30] and the references therein. According to equation (18), the performance of the OISN system in terms of the quality factor has been affected by the received optical power and the level of the noise. In the same manner, considering equation (17), the transmitted power; light acquisition time at the transmitter and the receiver; the laser beam waist radius; and the satellite telescope diameter at the transmitter and the receiver are proportionally related to the received power (i.e., proportionally related to the OISN system performance in terms of the quality factor). On the other hand, the distance between satellites, telescope availability; wavelength; and the angle of the radial pointing error are inversely related.

3 Simulation results and comments on simulation

The simulation results presented in this section demonstrate the effect of pointing error due to vibration on the optical communication quality between satellites for the OISN system. Indeed, the simulation presented three scenarios: first, a simulation study the relation between OISN system parameters with zero pointing error; second, the transmitter only pointing error is considered; finally, both transmitter and receiver pointing errors are considered in the simulation. Note that simulation results are created using MATLAB R2019 and OptiSystem with a computer equipped with an Intel Core i7 2.6 GHz Processor and 16 GB RAM. The system that was implemented by the OptiSystem is shown in Figure 2. The considered numerical parameter values represent a state of art for such systems used in many published literature; see, for example, refs [13–18] and the references therein.

Figure 3 shows the quality factor (Q_{factor}) as a function of the transmitted power (P_{in}(W)) for different wavelengths with zero pointing error. The parameters' values used in the simulation of this figure are presented in Table 1. It can be seen that the quality factor increases

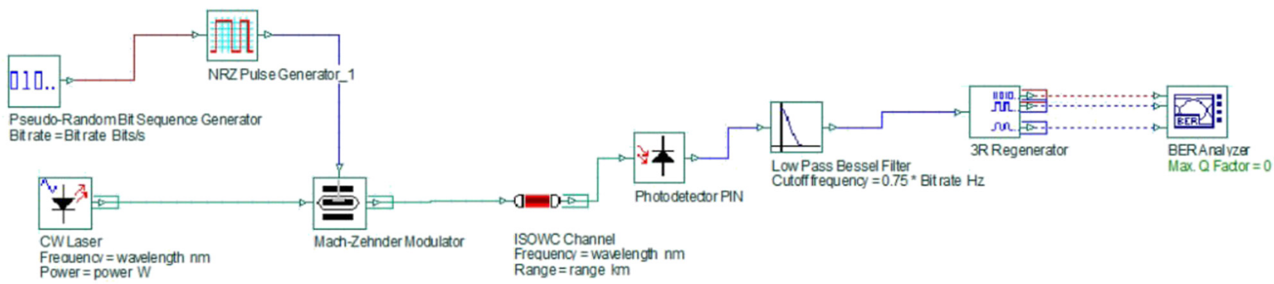

Figure 2: The OISN system was implemented by the OptiSystem.

linearly with transmitted power. Indeed, this result matched with the existing literature, such as refs [31,32]. In addition, the quality factor degraded with increasing the wavelengths. That is, using the wavelength 850 nm leads to better results than the other considered wavelengths. Actually, this result agrees with the result listed in refs [14,33].

Figure 4 expresses the quality factor (Q_{factor}) as a function of the transmitted power ($P_{\text{in}}(\text{W})$) for different distances ($L_{\text{TR}}(\text{km})$) between satellites of the OISN system with zero pointing error. The parameters' values used in the simulation of this figure are listed in Table 1. It is clear that the quality factor increases linearly with transmitted power. In addition, the quality factor degraded with increasing the communication distance between satellites. Obviously, the best communication distance is the shortest for the considered conditions mentioned earlier, where 5,000 gives reasonable results. It should be noted that this result matched with the ones listed in the literature, such as refs [14,31,32,34].

Figure 5 presents the quality factor (Q_{factor}) as a function of the laser wavelength ($\lambda(\text{nm})$) for different optical modulation schemes with zero pointing error. The parameters' values used in the simulation of the figure are presented in Table 1. It can be seen that the quality factor decreases linearly with increasing the wavelength for the considered wavelengths. In addition, the quality factor has reasonable results for the nonreturn to zero (NRZ) optical modulation scheme. Actually, this result agrees with the result listed in refs [14,16].

Figure 6 shows the quality factor (Q_{factor}) as a function of the transmitted power ($P_{\text{in}}(\text{W})$) for different optical telescope optics diameters ($d_{T_x}(\text{cm})$) with zero pointing error. The parameters values used in simulation of the figure are listed in Table 1.

It can be seen that the quality factor increases linearly with transmitted power. In addition, the quality factor has been enhanced by increasing the telescope diameter, which agrees with the existing literature, for instance, refs [14,31,33,34]. Figure 7 presents the quality factor (Q_{factor}) as a function of the transmitted power ($P_{\text{in}}(\text{W})$) for different telescope efficiency (i.e., both η_{T_x} and η_{R_x}) with zero pointing error. The parameters values used in simulation of the figure are listed in Table 1.

It can be seen that the quality factor increases linearly with transmitted power. In addition, the quality

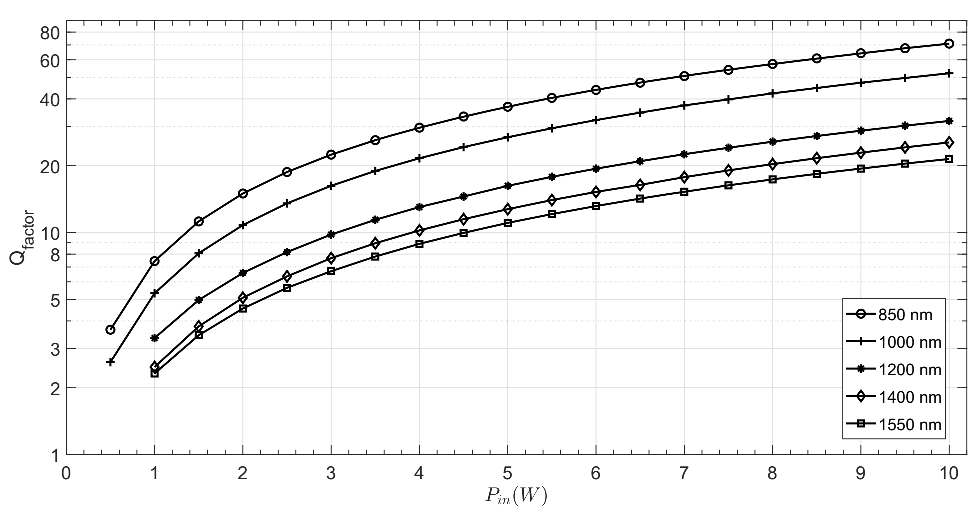

Figure 3: Quality factor (Q_{factor}) as a function of the transmitted laser power ($P_{\text{in}}(\text{W})$) for a different laser wavelengths W/zero pointing error.

Table 1: Parameters used in OptiSystem for the simulation of Figure 3

P_{in} (W)	λ (nm)	L_{TR} (km)	d_{T_x} (cm)	d_{R_x} (cm)	Modulation	Line width (kHz)	Bit rate (Gpbs)	Extinction ratio (dB)
x	x	5,000	15	15	NRZ	100	10	30

η_{T_x} (%)	η_{R_x} (%)	θ_{T_x} (μrad)	θ_{R_x} (μrad)	Cutoff frequency (Hz)	Additional losses (dB)	Propagation delay (ps/km)	Responsivity (A/W)	Dark current (nA)
97	97	0	0	7.5	0	0	1	10

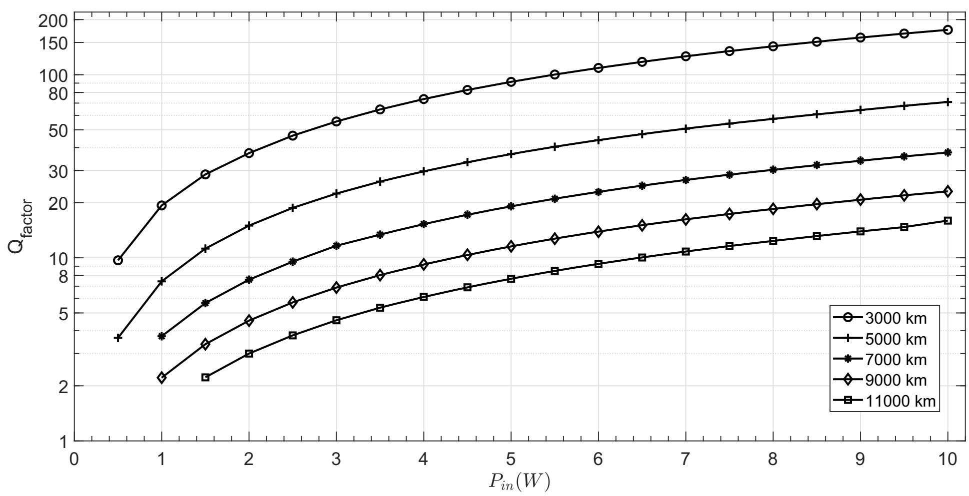

Figure 4: Quality factor (Q_{factor}) as a function of the transmitted laser power (P_{in}(W)) for different distances (km) between satellites W/zero pointing error.

factor has been improved by increasing the telescope efficiency, while the worst behavior has been shown at 20% efficiency. Overall, the quality factor is enhanced by increasing the transmitted power combined with increasing the telescope diameter and efficiency and decreasing the communication ranges with a suitable wavelength and optical modulation scheme. That is, the aforementioned results show that the values of the following parameters

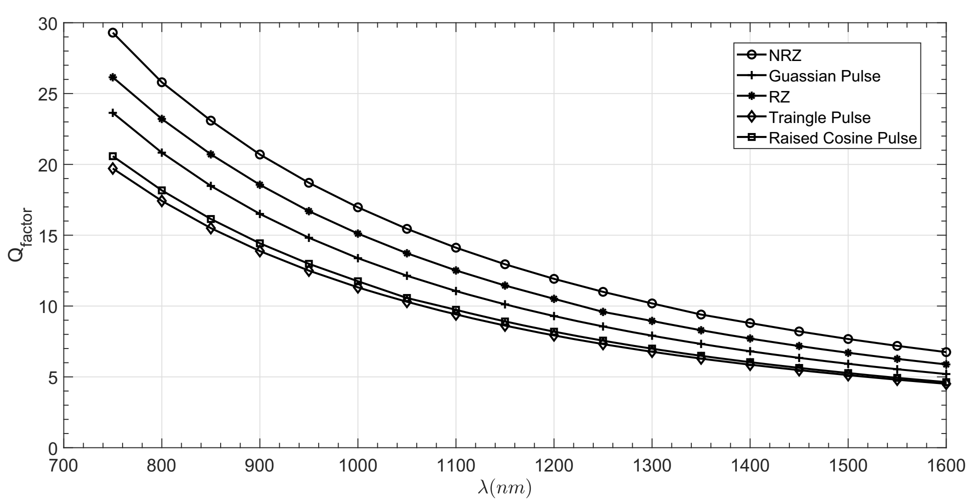

Figure 5: Quality factor (Q_{factor}) as a function of the transmitted laser wavelength (λ(nm)) for different optical modulation schemes W/zero pointing error.

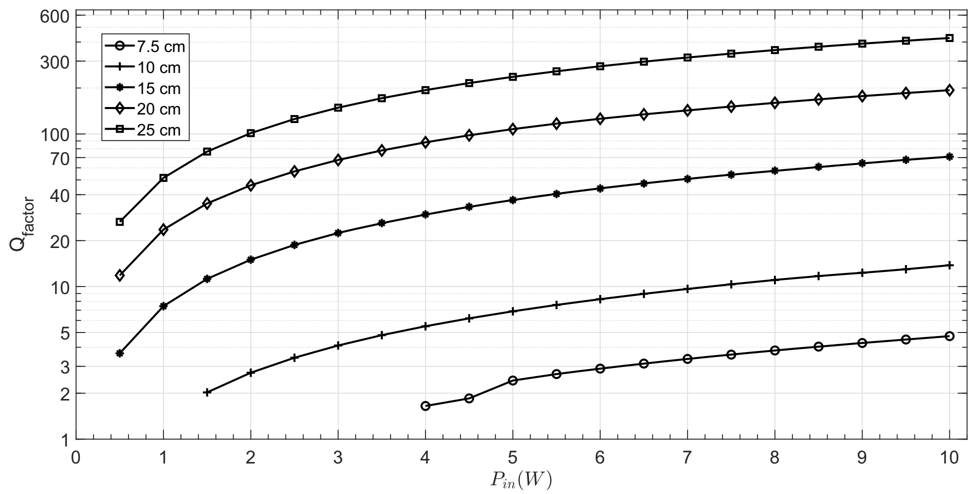

Figure 6: Quality factor (Q_{factor}) as a function of the transmitted laser power (P_{in}) for a different telescope diameters (cm) W/zero pointing error.

give reasonable results, and they will be used for the rest of the simulation: 850 nm as a laser wavelength, NRZ optical modulation scheme; 15 cm optical telescope diameter; 5,000 km communication range; 97% optical telescope efficiency, where the pointing error due to vibration is considered to be zero. Therefore, those parameter values will be used for the rest of the simulations. The existing literature, for instance, refs [14,16,31,33,34], validate this work results. That is, table 1 in ref. [34] shows the key design parameters used for inter satellites link. It expresses that the telescope diameter is 12.5 cm, and the link distance is 5,100 km, which validates the parameters' values found in this work. In addition, ref. [31] states that the telescope diameter was chosen to be 15 cm, and the relation between the transmitted power and the quality factor is proportional, which are supporting the data used in this work. Moreover, table 1 in ref. [33] listed 850 nm wavelength and 15 cm telescope diameter as design parameters values, which match the data used in this work.

Figure 8 shows the quality factor (Q_{factor}) as a function of the transmitted power (P_{in}(W)) considering only the transmitter with different pointing errors, where the other parameters are listed in Table 1. The interpretations of this figure are many. As the transmitted power of the laser increased, the quality factor improved. In addition, as the pointing error increased, the quality factor degraded. Indeed, this result matched with the existing literature, such as ref. [31].

Figure 9 shows the quality factor (Q_{factor}) as a function of the distance between satellites within the OISN

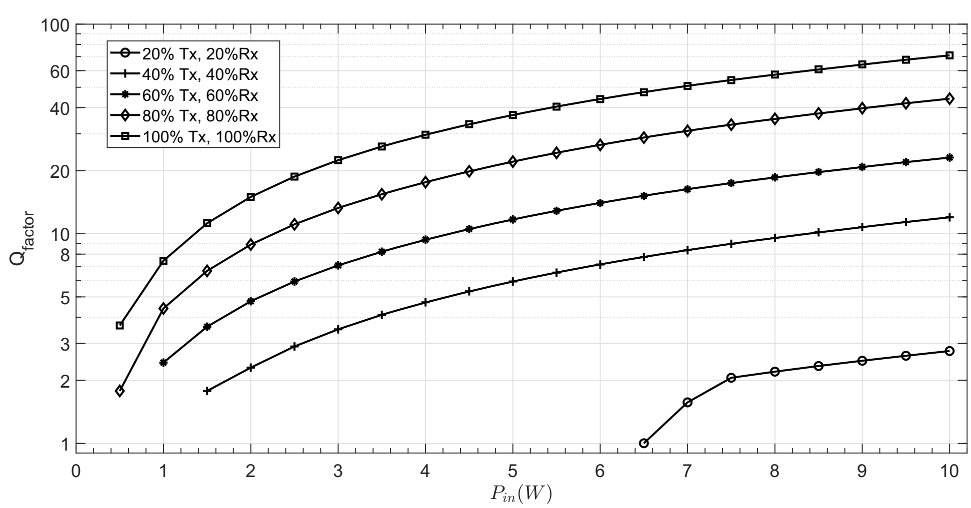

Figure 7: Quality factor (Q_{factor}) as a function of the transmitted laser power (P_{in}) for a different telescope efficiency W/zero pointing error.

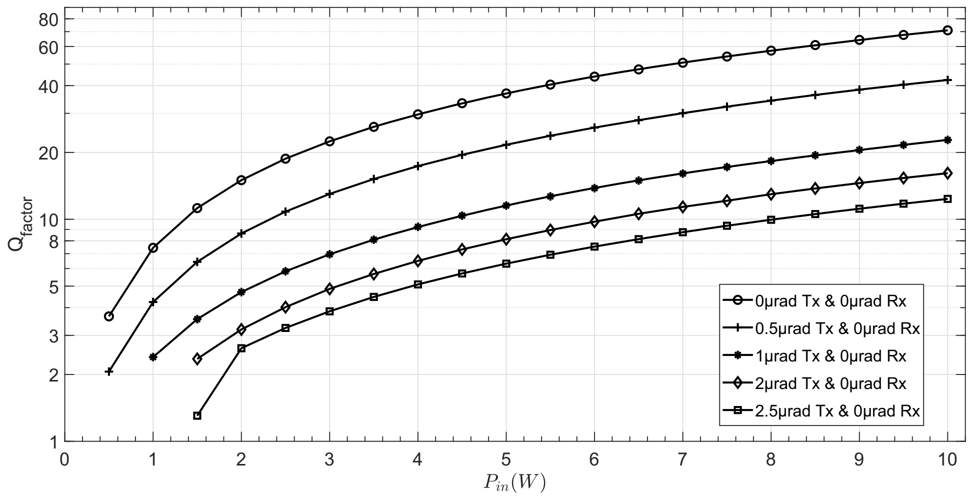

Figure 8: Quality factor (Q_{factor}) as a function of the transmitted laser power (P_{in}(W)) for a different transmitter only pointing error.

system considering only the transmitter with different pointing errors, where the other parameters are listed in Table 1. Furthermore, it is shown that the quality factor degraded with increasing the transmitter pointing error and increasing the distance between satellites of the OISN system.

Figure 10 shows the quality factor (Q_{factor}) as a function of both transmitter and receiver optical telescope diameters ($d_{T_x\&R_x}$(cm)) considering only the different transmitter pointing errors, where the other parameters are listed in Table 1. This figure has an interesting interpretation. The quality factor degraded with increasing the transmitter pointing error. It is partially increasing with increasing the optical telescope diameter for the low transmitter pointing error. Specifically, by increasing the pointing error, initially, the quality is linearly increasing with the diameter, and then the relation is *vice-versa* with increasing the telescope diameter. That is, the 15 cm telescope diameter gives the optimal quality factor value. The interpretation is that, as the optical telescope diameter increases up to 15 cm, the optical signal power received increases, leading to improving the quality factor considering small values of pointing error. In contrast, for large values of pointing error, increasing the telescope diameter by more than 15 cm led to an increase in the level of the error captured by the telescope, which degraded the quality factor.

Figure 11 shows the quality factor (Q_{factor}) as a function of the telescope efficiency with only transmitter different pointing error, where the other parameters are listed in Table 1. It can be seen that the quality factor

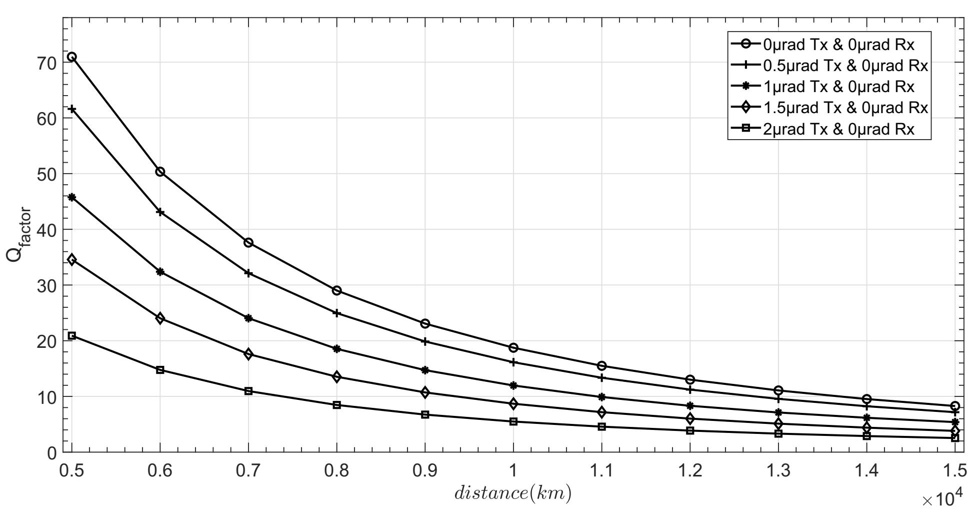

Figure 9: Quality factor (Q_{factor}) as a function of distances between satellites for a different transmitter only pointing error.

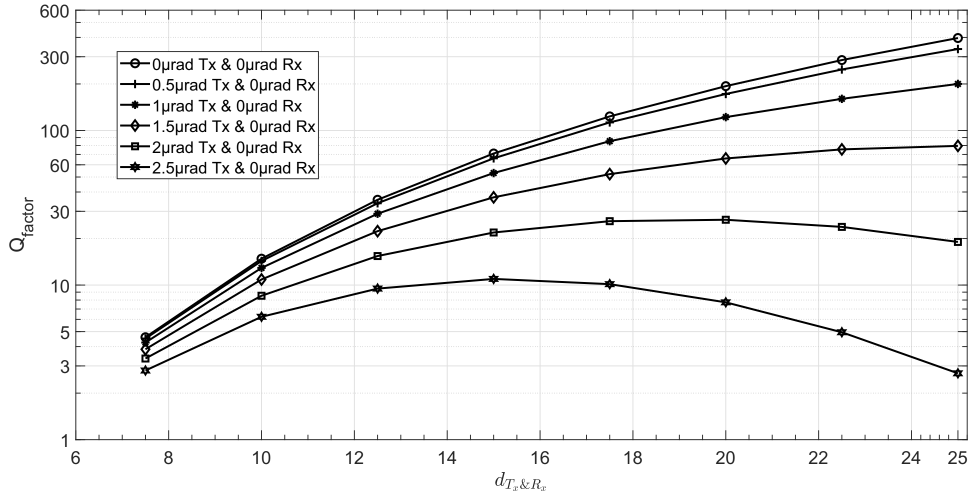

Figure 10: Quality factor (Q_{factor}) as a function of telescope diameters (cm) for a different transmitter only pointing error.

has been enhanced by increasing the telescope efficiency, while the quality factor degraded by increasing the pointing error. That is, increasing the pointing error leads to an increase in the error in the received signal, and increasing the efficiency tends to compensate partially for the effect of the pointing error.

Figure 12 shows the quality factor (Q_{factor}) as a function of the transmitted power (P_{in}(W)) considering different pointing errors for both transmitter and receiver, where the other parameters are same used for Figure 8, which is listed in Table 1. In addition to the interpretations that have been listed in Figure 8, Figure 12 shows that having a pointing error in both transmitter and receiver deteriorates the quality factor significantly. Moreover, the maximum pointing error that the system can handle is (2 μrad), where more than this pointing error, no power can be caught by the receiver. In the same manner, ref. [33] expresses the same results.

Figure 13 shows the quality factor (Q_{factor}) as a function of the distance between satellites within the OISN system considering the transmitter and the receiver with different pointing errors, where the other parameters are the same used for Figure 9, which is listed in Table 1. In addition to the interpretations of Figure 9, it can be seen that considering pointing error in both transmitter and receiver lead to faster degradation of the quality factor with the distance between satellites considering different scenarios of the pointing errors for the transmitter and receiver. Having more pointing errors at the receiver than that of the transmitter leads to more quality factor degradation.

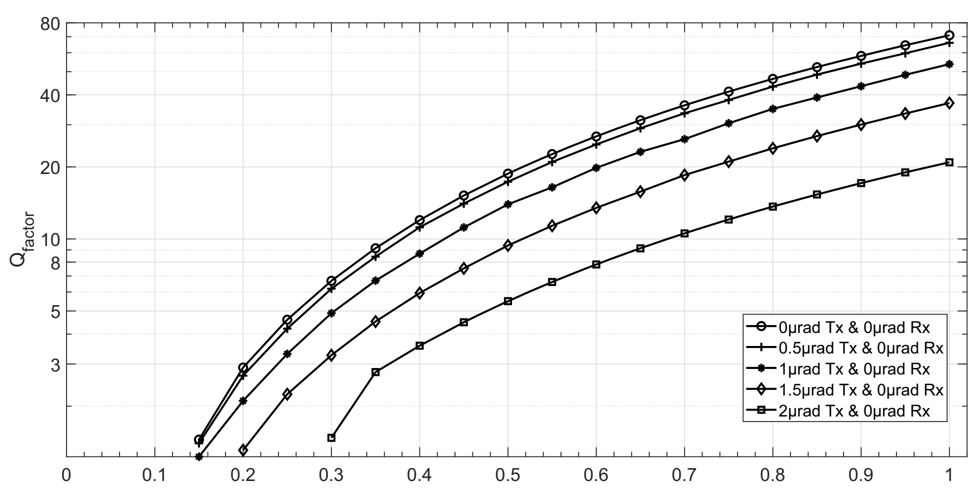

Figure 11: Quality factor (Q_{factor}) as a function of the telescope efficiency with only transmitter different pointing error.

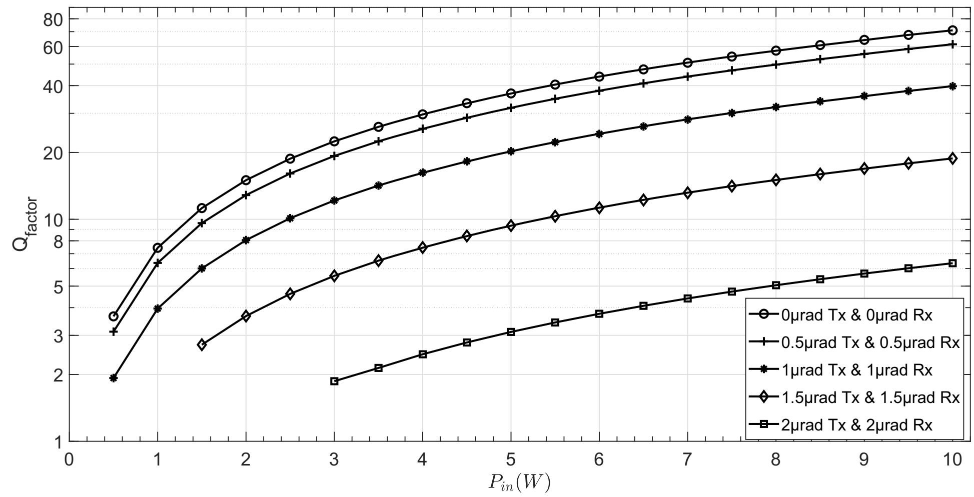

Figure 12: Quality factor (Q_{factor}) as a function of the transmitted laser power (P_{in}(W)) for different transmitter and receiver pointing errors.

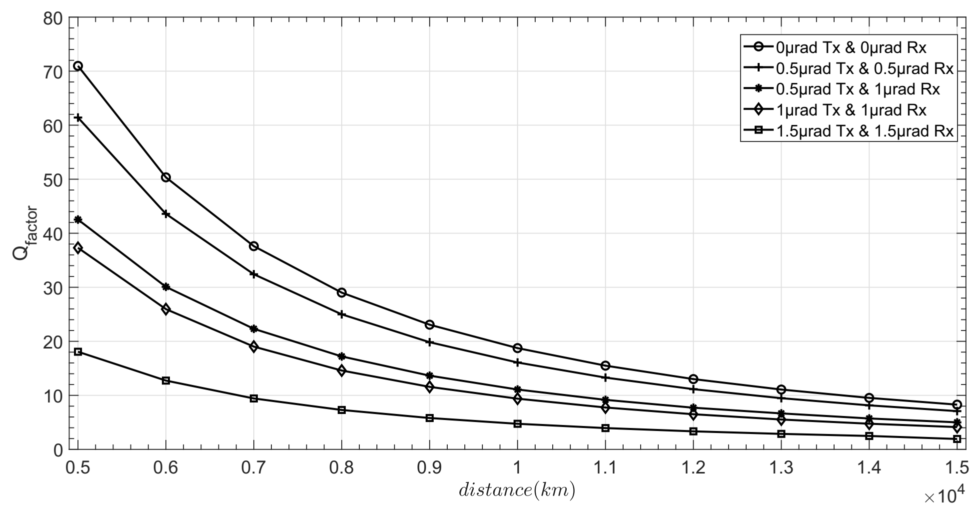

Figure 13: Quality factor (Q_{factor}) as a function of distances between satellites for different transmitter and receiver pointing errors.

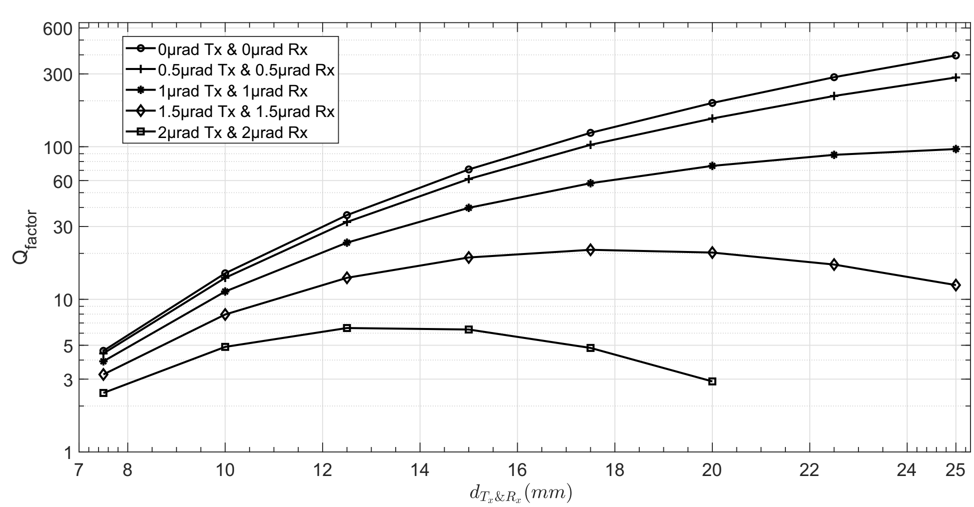

Figure 14: Quality factor (Q_{factor}) as a function of both transmitter and receiver optical telescope diameters (dTx&Rx (cm)) for different transmitter and receiver pointing errors.

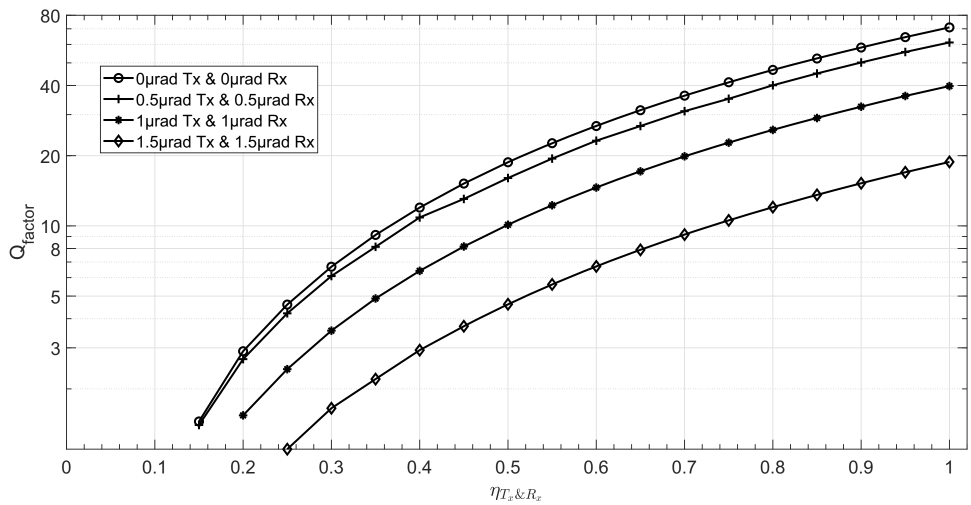

Figure 15: Quality factor (Q_{factor}) as a function of the telescope efficiency for different transmitter and receiver pointing errors.

Figure 14 shows the quality factor (Q_{factor}) as a function of both transmitter and receiver optical telescope diameters ($d_{T_x\&R_x}$ (cm)) considering only the transmitter different pointing errors, where the same parameters have been used for Figure 10, and they are listed in Table 1. In addition to the interpretations of Figure 10, Figure 14 shows faster degradation of the quality factor with telescope efficiency considering different scenarios of the pointing errors for the transmitter and receiver. Moreover, the maximum pointing error that the system can handle is (1.5 μrad), where more than this pointing error, no power can be caught by the receiver. Overall, in the same manner, results have been presented for only transmitter pointing error scenarios, considering the pointing error at both transmitter and receiver leads to more degradation of the quality factor, and receiver side pointing error has more effect on the quality factor, where the 15 cm telescope diameter gives near-optimal quality factor value (Figure 15).

Next, the main point that can be concluded will be presented.

4 Conclusion

Over space optical communications are considered the critical technology for high-speed and large-capacity communications. The laser light can be used as a signal that carries information and data with a line-of-sight, high-bandwidth, and communication link between remote sites. Indeed, the laser beam pointing to or from a moving object, such as a satellite, is one of the most challenging processes for optical space communications. In this work, the effect of the pointing error over the performance of the laser communication link of the OISN system in terms of the quality factor is investigated using the most current parser (i.e., OptiSystem simulator). The simulation results validate the mathematical model that has been stated in terms of the relation between the OISN system parameters and the system performance. As a result, it is found that the parameters that can be used for the optical communication link between satellites of the OISN system. In addition, the existence of pointing error due to vibration at one side of the optical-link leads to degradation of the performance of the OISN system in terms of the quality factor for different laser beam power, distances between satellites, telescope diameters, and telescope efficiencies. Moreover, existing pointing errors at the two sides of the optical link lead to rapid degradation of the considered OISN system performance even with the increase of the laser power or telescope diameter, which tend to compensate for its effect initially and then quit (i.e., for the considered system parameters, 15 cm telescope diameter gives near-optimal quality factor). Implementing the considered system practically is one of the points of a future job.

Conflict of interest: The authors declare that they have no conflict of interest.

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