Pointing Error Reduction Using Fiber Bundle-Based Receiver Design for 200km Inter-Satellite Optical-Wireless Communication (Isowc) Link

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Abstract

Free Space Optical links have gained significant importance in future generation space optical communication, particularly to establish a reliable optical inter-satellite optical wireless link between two satellite platforms. But the performance of Optical wireless link is degraded very much due to vibration imposed by various sources like; thermal storms, other heavy particles collisions. To address this problem a fiber bundle-based receiver approach other than conventional array of photodetector is required to mitigate the effects of pointing error. The result shows that the effect of pointing errors is reduced in the fiber bundle-based receiver system in compare to conventional receiver and this newly designed receiver system is able to cope up to 10 urad pointing error to achieve minimum Bit Error Rate (BER) and Q-factor for a data rate of 1 Gbps over a 200 km distance. It is practically implementable in Low Earth Orbit (LEO) satellite optical wireless communication link.

Keywords: Inter-Satellite Optical-Wireless Communication (IsOWC), Bit Error Rate (BER), Q-factor, pointing error, Fiber bundle-based receiver.

1. Introduction

Optical wireless communication (OWC) utilizes pointed optical beam to carry data through atmosphere or free space. OWC is considered as a future generation space communication for high speed data rate. It is being used for a variety of applications, like airborne internet, inter- satellite communication, battlefield communication and disaster area wireless networking [1- 4]. The random nature of atmospheric turbulence channel, which affects every Free Space Optical (FSO) link regardless of the transmission range, makes FSO link difficult to predict and to counteract. This random nature of atmospheric turbulence causes the random walk of the focal point of the incident optical beam in the focal plane receiver [5] effectively the performance parameter of the FSO link fall below the threshold in a way that causes periods of disconnection. This random walk of source beam creates pointing error. In addition, errors inherent due to the platform vibration, positioning equipment, attenuation due to weather, atmospheric turbulence and Global Positioning System (GPS) signals errors increase the difficulty of establishing a connection between the transceivers [11]. This pointing error problem is even more severe in a mobile communication where one or both transceivers are moving. In order to achieve a reliable inter-satellite optical wireless link, it is necessary to reduce the problem of pointing errors between the two transceivers which are trying to communicate. Several solutions have been proposed to address the pointing error problem and demonstrated in recent years [7-10]. Successful links have been established between satellites and ground stations, as well as between ground stations and other mobile objects such as platforms, airplanes and ships

[11]. However, the amount of performance degradation due to pointing error can be reduced through the design of array of photodetector in conventional receiver [20]. Most optical wireless receivers have very narrow fields of view (FOV) due to which they cannot tolerate large pointing errors. But still it has very less field of view, it is not much suitable to cope pointing error in optical wireless communication link.

The solution to this problem is a redesign of the receiver in which an array of thin lenses at the receiver, rather than a single lens, coupled to an array of large-core fibers. Another advantage of this FSO receiver is that it has more lenses to capturing light so whenever the signal moves off from centre lens to another associated lens then it will capture the light, thus holding signal strength and integrity. In this receiver design, a simulation was made on Opti system simulator and used to investigate how the turbulence, pointing error, transmitted power, link range, the number of collecting fiber and fiber size at the receiver interact and influence the design and control of turbulence and pointing error problem in FSO link

The paper is organized as follows: Section 2 describes the complete fiber bundle based Inter- Satellite Optical-Wireless Communication (IsOWC) system. Section 3 discusses the mathematical analysis of received power calculation of the fiber bundle-based system. Section 4 represents the IsOWC system simulation parameter. Section 5 discusses the results of proposed fiber bundle-based system. Finally, Section 6 concludes this paper.

2. System description:

To make an analysis of pointing error in the optical wireless communication link, it is necessary to build the pointing error environment setup which is described below.

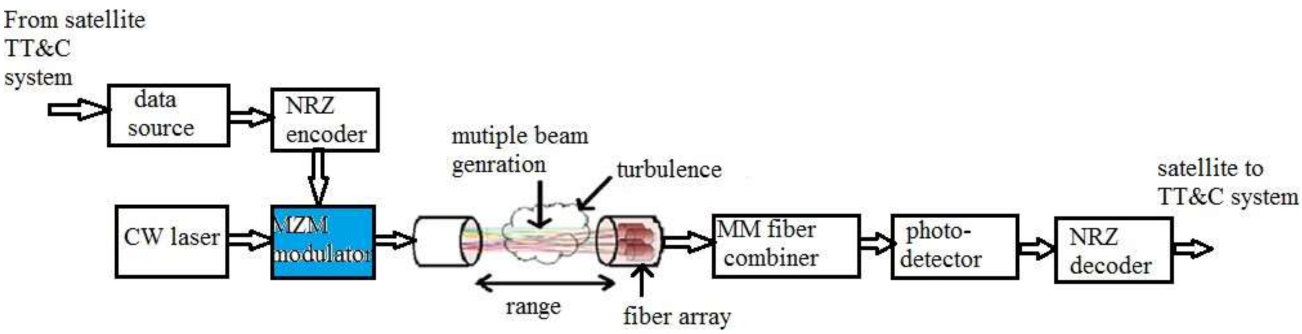


Fig-1: Fiber bundle based IsOWC system

Where NRZ means non return to zero, CW laser means continuous wave, MZM means Mach- Zehnder modulator

In Fig-1, an optical transmitter consists of data source generator, NRZ modulated pulse generator, optical CW source and optical Mach-zahender (MZM) modulator. The opticaltransmitter receives information as data from the satellite"s telemetry, tracking and communication (TT&C) system. The TT&C system collects information from all sensors established on the board of the satellite and sends this information via IsOWC link to the satellite control station. The TT&C system located on earth provides the information related to the link range and position of the target satellite. The CW laser is the optical laser source which generates carrier optical wave for TT&C data. The signal coming from TT&C system is being encoded first by NRZ modulated pulse generator then optically modulated by MZM modulator before it is being transmitted. The received signal from OWC telescope travel through strong turbulence channel which is being modelled by gamma-gamma probability density function (PDF) model [6] which is discussed in next section. At the receiving end, the signal is first detected by a 19 hexagonal array of parabolic index fiber bundle with a core diameter of 400 um. Before signal enters into the fiber, it first impinges on a thin lens with 50 mm diameter and then each lens is adjusted such that it focuses the light into the fiber with total internal reflection angle and also provides a large field of view. This arrangement is helpful in mitigating pointing error which is created by turbulence and vibration. With the help of Multi-Mode (MM) fiber combiner, all the beams collected from the fiber bundle are combined. Then this signal is processed conventionally i.e. first detected by PIN diode and then recovered back by using low pass Bessel filter. The signal is being first analyzed by data recovery tool and then sent to TT&C system. Here all TT&C system data is generated through pseudorandom binary sequence (PRBS) generator. And also, conventional receiver is treated as array of photodetector.

3. Atmospheric Turbulence Channel

Atmospheric turbulence is induced due to the random fluctuation of atmospheric refractive index along the path of the optical radiation traversing the atmosphere. The interaction between the optical beam and the turbulent media results in random amplitude variations (scintillation) of the information-bearing optical beam which results in random variation of the received optical power, this led to the system performance degradation. This scintillation of the optical beam is modelled by gamma-gamma turbulence model.

The Gamma-Gamma Turbulence Model

Andrews and Phillips developed a universal probability density function (PDF) model of irradiance fluctuations [6]. In this, the modulation of the inner scale size over the optical link length by the outer scale size of the atmosphere, making it suitable for modelling weak-to- strong turbulence conditions**.**

The resultant probability of a given intensity (I) is given by as:

$$p(I)= \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta)/2} K_{\alpha-\beta} (2\sqrt{\alpha\beta I}) \quad \text{-----------} (1.1)$$

where $1/_{\alpha}$ and $1/_{\beta}$ are the variances of the small- and large-scale eddies, respectively, $\Gamma(\dots)$is the Gamma function and $K_{\alpha-\beta}(\dots)$ is the modified Bessel function of the second kind.

And coefficient is given by as:

$$\alpha=\exp\left[\frac{0.49\sigma_R{}^2}{(1+1.11\sigma_R{}^{12/5})^{5/6}}\right]-1$$

$$\beta=\exp\left[\frac{0.51\sigma_R{}^2}{(1+0.69\sigma_R{}^{12/5})^{5/6}}\right]-1$$

The Rytov variance is calculated from:

$$\sigma_R{}^2 = 1.23c_R{}^2k^{7/6}z^{11/6} \quad \text{-----------} (1.2)$$

Where, $c_R{}^2$ is the parameter Index refraction structure, k is the optical wave number and z is the range. This model will then be used to characterize the behavior of the received signal and for the error performance of short to very long FSO links.

4. Structure of the Receiver

A signal from a distant transmitter is incident on the receiver's optical telescope system. The scintillation and misalignment cause redistribution of the mean intensity of the beam, so that the peak intensity point(s) may no longer be near the centre of the effective beam. To address these issues, the optical system at the receiver is divided into multiple subsystems in parallel with each other and having the same basic design. Each system has the ability to capture rays entering at a wider range of incident angles than traditional FSO receivers, and the use of systems in parallel improves the maximum displacement of the incident ray that can be tolerated. The parallel collection also makes it more likely that the peak intensity point(s) will fall on a part of the receiver where a large fraction of the power can be collected and directed toward the photo detector. The individual signals are then combined to produce a composite signal for detection and further processing.

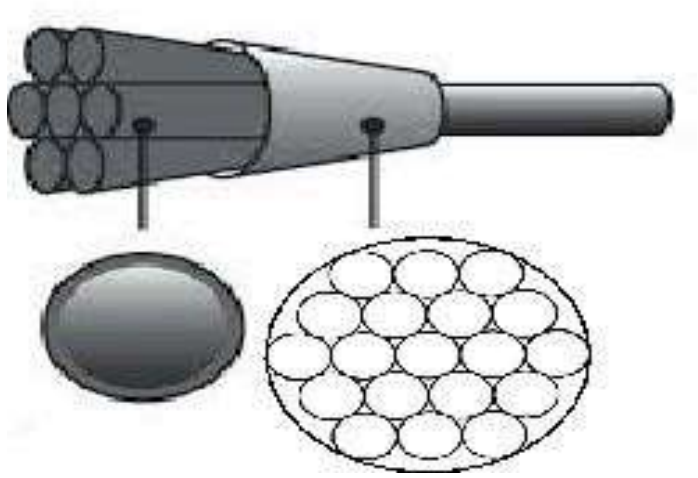
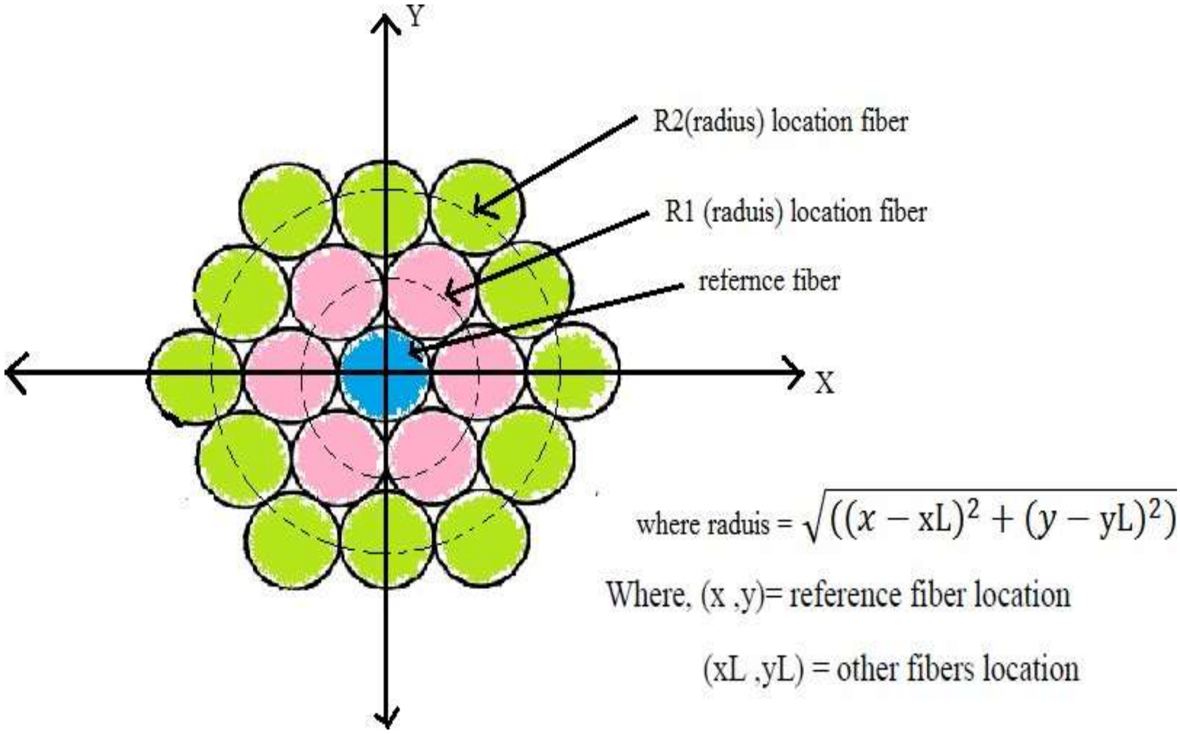


Fig 2: Basic diagram of fiber array

This receiver design consists of a hexagonal array of fiber and each fiber is closely packed in hexagonal structure as shown in Fig 2. Each fiber is having the lens in front of it to focus information bearing optical radiation. This receiver design allows a larger viewing angle, also called the field of view (FOV). The creation of a larger viewing angle will not only help in cases of mitigating the effects of turbulence but will also help mitigate the effects of pointing error.



4. Mathematical analysis of received power calculation: It is very important to develop mathematical modelling to analyze the performance of all simulation

setup in Fig 1. The mathematical analysis of FSO link is presented below.

Fig-3: Geometrical array of fiber bundle

Fig 3 shows the basic arrangement of a hexagonal array. It provides the geometrical position of the fiber bundle which is put into the receiver. Here are three cell of fiber which is blue, pink and green. Each radius (R1 & R2) of the cell is calculating a different exponential factor for received power in equation number (1.3).

The optical wireless link budget equation is given by as follows [17-19]:

$$P_R = P_T\, \eta_T \eta_R (\exp(-(\frac{\sqrt{((x-xL)^2+(y-yL)^2)}}{dR})^2)) \left(\frac{\lambda}{4\pi Z}\right)^2 G_T G_R L_T L_R \text{ ------- (1.3)}$$

Where, P_T is the transmitted optical power; η_T is the transmitter optics efficiency; η_R is the receiver optics efficiency; (x, y) is reference fiber location; (xL, yL) is other all fiber location from the reference point; dR is the fiber bundle receiver diameter; λ is the wavelength; Z is the link range between the two satellite; G_T and G_R are the transmitter and receiver telescope gain, respectively; L_T is the transmitter pointing loss factor and L_R is the receiver pointing loss factor.

The transmitter gain that can be expressed by:

$$G_T = \left(\frac{\pi D_T}{\lambda}\right)^2$$

Where, D_T is the transmitter telescope diameter. Similarly, the receiver gain that can be expressed by:

$$G_R = \left(\frac{\pi D_R}{\lambda}\right)^2$$

Where, D_R is the receiver telescope diameter. The approximate transmitter telescope pointing loss factor is given by:

$$L_T = \exp(-G_T {A_T}^2)$$

Where, A_T is transmitter azimuth pointing error angle. The approximation receiver pointing loss factor by:

$$L_R = \exp(-G_R {A_R}^2)$$

Where, A_R is the receiver azimuth pointing error angle.

6. About Opti system software

Opti system is a comprehensive, innovative, rapidly evolving software design suite that enables users to test, plan, and simulate almost every type of optical links in the transmission layer of modern optical networks. It is a system level simulator based on the realistic modelling of optical communication system. It possesses a powerful new simulation environment and a hierarchical definition of system components. Its capabilities can be extended easily with the addition of new user components and can be interfaced to a wide range of tools. It offers graphical user interface (GUI) controls on the optical component layout and net list, component models and visually presents analysis and scenarios.

7. Simulation Paramters

The proposed IsOWC system is designed and simulated for the signal wavelength 1550 nm. The details regarding the simulation parameters are given in Table 1. The simulation parameters are considered as per the practical point of view of IsOWC sector and the telecommunication standardization provided by the international telecommunications union and telecommunication (ITU-T).

Table-1: simulation parameter

Parameter	Value
Operational wavelength	1550 nm
Bit rate	1 Gbps
Output power	1 mW
Extinction ratio of Modulator	30 dB
OWC type	Line of sight
Transmitter aperture	50 mm
Receiver aperture	250 mm
Transmitter Optics Efficiency	1
Receiver Optics Efficiency	1
Turbulence level	strong
Number of fiber	19
Thin lens diameter	50 mm
Thin lens focal length	1 mm
Core/ cladding diameter	400/440 um
Fiber type	Parabolic index multimode fiber
Fiber length	0.2 m
Responsivity of PIN	1 A/W
Dark current	10 nA
Sequence length	128
Sample per bit	64

8. Performance analysis of inter-satellite optical-wireless communication (IsOWC) system

To make practically LEO orbit satellite link, it is necessary to make LEO orbit communication range more than 160 km. So, in this simulation power is increased up to eye safety level at 10 dBm. And then inter satellite link is analyzed in pointing error environment as follows. In this section, all results are based on simulation setup shown in Fig 1. The results analysis of the proposed design is done in two sections: (A) Effect of pointing error on Q-factor and BER in strong turbulence condition. (B) Effect of pointing error on Q-factor and BER with Link Distance of Inter satellite Communication.

(A) Effect of pointing error on Q-factor and BER in strong turbulence condition

In this section, the proposed IsOWC system, as given in Fig 1, is simulated for bit-rate of 1 Gbps. The basic receiver parameters used in the simulation are given in table 1. The link range between two satellites is set at 200 km. The input power supplied is 10 dBm with an optical wavelength of 1550 nm. Here the transmitter and receiver aperture diameter value are 50 mm and 250 mm respectively. When we vary the pointing error between at 1 to 10 urad for distance 200 km, we obtain good results for a fiber bundle-based receiver as compared to a conventional array of photodetector receiver for a bit rate of 1 Gbps. The graph is plotted between Q-Factor of IsOWC system and pointing error in strong turbulence. It is also observed from the fig 4 that as we increase pointing error, the Q-factor of IsOWC system is slightly reduced as compared to a conventional receiver. From the data recovery analyzer, the value of Q-Factor and Minimum BER is analyzed and values are varied up to threshold BER= 10-9 which is the minimum BER required for reliable optical wireless communication can take place, above this value of BER, our optical link breaks for conventional array of photodetector receiver system but not for the fiber bundle-based receiver system.

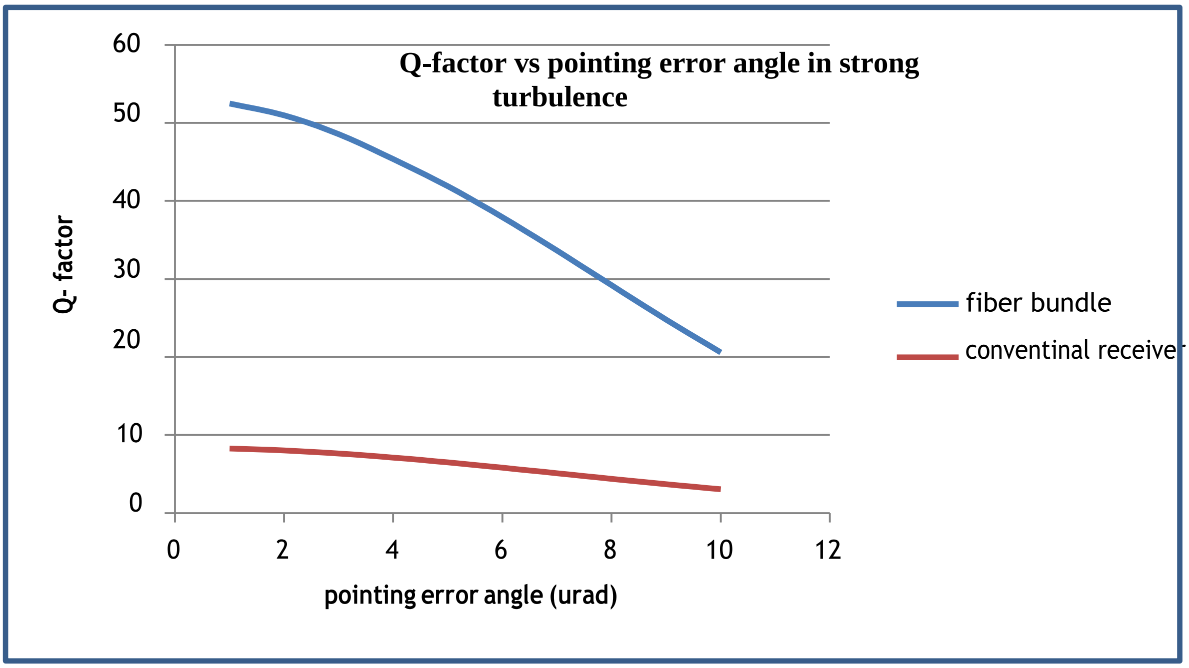


Fig 4: Effect of pointing error on Q-factor

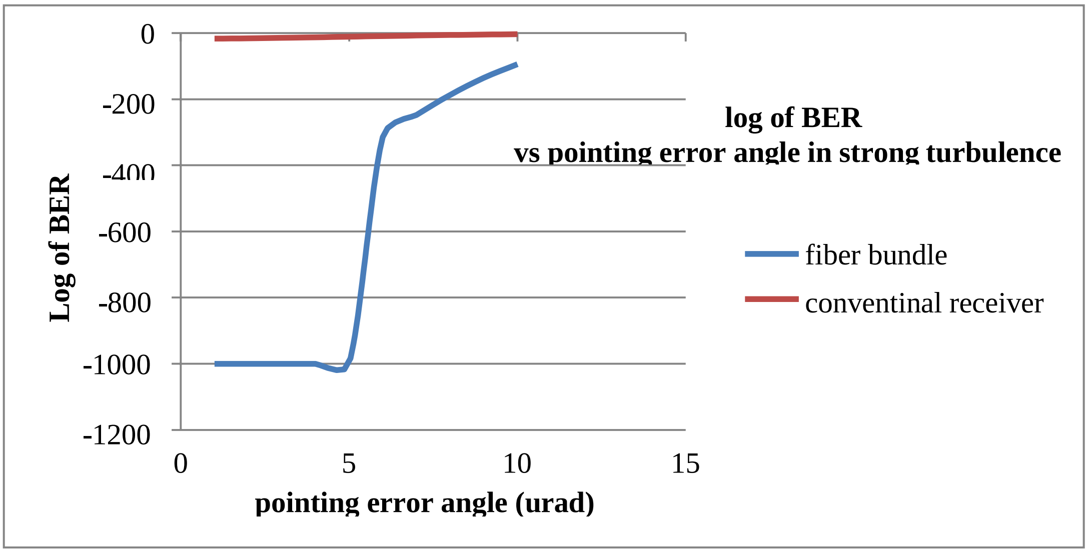


Fig 5: Effect of pointing error on BER

Fig 4 reveals that Q factor exponentially decay as pointing error angle increases which closely approximates the mathematical equation (1.3). It is also observed from figure 4 that conventional receiver is much affected by pointing error variation as compared to fiber bundle-based receiver. It is also observed Fig 5 that as we are increasing pointing error in strong turbulence, BER gets more worst for the conventional array of photodetector receiver.

(B) Effect of pointing error on link distance of inter-satellite communication system

In this part, the system is simulated for various link distances. The IsOWC system performance is being analyzed by the BER and Q-Factor by varying the distance between two satellites with different pointing error, the value of system Q-Factor and BER is obtained by data recovery analyzer. The graph is plotted between system Q-factor and link distance, BER and link distance. The inter satellite link is distance dependent for pointing error, but as we increase the range, the Q-factor and BER of the link decreases because of more severe effect of atmospheric turbulence.

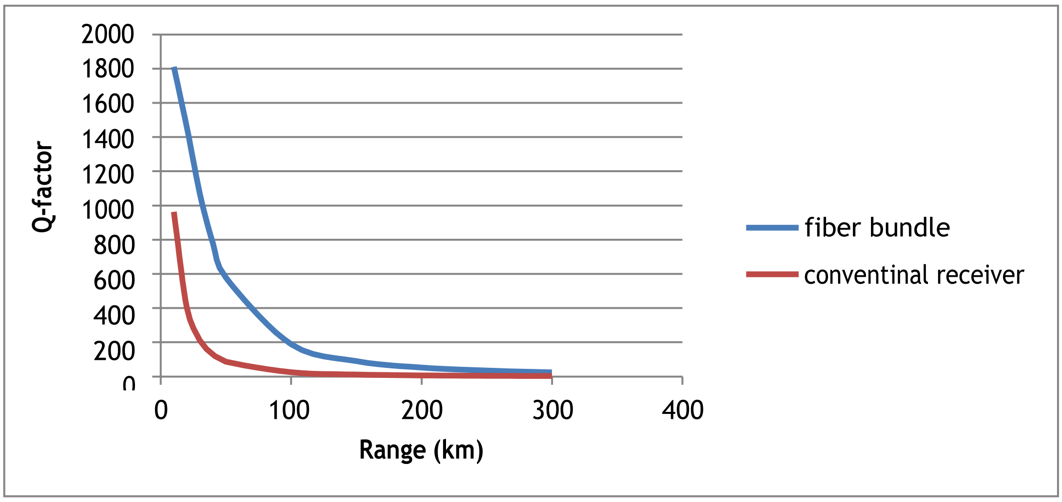


Fig 6: Effect of IsOWC link distance on Q-factor

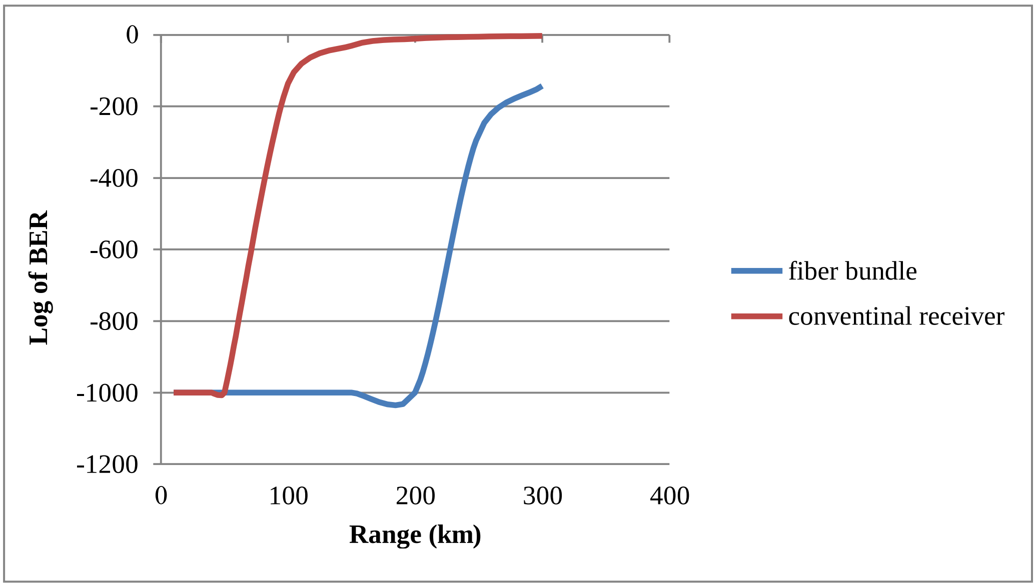


Figure 7: Effect of IsOWC link distance on BER

From Fig 6 & 7, it is observed that greater transmission distances are achieved for fiber bundle based receiver in compared to a conventional array of photodetector receiver for same system parameter. It is also observed from Fig 7 that Log of BER curve for the conventional receiver is rapidly decaying by an increase in range after that 50km while on other end fiber bundle based receiver is start decaying after that 200km range. From above conclusion, we need a wider field of view (FOV) at the receiver for longer range which is provided by the fiber bundle based receiver. So we are getting better results for a fiber bundle based receiver in compared to a conventional receiver.

9. Conclusion

In this research, we have investigated an inter-satellite optical-wireless communication link with bundle based receiver module and presented an analysis of inter-satellite optical- wireless communication system in variable pointing error. The result shows that the pointing errors are reduced in the fiber bundle based receiver system and this system is able to cope up to 10 urad pointing error to achieve minimum BER and Q-factor for a data rate of 1 Gbps over a 200km distance. So by the use of fiber bundle based receiver an efficient improvement in pointing errors of the inter-satellite optical-wireless communication system is achieved, which further helps in increasing the range of the system because of large FOV provided by the fiber bundle based receiver. Hence it is practically implementable in LEO orbit satellite optical wireless communication link.

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Conflicts of Interest:

There are no known conflicts of interest associated with this research paper and there has been no significant financial support for this work that could have influenced its outcome.

Funding Statement:

This research paper did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.