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Modelling and Performance Analysis of 2.5 Gbps Inter-satellite Optical Wireless Communication (IsOWC) System in LEO Constellation

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Abstract —Free space optical wireless communication plays an important role in satellite communications. In the future, inter-satellite optical wireless communication (IsOWC) systems will be one of the most important applications for connecting one satellite to another in the same orbit or different orbits. IsOWC systems offer high data rates, minimum delay, minimum signal attenuation, small size, fewer power requirements and narrow beam divergence compared with that of present microwave satellite communication systems. Here, a low earth orbit (LEO) satellite constellation is modelled, and an IsOWC system channel is analysed for different modulation types, wavelengths, transmitter output powers, optical apertures and link distances. OptiSystem 7.0 and Matlab were used for modelling and simulation.

Index Terms**—**Optical wireless channel, inter-satellite link, Inter-satellite optical wireless communication (IsOWC), Q factor, BER, OptiSystem.

I. INTRODUCTION

Laser communication is able to send information at data rates up to several Gbps across distances that span thousands of kilometres. With high laser transmitter output power; optical wireless communication technology has found application in space communication. Therefore, optical wireless communication is substantially developed.

In 1977, the European Space Agency (ESA) issued a technological research contract for the assessment of modulators for high data-rate laser links in space. In 2001, SPOT-4 operating at 832 km, and ARTEMIS, operating at 31,000 km, exchanged the first-ever transmission of an image by laser link from one satellite to another satellite. The terminals exchanged high definition imagery data at 50 megabits per second [1], [2]. After this experiment, the first bidirectional LEO-LEO inter-satellite optical communication link was performed at a data rate of 5.6 Gbps and at a link distance of 4900 km between TerraSAR-X and NFIRE satellites [3].

A. Hashim achieved a data rate of 1 Mbps at a link distance of 5000 km with NRZ modulation [4].

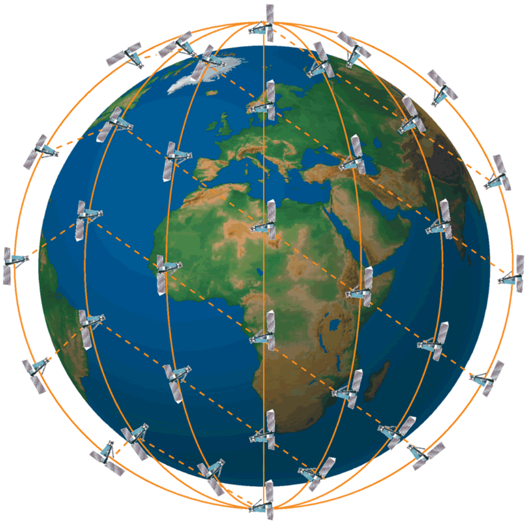

Fig. 1. Low Earth Orbit (LEO) satellite constellation

Here, an LEO-LEO inter-satellite optical wireless communication (IsOWC) channel is modelled, simulated and analysed for different optical apertures, transmitter output powers, wavelengths and link distances.

II. INTER-SATELLITE OPTICAL WIRELESS COMMUNICATION SYSTEM (IsOWC)

A. Low Earth Orbit (LEO) Satellite Orbit Properties

LEO satellites are commonly used for global coverage where several satellites are launched into space to perform a single mission [5]. LEO orbit altitudes vary between 160 km and 2000 km and have a rotational period of approximately 90 minutes. Therefore, these satellites quickly change their position relative to a corresponding ground station. In order to achieve global coverage, a large number of satellites are needed for continuous connectivity. Fig. 1 displays LEO satellite constellation.

LEO satellites can also be used for discontinuous coverage. In this type of application, the satellite stores the received data while passing over one part of the earth and transmits it later while passing over another part.

LEO satellite orbits generally take a circular trajectory. In a circular orbit, period of LEO satellites T_L and rotational period of the earth T_E should satisfy equation (1) [6];

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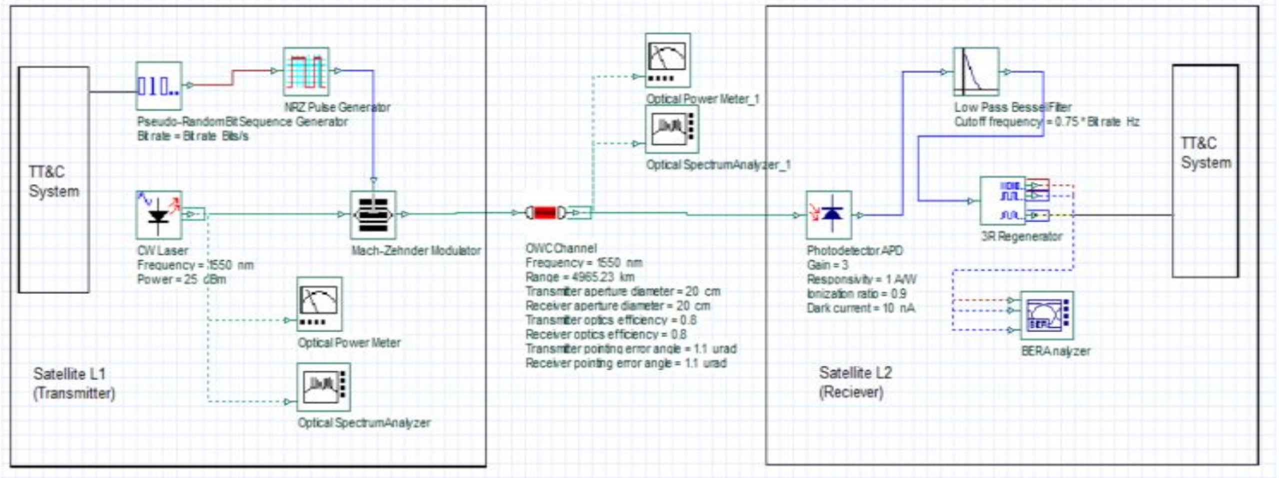

Fig. 2. LEO-LEO IsOWC system design

$$T_L \; x \; K_1 = T_E \; x \; N \tag{1}$$

where N and K_1 are all integers and the rotational period of the earth is taken as 86164.09 seconds. By using Keppler's third law the period of LEO satellite is formulated as;

$$T_L = 2\pi\sqrt{(R_E + h_L)^3/GM} \tag{2}$$

where R_E is the equatorial radius, and G and M are the gravitational constant and earth mass, respectively. Using Keppler's third law, and assuming integers N = 1 and K_1 = 14, the height of the orbit is calculated as h_L = 880.55km. At this altitude in a circular LEO orbit the distance between two consecutive satellites is calculated by the formula given below [7];

$$|L_1L_2| =$$

$$\sqrt{\left|R_E + h_{L_1}\right|^2 + \left|R_E + h_{L_2}\right|^2 - 2\left|R_E + h_{L_1}\right|\left|R_E + h_{L_2}\right|\cos\theta}$$

$$|L_1L_2| = 4965.23 \text{ km} \tag{3}$$

In the OptiSystem, IsOWC system between two satellites in circular orbit at a height of 880.55 km is modelled.

B. *Inter-satellite Optical Wireless Communication (IsOWC) System*

According to the abovementioned scenario, a transmitter consists of a pseudo-random bit sequence (PRBS), non-return-to-zero (NRZ) pulse generator, continuous wave (CW) laser and a Mach-Zehnder optical modulator (MZM).

An optical wireless communication channel is identified by wavelength, link distance between two satellites, optical efficiency of the laser transmitter and receiver, transmitter and receiver antenna apertures (telescope parameters) and pointing errors.

A receiver consists of an avalanche photo-detector (APD) as an optical-electrical signal converter, a low pass Bessel filter (LPBF) and 3R regenerator and also a bit error rate (BER) analyser to analyse the quality of communication.

OptiSystem IsOWC system design scenario is shown in Fig. 2.

The received optical power is calculated;

$$P_R = P_T\eta_T\eta_R G_T G_R L_T L_R(\lambda/4\pi d)^2 \tag{4}$$

where G_T and G_R are the transmitter and receiver antenna gain, η_T and η_R are the transmitter and receiver optical efficiencies, L_T and L_R are the transmitter and receiver optical losses, P_T is the transmitter power, λ is the signal wavelength and d is the distance between two satellites. Fig. 3 shows the distance between two satellites [7].

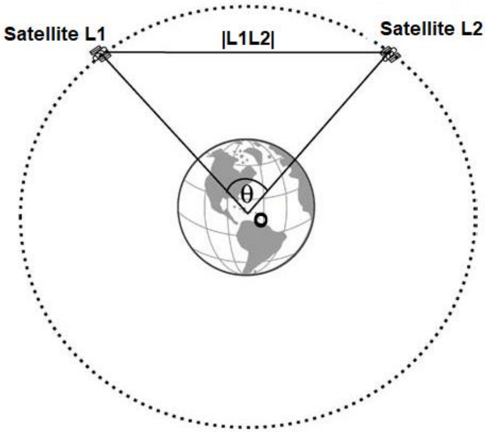

Fig. 3. Distance between two satellites [7]

III. SIMULATION PARAMETERS

LEO-LEO simplex IsOWC channel model is used for simulation. The channel is simulated for 12.5 cm, 15 cm and 20 cm antenna apertures for transmitter and receiver at link distances between 2000 km and 4965.23 km.

Transmitter and receiver optical efficiencies and pointing errors are taken as 0.8 µrad and 1.1 µrad, respectively [8]. The communication channel is simulated for 980 nm, 1064 nm, 1310 nm and 1550 nm wavelengths and 15 dBm, 20 dBm and 25 dBm transmitter output powers. The resultant communication data rates vary between 200 Mbps and 2.5 Gbps at 4965.23 km link distance. Table I shows all the simulation parameters.

BER, the quality (Q) factor and eye diagrams are used to analyse the performance of the system. Q factor is a function of the signal to noise ratio (SNR) and it defines the quality of performance of the receiver system. Q factor is also directly proportional to transmitter output power and antenna apertures. Contrastingly, Q factor is inversely proportional to BER.

BER is the number of the bit errors per unit time and defines the quality of the communication channel. In this study a maximum BER of $< 10^{-9}$ has been accepted to achieve error-free communication.

IV. Results and Discussion

A. *Relationship between Q Factor and Modulation Types*

Modulation type plays an important role in a high-quality communication system. LEO-LEO IsOWC system is simulated for NRZ, return-to-zero (RZ), On-off key (OOK (Sine)) and Gaussian modulation types at a data rate of 200 Mbps and a link distance of 4965.23 km. Antenna apertures and transmitter output power are selected as 20 cm and 25 dBm, respectively.

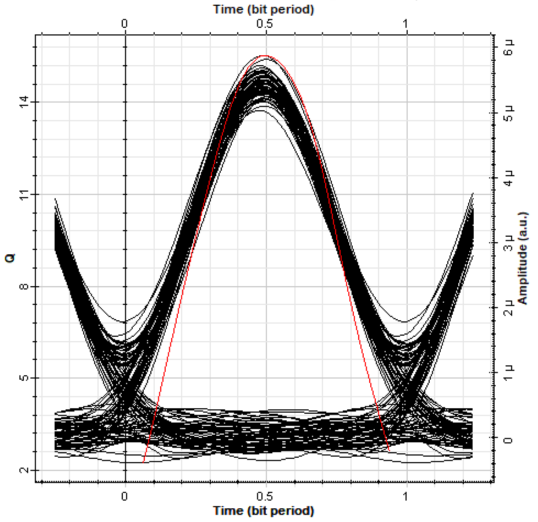

Fig. 4. Eye diagram of OOK (Sine) modulation

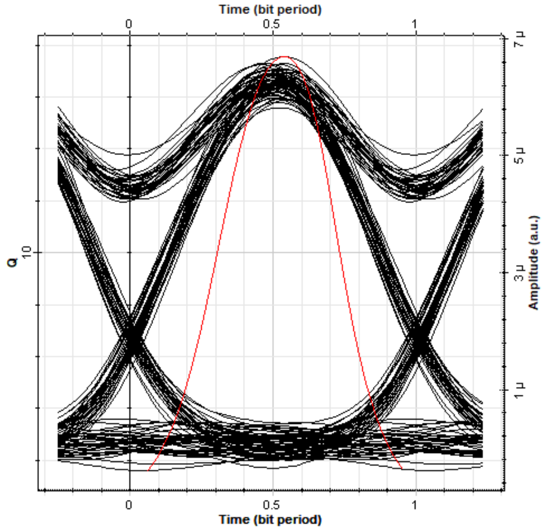

Fig. 5. Eye diagram of Gaussian modulation

Simulation results are given with eye diagrams as shown in Fig. 4, Fig. 5, Fig. 6 and Fig. 7. Q factor is 20.58 for NRZ, 17.55 for Gaussian, 15.83 for RZ and 15.52 for OOK (Sine). It is observed that NRZ modulation is the best modulation type.

Here, NRZ modulation type is selected as a simulation parameter.

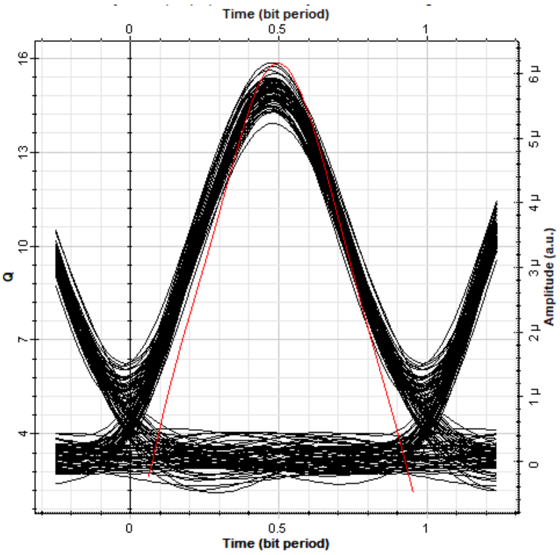

Fig. 6. Eye diagram of RZ modulation

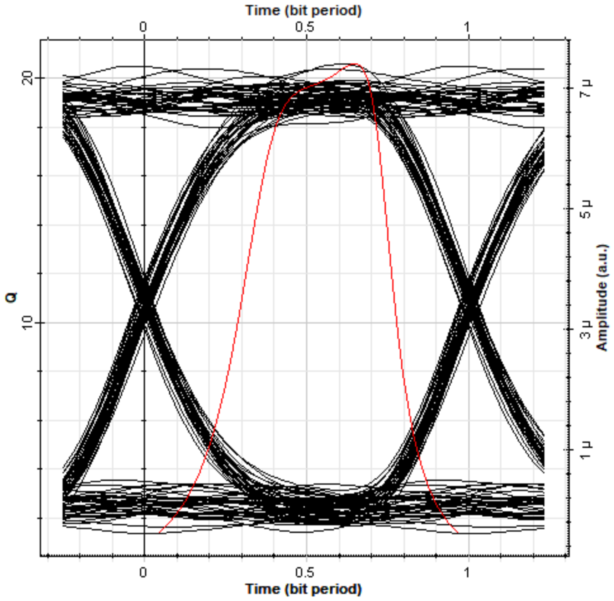

Fig. 7. Eye diagram of NRZ modulation

B. *Relationship between Q Factor and Signal Wavelength*

IsOWC channel is simulated for 980, 1064, 1310 and 1550 nm wavelengths at a link distance of 4965.23 km. Link parameters are defined as a transmitter output power of 25 dBm, antenna apertures of 20 cm and a bit rate of 2.5 Gbps.

The effect of signal wavelength on the performance of the system is displayed using eye diagrams (Fig. 8, Fig. 9, Fig. 10 and Fig. 11). As shown in the eye diagrams, the shortest wavelength has the highest Q factor (8.08), and thus better system performance is obtained. Table II shows Q factor values for all wavelengths.

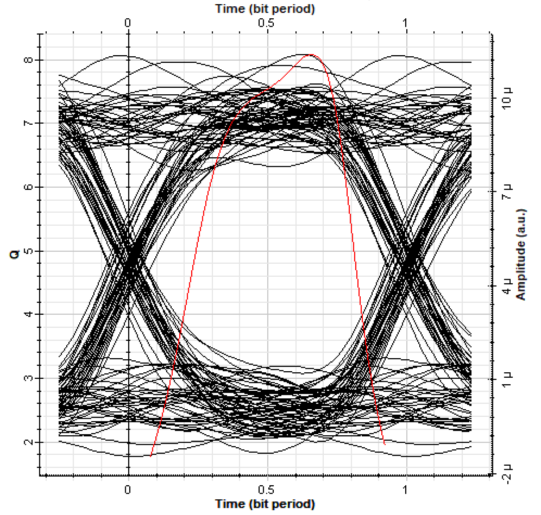

Fig. 8. 980 nm wavelength and Q factor

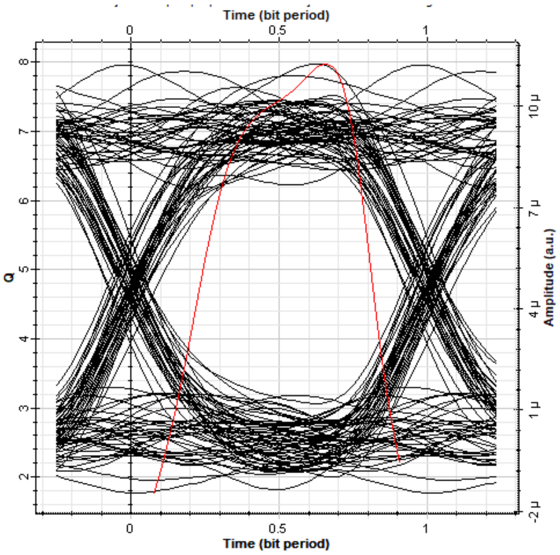

Fig. 9. 1064 nm wavelength and Q factor

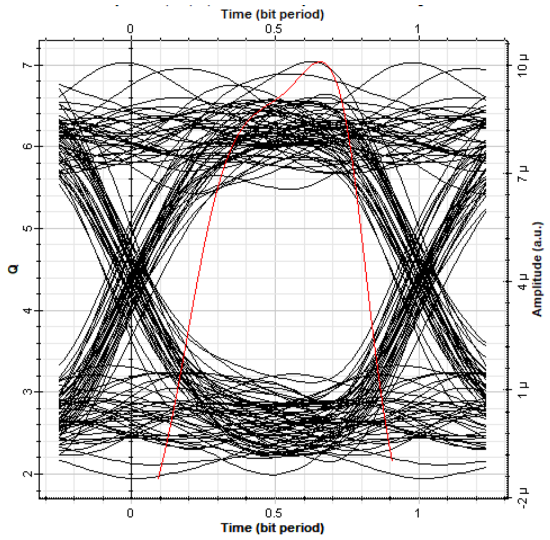

Fig. 10. 1310 nm wavelength and Q factor

TABLE II: Q FACTOR FOR DIFFERENT WAVELENGTHS

Wavelength	Q factor
980 nm	8.08
1064 nm	7.97
1310 nm	7.03
1550 nm	5.91

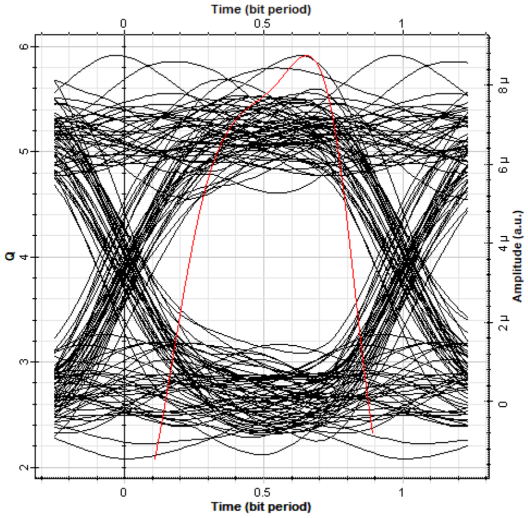

Fig. 11. 1550 nm wavelength and Q factor

In practice, short wavelengths are more prone to scattering and attenuation than long wavelengths. Therefore, the longest possible wavelength that can be used is 1550 nm.

Here, line of sight communication (LoS) is assumed, therefore there is no obstruction in the communication channel.

C. Relationship between Q Factor and Antenna Apertures

Antenna aperture is an important parameter, affecting the performance of the system and antenna gain. Increasing antenna aperture increases Q factor. For IsOWC calculations, a transmitter power of 25 dBm and a wavelength of 1550 nm are taken.

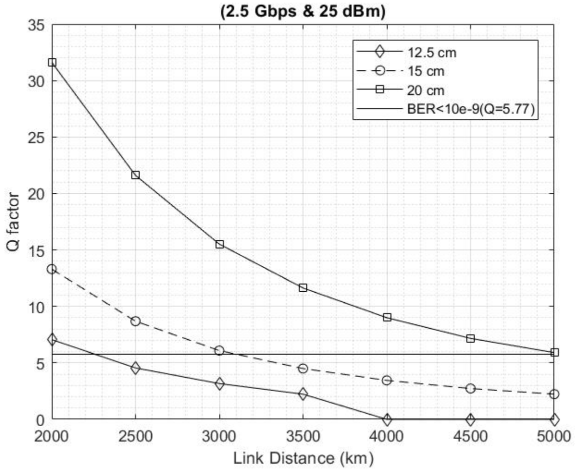

Fig. 12. Q factor vs. distance for different apertures (2.5Gbps)

In a simulated LEO-LEO IsOWC system, the maximum link distances are 2200 km and 3000 km for antenna apertures of 12.5 cm and 15 cm, respectively, at a data rate of 2.5 Gbps as shown in Fig. 12.

Maximum link distances are 2500 km and 3500 km for antenna apertures of 12.5 cm and 15 cm, respectively, at data rates of 1.5 Gbps as shown in Fig. 13.

To achieve data rates of 2.5 Gbps and 1.5 Gbps, antenna apertures should be a minimum of 20 cm to provide inter-satellite communication at a link distance of 4965.23 km as seen in Fig. 12 and Fig. 13.

It is observed that Q factor is inversely proportional to link distance and data rates. If the transmitter output power and antenna apertures are constant, data rates can be decreased to provide communication at a greater link distance.

For data rates of 1.5 Gbps, the simulation results are given using eye diagrams (Fig. 14, Fig. 15 and Fig. 16).

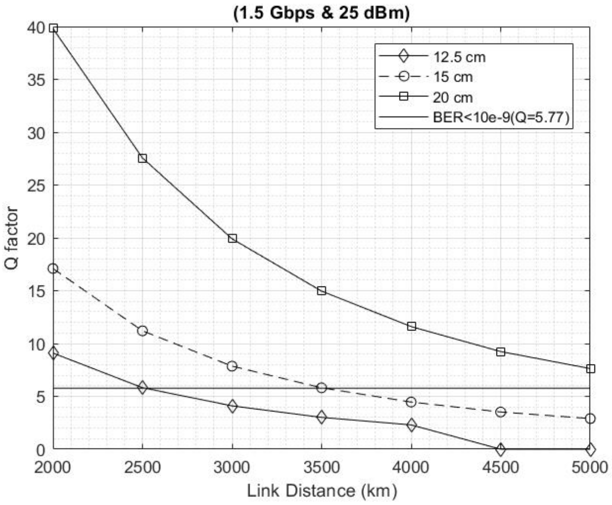

Fig. 13. Q factor vs. distance for different apertures (1.5Gbps)

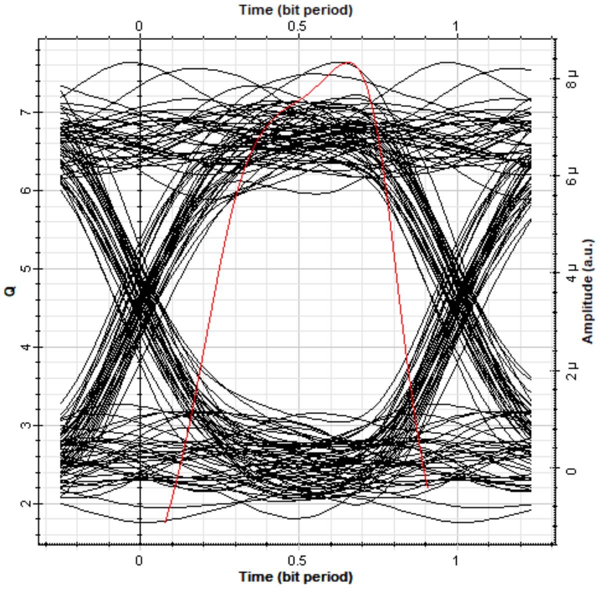

Fig. 14. Q factor for 20 cm aperture (1.5 Gbps)

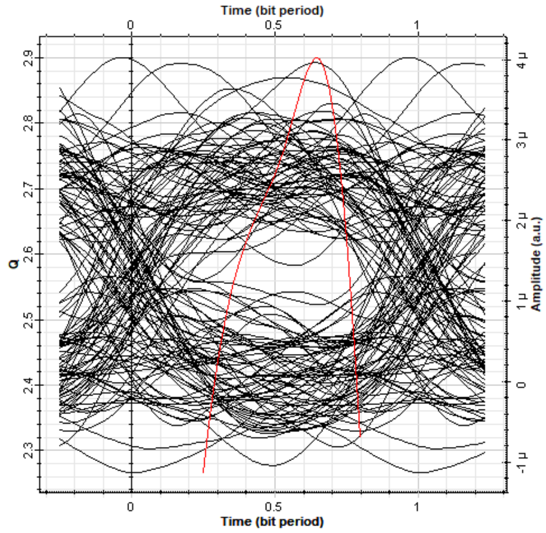

Fig. 15. Q factor for 15 cm aperture (1.5 Gbps)

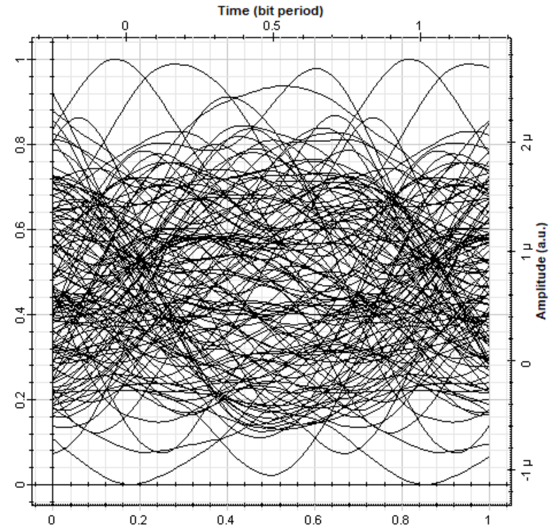

Fig. 16. Q factor for 12.5 cm aperture (1.5 Gbps)

D. Relationship between Received Power and Antenna Apertures

The laser beam is narrow and this provides an advantage in transmitting majority of the laser power to the receiver.

Table III shows received powers obtained from simulation and theoretical calculation for different apertures in the modelled inter-satellite communication system.

The simulation results have the same values as the theoretical calculations.

TABLE III: RECEIVED POWER LEVELS FOR DIFFERENT APERTURES

Aperture (cm)	Theoretical calculation (dBm)	Simulation result (dBm)	Difference (dBm)
12.5	−36.6390	−36.639	0.000
15	−33.7686	−33.768	−0.006
20	−29.5266	−29.526	−0.006

TABLE IV: Q FACTOR AND BER FOR DIFFERENT DATA RATES

Transmitter power	Data rate	Q factor	BER
15 dBm	25.5 Mbps	5.93	$1.46x10^{-9}$
20 dBm	255 Mbps	5.92	$1.55x10^{-9}$
25 dBm	2.5 Gbps	5.91	$1.66x10^{-9}$

E. Relationship between Transmitter Power and Data Rate

Table IV shows Q factor, BER values and available maximum data rates for different transmitter output powers at a link distance of 4965.23 km and maximum antenna apertures of 20 cm.

It is observed that if transmitter output power is increased, the available maximum data rate is also increased at the same link distance. For the designed LEO-LEO IsOWC system, the obtained higher data rate is 2.5 Gbps with 25 dBm (316 mW) of transmitter power.

V. CONCLUSION

In this paper, LEO constellation has been designed for global coverage and LEO-LEO inter-satellite optical wireless communication system has been modelled and simulated by using OptiSystem 7 software. The system performance (BER and Q factor) has been analysed for different data rates, antenna apertures, wavelengths and link distances. The following are the conclusion of these analyses:

- As the distance between satellites increases, free space path loss (FSL) and the pointing error due to beam divergence angle also increase. Lasers with lower wavelength and higher output power can be selected to reduce FSL.
- As the optical antenna aperture increases, the gain of the optical antenna increases. However, depending on the selected satellite type, the total payload and size limitations constrain the use of telescopes that have a larger aperture.
- It is observed that sending data with a bit rate of several Gbps across distances of thousands of kilometres is possible with optical wireless communication.

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