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Investigation and analysis of inter-satellite- optical wireless communication system based on dense-wavelength-division multiple-access

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ABSTRACT

Optical wireless communication offers high data rates applications due to license-free and wide-bandwidth access techniques and cost-effective implementations. Recently, the world introduced to a revolutionary technology called Inter-satellite optical communication that aims to establish transmission among satellites. However, transmitting pointing errors is the main issue in creating an inter-satellite link, which leads turbulences in the connection. This article aims to study the implementation of an optical wireless communication system in satellite communication. In this work, we investigate and analysis of data rate of 16-channel in inter-satellite optical wireless communication systems (Is-OWC) based on dense-wavelength-division multiple-access (DWDM) with standard downlink channel spacing DWDM (ITU grid specification). Computer simulations are carried using Opti-system over different wavelengths between two satellites transmit 160 Gbps over 7000 km. This evaluation performance is based on eye diagrams, BER, optical spectrum and Q-Factor with minimum input power under turbulences of transmitter pointing error angle

Keywords: Inter-satellite optical wireless communication, DWDM, transmitter-pointing error.

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1. Introduction

Optical communication has given new efficient systems of passing information faster and more secure [1, 2]. During the last decades, from long-length fibers, the communication evolved to a robust wireless communication system [3-7]. Recent advancement has paved the way of the concept of implementing an optical wireless communication (OWC) technology in space communications [5, 8]. Inter-satellite communication is one of the OWC types developed to inter-connect the satellites. Because of its inherent characteristics, this promising wireless technology is expected to be the next-generation technology. In addition to its advancements, its features include a higher data rate, increased bandwidth, unregulated spectrum, immune to interference, transmission security and low transmission power [9, 10]. More than six thousand satellites are orbiting the Earth, where the number increases yearly. Therefore, the previous decade showed that OWC technology has passed through several improvements [11-13]. The increasing of the number of satellites orbiting Earth imposes to develop new methods for establishing networks among the satellites to communicate with each other. Consequently, transmit data among them, send data from one to another, and lastly to broadcast it to the stations. Laser satellite communication connects satellites and allows the transmission to thousands of kilometers for high data rates (several Gbps). Recently, OWC technology was adapted to space communication. The developed technology is called as Inter satellite optical wireless communication (Is-OWC) [14]. For the satellites orbiting around the Earth, Free-space optical communication offers a communicating method among them. It is well known that Optical communication provides faster, efficient and more secure in transmitting information [9]. Over wired communication, wireless communication provides better features in terms of maximum bandwidth, reliability, security, mobility, etc. With rapid advancements in wireless communication technologies, recent years witnessed that they replaced the need for wire connections [15-17]. The Is-OWC is a promising technology from the proposed applications of Free-space optical communication technology. Hopefully, it is expected to implement in the space in the near future. Over present microwave satellite systems, it will be low-cost, low power, small size, lightweight with high bandwidth [18, 19]. Due to its innumerable advantages, the idea of the Is-OWC has gained widespread attention in a short time in comparison with RF counterpart [20, 21].There are several significant features of using OWC instead of RF in space communication (e.g., lightweight circuitry, easy reconfiguration, etc.) along with different applications [21]. Additionally, many great efforts have been made to improve the capacity and distance of WOC. More specifically, in 2010, the authors in [14, 17] investigated the performance of the Is-WOC link in terms of data transfer between satellites and Low Earth Orbit. In the study, the distance was tested from 5000 km to 0 km with ten dBm input power and 1550 nm wavelength. Five levels of bit rates were considered (10 Gbps, 1Gbps, 100 Mbps, 10 Mbps and 1 Mbps). To achieve better performance, the authors argued to deploy an amplifier to increase the travel distance. It is worth mentioning that transmission at 1550 nm is implemented to improve its compatibility with existing devices and to minimize the impact of scattering. After three, to improve the performance of the Is-OWC link, the authors in [18] used a square root module and enhanced the link by 48% in comparison with the traditional detection. This system was simulated using opt-system by sitting the data rate as1.25 Gbps for 5000 km distance. One year later, a study proposed to investigate the impact of changing wavelengths between the wavelength between two satellites [19]. The authors introduced an optical inter-satellite link (ISL), and the study was carried using a data rate of 3 Gbps at 1300 km distance. For transmitting 10 Gbps at 5000 kilometers distance, the Is-OWC system based on DWDM was suggested in 2015 [22]. By varying the levels of input power, the authors argued a comparative analysis of using two modulation techniques (NRZ and RZ). The main conclusion of the simulations showed the best performance achieved by using RZ modulation in 30 dBm input power. However, the arrival of high input power must be at the same time. On the other hand, using NRZ modulation with 20 dBm input power was the favorable outcomes. Recently, the hybrid WDM–PI Is-OWC system has been proposed in [23]. The authors considered transmitting pointing error influences and transmit over 10000 km for 120 Gbps data rate. A new promising method was introduced in 2016 to achieve low power communication between two Low Earth Orbiting (LEO) satellites [24]. With 2.5 Gbps data rate and 27.02 dBm as minimum input power, the authors demonstrated that it is possible to achieve standard system error-free communication two LEO satellites (5000 km). In the same year, to achieve 120 Gbps data transmission, the authors in [25] simulated transmission of 20 × 6 Gbps over Is-OWC over a distance of 5000 km. The study argued that NRZ modulation behaves better than using RZ modulation in transmission of the proposed system. In 2018, the authors in [26] proposed an MDM based Is-OWC system using MDRZ-DQPSK, DRZ-DQPSK and CSRZ-DQPSK modulation techniques. To enhance the system's capability, the MDM multiplexer is based on integrated 64 Laguerre Gaussian modes. Accordingly, the system of 46 channels is simulated for various data over different distances (between 4500 km and 900 km). In 2019, the MDM Is-OWC system was presented using some modulation schemes, such as DQPSK, DPSK and Manchester [27]. Over various distances (between 3750 km and 750 km), The system tested for data rates of 40, 20 and 10 Gbps. In the same year, the authors in [28] designed the Is-OWC system based DP-QPSK modulation technique, where the system was tested for a data rate of 100 Gbps over 15,600 km distance. The target of the system considered achieving of BER and forward error correction log of BER value as 3.8×10^{-3} and - 2.42, respectively. Furthermore, for different data rates, the authors calculated the maximum possible transceiver distance. Moreover, for different inta and inter orbit satellites, the maximum possible data rate calculated. In this article, we designed a standardized system with easily found available pieces. Our aim in this work is to develop a low cost and less complicated system. Therefore, this work investigates and analyzes the transmission of a data rate of 16-channel Is-OWC based dense-wavelength-division multiple-access (DWDM). In the design, the distances vary up to 7000 km, with up to 160 Gbps. The rest of the paper is organized as follows. Section 2 presents the design of a DWDM based Is-OWC system. Section 3 evaluates system performance and discusses the achieved results. Finally, Section 4 concludes the paper and identifies some future direction.

2. System model

The design of the DWDM multiplexing based Is-OWC modeled in opti-system [7, 29, 30] and MATLAB [31, 32] software is represented in Figure 1. In this system, 16 channels are generated by using a satellite optical transmitter based on different wavelengths starting from 1538.98 nm to 1566.31. wavelengths have a channel spacing of 1.58 nm with standard downlink channel spacing DWDM (ITU grid specification). The design consists of the following parts:

1. Data generator at 10 Gbps with 16 channels (total is 160 Gbps).
2. Pulse generator based on NRZ, laser, and multiplexer (which will multiplex 16 wavelengths).
3. TX-laser power is set to 30 dBm (as listed in Table 1) and post-optical amplifier with a gain of 5 dB.

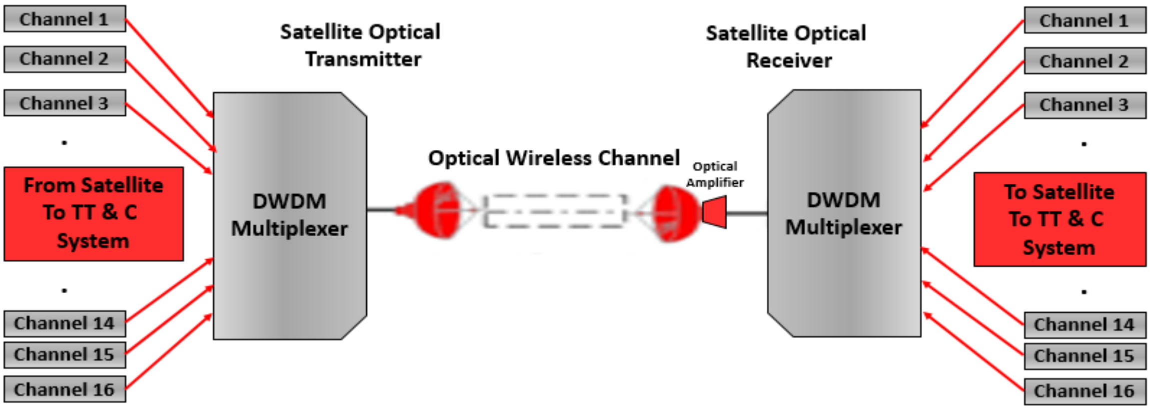

Figure 1. 16 Channels DWDM over Is-OWC system

Table 1. Parameters used for DWDM-Is-OWC system

No.	Parameters	Value
1	IS-OWC channel distance	2000 To 7000 Km
2	Is-WOC wavelengths	1550 nm
3	Bit Rate	160 Gbps
4	Optical Amplifier (gain)	5 dB
5	Total Channels	16 channels
6	Pulse Generator	NRZ
7	Receiver pointing error	1.1 µrad
8	Transmitter pointing error	1.1 µrad
9	Receiver Aperture Diameter	15 cm
10	Transmitter Aperture Diameter	15 cm
11	Additional losses	5 dB
12	Channel spacing	1.58 nm
13	TX Laser power	30 dBm

The transmitter and receiver are shaped with the OWC channel containing an optical antenna having 15 cm and 15 cm of aperture diameter, respectively. Additionally, we considered the OWC channel to be outer space. The following mathematical equation describes the Is-OWC channel [33, 34] where each parameter is defined in Table 2.

$$P_R = P_T \, \eta_T \, \eta_R \left(\frac{\lambda}{4\pi Z}\right)^2 G_T G_R L_T L_R \qquad (1)$$

Table 2. Descriptions of the items of equation 1

Item	Description
P_T	Transmitter optical power
η_T	Optical transmitter efficiency
η_R	Optical receiver efficiency
Z	Distance between the transmitter and the receiver
L_R	Receiver pointing loss factor
L_T	Transmitter pointing loss factor
G_R	Receiver telescope gain
G_T	Transmitter telescope gain
λ	Wavelength

We assume that both the transmission and recipient antennas are ideal with the additional losses (e.g., mispointing) and an optical efficiency equals to 1. The following equation shows signal losses [35].

$$\boldsymbol{R_L}(\lambda/4\,\pi D)^{\,2} \qquad (2)$$

where the D refers to is the distance between receiver and transmitter. Additionally, the 16 satellite optical receivers are used to convert light into an electrical current. Besides, we use Low Pass raised cosine filter as an electrical filter. Finally, the performance of our system is ev+aluated using eye diagrams, BER and Q-Factor

3. Results and Analysis

The performance measurements of 16-channel Is-OWC systems up to 7000 Km distance-based DWDM with capacity up to 160 Gbps are based on the eye diagrams, BER, optical spectrum and Q-Factor. We divide the evaluation into two parts. In the first part, we investigate the impact of the optical amplifier for the Is-OWC system. More specifically, we illustrate the outcomes of DWDM over the Is-OWC system with and without an optical amplifier. Figure 2 shows the results of eye diagrams, BER and Q-Factor measurements before using the optical amplifier. After using the amplifier, we consider the eye diagram to be open eye and clear. At 7000 km distance, BER and Q-Factor before using the optical amplifier are 1.62E-11 and 6.61637, respectively. Whereas, without using an amplifier, they became 2.39E-08 and 5.45104, respectively. Figure 3 illustrates the findings of BER and Q-Factor results based on DWDM with and without optical amplifier over Is-OWC starting distance from 2000 Km to 7000 Km. From Figures 2 and 3, we can conclude that the DWDM over Is-OWC gives batter results using an optical amplifier with minimum power. In the second part, we evaluate the BER and Q-Factor of our system by using optical amplifiers over different distances starting from 2000 Km to 7000 Km. Figures 4 and 5 show the performance measurement of average BER and Q-Factor for the DWDM over Is-OWC of 16 channels at the distances. Additionally, in Figures 6 and 7, the eye diagram is open eye and clear for all the channels at a distance of 7000 Km.

From the above results, we can conclude that the system can transfer 160 Gbps from a distance 2000 Km to 7000 Km with good quality. Lastly, Figure 8, the optical spectrum of combined channels under the transmitter pointing error of 1.1 µrad. Consequently, a reduction of the power level of the optical signal at the receiver.

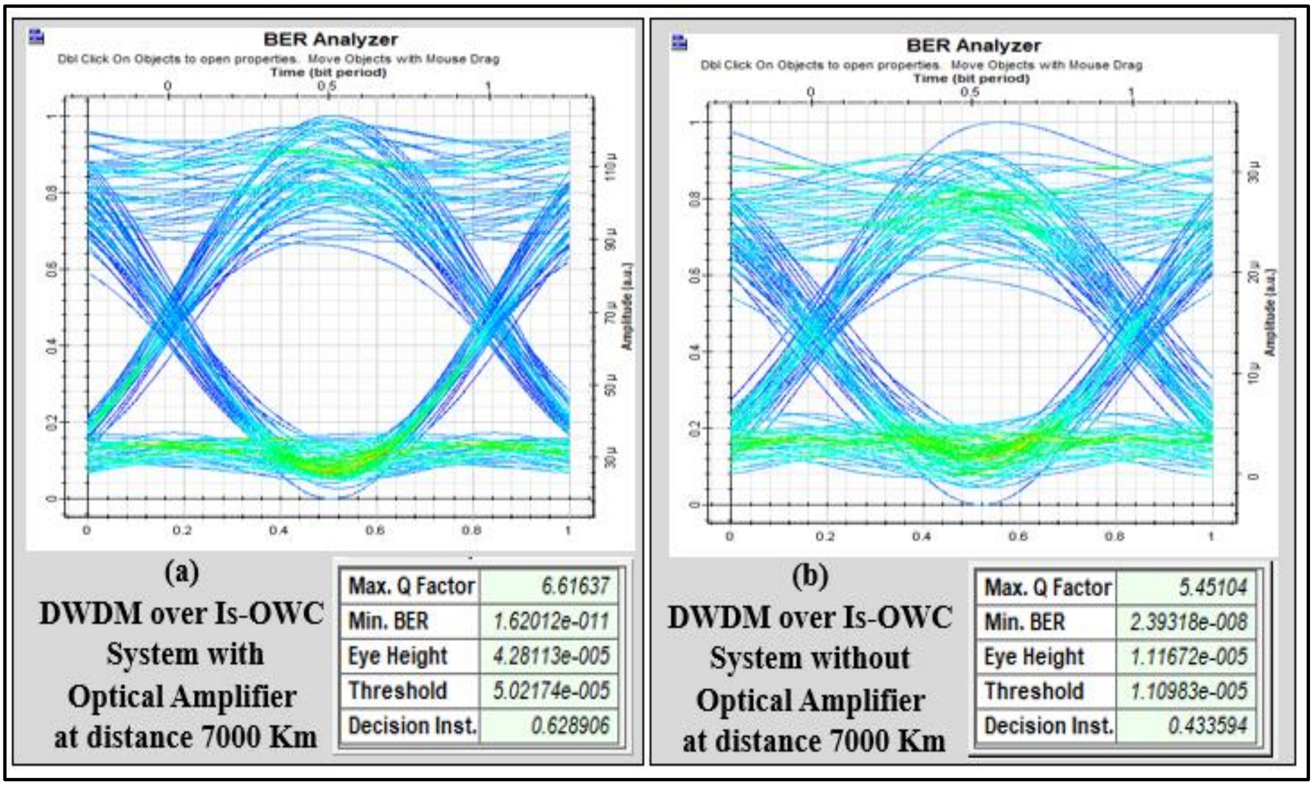

Figure 2. The eye diagrams, BER, and Q-Factor measurements for (a) DWDM over Is-OWC System with the optical amplifier at a distance 7000 Km (b) DWDM over Is-OWC system without optical amplifier at a distance 7000 Km

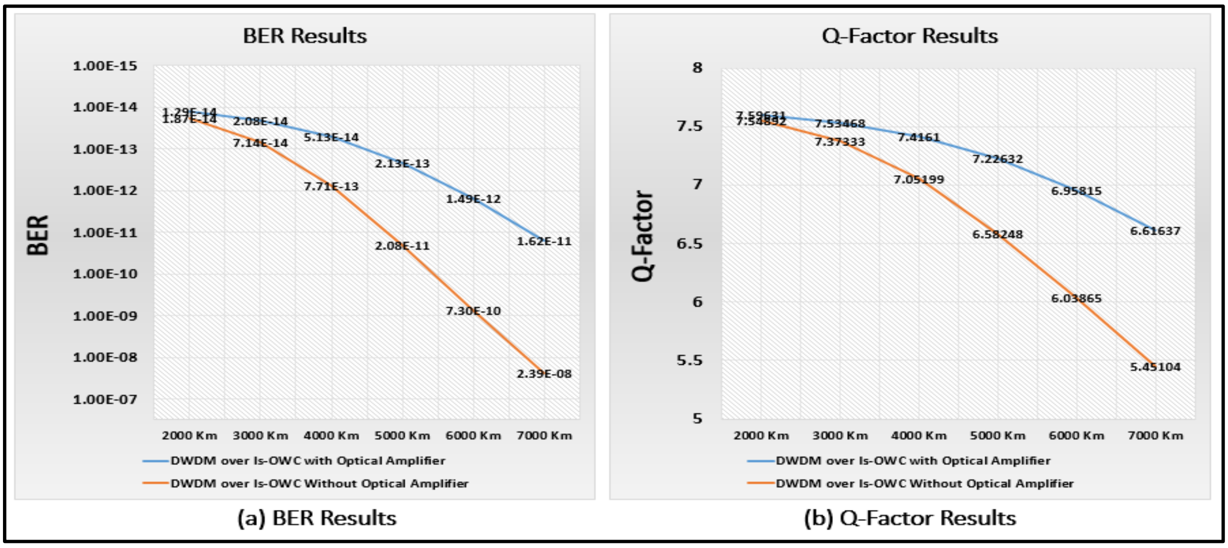

Figure 3. BER and Q-Factor results based on DWDM with and without Optical Amplifier over different Is-OWC distance

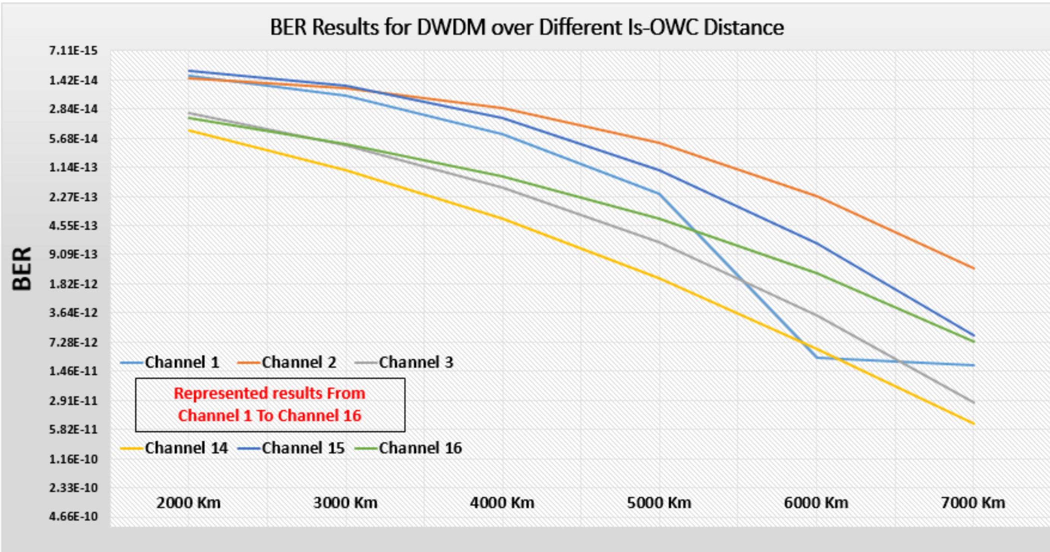

Figure 4. BER results for dwdm over different is-owc distance

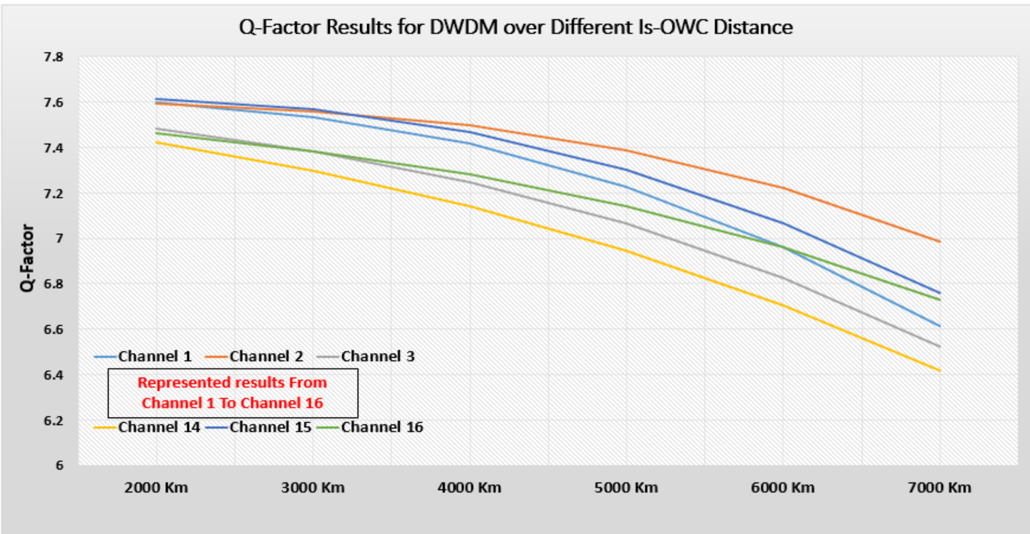

Figure 5. Q-Factor results for dwdm over different is-owc distance

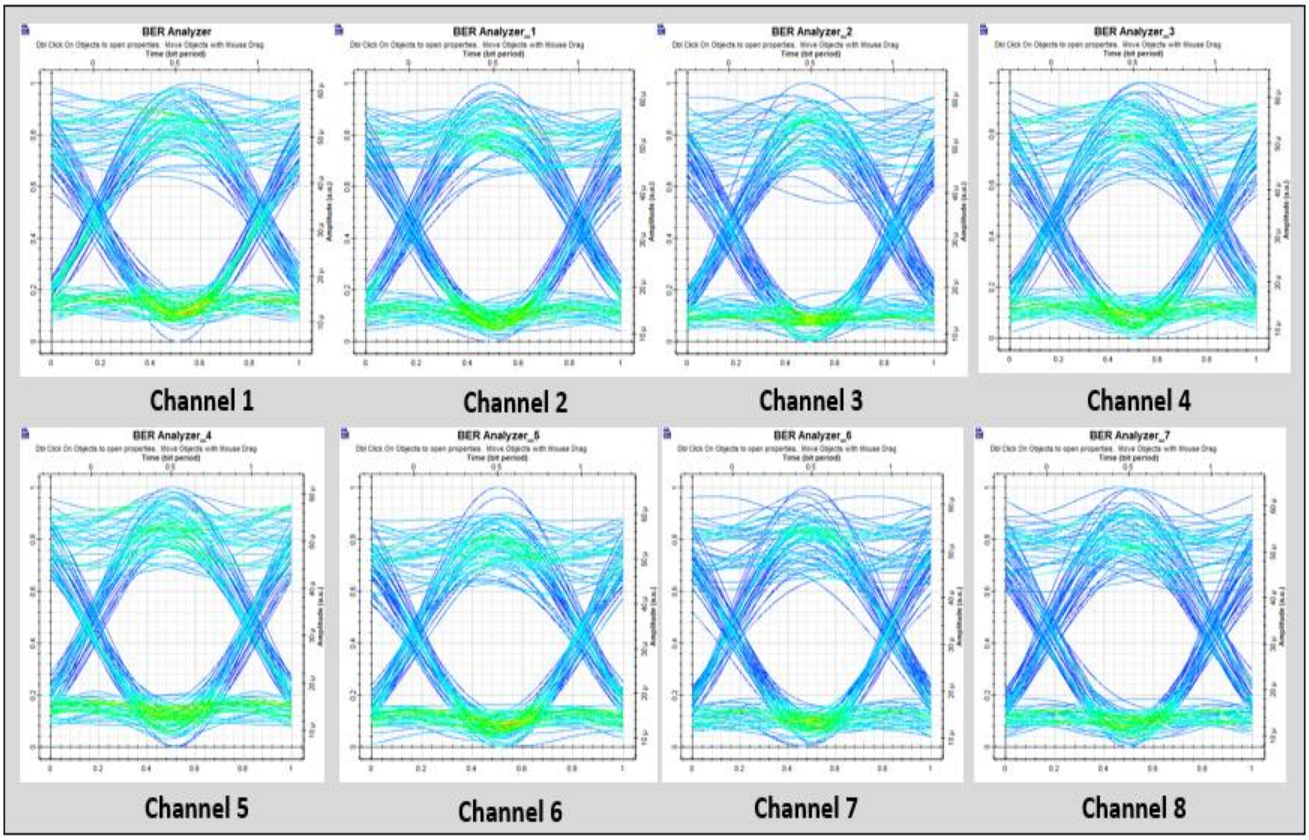

Figure 6. The eye diagrams measured for channel 1 to channel 8

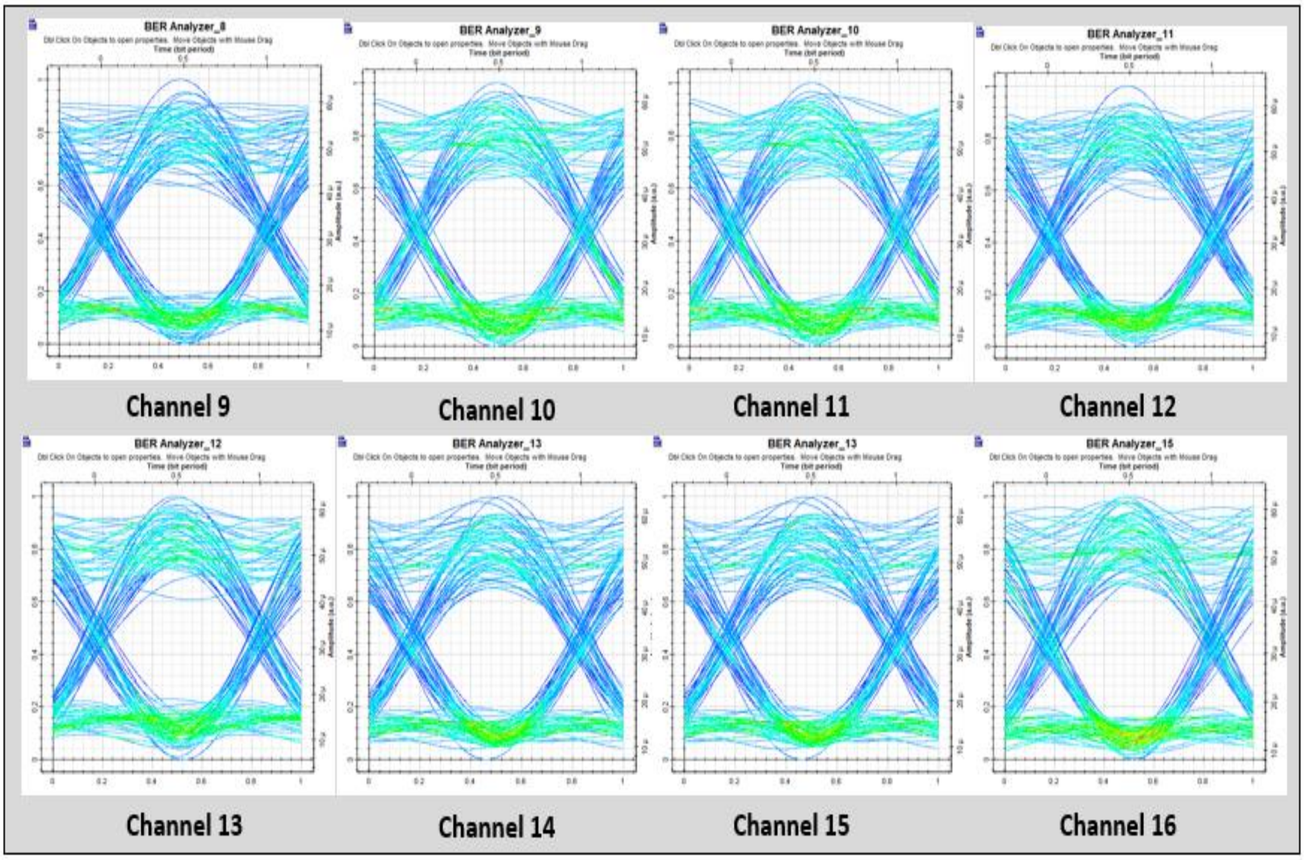

Figure 7. The eye diagrams measured for channel 9 to channel 16

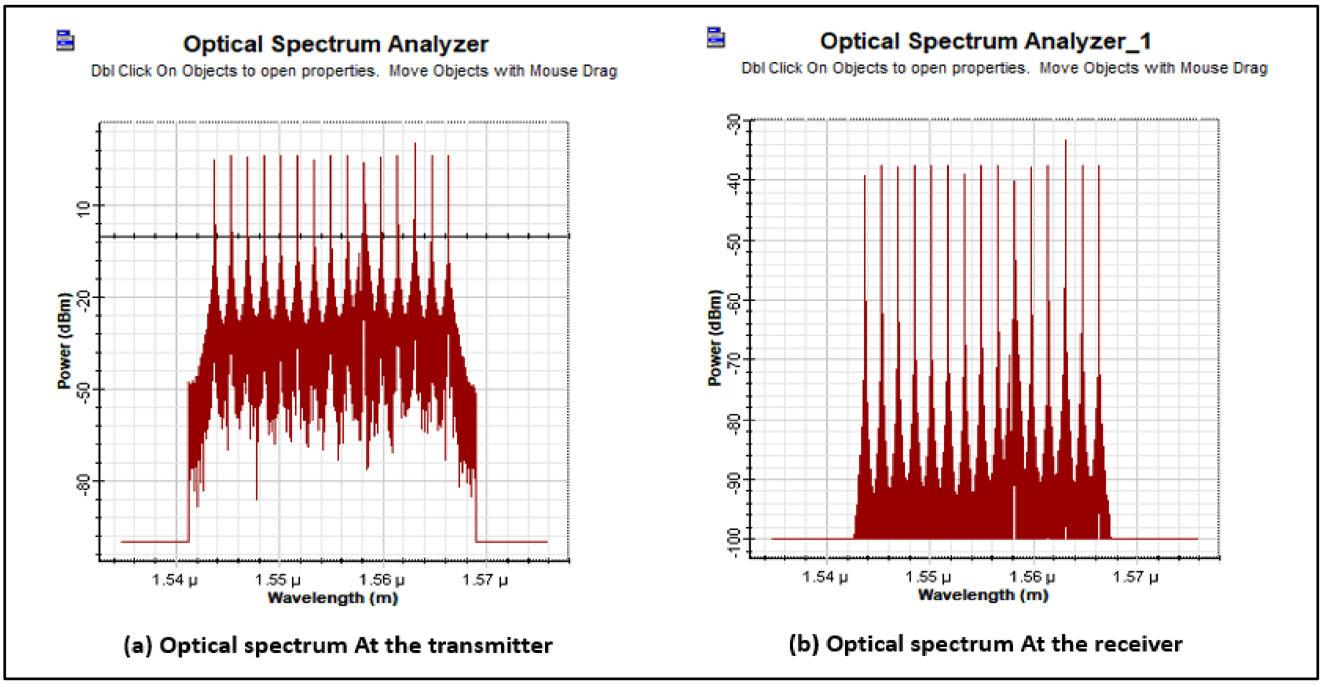

Figure 8. Optical spectrum under the influence of transmitting pointing error 1.1 μrad.

4. Conclusion

Year by year, the number of satellites is increasing, which creates a crucial issue of establishing networks among them for efficient communication with high capacity. Consequently, how to transmit data among them, send data from one to another, and lastly to broadcast it to the ground stations. In this article, we investigated and analyzed the transmission of a data rate of 16-channel Is-OWC based DWDM. Performance evaluations demonstrated that our system can send 160 Gbps data rates over a 7,000 km link with an optical amplifier with minimum power. The transmission can be up to 1.1 μrad transmitting pointing error with acceptable BER and Q-Factor. Therefore, our study concerned about using an optical wireless communication system in space communications.

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