Performance Analysis of Inter-satellite Optical Wireless Communication (IsOWC) System with Multiple Transmitters/Receivers

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Abstract. The satellite communications networks have certainly been innovated recently by Inter-satellite optical wireless communication (IsOWC) networks. The prerequisite for next generation mobile satellite communication is superior multimedia facility for consumers at anytime and anywhere. The proposed optical communication system is designed and analysed to improve data transmission quality over the distance between two geostationary (GEO) satellites greater than 36000 km. This trend is to achieve high speed transmission with minimizing the presence possibility of free space loss in transmission that can occur in satellite communication via the longest range. Numerous transceivers IsOWC is a hopeful way to deal with be utilized related to different earth stations as a system utilized between the geosynchronous satellites. The wireless transmission creates the opportunity at high optical power without free space loss. The results of the simulated system showed that with 32 transmitters/receivers IsOWC, the Q-factor values of 36.526, 12.176 and 4.015 are obtained at 38000 km range at laser power of (19, 14 and 9) dBm, respectively. The proposed system is operated at 19 dBm optical power and different values of aperture size and the best values of Q-factor and BER are 41 and $10^{-250}$, respectively, for highest diameter value of 20 cm. The operation of the system with various values of bit rate is verified as well. It is seen that the best system performance is at 0.032 Gb/s bit rate and will be of lower as the bit rate increases until it roughly fixes at 32 Gb/s. This research offers the treatment for the transmission problem for ultra-speed application in mobile satellite systems.

Keywords. Inter-satellite optical wireless communication (IsOWC), Q-factor, bit error rate (BER), multiple transmitters/receivers, range.

1. Introduction

In the short term, Satellites whose numbers are annually increasing, has being played the greatest role at numerous fields of our life that provide a lot of services such as cellular mobile networks, exchange of information (data), Internet of every things, downloading of video conference, multi-media communications. Inter-satellite optical wireless communication (IsOWC) is essential to be efficiently connected two satellites with the lowest delay time. Optical wireless communication opens up the idea to incorporate optical wireless networking into space technology. IsOWC offers huge advantages and facilities for example; in terrestrial communication connection no licensing is necessary. In this
technology, tolerance to radio frequency interference or depletion has added safety features. The point-to-point laser signal is extremely difficult to intercept. It is very challenging to jam or tap the IsOWC connection, with a narrow beam angle for several mili-radians. Today's information up to several Gbps at data rates and a distance of thousands of kilometres can be sent utilizing Laser communication. IsOWC system was not operated with a single Tx/Rx (IsOWC but as the combination was increased such as 2 up to 8 transmitters/receivers (Txs/Rxs) or the multiple laser beams, the system began to operate and accomplished. It was found that very high data rates up to 18 Gbps are achieved with 8 Txs/Rxs IsOWC connections [1]. Both simulated and practical models of various numbers 4×4 Txs/Rxs using free space optical (FSO) of 1 km length channel were compared with the theoretical one. It was revealed that large laser power and aperture diameters were needed for communication over distance of 5000 km with Low Earth Orbit (LEO)-LEO satellite communication [2]. Great received power value was -25 dBm for 4 Txs/Rxs of IsOWC system over 5000 km range. It was concluded that data rates up to 5.6 Gbps are attained using the variety of transceivers at an improved BER of 10−16 [3]. 5 Mbps to 5 Gbps Simplex IsOWC system over LEO range and Medium Earth Orbit (MEO) links was simulated over distance up to 2500 km. Large laser power of wavelengths 850, 950, 1310, and 1550 nm and low bit rate were needed for longer distance transmission and transmission at 1550 nm reduces the scattering effect of in IsOWC systems [4]. A satellite is a body that circles another item in space or revolves around it. The possibility of making man-made satellites capable of relaying telephone channels and transmitting programmes was written by Arthur Clarke in 1945. A satellite that orbits around the earth at altitude of 360000 km is called Geosynchronous Orbit (GEO) which is useful for telephone transmission and broadcasting systems. Optical inter-satellite link was modelled between two separate satellites at a distance of 1700 km of 3 Gbps data rate using different modulation formats [5]. Optical system was modelled and simulated using FSO connection with four Txs/Rxs and its performance was assessed under bright, hazy and fog conditions. It was found that raising the attenuation would cause reducing the efficiency of the FSO system but better performance was achieved with 4Txs/Rxs [6]. High speed IsOWC network was designed and simulated using space and polarization diversity techniques. The system performance with laser power of 25 dBm and data rate of 7.63 Gbps for a connection distance of 6,000 km was carried out [7]. Comparison performance of optical inter-satellite connection (ISC) for different bit rates and operating wavelengths was accomplished. It was found that performance of the system was high at low wavelengths and small distances [8]. The modelled of 10 Gbps DWDM system includes a 32-channel IS-OWC network operating via NRZ and RZ modulation schemes and varying laser power rates over a 5000 km long distance [9]. The successful performance was obtained by the analysis of FSO and multiple Txs/Rxs at different range values. The best performance of the 8×8 arrangements was at a distance of 5 km]. 10 Gbps data rate was achieved by using a 4×4 transceiver and advanced modulation schemes to perform the enhanced system performance of ISC using optical connection over 6000 km Usage of QPSK modulation format in an IsOWC framework to achieve a higher data rate of 40 Gbps [11]. IsOWC system was developed between LEO and geostationary (GEO) satellites at a bit rate of 10 Gbps, separated by a distance of 40,000 Km. 30 dB optical gain amplifier and 4 dB noise Figure were utilized in front of the OWC channel due to free channel attenuation. It was found that IsOWC performance was affected by wavelength and aperture diameter [12]. 15 Gbps simplex IsOWC performance system was determined via transmission distance of 1000 km. It was revealed that as the data rate rises, the Q factor decreases [13]. 2.5 Gb/s simplex LEO-LEO IsOWC system had planned and evaluated over 5000 km linking distances for various modulation types, wavelengths, transmitted power and aperture diameter for global coverage [14].

Study and comparison three models of dispersion compensated fiber was reported [15]. An optical wireless communication link based on IR transmitter / receiver was presented [16]. Various nonlinear modulation formats for optical wireless communication was demonstrated [17].

Our system designs simple and multiple Txs/Rxs IsOWC which has such specifications that are used for the first time is not performed. The data signals are transmitted with very high speed data wirelessly over free space distance greater than 36000 km that is for GEO satellites communication
systems without using any type of amplification before transmission or after receiving. The digital data from telemetry tracking and communication (TT&C) satellite’s subsystems is encoded by the NRZ pulse generator and it is used to modulate the optical signal in IsOWC system and better quality than the former systems is obtained. The extends of the improvement in the system performance is as a result of decreasing received power, increasing the aperture size of antennas, and bit rate of data transmission. The article is arranged such that the system setup design is explained in section two. The demonstration of the results and clarification their discussion are reported in section 3. Section four describes the important conclusions obtained from the proposed system.

2. System Setup Design
The IsOWC system with multiple transmitters/receivers is designed and simulated using OptiSystem software version 14.0, where the system’s block diagram is displayed in Figure 1. The contents of IsOWC system are; the satellite transmitter, wireless communication channel, and the receiver of the satellite. The pseudo random binary sequences from TT&C subsystems of the satellite are delivered to the nonreturn-to-zero (NRZ) pulse generator to be encoded. Then these random rectangular NRZ electrical pulses will externally modulate the light output carrier from continuous wave (CW) laser of 1550 nm using the Mach-Zehnder modulator (MZM)). The intensity optical signal is split into four outputs and the transmitter diversity of 4×8 transmitters is generated using another splitter of eight branches to produce the thirty two laser beams. The signals of these laser beams are combined to deliver an optical signal to an optical wireless link. The setup of optical wireless communication can be simulated using two radiator elements located at certain distance between them and the wireless communication channel. At the satellite receiver, the optical received power \( P_{rx} \) can be written in terms of the optical transmitted power \( P_{tx} \) and the optical efficiency of both of transmitter and the receiver \( \eta_{tx}, \eta_{rx} \), respectively, as given in equation (1):

\[
P_{rx} = P_{tx} \eta_{tx} \eta_{rx} \left( \frac{\lambda}{4\pi R} \right) G_{tx} G_{rx} L_{tx} L_{rx}
\]  

The other parameters by which the received power can be calculated are the wavelength \( \lambda \), the range \( R \), the gain of the transmit and receive optical antennas \( G_{tx}, G_{rx} \), and \( L_{tx}, L_{rx} \) are the transmit and receive pointing loss factor. The pointing loss factor can be evaluated using the \( G_{rx} \) and the radial pointing error angle \( \theta \) as demonstrated equation (2):

\[
L = e^{-\left(\frac{G_{rx}}{\theta^2}\right)}
\]  

The aperture diameter of the optical antennas for multiple transmitters/receivers (Txs/Rxs) is too small compared to that of RF signals and equal to 20 cm. The modulated optical signals propagated through free space without any amplification utilizing four optical wireless communication channels that perform the wireless path. The signals without any type of losses are collected by combiner and will be outputted at the received telescopes. However, the optical signals are delivered to the receiver side for processing purpose. The front part of the receiver is the positive intrinsic negative (PIN) photodiode which does not contain gain stage, and then the electrical output signals are analysed after passing through the Bessel low pass filter (BLPF) using eye diagram analyzer. The parameters of the designed IsOWC system are listed in Table 1.
Figure 1. IsOWC with MTxs/Rxs System’s configuration.

Table 1. Parameters of the IsOWC system.

| Component       | Parameter                        | Value and Unit       |
|-----------------|----------------------------------|----------------------|
| system Layout   | Bit rate                         | 32 Gb/s              |
|                 | Sequence length                  | 128 bits             |
|                 | Samples per bit                  | 64                   |
|                 | Number of samples                | 8192                 |
| CW laser        | Wavelength                       | 1550 nm              |
|                 | Power                            | 19 dBm               |
|                 | Linewidth                        | 10 MHz               |
| External modulator | Extinction ratio                | 30 dB                |
|                 | Frequency                        | 1550 nm              |
|                 | Transmitter aperture diameter    | 20 cm                |
|                 | Receiver aperture diameter       | 20 cm                |
| OWC channel     | Transmitter optics efficiency    | 0.8                  |
|                 | Receiver optics efficiency       | 0.8                  |
|                 | Transmitter pointing error angle | 1.1 urad             |
|                 | Receiver pointing error angle    | 1.1 urad             |
| PIN photodiode  | Responsivity                     | 1 A/W                |
|                 | Dark current                     | 5 nA                 |
|                 | Thermal power density            | $1 \times 10^{-24}$ W/Hz |
| BLPF            | Cutoff frequency                 | 0.75 × Bit rate      |
3. Results and Discussion
The transmission performance over a range of greater than 36000 km satellite communication systems is tested by the aid of main four approaches using multiple transmitters/receivers IsOWC system. The range between two geosynchronous satellites is varied or the range between geosynchronous satellite and terrestrial stations is varied at constant transmitting optical power. Quality is discussed as a consequence of the effect of: electric received power, aperture size of the antennas, and system bit rate as described in the following four sections.

3.1. Varying the Range at Constant Optical Power
First, the performance of the 32 Txs / Rxs IsOWC system is tested in the BER term as a function of the range at various laser power values such as 19, 14, 9 dBm as shown in Figure 2. It is obvious that as the signal travels over longer range of wireless path, the system BER decreases with increasing the received power. The BER increases more slowly after range more than 50000 km at 14 and 9 dBm. As the laser power increases, at a shorter range in km, the minimum BER will be obtained in such a way that it is around $10^{-290}$, $10^{-220}$, and $10^{-292}$ for (9, 14, and 19) dBm, respectively. This means that the transmission over optical wireless is better than that of optical link, where the later suffers from the nonlinear effects at higher laser power. This is approved in the quality factor of IsOWC system as demonstrated in Figure 3 as well. Where the best quality of the system operation is gained at 19 dBm laser power and the Q-factor decreases and the system performance deteriorates as the signal propagated over longer range. Figure 4 displays the eye diagram at the receiver after the satellites' signals travel across free space range of 10000, 20000, and 36000 km when the optical power of carrier is 19,14 and 9 dBm. The corresponding achievement of good acceptable system quality is clarified at range >36000 km and laser power of 19, 14 and 9 dBm in Table 2.

3.2. System Quality against Received Power
In general, the designed system operates at transmission satellite range of different values; for example, 72000, 57000, 42000 and 27000 are achieved with varying the received electrical power as shown in Figure 5. It is found that BER is of great values at longer range then at a certain range of propagation, the BER decreases slightly as the received power increases. This trend is that the strong 1550 nm wavelength satellite signal will not be affected during propagation by free space losses such as Rayleigh and Mei scattering which is inversely proportional to the wavelength. Figure 6 crystallize the best quality system performance, where the transmission of wireless satellite signal is the strongest for the shortest optical wireless communication path (27000 km), while the weakest one is for the longest range (72000 km). Therefore, 32 Txs/Rxs IsOWC system operates well along greater than 36000 km range which equal to 42000 km.

3.3. Effect of Antennas Aperture Size
The antennas aperture diameter used in our proposed system is measured in centimetre i.e. means smaller than that used in RF transmission which is in meter. At a certain laser power of 19 dBm, the Q-factor and BER are drawn against the range for aperture diameters of (20, 16, 15 and 12) cm as shown in Figures 7 and 8, respectively. The aperture diameter of transmit and receive antennas affects the quality of the IsOWC system, the larger aperture size the better performance is. The Q-factor and BER values are 41 and $10^{-250}$, respectively, at 20 cm aperture diameter. The reason for this occurrence is as the diameter increases the aperture size of the antenna will be larger, then the antennas at the input and output of optical wireless channel will have greater gain and the stronger satellite signal will be obtained.

3.4. System Operation at various bit rate
The effect of increasing bit rate of 32 Txs/Rxs IsOWC system is test and simulated as well. Figure 9 demonstrates the quality of the designed system versus range as it varies from 60000 km and goes...
further away to 100000 km. The best system performance is at 0.032 Gb/s bit rate and will be of lower as the bit rate increases until it roughly fixes at 32 Gb/s.

Figure 2. BER versus range for 19, 14, and 9 dBm laser power.

Figure 3. Q-factor versus range for 19, 14, and 9 dBm laser power.
Figure 4. Eye diagram at range of (10000, 20000 and 36000) km for laser power of (a) 19 dBm, (b) 14 dBm (c) 9 dBm.

Table 2. System quality comparison for two values of laser power.

| Range (km) | Laser power=19 dBm | Laser power=14 dBm | Laser power=9 dBm |
|-----------|-------------------|-------------------|-------------------|
|           | Q-factor | BER    | Q-factor | BER    | Q-factor | BER    |
| 10000     | 346.70   | 0      | 138.958  | 0      | 50.426   | 0      |
| 20000     | 111.05   | 0      | 39.949   | 0      | 13.085   | 1.984×10⁻³⁹ |
| 36000     | 40.54    | 0      | 13.105   | 1.523×10⁻³⁹ | 4.818   | 7.207×10⁻⁶  |
Figure 5. BER versus received power for different range values.

Figure 6. Q-factor versus received power for different range values.
Figure 7. Q-factor versus range for (20, 16, 15, 12) cm aperture diameter of the optical antenna.

Figure 8. BER versus range for (20, 16, 15, 12) cm aperture diameter of optical antenna.
Figure 9. Q-factor versus range for different values of bit rate.

4. Conclusion
So many more satellites are being launched in space to perform numerous tasks for the benefit of society. The target of the research is to design and analyses IsOWC system in order to achieve its improved performance. Wireless data transmission via free space channel along range greater than 36000 km with minimum BER for GEO satellite communication systems is achieved utilizing 32 Txs/Rxs to obtain lossless high data rate transmission. The quality of the system is 40.799 and 17.019 for transmission range of (38000 and 60000) km at low received power of -80.661. Good system quality versus received power is obtained for range greater than 36000 km. Q-factor is 34 at 20 cm antennas diameter over transmission distance of 40000 km. The possibility of high data rate transmission can be achieved, fixed system performance is extremely got at 32 Gb/s and it is better as the bit rate decreases. Finally it is preferable to increase number of multiple transmitters/receivers IsOWC to control and decrease the errors that may be occurs for very long range and high data rate GEO satellite transmission that is necessary for 5G cellular mobile networks.

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