Published in IET Communications
Received on 25th January 2012
Revised on 13th June 2012
doi: 10.1049/iet-com.2012.0044

ISSN 1751-8628

Inter-satellite optical wireless communication system design and simulation

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Abstract: An ultra-high bit-rate inter-satellite optical wireless communication (IsOWC) system is proposed in thisstudy. The system is designed and simulated up to the bit-rate of 400 Gbps. The proposed system is a non-diffused link or line-of-sight setup, which uses coherent optical quadrature phase-shift keying (QPSK) modulation technique. The performance of the system is analysed in terms of *Q*-factor, bit-error rate, eye opening and so on. The coverage distance observed with an input power level of 30 dBm for a bit-rate of 400, 160 and 100 Gbps are 4767, 7542 and 9532 km, respectively. Finally, the maximum bit-rate that can be communicated, for inter-satellite link at different orbits such as low-Earth orbit, medium-Earth orbit and geostationary Earth orbit are presented. To the best of the authors knowledge for the first time they have proposed a novel QPSK modulation technique for the design of IsOWC system for achieving higher coverage distance and data rate, which was not been addressed in any current or earlier publications.

1 Introduction

The mobile satellite communications systems of next generation will provide high-quality and flexible multimedia services to users at anywhere and at any time [1]. Communication between any two places in the Earth is an attractive goal. One of the feasible solutions to achieve this goal is networking the satellites together with the Earth stations. Especially, when the communication is required between two places, which are opposite to each other of the globe, then the information should be transmitted through the nearby satellite, the satellite then sends the information to its nearby satellite and so on. By virtue of this inter-linking process the group of satellites transmits the information down to the ground destination station. Thus inter-satellite link (ISL) plays an important role for the communication purpose for global coverage. These satellites should have high-speed switching and processing capabilities. This system is complicated and made up of many units. The traditional geostationary Earth orbit (GEO) satellites are not suitable for this purpose because, they have (i) high propagation loss; and (ii) large transmission delay. Instead of this kind of satellites, the low-Earth orbit (LEO) and medium-Earth orbit (MEO) satellites are highly suitable for the global coverage and communication purpose. Teledesic, Sativod, Celestri, sky-bridge and M-star systems are few of the examples [2].

ISL using optical link has many advantage comparing to microwave link, such as (i) higher band width, (ii) lower transmission power, (iii) smaller size and weight of the terminals and (iv) higher immunity to interference and so on. All of these reasons are vital for a satellite communication system, because it can reduces the payloads and consequently reduces the costs. However, owing to small beam divergence, pointing, acquisition and tracking are more critical in optical link. The required tracking accuracy is typically of the order of 1 μrad [3]. This requires closed-loop tracking, which is the only disadvantage of the system. This can be taken care by using servo-motors, which locks the beacon signals of the satellites [4, 5].

The proposed inter-satellite optical wireless communication (IsOWC) system uses lasers as a signal carrier. This is the key technology for realising an ultra-high speed and long-haul communication system. The coverage distance of the IsOWC system depends on many parameters, such as type of modulation used, input power, operating wavelength, receiver sensitivity and so on. Hashim *et al.* [6] proved that among all ON–OFF keying techniques non-return-to-zero (NRZ) is the best scheme, for obtaining maximum coverage distance of the link. Comparing to ON–OFF keying techniques phase-shift keying (PSK) technique is preferable for free-space optical communication, as it does not require any adaptive thresholding method [7, 8]. Sodnik *et al.* [9] used binary PSK (BPSK) modulation technique for ISL. In this paper, we have used coherent optical quadrature PSK (QPSK) technique, as its spectral efficiency is double to that of BPSK technique [10]. Hashim *et al.* found a coverage distance of 5000 km for a bit-rate of 1 Mbps communication, but with our proposed system we achieved a bit-rate of 438 Gbps for a coverage distance of 5000 km.

2 Inter-satellite link

The first inter-satellite communication using optical link was successfully achieved on March 2003 between Artemis and Satellite Pour L Observation De La Terre-4 (SPOT-4) [11]. It was a simplex communication system, from Artemis to SPOT-4 and was done by using bit-rate of 50 Mbps, with optical signal wavelength of 850 nm and power of 120 mW. Artemis was placed in the GEO satellite while SPOT-4 was in LEO at altitude of 832 km. Then during the year December 2005, a full-duplex communication between Artemis and Kirari was achieved. These two experiments have proved that IsOWC is possible.

Satellites are parked in several orbits around the Earth. They are LEO, MEO and geosynchronous orbit (GEO) [6]. The LEO lies outside of the Earth's atmosphere up to the inner Van Ellen belt, which is less than 1500 km of altitude [12]. For LEO satellites, a group of satellites are sent to space with a common mission and a direct communication link between them will allow the communication faster and hence make the satellites less dependent on ground stations [6]. ISL can also be used between satellites at different orbits, for example, from MEO to LEO and from GEO to LEO satellites [12]. The intra-satellite distance between LEO–LEO and MEO–MEO satellites are found to be less than or equal to 5860 and 18 460 km, respectively [13]. Similarly between LEO and GEO the distance is of 45 000 km [9]. For these distances the maximum bit-rate that can be communicated for ISL is obtained in this paper, with the proposed setup.

3 IsOWC system

IsOWC system uses a laser beam as a wireless connectivity between transmitter and receiver, free-space as propagation medium for carrying information. The performance of the system is greatly influenced by the propagation medium [14, 15]. Thus, the selection of modulation technique is a vital role in the design process of the system. There are two types of optical wireless communication (OWC) systems: (i) non-line-of-sight or diffused-link (DL) system and (ii) line-of-sight (LOS) system. The DL system solves the problem of mobility, severe shadowing but has a huge loss because of the multipath propagation. On the other hand, LOS or directed beam system provides excellent transmission capacity, but subjected to severe shadowing problems and restricted mobility. For IsOWC system, the coverage distance required is of the order of thousands of kilometres, thus it uses only LOS systems. For the LOS system, the received power is given by [16]

$$P_R = P_T \eta_T \eta_R G_T G_R L_T L_R (\lambda / 4\pi z)^2 \quad (1)$$

where P_R is the received power; P_T is the transmitted power; η_T is the optics efficiency of the transmitter; η_R is the optics efficiency of the receiver; G_T is the transmitter gain; G_R is the receiver gain; L_T is the transmitter pointing loss factor; L_R is the receiver pointing loss factor; λ is the operating wavelength; and z is the distance between transmitter and receiver.

The transmitter gain is given by [17]

$$G_T = (\pi D_T / \lambda)^2 \quad (2)$$

where D_T is the transmitter telescope diameter.

The receiver gain is given by [17]

$$G_R = (\pi D_R / \lambda)^2 \quad (3)$$

where D_R is the receiver telescope diameter.

Here, the transmitter pointing loss factor is given by [16]

$$L_T = \exp(-G_T \theta_T^2) \quad (4)$$

and the receiver pointing loss factor is given by [16]

$$L_R = \exp(-G_R \theta_R^2) \quad (5)$$

where θ_T and θ_R are the transmitter and receiver pointing error, respectively.

From (1), we can conclude that there exists a trade-off between coverage distance and the received power, that is, as the coverage distance increases, the received power decreases. Again for higher bit-rate of the system, the receiver sensitivity should be high for maintaining the same optical signal-to-noise ratio [18]. Thus as the bit-rate of the system increases, the coverage distance decreases.

4 Coherent optical QPSK modulation technique

The block diagram of coherent optical QPSK transmitter is shown in Fig. 1 [19]. The number of bits per symbol considered here is two. It consists of PSK sequence

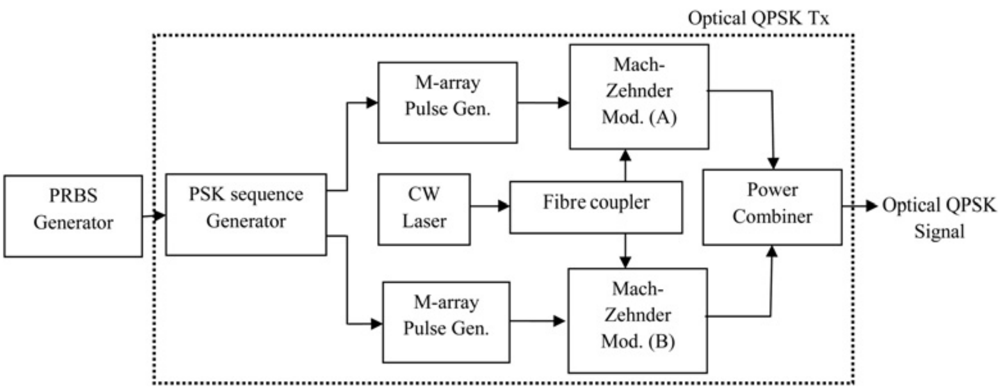

Fig. 1 *Block diagram of coherent optical QPSK transmitter*

IET Commun., 2012, Vol. 6, Iss. 16, pp. 2561–2567
doi: 10.1049/iet-com.2012.0044

Table 1 *I* and *Q* signals as per the incoming symbol

Symbol	*I* signal	*Q* signal
00	1	0
01	0	1
10	0	−1
11	−1	0

generator, which generates the in-phase (I) and quadrature signals (Q) as given in (6) and (7), respectively. The details of I and Q signals as per the incoming symbol are given in Table 1. The output of the PSK sequence generator is given to the M-array pulse generator, where $M = 4$. Using a coupler the optical signal is fed to the Mach–Zehnder (MZ) modulator and at the end both I and Q signals is combined using an optical power combiner as shown in Fig. 1. The I and Q signals are given by Benedetto *et al.* [19]

$$I_i = \cos(\phi_i) \tag{6}$$

$$Q_i = \cos(\phi_i) \tag{7}$$

where $\varphi_i = 2\pi(i-1)/M$, $i = 1, 2, 3, 4$ and $M = 4$.

5 Proposed system

The block diagram of the proposed IsOWC system is given in Fig. 2. It consists of transmitter, OWC channel and the receiver with few visualisers. Transmitter consists of pseudo-random bit sequence (PRBS) generator followed by optical QPSK transmitter. The output of the transmitter is given to the OWC channel, which consists of a transmitter telescope, the wireless communication channel and the receiver telescope. The output of the receiver telescope is given to the optical QPSK receiver, which coherently detects the optical signal using a local oscillator (laser). It uses a balanced-detection technique and produces the information signal in the electrical domain. Then the electrical signal is amplified, filtered using a low-pass filter and given to the input of an M-array threshold detector as shown in Fig. 2. Then the PSK decoder is used to produce the value of j for the phase of each signal input k

$$\phi_k = \tan^{-1}(Q_k/I_k) \tag{8}$$

$$j = (((\phi_k - \phi)M)/2\pi) + 1 \tag{9}$$

and convert the values of j to the equivalent binary sequence [19]. Hence, fresh 0 and 1 s are reproduced. Here, the bit-error rate (BER) analyser is used to observe the BER, eye diagram, eye opening etc. Oscilloscope is used to observe the electrical signal in time domain; optical spectrum analyser is used to observe the optical signal spectrum.

Table 2 Simulation parameters of IsOWC system

Parameters	Values
OWC type	line of sight
bit-rate, Gbps	1–400
modulation	coherent optical QPSK
operating wavelength, nm	1550 and 1064
transmitter power, dBm	30, 25, 20
local oscillator power at the receiver, dBm	11
sequence length	128
samples per bit	64
line width of laser, MHz	0.1
dark current, nAmp	10
responsivity of PIN, A/W	1
transmitter aperture diameter, mm	150
receiver aperture diameter, mm	150
transmitter optics efficiency	0.8
receiver optics efficiency	0.8
transmitter pointing error, µrad	1.1
receiver pointing error, µrad	1.1
additional losses (pointing loss, synchronisation loss etc.), dB	1

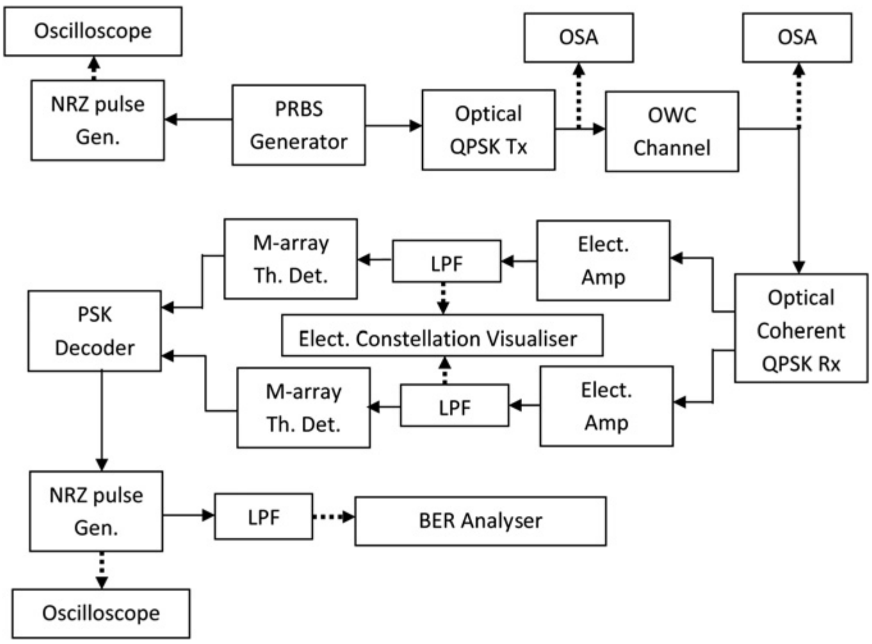

Fig. 2 *Block diagram of the proposed IsOWC system*

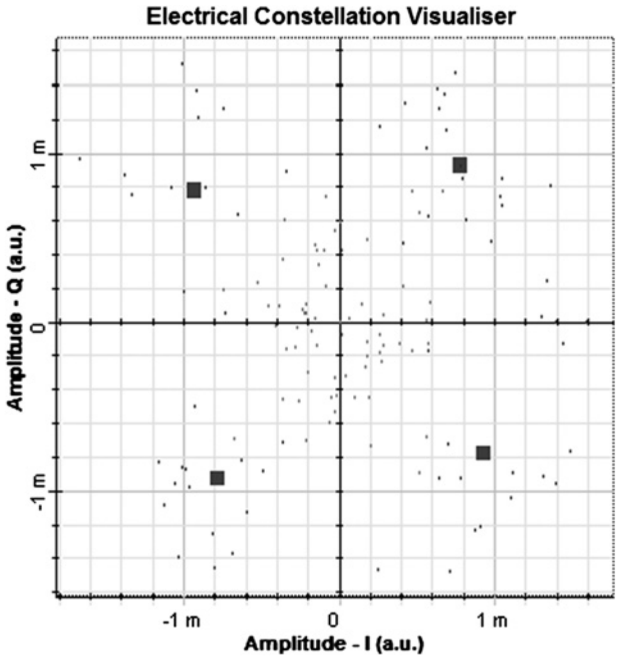

Fig. 3 *Signal constellation diagram at the 400 Gbps IsOWC receiver*

6 Simulation

The proposed system of IsOWC, given in Fig. 2 is designed and simulated for the optical signal of wavelength 1550 nm. The details regarding the simulation parameters used for the system are given in Table 2. The parameters are considered as per the practical scenario of IsOWC [20]. Local oscillator power considered at the receiver is 11 dBm [21]. Free-space path loss is also taken into consideration. Bit-rate used is 1–400 Gbps as per the telecommunication standardisation sector of the international telecommunications union (ITU-T) [22–24].

7 Results and discussion

At first, the proposed IsOWC system, as given in Fig. 2, is designed and simulated for bit-rate of 400 Gbps. The simulation parameters used are given in Table 2. Input power applied is 30 dBm with optical signal wavelength of 1550 nm. Fig. 3 shows the signal constellation diagram at the receiver, at a distance of 4767 km, which is as expected for QPSK modulation scheme. At the receiver, using PSK decoder fresh 0 and 1 s are regenerated. Fig. 4 shows the eye diagram and Q-factor of the setup at the receiver. The Q-factor and BER obtained are 2248.59 and 0, respectively, at a distance of 4767 km, as fresh electrical signals (0 and 1 s) are regenerated. The eye opening is also as desirable. Figs. 5 and 6 show the input and output electrical signal of the proposed system, at the transmitter and receiver, respectively. Comparing Fig. 5 with Fig. 6, we can conclude that the desired signal is recovered satisfactorily at the receiver. Further increasing the distance, the signal received is a distorted one and the Q-factor obtained is 0. Hence for the proposed IsOWC system, the coverage

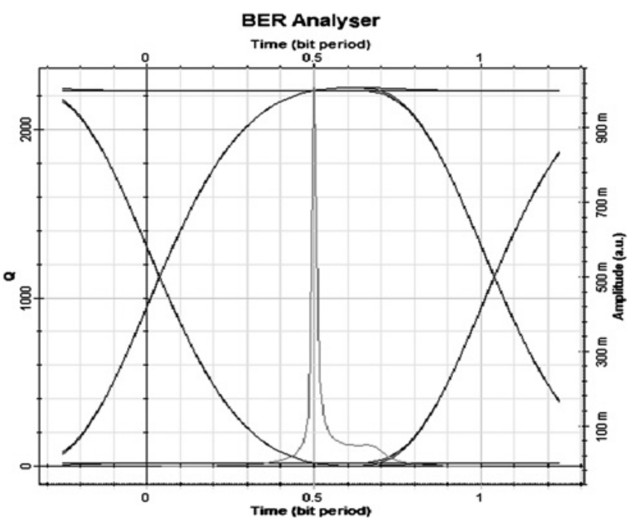

Fig. 4 *Eye diagram and Q-factor at the receiver of 400 Gbps IsOWC link*

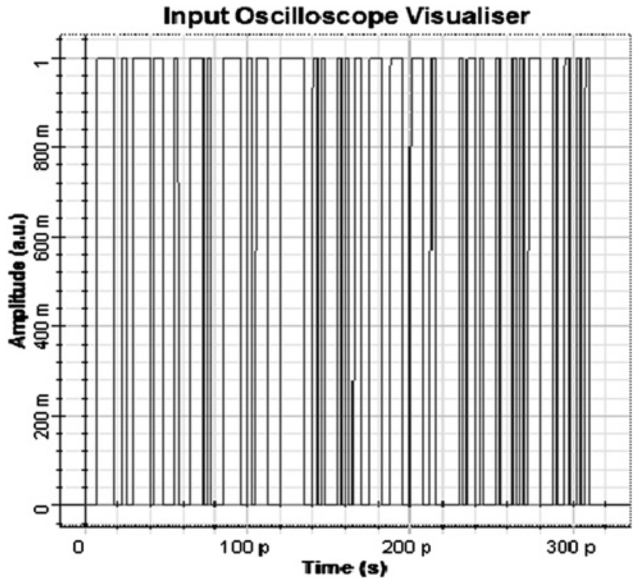

Fig. 5 *Electrical signal applied to the input of 400 Gbps IsOWC link*

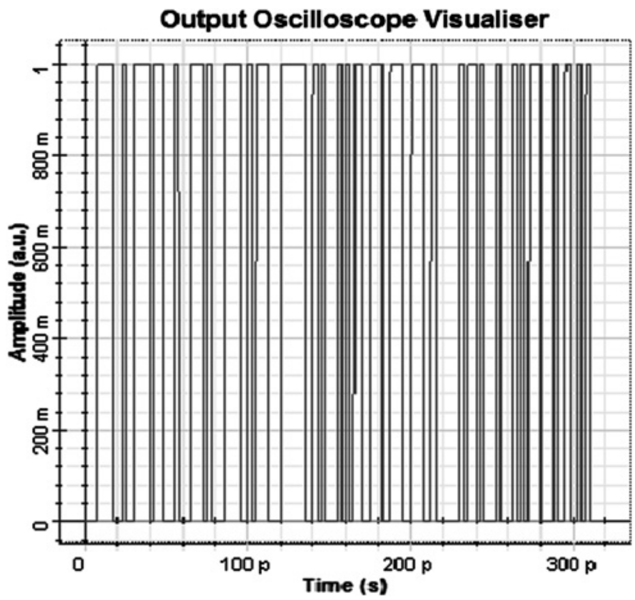

Fig. 6 *Electrical signal obtained at the output of 400 Gbps IsOWC link*

Table 3 Comparative analysis of theoretically calculated value and the simulation results obtained for the received power of the proposed system at various coverage distances

Distance between T_x and R_x, km	Theoretically calculated value of the received power, dBm	Power received observed from the simulation setup, dBm	Difference between the theoretical value and the simulation result, dBm
1000	−15.7811	−15.781	0.0001
2000	−21.8017	−1.802	0.0003
3000	−25.3236	−25.324	0.0004
5000	−29.7605	−29.761	0.0005
7000	−32.6831	−32.682	0.0011
10 000	−35.7811	−35.781	0.001
15 000	−39.3030	−39.303	0
20 000	−41.8017	−41.802	0.0003
25 000	−43.7399	−43.740	0.0001
30 000	−45.3236	−45.324	0.0004
35 000	−46.6625	−46.662	0.0005
40 000	−47.8223	−47.822	0.0003
45 000	−48.8454	−48.845	0.0004

distance obtained is 4767 km for 400 Gbps bit-rate. Then the system is simulated for various coverage distances. The power received at various coverage distances is observed and the same is also calculated theoretically using (1)–(5). Table 3 shows the received power values, both by simulation results and by theoretical analysis. The difference observed is very less. Hence, we can conclude that the simulation results and the theoretical values are nearly same.

Then the bit-rate of the system is varied and the coverage distance is obtained for various bit-rates. Fig. 7 shows the coverage distance obtained for varying bit-rate and input power level. It is observed that as the bit-rate decreases, the coverage distance increases as discussed in Section 3 and also for low-input power, the coverage distance is less.

As the maximum distance between LEO satellites is 5860 km, it is observed with the proposed IsOWC system that, the maximum bit-rate that can be communicated for this coverage distance is found to be 265 Gbps, with input power level of 30 dBm. Table 4 summarises the maximum bit-rate that can be communicated for LEO–LEO, MEO–MEO and LEO–GEO satellites. It is observed that a bit-rate of 4.19 Gbps can be communicated, for a coverage distance of 45 000 km. At last the system is also simulated for 1064 nm wavelength for comparison purpose. The performance of 1550 nm is found to be better than 1064 nm as given in Table 5.

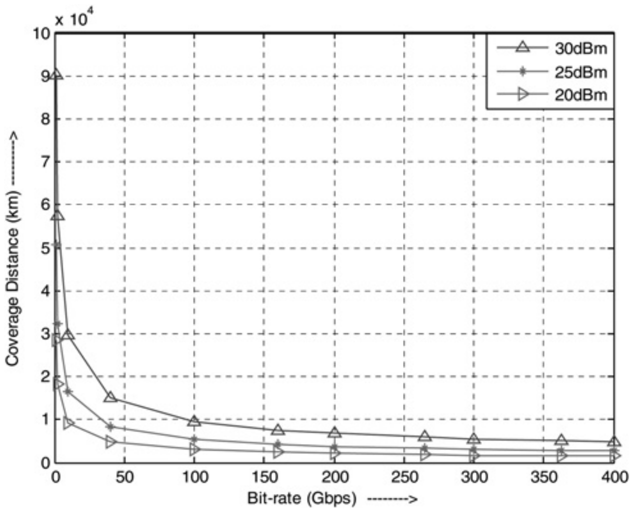

Fig. 7 *IsOWC coverage distance for varying bit-rate and input power*

In this work, we have analysed the design tradeoff between complexity of the proposed system and reachability distance. A one-level increase in the system design complexity has doubled the spectral efficiency of the proposed system, and the use of 1550 nm operating wavelength significantly improves coverage distance for very high data rate applications. The motivation behind selecting the 1550 nm in place of 1064 nm wavelength is the compatibility with the existing optical components (e.g. optical modulators, demodulators, high-power laser diodes and amplifiers) and minimise the scattering effect of atmosphere and to increase the coverage distance [25]. It has been shown by means of the simulated results and theoretical analysis that the coverage distance for the proposed system is extremely high comparing to the existing technologies namely ON–OFF keying and BPSK-based systems at 1550 nm wavelength as given in Table 5.

8 Power budget analysis of the proposed system

8.1 Simulation result

Employing coherent QPSK modulation technique for the proposed IsOWC system the receiver sensitivity observed was −29.348 dBm. The input power requirement of the proposed setup is given by, $P_{\text{in}} =$ insertion loss of the QPSK modulator + free-space path loss + sensitivity of the receiver.

Table 4 Maximum bit-rate that can be communicated between satellites

Satellites link	Input power, dBm	Maximum distance between the satellites, km	Maximum bit-rate that can communicated, Gbps
LEO–LEO	30	5860	265
MEO–MEO	30	18 460	27
LEO–GEO	30	45 000	4.19

Table 5 Comparative analysis of proposed system with benchmarked IsOWC configuration designed by Sodnik *et al.* [9] and Hashim *et al.* [6] have been listed below

Parameters	Sodnik *et al.* (1064 nm)	Proposed (1064 nm)	Hashim *et al.* (1550 nm)	Proposed (1550 nm)
modulation	BPSK	QPSK	NRZ	QPSK
bit-rate	5.6 Gbps	5.6 Gbps	1 Mbps	(a) 5.6 Gbps (b) 438 Gbps
coverage distance	6000 km	6000 km	5000 km	(a) 40 067 km for 5.6 Gbps (b) 5000 km for 438 Gbps

Here, we obtained from the simulation setup, insertion loss of the QPSK modulator = 3.010 dB, free-space path loss = 56.374 dB. Thus, $P_{in} = 3.010 + 56.338 - 29.348 = 30$ dBm.

8.2 Theoretical result

For QPSK modulation, a pair of data signals is applied to the two sub-lithium niobate MZ modulators, to achieve the in-phase and quadrature components. The output signal (R) can be expressed by [26]

$$R = \frac{A^{LW}}{2} e^{i\pi/4}\, e^{i2\pi t f_0} \{\cos[g_1(t)/2] + i\cos[g_2(t)/2]\} \quad (10)$$

where A^{LW} is the laser input signal amplitude, f_0 is the operating frequency, $g_1(t)$ and $g_2(t)$ denote induced optical phase differences in MZ (A) and MZ (B), respectively, as shown in Fig. 1. The MZ structure has optical phase difference of $\pi/2$ between the two arms. By using four symbols of (g_1, g_2), we can generate a QPSK signal, where the phases of the symbols are 0, $\pi/2$, π and $3\pi/2$. Here the insertion loss of the optical integrated QPSK modulator found is 5.1 dB [26]. The free-space path loss is calculated using (1)–(5) is 56.335 dB and the coherent QPSK demodulator, sensitivity is found to be −30 dBm [27]. Thus, the input power required for the setup will be

$$P_{in} = 5.1 + 56.335 - 30 = 31.435 \text{ dB}$$

The simulated results were compared with the theoretical values. However, the simulation values were found to be lower than the theoretical values. This small amount of difference is obvious because in simulation connector loss, pig tail losses are not included.

9 Comparison with related research work

From the literature, we have observed that, Sodnik *et al.* [9] proposed the IsOWC system with bit-rate of 5.6 Gbps using BPSK modulation technique and they achieved a coverage distance of 6000 km for operating wavelength of 1064 nm. But with our proposed IsOWC configuration, which uses QPSK modulation technique and 1550 nm operating wavelength, we achieved a coverage distance of 40 067 km for the same bit-rate (5.6 Gbps). However, for the coverage distance of 6000 km, we obtained a bit-rate of 252.6 Gbps. Similarly, when we simulated our proposed system for 1064 nm wavelength, we obtained the same coverage distance as obtained by Sodnik *et al.* this is because the BER is same for BPSK and QPSK modulation technique but the spectral efficiency of QPSK system is double to that of BPSK system [10]. Because of the inherent advantages of 1550 nm wavelength over 1064 nm, the preferred option for FSO links is to select the longer wavelengths so as to minimise the scattering effect of atmosphere and to increase the coverage distance [25]. The other advantage of 1550 nm includes the compatibility of the optical components, that is, with optical modulators, demodulators, high-power laser diodes and amplifiers. Again laser diodes operated with 1550 nm are safe for eye, comparing to 1064 nm, hence high-power laser diodes can be used at 1550 nm. Hashim *et al.* [6] proposed the IsOWC system using NRZ modulation and they proved that a coverage distance of 5000 km is obtained for a bit-rate of 1 Mbps. However, our proposed system provides 438 Gbps bit-rate for a coverage distance of 5000 km. Table 5 summarises the comparative analysis of the proposed system with the recently published benchmarked research works.

10 Conclusion

In our work, we have proposed an ultra high bit-rate IsOWC system, which uses coherent optical QPSK modulation technique. We have reported about the design and performance of the system for bit-rate up to 400 Gbps. We obtained a coverage distance of 4767, 7542 and 9532 km, respectively, for the bit-rate of 400, 160 and 100 Gbps, with an input power level of 30 dBm. The system may further be analysed for advanced modulation formats and also for higher coverage distances.

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