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Analysis of hybrid PDM-4QAM-OFDM for inter-satellite/mechatronic telecommunication using FSO system

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Abstract

In this paper, the designing and simulation of 400 Gbps polarisation division multiplexing-quadrature amplitude modulation-orthogonal frequency division multiplexing (PDM-4QAM-OFDM)-based inter-satellite optical wireless communication (IsOWC)/mechatronic telecommunication system for improving the link information carrying capacity was carried out. With quadrature amplitude modulation (QAM) encoding, the performance of the executed system has been addressed using metrics such as signal to noise ratio (SNR) and total received power (RP). The performance with suggested system has been examined in relation to the effects of various factors such as operating wavelength, transmission power, and receiving pointing error angle. Moreover, a better identification method for improving connection reach between mechatronic devices/satellites has been revealed in this study. A performance comparison of the proposed system with other implemented approaches has been made in the final step.

1. Introduction

Since 1960 there have been significant technological advances achieved by commercial businesses, governmental organisations, academic institutions, and independent researchers [1]. In space, communication systems/ mechatronic telecommunication systems, optical wireless communication (OWC) systems performed as a reliable and practical method for information trans-reception. OWC networks provide several benefits, including a wide channel bandwidth, fast connections, plenty of open frequencies spectrum, resistance to various interference and encrypted systems [2–4]. Due to these advantages, OWC connections are now being used for a wide range of practical purposes, including deep space communications, inter-satellite links, terrestrial links, fibre backhaul, mechatronic telecommunication, and military access [5, 6]. Data transreception is successfully implemented by OWC system between satellites/mechatronic telecommunication systems in the same or different orbits [7]. In contrast to conventional microwave and radio frequency (RF) communication systems, laser beams are used in OWC system to minimize signal power loss [8].

Except for using free space rather than cable technology as the transreception, OWC connections operate with exactly same principles as other communication technology systems. In order to successfully transfer data signals in different satellites/mechatronic telecommunication systems, which is already executed in previous works, there must be a straight connection between transreceivers [9]. Satellites/mechatronic tele-communication devices have fixed orbits around the planet. One rotation around the Earth's surface is completed by satellites/mechatronic telecommunication device in the low Earth orbit (LEO) in around 2–4 h. Medium Earth orbits (MEOs) are defined as orbits with altitudes more than 6000 km. MEO can be used for remote sensing applications and orbit the planet in 5–12 h. It takes a geostationary (GEO) satellite/GEO mechatronic device 24 h to rotate around the Earth's surface from an orbital altitude of 36 000 km. There are

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three GEOs that can be used for global communication by positioning them at 120 degrees from the equator [10].

If multipath fading effects are there, there must be some steps to reduce this effect on subcarriers. Several subcarriers are used to transreceive data concurrently [11]. A technique is applied to the system input to create subcarriers which prevents the receiving terminal demodulator units from picking up frequencies other than their own [12]. To create a transreceiver with high-speed networks, an orthogonal frequency division multiplexing (OFDM) technology that integrates coherent detection is applied [13]. On the other hand, a wavelength division multiplexing (WDM) was used in previous publications as a way to increase the information capacity in OWC lines. In Ref. 14, the use of optical subcarrier multiplexing to transmit 4 × 1.8 Gbps of data across an OWC connection that is 5000 km long was discussed. According to Ref. 15, they transmit 4 × 100 Gbps of data across an OWC connection that is 4000 km long. The study in Ref. 16 documents the transmission of 80 Gbps data across a 5000 km OWC connection using an 8-channel WDM system. In Ref. 17, it has been shown that 160 Gbps are transreceived with an 8-channel WDM-based OWC connection that covers a hybrid system across a distance of 1000 km. Several lasers and apertures are used in WDM networks to concurrently broadcast numerous infor-mation signals, increasing the system cost and complexity [18]. In order to transmit several information signals simultaneously using orthogonal polarisation states of a single wavelength laser, a method known as polarisation division multiplexing (PDM) is used [19]. This approach increases the link capacity for information transmission. The research in Ref. 20 shows how to use PDM to transmit 112 Gbps of data via a single mode fibre across a distance of 2400 km. In Refs. 21 and 22, it is shown how 112 Gbps data may be sent via 1 channel using WDM optical fibre networks.

In this research, a study of 400 Gbps polarisation division multiplexing-quadrature amplitude modulation-orthogonal frequency division multiplexing (PDM-4QAM-OFDM)-based OWC for intersatellite/mechatronic telecommunication systems over a 9126 km connection under various system parameters was carried out. Section 2 covers the system design, section 3 presents the simulated results, and section 4 provides conclusions.

2. System design

The proposed research which is PDM-4QAM-OFDM-based OWC connection is shown schematically in Fig. 1 and was created using Optisystem. Fundamental idea of PDM in OWC is to transreceive converted data bits into optical signals concurrently utilizing the previously used wavelengths across polarisation states (orthogonally), hence increasing the capacity and spectral efficiency of the system.

In this study, a pseudo random bit sequence (PRBS) generator creates 400 Gbps data which are further split into different parallel signals using a serial to parallel (S/P) converter. Next, a quad-level and 2-bit-per-symbol quadrature amplitude modulation (QAM) encoder encodes the signal. In this study, a 30 dBm continuous wave (CW) laser with an 850 nm and 1550 nm wavelength is used. The signal is split into two orthogonally polarised states by a polarisation splitter when it receives the input from the CW laser. Using an optical modulator, each horizontal (X) and vertical (Y) pulse with QAM modulation, modulates OFDM signals. Afterwards, polarisation combiner combines both OFDM signals. For extending the link reach, this signal is then flat gain amplified and sent across open space.

On the receiver side, a polarisation splitter converts the signal into several states after being amplified by a flat gain amplifier at the receiver terminal (X and Y). Next, for information signal recovery, these signals are sent in the direction towards a coherent detector with a local oscillator and then further executed through OFDM demodulator and QAM decoder. The simulation parameters used are listed in Table 1. The realistic OWC situation has been considered while choosing the simulation settings.

3. Results and discussion

The results of the simulated analysis is discussed and performed in this part of the research work. Figure 2 compares total power and signal to noise ratio (SNR) of the transreceived signal towards increasing link range. The results show that SNR and total received power (RP) in the proposed scheme decrease as the link range increases. Calculated SNR values for the received signal on links with the range of 6721 km, 8164 km, and 9126 km, are 57.17 dB, 46.20 dB, and 41.52 dB, respectively. The results show

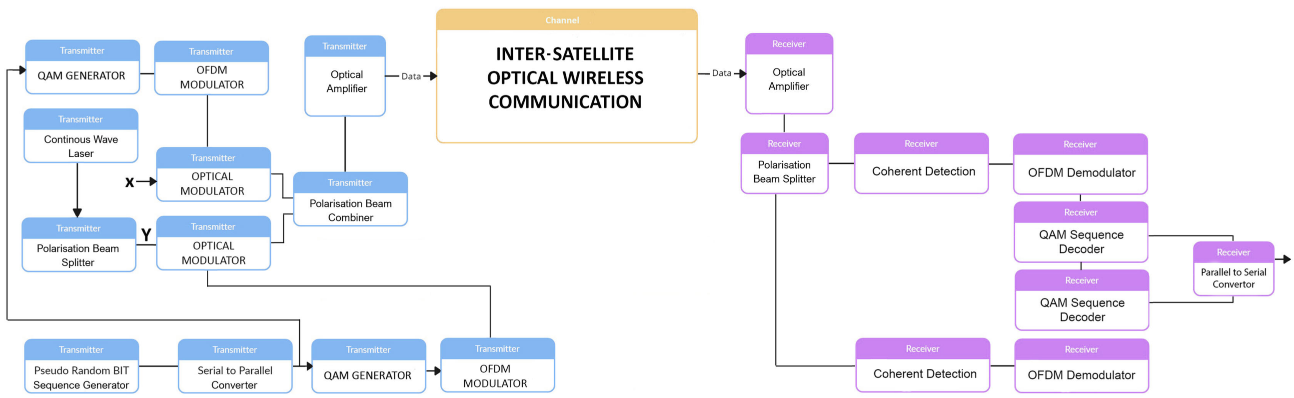

Fig. 1. PDM-4QAM-OFDM-based OWC link block diagram for inter-satellite/mechatronic telecommunication.

Table 1.
Simulation parameters used [23].

Parameter	Value
Frequencies used	850 and 1550 nm
Power of laser	30 dBm
Bit rate and laser line width	400 Gbps and 0.1 MHz
Transreceiver aperture diameter	150 mm
Transreceiver optical efficiency	0.8
Transmitter pointing error angle	0 µrad
Receiver pointing error angle	1 µrad
Sequence length and sample per bit	8192 and 4
Amplifier gain	20 dB
Additional losses	1 µrad

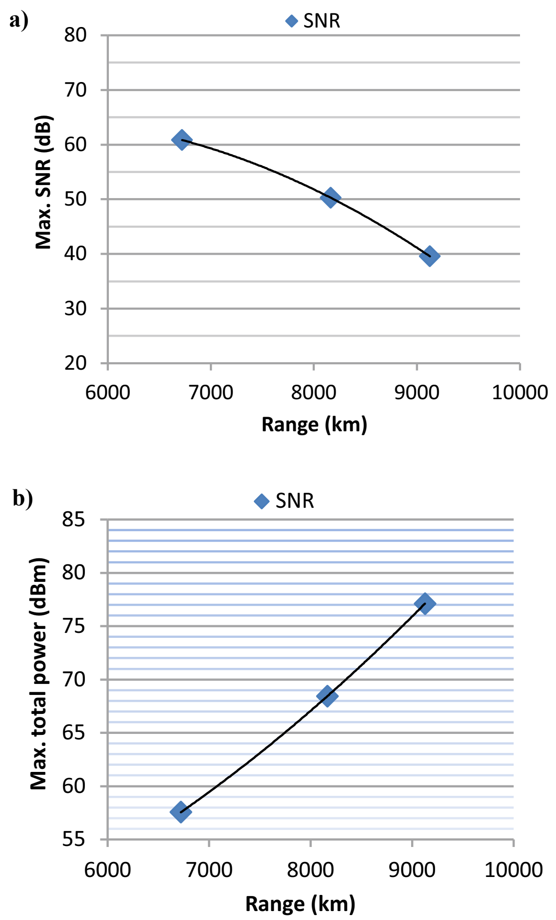

Fig. 2. Measurement of SNR (a) and total power R_P (b) *vs*. transmitting range with QAM scheme.

that adopting the proposed technique increased SNR at a 9126 km link range by 49.45%. Like this, the proposed scheme of a total received signal power is calculated as −51.56 dBm, −68.44 dBm, and −77.10 dBm, for trans-receiver ranges of 6721 km, 8164 km, and 9126 km, respectively. As the results show, this implemented work transmits data at 400 Gbps with acceptable SNR and received power over a connection distance of 9126 km.

The performance comparison of the suggested system employing various operating wavelengths is shown in Fig. 3. The results show that for link ranges of 6721 km, 8164 km, and 9126 km respectively, the SNR of the received signal is calculated as 57.17 dB, 46.20 dB, and 41.52 dB for the 850 nm operating wavelength and 52.83 dB, 41.92 dB, and 37.24 dB for the 1550 nm operating wavelength. The results show that employing the 850 nm wavelength as opposed to the 1550 nm wavelength leads to a 15.75% gain in SNR with a 9126 km link range.

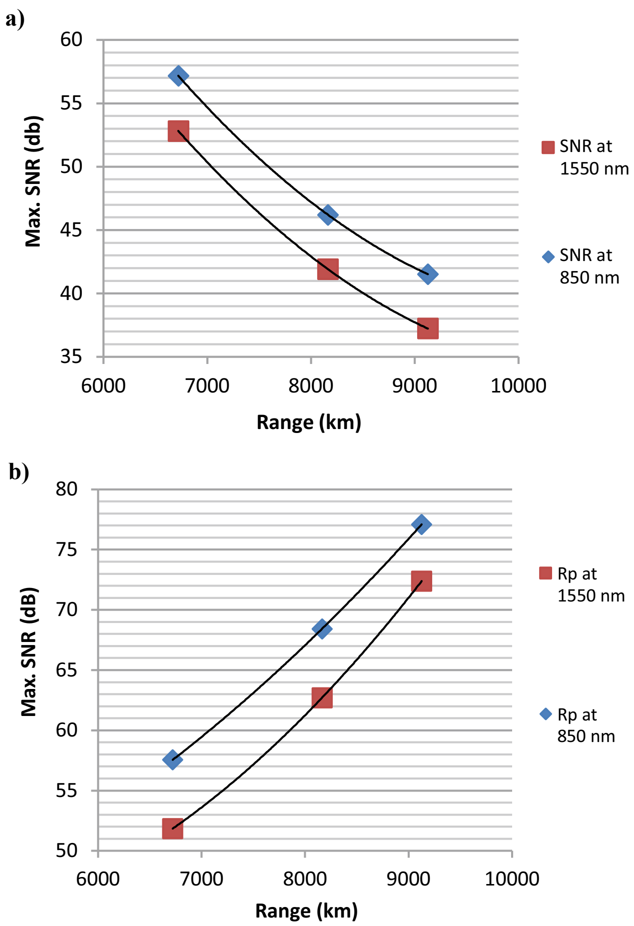

Fig. 3. Measured SNR (a) and R_P (b) *vs*. transmitting range at 850 nm and 1550 nm wavelength.

The received signal strength is calculated to be −51.56 dBm, −68.44 dBm, and −77.10 dBm at the 850 nm operating wavelength and −52.83 dBm, −63.72 dBm, and −68.38 dBm at the 1550 nm operating wavelength for link ranges of 6721 km, 8164 km, and 9126 km, respectively. According to the findings, the performance at the 850 nm operating wavelength is noticeably superior to that of the 1550 nm operating wavelength.

In this study, the impact of receiver aiming error angle and transmission power level on the functionality of the suggested system was also discussed. At a connection distance of 6721 km, Figure 4 presents the SNR value and the received total signal power as changing pointing angle. The findings demonstrate that system accuracy decreases as receiver angle rises. Also, receiver errors affect the calibre of incoming signal to the receiver which is considerably enhanced by raising the signal power. For 1 µrad, 3 µrad, and 5 µrad aiming error angles, the received signal SNR with a transmission power of 15 dBm is calculated as 43.19 dB, 32.41 dB, and 5.06 dB, and with a transmission power of 30 dBm as 57.18 dB, 46.41 dB, and 25.06 dB.

For 1, 3, and 5 µrad aiming error angles, the received signal with respect to total power at transmission power of 15 dBm is calculated as −68.56 dBm, −74.21 dBm, and −77.61 dBm, and transreception power of 30 dBm as −58.56 dBm, −69.24 dBm, and −79.46 dBm.

The main issue with OWC connections is aiming errors brought on by background noise radiations and satellite/mechatronic vibrations, which lead to distortion and reduction of quality in signal. The authors also discuss how the proposed link performance was boosted by adopting an improved detection method at receiver terminal that used a square root device (SQRT) [24], which will also boost the system tolerance for optical impairments including aiming inaccuracy and background radiation. Schottky diodes may be used to build the SQRT device [25].

The outcome of the research, with and without applying suggested improved approach, is shown in Fig. 5. Using the suggested improved detection approach, the results demonstrate an increase in SNR and total R_P at a connection distance of 9126 km.

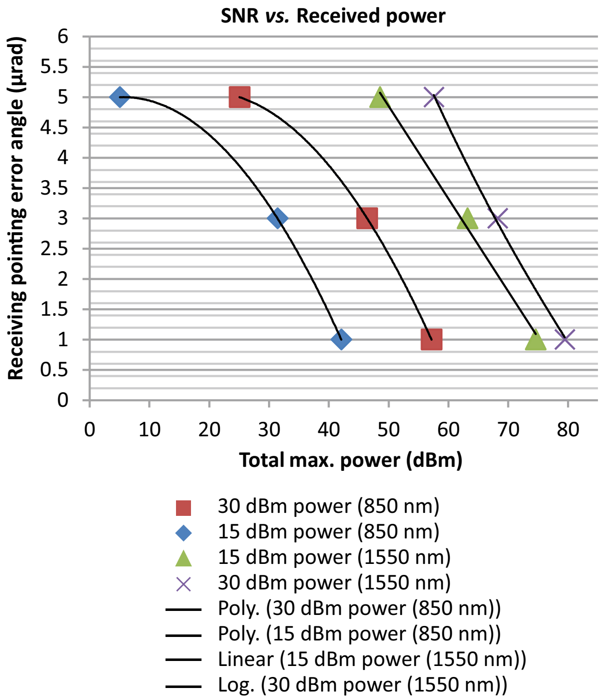

Fig. 4. Measured SNR *vs.* receiver pointing error angle at 15 and 30 dBm power levels for 850 nm and 1550 nm wavelength.

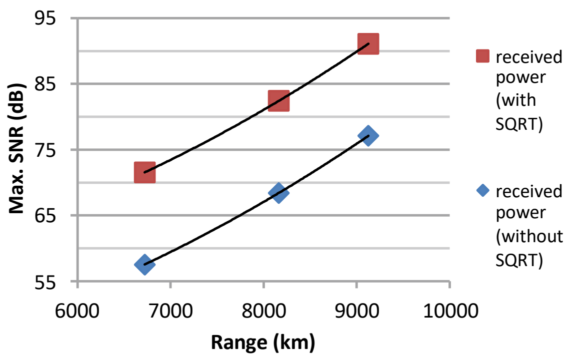

Fig. 5. Transreception range *vs.* maximum total power at different SNR with and without using the proposed SQRT-based system.

This study compares the performance of the OWC connection based on the proposed work, with and without using the suggested PDM approach. The results shown in Fig. 6 demonstrate that by employing the PDM, there is a penalty in SNR of 2.69 dB and penalty in R_p of 7.03 dB at a range of 9126 km which can be tolerated towards data transreception. Figure 7 shows the SNR at 15 dBm power at 850 nm wavelength without PDM, SNR at 15 dBm power at 850 nm wavelength with PDM, SNR at 30 dBm power at 850 nm wavelength without PDM, SNR at 30 dBm power at 850 nm wavelength with PDM, SNR at 15 dBm power at 1550 nm wavelength without PDM, SNR at 15 dBm power at 1550 nm wavelength with PDM, SNR at 30 dBm power at 1550 nm wavelength without PDM, and SNR at 30 dB m power at 1550 nm wavelength with PDM.

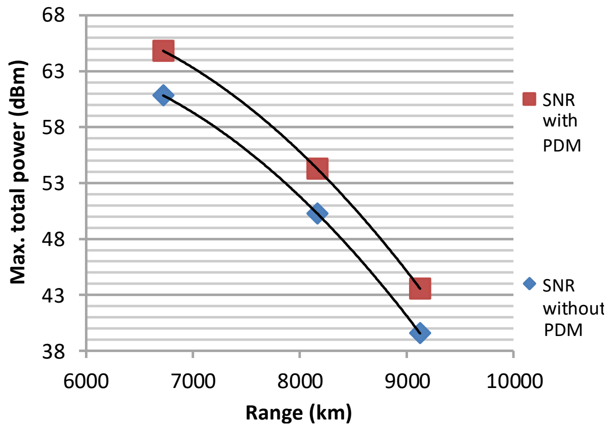

Fig. 6. Transreception range vs. maximum total power at different SNRs with PDM and without PDM based on the proposed system.

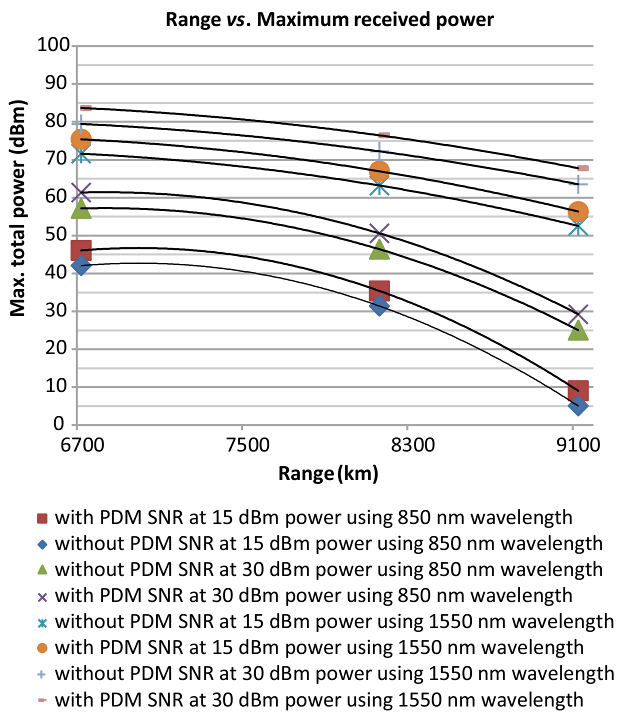

Fig. 7. Transreception range *vs.* maximum total power at different SNRs based on the proposed system.

This work also compares the performance results in Table 2 between the proposed 400 Gbps OWC system and previously published works. The outcome shown in Table 2 demonstrates that the suggested work outperforms earlier studies in terms of data transreception rate and highest attainable connection range.

Table 2.
Simulated results analysis with recent published works.

Credentials	Modulation/ multiplexing technique	Data transfer range (km)	Transreceived rate
Kumar *et al.* [14]	Optical subcarrier multiplexing	4×1.8 Gbps	5000
Gupta *et al.* [15]	CO-QPSK including WDM with DSP	$4\lambda\times10$ Gbps	4000
Kumari *et al.* [16]	WDM	$8\lambda\times10$ Gbps	5000
Shatnawi *et al.* [17]	WDM incorporating hybrid AMI-PI	$8\lambda\times20$ Gbps	1000
In this work	Hybrid PDM-4QAM-OFDM	400 Gbps	9126

4. Conclusions

In this paper, the design of PDM-4QAM-OFDM-based OWC for satellite/mechatronic system is carried out and further results are presented. The results demonstrate that the proposed link connectivity between two satellites/ mechatronic systems is over 9126 km with the encoding technique and the appropriate SNR and R_p. Also, it can be concluded from the data that the operating wavelength of 850 nm performs noticeably better than the operating wavelength of 1550 nm. The results show that as the receiver pointing error angle grows, the performance of the proposed system diminishes; nevertheless, when the signal transmission power level is increased, the quality of the received signal improves. By placing a SQRT at the receiver terminal, an improved detection approach is also shown in this study, which results in a 26 dB increase in SNR and total power of the received signal at a 9126 km link range. Moreover, the suggested PDM-4QAM-OFDM-based OWC/telecommunication system impact on performance is examined. The results indicate that the system total transmission capacity may be maintained with a 4.69 dB reduction in SNR of the received signal at a connection distance of 9126 km.

Authors' statement

The authors confirm contribution to the paper as follows: study conception and design: S.S.; data collection: S.S.; analysis and interpretation of results: S.S. Author, draft manuscript preparation: S.S. All authors S.S., N.S.G., and B.K. reviewed the results and approved the final version of the manuscript.

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