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1.6 Tbps Inter-Satellite Optical Wireless System (IsOWS) Using Double Sidebands Suppressed (DSS) DP-QPSK

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***Abstract*— Dual polarization in coherent multilevel modulations is capacity enhancing technique and is center of choice of the researchers for IsOWS communication. In proposed work, a high capacity i.e. 16 × 100 Gbps system is demonstrated over 16000 km IsOWS link using DSS dual polarization Quadrature phase shifting keying (DP-QPSK) modulation. For the suppression of sidebands in the DP-QPSK carrier spectrum, a null biased Mach-Zehndar modulator (MZM) is considered with input radio frequency (RF) in millimetre range (3 GHz- 300 GHz). Further, a comparison of QPSK, DP-QPSK, DP-QPSK with orthogonal frequency division multiplexed modulation (OFDM), and proposed DSS-DP-QPSK is performed to find out optimal technique for IsOWS systems. Investigation is conducted for evaluation of systems in terms of following parameters such as error vector magnitude percentage (EVMP), received power, and log BER. Results revealed that QPSK, DP-QPSK and DP-QPSK-CO-OFDM covered distance 13200 km, 14500 km, and 15600 km respectively but proposed system surpassed their performance and covered 16000 km successfully.**

Index Terms: **IsOWS, DSS, DP-QPSK, OFDM, EVMP.**

1.INTRODUCTION

Laser communication (LC) has enormous bandwidth as compared to broadband light mediums such as Light emitting diodes (LED) and utilization of LC in wireless communication is very prominent and termed as Wireless optical communication (WOC) [1]. There are three major types of WOC such as (1) IsOWC (2) Terrestrial optical wireless communication i.e. Free space optical communication (FSO) and (3) Indoor communication such as Visible Light Communication (VLC) [2]. Deployment of LC in space for satellite communication has replaced RF communication due to many advantages such as security, speed, capacity and absence of electromagnetic induction (EMI) [3]. IsOWS are extensively deployed in the different earth orbits such as Lower earth orbits (LEO) ranges from 160 km to 1,000 km, Medium earth orbit (MEO) extends from 10,000 to 20,000 km from earth, and Geosynchronous earth orbit (GEO) cover distance greater than 35786 km [4]. In the beginning of developments in the IsOWS communications, first link was established between SPOT-4 and ARTEMIS by the European Space Agency and successfully conducted transmission between two satellite at 50 Mbps [5]. Several parameters in satellite communication plays important role such as size of antennas, pointing errors, link lengths, wavelength of operation, launched power, and pulse shaping modulation to decide the final performance of the IsOWS system [6]. Line of sight (LOS) is utmost requirement for the establishment of link and efficient data transfer between in IsOWS. Misalignment in LOS introduces pointing angle loss and degrade performance of system. Major grounds of pointing errors are mechanical vibrations, Electronic disturbances, and platform jitters [7]. Different modulation such as compressed spectrum return to zero (CSRZ), Duo-binary return to zero (DRZ) and Modified DRZ (MDRZ) modulation in IsOWS at 10, 20, 40 Gbps were demonstrated in [8] for 1250 km and for higher bit rates, MDRZ was recommended. Influence of pointing errors were studied in [9] with capacity 6*20 Gbps and wavelength division multiplexing (WDM) polarization interleaved (PI) technique over 1000 km. Suppression of polarization crosstalk in WDM-PI was better as compared to only WDM system in IsOWS. Highly spectral efficient modulation such as OFDM was investigated over IsOWS at 10 Gbps using differential phase shift keying (DPSK) instead of Quadrature amplitude modulation (QAM) and outcomes revealed that DPSK increased distance to 20,000 km [10]. Coherent (CO) QPSK at 40 Gbps for

4 channels was proposed in satellite communication in [11] and covered 4250 km successfully due to capacity doubling properties of QPSK. In the continuation to [8], three other modulations such as DPSK, Chirped and alternate mark inversion (AMI) were investigated over 2500 km link at 10, 20 and 40 Gbps in [12]. AMI based satellite system surpassed the performance of DPSK and chirped modulation at 40 Gbps. The designing and simulative analysis of 400Gbps CO-OFDM based IsOWS system incorporating polarization division multiplexing techniques over 60,000kms was conducted in [13].IsOWS with DP using QPSK are studied recently in [14] for single channel at 160 Gbps over 40,000 km and in [15] for 1.6 Tbps using DP-QPSK-CO-OFDM and covered 15600 km at log BER -2.42. Incorporation of DP-QPSK in CO-OFDM system drastically improved the spectral efficiency, dispersion tolerance, multipath fading resistance etc but performance can be improved further.

In this work, a 1.6 Tbpssystem is demonstrated over IsOWS link using DSS-DP-QPSK and for DSS, a null biased MZM is considered with 300 GHz RF signal. Further, a comparison of QPSK, DP-QPSK, DP-QPSK with CO-OFDM, and proposed DSS-DP-QPSK is performed in terms of following parameters such as EVMP, received power, and log BER.

2. PRINCIPLE OF MODULATION TECHNIQUES AND DSS GENERATION

OFDM is a multicarrier modulation technique in which greater data rate bit streams are divided into lower data rate subcarriers. The time domain representation of an OFDM baseband signal is [16]

$$B_{OFDM}(t) = \sum_{-\infty}^{\infty} \sum_{-\frac{S_S}{2}+1}^{\frac{S_S}{2}} K_{j,i} \Pi(t - iT_S) exp^{j2\pi} fr_j (t - iT_S) \quad (1)$$

Where $S_S$is number of subcarriers, fr_j is jth subcarrier center frequency, $K_{j,i}$ is jth subcarrier in data symbol ith. Guard interval is G_I, observation time interval t_s, symbol interval of OFDM T_S, rectangular pulse waveform Π(t) (equation 2) and symbol extension is performed in interval $[G_I, 0]$.

$$\Pi(\mathrm{t}) = \begin{Bmatrix} 1, (-\mathrm{G_I} < t < \mathrm{t_s} \\ 0, \mathrm{t} \leq -\mathrm{G_I}, \mathrm{t} > \mathrm{t_s} \end{Bmatrix} \quad (2)$$

OFDM signal in time domain after up-conversion is given as

$$O(t) = \exp\big(j(A_L t + P_L)\big) . B_{OFDM}(t) \quad (3)$$

$A_L$and P_LLrespectively are the angular frequency and phase of the laser. O(t) is an OFDM signal in the optical domain that propagates through the atmosphere. To detect an optical OFDM signal, I(t) is the impulse response, and a coherent receiver is required.

$$O'(t) = \exp\big(j(A_L t + P_L)\big) . B_{OFDM}(t) \otimes I(t) \quad (4)$$

The QPSK encoder is used in CO-OFDM systems to convert serial data to parallel data by providing four phase shift to the 00, 01, 10,11 pair of bits such as 0^0, 90^0, 180^0, and 270^0. Due to its double spectral efficiency over QPSK and reduced interference due to various polarization states, dual polarization QPSK modulation has recently attracted the interest of academics. In DP-QPSK, the laser signal is split into two polarization states and assigned to each QPSK transmitter. A polarization rotator splits the laser's polarization into horizontal and vertical polarized output.A polarization combiner is included in the system for the accumulation of two separate polarizations. In Equation (5) (6), the DP-QPSK signal is expressed as [17]

$$Q_{DP-QPSK,\ X} = Q_X(\mathrm{t}) \exp (\mathrm{j}2\pi f_c t) \exp[P_{m,X}(t)] \quad (5)$$

$$Q_{DP-QPSK,\ Y} = Q_Y(\mathrm{t}) \exp (\mathrm{j}2\pi f_c t) \exp[P_{m,Y}(t)] \quad (6)$$

Where amplitude of X and Y polarization signals are Q_X(t) and Q_Y(t) respectively, carrier wave frequency f_c, phases of electrical modulation signals are $P_{m,X}$, $P_{m,Y}$ for polarization X and Y respectively. Output of coherent receiver for X polarized signal is expressed as in equ. (7) (8)

$$X_I = R\sqrt{2L_{LO}} Q(\mathrm{t}) \quad \cos(2\pi(f_{c-}f_{LO})t) + P_{m,X}(t) - P_{LO}(t)] \quad (7)$$

$$X_Q = R\sqrt{2L_{LO}} Q(\mathrm{t}) \quad \cos(2\pi(f_{c-}f_{LO})t) + P_{m,X}(t) - P_{LO}(t)] \quad (8)$$

Where electrical power of received in-phase and Quadrature component is X_I, X_Q respectively, launched power of local oscillator L_{LO}, P_{LO}phase of oscillator and frequency of local oscillator is f_{LO}, photo diode responsivity is R.

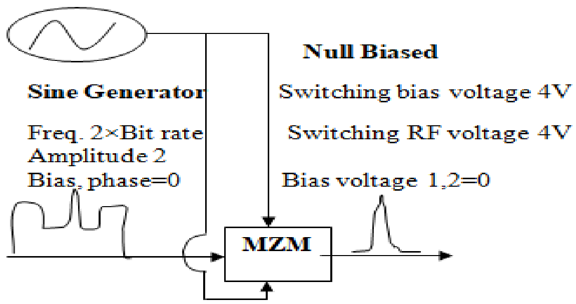


Figure 1 Generation of DSS carrier

With an RF signal (sine generator) having frequency 2 × bitrate, amplitude 2, phase 0, and bias 0, a LiNbO3 dual drive modulator with parameter switching bias voltage and RF voltage 4V is utilized to suppress the double sideband. DSS is to improve spectral efficiency and reduce sidebands that appear after OFDM modulation is employed as shown in Figure 1.

3. SYSTEM SETUP

For the implementation of proposed work, Optisystem is considered and system diagram is depicted in Figure 2 (a). Total 16 channels each at 100 Gbps at channel spacing of 100 GHz and modulated with DSS-DP-QPSK from frequency 192.4 THz to 193.9 THz.

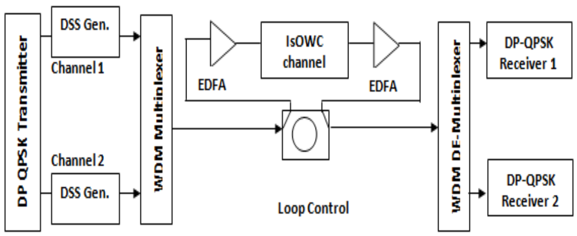


Figure 2 (a) Proposed 100 Gbps/λ WDM-IsOWC system using DSS-DP-QPSK

Internal structure of DP-QPSK is given in Figure 2 (b) which consists of pseudo random bit sequence generator which provide 100 Gbps serial bit stream, followed by serial to parallel convertor and QPSK modulator X and Y. Laser signal is divided into two parts and given to QPSK X modulator and Y modulator. Polarizations are combined by pol. combiner with polarization combiner.Each channel passed through DSS generation module and it is performed by using peak biased MZM and RF signal. Output of DP-QPSK transmitter is given to DSS generator having sine wave frequency of 300 GHz, switching bias voltage and RF voltage 4V, amplitude 2, phase 0, and bias 0. Conceptual diagram of DSS generator is already depicted in Figure 1.

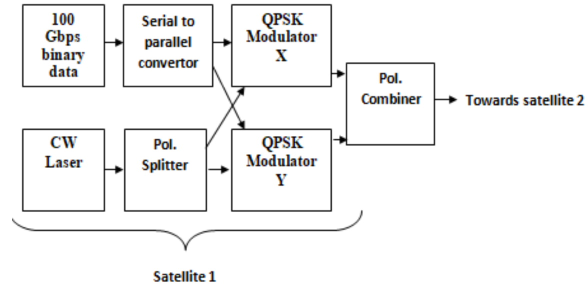


Figure 2 (b) Representation of internal structure of DP-QPSK and Transmissions channel

Combined signals are communicated from satellite to IsOWC channel as shown in Figure 2(c) which consists of amplifiers and IsOWC channel and signals received by satellite 2. Internal structure of receiver which has photodetectors PIN for the photons to electrons conversion and used balanced detection and Local oscillator synchronization. Noise such as shot and Quantum emerges in converted electrical signal and noise rectification is performed by passing signal through Low pass filters (Bessel Filter).

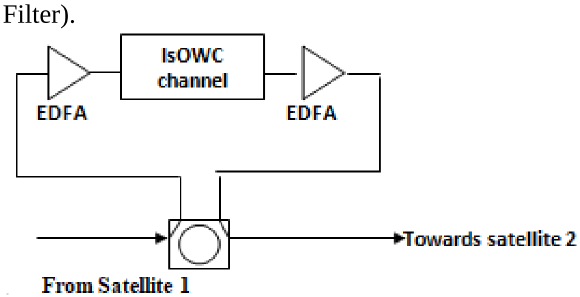


Figure 2 (c) Loop Control of IsOWC channel

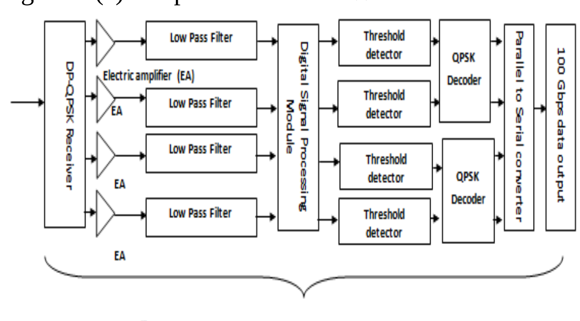


Figure 2 (d) Internal structure of DP-QPSK Receiver

Table 1 System specification of proposed 1.6 Tbps DP-QPSK system

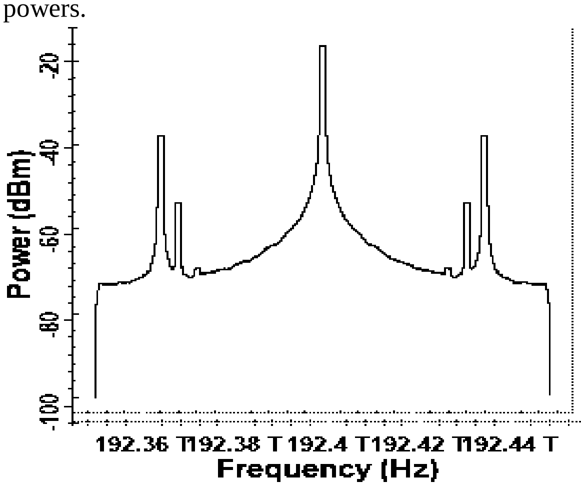
Parameters	Values
Data Rate	100 Gbps
Total capacity and Input Power	1.6 Tbps and 30 dBm
Starting Frequency and	192.4 THz and 100

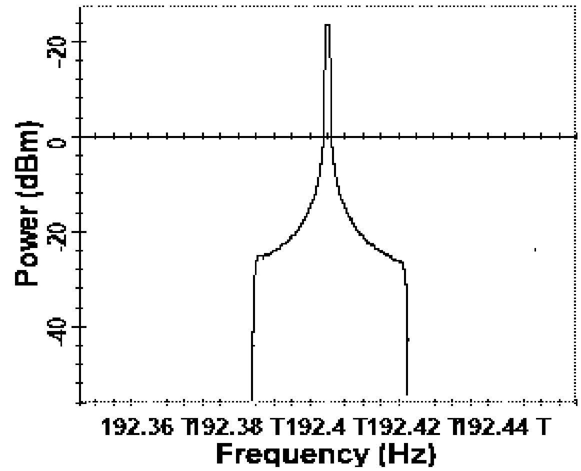
Spacing	GHz
Modulation	DSS based DP-QPSK
Symbol rate	25 Symbols/sec
Polarization States	2
Bits Per Symbol	2
Amplifiers	EDFA
IsOWC channel Length	11000 km – 16000 km
Transmitter and receiver Aperture Diameter	15 cm

Further carrier phase estimation, frequency offset estimation, dispersion compensation, nonlinear compensation, equalization and normalization is carried out by Digital signal processing (DSP) and followed by threshold detection, QPSK decoders, and BER test set as shown in Figure 2 (d) . Simulation parameters of proposed work are shown in Table 1.

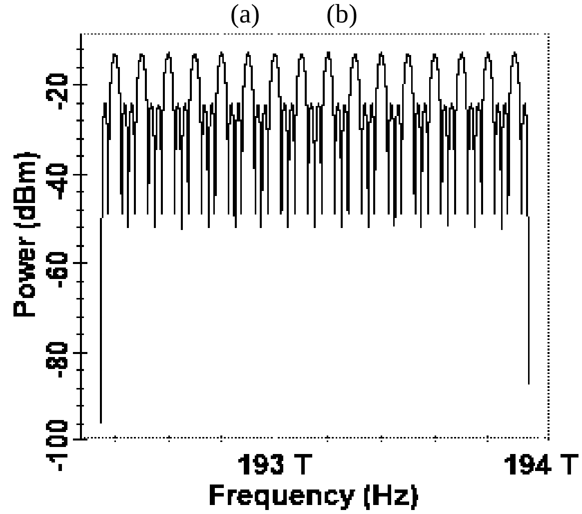
4. RESULTS AND DISCUSSIONS

In this section, the proposed DP-QPSK with DSS generation is discussed and investigated using Optisystem simulation software. For the simulation, the values of various parameters of the employed components are collected from real-world systems. Figure 3 (a) shows the optical carrier spectrum obtained at the end of the DP-QPSK, which has high power sidebands. In order to suppress sidebands, the DP-QPSK output is routed through a LiNbO3 modulator, which is driven by a sine generator. The RF frequency is 300 GHz, and sidebands are suppressed at the module's output, leaving only the carrier, as shown in Figure 3. (b). The power of sidebands can be adjusted when the RF frequency changes. Figure 3 (c) represents the carrier spectrums of 16 channels after multiplexer with their respective powers.





(a) (b)



(c)

Figure 3 Representation of carrier spectrums after (a) Transmitter (b) DSS generation (c) Multiplexer

Performance of different modulations such as QPSK, DP-QPSK, DP-QPSK-CO-OFDM and DSS-EC-DP-QPSK is analyzed in terms of log BER at varied distances from 11000 km to 16000 km as depicted in Figure 4. Results indicates that proposed DSS-DP-QPSK provide minimum bit errors as compared to other modulations in IsOWC system. Reason behind the best performance of DSS-DP-QPSK system is sidebands suppression which reduces the gain distribution on sidebands. Moreover DSS also increase the bandwidth efficiency by narrowing the optical spectrum DP-QPSK. Comparison of modulations also reveals that QPSK alone experience highest errors of bits and values of log BER for all the modulations is given in Table 2.

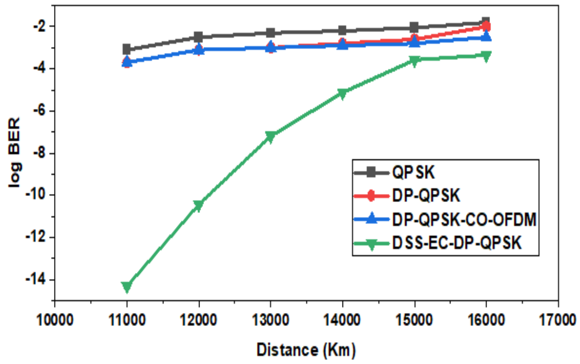


Figure 4 Effect of IsOWC distances on log BER for different modulations

Table 2 Values of Log BER at varied distances for QPSK, DP-QPSK, DP-QPSK-CO-OFDM and DSS-EC-DP-QPSK

Distance (Km)	QPSK	DP-QPSK	DP-QPSK-CO-OFDM	DSS-EC-DP-QPSK
11000	-3.1	-3.7	-3.7	-14.32
12000	-2.5	-3.1	-3.1	-10.44
13000	-2.3	-3	-3	-7.19
14000	-2.2	-2.8	-2.9	-5.13
15000	-2.05	-2.6	-2.8	-3.98
16000	-1.8	-2	-2.5	-3.35

Figure 5 shows the error vector magnitude percentage (EVM%) for investigated modulations at varied distance such as 11000 km, 12000 km, 13000 km, 14000 km, 15000 km and 16000 km. It is evident that symbols deviate from their ideal positions in the constellations as distance increases and percentage of EVM is termed as EVM%. Therefore, maximum EVM% is observed at 16000 km and minimum at 11000 km. Least EVM% is observed in proposed system and followed by DP-QPSK-CO-OFDM system as shown in Table 3.

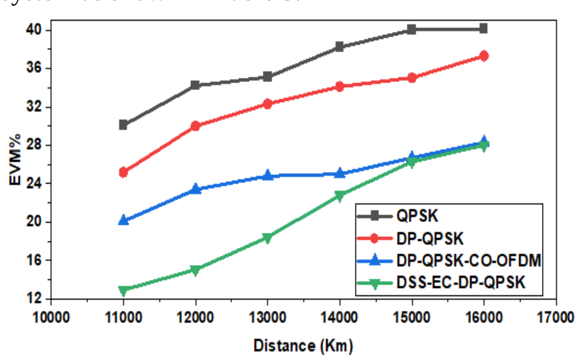


Figure 5 Performance of different modulations at varied IsOWC distance in terms of EVM%

Table 3 Values of EVM% at varied distances for QPSK, DP-QPSK, DP-QPSK-CO-OFDM and DSS-EC-DP-QPSK

Distance	QPSK	DP-QPSK	DP-QPSK CO-OFDM	DSS-DP-QPSK
11000	30.1	25.2	20.1	12.94
12000	34.2	30	23.4	15.06
13000	35.1	32.3	24.8	18.43
14000	38.2	34.1	25	22.8
15000	40	35.03	26.7	26.29
16000	40.1	37.3	28.3	28.02

Shot and quantum noise photo detectors are taken into account while analyzing received power. Maximum received power is observed in proposed system due to less gain distribution across the sidebands, and carrier with DSS amplifies more. This system also has a lower power penalty and a higher receiver sensitivity as shown in Figure 6. As a result, in the proposed system, the combined effects of DSS and DP-QPSK give high received power, followed by DP-QPSK with OFDM. Values of received powers in case of all the modulations at diverse IsOWC distance are presented in Table 4.

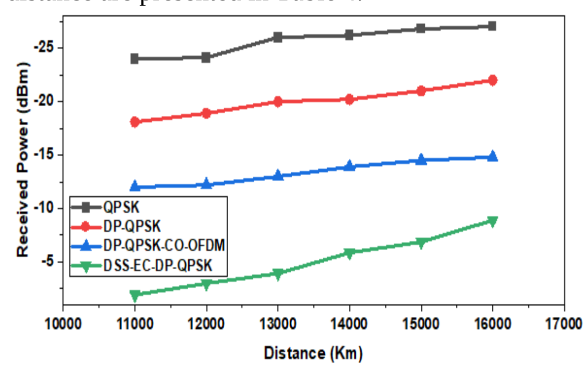


Figure 6 Received Power versus IsOWC distance for diverse modulations

Table 4 Values of Received powers at varied distances for QPSK, DP-QPSK, DP-QPSK-CO-OFDM and DSS-EC-DP-QPSK

Distance	QPSK	DP-QPSK	DP-QPSK - CO-OFDM	DSS-DP-QPSK
11000	-24	-18.1	-12	-1.93
12000	-24.1	-18.9	-12.2	-3
13000	-26	-20	-13	-3.93
14000	-26.2	-20.2	-13.9	-5.86
15000	-26.8	-21	-14.5	-6.88
16000	-27	-22	-14.8	-8.9

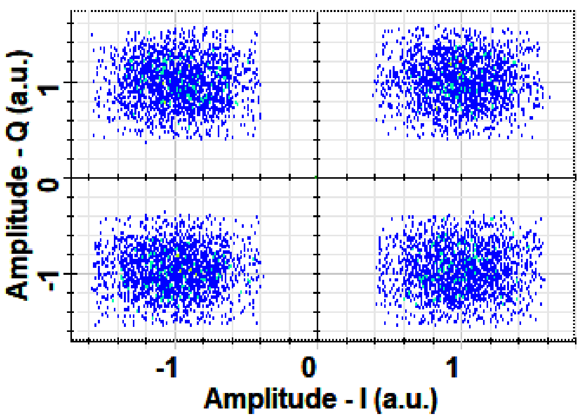


Figure 7 Constellation diagram of proposed DSS-DP-QPSK system at 16000 km IsOWC distance

Table 5 illustrates the greatest distance between satellites obtained at various data rates using various modulations. According to the author's best knowledge, the proposed technique can reach 16000 km at 100 Gbps and this is the maximum distance at 1.6 Tbps.

Table 5 Distance achieved by different modulations in IsOWC system

Data rate (Gbps)	QPSK (km) [15]	DP-QPSK (km) [15]	DP-QPSK with CO-OFDM [15]	DSS-DP-QPSK [proposed]
10	34,800	48,000	55,000	57,000
20	27,600	34,800	37,000	38,500
40	20,700	24,900	27,500	28,300
100	1,3200	14,500	15,600	16,000
200	9,300	10,900	12,000	12,200

Further, a comparison between existing work in (15) is listed in Table 6 at different system assessment parameters such as speed, capacity. Modulations, log BER, received power, and maximum distance. It is observed that proposed system better than all other investigated modulations in IsOWC system.

Table 6 Comparison of Existing work and Proposed work

Parameters	Existing Work [15]	Proposed Work
Data Rate	100 Gbps	100 Gbps
Capacity	1.6 TBPS	1.6 TBPS
WDM Channels	16	16
Technique used	CO-OFDM-DP-QPSK	DSS-DP-QPSK
comparison and techniques	QPSK,DP-QPSK,CO-OFDM-DP-QPSK	CO-OFDM-DP-QPSK,DP-QPSK,QPSK
log BER @ 15600 km	-2.6 For CO-OFDM-DP-QPSK	-3.9 for DSS-EC-DP-QPSK
EVM % at 15600km	27.2	26.40
Recieved power at 15,600 km	-14.8	-7.20
Maximum distance	15,600 km	16000 km

5.CONCLUSION

In this work, using DSS optical carrier and DP-QPSK at 100 GHz frequency spacing, a high capacity 16 × 100 GbpsIsOWC system is proposed. DSP is used to control carrier phase estimation, frequency offset estimation, nonlinear correction, and dispersion in the system. The DSS generation unit was used to suppress sidebands in the optical carrier, and the peak point and RF signal were generated using LiNbO3 MZM. Proposed system has covered the maximum 16000 km link distance using DSS, and DSP. While DP-QPSK-CO-OFDM system can covered 15,600 km, DP-QPSK achieved 14,500 km and QPSK attained 13,000 km distance at 30 dBm input power and targeted FEC log BER of -2.42. Also EVM% is minimum in case of DSS-DP-QPSK and received power is maximum. As a result, it is clear that the inclusion of DSS generation in the proposed system significantly improved performance. Integration of mode division multiplexing in the suggested system can be done in the near future to reduce the number of laser sources and lower the system's cost.

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