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PAPERS

Performance investigation of long-haul high data rate optical OFDM IM/DD system with different QAM modulations

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In this paper and as a first time, we have designed and simulated 100 Gbps long haul intensity modulation and direct detection (IM/DD) optical orthogonal frequency division multiplexing (OFDM) system with high order modulation techniques by using optisystem software QAM IM/DD OFDM system was analyzed and simulated to provide high data rate for downstream signal by using dispersion compensation fiber (DCF) inside fiber link. 4-QAM OFDM system demonstrated the best BER performance compared to other simulated systems for long haul transmission distance. For comparison and investigation, important results as eye diagram, Q factor, Eb/No and BER are explained against propagation length for every simulated system.

K e y w o r d s: intensity modulation and direct detection (IM/DD), orthogonal frequency division multiplexing (OFDM), quadrature amplitude modulation (QAM), bit error rate (BER)

1 Introduction

OFDM is a multicarrier modulation technique that divides a high data rate modulating stream into a subsequence of symbols with each symbol of a subsequence modulating a subcarrier [1,2]. Recently, optical OFDM is considered as a promising technology for long-haul high-data rate optical transmission systems by adding cyclic prefix that avoided inter-carrier interference (ICI) and inter symbol interference (ISI) [3-5]. Quadrature amplitude Modulation (QAM) with OFDM technique increases both the capacity and efficiency of optical systems to support high data rate and low bit error rate (BER). Intensity modulation/direct detection (IM/DD) system is a cost-effective optical communication system which finds wide applications in free-space optical communication, indoor visible light communication, light based underwater wireless communications and optical wireless OFDM communications [6-10].

IM/DD system consists of two main components such as Mach-Zehnder Modulator (MZM) at the transmitter and photodetector (PD) at the receiver [11]. This system is considered a cost-effective system compared to coherent detection OFDM (CO-OFDM) which uses another optical source (local oscillator) at the receiver so this system is very simple and is not complicated to implement [12-14]. In IM/DD optical system, the information can be positive (unipolar) due to carry on the intensity of the optical signal compared to non-optical OFDM system that carries the information on the electrical field so the signal will be both positive and negative values (bipolar) [15].

1.1 Related works

According to previous researches, 16-QAM OFDM wavelength-division-multiplexing (WDM) passive optical network (PON) and direct detection were simulated for downstream data rate of 10 Gbps, upstream data rate of 2.5 Gbps and propagation length of 70 km [16]. Performances of both CO-OFDM and long-haul 100-Gb/s DDO-OFDM [17] WDM systems were compared by simulation. System parameters were chosen to get a good performance and low cost WDM OFDM system such as laser linewidth launched power and system dispersion tolerances [18]. In [19], performance of Radio over Fiber (RoF) systems with an IM/DD technique were presented. Simulation results of these systems using direct and external modulations with a MB-OFDM signal were described. In [20], proposed optical (PO-OFDM) is considered as a new type of intensity optical OFDM modulations that was presented and compared with other systems such as DC biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical orthogonal frequency division multiplexing (ACO-OFDM). Hermitian symmetry method [21] is used to convert the complex signal to real and positive signal. In [22], OFDM IM/DD system with different modulation techniques was demonstrated such as QAM and Phase Shift Keying (PSK). 16-QAM and 16-PSK modulation with different number of subcarriers was applied to IM/DD system to achieve the best bit error rate (BER) performance. According to best BER, the downstream data rate and transmission distance were chosen to be 10 Gbps and 100 km, respectively. After comparing other modulation, IM/DD system with 16-QAM and 128 subcarriers achieved the best BER performance.

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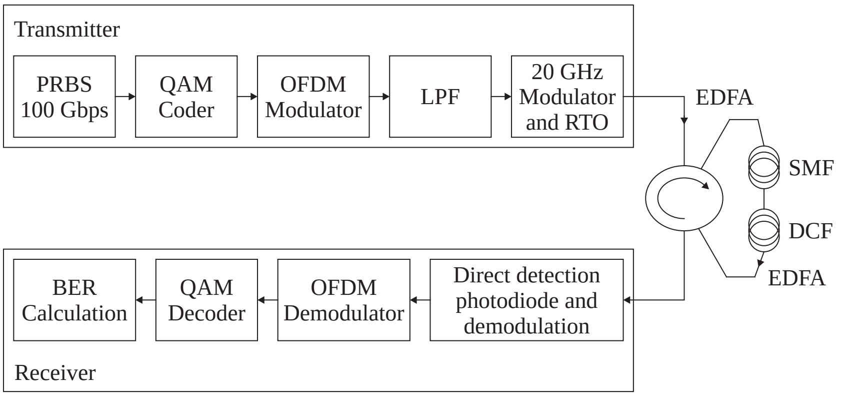

Fig. 1. OFDM IM/DD system block diagram

Table 1. Main parameters of OFDM modulator

Parameter Name	Value
Subcarrier numbers	512
FFT points	1024
Position array	256
Cyclic prefix	100 symbol extension
DAC interpolation	Cubic
Number of training OFDM symbols	2

Table 2. Main simulation parameters

Optisystem Global parameters	Value
Bit rate	100 Gbps
Sequence length	32768 to 65536
Samples per bit	2 to 8
Number of samples	65536 to 262144

1.2 Contributions and novelties of the paper

The list of essential contributions and novelties ensured by this paper is as follows

- IM/DD OFDM system with 100 Gbps data rate and different QAM orders are designed by Optisystem software [23] and compared to achieve the best BER performance
- According to QAM order, propagation length changed to show its effect on BER values and other parameter results are showed such as Q factor, constellation diagram and signal spectrum:
- Dispersion compensation fiber (DCF) is used to improve the transmission performance of designed systems.
- As a result, IM/DD system with using 4 QAM achieved the best BER performance for long haul transmission channel.

We describe the system model, simulation results and the discussion are given.

2 System model and description

The block diagram of our system is shown in Fig. 1. The system architecture and simulation results were designed and simulated on OptiSystem software. At central office, digital bits are generated from the BER test set that has a global bit rate of 100 Gbps as a reference bit rate of system. The number of subcarriers is 512 and the number of FFT points is 1024 so the generated bit rate is 50 Gbps by BER test set. The main Optisystem simulation parameters and OFDM modulator parameters are given in Tab. 1 and Tab. 2. To avoid ISI between OFDM symbols, cyclic prefix of 100 is inserted for each OFDM symbol after IFFT.

QAM sequence generator is used to convert generated bits into symbols according to the number of bits per symbol. M-ary sequence generator converts the generated symbols to multilevel pulses. In OFDM modulator, QAM symbols are modulated into multiple orthogonal sub-carriers. However, the numbers of subcarrier must be half of Fast Fourier Transform (FFT) points. Lower-rate subcarrier tones will take frequency ranges from 0 to 12.5 GHz. The position array in OFDM modulator is used to specify the locations of subcarriers being used and it must be half of the number of total subcarriers. Then, $I-Q$ OFDM modulated signals will pass to low pass filter that has cutoff frequency of (0.65 $\times$symbol rate). Quadrature modulator is used to raise the frequency of OFDM signals up to 20 GHz. MZM (Mach-Zehnder modulator) is used to modulate the RF electrical signal to the optical domain by using continues wave laser at 193.1 THz and power of 2 dBm. MZM is operating at quadrature point because of the applied voltage to its arms equal to half switching RF voltage. Table 3 and 4 summarize the parameters of CW laser and PIN photo detector, respectively.

After MZM, the optical signal is amplified by using optical amplifier that has 10 dB gain and 4 dB noise floor as main parameters. The resulting optical signal is then transmitted over (50+10$\times$Number of loops) km SMF with a dispersion of 16 ps/nm/km, attenuation of 0.2 dB/Km, a nonlinearity coefficient of 2.6×10^{-20} and a dispersion slope of 0.08 ps/nm^2/km. DCF is used to

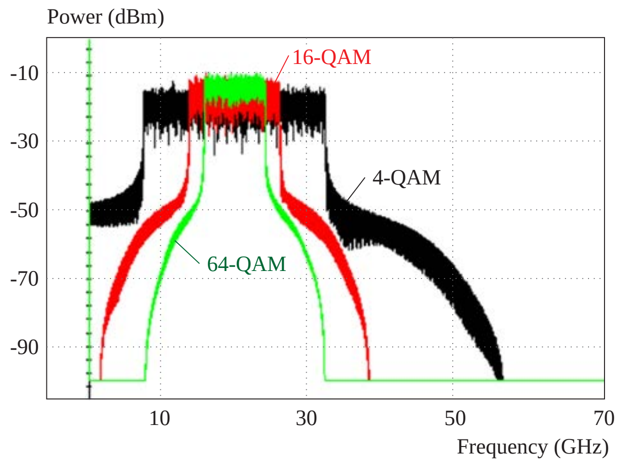

Fig. 2. Transmitted electrical OFDM spectrum of 4-QAM, 16-QAM and 64-QAM after quadrature modulator

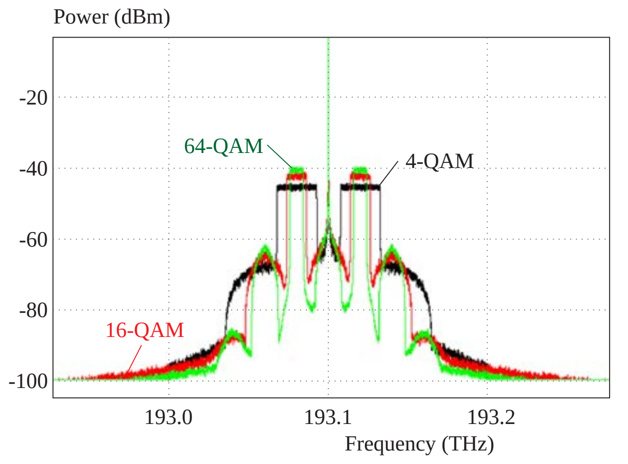

Fig. 3. Transmitted optical OFDM spectrum of 4-QAM, 16-QAM and 64-QAM after MZM

Table 3. CW laser specifications

CW laser parameters	Values
Centre frequency	193.1 THz
Power	2 dBm
Linewidth	0.1 MHz
Phase	0

Table 4. PIN Photodetector specifications

PIN photodetector parameters	Values
Responsivity type	InGaAs
Dark current	10 nm
Shot noise distribution	Gaussian

compensate dispersion that occurred from the main optical fiber and to improve the performance of transmission. Inside the loop, the value of DCF is calculated according to the length of main optical fiber that equals to 50 km so DCF length and dispersion are chosen to be 10 km and -83.75 ps/nm/km, respectively. Another amplifier that located inside the loop is used to amplify the optical signal and to compensate for the loss. The amplified optical signal is filtered by using Gaussian optical filter that has central frequency of 193.1 THz and bandwidth of 70 GHz.

At the receiver part, PIN photodetector converts the optical signal to an electrical signal. The PIN photodetector has a dark current of 10 nA, a thermal power density (15×10^{-24}W/Hz) and a center frequency of 193.1 THz. Electrical amplifier is used to amplify the received electrical signal. Quadrature demodulator is used to down convert and recover the amplified signal to be in range 0 and 12.5 GHz. OFDM modulator and demodulator parameters are same in order to recover the transmitted QAM symbols correctly. Finally, the QAM sequence detector decode the received symbols to bits according to bits per symbol. BER test set is used to evaluate BER and its log.

3 Simulation results and discussion

Our system is simulated and analyzed for different QAM orders versus propagation length by using Optisystem software as shown in Fig. 1. QAM coding is used to generate symbols and is considered the best coding compared to others. Different QAM orders are used to make a fair comparison and are applied to IM/DD OFDM system to check the transmission performance and improve system budget. The laser linewidth is set to 0.1 MHz and its power to 2 dBm to minimize the effect of fiber nonlinearity. Number of loops are changed according to the effect on transmission performance and BER results so our aim is to find the optimum propagation length to achieve BER of 10^{-3}.

Figure 2 shows the transmitted electrical OFDM spectrum of the system at center frequency 20 GHz for every QAM order after quadrature modulator. As shown in Fig. 2, the bandwidth of the signal decreases as the number of bits per symbol increases so it approximately equals to 25 GHz, 13 GHz and 9 GHz, respectively. The main parameters of quadrature modulator are frequency, gain and bias. Bias of quadrature modulator is set to be 2 to avoid negative values of OFDM signal. The generated electrical OFDM signal must be positive and real in all simulated systems.

Figure 3 shows the transmitted OFDM optical spectrum of different QAM orders after MZM that has main parameters such as extinction ratio of 30 dB, switching RF voltage of 4 volt and bias voltage of 2 volt. MZM architecture consists of one input optical arm that can split the incoming light into two parts then they are modulated with two incoming electrical signals and recombined by the output optical branch. MZM's are generally operated

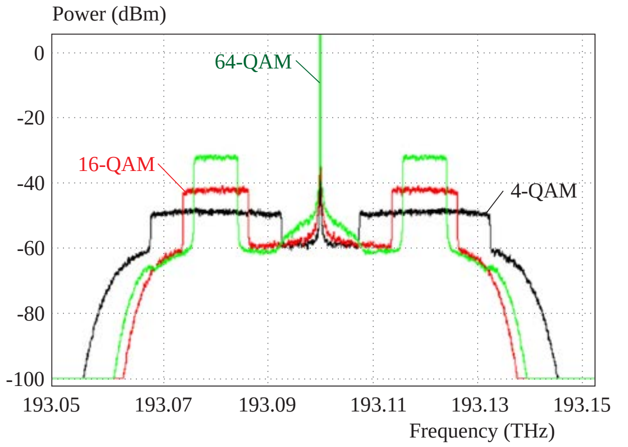

Fig. 4. Received optical OFDM spectrum of 4-QAM, 16-QAM and 64-QAM after Gaussian optical filter

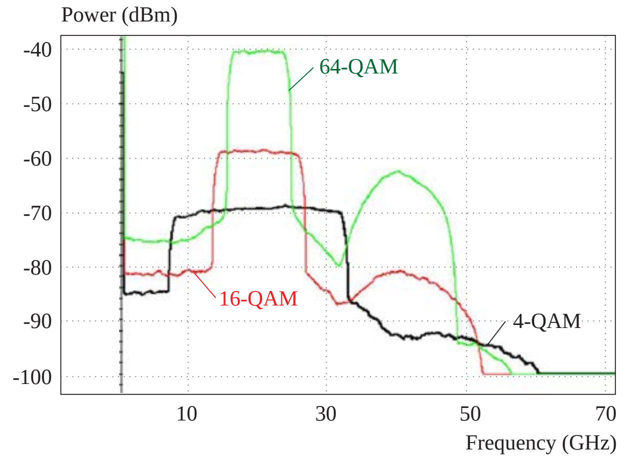

Fig. 5. Received electrical OFDM spectrum of 4-QAM, 16-QAM and 64-QAM after PIN photodetector

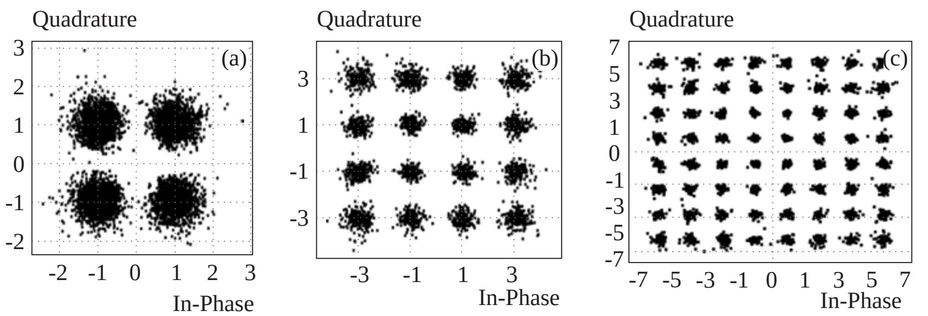

Fig. 6. Constellation diagram of received (a) 4-QAM, (b) 16-QAM and (c) 64-QAM

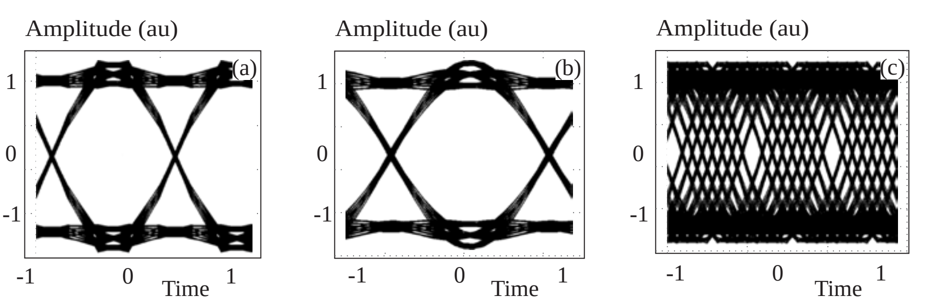

Fig. 7. Eye diagram of received (a) – 4-QAM, (b) – 16-QAM and (c) – 64-QAM

at three bias points such as peak, null and quadrature. According to bias value of quadrature modulator, MZM is operated on quadrature point. Different values of bias voltages that are applied on MZM equal to half the value of switching RF voltage.

This transmitted signal is amplified by optical amplifier before passing to the channel. The amplified signal is transmitted over the channel that consists of SMF optical fiber, DCF and optical amplifier. The transmitted signal passed through a loop to increase the propagation length. Figure 4 shows the received optical OFDM spectrum after passing through Gaussian Optical Filter that is used to decrease the noise channel and cut side lobes. Center frequency of gaussian optical filter is still constant and equal to 193.1 GHz but its bandwidth is changed according to the order of QAM.

Figure 5 shows the received electrical OFDM spectrum of the system at center frequency 20 GHz after PIN photodetector. Responsivity of PIN photodetector is chosen to be InGaAs that is preferred for high frequencies. The center frequency of modulated electrical signal is 20 GHz as shown in Fig. 5 and the bandwidth of it changes according to QAM order.

The received signal is amplified by electrical amplifier that has gain of 16 dB. Quadrature demodulator is used to demodulate the received electrical signal, convert it from high frequency to low frequency and extract $I-Q$ signal. $I-Q$ demodulated signal is filtered by using low pass cosine roll off filter. OFDM demodulator is used to

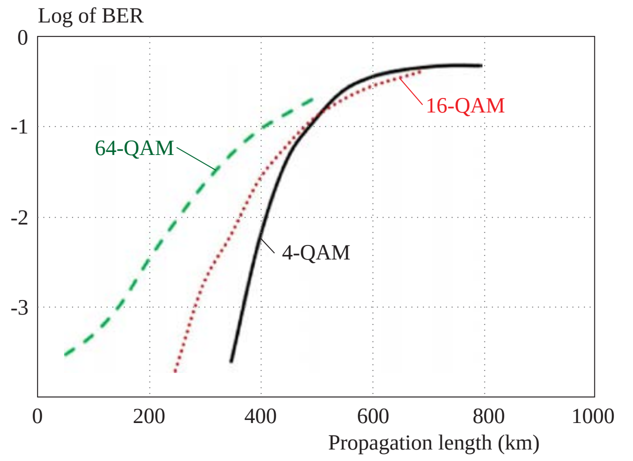

Fig. 8. BER results of received different QAM orders at different propagation length

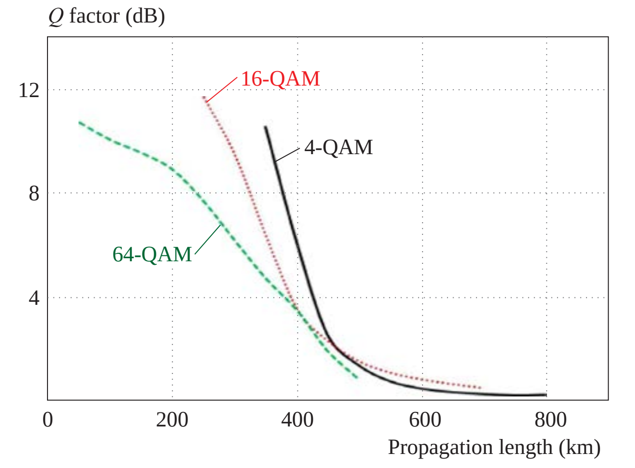

Fig. 9. Q factor results according to propagation length for simulated systems

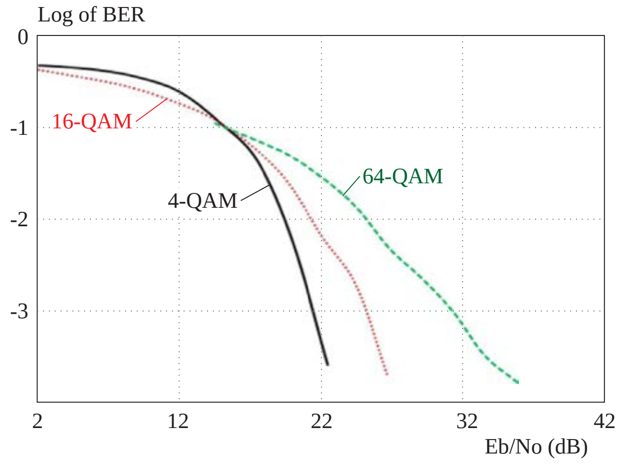

Fig. 10. BER as a function of Eb/No for all simulated systems

modulate $I-Q$ demodulated signal into multiple orthogonal sub-carriers. QAM sequence decoder is used to decode demodulated OFDM signal to a binary signal. BER test set is used to calculate BER results that compare the transmitted bits with received bits. Q factor, BER and Eb/No ratio are main measurement factors to calculate the system performance so Q factor is related to BER by using equation (1), [24]

$$BER = \frac{1}{\sqrt{2\pi}Q}\exp\left(-\frac{Q^2}{2}\right). \tag{1}$$

Figure 6 shows the constellation diagram of the received electrical signal for 4-QAM, 16-QAM and 64-QAM at propagation length of 400 km, 300 km and 150 km, respectively. While propagation length increases, the order of QAM decreases to obtain the best value of BER and constellation diagram as shown in Fig. 6. Energy per symbol to noise power spectral density and energy per bit to noise power spectral density are related to each other according to the following Equation (2) [25].

$$\frac{E_s}{N_o} = \frac{E_b}{N_o}\log_2 M. \tag{2}$$

Eye diagram is used to calculate the combined effects of channel noise and ISI on the performance of a baseband pulse-transmission system. For minimum propagation length, Fig. 7 shows the eye diagram of 4-QAM, 16-QAM and 64-QAM, respectively. Eye opening can be represented by one-bit period and according to Fig. 7 the result of opening seems very clear.

For comparison, Fig. 8 shows propagation length in term with BER values. For example, using different QAM orders, maximum propagation length of every system can be obtained as 400, 300 and 150 Km at BER of 10^{-3}. 4-QAM IM/DD OFDM system achieved the best BER performance for long haul transmission system as shown in Fig. 8.

Figure 9 shows Q factor values against propagation length for different simulated systems. For all simulated systems, the maximum Q factor is evaluated to be 6, 9 and 9 dB according to BER of 10^{-3} and maximum propagation length. In Fig. 9, it is noted that 4-QAM IM/DD OFDM system satisfied the best Q factor value for long haul optical communication systems as Q factor of 6 dB

Figure 10 shows the relationship between BER and Eb/No for all simulated systems. At BER of 10^{-3}, Eb/No ratio increases as 20, 25 and 31 dB according to QAM order as shown in Fig. 10. E_b/N_o of 4-QAM system is lower than 64-QAM system by 11 dB as shown in Fig. 10. The simulation results are summarized in Tab. 5.

Referring to Tab. 5, the optimum value of propagation length is obtained to achieve BER of 10^{-3} for all simulated system. It can be seen that 100 Gbps IM/DD OFDM system achieved the best simulation results for 4-QAM at long haul transmission. DCF is used to improve the system performance, increase the transmission bit rate and compensate the dispersion of fiber channel. These simulation results are acceptable and reliability in optical communication.

Table 5. Propagation length, Q factor and Eb/No and $BER = 10^{-3}$ for different QAM orders in 100-Gb/s OFDM IM/DD system

QAM order	Propagation length (km)	Q factor	Eb/No (dB)
4-QAM	400	6	20
16-QAM	300	9	25
64-QAM	150	9	31

4 Conclusion

We have designed and investigated cost effective OFDM IM/DD system with different QAM orders (such as 4-QAM, 16-QAM and 64-QAM). IM/DD systems do not need another laser at the receiver like Coherent Detection OFDM systems. A 100 Gbit/s 4-QAM intensity modulated direct modulation OFDM system has been transmitted over 400 km SMF and achieved BER of 10^{-3}. At BER of 10^{-3}, 16-QAM and 64-QAM OFDM systems achieved the best simulation results at propagation length of 300 and 150 km, respectively. Dispersion compensation fiber DCF is considered as a good method to improve the system performance. Eye diagram, Q factor and Eb/No results are explained against propagation length for every simulated system. These systems are simulated and analyzed to achieve high performance and cost effective long-haul 100-Gbps optical OFDM IM/DD system.

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