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Performance Investigation of NRZ-DQPSK, CSRZ-DQPSK and MDRZ-DQPSK Modulation Techniques for 450 Channel UD-WDM System for Long Haul Communication

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In this paper, we have designed a 450-channel Ultra Dense-Wavelength Division Multiplexing (UD-WDM) system with a bit rate of 100 Gb/s per channel and channel spacing of 0.1 nm based on three spectral efficient advanced modulation techniques named Non-Return-To-Zero Differential Quadrature Phase Shift Keying (NRZ-DQPSK), Carrier Suppressed Return-To-Zero Differential Quadrature Phase Shift Keying (CSRZ-DQPSK), and Modified Duobinary Return-To-Zero Differential Quadrature Phase Shift Keying (MDRZ-DQPSK). The performances of all three modulation techniques mentioned above are investigated using various investigation parameters. We have also demonstrated the experimental setup for measuring attenuation and dispersion under the effect of various linear and nonlinear impairments. Along with the experimental setup, the simulation is performed using optisystem software and the simulation results indicated that the MDRZ-DQPSK modulation technique outperformed the other two modulation techniques. The maximum Quality-Factor (Q-factor) value of 11.3 dB and minimum Bit Error Rate (BER) value of 10^{-11}, minimum eye closure value of 1.44 dB, and minimum probability of error of 0.36 have been reported for MDRZ-DQPSK modulated system when varying distance has been taken into consideration. The maximum receiver sensitivity of −16 dBm, minimum received crosstalk value of −8.8 dB and maximum Q-factor value of 12.6 dB have been reported with varying numbers of channels. The maximum Q-factor of 13.6 dB, minimum BER value of 10^{-13}, and maximum output power of −38 dBm have been reported with varying input powers. The utilization of a large number of channels in this study enables unprecedented increases in data transmission speeds that were previously unattainable.

Keywords: Attenuation, Crosstalk, Dispersion, Eye closure, Q-factor

Introduction

We live in a world where the need for high-speed internet is increasing daily in every field like entertainment, work, education, and e-commerce due to the growth of various digital services, such as online streaming, video conferencing, and online gaming.[1] The solution to handle this continuously growing demand for the internet is the use of optical fiber communication systems. Optical fiber communication systems offer a range of benefits such as higher bandwidth, less attenuation, lower power consumption, and immunity to electromagnet interference, making them an ideal solution for providing high-speed internet to users. They enable faster data transfer rates, and more reliable connections and are easily scalable to meet future demand.[2] Furthermore, the use of Ultra Dense-Wavelength Division Multiplexing (UD-WDM) technology along with optical fiber communication is an effective way to maximize the capacity and also efficiency of optical fiber communication systems, enabling faster data transfer rates, greater flexibility, and scalability while reducing overall costs.[3]

UD-WDM is a technology that allows for the transmission of multiple signals over a single fiber optic cable by using different wavelengths of light. A single fiber optic cable's bandwidth capacity can be considerably increased via UD-WDM. Transporting more data over the same physical infrastructure by using more light wavelengths is crucial for fulfilling the rising need for high-speed data transfer in our more interconnected world.[4] The UD-WDM technology packs its channels closely together at a few GHz and transmits them across long distances using optical fiber cable.

The suggested approach is especially helpful for offering a practical solution without adding more fiber connections to increase transmission capacity. It is important to consider several factors such as linear and nonlinear effects, optical input power, and

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transmission distance to create a UD-WDM system that maximizes capacity while minimizing resource usage. However, the performance of UD-WDM systems is constrained by phenomena such as dispersion and nonlinearities, which become more pronounced as the transmission distance and the number of channels increases. Specifically, when an optical pulse is transmitted through a fiber, it experiences delay and dispersion, leading to pulse spreading and negatively impacting system performance.[5] Several dispersion control solutions are available to address the challenges posed by dispersion and nonlinearities in wavelength division multiplexed networks. However, as the transmission capacity of optical networks is enhanced, higher signal strength is needed at the transmitter end to ensure an acceptable Bit Error Rate (BER) at the receiver end. This increased power level can lead to signal distortions and system degradation due to fiber nonlinearity. This, in turn, can result in the attenuation, interference, and distortion of the signals that need to be transmitted.[6]

For our research work, we have designed a UD-WDM system with 450 channels at a bit rate of 100 Gb/s and channel spacing of 0.1 nm. Furthermore, along with the UD-WDM system, spectral efficient advanced modulation techniques with multi-bit per symbol also play an important role in increasing the channel capacity and mitigating the effects of signal distortion caused by various linear and nonlinear transmission impairments, improving signal quality and boosting transmission rate.[7] There are so many multi-bit per symbol advanced modulation techniques in use nowadays. For our present research work, we have used three spectral efficient advanced modulation techniques namely Non-Return-To-Zero Differential Quadrature Phase Shift Keying (NRZ-DQPSK), Carrier Suppressed Return-To-Zero Differential Quadrature Phase Shift Keying (CSRZ-DQPSK), and Modified Duobinary Return-To-Zero Differential Quadrature Phase Shift Keying (MDRZ-DQPSK) for the transmission of data at high speed. Furthermore, to reduce attenuation, distortion, and interference during the transmission of optical data, it's crucial to choose the right optical amplifiers and channel spacing. Here, in this research work, we have used the Erbium-Doped Fiber Amplifier (EDFA) which can easily handle the attenuation problem and also the channel spacing of 0.1 mm is used. Numerous types of research have been done on the performance of Dense Wavelength Division Multiplexing (DWDM) systems based on advanced modulation techniques by many researchers in the past few years.

Ehsan *et al.*[8] proposed a transceiver system for 5G and beyond optical communication that is both cost-effective and reliable and has a high capacity. To achieve greater efficiency, the system uses various techniques, including DQPSK, CSNRZ modulation, duobinary coding, Radio over Fiber (RoF), and DWDM. The system demonstrated impressive results, achieving a data rate of 1.792 Tbps and a maximum transmission distance of 1600 km with a BER of 10^{-12}, even when using lower laser power of −10 dBm and a higher number of channels. Sharan *et al.*[9] described the design architecture of a 32-channel DWDM system, in which each channel utilizes multi-level phase modulation formats operating at 40 Gbps. The proposed system was simulated with a 50 GHz channel spacing to assess the performance of both Differential Phase Shift Keying (DPSK) and Differential Quadrature Phase Shift Keying (DQPSK) modulation formats in a high-speed DWDM setup. The study found that the DQPSK format, with a narrower spectrum and higher power levels, exhibited better tolerance to dispersion and nonlinearities compared to the DPSK format. Furthermore, Chaouch *et al.*[10] investigated the impact of neighboring channels, operating at 10 Gbit/s NRZ, 40 Gbit/s DPSK, and 40 Gbit/s DQPSK, on a central 100 Gbit/s PM-RZDQPSK probe. While the polarization effects were not considered, the findings revealed that the NRZ format, through cross-phase modulation (XPM), had the most harmful effect on the probe. As the number of channels and power per channel increased, the DPSK and DQPSK formats became more critical. Wang *et al.*[11] analyzed the suitability of NRZ- and RZ-DQPSK for 112 Gb/s dense wavelength division multiplexing (DWDM) transmission. The study found that RZ-DQPSK is more resilient to cascaded filtering, chromatic dispersion, and non-linearities than NRZ-DQPSK. Of these factors, cascaded filtering was identified as the most crucial issue, particularly for channel spacing of 100 GHz. Tomáš *et al.*[12] presented a comparison of the performance of a 16-channel DWDM system operating at 100 Gbps, utilizing both NRZ-DQPSK and CSRZ-DQPSK optical modulation techniques. The study found that CSRZ-DQPSK demonstrated higher tolerance to fiber nonlinear effects, which translates to improved resistance to nonlinear effects and better overall performance. Therefore, using CSRZ-DQSPK can lead to achieving higher performance and improved resistance to nonlinear effects. Gill *et al.*[13] presented a comprehensive approach to designing MDM in an Inter-Satellite Optical Wireless Communication (OWC) system using three different modulation systems: CSRZ-DQPSK, DRZ-DQPSK, and MDRZ-DQPSK. The system is designed for 64 channels with varying distances ranging from 900 to 4500 km and different data rates. The results show that MDRZ-DQPSK modulation outperforms DRZ-DQPSK and CSRZ-DQPSK modulation with a higher Quality factor of 19.42 at a bit rate of 10 Gbps, particularly for distances up to 4500 km. Chitravelu & Muthu[14] investigated the tolerance of Stimulated Brillouin Scattering (SBS) for two simple configurations of DQPSK transmitters and compares them with the standard three Mach-Zehnder Modulator (MZM) scheme. The results show that the two and one MZM-based CSRZ-DQPSK transmitters exhibit better SBS tolerance than the conventional three MZM transmitter. Moreover, these transmitters are capable of providing an improved BER at higher power levels. Alsowaidi *et al.*[15] determined the most effective modulation format for a hybrid optical CDMA/DWDM system utilizing an Electro-Optic Phase Modulator (EOPM) operating at a data rate of 40 Gbps per channel, with a transmitted power of 22 dBm and transmission distance of 105.075 km. The study focused on three modulation formats, CSRZ, MDRZ, and RZ, and conducted numerical simulations to compare their performance. The results indicated that CSRZ is the optimal choice, outperforming MDRZ and RZ in terms of its ability to withstand optical fiber nonlinearity. Dhadhal *et al.*[16] investigated the use of MDRZ modulation in a DWDM long-haul communication system. They conducted the simulations for 32 channels, each with a data rate of 40 Gbps, and multiplexed with channel spacings of 80, 90, and 100 GHz, to achieve a total data rate of 1.2 Tbps. The simulation outcomes showed that the MDRZ modulation scheme with a 100 GHz channel spacing exhibited the highest performance. Pradhan *et al.*[17] enhanced the performance of a 16-channel fiber optic DWDM system with ultra-high capacity, by utilizing symmetrical dispersion compensation techniques and Dual-Polarization Quadrature Phase Shift Keying (DP-QPSK) modulation. Various advanced modulation schemes, including a Modified Duo-binary Return to Zero (MDRZ), Quadrature Phase Shift Keying (QPSK), and DP-QPSK, are evaluated for their efficacy in improving the system's performance. The simulations are conducted at a high data rate of 400 Gbps per channel.

Upon reviewing the literature, several limitations were identified regarding the investigation of system performance. These limitations included the number of channels utilized, transmission distance covered, modulation techniques employed, channel spacing, and the data rate per channel. In many instances, the investigations were conducted using a relatively small number of channels, covering limited transmission distances, and employing low data rates. As a result, the findings may not accurately represent the performance of systems operating under more challenging conditions. For our research work, we have designed a 450-channel UD-WDM system with a bit rate of 100 Gb/s per channel and channel spacing of 0.1 nm based on three spectral efficient advanced modulation techniques named NRZ-DQPSK, CSRZ-DQPSK, and MDRZ-DQPSK. We have also demonstrated the experimental setup for measuring attenuation and dispersion under the effect of various linear and nonlinear impairments.

Theoretical and Mathematical Analysis of the Proposed System

For our research work, we have designed a 450-channel UD-WDM system with a bit rate of 100 Gb/s per channel and channel spacing of 0.1 nm. UD-WDM stands for Ultra-Dense Wavelength Division Multiplexing, which is an advanced optical networking technology used to transmit large amounts of data over a single optical fiber. It is a variation of traditional Wavelength Division Multiplexing (WDM) technology, which uses different wavelengths of light to transmit multiple signals over a single optical fiber. UD-WDM technology increases the number of wavelengths that can be transmitted over a single fiber, allowing for higher data rates and greater capacity. This makes it possible to transmit terabits of data per second over a single fiber, which is essential for applications such as cloud computing, video streaming, and big data analytics.[18] Our current research work utilizes the three spectral efficient advanced modulation techniques named NRZ-DQPSK, CSRZ-DQPSK, and MDRZ-DQPSK. NRZ-DQPSK is a type of phase modulation that is commonly used in optical communication systems.

The NRZ encoding method means that the signal does not return to zero after each bit, which can simplify the transmitter design and reduce the complexity of the receiver. The differential encoding method helps to improve the noise tolerance of the signal. In NRZ-DQPSK, each data bit is represented by a pair of consecutive phase shifts, where the phase of the carrier signal changes by 0, 90, 180, or 270 degrees. The phase shift for each bit pair is determined based on the previous bit pair in the data stream, which is why it is called "differential" modulation. This helps to eliminate the need for a reference clock signal, which simplifies the receiver design. One of the main advantages of NRZ-DQPSK is its robustness to Polarization Mode Dispersion (PMD), which is a common issue in long-haul optical communication systems.[19] PMD is caused by variations in the polarization of the optical signal as it travels through the optical fiber, which can cause signal degradation. NRZ-DQPSK is less sensitive to PMD because it does not require a specific polarization of the optical signal. Another advantage of NRZ-DQPSK is its high spectral efficiency, which means that it can transmit more data over the same bandwidth compared to other modulation schemes. This makes it a popular choice for high-speed optical communication applications. The generation of the NRZ-DQPSK signal requires two modulation stages. So, two mach-zehnder modulators are used for generating NRZ-DQPSK signal. The NRZ-DQPSK signal with 33% and 67% duty cycle can be represented by Eqs (1) & (2) respectively[20]:

$$\mathrm{S_1(t)} = \sqrt{\frac{\mathrm{E_b}}{\mathrm{T}}}\,\mathrm{Sin}\left[\frac{\pi}{2}\left\{1 + \mathrm{Sin}\left(\frac{\pi \mathrm{t}}{\mathrm{T}}\right)\right\}\right] \quad \text{... (1)}$$

$$\mathrm{S_2(t)} = \sqrt{\frac{\mathrm{E_b}}{\mathrm{T}}}\,\mathrm{Sin}\left[\frac{\pi}{2}\mathrm{Cos}\left(\frac{\pi \mathrm{t}}{\mathrm{T}}\right)\right] \quad \text{... (2)}$$

where, E_b is the energy per bit and T is the time period of the signal. Also, the probability of error can be represented by Eq. (3) as[21]:

$$\mathrm{P_e} = \mathrm{Q_1(i,j)} - \frac{1}{2}\mathrm{K_0(ij)}\,e^{\frac{-(\mathrm{i}^2+\mathrm{j}^2)}{2}} \quad \text{... (3)}$$

where, Q_1 is first order Marcum function, K_0 is the modified Bessel function and the values of i and j are as follows:

$$\mathrm{i} = \sqrt{\left(2-\sqrt{2}\right)\frac{\mathrm{E_b}}{\mathrm{N_0}}} \quad \text{... (4)}$$

$$\mathrm{j} = \sqrt{\left(2+\sqrt{2}\right)\frac{\mathrm{E_b}}{\mathrm{N_0}}} \quad \text{... (5)}$$

where, N_0 is the power spectral density of noise and E_b is the energy per bit of the signal.

Furthermore, the other modulation technique which we have used here in our research work is CSRZ-DQPSK. CSRZ stands for Carrier Suppressed Return-to-Zero which is a format used for optical signals in which the carrier is suppressed, and the data is encoded as changes in the amplitude of the pulse. In CSRZ-DQPSK, the DQPSK modulation is applied to each sub-carrier in a DWDM system, and the CSRZ format is used to suppress the carrier.[22] This modulation technique is used in DWDM systems to increase the data capacity of the system by allowing multiple channels to be transmitted simultaneously over a single optical fiber. By using CSRZ-DQPSK modulation, a DWDM system can achieve high spectral efficiency, improved signal quality, and increased transmission distance. CSRZ-DQPSK is a preferred modulation format in DWDM systems due to its superior performance in terms of signal-to-noise ratio (SNR), chromatic dispersion tolerance, and polarization mode dispersion tolerance.[23] The suppression of the carrier in the CSRZ format helps to reduce the impact of the fiber dispersion and enables the transmission of signals over longer distances. In CSRZ-DQPSK modulation, a 4-level amplitude modulation is used to suppress the carrier and create the return-to-zero waveform. The sub-carriers are phase-modulated using DQPSK modulation, where each sub-carrier carries two bits of data per symbol.[24] The phase modulation of each sub-carrier is differentially encoded, which allows for better noise tolerance and simplifies the detection process at the receiver end. In the CSRZ-DQPSK modulation technique, the information bits in a combination of two bits per symbol are represented by the phase differences $\Delta\theta_i$ from symbol to symbol. There are different phase assignments between $\Delta\theta_i$ and logic dibits. The coding rules are as follows[25]:

$$\mathrm{C_I} = \left(\overline{\mathrm{I_m} \oplus \mathrm{Q_m}}\right)\left(\mathrm{I_m} \oplus \mathrm{C_{I-1}}\right) + \left(\mathrm{I_m} \oplus \mathrm{Q_m}\right)\left(\mathrm{Q_m} \oplus \mathrm{C_{Q-1}}\right) \quad \text{... (6)}$$

$$\mathrm{C_Q} = \left(\overline{\mathrm{I_m} \oplus \mathrm{Q_m}}\right)\left(\mathrm{Q_m} \oplus \mathrm{C_{Q-1}}\right) + \left(\mathrm{I_m} \oplus \mathrm{Q_m}\right)\left(\mathrm{I_m} \oplus \mathrm{C_{I-1}}\right) \quad \text{... (7)}$$

where, symbol $\oplus$ denotes exclusive OR operation. $I_m \in (0, 1)$ is the odd-numbered original information bit and $Q_m \in$ (0, 1) is the even-numbered original information bit, $C_I \in$ (0, 1) is the coded I-channel bit and $C_Q \in$ (0, 1) is coded Q-channel bit. To produce the absolute carrier phase, pair (C_I, C_Q) is used, which is produced with the help of pairs (I_m, Q_m) and (C_{I-1}, C_{Q-1}). The modulator is the same as the QPSK modulator except those two differential encoders must be included in each channel before the carrier multiplier. The BER for DQPSK signals can be calculated by using the formula given in Eq. (8). as[26]:

$$\mathrm{BER} \approx Q\left(\sqrt{\frac{4E_b}{N_o}} \sin\frac{\pi}{4\sqrt{2}}\right) \quad \dots (8)$$

where, E_b is representing the energy bit period and N_0 is representing the noise power spectral density. Furthermore, the other modulation technique which we have used here in our research work is MDRZ-DQPSK. MDRZ-DQPSK stands for "modified duobinary return-to-zero differential quadrature phase-shift keying". In MDRZ-DQPSK, two bits are transmitted simultaneously by using two orthogonal polarizations of light, with each polarization carrying a phase-modulated signal. The modulation of the signal is done using a modified duobinary encoding technique, which generates four levels of phase shift. These four levels are used to represent two bits of data, allowing for a higher data rate to be transmitted. MDRZ-DQPSK can be seen as an extension of the conventional duobinary modulation technique.[27] It uses a modified version of the duobinary encoding technique, which introduces additional phase shifts to create four levels of phase shift instead of the two levels used in conventional duobinary. The additional phase shifts allow for the encoding of two bits of data per symbol, which increases the data rate that can be transmitted. The use of differential encoding in MDRZ-DQPSK means that the receiver only needs to detect the phase shift between consecutive bits, rather than the absolute phase of each bit. This makes the system more robust against phase noise and other types of signal distortion. MDRZ-DQPSK has a great tolerance to chromatic dispersion and polarization mode dispersion compared to the other modulation techniques which make it more reliable for use in long-haul optical networks.[28] The modulator structure of the MDRZ-DQPSK modulation technique where MZM-1 and MZM-2 modulators are used to generate I and Q signal components having a phase shift of 90° with each other. The induced phase difference between the two arms of the modulator can be expressed by Eqs (9) & (10) as[29]:

$$\Delta\phi_I(t) = \frac{v_I(t)}{V_h}\pi \quad \dots (9)$$

$$\Delta\phi_Q(t) = \frac{v_Q(t)}{V_h}\pi \quad \dots (10)$$

where, $\Delta\phi_I(t)$ and $\Delta\phi_Q(t)$ are phase differences of I and Q signal components, $v_I(t)$ and $v_Q(t)$ are the applied voltage and V_h is the half-wave voltage. The transfer function of the IQ modulator is:

$$\frac{E_{out}(t)}{E_{in}(t)} = \frac{1}{2}\cos\left(\frac{\Delta\phi_I(t)}{2}\right) + j\sin\left(\frac{\Delta\phi_Q(t)}{2}\right) \quad \dots (11)$$

Using Eqs (9–11), it is possible to calculate amplitude modulation $A_{IQM(t)}$ and phase modulation $\phi_{IQM(t)}$ of IQ modulator as:

$$A_{IQM}(t) = \frac{1}{2}\sqrt{\left\{\cos^2\left(\frac{v_I(t)}{V_h}\pi\right) + \cos^2\left(\frac{v_Q(t)}{V_h}\pi\right)\right\}} \quad \dots (12)$$

$$\phi_{IQM}(t) = \arg\left[\cos\left(\frac{v_I(t)}{V_h}\pi\right),\ \cos\left(\frac{v_Q(t)}{V_h}\pi\right)\right] \quad \dots (13)$$

Furthermore, In UD-WDM systems, channel spacing also plays an important role. For proper transmission of multiple signals using WDM technology, proper channel spacing should be there to overcome intersymbol interference and crosstalk. The condition for minimum channel spacing between two channels can be expressed by Eq. (14) as[30]:

$$\Delta = 2\sqrt{\frac{(\alpha_1+\alpha_2)\rho}{\beta}} \quad \dots (14)$$

where, α_1 and α_2 are the attenuation factors of channel 1 and channel 2 respectively, β is the transmission coefficient, and ρ is the optical signal intensity. Furthermore, to avoid the attenuation and distortion of the signals, we have used EDFA amplifiers for our research work. Erbium-doped Fiber Amplifier (EDFA) is the most widely used optical amplifier in the DWDM-based optical communication systems that uses the Erbium-doped fiber as an optical amplification medium to directly boost the signals. Within essentially two bands, it allows for the immediate amplification of signals of various wavelengths. The first is the conventional, or C-band, having a range of wavelengths from 1525–1565 nm, and the second is the long, or L-band, with a wavelength range from 1570–1610 nm. It has two widely utilized pumping bands, 980 nm, and 1480 nm. The formula for calculating the gain of an EDFA amplifier is given by Eq. (15) as[31]:

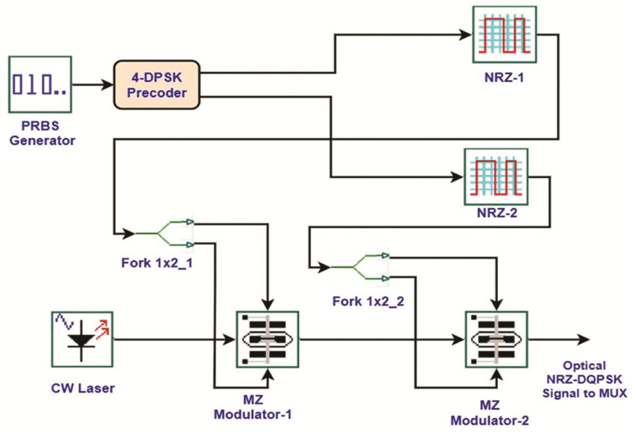

Fig. 1 — Block diagram for NRZ-DQPSK modulator

$$\mathrm{G_{EDFA}} = (\mathrm{P_{out}} - \mathrm{P_{ASE}})/\mathrm{P_{in}} \qquad \dots (15)$$

where, P_{in} and P_{out} are the input and output signal powers of the amplifier. P_{ASE} is the EDFA's ASE noise power. The noise figure is another parameter of EDFA, which is used to determine the degree of the signal-to-noise ratio of the amplifier and is defined as:

$$\mathrm{NF_{EDFA}} = 10\log\left(\frac{\mathrm{SNR_{in}}}{\mathrm{SNR_{out}}}\right) \qquad \dots (16)$$

where, $\mathrm{SNR_{in}}$ and $\mathrm{SNR_{out}}$ are the input and output signal-to-noise ratio respectively.

Modulator-Demodulator Architecture

Several spectral efficient multi-bits per symbol advanced modulation techniques are in use nowadays. For our present research work, we have used three such modulation techniques named NRZ-DQPSK, CSRZ-DQPSK, and MDRZ-DQPSK for data transmission at high speed. This section explains the block diagrams of the modulator and demodulator sections of all these modulation techniques along with the simulation setup of the designed UD-WDM system.

NRZ-DQPSK Modulator

The block diagram shown in Fig. 1 illustrates the structure of an NRZ-DQPSK modulator, which utilizes two arms of Mach-Zehnder Modulators (MZM) driven by in-phase and quadrature-phase signal components, with a phase shift of π/2 between them.

The modulator is designed to transmit data at a rate of 100 Gbps, which is generated by a Pseudo Random Bit Sequence (PRBS). The data is then precoded by a 4-DPSK precoder to prevent recursive decoding on the receiver side and finally shaped by an electrical Non-Return to Zero (NRZ) driver.[32] In the NRZ-DQPSK modulator, the information is conveyed by establishing the phase of a symbol relative to the phase of the previous symbol. On the other hand, QPSK conveys information by assigning an absolute phase to each symbol.

CSRZ-DQPSK Modulator

The block diagram of the CSRZ-DQPSK modulator, which is designed to provide a narrowed optical spectrum and high side lobe suppression is presented in Fig. 2. In communication systems, the DQPSK modulation technique is preferred over DPSK modulation because it offers higher spectral efficiency. The CSRZ-DQPSK modulator comprises a PRBS generator, which passes through a 4-DPSK precoder and is then used to drive two Non-Return-to-Zero (NRZ) pulse generators. These pulse generators are further used to drive two forks.

The first Mach-Zehnder (MZ) modulator is driven by the NRZ pulse generator, while the other MZ modulator is used for pulse carving. A continuous wave (CW) laser signal drives the two MZ modulators in a cascaded connection, and the third MZM is driven by a sine generator with a phase shift of 0o degrees. This configuration enables the CSRZ-DQPSK signal to be obtained. The CSRZ modulation technique performs well at lower bit rates, but when combined with DQPSK modulation, it provides a better Q-factor at higher bit rates. Overall, the CSRZ-DQPSK modulator is an effective solution for achieving a narrowed optical spectrum and high side lobe suppression in communication systems.[33]

MDRZ-DQPSK Modulator

The block diagram of the MDRZ-DQPSK modulator is illustrated in Fig. 3. Compared to NRZ-DQPSK and CSRZ-DQPSK modulation techniques, MDRZ-DQPSK provides a much narrower optical bandwidth and is more tolerant to dispersion. The modulator consists of a PRBS generator that generates a signal which is passed through a 4-DPSK precoder. The resulting signal is then split into two NRZ duobinary signals using delay and subtract circuits with time delay and electrical subtractor. These two signals are fed into two Mach-Zehnder modulators via a 1 × 2 fork and are concatenated with a third MZ modulator to achieve the MDRZ-DQPSK signal. MDRZ-DQPSK modulation technique offers several advantages, including better tolerance against nonlinear effects and the elimination of four-wave

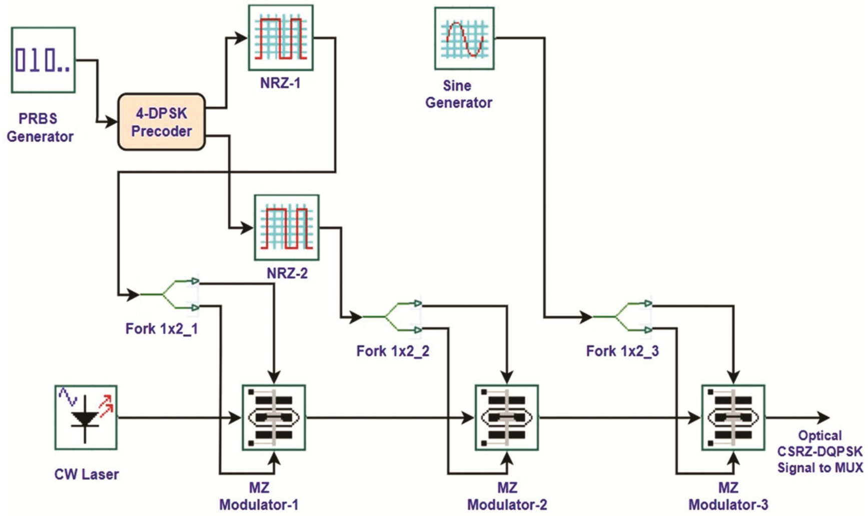

Fig. 2 — Block diagram for CSRZ-DQPSK modulator

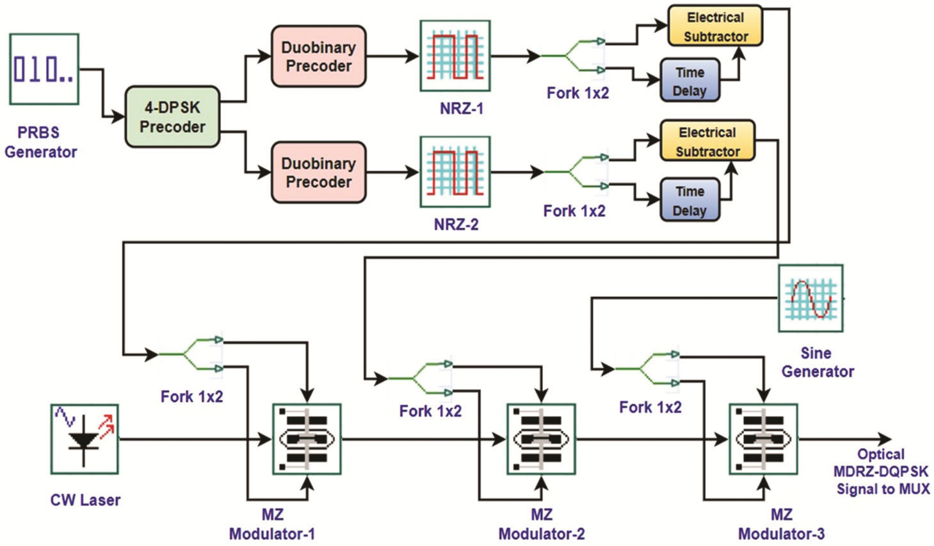

Fig. 3 — Block diagram for MDRZ-DQPSK modulator

mixing in the system, making it suitable for long-haul transmission systems. It supports a maximum Quality factor at high data rates and allows for higher launch powers compared to NRZ-DQPSK and CSRZ-DQPSK modulation techniques.[34]

Hybrid Demodulator

The block diagram of the hybrid demodulator for all three types of modulation techniques mentioned above for our research work is presented in Fig. 4.

Optical decoding of NRZ/CSRZ/MDRZ-DQPSK signals can be achieved using an optical delay and add interferometer arrangement. For simultaneous reception of both transmitted data streams, the decoder requires two Mach-Zehnder delay interferometers (MZDI) to match the phases of the I and Q branches, ensuring proper delay in the two arms and resulting in optical signal coherency and cancellation. The X-coupler-1 and X-coupler-2 are utilized to achieve this. Additionally, two balanced detectors, similar to DPSK demodulators, are required in the receiver to enable the upper and lower branches to execute the necessary phase separation of $\pi/4$ and $-\pi/4$. The system's performance is evaluated and measured using a BER analyzer connected to the regenerator.[35]

simulation and experimental setup

The block diagram in Fig. 5 depicts the simulation setup using optisystem software for a 450-channel

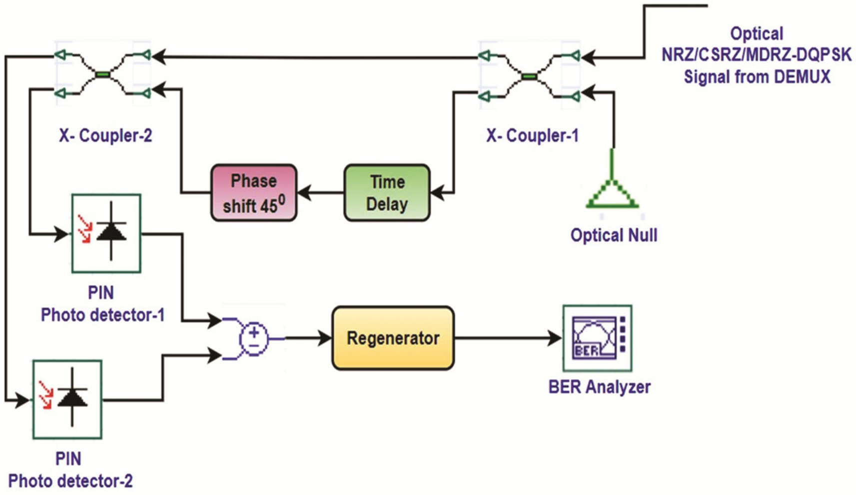

Fig. 4 — Block diagram for hybrid demodulator

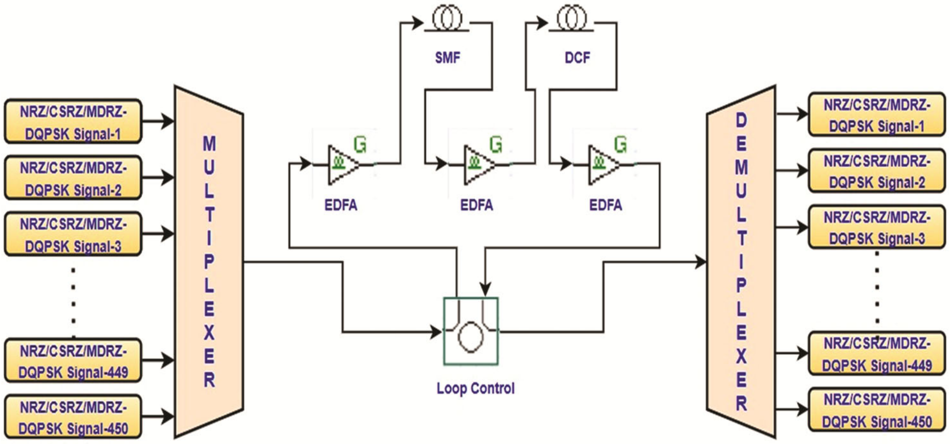

Fig. 5 — Block diagram for 450 channel UD-WDM system based on NRZ/CSRZ/MDRZ-DQPSK Modulation

UD-WDM system that utilizes NRZ-DQPSK, CSRZ-DQPSK, and MDRZ-DQPSK modulation techniques. It comprises three main sections: the transmitter section, the receiver section, and the transmission medium. In the transmitter section, 450 channels are modulated using the aforementioned techniques, resulting in 450 optical signals. These signals are then multiplexed into a single mixed signal using a dense multiplexer.

The mixed signal, consisting of 450 optical channels, is transmitted through a combination of Erbium-Doped Fiber Amplifiers (EDFAs) and optical fiber cables. The EDFAs amplify the optical signals at regular intervals along the fiber optic cable to ensure signal strength throughout the transmission. The high-speed transmission of 450 signals simultaneously is made possible through the use of dense multiplexing, which combines multiple signals into a single optical fiber. To ensure signal quality over long distances, multiple amplifiers are required, and in this system, three EDFAs are utilized. To cover a distance of 2000 km, the system employs 40 spans, with each span consisting of a 40 km long SMF and a 10 km long DCF, which helps reduce dispersion that can degrade signal quality. At the receiver end, the received signals are separated using a dense demultiplexer, and the individual signals are recovered using a demodulator arrangement. Transmitter section parameters are detailed in Table 1, while Table 2 provides relevant SMF and DCF parameters. The parameters for the receiver end are presented in Table 3. In summary, the system is designed to enable reliable and high-speed transmission of 450 signals over a distance of 2000 km, utilizing dense multiplexing, dispersion compensation, and multiple amplifiers.

Table 1 — Parameters of transmitter section

Parameters	Values
Transmission distance	2000 km
Modulation technique	NRZ/CSRZ/MDRZ-DQPSK
Data rate	100 Gb/s
Total number of channels	450
Wavelength	1587 nm
Amplifier used	EDFA
Applied input power	−4 dBm to 4 dBm
Channel spacings	0.1 nm
MZM extinction ratio	100 dB
EDFA gain	10 dB
EDFA noise figure	6 dB
CW laser noise threshold	−95 dB
CW laser noise dynamics	3 dB

Table 2 — Parameters of SMF and DCF

Optical fibers	SMF	DCF
Length of the fiber (km)	40	10
Attenuation per km (dB)	0.25	0.55
Dispersion (ps/nm/km)	17	−85
Maximum nonlinear phase shift (mrd)	3	3
Dispersion slop (ps/nm^2/km)	0.075	−0.3
Effective area (μm^2)	70	22
Differential group delay (ps/km)	0.2	0.2

Table 3 — Parameters of the receiver section

Parameters	Values
Responsivity of PIN photodetector	1 A/W
Dark current of PIN photodetector	10 nA
Coupling coefficient of X-coupler	0.5
Additional loss of X-coupler	0 dB
Phase shift	45°

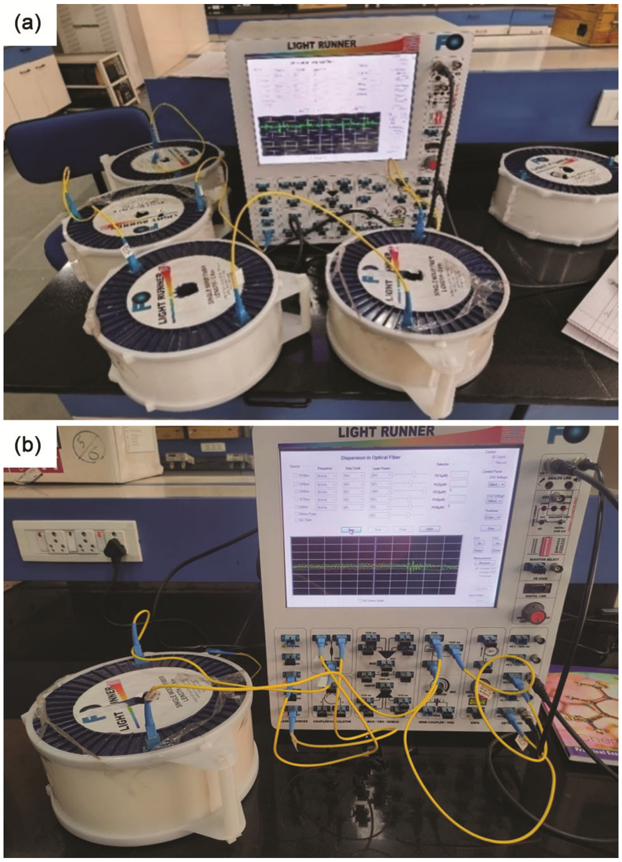

Fig. 6 — Experimental setup for measuring: (a) attenuation, (b) dispersion

Furthermore, in optical communication systems, various linear and nonlinear impairments can affect system performance and introduce attenuation and dispersion in the system. Attenuation refers to the loss of optical power as light propagates through the fiber, while dispersion refers to the spreading out of the optical pulse as it travels through the fiber.

To measure the effects of these impairments, the experimental setups are used as shown in Fig. 6(a) and Fig. 6(b) for measuring attenuation and dispersion respectively. Both setups include a transmitter, an optical fiber, and a receiver. The transmitter sends a modulated optical signal through the fiber, which is then received by the receiver.

Results and Discussion

We have developed a 450-channel UD-WDM system using optisystem software that utilizes advanced modulation techniques, namely NRZ-DQPSK, CSRZ-DQPSK, and MDRZ-DQPSK. Our system operates at a bit rate of 100 Gb/s per channel and has a channel spacing of 0.1 nm. To evaluate the performance of these modulation techniques, we examined various parameters such as BER, Q-factor, eye closure, received crosstalk, receiver sensitivity, probability of error, and received output power. We conducted experiments by varying the number of channels, transmission distance, and input power to test these parameters. The variation in Q-factor for the distance range of 200-2000 km for all the three modulation techniques i.e. MDRZ-DQPSK, NRZ-DQPSK, and CSRZ-DQPSK used for our simulation are illustrated in Fig. 7(a). The Q-factor is a crucial metric for evaluating the quality of an optical signal in a system and is calculated based on the signal-to-noise ratio (SNR). It is particularly important in UD-WDM systems, as it determines the maximum transmission distance and the number of wavelengths that can be combined. A higher Q-factor indicates a superior signal quality, enabling greater distances and more channels to be multiplexed. The statistical

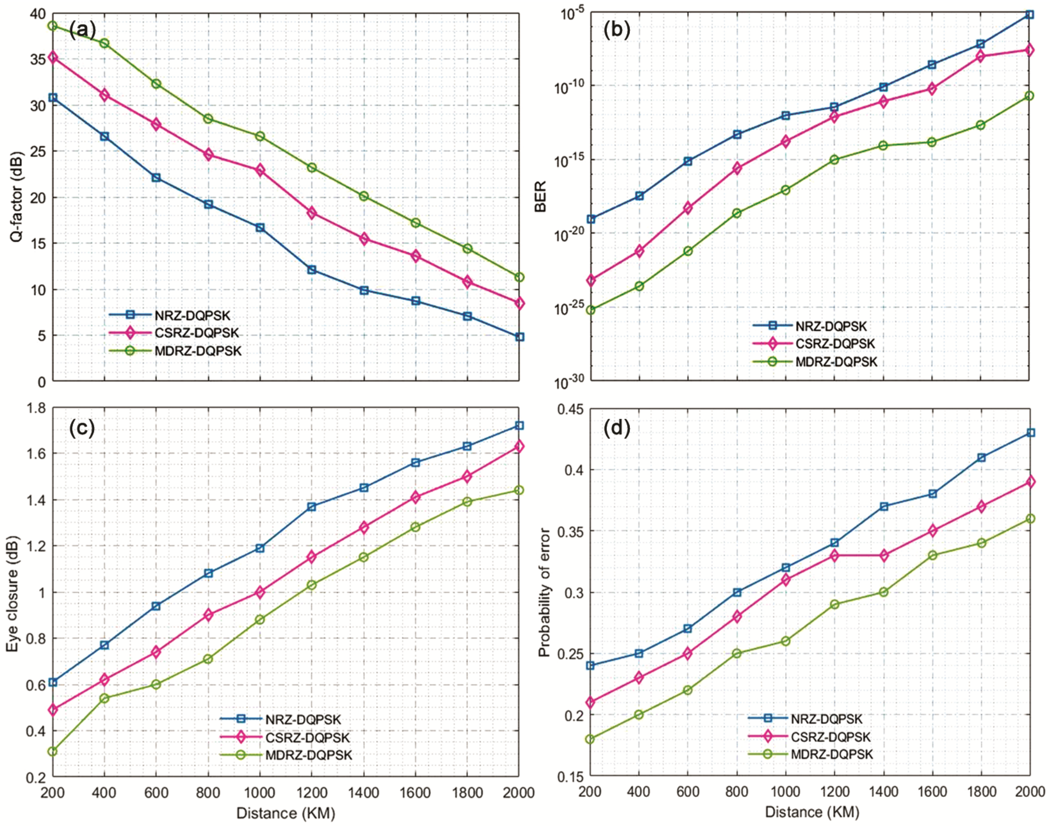

Fig. 7 — The variation in parameters against distance: (a) Quality factor, (b) Bit error rate (BER), (c) Eye closure, (d) Probability of Error

fluctuation of the received signal is represented by the quality factor (Q-factor) using the following Eq. (17) as[36]:

$$Q_{dB} = \frac{|\nu_0 - \nu_1|}{\sigma_0 - \sigma_1} \qquad \dots (17)$$

where, ν_0 and ν_1 are the mean and σ_0 and σ_1 are the received signal's standard deviation for binary data bit '0' and bit '1'. The Q-factor in terms of BER may be represented by Eq. (18) as follows[37]:

$$Q_{dB} = 20 \log \left[2^{\frac{1}{2}} \operatorname{erfc}^{-1} (2 \text{ BER})\right] \qquad \dots (18)$$

It is evident from Fig. 7(a) that MDRZ-DQPSK modulation outperformed the other two modulations in terms of Q-factor. As the distance increased, the Q-factor for all three modulations decreased, but the decline was more gradual for MDRZ-DQPSK. The Q-factor values for MDRZ-DQPSK vary from 38.6 dB to 11.3 dB, which is considerably better than CSRZ-DQPSK and NRZ-DQPSK, with Q-factor values ranging from 35.2 dB to 8.5 dB and 30.8 dB to 4.8 dB, respectively. This indicates that MDRZ-DQPSK modulation is more robust and can maintain better signal quality over long distances. This suggests that MDRZ-DQPSK provides higher-quality transmission and better tolerance to signal distortion over longer distances, making it a more reliable modulation scheme for long-haul communication systems.

Furthermore, Fig. 7(b) presents the BER variation across the distance range of 200–2000 km for all three modulation schemes used. The BER is a metric used to gauge the accuracy of transmitting digital data over a fiber-optic communication channel. It represents the proportion of incorrect bits that are received compared to the total number of bits transmitted. A lower BER signifies a more dependable transmission of information. BER can be represented in terms of the Q-factor by Eq. (19) as[38]:

$$\text{Bit error rate} = \frac{1}{2} \operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right) \qquad \dots (19)$$

It is clear from Fig. 7(b) that the performance of MDRZ-DQPSK is found to be superior to the other two modulation schemes, with a BER range of 10^{-26} to 10^{-11}. On the other hand, the BER range for CSRZ-DQPSK and NRZ-DQPSK is 10^{-24} to 10^{-8} and 10^{-20} to 10^{-6}, respectively. The results indicate that MDRZ-DQPSK can provide more reliable and robust performance over long distances, making it a suitable choice for communication systems with such requirements.

The variation in eye closure with varying distances from 200-2000 km for all three modulation techniques used is given in Fig. 7(c). Eye closure refers to the closing of the "eye pattern" of a digital signal, leading to a decrease in signal quality and an increase in the BER. An eye pattern shows the voltage levels of a digital signal over time and can indicate the signal's quality. A wide and open eye indicates a low BER and a high-quality signal, while a closed eye indicates a high BER and a poor-quality signal.[39] The results indicate that MDRZ-DQPSK exhibits better performance than the other two schemes in terms of eye closure, with a varied range of 0.31 dB to 1.44 dB. The variation range for CSRZ-DQPSK is 0.49 dB to 1.63 dB, while for NRZ-DQPSK, it is 0.61 dB to 1.72 dB. Eye closure is a critical factor in determining signal quality, and the results suggest that MDRZ-DQPSK provides a higher-quality signal with less eye closure compared to the other two modulation schemes.

Furthermore, Fig. 7(d) illustrates the variation in the probability of error for the same transmission distance from 200-2000 km for three different modulation schemes: MDRZ-DQPSK, NRZ-DQPSK, and CSRZ-DQPSK. The results show that MDRZ-DQPSK outperforms the other two modulation schemes in terms of the probability of error, with a varied range of 0.18 to 0.36. For CSRZ-DQPSK, the variation range is 0.21 to 0.39, while for NRZ-DQPSK, it is 0.24 to 0.43. A low probability of error is crucial for high-quality signal transmission, and the results suggest that MDRZ-DQPSK can provide a higher-quality signal with less probability of error compared to the other two modulation schemes. However, other factors such as available bandwidth, and the cost of the system should also be considered when selecting a modulation scheme.

Variation of different factors against number of channels from 50-450 for all three modulation techniques used for simulation are depicted in Fig. 8. Variation in receiver sensitivity with the varying number of channels is shown in Fig. 8(a). Receiver sensitivity in UD-WDM (Ultra-Dense Wavelength Division Multiplexing) systems refers to the minimum optical power level required at the receiver to detect a signal with a certain BER. It is a critical parameter in the design of optical communication systems because it determines the maximum distance over which a signal can be transmitted before it becomes too weak to be detected reliably.[40] The results in Fig. 8(a) demonstrate that MDRZ-DQPSK provides better receiver sensitivity than both CSRZ-DQPSK and NRZ-DQPSK modulation. The variation in receiver sensitivity is from −35.7 dBm to −0.16 dBm for MDRZ-DQPSK, from −37.5 dBm to −18 dBm for CSRZ-DQPSK, and from −39.2 dBm to −20

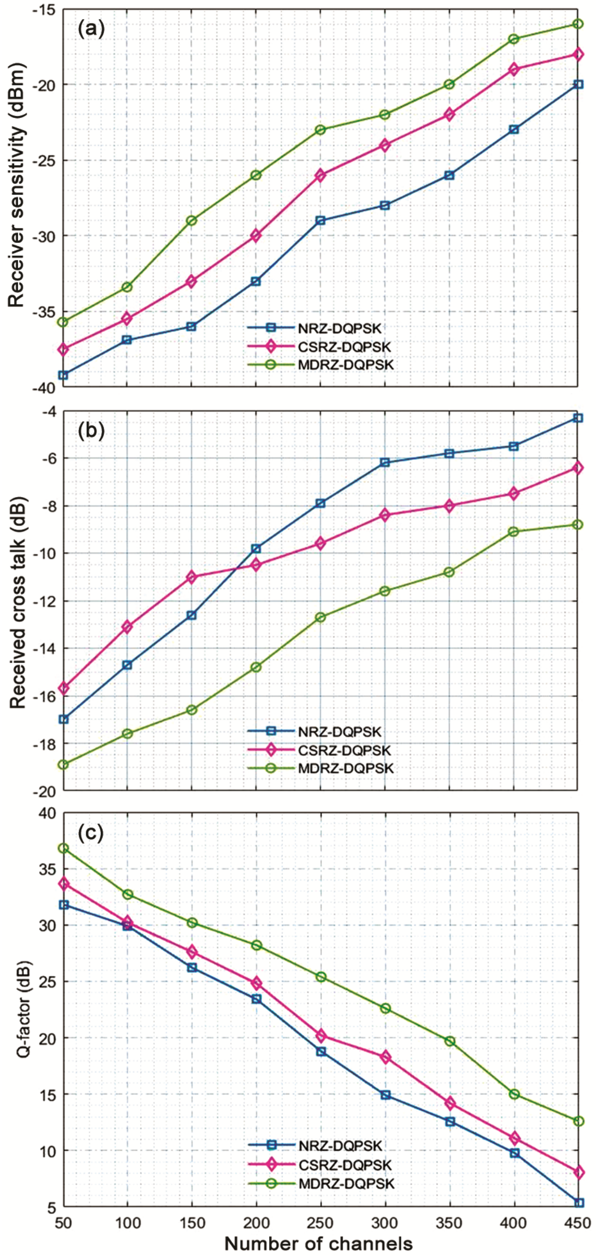

Fig. 8 — Variation of different factors against number of channels: (a) Receiver sensitivity, (b) Received crosstalk, (c) Quality factor

dBm for NRZ-DQPSK. The results indicate that the modulation format has a significant impact on the receiver sensitivity, and selecting the appropriate modulation format is crucial for achieving optimal system performance.

Furthermore, the variation in the received crosstalk with the varying number of channels from 50 to 450 is represented in Fig. 8(b). UD-WDM systems suffer from an unwanted effect called crosstalk, which occurs when signals transmitted on adjacent channels interfere with each other, leading to degraded system performance and errors. Crosstalk can be caused by various factors, including fiber characteristics and optical components. In a UD-WDM system, multiple channels of data are transmitted over a single fiber-optic cable, each using a different wavelength of light. However, due to the close proximity of these channels, some amount of signal leakage or crosstalk can occur, which can cause interference between the channels, resulting in errors and reduced system performance.

The formula for adjacent channel crosstalk may be expressed by Eq. (20) as[41]:

$$\mathrm{Crosstalk}_{\mathrm{adj.}} = 10\log 10\left(\frac{\mathrm{P_{int}}}{\mathrm{P_{des}}}\right) \quad \ldots (20)$$

where, P_{int} is the power of the interfering signal and P_{des} is the power of the desired signal.

The results in Fig. 8(b) demonstrate that MDRZ-DQPSK offers superior performance compared to CSRZ-DQPSK and NRZ-DQPSK in terms of received crosstalk. The received crosstalk ranges from −18.9 dB to −8.8 dB for MDRZ-DQPSK, from −15.7 dB to −6.4 dB for CSRZ-DQPSK, and from −17 dB to −4.3 dB for NRZ-DQPSK. The findings indicate that the increasing number of channels can result in a higher amount of received crosstalk, which can significantly impact the system's performance. Thus, selecting an appropriate modulation format is critical to minimizing crosstalk and maintaining system performance. The study suggests that MDRZ-DQPSK is the most suitable modulation format for high-capacity optical communication systems with multiple channels, as it provides the lowest level of received crosstalk among the three modulation formats examined. Furthermore, Fig. 8(c) depicts the variation of the Q-factor for the increasing number of channels from 50 to 450 for all three modulation formats: MDRZ-DQPSK, CSRZ-DQPSK, and NRZ-DQPSK. The results demonstrate that MDRZ-DQPSK provides superior performance compared to the other two modulation formats in terms of Q-factor. The Q-factor variation for MDRZ-DQPSK ranges from 36.8 dB to 12.6 dB, while for CSRZ-DQPSK, it ranges from 33.7 dB to 8.1 dB, and for NRZ-DQPSK, it ranges from 31.8 dB to 5.4 dB. These results indicate that the system's performance decreases as the number of channels increases, which is mainly due to the decrease in the Q-factor. The findings suggest that MDRZ-DQPSK is the most suitable modulation format for high-capacity optical communication systems with multiple channels, as it provides the highest Q-factor among the three modulation formats evaluated.

In Fig. 9(a) the variation of the Q-factor for the applied input power from −4 dBm to 4 dBm for the same three modulation formats: MDRZ-DQPSK, CSRZ-DQPSK, and NRZ-DQPSK is shown. The results indicate that MDRZ-DQPSK has a better Q-factor performance compared to CSRZ-DQPSK and NRZ-DQPSK across the range of applied input power. The Q-factor variation for MDRZ-DQPSK ranges from 36.4 dB to 13.6 dB, while for CSRZ-DQPSK, it ranges from 33.2 dB to 10.7 dB, and for NRZ-DQPSK, it ranges from 30.5 dB to 8.2 dB. These results demonstrate that the system's Q-factor is affected by the applied input power, and choosing the appropriate modulation format can enhance the system's performance. The variation in BER for the applied input power is given in Fig. 9(b). It is evident from the graph that the performance of MDRZ-DQPSK modulation is better than the other two types of modulation techniques. The BER for MDRZ-DQPSK varies from 10^{-29} to 10^{-13}, while for CSRZ-DQPSK, it ranges from 10^{-22} to 10^{-7}, and for NRZ-DQPSK, it varies from 10^{-20} to 10^{-5}.

These results indicate that MDRZ-DQPSK is more robust and has better error correction capability than the other two techniques. Thus, the use of MDRZ-DQPSK modulation is recommended for high-speed data transmission applications where signal quality and reliability is critical.

The output power variation for the applied input power for three types of DQPSK modulation: MDRZ-DQPSK, NRZ-DQPSK, and CSRZ-DQPSK Fig. 9(c). It is clear from the graph that MDRZ-DQPSK outperforms the other two modulation techniques in terms of output power. The MDRZ-DQPSK technique produces an output power ranging from −19 dBm to −38 dBm, while for CSRZ-DQPSK, it ranges from

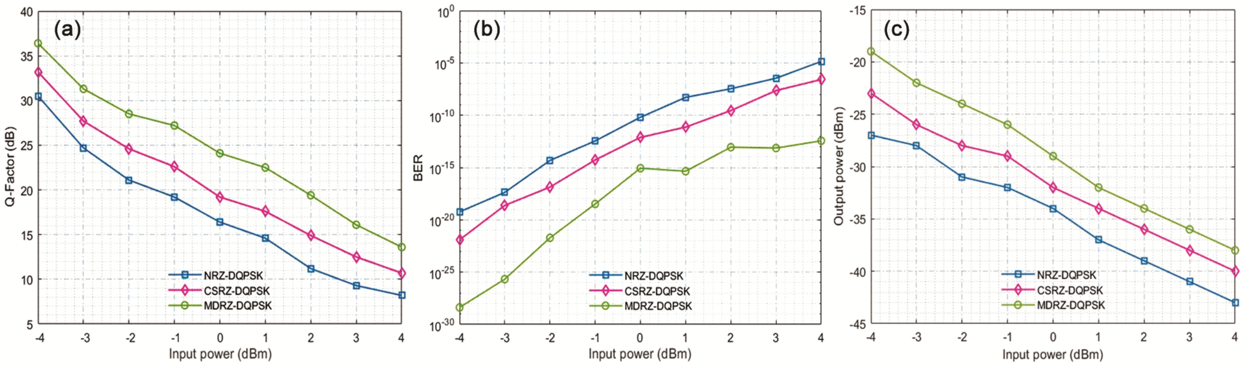

Fig. 9 — Variation of different parameters against power input: (a) Quality factor, (b) Bit error rate, (c) Output power

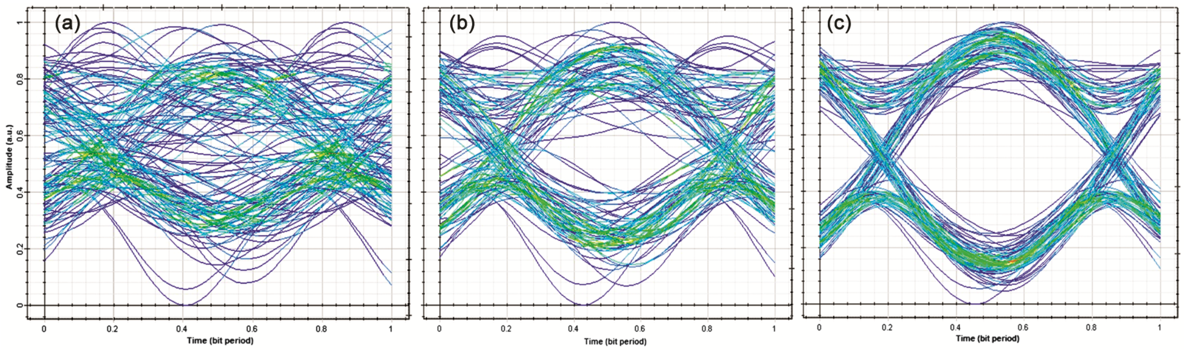

Fig. 10 — Eye diagram for different modulation techniques: (a) NRZ-DQPSK, (b) CSRZ-DQPSK, (c) MDRZ-DQPSK

Table 4 — Present work comparison with already done research works

Parameters	Ehsan *et al.*[8]	Sharan *et al.*[9]	Chaouch *et al.*[10]	Wang *et al.*[11]	Tomáš *et al.*[12]	Alsowaidi *et al.*[15]	Dhadhal *et al.*[16]	Present Work
Total no. of Transmitters	16	32	8	16	16	15	32	450
Modulation Technique used	CSNRZ, DQPSK, DB	DPSK, DQPSK	DPSK, DQPSK, PMRZ-DQPSK	NRZ-DQPSK, RZ-DQPSK	NRZ-DQPSK, CSRZ-DQPSK	CSRZ, MDRZ, RZ	MDRZ	NRZ/CSRZ/MDRZ-DQPSK
Transmission Distance (km)	1600	1000	960	560	750	105	250	2000
Channel Spacing (GHz)	100	50	50, 100	100, 200	100	25	80, 90, 100	12.5
Bit rate per Channel (Gb/s)	100	40	10, 40, 100	10, 40	100	40	40	100
Optical Amplifier used	EDFA	EDFA	EDFA	RAMAN	EDFA	SOA	EDFA	EDFA
BER value	10^{-12}	10^{-10}	10^{-12}	10^{-9}	10^{-10}	10^{-14}	10^{-13}	10^{-13}
Quality factor value (dB)	10.3	12	13.2	8.4	11.2	12.9	10.8	13.6

−23 dBm to −40 dBm, and for NRZ-DQPSK, it varies from −27 dBm to −43 dBm. These results indicate that MDRZ-DQPSK is more efficient in utilizing the input power and provides better output power compared to the other two techniques. Therefore, in high-speed data transmission applications, where power efficiency and reliability are crucial, MDRZ-DQPSK modulation is the recommended choice. Furthermore, Fig. 10 (a), (b) & (c) represent the eye diagram for NRZ-DQPSK, CSRZ-DQPSK, and MDRZ-DQPSK modulation techniques respectively.

From the eye diagrams, we can observe better eye-opening in the case of the MDRZ-DQPSK modulation technique as compared to NRZ-DQPSK, and CSRZ-DQPSK modulation techniques. The present research compared with the already done research works is shown in Table 4.

Conclusions

This paper investigated the performance of three spectral efficient advanced modulation techniques namely NRZ-DQPSK, CSRZ-DQPSK, and MDRZ-namely NRZ-DQPSK, CSRZ-DQPSK, and MDRZ-DQPSK for a 450-channel UD-WDM system with a bit rate of 100 Gb/s per channel and channel spacing of 0.1 nm. The performances of these techniques are evaluated using various parameters such as BER, Q-factor, eye closure, received crosstalk, receiver sensitivity, probability of error, and received output power. The study considers varying numbers of channels, transmission distance, and input power. Both experimental and simulation setups are used to evaluate the performance parameters, and the results indicate that MDRZ-DQPSK modulation outperforms the other two techniques in most cases achieving a maximum Q-factor of 11.3 dB, minimum BER of 10^{-11}, minimum eye closure of 1.44 dB, and minimum probability of error of 0.36 for varying transmission distances. Varying the number of channels resulted in a maximum receiver sensitivity of −16 dBm, minimum received crosstalk of −8.8 dB, and a maximum Q-factor of 12.6 dB. Varying input powers resulted in a maximum Q-factor of 13.6 dB, minimum BER of 10^{-13}, and maximum output power of −38 dBm. These results indicated that MDRZ-DQPSK is more efficient as compared to the other two techniques. Therefore, in high-speed data transmission applications, MDRZ-DQPSK modulation is the recommended choice.

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