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RESEARCH PAPER

Performance Optimization of WDM Long-Haul Lightwave Systems using Optimum Modulation Schemes.

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A B S T R A C T:

In this paper an optical communication system with N-Channel 40 Gb/s Wavelength Division Multiplexing (WDM) has been designed and optimized in the presence of Return-to-Zero Differential Phase Shift Keying (RZ-DPSK), Nonreturn-to-Zero (NRZ), Carrier Suppressed Return-to-Zero (CSRZ) and Modified Duo binary Return-to-Zero (MDRZ) modulation schemes. The system simulation is done using Optisystem simulator version-14 with multiple span Standard Single Mode Fiber (SSMF) transmission and the launched optical power range from (-10dBm to 10dBm). The effect of increase in launched power is studied in terms of Quality factor (Q-Factor), Bit Error Rate (BER), nonlinearity impairments and Eye Opening Penalty (EOP) for different modulation formats. The simulation results show that NRZ has highest Q-Factor of (38) and lowest BER with high nonlinear effects and system performance degradation with the increase of input optical power, while CS-RZ has the lowest Q-Factor of (6) with little nonlinear effect. On the other hand, RZ-DPSK offers high Q-Factor of (32) with high tolerant to nonlinear impairments and the system performance remains resilient to nonlinearity with the increase of input power. It is observed that RZ-DPSK has the lowest EOP that reaches only to 0.7 while NRZ has the highest EOP in which reaches to 4.5. Simulation results also show that RZ-DPSK has higher, wider and clearer eye diagram than other modulation formats. It is concluded that the light wave system with RZ-DPSK format offers the best performance, higher tolerance to nonlinearity and higher dispersion tolerance among other modulation formats.

KEY WORDS: Fiber optics, Q-Factor, BER, WDM, RZ-DPSK.
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INTRODUCTION :

Optical fiber communication is a good candidate that can handle a high data rate and forms the backbone of the communications infrastructure. To increase efficiency in optical fiber systems, a Wavelength Division Multiplexing (WDM) is a good choice to achieve it (Chenika, et al., 2014). Modern optical communication systems with high data rate and high capacity depend on advanced modulation techniques with coherent detection and formats that provide high spectral efficiency (Liu et al., 2014, Thuraya and Diana, 2015). With the rapid development of 40 Gb/s WDM long-haul optical communication system, the effects such as Four Wave Mixing (FWM) and Cross Phase Modulation (XPM) become significant and have to be minimized using applicable modulation schemes (Wei et al., 2006, Arazoo at al., 2016). Optical modulation scheme is an important issue that raises channel in capacity optical systems, that's why researchers focus on advanced optical modulation formats in upgrading light wave transmission capacity with better system reliability (Yong et al., 2008). Nonreturn-to-Zero (NRZ) format provides low optical bandwidth and

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high spectral efficiency in the linear regime at low data rate and for short range fiber optic communication and less tolerant to nonlinearity impairments (Singh and Kumar, 2013). Moreover, Return-to-Zero (RZ) format dominates NRZ, as it is more resilient to distortion and nonlinearity for higher data rate. Furthermore, Carrier Suppressed Return-to-Zero (CSRZ) scheme preferred for its high tolerance to Self Phase Modulation (SPM) and Group Velocity Dispersion (GVD) as the transmission performance improved. A Modified-Duobinary Return-to-Zero (MDRZ) has less jitter effect and distortion (Cheng and Conradi, 2002). The RZ-DPSK signal is achieved by two Mach Zehnder Modulators (MZM), RZ-DPSK is a promising candidate modulation scheme for long distance communication system due to its immunity to fiber nonlinear effects (Winzer and Essiambre, 2006).

(Li et. al.) compared the anti-nonlinear performance for different optical modulation schemes like RZ, NRZ, CSRZ and MDRZ. The simulation results show that CSRZ format offers higher tolerance to dispersion and nonlinearity than the other modulation formats. (Takeshi et. al.) investigated and analyzed different optical modulation formats, RZ, NRZ and CSRZ for free optical communication system. The results seen that RZ is a good candidate for light wave systems, where NRZ is has less complexity and cheaper as compared to RZ. (Amarpal et al.) simulated 8-channel 10 Gb/s NRZ DWDM light wave system with 10 GHz of channel spacing and up to 200 km, calculating power penalty by adjacent. (Kaler et al.) proposed DWDM systems using NRZ scheme with high capacity up to 1.28 Tb/s and 0.4 b/s/Hz of spectral efficiency.

In this paper a 16-channel 40 Gb/s WDM light wave system is designed, simulated and optimized using advanced optical modulation formats. Moreover, the simulation is carried out using Optisystem simulator version-14. In this software, Multi-Point Optimization (MPO) tool is achieved to get optimum parameters which is available in this software and the optimization is based on a nonlinear least-squares (LSQ) algorithm.

This organization of this paper is as follows. Sections 1 describes the basic theory and design of RZ-DPSK, NRZ, CS-RZ and MDRZ and their applications in light wave system. Section 2 outlines the dispersion managements in optical fiber communication system and the methods for compensating the dispersion with rules for designing optical fiber link. Section 3 is the simulation setup for the proposed system describing the parameters and the system block diagram for the four modulation formats. Section 4 outlines the results and discussion for the simulated light wave system. Section 5 is the overall conclusion and future works.

1. EXTERNAL MODULATORS

In external modulators, the laser that is subjected to a constant bias current emits a Continuous Wave (CW). A CW laser is used to emit light whose power is constant with time. A second component, known as modulator, is then used as a switch to let the light pass whenever the data corresponds to an "on" and to block it whenever the signal is an "off" (Wakita, 2013).

1.1 RZ-DPSK Modulation Format

An advanced modulation format that offer better resilience to nonlinear effects is Differential Phase Shift Keying (DPSK). Improving system performance to have longer transmission distance, Return-to-Zero DPSK (RZ-DPSK) is introduced. In this technique, an optical pulse comes out in each bit slot, with the binary encoded data as either a "0" or a "π" phase shift between bits. Figure 1 represents the general block diagram of a RZ-DPSK transmitter, the first electro-optical phase modulator, Mach-Zehnder Modulator (MZM) generates a conventional Nonreturn-to-Zero DPSK (NRZ-DPSK) signal, then sampled by a periodic pulse train (Xu et al., 2004). A key feature in DPSK transmitter is the precoder, in which recovers the receiver signal by differentially examining the pulse and the signal is encoded in a differential manner.

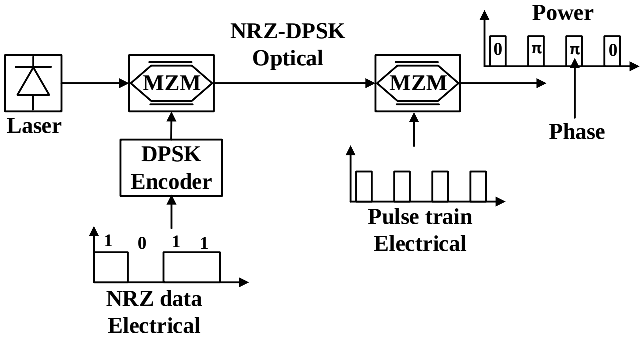


Figure 1. Block diagram for RZ-DPSK modulator.

1.2 NRZ Modulation Format

NRZ modulation format is a line code that ones are expressed as positive voltage and zeros are expressed as negative voltage (Mishina et al., 2006). When the transmitted code is "1", the optical pulse occupies the bit period and when there is no pulse, the signal code is "0". NRZ signal is generated using an MZM and Consecutive Wave (CW) laser as shown in Figure 2. Adjacent NRZ pulses can be expressed as a sum:

$$V_{o,n}(t) = \sum_{j=n-1}^{n+1} a_j S(t) \qquad (1)$$

where $V_{0,n}(t)$is the driving function for the ith pulse in a bit stream, a_j is the bit value (zero or one), and $S(t)$ is the shape function.

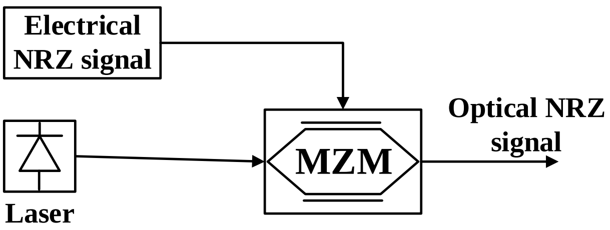


Figure 2. Block diagram of NRZ format.

1.3 CS-RZ Modulation Format

CS-RZ format is based on Return-to-Zero (RZ) format and links the separation of phase by π in each neighboring bit. In CS-RZ the pulse goes to zero between successive bits (RZ), and the field phase changes by π between neighboring bits. To create CS-RZ pulse, the NRZ signal is created by MZM modulator and the output is directed to another MZM (Sheetal et al., 2010). A block diagram for CZ-RZ transmitter is shown in Figure 3.

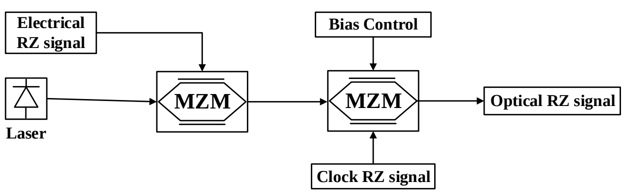


Figure 3. Block diagram of CS-RZ transmitter.

1.4 MDRZ Modulation Format

Another advanced optical modulation format is MDRZ in which suppresses all discrete frequency tones. MDRZ signal is generated firstly by creating an NRZ duo binary signal using a delay and subtracting circuit driving the first MZM then fed to another MZM having a phase of -90^{o}. In MDRZ format, the signal phase is changed between 0 and π for bits "1" while the phase of all "zero" bits are kept constant and a 180^{o} phase alteration among all successive "ones" is introduced (Cheng and Conradi, 2002). A block diagram for MDRZ transmitter is shown in Figure 4. Duo binary modulation transmitted signal can be expressed as:

$$x(t) = \sum_{k=-\infty}^{\infty} d_k q(t - k_s T), \;\; d_k = 0{,}1 \quad (2)$$

where d_k are the data bits, $q(t)$ is the transmitted pulse, $T = 1/R_d$ is the bit period and R_d is the data rate.

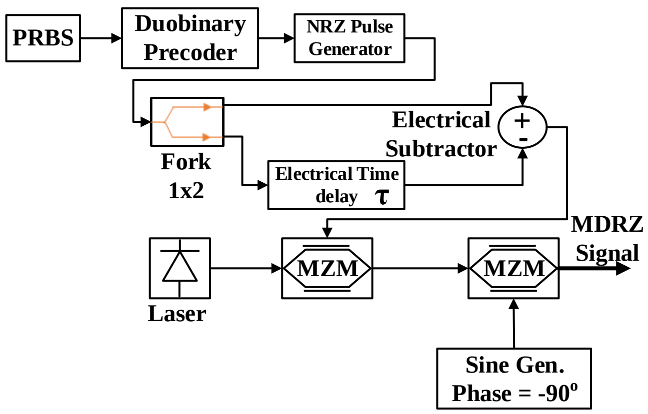


Figure 4. Block diagram for MDRZ transmitter.

2 DISPERSION MANAGEMENT

Dispersion is a phenomenon in which the velocity of the optical pulse propagating in the SSMF depends on the wavelength that deteriorates the optical fiber system performance. Minimizing dispersion in light wave systems is crucial and needs techniques to compensate it, one of the techniques is by employing Dispersion Compensating Fiber (DCF) that has dispersion characteristics opposite to that of SSMF (Kaler et al., 2002). A schematic diagram showing the effect of dispersion is illustrated in Figure 5. It is observed that the transmitted pulse been broadened due to dispersion effect and the received pulse is no longer distinguishable due to the overlap between adjacent bits. With long-haul optical communication system, the dispersion accumulates, which results in the reduction of the Optical Signal to Noise Ratio (OSNR), increase in Bit Error Rate (BER), and degrading system performance (Méndez and Morse, 2011). If β_{2j} and β_{3j} (j=1,2) are Group Velocity Dispersion (GVD) and Third Order Dispersion (TOD) parameters for the two fiber segments (SSMF and DCF), respectively, the conditions for complete dispersion compensation are:

$$\begin{aligned} \beta_{21}L_{SMF} + \beta_{22}L_{DCF} = 0 \\ \beta_{31}L_{SMF} + \beta_{32}L_{DCF} = 0 \end{aligned} \quad (3)$$

where L_{SMF} and L_{DCF} are lengths for single mode and dispersion compensating fibers, respectively. These conditions can be expressed in terms of dispersion parameter *D* and the dispersion slope *S* as function of the length *L* (Grobe and Eiselt, 2013) as:

$$\begin{aligned} D_{SMF}L_{SMF} + D_{DCF}L_{DCF} = 0 \\ S_{SMF}L_{SMF} + S_{DCF}L_{DCF} = 0 \end{aligned} \quad (4)$$

where D_{SMF} is the dispersion coefficient for the SMF [ps/nm/km], D_{DCF} is the dispersion coefficient for the DCF, S_{SMF} is the dispersion slope for the SMF [ps/nm^2/km] and S_{DCF} is the dispersion slope for DCF.

Figure 5. Effect of dispersion in optical fiber communication system.

3. SIMULATION AND SYSTEM MODEL

A proposed system setup diagrams for a 16-channel 40 Gb/s light wave system with different advanced modulation schemes which has been designed and simulated as shown in Figure 6. A 2^{14}-1 Pseudo Random Binary Sequence (PRBS) is used to drive the precoder and MZMs. The modulators modulate the signals with optical continuous wave signal provided by the CW laser source having line width of (0.1 MHz) with a variable input power from (-10 dBm to +10 dBm) in addition to WDM multiplexer with channel spacing of 50 GHz. The link consists of three spans with distance of 200 km, in each span an Erbium Doped Fiber Amplifier (EDFA) with a gain of 20 dB and Noise Figure (NF) of 6 dB is used to boost the signal to the desired power level for transmission through the three spans with the Amplified Spontaneous Emission (ASE) noise of 4.5 dB. For the three spans, SSMF is used and DCF with different lengths are used dispersion compensation, the DCF is put after the amplifier for post compensation. At the receiver, the optical signal recovered with Positive Intrinsic Negative (PIN) photodiodes with responsivity of 1 A/W, a dark current of 10 nA and thermal power density of $100*10^{-24}$ W/Hz. The filtering function implemented in the receiver (electrical filter) by Low Pass Bessel Filter of bandwidth with 0.8*bit rate to remove out the noise, then delivered to the BER analyzer. The simulated parameters are summarized in Table 1.

4. RESULTS AND DISCUSSIONS

The proposed system setup diagram for a 16-channel 40 Gb/s WDM light wave system, shown in Figures 6 is designed, simulated and optimized using advanced optical modulation schemes with input power from (-10 to 10 dBm). Simulation and optimization has been carried out using Optisystem simulator version-14 with multiple span SSMF transmission.

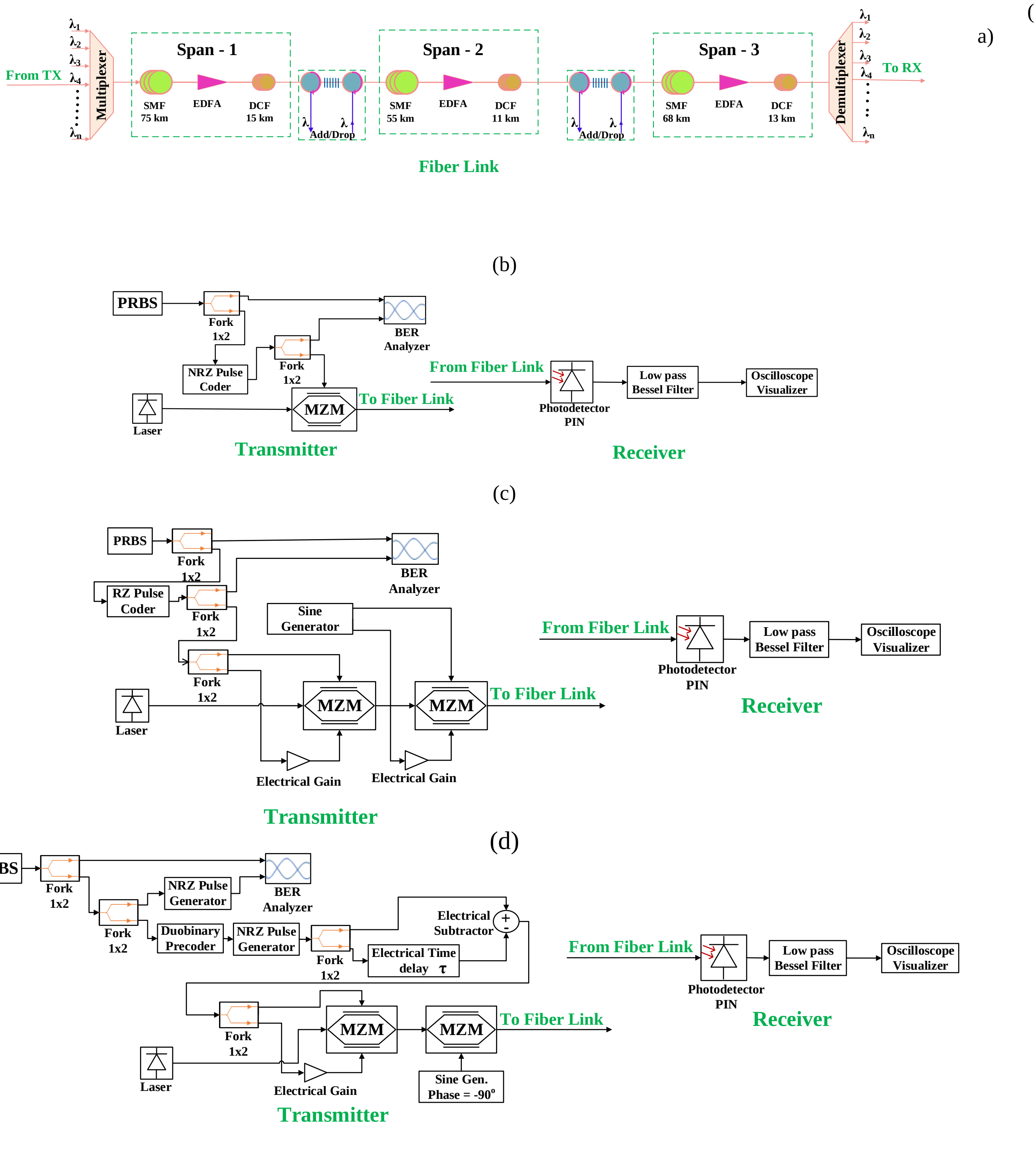


Figure 6. System setup: (a) Fiber link, (b) RZ-DPSK, (c) NRZ, (d) CS-RZ and (e) MDRZ formats

Table 1. Simulation parameters

Parameter	Value	Units
Bit rate	40	Gb/s
Sequence length	512	Bits
Samples/bit	64	
WDM channel spacing	50	GHz
Capacity	40 Gb/s x 16 Channel	
G.652 SSMF		
Attenuation, α	0.2	dB/km
Dispersion coefficient, *D*	16	ps/nm/km
Dispersion slope, *S*	0.08	$ps/nm^2/km$
Effective area, A_{eff}	80	μm^2
Nonlinear Refractive index	$26*10^{-21}$	m^2/W
Nonlinear coefficient, γ	1.19	$W^{-1}km^{-1}$
SSMF total length	200	km
DCF		
Attenuation, α	0.6	dB/km
Dispersion coefficient, *D*	-80	ps/nm/km
Dispersion slope, *S*	-0.21	$ps/nm^2/km$
Effective area, A_{eff}	30	μm^2
Nonlinear Refractive index	$30*10^{-21}$	m^2/W
Nonlinear coefficient, γ	4.27	$W^{-1}km^{-1}$

Figure 7 illustrates Q-Factor versus launched power. It is observed that NRZ format has higher Q-Factor of (38) at input power of (1.1dBm) and degrades to (6) at (10dBm), this is due to nonlinearity effect on this modulation format. In case of RZ-DPSK, the highest Q-Factor is (32.5) at input power of (5.5dBm) and degrades to only (30.5) at (10dBm). This means that RZ-DPSK modulation format is highly tolerant to nonlinear effects. It is also seen that CS-RZ format is less affected by nonlinearity, but it has minimal Q-Factor which reaches to (6.2) at input power of (10dBm). MDRZ format has moderate Q-Factor with observing nonlinear effects.

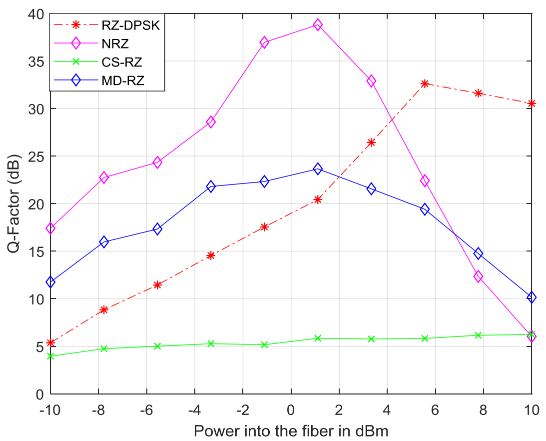


Figure 7. Q-Factor vs. optical launched power

Figure 8 gives the relationship for log of BER and input power to the link. It is shown that NRZ format has the lowest BER rate with high nonlinear effects, while RZ-DPSK has low BER and less affected by fiber nonlinearity.

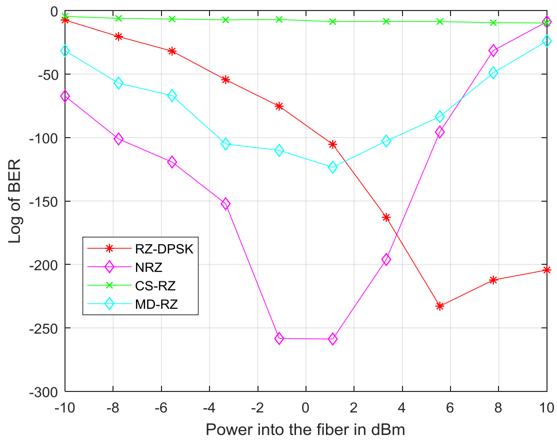


Figure 8. Log of BER vs. optical launched power

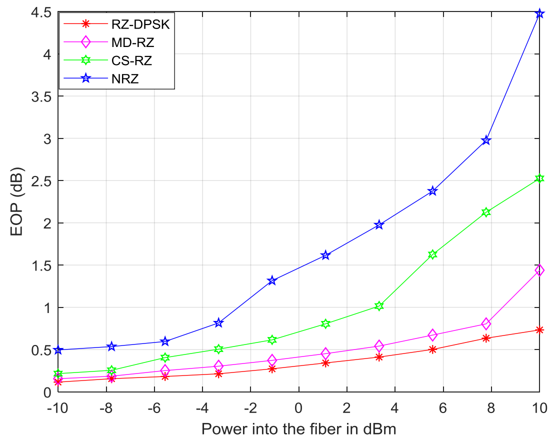
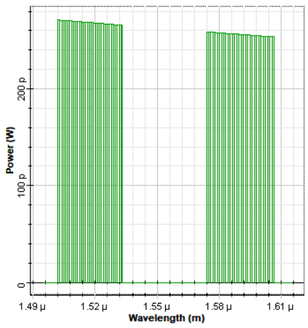
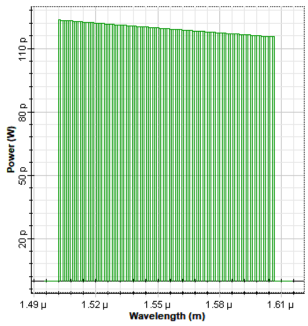


Figure 9. EOP increase with input optical power.

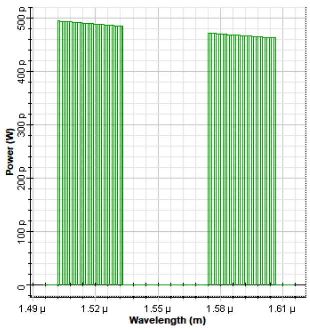
The Eye Opening Penalty (EOP) is plotted in Figure 9. It is seen that RZ-DPSK format has smallest EOP among the other formats and gives the system a stable performance. The receiver noise for the modulation formats is shown in Figure 10. It is observed that the light wave system with RZ-DPSK has less noise (84 pW), while system with NRZ gives the highest noise (500 pW).



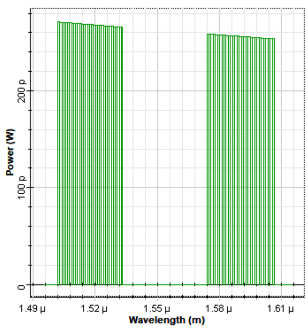
(a)



(b)



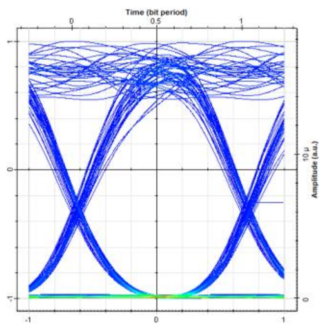
(c)



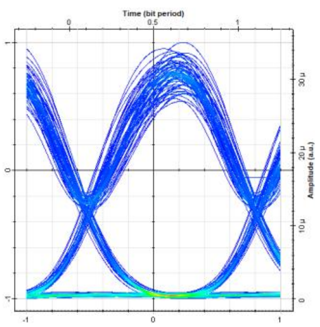
(d)

Figure 10. Receiver noise for: (a) NRZ, (b) RZ-DPSK, (c) CS-RZ and (d) MDRZ formats.

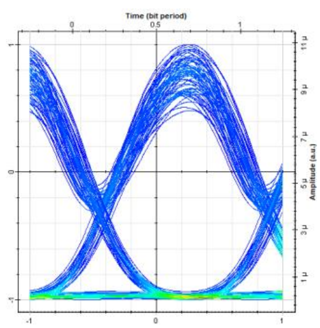
Figure 11 shows the eye diagrams for the modulation formats. It is seen that NRZ format has highest distortion in the eye diagram, while RZ-DPSK obtains higher amplitude, wider and clearer eye diagram with less distortion.



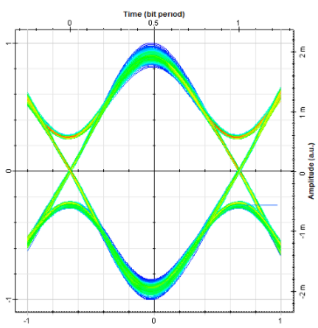
(a)



(b)



(c)



(d)

Figure 11. System eye diagram for: (a) NRZ, (b) CS-RZ, (c) MDRZ and (d) RZ-DPSK formats.

A comparative result between modulation schemes are summarized in Table 2. It is observed that NRZ offers highest Q-Factor but it is more affected by the nonlinearity with the increase of launched power with highest EOP of 4.5 dB. Overall, from Table 2 it is concluded that RZ-DPSK scheme offers better robustness to nonlinearity, highest eye height, minimum EOP and receiver noise.

5. DISCUSSIONS

1- In this paper a 16-channel 40 Gb/s WDM light wave system has been designed, simulated and optimized using advanced optimum modulation formats with multiple SSMF spans for the range of input optical power (-10dBm to 10dBm).
2- Simulation results show that NRZ has highest Q-Factor of (38) and lowest BER with high nonlinear effects and system performance degradation with the increase of input optical power.
3- The CS-RZ has the lowest Q-Factor of (6). On the other hand, RZ-DPSK offers high Q-Factor of (32) with high tolerant to nonlinear impairments and the system performance remains resilient to nonlinearity with the increase of input power.
4- It is observed that RZ-DPSK has the lowest EOP that reaches only to 0.7 while NRZ has the highest EOP for which it reaches to 4.5.
5- It is seen that RZ-DPSK obtains higher amplitude, wider and clearer eye diagram with less distortion among other modulation schemes. It is concluded that optical communication system with RZ-DPSK modulation format offer best performance, high system tolerance to nonlinearity and higher dispersion tolerance over a wide range of input optical power among other modulation formats.

Table 2 A comparison between modulation schemes

Modulation scheme/ Result	Q-Factor (dB)		Log. of BER		EOP (dB)		Receiver noise (pW)	Eye height (p.u.)
	Min.	Max.	Min.	Max.	Min.	Max.		
RZ-DPSK	5.5	33	-240	-5	0.1	0.7	120	2 m
NRZ	5.3	38	-255	-4.5	0.5	4.5	240	18 µ
CS-RZ	4	6	-5	-4	0.23	2.5	495	13 µ
MD-RZ	10	24	-120	-18	0.2	1.48	270	5 µ

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