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Analytical Study of DWDM Optical Long Haul Network with Symmetrical Dispersion Compensation

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Abstract

Objective: To design 40 Gbps ultra-dense wavelength division multiplexed (DWDM) optical network for 32 and 64 channels. **Methods:** Proposed DWDM architecture supports three different advance modulation schemes with symmetrical dispersion compensation unit. Performance of proposed work has been investigated using parameters bit error rate (BER) and quality factor. For efficient analysis, we employ variation in channel spacing, transmission length of fiber and input laser power, which is resulted into some significant observations. **Findings:** Carrier Suppressed Return to Zero (CSRZ) scheme exhibits a good quality factor with maximum achievable distance up to 4250 km due to highest tolerance to nonlinear effects. Modified Duobinary Return to Zero (MDRZ) modulation scheme also provides a good quality factor with laser power variation due to high receiver sensitivity, but with limited reach upto 2750 km. While Duobinary Return to Zero (DRZ) scheme provides moderate transmission coverage up to 3750 km in comparison to CSRZ and MDRZ, with a lesser quality factor due to effect of Inter Symbol Interference (ISI). We observe that an increase in number of simultaneous users through the channels results into performance degradation. **Application**: This work delivers very huge data rate and good spectral efficiency to sustain the current high traffic growth.

Keywords: Dispersion, Long Haul System, Optical Network, Symmetrical Compensation, DWDM

1. Introduction

Dense Wavelength Division Multiplexing (DWDM) is recognized all over the world, for satisfying major challenge of today's telecommunication network, i.e., very high traffic demand, integrated services on same physical infrastructure and efficient bandwidth[1–3]. Emerging technology of fourth generation of optical network, i.e., DWDM utilizes enormous potential bandwidth of fiber channel to accommodate multichannel simultaneously and service them together[4–6]. DWDM technology flourishes in presence of popular amplifier, i.e., Erbium Doped Fiber Amplifier (EDFA), which exhibits very wide spectral bandwidth. So EDFA can amplify multiple optical signals in a batch, supporting high capacity transmission and EDFA-DWDM systems together fulfill huge demand of current traffic and bandwidth hungry services by suddenly lifting transmission capacity of optical fiber[6–7]. DWDM performance is limited due to presence of phenomenon along fiber like dispersion and nonlinearities[8–12]. Dispersion can be compensated by pre, post and symmetric compensation techniques, among which symmetric compensation technique provides better performance[13]. To achieve high bandwidth efficiency, various suitable modulation schemes along with RZ and NRZ like Carrier Suppressed Return to Zero (CSRZ), Duo binary Return to zero (DRZ) and Modified Duo Binary Return to Zero (MDRZ) schemes are proposed at 40 Gbps by G. Bosco[14]. E. Pincemin et al. designed a 16 × 40 Gbps dispersion managed DWDM transmission system using NRZ scheme with analyzing effect of fiber types[15]. M. Pfennigbauer et al. worked on selection

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of MUX or DEMUX filter characteristics for NRZ, RZ and CSRZ DWDM system[16]. Y. Yu et al. worked on 16 DWDM system using NRZ and RZ schemes at different duty cycles like 33%, 50% etc[17]. D. Sharma et al. worked on optimized modulation scheme among CSRZ, DRZ, MDRZ, 33% DPSK, 66% DPSK and DQPSK schemes for DWDM system[18]. A.Sheetal et al. analyzed 40 Gbps long haul DWDM network with high capacity for CSRZ, DRZ and MDRZ advanced modulation schemes and pre, post and symmetrical dispersion compensation schemes[19]. S. Singh et al. evaluated 64 × 10Gbps and 96 × 10Gbps DWDM systems with hybrid optical amplifier for different modulation schemes like RZ, NRZ and DPSK[20]. L. Li et al. compared RZ, NRZ, CSRZ, DRZ, MDRZ schemes for 40Gbps DWDM system[21].

In this paper, an ultra-dense WDM optical network is designed at 40 Gbps bit rate for 32 and 64 channels with high data rates 1.28 Tbps and 2.56 Tbps and high spectral efficiency with channel spacing 100 GHz and 75 GHz The proposed work is efficiently analyzed for different modulation schemes CSRZ, DRZ and MDRZ for symmetrical dispersion compensation technique. During analysis, Key performance parameters like Maximum Quality factor (Max. Q factor) and Minimum Bit Error Rate (Min. BER) are plotted against transmission distance in terms of fiber length and power input to laser source. The bit error rate (BER) is the number of erroneous bits divided by the total number of transmitted bits during a fixed time interval. Q factor is directly related with BER as $BER = \frac{1}{2}\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right)$. Hence, this comprehensive study results into better understanding of advanced modulation schemes like CSRZ, DRZ and MDRZ in terms of key parameters BER and Q factor with variation in fiber length and laser power, corresponding into few interesting behavioral knowledge of these modulation schemes.

The paper is organized as follows: Section 2 describes the generation model of various modulation schemes and simulation set up of ultra-dense WDM optical network for 32 and 64 channels. Section 3 contains numerical result and discussion, while section 4 concluded interesting observations and conclusions.

2. Generation of Different Modulation Schemes

Here for the sake of better bandwidth utilization of optical fiber capacity, three advanced modulation schemes with their generation setups are shown.

2.1 Carrier Suppressed Return to Zero (CSRZ) Scheme

CSRZ has narrow optical spectrum and higher tolerance towards chromatic dispersion and Self-Phase Modulation (SPM) than conventional RZ and NRZ schemes[19–21]. In CSRZ transmitter setup, NRZ optical pulse passes through Machzhender Interferometer (MZI) modulator and phase modulator back to back, which is driven by a sinusoidal signal generator at half of the bit rate frequency, leads two adjacent bits out of phase, hence obtained spectrum will have a suppressed peak. Generation set up of CSRZ scheme is shown in Figure 1.

2.2 Duobinary Return to Zero (DRZ) Scheme

Optical modulation bandwidth of DRZ can be compressed upto data bit rate, which is half bandwidth of NRZ scheme. For sake of duobinary signal generation, a

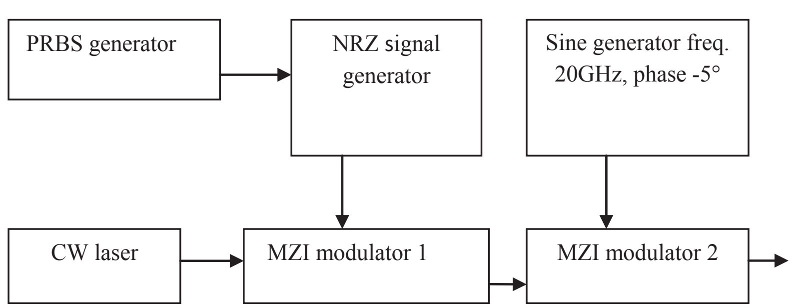

Figure 1. Schematic diagram of CSRZ modulation scheme generation.

duobinary precoder is used, which is composed of ex-or gate with delayed feedback path and generates NRZ duobinary pulse[19–21]. Two back to back MZI modulators are cascaded, generated NRZ duobinary pulse drive first modulator, while second one is driven by a electrical pulse of frequency 40 GHz and phase –90°. Generation set up of DRZ scheme is shown in Figure 2.

2.3 Modified Return to Zero (MDRZ) Scheme

To generate MDRZ pulse, firstly an NRZ duobinary signal is generated using delay and subtract circuit, driving first MZI modulator, cascaded with other MZI modulator, driven by a sinusoidal pulse of frequency 40 GHz and phase –90°. Generation of MDRZ signal differs from that of DRZ pulse, due to presence of delay and subtract circuit instead of delay and add circuit[19–21]. In MDRZ scheme, phase of all "zero" bits are kept constant and phase of bit "one" swing between 0 and π. Generation set up of MDRZ scheme is shown in Figure 3.

2.4 Schematic of Symmetrical Compensation Set Up

In symmetrical compensation scheme, Dispersion Compensation Fiber(DCF) fiber of length10 km is used in centre of two Standard Single Mode fiber (SSMF) fibers each of 25 km length, along with three EDFA with gain 10 dB, 5 dB and 10 dB respectively, while noise figure equal to 6 dB for all. Symmetrical compensation set up is shown in Figure 4.

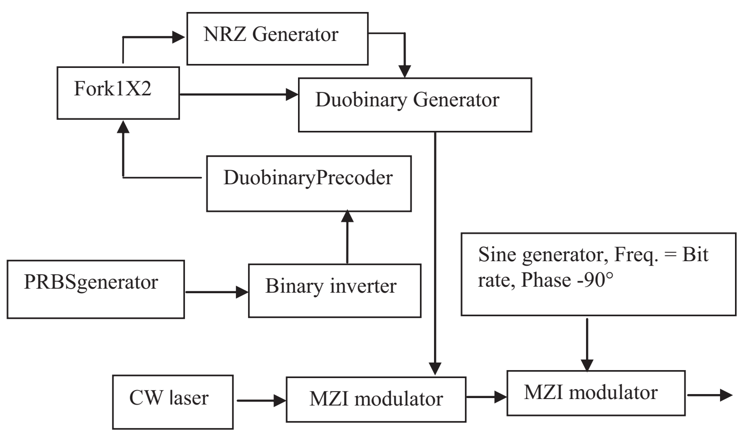

Figure 2. Schematic diagram of DRZ modulation scheme generation.

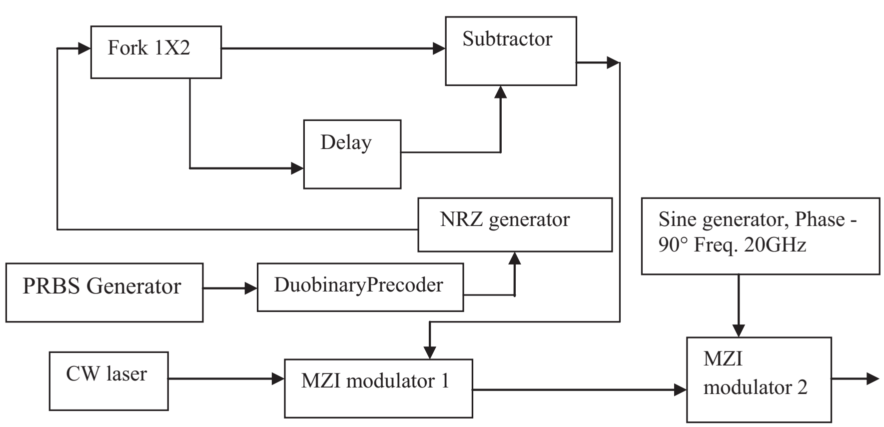

Figure 3. Schematic diagram of MDRZ modulation scheme generation.

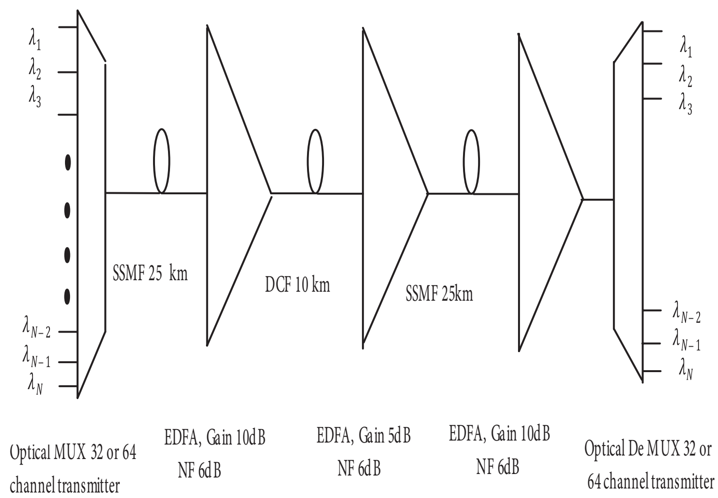

Figure 4. Schematic of symmetric compensation set up.

2.5 Simulation Setup

Here simulation set up of Ultra DWDM optical network, with ultra-high data rates ranging 1–2.5 Tbps is designed for 32 and 64 channels respectively at 40 Gbps bit rate with 100 GHz and 75 GHz channel spacing, shown in Figure 5. 40 Gbps bit rate is chosen due to very small effect of dispersion than that of 10 Gbps, so supporting ultra-long haul transmission[22]. The simulation set up is consist of a CW laser, data modulator (CSRZ, DRZ, MDRZ) and optical multiplexer of Bandwidth 100 GHz at transmission end, symmetrical compensation set up at channel, while at receiver end, optical demultiplexer (DeMUX) of Bandwidth 100 GHz is followed by a PIN detector and low pass Bessel filter. For purpose of key output parameters display, BER analyzer is used as a visualizer to plot key graphs. Min. BER and maximum Q factor is plotted against variation in fiber length in terms of number of loop at fixed laser power input 0 dBm and against varying laser power input (–20 to 50 dBm), for 32 and 64 channels, with 100 GHz and 75 GHz spacing, for both cases. But laser linewidth is kept constant i.e., 0 MHz. Centre frequency of very first channel is 193.1 THz. For 32 channels, centre frequency varies from 193.1 to 196.2 THz, while for 64 channels; this centre frequency varies from 193.1 to 199.4 THz in case of 100 GHz channel spacing[1]. On the other hand, taking 75 GHz channel spacing leads to variation of centre frequency from 193.1 to 195.425 THz for 32 channels, while 193.1 to 197.825 THz for 64 channels. Symmetrical compensation is used here, due to better performance than pre and post compensation, as reducing BER upto more extent, so repeater length is increased upto double value[13]. Symmetrical compensation model consists of 2 SSMF at ends of length 25 km, attenuation 0.2 dB/km, dispersion slope 0.075 ps/nm^2/km, while one DCF at centre of length 10 km, attenuation 0.5 dB/km and dispersion slope –0.3 ps/nm^2/km and three EDFAs, placed after each fiber with gain 0 dB, 5 dB and 10 dB and noise Figure 6 dB each. A low pass Bessel filter is introduced with specifications like cutoff frequency 50 GHz, Insertion loss 0 dB, depth 100 dB and filter order 3 for DRZ and CSRZ, and 2 for MDRZ scheme, placed at receiver section after PIN diode detector with Responsivity of 1A/W and dark current 0.1 nA, following a Demultiplexer with inbuilt Gaussian filter of order 4, for CSRZ and DRZ DWDM set up, while Gaussian filter order 2 for MDRZ DWDM set up. Different Gaussian and Bessel filter order combination is taken for better performance. Table 1 contains various parameters and their chosen values in the simulation set up during design.

3. Numerical Result and Discussion

Here simulation results of Ultra DWDM optical network are efficiently shown, with ultra-high data rates

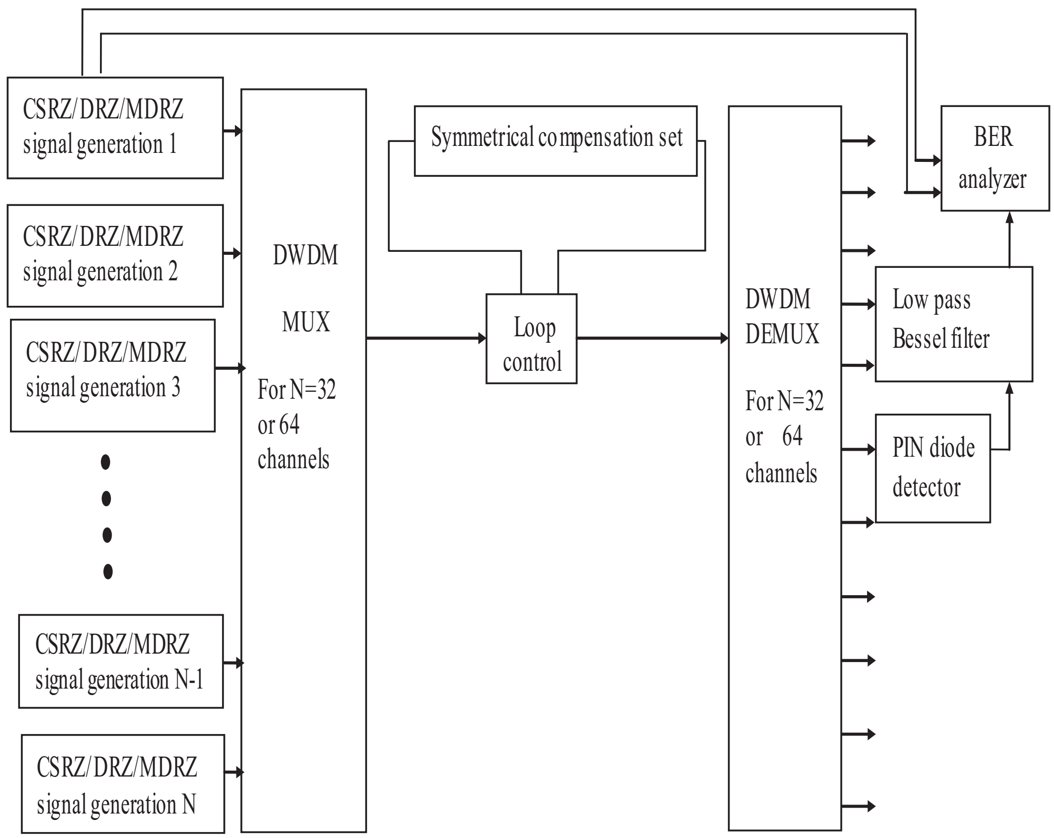

Figure 5. Simulation set up of 32 channels or 64 channels ultra-DWDM.

Table 1. Simulation parameters of 32 channels or 64 channels ultra-DWDM

Bit rate	40 Gbps
Sequence length	256
Sample/bit	32
WDM channel spacing	75 GHz, 100 GHz
Spectral efficiency	0.53 bit/s/Hz due to 75 GHz spacing 0.40 bit/s/Hz due to 100 GHz spacing
Centre frequency of first channel	193.1 THz
Number of channels	32, 64
Capacity	40 Gbps × 32 channel i.e., 1.28 Tbps 40 Gbps × 64 channel i.e., 2.56 Tbps
Distance	(50 × N spans)km, N = 5, 10, 15, 20, 25………

upto 1.28 Tbps and 2.56 Tbps for 32 and 64 channels respectively at 40 Gbps bit rate with spectral efficiency approaching 0.40 bit/s/Hz and 0.53bit/s/Hz for 100 GHz and 75 GHz channel spacing correspondingly. Firstly, Min. BER and maximum Q factor is plotted against variation in fiber length in terms of number of loop at fixed laser power input (0 dBm), for 32 and 64 channels, with 100 GHz and 75 GHz spacing, for both cases. Secondly, Min. BER and maximum Q factor is plotted against variation in laser power input (–20 dBm to 50 dBm), for 32 and 64 channels, with 100 GHz spacing at 250 km and 500 km fiber length.

3.1 Max. Q Factor and Min. BER Performance of Modulation Schemes; Varying Transmission Distance

Figure 6 exhibits Max. Q factor plot and Figure 7 exhibits Min. BER plot, both against transmission distance of fiber length (in km) reflecting the behavior of key modulation schemes i.e., CSRZ, DRZ and MDRZ respectively on varying number of channels (i.e., 32 and 64) and channel spacing (i.e., 100 GHz and 75 GHz). In Figure 6(a) and 7(a), for CSRZ modulation set up, 32 channels with 75 GHz spacing exhibits the best performance, extending up to 4250 km fiber length with max. Q factor 38.40 dB and min. BER3.20E-277. While, an increase in number of channels, degrades the performance in terms of maximum achievable distance upto only 2500–2750 km for 64 channels and 100 GHz spacing. In Figure 6(b) and 7(b), for DRZ modulation scheme, 32 channels with 75 GHz spacing gives best behavior of max. Q factor 34.12 dB and Min. BER 7.67E-264, covering the transmission distance of 3750 km. On the other hand, in DRZ modulation scheme, increasing the number of channels upto 64 with 100 GHz spacing covers a distance of 3500–3750 km. In Figure 6(c) and 7(c), case of MDRZ modulation scheme, 32 channels with 75 GHz spacing exhibits the best max. Q factor 40.10 dB and min. BER 3.28923E-316 covers 3000 km. On increasing number of channels, 64 channels with 75 GHz spacing covers 2750–3000 km but with poor Q factor and min. BER value. Among all three cases, 32 channels with 75 GHz spacing CSRZ modulation scheme serves best performance. Ideally, Max. Q factor keeps on decreasing nonlinearly maintaining critical value 6 dB[21,23] and Min. BER keeps on increasing nonlinearly with an increase in fiber length maintaining critical value 10E-9[21,24].

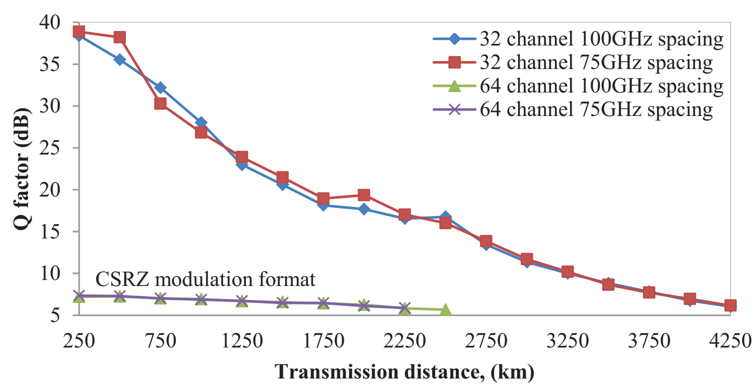

Figure 6.(a) Max. Q factor is plotted against transmission distance for CSRZ modulation scheme for 32 and 64 channels with 100 GHz and 75 GHz channel spacing for each case.

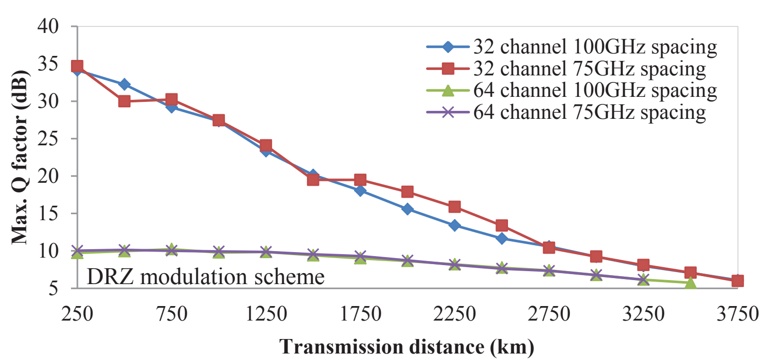

Figure 6.(b) Max. Q factor is plotted against transmission distance for DRZ modulation scheme for 32 and 64 channels with 100 GHz and 75 GHz channel spacing for each case.

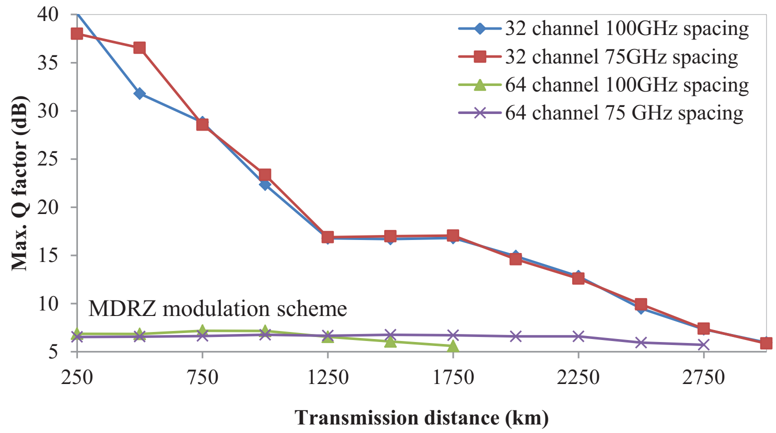

Figure 6.(c) Max. Q factor is plotted against transmission distance for MDRZ modulation scheme for 32 and 64 channels with 100 GHz and 75 GHz channel spacing for each case.

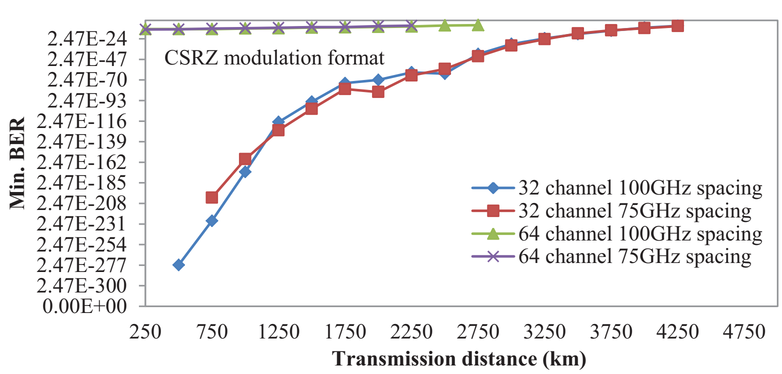

Figure 7.(a) Min. BER is plotted against transmission distance for CSRZ modulation scheme for 32 and 64 channels with 100 GHz and 75 GHz channel spacing for each case.

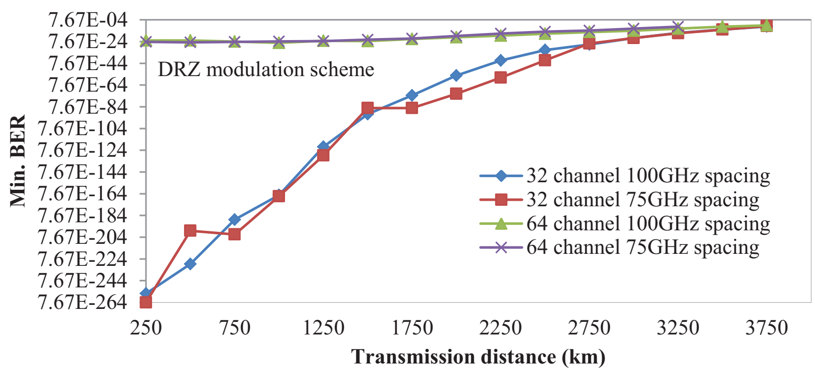

Figure 7.(b) Min. BER is plotted against transmission distance for DRZ modulation scheme for 32 and 64 channels with 100 GHz and 75 GHz channel spacing for each case.

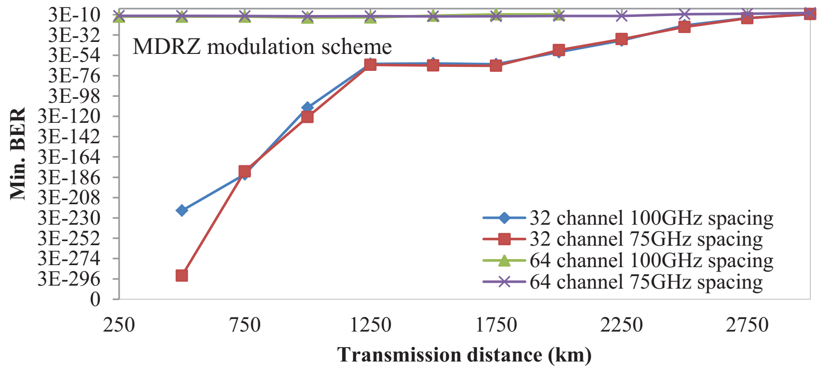

Figure 7.(c) Min. BER is plotted against transmission distance for MDRZ modulation scheme for 32 and 64 channels with 100 GHz and 75 GHz channel spacing for each case.

3.2 Max. Q Factor and Min. BER Performance of Modulation Schemes; Varying Laser Power Input

Figure 8 exhibits Max. Q factor plot and Figure 9 exhibits Min. BER plot, both against variation in laser power in dBm between –20 dBm to 50 dBm reflecting the behavior of key modulation schemes i.e., CSRZ, DRZ and MDRZ respectively on varying number of channels (i.e., 32 and 64) at 100 GHz channel spacing at fixed fiber length 250 km and 500 km. On observing Figure 8(a), 8(b) and 8(c) for CSRZ, DRZ and MDRZ modulation set up respectively, 32 channels with 100 GHz spacing at 250 km fiber length exhibits best performance in each case, with max. Q factor values 48.90 dB, 116.28 dB and 309.67 dB correspondingly, among all MDRZ scheme exhibits highest max. Q factor value. While, increasing the number of channels upto 64 with 100 GHz spacing at fiber length 500 km shows poor Max. Q factor values 45.43 dB, 37 dB, 29 dB for CSRZ, DRZ and MDRZ respectively. Ideally, Max. Q factor keeps on increasing nonlinearly with laser power variation again satisfying critical value of 6 dB[21,23] and afterwards remains constant after 20 dBm laser power, except 32 channel 100 GHz 250 km MDRZ scheme case.

In Figure 9(a), CSRZ scheme with 64 channels and 100 GHz spacing at 500 km fiber length exhibits best performance, with min. BER6.29341E-320. In Figure 9(b), DRZ modulation scheme with 64 channels and 100 GHz spacing gives best behavior of min. BER 6.7128e-318, at fiber length 250 km. In Figure 9(c), MDRZ scheme with 32 channels and 100 GHz spacing at 500 km fiber length, exhibits the best min. BER value 3.06151E-222. Among all three cases, 64 channels with 100 GHz spacing at 250 km fiber length DRZ modulation scheme serves best performance. Increasing laser power leads to less erroneous data transmission upto more fiber length. While, MDRZ with 32 channels and 100 GHz spacing at fiber length 500 km gives second best performance in terms of min. BER value 3.20082E-277, 4.188E-296 for CSRZ and DRZ scheme respectively according to Figure 9(a) and 9(b). From Figure 9(c), for MDRZ scheme, increasing the number of channels upto 64 and keeping same fiber length 500 km results into min. BER value of 4.96292 E-194. Ideally, Min. BER keeps on decreasing nonlinearly with an increase in laser power, while afterwards remains constant after 20 dBm laser power, along with satisfying critical BER value 10E-9[24,25]. Table 2 represents best results drawn among various modulation schemes like CSRZ, DRZ and MDRZ in tabular form as a summary.

Table 3 shows a comparison between proposed work and two reference papers namely A. Sheetal et. Al[19] and B. Patnaik et. Al[26] in terms of maximum transmission distance covered, number of channels utilized, data rates of Ultra DWDM systems, spectral efficiency as per channel spacing. It is observed that proposed work exhibits more

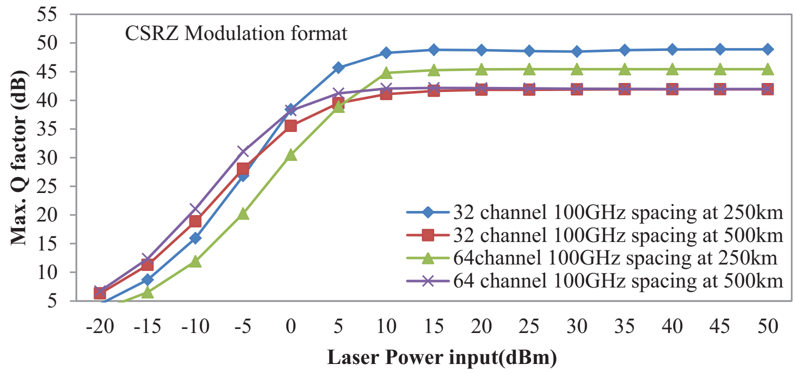

Figure 8.(a) Max. Q factor is plotted against Laser power input for CSRZ modulation scheme for 32 and 64 channels each with channel spacing 100 GHz at 250 km and 500 km fiber length.

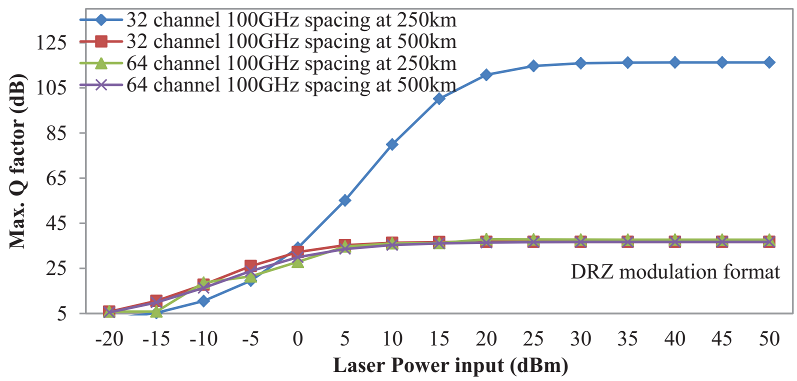

Figure 8.(b) Max. Q factor is plotted against Laser power input for DRZ modulation scheme for 32 and 64 channels each with channel spacing 100 GHz at 250 km and 500 km fiber length.

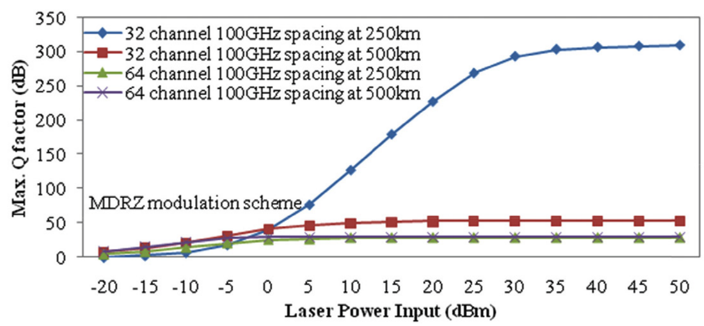

Figure 8.(c) Max. Q factor is plotted against Laser power input for MDRZ modulation scheme for 32 and 64 channels each with channel spacing 100 GHz at 250 km and 500 km fiber length.

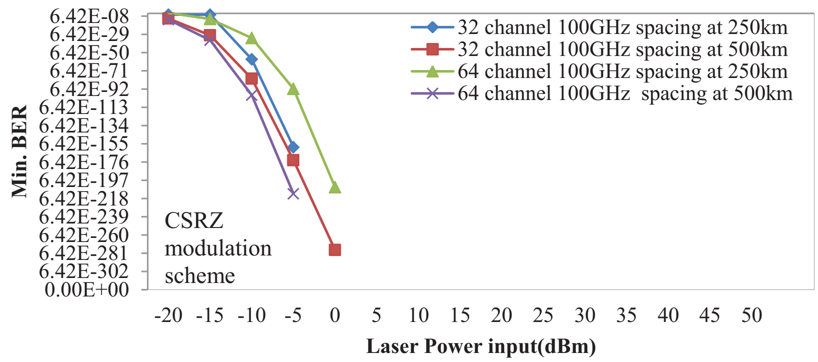

Figure 9.(a) Min. BER is plotted against Laser power input for CSRZ modulation scheme for 32 and 64 channels each with channel spacing 100 GHz at 250 km and 500 km fiber length.

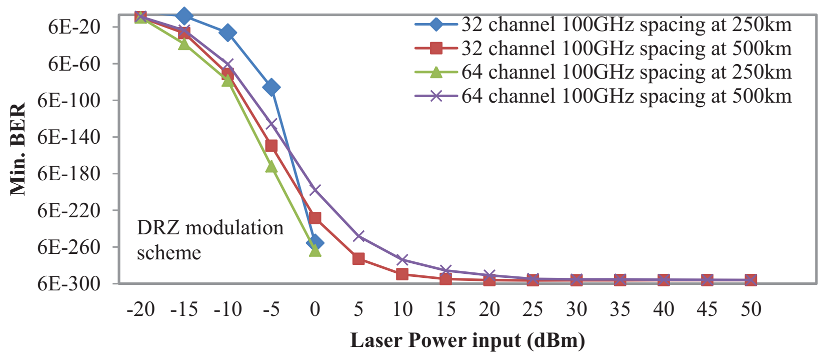

Figure 9.(b) Min. BER is plotted against Laser power input for DRZ modulation scheme for 32 and 64 channels each with channel spacing 100 GHz at 250 km and 500 km fiber length.

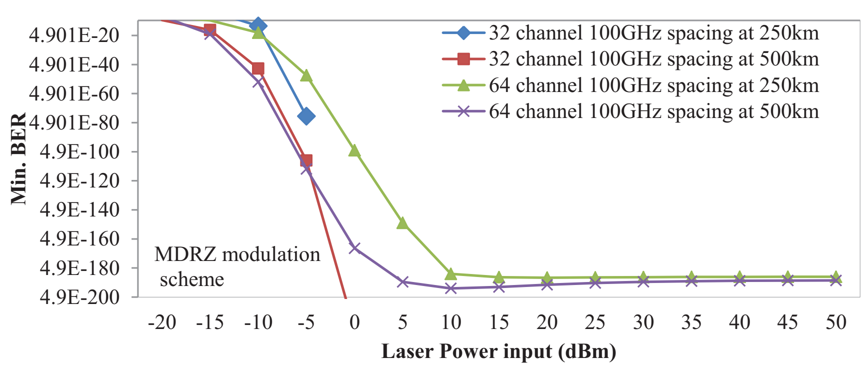

Figure 9.(c) Min. BER is plotted against Laser power input for MDRZ modulation scheme for 32 and 64 channels each with channel spacing 100 GHz at 250 km and 500 km fiber length.

Table 2. A summarized chart in terms of performance parameters as per modulation schemes

Modulation schemes		Variation with Fiber Length, km	Specifying best case	Variation with Laser Power (−20 to 50 dBm)	Specifying best case Channels/spacing/ Fiber Length	Maximum Transmission Reach
CSRZ	Max.Q factor	38.40 dB	32 channels, 75 GHz channel spacing	48.90 dB (Least)	32 / 100 GHz / 250 km	**4250 km (Highest)**
	Min. BER	3.20E-277		6.2934e-320	64 / 100 GHz / 500 km	
DRZ	Max.Q factor	34.12 dB		116.28 dB (Moderate)	32 / 100 GHz / 250 km	**3750 km (Moderate)**
	Min. BER	7.67E-264		6.7128e-318	64 / 100 GHz / 250 km	
MDRZ	Max.Q factor	40.10 dB		309.67 dB (Max.)	32 / 100 GHz / 250 km	**3000 km (Least)**
	Min. BER	3.2892e-316		3.0615e-222	32 / 100 GHz / 500 km	

Table 3. A Comparison chart in terms of type of research work made between the proposed work[19,26]

Type of Work	Max. transmission distance	Data rates	No. of channels	Channel spacing	Spectral efficiency
A. Sheetal et. Al[19]	2000 km	1.28 Tbps	16	25 GHz	1.6 bit/s/Hz
B. Patnaik et. Al[26]	1200 km	1.28 Tbps	64	100 GHz, 50 GHz	0.20 bit/s/Hz and 0.40bit/s/Hz
Proposed work	4250 km	1 Tbps	32	100 GHz, 75 GHz	0.40 bit/s/Hz and 0.53bit/s/Hz
	3500 km	2.5 Tbps	64	100 GHz, 75 GHz	0.40 bit/s/Hz and 0.53bit/s/Hz

than twice of the transmission distance covered using same modulation schemes.

4. Conclusion

An ultra-dense WDM network is being analyzed using CSRZ, DRZ and MDRZ modulation schemes with ultra-high data rates 1Tbps and 2.5 Tbps for 32 and 64 channels respectively, both with 100 GHz and 75 GHz spacing, corresponding spectral efficiency 0.40 bit/s/Hz and 0.53 bit/s/Hz. Based on analytical and numerical results, key conclusions drawn are as follows:

- CSRZ modulation scheme with 32 channels and 75 GHz spacing exhibits best performance covering transmission distance of 4250 km with good nonlinear and dispersion tolerance. MDRZ modulation scheme with 32 channels and 100 GHz spacing at 250 km fiber length serves best Max. Q factor with laser power variation shows good tolerance towards nonlinear effects. An increase in number of channels from 32 to 64 supports double simultaneous users, but results into performance degradation. A tradeoff is made in choosing MDRZ or CSRZ scheme as per need of maximum Q factor or maximum transmission distance.
- DRZ scheme with 32 channels and 75 GHz spacing provides moderate behavior in terms of transmission distance up to 3750 km, while with 32 channel and 100 GHz spacing at 250 km fiber length exhibits moderate behavior with laser power variation. DRZ scheme proves an optimum choice due to its moderate behavior.

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