Empirical analysis of polarization division multiplexing-dense wavelength division multiplexing hybrid multiplexing techniques for channel capacity enhancement

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ABSTRACT

This paper exemplifies dense wavelength division multiplexing combined with polarization division multiplexing with C-band frequency range-based single-mode fiber. In the proposed link, 32 independent channels with 16 individual wavelengths are multiplexed with two different angles of polarization. Each carrying 130 Gbps dual-polarization data with 200 GHz channel spacing claiming a net transmission rate of 4.16 Tbits/s with spectral efficiency of 69% with 20% side-mode-suppression-ratio (SMSR) and optical signal to noise ratio (OSNR) 40.7. The performance of the proposed techniques has been analyzed using optimized system parameters securing a minimum bit error rate (BER) 10-9 at a transmission distance up to 50 km.

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1. INTRODUCTION

The exponential increment in the supplication for data traffic was observed in the past few decades due to the inauguration of high-speed internet, social networking, live-streamed video conferencing, high-definition video streaming, cloud computing, and cable TV, which are powerful tools for 4th industrial revolution [1]. Optical fiber technology which has the potential to achieve terabit transmission links is expected to provide us solution to this intensive growing demand. Moreover, the fiber optics communication system is capable of the transmission of large data streams with low latency for both short and long-haul communication since its establishment in the early 1970s [2]–[6]. The installation time and cost for the system upgrade will dramatically decrease if the spectral efficiency or transmission capacity of any existing fiber system is improved without changing any part of the transmission or receiving sides. One approach is polarization division multiplexing (PDM) which will double the system capacity where two orthogonal polarized signals with a single wavelength traveled simultaneously in single-mode fiber [7]–[18]. In this modern era, the main focus of fiber optic communication is to achieve high data rates, high bandwidth, and high-speed data transfer. To compensate for the high demand for data this existing technology for fiber optics communication uses a combination of multiplexing techniques, which is dense wavelength division multiplexing (DWDM) and the other cornerstones technique PDM. One of the most important benefits of polarization division multiplexing is that the symbol rate can be reduced to half for the single polarization transmission enabling us to achieve high-speed transmission using relatively low-speed electronic devices.

This technique also provides an increase in bit rate without increasing the retribution of other parameters as in dispersion and most importantly the simplicity of the equipment that is used in this technique [19].

In recent research works the researchers have proposed various hybrid multiplexing techniques enlightening polarization division multiplexing, among the most common goals, was to achieve greater channel capacity over a significant transmission distance with satisfactory minimum bit error rate (BER) and Q-factor. Increasing transmission distance leads to deterioration of BER and jeopardization of net channel capacity. Pang *et al.* [20] worked with multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) gigabit fiber, based on polarization division multiplexing-dense wavelength division multiplexing (PDM-WDM) over single-mode fiber. Similar research was undertaken by Zhang *et al.* [21], where a PDM-WDM multiplexing system was used but with a pulse-amplitude modulation (PAM) technique with single mode fiber (SMF). Besides Zhang *et al.* [22] has conducted delicate research using a polarization division multiplexing-orthogonal frequency division multiplexing (PDM-OFDM) hybrid design based on nonreturn-to-zero (NRZ) modulation techniques where a maximum net channel capacity of 1.2 Gbits/s was reached over a transmission distance of 25 km standard-single mode fiber (SSMF). Few more researchers in [23] incorporated alternate mark inversion (AMI) in wavelength division multiplexing-polarization division multiplexing (WDM-PDM) 120 Gbps system over a free-space optical transmission system achieving a distance of 8 km. The hybrid PDM-WDM techniques were also undertaken by Chaudhary [24] where this system was used for inter-satellite communication under the influence of transmitting pointing errors over a distance of 1,000 km.

In this research, the preeminence of PDM-DWDM hybrid multiplexing techniques has been investigated by conducting optimization of several simulating parameters with different polarization angles (0° and 90°) over 32 optical communication channels. This hybrid technique has been introduced by 16 wavelengths with two orthogonal beam polarization (X-Polarization and Y-Polarization). This technique capitalized optically modulated data and has the capability to offer similar advantages including high-speed data transmission, cost-effectiveness, maintaining simplicity, higher bandwidth at the end-user, immunity to radiofrequency (RF) and electromagnetic interference. The outcome of this research work enabled us to transmit data at a maximum speed of 4.16 Tbits/s over a distance of 50 km SMF with a minimum log BER of -9.

2. RESEARCH METHOD

The proposed hybrid technique of optical fiber link interoperating 32-channel (X & Y polarization) of the PDM-DWDM transmission system is displayed in Figure 1. These 32 distinct channels with a 130 Gbps data rate per channel are multiplexed to realize a 4.16 Tbits/s optical fiber link. The channel spacing was optimized at 200 GHz to ensure the proper utilization of the bandwidth along with the counteraction of intersymbol interference. In between the dense wavelength division multiplexing (DWDM) multiplexer (MUX) and demultiplexer (DEMUX), the segment of optical fiber was SMF (G.652.D according to ITU-T standard) of 50 km, dispersion compensation fiber (DCF) of 9.85 km, and an optical amplifier for recovering dissipated power at the end of each segment. To optimize the PDM technique, it is important to fix the state of polarization (SOP) because it changes randomly over time. To control the state of polarization, a polarization controller needs to be used so that a high polarization extinction ratio (PER) can be ensured [19]. The two azimuth and ellipticity parameters helped to change the state of polarization from the polarization controller. Because when the fiber length increases the differential group delay increases [25]. So, fiber length also influences the quality factor. It has been shown that when the distance is 50 km, the quality factor Q=7.4 obtained with 130 Gbit/s and 200 GHz channel spacing but with increasing fiber length along with the bit rate, the quality factor degraded Q<6.

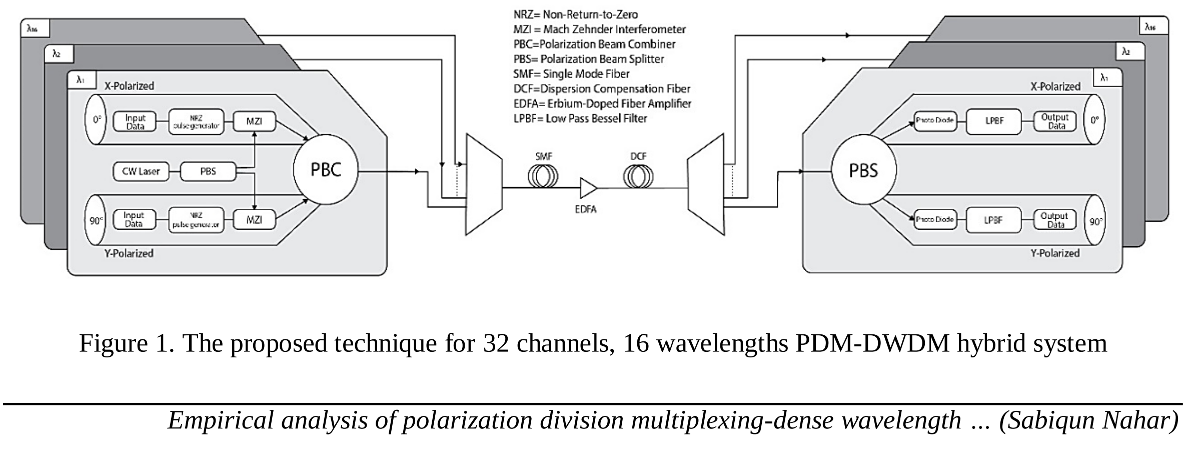

Figure 1. The proposed technique for 32 channels, 16 wavelengths PDM-DWDM hybrid system

2.1. Design of a single channel

Figure 2 illustrated each channel capable of transmitting 130 Gbit/s over a single channel by pseudo-random bit sequence generator (130 Gbit/s, Order=2^{10}-1) has sent to NRZ pulse generator (3.2 THz sample rate), and then both X and Y polarized signal was fed to the Mach-Zehnder interferometer (MZI) modulator (extinction ratio 30 dB, -1 symmetry factor). The laser beam from a continuous laser was connected to the polarization controller via MZI modulator, the continuous laser source had 10 dBm power, 0.01 MHz linewidth, (-100 dB) threshold noise, and noise dynamic 3 dB. The polarization controller appointed the angle of polarization which was 0° and 90° and the channel spacing was set at 200 GHz. The polarization beam combiner combined these two orthogonal beams (X-Polarization and Y-Polarization) which were directed towards the DWDM multiplexer. The 16×130 Gbps information signal at the input of DWDM-MUX was transmitted over a 50 Km distance. To describe the polarization state of these two orthogonal beams, the Stokes theorem would be a factor to be taken care of, because the Stokes parameters are a set of values that provides the polarization states of a light beam that is used to be traveled. Those parameters are merged into a vector form which is known as [26], [27].

$$S_{\theta} = \begin{bmatrix} S0 \\ S1 \\ S2 \\ S3 \end{bmatrix}$$

Here θ is the polarization angle, and S_0 is the intensity of the light beam. It also can be defined as $S_0 = I$, where I will be the total intensity of light. (S1, S2, S3) are the Cartesian coordinates of the three-dimensional vector position in space of the light beam in this technique, the polarization angles were 0° and 90° so for 0° linearly polarized light, the Stokes vector will be,

$$S_0 = [1\ 1\ 0\ 0]$$

and also, for 90° linearly polarized light, the stokes theorem will be as,

$$S_{90^\circ} = [1\ -1\ 0\ 0].$$

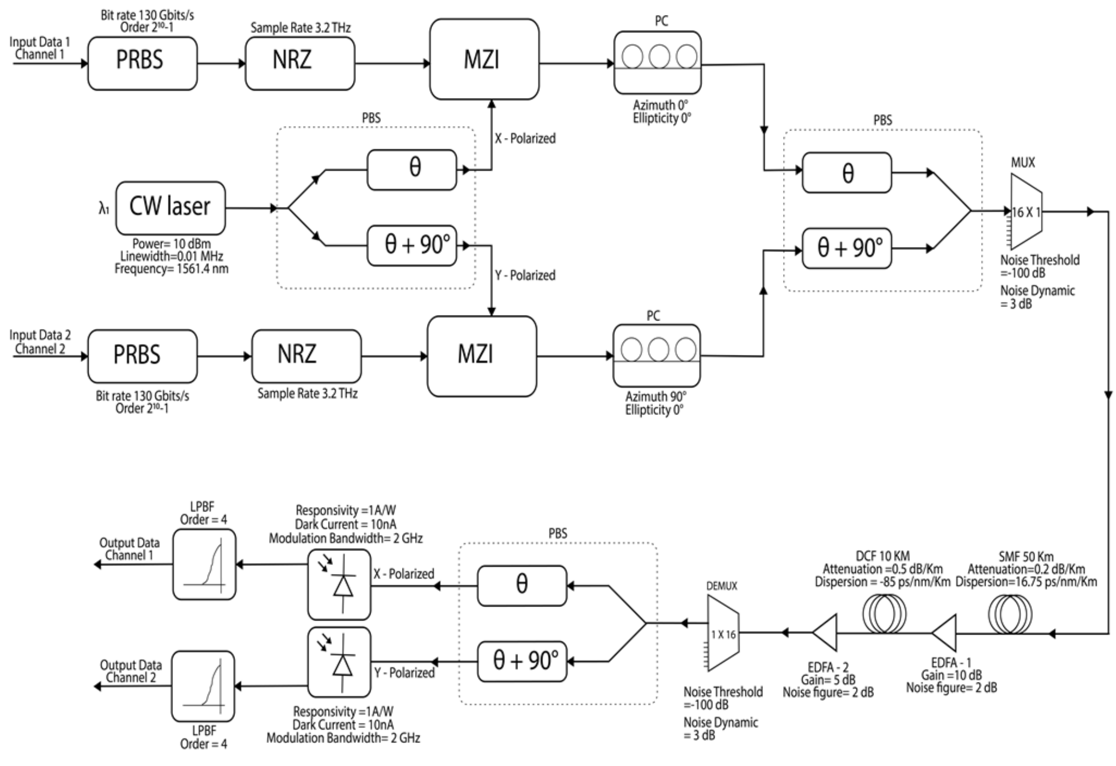

Figure 2. Design of a single channel of single wavelength, dual polarized signal at both transmission and receiving end

2.2. Receiving end

At the receiving side, 16 polarization beam splitters have been connected and each splitter divides two orthogonal polarization beams (X-Polarized & Y-Polarized) to separate two common frequency channels from the transmission end. The dual outputs of the splitter are connected with a photodiode (Responsivity=1A/W, Dark current=10 nA, Junction capacitance=3 pF, Modulation Bandwidth=2 GHz). The lowpass Bessel filter (cut off frequency=75 GHz, Depth=100 dB). This filter provides constant group delay which provides eye-opening height and also helped to achieve a minimum bit error rate of 10^{-9} in the receiving end. There is a relation between polarization mode dispersion and differential group delay. This relation can be introduced in an equation of Stokes theorem which is given,

$$\vec{\tau} = \tau . \hat{q} \quad [19]$$

where τ is the group delay time and $\hat{q}$ defines the slowest principal state of polarization.

Since polarization multiplexing devices are very sensitive to linear and non-linear effects, the system parameters are largely affected if any modifications are made in the polarization controller, polarization beam splitter, or polarization beam combiner. There are lots of ways to compensate for the polarization mode dispersion such as using advanced or complex modulation techniques, Using linear, non-linear filters, and polarization emulators. In this paper, a polarization emulator has been used on the receiving side so that it could control the delay between both polarizations at the receiving end.

2.3. Fiber section

In optical networks the demand for bandwidth has become more popular nowadays, to overcome the increasing demand for bandwidth installation of new fiber-optic could be expensive, so it would be a wise decision to use the existing fiber-optic network very effectively. The main parameter that bothers the optical fiber network is attenuation and dispersion. An efficient network design could improve the use of two polarization axes and the use of fiber defends polarization which allows the use of two polarization planes. The proposed technique has clarified that single-mode fiber could be the safest option for maintaining both wavelength division multiplexing and polarization division multiplexing. For single-mode fiber, the dispersion was 16.75 ps/nm/km and the attenuation was 0.2 dB/km. To compensate for this parameter DCF has been used. The attenuation value of DCF was 0.5 dB/km and the dispersion value was -85 ps/nm/km. Analyzing the polarization multiplexing, required two signal sources, one with horizontal polarization (X-Polarization) and the other with vertical (Y-Polarization). It is also necessary to combine both of the signals into one conjoint fiber with the polarization beam combiner. To detect these multiplexed signals, it is essential to keep both original polarization axes and rotation angles at the correct angle. Polarization beam splitter (PBS) systemized the correct rotation signals and then it splits both signals to send them to the correct receiver. By the polarization beam combiner, two individual polarization signals have been sent into the optical fiber. Both input signals are linearly polarized. Therefore, there was no need of adding linear fiber polarizers. While both signals were linearly polarized, to avoid inconvenience angle rotation, a polarization controller was used for both signals for the position of linearly horizontal and vertical polarization. There were no problems with the synchronization of both signals, the system operates well enough without interferences.

3. RESULTS

3.1. Performance evaluation of PDM-DWDM with different channel spacing (50, 100, and 200 GHz) using optimized simulation parameters

The design criteria for this research involve the construction of a PDM-DWDM hybrid multiplexing system with a high-speed data transfer rate and enhanced channel capacity for a short distance of up to 50 km using SMF. Channel spacing is one of the most important issues when designing a DWDM system. The channel spacing of a particular system predominantly affects its performance, as a result finding the optimized channel spacing is crucial. Reducing channel spacing might lead to interferences in the adjacent channels and the receiver sensitivity is required to be increased. However, this action will lead to an increase in the number of channels in a specific bandwidth which will enhance the channel capacity of the system. In this research, the performance analysis of the PDM-DWDM hybrid system was primarily performed for 3 different channels spacing, i.e., 50, 100, and 200 GHz. In each case, the parameters like laser power, and bandwidth of DWDM were optimized considering their commercial availability. The optimized parameters were displayed in Table 1. For each channel spacing, the bit rate of each channel was progressively increased and the maximum allowable bit rate was found. The BER increases with the bit rate per channel and hence the min log BER was set at -9. For the min log BER of -9, the maximum allowable bit rate per channel was found to be 32, 65, and 130 Gbits/s for the channel spacing of 50, 100, and 200 GHz respectively. Each laser wavelength being bi-polarized the channel number stands at 32. Each laser frequency is carrying two-bit streams of dual-polarized data; hence the total channel number becomes 32.

Table 1. Optimized simulation parameters and total channel capacity for the channel spacing of 50, 100, and 200 GHz

Parameters	50 GHz	100 GHz	200 GHz
Optimized laser power	4 dBm	4 dBm	10 dBm
Optimized Bandwidth for WDM	50 GHz	80 GHz	160 GHz
Number of Channels	16λ×2	16λ×2	16λ×2
Spectrum Range	0.75 THz	1.5 THz	3 THz
Maximum allowable bit rate per channel for min Log BER -9	32 Gbits/s	65 Gbits/s	130 Gbits/s
Total channel capacity	1.024 Tbits/s	2.08 Tbits/s	**4.16 Tbits/s**
Total channel capacity for the spectral range of 3 THz	**3.706 Tbits/s**	**3.942 Tbits/s**	N/A

For the 50 GHz system, a spectral range of 0.75 THz was used with the total capacity of 1.024 Tbits/s, whereas for the 100 GHz channel spacing system a spectral range of 1.5 THz was used with the total capacity of 2.08 Tbits/s. However, for a 200 GHz channel spacing system even if a larger spectral range were used i.e., 3 THz the total capacity can be calculated to 4.16 Tbits/s. In the spectral range of 3 THz for a 50 GHz channel spacing system, when 32×4=128 channels are added, it was found to have a total capacity of 3.706 Tbits/s. The same illustrations were applied for the 100 GHz channel spacing system, with 32×2=64 channels coupled in total over a spectral range of 3 THz, giving us a total capacity of 3.942 Tbits/s However, for a 200 GHz channel spacing system, if only 32 channels (16 wavelengths) were deployed the total capacity was calculated to be 4.16 Tbits/s. From the analysis stated above, it can be concluded that the channel spacing of 200 GHz will be suitable according to our design criteria.

The degradation of the BER and Q-factors over 250 km distance is added in Figures 3 and 4 respectively, where we can observe the Q factor decreases with an increase in Tx distance. The extinction ratio also falls as we increase the transmission range and they are added in Figure 5. Considering min log BER, Q-factor, and extinction ratios it can be concluded that this system will perform consummately with the maximum distance up to 50 km, with the channel spacing of 200 GHz with optimized parameters as mentioned in Table 1 since the acceptable log BER is below -9 and from Figure 3 it can be observed that for the distance below 50 km the BER is acceptable [28], [29].

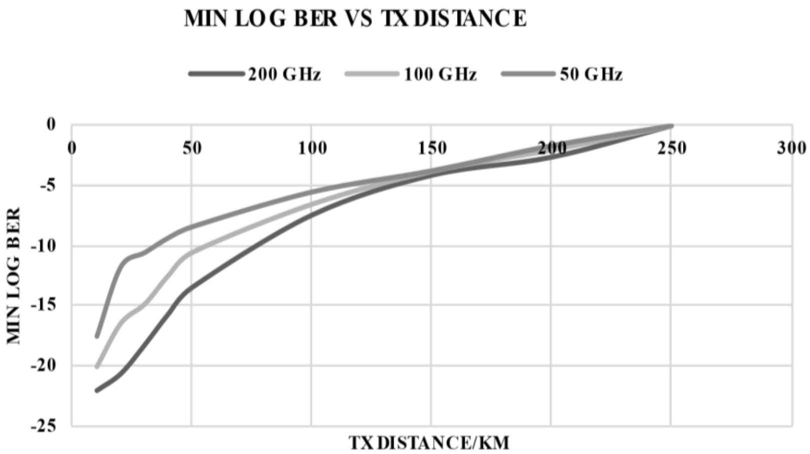

Figure 3. Min Log BER vs Tx distance up to 250 km

The eye diagram degrades as the transmission distance increases. The Q factors drastically fall with the increase in transmission distance and the eye height fades too. As a result, the maximum transmission distance for this system at this bit rate cannot exceed 50 km. Figure 6 shows the eye diagram over a distance from 10-50 km and it can be observed that the eye diagram remains distinct and clear up to 50 km distance and the min BER remains in the acceptable range. Figure 7 shows the transition of min BER and Q-factor over a bit period for the 5-transmission distance, i.e., 10-50 km in 10 km intervals.

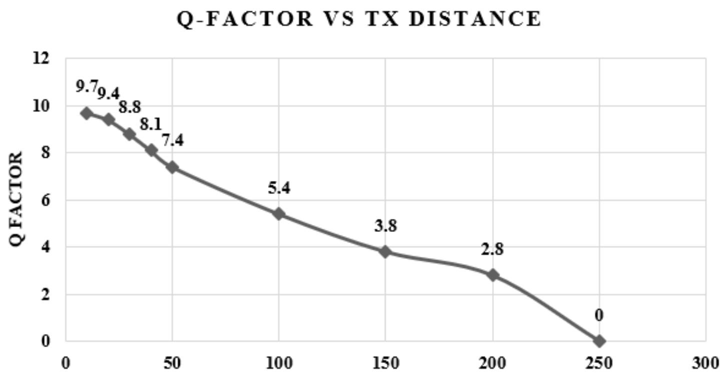

Figure 4. Q-factor vs Tx distance up to 250 km

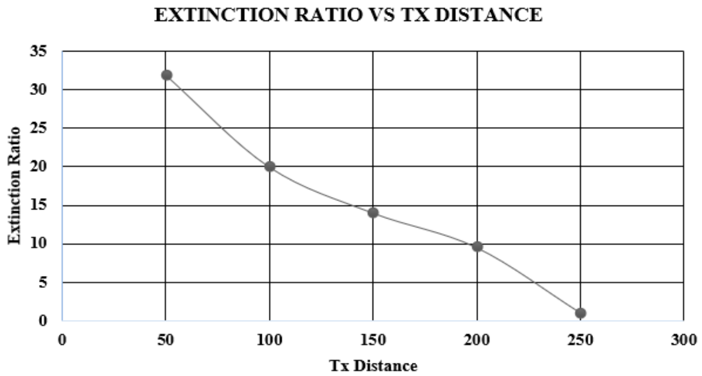

Figure 5. Extinction ratio vs Tx distance up to 250 km

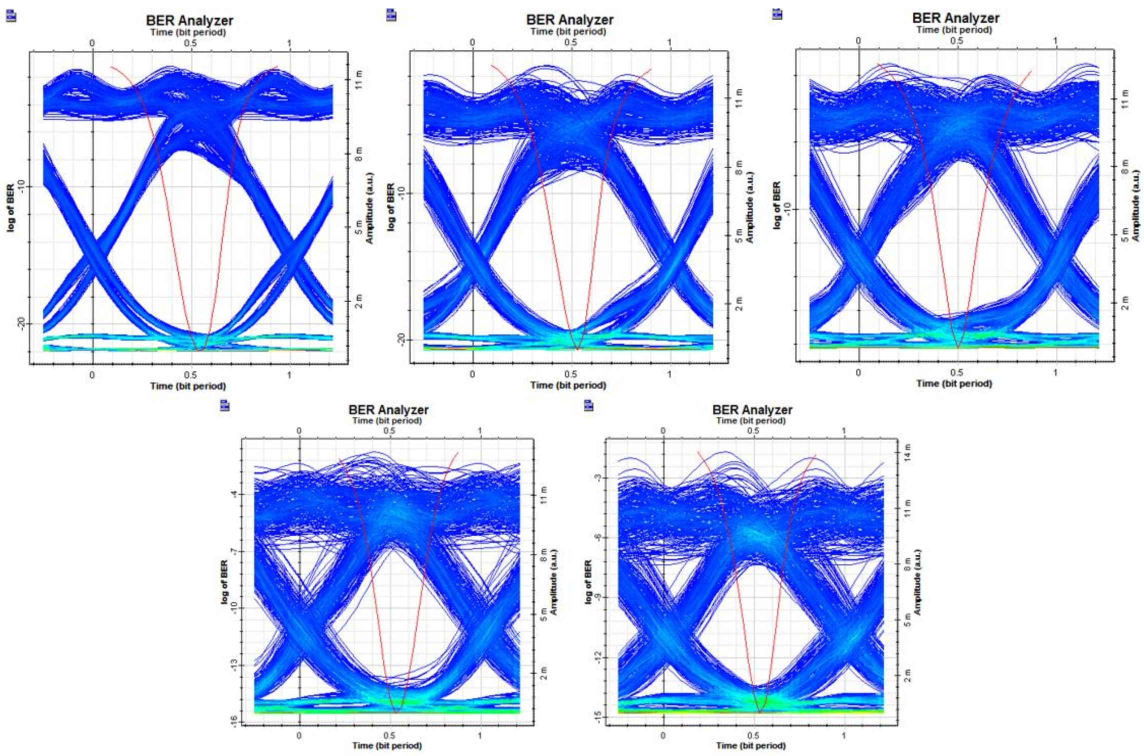

Figure 6. Degradation of eye diagram over a transmission distance of 10-50 km in 10 km intervals

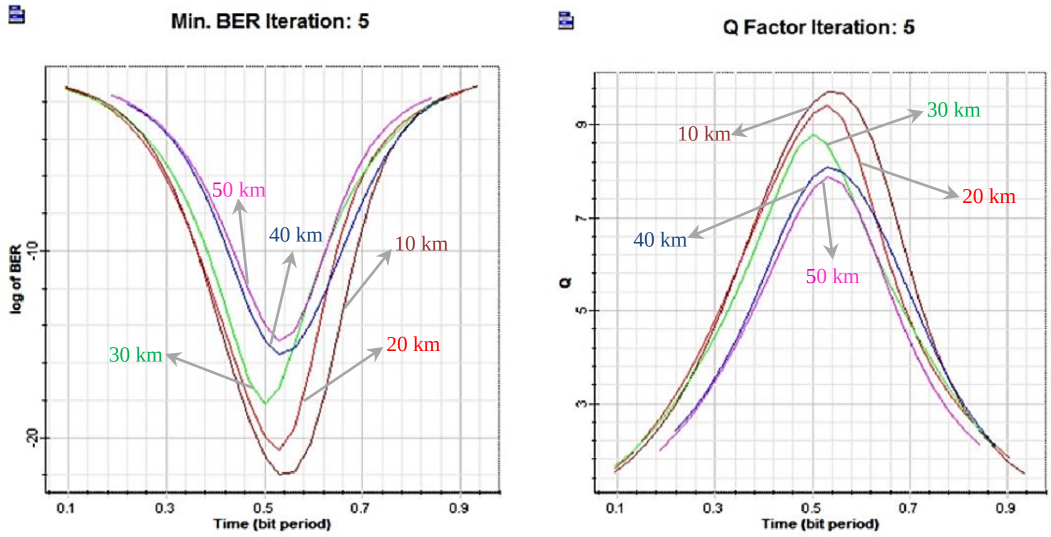

Figure 7. Transition of min BER and Q-factor over a bit period for the 5-transmission distance, i.e., 10-50 km in 10 km intervals

3.2. Performance evaluation of PDM-WDM from optical spectrum analyzer (OSA) for channel spacing of 200 GHz over 50 km distance using optimized simulation parameters

Figure 8 shows the optical spectrum extracted from the dual-port OSA from the DWDM MUX and DEMUX along with the distance of 250 km. 16 distinct lines can be observed representing 16 CW lasers operating over the frequency range from 192 to 195 THz. With the channel spacing set at 200 GHz and laser power and line width of 10 dBm and 0.01 MHz respectively, it can be observed that the lines are equally spaced and uniformly allocated over the spectral range of 3 THz. When converted to wavelength it lies over the range of 1,537 to 1,561 nm, which is only 0.84% away from the 1550 nm milestone which is considered to be the lowest loss window.

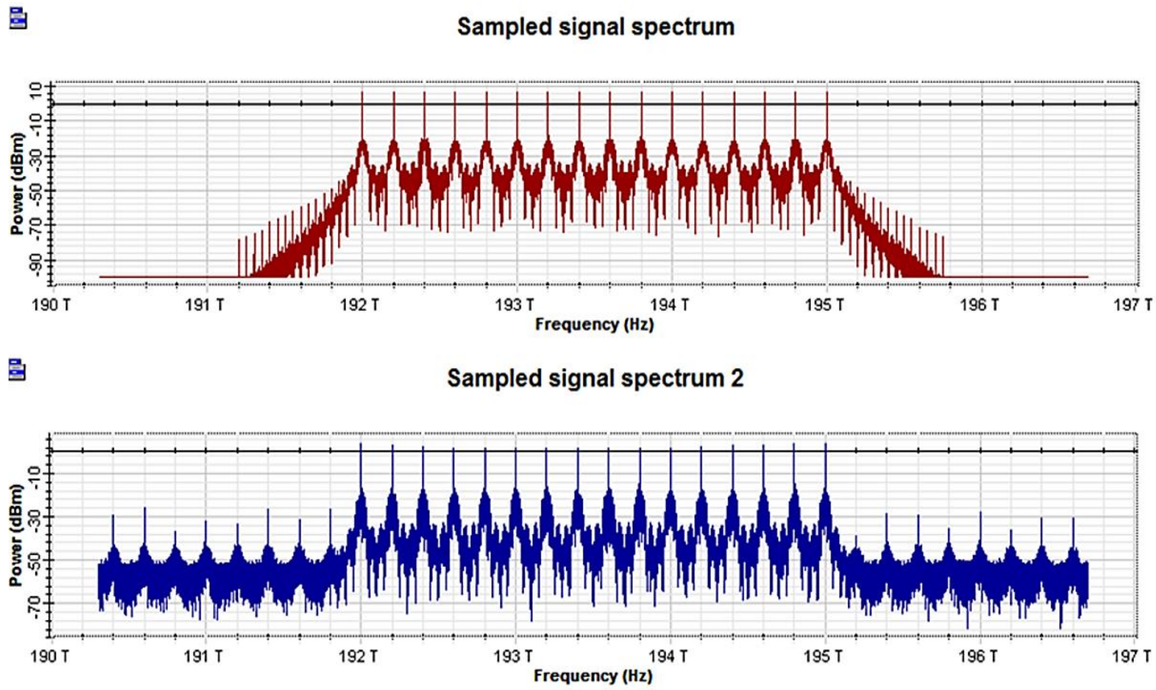

Figure 8. Optical spectrum from dual port OSA connected to DWDM and DEMUX over a transmission distance of 250 km

All the spectral lines are having almost equal heights, allocating equal and sufficient power in all channels. The variation of the lowest side-mode-suppression-ratio (SMSR) over a distance of 250 km is shown in Figure 9. The spectral efficiency for this proposed system was found around 69% with a minimum optical signal to noise ratio (OSNR) of 36.87. The spectral efficiency can be calculated by the ratio of net throughput (130 Gbits/s) and the channel Bandwidth (3/16 THz). The variation of minimum OSNR over a transmission distance of 250 km is represented in Figure 10. The BER performance of the network was observed by plotting min Log BER against min OSNR as displayed in Figure 11. According to IEEE standards, the forward error correction (FEC) limit which is the limit below which the OSNR of this system cannot degrade, was set at log BER -3, and corresponding to that the OSNR threshold was found to be 38 dB which is below our minimum OSNR at a distance of 50 km, i.e., 40.7 dB [30].

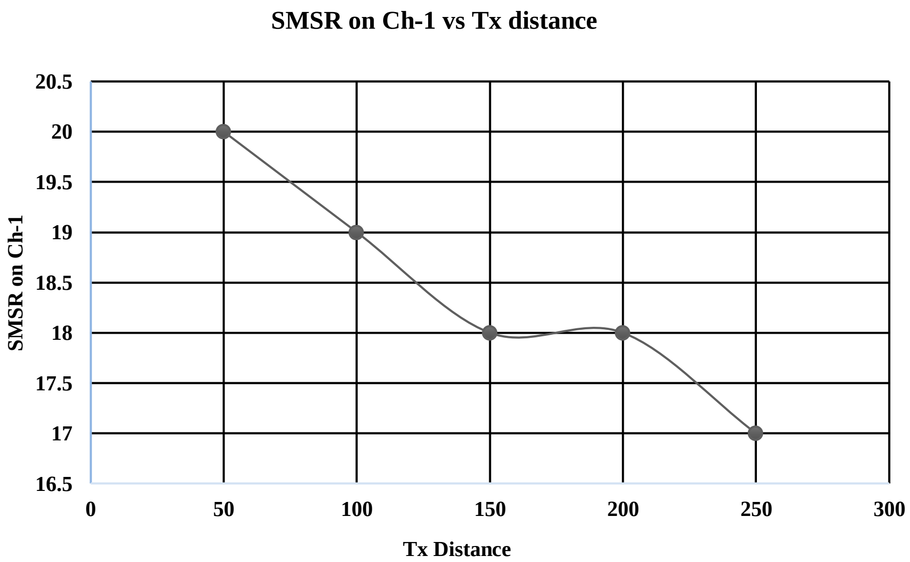

Figure 9. Variation of lowest SMSR over a distance of 250 km

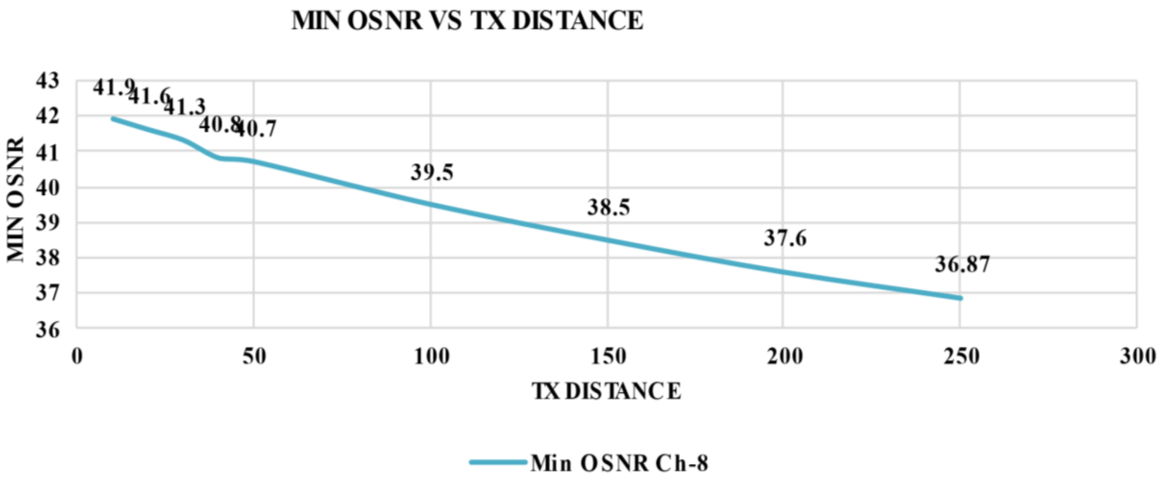

Figure 10. variation of minimum OSNR over a transmission distance of 250 km

3.3. Comparison with other hybrid techniques

The proposed link was compared with several PDM-WDM hybrid techniques designed by various researchers using different modulation techniques. They are summarized in Table 2. The comparison can be drawn based on several factors like bandwidth usage, transmission distance, transmission medium, net channel capacity, modulation techniques, and simplicity. Our proposed technique involves the optimization of several simulative factors which are often not considered in research work. Morant [22] worked with a

PDM-OFDM multiplexing system based on NRZ modulation over a distance of 22.6 km SSMF with a net speed of 1.2 Gbits/s whereas our proposed technique has attained a net speed of 4.16 Tbits/s over a range of 50 km. Pang [20] designed a WDM-PDM hybrid technique based on a 16-QAM modulation technique reaching a distance of 22.8 km over SMF with a net data rate of 1.59 Gbits/s. Zhang [21] also performed an analysis on the WDM-PDM technique with the PAM-4 modulation technique reaching a maximum distance of 40 km on SMF and a net capacity of 550 Gbits/s. The proposed technique outperforms them all in simplicity, bandwidth usage, transmission distance, and channel capacity.

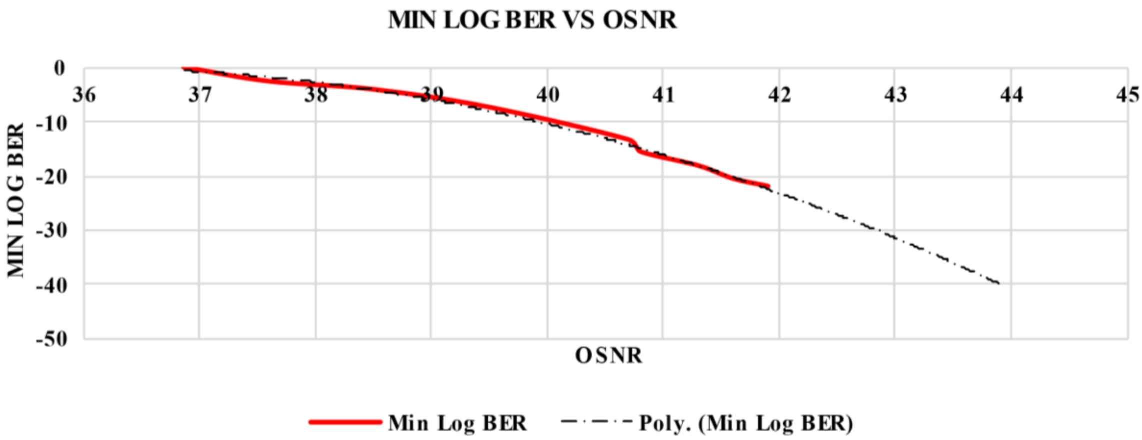

Figure 11. Min log BER vs Min OSNR, FEC threshold seen at the value of 38 dB

Table 2. Performance comparison of the proposed system with the previous works

Researchers	Hybrid Technique	Net data rate	Transmission range	Number of channels	Transmission medium	Modulation technique
Pang [20]	PDM-WDM	1.59 Gbits/s	22.8 km	3	SMF	16 QAM
Zhang [21]	PDM-WDM	550 Gbits/s	40 km	11	SMF	PAM-4
Morant [22]	PDM-OFDM	1.2 Gbits/s	25 km	3	SSMF	NRZ
Proposed Technique	PDM-DWDM	4.16 Gbits/s	50 km	32	SMF	NRZ

4. CONCLUSION

The proposed system associates performance analysis of hybridization PDM-DWDM multiplexing technique through the passage of single-mode fiber with a net speed of 4.16 Tbits/s in C-band with optimized system parameters up to a transmission range of 50 km. The system incorporates 32 independent channels (16 frequencies), each channel retaining a bit rate of 130 Gbits/s, making the overall capacity 4.16 Tbits/s (32×130 Gbits). The outcomes of this research grant us 69% spectral efficiency, 20% SMSR in each channel, good Q-factor, enhanced channel capacity, safe OSNR, and satisfactory minimum BER, in comparison to the traditional system using SMF. This advocates the superiority in the performance of our proposed hybrid model although an elementary and cheaper modulation technique was used for the designing of a high-speed network system.

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