High-speed multi-channel long-haul coherent optical transmission system

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ABSTRACT

In this work, high-speed transmission over the long-haul optical channel using orthogonal frequency division multiplexing (OFDM) was investigated. Furthermore, we recommend mixing polarization division multiplexing (PDM) with coherent OFDM (CO-OFDM) and quadrature amplitude modulation (16-QAM) to improve spectral efficiency (SE) while transmitting over a wavelength division multiplexing (WDM) system. An 800 Gb/s WDM PDM-CO-OFDM-16QAM transmission system with various channel spacing of 100 GHz, 50 GHz, and 25 GHz is examined utilizing the OptiSystem (2021) version 18.0 software package over ten spans of 60 km standard single-mode fiber (SSMF). Different channel spacing WDM systems have been compared in terms of performance and SE. The results reveal that the WDM system with 100 GHz channel spacing has a longer transmission range and needs minimal optical signal to noise ratio (OSNR) at the reception. The 25 GHz channel spacing WDM system exceeds the others in terms of SE. Further, the effect of ultra-low loss and large effective area fiber in lowering span loss and nonlinear effects for 25 GHz channel spacing WDM system is investigated. The findings show that the system performance with the new fiber outperforms the SSMF. The acceptable bit error rate (BER) for this study is 0.033 (20% concatenated forward error correction (FEC) threshold).

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1. INTRODUCTION

In recent years, the accelerating growth of internet traffic has become a vital challenge for high-rate optical networks. Consequently, optical orthogonal frequency division multiplexing (OFDM) is becoming extremely relevant to dealing with the effects of chromatic dispersion and polarization mode dispersion (PMD) while simultaneously increasing spectral efficiency (SE) [1], [2]. Rather than sending one wideband signal, OFDM technology sends several little sub-bands orthogonally [3]. Furthermore, using the coherent detection method with OFDM might compensate for connection defects digitally [4]. The use of polarization division multiplexing (PDM) and higher-order modulation schemes are two additional ways to improve the system's spectral efficiency [5], [6].

One of the most appropriate methods for increasing the data transfer rate in optical transmission systems is wavelength division multiplexing (WDM). When sending multiple optical data flows together and at the same time through one optical cable, the transmission capacity increases typically without the need to add another cable [7]–[9]. The resulting signal is then transmitted via optical fiber. The optical flows are separated individually on the receiving side to extract original data from the independent receiving devices.

Assuming N optical single-channel lines with data rates B_1, B_2, ... B_N are all at the same time sent across a fiber of finite length, the overall data rate of the WDM connection as in (1).

$$B_T = B_1 + B_2 + \cdots B_N \quad (1)$$

The total capacity of the transmission system is enhanced by a factor of N when all lines have the same data rates. The total count of lines N, the data rates B of every line, and the frequency spacing $\Delta\nu_{ch}$ between two adjacent channels are the most critical design factors for a WDM system. The term $(N \times B)$ refers to system capacity, and the $(N \times \Delta\nu_{ch})$ accounts for the overall bandwidth used by a WDM system [10], [11]. The (2) is the description of spectral efficiency (η_s).

$$\eta_s = B/\Delta\nu_{ch} \quad (2)$$

A WDM transmission system's capacity can be raised in various methods, including utilizing a broader optical bandwidth, enhancing spectral efficiency, or combining the two. Using a broader optical bandwidth often necessitates the installation of farther optical amplifiers and other optical elements; thus, increasing spectral efficiency seems to be the most cost-effective option. For the best SE WDM system, spacing between adjacent channels must be minimized; hence the fiber nonlinearity impacts such as self-phase modulation (SFM), cross-phase modulation (XPM), four-wave mixing (FWM), and stimulated Raman scattering (SRS) in parallel with crosstalk effect, increases and degraded the transmission performance [12], [13].

The fast development in optical fiber has lately created a new age of potentials: ultra low loss fiber [14] and large-effective-area fiber [15]. Compared with SSMF, the optical signal to noise ratio (OSNR) for ultra low loss fiber systems will be improved by reducing fiber loss. Additionally, the appropriate optical power increases as the optical cable's effective area increases, which is essential to improving the received OSNR. Consequently, a low loss with large effective area fiber could be an excellent alternative for improving a high-speed optical network transmission performance [16]. It has been completed and deployed for undersea installations, as stated in ITU-T recommendation G.654. The ITU-T gives the G.654.E definition as a new ultra-low-loss fiber with a large effective area capable of supporting high-speed transmission for terrestrial use. Various systems and practical tests [17]–[23] include the G.654. E fiber to decrease the nonlinearity effect and losses in single and multi-channel transmission systems.

This work aims to analyze the effect of channel spacing on spectral efficiency and transmission performance for an (8×100 Gbps) WDM-PDM-CO-OFDM-16QAM system across (10×60 km) link of SSMF using the optisystem 18 software. Three-channel spacings of 100 GHz, 50 GHz, and 25 GHz are used in this investigation. Further, we will replace the SSMF with G.654E fiber for a narrower channel spacing WDM system with higher SE to enhance the long-haul transmission performance by decreasing the nonlinearity effect and attenuation in the transmission medium. The OSNR, launching power effectiveness on BER, constellation diagrams, and eye diagrams were the focus of our attention. The suggested system is examined using an inline Erbium-doped fiber amplifier (EDFA) and dispersion compensation fiber (DCF) to boost the optical signal and mitigate the dispersion, respectively. The reference BER used in this study is 0.033 (20% overhead concatenated forward error correction (FEC) threshold) [19].

2. RESEARCH METHOD

As shown in Figure 1, the 800 Gb/s WDM PDM-CO-OFDM-16QAM transmission system is designed using numerical simulation software, optisystem 18. The suggested system is divided into three parts: transmitter, optical channel, and receiver. Table 1 shows the global simulation settings.

Table 1. Global simulation parameters

Parameters	Value
Data rate (Gb/s)	100
Symbol rate (GS/s)	12.5
Sequence length (bit)	32768

2.1. Transmitter setup

Before adopting 16-QAM encoding, a pseudo-random binary sequence (PRBS) generator produced 100 Gb/s data bits that were divided into odd and even data streams using a serial to parallel adapter. The OFDM modulator modulates the resulting signal. Then the in-phase and quadrature parts of the OFDM signal pass through a low pass filter (LPF). After that, two Mach-Zehnder modulators (MZM) were used to convert the RF-OFDM signal from the electrical to an optical domain for each polarization component of a CW laser beam. A polarization beam combiner (PBC) joins the two perpendiculars modulated optical signals, achieving PDM. The optical multiplexer is then used to simultaneously send all eight PDM-CO-OFDM-16QAM optical signals to the optical channel. Table 2 shows the transmitter parameters.

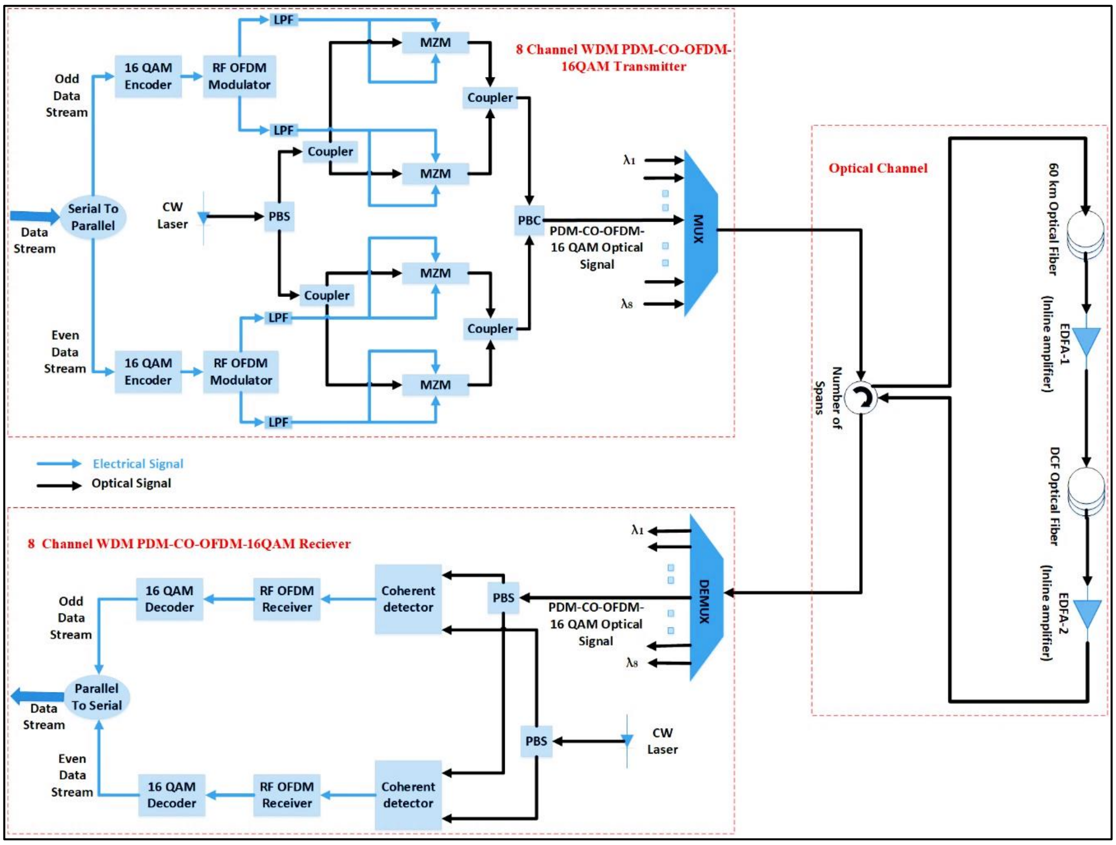


Figure 1. Proposed model of 8 channel WDM-PDM-CO-OFDM-16QAM optical communication system

Table 2. Transmitter parameters

Parameters	Value
– CW laser for central channel	
Frequency (THz)	193.1
Linewidth (MHz)	0.1
Power (dBm)	Variable
– OFDM modulator and demodulator	
Total number of subcarriers	128
Number of carrying subcarriers	80
Number of pilot symbols	6
Number of training symbols	10
Number of prefix point	10
Average OFDM power (dBm)	15
– Mux/Demux	
Frequency spacing (GHz)	100, 50, and 25
Bandwidth (GHz)	25
Insertion loss (dB)	2
Filter type	Gaussian
Filter order	4

2.2. Optical channel

Ten spans of SSMF cable or G.654.E fiber cable make up the optical channel. The DCF is utilized to compensate for the dispersion effect in each loop. Also, two optical amplifiers (EDFA's) in every loop equalize the attenuation of SSMF or G.654.E fiber with the corresponding DCF. Table 3 shows the channel characteristics.

Table 3. Optical channel characteristics

Parameter	SSMF	G.654E [23]
	Value	
Span length (km)	60	60
Attenuation coefficient (db/km)	0.2	0.168
Dispersion coefficient (ps/nm/km)	16.75	21
Fiber nonlinearity (m^2/W)	0.075	0.07
Fiber nonlinearity (m^2/W)	26×10^{-21}	22×10^{-21}
Effective area (μm^2)	80	125
	EDFA-1	
Gain (dB)	12	10.08
Noise figure (dB)	4	4
	DCF	
Span length (km)	11.8	14.8
Attenuation coefficient (db/km)	0.5	0.5
Dispersion coefficient (ps/nm/km)	-85	-85
Dispersion slope coefficient (ps/nm^2/km)	-0.375	-0.375
Dispersion slope coefficient (ps/nm^2/km)	26×10^{-21}	26×10^{-21}
Effective area (μm^2)	22	22
	EDFA-2	
Gain (dB)	5.9	7.4
Noise figure (dB)	4	4

2.3. Receiver setup

The eight PDM-CO-OFDM-16QAM incoming optical signals were passed through an optical Demultiplexer to separate them individually. After that, a polarization beam splitter (PBS) splits each signal into two polarization components, which are then fed into a coherent detector to capture the RF-OFDM signal with the assistance of a local oscillator (LO) laser, with settings as shown in Table 4. The OFDM demodulator retrieves the original symbols and then the original bits by the 16-QAM decoder. Lastly, the digital data stream is collected by parallel to the serial converter. The OFDM demodulator,16-QAM decoder, and Demultiplexer settings are identical to those of the transmitter.

Table 4. LO settings for a center channel of the WDM system

Parameters	Value
Frequency (THz)	193.1
Linewidth (MHz)	0.1
Power (dBm)	10

3. RESULTS AND DISCUSSION

To understand the approximate transmission distance that can be reached with various channel spacing WDM systems. The transmission performance of the PDM-CO-OFDM-16QAM system was first simulated for 100 Gb/s single-channel, then 800 Gb/s multi-channel with 100, 50, and 25 GHz channel spacing. As shown in Figure 2, The WDM system had a shorter transmission distance than the single-channel system. Also, as the channel spacing decreases for WDM, the system’s BER worsens.

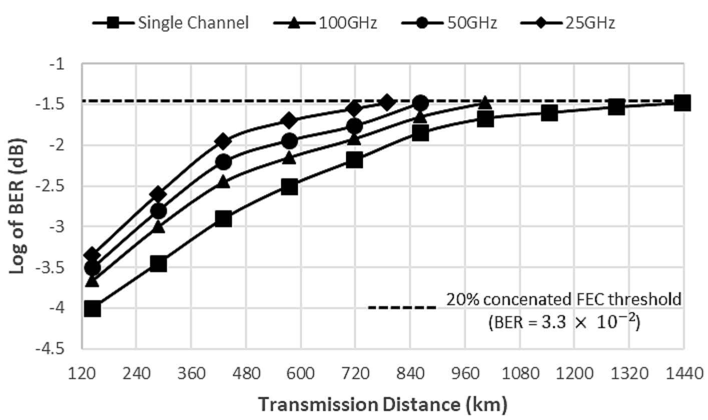
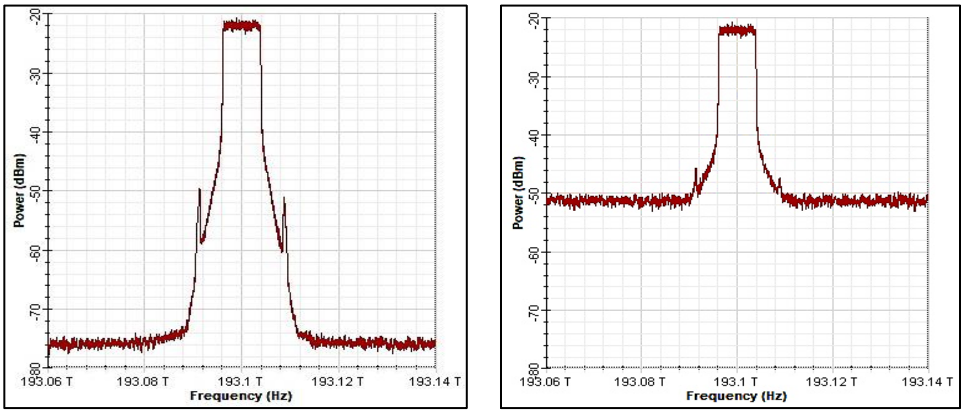


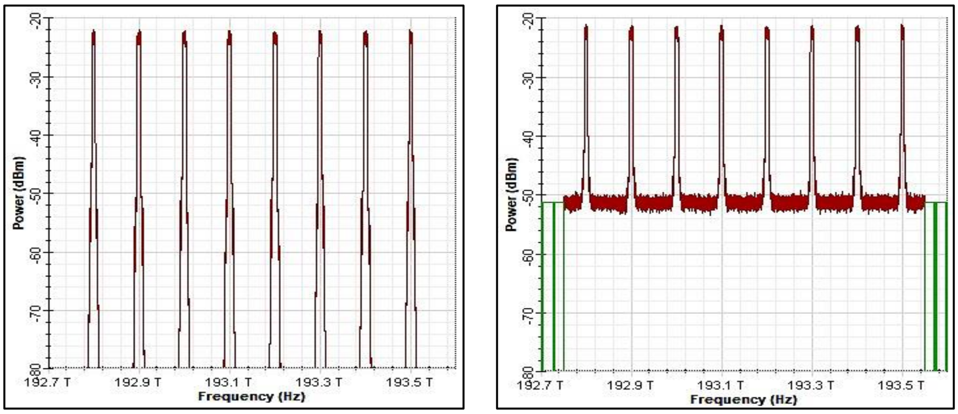
Figure 2. BER vs transmission distance for single channel and multi-channel systems with different channel spacing at center channel of 193.1 THz

Figure 3 to Figure 6 depict the optical transmission spectrum for single-channel and WDM systems on transmission and reception end after 718 km of SSMF and DCF: Figure 3(a), Figure 3(b) for single-channel system; Figure 4(a), Figure 4(b) for 100 GHz channel spacing WDM system; Figure 5(a), Figure 5(b) for 50 GHz channel spacing WDM system; and Figure 6(a), Figure 6(b) for 25 GHz channel spacing WDM system. Concerning WDM systems, each has a different spectral bandwidth corresponding to the distance between adjacent channels. For 100 Gbps single-channel data rate, the allowable SE for 100, 50, and 25 GHz channel spacing WDM systems are 1, 2, and 4 bits/sec/Hz, respectively. To put it more simply, a WDM system with 25 GHz spacing can transfer the highest data rate within restricted optical bandwidth, followed by 50 GHz and 100 GHz, respectively.



(a) (b)

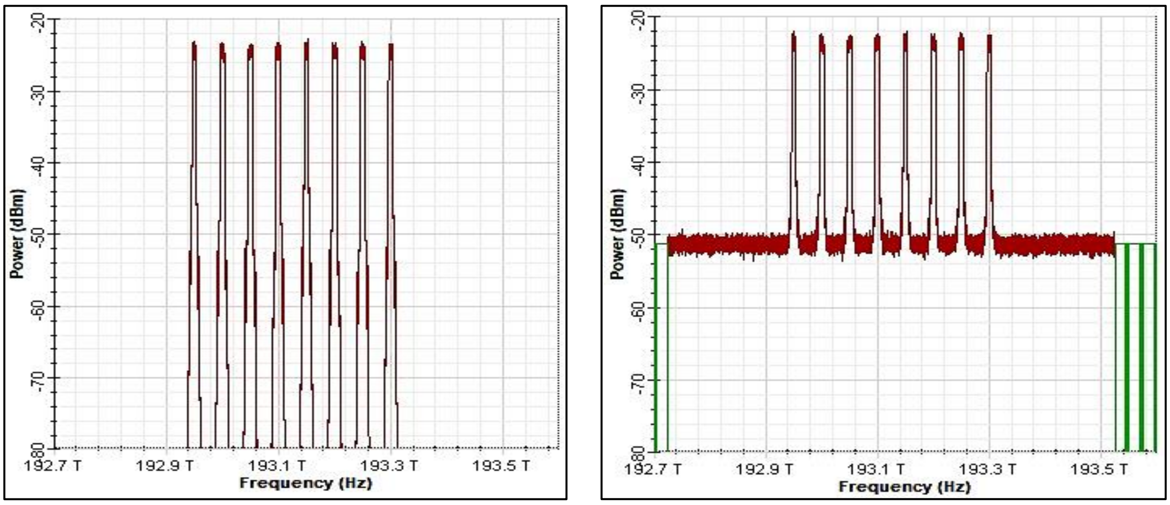
Figure 3. Optical spectrum of single channel at (a) transmitted end and (b) received end



(a) (b)

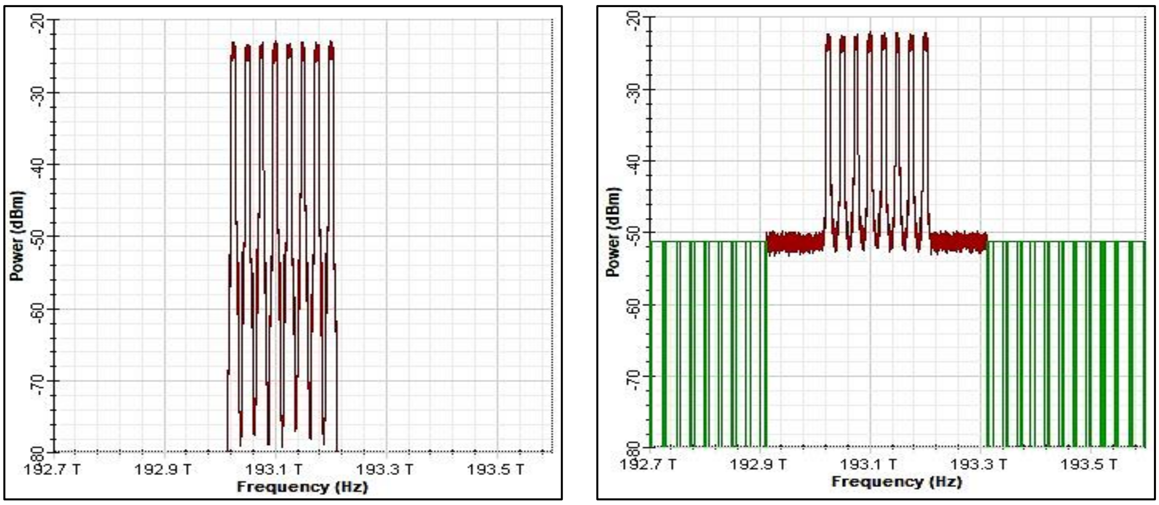
Figure 4. Optical spectrum of 100 GHz channel spacing WDM system at (a) transmitted end and (b) received end

So over 718 km link, Figure 7 shows the influence of launching power on BER for both single-channel and WDM systems. For specific launching power values, the single-channel system has BER values above the 1.48 dB FEC limit, whereas the WDM system exceeds a threshold limit for just some power values. The single-channel system also addresses the best BER, allowing for a longer transmission distance. 100 GHz channel spacing WDM system has a better BER value than 25 GHz and 50 GHz channel spacing systems. Similarly, the BER performance of 50 GHz is better than that of 25 GHz. The performance gap between systems can be attributed to crosstalk between adjacent channels, which causes the BER for WDM systems to degrade steadily. Furthermore, when the nonlinear effect increases in WDM systems, the optimum optical power required to launch in fiber decreases, resulting in a shorter transmission connection. Briefly, as the distance between adjacent channels reduces, more channels can be sent within a restricted bandwidth, and the system’s SE rises; extra crosstalk and phase shift effects occur, leading to additional bits error and short transmission length.



(a) (b)

Figure 5. Optical spectrum of 50 GHz channel spacing WDM system at (a) transmitted end and (b) received end



(a) (b)

Figure 6. Optical spectrum of 25 GHz channel spacing WDM system at (a) transmitted end and (b) received end

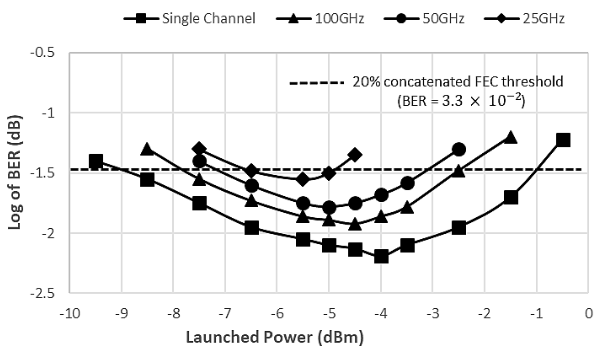


Figure 7. BER vs launching power for single channel and multi-channel with different channel spacing at center channel of 193.1 THz

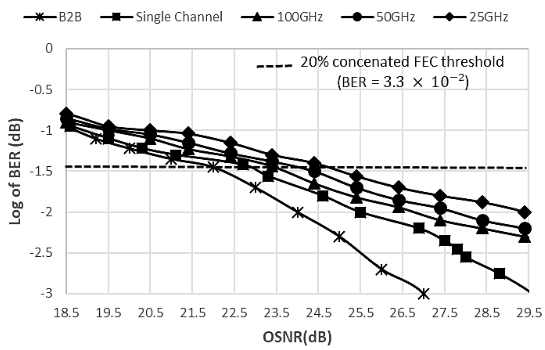


Figure 8. Effect of OSNR level on BER for single channel and multi-channel system with different channel spacing

Figure 8 depicts the BER's reliance on received OSNR of center channel = 193.1 THz for a single-channel back-to-back and over 718 km link systems. Irrespective of the number of channels delivered, the graph shows that increasing OSNR improves the system's BER for B2B and SSMF transmission. Furthermore, the OSNR tolerance for the desired BER = 0.033 seems lower in the 25 GHz WDM system. This appears to be in accordance with the concept that the needed OSNR for a WDM system is inversely proportional to the distance between adjacent channels. As a result, the WDM system delivering extra channels within limited bandwidth should have a narrower spacing value with a higher OSNR level. The required OSNR to reach a BER of 0.033 for single-channel B2B transmission and over 718 km link is 22 dB and 23 dB, respectively. On the other side, the required OSNR over SSMF transmission for 100 GHz, 50 GHz, and 25 GHz channel spacing WDM systems has risen to 23.7 dB, 24.3 dB, and 25 dB, respectively.

The results show that a single channel system has a minor OSNR requirement, followed by 100 GHz, 50 GHz, and 25 GHz channel spacing WDM systems, respectively. That difference in OSNR tolerance on desired BER is due to the decreased spacing between adjacent channels, increased crosstalk, and phase shift effects, restricting the detectability to retrieve the information accurately. Table 5 displays the constellation diagrams with eye diagrams for single-channel and WDM systems at SSMF transmission.

According to the above analyses, the WDM system with 25 GHz channel spacing has the best SE but a lower transmission length ability. We will do additional research on 25 GHz channel spacing to see if we can get a longer distance with higher transmission performance while keeping the SE high. The G.654.E fiber will be the alternative for this enhancement in this investigation.

Figure 9 compares the maximum transmission reach over SSMF and G.654.E fiber versus the optical power necessary to meet FEC BER. Compared to SSMF, the G.654.E fiber offers a longer transmission distance over a greater input power level. The G.654.E has an adequate launch power of -4.5 dBm, which is 1 dB higher than the SSMF's. The variation in the effective area between G.654.E fiber and SSMF accounts for this increase. The large area fiber helps distribute optical power in the core and reduces optical power density in the center, which should not exceed a certain threshold. Another meaning, additional optical power disperses along with a wider core and collects before the nonlinear threshold is reached.

Figure 10 describes the relation between OSNR and transmission range for an 800 Gb/s WDM PDM-CO-OFDM-16QAM system with 25 GHz channel spacing over SSMF and G.654.E fiber. We can observe that the OSNR value at the receiving point drops as the range expands for both fiber types. For all transmission distances, the G.654.E fiber has a 2 dB higher OSNR than SSMF. This increase can be attributed to a 1 dB gain in launching power and a 1 dB reduction in span loss. Consequently, G.654.E fiber can deliver an extended transmission range while improving performance. Compared with SSMF, the G.654.E fiber gives a clearer constellation plot and a broader opened eye diagram, as shown in Figure 10 and Figure 11, respectively.

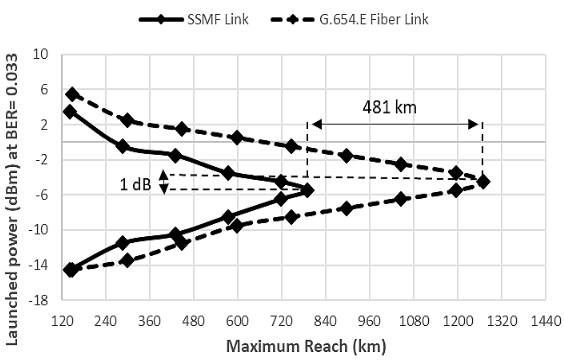


Figure 9. Launched optical power required to reach maximum distance with BER = 0.033 for 800 Gb/s WDM PDM-CO-OFDM-16QAM system over SSMF and G.654.E Fiber link at center channel of 193.1 THz

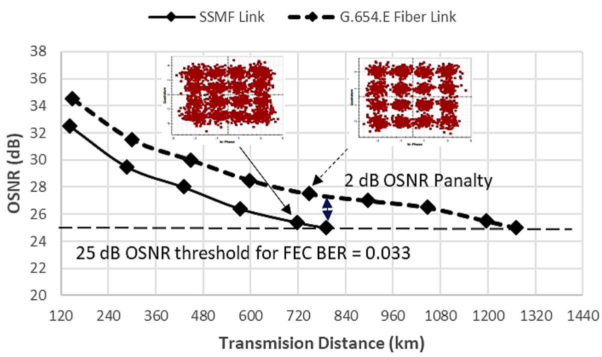


Figure 10. Received OSNR vs transmission distance for 800 Gb/s WDM PDM-CO-OFDM-16QAM system over SSMF and G.654.E fiber at center channel of 193.1 THz (inset: received constellation plot)

Table 6 compares related works. It was determined that our system outperformed previous attempts in terms of spectral efficiency. In contrast to those other works, ours had a maximum SE of 4 bit/sec/Hz at 25 GHz channel spacing over a suitable long-haul range.

Table 5. Received constellation plots with eye diagrams for (8×100) Gbps WDM PDM-CO-OFDM-16QAM for different channel spacing and single-channel after 718 km link at center channel of 193.1 THz

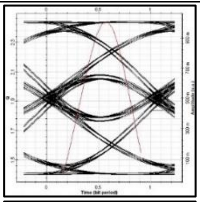
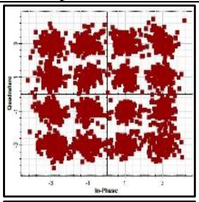
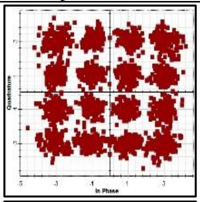
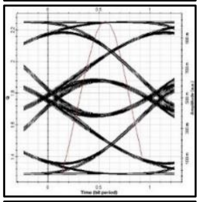
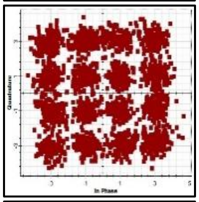
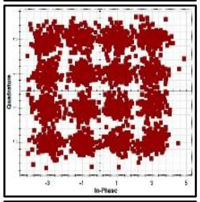
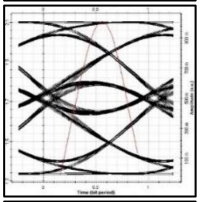
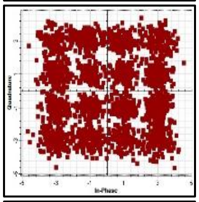
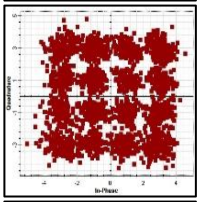
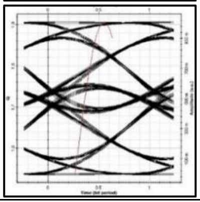
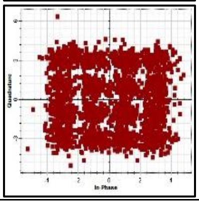
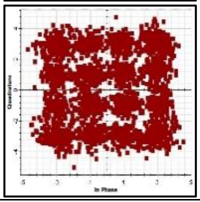
System type	$\Delta\nu_{ch}$ (GHz)	SE (bit/s/Hz)	OSNR (dB)	BER (dB)	Eye diagram at receiver side	Recovered constellation diagram at receiver	
						X-polarization	Y-polarization
Single-channel	–	8	27	-2.19			
Multi-channel	100	1	26.5	-1.92			
Multi-channel	50	2	26	-1.77			
Multi-channel	25	4	25.5	-1.55			

Table 6. Comparison between our work with previous works

Technology	Capacity	$\Delta\nu_{ch}$ (GHz)	SE (bit/sec/Hz)	BER at center channel	Maximum reach (km)
WDM CO-OFDM-4QAM [24]	$20\,\lambda \times 50$ Gbps	50	1	1×10^{-2}	1800
WDM PDM-CO-OFDM-QPSK [25]	$16\,\lambda \times 100$ Gbps	50	2	1×10^{-3}	1440
WDM PDM-CO-OFDM-16QAM [26]	$8\,\lambda \times 100$ Gbps	50	2	1×10^{-12}	480
WDM CO-OFDM-4QAM [27]	$4\,\lambda \times 10$ Gbps	50	0.2	1×10^{-4}	600
WDM CO-OFDM-16QAM [28]	$4\,\lambda \times 10$ Gbps	100	0.1	2.9×10^{-3}	120
WDM CO-OFDM-4QAM [29]	$4\,\lambda \times 25$ Gbps	50	0.5	0	120
DWDM DP-DD-DQPSK [30]	$64\,\lambda \times 14$ Gbps	100	0.14	–	720
WDM PDM-CO-OFDM-16QAM (present work)	$8\,\lambda \times 100$ Gbps	25	4	3.3×10^{-2}	1271

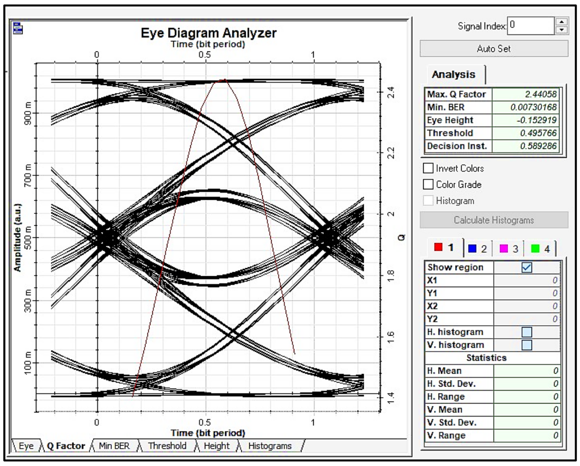


Figure 11. Eye diagram at receiver side for 25 GHz channel spacing WDM system after ten spans of G-654.E fiber

4. CONCLUSION

This research proposed a multi-channel 800 Gbps transmission system that employs a mixture of PDM and CO-OFDM technologies to enhance spectral efficiency and reduce the connection effect. The performance of the proposed eight-channel WDM PDM-CO-OFDM-16QAM system over a 60 km SSMF span is investigated for different channel spacings. The research reveals that the WDM system with 100 GHz channel spacing had the lowest OSNR need and the maximum transmission distance. On the other hand, the spectral efficiency of the 25 GHz channel spacing WDM system is the highest. Further, the impact of ultra-low loss with large effective area fiber on multi-channel PDM-CO-OFDM-16QAM system performance over 25 GHz channel spacing is examined, with results showing successive transmission of 800 Gbps traffic; over a distance of 1271 km. Fiber loss will decrease when ultra-low loss fiber with a large effective area is employed, and more optical power is available to control OSNR falls. As a result, as opposed to a system using SSMF, the G-654.E Fiber system achieved more transmission range and superior BER performance. For future work, a different number of transmitted channels (16 and 32 channels) through narrower channel spacing WDM System (12.5 GHz and even less) could be used in parallel with high order modulation formats (64-QAM,128-QAM, and 256-QAM) across G.654.E fiber for ultra-high data rate transmission over long haul distance.

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