# Spectral efficiency and performance improvement of coherent optical transmission system

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**ABSTRACT**

This paper presents an orthogonal frequency division multiplexing (OFDM) for a long-haul optical transmission system with high-rate transferability to alleviate dispersion effects. In addition, we suggest combining polarization division multiplexing (PDM) with coherent OFDM (CO-OFDM) to increase spectral efficiency (SE). Based on OptiSystem (2021) version 18.0" software package, a 100 Gbps single-channel PDM-CO-OFDM transmission system is investigated using different modulation formats; bipolar phase keying (BPSK), quadrature phase shift keying (QPSK), Eight-Phase-Shift Keying modulators (8-PSK), and quadrature amplitude modulation (16-QAM). A 60 km span of standard single-mode fiber (SSMF) cable is employed in this investigation. The system's performance and spectral efficiency have been evaluated by comparing against the different modulation schemes. The outcomes that were got show that the BPSK modulation scheme has the longest transmission distance and requires a lesser level of optical signal to noise ratio (OSNR) at the receiver side. Concerning spectral efficiency, 16-QAM outperforms the others. Farther, the impact of employing ultra-low loss and large effective area fiber in reducing loss and nonlinear effects in the optical channel for 16-QAM modulation formats is examined. The result found that the system with advanced fiber has superior performance than the SSMF. The bit error rate (BER) of 0.033 (20% concatenated forward error correction (FEC) threshold) is used as a baseline.



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## 1. INTRODUCTION

In the last few years, the exponential expansion of internet traffic has been an essential issue for the High-speed optical network. As a result, optical orthogonal frequency-division multiplexing takes further importance to mitigate the effect of chromatic dispersion and polarization mode dispersion (PMD) and also improve the spectral efficiency [1]-[3]. Orthogonal frequency division multiplexing (OFDM) technology sends a series of narrow-band subcarriers orthogonally, instead of transmitting a single broadband signal to carry information [4], [5]. In addition, utilizing the coherent detector in parallel with OFDM could adjust for channel impairments through digital signal processing [6], [7].

Further techniques for increasing the spectral efficiency of an optical transmission system are to use of polarization division multiplexing (PDM) and higher-order modulation schemes [8]-[10]. The higher-order modulation needs a greater optical signal-to-noise ratio (OSNR) to get the optimum bit error rate [11]. Thus, more optical power must be shot into the fiber to boost OSNR after long-distance transmission. Unfortunately, when the transmitted power keeps rising, the fiber nonlinearity effects appear and disturb transmission quality [12].

The optical fiber technological advance has recently opened a new era of possibilities: ultra low loss fiber presented in [13] and large-effective-area fiber in [14]. After sending the optical signal over the fiber, the received OSNR will be enhanced by decreasing fiber loss. Also, when the effective area of the fiber is expanded, more optical power can be shot into the fiber connection, which is vital for enhancing the received OSNR. As a result, a fiber optic cable with a low attenuation coefficient and a large effective area fiber might be a good choice for enhancing the transmission performance of a high-speed optical network. It has been carried out and implemented for the submarine cable systems [15] and is described by telecommunication standardization sector (ITU-T) recommendation G.654.

The ITU-T defines the G.654.E standard as a different class of ultra-low-loss with large-effective-area fiber to handle 100s Gbit/s and beyond for terrestrial applications. Many planning strategies and real-time experiments [16]-[21] use the G.654.E fiber to alleviate the link attenuation and nonlinearity problem.

This work aims to analyze the effect of modulation format on the performance and spectral efficacy for a 100 Gbps single-channel polarization-division multiplexed coherent optical OFDM (PDM-CO-OFDM) transmission system over multiple spans of 60 km SSMF using OptiSystem (2021) version 18.0" software package. Different modulation formats are used in this investigation, like binary phase shift key (BPSK), quadrature phase shift key (QPSK), 8-phase shift key (8-PSK), and 16-quadrature amplitude modulation (16-QAM). Farther, to get a more significant benefit for a higher spectral efficiency modulation scheme across the long-haul transmission, we will change the standard mode fibers (SMF) by G.654E fiber to reduce the transmission loss and nonlinearity effect. We concentrated on the bit error rate (BER's) response to OSNR and launching power. The span loss and dispersion effects have been compensated using an inline erbium-doped fiber amplifier (EDFA) and digital component at the receiver side, respectively. The BER of $3.3 \times 10^{-2}$ (20% overhead concatenated forward error correction (FEC) threshold) is used as a baseline for system performance [15].

## 2. THE RESEARCH METHOD

The 100 Gbps PDM-CO-OFDM transmission system with no inline dispersion compensation unit is built with a commercial simulation computer software, optisystem 18, as seen in Figure 1. There are three primary sections to the proposed system: Transmitter, optical fiber connection, and receiver. Layout simulation parameters are seen in Table 1.

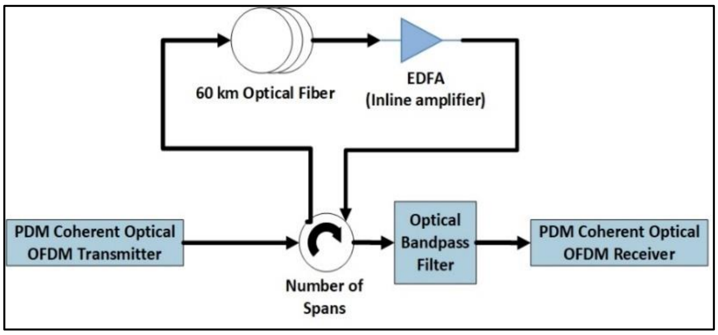



Figure 1. Conceptual design of PDM Coherent optical OFDM communication system

Table 1. Layout simulation parameters

| Parameters | value |
|---|---|
| Data rate (Gb/s) | 100 |
| Symbol rate (GS/s) | 50 for BPSK, 25 for QPSK, 16.6 for 8-PSK and 12.5 for 16-QAM |
| Sequence length (bit) | 32768 |

### 2.1. Transmitter design

The transmitter architecture is illustrated in Figure 2. A pseudo-random binary sequence (PRBS) produced 100 Gb/s data bits segmented into odd and even data flows by serial to parallel converter before using phase-shift keying (PSK)/quadrature amplitude modulation (QAM) mapping. A 128-subcarrier OFDM modulator is utilized to create an radio frequency (RF)-OFDM signal. After that, the in-phase and quadrature sections of the RF-OFDM signal travel via the low pass filter (LPF) to cancel some unwanted frequencies. The electrical to optical signal translation is accomplished by employing the two Mach–Zehnder modulators (MZM) to modulate each polarization of continuous-wave (CW) laser by RF-OFDM signal. For dual-polarization transmissions, a polarization beam combiner (PBC) merges the modulated light waves. Finally, The PDM-CO-OFDM-PSK/QAM signal launches in an optical fiber link. the transmitter settings are seen in Table 2.

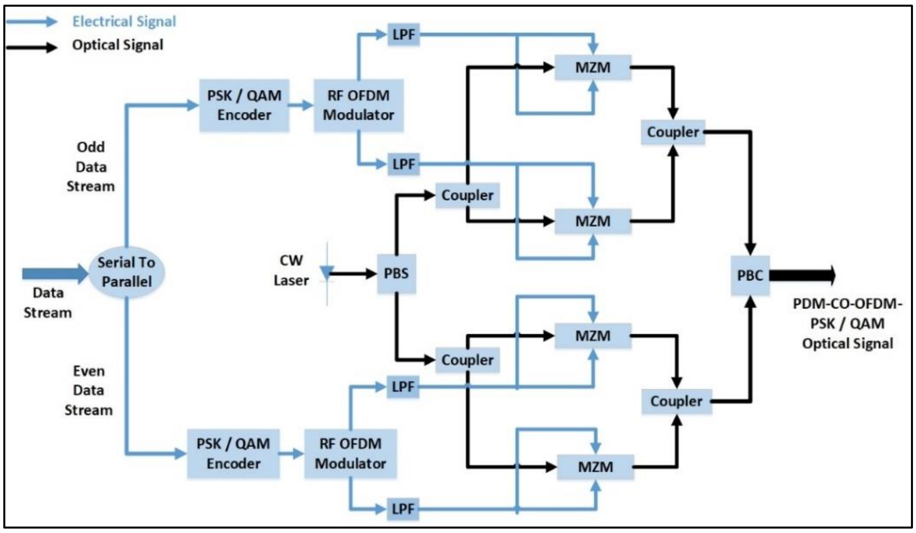



Figure 2. Block diagram of PDM optical CO-OFDM transmitter

Table 2. Transmitter settings

| Parameters | Value |
|---|---|
| CW laser | |
| Frequency (THz) | 193.1 |
| Linewidth (MHz) | 0.1 |
| Power (dBm) | variable |
| OFDM Mod. and Dem. | |
| 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 |

## 2.2. Optical channel

Two optical links of SSMF are used in this study, 1200 km with BPSK/QPSK and 4800 km with 8-PSK/16-QAM. Furthermore, the G.654.E fiber is installed as an enhancement solution for the 16-QAM transmission system. The fibers' characteristic features are listed in Table 3.

Table 3. Optical link characteristics

| Parameter | SSMF | G.654.E[20] |
|---|---|---|
| | Value | |
| Span Length (km) | 60 | 60 |
| Attenuation Coefficient (db/km) | 0.2 | 0.168 |
| Dispersion Coefficient (ps/nm/km) | 16.75 | 21 |
| Dispersion Slope coefficient (ps/$nm^2$/km) | 0.075 | 0.07 |
| Fiber nonlinearity ($m^2$/W) | $26 \times 10^{-21}$ | $22 \times 10^{-21}$ |
| Effective Area ($\mu m^2$) | 80 | 125 |
| EDFA-1 | | |
| Gain (dB) | 12 | 10.08 |
| Noise Figure (dB) | 4 | 4 |

### 2.3. Receiver design

The receiver architecture is illustrated in Figure 3. The incoming optical signal was separated into two polarization components by a polarization beam splitter (PBS). each one was inserted into an optical-to-electronic translator to get an RF-OFDM signal. By Using 2×2 balanced PIN photodetectors and a local oscillator (LO) laser (193.1 THz Frequency, 0.1 MHz line width), the coherent detector extracts two OFDM signal components (in-phase and quadrature components). The OFDM demodulator and PSK/QAM decoder with the same parameters on the transmitter side are used to recover parallel data streams. Finally, the serial data stream is extracted by parallel to the serial converter.

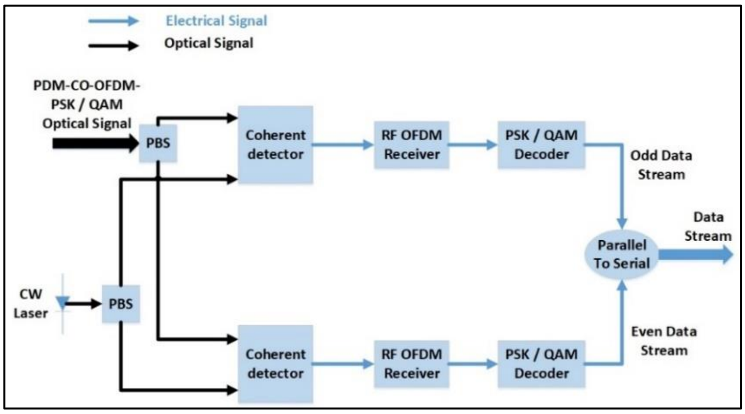
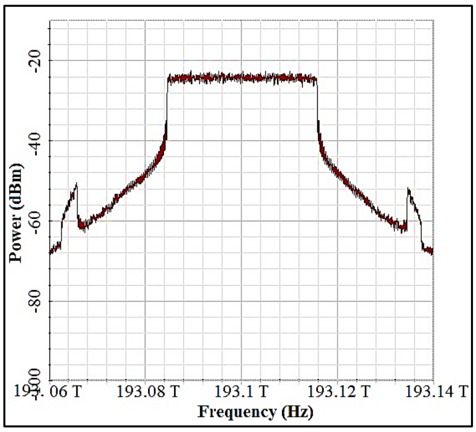



Figure 3. Block diagram of PDM optical CO-OFDM receiver

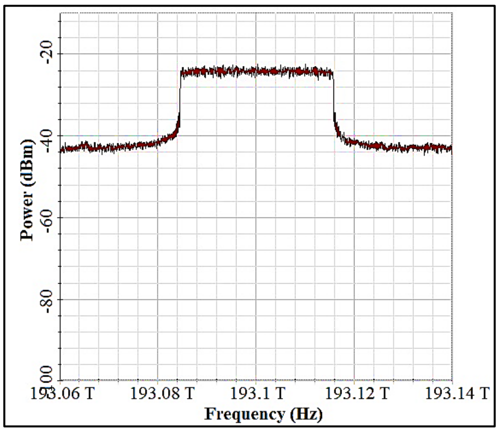
## 3. RESULTS AND DISCUSSION

To get an idea of the precise spectral efficiency conceivably achievable with the different modulation schemes. We initially simulated the transmission performance of 100 Gb/s single-channel PDM-CO-OFDM systems utilizing the two lower-order modulation formats (BPSK/QPSK) over 4800 km link and the higher-order (8-PSK/16-QAM) over 1200 km with EDFA-only amplification. We compensated the dispersion digitally at the receiver side.

Figures 4-7 show the optical signal spectrum for different modulation scheme systems at the transmitter and receiver sides: Figure 4(a), Figure 4(b) for BPSK; Figure 5(a), Figure 5(b) for QPSK; Figure 6(a), Figure 6(b) for 8-PSK; and Figure 7(a), Figure 7(b) for 16-QAM. With 100 Gb/s considered data rate, each system has a different spectral efficiency corresponding to the number of bits per symbol. The possessed spectral efficiency (SE) for BPSK QPSK,8-PSK, and 16-QAM systems are 2,4,6 and 8 bits/sec/Hz, respectively. In other words, for limited optical spectrum bandwidth required transmission, the 16-QAM system can transmit the highest data rate, followed by 8-PSK, QPSK, and BPSK, respectively.

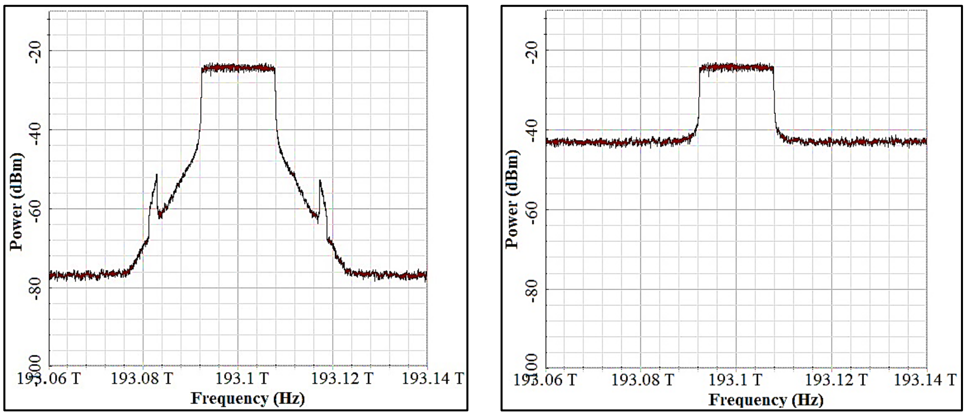



(a)




(b)

Figure 4. Optical spectrum of BPSK at (a) transmitted side and (b) received side




(a) (b)

Figure 5. Optical spectrum of QPSK at (a) transmitted side and (b) received side

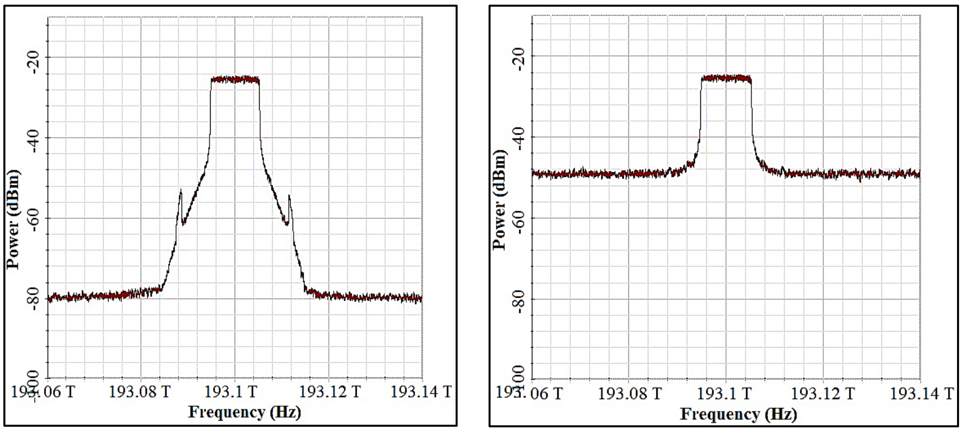



Figure 6. Optical spectrum of 8-PSK at (a) transmitted side and (b) received side

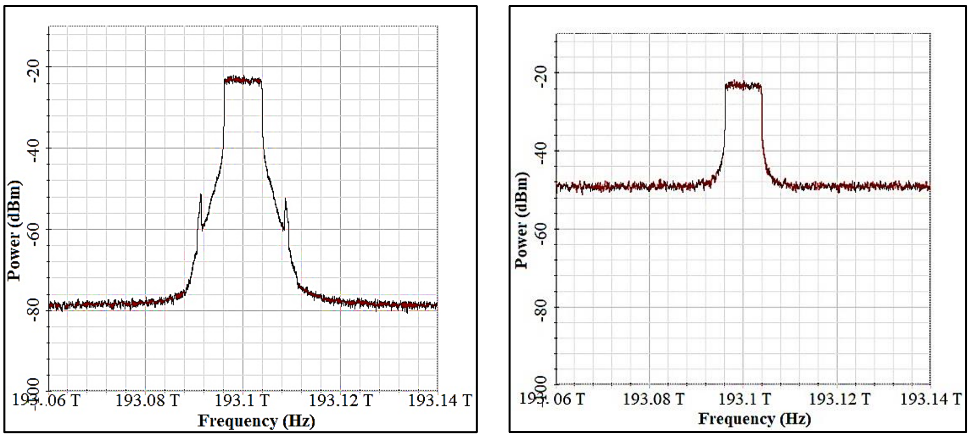
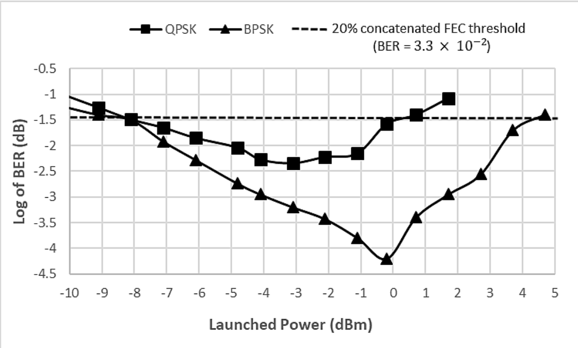
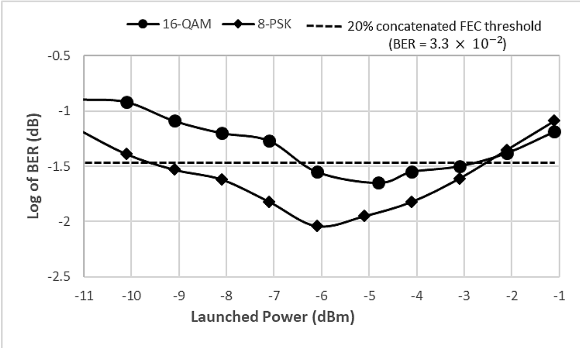



Figure 7. Optical spectrum of 16-QAM at (a) transmitted side and (b) received side

Figure 8 shows the relationship between BER and optical launched power for different modulation scheme systems. Figure 8(a) demonstrates the effect of launching power on BER for both lower-order modulation formats (BPSK and QPSK) over the 4800 km standard single mode fiber (SSMF) link. The BPSK system has BER values that surpass the 1.48 dB FEC limit for most launching power values, whereas the QPSK system exceeds a certain threshold for some power values. Also, the BPSK handles a significant BER margin to reach a more considerable transmission distance. Each higher-order modulation formats (8-PSK and 16-QAM) over 1,200 km link is demonstrated in Figure 8(b). Compared with 16-QAM, the 8-PSK modulation format has also achieved better BER performance; hence, a more extended link is possible. This difference in performance between the modulation formats is due to the space length between adjacent symbols that make the system reasonably immune against distortions and noise as space increases. In other words, as the number of bits per symbol increases, the system's SE increases, narrower space between adjacent symbols becomes, and negatively more error bits occur and hence limited transmission distance.



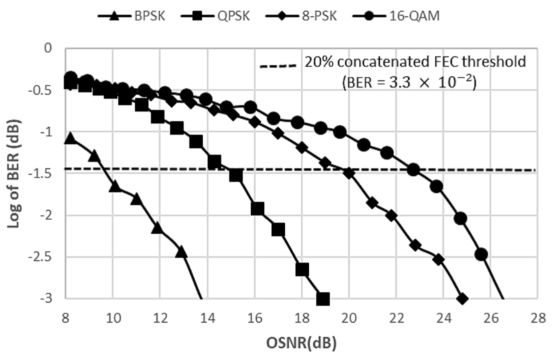

(a)



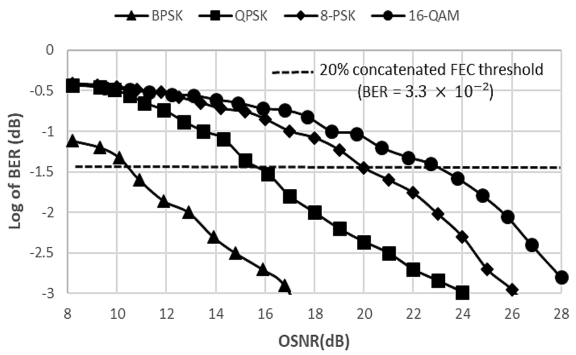

(b)

Figure 8. BER vs. launched power for 100 Gb/s PDM-CO-OFDM system for (a) BPSK and QPSK over 4800 km and (b) 8-PSK and 16-QAM over 1200 km

Figure 9 presents the relationship between BER and OSNR. Figures 9(a) and 9(b) show the BER's dependence on received OSNR of center channel=193.1 THz using BPSK, QPSK, 8-PSK, and 16-QAM signals, for back-to-back system and over the two-range transmission distance with SSMF fiber. Figure 9 shows that raising OSNR enhances the system's BER for B2B and SSMF transmission, regardless of the modulation techniques used. In addition, a higher-order modulation scheme with further bits per symbol seems to have a smaller OSNR tolerance for the desired BER of $3.3\times10^{-2}$ (20% concatenated FEC threshold). This seems consistent with the idea that the required OSNR for modulation format is inversely proportional to the displacement between neighboring constellation points, i.e., Euclidean distance. Therefore higher-order modulation, which sends extra bits per symbol, has a shorter Euclidean distance and greater OSNR need. For the B2B transmission scenario, the OSNR is necessary to achieve the desired BER of $3.3\times10^{-2}$ is noticed as 9.5 dB, 15 dB, 20 dB, and 22.7 dB for BPSK, QPSK, 8-PSK, and 16-QAM signals, respectively. On the other hand, the necessary OSNR for SSMF transmission has risen to 10.5 dB, 15.8 dB, 20 dB, and 23 dB for BPSK, QPSK, 8-PSK, and 16-QAM signals, respectively.




(a)

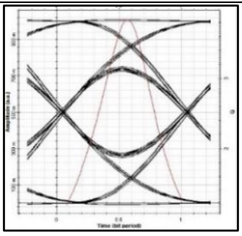
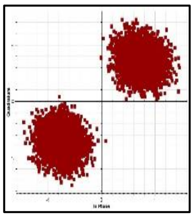
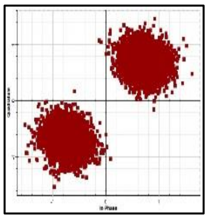
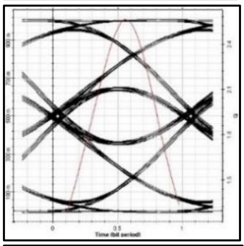
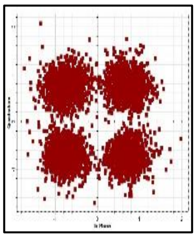
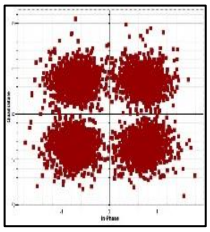
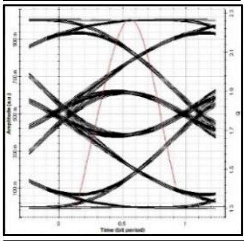
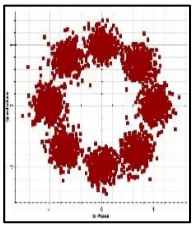
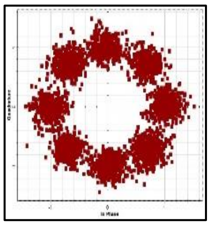
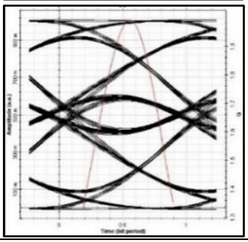
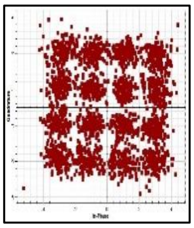
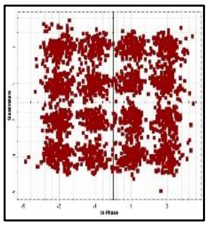



(b)

Figure 9. BER vs. OSNR for 100 Gb/s PDM-CO-OFDM system with different modulation formats for (a) B2B and (b) 4800 and 1200 km link for the lower and higher-order modulation formats, respectively

The findings demonstrate that the BPSK scheme has the lowest OSNR need and the longest transmission distance, trailed by QPSK, 8-PSK, and 16-QAM. This is due to extending the transmitted signal level (bits/symbol), decreasing the space between consecutive constellation points, then limiting the detection ability to extract the data correctly. Table 4 shows the constellation and eye diagrams for several modulation schemes at SSMF transmission.

Table 4. Recovered constellation and eye diagrams for 100 Gbps PDM-CO-OFDM for different modulation formats

| Modulation Format | Link (km) | SE (bit/s /Hz) | Receiv-ed OSNR (dB) | BER (dB) | Eye diagram at receiver side | Recovered constellation diagram at receiver X-polarization | Y-polarization |
|---|---|---|---|---|---|---|---|
| BPSK | 4800 | 2 | 19 | -4.2 |  |  |  |
| QPSK | 4800 | 4 | 20 | -2.3 |  |  |  |
| 8-PSK | 1200 | 6 | 22.9 | -2 |  |  |  |
| 16-QAM | 1200 | 8 | 24.2 | -1.6 |  |  |  |

The previous comparison results show that 16-QAM has higher SE with shorter transmission distance capability. We will make further analysis for 16-QAM to reach a more considerable distance with better transmission performance in parallel with its high SE. in this study, the G.654.E Fiber will be the solution for this improvement.

Figure 10 shows the maximum reachable transmission distance over SSMF and G.654.E Fiber against the required launching power to achieve FEC BER. Compared with SSMF, the G.654.E fiber allows a more significant transmission distance over a more comprehensive input power range. The optimal launch power for the G.654.E is -3.8 dBm which is more than the optimal power of SSMF by 1 dB. This increment is due to the effective area difference between G.654.E Fiber and SSMF. The large area fiber spreads out the optical power in the core and lowers the optical power density in the center, which has a limit that must not be surpassed. Another way, extra optical power can be distributed across a larger core and received before the nonlinear limit is exceeded.

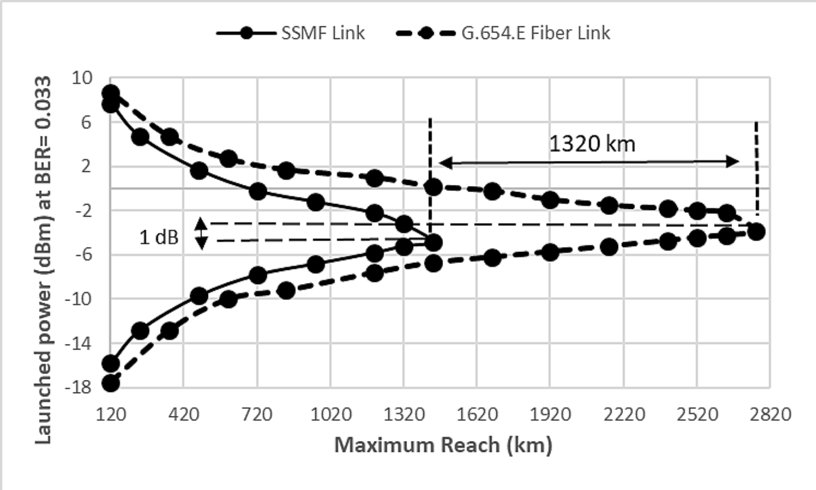



Figure 10. Launched power required to reach maximum distance with BER=0.033 for 100 Gb/s PDM-CO-OFDM-16QAM system over SSMF and G.654.E Fiber

Figure 11 shows the relationship between the OSNR and transmission distance for 100 Gb/s PDM-CO-OFDM-16QAM System over SSMF and G.654.E Fiber. for two fiber types, we can see that the OSNR level at the receiver side decreases as the distance increases. Compared with SSMF, the G.654.E Fiber has a higher OSNR level for all transmission distances by 3 dB. This improvement results from a 1 dB launching power increment and a 2 dB span loss difference between the two fiber types.

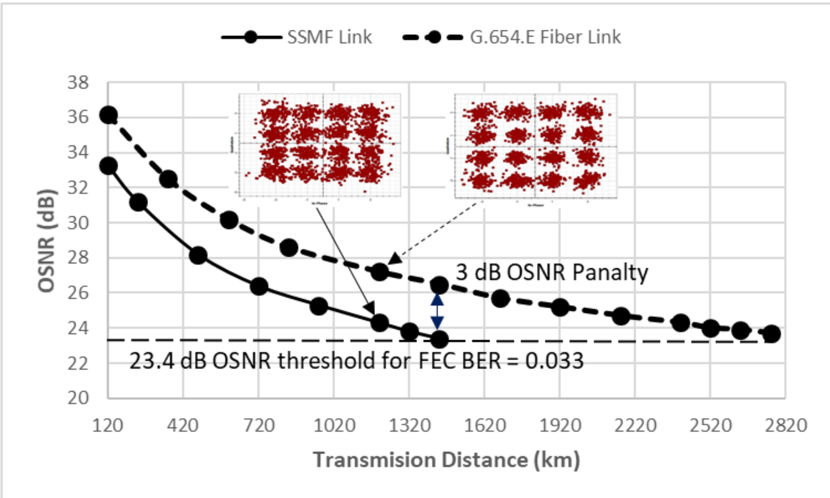



Figure 11. OSNR vs. transmission distance for 100 Gb/s PDM-CO-OFDM-16QAM System over SSMF and G.654.E Fiber (Inset: Recovered constellation diagrams after 1200 km)

As a result, a longer transmission distance can be reached with G.654.E fiber with better performance. Figure 11 and Figure 12 show how the G.654.E fiber produces a brighter constellation plot and a bigger opening eye diagram when compared to SSMF at a 1200 km transmission distance. Table 5 shows a comparison of works that are related. In terms of transmission distance, it was discovered that our system exceeded previous ones. Unlike those other studies, ours had a longer link of 2760 km at -3.8 dBm launching power with an acceptable BER.

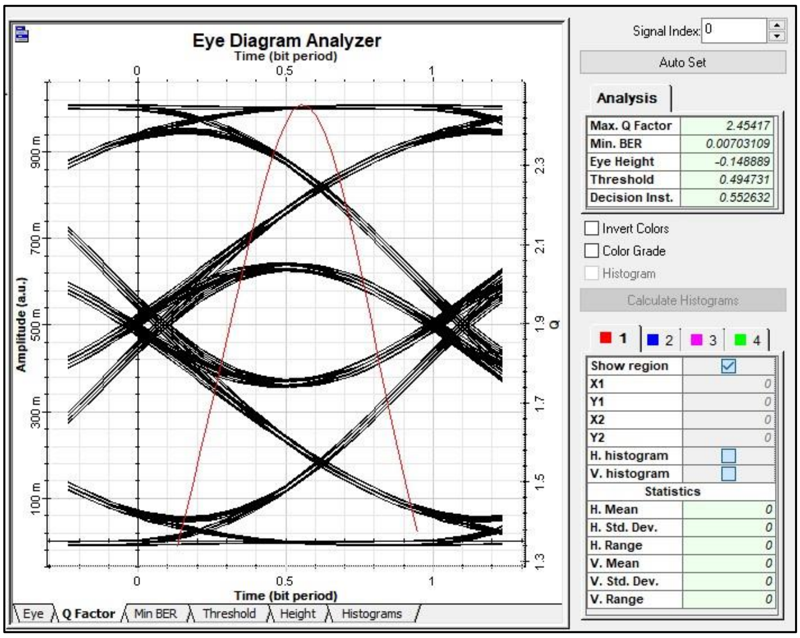



Figure 12. Eye diagram at the received side for a 16-QAM system over G.654.E fiber

Table 5. Comparison table between our work with previous related ones

| Technology | Capacity (Gb/s) | Optimum launching power (dBm) | SE (bit/sec/Hz) | BER | Maximum reach (km) |
|---|---|---|---|---|---|
| DP-CO-OFDM-16QAM [22] | 100 Gbps | -5 | 8 | $1 \times 10^{-9}$ | 576 |
| DP-CO-OFDM-16QAM [23] | 100 Gbps | ----- | 8 | 0.57 | 1000 |
| DP-CO-OFDM-QPSK [24] | 20 Gbps | -6 | 4 | $\approx 1.7 \times 10^{-3}$ | 1000 |
| DP-CO-OFDM-QPSK [25] | 100 Gbps | -4 | 4 | $\geq 1 \times 10^{-5}$ | 936 |
| CO-OFDM-16PSK [26] | 60 Gbps | ------- | 8 | $1 \times 10^{-3}$ | 250 |
| CO-OFDM-16QAM [27] | 40 Gbps | ------- | 4 | 0 | 150 |
| PDM-CO-OFDM-16QAM [28] | 100 Gbps | -1 | 8 | $1 \times 10^{-12}$ | 960 |
| PDM-CO-OFDM-16QAM (Present Work) | 100 Gbps | -3.8 | 8 | $3.3 \times 10^{-2}$ | 2760 |

## 4. CONCLUSION

The current study describes a single channel 100 Gbps system that uses a combination of PDM and CO-OFDM techniques to increase spectral efficiency and transmission range and offer connection influence resistance. The suggested PDM-CO-OFDM system's performance over a 60 km SSMF span is explored for various levels of modulation formats, and the study found that BPSK schemes have the lowest OSNR requirement and the longest reach. In contrast, 16-QAM has the maximum spectral efficiency. Furthermore, ultra-low loss and large effective area fiber on single-channel PDM-CO-OFDM system performance is also numerically examined, with findings demonstrating the transmission of 100 Gbps 16-QAM traffic across a distance of 2760 km. Using ultra-low loss fiber with a large effective area reduces span loss and allows more launching power to adjust the OSNR drops. Therefore, compared to a system employing SSMF, the system with G-654E Fiber reached extra transmission distance and displayed a better BER performance. In the future, high-level schemes like M-QAM (32-QAM, 64-QAM, 128-QAM, 256-QAM) could be employed with G.654.E fiber to improve spectral efficiency (SE) over the long haul transmission.

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