Performance evaluation of a 160 Gbps PDM-16-QAM-OFDM RoF transmission using DSP algorithms

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This paper presents the design and performance analysis of a high-capacity radio-over-fiber (RoF) transmission system based on polarization division multiplexing (PDM), 16-ary quadrature amplitude modulation (16-QAM), and orthogonal frequency division multiplexing (OFDM). The proposed system transmits 160 Gbps data over optical fiber and employs advanced signal processing techniques at the receiver, including channel estimation and carrier phase estimation, to mitigate the adverse effects of channel impairments and enhance signal quality. System performance is comprehensively evaluated using bit error rate (BER), error vector magnitude (EVM), and received optical power as key metrics. Simulative results demonstrate reliable 160 Gbps data transmission along 110 km range with log(BER) values ≤ -2.42 i.e. below the forward error correction (FEC) threshold and EVM percentages within acceptable limits ($\leq 18\%$). Additionally, receiver sensitivity is assessed under various transmission scenarios, including back-to-back, 50 km, and extended 110 km fiber links, through BER and EVM versus received optical power analyses and constellation diagram observations for both X and Y polarizations. The findings confirm the effectiveness of the proposed signal processing methods in maintaining high-quality transmission and provide valuable insights for the development of robust, high-speed RoF systems.

1. Introduction

The relentless growth in global data traffic, driven by the proliferation of high-definition video streaming, cloud computing, 5G wireless networks, and the Internet of Things (IoT), has created an urgent demand for high-capacity, reliable, and spectrally efficient communication systems [1, 2]. Optical fiber communication, with its vast bandwidth and low attenuation, has emerged as the backbone of modern telecommunication infrastructure [3]. However, as data rates continue to escalate, conventional transmission techniques are increasingly challenged by fiber nonlinearities, chromatic dispersion, polarization mode dispersion, and other channel impairments [4, 5]. To address these challenges and meet the ever-increasing capacity requirements, advanced modulation formats and multiplexing techniques have been explored extensively in recent years.

Polarization Division Multiplexing (PDM) is a pivotal technology in this context. PDM increases the data transmission capacity of optical systems by exploiting two orthogonal polarization states of light, allowing separate data streams to be transmitted simultaneously over the same wavelength [6 – 9]. This effectively doubles the spectral efficiency without requiring additional bandwidth, making PDM a cornerstone of high-capacity optical networks. When combined with sophisticated modulation schemes such as 16-Quadrature Amplitude Modulation (16-QAM), which encodes data by varying the amplitude of two carrier waves to create 16 distinct signal points, the potential for even greater spectral efficiency is realized.

16-QAM is widely recognized for its balance between data rate and resilience to noise, making it a preferred choice for advanced optical transmission systems.

Orthogonal Frequency Division Multiplexing (OFDM) further enhances the robustness and efficiency of optical communication systems. OFDM is a multi-carrier modulation technique that divides a high-rate data stream into multiple lower-rate streams, each transmitted over orthogonal sub-carriers [10, 11]. This approach mitigates the effects of chromatic dispersion and polarization mode dispersion, which are significant impairments in high-speed fiber optic links [12]. The synergy of PDM, 16-QAM, and OFDM forms a powerful transmission paradigm capable of supporting ultra-high data rates with improved tolerance to channel distortions.

Despite these advancements, high-speed optical transmission systems remain susceptible to various channel impairments, including phase noise, frequency offsets, and fiber nonlinearities. Accurate channel estimation and carrier phase estimation are therefore essential for reliable signal recovery at the receiver [13]. Channel estimation techniques enable the characterization and compensation of distortions introduced by the transmission medium, while carrier phase estimation algorithms correct phase noise and frequency offsets, both of which are critical for coherent detection systems [14 – 16]. The effectiveness of these signal processing techniques is typically evaluated using performance metrics such as Bit Error Rate (BER), Error Vector Magnitude (EVM), and received optical power, which

collectively provide a comprehensive assessment of system reliability and signal quality.

The evolution of high-capacity optical transmission systems has been marked by significant milestones in recent years. Recent studies have demonstrated the potential of combining PDM and OFDM to significantly enhance the performance of optical communication systems. For example, the development of hybrid PDM/OFDM techniques for free-space optics (FSO) and fiber systems has shown promising results in terms of capacity and robustness under various channel conditions. In [17], the authors report that integrating PDM with OFDM can improve system resilience to atmospheric turbulence and increase overall throughput, highlighting the adaptability of these techniques to both fiber and FSO links.

The application of higher-order QAM formats, particularly 16-QAM, within OFDM frameworks has also been widely studied. In the context of direct detection optical-OFDM systems, the use of 16-QAM has been shown to provide high spectral efficiency and support elevated data rates. A study by Sharma et al. as reported in [18] demonstrated that 16-QAM modulation in optical-OFDM systems achieves superior performance in terms of BER and Q-factor compared to lower-order schemes, while also maintaining compatibility with existing optical components. Similarly, Zhao and Ellis in [19] experimentally demonstrated the enhanced dispersion tolerance of coherent offset-16QAM OFDM, achieving 38 Gbps transmission over 840 km without guard intervals and showing that PDM offset-QPSK OFDM can yield a 23% net capacity increase over conventional OFDM at similar transmission distances.

Channel estimation and carrier phase recovery are critical for the reliable operation of high-speed OFDM-based systems, especially in the presence of phase noise and other channel impairments. Wang et al. in [20] analyzed joint channel estimation, carrier frequency offset, and phase noise estimation in OFDM relay systems, proposing algorithms that significantly improve data detection accuracy in challenging environments. Their work underscores the importance of advanced signal processing for maintaining low BER and high signal fidelity in practical deployments.

Recent advancements in RoF technologies have pushed the boundaries to achieve higher data rates and longer transmission distances with optimized power efficiency and system simplicity. Al Deen and Haider in [21] demonstrated the successful transmission of a 28 GHz 64-QAM signal at 10 Gbps over single-mode fiber exceeding 140 km without optical amplifiers, utilizing dual parallel Mach-Zehnder modulators to enhance bandwidth and reduce latency. Their work highlights significant progress towards scalable, energy-efficient long-haul RoF systems for next-generation communication networks. Complementing this, Matsuura in [22] reviewed high-power optical fiber transmission approaches, introducing innovative fiber architectures like double-clad and hollow-core fibers, which sustain high power and enable integrated optical data and power delivery—a crucial step for minimizing nonlinear impairments. Chen et al. in [23] further exemplified cutting-edge RoF links by developing a high-power, broadband minimalist wireless base station RoF system that harnesses advanced phase modulation to counteract stimulated Brillouin scattering and facilitate high spectral efficiency across long distances. The integration of these advanced techniques has enabled the realization of high-capacity RoF systems. For instance, a 16-channel, 160 Gbps wavelength division multiplexed (WDM) RoF system was simulated and evaluated by Kumar et al. in [24], who reported optimum performance at specific input power levels and demonstrated the effectiveness of dispersion compensation and fiber Bragg gratings in mitigating channel impairments. Their evaluation, using BER, Q-factor, and eye diagrams, provides a benchmark for the performance of modern WDM-RoF systems.

Collectively, these studies illustrate the significant progress made in the field of high-speed optical communications through the use of PDM, OFDM, and high-order QAM, as well as the necessity of robust channel estimation and phase recovery algorithms. However, further research is needed to optimize these technologies for even higher data rates, longer transmission distances, and greater resilience to real-world impairments.

While the aforementioned studies have collectively propelled the field of high-speed optical transmission, several challenges remain. The integration of PDM, 16-QAM, and OFDM, though promising, introduces complexities in signal processing, particularly at the receiver. Channel impairments such as polarization mode dispersion, phase noise, and nonlinearities can significantly degrade signal quality, necessitating robust estimation and compensation techniques. Moreover, the increasing demand for higher data rates and longer transmission distances calls for a holistic evaluation of system performance using multiple metrics, including BER, EVM, and receiver sensitivity.

The present work is motivated by the need to address these challenges through the design and analysis of a 160 Gbps PDM-16-QAM-OFDM based radio-over-fiber(RoF) transmission system. The proposed system leverages advanced channel estimation and carrier phase estimation algorithms at the receiver to enhance signal recovery in the presence of channel distortions. Performance is rigorously evaluated using BER, EVM, and received optical power, providing a multi-faceted perspective on system reliability and signal quality. Additionally, receiver sensitivity is assessed under various transmission scenarios, including back-to-back, intermediate, and extended fiber links, using BER versus received optical power, EVM versus received optical power, and constellation diagram analyses for both X and Y polarization channels.

The remainder of this paper is organized as follows. Section II details the system architecture and describes the implementation of PDM, 16-QAM, and OFDM in the proposed transmission scheme. Section III reports and analyzes the results, including BER, EVM, receiver sensitivity, and constellation diagrams. Finally, Section IV concludes the paper with a summary of key findings and suggestions for future research directions.

2. System design

In this study, a 160 Gbps data transmission system is implemented using PDM combined with in-phase quadrature modulation and coherent detection, as illustrated in Fig. 1. The PDM technique splits a single high-speed signal into two parallel bit streams, each transmitted over orthogonally polarized beams generated by a single laser diode operating at 193.1 THz. This method effectively doubles the data rate and enhances spectral efficiency. To improve signal quality and mitigate the effects of channel distortions and weather-related attenuation, carrier phase estimation (CPE) and channel estimation algorithms are applied at the receiver. At the transmitter side, the 160 Gbps input data is first processed by a serial-to-parallel converter that divides the bit stream into two equal parts. Each part undergoes 16-QAM mapping using dedicated sequence generators, and both resulting bit streams are then modulated using OFDM with 512 sub-carriers. These OFDM-modulated signals are optically modulated onto two orthogonal polarized beams, which are subsequently combined using a polarization combiner. An mm-wave signal is then modulated over the optically modulated signal using a Mach Zehnder modulator before transmission through a single-mode fiber (SMF). The simulation parameters used in this work are detailed in Table 1.
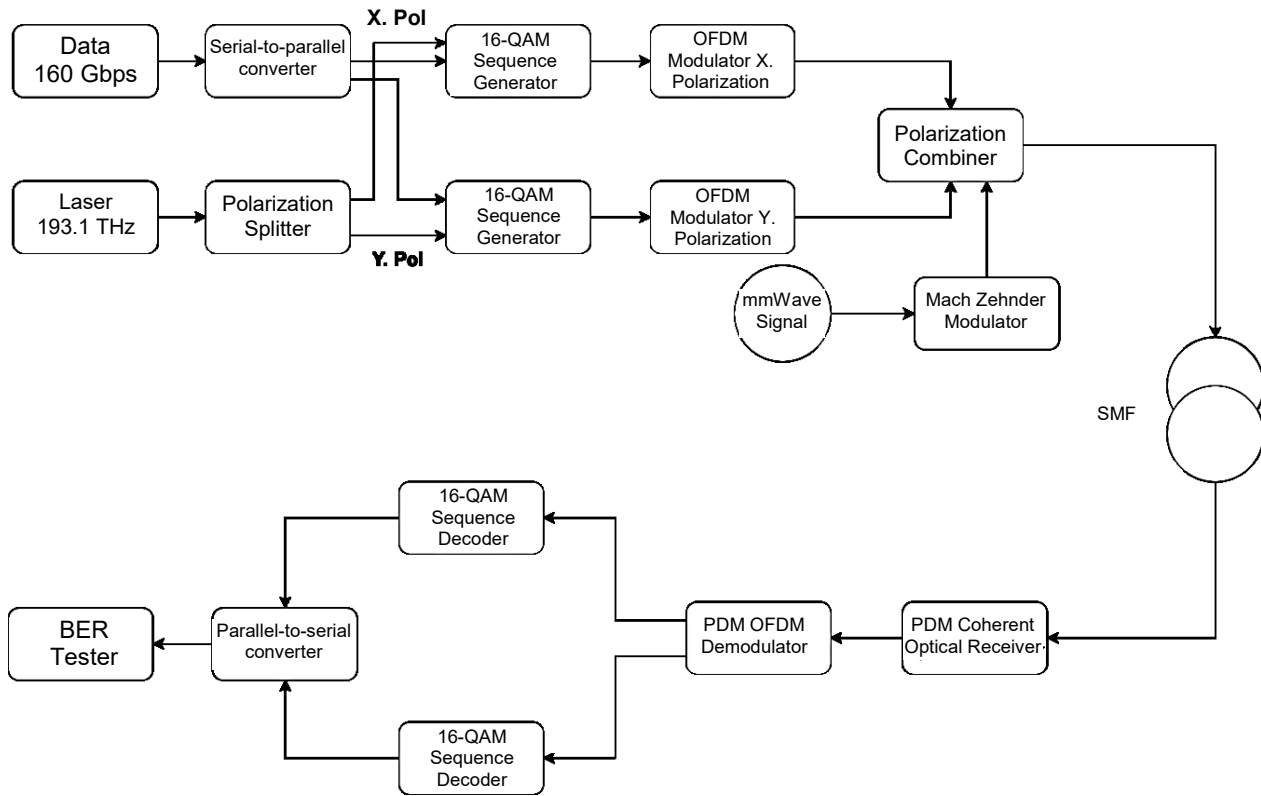

Fig. 1. Proposed 160 Gbps PDM-16-QAM-OFDM-RoF Transmission system setup

Table 1. Simulation parameters for PDM-16-QAM-OFDM-RoF transmission system

Parameters	Values
Data rate	160 Gbps
Symbol rate	20 Gbps
QAM bits per symbol	4
QAM variant	PDM-16-QAM
Sequence Length	65536
Fiber attenuation	0.2 dB/km
Dispersion coefficient	17 ps/(nm-km)
Number of Samples	2097152
CW Laser Power	15 dBm
Laser Linewidth	100 e-012 MHz
RF Frequency	40 GHz
SMF Length	0 – 190 km
EDFA Gain and Noise Figure	20 dB and 4 dB
Match Filter Bandwidth	50 GHz
Cut-off Filter	PIN
DSP Algorithms	Channel estimation, CPE

At the receiver, a PDM coherent receiver demultiplexes the incoming orthogonal optical beams. Each separated beam undergoes individual demodulation through an OFDM demodulator. The original information is then reconstructed using 16-QAM sequence decoders, which decode the modulated signals back into binary data. Following this decoding process, a parallel-to-serial converter combines the two parallel data streams into a single serial output. Finally, the system evaluates signal integrity using a BER tester to quantify transmission quality and performance. This receiver architecture ensures accurate recovery of the transmitted 160 Gbps data while providing critical performance metrics through BER analysis.

3. Results and discussion

In this section, we report and discuss the performance analysis of the proposed 160 Gbps 16-QAM enabled PDM-OFDM-based RoF transmission system using advanced signal processing techniques. We have evaluated the system's performance using BER, EVM and constellation graphs as the key performance indicator with increasing range of fiber transmission and receiver sensitivity analysis. Fig. 2 (a), (b), and (c) reports the BER, EVM, and the received power plots of the received signal (X and Y polarization signals) with increasing range of fiber transmission respectively. The results report that log(BER) is -3.44, -1.38, -0.79, and -0.47 for X polarized signal and -3.14, -1.75, -0.96, and -0.47 for Y polarized signal at 100, 130, 160, and 190 km fiber range

respectively. Similarly, EVM % is reported as 12.01, 23.51, 32.10, and 60.80 % for X polarized signal and 12.32, 20.43, 29.42, and 55.36 % for Y polarized signal at 100, 130, 160, and 190 km fiber range respectively. Alternatively, the received optical power is reported as -14.94, -20.39, -24.27, and -26.21 dBm for X polarized signal and -12.00, -17.282, -21.22, and -23.21 dBm for Y polarized signal at 100, 130, 160, and 190 km fiber range respectively. The results show that the BER, EVM, and received optical power degrades with increasing fiber range transmission. The maximum reported range at a good log(BER) (≤ −2.42) and EVM % (≤ 18%) is 110 km for both X and Y polarized signal using the proposed 160 Gbps 16-QAM signals enabled PDM-OFDM-based RoF transmission system.

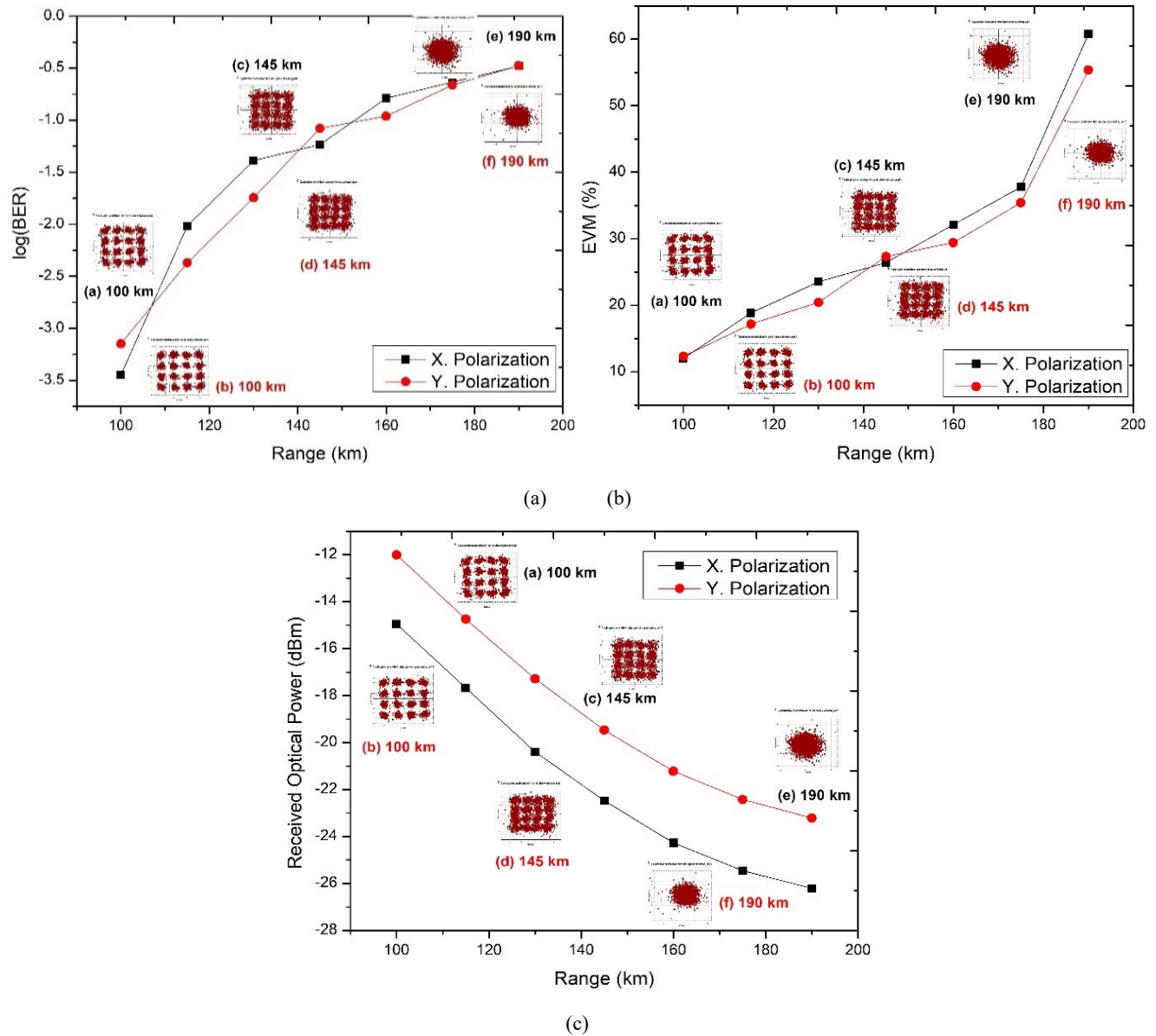(a)   (b)

(c)

Fig. 2. (a) log(BER), (b) EVM%, (c) received optical power versus fiber transmission range (colour online)

The proposed system utilized advanced signal processing techniques i.e. channel estimation and CPE at the receiver terminal to mitigate the adverse effects of channel distortions on the received signal quality. Fig. 3 (a), (b), and (c) reports the constellation of the received signals before signal processing techniques, after channel estimation, and after CPE at the receiver terminal for X polarized signal. Similarly, Fig. 4 (a), (b), and (c) reports the constellation of the received signals before signal processing techniques, after channel estimation, and after CPE at the receiver terminal for Y polarized signal. From the constellation, it can be clearly seen that there is an improvement in the received signal quality for both the X and Y polarized signals by deploying the proposed signal processing techniques.

X polarization constellation before channel estimation, port 1

X polarization constellation after channel estimation, port 1

(a)   (b)

X polarization constellation after carrier phase estimation, port 1
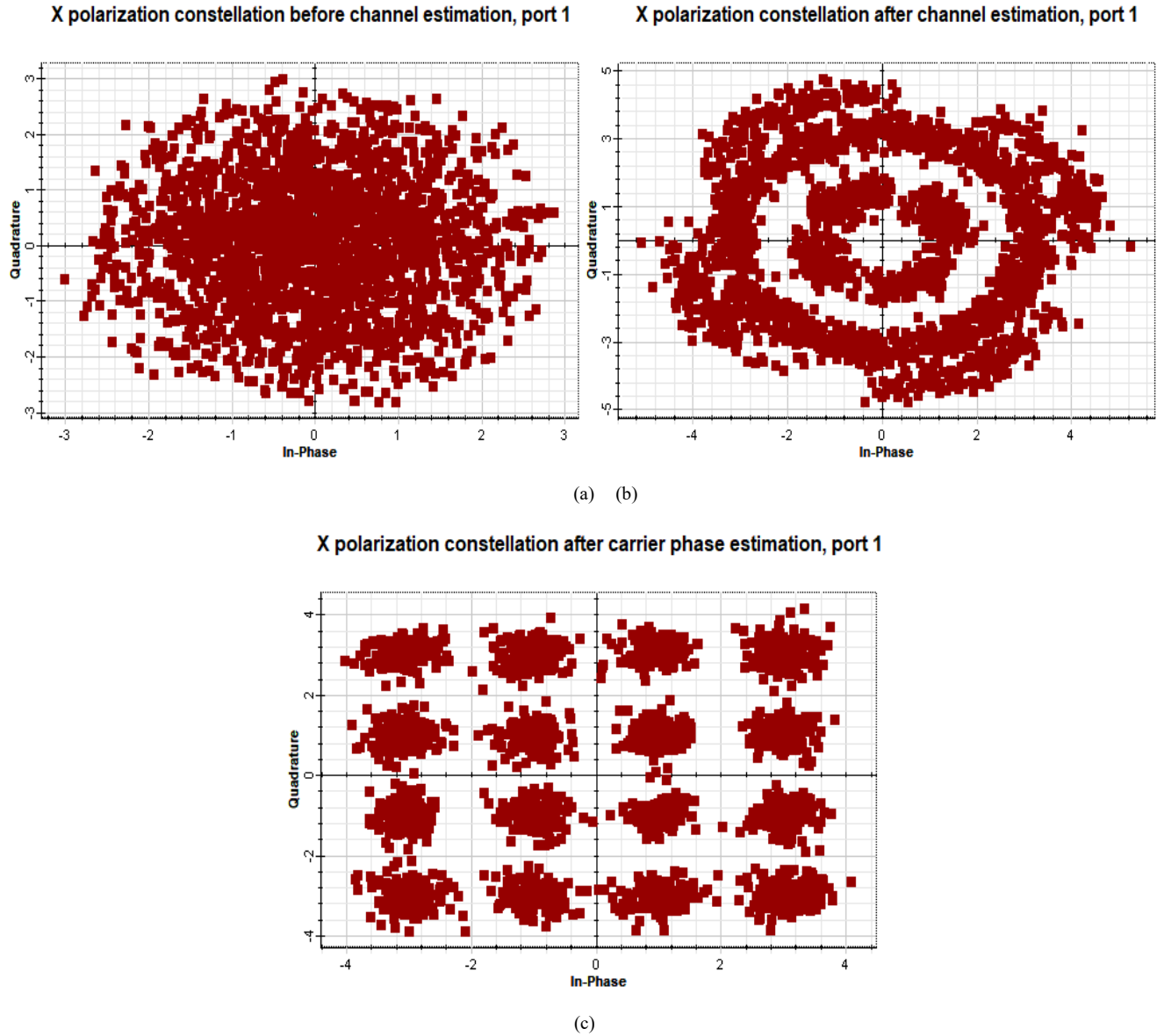
(c)

Fig. 3. Constellation for received X polarized signal (a) before channel estimation, (b) after channel estimation, and (c) after CPE (colour online)
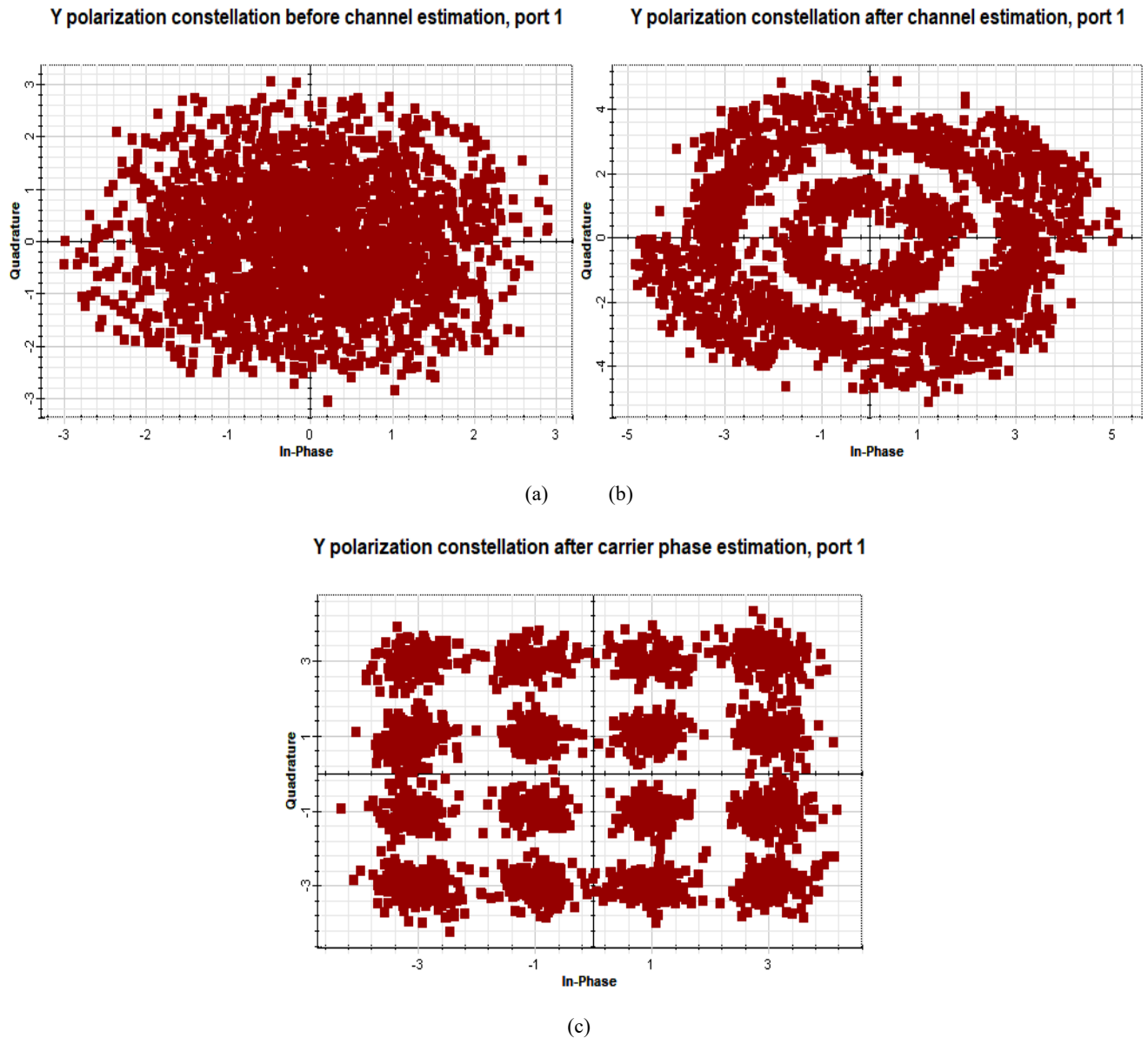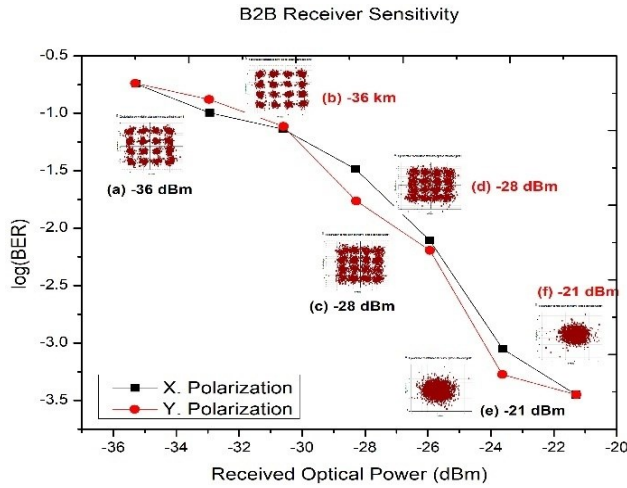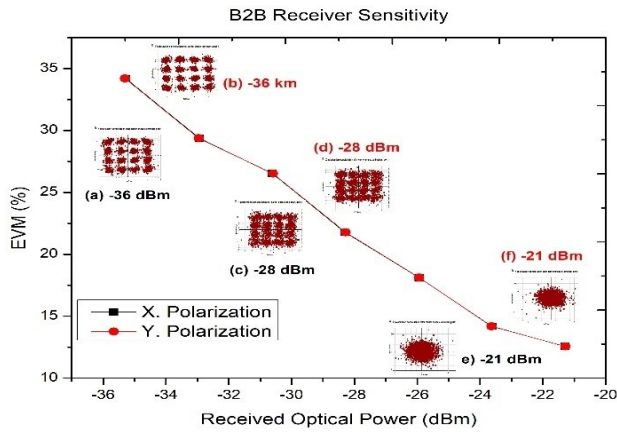
Y polarization constellation before channel estimation, port 1

Y polarization constellation after channel estimation, port 1

(a)   (b)

Y polarization constellation after carrier phase estimation, port 1

(c)

Fig. 4. Constellation for received Y polarized signal (a) before channel estimation, (b) after channel estimation,
and (c) after CPE (colour online)

Further we have carried out the receiver sensitivity analysis of the proposed system to find out the maximum optical power required at the receiver terminal to achieve and acceptable BER and EVM% levels for both X and Y polarized signals. Fig. 5 (a) and (b) reports the receiver sensitivity analysis for back-to-back (B2B) transmission using the proposed system. The results report that log(BER) is -0.744, -1.13, -2.10, and -3.44 for -35.28, -30.60, -25.94, and -21.28 dBm received optical power for X polarized signal respectively whereas log(BER) is -0.73, -1.11, -2.19, and -3.44 for -35.30, -30.59, -25.93, and -21.28 dBm received optical power for Y polarized signal respectively. Alternatively, the EVM% is 34.20, 26.51, 18.12, and 12.56 % for -35.28, -30.60, -25.94, and -21.28 dBm received optical power for X polarized signal

respectively whereas EVM% is 34.20, 26.51, 18.12, 12.56 % for -35.30, -30.59, -25.93, and -21.28 dBm received optical power for Y polarized signal respectively. The results show that for B2B transmission received optical power required is ~ -25 dBm for both X and Y polarized signals to achieve acceptable BER and EVM % levels at the receiver.
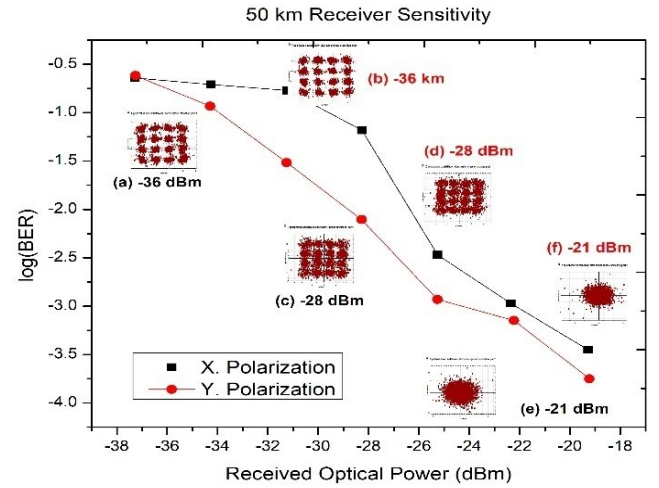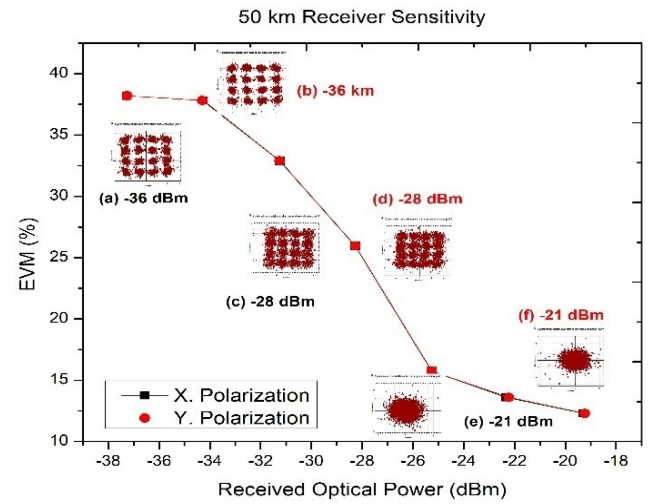
Fig. 5. (a) log(BER) (b) EVM % versus received optical power for B2B transmission (colour online)

Fig. 6. (a) log(BER) (b) EVM % versus received optical power for 50 km transmission (colour online)

Fig. 6 (a) and (b) reports the receiver sensitivity analysis for 50 km transmission using the proposed system. The results report that log(BER) is -0.64, -0.76, -2.47, and -3.44 for -37.26, -31.24, -25.25, and -19.28 dBm received optical power for X polarized signal respectively whereas log(BER) is -0.61, -1.51, -2.93, and -3.75 for -37.25, -31.25, -25.26, and -19.22 dBm received optical power for Y polarized signal respectively. Alternatively, the EVM% is 38.20, 32.89, 15.74, and 12.29 % for -37.26, -31.24, -25.25, and -19.28 dBm received optical power for X polarized signal respectively whereas EVM% is 38.20, 32.89, 15.74, and 12.29 % for -37.25, -31.25, -25.26, and -19.22 dBm received optical power for Y polarized signal respectively. The results show that for 50 km transmission received optical power required is ~ -22dBm for both X and Y polarized signals to achieve acceptable BER and EVM % levels at the receiver.

Fig. 7 (a) and (b) reports the receiver sensitivity analysis for 110 km transmission using the proposed system. The results report that log(BER) is -0.64, -0.75, -1.51, and -3.75 for -40.80, -32.90, -24.86, and -16.85 dBm received optical power for X polarized signal respectively whereas log(BER) is -0.44, -1.38, -1.91, and -2.97 for -40.91, -32.82, -24.85, and -16.86 dBm received optical power for Y polarized signal respectively. Alternatively, the EVM% is 45.37, 36.38, 22.00, and 13.94 % for -40.80, -32.90, -24.86, and -16.85 dBm received optical power for X polarized signal respectively whereas EVM% is 45.37, 36.38, 22.00, and 13.94 % for -40.91, -32.82, -24.85, and -16.86 dBm received optical power for Y polarized signal respectively. The results show that for 50 km transmission received optical power required is ~ -20 dBm for both X and Y polarized signals to achieve acceptable BER and EVM % levels at the receiver.

(a)

(b)

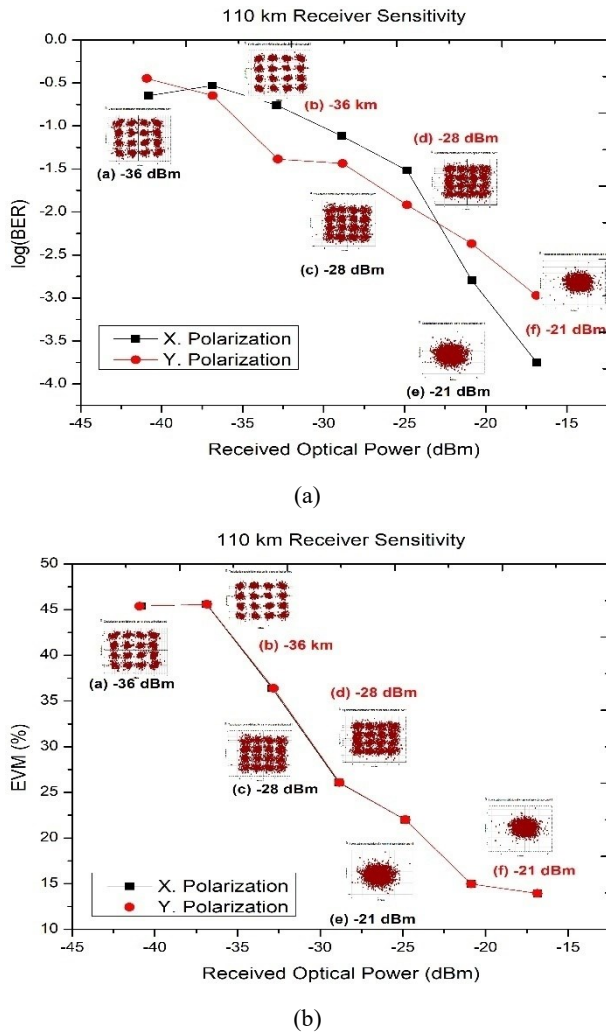*Fig. 7. (a) log(BER) (b) EVM % versus received optical power*
for 110 km transmission (colour online)

From the above reported results, it can be seen that the receiver sensitivity in the case of B2B transmission is -25 dBm which increases to -22 dBm in the case of 50 km transmission and -20 dBm in the case of 110 km transmission. So, there is a 3 dB power penalty at the receiver for 50 km transmission and 5 dB power penalty at the receiver for 110 km transmission.

4. Conclusions

This work has presented a comprehensive analysis of a 160 GbpsRoF system utilizing PDM, 16-QAM modulation, and OFDM techniques. By integrating advanced channel estimation and carrier phase estimation algorithms at the receiver, the system effectively mitigates common fiber impairments and maintains signal integrity. The evaluation using BER, EVM, and received optical power metrics confirms that the proposed approach delivers 160 Gbps transmission along 110 km fiber range with performance well within acceptable thresholds (i.e. $\log(BER) \leq -2.42$ and $EVM\% \leq 18\%$). Receiver

sensitivity studies further demonstrate the robustness of the system under various transmission scenarios, including both short and extended fiber links. The use of constellation diagrams for both polarization channels provides visual confirmation of improved signal quality due to enhanced receiver processing. These results align with recent advancements in the field and underscore the value of combining PDM, OFDM, and higher-order QAM for next-generation optical networks. The proposed system not only achieves high spectral efficiency but also offers scalability for future capacity upgrades.Practical implementation of high-capacity RoF systems, proposed in this work faces challenges including precise optical component alignment, real-time digital signal processing load, and mitigation of fibernonlinearities.In future works, integration of RoF with free space optics communication systems representing a promising extension that combines the high capacity and reliability of fiber optics with the flexibility and wireless reach of FSO links can be considered for last-mile access networks.

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