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Research Paper

Mitigate symbol error rate (SER) of 5G Backhaul in radio over fiber (RoF) system

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ABSTRACT

Fiber systems for transmitting millimeter wave (MMW) signals have recently become increasingly popular for upcoming wireless communication applications, including 5G and beyond networks. This study into the developments in the combination of wireless and optical networks, this paper utilizes this combination and reduces the symbol error rate (SER). The proposed system employs a 4*x*4 Multi-Input Multiple-Output (MIMO) wireless signal; MIMO can be utilized to improve coverage and increase capacity through spatial multiplexing. MIMO systems are an essential component of today's wireless networks, and they have been widely utilized in recent times to achieve great spectrum and energy efficiency. In this paper, the 4*X*4 MIMO is used to support the transmission link and increase throughput. Then, the subcarrier is modulated with a millimeter-wave using a Match Zender Modulator (MZM). The signal is transmitted through a (45-50-75) kilometer optical fiber, thus enhancing the capacity and frequency and increasing errors. The proposed system mitigates this error by utilizing multiple compensator that offset the SER. The VPIphotonics software program and Python are used.

1. Introduction

A search of current ROF advancements that integrate networks containing wireless and optical. Much attention is being paid to the 60 GHz frequency range worldwide to deploy tiny cells and address capacity demands while offering users excellent data rates [1]. Using millimeter-wave communications meets upcoming 5G network bandwidth requirements, but producing frequencies in the electronic domain can be challenging and expensive. Millimeter-wave frequencies can be produced in a way that is effective and compatible with fiber transmission infrastructure by utilizing photonic techniques like optical heterodyning [2]. The viability of small, fully programmable integrated microwave photonic processors has been advanced by this demonstration [3]. In the [4], a survey that emphasizes small-cell arrangements in urban settings is used to evaluate this technology through measurements and capacity assessments. The results are quite positive; experiments in New York City show that major outdoor, even in an urban canyon setting. Experimentally demonstrate and model a network design for the transportation of mm-waves based on RoF techniques to move signals in the front hauling section of the upcoming 5G generation of mobile systems [5]. A lightning-fast fiber-wireless backhaul system with wavelength-division multiplexing has been developed to offer a network of communication for High-Speed Trains (HSTs) that is speedy and error-free [6]. An effective wireless front-hauling solution is radio signal encapsulation onto a fiber mm-wave system. Three signals are successfully transmitted simultaneously via the system [7]. A brand-new function split option for the Next Generation Fronthaul Interface (NGFI) is presented utilizing a bandpass delta-sigma modulated all-digital RF transmitter. FPGA is used to create proof of the concept of all digital radio frequency transmitters depending on SDM Delta Sigma Modulation [8]. All RoF transmissions have gained a lot of interest due to how much the frontend hardware is simplified by digital processing [9]. When minimizing network backhaul traffic, an anisotropic path loss model considers the limited radio resource and the variations in arrival times for multiple coordination links [10]. The Polynomial-Cancellation-Coded Orthogonal Frequency Division Multiplexing, PCCOFDM, performance in an Orthogonal Frequency Division Multiple Access (OFDMA) multiuser system is analyzed and compared [11]. The author in [12], massive Multiple-Input Multiple-Output (mMIMO) offers the integrated silicon photonic RoF transmitter and receiver made of the linear (SiGe-BiC MOS) trans-impedance amplifier and a Geon-Si waveguide photodiode that are both modulated on-silicon lasers directly. It is proved that a Long-Term Evolu¬tion (LTE) signal [13]. The new non-standalone $5G$ radio framework was used with an effective optical-wireless architecture, and the system was evaluated against similar studies in the literature [14]. An experimental multiband $5G$ NR Optical Fronthaul (OFH) based radio over fiber system was created (DPD) [15]. [16] provides an innovative, first-of-its-kind DPD based on NN training and architecture approach for improving RoF connection efficiency, an experi¬mental comparison study between NN and Volterra (MP/GMP) on DPD approaches. A hybrid-ring and tree RoF transmission scheme with self/disconnection prevention. It can support high base station (BS) distribution density in an urban region and improve quality of services thanks to self/disconnection protection [17]. A hybrid microwave photonic receiver proto type that combines Silicon Nitride (Si3N4) integrated adjustable microring filters with Lithium Niobate (LiNbO3) dual parallel phase modulators [18]. The testing of an Enhanced Mobile Broadband (eMBB) 5G (MIMO) hybrid fiber-wireless (Fi-Wi) structure (DPD)is proposed in[19]. MIMO systems are recognized as a crucial emerging technology for future generations of wireless communication systems [20]. Radio over Fiber (RoF) is a key application in fiber optic systems. In RoF, light is modulated to a radio frequency and transmitted via fiber optics for seamless wireless access. Technically, RoF is a hybrid system that integrates wireless and optical technologies, resulting in high capacity, high data rates, transparency, and mobile solutions [21].

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Nomenclature:

List of variables:

A	Amplitude
BER	Bit error rate
$Bit\ rate$	Bit rate (GB S-1)
EVM	Error vector magnitude
F	Frequency (Hz)
P	Power (watt)
SER	Symbol error rate
v	Voltage
$Symbol\ rate$	Symbol rate (Bd)

Greek Symbols:

ω_o	Angular frequency
ϕ_o	Phase angle
τ_d	Time delay
$\beta_{(\omega)}$	Propagation constant

RF communication technology has several drawbacks, such as the time required to obtain a spectrum frequency license and lower security than optical communication [22]. Signals transmitted through a wireless communication channel are affected by a harsh physical environment in a complex way. Obstructions like mountains, buildings, and trees cause signal diffraction, reflection, and scattering. As a result, the received signals at the receiver end experience distortions, delays, interference, and various phase shifts due to the generation of multipath signals [23]. In FSO (Free Space Optics) transmission, the signal is influenced by atmospheric attenuation and turbulence conditions [24]. A radio-over-fiber system can deliver high-speed data transmission for 5G and next-generation networks [25]. It can be noted the Error Vector Magnitude (EVM) decreased by utilizing the PMD compensator in the previous study [26]. The suggested system concentrates on the receiving side and attempts to minimize errors related to different fiber optic cable lengths to improve overall system performance.

This paper clarifies the effective use of compensators in 5G backhaul and Radio-over-Fiber (RoF) systems. Initially, the implementation of $4X4$ MIMO technology enhances performance and higher operating frequencies but increases the error rate. To reduce this error, such as SER, and improve system performance, Polarization Mode Dispersion (PMD) and Digital Back Propagation (DBP) compensators are used.

2. Methodology and experimental

Integrating photonic technologies into fiber-wireless systems to generate, transmit, and convert signals to MMW/THz frequencies is highly attractive. This section provides a comprehensive analysis and detailed description of our system. In the initial subsection, we establish that the production of the electrical signal is initiated by the synthesizer, as depicted in Fig. 1 and Fig. 2. This process entails the manipulation of appropriate sidebands for both the millimeter wave signal and the laser, leading to the creation of a source that emits two different wavelengths simultaneously. Afterward, these signals are fed into a Mach Zehnder Modulator (MZM) to generate the optical signal. Afterward, a suitable pair of sidebands is chosen by passing the produced optical signal through a configured waveguide grating, which acts as a demultiplexer. Two suitable sidebands are chosen. The employed methodology can generate a millimeter wave (MMW) output with adjustable frequency [27].The expression for the MMW generator are presented in Eqs. 1, up to Eq. 6:

$$E(t) = 2A + A_1 - A_2 \tag{1}$$

$$The\phi + t = \phi_o(t) + 3\phi_1(t) \qquad \phi - t = \phi_o(t) - 3\phi_1(t) \tag{2}$$

$$E_1(t) = IL \times E(t) \times A_3 = IL \times A + A_3 \times A_1 + IL \times A - A_3 \times A_2 \tag{3}$$

$$E_2(z,t) = 2IL \times A + A_4 - 4\pi \times e^{-\gamma z} \times A_6 - A_7) - A_5 \tag{4}$$

Or it can be expressed as:

$$E_2(z,t) = B + A_6 + B - cos\left[(\omega_o - 3\omega L_o)z + \phi - t\right] \tag{5}$$

$$\pm B = IL \times A \pm cos(2\pi V_\pi \times S(t - (\omega_o \pm 3\omega L_o) - \beta(\omega_o \pm 3\omega L_o x)z) \tag{6}$$

Where:

$A_1 = cos\left[(\omega_o + 3\omega L_o)(t + \tau_d) + \phi + (t + \tau_d)\right]$

$A_2 = cos\left[(\omega_o - 3\omega L_o)t + \phi - t\right]$

$A_3 = cos(2\pi V_\pi S(t) - 4\pi))$

$A_4 = cos(2\pi V_\pi S(t - (\omega_o + 3\omega L_o) - 1\beta(\omega_o + 3\omega L_o)z)$

$A_5 = cos(2\pi V_\pi S(t - (\omega_o + 3\omega L_o) - 1\beta(\omega_o - 3\omega L_o)z)$

$A_6 = cos\left[(\omega_o + 3\omega L_o)(t + \tau_d) - \beta(\omega_o + 3\omega L_o)z + \phi + (t + \tau_d)\right]$

$A_7 = cos\left[(\omega_o - 3\omega L_o)t - \beta(\omega_o - 3\omega L_o)z + \phi - t\right]$

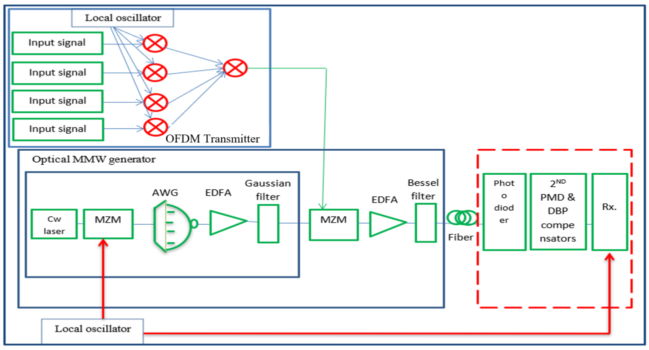


Figure 1. The propose system

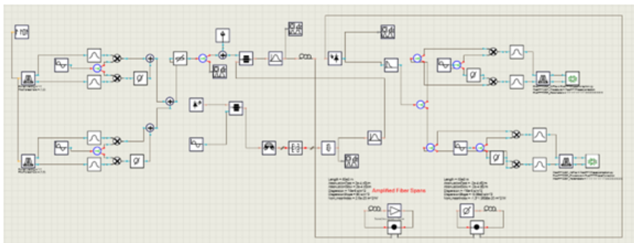


Figure 2. The proposed system (VPIphotonics window)

The amplitudes of sidebands are labelled as $A+$ and $A-$, respectively. The symbols ω_o, $\phi_o(t)$ represent the angular frequency and phase of the optical signal emitted by the laser, respectively. The Local Oscillator (LO) generates an electrical signal with a specific angular frequency and phase. The variable τ_d represents the time delay associated with the differences in optical path frequencies between the two optical sidebands.

Our experimental configuration uses an Erbium-Doped Fabre Amplifier (EDFA) to enhance the optical power. In addition, we employ an optical bandpass filter (OBPF) to decrease the noise caused by the amplified spontaneous emission. Subsequently, the resulting optical signal with two distinct tones is fed to a second Mach-Zehnder Modulator (MZM) to modulate it with the Radio Frequency (RF) signal. An RoF signal is generated by the amalgamation of wireless signals transmitted on the millimeter wave (MM-Wave) carrier. The following (EDFA) amplifies the resulting signal while a secondary Optical Bandpass Filter (OBPF) is utilized. The mathematical representation of the modulated signal can be expressed [27]:

The acronym (IL) stands for insertion loss. The switching voltage of the optical modulator, represented as V_π, is a crucial parameter in this field. The variable $S(t)$ shows the wireless signal supplied to the modulator. Afterward, the signal is transmitted into a Fibre that covers a distance of $(45 - 50 - 75)$ kilometers and then forwarded to the receiver side. Chromatic dispersion is the impact of the channel (optical fibre) on the propagating signals (light) inside it. Chromatic dispersion results from different propagation velocities of different wavelengths included in the light signal due to wavelength dependence of the refractive index of the core layer material. This dispersion is defined by a propagation constant $\beta_{(\omega)}$, and an amplitude attenuation [27]. Following that, the signal passes up-conversion (Up-conversion entails the absorption of two or more photons with lower energy and the subsequent emission of a single photon with higher power. This phenomenon can be enabled by specialized materials called up-conversion phosphors or through nonlinear optical processes) by utilizing a high-bandwidth photodiode, resulting in the signal's transformation [27]. Additionally, we analyze the impact of using Fibre on systems that support MIMO transmission after the optical transmission stage.

Furthermore, to decrease the SER. A Polarisation Mode dispersion (PMD) compensator is used to correct the errors mentioned. The original wireless signals are multiplied with an LO and amplified using a low-noise amplifier. The frequency of the LO output signal is identical to the frequency of the millimeter wave (MMW) signal provided at the transmitter site. Digital Back Propagation (DPB) The main effect of the phenomenon can be briefly described as a group delay, which happens while two signal components sent along the central axis of the fibre are in motion. The description provided is insufficient for signal bandwidths that are significant in the context of optical communications; the compensator only requires a single polarisation controller and a programmable delay; in this research, to improve the functionality of our system, we used a programmable delay and a single polarisation controller. The single polarisation controller was crucial for modifying the optical signals' polarisation state to ensure ideal alignment for both transmission and reception. Reducing polarization-dependent losses and preserving signal integrity depends on this alignment—additionally, the programmable delay allowed for exact regulation of the system's signal propagation time. We could precisely synchronize the signals by adjusting the delay, which is essential to lowering inter-symbol interference and enhancing system performance in general. These elements were crucial to our test setup because they provided the control and adaptability required to ensure dependable and excellent data transfer in our $5G$ backhaul RoF system—the purpose of compensations is to mitigate dispersion and minimize SER. SER values are utilized for assessment and to illustrate the optimization of connection parameters. Ultimately, the broadcast intermediate frequency (IF) is obtained by merging the LO-generated signal with the received millimeter wave (MMW) signal. The proposed model explicitly targets the recipient end and the operations involved in low-latency technology, high-capacity, and advanced systems that rely on Radio-Over-Fibre (RoF) technological devices. Combining wireless and optical networks provides a promising approach to enhancing capacity and mobility.

Table 1. The system parameters

Parameters	Value and Unit
Local oscillator for $5G$	01.0 v
Local oscillator for optic	02.7 v
MZM of mm-wave	30 dB
MZM of electrical and mm-wave	15.0 dB
Average power of photodiode	15.0 mw
Emission frequency of laser	$193.1x10^{12}$ Hz

Table 2. The system requirements

Requirements	Value and Unit
Requirements	10 MBd
Symbol rate	1024
Number of symbols	5 Gb/s
Bit rate	16
Sample per symbol	2.5 GHz
Carrier frequency	16
Number of carrier	0.125
Cyclic prefix	15 dB
The attenuator of electrical signal	9 dB

3. Results and discussion

The system is implemented by utilizing the software VPIPhotonics and Python. The $5G$ standard can provide speeds of up to 20 (Gb/s) and has a bandwidth of $3.2(GHz)$. This cellular technology uses the widely acknowledged OFDM modulation technique. The desired transmission rate determines the choice of modulation schemes, such as $64-QAM$, for the individual subcarriers produced by $OFDM$ and $MIMO$ techniques. By using these modulation techniques, a channel may be split up into several smaller subcarriers. To perform the test, a signal with a sample mode bandwidth of 1280 gigahertz $(1280GHz)$ and a data rate of $(5Gb/s)$ has to be produced. In this study, the OFDM (modulation and demodulation) was implemented using $Python$. Python has strong libraries and tools, such as NumPy and SciPy, which make it able to manage the complex mathematical processes needed for OFDM efficiently. The modulation procedure involved converting the input data onto sub-carriers using methods such as 64-QAM. An Inverse Fast Fourier Transform $(IFFT)$ was then used to convert the frequency domain data into a time domain signal. To demodulate the received time-domain signal, a Fast Fourier Transform (FFT) was used to analyze it and return it to the frequency domain. The signal is subsequently transmitted, employing $64QAM$ and MIMO $(4X4)$ models with parameters and requirements as listed in Table 1 and Table 2 to improve the data rate. However, this increase in capacity is accompanied by an increase in errors. To address this problem, the compensators are utilized.

Table 3. SER at 14sub-carrier

System	Fiber length	SER
$2X2$ $MIMO$ without compensators	45 km	3.860×10^{-7}
$4X4$ $MIMO$ without compensators	45 km	0.113×10^{0}
$4X4$ $MIMO$ with compensators	45 km	1.130×10^{-8}
$4X4$ $MIMO$ with compensators	50 km	5.430×10^{-8}
$4X4$ $MIMO$ with compensators	75 km	7.230×10^{-5}

4. Symbol error rate (SER) reduction

The mathematical definition of the SER is the ratio of symbol errors to the total number of transmitted symbols. Usually, a percentage or a fraction is used to express it [28]. The following formula, EQ. 7, is used to get the SER.

$$SER=\frac{Number\ of\ Symbot\ Errors}{Total\ Number\ of\ Transmitted} \tag{7}$$

To determine the Symbol Error Rate (SER), the received symbols must be compared with the expected symbols at the receiver. Accurate determination of the SER requires knowing the transmitted symbols at the receiver. Techniques such as pilot symbols, training sequences, and forward error correction (FEC) can achieve this. These methods allow the receiver to estimate or recover the transmitted symbols even in the presence of errors. Several factors, including the modulation technique, interference, receiver configuration, and channel conditions, influence the SER. A higher signal-to-noise ratio (SNR) typically results in a lower SER, indicating better performance. Also, more robust modulation schemes like higher-order constellations can lead to lower SER values and increased noise resistance, [28]. The symbols and the symbol error probability as shown in equation, Eq.8.

$$P(bit\ error)=\frac{1}{m}P(Symbol\ Error) \tag{8}$$

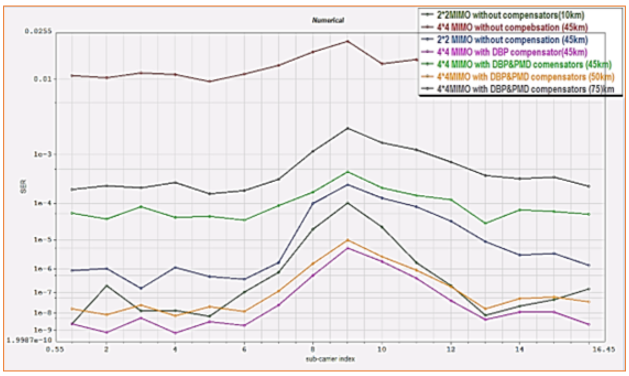
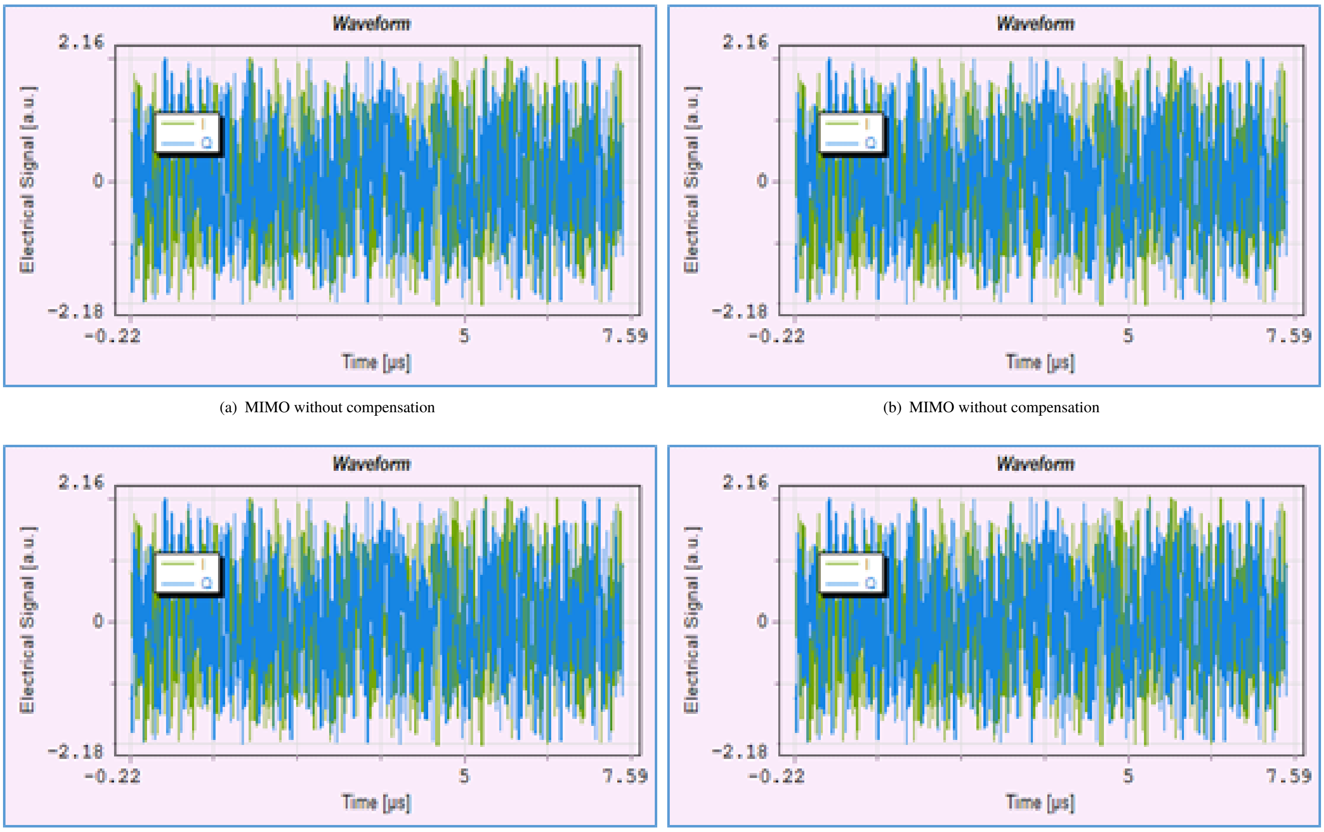


Figure 3. SER vs. multi sub-carrier

This paper presents the values of SER versus multiple sub-carriers, as illustrated in Fig. 3, and discusses the observed decrease in these values. Figure Fig. 3 illustrates how the utilization of compensators decreases the Symbol Error Rate (SER) compared to multi-sub-carrier systems at different lengths of the optical channel. The values can be compared to Table 3 below. Figure Fig. 4 shows the waveform with Sub-14 at 45km after compensators are utilized. Reduced demand for electric power will be especially beneficial for the mass deployment of small cells. Another important approach is remote power delivery via fibre links in conjunction with data signals. The result of power is clear, as shown in Fig. 5.



(a) MIMO without compensation

(b) MIMO without compensation

(c) MIMO with DBP

(d) MIMO with DBP and $2^n d$ PMD

Figure 4. The waveforms at sub-14 where (a) 2×2 MIMO without compensation (b) 4×4 MIMO without compensation (c) 4×4 MIMO with DBP (d) 4×4 MIMO with DBP and $2^n d$ PMD

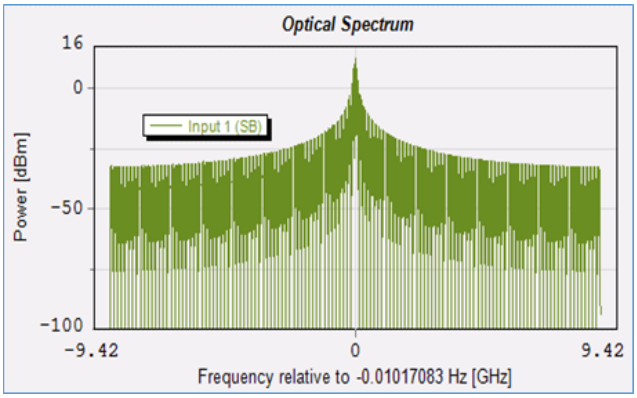


Figure 5. The power at sub-carrier 14, $4X4$ MIMO with DPB and PMD, 45 *km* length.

5. Conclusion

This research aims to clarify the efficient utilization of compensators in the context of $5G$ backhaul and ROF systems. The deployment of $4X4$ $MIMO$ as a substitute resulted in a higher frequency and a raised error rate. To mitigate the symbol error rate (SER) and improve system performance, the compensator known as Polarization Mode Dispersion compensators (PMD) is utilized, followed by Digital Back Propagation (DBP) compensators. Because of the increasing transmission rates, polarisation mode dispersion (PMD) is becoming a significant challenge in optical fibre systems. The DBP and PMD compensators efficiently reduce dispersion and nonlinearity effects through their compensation mechanism. The findings demonstrate the improvement of the system and the decrease in errors. This is evident in the results. Future work will try to develop the proposed system by utilizing channel estimation and increasing the fiber length.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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