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Mitigate the Errors of 5G Backhaul in Radio-over-Fiber (RoF) System

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ABSTRACT

The utilization of fiber systems for transmitting millimeter-wave (MMW) signals has gained significant traction in recent years, particularly for advanced wireless communication applications such as 5G and beyond. This paper explores the integration of wireless and optical networks to enhance performance by reducing the error vector magnitude (EVM) and symbol error rate (SER). The proposed system employs a 2×2 multiple-input multiple-output (MIMO) configuration, which improves coverage and increases capacity through spatial multiplexing. MIMO systems are critical to modern wireless networks, providing superior spectrum and energy efficiency compared to earlier single-input-single-output systems. Following MIMO processing, a millimeter-wave signal is modulated onto the subcarrier using a Mach-Zehnder modulator (MZM). The signal is sent across a (50 and 70)-kilometer optical cable, which boosts data rate and frequency but introduces errors. The proposed method uses a convolutional neural network (CNN) correction to lower these errors and equalize to balance the SER and EVM. VPIphotonics and Python programming are utilized to put the system into practice. The proposed system has a bandwidth of 17 GHz and a data rate of 56.656 Gb/s; the center frequency is 160 GHz with EVM ≈ 3% at the 50 km distance and ≈ 4% at the 70 km fiber channel length.

1. INTRODUCTION

The review of current advancements in RoF that integrate wireless and optical networks. The 60 GHz frequency spectrum is receiving a lot of interest globally as a means of deploying small cells, meeting capacity demands, and providing customers with high-speed data rates [1]. Use millimeter-wave communications meet upcoming 5G network bandwidth requirements. 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]. 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 [4]. An effective wireless fronthauling solution is radio signal encapsulation onto a fiber mm-wave system. Three signals are successfully transmitted simultaneously via the system [5]. A brand-new function split option for the next generation fronthaul interface (NGFI) uses a bandpass delta-sigma modulated all-digital RF transmitter. FPGA is used to create proof of the concept of all digital radio frequency transmitters depend on SDM Delta Sigma Modulation [6]. All RoF transmissions have gained a lot of interest due to how much the frontend hardware is simplified by utilizing digital processing [7]. When minimizing network backhaul traffic, an anisotropic path loss model takes into account the limited radio resource, and the variations in arrival times for multiple coordination links [8]. Polynomial-cancellation-coded orthogonal frequency division multiplexing (PCCOFDM) performance in an orthogonal frequency division multiple access (OFDMA) multiuser system is analyzed and compared [9, 10] concentrate on massive multiple-input multiple-output (mMIMO), offer 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 provided that a Long-Term Evolution (LTE) signal [11]. The non-standalone 5G new radio framework was used with an effective optical-wireless architecture, and the system was evaluated against similar studies in the literature [12]. An experimental multiband 5G NR Optical Fronthaul (OFH) based radio over fiber (RoF) system was created (DPD) [13, 14] provides an innovative, first-of-its-kind DPD based on NN training and architecture approach for improving RoF connection efficiency, an experimental comparison study between NN and Volterra (MP/GMP)-based 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 the quality of services thanks to self/disconnection protection [15]. A hybrid microwave photonic receiver prototype that combines Silicon Nitride (Si3N4) integrated adjustable mirroring filters with Lithium Niobate (LiNbO3) dual parallel phase modulators [16]. The testing of an enhanced mobile broadband (eMBB) 5G (MIMO) hybrid fiber-wireless (Fi-Wi) structure (DPD) is proposed in MIMO systems are recognized as a crucial emerging technology for future generations of wireless communication systems [17]. 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. RF communication technology has several drawbacks, such as the time required to obtain a spectrum frequency license and lower security than optical communication. Signals transmitted through a wireless communication channel are affected by a harsh physical environment in a complex way. A radio-over-fiber (RoF) system can deliver high-speed data transmission for 5G and next-generation networks. The EVM is decreased by the 2nd Polarization Mode Dispersion (2nd PMD) compensator in our previous research [18].

This paper outlines the development of a wireless backhaul system that integrates MM-wave and RoF technologies for 5G networks. We focus on integrating and synchronizing these technologies to ensure fast, error-minimized wireless signal transmission and tackle long fiber channel challenges. The study aims to design a system capable of handling large data volumes and meeting the strict specifications of 5G networks while maintaining high performance. We also discuss the use of 2×2 MIMO technology and compensators in addressing signal issues like distortion and dispersion in optical fiber communication systems.

2. RELATED WORK

Recently, studies have verified the effectiveness of a CNN-based signal decoder [19, 20]. CNNs, the focus of much research, are widely used in applications such as image identification and speech recognition. One significant property of CNNs is their capacity for parallel calculations. The CNN-created decoder in request has an input layer, multiple convolutional layers, and an output layer. The issue statement focuses on the challenge of developing an effective and fast wireless signal transmission system for 5G backhaul networks. The objective is to combine the functionalities of RoF and MM-Wave systems to reach maximum efficiency and respond to the growing need for high-speed data transfer in 5G networks. After studying the previous research, it can be noted Bekkali and Nishimura [21] propose wireless with 20 km fiber distance, 10Gb/s, and EVM is 12.5%, while Udalcovs et al. [22] propose optical and LTE at a fiber distance (10 km) with a data rate of 10Gb/s. In contrast, the studies [23-26] propose RoF and 5G at short fiber distances ranging (from 500 m-5 km) with data rates equal and less than 2Gb/s, and the EVM of reference [26] is 12.5%. The literatures [3, 27-31] present a rate not exceeding 5Gb/s and fiber distance (10 km-25 km), and Pandey et al. [32] and Santhanam [33] propose the system with fiber distance (30 km-45 km) and data rate 9Gb/s and 20Gb/s, Azzahhafi et al. [34] present the system with high data rate 122.5Gb/s but the channel distance is 25 km, which is datregarded short distance in RoF. Hameed [31] presents the system with a distance (of 10 km-135 km), but it gets the best performance at 10 km with a data rate of 5Gb/s. Mohammed et al. [35] and Vallejo et al. [36] have EVM higher than 8%. The challenge is creating a system that can smoothly integrate these technologies, guaranteeing reliable and efficient transmission of wireless signals while optimizing the network's capacity and coverage with high data rate and long fiber distance with smaller errors (EVM, SER, BER) and spectral efficiency. Signals transmitted using optical fiber channels experience many losses while travelling vast distances. The leading causes of these losses are fiber dispersion and nonlinear distortions. Fibre dispersion is a phenomenon where signals spread out linearly, whereas nonlinearity is a highly undesirable characteristic of modern communication systems. Nonlinearity can lead to intermodulation distortion, neighboring channel interference, phase distortion, and harmonic distortion. The primary nonlinear effect in fibres in most communication systems is Kerr nonlinearity. This nonlinearity happens due to the relationship between the refractive index and the strength of the signal. As high-capacity, long-haul optical fiber communication systems are deployed, the impact of propagation flaws becomes more pronounced across greater fiber distances, leading to substantial signal distortion. Our research focuses on using CNN compensator and equalization editors.

3. METHODOLOGY AND EXPERIMENT

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 synthesizer initiates the electrical signal production, as depicted in Figures 1 and 2.

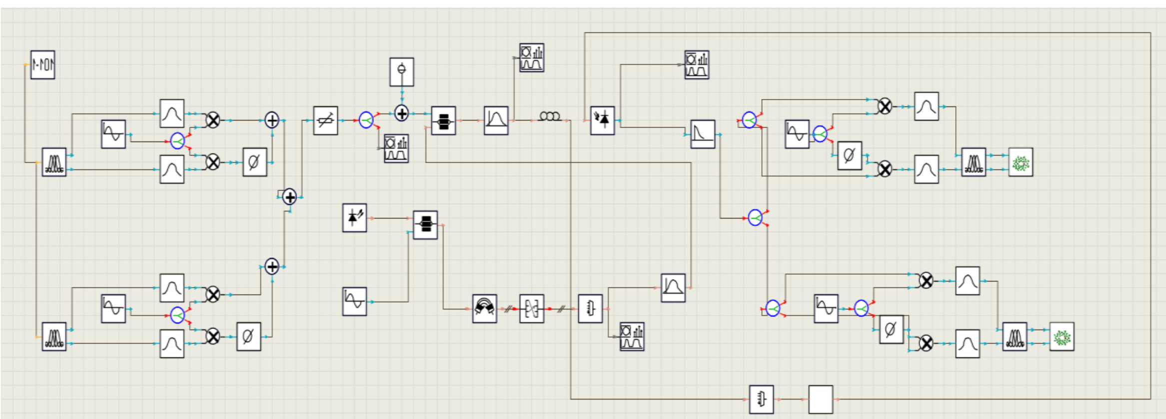


Figure 1. The propose system (Vpiphotonics window)

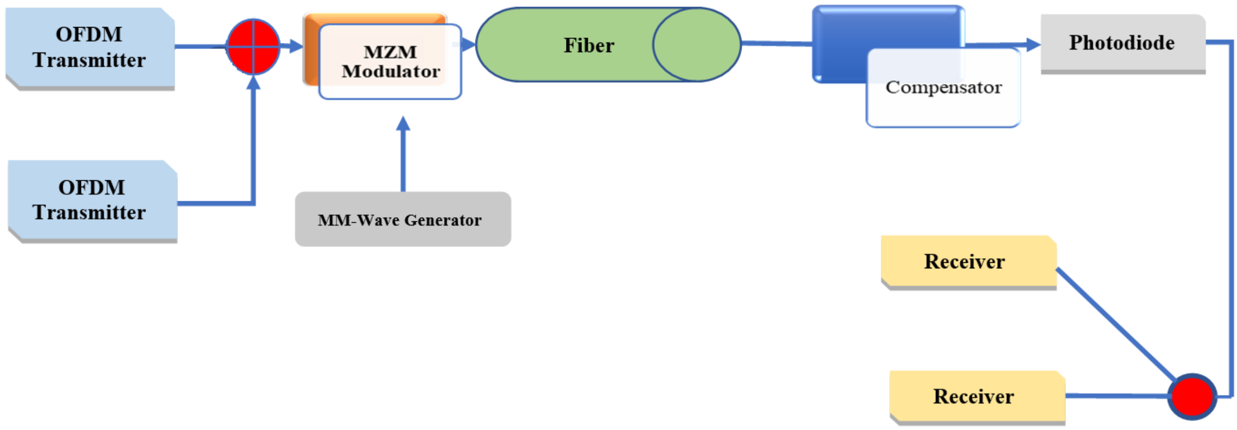


Figure 2. The propose system

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. Afterwards, these signals are fed into a Mach Zehnder Modulator (MZM) to generate the optical signal. Then, 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, the expression for the MMW generator is presented as Eq. (1) & Eq. (2) follows [4]:

$$E(t) = A + \cos[(\omega_0 + 3\omega L_O)(t + \tau_d) + \phi + (t + \tau_d)] + A\cos[(\omega_0 - 3\omega L_O)t + \phi_-(t)] \quad (1)$$

where,

$$\phi_+(t) = \phi_0(t) + 3\phi_1(t), \phi_-(t) = \phi_0(t) - 3\phi_1(t) \quad (2)$$

The amplitudes of sidebands are labelled as A+ and A-, respectively. The symbols ω_0 and $\phi_0(t)$represents the angular frequency and phase of the optical signal emitted by the laser, respectively. The Local Oscillator (LO) generates an electrical signal with specific angular frequency and phase. The variable τd represents the time delay associated with the differences in optical path frequencies between the two optical sidebands. In our experimental setup, we use an optical bandpass filter (OBPF). furthermore, to mitigate the noise resulting from the increased spontaneous emission. The two different tones that come from this process are then sent into a second Mach-Zehnder Modulator (MZM) in order to modulate it with the radio frequency (RF) signal. Combining wireless signals that are sent on the millimeter wave (MMW) carrier results in the creation of a RoF signal. The following secondary Optical Bandpass Filter (OBPF) is used. The mathematical representation of the modulated signal can be expressed as the fallowing Eq. (3) [4]:

$$\begin{aligned} E1(t) &= IL.E(t).cos\left(\frac{\pi}{2V\pi}S(t) - \frac{\pi}{4}\right) \\ &= IL. + cos\left(\frac{\pi}{2V\pi}S(t) - \frac{\pi}{4}\right) \\ &\times \cos[(\omega_0 + 3\omega L_O)(t + \tau d) + \phi + (t + \tau d)] \\ &+ IL.Acos\left(\frac{\pi}{2V\pi}S(t) - \frac{\pi}{4}\right) \\ &\times cos[(\omega_0 - 3\omega L_O)t + \phi_-(t)] \end{aligned} \quad (3)$$

The acronym "IL" stands for insertion loss. The switching voltage of the optical modulator, represented as Vπ, is a crucial parameter in this field. The variable S(t) shows the wireless signal that is supplied to the modulator. Afterwards, the signal is transmitted into a Fibre that covers a distance of (100) kilometres, and then forwarded 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 (β(ω)) and an amplitude attenuation. 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 energy. This phenomenon can be enabled by specialized materials called up-conversion phosphors or through nonlinear optical processes) through the utilization of a high-bandwidth photodiode, resulting in the signal's transformation [4] has the following Eq. (4).

$$\begin{aligned} &E_2(z,t) = IL.A + \\ &\cos\left(\frac{\pi}{2V\pi}S(t - (\omega_0 + 3\omega L_O)^{-1}\beta(\omega_0 + 3\omega L_O)z)\right. \\ &\left.\frac{\pi}{4}\right)e^{-\gamma z}.\cos[(\omega_0 + 3\omega L_O)(t + \tau d) - \\ &\beta(\omega_0 + 3\omega L_O)z + \phi_+(t + \tau d)] + IL.A \\ &-\cos\left(\frac{\pi}{2V\pi}S(t - (\omega_0 - 3\omega L_O)^{-1}\beta(\omega_0 - 3\omega L_O)z)\right. \\ &\frac{\pi}{4}e^{-\gamma z}.cos[(\omega_0 - 3\omega L_O)t\beta(\omega_0 - 3\omega L_O)z\phi_-(t)] \end{aligned} \quad (4)$$

And can be expressed as Eqs. (5) and (6) [27].

$$\begin{aligned} &E_2(z,t) = B + \cos[(\omega_0 + 3\omega L_O)(t + \tau_d) \\ &-\beta(\omega_0 + 3\omega L_O)z + \phi_+(t + \tau_d)] \\ &B_-\, cos[(\omega_0 - 3\omega L_O)z + \beta[(\omega_0 - 3\omega L_O)z + \phi_-(t)]] \end{aligned} \quad (5)$$

where,

$$\begin{aligned} &B\pm = IL.A\pm.\cos\left(\frac{\pi}{2V\pi}S(t - (\omega_0 \pm 3\omega L_O)^{-1}\right. \\ &\left.\beta(\omega_0 \pm 3\omega L_0 x)z) - \frac{\pi}{4}\right)e^{-\gamma z} \end{aligned} \quad (6)$$

Additionally, we analyze the impact of using fiber on systems that support MIMO transmission after the optical transmission stage. The original wireless signals are multiplied with a LO, followed by amplification 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. The purpose of compensation to mitigate the SER and EVM. Those values are utilized not only for assessment, but also to illustrate the optimization of connection parameters. The proposed model specifically targets the recipient end the operations involved in high data rate technology, high-capacity, and advanced fiber-wireless systems that rely on RoF technological devices. Combining wireless and optical networks provides a promising approach to enhancing capacity and mobility. This paper looks at the impacts of a variety of compensators, including sophisticated Deep Neural convolution neural network, and Digital Signal Processing algorithms like equalization.

4. THE PROPOSED SYSTEM BY UTILIZING CNNS

ANNs, or artificial neural networks, are models for machine learning. The input layer, the hidden layer, and the output layer are the three main parts of an ANN as shown Figure 3. Hidden units, weights are applied to the connections between neurons, indicating the intensity and significance of the inputs, so termed because their values are not directly observed or known, are found in the hidden layer. Convolutional Neural Networks (CNNs) is a type of deep learning ANN.

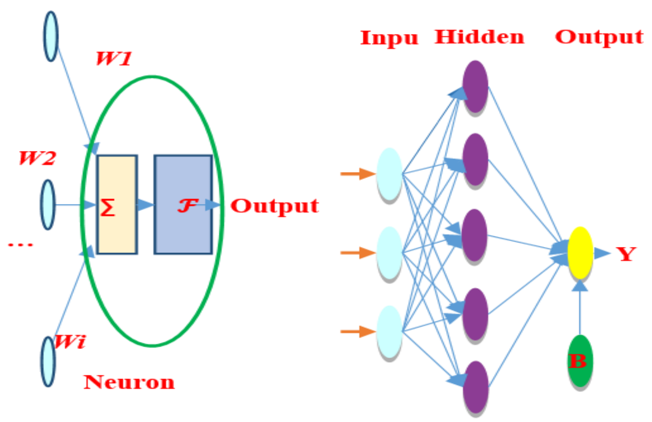


Figure 3. The architecture of ANN

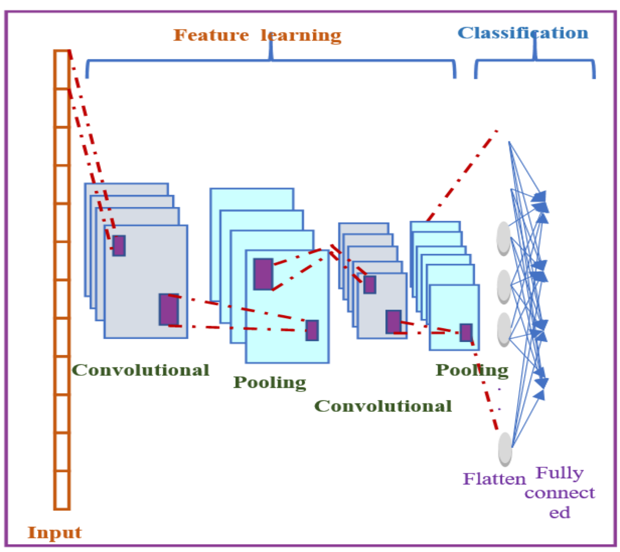


Figure 4. The architecture of CNN

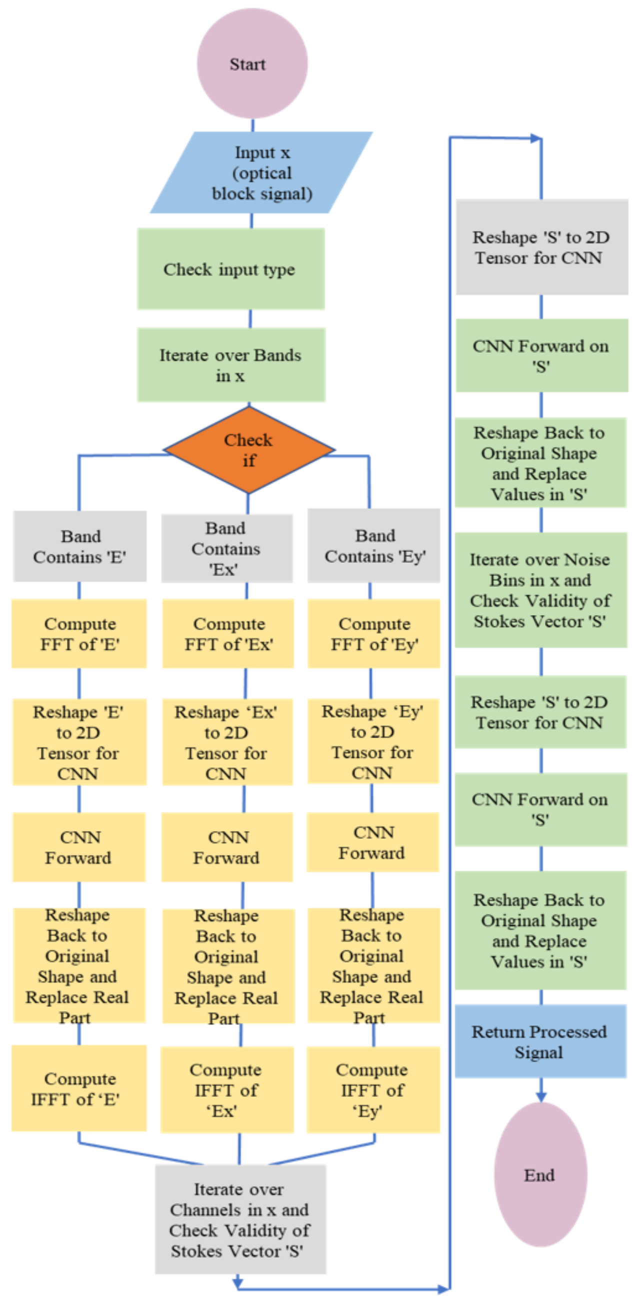


Figure 5. The algorithmic of CNN

The capability of CNN to automatically and adaptively learn spatial structures of features from input signal sources is the fundamental idea behind CNNs. CNNs are very useful for problems involving signal processing and identification because they make use of a number of important elements and ideas as shown Figure 4.

CNNs are trained using backpropagation, which minimizes the discrepancy between the expected and actual outputs by adjusting the model's parameters (weights and biases). The CNN compensator, a Python built-in, is a useful tool in the system for increasing the effectiveness of several tasks, including signal processing. Using a deep learning architecture, CNN applies convolutional layers one after the other to extract features from input data. These layers are enhanced with activation functions like ReLU (Rectified Linear Unit), which introduce non-linearity, a crucial element for learning complex patterns. Pooling layers then reduce the spatial dimensions, making feature selection easier and maintaining computational efficiency. CNN also employs techniques like dropout regularization to prevent overfitting and preserve dependable performance across a range of datasets. By following this rigorous procedure, Since Python's CNN compensator effectively learns complicated correlations among data, it is a great tool for jobs requiring high accuracy and flexibility in real-world applications, it can be noted in the algorithm code as shown in Figure 5, which is used in the proposed system. The input size of 4, which represents the length of the input data sequence, is used for building the CNN compensator. Each feature is processed independently by the network using a single input channel. The output channel is set to 1 so that a single output feature may be generated. The network can capture local dependencies in the input sequence with a kernel size of three in the convolutional layers. The hidden size of 256 determines the number of neurons in the fully connected layer, which comes after the convolutional layers and allows for intricate feature extraction and nonlinear transformations. The CNN compensator's architecture, implemented in Python in the coding algorithm as shown in Figure 5 utilizing frameworks like TensorFlow or PyTorch, makes it better suited to handle tasks like signal compensation or feature extraction with high accuracy and efficiency. Moreover, patterns in the input data may be learned from and used to adjust the CNN compensator.

5. THE PROPOSED SYSTEM BY UTILIZING EQUALIZATION

Equalization, or EQ, is adjusting the ratio of one frequency component to another in a data stream. Specific frequency ranges must be amplified or decreased to achieve the right tonal balance. In RoF systems integrated with 5G technology, equalization is crucial for reducing the impacts of signal degradation and distortion during transmission via the optical channel. The RF signal frequently faces impairments like dispersion and attenuation after being transferred across the fiber optic link and converted from an optical to an electrical signal. These impairments disproportionately influence different frequency components. The equalization function applies an equalizer to the signal to achieve the appropriate tonal balance, modifying the amplitude of particular frequency bands. Filter Signal GaussBP, the primary function, first determines if the input is a valid optical signal. Next, the Fast Fourier Transform (FFT) transforms the signal into the frequency domain, where the Gaussian bandpass filter is applied. The Inverse Fast Fourier Transform (IFFT) is then used to transform the signal back to the time domain. If an equalizer is supplied, equalization is used. The function uses the Gaussian bandpass filter to filter the signal's channels and noise bins. A filtered optical block signal with improved signal strength is the result. appropriate for 5G fiber optic high-speed communication networks. The finite impulse response (FIR) filter is the equalizer utilized in the coding algorithm, as shown in Figure 6.

Finite Length: There are only a limited number of coefficients in the equalization array [0.2, 0.5, 1.0, 0.5, 0.2]. Because FIR filters have a limited impulse response, their output response eventually zeroes out.

Linear Convolution: The linear convolution of two sequences may be calculated using the np.convolve function. Herein, it convolves the equalizer coefficients [0.2, 0.5, 1.0, 0.5, 0.2] with the input signal x.

Features: Because of its stability, simplicity of usage, and linear phase response (when symmetric), FIR filters are frequently employed in digital signal processing. Applications needing precise control over frequency response and linear-phase filtering can benefit from their use.

As consequently, the equalizer that has been implemented in the sample of code that has been supplied is a linear FIR filter).

Digital communication systems are among the many signal-processing applications that frequently utilize this filter for equalization.

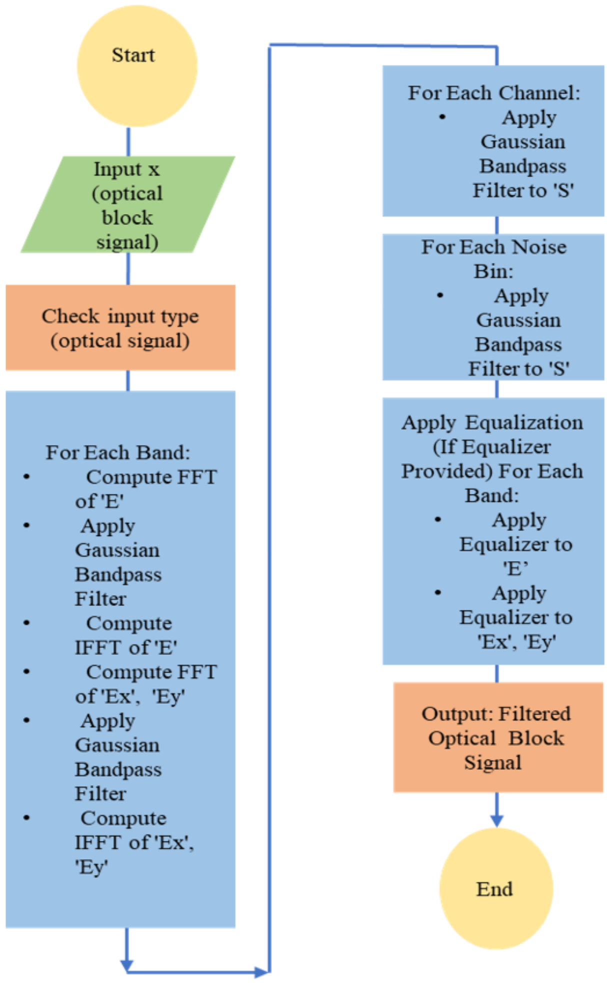


Figure 6. The algorithmic of equalization

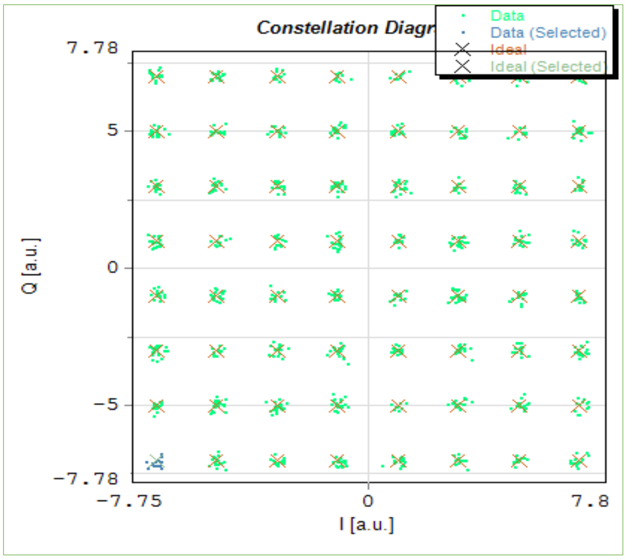
6. RESULTS AND DISCUSSION

The system is implemented by utilizing software VPIPhotonics and Python. The system optimizes EVM, minimizes SER, and successfully mitigates mistakes by using a CNN compensation. Using equalization and CNN compensation at the receiving end after the fiber link can significantly reduce EVM compared to systems without compensators. Equalization mainly corrects linear distortions by reducing the impact of dispersion and inter-symbol interference (ISI) generated during transmission across the fiber channel.

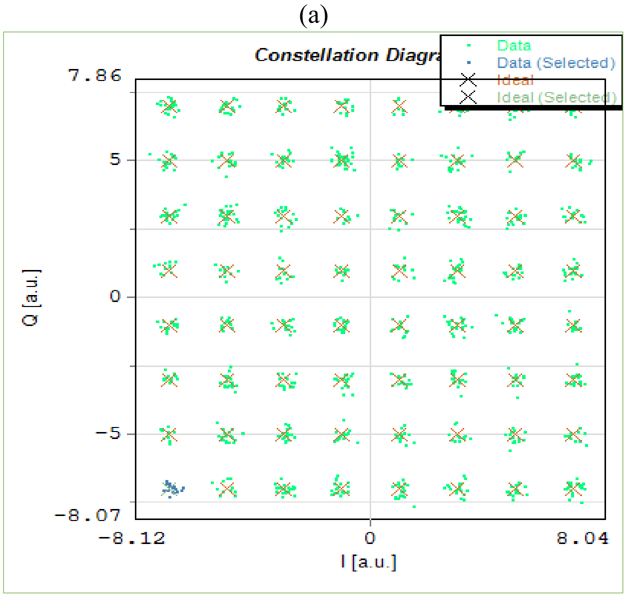
6.1 The results of compensated system by equalization

Using an equalizer with a FIR filter is a common technique in digital signal processing to enhance signal quality and minimize distortions in communication networks. FIR filters are advantageous for equalization because of their inherent stability. Furthermore, they exhibit a linear phase response, resulting in little phase distortion of the signal. Adjusting the filter coefficients allows a FIR equalizer to address specific problems such as frequency-selective fading, channel distortion, and intersymbol interference. FIR equalizers are adaptable and may efficiently improve signal clarity and boost system performance, especially in complex communication scenarios where precise signal correction is crucial. Studying constellation diagrams at distances of 50 km and 70 km provides valuable insights into signal integrity and performance, as seen in Figure 7 and Figure 8.

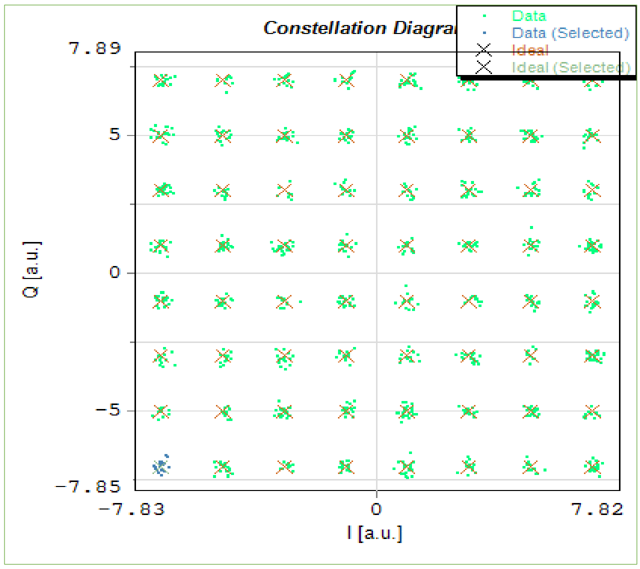
Upon analyzing the EVM performance of several subcarrier configurations and techniques, it is evident that there are notable differences between the standards The equalized method has improved the EVM values as in Figure 9, particularly for sub-2, which has an EVM of (0.03) compared to (0.031) for sub-14, (0.034) for sub-6, and (0.043) for sub-10. This indicates that equalization effectively decreases the magnitude of errors. The improvement of EVM by equalization highlights its role in enhancing signal quality and minimizing aberrations that might affect performance across a 50 km distance.



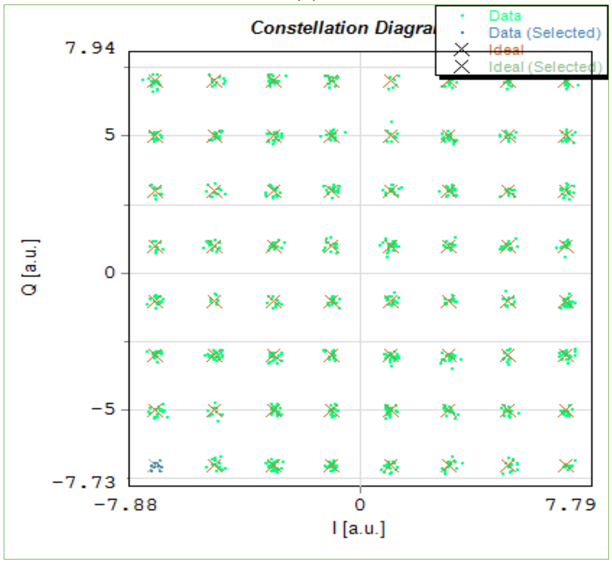
(a)



(b)

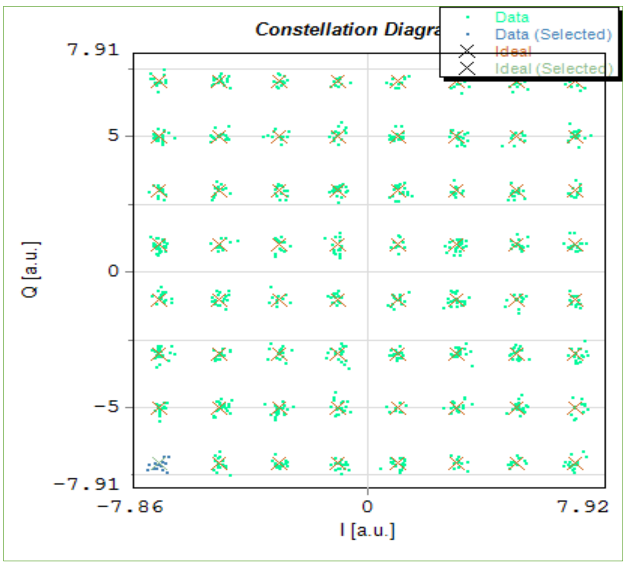


(c)

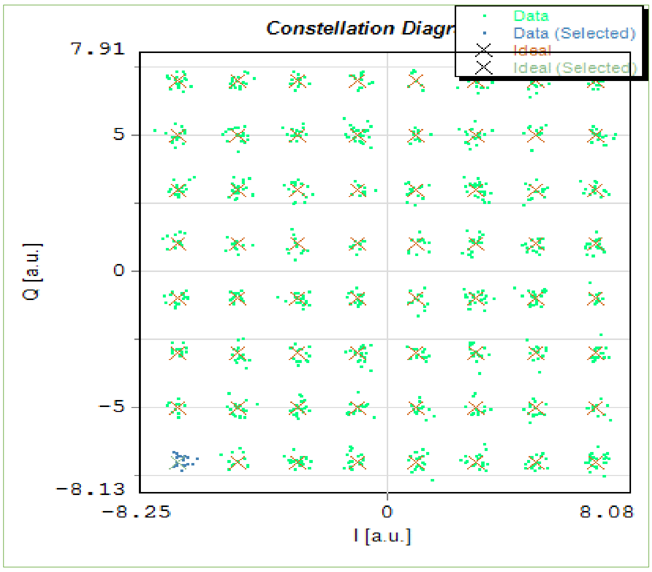


(d)

Figure 7. The constellation diagram of the equalized system over 50 km length (a) 14-sub carrier (b) 10-sub carrier (c) 6-sub carrier (d) 2-sub carrier



(a)



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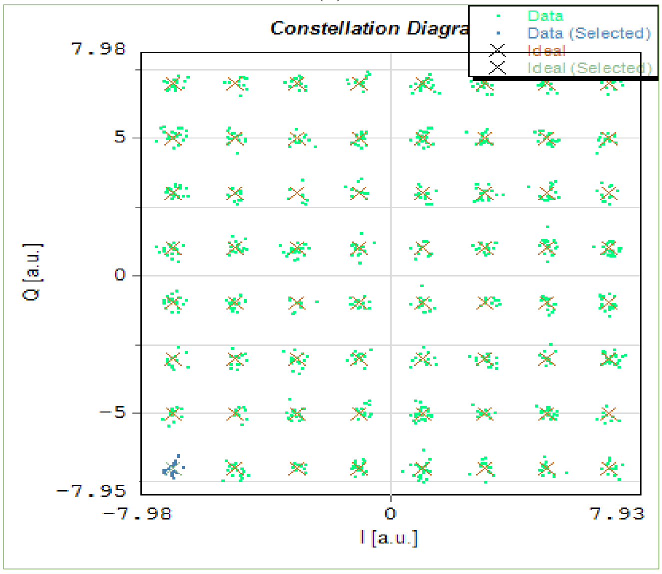

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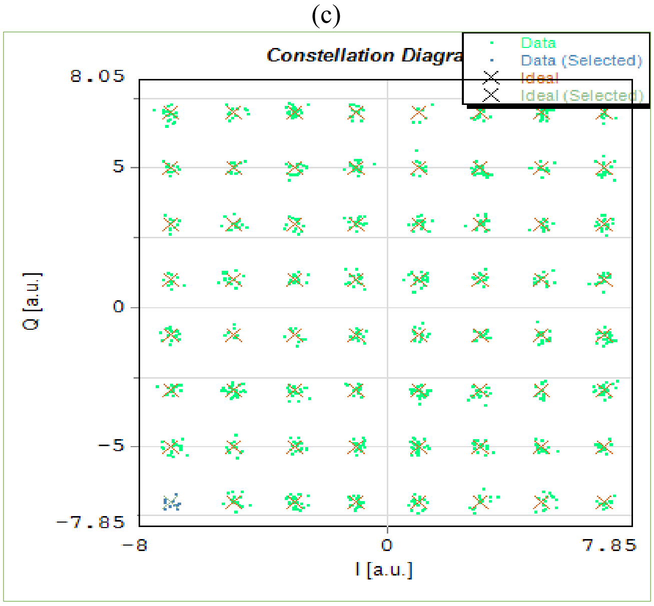


(d)

Figure 8. The constellation diagram of the equalized system over 70 km length (a) 14-sub carrier(b) 10-sub carrier (c) 6-sub carrier (d) 2-sub carrier

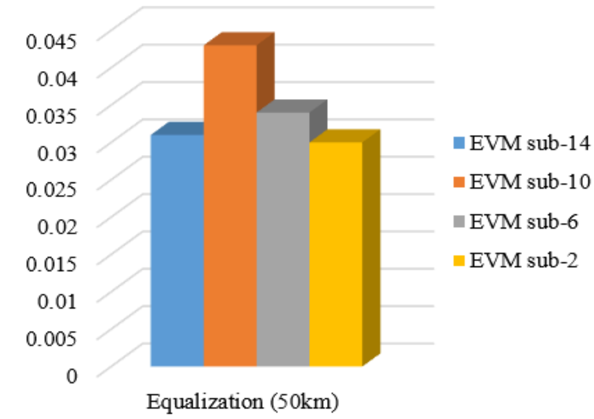


Figure 9. EVM of the compensated proposed system by using equalization over 50 km fiber length

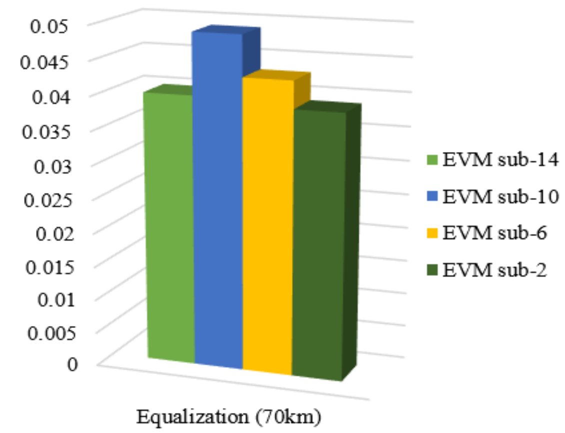


Figure 10. EVM of the compensated proposed system by using equalization over 70 km fiber length

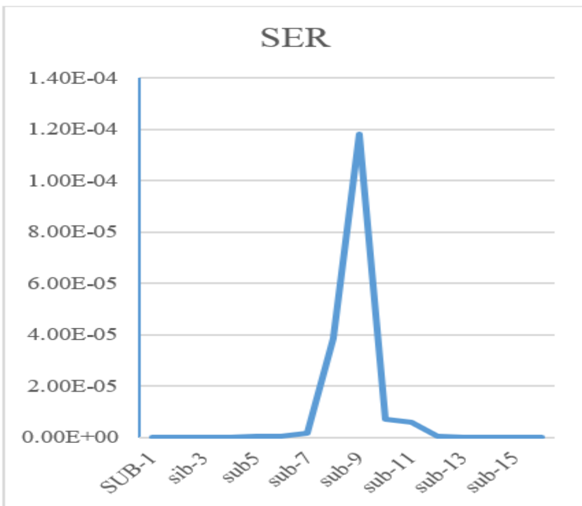


Figure 11. The SER of the proposed system after using equalization over 50 km length

An evaluation of EVM performance across a 70 km connection reveals significant differences between the uncompensated and equalized systems. The equalized system shows a substantial enhancement in EVM values. The equalized EVM values are, (0.04) for sub-14, (0.49) for sub-10, (0.43) for sub-6, and (0.39) for sub-2, as shown in Figure 10. This improvement highlights the effectiveness of equalization in correcting distortions and enhancing the signal quality throughout the 70 km distance.

The SER data explains the system's performance at different distances and settings, as seen in Figure 11. The system adjusted to a distance of 50 km has very low SER values for all subcarrier spacings. The SER values are, (6.99E-08) for sub-14, (2.93E-05) for sub-10, (8.22E-07) for sub-6, and (3.79E-08) for sub-2. The results highlight the effectiveness of equalization in significantly reducing symbol errors, demonstrating its ability to enhance signal quality and accuracy by compensating for impairments and distortions. Over 70 km length, the SER is seen in Figure 12.

The results of the equalized system are reviewed as shown in Table 1.

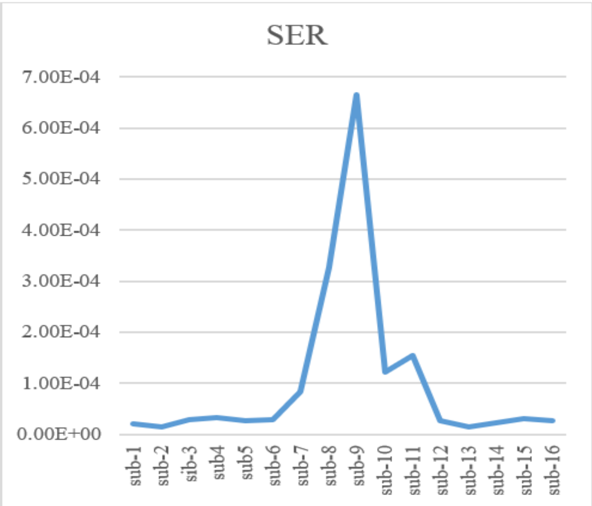


Figure 12. The SER of the proposed system after using equalization over 70 km length

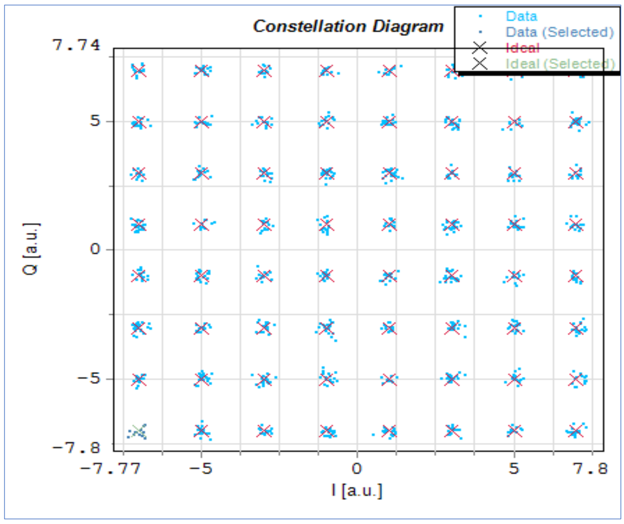
Table 1. The results of the equalized system

Length	Sub-carrier	EVM	SER	BER
50 km	2	0.03	3.79E-08	6.32E-09
	6	0.034	8.22E-07	1.37E-07
	10	0.043	0.0000293	1.37E-07
	14	0.031	6.99E-08	1.17E-08
70 km	2	0.39	0.00000914	1.52E-06
	6	0.43	0.0000329	5.48E-06
	10	0.49	0.000176	2.93E-05
	14	0.04	1.17E-06	1.95E-07

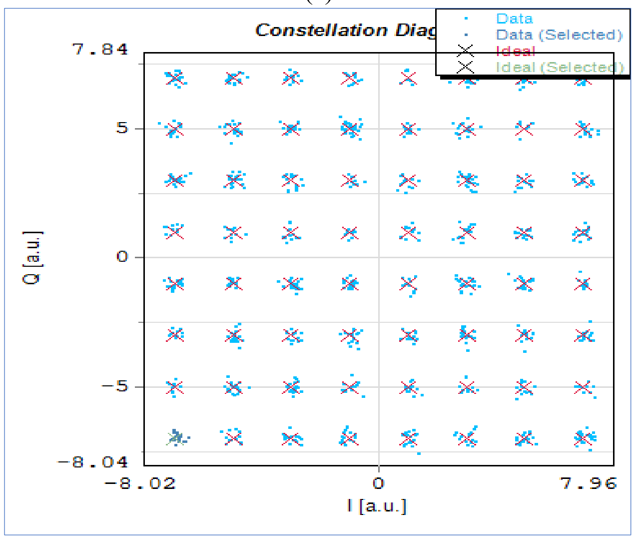
6.2 The results of the compensated system by CNN

A constellation diagram is a crucial tool in digital communications. It is employed to represent and assess signal modulation schemes' efficacy visually. The complex plane is a visual depiction wherein every point corresponds to a unique combination of phase and amplitude in the transmitted signal. The constellation diagram can be seen over 50 km, as shown in Figure 13, and over 70 km, as shown in Figure 14.

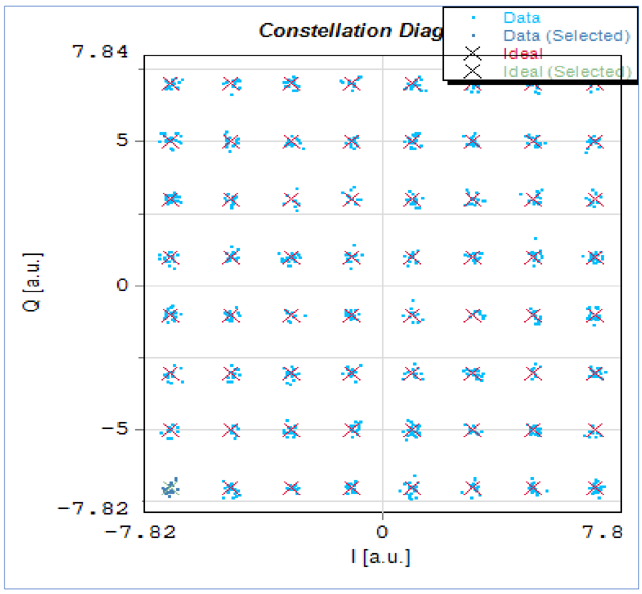
The EVM analysis enables meaningful comparisons between an uncompensated system and a compensator utilizing a CNN for a 50 km transmission. The EVM values for the CNN compensator are as follows: (0.031) for sub-14, (0.04) for sub-10, (0.032) for sub-6, and (0.03) for sub-2, as shown in Figure 15. Smaller values indicate a more effective correction of distortions and a denser grouping of constellation points, resulting in improved signal quality. The CNN's ability to adapt and learn from the signal characteristics enables it to effectively reduce errors to a greater extent than the standard uncompensated approach. This improvement showcases the capacity of CNN compensators to boost system performance by lowering impairments and enhancing the overall signal quality.



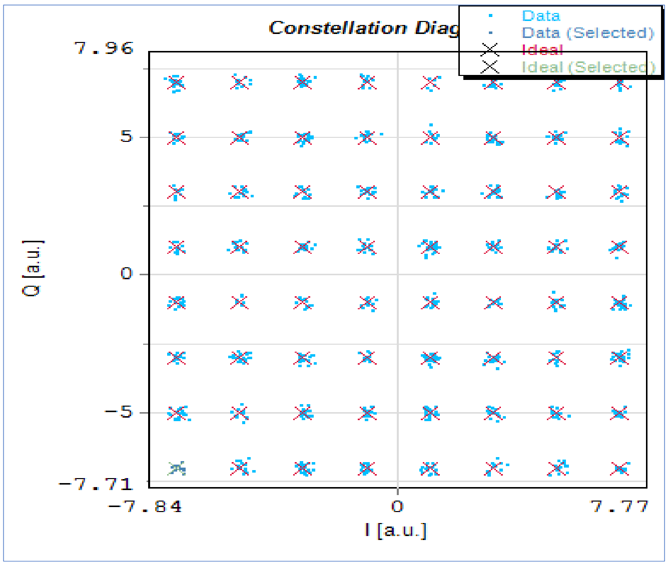
(a)



(b)

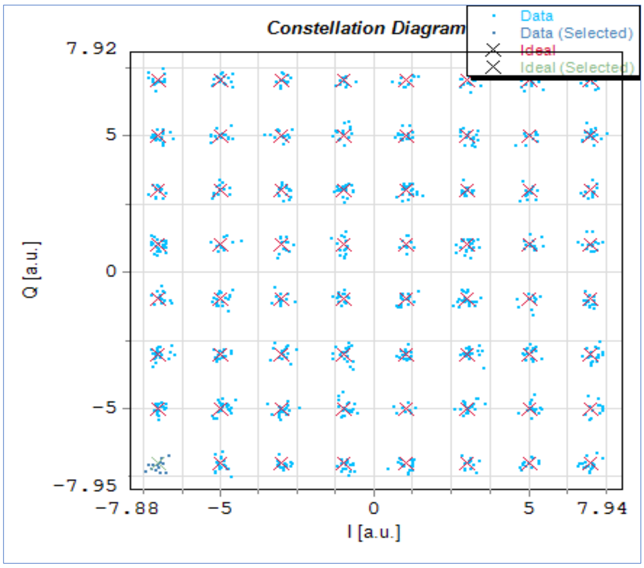


(c)

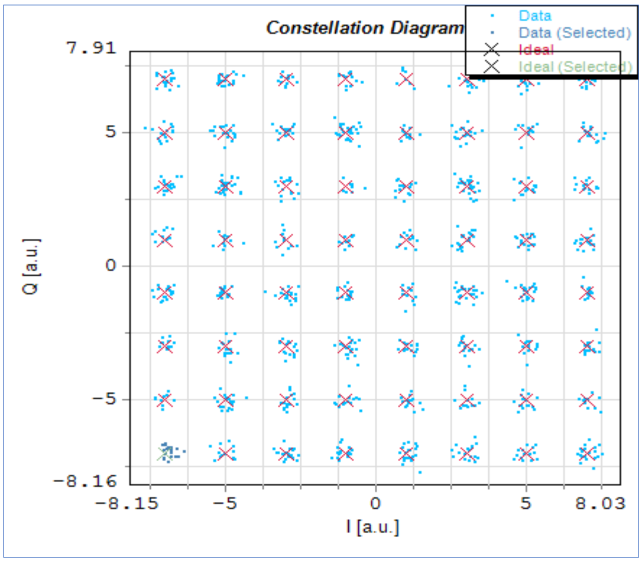


(d)

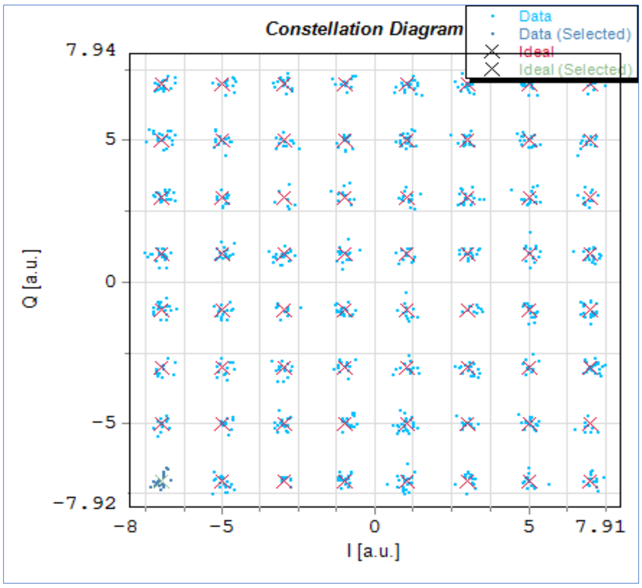
Figure 13. The constellation diagram of the CNN system over 50 km length (a) 14-sub carrier (b) 10-sub carrier (c) 6-sub carrier (d) 2-sub carrier



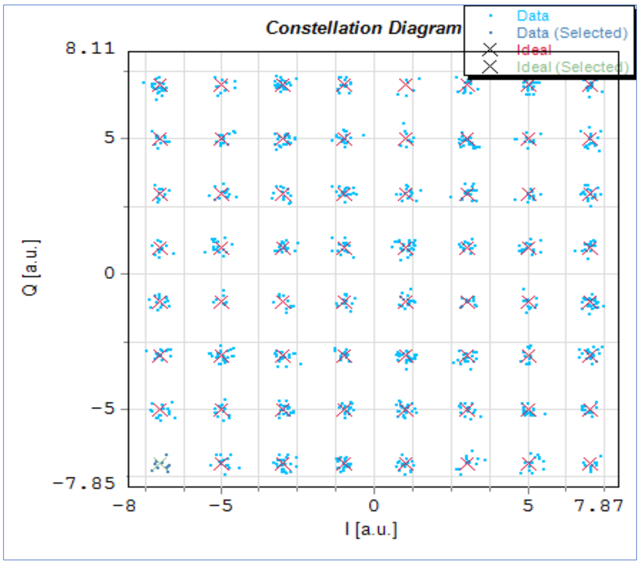
(a)



(b)



(c)



(d)

Figure 14. The constellation diagram of the CNN system over 70 km length (a) 14-sub carrier (b) 10-sub carrier (c) 6-sub carrier (d) 2-sub carrier

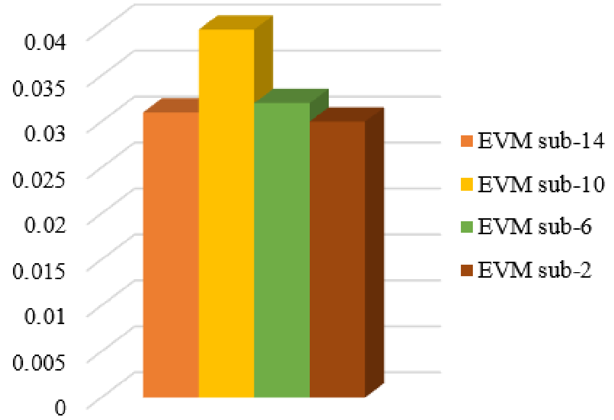


Figure 15. EVM of the proposed system as compared with after using CNN over 50 km fiber length

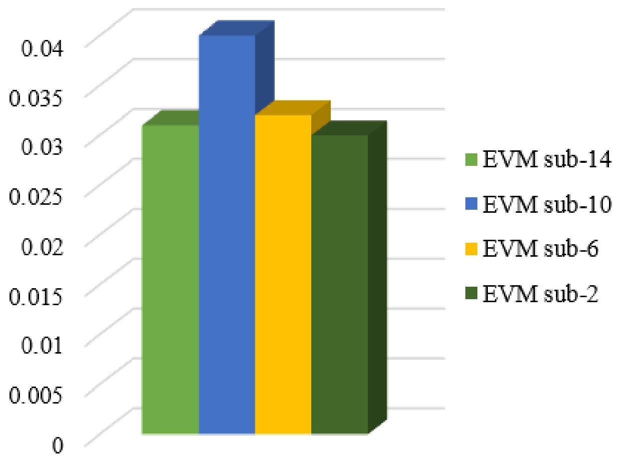


Figure 16. EVM of the compensated proposed system by using CNN over 70 km fiber length

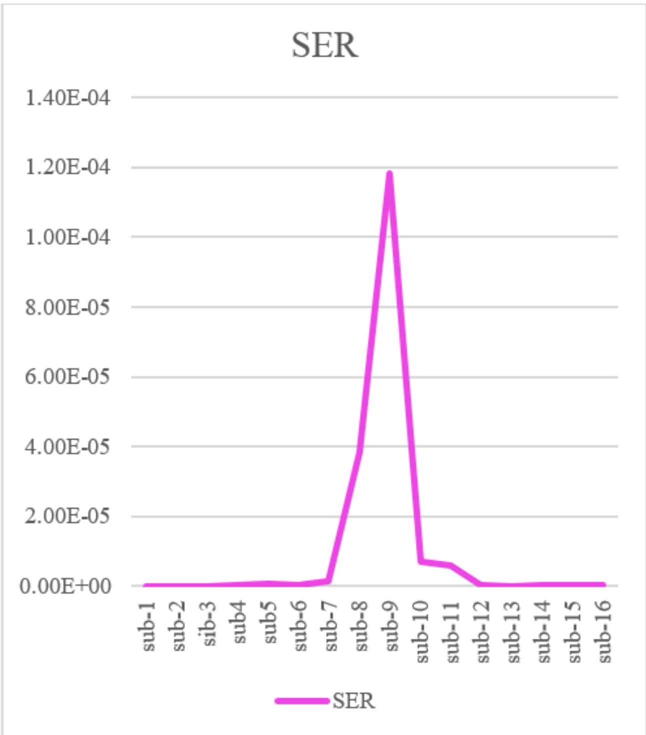


Figure 17. The SER of the compensated proposed system by using CNN over 50 km length

The EVM values for the CNN-based system are considerably reduced: (0.041) for sub-14, (0.047) for sub-10, (0.042) for sub-6, and (0.04) for sub-2 taken at a distance of 70 km. As shown in Figure 16, the reduced EVM values indicate that the CNN is more vital to correct signal impairments, resulting in considerably improved signal fidelity and accuracy. The CNN compensator has improved notably, demonstrating its ability to overcome performance challenges that arise over long distances. It provides a reliable solution for maintaining high-quality communication in extended transmission scenarios.

The examination of SER over distances of 50 km and 70 km reveals a notable disparity between the uncompensated and CNN-based systems. This highlights their performance and effectiveness in handling errors during signal transmission. At a distance of 50 km, the CNN produces SER values: (1.17E-07) for sub-14, (7.35E-07) for sub-10, (2.8E-07) for sub-6, and (1.21E-08) for sub-2, as shown in Figure 17. The figures indicate a substantial reduction in symbol errors, showcasing CNN's capacity to enhance signal quality and accuracy using advanced error correction and adaptation methods.

The CNN system is 70 km away, the SER values reach of (3E-05) for sub-14, (1E-04) for sub-10, (2.87E-05) for sub-6, and (1.51E-05) for sub-2, as shown in Figure 18.

Finally, All the results of the compensated system by CNN are shown in Table 2.

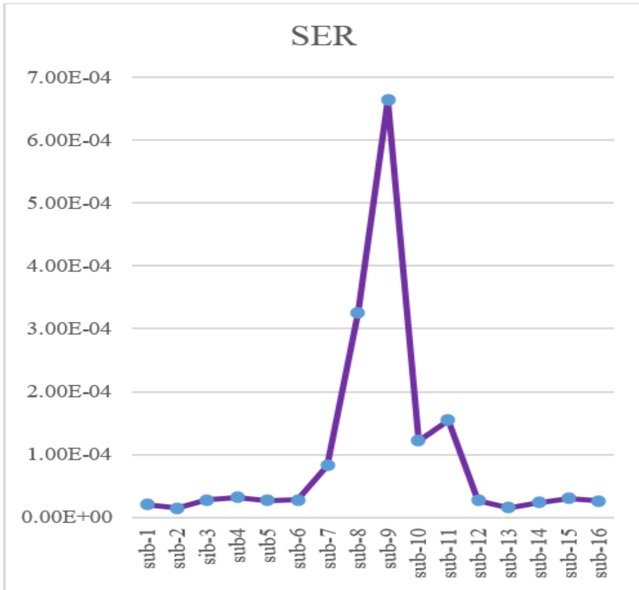


Figure 18. The SER of the proposed system after using CNN over 70 km length

Table 2. The results of the compensated system with CNN

Length	Sub-Carrier	EVM	SER	BER
50 km	2	0.03	1.21E-08	1.89E-10
	6	0.032	2.80E-07	4.67E-08
	10	0.04	7.35E-06	1.225E-06
	14	0.031	1.17E-07	1.95E-08
70 km	2	0.04	0.0000151	2.36E-07
	6	0.042	0.0000287	4.78E-06
	10	0.047	0.000126	0.000021
	14	0.041	0.0000341	5.68E-06

7. SUMMARY

In this dissertation, the 5G backhaul wireless with the ROF and MIMO system convergence is proposed and then compensated by three categories: circuit compensators, DSP in real-time compensator circuits, and neural network compensators. The aim is achieved by implementing the MIMO system, effectively reducing channel impairments and improving the system's overall performance with a high data rate. DSP and neural network compensation techniques highlight the key contribution; for instance, the GAN compensators in this field have not been utilized previously.

The results of the current study can be with previous studies, as shown in Table 3.

Table 3. Literature survey

Ref.	Year	Architecture	Modulation	Length	MM-Wave	Optical Modulation	EVM	SNR (dBm)	SER	Bandwidth	BER	Data Rate	MIMO	Fronthaul
[28]	2020	RoF&5G	256-QAM &OFDM	10 km	-	DD-MZM	3.5%	-	-	200MHz	-	1.7Gb/s	2×2	Optical
[32]	2020	RoF&5G	M-QAM	30 km	-	DML	8%	-	-	-	-	9Gb/s	-	-
[29]	2021	RoF&5G	OFDM	10 km	25.5GHz	MZM	-	-	-	800MHz	3.8E-03	1.4Gb/s	-	Optical
[17]	2021	RoF&5G	256-QAM &OFDM	22 km	-	DD-MZM	2.7%	-	-	50MHz	-	-	-	Optical
[24]	2021	RoF&5G	256-QAM	5 km	-	DD-MZM	4%	-	-	400MHz	-	1.7Gb/s	2×2	Optical
[37]	2022	RoF&5G	QPSK	14.43 km	-	MZM	11.6%	-	-	10MHz	-	-	-	-
[38]	2022	RoF&5G&6G	256-QAM	10 km	-	MZM	2.5%5G-3.1% 6G	-	-	-	-	-	-	Optical
[39]	2022	RoF&5G	256QAM &OFDM	10 km	-	DDMZM	3.5%	-	-	20MHz	-	-	2×2	Optical
[30]	2023	RoF&5G	MQAM &OFDM	12.5 km	-	DDMZM	4.4%	-	-	100KHz	-	590Mb/s	-	Optical
[36]	2023	Optical & LTE	MQAM &OFDM	10 km	-	-	9%	23	-	20MHz	-	-	-	-
[40]	2023	RoF&5G	256QAM	10 km	-	DD-MZM	1.65%	-	-	50MHz	-	-	-	Optical
[34]	2023	RoF&5G	64-QAM &OFDM	25 km	60GHz	DP-MZM	12.5%	5	-	7.2GHz	E-01	122.5Gb/s	4×4	Optical
[41]	2023	RoF&5G	256QAM	10 km	-	MZM	1.9%	-	-	20MHz	-	-	-	Optical
[25]	2024	RoF&5G	16QAM	500 m	-	LD	1.5%	-	-	50MHz	-	4.2Gb/s	-	Optical
[42]	2024	RoF&5G	256QAM &OFDM	20 km	-	-	3.41%	-	-	100MHz	-	1.25Gb/s	-	-
[33]	2024	RoF&5G	-	40 km	186GHz	DP-MZM	-	-	-	-	E-09	20Gb/s	-	5G
[43]	2024	RoF&5G	256QAM	10 km	-	DD-MZM	1.65%	-	-	-	-	-	-	Optical
[31]	2024	RoF&5G	ASK	10 km	-	DD-MZM	-	-	-	-	5.02E-14	5Gb/s	-	5G
Proposed system	Present	5G&RoF	64-QAM &OFDM	50 km 70 km	90MGHz	MZM	≈ 3 % ≈ 4 %	28.3 25.89	1.21E-08 1.51E-05	17.888GHz	2.01667E-09 2.51667E-06	56.656Gb/s	2×2	Optical

8. CONCLUSION

Different compensators should be integrated to effectively deal with signal impairments and optimize the overall system performance to improve the performance of high-speed communication systems, especially those operating. This paper examines the effects of two compensators, DSP algorithms (such as equalization), and advanced DNNs like CNN. The system proposed with a bandwidth of 17 GHz is necessary to accommodate this velocity and reach a data rate of 56.656 Gb/s. The center frequency is 160 GHz, and the duration is 7.37 μs over fiber length (50 km, 70 km) with EVM ≈ 3% at 50 km distance and ≈ 4% at 70 km fiber channel length for 2×2 MIMO. algorithm methods, such as equalization and CNN, equalization techniques rectify phase distortions and amplitude, decreasing errors. These plans improve the correctness of signal recovery and boost the system's capacity to preserve high data rates with the smallest errors. CNNs excel in receiving involved patterns and offering flexible adjustments, substantially reducing EVM, and SER concluded enhanced signal precision and weakened distortion

In the future, work can be employed experimentally in hardware systems and can be employed the 6G technology in the proposed system.

REFERENCES

[1] Alghorani, Y. (2017). Photonic hybrid precoding for millimeter wave RoF systems. arXiv preprint arXiv:1707.00330. https://doi.org/10.48550/arXiv.1707.00330

[2] Novak, D., Waterhouse, R.B., Nirmalathas, A., Lim, C., et al. (2015). Radio-over-fiber technologies for emerging wireless systems. IEEE Journal of Quantum Electronics, 52(1): 1-11. https://doi.org/10.1109/JQE.2015.2504107

[3] Browning, C., Martin, E.P., Farhang, A., Barry, L.P. (2017). 60 GHz 5G radio-over-fiber using UF-OFDM with optical heterodyning. IEEE Photonics Technology Letters, 29(23): 2059-2062. https://doi.org/10.1109/LPT.2017.2763680

[4] Agrawal, G.P. (2000). Nonlinear fiber optics. In Nonlinear Science at the Dawn of the 21st Century, pp. 195-211. https://doi.org/10.1007/3-540-46629-0_9

[5] Rangan, S., Rappaport, T.S., Erkip, E. (2014). Millimeter-wave cellular wireless networks: Potentials and challenges. Proceedings of the IEEE, 102(3): 366-385. https://doi.org/10.1109/JPROC.2014.2299397

[6] Patiño-Carrillo, A., Puerto-Leguizamón, G., Suárez-Fajardo, C. (2018). Bidirectional single sideband transmission of millimeter waves over fiber for 5G mobile networks. TecnoLógicas, 21(43): 15-26. https://doi.org/10.22430/22565337.1053

[7] Dat, P.T., Kanno, A., Yamamoto, N., Kawanishi, T. (2018). Seamless convergence of fiber and wireless systems for 5G and beyond networks. Journal of Lightwave Technology, 37(2): 592-605. https://doi.org/10.1109/JLT.2018.2883337

[8] Dat, P.T., Kanno, A., Inagaki, K., Rottenberg, F., Yamamoto, N., Kawanishi, T. (2018). High-speed and uninterrupted communication for high-speed trains by ultrafast WDM fiber-wireless backhaul system. Journal

of Lightwave Technology, 37(1): 205-217. https://doi.org/10.1109/JLT.2018.2885548
[9] Wang, J., Jia, Z., Campos, L.A., Knittle, C. (2019). Delta-sigma modulation for next generation fronthaul interface. Journal of Lightwave Technology, 37(12): 2838-2850. https://doi.org/10.1109/JLT.2018.2872057
[10] Li, H., Verplaetse, M., Verbist, J., Van Kerrebrouck, J., et al. (2020). Real-time 100-GS/s sigma-delta modulator for all-digital radio-over-fiber transmission. Journal of Lightwave Technology, 38(2): 386-393. https://doi.org/10.1109/JLT.2019.2931549
[11] Chen, J., Ge, X., Zhong, Y., Li, Y. (2019). A novel JT-CoMP scheme in 5G fractal small cell networks. In 2019 IEEE Wireless Communications and Networking Conference (WCNC), Marrakesh, Morocco, pp. 1-7. https://doi.org/10.1109/WCNC.2019.8886024
[12] Kongara, G., He, C., Yang, L., Armstrong, J. (2019). A comparison of CP-OFDM, PCC-OFDM and UFMC for 5G uplink communications. IEEE Access, 7: 157574-157594. https://doi.org/10.1109/ACCESS.2019.2949792
[13] Bonfante, A., Giordano, L.G., López-Pérez, D., Garcia-Rodriguez, A., Geraci, G., Baracca, P., Butt, M.M., Marchetti, N. (2019). 5G massive MIMO architectures: Self-backhauled small cells versus direct access. IEEE Transactions on Vehicular Technology, 68(10): 10003-10017. https://doi.org/10.1109/TVT.2019.2937652
[14] Khwandah, S.A., Cosmas, J.P., Lazaridis, P.I., Zaharis, Z.D., Chochliouros, I.P. (2021). Massive MIMO systems for 5G communications. Wireless Personal Communications, 120(3): 2101-2115. https://doi.org/10.1007/s11277-021-08550-9
[15] Van Gasse, K., Van Kerrebrouck, J., Abbasi, A., Verbist, J., Torfs, G., Moeneclaey, B. (2018). III-V-on-silicon photonic transceivers for radio-over-fiber links. Journal of Lightwave Technology, 36(19): 4438-4444. https://doi.org/10.1109/JLT.2018.2845743
[16] Borges, R.M., de Souza Lopes, C.H., Lima, E.S., de Oliveira, M.A., Cunha, M.S.B., Alexandre, L.C., da Silva, L.G., Pereira, L.A.M., Spadoti, D.H., Romero, M.A., Junior, A.C.S. (2021). Integrating optical and wireless techniques towards novel fronthaul and access architectures in a 5G NR framework. Applied Sciences, 11(11): 5048. https://doi.org/10.3390/app11115048
[17] Hadi, M.U., Awais, M., Raza, M., Ashraf, M.I., Song, J. (2021). Experimental demonstration and performance enhancement of 5G NR multiband radio over fiber system using optimized digital predistortion. Applied Sciences, 11(24): 11624. https://doi.org/10.3390/app112411624
[18] Ali, S.M., Hussein, E.A. (2024). Enhancement 5G backhaul in radio-over fiber (RoF) system by eliminate error vector magnitude. In 2024 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA), Istanbul, Turkiye, pp. 1-5. https://doi.org/10.1109/HORA61326.2024.10550590
[19] Sharma, T., Chehri, A., Fortier, P. (2021). Review of optical and wireless backhaul networks and emerging trends of next generation 5G and 6G technologies. Transactions on Emerging Telecommunications Technologies, 32(3): e4155. https://doi.org/10.1002/ett.4155
[20] Lee, J., He, J., Wang, Y., Fang, C., Wang, K. (2020). Experimental demonstration of millimeter-wave radio-over-fiber system with convolutional neural network (CNN) and binary convolutional neural network (BCNN). arXiv preprint arXiv:2001.02018. https://doi.org/10.48550/arXiv.2001.02018
[21] Bekkali, A., Nishimura, K. (2016). Seamless convergence of radio-over-fiber and millimeter-wave links for highly resilient access networks. In 2016 IEEE Wireless Communications and Networking Conference, Doha, Qatar, pp. 1-6. https://doi.org/10.1109/WCNC.2016.7565077
[22] Udalcovs, A., Levantesi, M., Urban, P., Mello, D.A., Gaudino, R., Ozolins, O., Monti, P. (2020). Total cost of ownership of digital vs. analog radio-over-fiber architectures for 5G fronthauling. IEEE Access, 8: 223562-223573. https://doi.org/10.1109/ACCESS.2020.3044396
[23] Kim, J., Sung, M., Cho, S.H., Won, Y.J., Lim, B.C., Pyun, S.Y. (2019). MIMO-supporting radio-over-fiber system and its application in mmWave-based indoor 5G mobile network. Journal of Lightwave Technology, 38(1): 101-111. https://doi.org/10.1109/JLT.2019.2931318
[24] Hadi, M.U., Basit, A., Khurshid, K. (2021). MIMO enabled multiband 5g NR fiberwireless using sigma delta over fibertechnology. In 2021 International Bhurban Conference on Applied Sciences and Technologies (IBCAST), Islamabad, Pakistan, pp. 1007-1010. https://doi.org/10.1109/IBCAST51254.2021.9393263
[25] Souza, L.C., Andrade, T.P., Pinto, F.B., Lima, E.S., Junior, F.M., Anderson, E.L., Junior, A.C.S. (2024). Enabling next-generation gbps full-duplex communications systems applying radio-and power-over-fiber integration. Optics Communications, 557: 130315. https://doi.org/10.1016/j.optcom.2024.130315
[26] Habib, U., Aighobahi, A.E., Quinlan, T., Walker, S.D., Gomes, N.J. (2017). Demonstration of radio-over-fiber-supported 60 GHz MIMO using separate antenna-pair processing. In 2017 International Topical Meeting on Microwave Photonics (MWP), Beijing, China, pp. 1-4. https://doi.org/10.1109/MWP.2017.8168700
[27] Lopes, C.H.D.S., Lima, E.S., Pereira, L.A.M., Borges, R.M., Ferreira, A.C., Abreu, M. (2020). Non-standalone 5G NR fiber-wireless system using FSO and fiber-optics fronthauls. Journal of Lightwave Technology, 39(2): 406-417. https://doi.org/10.1109/JLT.2020.3029500
[28] Hadi, M.U., Ghaffar, S., Murtaza, G. (2020). 5G NR MIMO enabled multiband fiber wireless system using analog optical front haul. In 2020 IEEE 17th International Conference on Smart Communities: Improving Quality of Life Using ICT, IoT and AI (HONET), Charlotte, NC, USA, pp. 59-620. https://doi.org/10.1109/HONET50430.2020.9322818
[29] Rommel, S., Grivas, E., Cimoli, B., Dodane, D., Morales, A., Pikasis, E., Bourderionnet, J., Feugnet, G., Carvalho, J.B., Katsikis, M., Ntontin, K., Kritharidis, D., Spaleniak, I., Mitchell, P., Dubov, M., Monroy, I.T. (2021). Real-time high-bandwidth mm-wave 5G NR signal transmission with analog radio-over-fiber fronthaul over multi-core fiber. EURASIP Journal on Wireless Communications and Networking, 2021: 43. https://doi.org/10.1186/s13638-021-01914-6
[30] Pereira, L.A., Lima, E.S., Mendes, L.L., Cerqueira Jr, S. (2023). Machine learning-based digital pre-distortion scheme for RoF systems and experimental 5G mm-

waves fiber-wireless implementation. Journal of Microwaves, Optoelectronics and Electromagnetic Applications, 22: 172-183. https://doi.org/10.1590/2179-10742023v22i1270779
[31] Hameed, A.A. (2024). Optimizing 5G front haul: Efficient design and implementation of a fiber optic communication architecture. Journal of Al-Azhar University Engineering Sector, 19(71): 748-760. https://doi.org/10.21608/auej.2024.262947.1590
[32] Pandey, G., Choudhary, A., Dixit, A. (2020). Radio over fiber based fronthaul for next-generation 5G networks. In 2020 22nd International Conference on Transparent Optical Networks (ICTON), Bari, Italy, pp. 1-4. https://doi.org/10.1109/ICTON51198.2020.9203207
[33] Santhanam, S. (2024). Performance analysis of optical millimeter wave generation in radio over fiber system for 5G applications. In 2024 2nd International Conference on Networking and Communications (ICNWC), Chennai, India, pp. 1-8. https://doi.org/10.1109/ICNWC60771.2024.10537488
[34] Azzahhafi, H., El Yahyaoui, M., El Moussati, A., El Zein, G., Armada, A.G. (2023). Enhanced 4×4 MIMO RoF architecture for 5G mmWave indoor applications at 60 GHz unlicensed band. Optics Communications, 533: 129266. https://doi.org/10.1016/j.optcom.2023.129266
[35] Mohammed, M., Khan, M.B., Bashier, E.B.M. (2016). Machine Learning: Algorithms and Applications. CRC Press. https://doi.org/10.1201/9781315371658
[36] Vallejo, L., Ortega, B., Mora, J., Nguyen, D.N., et al. (2023). Demonstration of M-QAM OFDM bidirectional 60/25 GHz transmission over 10 km Fiber, 100 m FSO and 2 m radio seamless heterogeneous fronthaul link. Optical Fiber Technology, 77: 103161. https://doi.org/10.1016/j.yofte.2022.103161
[37] Altuna, R., López-Cardona, J.D., Al-Zubaidi, F.M., Montero, D.S., Vázquez, C. (2022). Power-over-fiber impact and chromatic-induced power fading on 5G NR signals in analog RoF. Journal of Lightwave Technology, 40(20): 6976-6983. https://doi.org/10.1109/JLT.2022.3205743
[38] Hadi, M.U., Murtaza, G. (2022). Fibre wireless distributed antenna systems for 5G and 6G services. Electronics, 12(1): 64. https://doi.org/10.3390/electronics12010064
[39] Hadi, M.U., Song, J., Soman, S.K.O., Rahimian, A., Cheema, A.A. (2022). Experimental evaluation of hybrid fibre-wireless system for 5G networks. Telecom, 3(2): 218-233. https://doi.org/10.3390/telecom3020014
[40] Hadi, M.U. (2023). Experimental demonstration of transport over fiber using 5G NR with performance enhancement using DPD. Optics Communications, 531: 129226. https://doi.org/10.1016/j.optcom.2022.129226
[41] Hadi, M.U. (2023). Towards optimization of 5G NR transport over fiber links performance in 5G Multi-band Networks: An OMSA model approach. Optical Fiber Technology, 79: 103358. https://doi.org/10.1016/j.yofte.2023.103358
[42] Yamamoto, Y., Takahashi, Y., Suga, M., Arai, T., Toshinaga, H., Kita, N., Onizawa, T. (2024). Experimental results of multiplexing transmission of 256-QAM 5G NR signal with control signal by SCM over 20-km analog RoF link. Optics Communications, 570: 130862. https://doi.org/10.1016/j.optcom.2024.130862
[43] Hadi, M.U., Danyaro, K.U., Alqushaibi, A., Qureshi, R., Alam, T. (2024). Digital predistortion based experimental evaluation of optimized recurrent neural network for 5g analog radio over fiber links. IEEE Access, 12: 19765-19777. https://doi.org/10.1109/ACCESS.2024.3360298