A NONLINEAR EQUALIZATION METHOD USING DEEP LEARNING TO IMPROVE ROF TRANSMISSION QUALITY OF A CONTINUOUS-PHASE FREQUENCY MODULATED TWO-CHANNEL C-RAN CONNECTION

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Abstract: Radio over Fiber (RoF) stands as a cutting-edge technology poised to revolutionize emerging wireless networks, especially in the context of fifth-generation Cloud-Radio Access Networks (C-RAN). Concurrently, with the pervasive integration of deep learning across diverse domains such as communication and data processing, this investigation delves into the nonlinear effects observed in a fronthaul interface. The exploration employs numerical simulations to assess the impact on two wireless signal channels operating in the VHF frequency band, utilizing continuous-phase frequency-shift keying (CPFSK) modulation. Moreover, this study introduces a novel approach to address nonlinear impairments during extensive data transmission. Specifically, a nonlinear equalizer leveraging a deep neural network (DNN) is proposed and implemented. The experimental phase, involving a transmission spanning 50 kilometers, underscores the effectiveness of employing a DNN with six hidden layers in significantly mitigating nonlinear distortion. This research contributes valuable insights into the nonlinear dynamics of fronthaul interfaces, offering a potential solution for enhancing the robustness of long-distance data transmission in wireless networks.

Keywords— RoF, CPFSK, nonlinear equalization, DNN.

I. INTRODUCTION

In contemporary society, there has been a substantial increase in the need for widespread access to high-speed information across various platforms, encompassing both fixed and wireless services [1],[2]. As a result, optical fiber technology has gained popularity as an integral component of information infrastructure [3]. To fulfill the demands of rapid data transmission in wireless networks such as 4G, 5G, and beyond [4],[5], optical fiber-based information systems have been adopted to address the challenges in wireless communication processing [6]. This adoption is primarily, due to their ability to leverage the high bandwidth and low signal loss characteristics offered by optical cables [7],[8], a technology known as radio over fiber (RoF). Within a RoF framework, optical fiber links are employed to distribute Radio Frequency (RF) signals from a central hub to remote antenna units (RAUs) [9].The notable advantages of RoF technology include its minimal signal loss, extensive bandwidth capacity, immunity to RF interference, reduced power consumption, and support for multi-operator and multi-service functionalities. Therefore, RoF has become the preferred choice over traditional RF signal processing methods. Essentially, Radio Over Fiber serves as an optical link for transmitting modulated RF signals, facilitating the bidirectional transmission of both downlink and uplink RF signals between the Central Station (CS) and Base Station (BS). Key prerequisites for the RoF link architecture include bidirectional operations, limited transmission distance, and the integration of high-performance optical components [10].

Presently, the Radio over Fiber (RoF) technology serves as a fundamental platform for establishing an innovative architectural concept known as the centralized Cloud Radio Access Network (C-RAN) [11],[12]. This network architecture effectively manages centralized Baseband Units (BBUs) across multiple Base Stations (BSs) and Remote Radio Heads (RRHs) [13]. The cost-effective connectivity between these BBUs and RRHs is facilitated through a distribution network referred to as 'fronthaul.' RoF technology stands out as the most suitable option for enabling the fronthaul process, owing to its inherent characteristics. Notably, in certain emerging small cell base station systems within the C-RAN framework [14], the connection to RRHs is achieved through either Free-Space Optical (FSO) [15] or RoF [16] techniques. The primary objective behind the implementation of RoF is to establish a streamlined and economical approach for transmitting wireless signals from Base Stations to remote antenna units. Several variations of RoF exist, including Analog RoF (A-RoF) [17],[18]. However, the nonlinear nature of these transformations poses a significant

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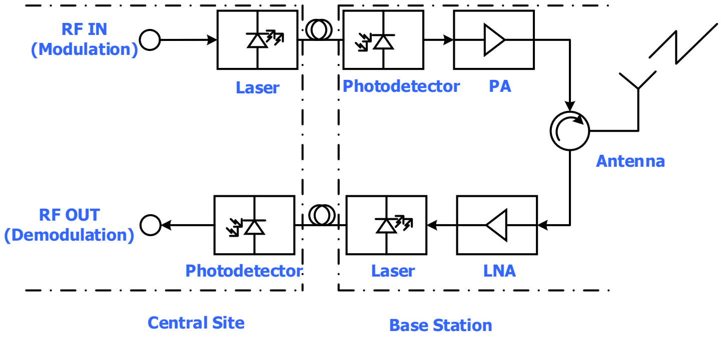

Fig.1 Application diagram of a fundamental RoF system.

challenge that necessitates complex compensatory measures [19]. To address the limitations associated with A-RoF, the adoption of Digital RoF (D-RoF) has emerged as a viable alternative [10], [20], [21]. RoF system combines the disadvantages of wireless transmission and optical transmission in its ability to transmit signals over radio waves using fiber optics. The relatively large influence on the transmission and system quality is the nonlinear effect. Therefore, researchers are looking for effective nonlinear balancing methods.

The realm of deep learning has brought about transformative changes in numerous areas of research, such as the recognition of visual objects, speech patterns, and language translation services. DNNs streamline the process of identifying distinct attributes within unprocessed data [22]. The publication [23] outlines the conception and execution of a digital pre-distortion (DPD) strategy rooted in a machine learning (ML) algorithm. This approach has been envisioned for the upcoming sixth generation of mobile communications (6G) within the analog radio over fiber (A-RoF) system. In [24], the researchers suggest a channel estimation model that takes into account nonlinear impairments. This model relies on a deep neural network (DNN) and is designed to optimize dynamic modulation formats and guard band assignments for RoF broadcasting systems. Nonlinear equalizers based on DNNs have been created for telecommunication networks, aiming to counteract signal deterioration within diverse network structures, including passive optical networks (PONs) [25], optical connections [26], direct-detection optical systems [27], [28], as well as coherent optical systems [29]-[31]. DNN-based strategies have proven to surpass traditional linear and nonlinear equalizers in terms of performance.

In this article, we establish a Digital Radio over Fiber (D-RoF) information system with two wireless channels utilizing two advanced phase modulation techniques, namely Differential Phase Shift Keying (DPSK), for the C-RAN connection and investigate parameters related to nonlinearity such as refractive index n_2. Subsequently, we examine the impact of nonlinearity on the system. We then propose the use of a Deep Neural Network (DNN) model to compensate for nonlinearity in order to enhance transmission quality. Realistic simulation results are implemented using Optisystems and Python simulation tools, evaluating the information performance through quality parameters.

II. MODEL SYSTEM

Fig.1 illustrates a basic Radio over Fiber (RoF) system. In the downlink transmission phase, the RF signal undergoes modulation through a diode laser, resulting in an intensity-modulated optical signal at the Central Site (CS). These signals are then transmitted via an optical fiber to the Base Station (BS). At the BS, the signals are directly demodulated using an optical diode to retrieve the RF signal. Subsequently, they are amplified and broadcasted through an antenna. From the perspective of modulation and demodulation, RoF technology is known as Intensity Modulation - Direct Detection (IM-DD). The inverse process occurs during uplink transmission, wherein the RF signals from the antenna at the BS are directly modulated by a diode laser. The received optical signals are then transmitted through an optical fiber to the CS. At the CS, the intensity-modulated optical signals are directly demodulated using a Photo Detector (PD) diode to recover the RF signal. Following this, the signals are amplified and further processed.

Fig.2 depicts the fundamental concept of a two-channel data Radio over Fiber (RoF) information system (CH1 and CH2) employing phase shift keying modulation techniques without requiring pre-FEC (Forward Error Correction). Within each channel, a pseudo-random bit sequence (PRBS) generates square waveforms, which are converted into baseband signals at a frequency of f_B and a bit rate of R_b. These signals are subsequently modulated with an RF (Radio Frequency) carrier frequency of f_C using a frequency-shift modulation technique, altering the carrier frequency to f_C. The two channels utilize RF carrier frequencies, f_{C1}=250 GHz and f_{C2}=255 GHz, employing continuous phase frequency shift keying (CPFSK) as the modulation method. These modulation types eliminate the need for a combined reference signal at the receiver, as they operate as non-coherent modulation schemes. Following modulation, each channel's signal undergoes filtration through a bandpass filter (BPF) employing a Bessel filter to isolate the desired frequency band and eliminate unwanted frequency components. The two RF signals are combined at a combiner, generating two RF spectra corresponding to the high-frequency carrier frequencies, f_{C1} and f_{C2}. The filtered signals from the BPFs

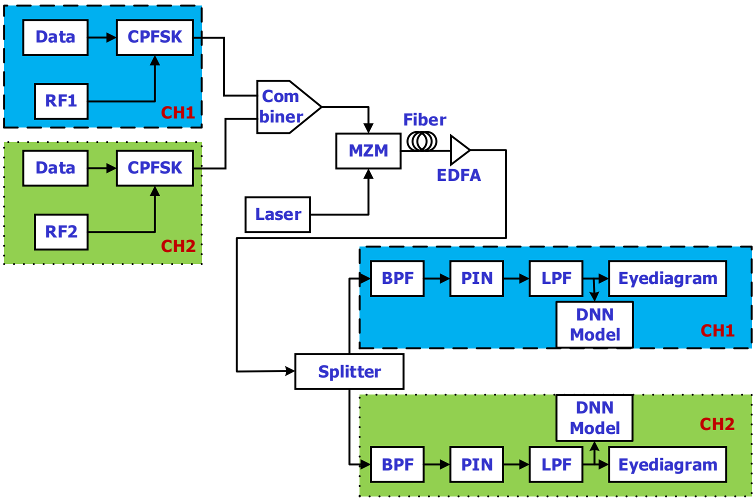

Fig.2. Numerical simulation setup diagram for RoF system using DNN model.

are further processed within the combiner (Combiner). Subsequently, the combined output passes through an external modulator, transitioning the carrier frequency from the RF frequency to an optical frequency at f_0 = 193.1 THz, corresponding to a wavelength of λ_0=1/f_0= 1552.52 nm. The external optical modulator relies on a Mach-Zehnder Modulator (MZM), constructed based on the Mach-Zehnder Interferometer (MZI) principle. In this configuration, a continuous-wave laser source emits a narrow-linewidth laser spectrum at a wavelength of 1552.52 nm using a semiconductor laser. This optical signal is then introduced into the MZI, either through direct modulation or by utilizing Bragg grating nonlinearity with a pre-defined wavelength of 1550 nm. The MZI structure involves symmetric optical path splitting or an effective phase shift in multiples of 2π.

In an optical branch, the signal passes through a phase modulator controlled by voltage, with the voltage source mainly being the RF carrier signal from the output of the combiner. After passing through the MZM, the two sideband spectra of each RF signal channel, in the low and high-frequency sides, are $f = f_0 + f_c \pm f_B$. They are filtered by an optical bandpass filter (OBPF) with a frequency of $f_0 + f$ and a bandwidth of 1.5×R_b. Then, this optical signal is transmitted through a single-mode optical fiber with a length of L=50km, assuming a low attenuation coefficient of α = 0.2 dB/km. An Erbium-Doped Fiber Amplifier (EDFA) with a gain factor G=20 dB is used to amplify the optical signal to compensate for the losses. The single-mode optical fiber is assumed to have a standard average chromatic dispersion parameter D = 16.75 ps/nm/km, and there is no need for the dispersion compensation process because the distance.

At the receiver's end, an optical amplifier transmits the optical signal through an optical bandpass filter (OBPF) set at a central frequency of 193.12 THz to filter the upper sideband of the optical signal. Subsequently, this signal passes through an optical splitter, leading to an optical receiver employing a PIN photodiode. This optical splitter demodulates the filtered optical signal and directly converts it into a baseband signal. To eliminate high-frequency components, a low pass filter (LPF) is applied. Within the signal processor, at the data signal output, operations such as signal restoration and nonlinear equalization are conducted based on the DNN model. Furthermore, the Signal Meter and Eye Diagram Analyzer tools can be utilized to monitor signal quality. The specific parameters defining the information system's design are outlined in Table 1.

Table 1. System description parameters

Parameter	**Value**
Bit Rate R_b	1Gbps
Frequency f_0	193.1 THz
Laser output power P	0 dBm
Length L	50 km
Attenuation coefficient α	0.2 dB/km
Dispersion coefficient D	16.75 ps/nm/km
Gain G	20 dB
Radio frequency 1	250 GHz
Radio frequency 2	255 GHz

This study involves the construction of a DNN model (Fig. 2) comprising seven layers, including one input layer, six hidden layers, and one output layer, each containing 2048 nodes. The nonlinear function of this neural network is referred to as "LeakyReLU"[32]. To enhance the learning process, the Dropout technique is implemented, randomly deactivating some nodes during training at a 5% rate after each iteration. Within the network, the output layer corresponds to the specific output number of the problem, utilizing the term "linear" for the activation function of this final layer. The "Adam" optimizer and cross-entropy function are applied to simulate and implement the optimization process. The learning rate plays a crucial role in the learning model, initially set to 0.001 to facilitate learning. In cases where the model deteriorates or validation errors increase consistently for three consecutive cycles, the learning rate is reduced by 0.2 times until it reaches a minimum of 0.00001. An early stopping method is employed to prevent overfitting. The

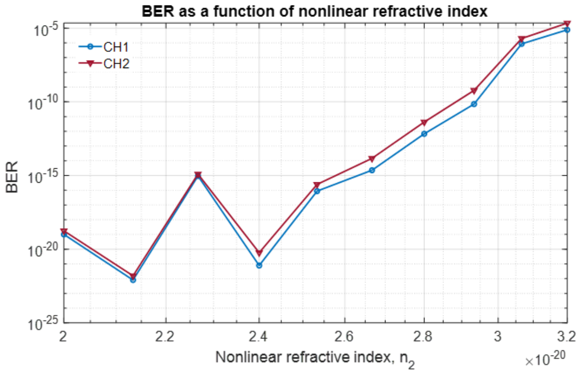

Fig.3 Bit error rate BER as a function of n_2.

training process concludes when the validation error function ceases to decrease after a specific number of epochs. Lastly, the proposed model is evaluated using the test data output of the LPF (Low Pass Filter) unit as depicted in Fig.2 dataset. The criterion is examined for the analysis utilizing the eye-diagram specification.

III. SIMULATION RESULTS AND DISCUSSION

The numerical simulation was conducted using the commercial simulation tool OptiSystems for a two-channel wireless system operating with baseband digital signals at a speed of R_b =1 Gb/s. The RF signals underwent modulation at carrier frequencies of 250 GHz and 255 GHz before being transformed into optical signals at a wavelength of 1550 nm via an external optical modulator (MZM). Next, these filtered signals were directed through an optical splitter that converted the optical signals directly into baseband signals. To eliminate high-frequency components, a low-pass filter with a cut-off frequency of 0.75 times the Bit Rate (Hz) was employed, resulting in the retrieval of the transmitted data. Here, we use a DNN model to process the signal, when the signal is affected by nonlinearities. The DNN model has 2 inputs and 2 outputs corresponding to 2 channels.

First, we investigate the influence of nonlinear refractive index n_2 on the bit error rate (BER). Fig.3 illustrates the relationship between the bit error rate and the nonlinear refractive index, where an increase in the nonlinear refractive index results in a decrease in BER. When $n_2 = 32\times10^{-21}$, the BER of both channels approximates 10^{-5}. This indicates a significant impact of nonlinearity on the system's performance. Therefore, to address the nonlinear phenomenon when transmitting through the optical fiber channel, we employed a Deep Neural Network (DNN) model

Fig.4 (a, b) and Fig.5 (a, b) illustrate the eye diagrams of the two transmission channels, respectively, before and after the utilization of the DNN model. In digital communication systems, especially optical communication systems, the eye pattern or eye diagram is used to visualize the system's performance for advanced modulation schemes like CPFSK. The eye pattern is a graphical representation that shows the digital signal sampled and applied to the vertical axis repeatedly with the data rate used to trigger horizontal scanning. From Fig.4 and Fig.5, it is easy to observe that channels 1 and 2 exhibit similar

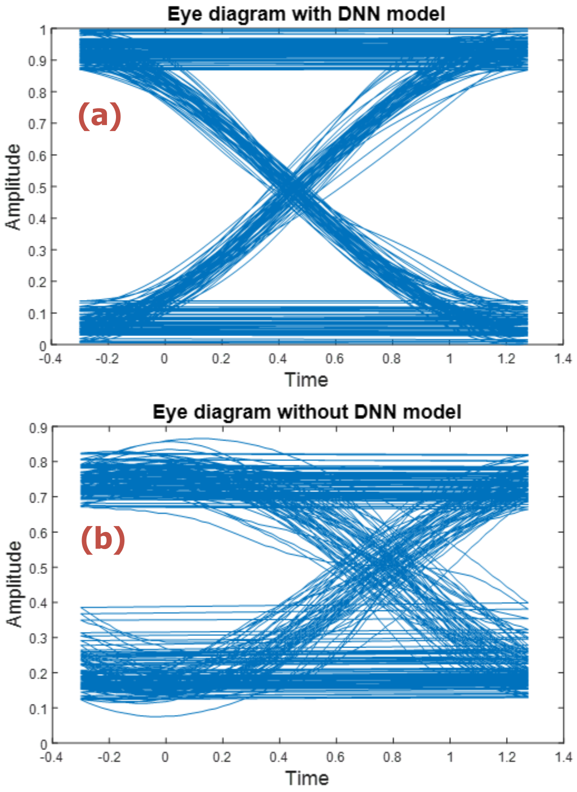

Fig.4. Eye diagram for channel 1: (a) with DNN model, (b) without DNN model.

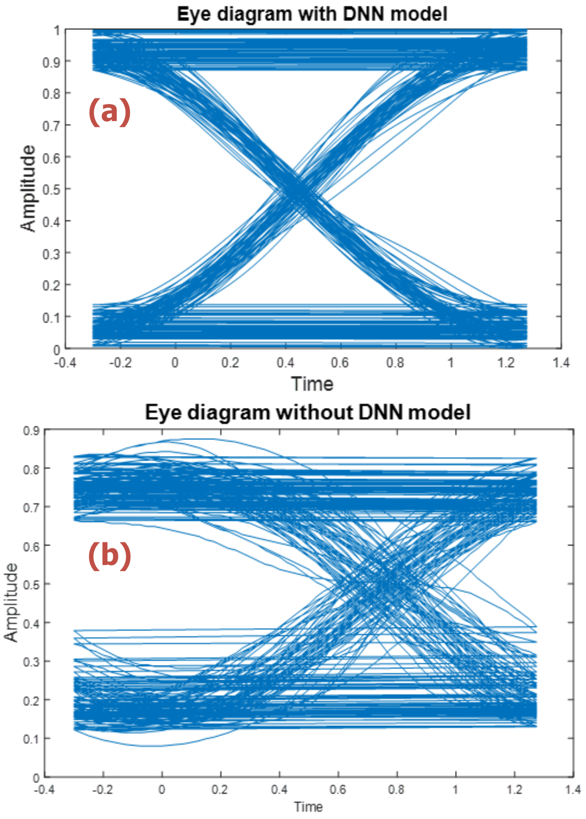

Fig.5. Eye diagram for channel 2: (a) with DNN model, (b) without DNN model.

eye diagrams, but the distinction lies between Fig.4a and Fig.4b, as well as Fig.5a and Fig.5b. Fig.4a and Fig.5a represent the eye diagrams of channel CH1 and CH2 without data processing, where their eye diagrams are relatively small with considerable jitter. However, after undergoing training in the DNN model, it is evident that the results shown in Fig.4b and Fig.5b depict larger, clearer eye diagrams with significantly reduced jitter.

CONCLUSION

This research article introduces an investigation into the proposed conFiguration of a radio over fiber (RoF) system, utilizing advanced modulation techniques like CPFSK, and employing the DNN model to achieve nonlinear compensation along the transmission line. Through numerical simulations conducted using OptiSystem simulation tool and Python programming language, the study demonstrates that the system can tolerate a nonlinear refractive index of up to 32×10^{-21} (m^2/W). The simulation outcomes reveal that an increase in the nonlinear refractive index corresponds to an increase in the bit error rate (BER), subsequently countered by the DNN model to rebalance the nonlinearity and enhance system performance. This informational network model holds significance for applications involving connectivity between BBU and RRH units in a Next Generation Broadband Cloud Radio Access Network (C-RAN).

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PHƯƠNG PHÁP CÂN BẰNG PHI TUYẾN SỬ DỤNG HỌC SÂU ĐỂ NÂNG CAO CHẤT LƯỢNG TRUYỀN DẪN ROF CỦA KẾT NỐI C-RAN HAI KÊNH ĐIỀU CHẾ TẦN SỐ PHA LIÊN TỤC

Tóm tắt: Radio over Fiber (RoF) là một công nghệ tiên tiến sẵn sàng cách mạng hóa các mạng không dây mới nổi, đặc biệt là trong bối cảnh Mạng truy cập vô tuyến đám mây (C-RAN) thế hệ thứ năm. Đồng thời, với sự tích hợp sâu rộng của học sâu trên nhiều lĩnh vực khác nhau như truyền thông và xử lý dữ liệu, nghiên cứu này đi sâu vào các hiệu ứng phi tuyến được quan sát thấy trong giao diện truyền dẫn trước. Quá trình thăm dò sử dụng mô phỏng số để đánh giá tác động lên hai kênh tín hiệu không dây hoạt động ở dải tần số VHF, sử dụng phương pháp điều chế khóa dịch tần số pha liên tục (CPFSK). Hơn nữa, nghiên cứu này giới thiệu một cách tiếp cận mới để giải quyết các suy giảm phi tuyến trong quá trình truyền dữ liệu rộng rãi. Cụ thể, một bộ cân bằng phi tuyến tận dụng mạng lưới thần kinh sâu (DNN) được đề xuất và triển khai. Giai đoạn thử nghiệm, bao gồm đường truyền kéo dài 50 km, nhấn mạnh tính hiệu quả của việc sử dụng DNN với sáu lớp ẩn trong việc giảm thiểu đáng kể độ méo phi tuyến. Nghiên cứu này đóng góp những hiểu biết có giá trị về động lực phi tuyến của các giao diện truyền dẫn trước, đưa ra một giải pháp tiềm năng để tăng cường độ bền của việc truyền dữ liệu đường dài trong mạng không dây.

Từ khóa— RoF, CPFSK, cân bằng phi tuyến, DNN.

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