Autoencoder Learning of Nonlinear Constellation Shape for Fiber-Wireless Convergence System

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Abstract: We propose and experimentally demonstrate a novel nonlinear constellation shape auto-optimization method with a complex-valued 2D-ANN equalizer. Up to 70% lower BER compared with the conventional format is achieved at 50 Gbps in fiber-MMW system.

1. Introduction

Artificial intelligence (AI) has attracted great research interest for coherent optical communication with various applications in sensing, system identification, and intelligent computing [1-2]. For the physical layer, AI has shown a great potential either to optimize individual digital signal processing (DSP) blocks or, more surprising, to optimize the whole DSP blocks as a cascade of neural networks (NN), referred to as an end-to-end autoencoder (AE) [3]. Moreover, NN-based equalizations have been proposed to compensate for the nonlinear impairments of transmitters and receivers [4-5]. In the physical layer, the recent development in the field of fiber-millimeter wave (MMW) convergence has been as a promising option in the sixth-generation mobile network (6G) because of its seamless conversion between optical and wireless signals, flexible multichannel aggregations, and efficiency [6]. On the other hand, AI has become one of the cornerstones of the 6G transmission system, as the native AI in 6G will take advantage of end-to-end architecture to improve overall performance [7-8]. To meet the higher throughput demand and nonlinear robustness, advanced modulation formats and efficient equalizer are essential. However, the nonlinear impairment caused by the imperfect optoelectronic devices, including the digital-to-analog converter, the photodiode, modulators, and complex channel environment, is inevitable in a practical system. Therefore, the achievable data rate and system capacity would severely deteriorate.

In this work, we propose and experimentally demonstrate a novel nonlinear constellation auto-optimization based on an autoencoder to compensate for the nonlinear impairments in the fiber-wireless convergence system at 92.5 GHz. Moreover, we introduce an efficient two-dimensional artificial neural network (2D-ANN) equalizer with a complex-valued structure to compensate for the nonlinear redundancy. Aiming at the nonlinearity strengths in the optoelectronic devices and complex channels, the AE-based constellation auto-optimization is implemented based on the end-to-end fiber-wireless convergence system. In the experiment, a 50 Gbit/s 32QAM signal is transmitted through a 20 km fiber and a 6 m wireless link. The AE-optimized constellation performs a lower BER under both linear and nonlinear conditions, and a decrement up to 70% in BER is achieved under a strong nonlinear strength.

2. Principles

The AE-based constellation auto-optimization framework is established based on high-order quadrature amplitude modulation (QAM) with fiber and W-band wireless convergence system as shown in Fig. 1. The framework models

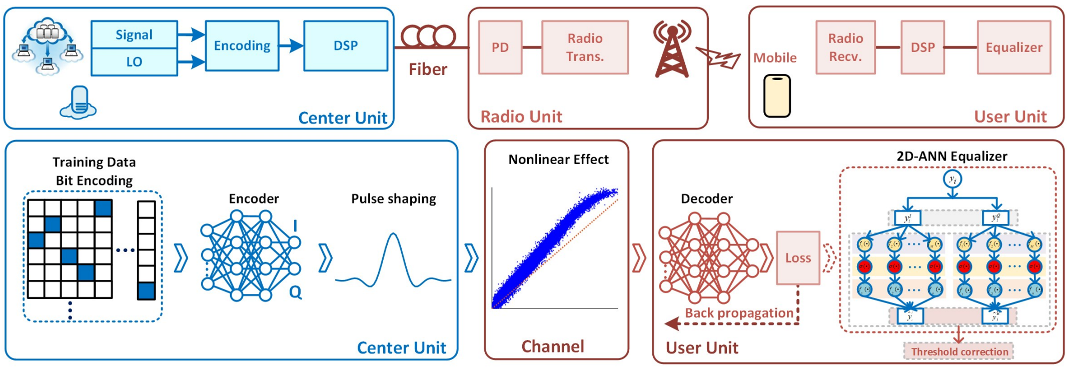

Fig. 1. Diagram of the autoencoder-based constellation auto-optimization framework.

the entire process in data encoding, modulation, channel transmission, decoder, and a complex-valued 2D-ANN equalizer with lower complexity. The training sequence is fed into the framework, and one-hot bit is encoded. The encoder that maps coding symbols to constellation points is modeled as a multi-layer fully connected neural network. The constellation points are sent into pre-processing DSP layers that fulfill the high-order QAM modulation process. A complex-valued signal is then generated by combining the two outputs of the modulation layer and is ready to be sent into the fiber and wireless channel. In this paper, we mainly analyze the strengths of the nonlinear effect caused by optoelectronic devices and fiber and wireless nonlinear transmission links. Signals with higher power suffer more nonlinear distortion than those with lower power, mainly when applying high-order modulation.

Following the channel, the demodulation process of received symbol is implemented as an NN-based to recover the constellation. A mathematically derived loss function is used to pursue the best performance end-to-end. The encoder NN is learning both constellation shaping and bit-level mapping rule by minimizing the average BER value. Meanwhile, the loss function takes the constellation point with optimal power at the encoder side. Such a loss function leads to a constellation with a small peak-average power ratio (PAPR) which is assured by reducing the maximum transmitting power and strong nonlinear resistance. In addition to the encoding, nonlinear equalization of the received symbol is essential. We introduce an efficient complex-valued 2D-ANN equalizer, which brings extra resistance to nonlinear redundancy, including the conventional high-order QAM constellation.

3. Experiment and Discussions

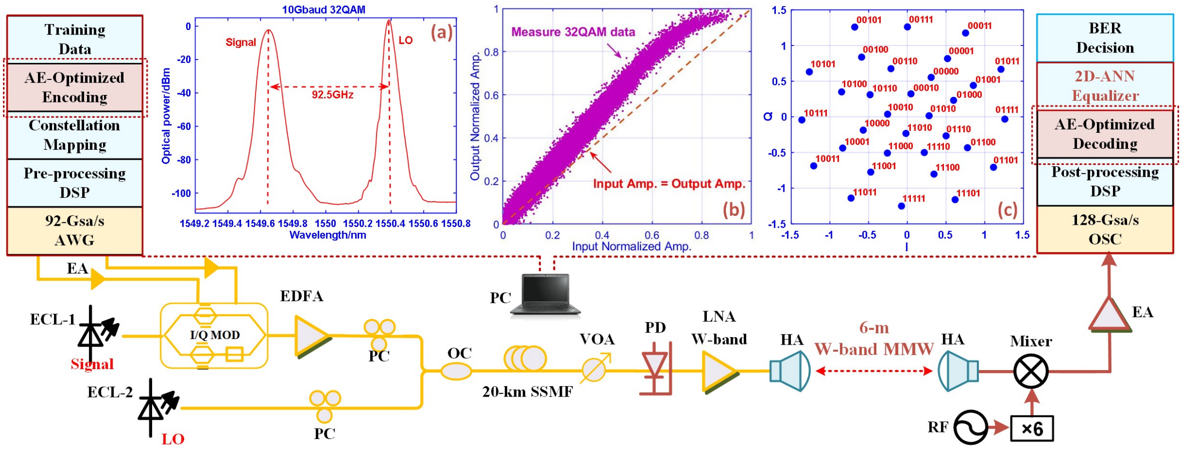

Fig. 2. Experimental setup, including the optical spectrum of 10 Gbaud 32QAM signal after the optical coupler (OC) (a), nonlinear impairments in fiber-wireless transmission system (b), and the AE-optimized constellation with bit-level mapping (c).

Figure. 2 depicts the experimental setup of our demonstrated 32QAM delivery over 20 km standard single-mode fiber (SSMF) and 6 m wireless link at W-band. A personal computer (PC) connects the transmitter and receiver to realize the integration of the end-to-end data transmission system. At the transmitter side, the training data is encoded and mapped into symbol as usual. The baseband symbol is digital-to-analog (DAC) converted by a 92 Gsa/s arbitrary wave generator (AWG). We employed two free-running tunable external cavity lasers (ECL-1 and ECL-2) with 100 kHz linewidth to generate MMW signals. After being amplified by a 40 GHz cascaded electrical amplifier (EA), the boosted 32QAM signal is used to drive a 35 GHz I/Q modulator. The data rate is 50 Gbit/s with a roll-off factor of 0.5. An erbium-doped fiber amplifier (EDFA) is used to compensate for the fiber transmission loss. ECL-2 works as a local oscillator (LO), which has a frequency space of 92.5 GHz with the modulated ECL-1 and ECL-2, as shown in Fig. 2(a). Note that a W-band photodiode (PD) is polarization sensitive, and hence two polarization controllers (PCs) are necessary to adjust the incident direction to maximize output power. The optical signal and ECL-2 are combined by an optical coupler (OC), and the coupled light beam can be delivered over 20 km SSMF. A variable optical attenuator (VOA) adjusts received optical power (ROP) into PD to control the nonlinear strength, and then the MMW signals are boosted by a cascaded electrical low-noise amplifier (LNA). At the wireless transmitter, the generated 92.5 GHz signal is emitted from W-band antenna (HA) with a gain of 26 dBi gain, and another HA is employed to receive W-band signal.

At the Wireless receiver, it is driven by an electronic LO source to implement analog down-conversion and consists of a mixer, 12 frequency multiplier chain, and captured by an oscilloscope (OSC). The received signal is demodulated, equalized, and decoded with the help of the 2D-ANN equalizer. Fig. 2(b) illustrates the typical nonlinear effect in the fiber-wireless system, the received signal is not linear as the amplitude of the transmitted

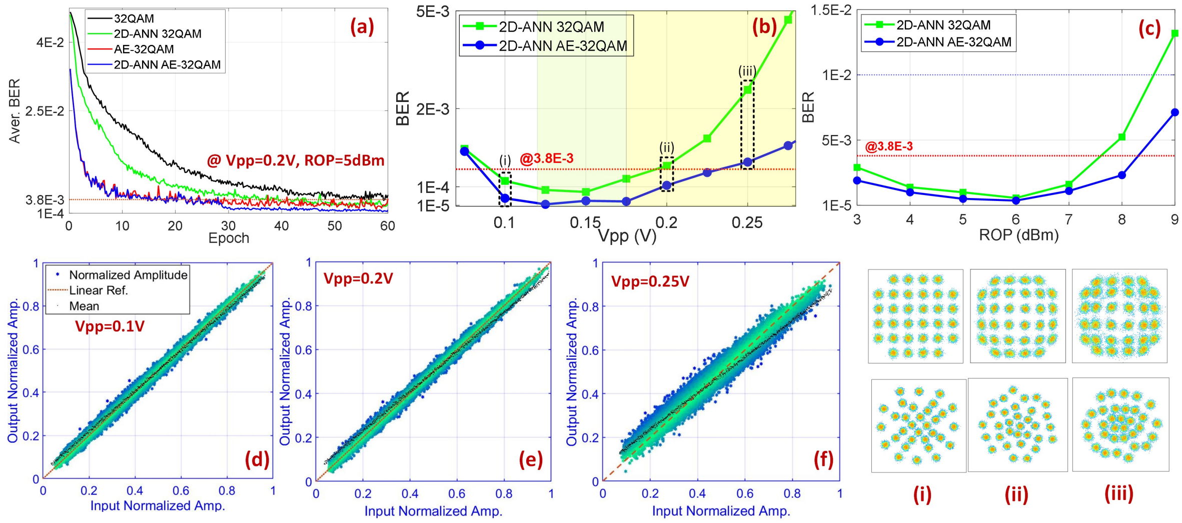

Fig. 3. (a) The iteration BER with different schemes. (b) The BER performance of the constellations with different Vpp when ROP is 5 dBm. (c) The BER of the constellations with different ROP when Vpp is 0.1 V. (d)-(f) The optimized nonlinearities.

signal increases. Obviously, the detrimental nonlinear effect becomes severe for signals with higher power and further decrease the performance of the system. The AE-optimized constellation with bit-level encoding work well for improving the BER performance. Fig. 2(c) shows one AE-optimized 32QAM, which is robust to the nonlinear effect. The introduction of the 2D-ANN equalizer brings extra nonlinear compensation of the nonlinear redundancy to the constellations, including the conventional constellation.

Fig. 3(a) presents the average BER curves versus training epochs for different scheme. It can be seen that AE-optimized scheme with 2D-ANN equalizer achieves the best BER performance. To present different strengths of nonlinear effects, the peak-to-peak voltage (Vpp) of the output signal of the AWG is adjusted from 0.075 V to 0.30 V when the ROP is 5 dBm. Fig. 3(b) illustrates measured average BER as a function of Vpp. In the first region where Vpp ranges from 0.075 V to 0.125 V, nonlinearity is weak, and the larger distance between the constellation points enables better performance under the same condition, as shown in Fig. 3(i). The second Vpp region ranges from 0.125 V to 0.175 V, where nonlinearity is middle, as shown in Fig. 3(ii), the nonlinear effect starts to affect the shape of the 32QAM, resulting in an expansion in the center part and a squeezing in the outer area. The third region ranges from 0.175 V to 0.30 V, where the BER performance is seriously affected by the nonlinearity, as shown in Fig. 3(iii), the strong nonlinearity affects the shape of the 32QAM. However, the points in the received optimized constellation can be clearly distinguished, and the AE-optimized 32QAM brings a 70% lower BER when Vpp is 0.275 V. To visualize the nonlinearity weakening of received signal, the input and output normalized amplitude diagrams of the optimized constellation after the 2D-ANN equalizer are shown in Fig. 3(d)-(f). The black points are the mean of the output versus input amplitude, and the red line is the linear reference. Obviously, the nonlinear effects are well mitigated, even under the stronger nonlinear strength. Fig. 3(c) further shows the BER performance when Vpp is 0.1 V varying the ROP. Taking advantaging of the bit-level mapping and the 2D-ANN equalizer, the optimized constellation has strong nonlinear resistance and achieves better BER performance.

4. Conclusion

We propose and experimentally demonstrate the novel autoencoder-based learning of nonlinear constellation shape method in the fiber-wireless convergence system. Further, the complex-valued 2D-ANN equalizer brings extra compensation to the nonlinear redundancy of the optimized constellations, including the conventional constellation. The experimental demonstrated of a 20 km SSMF and 6 m wireless transmission is achieved at 50 Gbit/s, showing up to 70% decrement in BER under a strong nonlinear strength.

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