Intelligent End-to-End Nonlinear Constellation Auto-Optimization in W-band Fiber-MMW Integrated Transmission for 6G Access

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Abstract: We propose and experimentally demonstrate an intelligent end-to-end nonlinear constellation auto-optimization method for fiber-MMW integrated 6G access network. Up to 60% lower bit-error-rate compared with the conventional constellation is achieved at 50-Gbps W-band fiber-MMW access. © 2022 The Author(s)

1. Introduction

Artificial intelligence (AI) has become one of the cornerstones of the sixth-generation wireless communication (6G), as the network is expected to integrate connecting, sensing, and intelligent computing at anytime and anywhere for anyone [1]. The 6G will have more than 1000 times the capacity in 5G [2], and the native AI in 6G will take the advantage of end-to-end (E2E) AI design as well as a machine learning platform to achieve customized optimization from the network layer to physical layer [3]. In the physical layer, fiber-wireless integration is a key technology that supports radio access networks (RAN) in 6G [4-5]. To meet the high throughput demand, we have observed that it has become more and more complicated due to increasing data transmission speed, extremely high frequency, advanced modulation formats, and heterogeneous architecture. For example, carrierless amplitude-phase (CAP) modulation with advanced formats, as a single-carrier modulation that has a low peak-average power ratio (PAPR), was widely studied in fiber-millimeter (MMW) access network [6] enabling a high average power to achieve a larger coverage. However, being a time-domain modulation scheme, CAP modulated signal suffers from nonlinear effects in the electrical-to-optical (E/O) and optical-to-electrical (O/E) conversion process, therefore the quality and distance are limited.

In this paper, we propose and experimentally demonstrate an intelligent nonlinear E2E constellation auto-optimization method based on neural networks (NN) to compensate for the nonlinear impairments in the fiber-millimeter wave (MMW) integrated 6G access network. Aiming at the strengths of nonlinearity in the E/O, O/E, IF to RF and RF to IF conversion process, the E2E constellation auto-optimization is implemented based on the channel model before transmission. In the experiment system, a 50-Gbit/s signal is transmitted through a 10-km fiber and a wireless W-band MMW link. The E2E-optimized constellations perform a lower bit error rate (BER) under both linear and nonlinear conditions, and a decrement up to 60% in BER is achieved under a strong nonlinear effect. It shows that the optimization enables the systems to work in a larger dynamic range of transmitting power.

2. Principles

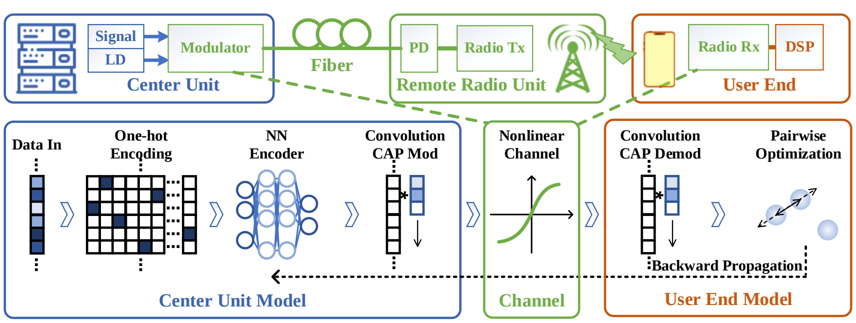

Fig. 1. Diagram of the E2E constellation optimization framework.

The E2E-optimization framework is framed based on a CAP modulation system with an adjustable nonlinear channel as shown in Fig. 1. The framework models the entire process in transmission, including modulation, channel, and demodulation. The randomly generated training data is fed into the framework symbol by symbol firstly, and one-hot encoded. The encoder that maps symbols to constellation points is modeled as a 2-layer fully connected neural network. The constellation points are sent into two separate convolution layers corresponding to the shaping filters that fulfill the CAP modulation process. A real signal is then generated by adding the two outputs of the convolution together and is ready to be sent into the channel. The channel model considers mostly the nonlinear effect in the systems. An S-curve equation is utilized to simulate the nonlinear effect. The S-curve is described as $\zeta_{a,b,c}(x) = a/(1+e^{-bx})+c$, where a, b, and c are the parameters that adjust the shape of the curve.

Following the channel, the process of CAP demodulation is similar to the CAP modulation. Two convolution layers act as the matching filters at the receiver side and recover the constellation. A specially designed loss function is used to pursue the best symbol error rate (SER) performance. This loss function calculates the center point of the points corresponding to each symbol, finds the two center points with the smallest distance, and then propagates the gradient to pull these two points away. Meanwhile, the loss function takes the constellation point that has the largest power at the encoder side and pulls it to the center of the plane. Such a loss function leads to a constellation that has both small PAPR which is assured by reducing the maximum transmitting power and strong noise resistance which is guaranteed by maximizing the minimum distance between the received constellation points.

In addition to the constellation, encoding of the constellation is essential for transmission. We optimize the bit-level encoding of the E2E-optimized constellation by pair-wise optimization. In each iteration of the optimization, two points are selected randomly to be swapped, the total Hamming distance is investigated to determine whether accept the swap or not. After iterations, the encoding may converge to a locally optimal solution.

3. Experiment and Discussions

Fig. 2(a) to 2(d) show the constellations including the conventional grid and the 3 E2E-optimized ones. These 3 constellations are optimized with 3 different strengths of the nonlinear effect. The one with a linear channel shows roughly a hexagonal arrangement, which is the densest arrangement mathematically. The stronger the nonlinearity, the denser the middle part of the constellation, and the sparser the outer points. The optimized bit-level encoding with the iteration step count of 1,000,000 is shown in these subfigures as well.

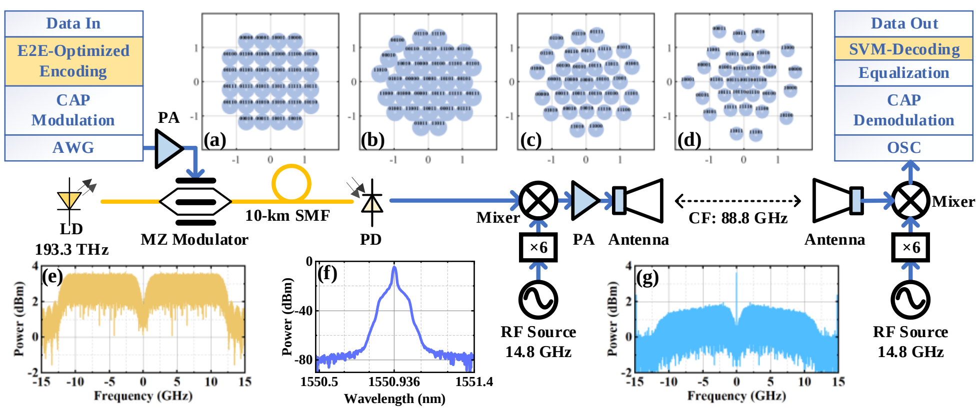

Fig. 2. Experimental setup, the constellations including the conventional grid constellation (a), the E2E-optimized constellation (b) - (d), the spectrum of the transmitting signal (e), the optical spectrum (f), and the spectrum of the received signal (g).

The E2E-optimized constellations are then examined in a fiber-MMW hybrid transmission system. In the digital preprocesses, the original data stream is firstly coded into symbols as usual. The symbols are then mapped into 4 different constellations individually in each test. CAP modulation is applied to the mapped signal, and the modulated signal is sent into an arbitrary waveform generator (AWG, Keysight M8194A). Fig. 2(e) shows the spectrum of the CAP signal. A laser diode (LD) emits light into a Mach-Zehnder (MZ) modulator (Fujitsu FTM7938EZ). The frequency of the laser is 193.3 THz and the MZ modulator is driven by the amplified signal from the AWG by a power amplifier (PA). The modulated signal light, with the spectrum of Fig. 3(f), passes through a 10-km single-mode fiber (SMF) and is collected by a photodiode (PD) converting the optical signal to an electrical signal. The local oscillator (LO) of the W-band mixer is a radio frequency (RF) source (Agilent 83630B) operating at 14.8 GHz with a times-6 frequency multiplier, which means the center frequency (CF) of the MMW is 88.8 GHz. The modulated MMW signal is amplified by a W-band PA and then transmitted by a horn antenna. A receiving horn antenna is placed 1 meter away from the transmitter. A second mixer performs the down-conversion and the signal is collected by an oscilloscope (OSC, Agilent DSA-X 96204Q). The received spectrum is Fig. 3(g) and the signal is CAP demodulated, equalized, and decoded with the help of the support vector machine (SVM). The E2E-optimized constellations work well with the conventional nearest-neighbor judgment. The introduction of the SVM brings an extra resistant of the nonlinear effect to the constellations including the grid one.

As mentioned, the loss function takes both maximum transmitting power and minimum receiving distance. The weight λ that adjusts the maximum power before adding these two criteria together dominants the training result. Fig

3(a) shows how λ changes the constellation. When λ is too large, the power dominates. In contrast, when λ is too small, a constellation with a large PAPR is obtained. In Fig 3(i) to (iv), the blue dots are the transmitting constellation, and the gray dots are the received points with a signal-to-noise ratio (SNR) of 20 dB, and the red dots are the center of the received points. The training process converges after 40 epochs, and the optimized λ is 0.1.

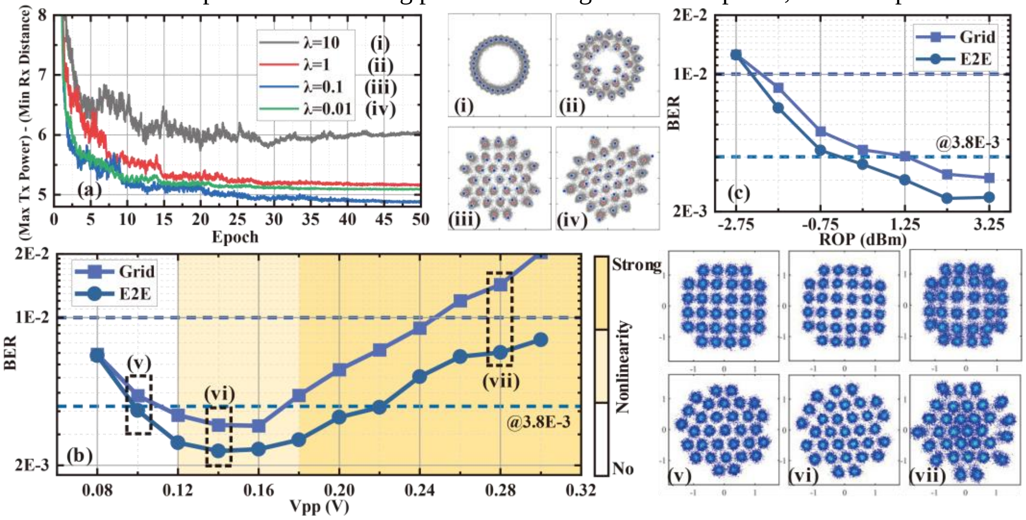

Fig. 3. (a) The iteration losses with different λ. (b) The BER performance of the constellations with different Vpp when ROP is 2.25 dBm. (c) The BER of the constellations with different ROP when the Vpp is 0.14 V.

To present different strengths of nonlinear effect, the peak-to-peak voltage (Vpp) of the output signal of the AWG is adjusted from 0.08V to 0.30V when the received optical power (ROP) of the PD is 2.25 dBm. Fig. 3(b) shows the BER performance of the E2E-optimized constellations compared to the grid constellation. The signal bandwidth is 10 GHz with a roll-off factor of 0.2, therefore the data rate is 50 Gbit/s. Because of the PA that drives the modulator, the nonlinear effect in the system starts to affect when the Vpp goes higher than 0.12 V, and the higher the Vpp, the stronger the nonlinear effect. When Vpp is 0.08 V, the signal power is too small for the system to recover the signal from the noise effectively, and the grid constellation and the linear one performance almost the same BER. The SNR grows with the Vpp increases in the linear area, and the larger distance between the constellation points enables better performance under the same condition. When Vpp comes to 0.14 V, as shown in Fig. 3(vi), the nonlinear effect starts to affect the shape of the grid constellation, resulting in an expansion in the center part and a squeezing in the outer area. In comparison, the points in the received E2E-optimized constellation can be clearly distinguished. When Vpp goes up to 0.26 V, the nonlinear effect strongly affects the shape of the grid constellation, and the BER of the grid constellation increases over the 20% forward error correction (FEC) threshold of 0.01. By contrast, the E2E-optimized constellation brings a 60% lower BER when Vpp is 0.3 V, where the BER of the grid constellation is 0.02 and the one of the E2E is 0.008. It can be seen from the result that no matter how strong the nonlinear effect is, the received E2E-optimized constellation are almost uniformly distributed, and the E2E-optimized constellations perform better BER than the grid one. Fig. 3(c) further shows the BER performance of the constellations when Vpp is 0.4 V varying the ROP. Taking advantage of the Gray code, the difference between the BER is smaller than the gap between the SER. However, the E2E-optimized one leads in all the tests. When ROP goes lower than -2.75 dBm, the optical signal power no longer supports the transmission.

4. Conclusion

We proposed an intelligent NN-based E2E constellation auto-optimization method for fiber-MMW integrated 6G access network. The E2E-optimized constellations compensate for the nonlinear impairments in the whole system, enabling the native intelligence for the fiber-MMW integrated 6G access. The experimental demonstration of a 10-km SMF and W-band MMW transmission system is achieved with 50 Gbit/s through the E2E-optimized constellations, showing up to 60% decrement in BER under a strong nonlinear effect.

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