100Gb/s/λ IM-DD PON using 20G-class optical devices by machine learning based equalization

Lilin Yi, Peixuan Li, Tao Liao, Weisheng Hu

State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Institute for Advanced Communication and Data Science,Shanghai Jiao Tong University, Shanghai 200240, China, lilinyi@sjtu.edu.cn

Abstract *We propose the novel machine learning based equalization algorithm for IM-DD PON and extend the capacity of PON from 50Gbps/λ to 100Gbps/λ. 100Gb/s PAM8/PAM16 IM-DD transmission is achieved over 25km SSMF using 20G-class optics.*

Introduction

Nowadays, there are many applications and market-demanding factors driving the need for higher-speed access network, such as the rapid growth of the high-definition video streaming services, the burst of smart devices of Internet of Things (IoT) and the development of wireless backhaul of 5G [1]. Currently standard groups like IEEE 802.3ca and ITU-T SG15 are working on their 50Gbps/λ passive optical network (PON) industry standard, aiming at deployment in the next few years. Besides, several feasible 50Gbps/λ solutions have been proposed during the past several years. Due to the nature requirement of low cost in PON, optics with limited bandwidth, advanced modulation formats and advanced equalization algorithms are widely chosen as the main research topic of 50Gbps/λ PON. Algorithms like feed-forward equalization, maximum likelihood sequence estimation, volterra nonlinear equalization and machine learning based equalization have been investigated to overcome the limitation of channel impairment [2-4]. To further increase the loss budget, some optical functions have also been introduced such as dispersion shifted fiber (DSF) and semiconductor optical amplifier (SOA) [5-7]. Based on our proposed machine learning based equalization technique, we have also realized 50Gbps/λ PON with 29-dB loss budget[8].

While the research and standardization of 50Gbps/λ are steadily progressing, we decide to push the limits and pay more attentions to the next step 100Gbps/λ research. In the intensity modulation and direct detection (IM-DD) community, there is a solid foundation of 100Gbps transmission, and we have also made some attempts based on our proposed machine learning based equalization technique [9].

In this paper, we introduce the novel machine learning based equalization for high-speed PON applications and show the experimental demonstration of 50Gb/s IM-DD PON based on 10G-class optics and 100Gb/s IM-DD PON based on 20G-class optics.

56Gb/s IM-DD PON based on Machine Learning

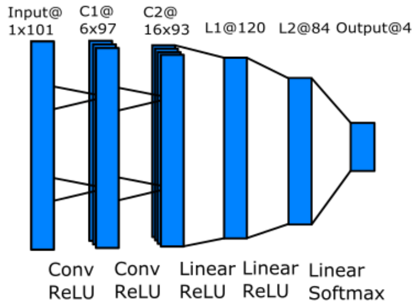

Fig. 1: Network Structure

The proposed machine learning based equalization algorithm is based on convolutional neural network (CNN), of which the structure is shown in Fig. 1. It consists of 5 layers, with 2 convolutional layers followed by 3 linear layers interleaved by rectified linear unit (ReLU) nonlinear activation layers. The input signal is a T-spaced time domain window of 101. After the processing of the network, the output signal is decreased to M units, which denotes the M-th symbol of M-PAM signal. The training process is completed with the help of mini-batch gradient descent algorithm with batch size of 128. After each batch of forward processing, the cross entropy loss signal is calculated and back-propagated to the first layer of the network, and then the network parameters are adjusted with this gradient. When training, the neurons are randomly removed to increase capability of generalization, which is called "Dropout". The dropout probability of 0.1 is used. The dataset contains ten independent PRBS15 sequences, with 60% for training, 20% for cross validation and 20% for test.

The experimental setup is shown in Fig. 2(a). At transmitter side, the 56Gbps PAM4 signal is generated by the delay-attenuate-add scheme of two 28Gbps PRBS15 NRZ signal generated by Keysight N4960A pulse pattern generator (PPG). 10G-class O-band DML and 10G-class APD with 25km SSMF transmission are tested. The output power of DML is set to 10 dBm to improve the link loss budget.

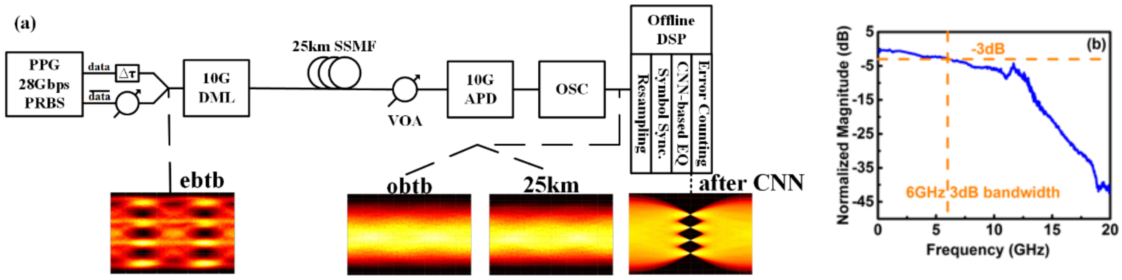

Fig. 2: (a) Experimental setup and DSP flow chart and (b) channel frequency response for 56Gb/s IM/DD PON

After the optical channel, the signal is digitally sampled by the DSO, then the offline digital signal processing is performed to evaluate the system performance. As shown in Fig. 2(b), the total 3-dB channel bandwidth is 6 GHz. The eye diagrams of electrical back-to-back, optical back-to-back and 25-km transmission can also be found in Fig. 2.

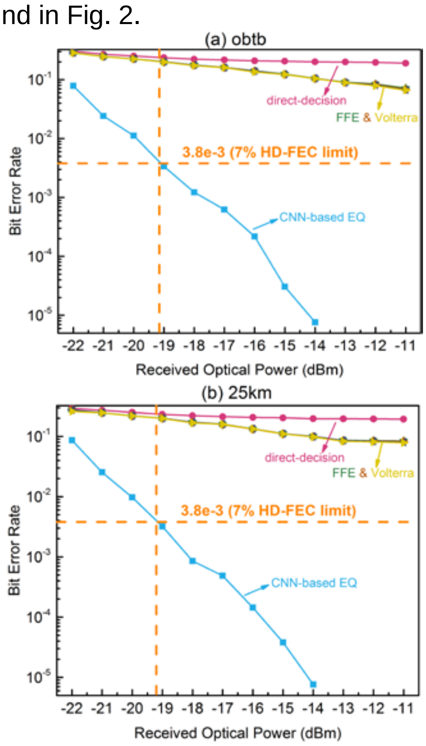

Fig. 3: BER performance comparison for (a) optical back-to-back and (b) 25km transmission

Figure 3 shows the BER performance of different equalization algorithms under the condition of the experimental setup. Different configuration of FFE, volterra nonlinear equalizer are tested. With the help of our proposed machine learning based equalizer, receiver sensitivity of -19.2dBm is achieved for optical back-to-back and 25km SSMF transmission. Considering 10-dBm output of the DML, total loss budget of 29.2dB is achieved.

100Gb/s IM-DD PON based on Machine Learning

We further evaluated the performance of our proposed machine learning based equalization for 100Gb/s IM-DD PON applications. The network structure is shown in Fig. 4.

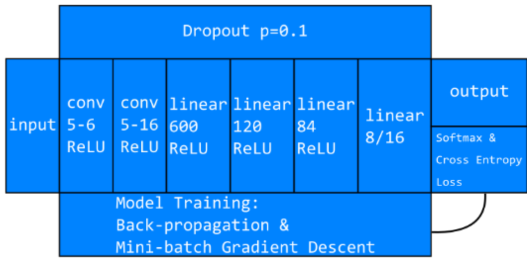

Fig. 4: Network Structure and Configuration

Comparing to the previous network setup, one more linear layer is added to the network to increase the total network learning capability. What's more, the output layer is adjusted to 8 or 16 based on whether PAM8 or PAM16 is transmitted. The network is trained using mini-batch gradient descent with a batch size of 512, which take the advantage of the parallel computing capability of GPU and largely accelerate the training process. In addition, dropout with p=0.1 is also introduced to deal with the over-fitting problem. The dataset is composed of 10 independent PRBS15 receiving symbols, divided in a ratio of 6:2:2 for training, cross validation and testing.

The experimental setup can be found in Fig. 5. The 33GBd PAM8 and 25GBd PAM16 signal are generated by a Keysight 8196A arbitrary waveform generator. Then the signal is

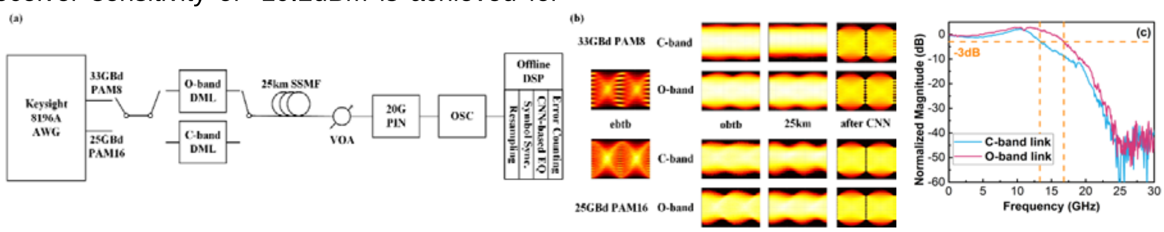

Fig. 5: (a) Experimental Setup (b) Eye Diagram (c) Frequency Response for 100Gb/s IM-DD PON.

loaded onto light by two different DML in C-band and O-band. After 25km SSMF transmission, a 20G PIN is used to perform the photoelectric conversion. Then the signal is digitized and recorded by the DSO, after which offline DSP is performed.

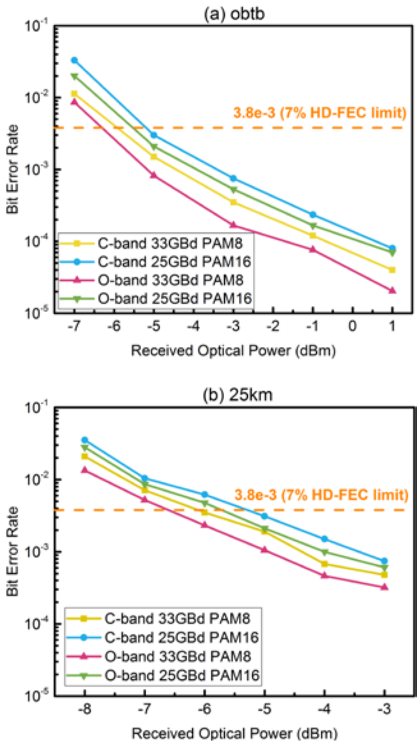

Fig. 6: BER performance comparison of different modulation formats and optics for (a) optical back-to-back and (b) 25km-SSMF transmission

Figure 6 shows the BER performance comparison of different modulation formats and optics for optical back-to-back and 25km SSMF transmission. All the transmission configuration achieves BER under 7% hard-decision forward-error-correction (HD-FEC) limit of 3.8e-3. The BER performance is similar for both optical back-to-back and 25km SSMF transmission. The achieved receiver sensitivity range from -6.5 dBm to -5.5 dBm. What's more, due to the higher bandwidth, the performance of O-band link outperforms C-band. As for the comparison between optical back-to-back and 25km SSMF transmission, dispersion in C-band does not seem to introduce significant penalty to the BER performance, which might be explained by the strong linear equalization capability of CNN and implies that longer transmission distance can also be supported. What's more, even with higher baud rate, the BER performance of 33 GBd PAM8 is better than 25 GBd PAM16, which might be accounted for the higher susceptibility of PAM16 to device nonlinearity and noise. Thus, 33G PAM8 might be a feasible solution for 100Gb/s PON.

In this experiment, the loss budget is only around 16 dB considering 10-dBm output power of DML. The loss budget can be improved by using APD and SOA-based pre-amplifier or advanced CNN algorithms with optimized structure, which are under our investigations. In addition, compared with CNN, recurrent neural network (RNN) is more suitable for sequence signals. We will further investigate RNN-based equalization algorithms and its-variants such as reservoir computing for improved performance and reduced complexity.

Conclusions

We propose the novel machine learning based equalization technique based on CNN network and test its performance under the condition of 56Gb/s PAM4 and 100Gb/s PAM8/PAM16 transmission. The algorithm shows its strength in each of the test configurations.

References

[1] P. Miguelez, "What Applications are Driving Higher Capacity in Access?," in *Proc. OFC*, paper M2B.1, 2018.

[2] M. Tao, L. Zhou, H. Zeng, S. Li, and X. Liu, "50-Gb/s/λ TDM-PON Based on 10G DML and 10G APD Supporting PR10 Link Loss Budget after 20-km Downstream Transmission in the O-band," in *Proc. OFC*, paper Tu3G.2, 2017.

[3] X. Li, S. Zhou, F. Gao, M. Luo, Q. Yang, Q. Mo, Y. Yu, and S. Fu, "4×28 Gb/s PAM4 Long-Reach PON Using Low Complexity Nonlinear Compensation," in *Proc. OFC*, paper M3H.4, 2017.

[4] C. Ye, D. Zhang, X. Huang, H. Feng, and K. Zhang, "Demonstration of 50Gbps IM/DD PAM4 PON over 10GHz Class Optics Using Neural Network Based Nonlinear Equalization" in *Proc. ECOC*, paper W.2.B.4, 2017.

[5] L. Xue, L. Yi, P. Li, and W. Hu, "50-Gb/s TDM-PON Based on 10G-Class Devices by Optics-simplified DSP," in *Proc. OFC,* paper M2B.4, 2018.

[6] J. Zhang, J. S. Wey, J. Yu, Z. Tu, B. Yang, W. Yang, Y. Guo, X. Huang, and Z. Ma, "Symmetrical 50-Gb/s/λ PAM-4 TDM-PON in O-band with DSP and Semiconductor Optical Amplifier Supporting PR-30 Link Loss Budget," in *Proc. OFC,* paper M1B.4, 2018.

[7] K. Zhang, Q. Zhuge, H. Xin, Z. Xing, M. Xiang, S. Fan, L. Yi, W. Hu, and D. V. Plant, "Demonstration of 50Gb/s/λ Symmetric PAM4 TDM-PON with 10G-class Optics and DSP-free ONUs in the O-band," in *Proc. OFC*, paper M1B.5, 2018.

[8] P. Li, L. Yi, L. Xue, and W. Hu, "56 Gbps IM/DD PON based on 10G-Class Optical Devices with 29 dB Loss Budget Enabled by Machine Learning," in *Proc. OFC*, paper M2B.2, 2018.

[9] P. Li, L. Yi, L. Xue, and W. Hu, "100Gbps IM/DD Transmission over 25km SSMF using 20G-class DML and PIN Enabled by Machine Learning," in *Proc. OFC*, paper W2A.46, 2018.