645-Gbit/s/carrier PS-16QAM WDM Coherent Transmission over 6,800 km Using Modified LSTM Nonlinear Equalizer

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Abstract *We experimentally demonstrated a 645-Gbit/s/carrier WDM coherent transmission over 6,800-km based on 106-Gbaud PS-16QAM by utilizing modified PS-suitable LSTM-NLE. Our results show that 55% reach improvement is obtained by LSTM-NLE. We also compared performance and computational complexity of LSTM-NLE, Bi-LSTM-NLE and VNLE.*

Introduction

In recent years, the optical fiber communication industry has begun to vigorously develop next-generation WDM coherent optical transmission systems with a net-bit-rate above 400 Gbit/s[1-4]. Long-haul coherent transmission requires enough tolerance for OSNR, which can be improved by probabilistic shaping (PS) technique with a power-efficient Maxwell-Boltzmann distribution. In our work, we utilized PS to extend transmission distance in 600G+ long-haul WDM transmission. We also compared 100-Gbaud regular-16QAM to 106-Gbaud PS-16QAM with 3.82-bit/symbol entropy. The PS signal is generated by the combination of constant-composition distribution matcher (CCDM) and low-density parity-check (LDPC) encoder with 24%-overhead. The LDPC threshold is 3.8×10^{-2} BER[5,6].

The nonlinear impairment has become a key limiting factor of transmission distance. With the development of machine learning, nonlinear equalizer (NLE) based on recurrent neural networks (RNN)[7,8] has become a recent research hotspot. Long short-term memory (LSTM) neural network[9], as a special kind of RNN, can overcome the problem of gradient disappearance and gradient explosion in training. Ref.[9] has applied LSTM-NLE to WDM coherent transmission based on 16QAM. However, the LSTM-NLE using cross-entropy error as loss function is not suitable for PS signals, because cross-entropy is not good at handling data with ununiform probabilistic distribution. In order to make LSTM-NLE more suitable for PS signals, we adopted mean-square error (MSE) as loss function, and made the LSTM neural network fit the amplitudes of the in-phase and quadrature components of the QAM signal. Moreover, it has been reported that the performance of NLE based on bi-directional LSTM (Bi-LSTM) is better than LSTM-NLE[10]. However, the computational complexity of Bi-LSTM-NLE will also double. Therefore, in our work, we compared the performance of modified LSTM-NLE to modified Bi-LSTM-NLE with the similar complexity. We also compared modified LSTM-NLE with traditional Volterra-based NLE (VNLE).

In addition, the LSTM or Bi-LSTM NLE mentioned below all refer to our modified LSTM or Bi-LSTM NLE.

Experimental setup

The experimental setup of the transmission for 106-Gbaud PS-16QAM WDM signal is shown in Fig.1[2]. At the Tx side, the light source at 1552.675-nm from an ECL with 100 kHz linewidth is fed into the I/Q modulator with 33-GHz 3-dB bandwidth, which is driven by the pre-equalized PS-16QAM signal from two high-speed DACs with 35-GHz bandwidth and 106-

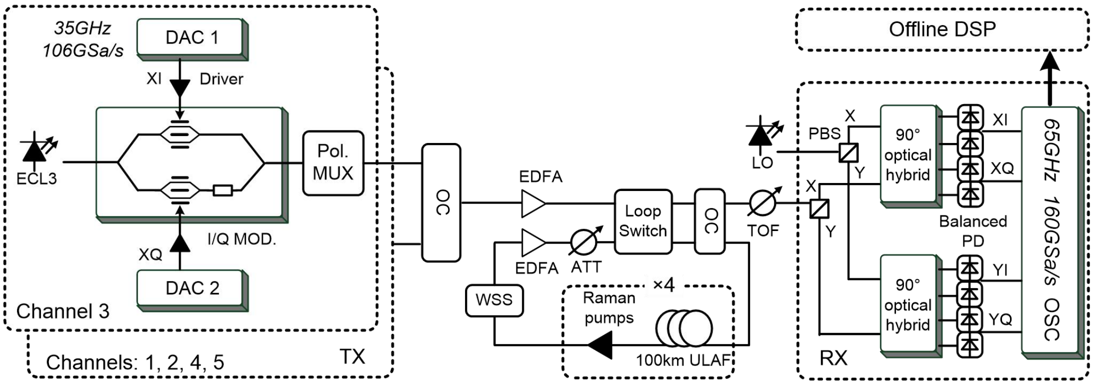

Fig. 1: Experimental setup of 5-channel WDM transmission based on 106-Gbaud PM PS-16QAM.

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GSa/s sampling rate. We have five sub-channels with 125-GHz spacing, including one measured channel (Ch. 3) and four adjacent loading channels (Ch. 1, 2, 4 and 5). After optical modulation and polarization multiplexing, five sub-channels are combined by an optical coupler. Then, the WDM signals are launched into a fiber loop, consisting of several spans of 100-km ULAF amplified by a backward-pumped Raman amplifier. Fig. 2 (a) and (b) show the optical spectra of WDM signals before and after 6,400-km transmission at 0.5-nm resolution. After ULAF transmission, we utilize a tunable optical filter (TOF) to select the desired sub-channel. The polarization and phase-diversity are achieved by using two polarization beam splitters (PBSs) and two 90-degree optical hybrids. Then, four 65-GHz balanced photodetectors are used to realize photo-electric detection. Afterwards, a digital oscilloscope (OSC) with 160-GSa/s sampling-rate and 65-GHz bandwidth is used to realize the digitization and sampling of received signals. Finally, the offline DSP is applied to sampled signals.

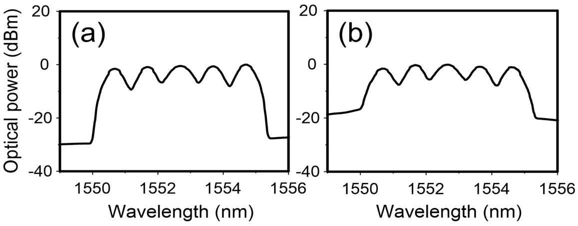

Fig. 2: The optical spectra of 5-channel WDM PS-16QAM signals (a) before and (b) after 6,400-km transmission.

Nonlinear Equalizer Schemes

The beginning steps of our DSP scheme are the same as that of common coherent transmission. We implemented NLE as the last step of the DSP to reduce the impact of other factors on NLE training. In this work, we have three NLE schemes, including VNLE and LSTM-NLE, and Bi-LSTM-NLE.

The VNLE we utilized is based on 2-order Volterra series. Our VNLE scheme shown in Fig. 3 contains four independent 2-order VNLEs, corresponding to in-phase / quadrature components of two polarizations, respectively. We tried multiple sets of parameters, and selected the one with the best equalization performance. Finally, the first-order memory length M_1 and second-order memory length M_2 are set to 41 and 299.

For LSTM scheme, we used two independent modified PS-suitable LSTM-based NLEs, corresponding to two polarizations. The structure of our LSTM-NLE is shown in Fig. 4. The length of input symbols N is 70. The number of LSTM and linear layers, H and L are 140 and 100, respectively. In order to make LSTM-NLE more suitable for PS signals, we adopted MSE as loss function, and made the LSTM neural network fit the amplitudes of the in-phase and quadrature components of the QAM signal. For Bi-LSTM-NLE, we changed the LSTM layer in Fig. 4 to Bi-LSTM layer. The computational complexity of three NLE schemes is shown in Tab. 1. We measured complexity by calculating Multiply-accumulate operation (MACC) per symbol. We adjusted the parameters of LSTM-NLE and Bi-LSTM-NLE to make complexity of three schemes very close.

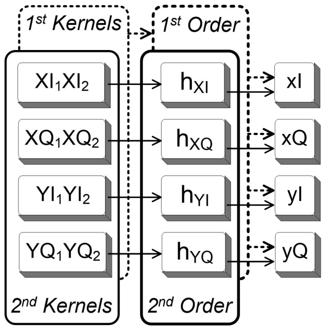

Fig. 3: Principle of VNLE scheme.

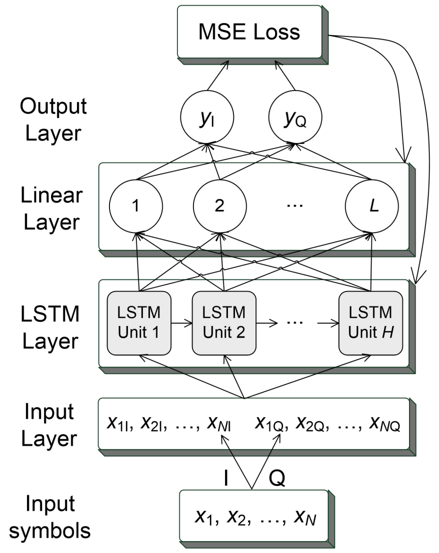

Fig. 4: Structure of modified LSTM-NLE.

Tab. 1: Computational complexity of three NLEs.

NLE	Parameters	MACC per symbol
VNLE	M_1=41 M_2=299	=2(M_2^2+M_2+M_1) =**179,482**
LSTM NLE	N=70 H=140 L=100	=4H(2N+H)+HL+2L =**171,000**
Bi-LSTM NLE	N_b=50 H_b=100 L_b=60	=8H_b(2N_b+H_b)+2H_bL_b+2L_b =**172,120**

Experimental results

The experimental results of BER versus OSNR for subchannel-3 WDM signals under BtB condition are illustrated in Fig. 5. Our results show that PS-16QAM can bring about 1.5-dB sensitivity gain compared with regular-32QAM signal considering 3.8×10^{-2} LDPC threshold[5,6]. In addition, around 1.3-dB sensitivity gain can be achieved by LSTM-NLE. For Bi-LSTM-NLE, when the complexity is close to or even slightly higher than that of LSTM-NLE, the performance of Bi-LSTM is slightly worse than that of LSTM. So we choose to use the more cost-effective LSTM-NLE in our transmission experiment.

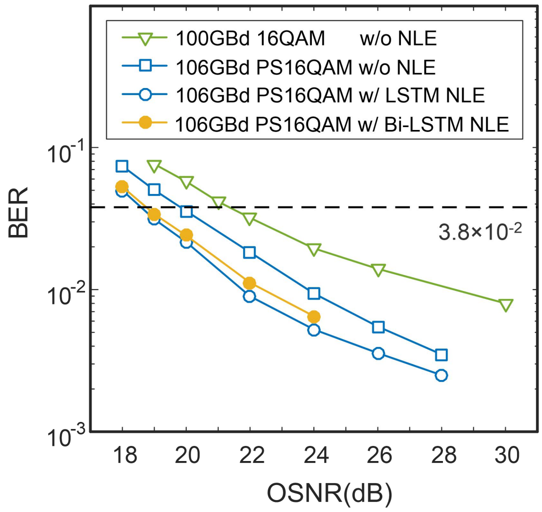

Fig. 5: BER versus OSNR under BtB condition.

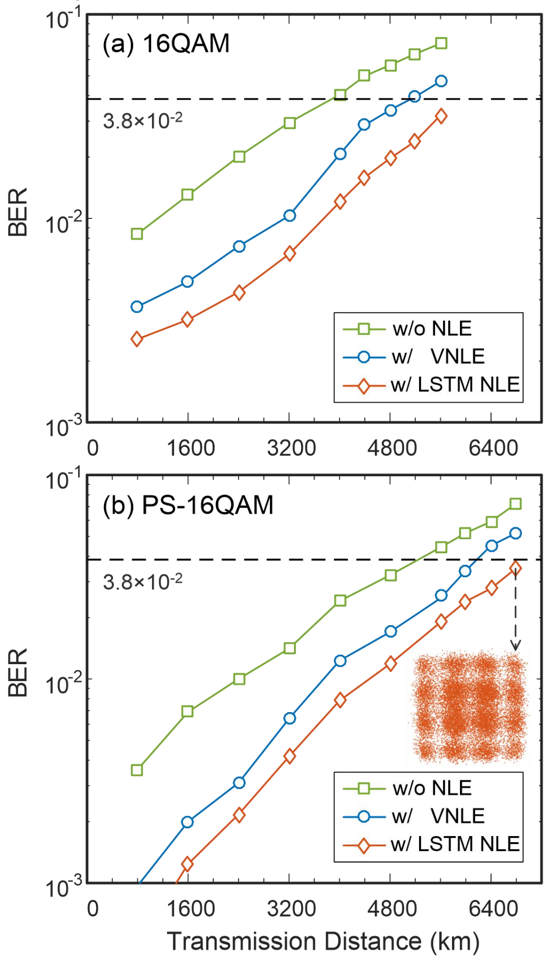

Fig. 6: BER versus ULAF transmission distance.

The transmission results of 100-Gbaud 16QAM and 106-Gbaud PS-16QAM signals are shown in Fig.6 (a) and (b), respectively. The VNLE can improve the transmission distance from 3,600 km to 4,800 km for 16QAM signal, and from 4,800 km to 6,000 km for PS-16QAM signal. By utilizing LSTM-NLE with a complexity lower than VNLE, the transmission distance can be further extended to 5,600 km and 6,800 km for 16QAM and PS-16QAM signals, respectively. Our results show that 55% reach improvement is obtained by LSTM-NLE. The LSTM with lower complexity outperforms VNLE by around 17% reach improvement. In addition, the constellations before NLE, after VNLE and after LSTM-VNLE for PS-16QAM signal after 5,600-km transmission are shown in Fig.7 (a), (b) and (c).

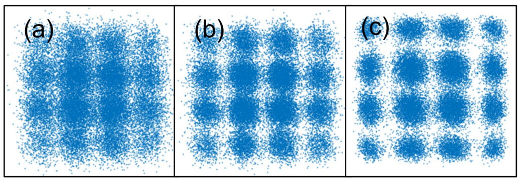

Fig. 7: Constellations (a) before NLE, (b) after VNLE and (c) after LSTM-VNLE.

Conclusions

We experimentally demonstrated a 5-channel 125-GHz-grid ultra-long-haul WDM coherent transmission over 6,800-km Raman amplified ULAF with a net-bit-rate of 645 Gb/s/carrier based on 106-Gbaud polarization-multiplexed PS-16QAM. The transmission distance is extended from 4,800 km to 6,000 km by utilizing modified PS-suitable LSTM-NLE.

We also compared performance and computational complexity of LSTM-NLE, Bi-LSTM-NLE and VNLE. Our results show that the LSTM-NLE with lower computational complexity performs better than Bi-LSTM-NLE and VNLE. The LSTM-NLE with lower computational complexity outperforms the VNLE by around 17% reach improvement.

Acknowledgements

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