Simplified TC-MLSE Equalizer for 210-Gb/s PAM-8 Signal Transmission in IM/DD Systems

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Abstract: We propose and experimentally demonstrate a trellis-compression MLSE in a 210-Gb/s PAM-8 signal transmission over 2-km SSFM transmission. We find TC-MLSE can reduce the complexity by 98% with only 0.2-dB penalty compared with conventional MLSE.

1. Introduction

Driven by the continuous growth in the data demand of Internet applications, such as video streaming services, virtual/augmented reality (VR/AR) and 5G communication, there is increasing requirement of large capacity transmission in optical access network and datacenter interconnects (DCIs). Conventional intensity modulation and direct-detection (IM-DD) has been considered as a cost-effective solution for 100 Gb/s and beyond communications due to its simple configuration and easy integration [1]. Larger than 200-Gb/s per lane is expected to scale up to 1.6 Tb/s to reduce the requirement of more optical lanes and the complexity of integration [2]. To alleviate the bandwidth requirement, advanced modulation formats have to been implemented to alleviate the band-limited effect. Due to the simpler architecture and lower energy consumption, higher order PAM signaling has become the potential modulation scheme for the high capacity short-reach applications [3]. For data rate up to 200 Gb/s per wavelength, continually adopting PAM-4 format will strongly rely on optical transceiver's bandwidth and more complex receiver DSP. Therefore, the implementation of PAM-8 has been put on the agenda. However, PAM-8 signaling is more sensitive to inter-symbol interference (ISI) and nonlinear distortions, i.e. signal-to-signal beating interference (SSBI) compared with PAM-4. The popular solutions to deal with these distortions is adaptive equalization at the receiver such as feedforward equalizer (FFE), volterra nonlinear equalizer (VNLE), decision-feedback equalizer (DFE) and maximum likelihood sequence estimation (MLSE). MLSE has been proved to be the optimal signal detection for removing ISI distortions without noise enhancement or error propagation [4]. However, ultra-high computational complexity is required to implement MLSE, especially for higher order modulations or systems having a long delay spread. Therefore, it is essential to reduce the computational complexity of MLSE for practical implementation of PAM-8 scheme. A reduced-state MLSE based on channel estimation has been proposed to lower the complexity of MLSE at O-band by making a coarse pre-decision at the output of FFE and hence limit the possible states in MLSE [5]. However, the size of memory length L is constrained for lower complexity, while the channel response is determined by L+1 coefficients. Therefore, it will result in an imprecise error estimation and lead to degradation of MLSE in dispersion medium channel.

In this paper, we propose and experimentally demonstrate a trellis-compression MLSE (TC-MLSE) in a 201- or 210-Gb/s PAM-8 signal transmission over 2-km standard single mode fiber (SSMF) IM-DD system at C-band. We first set a look-up-table that records the occurrences of the state of the transmit sequence and its possible received sequences. Then, the mean values of every state are utilized for homologous error computation. Therefore, the performance of TC-MLSE will not suffer from the limited memory length. Then, we coarsely divide the received signal after FFE into 7 decision region to reduce the possible states for MLSE. Based on this, the state-trellis graph is compressed to lower complexity. The overall performance of TC-MLSE is related to FFE. So, we need to optimize the tap number and step length of FFE. We can also adjust the memory length of TC-MLSE for each region since the influence from modulator nonlinearity or interference is different for these electrical levels. We can balance the performance and complexity. We transmit 210-Gb/s PAM-8 signal over 2-km SSMF with the proposed TC-MLSE, reduced-state MLSE, conventional MLSE and VNLF. We find that TC-MLSE and conventional MLSE outperforms the other two schemes. The TC-MLSE can reduce the complexity by 98% with only 0.2-dB penalty in received optical power (ROP) compared with conventional MLSE.

2. Principle of TC-MLSE

Difference between MLSE based on look-up table or channel estimation is the way to calculate the error metric. For MLSE based on channel estimation, the error metric is denoted as,

$$error = \left(y_k - H * X\right)^2 \quad (1)$$

where H is the channel response and X is transmitted symbol sequence. In reduced-state MLSE, the channel response is decided by the memory length L in MLSE processing, which is limited to lower the complexity. This will lead to its performance degradation in dispersion medium channel. For MLSE based on look-up table, we first set a look-up-table that store different state for different transmitted symbols. Then, the H*X can be replaced by the table to estimate the error. Fig. 1(a) presents the schematic diagram of TC-MLSE based on look-up table. The blue dotted line in Fig. 1(a) is the process of generating trellis graph with all states in conventional MLSE algorithm. The red part indicates modification to the trellis graph. The FFE is implemented before MLSE to eliminate the ISI and make a pre-decision to the received signals. Then, we can estimate the possible levels of each symbol by the pre-decision. For PAM-8 signal, it has eight levels as [-7, -5, -3, -1, 1, 3, 5, 7]. For example, if the pre-decision result of one symbol is 5.5, the corresponding result decided by MLSE has a higher probability of being 5 or 7. Therefore, we can abandon those levels which have quite lower probability and regenerate the state-trellis graph with states composed of levels having higher probability. In this paper, we reserve only 2 possible levels for each symbol to regenerate state-trellis graph. Figs. 1(b) and 1(c) show the state-trellis graphs before and after compression, respectively. As shown in Fig. 1(b), for conventional MLSE based on look-up table, M^{L+1} states are taken into consideration for each symbol and each state is transferred to other M states. In the compressed state trellis graph as shown in Fig. 1(c), the states number of each symbol and the state transition of every states is reduced to 2^{L+1} and 2, respectively. Thus, the number of paths traversed by Viterbi algorithm decreases greatly, so is the computational complexity of MLSE. Note that the BER performance can achieve better performance by replacing FFE with other equalizers like VNLE and DFE to obtain better performance. However, the performance and complexity of equalization scheme should be taken into consideration simultaneously.

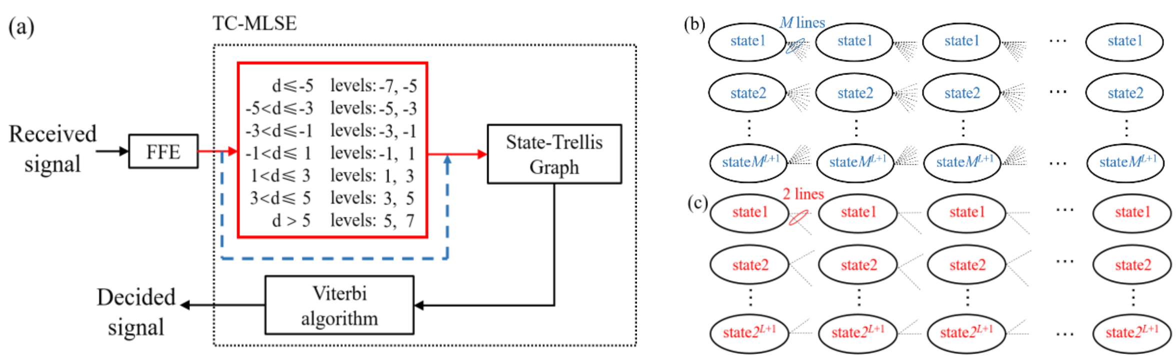

Fig. 1. (a) Block diagram of TC-MLSE, state-trellis graph of (b) conventional MLSE, (c) TC-MLSE.

3. Experimental investigation and results discussion

Fig. 2 shows the experimental set up of the IM-DD system. At the transmitter, a 2^{20}-point pseudo-random bit sequences (PRBS) has been used to generate the digital PAM-8 signal off-line and the symbol rate is 67 or 70 Gbaud. After resampling, Nyquist shaping is realized by a root raised cosine (RRC) filter with 0.05 roll-off factor. To compensate the ISI induced by bandwidth limitation, linear pre-equalization is performed with a FIR filter whose tap

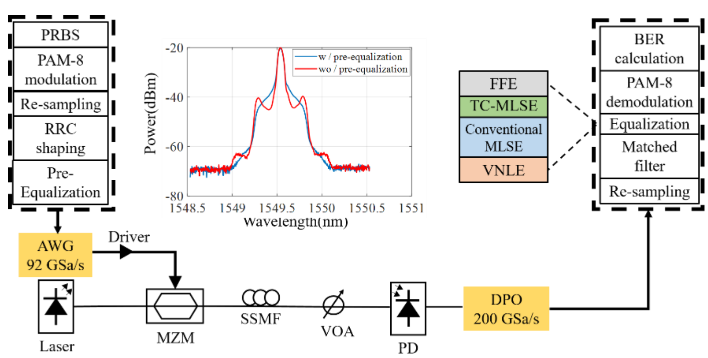

Fig. 2. Experimental setup of PAM-8 IM/DD system. (a) The optical spectra of the transmitted 201-Gb/s PAM-8 signal with and without pre-equalization.

coefficients are obtained from the receiver side FFE at B2B. Then, the electrical PAM-8 signal is loaded into the arbitrary waveform generator (AWG) operating at 92 GSa/s with 32-GHz bandwidth and modulated by a 40-GHz Mach-Zehnder modulator (MZM). The laser is operated at 1549.5 nm and the output power is set to 12.9 dBm. Fig. 2(a) shows the optical spectra of the 201-Gb/s PAM-8 signal with and without pre-equalization. After 2-km SSMF transmission, the optical signal is directly detected by a TIA-free single-ended photodiode (PD) with 3-dB bandwidth of 40 GHz and sampled at 200 GSa/s by a 59-GHz digital phosphor oscilloscope (DPO). The variable optical attenuator (VOA) is adopted to adjust the received optical power (ROP). Subsequently, the received signal is processed offline. The receiver DSP is also presented in Fig. 2(a), including resampling, matched filter, equalization, PAM-8 demodulation and BER calculation. As for equalization, VNLE, TC-MLSE and conventional MLSE have been employed and compared.

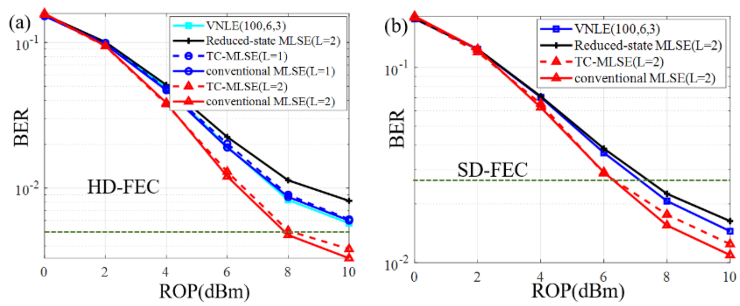

Fig. 3. BER performance of (a) 201-Gb/s, (b) 210-Gb/s PAM-8 signal transmission over 2-km SSMF.

Table 1. Comparisons of equalizers.

Equalization scheme	Tap Number	Multiplications
Reduced-state MLSE	$L = 2$	182
VNLE	(100,3,6)	131
TC-MLSE	L =1/2	83 / 91
Conventional MLSE	L =1/2	587 /4171

Figs. 3(a) and (b) show BER performance of the 201- and 210-Gb/s PAM-8 signal with pre-equalization after 2-km SSMF transmission, respectively. For comparison, we use a 3-rd order VNLE (100, 6, 3) and reduced-state MLSE (L=2) cascaded a 150-tap FFE. In Fig. 3(a), among these equalization schemes, only the BER performance of conventional MLSE and TC-MLSE (L=2) cascaded a 75-tap FFE can achieve the HD-FEC limit of 5.0×10^{-3} at ROP of 7.9 dBm and 8.1 dBm, respectively. The reduced-state MLSE cannot reach the same performance since the fiber dispersion induce larger channel memory length. The BER performance of the received 210-Gb/s PAM-8 signal is shown in Fig. 3(b) and the receiver sensitivity at SD-FEC limit is 6.25 dBm. There is only 0.2-dB penalty by using TC-MLSE compared with conventional MLSE. Despite having a lower complexity, TC-MLSE (L=2) outperforms VNLE. We summarize the tap number, computational complexity of different equalization schemes for 201-Gb/s PAM-8 signal transmission over 2-km SSMF in Table 1. The M^{L+2} multiplications are required in conventional MLSE based on look-up table. While, in TC- MLSE, M shrink to 2, which lead ~98% computational complexity reduces as shown in Table 1.

4. Conclusions

In this paper, we have proposed and experimentally demonstrated the TC-MLSE in beyond 200-Gb/s PAM-8 signal transmission over 2-km SSMF at C-band in IM/DD system. We find that the TC-MLSE performs as well as conventional MLSE but with ~98% complexity reduces.

5. References

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