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Compressed Look-up Table-based Implementation Friendly MLSE Equalizer for C-Band DSB IM/DD Transmission

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Abstract *We propose a complexity-reduced LUT-MLSE for DSB C-band IM/DD transmission based on pre-decision-assisted trellis compression and path-decision-assisted Viterbi algorithm with a 99.65% complexity reduction. We successfully demonstrate a 20-km 100-Gb/s PAM-6 and a 30-km 80-Gb/s PAM-4 C-band transmission over dispersion-uncompensated links. ©2022 The Authors*

Introduction

With the growing capacity demand for data center interconnection (DCI) and 5G mobile fronthaul, the next-generation Ethernet links, such as 800 GbE and 1.6 TbE, require over 100Gb/s/ λ intensity modulation direct detection (IM/DD) transmission. High order pulse amplitude modulation (PAM), such as PAM-6 and PAM-8, has become a promising solution. The major limitation of the reach and capacity of C-band IM/DD transmission lies in the dispersion-induced power fading effect. Single sideband (SSB) and vestigial sideband (VSB) signal can mitigate the power fading effect, but they require costly IQ modulator and optical band-pass filter (OBPF) [1]. By contrast, dual sideband (DSB) signal which can be easily generated by Mach-Zehnder modulator (MZM) and directly modulated laser (DML) is still the mainstream option for ER/ZR optical module standards. One solution to the power fading problem of DSB is Tomlinson-Harashima precoding (THP), which can extend the reach of 42-Gbaud DSB PAM-4 transmission to over 80 km [2,3]. However, THP at the transmitter end requires decision-feedback equalization (DFE) coefficients to be trained at the receiver end. The required extra coefficients feedback process is complex for DCI applications.

Compatible with the mainstream IM/DD optical module architecture, applying maximum likelihood sequence estimation (MLSE) in receiver DSP is a cost-effective equalization scheme [4]. MLSE based on look-up table (LUT) has been proved to have better capacity on dispersion equalization than conventional MLSE using finite impulse response (FIR) model in our previous work [5]. The difficulty of applying MLSE in IM/DD lies in the computational complexity ,which is decided by the size of state transition trellis in Viterbi algorithm. If the memory length of the channel is $L+1$, the trellis contains M^L states each layer for PAM-*M* format. A state trellis compression method for higher order PAM format has been proposed using pre-decision to reduce the number of probable states [6,7]. However, as the fiber link extends, a feedforward equalizer (FFE) is not sufficient to shorten the memory length. It still needs an over 5-memory-length LUT to record the residual inter-symbol interference (ISI). When calculating the possibility, each symbol needs to consider hundreds of states, which is unrealizable for hardware implementation.

In this work, we propose a complexity-reduced LUT-MLSE for middle-reach dispersion-limited IM/DD system and experimentally demonstrate a 100-Gb/s PAM-6 or 80-Gb/s PAM-4 transmission over 20/30-km SSMF in a C-band IM/DD system. Key contribution is the complexity reduction of LUT-MLSE from two aspects: one is to use pre-decision to compress the states trellis for decreasing the base value of complexity; the other is to use path-decision-assisted Viterbi algorithm to decrease the index value of complexity [5]. The proposed MLSE reduces the number of multiplications by 99.65% with nearly no performance degradation.

Principle

For a middle-reach DSB IM/DD transmission in C-band, the dispersion-induced power fading effect leads to nonlinear channel response. The MLSE using a LUT to record symbol pattern dependent ISI can better model the notches on frequency response than conventioanl linear FIR-based MLSE. In LUT-based MLSE, as is mentioned in [8], the probability of the sequence $(s_1, \ldots, s_N)$ can be calculated by:

$$P_{s_1,\ldots,s_N} = \sum_{k=1}^{N} \left| r_k - s_k - A_k \right|^2 \quad (1)$$

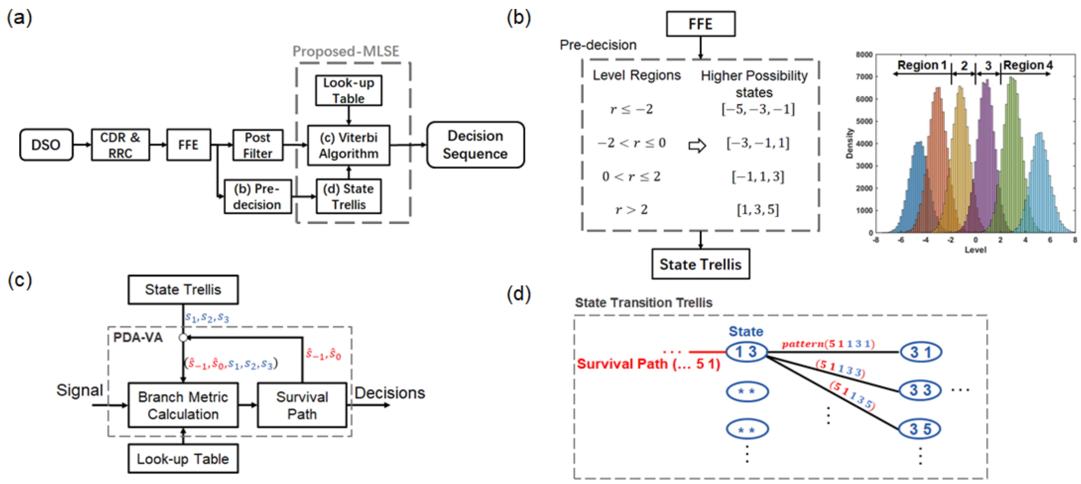

Fig. 1: (a) Framework of the proposed MLSE; (b) The pre-decision-assisted trellis compression algorithm according to noise distribution; (c) The functional block diagram of PDA-VA ($L = 4, P = 2$); (d) Example of a partial state transition trellis.

$$A_k = f(s_{k-L},\ldots,s_k) \qquad (2)$$

where s_k and r_k are the k-th symbols of the sequence before and after channel transmission. A_k is the ISI distortion determined by the symbol pattern $(s_{k-L},\ldots,s_k)$, which is recorded in LUT ($L+1$ is the memory length of the channel). As is shown in Fig. 1(a), our scheme consists of three cascaded parts. Firstly, the FFE truncates the channel responce and partially compensate the linear impairments of the channel. Secondly, because of the noise enhancement arising from the FFE, a short post filter performs the desired impulse response (DIR) shaping to whiten the noise. Lastly, the proposed LUT-based MLSE uses Viterbi algorithm to search the state trellis for the most probable sequence. We adopts two methods to reduce the complexity of MLSE:

A. Pre-decision-assisted Trellis Compression

Aiming to reduce the number of states required for constructing the state trellis of Viterbi algorithm, prior to Viterbi algorithm, the signal level is divided into several regions according to the distribution of noise, and pre-decision is applied to abandon the states with lower possibility. Therefore, the state transition trellis can be constructed with the most possible states. Because of the post-filter-induced ISI, pre-decision is arranged prior to the post filter and posterior to the FFE.

According to the distribution of received training symbols, the received PAM-6 signal is divided into 4 regions as is shown in Fig.1 (b). Each region is corresponding to three most possible decisions. For instance, if the level of a received symbol is -3.1, the possibility of this symbol being -5, -3 and -1 is higher. And the states of being 1, 3 and 5 are abandoned in the trellis. Thus, the trellis only contains 3^L states each layer rather than 6^L, as is shown in Fig.1 (d).

B. Path-decision-assisted Viterbi Algorithm

To reduce the complexity of MLSE with long memory length, we propose the path-decision-assisted Viterbi algorithm (PDA-VA) [5]. If the memory length of channel model recorded in LUT is $L+1$, the state transition trellis is constructed with a shorter memory length of $P+1$ $(P < L)$, which has M^P state nodes and M^{P+1} branches in each layer. Different from the conventional VA, the proposed method traces back the last $(L-P)$ tentative decisions of the survival path recorded by the state node in the upper layer and extends the corresponding $(P+1)$-length pattern of the branch to $(L+1)$ symbols to look up the table and calculate the branch metric. Coupled with trellis compression, the proposed VA only needs to calculate 3^{P+1} branch metrics for each symbol.

For instance, as shown in Fig. 1 (c) and (d) ($L = 4$, $P = 2$), when calculating the branch metric between the state (s_1, s_2) and (s_2, s_3), the conventional VA is supposed to use the pattern (s_1, s_2, s_3) to look up the table. However, in the proposed PDA-VA, the pattern can be extended to $(\hat{s}_{-1}, \hat{s}_0, s_1, s_2, s_3)$ using the tentative decisions of the survival path $(\ldots \hat{s}_{-1}, \hat{s}_0)$.

Experiment setup

Fig. 2(a) shows the experimental setup of the 100-Gbps IM/DD transmission system. At the transmitter, the binary sequence is mapped into PAM-4/6 format. The PAM-6 signal is interleaved by the real part and imaginary part of QAM-32 format. Considering the electrical bandwidth limitation, the 40-Gbaud PAM signal is first applied with an FIR filter for the purpose of pre-emphasis, and then with another 64-tap root-raised cosine (RRC) filter with roll-off factor of 0.6 to narrow the electrical bandwidth to 32 GHz. The off-line generated signal is loaded into an arbitrary waveform generator (AWG, Keysight M8195A) with 3-dB bandwidth of 25 GHz and

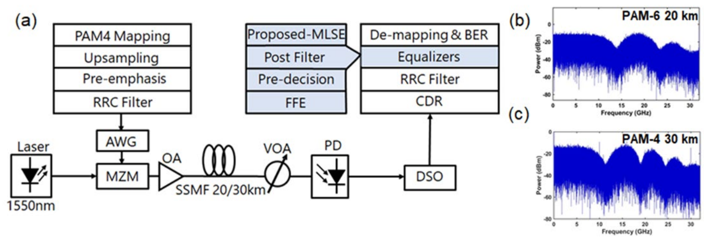

Fig. 2: (a) Experimental setup of the IM/DD transmission; (b) and (c) Electrical spectrum of PAM-6/PAM-4 signal after 20/30-km transmission.

Tab. 1: Complexity of equalizers (multiplier numbers include MLSE schemes' FFE and PF).

Equalizers	Taps/Memory length	Multipliers
VNLE	(91, 21, 7)	406
Conventional FIR-MLSE	$L = 4$	46751
Conventional LUT-MLSE	$L = 4$	7871
Proposed MLSE	$L = 4, P = 2$	122

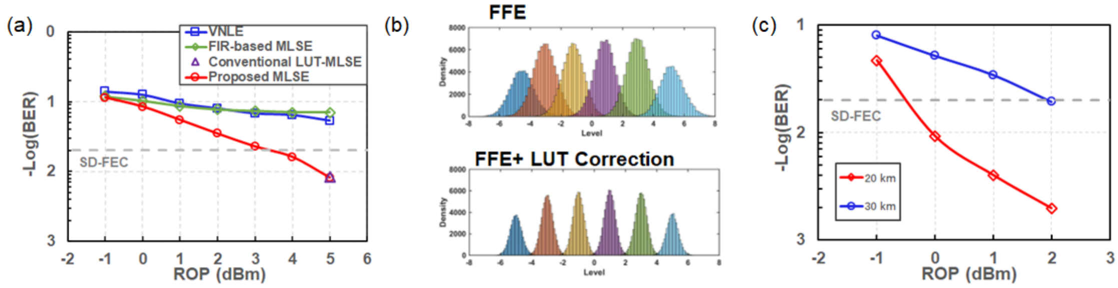

Fig. 3: After 20km SSMF PAM-6 IM/DD transmission, (a) BER versus ROP curves using three equalizers, (b) histogram of PAM-6 signal after FFE and LUT-correction [5]; (c) BER versus ROP curves of the proposed MLSE after PAM-4 20/30-km transmission.

sampling rate of 64 GS/s. We use a 1550 nm continuous-wave laser with 100-kHz linewidth as the optical source. Before the fiber link transmission, an Erbium-doped fiber amplifier (EDFA) boosts the launching power to 10.5 dBm. After 20-km or 30-km SSMF transmission, the received optical power (ROP) into the receiver is controlled by a variable optical attenuator (VOA). Then the optical signal is directly detected by a single-end photodiode (PD). An oscilloscope with 36-Ghz electrical bandwidth at 80-GSa/s sample rate is used to sample the electrical PAM signal. The received signal is processed offline, and the DSP includes clock data recovery (CDR), RRC filter, equalizers, PAM de-mapping and BER counter. The equalizers including a 91-taps FFE based on least mean square (LMS) algorithm, a 4-taps FIR filter as a post filter, and the proposed MLSE. We use a training sequence of 350000 symbols to calculate and establish the look-up table.

Results and Discussion

We first compare our LUT-MLSE scheme ($L = 4$, $P = 2$) with another two common equalizers in 20km SSMF PAM-6 IM/DD transmission, including conventional FIR-based MLSE (5-memory length) and 3-order Volterra nonlinear equalizer (VNLE) (91, 21, 7). Tab. 1 compares the complexity of the equalizer schemes. Fig. 3(a) shows the BER versus ROP curves of the three equalizers in comparison. Only the BER performance of the proposed scheme achieves 8.2×10^{-3} after 20-km transmission at ROP of 5-dBm, which is below the 20% soft-decision forward error correction (SD-FEC) threshold. And the BERs of the other two equalizers are both higher than the threshold. Comparing performance difference of the proposed MLSE and conventional LUT-MLSE at 5-dBm ROP, using PDA-VA to compress the branch number together with pre-decision assisted trellis compression result in nearly no performance degradation. Besides, the performance of MLSE algorithm mainly depends on the accuracy of channel model. FIR-based MLSE is the optimal performance receiver only when the channel is a partial impulse response channel. As is shown in Fig. 3(b), considering dispersion-induced frequency notches, using a more general LUT-based ISI model will lead to less residual noise and distortion than FIR model. Fig. 3(c) shows the performance of the proposed MLSE after PAM-4 20/30-km transmission. After 30-km SSMF transmission, it achieves a BER of 1.9×10^{-2} at ROP of 2-dBm and reaches the SD-FEC threshold.

Conclusions

In this paper, a LUT-MLSE equalizer using pre-decision and path-decision to compress trellis is proposed for C-band IM/DD transmission. With the proposed LUT-based MLSE, we experimentally demonstrate an IM/DD transmission of 100-Gb/s PAM-6 over 20-km SSMF or 80-Gb/s PAM-4 over 30-km SSMF without any optical dispersion compensation and pre-coding. It achieves almost the same performance with the conventional LUT-MLSE, but with a 99.65% complexity reduction.

Acknowledgements

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