Advanced MLSE with Simple Soft Output Achieving High NGMI for SD-FEC in IM-DD Transmission with Severe Bandwidth Limitation

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Abstract: We propose a simple LLR-calculation method which modifies the LLR distribution using hard-decision information for IM-DD systems with MLSE and SD-FEC. The proposed method achieves high NGMI in 128-Gbaud PAM4 transmission with 40-GHz bandwidth limitation. © 2024 The Author(s)

1. Introduction

The amount of data-center traffic is rapidly increasing because of the heavy use of cloud services with rich contents. Datacom networks deploy Ethernet interfaces to economically support short-reach transmission, which utilize the intensity-modulation and direct-detection (IM-DD). In IEEE802.3 400GBASE-FR4 and 400GBASE-LR4, 100 Gbps/ch 4-level pulse-amplitude modulation (PAM4) has been adopted [1], and higher capacity specifications, such as 200 Gbps/ch PAM4, are discussed. The higher modulation rates induce large signal distortion due to the bandwidth limitation (BWL) by the transceiver components and lower sensitivity due to the fewer photons per symbol. Regarding BWL, several studies have been reported on solving severe inter-symbol interference (ISI) in IM-DD systems, and maximum likelihood sequence estimation (MLSE) has received much attention [2-4]. IEEE802.3 discusses an application of soft-decision forward error correction (SD-FEC) for sensitivity degradation [5, 6], and several transmission experiments using MLSE and SD-FEC have been reported [7-9].

SD-FEC is carried out using the log-likelihood ratio (LLR) as soft output information. The LLR is conventionally calculated using the soft output Viterbi algorithm (SOVA) in MLSE, and the calculation is very complicated [10]. Simple calculation methods have been reported, but it is difficult to optimize hyper parameters with these methods [11, 12]. In this paper, we propose a simple LLR-calculation method for IM-DD systems with MLSE and SD-FEC. It is used to modify the LLR distribution on the basis of the hard-decision information obtained from the Viterbi algorithm (VA) and the calculation complexity is much less than that with the SOVA. We demonstrate a 128-Gbaud O-band PAM4 transmission, showing that the proposed method including parameter optimization achieved a higher normalized general mutual information (NGMI), which corresponds to the performance index in SD-FEC systems.

2. Proposed method in MLSE scheme

The procedure of the proposed LLR-calculation method in the MLSE scheme is as follows. We first calculate a temporal bitwise LLR from the minimum of path metrics for each bit consisting of a PAM4 symbol in the VA, as shown in Eq. (1) [11], where n is a time index, LLR'_n is the temporal LLR for the n-th bit, l_i is i-th path metric in the VA, U_j is a set of indexes that corresponds to bit $j \in \{0,1\}$, and σ is the standard deviation of the noise distribution in a transmission line. This calculation method is called Method I. Although this method is very simple, the gain from trace back is not acquired. The trace back corresponds to backward sequence estimation in the VA and improves the accuracy of bit decisions. Thus, it is difficult for this method to achieve the same NGMI as that of the SOVA.

We then update the temporal LLR obtained from Eq. (1) in accordance with the result of the hard decision, $\hat{b}_n \in \{0,1\}$, obtained by the trace back. The update rule is shown as Eq. (2), where c is a shift parameter optimized using Eq. (3), $b_n \in \{0,1\}$ is the n-th transmitted bit, N is the number of known bits used to optimize c, and μ is a step-size parameter. In Eq. (5), $H(c)$ is a cross entropy and is minimum at the optimal c, where M is the number of PAM levels. This method is called Method II. As shown in Eq. (2), the distribution of the LLR is shifted in accordance with the result of bit decisions obtained from the trace back in the VA. Therefore, Method II should achieve a higher NGMI than Method I.

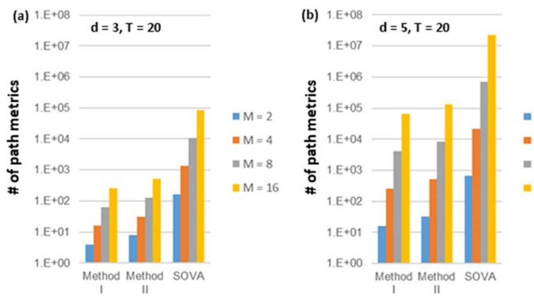

Fig. 1. Required number of path metrics for LLR calculation.

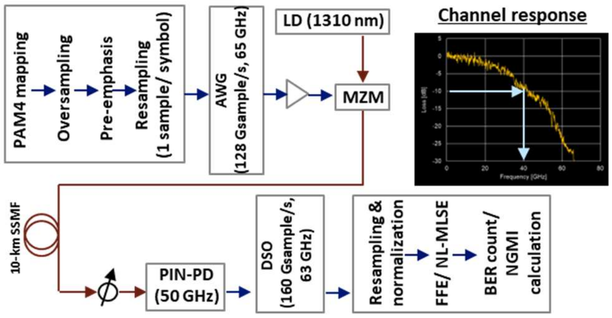

Fig. 2. Experimental setup and channel response.

The required numbers of path metrics utilized to calculate the LLR in Methods I, II, and SOVA are shown in Figs. 1 (a) and (b), where T is the trace-back length in the VA, and d is the memory length of the desired impulse response filter (DIRF) in MLSE. As shown in these figures, Methods I and II are much simpler than the SOVA.

$$LLR_n{}' = \left(\min_{i\in U_0} l_i - \min_{i\in U_1} l_i\right)/(2\sigma^2) \quad (1), \qquad LLR_n = LLR_n' - c(-1)^{\hat{b}_n}/(2\sigma^2)^2 \quad (2),$$

$$c \to c + \mu \textstyle\sum_{n=1}^{N}\left[(-1)^{b_n+\hat{b}_n}\left\{1 - e^{-H_n(c)}\right\}\right] \quad (3), \qquad H_n(c) = \ln[1 + \exp\{(-1)^{b_n} LLR_n(c)\}] \quad (4),$$

$$H(c) = \frac{\log_2 M}{N \ln 2} \textstyle\sum_{n=1}^{N} H_n(c) \quad (5).$$

3. Experimental setup and results

We evaluated the performance of the proposed method through a demonstration of 128-Gbaud PAM4 10-km O-band transmission using NL-MLSE as the advanced MLSE scheme, which is able to emulate nonlinear channel response [4]. Figure 2 shows the experimental setup. An arbitrary waveform generator (AWG) generates an electrical signal sequence in which the order of the pseudo-random binary sequence (PRBS) is 15. A Mach-Zehnder modulator (MZM) converts the electrical signal into an optical signal. The optical signal is transmitted through 10-km standard single-mode fiber (SSMF) and received with a PIN photodiode (PD). The chromatic dispersion (CD) is -8.0 ps/nm at the carrier wavelength of 1310 nm. A digital storage oscilloscope (DSO) converts the received signal into a digital signal sequence which is demodulated using a conventional feed forward equalizer (FFE) or NL-MLSE with T of 20. The finite impulse response filter in the FFE and NL-MLSE has 45 T/2-spaced taps. The adaptive low-pass filter and DIRF in NL-MLSE have T-spaced taps and d is 5, in which the tap coefficients are updated by recursive least square (RLS) algorithm. The DIRF consists of a 3rd-order Volterra filter in which the Volterra kernels are pre-trained by the first 1000 symbols. Figure 2 also shows the channel response of the experimental setup, in which the 10-dB bandwidth is 40 GHz.

Figures 3 (a) and (b) show the histograms of the LLR distribution at the received optical power (ROP) of 3 dBm for Methods I and II, respectively. With Method II, the LLR distribution shifted outwardly, and the shifted distribution was induced to achieve a higher NGMI. Figure 3 (c) shows the relationship between the number of iterations for updating c and the value of c, where N and μ were 1000 and 10^{-7}, respectively. The convergence of c was completed at 2000 iterations at least, and c converged more rapidly for the lower ROP. Figure 4 (a) shows the relationship between ROP and NGMI for the FFE and NL-MLSE with Method I or II. NGMI was calculated on the basis of the bitwise LLR [13]. Figure 4 (a) also shows the c adopted for Method II, which was obtained from Fig. 3 (c). The c does not depend greatly on ROP. Methods I and II achieved a higher NGMI in each ROP than in the FFE. Method II achieved an NGMI that is approximately 0.05 higher than that with Method I for each ROP. Figure 4 (b) shows the relationship between bit error ratio (BER) and NGMI. The dashed line means the theoretical curve in the additive white Gaussian noise (AWGN) channel. It was assumed that the SOVA exhibits the almost the same performance

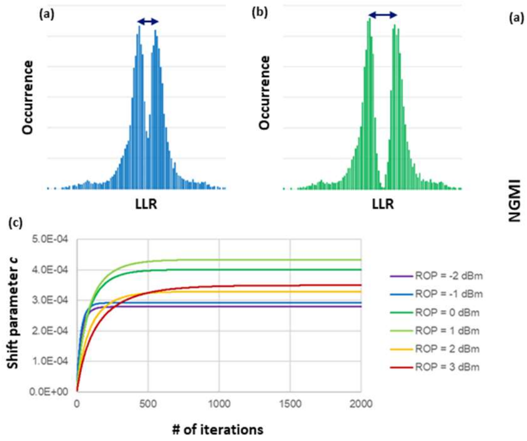

Fig. 3. LLR distributions in (a) Method I and (b) Method II, and (c) convergence characteristics of shift parameter c in Method II.

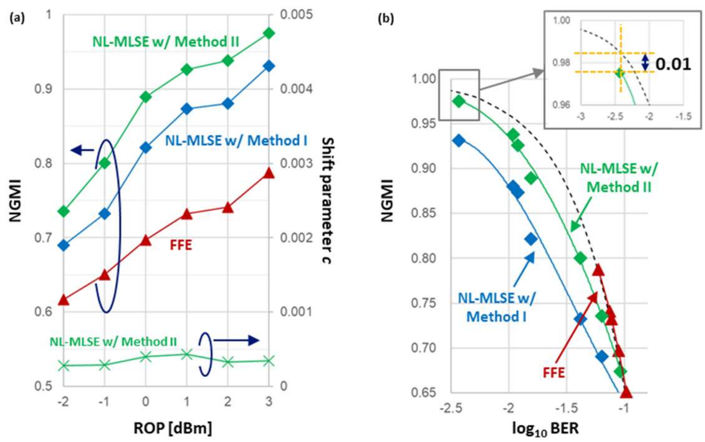

Fig. 4. (a) Relationship between ROP and NGMI or shift parameter c, (b) Relationship between BER and NGMI.

with the theoretical curve. Methods I and II had differences from the theoretical curve because of the simplified calculation including hard-decision information in the LLR calculation. However, Method II achieved sufficiently high performance, and the difference between Method II and the SOVA was only an NGMI of 0.01 at the $\log_{10} BER$ of -2.4.

4. Conclusion

A simple LLR-calculation method for IM-DD systems with MLSE and SD-FEC was proposed. The proposed method shifted the LLR distribution outwardly on the basis of the bit decision obtained from the trace back in the VA and the shifted distribution resulted in higher NGMI. The proposed method required much less complexity than that in the SOVA. We experimentally investigated an advanced MLSE scheme with the proposed method through 128-Gbaud PAM4 10-km transmission with the 10-dB bandwidth of 40 GHz and showed that the proposed method achieved a higher NGMI than that with a conventional linear equalization. We also showed that the hyper parameter with the proposed method was optimized using a simple update rule. This means that soft-output MLSE schemes with low complexity in digital signal processing are applicable to high baud-rate systems using SD-FEC.

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