O-Band 10-km PAM Transmission Using Nonlinear-Spectrum-Shaping Encoder and Transition-Likelihood-Based Decoder with Symbol- and Likelihood-Domain Feedbacks

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Abstract *We show that a nonlinear-spectral-shaping scheme with transition-likelihood-based decoder including symbol- and likelihood-domain feedbacks enhances the tolerance to bandwidth limitation and achieves KP4-FEC threshold in 10-km O-band transmission of 93-Gbaud PAM4 with very severe bandwidth limitation in which the 20-dB bandwidth is 40 GHz.*

Introduction

Rapid increase of the amount of data centre traffic due to mobile broadband or cloud services requires the capacity increase of Ethernet link based on an economical approach. IEEE802.3 has already completed the standardization of 400GbE and 100-Gb/s 4-level pulse amplitude modulation (PAM4) O-band transmission with KP4-FEC is adopted in 400GBASE-FR4 and 400GBASE-LR4-6[1]. The next-generation Ethernet links such as 800GbE or 1.6TbE will require the increase of data rates even more. Therefore, the signal baudrate must be higher and broad-bandwidth electrical and optical devices will be required for PAM4 transceiver because of the broader signal spectrum. For the enhancement of transmission performance in intensity-modulation and direct-detection (IM-DD) system, many studies are reported[2]–[8]. Also, several approaches with coded modulation have been proposed[6]–[10], and we have proposed a nonlinear-spectral-shaping scheme using a simple encoder, which is called nonlinear-differential-coded PAM (NLDCP)[11].

In this paper, we show that it makes NLDCP more tolerant to bandwidth limitation (BWL) to apply a combination of symbol-domain feedback with likelihood-domain feedback to the decoding scheme. We demonstrate an O-band 186-Gb/s 10-km transmission with the 20-dB bandwidth of 40 GHz, in which KP4-FEC threshold is achieved without any Volterra equalizers.

Characteristics of NLDCP

The encoding in NLDCP for PAM-m signal is expressed as an equation shown below[11].

$$v_n = \begin{cases} u_n + m & (u_n < \lfloor \alpha v_{n-1} \rfloor) \\ u_n & (u_n \geq \lfloor \alpha v_{n-1} \rfloor) \end{cases}, \qquad (1)$$

where u_n and v_n are the original PAM symbol and the encoded symbol, respectively. $u_n \in \{0,1,\cdots,m-1\}$ and $v_n \in \{0,1,\cdots,M-1\}$. Parameter α is cut-off coefficient, $0 \leq \alpha < 1$. Operator $\lfloor \cdot \rfloor$ is the floor function, which is a nonlinear operator. n is time index. The decoding is expressed as an equation shown below.

$$u_n = v_n - m\lfloor v_n/m \rfloor, \qquad (2)$$

which corresponds to modulo operation. The power spectrum density of the encoded symbol is expressed as an equation show below.

$$S(f) = \frac{(1-\alpha)^2}{1+\alpha^2-2\alpha\cos(2\pi f/f_B)}, \qquad (3)$$

where f_B is signal baudrate. The larger α makes the narrower signal spectrum. The number of levels of v_n depends on α. For example, $M = 6$ for $\alpha = 1/2$ and $M = 8$ for $\alpha = 2/3$ in the case with $m = 4$. The one-memory nonlinear coding shown in Eq. (1) restricts the symbol transition of the encoded symbol v_n. The original PAM symbol u_n is encoded on the symbol transition of v_n.

In NLDCP, there are two decoding schemes. One is modulo-based decoding (MBD) shown in Eq. (2). In this scheme with $m = 4$, for example, the decoding is realized by modulo operation after 6-level symbol decision in the case with $\alpha = 1/2$. This scheme is very simple while the tolerance to additive white Gaussian noise (AWGN) is lower than that in the conventional PAM4 because this scheme requires 6-level symbol decision. The other is likelihood-based decoding (LBD), in which the original PAM4 symbol is directly obtained without the 6-level decision in order to avoid the tolerance reduction to AWGN[11]. Figure 1 shows the block diagram of these decoding schemes, in which the upper and the lower parts of the diagram correspond to MBD and LBD, respectively. LBD includes likelihood-domain feedback (LDF). In NLDCP, the original PAM4 symbols correspond to the symbol transitions and the accurate calculation of the transition likelihoods requires likelihoods of the previous symbols. Therefore, LDF is necessary in LBD. The lower of the diagram also includes symbol-domain feedback (SDF). This feedback leverages the previous

$$l_{r_{n-1}r_n} = \left|\sum_{i=0}^{1} d_i r_{n-i} + \sum_{i=2}^{D-1} d_i \hat{x}_{n-i} - \sum_{i=0}^{C-1} c_i s_{n-i}\right|^2 + \min_{r_{n-2}} l_{r_{n-2}r_{n-1}} - \min_{r_{n-1}}\left(\min_{r_{n-2}} l_{r_{n-2}r_{n-1}}\right). \quad (4)$$

decision in order to realize the longer channel response in the calculation of the transition likelihoods and enhances the decoding performance. The logarithm likelihood of the transition from symbol r_{n-1} to symbol r_n is defined as Eq. (4). This equation includes SDF using symbol $\hat{x}_{n-i}$ and LDF using likelihood $l_{r_{n-2}r_{n-1}}$. Symbol s_n is an output sequence from the feed-forward equalizer (FFE) and symbol r_n is a 6-level candidate sequence. Symbol $\hat{x}_n$ is PAM4 sequence generated from bit decision in LBD and this term is a contribution of SDF. c_i and d_i are tap coefficients of channel-shortening filter (CSF) and desired-impulse-response filter (DIRF), respectively. These filters are T-spaced finite-impulse-response (FIR) filters. C and D are tap lengths of CSF and DIRF, respectively. The logarithm likelihood ratios (LLRs) for the most significant bit (MSB) and the least significant bit (LSB) are obtained from the transition likelihood, in which PAM4 mapping is based on Gray code. We think that LBD with SDF and LDF can be considered as an application of decision feedback sequence estimation[12] to nonlinear spectral shaping.

Experimental results

We investigate the transmission performance of NLDPC with MBD or LBD through 10-km O-band 180- and 186-Gb/s transmission experiments. Figure 2 shows the experimental configuration. In the experiments, an arbitrary waveform generator (AWG) and Mach-Zehnder modulator (MZM) generate 90- or 93-Gbaud NLDCP signal for the case with $\alpha = 0$ and $\alpha = 1/2$ at the transmitter. The NLDCP signal is based on PAM4 symbol and this means $m = 4$. The case with $\alpha = 0$ corresponds to the conventional PAM4 signal, which is not encoded. Nyquist shaping with the roll-off factor of 0.01 is applied to the signal. The order of pseudo-random binary sequence (PRBS) is 15. The frequency response of the experimental configuration is shown in Fig. 2, in which the 20-dB bandwidth is 40 GHz. The optical signal propagates along 10-km single-mode fibre (SMF) and the amount of chromatic dispersion (CD) is -8.0 ps/nm at the signal wavelength of 1310.0 nm. The fibre-input power is 7 dBm. There is no optical amplifier in the experiments. The optical signal is directly detected by a PIN-PD and sampled by a digital storage oscilloscope (DSO). Then, the samples are demodulated using a FFE with T/2-spaced 45 taps. For the case with LBD, CSF and DIRF consist of T-spaced taps which are updated by decision-directed least mean square (DD-LMS) algorithm. Nonlinear Volterra equalizers are not used in the experiments.

Figures 3 (a) and (b) show the relationship between the received optical power and bit error ratio (BER) for 90- and 93-Gbaud signals in back-to-back (B2B) configuration, respectively. The bitrates including forward-error-correction (FEC) overhead are 180 Gb/s and 186 Gb/s in Figs. 3 (a) and (b), respectively. For LBD with LDF, $C = 5$ and $D = 2$. For LBD with SDF and LDF, $C = 5$ and $D = 5$. As shown in these figures, NLDCP has the higher performance

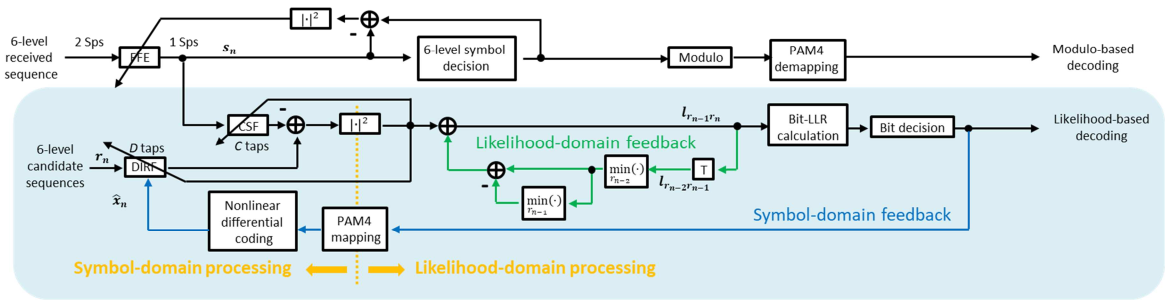

Fig. 1: Modulo-based decoding and likelihood-based decoding with symbol- and likelihood-domain feedbacks

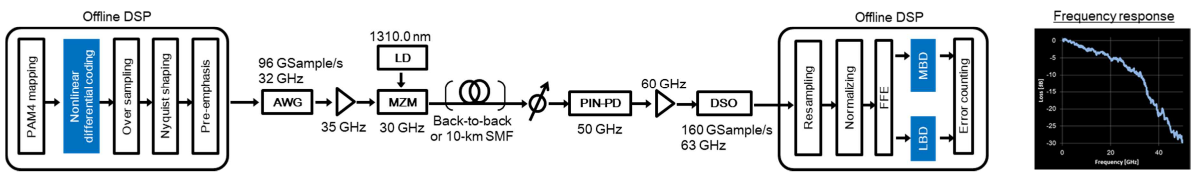

Fig. 2: Experimental configuration

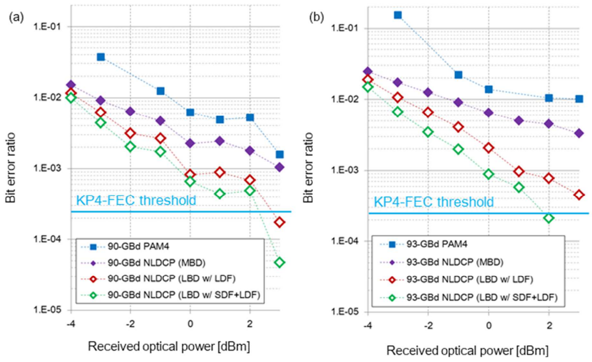

Fig. 3: B2B performance for (a) 180-Gb/s and (b) 186-Gb/s signals

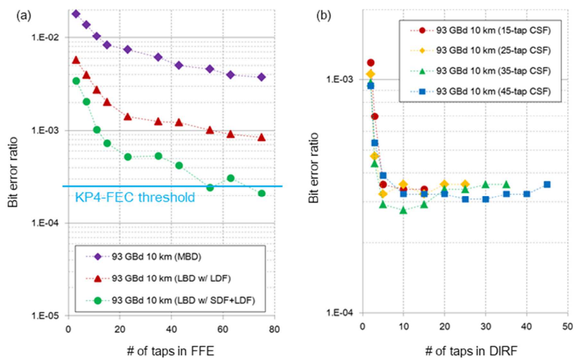

Fig. 4: (a) FFE-tap-length and (b) DIRF-tap-length dependencies in 10-km transmission for 186-Gb/s signals.

than the conventional PAM4 has in both 90 Gbaud and 93 Gbaud. SDF and LDF improve the performance and the larger improvement is obtained in 93 Gbaud. This means that SDF and LDF realize the larger improvement in the more severe BWL.

Figure 4 (a) shows that the relationship between the number of taps in FFE and BER in 10-km transmission for 93-Gbaud NLDCP, in which the received optical power is 3 dBm. As shown in this figure, LBD with SDF and LDF achieves KP4-FEC threshold in the case with 75-tap FFE, in which the BER at KP4-FEC threshold is 2.4E-4. Figure 4 (b) shows that the relationship between the number of taps in DIRF and BER in 10-km transmission for 93-Gbaud NLDCP, in which the number of taps in FFE is 45. The case with $D = 2$ corresponds to LBD only with LDF. The received optical power is 3 dBm. As shown in this figure, SDF makes NLDCP more tolerant to BWL and the performance does not have much dependency on the number of taps in CSF.

Figures 5 (a) and (b) show that the relationship between the received optical power and achievable bitrate for the cases with hard-decision FEC (HD-FEC) and soft-decision FEC (SD-FEC), respectively. The baudrate is 93 Gbaud. The number of taps is 45 in FFE. For LBD with LDF, $C = 5$ and $D = 2$. For LBD with SDF and LDF, $C = 5$ and $D = 5$. The achievable bitrate is a product of baudrate and generalized mutual information (GMI). GMI with HD-FEC and GMI with SD-FEC are calculated from BER and bit LLR, respectively[13]. The achievable bitrate depends on a decoding scheme. For example, NLDCP using MBD cannot achieve 180 Gb/s in 10-km transmission as shown in Fig. 5 (a). On the other hand, NLDCP using LBD with SDF and LDF achieves 180 Gb/s at the received optical power of about 0 dBm in 10-km

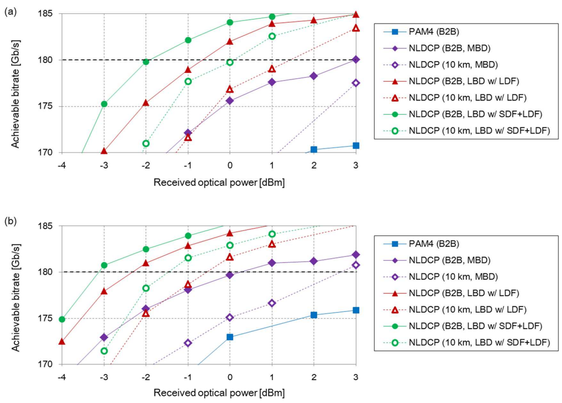

Fig. 5: Achievable bitrate for the cases with (a) HD-FEC and (b) SD-FEC in 10-km transmission for 93-Gbaud signals

transmission. As shown in Fig. 5 (b), PAM4 cannot achieve 180 Gb/s even in the case with the received optical power of 3 dBm. NLDCP using LBD with SDF and LDF achieves 180 Gb/s at the received optical power of -1.5 dBm in 10-km transmission while NLDCP using MBD requires 2.5 dBm to achieve 180 Gb/s. The application of LBD with SDF and LDF to NLDCP realizes 4-dB improvement on the received optical power in 93-Gbaud 10-km transmission.

Conclusion

We investigated the transmission performance of high-baudrate PAM4 using nonlinear-spectral shaping scheme with transition-likelihood-based decoder including symbol- and likelihood-domain feedbacks in a severe bandwidth limitation. We confirmed that the scheme enhanced the tolerance to bandwidth limitation and showed that KP4-FEC threshold was achieved in 186-Gb/s 10-km transmission with the 20-dB bandwidth of 40 GHz, in which the achievable bitrate for the cases with HD-FEC and SD-FEC was estimated.

References

[1] IEEE 802.3cu-2021 - IEEE Standard for Ethernet - Amendment 11: Physical Layers and Management Parameters for 100 Gb/s and 400 Gb/s Operation over Single-Mode Fiber at 100 Gb/s per Wavelength

[2] X. Chen *et al.*, “Single-wavelength and single-photodiode 700 Gb/s entropy-loaded PS-256-QAM and 200-GBaud PS-PAM-16 transmission over 10-km SMF”, in *Proc. ECOC*, Th3A-2, 2020.

[3] Q. Hu *et al.*, “120 Gbaud IM/DD PAM4-transission over 1.5 km SMF Using a single CMOS DACwith < 20 GHz analog bandwidth”, in *Proc. ECOC*, Tu1E-5, 2020.

[4] T. Wettlin *et al.*, “Improvement of Tomlinson-Harashima precoding performance for bandwidth-limited IM/DD systems”, in *Proc. ECOC*, We2D-5, 2020.

[5] D. Che *et al.*, “Rate adaptation by low-cost complementary mapper shaping for short-reach IM-DD systems”, in *Proc. ECOC*, We2D-7, 2020.

[6] J. Renaudier *et al.*, “Multi rate IMDD transceivers for optical interconnects using coded modulation”, in *Proc. OFC*, Tu2J.2, 2020.

[7] N. Stojanovic *et al.*, “4D PAM-7 trellis coded modulation for data center”, *Photonics Technology Lett.*, vol. 31, no. 5, pp. 369–372, 2019.

[8] Y. Fu *et al.*, “Computationally efficient 120 Gb/s PL equalized 2D-TCM-PAM8 in dispersion unmanaged DML-DD system”, in *Proc. OFC*, T3I.5, 2020.

[9] A. R. Calderbank *et al.*, “Baseband trellis codes with a spectral null at zero”, *IEEE Transactions on Information Theory*, vol. 34, no. 3, pp. 425–434, 1988.

[10] J. S. Park *et al.*, “A spectral shaping nonlinear binary coded modulation with Gray-mapped QAM signals”, in *Proc. The Military Communications Conference*, pp. 2363-2368, 2010.

[11] S. Yamamoto *et al.*, “Nonlinear differential coding for spectral shaping of PAM signal in high-baudrate short-reach optical transmission”, *Journal of Lightwave Technology*, vol. 39, no. 4, pp. 1064–1071, 2021.

[12] A. Duel-Hallen *et al.*, “Delayed decision-feedback sequence estimation”, *IEEE Transactions on Communications*, vol. 37, no. 5, pp. 428–436, 1989.

[13] A. Alvarado *et al.*, “Replacing the soft-decision FEC limit paradigm in the design of optical communication systems”, *Journal of Lightwave Technology*, vol. 33, no. 20, pp. 4338–2352, 2015.