93-Gbaud PAM4 O-Band Transmission Using Nonlinear Spectral Shaping with Transition-Likelihood-Based Decoding

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Abstract *We propose a combination scheme of nonlinear differential coding and transition-likelihood-based decoding to realize spectral shaping and enhance the tolerance to bandwidth limitation in high-baudrate short-reach IM-DD system. We demonstrate 186-Gb/s 10-km transmission through an O-band experiment with the 3-dB bandwidth of 14 GHz.*

Introduction

With the wide spread of cloud services and mobile broadband applications, the amount of data-centre traffic is rapidly increasing. This trend requires increase of the Ethernet link capacity based on an economical approach. In IEEE802.3 standardization, 400GbE has been completed, in which 50-Gb/s 4-level pulse amplitude modulation (PAM4) and O-band wavelength-division-multiplexing (WDM) are mainly utilized[1]. In order to realize the next-generation Ethernet links such as 800GbE or 1.6TbE, the increase of data rates is necessary. This means that the signal bandwidth is broader and requires the broader-bandwidth electrical and optical devices for PAM4 transceiver. Many studies are reported for the improvement of transmission performance for short-reach intensity-modulation and direct-detection (IM-DD) systems[2]-[11]. On the other hand, several approaches using coded-modulation scheme have been proposed[9]-[13], and we have proposed spectral-shaping technique using a simple encoder, which is called nonlinear-differential-coded PAM (NLDCP)[14].

In this paper, we propose a combination scheme of NLDCP and likelihood-based decoding in which the original PAM symbol is estimated without the decision for the encoded symbol. We show that the proposed technique has the higher tolerance to bandwidth limitation (BWL) through a 186-Gb/s 10-km transmission experiment in which the BWL is 14 GHz and any Volterra equalizers are not utilized.

NLDCP with likelihood-based decoding

The coding procedure for NLDCP applied to PAM-*m* signal is defined as Eqs. (1) and (2)[14]. Term u_n is the original PAM symbol, $u_n \in \{0,1,\cdots,m-1\}$. Term v_n is the encoded symbol, $v_n \in \{0,1,\cdots,M-1\}$. n is time index. Parameter α is cut-off coefficient, $0 \le \alpha < 1$. Operator $\lfloor\cdot\rfloor$ is the floor function, which corresponds to the nonlinear operator in NLDCP scheme. Operator $mod(\cdot)$ is modulo function. Eqs. (1) and (2) correspond to encoding and decoding, respectively. The power spectrum density (PSD), $S(\omega)$, of the encoded symbol v_n corresponding to NLDCP signal is shown as Eq. (3). T is the modulation period of the encoded symbol v_n, and the signal baudrate f_B is corresponding to T^{-1}. As shown in Eq. (3), the spectrum shape of NLDCP signal is depending on α. This means that NLDCP scheme has flexibility to the bandwidth of the signal spectrum, and the larger α yields the narrower signal spectrum. The number of levels of v_n also depends on α. For example, in the case with $m = 4$, if $\alpha = 1/2$ and $\alpha = 2/3$, then $M = 6$ and $M = 8$, respectively. The symbol transition is restricted by the one-memory nonlinear coding and this realizes spectral shaping.

In NLDCP scheme, as shown in Eq. (2), we can easily decode v_n by modulo operator after 6-level symbol decision in the case with $\alpha = 1/2$, for example. However, in this decoding scheme, the tolerance to additive white Gaussian noise (AWGN) is lower than that in the conventional PAM4 because of the decision for the 6-level symbol v_n. For avoiding the reduction of the AWGN tolerance, we employ likelihood-based decoding in which the original PAM4 signal is directly obtained without the 6-level symbol decision. Figure 1 shows the symbol transition of the encoded symbol v_n. As shown in this figure, the symbol transition is strongly restricted. Each transition corresponds to each PAM4 symbol u_n because NLDCP is based on differential coding. Therefore, we can obtain the original PAM4 symbol from the likelihood not for the encoded symbols but for the transitions without 6-level symbol decision. Figure 2 shows the block diagram of the decoder which utilizes

$$v_n = \begin{cases} u_n & (u_n \ge \lfloor \alpha v_{n-1} \rfloor) \\ u_n + m & (u_n < \lfloor \alpha v_{n-1} \rfloor) \end{cases} \quad (1), \qquad u_n = mod(v_n, m) \; (2), \qquad S(\omega) = \frac{(1-\alpha)^2}{1+\alpha^2-2\alpha\cos\omega T} \quad (3).$$

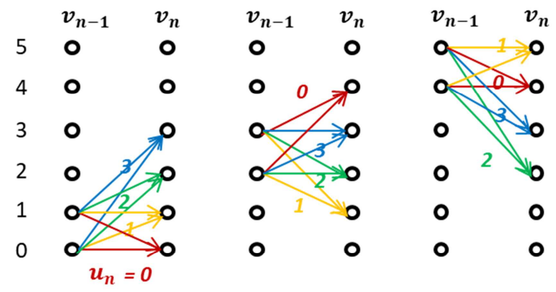

Fig. 1: Symbol transition of the encoded symbol v_n

likelihood for the transitions in order to decode the symbol v_n. The logarithm likelihood of the transition from symbol r_{n-1} to symbol r_n is defined as Eqs. (4) and (5).

$$l_{r_{n-1}r_n} = \left|\sum_{i=0}^{1} d_i r_{n-i} - \sum_{i=0}^{1} c_i s_{n-i}\right|^2 + m_{r_{n-1}} \quad (4),$$

$$m_{r_{n-1}} = \min_{r_{n-2}} l_{r_{n-2}r_{n-1}} - \min_{r_{n-1}}\left(\min_{r_{n-2}} l_{r_{n-2}r_{n-1}}\right) \quad (5),$$

where $m_{r_0} = 0$. Symbol s_n is an output sequence from the feed-forward equalizer (FFE) and symbol r_n is a 6-level candidate sequence. c_i is a tap coefficient of channel-shortening filter (CSF) and d_i is a tap coefficient of desired-impulse-response (DIR) filter. These filters are T-spaced 2-tap finite-impulse-response (FIR) filters. For the case with PAM4 mapping based on Gray code, the logarithm likelihood ratios (LLRs) for the most significant bit (MSB) and the least significant bit (LSB) are shown below.

$$LLR_{MSB} \propto \min_{(p,q)\in U_0\cup U_1} l_{pq} - \min_{(p,q)\in U_2\cup U_3} l_{pq} \quad (6),$$

$$LLR_{LSB} \propto \min_{(p,q)\in U_0\cup U_3} l_{pq} - \min_{(p,q)\in U_1\cup U_2} l_{pq} \quad (7),$$

where $U_{u_n} = \{(i,j) | i \in \{0,1,\cdots,5\}\}$. If $i < 2(u_n+1)$ then $j = u_n$, and if $i \geq 2(u_n+1)$ then $j = u_n + 4$. If the LLR is positive then the bit is 1 while the bit is 0 for the negative LLR. The decision based on the LLRs simultaneously realizes NLDCP decoding and PAM4 demapping. When we have the decision based on the LLRs, we can obtain the original PAM4 symbol u_n without the decision for 6-level symbol v_n.

Experiment and results

We investigate the transmission performance of NLDCP with likelihood-based decoding through an O-band transmission experiment without optical amplifiers. Figure 3 shows the experimental setup. In this this experiment, PAM4-based NLDCP signal for the case with $\alpha = 1/2$ is generated by a 96-GSample/s arbitrary waveform generator (AWG) and modulated by Mach-Zehnder modulator (MZM) at the transmitter. The baudrate of the signal is 90 Gbaud or 93 Gbaud. A raised-cosine-filter (RCF) with the roll-off factor of 0.01 is applied to the signal. The order of pseudo-random binary sequence (PRBS) is 15. Figure 3 (b) shows the frequency response of the experimental setup. The 3-dB and 10-dB bandwidths are 14 GHz and 32 GHz, respectively. The optical signal is transmitted through 10-km single-mode fibre (SMF), in which the zero-dispersion wavelength is 1319.3 nm. The wavelength of the signal is 1310.0 nm, at which the amount of chromatic dispersion (CD) is -8.0 ps/nm. The fibre-launched power is 7 dBm. The optical signal is directly detected by a 50-GHz PIN-PD and sampled at 160 GSample/s by a digital storage oscilloscope (DSO). The samples are demodulated using a FFE which has T/2-spaced taps. For the case with likelihood-based decoding, CSF and DIR filter consist of T-spaced 2 taps. These taps are updated by decision-directed least mean square (DD-LMS) algorithm. In this experiment, any nonlinear Volterra equalizers are not utilized. The received optical power is adjusted by a variable optical attenuator (VOA) at the receiver side.

Figures 4 (a) and (b) show the relationship between the received optical power and bit-error rate (BER) for the conventional PAM4 signal and NLDCP signal with modulo-based decoding

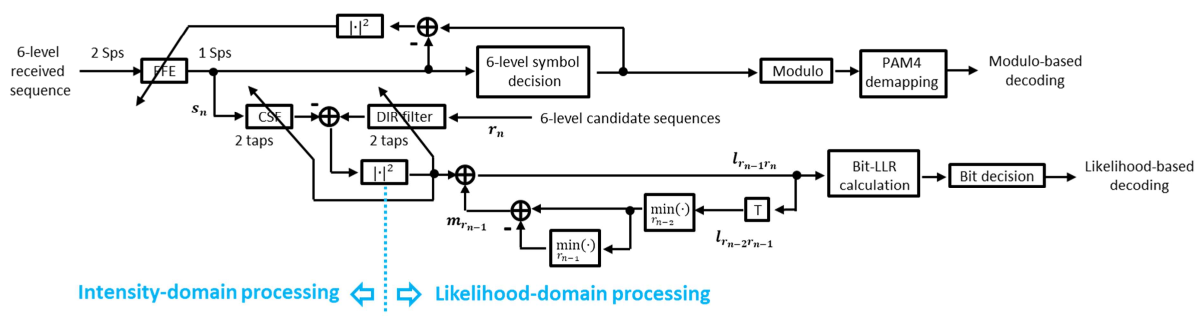

Fig. 2: Block diagram of modulo-based decoding and likelihood-based decoding

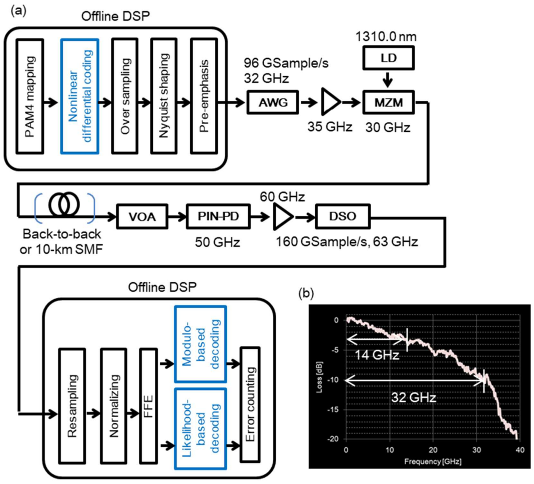

Fig. 3: (a) Experimental setup and (b) frequency response

or likelihood-based decoding in back-to-back (B2B) configuration, in which the threshold of 7% hard-decision forward-error-correction (HD-FEC) is BER of 3.8E-3. The conventional PAM4 corresponds to $\alpha = 0$. The bitrates including FEC over-head are 180 Gb/s and 186 Gb/s in Figs. 4 (a) and (b), respectively. The number of taps is 25 in FFE. As shown in these figures, neither the conventional PAM4 nor NLDCP with modulo-based decoding can achieve the FEC threshold for 186-Gb/s signal because of the sever BWL while NLDCP with likelihood-based decoding achieves it. The likelihood-based decoding yields the larger improvement of the performance for the higher bitrate. The required optical power at the FEC threshold in the case with likelihood-based decoding is about 4-dB lower than that in the case with modulo-based decoding for 186-Gb/s signal.

Figure 5 (a) shows the relationship between the received optical power and BER in 10-km transmission for 186-Gb/s NLDCP with modulo-based decoding or likelihood-based decoding, in which the number of FFE taps is 25. NLDCP with likelihood-based decoding achieves the FEC threshold while NLDCP with modulo-based decoding cannot achieve it even in the case with the received power of 3 dBm. Figure 5 (b) shows the relationship between the number of taps in FFE and BER for 186-Gb/s PAM4 and NLDCP in B2B configuration or 10-km transmission. The received optical power is 3 dBm. In 10-km transmission, NLDCP with modulo-based decoding requires 83-tap FFE to achieve the FEC threshold while NLDCP with likelihood-based decoding achieves it using 15-tap FFE.

Conclusions

We proposed a combination scheme of nonlinear-differential-coded PAM (NLDCP) and likelihood-based decoding for high-baudrate short-reach IM-DD transmission, in which NLDCP symbols were directly decoded without the decision for the 6-level NLDCP symbols in order to avoid the reduction of the tolerance to AWGN. We experimentally demonstrated 186-Gb/s 10-km transmission through an O-band experiment with the bandwidth limitation of 14 GHz, in which we showed that the proposed scheme had the higher tolerance to bandwidth limitation than that of the conventional PAM4 or NLDCP with modulo-based decoding.

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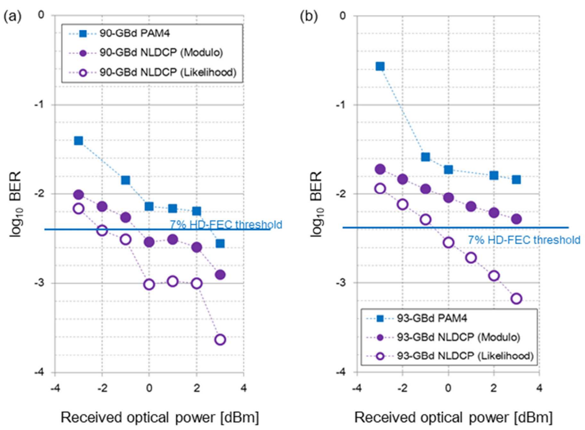

Fig. 4: B2B performance for (a) 180-Gb/s signals and (b) 186-Gb/s signals

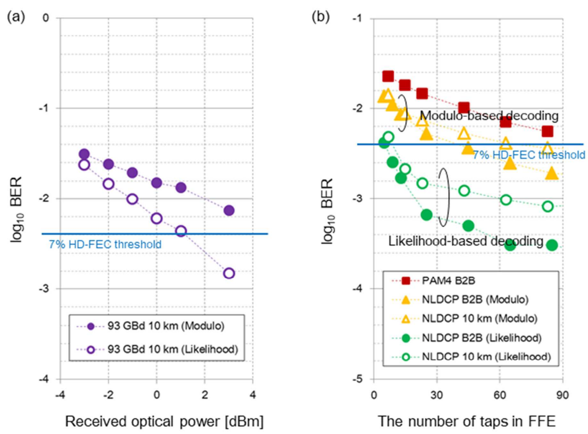

Fig. 5: (a) 10-km transmission performance for 186-Gb/s NLDCP and (b) tap-length dependency in B2B and 10-km transmission for 186-Gb/s PAM4 and NLDCP

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