O-Band 10-km Transmission of 93-Gbaud PAM4 Signal Using Spectral Shaping Technique Based on Nonlinear Differential Coding with 1-Tap Precoding

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Abstract: We propose a simple and flexible spectral shaping technique based on nonlinear differential coding for short-reach IM-DD transmission. Experimental results show the achievement of 7% HD-FEC threshold in 186-Gb/s 10-km transmission with 14-GHz bandwidth limitation. © 2020 The Author(s)

1. Introduction

The amount of data center traffic (DC) is rapidly increasing and the dealing with this requires increasing the capacity of Ethernet link based on an economical approach. 400GbE has been already completed for standardization. In 400GBASE-FR4 and LR4, 50-Gb/s 4-level pulse amplitude modulation (PAM4) and wavelength-division-multiplexing in O-band are adopted. For the next-generation Ethernet links such as 800GbE or 1.6TbE, the increase of data rates will be necessary even more. Therefore, the signal baud rate must be higher for the increase of the data rate, and this requires broad-bandwidth electrical and optical devices for PAM4 transceiver because of the broader signal spectrum. For the improvement of transmission performance in intensity-modulation and direct-detection (IM-DD) system, many studies are reported [1-5]. On the other hand, several approaches using trellis-coded-modulation (TCM) technique have been proposed in order to shape the signal spectrum [6, 7].

In this paper, we propose a simple and flexible nonlinear differential coding technique, which is called nonlinear-differential-coded PAM (NLDCP), in order to spectrally shape PAM signals. We confirm that the proposed technique enhances the tolerance to bandwidth limitation (BWL) through an O-band experiment. We also show that the proposed technique achieves 7% over-head hard-decision FEC (HD-FEC) threshold in 186-Gb/s 10-km transmission with the 3-dB bandwidth of 14 GHz, in which any Volterra filters or maximum likelihood sequence estimation (MLSE) are not utilized.

2. Scheme of nonlinear-differential-coded PAM

The coding procedure for NLDCP applied to PAM-*m* signal is defined below.

$$\tilde{u}(n) = mod(u(n) - \lfloor \alpha v(n-1) \rfloor, m), \ (1) \qquad v(n) = \tilde{u}(n) + \lfloor \alpha v(n-1) \rfloor, \ (2) \qquad u(n) = mod(v(n), m), \ (3)$$

where $u(n)$ is the original PAM symbol, $u(n) \in \{0,1,\cdots,m-1\}$. $\tilde{u}(n)$ is the precoded symbol, $\tilde{u}(n) \in \{0,1,\cdots,m-1\}$. $v(n)$ is the encoded symbol, $v(n) \in \{0,1,\cdots,M-1\}$. n is time index. Parameter α is a cut-off coefficient, $0 \le \alpha < 1$. Operator $\lfloor . \rfloor$ is the floor function, which is a nonlinear operator. Operator $mod(.)$ is modulo function. Equations (1), (2), and (3) are corresponding to precoding, encoding, and decoding, respectively. As shown in Eq. (2), NLDCP scheme is based on a differential coding which includes a nonlinear operator. The precoding shown in Eq. (1) realizes to avoid the occurrence of error propagation at the decoding, and this means that NLDCP scheme does not require a Viterbi decoder. Figure 1 shows the block diagram which corresponds to Eqs. (1) and 2. As shown in this figure, the precoding and encoding are based on the simple 1-tap architecture. Equations (1) and (2) are merged into the simple equation shown in Eq. (4). The power spectrum density (PSD), $S(\omega)$, of the encoded symbol $v(n)$ corresponding to NLDCP signal is expressed as the equation shown in Eq. (5), where T is the modulation period of the encoded symbol $v(n)$. The signal baudrate f_B is corresponding to T^{-1}.

$$v(n) = \begin{cases} u(n) & (u(n) \ge \lfloor \alpha v(n-1) \rfloor) \\ u(n) + m & (u(n) < \lfloor \alpha v(n-1) \rfloor) \end{cases}, \ (4) \qquad S(\omega) = \frac{(1-\alpha)^2}{1+\alpha^2 - 2\alpha \cos \omega T}. \ (5)$$

As shown in Eq. (5), the spectrum shape of NLDCP signal is depending on α. This means that NLDCP scheme has the flexibility to the bandwidth of signal spectrum. Figure 2 shows the PSD of NLDCP signal. As shown in this figure, the bigger α yields the narrower signal spectrum. The number of levels in the encoded symbol $v(n)$is also

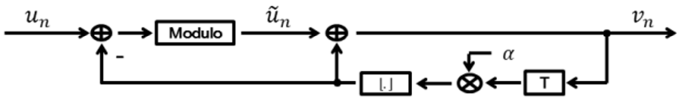

Fig. 1. Block diagram of encoder combined with precoder in NLDCP scheme

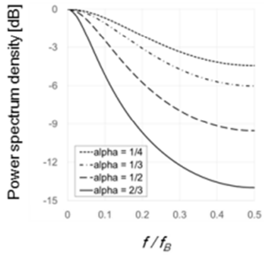

Fig. 2. PSD of NLDCP signal

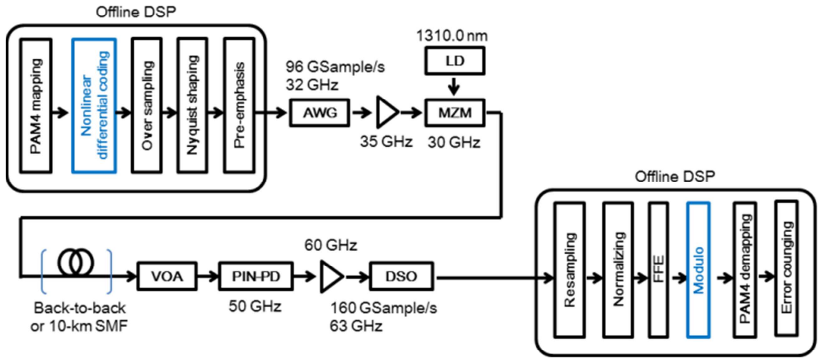

Fig. 3. Experimental configuration

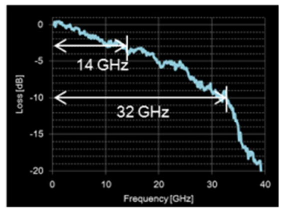

Fig. 4. Frequency response

depending on α. For example, if $m = 4$ and $\alpha = 1/2$, then $M = 6$. If $m = 4$ and $\alpha = 2/3$, then $M = 8$. The symbol transition is restricted by the one-memory nonlinear coding and this Markov chain has one-step transition probabilities. The state probability vector $\mathbf{w}_\alpha$ is derived as the eigenvector of the transition matrix [7]. Each element of the state probability vector corresponds to the occurrence probability of each level. For $m = 4$, the state probability vectors are shown below.

$$\mathbf{w}_{1/2} = (1/16 \quad 3/16 \quad 4/16 \quad 4/16 \quad 3/16 \quad 1/16)^{\mathrm{T}}, \qquad (6)$$

$$\mathbf{w}_{2/3} = (1/44 \quad 3/44 \quad 8/44 \quad 10/44 \quad 10/44 \quad 8/44 \quad 3/44 \quad 1/44)^{\mathrm{T}}, \qquad (7)$$

where $\mathbf{w}_{1/2}$ and $\mathbf{w}_{2/3}$ are the state probability vectors for the cases with $\alpha = 1/2$ and $\alpha = 2/3$, respectively. As shown in these equations, NLDCP signals are probabilistically shaped. The shaping gain is utilized to enhance the tolerance to the colored noise such as BWL in NLDCP scheme while that is utilized in order to enhance the tolerance to additive white Gaussian noise (AWGN) in the conventional probabilistic shaping [8].

3. Experiments and results

We investigate the transmission performance of NLDCP signal through an O-band transmission experiment without optical amplifiers. Figure 3 shows the experimental configuration. In this experiment, PAM4-based NLDCP signals for the cases with $\alpha = 1/2$ and $\alpha = 2/3$ are generated by a 96-GSample/s arbitrary waveform generator (AWG) and modulated by Mach-Zehnder modulator (MZM) at the transmitter. The baudrate of the signals is 90 Gbaud or 93 Gbaud. A raised-cosine-filter (RCF) with the roll-off factor of 0.01 is applied to the signals. The order of pseudo-random binary sequence (PRBS) is 15. The wavelength of signals is 1310.0 nm. Figure 4 shows the frequency response of the transmission system in this experiment. The 3-dB bandwidth is 14 GHz, and the 10-dB bandwidth is 32 GHz. The optical signals are transmitted through 10-km single-mode fiber (SMF), in which the zero-dispersion wavelength is 1319.3 nm. The amount of CD is -8.0 ps/nm at 1310.0 nm. The fiber-input power is 7 dBm. The optical signals are 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 feed-forward equalizer (FFE) which has T/2-spaced taps and those taps are updated by recursive-least-square (RLS) algorithm. The received optical power is adjusted by a variable optical attenuator (VOA) at the receiver side.

Figures 5 (a) and (b) show the relationship between the received optical power and bit error ratio (BER) for NLDCP signals and conventional PAM4 signal in back-to-back configuration (B2B), where 7% HD-FEC threshold is 3.8E-3. The symbol-level histograms are inserted. The conventional PAM4 corresponds to $\alpha = 0$. The bit rates including FEC over-head are 180 Gb/s and 186 Gb/s in Figs. 5 (a) and (b), respectively. The number of taps in FFE is 45. As shown in Fig. 5 (a), NLDCP with $\alpha = 2/3$ cannot achieve 7% HD-FEC threshold even at the received power of 3 dBm while NLDCP with $\alpha = 1/2$ achieves 7% HD-FEC threshold at the received power of 0 dBm. As shown in

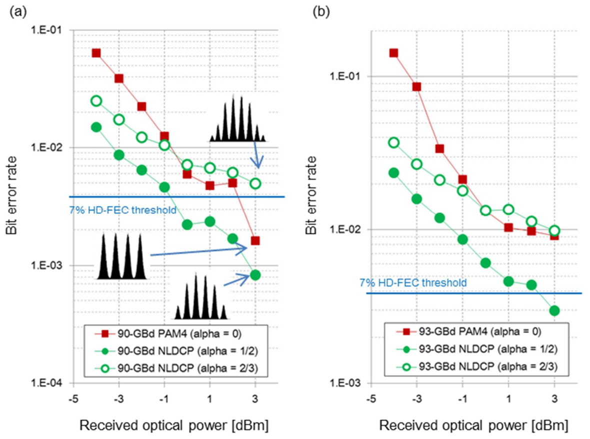

Fig. 5. Performance in B2B configuration for 90-Gbaud and 93-Gbaud signals

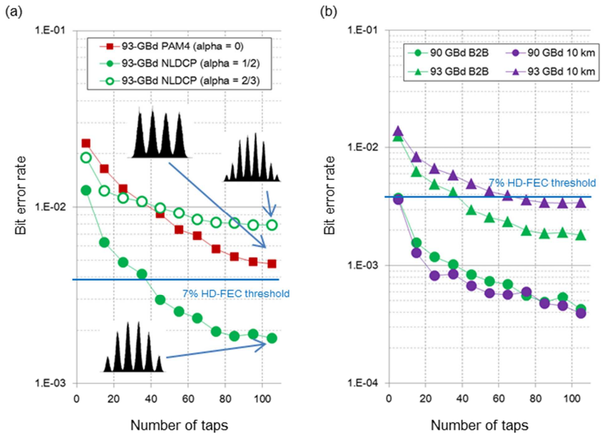

Fig. 6. Performance dependency on FFE tap length in B2B configuration and 10-km transmission

Fig. 5 (b), NLDCP with $\alpha = 1/2$ achieves 7% HD-FEC threshold while NLDCP with $\alpha = 2/3$ and conventional PAM4 cannot achieve it. For the conventional PAM4, there is error floor because of inter-symbol-interference (ISI) induced by electrical bandwidth limitation.

Figure 6 (a) shows the relationship between the number of taps in FFE and BER for 186-Gb/s NLDCP with $\alpha = 1/2$ and $\alpha = 2/3$ and conventional PAM4 signals in B2B configuration, in which the received optical power is 3 dBm. As shown in this figure, the conventional PAM4 and NLDCP with $\alpha = 2/3$ cannot achieve 7% HD-FEC threshold even in the case with 105 taps. On the other hand, NLDCP with $\alpha = 1/2$ achieves it in the case with 45 taps. For NLDCP with $\alpha = 2/3$, there is little improvement induced by the increase of tap length. This means that the main factor of the performance limitation is not ISI but AWGN in NLDCP with $\alpha = 2/3$. The cut-off coefficient of 2/3 is not suitable to the transmission system in this experiment because NLDCP with $\alpha = 2/3$ has 8-level symbol while NLDCP with $\alpha = 1/2$ has 6-level symbol. Figure 6 (b) shows the relationship between the number of taps in FFE and BER for 180-Gb/s and 186-Gb/s NLDCP with $\alpha = 1/2$ in the cases with B2B configuration and 10-km transmission. The received optical power is 3 dBm. As shown in this figure, 180-Gb/s 10-km transmission is achieved even in the case with 5-tap FFE and 186-Gb/s 10-km transmission is achieved when 75-tap FFE is utilized.

4. Conclusion

We proposed a simple and flexible spectral shaping technique based on nonlinear differential coding with 1-tap precoding for short-reach IM-DD transmission. The proposed technique realized nonlinear spectral shaping for PAM signal and enhanced the tolerance to bandwidth limitation (BWL). We demonstrated that 186-Gb/s 10-km transmission with 14-GHz BWL through an O-band experiment without optical amplifiers, in which any Volterra filters or MLSE are not utilized. We confirmed that the proposed scheme achieved 7% HD-FEC threshold at the received power of 3 dBm while the conventional PAM4 cannot achieve the threshold. The proposed method is suitable to high-baudrate IM-DD system which consists of narrow-bandwidth components.

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