84-GBaud/λ PAM-4 Transmission over 20-km using 4-λ LAN-WDM TOSA and ROSA with MLSE Based on Nonlinear Channel Estimation

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Abstract: We demonstrate 168-Gbps/λ PAM-4 transmission over 20-km using 4-λ LAN-WDM TOSA and ROSA with BER below the HD-FEC limit under 24-GHz bandwidth limitation and -39.7-ps/nm chromatic dispersion by applying MLSE based on nonlinear channel estimation.

1. Introduction

Recently, the rapid growth of data center (DC) network traffic is a major challenge. For this purpose, Ethernet has been introduced to provide economical, high-capacity short-reach transmission such as intra and inter DC connections. The modulation rate, numbers of symbol levels, and wavelength channels requirements for intensity-modulation direct-detection (IM-DD) systems are rapidly increasing. Currently, 400GbE is standardized for 100-Gbps 4-level pulse amplitude modulation (PAM-4) and wavelength division multiplexing (WDM) in the O-band. There are several problems in realizing an economical and high-capacity IM-DD system in the future. The main problem is significant signal quality degradation due to inter-symbol-interference (ISI) caused by the bandwidth limitation and the chromatic-dispersion (CD) [1-3]. Therefore, several studies on the LAN-WDM or the CWDM transmitter optical sub-assembly (TOSA) have recently been reported with maximum likelihood sequence estimation (MLSE) as a receiver-side signal processing technique [4] or Tomlinson-Harashima Precoding (THP) as a transmitter-side signal processing technique [5]. We have also proposed transmitter-side and receiver-side signal processing techniques such as nonlinear trellis-coded-modulation and maximum likelihood sequence estimation based on nonlinear channel estimation (NL-MLSE) to combat large ISI due to severe bandwidth limitation induced by low cost devices [6, 7].

In this paper, we record 168-Gbps/λ PAM-4 transmission over 20 km with a bit-error-rate (BER) below the 7% overhead hard-decision forward error correction (HD-FEC) limit of 3.8×10^{-3} using 4-λ LAN-WDM TOSA and 4-λ LAN-WDM receiver optical sub-assembly (ROSA) by applying NL-MLSE.

2. NL-MLSE based on a third-order Volterra filter

We describe NL-MLSE based on a third-order Volterra filter. Figure 1 shows a block diagram of the scheme's structure. A channel shortening filter (CSF) is a finite impulse response (FIR) filter, and its role is to reduce the amount of calculation of Viterbi algorithm by shortening the impulse-response length of the received signals. A desired impulse response (DIR) filter emulates the channel response. MLSE performance generally depends on the estimation accuracy of the DIR filter. However, device nonlinearities must be considered for the high baud rate transmission systems because the electrical and optical components in the transmission system have nonlinear channel responses. In conventional MLSE, the linear filter is used as a DIR filter, but the linear filter has no effect for nonlinear transfer functions. Therefore, we apply a third-order Volterra filter to the DIR filter to enable higher channel-estimation accuracy. Unlike usual receiver-side equalization, applying Volterra filter to DIR filter does not enhance noises from channels in MLSE scheme.

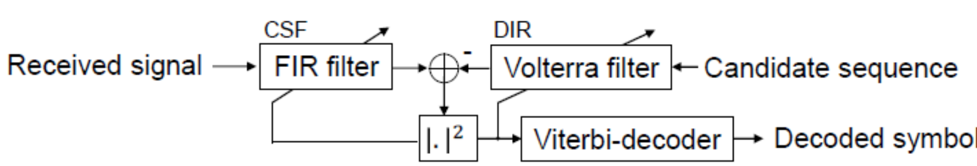


Fig. 1. Block diagram of NL-MLSE.

An output of m-memory, third-order Volterra filter is expressed as

$$f(x_1, \cdots, x_m) = \sum_{a=1}^{m} k_a x_a + \sum_{a=1}^{m} \sum_{b=1}^{m} k_{ab} x_a x_b + \sum_{a=1}^{m} \sum_{b=1}^{m} \sum_{c=1}^{m} k_{abc} x_a x_b x_c \qquad (1)$$

where $(x_1, \cdots, x_m)$ is a signal sequence such as an input of DIR filter, and ($k_{1\sim m}$, $k_{11\sim mm}$, $k_{111\sim mmm}$) are kernels of the Volterra filter. In this case, NL-MLSE has $\sum_{i=1}^{3} {}_{m+i-1}C_i$ kernels considering duplication in DIR filter. The amount of nonlinear calculation increases compared to the conventional MLSE in which a linear filter is utilized as DIR filter. Therefore, there are following two methods for reducing the amount of calculation of NL-MLSE.

Method-1: Omit the second-order Volterra kernels and use only the first- and third-order kernels.

$$f(x_1, \cdots, x_m) = \sum_{a=1}^{m} k_a x_a + \sum_{a=1}^{m} \sum_{b=1}^{m} \sum_{c=1}^{m} k_{abc} x_a x_b x_c \qquad (2)$$

Method-2: Further omit the non-diagonal kernels from Method-1, and use only the diagonal kernels.

$$f(x_1, \cdots, x_m) = \sum_{a=1}^{m} k_a x_a + \sum_{a=1}^{m} k_a x_a^3 \qquad (3)$$

As a result, NL-MLSE has ${}_{m+2}C_3 + {}_{m}C_1$ and $2\,{}_{m}C_1$ kernels in DIR filter by using Method-1 and Method-2, respectively. Method-2 is more effective than Method-1 in reducing the amount of calculation.

3. Experimental setup and Results

We experimentally evaluate the 168-Gbps/λ (84-GBd) PAM-4 performances in back-to-back and 20-km standard single-mode fiber (SSMF) transmission in O-band. Figure 2 shows the experimental setup. In these experiments, electrical PAM-4 signals are generated by a 96-Gsample/s arbitrary waveform generator (AWG) and modulated to optical signals by a 4-λ LAN-WDM TOSA which consists of electroabsorptive modulated lasers (EMLs) with integrated semiconductor optical amplifiers (SOAs) and a wavelength multiplexer. Transmitted optical signals are directly detected by a 4-λ LAN-WDM ROSA which consists of a wavelength de-multiplexer, avalanche photo diodes (APDs) and trans-impedance amplifiers (TIAs) and sampled at 160 Gsample/s by a digital storage oscilloscope (DSO). The sampled signals are demodulated using a feed-forward equalizer (FFE), conventional MLSE or NL-MLSE before bit error counting. Both the FFE and CSF in the MLSE have 45 T/2-spaced taps. The DIR filter of the MLSE has T-spaced taps, and the memory length is only three. The fiber-launched power is 5.4 dBm/λ. The received optical power is adjusted by a variable optical attenuator (VOA). The amounts of CD are -39.7, -32.0, -24.1, and -16.1 at the Lanes 0, 1, 2, and 3, respectively. Transmission experiment is driven for each lane individually due to our experimental equipment. Figure 2 also shows the total frequency response of the transmission system. The 3-dB and 10-dB bandwidth are 24 GHz and 29 GHz.

Figure 3 shows the results of 84-GBd PAM-4 in 20-km transmission at each lane where the received optical power is -3 dBm. These results show that demodulation by FFE (circle) cannot achieve below a BER of 3.8×10^{-3} which corresponds to the 7% overhead HD-FEC limit in all wavelength channels. On the other hand, by applying MLSE (conventional: triangle, second-order NL-MLSE: square, third-order NL-MLSE: star), the 20km transmission performance in all wavelength channels achieve below the HD-FEC limit. For Lane 3, the longest wavelength channel, all results of applying MLSE are below the BER of 2.4×10^{-4} which corresponds to the KP4 FEC limit. It can be seen that the transmission characteristics deteriorate due to the influence of CD in the shorter wavelength channels. In addition, the best performance is obtained by demodulating by NL-MLSE applying the third-order Volterra filter.

We compare the performances of the 84-GBd PAM-4 in back-to-back and 20-km transmission for each demodulation methods at Lane 0, which is the shortest wavelength channel. Figure 4 shows the relationships between the received optical power and BER for conventional MLSE (triangle) which can estimate the linear ISI, NL-MLSE (square) which

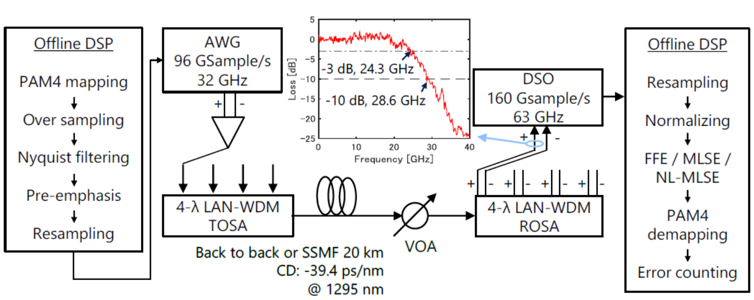


Fig. 2. Experimental setup, frequency response and DSP decks.

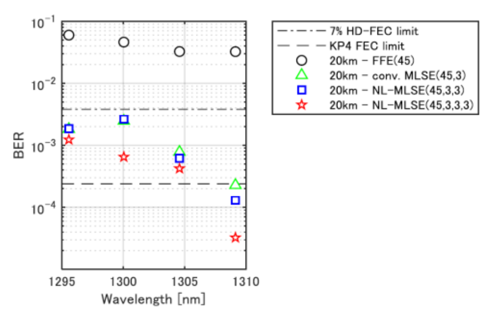
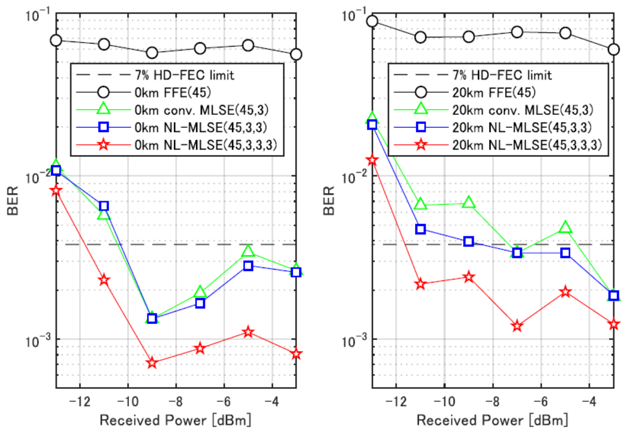
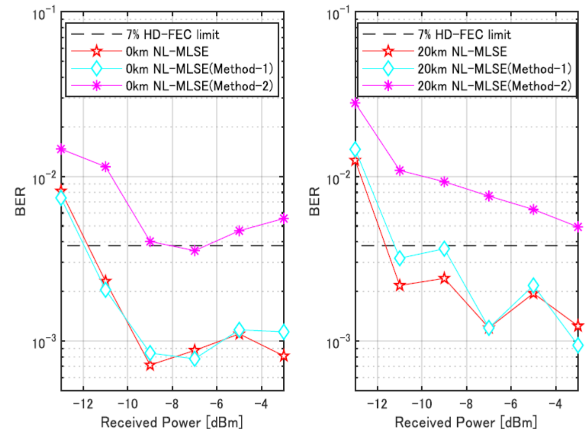


Fig. 3. 168-Gbps/λ PAM-4 performance of individual lanes in 20-km transmission.



(a) (b)

Fig. 4. 168-Gbps/λ PAM-4 performance comparison between FFE, conventional MLSE and NL-MLSE in (a) B2B and (b) 20-km transmission at Lane 0.



(a) (b)

Fig. 5. 168-Gbps/λ PAM-4 performance comparison between NL-MLSE and simplified NL-MLSE in (a) B2B and (b) 20-km transmission at Lane 0.

can estimate the second-order nonlinear distortion, and NL-MLSE (star) which can estimate even the third-order nonlinear distortion. The third-order NL-MLSE has the better performance than that of the other schemes. The third-order NL-MLSE is able to below the HD-FEC limit at the received power of -11 dBm even in 20-km transmission because the third-order Volterra filter emulates the nonlinear channel response well.

In the previous section, two methods are proposed to reduce the calculation amount of NL-MLSE that can estimate the third-order nonlinearity. We compare the 84-GBd PAM-4 transmission performance in back-to-back and 20-km transmission at Lane 0 in order to investigate the performance of these methods. As shown in Figure 5, there is little difference between the conventional third-order Volterra filter (star) and Method-1 (diamond). This indicates that the second-order kernels have little effect on the transmission system in this experiment because they represent output asymmetries for low-level and high-level inputs. On the other hand, Method-2 (asterisk) clearly deteriorates the performance. The performance degradation is because the signal is nonlinearly distorted after ISI occurs. The nonlinear waveform distortion cannot be estimated by only the diagonal kernels. These results show that the second-order kernels are not so important in order to estimate the channel response in high-capacity IM-DD systems while the third-order kernels including non-diagonal elements are necessary to estimate the nonlinearity of the channel response.

4. Conclusion

We demonstrated that the 168-Gbps/λ PAM-4 20-km SSMF O-band transmission with the BER below 7% overhead HD-FEC limit using 4-λ LAN-WDM TOSA and ROSA applying MLSE based on nonlinear channel estimation (NL-MLSE) using the third-order Volterra filter. We also showed two methods for reducing the calculation amount of NL-MLSE by decreasing the scale of the Volterra filter. Finally, we confirmed that NL-MLSE without the second-order kernels achieves 168-Gbps/λ PAM-4 20-km transmission, in which there is little penalty comparing to the case using the conventional third-order Volterra filter. We believe that NL-MLSE applying the method is a very effective scheme to realize economical and high-capacity IM-DD system.

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