4-lambda LAN-WDM 1.6-Tb/s 2-km Transmission with Nonlinear Maximum Likelihood Sequence Estimation.

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Abstract: We demonstrate, for the first time, a capacity of 1.6 Tb/s over 2 km of single-mode fiber on the O-band LAN-WDM grid with 4-lane 400-Gb/s/lane signals with 155-GBd PAM-8 signals enhanced by NL-MLSE. © 2024 The Author(s)

1. Introduction

The demand for switching capacity to handle the enormous data center network traffic continues to grow. To meet this demand, the bitrates (b/s) per lane of optical interfaces need to be increased, thereby reducing the number of switch ports, saving space, and reducing power consumption. Figure 1(a) shows the IEEE 802.3 standards for optical interfaces used primarily for intra-building (2-10 km) and inter-building (2-40 km) connections, as well as ongoing standardization objectives (IEEE P802.3dj). Although there are standards with the same transmission distance and capacity but with different speeds per lane, numbers of lanes, and multiplexing methods, this figure shows the configuration with the fewest lanes and fibers used, i.e., the most space-saving and lowest power consumption. For the 800-Gb/s standard, wavelength division multiplexing (WDM) with four lanes of 200 Gb/s in 4-level pulse amplitude modulation (PAM-4) format with a simple intensity-modulated direct detection (IM-DD) configuration is being considered for both 2 and 10 km, while for the 1.6-Tb/s standard, only a parallel single-mode fiber (PSM) using eight single-mode fibers (SMFs) with eight lanes of 200 Gb/s for 2 km is within the objective [1].

There are several studies for 1.6-Tb/s transmission over 10-km in O-band IM-DD using not only WDM but also a space division multiplexing (SDM) configuration that is more tolerant to the penalty due to chromatic dispersion (CD) [2, 3]. The feasibility demonstration using only WDM is also critical to speed up the discussion on the next-generation standards. The studies on the high-capacity multiplexing using only WDM in the O-band are summarized in Figure 1(b). 400-Gb/s and 800-Gb/s have been demonstrated with 4-lambda WDM [4, 5], while 1.6-Tb/s has only been realized with 8-lambda WDM with 200-Gb/s/lane [6].

To realize 1.6-Tb/s transmission while minimizing the increase in the number of lanes, the speed per lane needs to be increased, but IM-DD systems face the problem of increasing the penalty due to CD when increasing transmission speed. In addition, in lane multiplexing using WDM, the increased effect of CD in lanes far from the zero-dispersion wavelength must also be considered. For example, in the 400-Gb/s standard that has already been established, lanes with a speed of 100 Gb/s/lane are arranged in a coarse WDM (CWDM) grid with about 3.5-THz channel spacing for 2 km, and the same configuration is used in long reach (LR), the conventional standard for 10-km transmission. However, the effect of CD is noticeable in a CWDM grid, and a maximum transmission distance of 6 km is specified in 400GBASE-LR4-6 [7]. Therefore, the next-generation 800GBASE-LR4 adopts a LAN-WDM grid with a narrower channel spacing of 800 GHz, reducing the impact of CD.

In this study, we propose that the future generation standard of 4-lambda 1.6-Tb/s achieves 2-km transmission with less CD impact by applying a LAN-WDM grid instead of a CWDM grid. Furthermore, we demonstrate 4-lambda1.6-Tb/s, 2-km transmission with 400-Gb/s/lane of 155-GBd PAM-8 in a LAN-WDM grid while achieving the bit error rate (BER) threshold for a soft-decision forward error correction (FEC) for all wavelength channels using our digital signal processing (DSP) technique of nonlinear maximum likelihood sequence estimation (NL-MLSE).

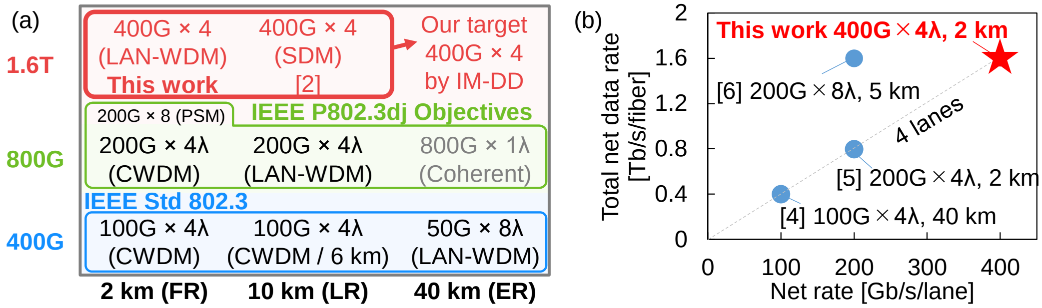

Fig. 1. (a) Status of Ethernet standardization and the position of our research and (b) O-band IM-DD experiments with WDM.

2. Experimental setup for 1.6-Tb/s 2-km 4-labmda LAN-WDM transmission

The experimental setup for 400-Gb/s/lane, 1.6-Tb/s back-to-back and 2-km transmission using LAN-WDM with 4-lambda WDM is shown in Figure 2(a). The transmitter consists of an arbitrary waveform generator (AWG), laser diodes (LDs), lithium niobate Mach-Zehnder modulators (LN-MZMs), and couplers. The 400 Gb/s/lane is generated on the basis of Mersenne Twister pseudo-random series in 155-GBd PAM-8 format, and electrical signals are generated at 256-GSa/s AWG with a bandwidth of 80 GHz. A 400-Gb/s PAM-8 signal at 155 GBd is less affected by bandwidth limitations than a 400-Gb/s PAM-4 signal at over 200 GBd. In addition, since 2-km transmission has a larger power budget than 10-km transmission, the increase in required signal-to-noise ratio (SNR) due to PAM-8 is not so much of an issue. This electrical signal is subjected to Nyquist filtering with a roll-off of 0.1 and digital pre-emphasis of 1025 taps reflecting the transfer function of this setup. We assume that future 4-lane 1.6-Tb/s Ethernet will use the 64B/66B encoding and 256B/257B transcoding, used in the latest Ethernet [7] and considered in the current task force [1], and a soft-decision FEC (O-FEC) [8] with overhead of 15.315% instead of the conventional KP4-FEC [7]. Thus, we select 155-GBd PAM-8 having a gross rate of 465 Gb/s and a bit rate of 401.673 Gb/s excluding the overhead of the O-FEC and the transcoder. The 155-GBd PAM-8 signal can accommodate a net 400 Gb/s/lane for Ethernet. Optical sources are generated by four LDs (L0: 1295.56 nm, L1: 1300.05 nm, L2: 1304.58 nm, and L3: 1309.14 nm, respectively) whose wavelengths are matched to the LAN-WDM grid. The four different wavelength sources, L0 and L2, L1 and L3, are combined by two polarization-maintaining couplers and input to different modulators. Two 155-GBd PAM-8 signal series with half-shifted data frames to each other are generated into two optical signal series by a pair of LN-MZMs with a bandwidth of 65 GHz. The power to swing the MZM is optimized by adjusting the output of the AWG. The optical signals output from the two modulators are further coupled together and input to the receiver via a 2-km SMF or directly to the receiver. As shown in Figure 2(b), the optical signals of the 155-GBd PAM-8 are transmitted as four wavelength channels over 2-km SMF.

In the receiver system, the measurement lane of optical signals is extracted by an optical band path filter (OBPF). After the optical signals are amplified by a praseodymium-doped fiber amplifier (PDFA) and adjusted to 12-dBm by a variable optical attenuator (VOA), a PIN photodiode (PIN-PD) converts the optical signals to electrical signals. The electrical signals are converted to digital signals by a digital storage oscilloscope (DSO) and decoded by an offline DSP. The signal spectrum is flat at this stage, indicating that digital pre-emphasis has been correctly applied. The decoding algorithm is our previously proposed NL-MLSE [9] with 5-memory after 45-tap linear equalizer. The NL-MLSE improves the performance of conventional MLSE with the replication of the actual transmission system transfer function, including device nonlinearity avoiding noise enhancement due to nonlinear equalizing. In 5-memory NL-MLSE, a desired impulse response filter (DIRF) replicates a transfer function that consists of a third-order Volterra series expansion expressed as $f(x_n) = \sum_a (p_a x_a + \sum_b (q_{ab} x_a x_b + \sum_c r_{abc} x_a x_b x_c))$, where the symbol index numbers n, a, b, and c are satisfied with $a \geq b \geq c$ and are integers between -4 and 0, and p_a, q_{ab}, and r_{abc} represent linear, second-order, and third-order kernel weights, respectively. The total number of kernels is 55, consisting of 5 linear, 15 second-order, and 35 third-order kernel weights. For comparison of decoding algorithm, we also use a conventional 45-tap feed forward equalizer (FFE) and 5-memory conventional MLSE with a 45-tap linear equalizer.

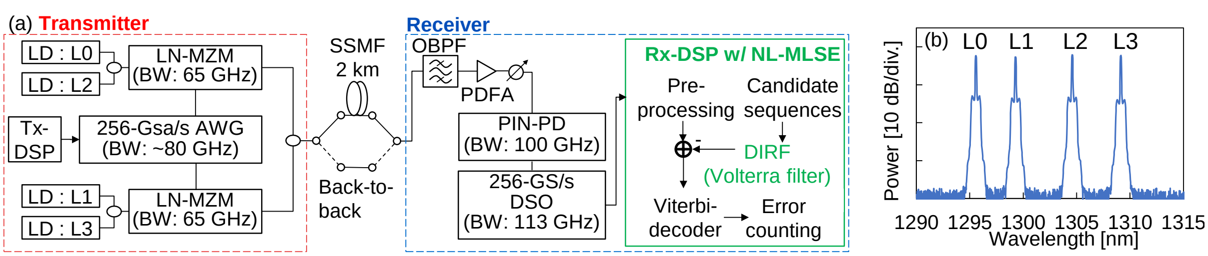

Fig. 2. (a) Experimental setup of back-to-back configuration and 2-km transmission and (b) optical signal spectrum of 1.6-Tb/s LAN-WDM at the output of 2-km SMF.

3. Experimental results of 400-Gb/s/lane back-to-back configuration and 1.6-Tb/s 2-km transmission

Figure 3(a) shows the AWG output dependence of the back-to-back characteristics with the signal wavelength as L0. The BER improves as the AWG output is increased, and the application of NL-MLSE improves BER more than conventional linear MLSE. In other words, increasing the MZM swing width improves SNR, while also increasing the effect of nonlinear response.

Figure 3(b) shows the results of a 2-km transmission with 4-lambda LAN-WDM at 400 Gb/s/lane. The AWG output is set to 2.7 V. The BER for each channel was less than 2.0×10^{-2}, i.e., the O-FEC threshold [8] in all the decode algorithms. This indicates that a 2-km transmission of 1.6-Tb/s using 4-lane WDM with a transmission rate of 400 Gb/s/ lane has been achieved. There is no clear correlation between the transmission characteristics of each wavelength channel and the amount of CD. Furthermore, in L0, there is no difference in transmission performance depending on the demodulation algorithm, while in lanes other than L0, the transmission performance does not improve with conventional MLSE. However, it improves when NL-MLSE is used. This suggests that linear waveform distortion is sufficiently equalized by the linear equalizer installed at the previous stage of the MLSE, and that there is no effect of noise enhancement, i.e., no excessive bandwidth limitation is caused. The amount of BER improvement due to NL-MLSE at L1 and L2 is almost the same as the improvement obtained when the AWG output is increased to 2.7 V in back-to-back experiments, so the nonlinear response penalty due to CD is not as dominant as the nonlinear response penalty when the swing width of the MZM is increased. The fact that the effect of NL-MLSE is not visible at L0 and that the effect of NL-MLSE is larger at L3 than at other lanes cannot be explained by the previous discussion and requires a more in-depth discussion of the changes in the transmission channel response conditions over the measurement time and the effects of the combination of different nonlinear responses. Under the conditions of the experiment, the problem of a large peak-to-average power ratio (PAPR), or SNR degradation due to digital pre-emphasis, is not noticeable, and the advantage of a flat received signal spectrum is apparent. Figure 3(b) also shows the wavelength-dependent characteristics of the CD of the 2-km fiber. The zero-dispersion wavelength of the transmission fiber used is 1320 nm, and the CD in the shortest wavelength channel, L0, is −4.2 ps/nm.

Figure 3(c) shows received electrical signal spectra of the signals after transmission and back-to-back signal of 155-GBd PAM-8 with a bandwidth of 77.5 GHz. As shown in this figure, the spectra of L2 and L3 on the long wavelength side show almost the same characteristics as the back-to-back spectrum, indicating that there is almost no penalty due to CD. For L0 and L1, a slight distortion of the signal spectrum due to CD is visible at frequencies above 50 GHz, but the transmission performance penalty is sufficiently suppressed by DSP.

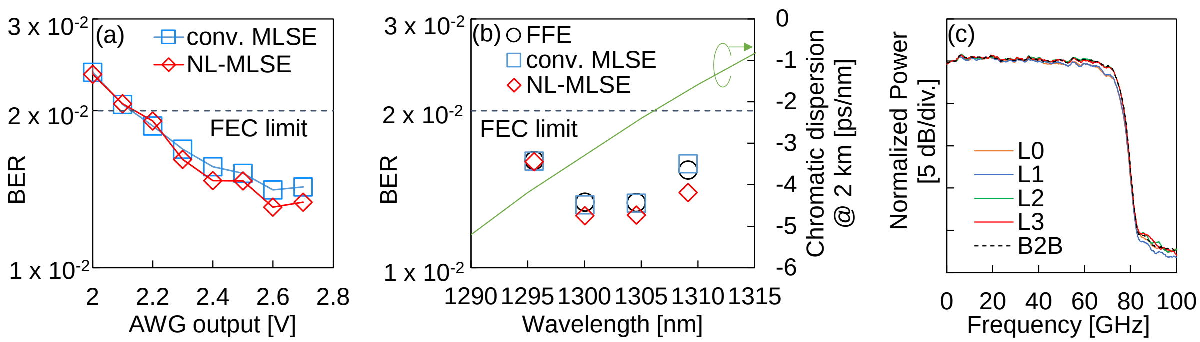

Fig. 3. (a) BER of back-to-back characteristics vs. AWG output at L0, (b) BER for each WDM channel and CD characteristics at 1.6-Tb/s 2-km transmission and (c) electrical signal spectra of received signals and back-to-back signal.

4. Conclusion

We demonstrated the first 1.6-Tb/s 2-km O-band transmission experiments of 400 Gb/s/lane (155 GBd PAM-8) on a LAN-WDM grid in the IM-DD scheme with NL-MLSE. This result contributes to the discussion on future Ethernet 1.6-Tb/s standards and to the continued evolution of large-scale data center networks.

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