## 1.6-Tb/s (4 SDM × 400 Gb/s/lane) O-band Transmission over 10 km of Installed Multicore Fibre

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Abstract Record 400-Gb/s/lane net-rate (155-GBd PAM-8) IM-DD signals are transmitted in the O-band over installed 10-km 4-core fibre using in-house broadband InP-DHBT amplifier and our nonlinear-MLSE, achieving a 1.6-Tb/s total capacity for future data-centre Ethernet networks. ©2023 The Author(s)

#### Introduction

The Ethernet switching capacity required for intra- and/or inter-building connections in data centre networks (DCNs) has continually grown to meet the demand for various services such as cloud and 5G applications. To cope with this, an Ethernet task force is currently in progress for IEEE standardization for transmission capacities of 400G and 800G and higher bitrates (b/s) using 200 Gb/s/lane signal with 4-level pulse amplitude modulation (PAM-4), as shown in the blue area of Fig. 1, with a focus on 2-km (FR) and 10-km (LR) transmissions [1]. Intensity-modulated direct detection (IM-DD) systems with low-cost configurations are effective for Ethernet, which has been increasing in terms of speed and number of lanes with wavelength division multiplexing (WDM) and parallel single mode fibre (PSM). Since IM-DD systems cannot fully compensate for the effect of chromatic dispersion (CD), it is common to use the O-band, where the CD at the signal wavelength is near zero in the fibre. Figure 1 summarizes the research results for O-band IM-DD systems, in terms of transmission speed per lane with transmission speeds of 100 Gb/s or higher (a) and total transmission capacity per fibre (b). Most of the reports [2-7] of high transmission rates per lane up to 348.62 Gb/s (134-GBd PAM-8) [3] are with single lanes (see Fig. 1(a)). Some research results have demonstrated that the use of multiple lanes can lead to a transmission capacity exceeding that reported for single lanes even at

relatively low transmission speeds per lane in laboratory [8-13] and field experiments [14] (see Fig. 1(b)). In studies with a very large number of lanes (16 or more) within 2 km [8-11], space division multiplexing (SDM) is combined to ensure that the range of wavelengths used in WDM is not extended too far due to CD limitations occurring even in the O-band. However, a high-capacity transmission of 1.6 Tb/s over 10 km in O-band, which is essential for intra- and inter-building connections in future DCNs, has not been realized except using coherent systems [15]. Also, for maintaining economic advantage of IM-DD systems, the new Ethernet standardization needs to reduce the number of multiplexing channels, i.e., fewer lanes with a faster transmission rate per lane.

In this study, we demonstrate 1.6-Tb/s transmission over 10 km with 400 Gb/s/lane multiplexed by 4-core fibre installed on the premises of our laboratory. As can be seen in Fig. 1(a), we have realized, for the first time in the Oband IM-DD, the transmission of 400 Gb/s/lane with 155-GBd PAM-8 using in-house InP-DHBT amplifier and our proposed nonlinear maximum likelihood sequence estimator. In high-speed signal transmission, CD degrades the transmission performance for 10 km more significantly than that for 2 km at the WDM configuration even in the O-band. Therefore, we propose an SDM configuration to realize multiplelane single-fibre transmission near the zerodispersion wavelength. To the best of our





knowledge, as shown in Fig. 1(b), we realize the first-ever 1.6-Tb/s (400 Gb/s/lane × 4 SDM) 10km transmission in the O-band IM-DD systems.

# 400-Gb/s/lane 155-GBd PAM-8 signal generation in O-band

Figure 2 (a) shows an experimental setup featuring a back-to-back configuration for 400-Gb/s/lane 155-GBd PAM-8 signal generation in the O-band. In the transmitter system, highsymbol-rate PAM-8 signals of 155 GBd are generated by an arbitrary waveform generator (AWG) with an analogue bandwidth of around 80 GHz operating at 256 GSa/s, which is a prototype from Keysight Technologies M8199B, and an inhouse InP-DHBT amplifier module with a >130-GHz bandwidth [16]. We assume that future 4lane 1.6-Tb/s Ethernet will use the 64B/66B encoding and 256B/257B transcoding, used in the latest Ethernet [17] and considered in the current task force [1], and a soft-decision FEC (O-FEC) [19] with overhead of 15.315% instead of the conventional KP4-FEC [17]. 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 signals are generated by a lithium niobate Mach-Zehnder modulator (LN-MZM) with a bandwidth of 65 GHz. The modulated optical source, with an optical wavelength of 1305 nm that is emitted from the laser diode (LD) is amplified up to 20 dBm by using a praseodymium-doped fibre amplifier (PDFA) while maintaining the polarization state by a polarization controller (PC). The modulated optical signals are amplified up to 20 dBm as the output of the transmitter system. The power of the transmitter output is adjusted from -5 dBm to 13.6 dBm by a variable optical attenuator (VOA) as the input of the receiver system. From the optical signal spectrum at the transmitter side in Fig. 2(b), an ultra-wideband signal of 155 GBd is obtained by broad-band devices, e.g., an inhouse InP-DHBT amplifier module. In the receiver system, the out-of-band ASE noise in the optical signals is removed by an optical band path filter (OBPF). A PIN photodiode (PIN-PD) converts 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 decoder is our previously proposed nonlinear maximum likelihood sequence estimator (NL-MLSE) [9] with 5-memory. The NL-MLSE improves the performance of conventional MLSE with the replication of the actual transmission system transfer function, including device nonlinearity. In 5-memory NL-MLSE, а desired impulse response filter (DIRF) replicates a transfer function that consists of a Volterra series expansion expressed as  $f(x_n) = \sum_a (p_a x_a + p_a x_a)$  $\sum_{b}(q_{ab}x_{a}x_{b} + \sum_{c}r_{abc}x_{a}x_{b}x_{c}))$ , where the symbol index numbers n, a, b, and c are satisfied with  $a \ge b \ge c$  and are integers between -4 and 0, and  $p_a$ ,  $q_{ab}$ , and  $r_{abc}$  represent linear, 2nd, and 3rdorder kernel weights, respectively. The total number of kernels is 55, consisting of 5 linear, 15 2nd-order, and 35 3rd-order kernel weights.

Figure 2 (c) shows the back-to-back characteristics of the 400-Gb/s signals. The receiver input optical power in this figure is the optical power of the input of the receiver system. A conventional feed-forward equalizer (FFE) is used as a comparison for decoding algorithms. As shown in this figure, NL-MLSE improved the bit error rate (BER) compared with FFE for all receiver input powers. That is, NL-MLSE could extend the margin for a power budget of 400-Gb/s/lane signals at the receiver side.

#### 1.6-Tb/s 10-km O-band SDM transmission 4core 1-km fibre installed in NTT labs' cable tunnel

Figure 3 (a) shows the experimental setup for 1.6-Tb/s transmission with the transmission wavelength set near the zero-dispersion wavelength using 4-core fibre. The transmitter and the receiver in this figure are the same as those in Fig. 2(a). To input optical signals into each core of the 4-core fibre, optical signals are split into four branches. At this time, fibres of different lengths of 10 to 30 m are connected before input to each core to decorrelate the signals. Each of the branched optical signals is input into each core of the 4-core fibre by a fan-in fan-out (FIFO) device. We transmitted the 400-Gb/s/lane signals through a 10-km multicore fibre



Fig. 1: (a) Experimental setup of back-to-back configuration, (b) optical signal spectrum at the transmitter side and (c) BER of B-to-B characteristics vs. received optical power at 155-GBd PAM-8 signal.

testbed installed in the NTT laboratory's cable tunnel to emulate a field-deployed fibre, consisting of 10 spliced pairs of 1-km-long 4-core 125-µm-standard-cladding fibre cables designed with a step-index profile [18]. Figure 3 (b) shows that the zero-dispersion wavelength of each core of the multi-core fibre was within  $\pm 0.33$  nm of the centre wavelength. The measured signal wavelength was set to 1305 nm at the zerodispersion wavelength. Optical signals output from the installed fibre were split into outputs from each core by a FIFO device. The optical signal to be measured was then selected by the optical switch and received by the receiver system.

Figure 3 (c) shows the 10-km installed multicore fibre transmission performance with conventional FFE and our proposed NL-MLSE for each core. By using NL-MLSE, the BER for each core was less than 2.0×10<sup>-2</sup>, i.e., the O-FEC threshold [19]. That is, we successfully achieved 400-Gb/s/lane net and 1.6-Tb/s IM-DD transmission over the installed 10-km 4-core fibre. Assuming that the next standard 10-km 800GbE is realized with 4 lanes of 200 Gb/s/lane PAM-4 in LAN-WDM, it can be estimated that a transmitter using a fixed wavelength light source will have sufficient dispersion tolerance for a 2-1.6-Tb/s transmission in this km SDM configuration. The multi-core fibre, which enables transmission in multiple lanes with aligned dispersion characteristics, and a transmitter that modulates the light sources branched from a single wavelength-tunable light source matched to zero dispersion wavelengths, enable 10-km 1.6-Tb/s transmission with suppressed chromatic dispersion effects.

To discuss the effect of the NL-MLSE on the 10-km-transmission signals at core 3, we compared the transmission performances of conventional MLSE and NL-MLSE as a function

of the number of kernels in the DIRF as shown in Fig. 4(a). We fine-tuned the number of 3rd-order kernels by removing kernels with a lower effect by our proposed algorithm in [20]. The performance with linear and the 2nd-order kernels was better than that with conventional MLSE (which considers only linear terms). Figure 4 (b) shows the absolute values of the kernel weights for a 5-memory 3rd-order Volterra filter with 35 3rd-order kernels after DIRF convergence. Note that where the values of kernel weights are colourless, they represent duplicate combination terms and were values of kernel weights that were not used in the actual calculation. Since the 3rd-order kernels were firmly present, the increase in the number of kernels had the effect of improving the performance of NL-MLSE (see the area surrounded by dotted lines in Fig. 4(a)).

### Conclusion

We demonstrated, for the first time, 1.6-Tb/s 10km O-band IM-DD transmission experiments with 400-Gb/s/lane over installed 4-core fibre. The highest speed, a 400-Gb/s/lane with 155-GBd PAM-8, was achieved in the O-band by using a broadband InP-DHBT amplifier and an NL-MLSE. We proposed an SDM configuration for multi-lane single-fibre transmission to transmit near the zero-dispersion wavelength with a high-symbolrate 400-Gb/s/lane signal. This demonstration shows the potential for further scalability improvements in future DCNs with Ethernet.

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Fig. 4: (a) BER vs. number of kernels in DIRF of MLSE and (b) absolute values of 3rd-order kernel weights.

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