1.6Tb/s Transmission Feasibility Employing IM/DD for Datacentre Networks

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Abstract *We demonstrate the feasibility of an aggregate data-rate of 1.6Tb/s using 200Gb/s per lane. Eight O-band wavelengths carrying 112GBd PAM4 are employed to demonstrate transmission over 2km of SSMF at the HD-FEC threshold of* $1.75{\times}10^{-3}$.

Introduction

Recent advances in cloud-based services have contributed to an exponential growth in datacentre traffic. According to recent estimates, in the near future, datacentre traffic will increase with a compound annual growth rate of 27%[1]. As a result, the throughput demands of the switches inside datacentre will grow accordingly.

Currently, commercial high-speed Ethernet switches achieve throughputs of 12.8Tb/s with logical interfaces of up to 400GE. Furthermore, several vendors announced the availability of 25.6Tb/s throughput switches to address the ever-increasing datacentre traffic. Accordingly, doubling or even quadrupling of Ethernet speeds to 800GE and 1.6TE is foreseen[2]. Recently, an 800G pluggable multi source agreement (MSA) was formed to target specifications for the physical layer interface for datacentre networks with a link length of up to 2km[3].

For these short-reach applications, intensity modulation direct detection (IM/DD) systems are very attractive. Compared to the coherent counterparts, IM/DD systems provide smaller footprint, lower power consumption, heat dissipation and lower unit cost. Currently, active IEEE standards dictate the per lane data-rate of up to 100Gb/s employing 4-level pulse amplitude modulation (PAM4) format[4]. Employing the standard per lane data-rate, 400GE transmission is achieved by four wavelengths using coarse wavelength division multiplexing (CWDM4) around the zero chromatic dispersion (CD) wavelength of 1310nm for standard single mode fibre (SSMF). To support transmission of higher data-rates, recently a continuous wave WDM MSA was formed. This consortium aims to standardize specifications of O-band sources for communication applications requiring 8, 16 or 32 lanes[5].

Keeping the per lane data-rate fixed and simply increasing the number of lanes to achieve future Ethernet standard data-rates of 800GE and 1.6TE is not a cost and power-efficient solution. Hence, increase in per lane data-rate is highly desirable[1]. Several publications have recently reported data-rates in excess of 200Gb/s per lane employing single modulator and single photodetector (PD) with PAM[6]-[11]. In this article we demonstrate the transmission feasibility of the future Ethernet standard data-rate of 1.6Tb/s over short optical links up to 2km. To achieve this, we double the number of CWDM lanes used as well as the per lane data-rate compared to the current IEEE standard for 400GE[4]. O-band transmission over SSMF is employed to minimize penalties due to CD.

1.6Tb/s transmission employing IM/DD

Recently the micro-optic WDM (MWDM) wavelengths were proposed for 5G front-haul applications[12]. In order to increase the number of channels over a single fibre, standard CWDM lasers are used and their wavelengths are detuned by ±3.5nm employing thermoelectric coolers (TEC). The advantage of this approach is that the commercially available CWDM4 sources can be employed with the mere addition of a TEC. The same approach is assumed here and the 8 wavelengths of MWDM are given in Tab. 1. Considering a zero dispersion wavelength of 1310nm for SSMF, the accumulated CD values corresponding to each wavelength after 2km transmission are also reported. A net data-rate of 200Gb/s per wavelength is achieved employing PAM4 format with a symbol-rate of 112GBd. On

Tab. 1: MWDM wavelengths calculated from the standard CWDM wavelengths and accumulated CD values after 2km SSMF transmission

No.	CWDM4 [nm]	Δ [nm]	MWDM8 [nm]	Acc. CD [ps/nm]
1	1271	-3.5	1267.5	-8.2
2		+3.5	1274.5	-6.8
3	1291	-3.5	1287.5	-4.2
4		+3.5	1294.5	-2.9
5	1311	-3.5	1307.5	-0.5
6		+3.5	1314.5	0.8
7	1331	-3.5	1327.5	3.2
8		+3.5	1334.5	4.4

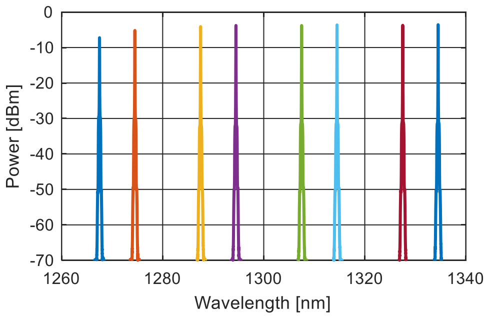

Fig. 1: Spectra of the modulated 8 MWDM wavelengths

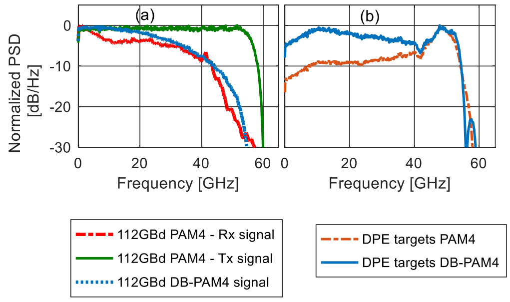

Fig. 3: (a) Tx, Rx and DB-PAM4 PSD, (b) Tx PSD with DPE

top of payload data, a 12% FEC overhead is included, which is sufficient for the HD-FEC RS(1023,913) code. The net coding gain of this code is 8.19dB at a bit error ratio (BER) of 10^{-15} and the threshold input BER is 1.75×10^{-3}. Spectra of the modulated MWDM wavelengths are shown in Fig. 1. The power budget is calculated considering penalties of link insertion loss, transmitter dispersion penalty, differential group delay and multipath interference, as discussed in[12]. Here, we assume the same values and include 3dB of Mux/Dmux losses on top[14]. The total power budget sums up to 11.7dB for each lane. Considering a typical transmitter optical output power of 2dBm, receiver sensitivity is calculated to be ≤-9.7dBm.

Experimental setup, results and discussion

A diagram of the experimental setup is shown in Fig. 2. Transmitter (Tx) digital signal processing (DSP) was performed offline. First of all, a 112GBd PAM4 symbol sequence (pseudo random quaternary sequence (PRQS)) was generated[15]. Upsampling to 120Gsamples/s, pulse shaping and digital preemphasis (DPE) then followed. The resulting waveform was uploaded to the memory of an AWG, which operated continuously at a sampling rate of 120Gsamples/s. The DPE filter coefficients were first calculated by comparing the received and the transmitted waveforms employing an indirect learning architecture[16]. The DPE filter compensated for the linear distortions (magnitude and phase) arising from all the electrical and electro-optical components in the whole system.

Fig. 3(a) shows the power spectral density (PSD) of transmitted and received waveforms for the 112GBd PAM4 signal. As a reference, the PSD of duobinary (DB) shaped 112GBd PAM4 waveform is also shown in the same plot. It is worth noting that the received signal suffers drastic attenuation due to the bandwidth limitation of the channel especially at frequencies >40GHz. At the Nyquist frequency of 56GHz, the received signal is >25dB attenuated. Comparing the PSD of an ideal 112GBd DB-PAM4 signal (Fig. 3(a) blue dashed curve) to that of the received signal, much similarity is observed with a maximum difference up to 5dB. Consequently, it is relatively simpler to precompensate the Tx signal targeting DB-PAM4 shape, which is also the approach adopted here. A comparison of digital Tx signal PSD after DPE targeting PAM4 and DB-PAM4 shapes is shown in Fig. 3(b). The relative attenuation at zero frequency compared to the high frequencies is ~9dB higher in case of PAM4 target.

The electrical waveform generated by the AWG was amplified by a driver amplifier, the output of which drove a Mach-Zehnder modulator (MZM). The MZM was fed in by a laser source whose wavelength was tuned to the considered MWDM wavelengths according to Tab. 1. The laser power was fixed at 12dBm for each wavelength.

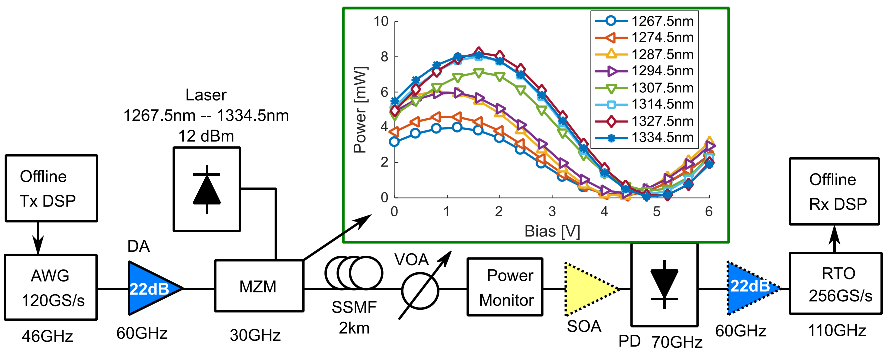

Fig. 2: Experimental setup. Inset: MZM characteristics. DSP: digital signal processing, AWG: Arbitrary Waveform Generator, DA: Driver Amplifier, VOA: Variable Optical Attenuator, SOA: Semiconductor Optical Amplifier, PD: Photodetector, RTO: Realtime Osc.

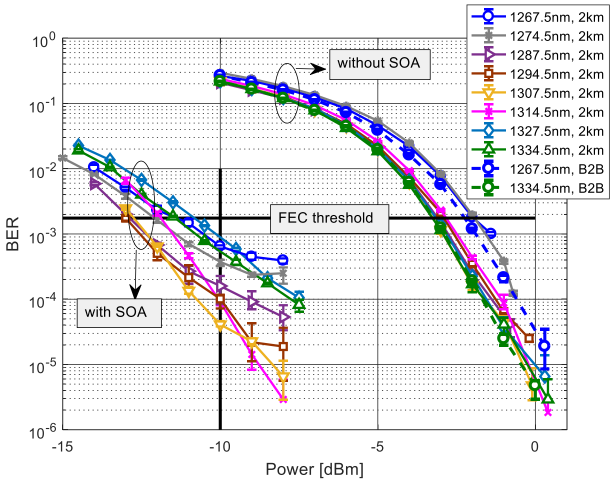

Fig. 4: BER vs power for the 8 wavelengths

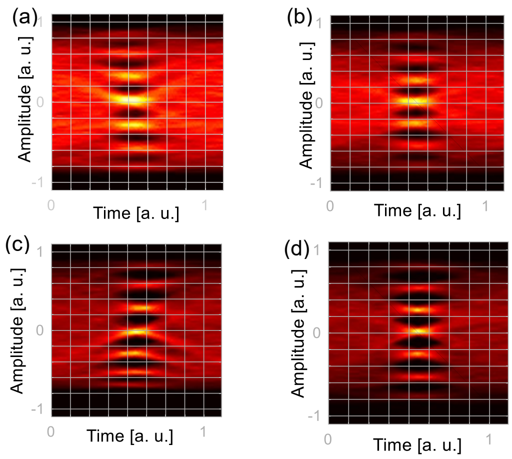

Fig. 5: Eye diagram after FFE for 1334.5nm at -3dBm
Without SOA: (a) Linear FFE (b) NL FFE
With SOA: (c) Linear FFE (d) NL FFE

It is worth mentioning that the MZM used in this experiment is a commercial device meant for C-band operation. Consequently, its characteristics vary significantly depending on the specific wavelength used from the MWDM list. The MZM transfer curves for different wavelengths are reported in Fig. 2 inset. The insertion loss of the MZM was ~3dB higher and extinction ratio was ~5dB lower for 1267.5nm compared to 1334.5nm. The bias of the MZM was adjusted to minimize the BER at each wavelength individually. The modulated output power of the MZM at the operational point was ≥2.0dBm for each wavelength.
The output of the MZM was fed into 2km SSMF, which provided a loss of 2dB. The output of the SSMF was fed into a variable optical attenuator (VOA) to vary the optical power. In the first experiment, no SOA was used and VOA output impinges the PD directly. The electrical waveform output from the PD was amplified by an electrical amplifier similar to the one used as DA and sampled by a real-time oscilloscope (RTO) which operated at 256Gsample/s, had an analogue 3dBbandwidth of 110GHz and a digital resolution of 10 bits. The captured digital waveforms were processed offline for performance evaluation.
The Rx DSP steps include resampling, timing recovery, equalization, and BER calculation. The equalizer uses a 3rd order Volterra structure with 251 linear taps, 9 2nd-order taps and 7 3rd-order taps. In view of the severe bandwidth limitations of the setup, the feed-forward equalizer (FFE) targets a DB-PAM4 shape, so that noise enhancement due to equalization can be avoided[7]. Consequently, after FFE, there is a known inter-symbol interference (ISI) among adjacent symbols. This ISI was removed using a Viterbi equalizer. The BER of the 8 MWDM wavelengths after 2km transmission is shown in Fig. 4. Without SOA amplification, apart from 1267.5nm and 1274.5nm, the performance of all the other wavelengths is quite similar, with each wavelength reaching the FEC threshold for a received optical power of ~-3dBm. For the two shortest wavelengths, the sensitivity is ~1dB worse, which is attributed to the diminished MZM extinction ratio rather than the transmission penalties. This observation is clearer as similar penalty is observed comparing back-to-back performance of the shortest and the longest wavelengths (shown in the same plot with dashed lines). For the measurements with SOA, the X-axis refers to the optical power input to the SOA while a constant 7dBm optical power impinges the PD, which results in the lowest BER. The inclusion of a SOA improves the sensitivity by ~9dB and the FEC threshold is reached at ≤-10dBm for all the wavelengths. Hence, all the wavelengths satisfy the considered power budget and error free transmission of 1.6Tb/s is established. The impact of nonlinear equalization as well as optical amplification is illustrated by the eye diagrams shown in Fig. 5 for 1334.5nm at a received optical power of -3dBm. Employing a SOA, a significant eye opening is observed comparing Fig. 5(a)/(b) to (c)/(d). The 7 levels in the eye diagram correspond to the DB-PAM4 output from the equalizer. When only linear FFE is employed, a level-dependent skew is clearly observed from Fig. 5(a) and (c). The skew is completely removed by the nonlinear FFE as visualized in Fig. 5(b) and (d).

Conclusions

We successfully demonstrated 1.6Tb/s net data-rate transmission feasibility employing eight MWDM wavelengths in the O-band for datacentre interconnects up to 2km. Power budget of 11.7dB is successfully satisfied with transmitter output power of 2dBm per wavelength and SOA based amplification.

References

[1] Cisco Global Cloud Index: Forecast and Methodology, 2015–2020, [online] Available: https://www.iotjournaal.nl/wp-content/uploads/2017/02/white-paper-c11-738085.pdf

[2] John D'Ambrosia, "Beyond 400 Gigabit Ethernet", [online] Available: https://www.novuslight.com/beyond-400-gigabit-ethernet_N9811.html

[3] 800G pluggable MSA, [online] Available: https://www.800gmsa.com/

[4] 802.3-2018 - IEEE Standard for Ethernet, [online] Available: https://standards.ieee.org/standard/802_3-2018.html

[5] CW-WDM MSA, [online] Available: https://cw-wdm.org/

[6] Talha Rahman, *et al.*, "LUT-assisted pre-compensation for 225 Gb/s/λ O-band transmission", ECOC, Sep. 2019, Dublin

[7] Jinlong Wei, *et al.*, "Experimental comparison of modulation formats for 200 G/λ IMDD data centre networks", ECOC, Sep. 2019, Dublin

[8] Tom Wettlin, *et al.*, "Comparison of PAM Formats for 200 Gb/s Short Reach Transmission Systems", OFC, Mar. 2020

[9] M. Jacques *et al.*, "Net 212.5 Gbit/s Transmission in O-Band with a SiP MZM, One Driver and Linear Equalization," OFC, Mar. 2020, Th4A.3

[10] N. Diamantopoulos *et al.*, "Net 321.24-Gb/s IMDD Transmission Based on a >100-GHz Bandwidth Directly-Modulated Laser," OFC, Mar. 2020, Th4C.1

[11] S. T. Le, *et al.*, "1.6Tbps WDM Direct Detection Transmission with Virtual-Carrier over 1200km," OFC, Mar. 2018.

[12] China Communications Standards Association, [online] Available: http://www.ccsa.org.cn/english/

[13] Enabling the next generation of cloud & AI using 800Gb/s optical modules, sec. 4.2, [online] Available: https://cdn-cms.f-static.net/uploads/2598123/normal_5e69e237de8a9.pdf

[14] Sumitomo AWG [online] Available: https://global-sei.com/fiber_optic_interconnect/products/FlexBeamGuidE/TFF_AWG.html

[15] Ilya Lyubomirsky, "PRQS Test Patterns for PAM4", IEEE 802.3bs 400GbE Task Force, [online] Available: https://www.ieee802.org/3/bs/public/15_09/lyubomirsky_3bs_01_0915.pdf

[16] G. Khanna, *et al.*, "A Robust Adaptive Pre-Distortion Method for Optical Communication Transmitters," in *IEEE PTL*, vol. 28, no. 7, 2016.