Partial Response O-band EML Transmission Beyond 300-GBd with a 128/256 GSa/s DAC

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Abstract: We experimentally compared 128 and 256-GSa/s DACs using partial response signaling. Transmission of 310-GBd OOK is demonstrated with a single 128 GSa/s DAC for up to 5-km without optical amplification (net 268.84Gb/s, AIR ≈ 300Gb/s).

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1. Introduction

Due to the increasing reliance on cloud-based services for storage as well as processing of data, the data traffic through the data centers continues to grow exponentially. In order to keep up with the growing demands, Ethernet standards have also evolved to 400 GbE and discussions are ongoing for 800 GbE and 1.6 TbE standardization [1]. For the short reach interconnects within datacenters, intensity-modulation direct-detection (IM/DD) systems are highly attractive due to their simpler architecture and lower power consumption. Furthermore, to avoid penalties due to fiber dispersion, operation in O-band (where dispersion-related penalties are minimal) is adopted. Electro-absorption modulators with a distributed feedback laser on a single chip (externally modulated laser, EML) have a smaller footprint as well as lower insertion loss than the Mach-Zehnder-Modulators, making them well suited for short-reach optical interconnect applications. Reduction in the number of optical components is highly desired to reduce system costs as well as power consumption, which can be achieved by transmitting large symbol-rates on each optical lane. The main restrictions are the bandwidth of electro-optical components as well as the sampling speed of digital-to-analog converters (DAC) and analog-to-digital converters (ADC). In order to mitigate penalties due to bandwidth limitations, partial response signaling using polybinary filtering can be used. The resulting inter-symbol interference can be recovered using maximum-likelihood sequence estimation (MLSE) at the receiver. Furthermore, symbol-rates higher than DAC / ADC sampling rate may be transmitted employing a subsampling approach. Recent high symbol-rate demonstrations with high bandwidth C-band components have utilized this scheme [2][3].

In this article we report the experimental transmission of symbol-rates up to 350 GBd employing a DAC with sampling rate of 128 or 256 GSa/s and ADC with sampling rate of 256 GSa/s. We optimized the performance by sweeping the memory of the polybinary filter at the Tx (and MLSE at Rx) for each symbol rate. In this experiment, we employ an O-band EML, which has a bandwidth of ~55 GHz and demonstrate transmission up to 5 km.

2. Experimental Setup and DSP

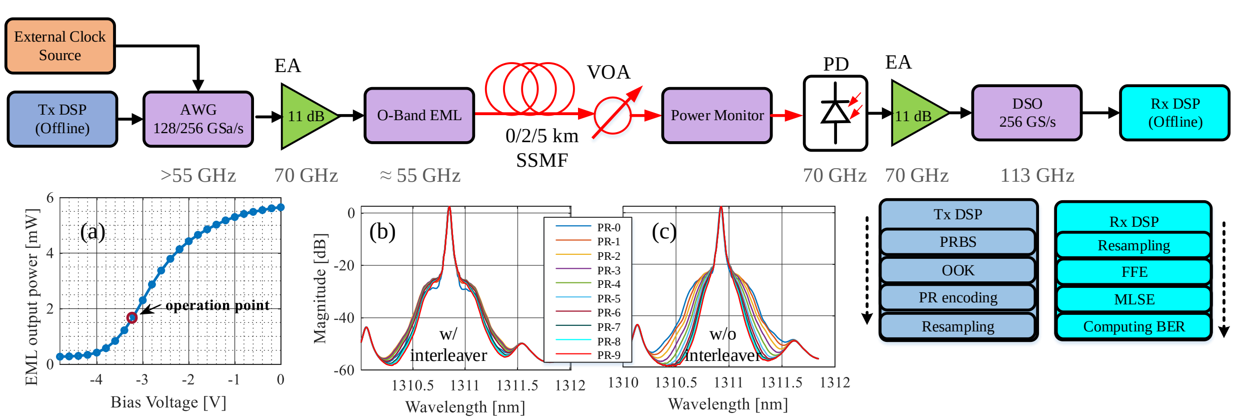

Fig. 1: Diagram of the IM/DD transmission system with transceiver offline DSP. Inset (a) shows the transfer curve of the EML. Inset (b) and (c) show the optical spectrum with different orders of partial response with and without interleaver, respectively.

Fig. 1 depicts the schematic diagram of the experimental setup. The 3 dB bandwidth (BW) of each electro-optical component is reported below the corresponding blocks. Both the transmitter and receiver use offline digital signal processing (DSP). At the transmitter-side, a pseudorandom binary sequence (PRBS) is generated and mapped to on-off keying (OOK) symbols. Afterwards, partial response (PR) encoding [4] is performed to concentrate the signal energy in the low-frequency region. The PR encoded signal is then resampled to match the sampling frequency of the arbitrary wave generator (AWG). The resampling is performed in frequency domain to remove the surplus high-frequency components which lead to aliasing. To this end an anti-aliasing filter is employed. Afterwards the signal is converted in the time domain. Afterwards, the resampled signal is quantized and fed to the AWG.

In this paper, transmission is demonstrated with 230 GBd to 350 GBd OOK signals. In single-channel mode, employing a 64 GHz external clock source, the DAC can operate at 128 GSa/s sampling frequency. Moreover, with a passive interleaver, which combines two DAC channels, keeping the external clock source fixed at 64 GHz, the sampling frequency can be increased up to twice. Additionally, an electrical amplifier is necessary to compensate for the losses induced by the passive combiner [5]. Although the sampling frequency is doubled, even after system calibration the channel end-to-end BW degrades by up to 10 GHz. The generated PR encoded symbols for different symbol rates are resampled at either 128 GSa/s or 256 GSa/s. The optical spectrum of the OOK signal with symbol rate of 310 GBd with PR encoding of orders 0 to 9 is shown in Fig. 1(b) and (c), where Fig. 1(b) is obtained while using interleaver and Fig. 1(c) is obtained with single DAC. Comparing the signal without PR encoding (PR-0) it can be seen that the signal power degrades mainly due to the less available BW for the scenario with the interleaver.

Afterwards, the resampled signal is quantized and fed to the AWG. A 70 GHz electrical amplifier (EA) with fixed gain of 11 dB amplifies the output of the AWG. The amplified electrical signal is modulated with an O-band EML (3 dB BW ≈ 55 GHz), which is biased at -3.1V for linear operation (EML transfer curve is presented in Fig. 1 (a)) whereas a 60 mA current is supplied to the integrated laser diode of the EML. The integrated laser has a center frequency of ≈ 1310.9 nm. At the bias point, the optical output power is approximately 4.2 dBm. During the experiments, the investigations were done in optical back-to-back (B2B) configuration and for a transmission distance of 2 km over standard single mode fiber (SSMF). Additionally, for a 5-km transmission a sweep of the received optical power (ROP) is performed for the 310-GBd OOK case. A variable optical attenuator (VOA) is inserted after the SSMF to sweep the ROP. The optical signal is then detected and converted to an electrical signal with a 70 GHz PIN photodetector (PD). A commercial transceiver would contain a transimpedance amplifier (TIA) after PD. However, this experiment is conducted with a 11 dB fixed gain 70 GHz electrical amplifier (EA) due to the unavailability of a TIA. Besides, an optional inline optical power monitor is inserted between the VOA and the PD to monitor the ROP.

The amplified electrical signal is then quantized and captured with a digital storage oscilloscope (DSO), which operates at 256 GSa/s with 3 dB BW of 113 GHz. Data is captured for different symbol rates and without PR encoding to 9th order PR-encoding. Up to 9. In each configuration Four million samples are used for receiver-side offline processing. The received signal is then resampled to 1 sample per symbol. To avoid timing offset, during data capture, the clock of the DSO was synchronized with the AWG. The resampled symbols are then equalized with feed-forward equalization (FFE) with 451 linear taps to minimize the effect of reflections from the discrete component setup, long copper cables and connectors. Then to revert the induced controlled inter-symbol interference (ISI) with different order PR encoding and recover the binary sequence, maximum likelihood sequence estimation (MLSE) [6] is utilized. The memory length of the MLSE depends on the PR order. For MLSE, 1.5 million symbols were used as training symbols to get the channel model, which is then used as Trellis input and performed the maximum likelihood sequence estimation on 2.5 million symbols. Then the bit error ratio (BER) is evaluated by error counting on the recovered binary symbols.

3. Result and Discussions

In the experiments, transmissions are performed with OOK from 230 GBd to 350 GBd employing PR encoding and sub-sampling. The PR order is varied from 0 to 9. Fig.2 shows the experimental results in terms of pre forward error correction (FEC) BER as a function of the PR order. Comparing between the scenarios without interleaver (Fig. 2 (a)-B2B and (b)-2-km) to scenarios with interleaver (Fig. 2 (c)-B2B and (d)-2km), the results obtained without interleaver show better performance in all cases. In both cases, B2B and 2km data are captured at 4.2 dBm and 3 dBm, respectively. The power difference of 1.2 dB is due to fiber attenuation (0.66 dB) and insertion loss. Additionally, results presented in Fig. 2 indicate that the optimal PR order shows an upward trend from lower to higher symbol rates. However, for the scenarios with interleaver, a higher-order PR does not essentially improve the performance, while the optimum PR order lies between 4 and 7. On the contrary, for the scenarios without interleaver, higher order PR is beneficial for high symbol rates.

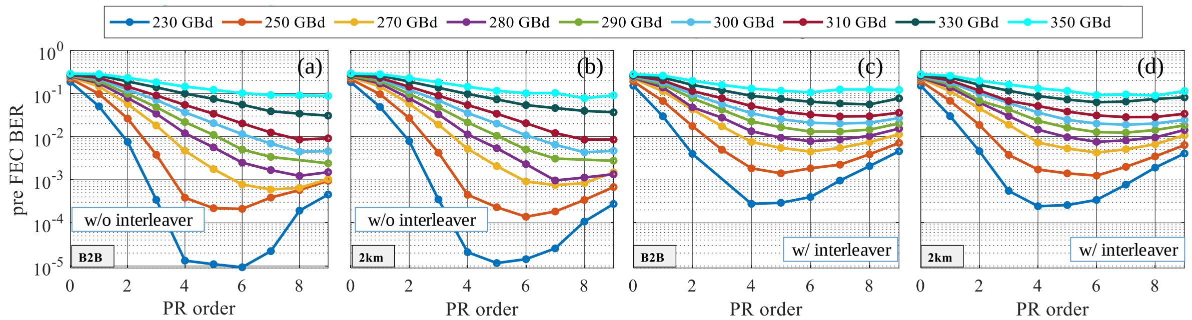

Fig. 2: Experimental results of OOK with different symbol rates employing PR encoding with order from 0 to 9. Results without interleaver for both B2B and 2km are presented in (a) and (b) and without interleaver in (c) and (d), respectively.

Fig 3 (a) shows the lowest possible BER achieved with different order PR as a function of the symbol rate for the B2B and 2-km cases both with and without interleaver. The BER degradation observed with the interleaver is due to the lower available BW (which can be observed in Fig. 1(b)). Assuming a soft-decision (SD) FEC with overhead of 15.31% and threshold of 2×10^{-2} [7], the highest net rate is 260.16-Gb/s with and 268.84-Gb/s without interleaver. Fig. 3(b) translates the BER to the achievable information rate (AIR), considering both hard-decision (HD) and SD. 310-GBd OOK without interleaver results in the highest AIR of ≈ 300-Gb/s.

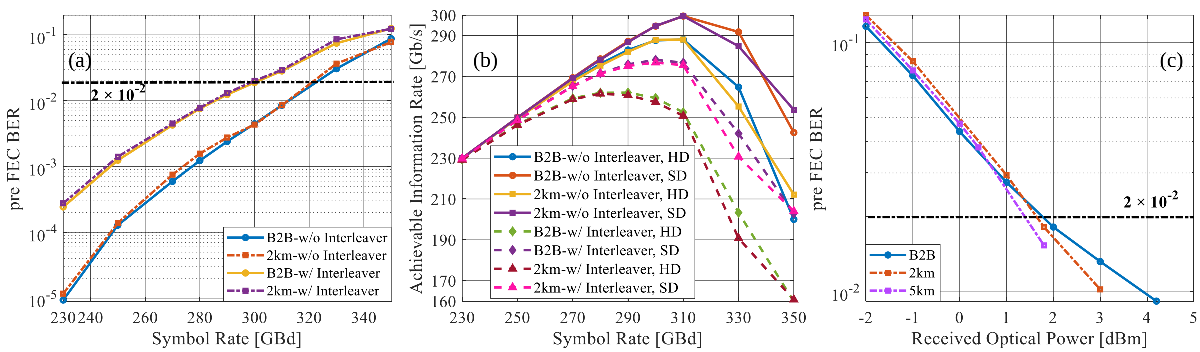

Fig. 3: Experimental results for different symbol rates with and without interleaver for B2B and 2km (a). (b) shows the achievable information rate obtained with HD and SD. A ROP sweep for 310 GBd with PR-8 for B2B with 2 and 5km is shown in (c).

A ROP sweep without interleaver with 310 GBd OOK with PR-8 is presented for B2B and transmission distance for 2 km and 5 km in Fig. 3(c). For all cases, the BER at the maximum ROP is below the SD-FEC BER. However, a negative penalty of 0.5 dB is observed for 5 km transmission. The negative penalty may be attributed to the compensation of the EML chirp by the residual fiber chromatic dispersion at the wavelength of 1310.9 nm.

4. Conclusions

We have experimentally investigated the transmission of OOK with different symbol rates in the cases of a single DAC operating at 128 GSa/s and a dual DAC with passive interleaver with sampling rate of 256 GSa. The signal is generated employing PR encoding and subsampling to match the DAC sampling rate. With passive interleaver, though the sampling rate gets higher, but the available BW degrades. This also leads to better performance with a single DAC, where oversampling does not necessary and bring any gain. With a single DAC up to 310 GBd OOK transmission is successfully demonstrated for B2B and up to 5 km reach and achieves a BER below 2×10^{-2}. The net rate is 268.84 Gb/s and the AIR ≈ 300 Gb/s with SD FEC.

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