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High-Speed Intra-Datacenter Connections Based on VCSEL-MMF Links: Advances and Solutions

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Abstract: We discuss recent advances and solutions to achieve high-speed transmission rates in intra-datacenter connections based on VCSEL and MMF technologies, as required by the ever-growing capacity demand pushed by recent and wide-spread AI-powered applications.

1. Introduction

The widespread of applications exploiting artificial intelligence (AI), particularly large language models (LLMs), is driving an unprecedented increase in the computing capacity required by hyperscale datacenters. Training modern LLMs, characterized by trillions of parameters, necessitates the parallel interconnection of thousands of GPUs, making intra-datacenter connectivity a primary scalability challenge. Optical interconnects have emerged as an effective solution for short-reach links, with systems based on directly modulated vertical-cavity surface-emitting lasers (VCSELs) and multimode fibers (MMFs) already widely deployed in the form of active optical cables and pluggable transceivers (TRX). These solutions are especially relevant for links shorter than 30 m, which account for approximately 40% of datacenter connections and are expected to maintain a similar share in the coming years [1].

Current short-reach TRX typically operate at 100 Gb/s per lane using four-level pulse amplitude modulation (PAM4) format, often combined with short-wavelength division multiplexing (SWDM) across four wavelengths to achieve aggregate data rates of 400 Gb/s. However, the growing demand for higher throughput has created strong momentum toward per-lane speeds of 200 Gb/s and beyond [2], but not without limitations and challenges.

2. Recent Advances and Solutions

Indeed, although with this technology the transmission distance is limited by modal dispersion and bandwidth constraints of MMF, the main limitations to reach such high rates are represented by the bandwidth of the TRX components, i.e. the VCSEL and the photodiode cascaded with the transimpedance amplifier (TIA), and the noise generated by these components–relative intensity noise (RIN) of the VCSEL and thermal noise of the TIA, quantified by input referred noise density (IRND). Besides technological progresses in increasing bandwidth and reducing noise levels of TRX [3,4], higher order PAM formats, like PAM6 and PAM8, or more advance modulation formats, like discrete multi-tone (DMT), may represent potential cost-effective solutions [5,6]. In addition, VCSEL pre-emphasis and more complex digital signal processing (DSP) equalization can help in mitigating TRX bandwidth limitations together with stronger forward error correction (FEC) codes to operate at higher bit error rate (BER) threshold [7,8]. However, many recent demonstrations, like those in [4,7,8], remain confined to back-to-back or highly specific link configurations, with limitation in scope due to the significant statistical variability inherent in VCSEL–MMF links.

2.1. Pulse Amplitude Modulation Formats and Transceiver Requirements

In [9], we presented an extensive simulation statistical analysis on the performance of 200G per lane TRX for next-generation intra-datacenter based on VCSEL-MMF links. There, we investigated the impact of the TRX bandwidth and of different levels of RIN and thermal noise on a 4-lane (850 nm, 880 nm, 910 nm and 940 nm) SWDM system delivering 800G aggregated net rate and operating at a BER threshold (BER_T) of $4 \cdot 10^{-3}$ (Enhanced FEC) using PAM4, PAM6 and PAM8. For this study, a large dataset of thousands of OM3 and OM4 MMF fibers was coupled with 9 different VCSELs characterized in our lab. Because of the statistical variability of MMF, the maximum distance (L_{MAX}) on each lane is defined as the distance guaranteed by the 99% of VCSEL-MMF links. For both OM3 and OM4, we showed the L_{MAX} for the three modulation formats with maximum

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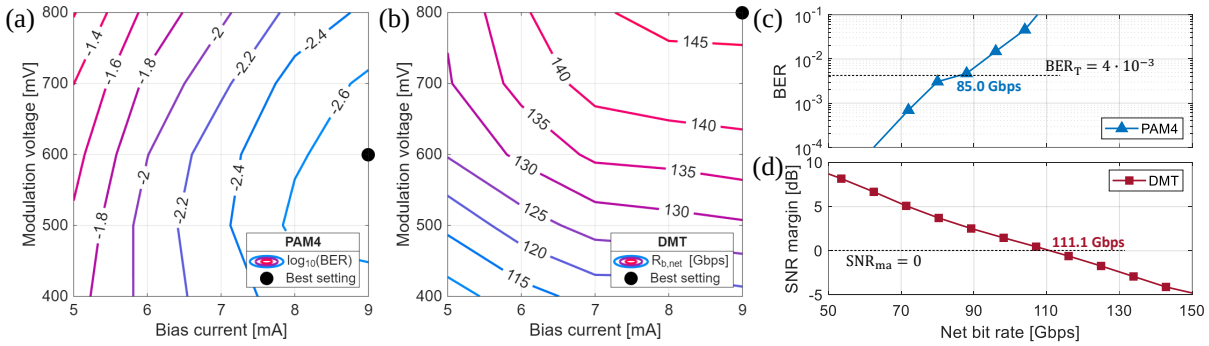

Fig. 1. (a) Optimization of bias current and modulation voltage to minimize the BER in B2B scenario for PAM4 at 120 Gb/s, (b) optimization of bias current and modulation voltage to maximize the transmission rate in B2B scenario for DMT with 9 dB clipping ratio. Maximum net bit rate for transmission over a 90 m OM3 fiber in case of (c) PAM4 and (d) DMT.

likelihood sequence estimation equalization (MLSE) for the selected values of transceiver bandwidth and RIN and IRND levels: $BW_{trx} = 40$GHz, RIN=-148 dBe/Hz and thermal noise IRND=18 pA/$\sqrt{\text{Hz}}$. In both cases, there was a clear advantage in terms of maximum distance when PAM8 is used, as it is less impacted by bandwidth limitations thanks to the lower symbol rate, but at the cost of a more complex DSP. Instead, PAM6 proved to be a potential trade-off solution between distance and complexity.

2.2. A Promising Advanced Modulation Format: Discrete Multi-Tone

An interesting alternative candidate as modulation format for next-generation VCSEL-MMF links is represented by DMT, thanks to its tight adaptability to the channel response through bit and power loading, performed assuming a feedback from receiver to transmitter, and the use of a simpler parallel DSP. In [10], we experimentally compared it with respect to PAM4. The key results are reported in Fig. 1. We initially performed a preliminary optimization of bias current and modulation voltage in back-to-back (B2B) scenario for both PAM4 and DMT. In case of PAM4 (Fig. 1(a)), we achieved a transmission rate of 120 Gb/s, selecting the configuration that minimized the BER as the optimal setting. Instead, for DMT (Fig. 1(b)), we maximized the net bit rate at the $BER_T = 4 \cdot 10^{-3}$ through a rate-adaptive approach, together with clipping ratio and cyclic prefix optimization. Afterwards, we determined the maximum achievable bit rate when transmitting over a 90-m OM3 fiber. The results, reported in Figs. 1(c) and 1(d), respectively for PAM4+MLSE and DMT, show a bit rate of 111.1 Gb/s in case of DMT against the 85 Gb/s of PAM4, proving the advantage of DMT when the channel is strongly frequency selective.

3. Conclusions

In this paper, we overviewed recent advances and possible solutions for next-generation high-speed intra-datacenter links based on VCSEL-MMF technology. Focusing on the modulation formats, we showed the potential of PAM6 and PAM8 over PAM4 to mitigate the impact of TRX bandwidth limitations, but a careful evaluation of the complexity is necessary in case of PAM8. Interesting results were obtained using DMT, that thanks to bit and power loading algorithm, was able to deliver a 31% higher net bit rate compared to PAM4+MLSE.

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