# Challenges and Solutions for High-Speed Intra-Datacenter Connections Based on VCSEL-MMF Links



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***Abstract*—Around 30%-40% of intra-datacenter connections still rely on vertical cavity surface emitting lasers (VCSELs) and multi-mode fibers (MMFs), generally legacy OM3 and OM4. However, the next-generation systems will require transmission throughputs above 100G/lane, with targets towards 200G/lane. An open discussion is undergoing whether VCSEL-MMF technology is still suitable, so in this paper we discuss the challenges and the solutions for high-speed intra-datacenter connections.**



***Index Terms*—Intra-datacenters, multi-mode fibers, vertical Cavity surface emitting lasers,**


## I. Introduction

The rapid proliferation of cloud computing, artificial intelligence, and data-intensive applications has driven explosive growth in datacenter traffic, necessitating continual advancements in network infrastructure. To sustain the surging demand for bandwidth and low latency within datacenters, interconnect technologies have evolved dramatically over the past two decades. The transition from copper-based links to optical solutions has been a critical enabler of scalable, energy-efficient, and high-speed data communication, particularly for short-reach connections within and between server racks.

Among optical technologies, multi-mode Vertical-Cavity Surface-Emitting Lasers (VCSELs) combined with Multi-mode Fiber (MMF) have emerged as the dominant choice for short-distance datacenter interconnects. The low manufacturing cost, high modulation bandwidth, and ease of integration make VCSELs highly suitable for dense, high-speed links over MMF, which provides cost-effective, flexible cabling optimized for distances typically under few hundreds meters.

Early datacenter links using VCSEL-MMF technology operated at 1 Gb/s per lane, conforming to standards such as 1000BASE-SX in the early 2000s. These were sufficient for the initial phases of datacenter networking but quickly became inadequate as application requirements intensified. As a matter of fact, higher rates became necessary, which were supported by improvements in the MMF fiber specifications and in the VCSEL design, especially for higher modulation bandwidth. Speeds of 10 Gb/s per lane were standardized by the 10GBASE-SR, followed, in the mid-2010s, by the 100GBASE-SR4 standard, which enabled 100 Gb/s aggregate traffic using four lanes at 25 Gb/s. Further improvements in the VCSEL modulation bandwidth and the introduction of more advanced digital signal processing (DSP) enable increases in per-lane throughput up to 50 Gb/s, with the support of 400 Gb/s intra-datacenter aggregate bi-directional transmissions.

However, there are still open challenges to be overcome for the realization of high-speed VCSEL-MMF intra-datacenter links. Among them the VCSEL modulation bandwidth, fundamentally limited by undesired carrier dynamics and parasitic effects, and the modal dispersion affecting MMF, limiting the bandwidth-distance product. Additionally, increased signal attenuation, inter-symbol interference, and inter-lane crosstalk in dense VCSEL arrays complicate link reliability. Thermal management becomes critical as device power densities rise with speed, affecting both performance and longevity. Furthermore, the adoption of complex modulation formats such as four levels pulse amplitude modulation (PAM4) and advanced DSP to overcome physical limitations increases system complexity, power consumption, and cost. Manufacturing yield and cost control also pose challenges in scaling these technologies to meet the demands of hyperscale datacenters.

Given that $\sim$30%-40% of intra-datacenter connections still rely on VCSELs and MMFs [1], this paper discusses the challenges and the limitations of VCSEL-MMF links for high-speed datacenter transmissions and the possible solutions to reach such high rates. In Section II, a detailed analysis of the main limitations is presented, followed by the investigation of the use of discrete multi-tone (DMT) as a possible solution to


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counteract the channel bandwidth limitations in Section III. With this purpose, through simulations, we compare DMT with PAM4 and PAM8 for a target 200G/lane transmission. Then, the conclusions are drawn in Section IV.

## II. Challenges and Limitations of VCSEL-MMF Links for High-Speed Datacenter Transmission

VCSELs combined with multi-mode fiber (MMF) have become a reference technology for short-reach optical interconnects in datacenters due to their low cost, energy efficiency, and scalability. However, pushing these links to higher data rates—beyond 25 Gb/s per lane and toward 50 Gb/s and beyond—introduces significant technical challenges and physical limitations that must be addressed to maintain signal integrity and cost-effectiveness.

### *A. Intrinsic Bandwidth Limitations of VCSELs*

The modulation bandwidth of a VCSEL is primarily limited by the carrier recombination lifetime and parasitic capacitances and resistances within the device structure [2]. The intrinsic relaxation oscillation frequency typically restricts modulation speeds to the 20–30 GHz range for standard VCSELs. To achieve higher data rates, novel device structures, such as shorter cavity designs, oxide apertures optimization, and improved current confinement techniques, have been developed to push modulation bandwidths beyond 30 GHz [3], [4]. In [5], a first demonstration of lithographic-aperture VCSEL was shown with bandwidths above 29 GHz, that proved to be a promising solution for applications beyond 100G. However, increasing speed often results in trade-offs with output power, spectral linewidth, and device reliability.

### *B. Modal Dispersion and Bandwidth Constraints of Multimode Fiber*

Multi-mode fiber supports multiple propagation modes, each traveling at slightly different velocities, causing modal dispersion that broadens transmitted optical pulses and limits the achievable bandwidth-distance product. Standard OM3 and OM4 graded-index MMFs, commonly deployed in datacenters, offer modal bandwidths in the range of 2000 to 4700 MHz·km [6]. At rates higher than 25 Gb/s, transmission distances are severely limited by modal dispersion. In particular, at 50 Gb/s, the reach is limited to less than 100 m, if additional compensation is not implemented. Although the introduction of laser-optimized fibers with improved refractive index profiles helped in reducing modal dispersion and in extending the bandwidth [7], modal noise and differential mode delay (DMD) fluctuations are still problematic. This gets worse specially at very high speeds, with a substantial impact on link margin and signal integrity.

### *C. Signal Integrity Challenges: Attenuation, Crosstalk, and Inter-Symbol Interference*

At high bit rates, signals become more sensitive to degradations caused by fiber attenuation, modal noise and connector losses. As a matter of fact, at frequencies above 25 GHz, intersymbol interference (ISI) induced by modal dispersion and bandwidth limitations of electro/optical components further reduce the eye opening of PAM modulated signals, with a consequent increase of bit error rates (BER) [8].

Higher speeds are enabled by aggregate transmission in the form of dense VCSEL arrays used in parallel optical lanes, such as configurations with 4, 8 or 16 lanes, which however gives rise to crosstalk between channels degrading the signal-to-noise ratio (SNR) [9]. Thus, crosstalk management is fundamental, but it requires a more sophisticated receiver design, including precise alignment, improved packaging and advanced DSP techniques.

### *D. Thermal Management and Reliability Concerns*

The increase of power levels at which higher speed VCSELs are driven is responsible of the increment of temperatures and thermal effects. Among them we can list the reduction of VCSEL's output power, the increase of threshold currents and the acceleration of the aging process, which compromise both performance and device lifetime [10]. This means that efficient heat dissipation mechanisms, such as advanced packaging materials and active cooling, are essential but add complexity and cost.

### *E. Complex Modulation and Digital Signal Processing Overheads*

Alternative solutions to circumvent bandwidth limitations in high-speed VCSEL-MMF links rely on the adoption of advanced modulation formats like PAM4, that allows to effectively double the bits transmitted per symbol and reduce the SNR margin [11]. However, PAM4 requires a more sophisticated DSP for equalization and error correction, with a consequent increase of system complexity, power consumption and costs, in contrast with the constraints imposed by datacenter operators' on energy efficiency and budgetary [12]. So, the tradeoff between modulation complexity and cost is still a critical design challenge.

### *F. Manufacturing and Scalability Challenges*

Scaling VCSEL and MMF technology to support higher speeds while maintaining high manufacturing yield and low cost is nontrivial. High-precision fabrication, rigorous testing, and quality assurance are necessary to ensure device uniformity and reliability at scale [13]. Additionally, maintaining fiber quality and connector precision is essential for minimizing modal noise and ensuring consistent link performance.

## III. Progresses Towards 200G per Lane

Based on the considerations discussed in the previous section, it is clear that transmissions at rates higher than 100G, such as the 200 Gbps/lane envisioned for the next-generation datacenters, are not trivial. Different research directions are currently being investigated, that try to overcome, or at least to mitigate, these limitations. We have seen that one of the main limitations is represented at the transmitter side by the limited bandwidth of the VCSEL, which is strictly related to the technology itself. Also the relative intensity noise (RIN)

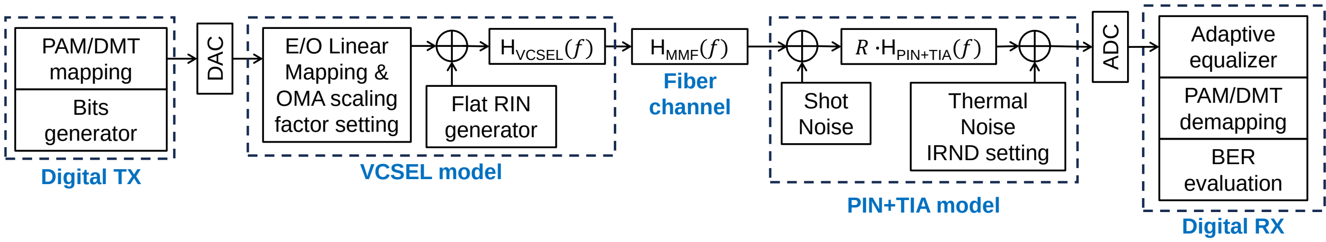


Fig. 1. Simulation setup. DAC: digital to analog converter; RIN: relative intensity noise; $R$: photodiode responsivity; IRND: input referred noise density; ADC: analog to digital converter.

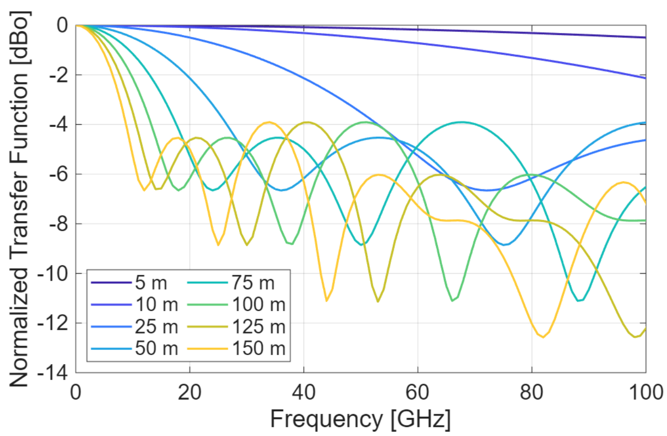


Fig. 2. Example of transfer functions for *Case 1* VCSEL-MMF link at different distances.

generated by the laser can have a significant impact on the system performance. Instead, at the receiver side, the limiting factors are the bandwidth of the cascade of the photodiode (PIN) with the transimpedance amplifier (TIA) and the input referred noise density (IRND). The impact of these two quantities in a system operating at 200 Gbps was investigated in [14], where the performance was studied in terms of maximum reach through simulations over a large dataset of OM3 and OM4 fibers coupled with a set of VCSELs. The results showed that for a PAM4 transmission, a transceiver (TRX) bandwidth of at least 40 GHz is needed to guarantee 20 m and 30 m for the 99% of OM3 and OM4 links, respectively.

However, assuming that the TRX has such a wide bandwidth, it shows that the maximum reach is now limited by the behavior of the channel, which is particularly frequency selective. A possible suitable solution is the use of discrete multi-tone (DMT) modulation format, an advanced modulation format based on multiple orthogonal subcarriers. Similar to the orthogonal frequency division multiplexing (OFDM), it performs bit and power loading algorithms to fully adapt to the channel frequency response. Compared to PAM, DMT requires the introduction of a cyclic prefix (CP) after each DMT symbols and it is characterized by a higher peak-to-average-power-ratio (PAPR), causing penalties [15]. In part this can be mitigated by clipping the DMT signal, where the optimal clipping ratios are in the range of 7 dB to 12 dB.

The adoption of DMT was already supported in [16], but it was tested for just a very short distance and it was not compared to PAM formats. So here, extending the analysis presented in [14], we provide a comprehensive comparison of DMT with PAM4 over three selected VCSEL-MMF links extracted from the dataset considered in [17] with the aim of determining the overall system reach.

## A. Simulation Setup

The simulation setup is shown in Fig. 1, for which we consider the same parameters as in [17]: RIN$= -148$ dBe/Hz, IRND$=18$ pA/$\sqrt{\text{Hz}}$, 40 GHz for VCSEL and and PIN+TIA bandwidth (simply indicated as transceiver bandwidth $\mathrm{BW_{trx}}$). For PAM, we test the performance of two adaptive equalizers, the feed-forward equalizer (FFE) and the maximum likelihood sequence estimation equalizer (MLSE). Enhanced forward error correction (E-FEC) is considered, corresponding to 10.35% FEC overhead and a BER threshold of $4 \cdot 10^{-3}$.

Regarding the DMT, the size of the fast fourier transform (FFT) is set to 1024, with 511 actual modulated subcarriers, the sampling frequency is 128 GS/s, the cyclic prefix is set to 9 dB, and the clipping ratio is optimized between 5 dB and 15 dB. By defining a signal-to-noise (SNR) margin ($\mathrm{SNR_{ma}}$) on each subcarrier, as the SNR distance (in dB) from the FEC threshold, we apply a margin adaptive DMT. This means that for the fixed rate of 200 Gbps net bit rate, bit and power loading based on Levin-Campello algorithm is implemented to maximize the $\mathrm{SNR_{ma}}$ on the worst performing subcarrier.

As mentioned previously, for the fiber channel we analyze three different links. In Fig. 2, we show the normalized transfer functions for increased distance of one of the three. From there we can clearly observe the frequency selectivity of the channel, especially its dependence on distance, and the presence of significant secondary lobes.

Before proceeding with the analysis, we first have to define the optical modulation amplitude (OMA), since it is a parameter that can be optimized to reach longer distances. It is defined as $OMA = 2\bar{P} \cdot OMA_{scale}$, where $\bar{P}$ is the average optical power and $OMA_{scale}$ is the OMA scaling factor. $\bar{P}$ is set to -1.75 dBm, while $OMA_{scale}$ is given by $OMA_{scale} = (ER-1)/(ER+1)$, with $ER$ being the extinction ratio, that can range from 0 to 1.

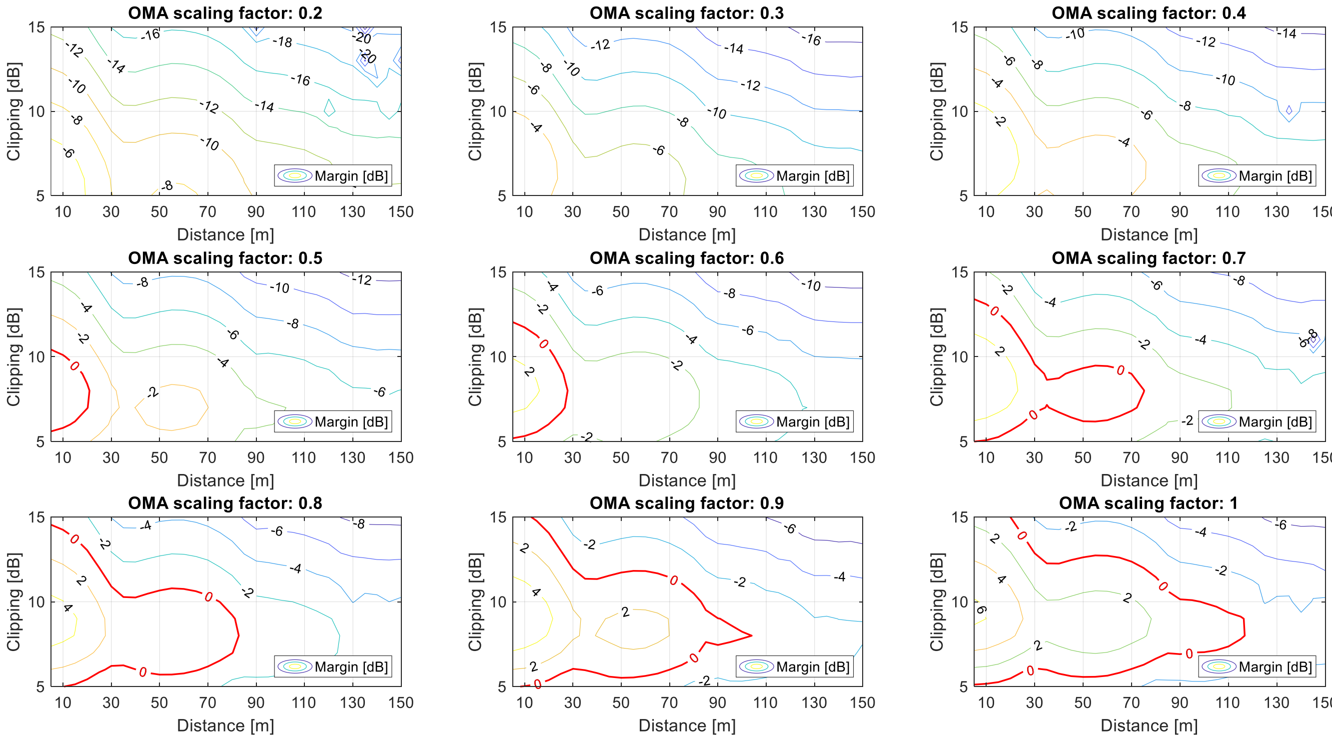


Fig. 3. DMT SNR margin as a function of distance and clipping for different OMA scaling factors and assuming $\mathrm{BW_{trx}} = 40$ GHz.

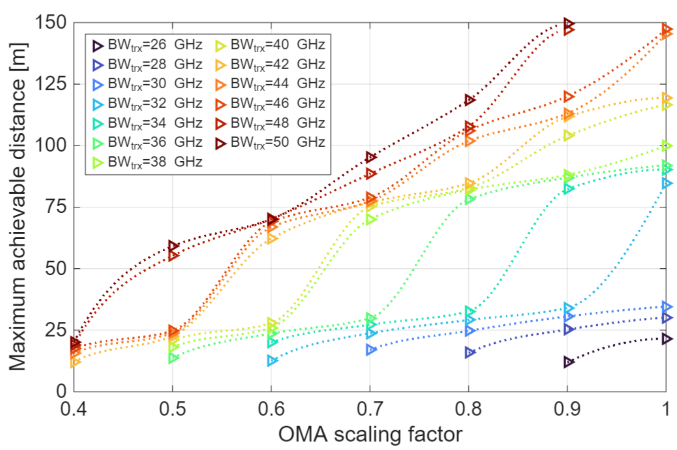


Fig. 4. Maximum achievable distance as a function of the OMA scaling factor for different values of transceiver bandwidth $\mathrm{BW_{trx}}$.

## *B. Simulation Results*

In Fig. 3 we present a set of contour plots showing the SNR margin as a function of transmission distance (x-axis) and clipping ratio (y-axis), varying the OMA scaling factor from 0.2 to 1, for the link with transfer functions in Fig. 2. Each subplot corresponds to a specific OMA scaling factor and assumes a transmitter bandwidth ($\mathrm{BW_{trx}}$) of 40 GHz. The red iso-curves mark the 0 dB SNR margin threshold, highlighting the boundary between feasible (positive margin) and infeasible (negative margin) transmission scenarios. In general, we can see that the system works only when the OMA scaling factor is at least 0.5, with longer distances achieved when the $OMA_{scale}$ is higher. In addition, moving on this iso-curves, we can determine the clipping value corresponding to the maximum achievable distance ($\mathrm{L_{max}}$) for each OMA scaling factor. The resulting values are reported in Fig. 4. We also tested narrower and wider $\mathrm{BW_{trx}}$ and, as expected, longer distances are achieved when the TRX bandwidth is wider. However, we can observe a saturation effect when $\mathrm{BW_{trx}} \geq 48$ GHz, especially for OMA scaling factors between 0.6 and 0.8.

In Fig. 5a), assuming $\mathrm{BW_{trx}} = 40$ GHz, a reasonable value to reach useful distances, we compare DMT with PAM4 and PAM8. The advantage of using DMT over PAM4 and PAM8 is visible only when the OMA scaling factor is at least 0.65 and 0.8, respectively, allowing to reach distances above 50 m. Instead, for $OMA_{scale} < 0.8$, PAM8 is the modulation format reaching longer distances, although it is less preferable due to the higher complexity of the MLSE. In Figs. 5b) and 5c), we report the comparison for the other two selected VCSEL-MMF links.

For case 2 (Fig. 5b)), there is no practical advantage of using DMT. On the other hand, for case 3, DMT outperforms only PAM4 when the OMA scaling factor is at least 0.65. The advantage of using DMT is clearly dependent on the shape of the transfer function of the channel, with advantages over PAM-M when notches and high secondary lobes are present.

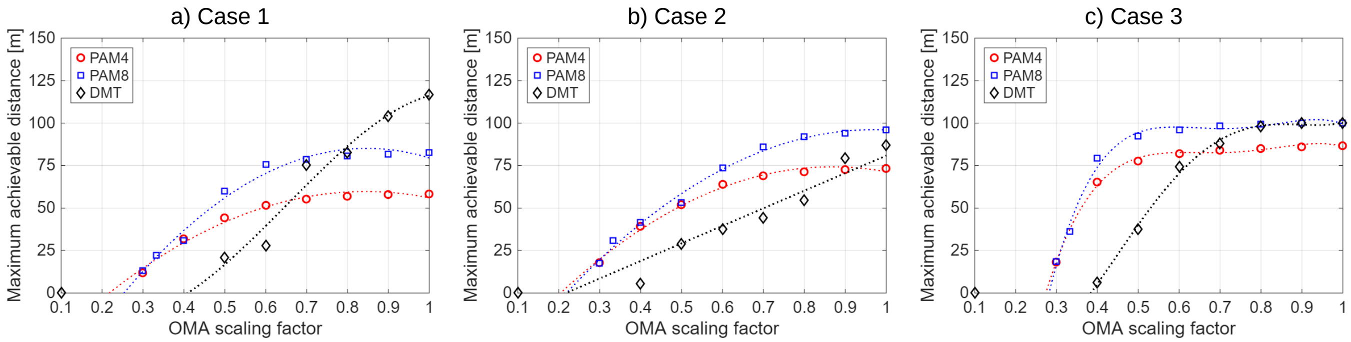


Fig. 5. Comparison of DMT with PAM4 and PAM8 in terms of distance as a function of OMA scaling factor for three different VCSEL-MMF links, assuming $\mathrm{BW_{trx}} = 40$ GHz.

## IV. Conclusions

We reviewed the challenges faced by VCSEL-MMF links for intra-datacenter connections to keep up with the future requirements of 200G/lane throughput. Assuming the possibility to fabricate TRX with large bandwidth (40 GHz), the frequency selective channel becomes the limiting factor to reach longer distances. We investigated the use of DMT for three selected VCSEL-MMF links, showing that its advantage over PAM4 and PAM8 depends on the optimization of clipping and OMA scaling factor, and especially on the frequency response of the channel. DMT proved its potential when the OMA scaling factor is high and when the frequency response of the channel presents notches and high secondary lobes.

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