DMT vs PAM: an Experimental Comparison over VCSEL-MMF Links for Intra-Datacenter Connections

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Abstract *DMT and PAM4 formats are experimentally compared over VCSEL-MMF links targeting rates >100 Gbps. The tight adaptability of DMT to the frequency-selective channel supports its adoption in the next-generation high-speed intra-datcenter connections. ©2025 The Author(s)*

Introduction

Directly modulated Vertical Cavity Surface Emitting Lasers (VCSEL) and Multi-Mode Fibers (MMF) represent one of the most deployed solutions for intra-datacenter links, also in the foreseeable future, mostly thanks to lower costs, massive production and easier modal coupling[1]. Commercial devices deliver 100 Gbps using four levels Pulse Amplitude Modulation (PAM4) format, but higher rates are expected in the next future[2]. However, the VCSEL-MMF link is inevitably frequency selective due to the modal dispersion that affects the MMF, potentially limiting the rates that can be achieved with PAM4. A possible solution is the implementation of advanced equalization schemes, such as the Maximum Likelihood Sequence Estimation (MLSE), or even more complex digital signal processing (DSP) including noise cancellation algorithm, partial response signaling and Volterra nonlinear equalizer (NLE)[3]. In alternative, to keep the DSP simple, Discrete-MultiTone (DMT) modulation is envisioned to be the technology enabling higher data rates over MMF[4],[5].

Originally introduced and adopted in copper-based Digital Subscriber Line (DSL) links[6], DMT is an advanced modulation format based on orthogonal digital multi-subcarriers. In particular, through the implementation of advanced bit and power loading algorithms, DMT is able to adapt the transmission to the channel frequency response, resulting to be advantageous when notches are present. For this reason, its potential use in optical communications was already investigated, like in transmissions over Plastic Optical Fiber (POF)[7].

While the absence of inter-symbol interference (ISI) permits the implementation of a one-tap feed-forward equalizer (FFE), the use of DMT has two main drawbacks: the necessity of inserting a cyclic prefix (CP), which further reduces the available net rate, and a larger peak-to-average power ratio (PAPR)[8]. This strongly penalizes DMT with respect to PAM when used for transmissions over peak-power constrained channels, like in Intensity-Modulation/Direct-Detection (IM/DD) systems[9], and it is one of the main reasons why – at the best of our knowledge – no commercial devices have been developed so far. To partially mitigate this, the DMT signal is usually clipped, with optimal clipping ratios (CR) ranging from 7 dB to 12 dB.

A recent comparison between DMT and PAM4, showed that, when operating at the same optical modulation amplitude (OMA), DMT outperforms PAM4 only if entropy loading is implemented[9]. Nevertheless, the analysis considered a single-mode fiber (SMF), which is less frequency selective than MMF, as modal dispersion is much weaker. To fill this lack of study for MMF links, in[10] we simulatively compared DMT (with bit and power loading) and PAM for transmissions at 200 Gbps over three worst case VCSEL-MMF links, finding that OMA plays a crucial role in determining the best modulation format.

In this paper, through experiments, we show a direct comparison between DMT and PAM4 over a more band-limited scenario than in[5]: OM3 fiber of 90 m length. For PAM4 two different adaptive equalizers – FFE and MLSE – are tested. The results, obtained after a careful optimization of modulation voltage ($\mathrm{V_{pp}}$) and bias current ($\mathrm{I_{bias}}$), show the potential of using DMT over MMF links instead of PAM4 to target transmissions above 100 Gbps net-rate, as required by the next-generation datacom systems. Additionally, the adoption of DMT represents a cost-effective solution because it al-

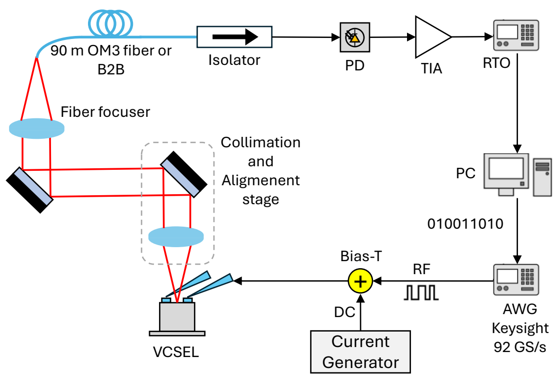

Fig. 1: Scheme of the experimental setup.

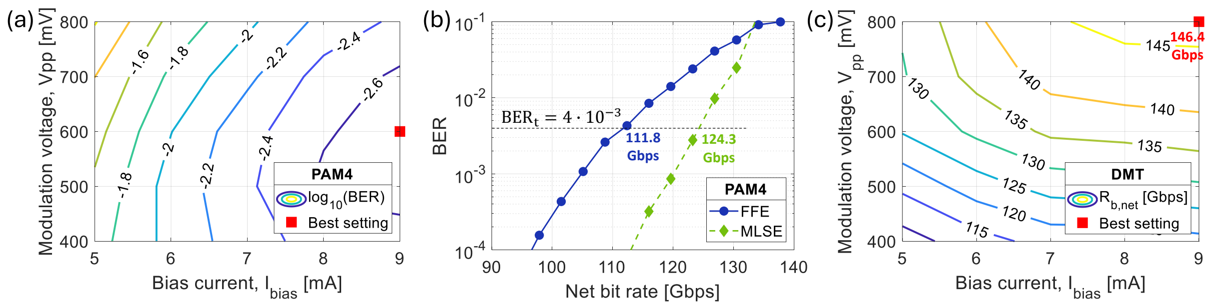

Fig. 2: (a) Optimization of bias current and modulation voltage to minimize the BER in B2B scenario for PAM4 with FFE at 120 Gbps, (b) determination of the maximum net bit rate at FEC threshold in B2B scenario for PAM4, and (c) optimization of bias current and modulation voltage to maximize the transmission rate in B2B scenario for DMT with 9 dB clipping ratio.

lows to fully exploit the already deployed datacenter infrastructures without substituting the legacy MMF links.

Experimental setup

The scheme of the experimental setup is illustrated in Fig. 1. Two configurations are possible: back-to-back (B2B) and transmission over a 90-m OM3 fiber. A fast Digital to Analog Converter (DAC) (AWG Keysight 92 GS/s, 32 GHz), connected to a 850 nm VCSEL with 26 GHz bandwidth via a bias-tee (Bias-T) and a 40 GHz RF probe, generates the PAM4 or DMT signal used to directly drive the VCSEL. A lens-mirror-lens system focuses the modulated light into the tested fiber or directly to the receiver (RX) chain if the B2B scenario is considered. The receiver section consists of an optical isolator, a photodiode (Thorlabs DX30BF) with 30 GHz bandwidth followed by a low noise transimpedance amplifier (TIA) with 50 GHz bandwidth. The received signals were sampled using a fast real-time oscilloscope (RTO) (Tektronix, 70 GHz -200 GS/s) and processed offline.

The digital signal processing (DSP) for the PAM4 signal includes adaptive equalization to mitigate bandwidth limitation effects and inter-symbol interference. Two different adaptive equalizer strategies are tested: a $T/2$-spaced Feed Forward Equalizer (FFE) with 20 taps, optionally followed by a Maximum Likelihood Sequence Estimation Equalizer (MLSE) with 16 states. Then, error counting is performed to compute the bit error rate (BER). Hard-Decision Forward Error Correction (HD-FEC) is considered, in particular the Enhanced-FEC (E-FEC)[11] with 10.35% FEC overhead and target bit error rate ($\mathrm{BER_t}$) equal to $4 \cdot 10^{-3}$.

Regarding the DMT, the frequency spectrum is divided into 1024 orthogonal subcarriers; only 511 of them are modulated to create a real-valued time-domain signal. The cyclic prefix is fixed to 16 samples, while the clipping ratio has been optimized. In this analysis, we implement both rate-adaptive (RA) and margin-adaptive (MA) DMT based on the Levin-Campello (LC)[12],[13] algorithm, optimized to operate at $\mathrm{BER_t} = 4 \cdot 10^{-3}$. Initially, a training quadrature phase shift keying (QPSK) sequence is transmitted to estimate the per-subcarrier signal-to-noise ratio (SNR). Then, bit and power loading are performed to optimize the bit allocation and the relative power on each subcarrier, according to the evaluated SNR and the allocation strategy. For the RA strategy, the bit rate is maximized, up to the point where the worst-performing subcarrier reaches the $\mathrm{BER_t}$. For the MA strategy, instead, the bit rate is fixed. A per-subcarrier SNR margin is defined, which represents the SNR difference (in dB) from the FEC threshold. In particular, the strategy maximizes the SNR margin on the worst performing subcarrier ($\mathrm{SNR_{ma}}$). If $\mathrm{SNR_{ma}} \geq 0$, then the $\mathrm{BER_t}$ (at the fixed data rate) is guaranteed.

Experimental results

As a first step, for both PAM4 and DMT, the optimal working condition that maximizes the rate is determined in B2B scenario, sweeping the bias current ($\mathrm{I_{bias}}$) and the modulation voltage ($\mathrm{V_{pp}}$) in the ranges 5-9 mA and 400-800 mV, respectively. The values for the upper bounds have been selected to prevent the device from damage.

For PAM4, the optimization is done in two stages considering the FFE equalizer. Initially, the different configurations of ($\mathrm{I_{bias}}$,$\mathrm{V_{pp}}$) are tested transmitting at a fixed rate of 120 Gbps (108.8 Gbps net rate) to select the configuration that minimizes the BER. This is shown in Fig. 2(a), where the best setting, represented by the red square, is found for $\mathrm{I_{bias}}$=9 mA and $\mathrm{V_{pp}}$=600 mV. Although the optimal bias current coincides with the upper bound, meaning that a higher value could potentially improve the performance, we imposed limits in order to have the VCSEL working in a safer region. After that, for this best configuration of $\mathrm{I_{bias}}$ and $\mathrm{V_{pp}}$, the system performance is analyzed at different bit rates. Fig. 2(b) reports the BER as a function of the net bit rate for the two equalizer strategies. The resulting maximum bit rates at the $\mathrm{BER_t}$ are 111.8 Gbps and 124.3 Gbps, respectively for FFE and MLSE. As expected, a higher bit rate is achieved with MLSE, as it is a more sophisticated equalizer than FFE.

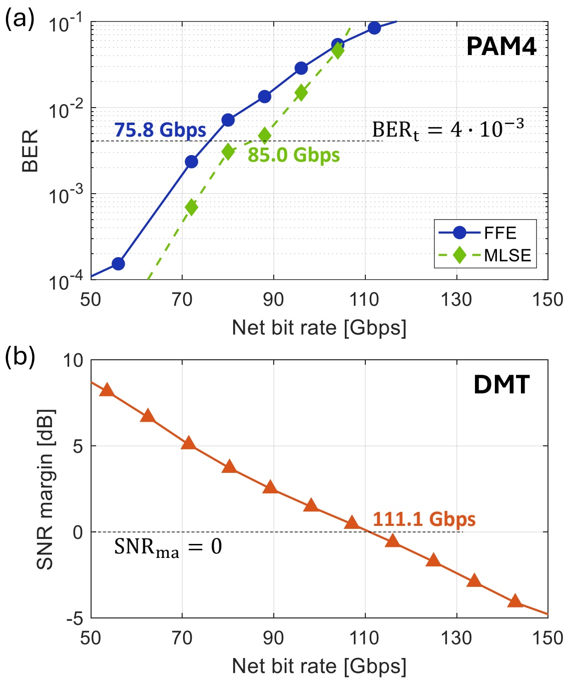

Fig. 3: Maximum net bit rate for transmission over a 90 m OM3 fiber in case of (a) PAM4 and (b) DMT.

Rate adaptive DMT is performed to define the best configuration of (I_{bias},V_{pp}) in B2B. Jointly, the clipping ratio is optimized as well. Fig. 2(c), obtained for the optimal CR=9 dB, illustrates the bit rate achieved by the different configurations of bias current and modulation voltage, showing that a maximum net bit rate of 146.4 Gbps can be reached setting I_{bias}=9 mA and V_{pp}=800 mV. Also here, the upper bounds of I_{bias} and V_{pp} have been selected to avoid damaging the VCSEL.

Compared to PAM4, the best value of V_{pp} is higher for DMT. This is explained by the Gaussian shape of the time-domain DMT signal and the implementation of clipping, which allow to better exploit the swing of the device and have a higher OMA, improving the performance. Following this optimization, already in B2B, with DMT it is possible to transmit at a bit rate which is 17.8% higher than PAM4 with MLSE, as DMT is able to better counteract the limited bandwidth of the VCSEL.

A reduction of the maximum bit rates is expected when the OM3 fiber is inserted in the transmission chain. As a matter of fact, due to chromatic and modal group dispersion, the presence of the fiber induces a further bandwidth limitation to the system. The impact on the PAM4 signal is shown in Fig. 3(a): the maximum net bit rate at the FEC threshold is now 75.8 Gbps and 85.0 Gbps in case of FFE and MLSE, respectively, corresponding to a decrease of 32.2% and 31.6% with respect to the B2B case.

For the DMT, the maximum net bit rate is determined performing a margin adaptive DMT. This is shown in Fig. 3(b), where the SNR_{ma} is reported as a function of the net bit rate. The maximum

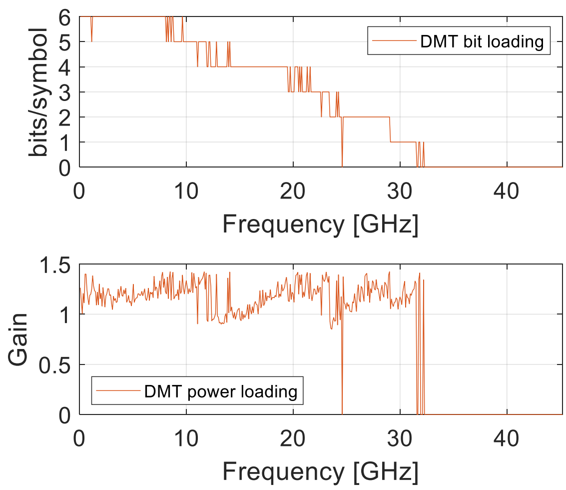

Fig. 4: Bit and power allocation given by the Levin-Campello algorithm for transmission at 111.1 Gbps over the 90 m OM3.

achievable bit rate, obtained for $SNR_{ma} = 0$ dB, is 111.1 Gbps, still a value higher than the PAM4 case. Compared to the B2B scenario, the bit rate reduction is 24.1%, lower than the ∼30% obtained with PAM4. This is a direct consequence of the high adaptability of the DMT to the frequency response of the channel. For reference, the per-subcarrier bit and power allocation returned by the LC algorithm is reported in Fig. 4. From there we can see that larger quadrature amplitude modulation (QAM) constellations are allocated at lower frequencies. Being the system band-limited, at higher frequencies smaller QAM constellations are allocated. For frequencies above 32 GHz, all the subcarriers are turned off, due to the strong band limitation effect.

Conclusions

An experimental comparison between DMT and PAM4 was carried out in B2B condition and for propagation over a 90 m of OM3 MMF, typical of legacy intra-datacenter connections. For PAM4, we tested two different equalizers, FFE and MLSE. To maximize the transmission rates, a preliminary optimization of I_{bias} and V_{pp} was performed in B2B for both DMT and PAM4, achieving bit rates >100 Gbps. Interestingly, this optimization showed that DMT performs better for higher values of V_{pp} than PAM4. Instead, when the fiber is present, only the DMT is able to deliver net bit rates above 100 Gbps, more precisely 111.1 Gbps. This corresponds to a reduction of 24.1% with respect to the B2B case against the ∼30% observed by PAM4, proving the ability of the DMT to adapt to the channel frequency response of the VCSEL-MMF link.

These results are in favor of the adoption of the DMT as transmission format for the next-generation intra-datacenter connections, for which transmissions at high bit rates are mainly limited by the VCSEL bandwidth and the frequency response of the MMF channel.

Acknowledgements

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