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Comparing PAM and DMT for VCSELs-modulated Links over MMF

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Abstract: We present a comparison between PAM and DMT for links over Multi-Mode Fiber, using directly-modulated Vertical Cavity Surface Emitting Lasers. We found that the OMA plays a crucial role in finding the best modulation format. © 2025 The Author(s)

1. Introduction

Discrete-MultiTone (DMT) is an advanced multicarrier modulation format, combining several orthogonal subcarriers with advanced bit and power loading algorithms, that has been first proposed and adopted for copper-based Digital Subscriber Line (DSL) links [1]. This allows to tightly optimize the transmission to the channel's frequency response, without introducing intersymbol interference. Therefore, DMT receivers normally employ only a one-tap feed-forward equalizer (FFE). However, this comes at a cost: the need to insert a cyclic prefix (CP) after each DMT symbol, and a significant increase of the Peak-to-Average Power Ratio (PAPR) [2].

For optical communications, there were many research works that used DMT for short reach communications, such as transmission over Plastic Optical Fiber (POF) [3] and Multi-Mode Fiber (MMF) [4]. Focusing on MMF links, it was predicted [4, 5] that the use of DMT is inevitable to further increase the data-rate over this medium. However, current Standards and Multi-Source Agreements (MSA) are all still based on single-channel transmission, leveraging on Pulse Amplitude Modulation (PAM) combined with advanced equalization techniques, such as Maximum-Likelihood Sequence Estimation (MLSE). In fact, there has been no report of development of commercial devices based on DMT. This is mainly due to the larger PAPR, which introduces a strong penalty on DMT (compared with PAM) on channels with a peak power constraint, such as the Intensity-Modulation/Direct-Detection (IM/DD) channel [6]. While this can be partially mitigated by clipping the DMT signal [2], the optimal clipping ratios are in the range of $7-12$ dB, which is still higher than the PAPR of PAM signals without pulse shaping. According to recent reports, at the same Optical Modulation Amplitude (OMA), DMT outperforms PAM only with the use of entropy loading [6], which has a significantly high complexity. However, in [6] the authors transmitted over SMF, which is weakly frequency selective compared to MMF, since it is immune to modal dispersion. Therefore, the goal of this work is a detailed simulative comparison, at the same OMA, of PAM (with MLSE equalization) and DMT (with bit and power loading), over the frequency-selective VCSEL-MMF link, considering data rates above 100 Gbit/s [4] targeted for the next-generation systems [7].

2. System model and simulation results

The system model, shown in Fig.1, is the same as in [8]. However, in addition to PAM4 format, also PAM8 and DMT are analyzed. At the transmitter (TX) side, the relative intensity noise (RIN) of the VCSEL is set to -148 dBe/Hz [10] and the cutoff frequency of the VCSEL transfer function ($\mathrm{H_{VCSEL}(f)}$) is 40 GHz [9]. At the receiver (RX), the model for the photodiode (PIN) and the transimpedance amplifier (TIA) includes shot noise and thermal noise, with input referred noise density (IRND) set to 18 pA/$\sqrt{\text{Hz}}$ [9]. The photodiode responsivity is R=0.5 A/W and the PIN+TIA transfer function ($\mathrm{H_{PIN+TIA}}(f)$) has 40 GHz cutoff frequency. After adaptive

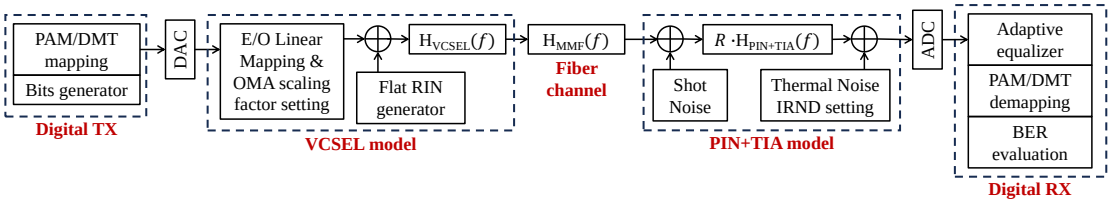

Fig. 1. Simulation setup. DAC: digital to analog converter; RIN: relative intensity noise; R: photodiode responsivity; IRND: input referred noise density; ADC: analog to digital converter.

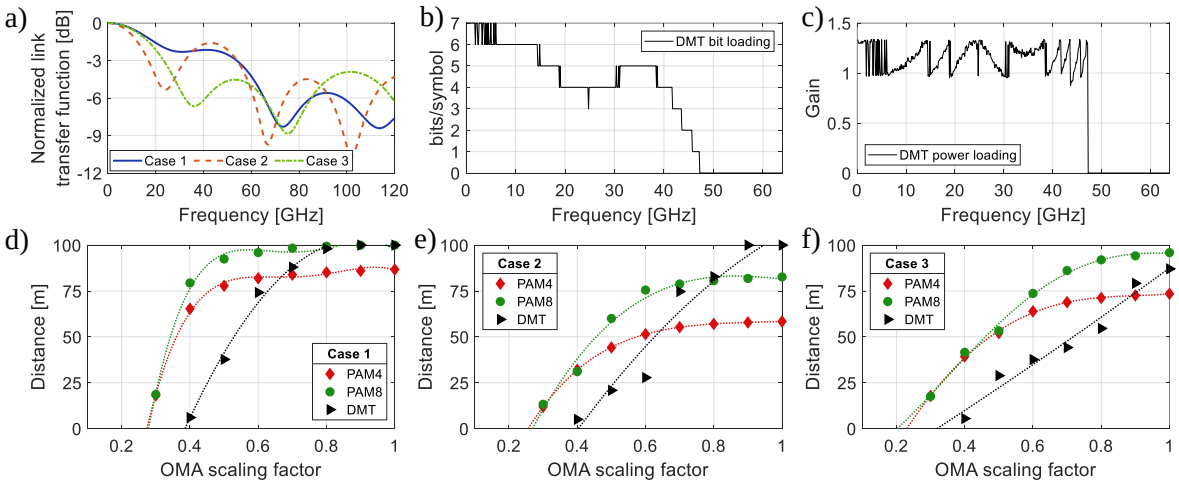

Fig. 2. a) Normalized transfer functions at 50 m of the analyzed VCSEL-MMF links. b,c) Example of DMT bit and power loading for Case 2 with 9 dB clipping ratio and 0.5 OMA scaling factor. PAM and DMT comparison in terms of distance as a function of OMA scaling factor for: d) Case 1, e) Case 2 and f) Case 3.

equalization (MLSE for PAM and one-tap FFE for DMT) and symbol demapping, the bit error rate (BER) is estimated through error counting.

In this analysis, the OMA is defined as $OMA = 2\bar{P} \cdot OMA_{scale}$, where $\bar{P}$ is the average optical power, set to -1.75 dBm, and OMA_{scale} is the OMA scaling factor. In particular, $OMA_{scale} = (ER-1)/(ER+1)$, with ER being the extinction ratio, can range from 0 to 1. Adaptive rate DMT is performed based on Levin-Campello algorithm to determine the optimal bit and power loading at the bit error rate (BER) threshold (BER_T). For bit loading, quadrature amplitude modulation (QAM) formats are allocated with a cardinality that depends on the signal-to-noise ratio (SNR) evaluated assuming the transmission of quadrature phase shift keying (QPSK) on all subcarriers. Other fundamental parameters of the DMT are the FFT size and the number of subcarriers, set to 1024 and 511, respectively. The cyclic prefix is 9, while clipping ratio is optimized between 5 dB and 15 dB. The sampling frequency of the digital to analog converter (DAC) is 128 GS/s for the DMT.

The comparison between PAM and DMT is assessed through time-domain simulations assuming transmission at 200 Gbit/s net bit rate and considering enhanced forward error correction (FEC) code: $BER_T = 4 \cdot 10^{-3}$ and 10.35% FEC overhead. In particular, three different worst case links are selected from the VCSEL-MMF dataset analyzed in [8]. The normalized transfer function at 50 m of the selected cases are reported in Fig. 2a). An example of DMT bit and power loading provided by the Levin-Campello algorithm is shown in Figs. 2b) and 2c), respectively, for Case 2, $OMA_{scale} = 0.5$ and 9 dB clipping ratio. From there, we can clearly see the adaptability of the DMT to the frequency response of the channel.

Figs. 2d)-f) show the distance reached by DMT and PAM as a function of the OMA scaling factor for the three cases of study. The advantage of DMT over PAM is strongly related to the characteristics of the channel, and it is greater especially if the transfer function presents high secondary lobes and notches, like in Case 2. However, it also depends on the OMA scaling factor. Indeed, DMT outperforms PAM4 only for large OMA_{scale}: $OMA_{scale} > 0.6$, for Case 1 and Case 2, and $OMA_{scale} > 0.9$ for Case 3. At the same time, we start to see the advantage of DMT over PAM8 for even larger values of OMA scaling factor compared to PAM4.

3. Conclusions

The performance of PAM and DMT is compared for VCSELs-modulated links over MMF. The obtained results showed the potential advantage of DMT over PAM4 for particularly frequency selective channels, assuming that larger OMA_{scale} values are reasonable from a hardware perspective. Although longer distances can be reached using PAM8, usually it is a less preferred solution due to the higher complexity of the MLSE.

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