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Nonlinear Digital Pre-Distortion over VCSEL-MMF optical IM-DD systems

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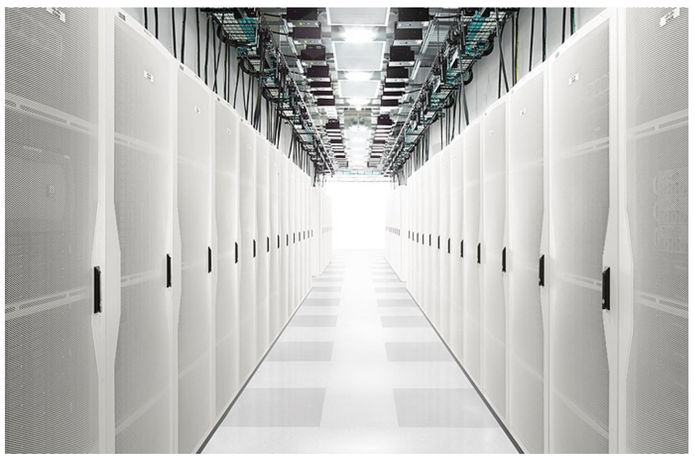
Research context and motivation

- Modern Datacenters Interconnects (DCI) internal traffic is continuously growing, requesting for a continuous increase in data rates in short-reach optical links (which can be more than 10000 in a single Datacenter).
- Marketwise, about 50% of these DCI internal optical links are Intensity Modulation-Direct Detection (IM-DD) optical links using Multi-Mode Fibers (MMF) and Vertical-Cavity Surface-Emitting Lasers (VCSEL), due to their high-power efficiency and significantly low manufacturing cost.
- Focusing on MMF lengths around 100 m, there is today a growing interest to find solutions targeting 100+ Gbit/s per λ using multilevel Pulse Amplitude Modulation (PAM) formats.



All experimental activities in this PhD have been carried out in the PhotoNext inter-departmental center on Applied Photonics

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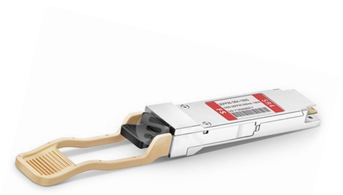
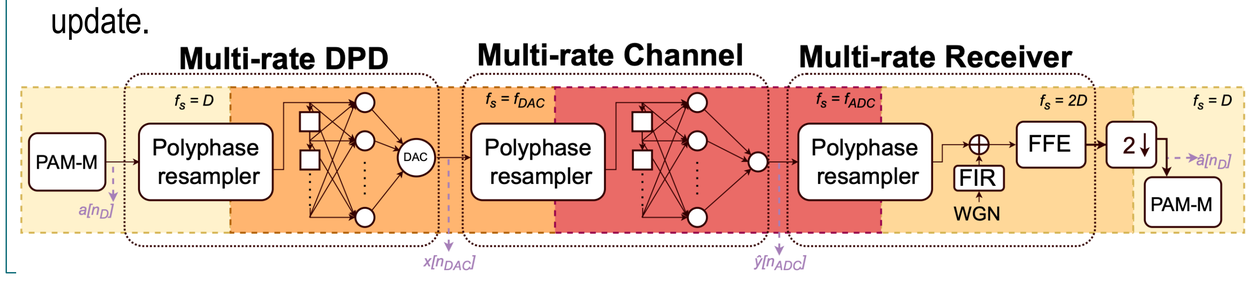


850nm 100m MMF 4x25 Gbps optical transceiver – Price:100 €

Novel contributions

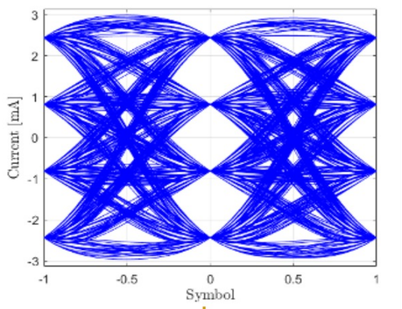
- We modeled a real experimental VCSEL-MMF IM-DD optical link (in Photonext Laboratory) as an Artificial Neural Network (ANN) Multi-rate End-to-end (E2E) system, whose novelty consists of working in parallel at the different sampling rates involved in the real transmission system (Baud Rate, DAC sampling frequency, ADC sampling frequency).
- With the Multi-rate E2E system, an ANN is trained as a DPD fulfilling natively the peak-to-peak dynamic constraints in the system.
- The nonlinear ANN DPD is trained jointly with an FFE post-equalizer, whose taps are optimized taking into account the non-flat in frequency experimental noise: its effect is introduced as an additive regularization term in the FFE Stochastic Gradient Descent update.

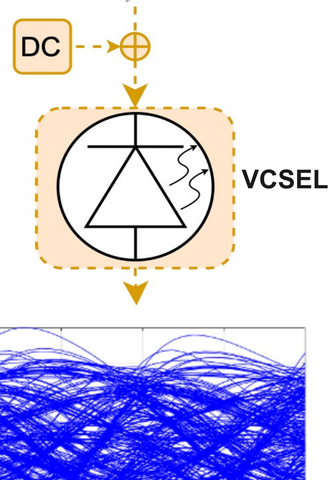


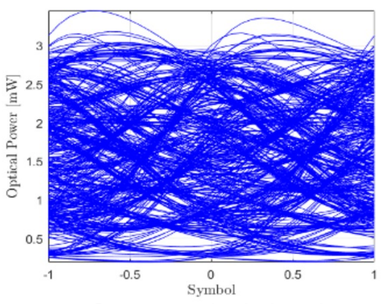
Addressed research questions/problems

- Extreme bit rates such as 100+Gbit/s over MMF-VCSEL optical links introduce severe impairments to the transmitted signals
- The VCSEL, as well as other components such as the Photodiode, the Digital-to-Analog (DAC) converter, or even the MMF, are severely band-limited.
- In addition, the VCSEL is a nonlinear device, that introduces nonlinear distortions on the signal which impair asymmetrically the symbol levels.
- An efficient solution to mitigate these impairments is using **Digital Signal Processing (DSP)** techniques, such as Post-equalization at the Receiver (RX) side and **Digital Pre-Distortion (DPD)** at the Transmitter (TX) side.
- However, the compensation of bandwidth limitations, which require the application of a high-filter effect on the transmitted signal, is problematic for both the post- and the pre- compensators. Applied at the RX side, this enhances the effect of the receiver noise. Applied at the TX side instead, this produces time-domain overshoots that tend to exceed the limited peak-to-peak dynamics of the DAC and the VCSEL.
- In the considered scenario, computational complexity also plays a key role: current MMF Ethernet cables target indeed the use of a linear Feed-Forward Equalizer (FFE).
- Nonlinear mitigation is thus more feasible at the TX side, since DPD can be implemented for instance by exploiting LUT-based solutions.

input electrical signal (eye-diagram)





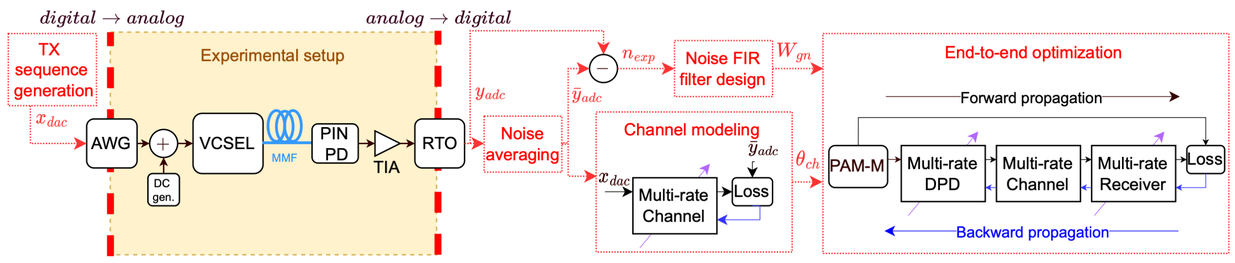


Output optical signal (eyediagram)

Adopted methodologies

- The optimization of an ANN DPD using the E2E approach consists of the following steps:

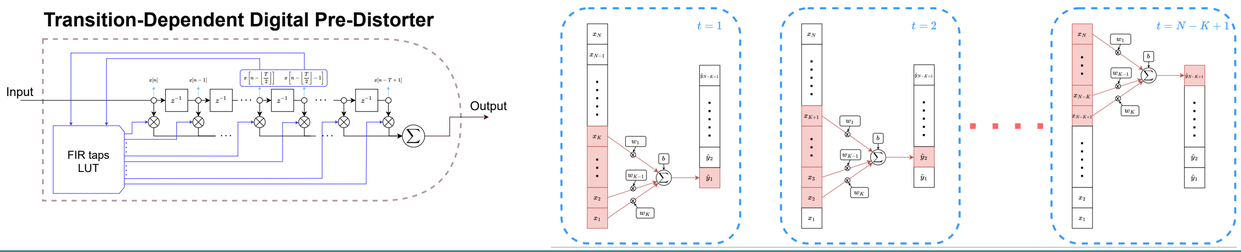
1. Acquisition of a PRBS PAM-M signal, transmitted over an experimental setup;
2. De-noising of the measurements by averagin out the noise over the PRBS period;
3. Channel Digital Twin modeling by training an ANN on the acquisitions denoised in step 2;
4. Modeling of the experimental noise extracted in step 2 through a FIR filter design;
5. End-to-end optimization of the Digital Pre-distorter, exploiting the Digital Twin of the channel and the noise FIR filter taps obtained in steps 3 and 4.



Future work

- The Multi-rate E2E system can be implemented as a Convolutional Neural Network, exploiting tools such as the Pytorch library to obtain an efficient and fast optimization technique for a nonlinear DPD.
- A simplified structure such as a Transition-Dependent Digital Pre-distorter can be adopted in place of an ANN, to obtain a DPD whose complexity is comparable to the one of a linear FIR DPD (i.e., with the same amount of multiplications per symbol).

$$Loss = \sum_{i}^{N-K+1} (\hat{y}_i - y_i)^2 \propto MSE \qquad w_i \leftarrow w_i - \epsilon \cdot \frac{\partial Loss}{\partial w_i}$$



Submitted and published works

- L. Minelli , F. Forghieri and R. Gaudino, "*End-to-end Deep Learning for VCSEL's Nonlinear Digital Pre-Distortion*", Italian Conference on Optics and Photonics, Trento, 2022 **(Accepted)**
- L. Minelli , A. Abdellatif and R. Gaudino, "*Optimization of 50G-PON APD-based receivers*", Italian Conference on Optics and Photonics, Trento, 2022 **(Accepted)**
- L. Minelli , F. Forghieri and R. Gaudino, "*Nonlinear Pre-distortion through a Multi-rate End-to-end Learning Approach over VCSEL-MMF IM-DD Optical Links*", European Conference on Optical Communication, Basel, 2022 **(Accepted)**
- L. Minelli, F. Forghieri, A. Nespola, S. Straullu and R. Gaudino, "*A Multi-Rate approach for nonlinear Digital-Pre-distortion using End-to-end Deep Learning in IM-DD systems*", Journal of Lightwave Technology **(Submitted)**

List of attended classes

- 01QORRV – Writing Scientific Papers in English (24/03/2022, 3 credits)
- 01RISRV – Public Speaking (14/11/2021, 1 credit)
- 01SHMRV – Entrepreneurial Finance(21/11/2021, 1 credit)
- 01SWQRV – Responsible research and innovation, the impact of social challenges (28/11/2021, 1 credit)
- 01TRLRV – Optical Transport Networks (02/09/2022, 6 credits)
- 01TXFSM – Machine learning and Deep Learning (20/07/2022, 10 credits)
- 02LWHRV – Communication (05/02/2022, 1 credit)

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