Multi-Parameter AI-Based Bandwidth Compensation for Energy-Efficient 800G Transmission

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Abstract: We propose a novel energy-efficient AI-based bandwidth compensation technique that jointly optimizes Tx and Rx static filters. Experimental demonstration in a 800G system reveals gains of more than 1 dB when compared with typical digital pre-emphasis.

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1. Introduction

The ever-growing increase of channel capacity demands, keeps pushing the scientific community, and the industry, to stretch the transmission symbol-rate to increasingly higher values. In fact, the next-generation of optical transceivers is already supposed to work at symbol-rates above 100Gbaud. [1] However, working at such high symbol-rates bear multiple challenges, namely regarding the limited resolutions on the digital-to-analog converter (DAC) and analog-to-digital converter (ADC), and the bandwidth limitations of the analog frontend. It is well accepted that a workaround to cope with these bandwidth limitations is applying digital pre-emphasis (PE) at the transmitter [2]. However, applying PE over the transmitted signal can also produce a degrading impact in the system, particularly because applying PE leads to signals with a higher peak-to-average power ratio (PAPR), that when combined with the limited effective number of bits (ENOB) of DACs leads to performance deterioration [3]. To address this problem, it has been shown that applying partial PE allows to optimize the trade-off between bandwidth compensation and PAPR increase [4]. In this sense, applying optical PE has also been demonstrated to provide some gain [5]. However, the conundrum of knowing how much PE to apply is still typically solved empirically, with models for this problem being very scarce in the literature [6].

Typical PE methods consist simply on the optimization of the pre-emphasis strength *i.e.* extracting the bandwidth limitations of the system with a zero-forcing (ZF) methodology and performing a scale factor optimization [7]. However, we have already demonstrated in simulation that in these bandwidth-limited scenarios, we can achieve extra performance gains by applying a bandwidth compensation filter in the receiver (Rx) digital-signal-processing (DSP) [8].

In this paper, we propose a novel bandwidth compensation technique aimed at low-power consumption DSP scenarios, where the bandwidth is jointly compensated at the transmitter and receiver sides, both to alleviate the PAPR burden for DAC and to reduce the implementation complexity of the Rx adaptive equalizer. This methodology is based on the simulation work already presented in [8], which is hereby extended and experimentally validated. In order to have a fine optimization of the system, we perform multi-parameter optimization of these bandwidth compensation filters, which leads to a signal-to-noise ratio (SNR) gain of 0.4 dB w.r.t. to a similar distributed (Tx + Rx) bandwidth compensation architecture with single-parameter optimization, and roughly 1 dB gain when compared with typical Tx only PE techniques.

2. Proposed Methodology

Fig. 1.a) shows the proposed technique to compensate for bandwidth limitations. This technique is aimed to a scenario where the transmitter (Tx) application-specific integrated circuit (ASIC) supports the integration of a pre-emphasis filter and the receiver (Rx) ASIC has in its DSP chain a chromatic dispersion block where the capability for bandwidth compensation can be integrated. The optimization of these bandwidth compensation filters can be processed offline by a micro-controller, in a one-time only calibration phase. This is represented in the figure in the blue-shadowed area. This optimization starts by transmitting the signal through a given channel, with a certain frequency response $H(f)$. Afterwards, we obtain the inverse channel response, $H^{-1}(f)$, by a ZF methodology, as one would do for a typical PE technique. The novel methodology presented in this work starts by taking this inverse

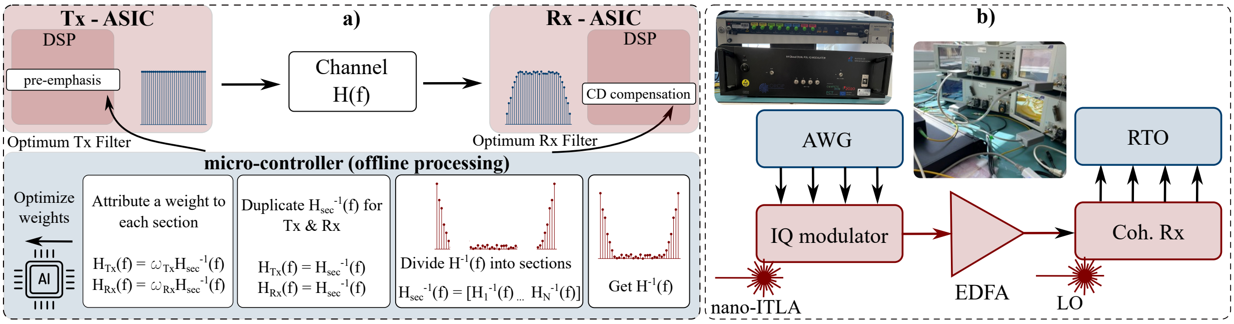

Fig. 1: a) Proposed architecture for bandwidth compensation. The optimization of the compensation is performed offline in the micro-controller and the optimum emphasis filters are integrated in the Tx pre-emphasis DSP, and the Rx CD compensation block. b) Experimental setup used for 800G transmission.

channel response and divide it in multiple sections (N), thus allowing a higher control of bandwidth compensation: $H_{\text{sec}}^{-1}(f) = [H_1^{-1}(f), H_2^{-1}(f), \ldots, H_N^{-1}(f)]$. This sectioned filter will be the template where the optimization will be performed. We proceed by duplicating these filters, one for the Tx and one for the Rx, and each of these filters will have associated to itself a weight (ω) that will control the amount of emphasis required in that spectrum band. Therefore we will have: $H_{\text{Tx}}(f) = \omega_{\text{Tx}} H_{\text{sec}}^{-1}(f)$ and $H_{\text{Rx}}(f) = \omega_{\text{Rx}} H_{\text{sec}}^{-1}(f)$. In order to avoid discontinuities in the filters, the frontier samples between sections are interpolated. Reaching this stage, we proceed by calculating the optimum values for ω_{Tx} and ω_{Rx}. This is accomplished using an artificial intelligence (AI) algorithm, namely, particle-swarm optimization (PSO). The optimization framework consists in finding the filters to be applied at the Tx and Rx that maximize the system performance. In this work, we implemented this algorithm to maximize the system normalized generalized mutual information (NGMI) [9]. It is worth noting that this Tx and Rx optimization is performed co-jointly, *i.e.*, both filters are optimized cooperatively to achieve better results.

3. 800G Experimental Setup

The experimental setup used for validation of our proposed bandwidth compensation technique is depicted in Fig. 1.b). At the transmitter side a 800G 64-QAM probabilistic constellation shaping (PCS) signal is generated and shaped with a root-raised cosine filter with 0.2 roll-off. Afterwards digital to electrical conversion is performed by an arbitrary waveform generator (AWG) with ~45 GHz bandwidth and a sample-rate of 120 GSa/s (Keysight M8194A). Afterwards, optical modulation is performed by a dual-polarization IQ modulator (35GHz bandwidth), over an optical carrier provided by a nano-integrated tunable laser assembly (nano-ITLA) with 13 dBm of output power. The modulated optical signal is amplified by an erbium-doped fiber amplifier (EDFA), and then received by a optical coherent receiver with 70 GHz bandwidth. Finally, 4 real-time oscilloscopes (RTO) with 70 GHz bandwidth and 200 GSa/s (Tektronix DPO77002SX-R3) are responsible for sampling and digitization of the I and Q components of the signal. Afterwards, typical DSP techniques are employed, which include: IQ imbalance compensation, a first CMA-based 2×2 equalizer (11 taps), frequency and phase recovery, a second LMS-based 2×2 equalizer (11 taps), symbol demapping and NGMI evaluation. In order to implement the proposed bandwidth compensation technique, we need to add to the DSP system two frequency domain filters, one at the Tx applying PE, and one at the Rx for post-compensation.

As noted from the above DSP description, we have limited the number of taps on both the CMA- and LMS-based dynamic equalizers (DE), following a practical energy-efficient design rule. However, as one should expect, this DSP power reduction comes at the expense of non-negligible performance penalty. Therefore, we started the experimental campaign by measuring the impact of limiting the DE memory depth. Fig. 2 a) shows how the SNR is affected by the number of DE taps for a signal with a symbol-rate of 94 Gbaud. This experiment was performed for 4 different scenarios, without any type of bandwidth compensation (black line), employing optimized ZF only in the Tx filter (red line), optimized ZF only on the Rx filter (blue line), and finally employing optimized ZF in both Tx and Rx filters (green line). As it is depicted in the Fig. 2.a) there is a considerable performance loss in reducing the DE number of taps; we can observe that reducing from 25 to 11 taps, leads to almost a 2 dB penalty when no compensation is applied. However, we can also observe that in these lower power scenarios, there is a considerable gain in applying the proposed methodology of two complementary static bandwidth compensation filters at the Tx and Rx, leading to roughly 1 dB gain over the non compensated signal. We have also depicted in Fig. 2.a) the relation between the number of DE taps and the normalized power consumption. We can observe that increasing the number of taps from 4 to 20, results in a 5-fold increase in the power consumed, thus it is critical to have techniques that help the system working with a low number of taps. With our sectioned approach for bandwidth compensation we aim at lowering the required number of taps thus decreasing the power consumption of the optics transceiver. Also note that, the DSP power consumption of FFT-based static filters is typically much lower than

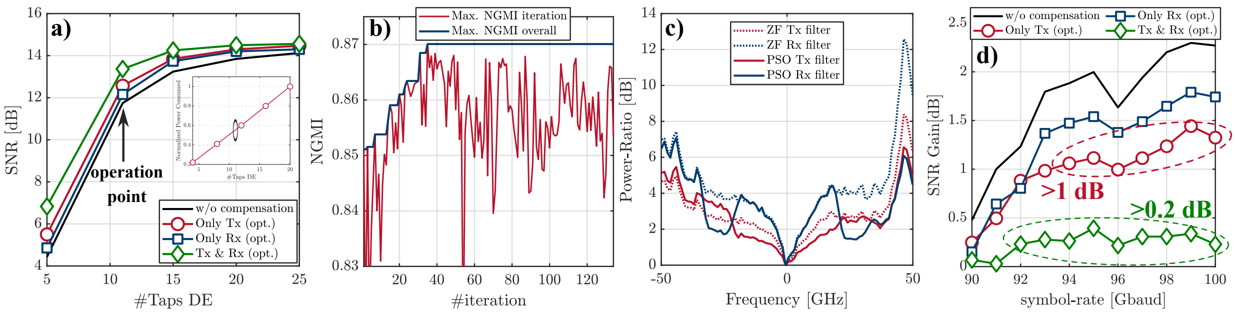

Fig. 2: a) Impact of the DE number of taps in the system SNR, for a symbol-rate of 94 Gbaud. b) NGMI evolution with the convergence of the PSO algorithm for a symbol-rate of 95 Gbaud. c) Optimum filters encountered by the ZF technique and the PSO proposed method (symbol-rate 95 Gbaud). d) SNR gain achieved with the proposed PSO methodology when compared with ZF techniques only in the Tx, Rx, and Tx+Rx.

that of time-domain adaptive filters, and therefore, the overall DSP power consumption can be optimized.

We proceed with the implementation of the proposed architecture for bandwidth compensation. To achieve better results, we consider that each filter is sub-divided into 5 independent sections, resulting in a total of 10 parameters to be optimized. The optimization of these parameters is done recurring to a PSO algorithm with 5 particles. An example of the results obtained during this optimization is depicted in Fig. 2.b). It is possible to observe that the algorithm converges to an optimum value within 50 iterations. The observed fluctuations in the instantaneous NGMI are caused by the randomness that is associated with the algorithm in order to avoid being stuck in a local minimum. Fig. 2.c) shows the optimum magnitude frequency response of the filters obtained (for Tx and Rx) with the ZF methodology and with the AI-based approach. We can observe that the proposed methodology of dividing the filter into multiple sections results in an extra degree of freedom that allows to selectively emphasize some parts of the spectrum, somehow counteracting the ZF solution in order to ultimately optimize the overall performance.

Finally Fig. 2.d) depicts the SNR gain achieved with the proposed methodology, when compared against typical PE techniques. These results were obtained for a variable symbol-rate between 90 Gbaud and 100 Gbaud, adjusting the PCS probability distribution to keep the bitrate fixed at 800 Gbps. The presented results show that there is a considerable gain in implementing both filters, one at the Tx and one at the Rx. This gain is further increased when considering the approach of cooperatively optimized sectioned filters. The presented results show that the proposed approach presents significant SNR gains across the entire range of tested symbol-rates. This gain can ascend to 0.4 dB when compared with the scalar-optimized ZF Tx+Rx methodology, and more than 1 dB when compared with typical Tx-only pre-emphasis.

4. Conclusions

In this work we have experimentally demonstrated a novel methodology for overcoming bandwidth limitations in high-baudrate coherent optical systems. This methodology is based in applying a PE filter at the Tx and a post-compensation filter at the Rx. To achieve the best performance, these filters are conjointly optimized by an AI-based algorithm. We demonstrated this approach experimentally, in a 800G scenario, achieving SNR gains of more than 1 dB when compared with typical Tx-only PE techniques. These gains are even more relevant considering that this approach can be performed fully offline in a calibration phase, and the Rx filter can be integrated in the CD compensation block typical to common optical transceivers, thus not requiring any structural changes to already existing commercial transceivers.

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