Direct-detection 25 Gb/s PON: PROs and CONs of digital signal processing at the transmitter side

Original
Direct-detection 25 Gb/s PON: PROs and CONs of digital signal processing at the transmitter side / Torres Ferrera, P.; Tipan, M.; Gaudino, R.; Cardenas, D.; Arevalo, G. V.. - ELETTRONICO. - 2020-:(2020), pp. 1-4. (Intervento presentato al convegno 22nd International Conference on Transparent Optical Networks, ICTON 2020 tenutosi a ita nel 2020) [10.1109/ICTON51198.2020.9203535].

Publisher:
IEEE Computer Society

Published
DOI:10.1109/ICTON51198.2020.9203535

Direct-detection 25 Gb/s PON: PROs and CONs of digital signal processing at the transmitter side

Pablo Torres-Ferrera[1*], **Myriam Tipán**[1], **Roberto Gaudino**[1], **Daniel Cardenas**[2], **Germán V. Arévalo**[3]
[1]*Politecnico di Torino, Dipartimento di Elettronica e Telecomunicazioni, Torino – Italy, *pablo.torres@polito.it*
[2]*Escuela Politécnica Nacional, Instituto Geofísico, Quito - Ecuador*
[3]*Universidad Politécnica Salesiana, Carrera de Ingeniería en Telecomunicaciones, Quito - Ecuador*

ABSTRACT

We evaluate the performance of direct-detection 25 Gb/s Passive Optical Networks (PON) with adaptive equalization at the receiver side, comparing three transmitter schemes: two including digital signal processing (DSP), namely square-root raised-cosine pulse shaping and pre-emphasis, and the third one without any DSP pre-compensation. We show that DSP at transmitter side can provide a performance advantage only under strong bandwidth limitations and when considering feed-forward equalization (FFE) at the receiver. When including decision-feedback equalization (DFE), the use of pre-compensation at transmitter does not provide any advantage under linear transmission.

Keywords: PAM-4, pulse shaping, pre-emphasis, transmitter, pre-equalization, pre-compensation, PON, DSP

1. INTRODUCTION

Next-generation of Passive Optical Networks (PON) are under active development and standardization [1]. The upcoming PON standards update will define specifications for 25 and 50 Gbps transmission per wavelength. One of the central technical discussions of this PON development has been about the alternatives to allow increasing the data rate while preserving the direct-detection (DD) scheme. One alternative relies on using devices with wide enough optoelectronic (O/E) bandwidth (BW) to keep the transceivers as simple as possible, i.e. maintaining the on-off keying modulation without digital signal processing (DSP). The other alternative considers the re-use of already available bandlimited O/E, incorporating DSP at transmitter (TX), receiver (RX) or both sides, to compensate for the strong BW limitations [2, 3]. In this paper, we focus on the second option, aiming to analyse the impact of including DSP at TX side when linear channel impairments are meant to be compensated by adaptive equalization at RX. Even though it is well-known that, from an operational point of view, RX equalization schemes are preferred than TX pre-compensation ones, several proposals for both PON and short-reach bandlimited DD systems incorporate DSP at both sides. Whereas it has been shown that under non-linear channel conditions the use of TX DSP pre-compensation provides an additional gain to the use of RX equalization alone [4], it has not been analysed in detail whether this situation still holds when only linear-impairments are meant to be corrected. Since the incorporation of DSP non-linear compensation increases considerably the complexity of the PON transceivers (which is critical at ONU side), we consider useful to analyse in which conditions TX DSP is still useful to be employed when non-linear compensation is avoided. To this end, in this contribution we compare the performance of three TX PON schemes: the first avoiding DSP, the second using standard square-root raised-cosine (SRRC) pulse-shaping, and the third using a one-pole one-zero pre-emphasis filter. At the receiver side, two adaptive equalizer options are considered: feed-forward (FFE) and decision-feedback (DFE). We show that the use of TX DSP can provide a gain performance under strong-bandlimited conditions in combination with FFE. This performance gain vanishes if DFE scheme is included. The paper is organized as follows: in Section II we detail our simulation setup, in Section III we present our core results and we conclude in Section IV.

2. SIMULATION SETUP

We modelled a linear optical transmission system, with intensity modulation and direct detection (Fig. 1). At the TX side, a rectangular 25 Gbps PAM-4 signal is generated. This signal drives directly a linear (and chirp-less) optical modulator when no pre-compensation is used (termed in the rest of the document as the “Rectangular”

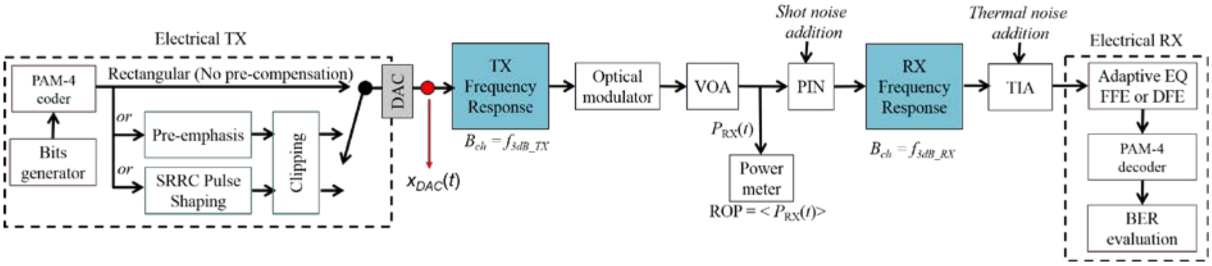

Figure 1. Simulation setup. Eye-diagrams shown in Figures 2 and 3 are evaluated after the DAC block.

case). When instead TX DSP pre-compensation is applied, the PAM-4 signal is digitally filtered by:

- A SRRC filter with one parameter to be optimized (the roll-off-factor), case termed as "SRRC" in the rest of the document; or
- A one-pole one-zero pre-emphasis filter composed by an inverse one-pole low-pass filter with a given f_{3dB} (called f_{P1}) cascaded with a one-pole low-pass filter with a given f_{3dB} (called f_{P2}). Both f_{P1} and f_{P2} are optimized, being $f_{P2} > f_{P1.}$

A clipping block follows (not used in the "Rectangular" case), which cuts the peaks of the pre-compensated TX signal with a given clipping level (CL) to be optimized, defined as the percentage of the unclipped peak-to-peak signal amplitude to be clipped (i.e. CL=0% means no clipping, CL=100% means clipping all the signal). The clipped signal, when TX DSP pre-compensation is assumed, drives the optical modulator. An extinction ratio ER = 8 dB is fixed for the three analysed TX schemes. A central goal of the paper is analysing the system performance under strong bandwidth limitations. We thus include in the simulator the TX and RX O/E frequency responses emulated as low-pass Super-Gaussian filters (SGF) with a given -3dB bandwidth (B_{ch}) and a given order n, set the same at both TX and RX [3]. Although we performed all the simulations setting a fixed bit rate of R_b = 25 Gbps, our conclusions can be generalized to any other bit rate value if the ratio between the channel bandwidth B_{ch} and the bit rate is the same. For this reason, we express our results in terms of the normalized channel bandwidth defined as $\%B_{ch} = 100 \cdot B_{ch}/R_b$. At the RX side, the optical signal is detected by a single PIN photodiode followed by a trans-impedance amplifier (TIA). The shot and thermal noise sources at the RX are modelled as additive white Gaussian noise random processes [3], with variance evaluated as follows, $\sigma_{sh}^2 = 2qB_sRP_{RX}(t)$ and $\sigma_{th}^2 = N_0B_s$ respectively. B_s is the one-sided simulation bandwidth, q is the electron charge and $P_{RX}(t)$ is the instantaneous PIN input optical power. The PIN responsivity is R=0.55 A/W and the RX noise density is set $N_0 = 3.1\text{x}10^{-22}$ A^2/Hz. Finally, the receiver signal is digitized and then equalized by a 20 taps FFE, followed by a 5 taps DFE (when declared). After equalization, PAM-4 decoding and decision, the bit error rate (BER) is evaluated through direct error counting over 10^5 bits. The main metric used to compare the system performance is the required received optical power (RROP), measured at the PIN input, needed to reach a given BER target, chosen as $\text{BER}_t=10^{-3}$.

3. RESULTS

We start by analysing the SRRC case against the Rectangular (no TX DSP pre-compensation) one. In Fig. 2 we show the corresponding RROP curves as a function of the normalized channel bandwidth $\%B_{ch}$ for different SGF orders n=1, 2 and 3 (parameter that sets the steepness of the O/E frequency response). Fig. 2.a shows results when using only FFE, and Fig. 2.b when also including DFE. Note that the DFE is always preceded by the FFE block, but for simplicity we termed this FFE+DFE structure just as "DFE" in the rest of the document. The roll-off-factor and the clipping level where both optimized together for every $\%B_{ch}$. We first observed that the RROP curves become flat for $\%B_{ch}$ higher than ~35%, both using FFE and DFE. Since PAM-4 is used as a modulation format, this value corresponds to 70% of the symbol rate, which is well-known to be a bandwidth condition with marginal penalty. We use this "broadband" RROP as a reference (RROP_0) to measure the power penalties (PP) due to bandwidth limitations reported in this document, that is RROP_0 = -14.3 dBm.

Regarding the FFE curves shown in Fig. 2.a, we can observe a region in which the use of SRRC shaping provides a performance gain as compared to the Rectangular case, for $\%B_{ch}$ lower than ~20%. For higher $\%B_{ch}$ no gain is observed. Considering a bit rate transmission of 100 Gbps, forecasted as the next jump for PON, this $\%B_{ch}$ range in which SRRC TX DSP is useful corresponds to devices with O/E BW within 15-20 GHz, which matches the actual BW of the 25G-class O/E used in data-centre interconnects and upcoming 25G-PON. Then, there is a room for improvement due to TX DSP in a 100Gbps downstream transmission re-using 25G-class technology, in which the TX complexity could be slightly increased at OLT side, while keeping simple the RX at the ONU side, by using FFE only, avoiding DFE.

The situation is different when including DFE equalization. From Fig. 2.b, we can observe that there is basically no difference between the RROP curves of SRRC and Rectangular cases. Therefore, the use of TX DSP in this situation does not provide any advantage, and can be completely avoided. In an upstream transmission, TX DSP can be avoided to maintain the ONU simple, and the increase of complexity coming from adding DFE can be absorbed by the OLT side, with a proper burst-mode RX.

The same or higher SRRC performance observed versus Rectangular is obtained after optimizing two TX parameters for every channel bandwidth value, as mentioned before. If this optimization is not performed, SRRC operation results in most cases in power penalties instead of power gains, as can be seen in the contour plots shown in Figures 2.c and 2.d, which shows the SRRC RROP for a strong bandlimited case ($\%B_{ch}$ = 16%) as a function of the SRRC roll-of-factor and the clipping level in %, for FFE and DFE, respectively. In the optimum region we can obtain a gain with respect to the no pre-compensated case of around 1.8 dB and 0.1 dB, for FFE and DFE respectively (at this $\%B_{ch}$, the RROP for FFE Rectangular is –10.0 dBm and for DFE Rectangular is –12.4 dBm). The reason why the SRRC case must be optimized to overcome (or to perform the same than) the Rectangular case comes from the fact that the ER (at the modulator output) is set the same in all situations,

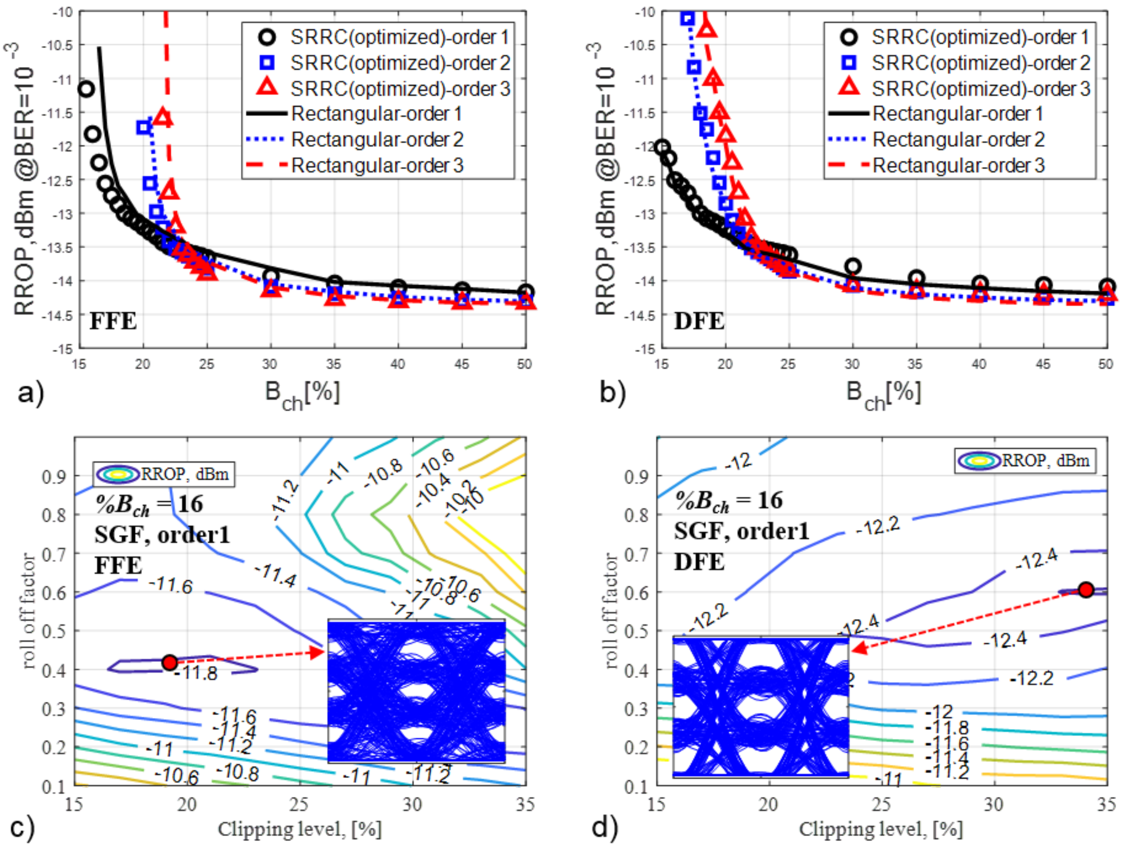

Figure 2. Required ROP as a function of normalized TX and RX BW (%B_{ch}) for different TX scenarios using a) FFE, b) DFE. RROP contour plots as a function of SRRC roll-off factor and clipping level (using SGFs n=1), for a %B_{ch}=16%, using c) FFE, d) DFE. Inset: Normalized $x_{DAC}(t)$ eye-diagrams for optimum point of operation.

irrespective of the SRRC roll-of-factor. Therefore, for low values of the roll-off-factor for which the signal eye-diagram exhibits big overshoots, the "effective" eye amplitude gets reduced. This situation is partially compensated by clipping the signal (see Insets of Fig. 2), but at the expense of introducing non-linear distortion. The optimum situation results from a trade-off between compressing the signal spectrum by reducing the roll-of-factor, and tolerating some non-linear distortion by clipping the signal to increase the "effective" eye amplitude.

We analyse now the use of the pre-emphasis filter. We avoid using a more complex pre-emphasis approach aided by a feedback link to send the channel characterization performed at the RX, to the TX. Instead, we employed a simpler one-pole one-zero filter to do the pre-emphasis with two free parameters to optimize: f_{P1} and f_{P2} (in combination with a third optimization parameter: the clipping level). Figures 3.a and 3.b show a comparison between the RROP obtained when using pre-emphasis, SRRC pulse-shaping and Rectangular shaping, as a function of the normalized channel bandwidth, using FFE and DFE, respectively. In both SRRC and pre-emphasis cases, the TX parameters are optimized for every %B_{ch} value. It is interesting to note that SRRC and pre-emphasis performs practically the same, since their corresponding RROP curves are basically overlapped. This fact indicates that the RX equalizer (especially DFE), is practically correcting all the linear impairments of the transmission, making converge the results even if using different DSP pre-compensation filters at TX side (see from Insets of Figures 2 and 3 that their output eye-diagrams are notoriously different).

As mentioned before, in the pre-emphasis case we optimized three parameters for every %B_{ch}, the two cut-off filter frequencies f_{P1} and f_{P2} in combination with the clipping ratio. In Fig. 3.c and Fig. 3.d we show an example of this optimization, setting %B_{ch}=16, and an optimized clipping level CL=25%, using FFE and DFE, respectively. As in the SRRC case, there is a range of parameters in which we obtain a gain (marginal for DFE) with respect of the no pre-equalization case (power gain of 1.8 dB and 0.2 dB for FFE and DFE, respectively).

As an initial hypothesis, we expected to obtain a higher gain by including TX DSP pre-compensation in combination with RX adaptive equalization, due to the presence of noise at RX side (which is well-known to be enhanced by equalization). Moreover, we expected this gain to increase by increasing the steepness of the O/E transfer functions (i.e. increasing the order *n* of the SGFs used to emulate this constraint). However, as discussed in this Section, the TX DSP pre-compensation gain is only evident under strong bandwidth limitations (at which anyway the system stops working when increasing the SGFs order -steepness-) and without DFE equalization.

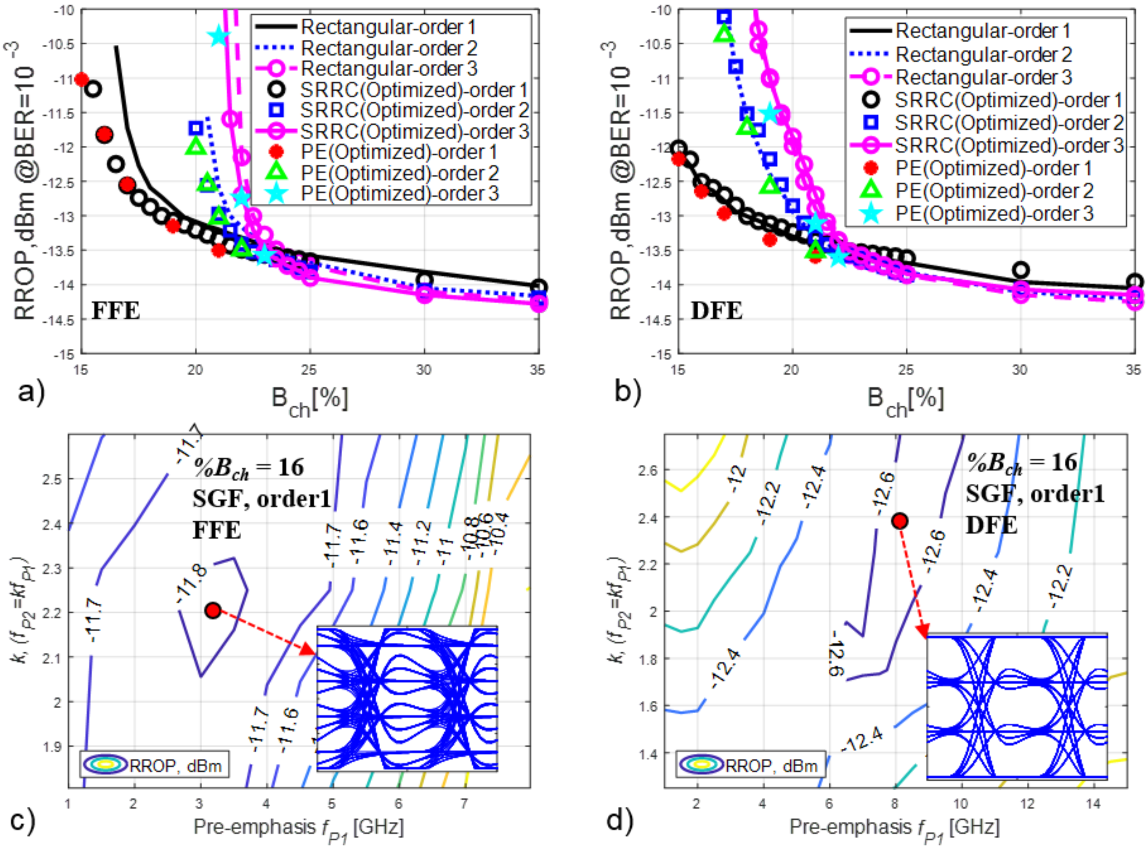

Figure 3. Required ROP as a function of normalized TX and RX BW (%B_{ch}) for different TX scenarios using a) FFE, b) DFE. Pre-emphasis case RROP contour plots as a function of the filter parameters f_{P1} and f_{P2}, for a %B_{ch}=16% and optimized clipping level CL = 25% (using SGFs of order 1 for TX and RX O/E), using c) FFE, d) DFE. Inset: Normalized $x_{DAC}(t)$ eye-diagrams for optimum point of operation. PE: Pre-Emphasis.

Since TX DSP pre-compensation requires an additional process of optimization, from an operational point of view the use of only DFE at RX side can be preferred if only linear impairments are meant to be corrected.

Finally, the power penalty of operating under strong bandwidth limitations (%B_{ch}=16) with respect to the broadband case ($RROP_0$=-14.3dBm), is PP = 2.4 dB and PP = 1.6 dB, using FFE and DFE, respectively, in combination with any of the two analysed TX DSP pre-compensation schemes.

4. CONCLUSIONS

TX pre-compensation is effective for very low bandwidth devices (15-20% of bit rate) and when only FFE is considered (1.8 dB maximum improvement). If using DFE or higher BW devices, there is practically no advantage of using TX pre-compensation. Future 100Gbps PON re-using 25G-class O/E can then benefit from adding some DSP at TX, thus avoiding more complex and power hungry DFE, especially at the ONU side where power consumption is a vital requirement. Pre-emphasis or SRRC perform identically, being the latter simpler to implement either digitally or analogically in the driver, albeit it requires further optimization than SRRC.

ACKNOWLEDGEMENTS

This work was done under the PhotoNext initiative at Politecnico di Torino (http://www.photonext.polito.it/).

REFERENCES

[1] E. Harstead, D. van Veen, V. Houtsma, P. Dom, "Technology Roadmap for Time-Division Multiplexed Passive Optical Networks (TDM PONs)," J. Lightwave Technology, 37 (2), pp. 657-664, 2019.

[2] P. Torres-Ferrera, V. Ferrero, M. Valvo, R. Gaudino, “Impact of the Overall Electrical Filter Shaping in Next-Generation 25 and 50 Gb/s PONs”, J. Optical Comm. Networking, 10 (5), pp. 493-505, 2018.

[3] P. Torres-Ferrera, H. Wang, V. Ferrero, M. Valvo and R. Gaudino, "Optimization of Band-Limited DSP-Aided 25 and 50 Gb/s PON Using 10G-Class DML and APD," J. Light. Technol., 38, pp. 608-618, 2020.

[4] H. Faig, B. V. Pedersen, S. Cohen, L. Gantz and D. Sadot, "Nonlinear System Identification Scheme for Efficient Compensators Design," J. Lightwave Technology, doi: 10.1109/JLT.2019.2963252, 2020.