Opportunities and Challenges When Using Low Bandwidth Optics for Higher Capacity PON Systems (*Invited paper*)

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Abstract: Next generation PON physical layer, targeting 50 Gbit/s/lambda, has to deal with optoelectronics bandwidth limitation. In this invited paper, we review the resulting required bandwidths and discuss the trade-off between receivers with or without equalization.
OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation; (060.4510) Optical communications.

1. Introduction

Passive Optical Network (PON) new standardization proposals are rapidly evolving and are today ready for the definition of 25 Gb/s (per wavelength) PON (25G-EPON under IEEE) [1-2], while the next step, focused on 50 Gb/s (HSP-PON, Higher Speed PON) is under discussion in ITU-T [3]. It is very likely that 50 Gb/s/λ will still follow the "mainstream" of previous PON standards, still being based on intensity modulation and direct detection (IM-DD), possibly coupled with some simple form of digital signal processing (DSP) at the receiver (RX). The main issue for this target is the bandwidth (BW) limitation of the optoelectronics (O/E) that can currently be manufactured at the (very low) PON target prices. More "revolutionary" approaches, such as coherent technology seems for the moment postponed to even higher bit rates (R_b). Our group at Politecnico di Torino, in close collaboration with Telecom Italia (TIM), has been active in this area for the last two years [4, 5]. In this invited paper, we summarize the main results of our work, focusing on possible physical layer solutions for 50 Gb/s/λ downstream transmission. We addressed the following alternatives: *i)* no equalization at the receiver vs. feed-forward (FFE) or decision-feedback (DFE) equalization; and *ii)* avalanche-photodiode (APD) vs. semiconductor optical amplifier (SOA)+ PIN receivers. For each case, we show the required O/E BW for three modulation formats: binary pulse amplitude modulation (PAM-2), quaternary PAM (PAM-4), and electrical duobinary (EDB). We then discuss the resilience to chromatic dispersion.

2. Experimental and simulation setups

The BW limitation impact is analyzed through an extensive set of numerical simulations. In parallel, experiments were also performed to confirm the theoretical results. The experimental and simulation setups are shown in Fig. 1a, and explained in detail in [5]. An off-line processing approach is used in the experiments, based on a 92 GSa/s arbitrary waveform generator (AWG) at transmitter (TX) and a 200 GSa/s real-time oscilloscope (RTO) at RX. When relevant, DSP in the receiver equalizer is performed downsampling the RTO output to 2 samples per symbol (2sps). For the key band-limiting elements (O-band 1310nm directly modulated laser (DML) and APD), we used 10G-class O/E similar to the ones used today for XGS-PON, investigating on extending their use to 25 Gbps and 50 Gbps. The optical distribution network (ODN) is composed by a 20-km SMF fiber, followed by a variable optical attenuator (VOA) used to set the total ODN loss, measured as the difference between the average transmitted power (P_{TX}) at the optical TX output and the received optical power (ROP) at the optical RX input. In all our experiments and simulations P_{TX} = 11.5 dBm. A FFE (2 sps, 20 taps) or a FFE+DFE (termed just DFE for simplicity, 2 sps and 20 taps for FFE, 1 sps and 5 taps for DFE) adaptive equalizer (AE) is used when indicated. For the simulation setup (see top of Fig. 1a), a linear intensity modulation optical TX is assumed. The SMF chromatic dispersion (CD) effect is included in the

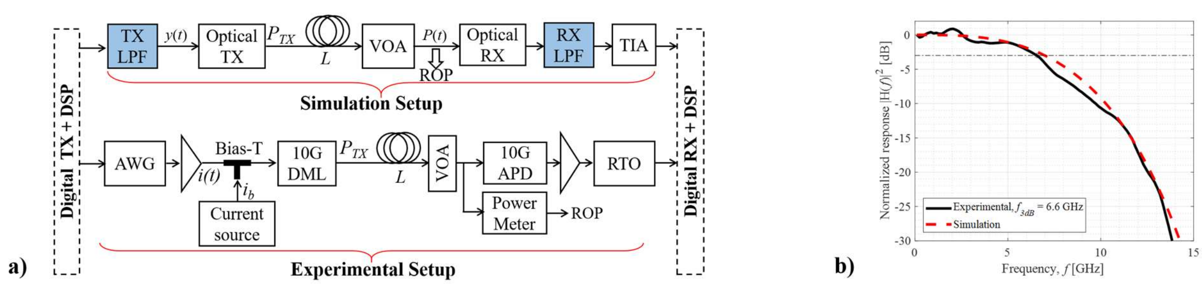

Fig. 1 a) Experimental and simulation setups. The Optical RX block can be an APD or a SOA+PIN (placing an optical filter at SOA output); b) Frequency response of the experimental transmission system (solid) and the emulated system frequency response used in simulations (dashed).

simulator (D=-0.2 ps/nm·km @1310 nm). In the RX, noises are modelled as additive white Gaussian noise random processes [4]. As optical RX, we considered two options: APD and SOA+PIN (placing an optical filter at the output of the amplifier). The APD has gain of 8.45 dB and noise factor of 11 dB. Regarding the SOA+PIN, we used a simplified model for the SOA, assuming a linear regime with gain of 12 dB, and a noise figure of 9 dB. The optical passband filter placed between the SOA and the PIN is modeled as a fifth order super-Gaussian filter (SGF) with -3dB BW of 400 GHz. For both APD and PIN, a responsivity of 0.7 A/W and a RX thermal noise density of $N_0 = 10^{-21}$ A^2/Hz were set and the effect of shot noise was taken into account. In our simulation, we used low-pass filters (LPF) to emulate the frequency response of the TX and RX. Since we want to analyze the performance of the system as a function of the system BW limitation, we used SGFs which allow changing continuously the -3dB and -20dB frequency (f_{3dB} *and* f_{20dB}) of the filter response [4]. The frequency response characterization of the full experimental transmission system (including the AWG and RTO) is shown in the solid black curve of Fig. 1b [5]. The most bandlimited device in our experimental setup is the APD+TIA. To match the experimental transfer function in our simulations, we consider a SGF with f_{3dB} = 14 GHz and f_{20dB} = 16 GHz at the TX, and one with f_{3dB} = 7 GHz and f_{20dB} = 13 GHz at the RX. The resulting total frequency response (TX + RX SGFs concatenation) is shown in the red dashed curve of Fig. 1b.

3. Performance versus available bandwidth using APD receiver

First, we performed a simulation analysis of the BW requirements with or without AE for R_b = 50 Gbps. Fig. 2a shows the maximum achievable ODN loss to guarantee a BER target of 10^{-2} as a function of the f_{3dB} of the TX and RX (assumed to be identical 2$^{\text{nd}}$ order SGFs). The results when using FFE are presented in solid curves. Dashed curves show the performance in the absence of AE, but only including a 4th-order Bessel filter with f_{3dB} equal to 75% of the baud rate and performing threshold optimization. As expected, a very high improvement due to equalization is achieved under strong bandlimited conditions. Assuming 10G-class devices with f_{3dB} ~10 GHz, the only feasible format is PAM-4 with AE. For f_{3dB} <10 GHz the need of a more powerful equalizer than FFE (as DFE) can be anticipated. If using instead 25G-class devices with f_{3dB} ~ 17.5 GHz, PAM-2 with AE and EDB with or without AE, appeared to be feasible alternatives. While the performance of PAM formats with and without AE converges under broadband conditions, EDB exhibits an optimum operation without AE at around f_{3dB}=17 GHz (~34% of R_b) and an increasing power penalty between equalized and not equalized cases for higher f_{3dB} values. This fact is consequence of the EDB approach used here, in which a binary (pre-coded) signal is sent at the TX side, while at the RX side a 3-level standard duobinary RX is employed, assuming the presence of enough bandwidth limitations to create the 3-level duobinary signal from a binary one (for more details see [4,5]).

An experimental analysis to support our simulation results is shown in Fig. 2b. BER vs ODN loss curves (solid graphs) are shown for different modulations, equalizers and R_b values. These results were obtained using the experimental setup shown in Fig.1a with the BW conditions reported in Fig.1b (an overall available f_{3dB} = 6.6 GHz was measured). The dashed graphs shown in Fig. 2b were obtained by means of simulations. A very good agreement between experiments and simulations is achieved (after setting in the simulation the proper laser chirp parameters of the used 1310 nm commercial DML). As anticipated, when strongly bandlimited 10G-class O/E are used for 50 Gbps operation, only PAM-4 with DFE is a feasible approach, able to reach an ODN loss of 25 dB (still far from the 29 dB required by most deployed ODNs). If the BW constraints are relaxed, i.e. decreasing the R_b to 25 Gbps to have an f_{3dB}/R_b ratio of ~26%, EDB and PAM-2 outperform PAM-4, as foreseen by the simulation results shown in Fig. 2a.

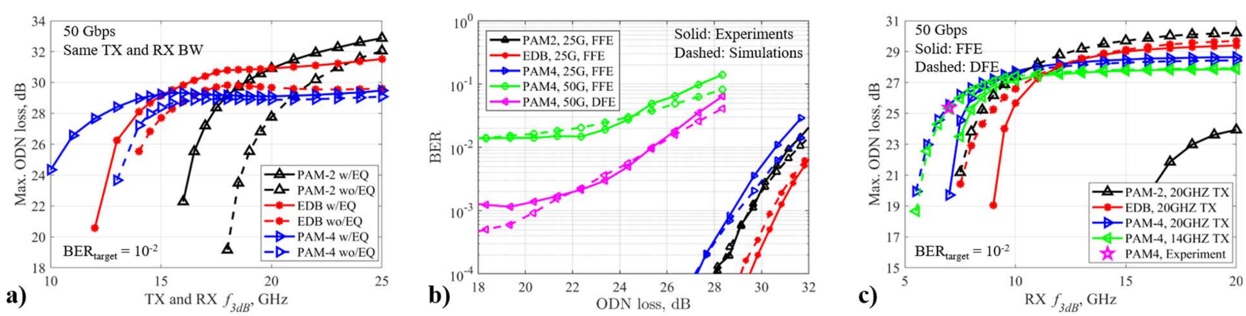

Fig. 2 a) Maximum ODN loss as a function of the TX and RX -3dB BW for different formats, comparing non-equalized and FFE-equalized cases, in optical BtB. b) Comparison of experimental and simulation BER versus ODN loss results for different modulation formats and bit rates [5] (L=20km). c) 50 Gbps simulated maximum ODN loss as a function of the RX f_{3dB}, considering optical TX with f_{3dB} = 14 or 20 GHz (L=20km)

Even if using DFE, attaining an ODN loss ≥29 dB for R_b = 50 Gbps using 10G-class bandlimited devices seems to be very challenging. Alternatives to achieve this goal have been reported recently, using machine-learning equalizer or other advanced DSP techniques, such as Volterra equalizers. However, the complexity of these techniques seems to be excessively high for the mid-term PON implementation [5]. As an intermediate feasible alternative, we explore here the use of O/E with higher BW but still using simpler FFE/DFE. We performed simulations changing the RX f_{3dB} and emulating two different optical TXs, one with the same f_{3dB} and f_{20dB} (14 and 16 GHz) of our 10G-class experimental device, and the other using higher f_{3dB} and f_{20dB} equal to 20 and 22.8 GHz, respectively, emulating 25G-class devices. The maximum ODN loss that can be achieved as a function of RX f_{3dB} is shown in Fig. 2c for different formats and equalizers. Considering PAM-4, a 29 dB ODN loss cannot be attained even if the TX and RX BW is large. In contrast, the 29 dB power budget can be achieved with both PAM-2 and EDB using the proper value of TX and RX f_{3dB} in combination with FFE or FFE+DFE equalizer, however, with a quite reduced power budget margin.

4. Performance versus available bandwidth and resilience to dispersion using SOA+PIN receiver

To increase the power budget, a SOA+PIN based architecture is analyzed. For simplicity, a chirp-less O-band optical TX is assumed. We reproduced similar graphs as those shown in Fig. 2c. The SOA+PIN results are plotted in Fig. 3a, from which it can be seen that the target ODN loss can be achieved even with bandlimited 10G-class O/E devices. For example, a 14-GHz TX in combination with a 12.5-GHz RX guarantee 29 dB of power budget if PAM-4 and FFE are used, and less BW constrained TX and RX would allow power budgets in excess of 31 dB with PAM-2 + DFE. Therefore, the SOA+PIN alternative seems to be a good candidate to implement 50 Gbps PON.

Finally, we tested the dispersion tolerance of the analyzed modulations and equalizers using SOA+PIN approach. We

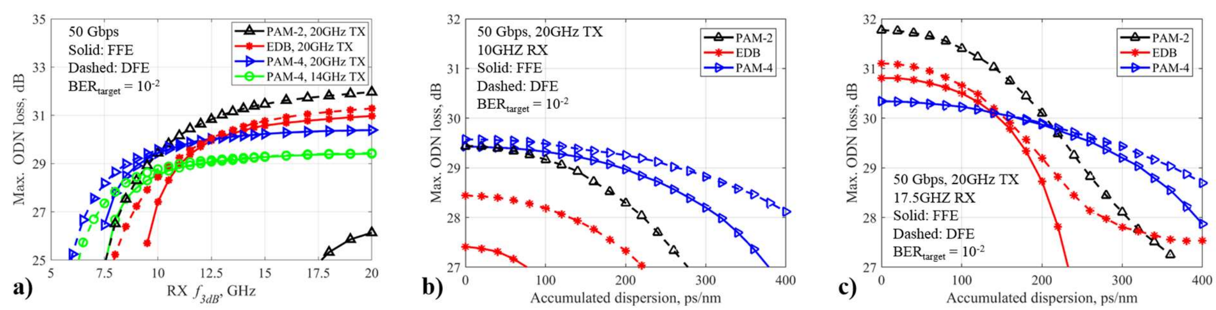

Fig. 3 a) 50 Gbps simulated maximum ODN loss as a function of the RX f_{3dB}, considering an optical TX with f_{3dB} = 14 or 20 GHz (L=20km). b) and c) Maximum ODN loss versus accumulated dispersion for a 20GHz TX in combination with a 10GHz RX or a 17.5GHz RX, respectively.

assumed a 20-GHz TX (25G-class) in combination with two RXs: one with f_{3dB} = 10GHz (10G-class) and one with f_{3dB} = 17.5GHz (25G-class). Maximum ODN loss as a function of accumulated dispersion curves are shown in Figs.3b and 3c, for 10G- and 25G-class RXs, respectively. For 50 Gbps O-band operation, PAM-2+DFE is the best solution, considering both 10G- and 25G-class RXs. A 100 ps/nm accumulated dispersion can be tolerated in both cases keeping a power penalty ≤ 0.5 dB, which means a $|D| \leq 5$ ps/nm·km tolerance at L = 20 km. This $|D|$ tolerance results in feasible operation for wavelengths between 1270–1360 nm, according to the ITU-T G.652 Recommendation. Regarding 50 Gbps C-band operation (@1550nm with D=17 ps/nm·km, assuming chirp-less TX), it could be possible only if using PAM-4+DFE and 25G-class devices, even though with very limited power margin.

5. Discussion and conclusion

The feasibility of 50 Gbps PON using bandlimited devices was analyzed, comparing different modulation formats, equalization options, and optical receiver architectures. Among the studied alternatives, the SOA+PIN PAM-2+DFE option is the best choice for O-band operation, whereas PAM-4+DFE could be considered for operation in C-band.

Acknowledgements: *the authors thank the support of the PhotoNext initiative at Politecnico di Torino. This work has been carried out in the framework of a collaboration contract with Telecom Italia.*

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