100+ Gbps/ 50 km C-Band Downstream PON Using CD Digital Pre-Compensation and Direct-Detection ONU Receiver

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100+ Gbps/λ 50km C-band Downstream PON using CD Digital Pre-Compensation and Direct-Detection ONU Receiver

Pablo Torres-Ferrera, Giuseppe Rizzelli, Valter Ferrero, *Senior Member, IEEE* and Roberto Gaudino, *Senior Member, IEEE*

***Abstract*— We experimentally demonstrate a single-wavelength 100 Gbps downstream PON transmission aided by chromatic dispersion digital pre-compensation (CD-DPC) using simple Digital Signal Processing (DSP) Finite Impulse Response (FIR) filters in combination with an IQ Mach-Zehnder Modulator (IQ-MZM) at the transmitter side and direct-detection receiver at the Optical Network Unit (ONU). A reach of 50 km over standard single-mode fiber in C-band and an Optical Distribution Network (ODN) loss of 28.5 dB are achieved. Transmission of 50 and 125 Gbps over 50 km of fiber is also tested, achieving 33 dB and 24 dB of ODN loss, respectively. The complexity of the filters, the optimization of the main design parameters and the tolerance of the CD-DPC to the uncertainty of the exact accumulated link dispersion are analyzed in detail.**

***Index Terms*— Passive Optical Networks PON, Chromatic Dispersion Compensation, Digital Signal Processing, 100 Gbps, PAM.**

I. Introduction

Passive Optical Networks (PON) operating at bit rates higher than 10 Gbps per wavelength (λ) are currently under development in order to cope with the ever increasing bandwidth demand in access networks. The recent PON standardization activities are going to release solutions for 25 Gbps/λ (25G-PON) and 50 Gbps/λ (50G-PON) [1–3], whereas next generation PON running at 100 Gbps/λ (100G-PON) has already been envisioned and it is currently an active research topic [4–15]. Achieving such high-data rates in the PON environment poses significant physical-layer challenges mainly due to optoelectronic (O/E) bandwidth (BW) limitations and chromatic dispersion (CD) if the "traditional" direct-detection (DD) scheme is preserved. To overcome the resulting physical layer impairments, the use of Digital Signal Processing (DSP) enabling higher order modulation formats and equalization has been studied in many scientific papers. In previous contributions [16–18], our group has analyzed in detail these important PON limitations, with particular emphasis on the impact of BW constraints.

To overcome the CD penalty problem, 25G- and 50G-PON standardization processes have considered only O-band transmission, since normal DD receivers would not work in C-band. The situation will be even more critical for upgrades to 100 Gbps/λ. In this future scenario, solutions for opening again C-band (or L-band) operation would potentially be interesting, due to lower fiber attenuation and, when needed, availability of reliable EDFA amplifiers, as investigated for instance in the Super-PON standard proposal [19] and in general in long-reach TWDM-PON works [20].

The problem of transmitting 50 or 100 Gbps in C- (or L-) band over the (at least) 20 km required by PON can today be addressed in principle using the following techniques:

i) Advanced modulation formats and coherent detection with electronic DSP [4–8]: this option solves any reasonable transmission problem for the foreseeable future, but its use in the PON area is still uncertain, due to cost issues for both the transmitter (TX) and receiver (RX) hardware, particularly at the ONU side.

ii) Single sideband advanced modulation coupled with Kramers-Kronig (KK) receiver [21]: this option may have severe drawbacks for PON since it usually gives poor receiver sensitivity and requires a RX electronic BW (and a DSP sampling rate) that is doubled compared to "traditional" DD receivers. Again, given the bit rates under discussion, this poses a major cost issue (in particular for 100 Gbps).

iii) Very recently, some pioneering works have demonstrated 100 Gbps C-band solution on a "traditional" DD optoelectronic approach using nonlinear adaptive equalizers based on neural networks [9–11]. However, the resulting DSP complexity is enormous and it would require a major upgrade in DSP chipsets.

At the recent OFC2020 Conference [13], our group proposed an alternative solution, specifically meant for the requirement of downstream (DS) PON, where the user-side ONU should preferentially stick to DD-RXs and simple DSP. Our proposal implements a CD Digital Pre-Compensation (CD-DPC) scheme based on very simple FIR filter processing (with reasonable number of taps as shown later) and a dual-arm IQ-MZM modulator, as shown in Fig. 1. Given a link with accumulated dispersion $D{\cdot}L$ the DSP-generated signal at the transmitter is pre-compensated by an amount corresponding to $-D{\cdot}L$ so that, at least in an ideal linear regime, the received

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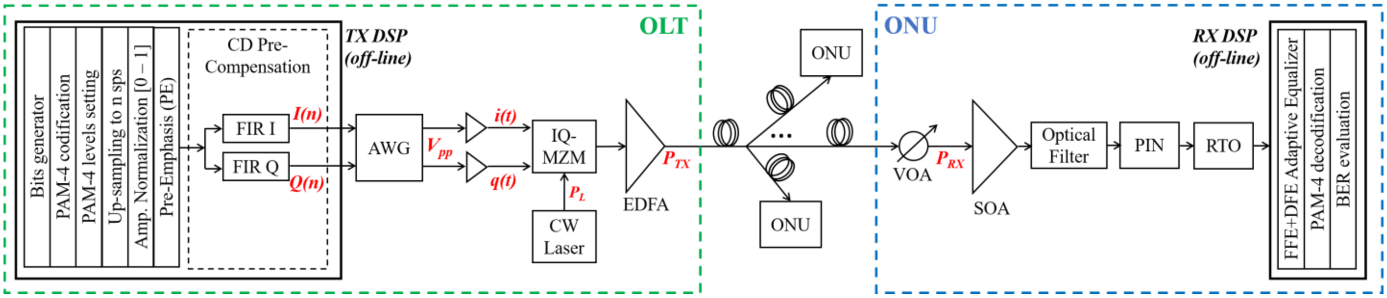

Fig. 1 Experimental and simulation PAM-4 setups. In simulations, the AWG/RTO blocks are emulated as DAC/ADC blocks. In the experimental setup, the total fiber length between EDFA output and VOA input is L=25 km or 50 km.

signal is unaffected by CD and can thus be DD received. This solution adds extra complexity to a traditional DD system, but only at the Optical Line Terminal (OLT) side, while the ONU is unaffected. The use of CD-DPC in DD systems has been reported before, but in different scenarios [21–23]. The novelty of our paper consists on introducing CD-DPC to the specific PON requirements, in particular analyzing through detailed simulations and experiments the complexity of the required digital filters at the TX, the power requirements and design parameters optimization, and the robustness of the CD-DPC to the mismatch between the compensated and the actual accumulated dispersion of the link.

In [13], we performed a numerical investigation through simulations. In this contribution, we significantly extend our simulation analysis, moreover we add an experimental demonstration, showing the feasibility of our proposal for PON. We discuss operation at 50, 100 and 125 Gbps over distances of 25 and 50 km in C-band over standard G.652 SMF, using as figures of merit the bit error ratio (BER), the achievable Optical Distribution Network (ODN) loss at a given BER target, and the system tolerance ΔL to the exact knowledge of the fiber length (i.e. the difference between the physical fiber length L and the length set in the CD-DPC algorithm). To the best of our knowledge, we have achieved a transmission record for DD-based PON systems [14, 21] and simple linear FIR-based DSP with the demonstration of 125 Gbps over 50 km and high admissible ODN loss (>24 dB) in C-band (D=+17 ps/nm/km). In our experimental results, we show a 1-dB penalty tolerance of ΔL=±2 km for 125 Gbps and 50 km in C-band. A large tolerance of ΔL=±16 km from a nominal L=50 km is obtained for 50 Gbps operation guaranteeing at least 29 dB of ODN loss. Regarding the 100 Gbps system, a tolerance of ΔL=±3 km from a nominal L=50km can be achieved targeting 27 dB of ODN loss. The maximum achievable ODN loss for 100 Gbps (50 Gbps) is 29 dB and 28.5 dB (33 dB and 32.5 dB) for a reach of 25 and 50 km, respectively.

Interesting application scenarios for our proposal would be Point-to-Point (PtP) ultra-high speed application over PON (such as for fronthauling or big business users), or the recently proposed Super-PON architecture [19, 20] (even though with smaller power budget compared to the 42 dB required by Super-PON at current lower bit rate targets), where distance is increased up to 50 km, but the differential distance among users on the same PON tree is expected to be limited to a few km. The Super-PON architecture envisions DWDM, thus typically requiring EDFA amplification and C+L band operation, so it will be CD-limited for any bit rate above 10 Gbps per wavelength.

The paper is organized as follows: in Section II, the experimental and simulation setups and their details are described, and then in Section III we present our simulation results considering a 100G-PON system reaching 25 km in C-band. In Section IV, the experimental results for 50, 100 and 125 Gbps PON transmission are shown. Finally, we conclude and discuss our work in Section V.

II. Experimental and Simulation Setup

A. *Experimental setup*

The experimental setup is shown in Fig. 1. At the TX DSP, a PAM-4 stream is off-line generated and processed. We found by experiments and simulations that a non-equispaced PAM-4 gives better performance than the more common equi-spaced PAM-4, due to the square-root relation between optical field and optical power and to the nonlinear response of the Mach-Zehnder modulator. After a heuristic optimization, we found that the optimal PAM-4 levels, normalized between zero and one, turned out to be {0, 0.3, 0.6, 1.0}. The signal is then up-sampled to m samples per symbol (SpS) (we discuss below the performance versus the parameter m). Next, a simple frequency pre-emphasis (PE) block is applied, when needed, by using an inverse low-pass one-pole filter with optimized -3dB frequency f_P, and a steep cut-off for frequencies higher than the baud rate, to partially pre-compensate electronic bandwidth limitations. The resulting signal is sent to the CD-DPC FIR-based complex filter that implements in the discrete-time an accumulated dispersion $-D{\cdot}L$, generating a discrete complex-valued signal $s(n) = I(n)+jQ(n)$. In our experiments, the CD-DPC FIRs work at m=3.68, 1.84 and 1.47 SpS, for bit rates R_b = 50, 100 and 125 Gbps, respectively, to match our arbitrary waveform generator (AWG) sampling frequency of 92 GS/s. The taps of the "FIR I" and "FIR Q" filters are evaluated as indicated in Equations (27) and (28) in [24], allowing to obtain reasonably short FIR filter (80 taps) even for the highest $D{\cdot}L$ values reached in our experiments. The CD-DPC output real-valued signals $I(n)$ and $Q(n)$ are digital-to-analog converted by the AWG and electrically amplified to generate the signals $i(t)$ and $q(t)$ that drive the 25G-class IQ-MZM. In all cases of interests, i.e. for high accumulated dispersion, the $I(n)$ and $Q(n)$ amplitude distributions are approximately Gaussian, but their peak-to-peak amplitude (V_{pp}) and mean value are different (in fact, the Q-mean is around zero, while the I one is around 0.5, when the PAM-4 input signal is normalized between zero and one). This fact is relevant to properly drive the IQ-MZM, by optimizing the V_{pp} of the signals $i(t)$ and $q(t)$ and the modulator bias. After the IQ-MZM, an EDFA amplifies the optical modulated signal, setting the average transmitted power P_{TX} to the desired level. After fiber transmission, a variable optical attenuator (VOA) is used to emulate the ODN loss, followed by a semiconductor optical amplifier (SOA), a 10-nm optical filter, a broadband PIN+TIA and a 200 GS/s real-time oscilloscope (RTO). The acquired digital signal is off-line processed at 2 SpS, using an adaptive 20-taps feed-forward equalizer (FFE) followed by a 5-taps decision-feedback equalizer (DFE), to compensate the O/E BW limitations and residual CD. After PAM-4 decoding, the BER is evaluated through direct error counting.

B. Simulation setup

In parallel to the experiment, we perform also numerical simulations whose parameters were set to match the experimental conditions. To emulate the physical frequency response of the TX and RX, we used 2nd order low-pass super-Gaussian filters (SGF) [16], with 20 and 35 GHz -3dB BW, respectively. The AWG and RTO are modelled as digital-to-analog and analog-to-digital converters, respectively, with a resolution of 6 bits for quantization. The IQ-MZM model assumed a squared cosine voltage-to-power conversion characteristic with equal power distribution into the arms, or equivalently a cosine relation in the voltage-to-optical field conversion. The modulator I and Q arms are biased at quadrature and null point, respectively. We set the IQ-MZM static insertion loss equal to 7 dB plus a dynamic modulation loss that depends on the V_{pp} of the driving signals. The EDFA is emulated as a linear and noiseless amplifier used only to set the proper transmitted power. When relevant, the impact of standard single-mode fiber (SSMF) Kerr nonlinearities was studied using the conventional non-linear Schrodinger equation (NLSE) solved numerical by the split-step Fourier method. The parameters of the SSMF at λ=1550 nm are: chromatic dispersion of D=17 ps/(nm·km), attenuation of 0.2 dB/km, effective area of 80 μm^2 and nonlinear index of 26×10^{-21} m^2/W. At the RX side, a variable optical attenuator is used to set the ODN loss, followed by a linear SOA with gain G = 11 dB and noise figure equal to 7 dB. An optical filter with pass-band of 75 GHz, modelled as a 5th order SGF is placed at the SOA output, emulating the DWDM filters envisioned for the TWDM-PON standard. We then assumed a PIN+TIA DD receiver with responsivity of 0.7 A/W and noise density of N_0 = 5×10^{-22} A^2/Hz. The shot and thermal noise sources at the RX are modelled as additive white Gaussian noise random processes [16], with variance evaluated as follows, $\sigma_{sh}^2 = 2qBsRP_i(t)$ and $\sigma_{th}^2 = N_0 B_s$ respectively. B_s is the one-sided simulation bandwidth, q is the electron charge and $P_i(t)$ is the instantaneous PIN input optical power. Both TX and RX DSP blocks are exactly the same as in the experimental setup. After PAM-4 decoding, the BER is evaluated through direct error counting over 10^5 bits.

III. Simulation Results

An extensive simulation campaign was performed to dimension the impact of the main design parameters of our proposed system, and to prepare and then interpret our experiments. We report in this Section our main simulation results. Unless otherwise stated, a 100 Gbps bit rate (gross, i.e. after FEC coding), 25 km reach and a P_{TX} = 11 dBm are considered. The BER target (BER_T) is set to 10^{-2}, as it is currently envisioned in 25G- and 50G-PON ongoing standardization efforts [2, 3] using LPDC FEC.

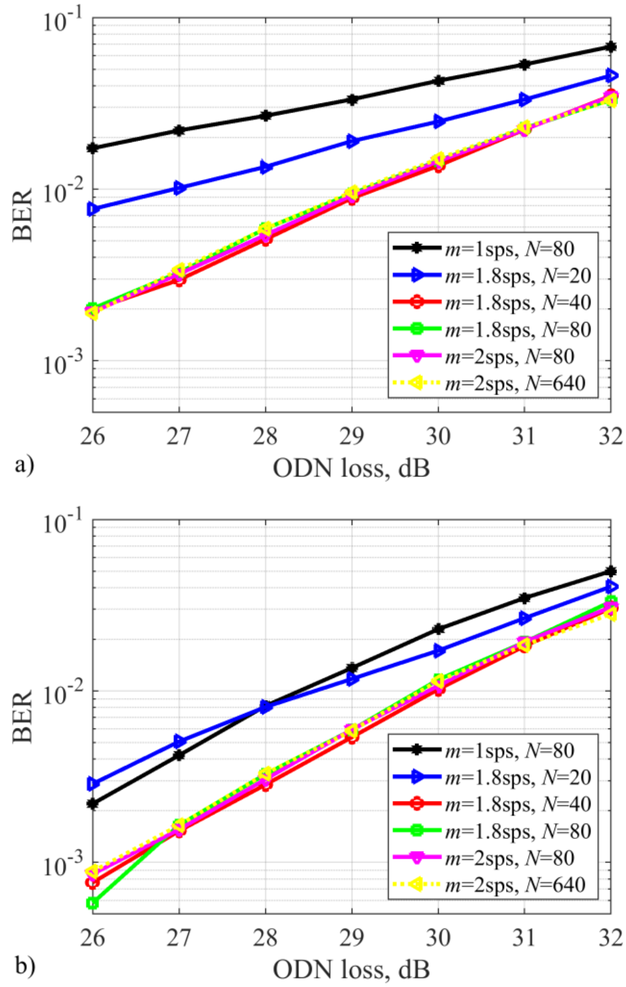

Fig. 2 BER as a function of ODN loss for different samples per symbol (m) and number of taps (N) of the CD-DPC FIRs, using a) FFE or b) FFE+DFE at RX side, for PAM-4, L=25 km and optimized driving signal amplitude. Bit rate: 100 Gbps.

We start by analyzing the complexity of the proposed TX DSP, which strongly depends on the CD-DPC FIR length and sampling rate. In Fig. 2, the performance (BER) as a function of ODN loss is displayed for different FIR number of taps (N) and PAM-4 samples per symbol (m), using FFE only (Fig. 2.a) of FFE+DFE (Fig. 2.b) at RX side. The case of m=1.8 SpS corresponds to a sampling rate of 92 GSa/s, equal to that of our experimental AWG. We show as a benchmark the performance for a very long FIR filter with N=640 taps and m=2 SpS. Compared to this ideal benchmark, we show that by setting at least m=1.8 SpS and N=40 taps, a negligible penalty is obtained. Using only m=1 SpS, even with more taps (N=80) results in a large penalty if DFE is not considered. Regarding the FFE+DFE case, the same conclusions can be drawn, except that the penalty of using only m=1 SpS is largely decreased to around 2 dB (at BER = 10^{-2}) as compared to the benchmark. As a good trade-off between performance and TX DSP complexity, in the rest of the simulations presented in this section we use m=1.8 SpS and the FFE+DFE approach at the RX DSP side (termed just "DFE" for simplicity in the rest of the manuscript).

In the results presented in Fig. 2, a fixed fiber length of 25 km was considered. In Fig. 3, the effect of varying the fiber length is analyzed. Curves of the achievable ODN loss to meet the BER_T against link length are shown, for different values of N. We confirm that N=40 taps are enough for 25 km operation. Instead, a larger N=80 number of taps are required to reach 50 km. In both cases (L=25 km and L=50 km), increasing the number of taps (above 40 or 80, respectively) do not provide any significant gain. Then, we use this values in the rest of our simulations (and experiments). From Fig. 3, it is also interesting to note that by setting a large enough number of FIR taps, the reach of the DD system can be largely extended to hundreds of kilometers at the price of a power penalty (PP) with respect to the back-to-back (BtB) situation of only ~2.5 dB (which moreover increases negligibly after ~100 km). In comparison, a PP of 0.5 and 1.6 dB with respect to BtB is obtained for L=25 km and L=50 km, respectively.

We continue by optimizing the peak-to-peak amplitude of the modulator driving signals (V_{pp}), which directly affects the optical modulation index (OMI) and the linearity of the IQ-MZM. The V_{pp} is set by amplifying the driving signals $i(t)$ and $q(t)$ with the same gain factor so that no IQ imbalance is introduced (however their V_{pp} is different, since they have different amplitude at the output of the CD-DPC, as mentioned before). In Fig. 4, BER versus V_{pp} of the in-phase signal (normalized to the modulator radio-frequency V_π) are shown, for different fiber lengths and fixed bit rate R_b=100 Gbps and ODN loss=29 dB (Fig. 4.a), and for different bit rates and ODN losses keeping fixed L=25 km (Fig. 4.b). In all cases an optimum V_{pp} value is obtained, which is a trade-off between modulator linearity and high values of OMI. Fig. 4.a shows that the optimum V_{pp} depends on L, since the peak-to-peak amplitude of the CD-DPC output signals depends on $D{\cdot}L$.

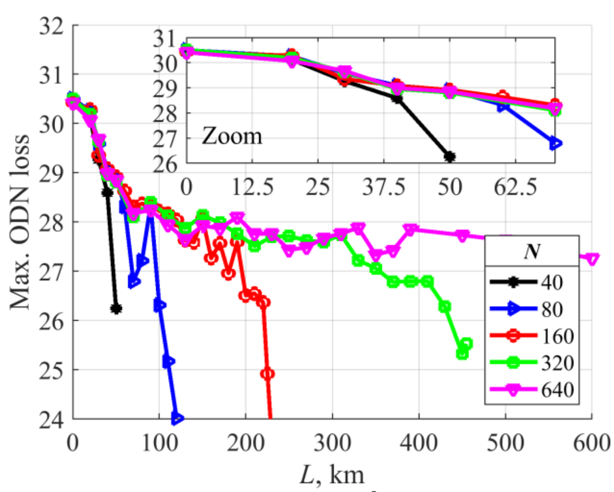

Fig. 3 Achievable ODN loss to get BER=10^{-2} as a function of the fiber length L for different values of the CD-DCP FIRs number of taps (N). m=1.8 SpS were set. The driving signals amplitude was optimized for every L. The inset shows a zoom over the first 70 km. PAM-4 Bit rate: 100 Gbps.

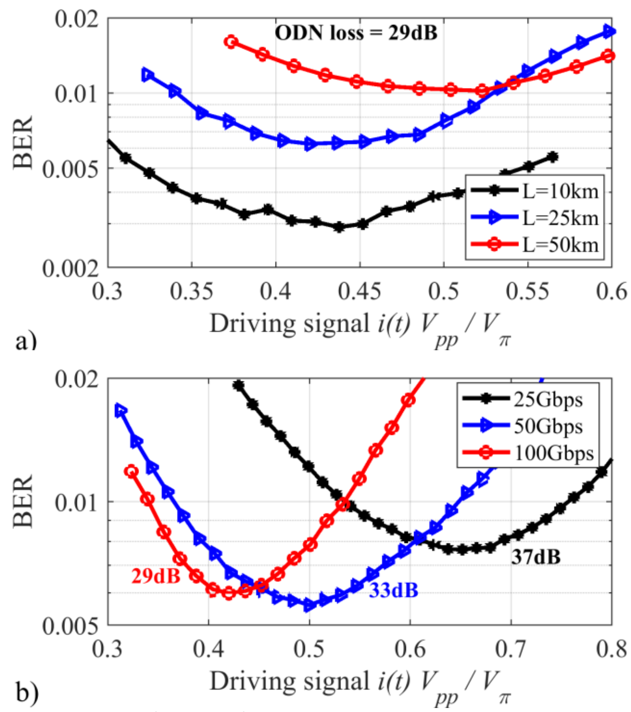

Fig. 4 BER as a function of the peak-to-peak in-phase signal amplitude V_{pp} at the modulator input normalized to the modulator RF V_π for a) different fiber lengths (L) and fixed R_b=100 Gbps and ODN loss=29 dB; and b) different pairs of bit rate and ODN loss and fixed L=25 km.

Similarly, Fig. 4.b shows that the V_{pp} optimum decreases as R_b increases, due to the fact that for increasing R_b the CD impact increases and thus the peak-to-average-power ratio of the two CD-DPC signals increases, demanding more linearity in the IQ-MZM and thus a smaller V_{pp}. Following the previous results, the V_{pp} parameter is optimized for every specific bit rate and fiber length values in the simulations and experiments presented in this contribution.

Fulfilling the power budget requirement is one of the main open challenges in future 50+ Gbps PON [1], which should be addressed by our proposed system in contrast with other C-band high-speed short-reach data-center DD-systems [14, 21, 22, 23] in which the power budget requirements are much more relaxed. Moreover, to be applicable to DS-PON, our proposal should enable communication with all ONUs at different distances or, more in general, should have a tolerance on the exact knowledge of the link length L. Thanks to the PON ranging algorithm, approximate knowledge of the path length for each given ONU is available at the OLT transmitter, but only with a given level of accuracy. We thus study the system tolerance to the mismatch ΔL between the fiber length numerically set in the CD-DPC (L_C) and the actual link length in a given path of a PON tree (L). The parameter ΔL is evaluated as $\Delta L = L_C - L$.

To analyze the aforementioned key points, in Fig. 5 curves of the achievable ODN loss versus ΔL are plot for different transmitter powers P_{TX}. For simplicity, in the previous simulation results, presented in Figures 2–4, a linear fiber was assumed. For the sake of accuracy when comparing different transmitted powers, in the curves shown in Fig. 5 the non-linear Kerr effect was considered, except on the dashed curve that was

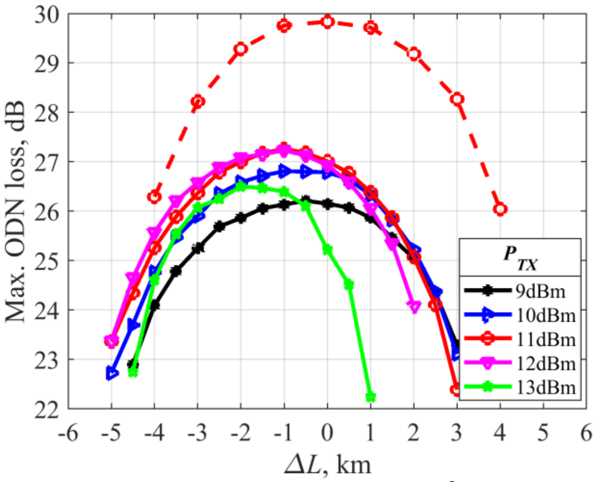

Fig. 5 Achievable PAM-4 ODN loss to get BER=10^{-2} as a function of fiber length mismatch ΔL for different transmitted powers P_{TX} and a fiber length of L=25 km (considering nonlinear Kerr effect). The dashed curve corresponds to simulation results assuming a linear fiber and P_{TX}=11 dBm. The driving signals amplitude was optimized for every ΔL and P_{TX}. Bit rate: 100 Gbps.

obtained under linear fiber conditions to be used as a reference (a fiber input P_{TX} = 11 dBm was set in this case). The driving signal V_{pp} was optimized for every P_{TX} and every compensated fiber length L_C value (which changes with ΔL, i.e. $L_C = L + \Delta L$). Our simulation results show that the optimum P_{TX} is within the 11–12 dBm range. A 3-dB penalty with respect to the linear situation is shown for P_{TX} =11dBm (we verified by additional simulations that this penalty due to fiber nonlinearity becomes negligible for transmitted powers below 2 dBm). We also observed that increasing the transmitted power reduces the ΔL tolerance range, confirming that nonlinear effects have a non-negligible impact on the CD-DPC technique resulting in a power penalty when moving into the non-linear regime.

It is also interesting to note that the maximum ODN loss is not achieved for ΔL=0 km but for a slightly negative ΔL. This indicates that the CD-DPC is slightly over-compensating CD. Moreover, the optimum ΔL shift decreases as P_{TX} decreases and disappears when fiber non-linearity is turned-off in the simulations. The actual explanation of this phenomenon is the well-known interaction of the fiber non-linearity (Kerr effect) and dispersion [25], since Kerr-induced self-phase modulation can partially compensate dispersion when D>0. Then, to achieve optimum performance, a slightly lower $D \cdot L$ value should be set in the CD-DPC.

IV. Experimental Results

In this Section, we report the experimental results obtained using the setup shown in Fig. 1. We took advantage of the guidelines found in our simulation analysis. In all of the experiments, a P_{TX} =11 dBm and N=80 taps were set, and the driving signals amplitude was optimized when changing the fiber length L, the ΔL value and the bit rate.

As stated before, fulfilling the PON power budget requirements and demonstrating tolerance to the exact knowledge of the $D \cdot L$ value of the link are the key points that should be addressed by our proposed system. Accordingly, the core results of our experimental work are given in Fig. 6, which shows experimental curves of the maximum ODN loss versus ΔL to achieve the BER_T = 10^{-2} for different bit rates and DSP (TX and RX) cases, for L=25 km (Fig. 6.a) and 50 km (Fig. 6.b). Due to strong bandwidth limitations, the use of pre-emphasis was crucial for 125 Gbps operation (see Fig. 7), whereas for 100 Gbps it provides a noticeable power gain. For 50 Gbps transmission, the BW constrains are relaxed, therefore, pre-emphasis is not needed and it is possible to avoid DFE (using only FFE) with only a small power penalty. In contrast, for the other two bit rates, 100 and 125 Gbps, removing DFE produces a large penalty, thus only the FFE+DFE approach is analyzed. The graphs of Fig. 6 were obtained after optimizing several parameters, such as the driving signals V_{pp}, the bias voltage of the IQ-MZM, the f_p of PE filter, and the P_{TX}. We show that the 50 Gbps system can reach ODN losses > 29 dB for a wide range of ΔL. For instance, a ΔL range of at least ±20 km and ±18 km (centered at L=25 km) is achieved using DFE and FFE, respectively. In other words, an ODN loss of 29 can be guaranteed for link lengths from 5 to 45 km using DFE, and from 7 to 43 km using only FFE. Similarly, a ΔL range of ±16 km (centered at L=50 km) is achieved using DFE, which means feasible operation from 34 to 66 km with an ODN loss = 29 dB. Therefore, our proposal is a suitable candidate to implement a future 50G Super-PON (even though with a more relaxed power

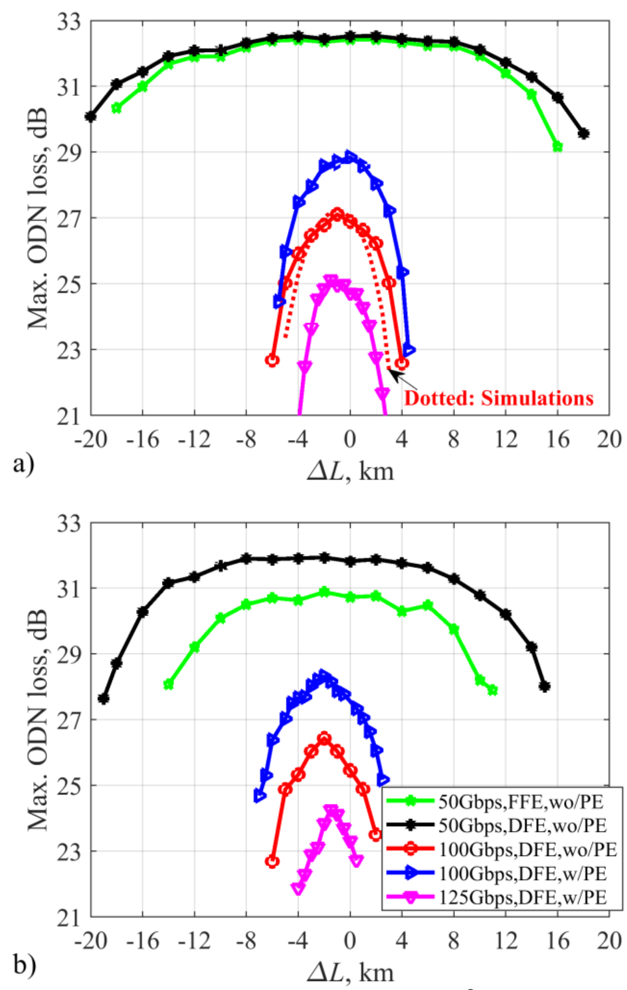

Fig. 6 Achievable PAM-4 ODN loss to get BER=10^{-2} as a function of fiber-length mismatch ΔL for different experimental scenarios and fiber length of a) L=25 km and b) L=50 km. In (a), the dotted curve corresponds to simulation results when P_{TX}=11 dBm and Kerr effect is on (taken from Fig. 5). In all the scenarios, the design parameters were optimized. PE: pre-emphasis, NL: fiber Kerr Non-Linearity.

budget than the current proposals for lower bit rates). Regarding the 100 Gbps system, a high ODN loss of ~29 and 28.5 dB can still be achieved for L=25 and 50 km, respectively, at the optimum ΔL and using pre-emphasis. An even faster 125 Gbps transmission is successfully demonstrated over 50 km achieving at least 24 dB of ODN loss, a high power budget value using DD receivers with relatively simple DSP [14].

The ΔL tolerance for different ODN loss targets is shown in Table I for all the analyzed cases shown in Fig. 6. The ΔL range is referred to the ΔL value that provides the maximum ODN loss. The possibility of relaxing ODN loss requirements for future 50G+ PON is under discussion, therefore, 25 and 27 dB are included in Table I as possible ODN loss targets. As discussed before, for 50 Gbps operation our proposal works well over a wide range of link lengths and ODN loss values ≥29 dB. For 100 and 125 Gbps operation, the achievable length range is widely reduced and lower ODN loss targets are achievable, thus making our 100G+ proposal more suitable for PtP WDM-PON solutions, where a dedicated lambda per ONU is used (such as in future high-capacity fronthauling applications) and thus Time Division Multiplexing (TDM) among different ONUs is not needed, so the CD pre-

TABLE I. PAM-4 SYSTEM TOLERANCE ΔL [km] RANGE FOR DIFFERENT ODN LOSS TARGETS

		ODN loss target, dB (BER=10^{-2})			
Case	***L*,km**	**25**	**27**	**29**	**31**
50 Gbps (FFE)	25	> ±18	> ±18	±18	±14
	50	> ±12	> ±12	±10	0
50 Gbps (DFE)	25	> ±20	> ±20	> ±20	±16
	50	> ±18	> ±18	±16	±11
100 Gbps (DFE)	25	±4	±0.1	N/A	N/A
	50	±3.0	N/A	N/A	N/A
100 Gbps (DFE+PE)	25	±5.0	±3.5	0	N/A
	50	±5.0	±3.0	N/A	N/A
125 Gbps (DFE+PE)	25	±0.2	N/A	N/A	N/A
	50	N/A	N/A	N/A	N/A

* N/A: Not Achievable.

compensation can be set on an ONU by ONU base. In [13], we also discussed some details regarding practical downstream CD-DPC implementations also for TDM to reach many ONUs at different lengths using the same lambda. In TDM, each DS frame must contain data slots for different ONUs (see Fig. 4 of [13]). Since the fiber length between the OLT and every ONU is different, the applied pre-compensation filter should be specific for the data sent to a given ONU, as well as the optimum amplitude. Therefore, the CD-DPC should be able to adapt dynamically on each TDM time slot. We are currently further studying this option.

As mentioned before, the introduction of frequency pre-emphasis is mandatory to compensate our optoelectronic hardware bandwidth limitations to achieve ODN losses>21 dB in a 125 Gbps transmission (and to increase the power budget of the 100 Gbps system). This fact is shown in Fig. 7.a, in which curves of BER vs ODN loss for different ΔL values using (solid curves) and not using (dashed curves) pre-emphasis are plotted, for R_b=125 Gbps. The BER_T can not be met in all the cases without pre-emphasis, in the analyzed range of ODN losses (that starts at 21 dB). In contrast, an ODN loss higher than 24 dB can always be achieved using pre-emphasis and setting the optimum $D \cdot L$ value in the CD-DPC algorithm, showing the

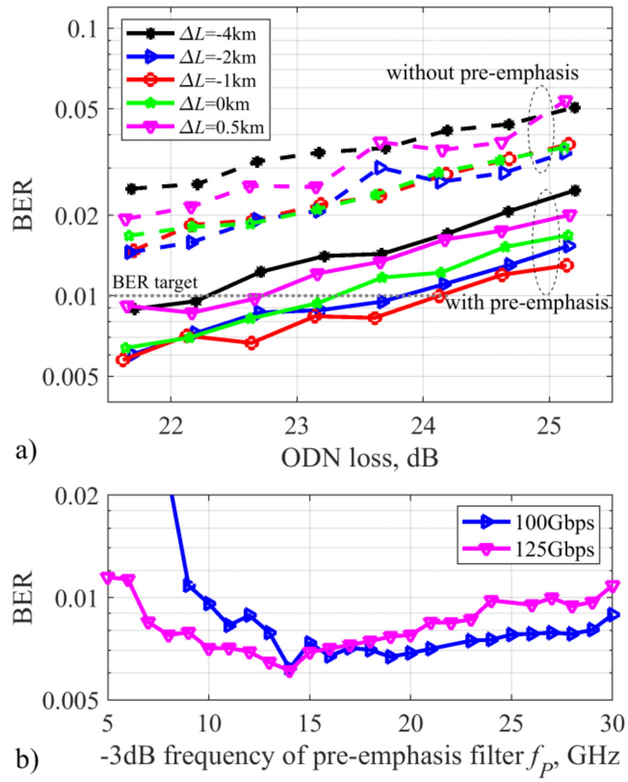

Fig. 7. BER as a function of: a) ODN loss for 125 Gbps operation with (solid) and without (dashed) pre-emphasis, for different ΔL values; b) the -3dB cut-off frequency f_P of the inverse one-pole filter used for pre-emphasis, setting a single ΔL and ODN loss value (around the optimum in each bit rate case).

advantage of pre-emphasizing the transmitted signal. A simple inverse one-pole filter was used as a pre-emphasis with a single free parameter, the -3dB frequency f_P, to be optimized. The optimization of f_P is shown in Fig. 7.b for two bit rates (100 and 125 Gbps), setting a single ΔL and ODN loss value (around the optimum in each case) to obtain the BER graphs. In Fig. 7.b it is shown than the optimum f_p for pre-emphasis is 14 GHz, irrespective of the signal R_b as expected.

Finally, the maximum achievable ODN losses for all the discussed cases are summarized in Fig. 8, considering the optimum ΔL for each scenario, and compared to the back-to-back (BtB) situation. A small penalty with respect to BtB is found for 50 Gbps and 100 Gbps with PE cases for both 25 km and 50 km fiber lengths, showing the good performance of the CD-DPC. The highest penalty, equal to 2.5 dB, is measured for 125 Gbps and L=50 km transmission. For 100 Gbps, a penalty of 1.8 dB is measured at L=50 km, close to the 1.6 dB predicted by simulations (see Fig. 3). Another confirmation of the good match between our simulations and experiments is shown in Fig. 6.a, in which one simulation graph (red dotted) is added to the experimental curves. The simulation graph in Fig. 6.a corresponds to the 100 Gbps case without pre-emphasis and L=25 km, which is exactly the same curve shown in Fig. 5 for a P_{TX}=11 dBm (P_{TX} set also in the experiments) and considering the nonlinear Kerr effect. Both 100 Gbps experimental and simulation curves matches very well in terms of maximum ODN loss, ΔL value (equal to -1 km) that provides the maximum ODN loss, and ΔL tolerance (shape of the curve) in general.

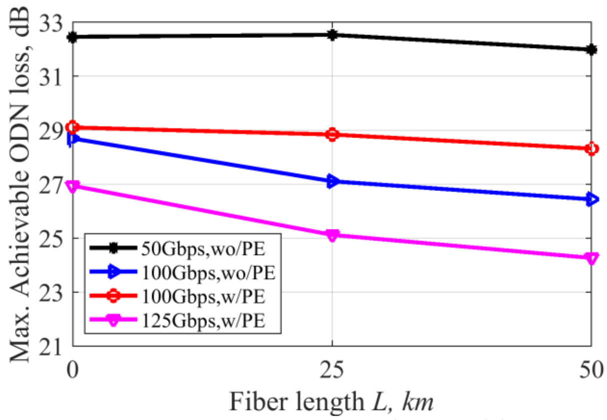

Fig. 8 Maximum achievable ODN loss as a function of fiber length L for different scenarios (optimum ΔL). The BtB corresponds to L=0 km case. In all the scenarios, the design parameters were optimized. PE: pre-emphasis.

V. Conclusion

We demonstrate through simulations and experiments a solution that sticks with direct detection at the ONU side but opens again the C- or L- band in future PON architectures at bit rates of 50 Gbps, 100 Gbps and above with DD ONU receivers and relatively simple DSP-based CD Pre-Compensation (two FIR filters with 80 taps for generating I- and Q- signals). The only constraint is that all ONUs on the same PON tree should be within a given ΔL tolerance, as discussed in detail. The proposed solution is directly applicable to PtP over PON and also for regular DS TDM PON up to a given ΔL tolerance in each PON tree. Though not discussed here for space limitation, the demonstrated tolerance to ΔL would also allow a tolerance on laser central wavelength and/or uncertainty in the knowledge of the fiber dispersion value D. Our future research work will study the extension of our idea to a dynamic time-slot by slot approach using dynamically switched-taps FIR filter approach.

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