100 Gbps PON L-band downstream transmission using IQ-MZM CD digital pre-compensation and DD ONU receiver

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Abstract: We propose a downstream direct-detection 100G-PON solution aided by chromatic dispersion digital pre-compensation using an IQ-MZM, allowing L-band operation and 29 dB power budget with low ONU complexity and without requiring single-sideband modulation.
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1. Introduction

The research and standardization in Passive Optical Networks (PON) is today considering transmission at 50 and 100 Gbps per λ [1], but such high-data rates poses significant physical-layer challenges due to optoelectronic bandwidth (BW) limitations and, for solutions outside the O-band, chromatic dispersion (CD). For instance, the current NG-PON2 standard uses the L-band for both the TWDM and P2P implementations at 10 Gbps per λ, and any future upgrade to higher bit rates would thus be strongly limited by CD. In recent years, different alternatives were proposed for 50G- and 100G-PON, typically based on advanced digital-signal-processing (DSP). However, most of them seems critical to be implemented in PON area. In fact, considering downstream (DS) transmission [2], these highly complex DSP need to be placed also in Optical Network Units (ONU) at the user side, which is the most cost-constrained element in PON. In this paper, we propose a DS 100G-PON solution that focuses on keeping a direct-detection (DD) single-photodiode receiver (RX) at the user side, plus simple feed-forward (FFE) adaptive equalization, avoiding the use of more complex Kramers-Kronig (KK) RX, single-sideband modulation or coherent detection. Our proposal enables 100 Gbps even in the L-band for the 20km typical PON distance, adding complexity only at the transmitter (TX) OLT side, where we use a DSP CD digital pre-compensation (CDDPC) scheme that generates the proper signals to be applied to a dual-arm In-phase and Quadrature Mach-Zehnder Modulator (IQ-MZM). We tested our CDDPC using PAM-4, but in general, it can work on any PAM-M solutions. The CDDPC idea was proposed before [3], but the novelty of our paper consists on introducing it to the specific PON scenario requirements, in particular analyzing by detailed simulations the complexity of the required digital filters at the TX, the power requirements, and how to prepare the TDMA stream to handle simultaneously ONUs at different lengths.

2. Simulation setup

The proposed solution is shown in Fig.1. In essence, given a link with accumulated dispersion $D{\cdot}L$ [ps/nm], an electrical PAM-4 signal is sent to a CDDPC finite impulse response (FIR)-based complex filter that implements in the discrete-time an accumulated dispersion $-D{\cdot}L$, generating a complex-valued signal that is applied to an IQ-MZM. After propagation, and when assuming a linear propagation regime, the received signal has no impact from CD (see Fig.1.g) and can then be received with a standard DD single-photodiode. More in details, in our simulations, at the TX side a 100 Gbps amplitude equispaced PAM-4 symbol stream is up-sampled to n samples per symbol (sps), normalized between zero and one and sent to a square-root block. The resulting samples are sent to two FIR filters implementing a $-D{\cdot}L$ CDDPC. The taps of the "FIR I" and "FIR Q" filters are evaluated as indicated in Equations (27) and (28) in [4], allowing to obtain very short FIR filter even for high $D{\cdot}L$ values, as we will discuss later. Due to the square-law conversion between optical field and electrical current at the DD receiver, a simple square-root look-up is introduced in the TX DSP to pre-compensate for this conversion. The resulting $I(t)$ and $Q(t)$ signals are normalized as: $i(t)=kV_{\pi}I(t)/max(I(t))$ and $q(t)=kV_{\pi}I(t)/max(I(t))$, where V_{π} is the voltage swing to have a π-shift in the IQ-MZM and k is a scaling factor to be optimized. The resulting $i(t)$ and $q(t)$ electrical signals drive the two arms of an IQ-MZM fed by a continuous wave (CW) laser with power P_L. We assumed that the IQ-MZM has a static insertion loss of 7 dB plus a dynamic modulation loss that depends on the value of k. The modulated optical signal is launched into a fiber of length L. At the RX side, a variable optical attenuator is used to set the optical distribution network (ODN) loss, followed by a semiconductor optical amplifier (SOA) with linear gain G and noise figure equal to 7 dB. An optical filter with pass-band of 75 GHz, modelled as a 5th order super-Gaussian filter (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 intensity referred noise density (IRND) of 32 pA/sqrt(Hz). The electrical signal is digitized and equalized using an adaptive FFE of 20 taps. After PAM-4 decoding, the BER is evaluated through direct error counting over 10^5 symbols. The TX and RX BW limitations are emulated by using 2nd order SGFs at each side with 25 GHz -3dB BW. In the insets of Fig. 1, the $I(t)$ and $Q(t)$ signals at the output of the 20 km FIRs (inset a) and b), respectively) can be observed, as well as their amplitude distribution (insets c) and d),

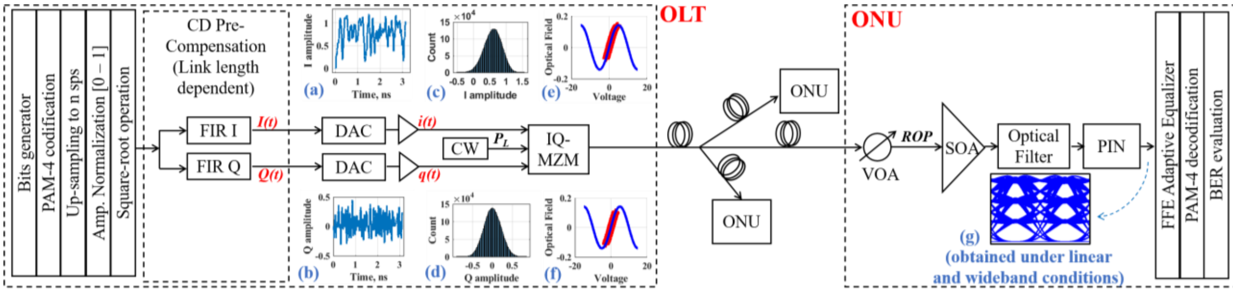

Fig. 1 Simulation setup; a) and b) *I(t)* and *Q(t)* signals at FIRs output; c) and d) Histogram of *I(t)* and *Q(t)*; e) and f) IQ-MZM field versus driving voltage curves indicating in red the *i(t)* (e) and *q(t)* (f) electrical to optical conversion for k = 1; g) Eye-diagram at PIN output, L=20km.

respectively). The two I and Q distributions look approximately Gaussian, but their peak-to-peak amplitude and mean value are different (in fact, the Q-mean is around zero, while the I one is around 0.5). This fact is relevant to properly drive the IQ-MZM, by optimizing the amplitude of the signals, which is achieved by setting the proper k value in the aforementioned $i(t)$ and $q(t)$ expressions (see Fig. 1.e and .f, where we qualitatively highlight in red the used voltages for unity k).

3. Results and discussion

We start by analyzing the complexity of the proposed DSP, which strongly depends on the FIR length and rate. In Fig. 2.a, the performance (BER) as a function of ODN loss is displayed for different FIRs number of taps (N_T) and PAM-4 samples per symbol (n) for L-band transmission (λ=1610 nm, D=20 ps/nm·km and L=20km). We show as a theoretical benchmark the performance for extremely high n=64 sps and N_T=2560. Compared to this ideal benchmark, we show that n=2 sps and N_T=40 taps has a very small penalty. Therefore, in the rest of our analysis we set these values. We prosecute by optimizing the k parameter that, indirectly, set the extinction ratio and linearity obtained in the IQ-MZM. In Fig. 2.b., BER versus k graphs are plotted for different L values. An ODN loss of 29 dB is set, assuming a P_L = 20 dBm and an SOA gain of 17 dB. The optimum k_{opt} value is a trade-off between operating a MZM linear regime for small k, and in a large-signal but nonlinearly distorted regime for high k. Fig. 2.b. shows that k_{opt} depends on L, since the CDDPC I and Q peak-to-peak amplitudes depends on $D{\cdot}L$. The values k_{opt} = 0.75, 0.85 and 0.95 for L = 5, 10 and 20 km, respectively, obtained for an ODN loss = 29 dB are used in the rest of the analysis. It is important to highlight that by using the optimum driving signals amplitudes, a target BER_T=10^{-2} can be achieved for different values of L, up to 20 km. This shows the relevance of the proposed technique.

The system power requirements are now analyzed. It has been extensively discussed that fulfilling the 50+ Gbps PON power budget is one of the main open challenges in PON [1] and the possibility of relaxing ODN loss requirements for future 50+ PON is under discussion. Fig.3.a shows contour plots of the maximum ODN loss vs. CW laser power P_L and SOA gain G. It is shown that P_L = 20 dB and G = 17 dB results in an ODN loss = 29 dB. These power requirements are high but still achievable with current state-of-the-art technology. More relaxed power values, for instance P_L = 17 dB and G = 15 dB, provide an ODN loss ≥ 25 dB, one of the future possible relaxed ODN targets for ultra-high bit rate PON. In the rest of our analysis, we focus anyway on achieving an ODN loss of 29 dB, thus we set P_L = 20 dB and G = 17 dB.

Our proposal, to be applicable to downstream PON, should demonstrate the option to serve many ONUs at different length (from 0km to 20km in current standards). The OLT transmitter knows approximately the path length for each given ONU, thanks to the PON ranging algorithm, but only with a given level of accuracy. We thus

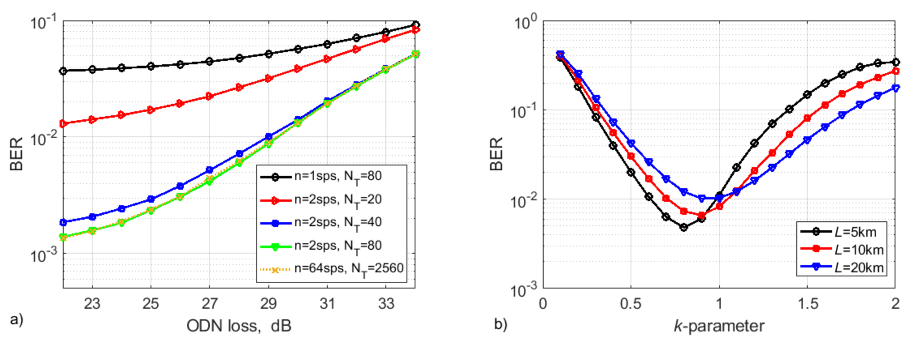

Fig. 2 a) BER as a function of ODN loss for different samples per symbol and number of taps of the FFE, for L=20km and optimized k=0.95; b) BER as a function of the amplitude driving parameter k for different fiber lengths, ODN loss = 29 dB, FIRs working at 2sps with 40 taps. In both cases, P_L = 20 dBm and G = 17 dB.

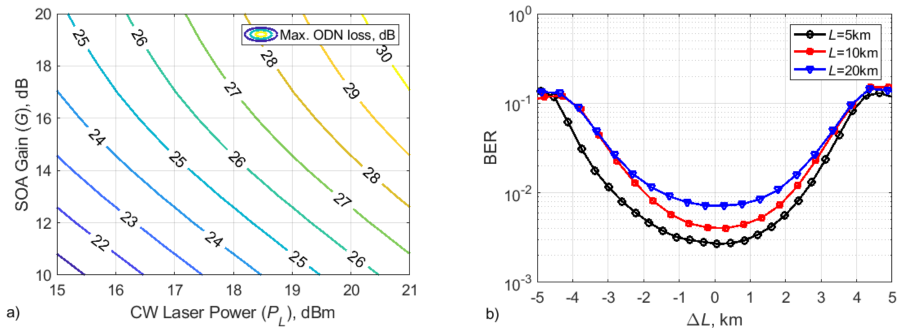

Fig. 3 a) Maximum ODN loss contour plots as a function of the CW laser power and the SOA gain targeting BER=1E-2, considering *L*=20km and an optimized *k*=0.95. b) Tolerance to the difference ΔL between the length assumed at the CD pre-compensation and the actual fiber length of the link, for ODN loss = 29 dB, P_L = 20 dBm and G = 17 dB, and optimized k = 0.7, 0.85 and 0.95 for L = 5, 10 and 20 km respectively.

performed a study on the tolerance of our solution to the mismatch ΔL between the fiber length set at the CDDPC and the actual fiber link length. In Fig. 3.b, BER graphs as a function of ΔL are shown for different nominal L = 5, 10 and 20 km. For the three analyzed cases, a tolerance on ΔL of at least ±1 km still gives minimal penalty. Based on the previous results, we now discuss some details regarding practical downstream CDDPC implementations under time division multiplexing (TDM) transmission where each DS frame must contain data for different ONUs (see Fig. 4.a). 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, as discussed before (see Fig. 2.b.). Therefore, the CDDPC should be able to adapt dynamically. In the FIR-based implementation, this adaptation requires a guard time (pre-amble) of at least N_T/n symbols at the beginning and end of every ONU data frame, to allocate the FIR transient time (see Fig. 4.a). In our case, 40 PAM-4 symbols for ONU data frame are required to this purpose (N_T = 40, n = 2 sps). The second consideration is the adaptive configuration. We propose here two different approaches. The first one, shown in Fig. 4.b., considers the use of a bank of 2x10 (I&Q) "static" FIR filters (fixed tap coefficients, including the optimum *k*-value), each working for a given *L* range, taking advantage of the "flat" performance over 2 km, as discussed before (see Fig. 3.b). By selecting the right filters couple, every ONU data can be properly CD pre-compensated. The second approach, shown in Fig. 4.c., uses only a couple of FIR filters whose taps coefficients are able to be dynamically reconfigured depending on the ONU data frame that have to be filtered. The optimum tap coefficients for different ranges of *L* (including the optimum *k*-value) can be saved in memory and dynamically extracted, as detailed in [5].

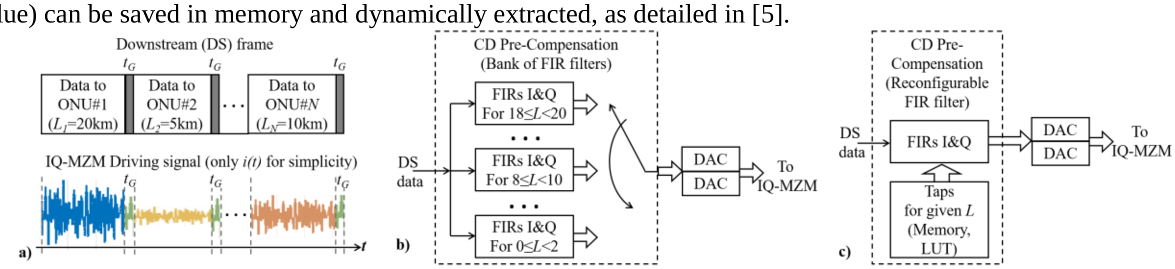

Fig. 4 a) TDM downstream transmission scheme assuming a dynamic dispersion pre-compensation for different ONU data with different link length. b) Dynamic CDDPC scheme based on the use of parallel FIR filters each for a given range of lengths. c) Dynamic CDDPC scheme based on the use of a reconfigurable FIR filter aided by memory to change its taps according the link length of the target ONU.

4. Conclusions

The feasibility of a 100G-PON L-band solution for downstream with 29 dB power budget and low complexity at the ONU side has been shown by numerical simulations. The pre-compensation technique can be performed using FIR filters with only 2 sps and 40 taps. A resilience of ±1 km to variations from the nominal length value was shown, allowing the use of a bank of 2x10 FIR filters to implement CD pre-compensation operations for all the possible PON link distances between 0 and 20 km.

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5. References

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