Assessment of Training Patterns Performances in the context of Burst Mode equalization for 50G-PON

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Abstract *50G-PON upstream burst mode requires training patterns to help both the digital signal processing convergence and the clock recovery. We evaluate the performances of 6 training patterns and conclude that the 32-bit long pattern is the best compromise between clock recovery and DSP convergence. ©2023 The Author(s)*

Introduction

The 50G-PON specification is the last of the Passive Optical Networks (PON) standard released by the International Telecommunication Union (ITU) [1]. It targets 50 Gb/s downstream, and up to 50 Gb/s in upstream (US) using a single wavelength in each direction, and Non-Return-to-Zero On-Off Keying (NRZ-OOK) is targeted. As its predecessor's, burst mode is to be used in upstream to share the time resource among users. However, at such bitrate, burst mode presents important challenges.

Digital Signal Processing (DSP) was proposed since the first definitions of 50G-PON to compensate limitations of the low-cost components to be employed such as 25G class receivers. Several DSP solutions exist, such as Feed Forward Equalization (FFE), which consists in a Finite Impulse Response (FIR) filter which compensate the bandwidth limitation of the components used in the transmission.

In upstream, the DSP must also meet the burst mode constraints which are inherent to PONs: while Optical Network Units (ONUs) emit one after the other, the burst mode receiver at the Optical Line Terminal (OLT) side and the associated DSP need to adapt in a nanosecond scale to the various channel paths (emitter bandwidth, receiver bandwidth, optical path distortion due to Chromatic Dispersion (CD) with different length of fiber, …), see Fig. 1a. We studied in [2] the time required for the algorithm of the FFE to converge, for different wavelengths and propagation length. The FFE was trained with a 2^{15}-1 Pseudo-Random Binary Sequence. However, the standard [3] proposes several preamble sequences to train the DSP. Those sequences can be repeated multiple times, but the total preamble duration should not last more than 152 ns according to the specifications to avoid a waste of useful bandwidth.

Legacy PON technologies (G-PON, XGS-PON) use a predefined preamble to help the Clock Recovery Unit (CRU) to converge and the Burst-Mode Trans-Impedance Amplifier (BM-TIA) [4] to adapt its gain to the incoming signal. A succession of 0s and 1s (noted 0xAAAA in this paper) is generally used, while another legacy 32 bits long preamble pattern, 0xBB521E26 (noted 0xBB52 for the sake of concision), is also proposed, see Fig. 1b. In practice in legacy PONs, the OLT specifies which preamble the ONU must generate, among the two previous options. A limited amount of preamble in the low layers of the PON protocol eases the interoperability on the field where equipment from several vendors is deployed.

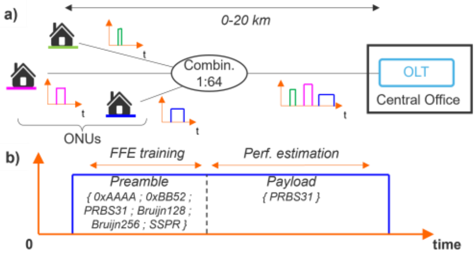

Fig. 1: Scheme of PON with upstream burst (a), and simplified representation of a burst (b)

The introduction of DSP in 50G-PON, and the need for the DSP to converge to the optimum performance, led to introduce new preamble patterns called "De Bruijn" patterns. Those "guarantee that within a single repetition period of the generated sequence of length 2^n, the number of occurrences of all possible substrings of length m, where $0<m\leq n$ will be uniform" [3].

We propose in this paper to compare the convergence time with new training patterns and legacy ones, to make the DSP converge. As the obtained FFE parameters varies from a training pattern to another, the performances are also compared in terms of relative sensitivity.

Experimental Setup and Methodology

Fig. 2 presents the experimental setup: a Pulse Pattern Generator (PPG) generates the 50 Gb/s NRZ-OOK electrical sequences which drive a 40 GHz bandwidth Mach-Zehnder Modulator (MZM). An External Cavity Laser (ECL) generates the 1270 nm optical carrier used to transport the signal. This wavelength is the center of the option 1 upstream band of [1], the most extreme option in terms of chromatic dispersion.

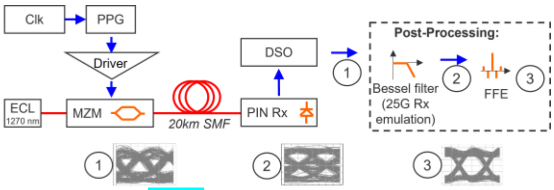

Fig. 2: Experimental setup.

The signal propagates through 20 km of Standard Single Mode Fiber (SSMF) before reaching a PIN photodiode and a Digital Storage Oscilloscope (DSO) with a 59 GHz Optical-Electrical bandwidth and a 200 GSa/s sampling rate.

The sampled signal is then post-processed: a 18.75 GHz 4th order Bessel-Thompson filter is first applied to emulate a 25G-class receiver used in 50 Gb/s upstream transmissions (see Fig. 2, insight "2"). Data are normalized so that the low and high levels are aligned with -1 and +1 levels, respectively. No additional attenuation is used, and the optical extinction ratio at MZM output exceeds 8 dB.

The last step of the process consists in equalizing the signal with an FFE. A 7-taps FFE is chosen, being the worst case in US according to [1]. We employ the same methodology than in [2] to make the FFE converge: at each iteration (bit per bit), the Least Mean Square (LMS) algorithm [5] estimates the Mean Squared Error (MSE) of the signal in comparing it to a reference sequence. The LMS uses the MSE to propose a new set of taps and eventually converge. Following our previous results [2], which optimized the convergence, the step-size "µ", is set to 0.1 for the iterations 1 to 500, then µ=0.01 from iterations 501 to 1000, and finally µ=0.001.

Six training patterns are used to emulate the preamble:

- 0xAAAA, a repetition of ones and zeros (legacy preamble).
- 0xBB521E26 (another legacy preamble)
- A 2^{31}-1 PRBS, emulating a long sequence of random payload data.
- A Short Stressed Pattern Random (SSPR) pattern [6], which consists in a sequence of 32762 bits made mainly of several 2^{28}-1 PRBSs made to be stress the wander and timing content.
- A 128 bit long De Bruijn pattern ("Bruijn128").
- A 256 bit long De Bruijn pattern (" Bruijn256").

Other length of De Bruijn sequences exist [3] but we demonstrated in [2] that a few hundred of bits was enough to converge.

Results and Discussions

We first present the offline convergence results in Fig. 3 a, in terms of MSE versus iterations. The convergence process is repeated 40 times in shifting the starting point to extract the average convergence curve. This process, performed offline, represent an ideal case compared to a practical implementation. The PRBS31 pattern (magenta solid line on Fig. 3 a) converges to 99% of its final value in 574 iterations (574 bits, 11.5 ns), as shows the magenta triangle. The Bruijn128 and Bruijn256 patterns (red dashed line and orange dash-dotted line respectively) converge to a similar final MSE value than PRBS31, in a similar quantity of iterations: 538 and 561 respectively. The MSE of the legacy 0xBB52 pattern (green dotted line on Fig. 3 a) does not progress much during the process: only 2 dB. However, as shown latter in the paper, the result in terms of final FIR function is satisfying and the eye diagram is open. Finally, the 0xAAAA pattern converges to 99% of its final value within 37 bits only (black triangle), which makes it the fastest of the 6 tested patterns. As 0xAAAA is the simplest pattern (alternance of 1s and 0s): it can be assumed that the lack of diversity in the data eases the convergence.

However, as shows Fig. 3 b, the Fourier Transform of the obtained FIR with the preamble 0xAAAA (black solid line) differs mainly from the others. The reason is that the alternance of 1s and 0s at 50 Gb/s results in a 25 GHz sine. The LMS then converges to a bandpass filter to remove the noise. As a result, once the FIR filter is applied to a PRBS31 signal emulating the payload of the burst and filtered by the 18.75 GHz

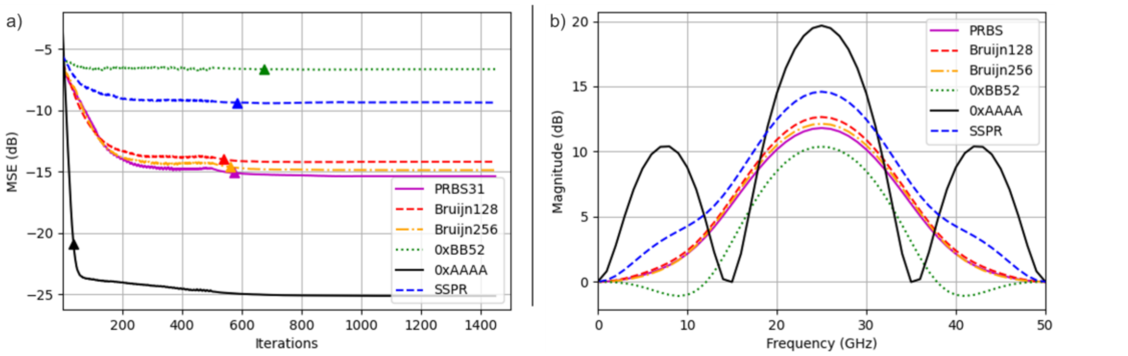

Fig. 3: Equalizer convergence in terms of MSE vs. iterations (a), and obtained transfer functions of the FIRs (FFE) (b), for the different training patterns. Triangle on Fig 3.a: convergence target reached.

Tab. 1: Summary of convergence duration, Ceq (noise enhancement factor) and TDEC, depending on the preamble.

Preamble:	PRBS31	Bruijn128	Bruijn256	0xBB52	0xAAAA	SSPR
Convergence (bits)	574	538	561	674	37	586
Ceq (dB)	3.0	3.1	3.0	2.1	1.2	2.8
TDEC (dB)	3.46	3.56	3.41	3.30	>7.0	3.56

bandwidth filter photodiode, the eye diagram obtained is closed (see Fig. 4, black). Fig. 3 b also shows the others FIR filters obtained after convergence of the different preamble patterns. PRBS31, Bruijn128, Bruijn256 and SSPR (magenta, red, orange, and blue on Fig. 3 b respectively) converge to a very similar FIR shape.

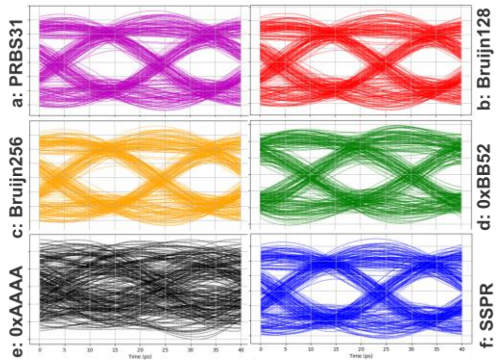

Fig. 4: Eye diagrams after Bessel filtering (25G-class APD emulation) and FFE, using the profiles obtained with different preambles.

We finally assess the transmission performance depending on the FIR obtained with the different preambles. To do so, we exploit the Transmitter and Dispersion Eye Closure (TDEC) [1]. TDEC exploits eye diagrams to estimate the penalty induced by a transmitter compared to an ideal one. In 50G-PON, the TDEC is assumed to directly estimate the impact of the transmitter quality to the sensitivity: a transmitter showing 1 dB more TDEC than another would lead to 1 dB worst sensitivity at the receiver. Thus, the lower the TDEC is, the better it is. The TDEC results, averaged over 40 samples, are summarized in Table 1. The same waveform is used to emulate the burst mode payload (generated with a 2^{31}-1 PRBS before being transmitted over 20 km of fiber, and filtered by a 18.75 GHz filter), while the previously obtained FIR filters are applied.

The Ceq, also known as the “noise enhancement factor”, is the main contribution to TDEC [7]. It computes the excess noise introduced by the FIR filter which usually enhance high frequency where the signal to noise ratio is low. The Ceq of the filters related to the patterns PRBS, Bruijn128, Bruijn256 and SSPR go from 2.8 to 3.1 dB (see Table 1), as the four obtained filters are very similar (see Fig. 3 b). The Ceq of legacy pattern 0xAAAA is the best one, with 1.2 dB, while legacy 0xBB52 converges to 2.1 dB. The best TDEC (3.30 dB) is obtained using the legacy 0xBB52 pattern, mainly because the FIR filter limits the noise enhancement. This also means that the 32-bit long legacy pattern 0xBB52 presents enough diversity to permit the algorithm to converge.

The new patterns (Bruijn128, Bruijn256) and PRBS31 and SSPR lead to a similar TDEC, in the range 3.41-3.56 dB. Finally, a TDEC exceeding 7 dB is obtained with the pattern 0xAAAA (the precise TDEC cannot be provided because of the eye closure, see Fig. 4e). Eye diagrams are provided in Fig. 4.

As all the patterns (except 0xAAAA) converge to similar FIR shapes and performance in terms of sensitivity, it could be considered to use fixed filters as we proposed in [4]. This would save preamble resources to the clock recovery and TIA convergence while keep using legacy preambles. Analog signal processing could also be used instead of a FIR (an amplifier with a specific frequency response), to relax the constraints on embedded convergence algorithms and power efficiency.

Conclusions

In conclusion, the clock recovery requires a maximum bit alternance density (as the 0xAAAA legacy pattern), while the DSP needs an important substrings variety to converge (as provided by De Bruijn patterns). We showed that the DSP fails to converge to a relevant configuration with the legacy 0xAAAA pattern, but we showed that the other legacy pattern, the 32-bit long 0xBB52, converges in less than 14 ns (700 bits) over the 150 ns offered by the preamble. 0xBB52 pattern, in addition to being a legacy pattern which proved its capacity to recover the clock, also shows the best performances in terms of relative sensitivity (TDEC: 3.30 dB), thus being a good compromise between DSP and clock recovery. The new De Bruijn patterns of length 128 and 256 bits, designed to help the convergence of the filter, present slightly worse performances (TDEC: 3.50 dB) while converging slightly faster.

Acknowledgements

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