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Abstract: 25 Gbps burst-mode upstream duobinary transmission in C-band using 10G optoelectronics and APD-based adaptive equalization receiver is analyzed and experimentally demonstrated. We show a memory-aided alternative that avoids the long training preambles (>2600 bits) needed in commonly proposed memoryless approaches.
OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation; (060.4510) Optical communications.

1. Introduction

The evolution of IEEE and ITU-T PON standards is today going toward 25+Gbps per wavelength in both directions, posing significant challenges in terms of optoelectronic (O/E) bandwidth (BW) and resilience to chromatic dispersion (CD). Current IEEE and ITU-T PON proposals for the next round of standards are thus going towards transmission in the O-band for both upstream (US) and downstream (DS) and assume a "sufficiently high" O/E BW. Several recent papers [1-5] have anyway shown the possibility to transmit 25 Gbps also in the C-band and/or using lower BW 10G-class O/E, provided that proper modulation formats and strong equalization techniques are used. Regarding modulation formats, electrical duobinary (EDB) [1-4] has proven to be in a "nice spot" between OOK and PAM-4 for this specific scenario, particularly if coupled with adaptive equalization (AE) at the receiver. In this paper, we thus investigate on the implementation of a 25 Gbps EDB transmission in C-band and over the required PON distance of 20 km, focusing on efficient but simple implementations of burst mode AE (BM-AE), as required in the US direction. BM-AE in PON is critical, since it must address all the following requirements:

1. The initial transient for the AE taps adaptation should be as fast as possible, to avoid requiring an additional preamble overhead (on top of the one already required for burst time and amplitude recovery in the "normal", i.e. not equalized, burst mode implementation) that would result in a reduction of the US transmission efficiency.
2. The US-PON burst payload can be extremely short, down to a few tens of bytes. Thus, any transient in BM-AE taps adaptation must be completely extinguished before the start of the payload; otherwise, the payload first FEC block can easily go into a FEC-failure condition. In other words, the bit-error rate (BER) should have already reached its nominal value (below the used FEC threshold) already at the very beginning of the payload.
3. Complex AE strategies, such as the recursive least square (RLS, [5]) are known to greatly reduce equalizer transient time, but they require a DSP that seems to be exceedingly complex in the low-cost PON scenario.

We carefully address all these issues in our paper. We thus propose experiments and then a simulative analysis of systems using EDB (to be able to use 10G-class APD-based receivers and transmission in C-band) and simple equalization strategy based on AE only at the receiver in a least-mean-square (LMS) feed-forward (FF) approach using 20 taps. We pay particular attention in finding an experimental approach to accurately measure a fine time-resolved BER (FTR-BER), to assess if the BER has already reached a "steady-state" condition even at the beginning of the burst. We found that, for a normal LMS-FF BM-AE independently trained, some thousand bits of header specifically devoted to equalizer taps training at the beginning of each burst would be needed. Moreover, we show that this overhead could instead be reduced to virtually zero bits if a slightly more complex strategy that includes a memory of the taps used for the previous burst from the same ONU is implemented (called the EQ-MEM strategy in the following). The novelty of our paper is thus in 1) the specific study of LMS-FF BM-AE for duobinary, 2) the focus on FTR- BER at the very beginning of the burst payload and 3) the detailed study of the EQ-MEM strategy.

2. Experimental results

The experimental setup is shown in Fig.1a. This same setup is detailed in a previous contribution [3] in which we analyzed the performance of EDB under high-speed (HS)-PON continuous mode transmission (CMT). The employed APD is a 10G-class one, which limits the 3-dB BW of the full O/E system to ~5 GHz, including the MZM external modulation (EML) at transmitter (TX). The EDB approach used here is based on the transmission of a binary pre-coded signal, processed using a 3-level duobinary AE at receiver (RX) side (called EDB1 in [3]). The BM-AE is first trained by a known training sequence of length L_{Tr}. After training phase, the equalizer adaptation is switched to blind decision-driven mode (also called "tracking" mode) over the payload bits. We analyze two BM-AE approaches (schematically depicted in Fig.1b). One, called EQ-MEM, considers the use of memory to store the final tap coefficients W of the BM-AE, to be used as the initial set of taps (W_0) when the next burst of the same ONU arrives [6]. The other avoids using memory; instead, two strategies to initialize W_0 are considered: i) setting all the taps equal to zero ("all-zero" case), and ii) setting all the taps equal to zero except the central one ("delta" case, the amplitude of central tap was optimized). We compare the previous BM-AE approaches operating under the following experimental conditions: received optical power (ROP) of -19.3 dBm and 20-km of SMF in C-band, in which a BER = 1E-3 was obtained in CMT achieving a power budget of 29 dB if a transmitted power of +10 dBm is set [3]. Twenty taps $T_s/2$ fractionally spaced and an optimized adaptation rate coefficient were set in the BM-AE.

As a starting scenario, a single burst with a long payload (L_P=2^{15} bits) was transmitted. In Fig.2a we plot the BER averaged over the full payload length as a function of L_{Tr} for the different BM-AE strategies. The advantage of using EQ-MEM is evident, since the training phase can even be avoided. Conversely, training is mandatory to reach the BER target (BER_T) when not using memory. In this condition, the delta case converges faster requiring only L_{Tr}~200 bits, while the all-zero case requires at least L_{Tr}~500 bits. However, these results need to be read carefully since a long payload was assumed. In this case, we observed (see Fig.3d) that even when the BM-AE does not reach convergence in the training phase, the adaptation keeps running in tracking mode and then convergence can be reached after some time (i.e. the BM-AE error reaches the "steady-state"). This fact means that some of the initial bits of the payload are still being used for BM-AE adaptation, resulting in high number of bit errors at the beginning of the data payload. This is an undesired effect since error-free operation in the full payload must be guaranteed after FEC. Computing the average BER over a long number of bits masks this effect, since only the first bits are affected by high error condition. Therefore, the BER information provided by Fig.2a can be misleading. To overcome this problem, we followed a more realistic approach in the rest of our analysis. We experimentally emulated the transmission of N = 100 bursts (from the same ONU), having a shorter payload length (the full burst length is L_{Tr} +L_P=5120 bits), which were stored at the RX side. Then, the payload of every RX burst was "sliced" into M smaller time slots of 256 bits. Bit error counting was performed over each time slot, and the BER was computed by accumulating the errors "per slice" over N different bursts (to have enough bits to guarantee accuracy at the BER_T) as graphically represented in Fig.1c. This average BER per time slot is called "fine time-resolved BER (FTR-BER)", and allows us to analyze the evolution of the errors (i.e. the BER) over time. By following this approach, we obtained the results depicted in Fig.2b, 2c and 2d for different initialization approaches, namely all-zeros, delta, and pre-evaluated (EQ-MEM), respectively. In the EQ-MEM approach, the complete first burst ("pilot burst", with length of 5120 bits) is used to train the BM-AE. From Fig.2d, we can see that the EQ-MEM approach produces a FTR-BER below the target for every time slot, irrespective on the value of L_{Tr}. Therefore, the training phase can effectively be avoided, which helps on increasing the data efficiency of the PON system (only one pilot burst at the beginning of the operation is needed). Conversely, as can be seen in Fig.2b and 2c, when memory is not used, a training sequence of a least L_{Tr} = 2560 bits is needed in combination with the delta initialization of the taps to achieve the required BER_T already at the beginning of the payload time slots. It is interesting to note that, for both

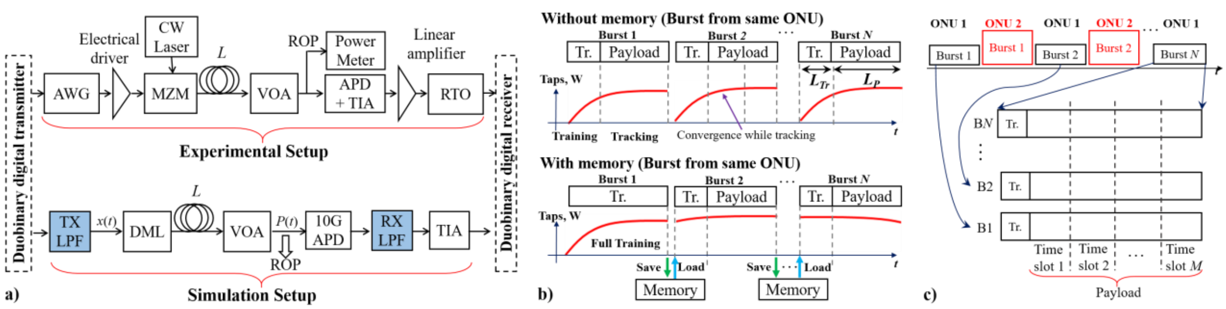

Fig. 1 a) Experimental and simulation setups; b) Burst-mode transmission approaches, c) the proposed fine time-resolved BER evaluation.

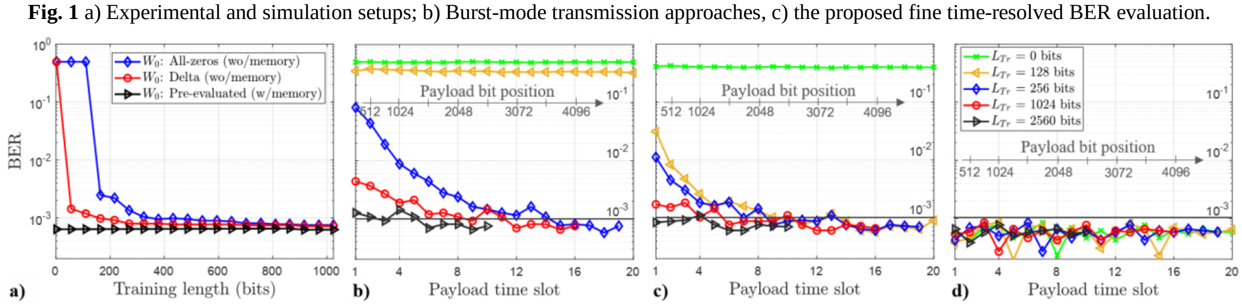

Fig. 2 a) Average BER of a single long payload burst (L_P =2^{15} bits) vs. training lengths (L_{Tr}) in bits.
Fine time-resolved BER over each of the 256-bits time slots for initial taps set to: b) all-zeros, c) delta, and d) with memory (EQ-MEM).

delta and all-zero cases, the BER_T cannot be achieved in the initial time slots if $L_{Tr} < 2560$ bits, while from Fig.2a it could be misunderstood that L_{Tr} ~500 bits were enough to reach the BER_T. Actually, previous works using also LMS [5] have reported much shorter values of L_{Tr} needed to guarantee the pre-FEC BER_T (close to those found for single-burst and long payload shown in Fig.2a). The referred results are anyway based on the mean square error (MSE) metric (which is proportional to BER) and tend to "mask" what happen at the very beginning of the payload, by showing an averaged metric over the *full* payload, giving an optimistic estimation. In fact, particularly remembering that PON payload can be as short as 48 bytes in ACK packets, it is very important to ensure stable BER_T even in the very first FEC blocks of the payload.

3. Simulated burst-mode upstream duobinary transmission by direct modulated laser (DML)

Once analyzed and experimentally demonstrated the EML case, in this section we report a similar set of results but now using a direct modulated laser (DML). Due to the lack of a suitable bandwidth DML in our experimental inventory, we performed this analysis by means of numerical simulations. A standard DML model that considers the effect of transient and adiabatic chirp [4], with realistic linewidth enhancement factor $\alpha = 3.2$ and adiabatic chirp coefficient $\kappa = 13$ GHz/mW, was used. The rest of the simulation blocks are shown in Fig.1a, and described in [3]. In [4], the impact of the relation between dynamic power, adiabatic chirp and dispersion on the performance of a direct-detection system is explained in detail. Based on this argument, we performed an extensive analysis (not shown here for space limitations) to optimize the transmitter power (P_{TX}) and extinction ratio (ER) in order to guarantee feasibility (power budget (PB) ≥29 dB for BER = 1E-3) for fiber lengths (L_F) up to 20-km in C-band. The results are shown in Fig.3a: the contour plots show the combination of ER and P_{TX} that results in a PB = 29 dB for different L_F. The intersection of the areas enclosed by these contour plots (highlighted in gray) shows the region in which the system is feasible from 0–20 km. The point of operation that was then chosen (ER=6dB and P_{TX}=8.5 dBm) is marked. We select ROP of -23 dBm, which results in a BER = 1E-3 (PB = 31.5 dB) in CMT. Under these simulation conditions, the same procedure explained in the previous Section 2 was repeated to analyze the FTR-BER evolution. The results are shown in Fig.3b and 3c, for EQ-MEM and delta case, respectively. Very similar conclusions as those extracted for EML case were obtained: in absence of memory, a training sequence of at least 2600 bits is required to achieve the BER_T from the start of the payload. Conversely, by using the EQ-MEM approach the training phase can be avoided. Fig.3d shows the BM-AE (short-time averaged) MSE evolution over time for the delta case (no memory) using L_{Tr} = 256 bits. It can be seen that the steady-state (convergence) of the BM-AE has not yet been achieved after training, but adaptation continues in the first part of tracking, affecting the initial bits of the payload (note that using our normalization on the signal, MSE=0.1 results in a BER slightly lower than 1E-3).

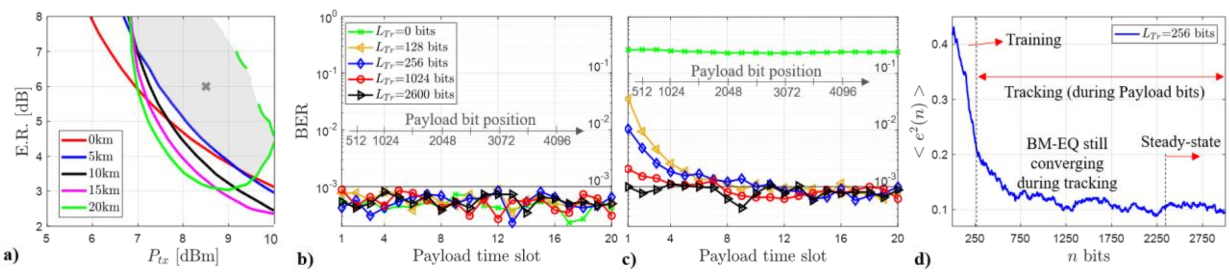

Fig. 3 a) Region of operation that guarantees feasibility in DML-based CMT for 0 to 20 km, and operational point. Fine time-resolved BER for different initial taps: b) EQ-MEM, c) delta. d) Error square evolution over time for a given L_{Tr} (for delta case).

4. Conclusions

Memoryless and memory-aided burst-mode equalization approaches were compared for 25 Gb/s PON by means of experiments (for EML) and simulations (for DML). Care was taken in computing the BER in a realistic mode, to avoid misleading measurements at the beginning of the payload. We showed that the memoryless approach requires >2600 training bits, which mandates an additional long preamble, while the memory-aided can completely avoid this requirement, thus increasing the data transmission efficiency.

Acknowledgements: *the authors thank the support of the PhotoNext initiative at Politecnico di Torino and Telecom Italia (TIM).*

5. References

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