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Compatibility between coherent reflective burst-mode PON and TWDM-PON physical layers

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Abstract: We discuss the compatibility between reflective PON architectures and the recently defined ITU-T G.989.1 TWDM-PON. Focusing on the upstream, we experimentally demonstrate that, by using burst-mode coherent detection at OLT, reflective PON can achieve the specification target set for TWDM-PON, without requiring precise wavelength accuracy at ONU. Compared to the companion ECOC 2013 paper, we investigate on the differential optical path loss (DOPL) issue, proposing a simple SOA gain control algorithm to achieve reliable transmission for DOPL up to 17 dB.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.1660) Coherent communications; (060.4080) Modulation.

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1. Introduction

FSAN has recently defined the architecture for NG-PON2 under Recommendation G.989.1, which will be based on TWDM-PON, as described in detail in [1]. FSAN decided to enforce a total backward compatibility with previous standards (namely G-PON, XG-PON and RF-video). In particular, the Optical Distribution Network (ODN) will still be splitter-based (i.e., without optical filters such as arrayed waveguide grating, or AWG) and it will require the same ODN losses defined for G-PON and XG-PON, i.e. the so-called “Class E1” (32 dB) and E2 (35 dB) [2]. TWDM-PON seems to be completely incompatible with most of the WDM-PON reflective architectures proposed in the literature in the last ten years [3–5], for a set of different reasons such as:

- most of the proposed WDM reflective PONs require the use of AWGs in the ODN;
- the achievable ODN loss is limited to typically 20-25 dB, due to several spurious effects such as the Rayleigh back-scattering (RBS) and the low RX optical power;
- most proposals use a dedicated λ for each ONU, and do not support burst-mode TDMA in the upstream (US). The recent decision by ITU-T for TWDM-PON is clearly a demonstration that most stakeholders in this field, such as Telecom operators, perceive that sharing each available wavelength by TDMA is, on the contrary, a must.

Working in this scenario and focusing only on the US link, our group has previously demonstrated that, by using self-coherent detection at the OLT, the following performances can be achieved:

- the ODN loss can be as high as 40 dB at 1.25 Gbps [6];
- the effects of the RBS can be almost completely cancelled by an adequate electrical filtering [6];
- the WDM filtering functionality can be moved from the ODN (performed by a standard $1xN_{ONU}$ passive splitter) to the ONU side [7].

Still, two important missing points to make this architecture compatible (at least in principle) with US TWDM-PON are a bit-rate upgrade to 2.5 Gbps and burst-mode operation. These are the two targets of this paper, where we demonstrate a 2.5 Gbps US burst-mode transmission based on a reflective PON. This paper is submitted to an Optics Express issue that contains selected papers from ECOC 2013 Conference. Compared to our ECOC parent paper [8], this one extends our previous results on the issue of differential optical path loss (DOPL), proposing a simple SOA gain control algorithm to achieve reliable transmission for DOPL up to 15 dB, as required in all ITU-T PON standards.

The architecture under analysis, shown in Fig. 1, may offer the following advantages:

- the US λ comb accuracy is completely set by the OLT and not by each individual ONU, as it happens on the contrary for TWDM-PON [1]. In the architecture of Fig. 1, each ONU needs to tune its optical filter by locking it on one of the N_λ already existing wavelength; so that the locking algorithm can be completely "local" to the ONU, without any distributed interaction with the OLT;
- as a result, subsequent upgrades to DWDM seem more feasible when using a number of wavelengths N_λ significantly higher than 4, and possibly a narrower frequency spacing (such as 50 GHz), since it is possible to avoid tunable lasers at the ONU;
- for each US wavelength, the required CW laser and coherent receiver at the OLT are shared by several ONUs (of the order of N_{ONU} / N_λ) so that their cost may be more reasonably justified.

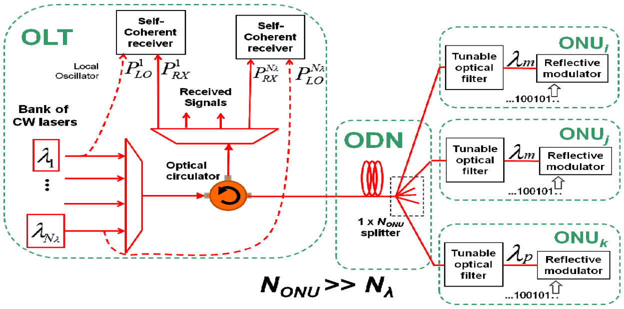

Fig. 1. Block diagram of the proposed architecture (only US transmission is shown).

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2. Experimental setup

The experimental demonstrator, shown in Fig. 2, is focused on burst mode transmission and detection operations, in a coherent reflective PON at 2.5 Gbps US. At the OLT side, a CW laser (external cavity, 1550.92 nm) is used both as a feed for US ONUs transmission, and as a local oscillator for the OLT coherent optical detection. The back-to-back (B2B) sensitivity of the receiver (by Neophotonics) is equal to −49.5 dBm @ BER = 10^{-3}, for an on-off keying (OOK) modulation format at a line rate of 2.5 Gbps. The OLT is linked by an optical circulator to the ODN, which uses 37 km of SMF buried metropolitan fiber running around the city center of Turin (Italy). The optical power launched into the fiber was set to 6 dBm, a relatively low launched power compared to the levels for XG-PON TWDM-PON, where launched power for Class E2 is up to 11 dBm [2].

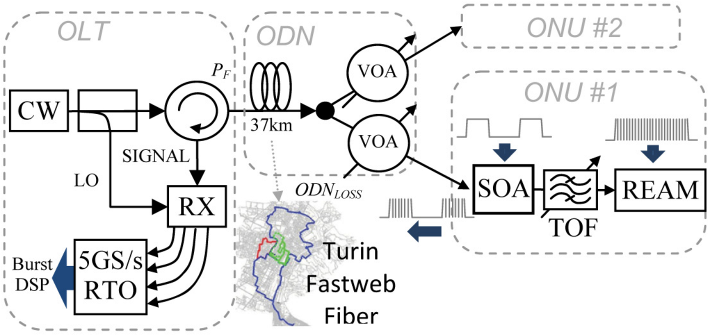


Fig. 2. Experimental setup (REAM: Reflective Electro Absorption Modulator, RTO: real time oscilloscope, SOA: Semiconductor Optical Amplifier, TOF: Tunable Optical Filter, VOA: Variable Optical Attenuator).

After the fiber, we inserted in the ODN path a variable optical attenuator (VOA) to emulate variable ODN loss, and a 1x2 optical splitter, to connect both ONUs. The CW signal reaching the ONU is reflected and modulated by means of a Reflective Electro Absorption Modulator (REAM). The SOA placed in front of the REAM amplifies the optical signal twice, first on the feed CW downstream (DS), and then on the reflected and modulated US signal. In order to emulate the ONU wavelength selection functionality, we placed a Tunable Optical Filter (TOF) between the SOA and the REAM. This TOF is also useful to partially filter out the ASE noise, and, thanks to its approximately 4 dB insertion loss, to avoid excessive SOA saturation in the US direction.

The 2.5 Gbps US signal is generated at the ONU by driving the REAM (reverse bias = 2V, modulation amplitude = $4V_{pp}$) by pure NRZ, while the optical packets are generated by switching on and off the SOA. This functionality is performed by driving its bias current with on-off rectangular electrical signal with proper amplitudes to carve 500 ns optical bursts, each containing 1250 bits at 2.5 Gbps.

The US signal at the ONU output propagates back through the ODN, and then it reaches the self-coherent receiver in the OLT, whose output electrical signals are captured by a 5 GS/s Real Time Oscilloscope and post-processed off-line, using a custom burst-mode digital-signal processing technique. In particular, the standard DSP solution [5,9], based on Viterbi-Viterbi carrier-phase estimation and LMS adaptive equalization was modified to work in burst mode operation, focusing on the alignment procedures on the received packets and on the convergence speed of the LMS algorithm [10, 11].

Each packet contains a short dummy-pattern at the beginning and end of each burst, 127 bits of sync-pattern and 1000 bits payload (8B/10B coded), as shown in Fig. 3. The dummy-pattern is useful for "absorbing" the rise and fall-time of the SOA acting as a gate, and also the transient effect of the coherent receiver AC-coupling. The sync-pattern is used for identifying the start of each packet and also for training the LMS algorithm, before switching to the LMS "decision-directed" mode, which should carry out the burst payload elaboration.

We implemented a TDMA transmission from two ONUs with 25 ns guard-time. The ONU under test is indicated in the following as the "reference ONU", while the other one is the "interfering ONU".

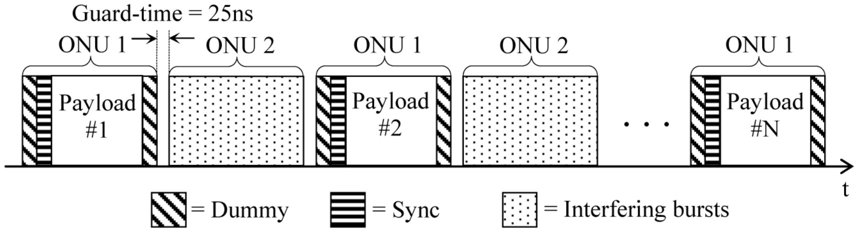
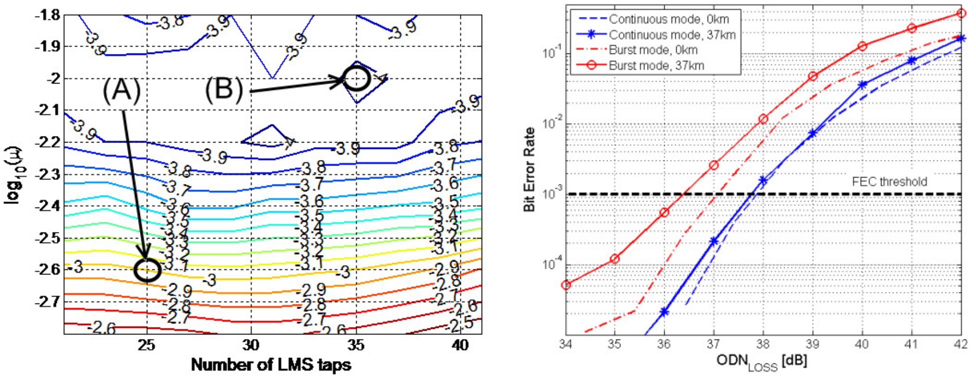


Fig. 3. Time relations of the useful and interfering optical US packets for two ONUs.

3. Experimental results

The first measurements campaign was focused on comparing continuous and burst mode transmission, for a single reference ONU. To optimize the coherent receiver DSP parameters in the unusual scenario required by the burst-mode operation, we evaluated the Bit Error Rate (BER) versus different values of μ (the key parameter which regulates the LMS convergence speed) and the amount of LMS filter taps [9]. The results of the optimization are shown in Fig. 4(a), where the circle "B" indicates the optimum values. Comparing the corresponding BER to the one obtained using the optimum values found in the continuous mode case (circle "A"), about a decade improvement on BER can be observed.



(a)

(b)

Fig. 4. (a): BER contour plot (showing $\log_{10}$(BER)) vs. LMS parameters. Optimum parameters for the continuous mode case (A) and for the burst mode case (B). (b): BER vs. $\mathrm{ODN}_{\mathrm{LOSS}}$ under different conditions (burst and continuous mode, back-to-back and 37 km).

After this DSP optimization, we evaluated the performances of the system in terms of BER versus ODN loss. By means of the VOA placed after the fiber (Fig. 2), we span different values of the overall ODN loss. Figure 4(b) summarizes the results obtained respectively for the continuous mode and the burst mode cases, either in back-to-back or after 37 km of fiber. In the burst mode case, for each value of ODN loss, we estimated the BER after averaging over 1800 received packets, corresponding to about $1.8\cdot10^6$ bits. The graph demonstrates that our system can tolerate more than 35 dB of ODN loss at a FEC threshold equal to BER = 10^{-3} for a launched optical power above 6 dBm, thus satisfying XG-PON E2 class requirement [2]. When working in burst mode, the LMS algorithm training phase is performed over 127 bits, while in continuous mode it is much slower (over 20000 bits). This is the explanation for the approximately 1 dB penalty between the continuous and the burst mode curves highlighted in Fig. 4(b).

We also investigated the performances of the system in terms of acceptable DOPL levels, which is a particularly critical issue in reflective PON since DOPL is seen twice (first in the DS than in the US) and may thus create huge power level differences at the OLT receiver. For instance, the DOPL = 15 dB XG-PON requirement would create up to 30 dB maximum variation among ONUs on the round trip path passive losses, a value that, if not properly handled, will be completely unacceptable for any type of optical receiver and, in particular, for a coherent receiver that usually has a low dynamic range due to ADC requirements. We propose the following countermeasure: the OLT receiver monitors the received power in each burst and try to obtain constant received power on all bursts by signaling to all ONUs how to reduce appropriately their SOA gains. In other words, we propose to implement an OLT-centralized automatic control algorithm on the ONUs SOA gain whose target is to equalize the received optical power at OLT. We implemented this algorithm by first measuring the SOA biasing current required for each ODN loss to obtain a constant received power at OLT. The results are shown in Table 1.

Table 1. SOA Bias Current (in mA) vs ODN Loss to Maintain a Constant Optical Power at OLT Receiver

ODN_{LOSS} [dB]	15	16	17	18	19	20	21	22	23	24	25
SOA_{BIAS} [mA]	36,9	37,8	38,7	39,6	40,5	41,4	43,2	45,0	46,8	48,6	50,4
ODN_{LOSS} [dB]	26	27	28	29	30	31	32	33	34	35	-
SOA_{BIAS} [mA]	52,2	54,9	57,6	61,2	64,8	68,4	73,8	81,0	86,4	90,0	-

We then measured the resulting BER as a function of different ODN losses using SOA settings in Table 1. The results are shown in Fig. 5: a BER$<10^{-3}$ is obtained for ODN losses ranging from 15 to 35 dB, thus for DOPL = 20 dB, which is even better than the DOPL = 15 dB required for XG-PON [2]. This is one of the main new result of this paper compared to our "parent" ECOC 2013 paper [8]. We would like to point out that all the points in Fig. 5 required only a single setting on the ONU SOA gain, while the OLT coherent receiver electrical gain control remained constant.

We also evaluate the BER in the presence of two interfering ONUs, both operating in burst mode. For this purpose, we activated the interfering ONU #2 in Fig. 2 and generated adjacent optical packets as shown in Fig. 3, working in the worst-case condition in terms of interference for such a system. The guard time between packets was 25 ns. We measured BER vs. ODN loss (setting it to the same value for the two ONUs, thus working in the condition DOPL = 0 dB) after 37 km of fiber. The results in Fig. 6(a) show that, even in presence of two interfering ONUs, we can still get BER$<10^{-3}$ up to the 35 dB ODN loss requirement by XG-PON class E2. The penalty due to crosstalk between the two ONUs is less than 1 dB.

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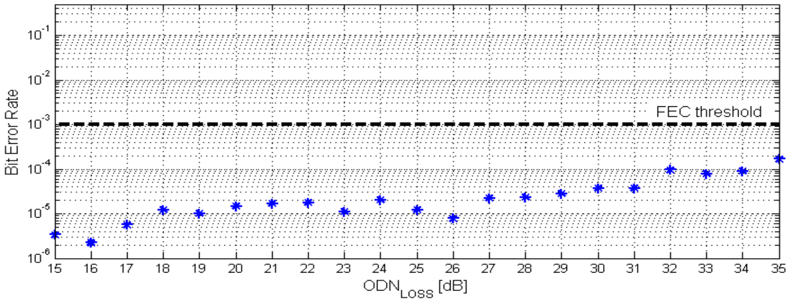

Fig. 5. BER vs. ODN$_{\mathrm{LOSS}}$ with a constant optical power level at the OLT.

We repeated the same measurements when changing the two ONU ODN losses, in order to span different DOPL values under real time, interfering burst mode transmission. The results are shown in Fig. 6(b), where the contour plot of $\log_{10}$(BER) for the reference ONUs is shown vs. the two ODN losses. The graph spans all ODN losses between 18 and 35 dB so that, in the extreme points, the reference ONU has a DOPL compared to the interfering ONU ranging from −17 to + 17 dB. For all points in the graph and on both ONUs, we apply the SOA gain control previously described. The result in Fig. 6(b) can be interpreted as follows: the BER contour plot are almost vertical since they depend almost only on the ODN seen by the reference ONU while they are almost independent of the interfering ONU ODN.

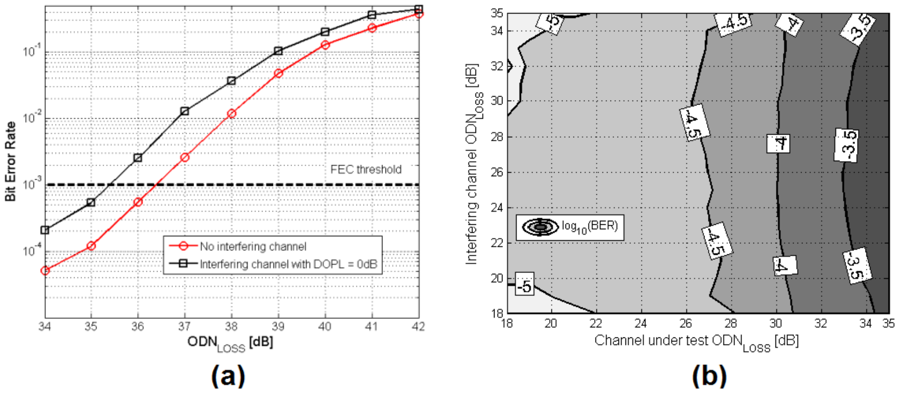

Fig. 6. (a): BER vs. ODN_{LOSS} after 37 km, for single ONU and for two simultaneous ONUs, DOPL = 0 dB. (b): BER contour plot (showing $\log_{10}$(BER)) vs. ODN_{LOSS} of channel under test vs. ODN_{LOSS} of interfering channel.

4. Conclusions

We have experimentally demonstrated a self-coherent reflective PON architecture with US bit rate equal to 2.5 Gbps, working in TDMA burst mode and with performance compatible with E2 XG-PON Class in terms of both ODN loss and DOPL, and compatible with US TWDM-PON requirements. One of the main results of this work, summarized in Fig. 6(b), is the demonstration that our architecture fully supports the simultaneous transmission of two TDMA ONUs, for ODN losses up to 35 dB and DOPL of more than 17 dB.

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