Demonstration of upstream WDM+FDMA reflective PON and real time implementation on an FPGA platform

Demonstration of upstream WDM+FDMA reflective PON and real time implementation on an FPGA platform

(Invited Paper)

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***Abstract* — We present a comprehensive set of measurements on the reflective PON upstream architecture conceived within the FABULOUS Project, in its 4-wavelengths configuration, showing the possibility of dramatically increasing the number of users or the bit-rate per user with respect to single-wavelength operation, demonstrating a 128 Gbps capacity up to interesting values of Optical Distribution Network losses. In addition, a comparison with the NG-PON2 standardized in G.989 at the same bit-rate is held, showing that accepting to reduce the per-wavelength bit-rate of our architecture to 10 Gbps in a 4-wavelengths network can provide great power budgets.**

Real-time implementation of the upstream on a FGPA platform is demonstrated as well, showing little penalty with respect to off-line experiments.

We also theoretically analyze possible performance improvements when higher-bandwidth modulators are used, and we discuss on the system flexibility offered by our proposal.

***Index Terms*— Passive Optical Network, FDMA, Reflective Mach Zehnder modulator, Self-coherent detection.**

I. Introduction

The FABULOUS European research project ([1]) has been widely disseminated so far, showing that a Frequency Division Multiplexing / Multiple Access (FDM / FDMA) approach to Passive Optical Networks (PON) in a reflective architecture can effectively address the requirements set by operators for NG-PON2, proposing an Optical Network Unit (ONU) for customer premises that can credibly be totally integrated on a Silicon Photonics platform (SiP) ([2, 3, 4]).

Using discrete commercial components and with the off-line processing approach, we have demonstrated that the proposed architecture is able to symmetrically transmit 1 Gbps to 32 users on a single wavelength withstanding a loss due to the Optical Distribution Network (ODN) in the order of 31 dB, in compliancy with class N2 as specified by XG-PON ([5]) and inherited by NG-PON2 ([6]) standards.

Even though the ITU-T choice for 40 Gbps capable PON in NG-PON2 has been for Time Division Multiplexing (TDM), we believe that the FABULOUS approach still makes sense for future PON evolutions, due to its scalability.

As a first straightforward step, we have improved our previous works performing a deep optimization and measurement campaign using 4 wavelengths, in order to demonstrate a 128 Gbps PON for relatively low ODN losses or a longer reach PON limiting the aggregate bit-rate to 40 Gbps (also for comparison purposes with G.989).

We have also demonstrated the feasibility of the implementation of the required Digital Signal Processing (DSP) by realizing real-time transmission experiments with Field Programmable Gate Array (FPGA) platforms. All the aforementioned activities are considering upstream (US) path only, that is the most challenging aspect for a reflective PON and that constitutes the main innovation of FABULOUS.

Finally, we have theoretically analyzed the performances our system should be able to achieve with an increased modulator bandwidth with respect to the 11 GHz unit we have experimentally used so far.

The paper is organized as follows:

- in Section II we will rapidly recall the FABULOUS architecture features, describe the WDM setup and analyze in deep the results for high-capacity and long-reach networks;
- in Section III we will describe the results of preliminary real-time US experiments using FPGA platforms;
- in Section IV we will perform an extensive theoretical analysis on possible evolution of the FABULOUS network, mainly based on the use of higher-bandwidth modulators;
- in Section V we will then draw some conclusions.

II. WDM Experimental Setup and Results

The fundamental FABULOUS features and parameters already described for the single-wavelength operation in our previous papers are preserved also in the WDM experiments presented in this Section. The main differences reside in the addition of WDM filters, that affect the power budget due to their insertion loss, and in the experimental setup by the

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insertion of interfering wavelengths.

For sake of clarity, only a fast recall of such features is reported in the following, and the interested readers should refer to [2, 3] to gain more details. The main characteristics of the FABULOUS architecture are shown in Fig. 1 and are summarized here:

- a standard power-splitter based ODN (no optical filtering in the ODN) over which we use a reflective upstream approach, where the Optical Line Terminal (OLT) generates both the modulated downstream (DS) wavelengths and the continuous wave (CW) wavelengths that will be modulated for the US, so that the ONU doesn't need any optical source;
- a reflective ONU, made by a semiconductor optical amplifier (SOA), a polarizing beam splitter (PBS) that splits the CW wavelength into two components and sends them in opposite directions in the modulating loop, two tunable optical filters, a Mach-Zehnder modulator (MZM) with a bandwidth of about 11 GHz and access to both electrodes. Such ONU turns out to be polarization independent and to be able to perform a 90° polarization rotation with respect to the CW ingress signal, that is preserved along all the US path regardless the birefringence of the fiber. The integrated ONU on SiP that is currently being realized, instead of one SOA external to the loop will have two SOAs: one in each arm after the PBS;
- a simplified single polarization (thanks to the 90° polarization rotation performed by the ONU) coherent receiver at the OLT, where the same external cavity laser source (ECL) is used for both CW seed for the US and local oscillator (LO);
- at the electrical level, the MZM 11 GHz available electrical bandwidth is divided in subcarriers (one per user). On every subcarrier, multilevel quadrature and amplitude modulation is used (M-QAM), to achieve high spectral efficiency, using Square-Root Raised Cosine (SRRC) shaping with roll-off factor 0.1 and without any spectral guard-band among carriers;
- crosstalk between channels is mitigated making the second harmonics of all sub-carriers fall in the middle of two adjacent channels, but the choice of the electrical channel under test (CUT) is made so to experience the highest inter-channel interference, so to evaluate a lower bound to the performances;
- in terms of receiver DSP we are employing a Feed-Forward adaptive Equalizer (FFE) with 31 complex taps adapted by Constant Modulus Algorithm, Carrier Phase Estimation (CPE) using the Viterbi-Viterbi algorithm, followed by a FEC scheme with hard-decoding capable of correcting up to an incoming Bit Error Rate (BER) of 10^{-2}.

The WDM experimental setup is depicted in Fig. 1. Four 100-GHz spaced CW optical seeds (at 1549.32, 1550.12, 1550.92 and 1551.72 nm) are generated at the OLT and sent to the ODN. The launched power is +9 dBm per wavelength, a level similar to the one specified in ITU-T G.989.2 for NG-PON2 TWDM channels for the higher ODN loss classes (such as N2 and E1 [6]). The ODN is composed by 37 km of real installed metropolitan buried SMF fiber, a variable optical attenuator (VOA) to act on the ODN loss and a 1x4 optical splitter. The four CW wavelengths, after going along the ODN, reach the input of two active reflective ONUs: the ONU under test that fully implements the FABULOUS ONU architecture performing the previously mentioned operations, and the interfering one, that emulates the reflection of all the WDM channels after their broadband FDMA modulation.

The ONU under test is programmed to generate a 16-QAM electrical signal at 1 Gbps net data rate, with 20% of overhead for a FEC capable of correcting up to 10^{-2}, and shaped with a SRRC filter with a roll-off factor of 10%, thus giving an overall electrical bandwidth occupation of 330 MHz, centered at 2.475 GHz. For the interfering ONU (ONU 2 in Fig. 1) we had to optically emulate the reflections of all the four wavelengths and the simultaneous modulation of all of them with a complete electrical FDMA signal that covers the full electrical band available by the Arbitrary Waveform Generator (AWG), apart from the spectral slice used by the ONU under test.

The performance of this worst-case scenario for two ONUs can be extended, without loss of generality, to estimate the performance of additional simultaneous ONUs on a single wavelength, just by adding the equivalent ASE noise that would be generated by other ONUs in the network, acting on an experimental setup that foresees noise loading. In particular, if the power spectral density noise of the reference ONU at the OLT receiver's input can be expressed as $G_{ASE}^{ref}(f)$ (equal to the SOA noise), we set the noise loading system in order to have:

$$G_{ASE}^{TOT}(f) = N_{ONU} \cdot G_{ASE}^{ref}(f) \quad (1)$$

yielding, for example in the case of 31 noise-loaded ONUs, to a signal-to-noise ratio (SNR) ranging from 19.1 dB with an ODN loss of 27 dB to 13.5 dB with an ODN loss of 33 dB.

At the OLT, we demodulated the wavelength and spectral slice of the ONU under test; to this end, the WDM US signal passes through an optical filter and then it is demodulated by means of a single polarization optical coherent receiver, where the transmitted CW signal is also used as local oscillator in a homodyne self-coherent setup. The single polarization operation is made possible by the ONU 90° polarization rotation that "comes for free" due to the structure of the ONU. Consequently, the coherent receiver does not require any polarization control, and it allows to halve the number of balanced detectors, ADC and DSP blocks.

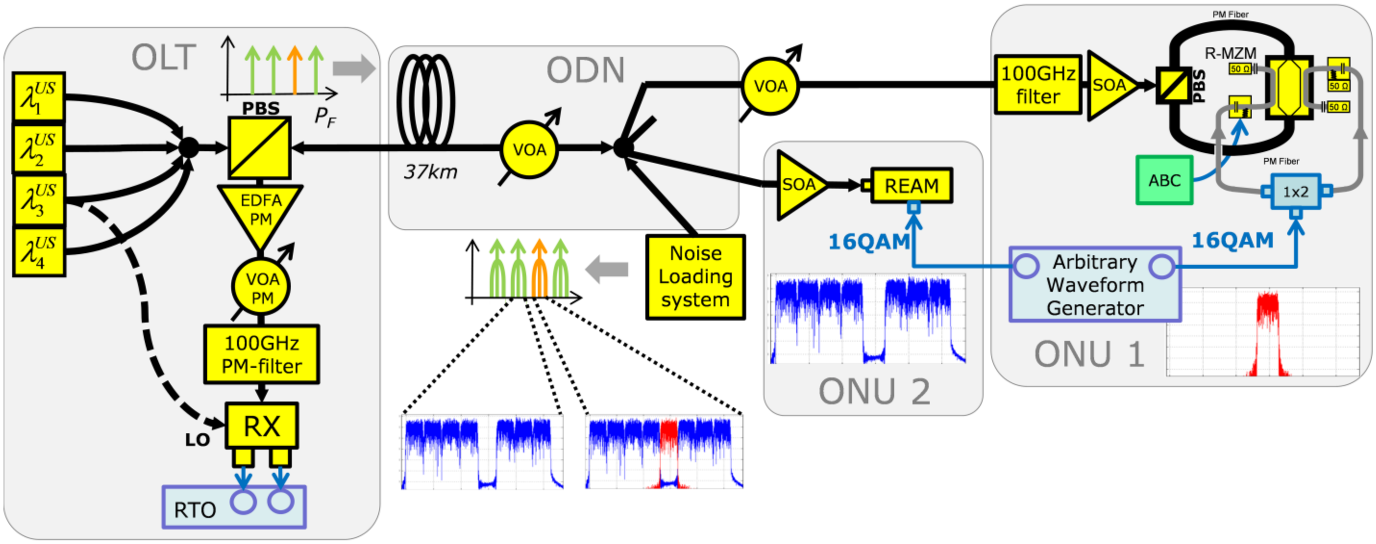

Fig. 1 Full off-line processing experimental setup with installed fiber, two active ONUs and noise loading emulator (PBS: polarizing beam splitter, VOA: variable optical amplifier, RTO: real time oscilloscope, SOA: semiconductor optical amplifier, ABC: automatic bias control, R-MZM: reflective Mach–Zehnder modulator, REAM: reflective electro absorption modulator).

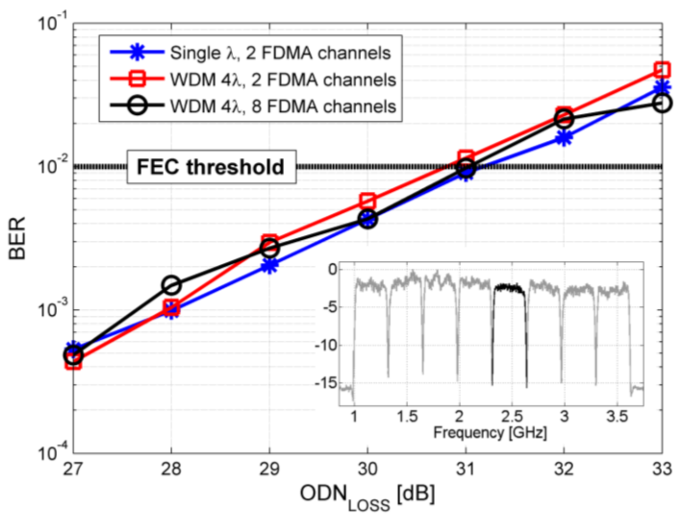

Fig. 2 Performance of the upstream transmission in terms of BER vs ODN loss with 2 active ONUs (32 emulated channels per wavelength using optical noise loading). It is evident that the simplified setup totally emulates the meaningful interferences.

The ONU generating the interfering electrical channels can either be a perfect replica of the ONU under test (as we did in [2]) or any other type of reflective ONU. For this set of experiment we decided to follow the second way, realizing the ONU by means of a SOA and REAM cascade; in this case, the polarization rotation is not present, thus the interfering signal reaches the OLT with a random state of polarization, creating a mismatch with respect to what experienced by the channel under test. Therefore, we took care of equalizing the power of all the electrical sub-carriers (the useful and the interfering ones) at the receiver side by acting on the SOA gain in all working conditions.

The OLT coherent receiver outputs are sampled by a real-time oscilloscope (RTO) running at 12.5 GSps and off-line processed in Matlab© with a DSP consisting of a sample-rate down-converting stage, reducing the sampled signal to 2 Sps, and the previously mentioned algorithms. The system performance are measured, in terms of BER of the channel under test as a function of the ODN loss, assumed to be the same for both ONUs. The SOA bias current of the interfering ONU has been set in order to force the interfering channel to emit the same electrical signal power of the channel under test.

Fig. 2 shows the experimental results in terms of BER vs. ODN loss for different number of wavelengths and FDMA channels, showing that WDM induced crosstalk is negligible, as we already demonstrated in [7].

A. High-capacity PON: 32 Gbps per wavelength

As we have demonstrated in previous works [2] that the FABULOUS architecture is capable of supporting 32 users at 1 Gbps each, with an ODN loss of 31 dB in compliancy with class N2, the most straightforward upgrade is transmitting the same bit-rate per user to 128 users, using 4 wavelengths, to try to go well beyond the current NG-PON2 G.989 targets. The respect of class N2 in such case is evident by Fig. 2 as well. Such performances have been achieved reserving an electrical bandwidth of 330 MHz per user and using 16-QAM modulation format on each electrical subcarrier. However, it is worth pointing out that increasing the number of users without increasing the power budget reduces the power budget available for fiber propagation due to the increased splitting loss. We do not believe that increasing the number of users to 128 is the only (or the best) option to be pursued, so we tested these other scenarios as well:

- 64 users at 2 Gbps: using 16-QAM and 660 MHz per user;
- 32 users at 4 Gbps, using 16-QAM and 1320 MHz per user.

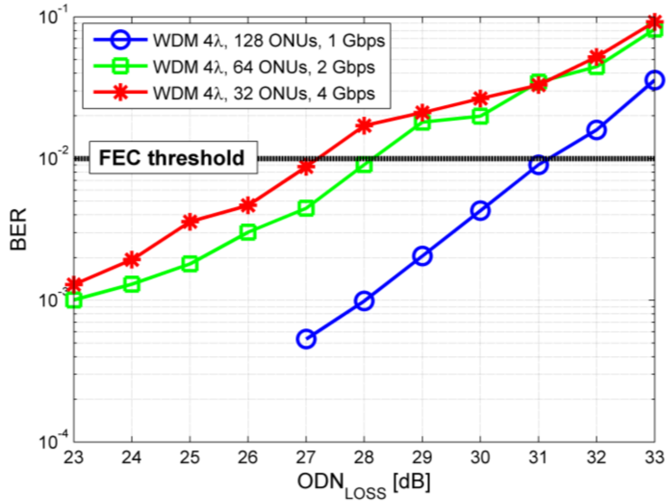

Fig. 3 Performance of the upstream transmission in terms of BER vs ODN loss with 128 ONUs working at 1 Gbps, 64 ONUs at 2 Gbps and 32 ONUs at 4 Gbps.

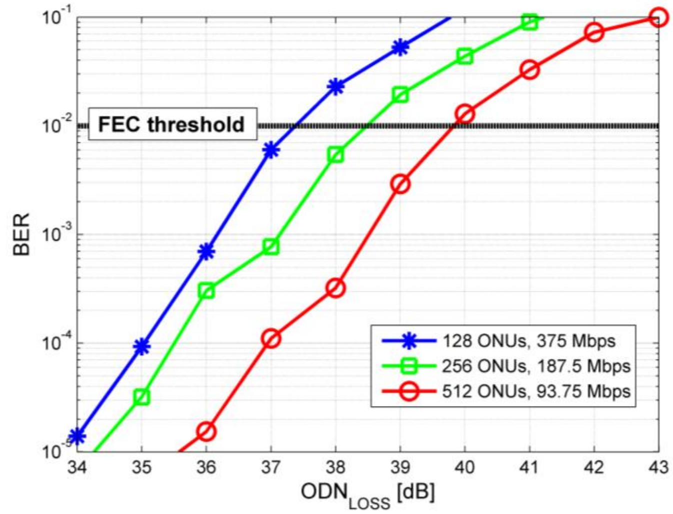

Fig. 4 Performance of the upstream transmission in terms of BER vs ODN loss with 128 ONUs working at 375 Mbps, 256 ONUs at 187.5 Mbps and 512 ONUs at 93.75 Mbps.

In Fig. 3 the results of the three possible configurations at 128 Gbps are reported, and the results are summarized in Table I, where together with the ODN loss we indicated the theoretical attenuation due to the power splitter for serving the different numbers of users and the remaining power budget for fiber loss and system margin.

TABLE I
PERFORMANCES FOR DIFFERENT NUMBER OF ONUS, 16-QAM

Number of ONUs	Bit-rate per ONU	Maximum ODN loss	Maximum splitter insertion loss [8]	Optical margin
32	4 Gbps	27 dB	18.1 dB	8.9 dB
64	2 Gbps	28 dB	21.5 dB	6.5 dB
128	1 Gbps	31 dB (Class N2)	25.0 dB	6.0 dB

It is interesting to notice that the configuration with 32 users, providing the lowest ODN loss, grants the largest power budget after splitting, while the configuration with 128 users, that is the only one compliant with some attenuation class defined in G.987.2, provides the lowest budget for fiber and margin, equal to the one provided by the 64 users configuration.

B. Large-splitting ratio PON: 10 Gbps per wavelength and over 37 dB

For a comprehensive comparison with NG-PON2, we believe it is also interesting to evaluate the FABULOUS performances at the same bit-rate foreseen by NG-PON2 TWDM-PON standard, but focusing on increasing the achievable ODN loss. For this purpose, we made an extensive measurement campaign sticking with the same conditions set in G.989, namely four wavelengths at 10 Gbps each. For this purposes, considering the usual 11 GHz of available modulator bandwidth, we moved to a more robust QPSK modulation format to be used on each subcarrier and varied the per-user electrical bandwidth targeting bit-rates in the order of a few hundred Mbps per user. Results are shown in Fig. 4 and summarized in Table II.

TABLE II
PERFORMANCES FOR DIFFERENT NUMBER OF ONUS, QPSK

Number of ONUs	Bit-rate per ONU	Maximum ODN loss	Maximum splitter insertion loss [8]	Optical margin
128	375 Mbps	37 dB (Class E2)	25.0 dB	12.0 dB
256	187.5 Mbps	38 dB (Class E2)	28.5 dB	9.5 dB
512	93.75 Mbps	39 dB (Class E2)	32.0 dB	7.0 dB

It is then evident that this architecture is capable, when using robust modulation formats and when not targeting very-high bit rates, to be compliant with NG-PON2 in terms of bit-rate while overcoming the attenuation foreseen even by the most challenging class E2, and thus being able to withstand an impressive number of users.

If from an operator point of view it is probably pointless to think of a 1:512 power splitter, we believe that these performances can be of particular interest when thinking of PON trees with two levels of splitting: a first level made by a 1:4 splitter and peripheral levels that could for example be made by 1:8 splitters, to serve users with 4 Gbps each, up to 1:128 splitters to serve communities of users with 93.75 Mbps each, as schematically depicted in Fig. 5.

III. REAL-TIME OPERATION: PRELIMINARY RESULTS

As DSP has big importance in allowing the FABULOUS architecture to reach the performances previously explained, we moved a step forward to demonstrate that such DSP is reasonably feasible considering the access networks market. In [9] we made an extensive analysis that lead us to conclude that implementing all the processing on a 65 nm CMOS platform would need a 7 mm^2 ASIC and have a power consumption lower than 5 W. In this work we also show that we recently implemented the DSP functions required for the proposed US transmission using commercial FPGA platforms, for both demonstrating real-time operation and the possibility of implementing our system using relatively low sample rates for the DSP.

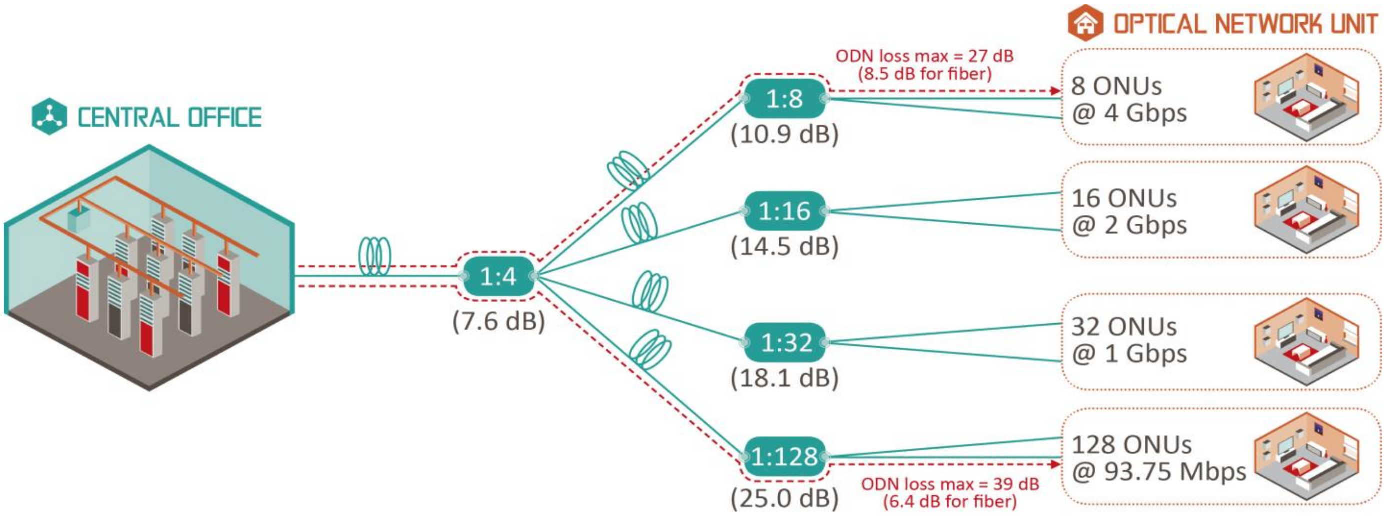

Fig. 5 Example of PON trees with two levels of splitting: a first level made by a 1:4 splitter and peripheral levels that could be made by 1:8 up to 1:128 splitters.

Compared to the system shown in Fig. 1, we removed the AWG and the RTO and substituted them with two FPGAs development boards.

The upstream transmitter board is equipped as follows:

- two Virtex 4 SX35 FPGAs running on a 300 MHz internal clock;
- two digital to analog converters (DAC) running at 1200 MSps;
- a broadband electronic IQ modulator designed for operation from 400 MHz to 6 GHz.

For what concerns the US receiver, the board is equipped as follows:

- a two-channels analog to digital converter (ADC) running at 1200 MSps which operates after self-coherent detection and electrical IQ demodulation;
- a Virtex 7 VX485T FPGA running on a 300 MHz internal clock.

Focusing on the higher layer interface part, the two boards embed a dummy Gigabit Ethernet real time traffic generator, as well as the logic needed to interface to an external traffic generator/checker or a PC. The real time demonstrator thus implements a “dedicated” Gigabit Ethernet connection for each ONU. The DSP section implemented in the FPGA closely follows the Matlab© code used for post-processing data, with differences related to hardware availability. In particular:

- the equalizer is implemented as a 4-to-1 downsampling filter (instead of a 2-to-1);
- the filter coefficients update algorithm is a delayed block LMS, because real-time coefficient update is not feasible;
- finite precision instead of floating point.

Data is transferred from the ADC board to the FPGA using a parallel bus of four samples per channel, so we implemented the adaptive equalizer as a 64 taps, 4 to 1 downsampling filter. We kept the blind Constant Modulus and Radius Directed algorithm stages, but, since the filter taps could not be updated every symbol because of the pipeline needed by the real-time hardware implementation of multipliers and adders, we used the Block Least Mean Square algorithm. The optimum step size of the algorithm was determined during our trials in the laboratory.

The CPE has been implemented using the full Viterbi-Viterbi algorithm already implemented for post-processing, with a memory of 16 symbols. A preliminary implementation of a simplified Viterbi-Viterbi algorithm, using only a subset of the constellation symbols, has been tested. In particular, we partitioned the 16-QAM symbols (according to their amplitudes) into three groups pertaining to three different rings, considering the inner and outer rings symbols as two QPSK constellations with different Signal-to-Noise Ratios (SNR). Using the simplified Viterbi-Viterbi algorithm, the intermediate symbols do not contribute to the phase estimation, simplifying the algorithm implementation. Unfortunately, the easier implementation was paid by some transmission penalty and was then discarded.

Together with the DSP, a real time system also needs a Physical Coding Sublayer (PCS) to handle Ethernet signalling, packing Ethernet frames in FEC frames and mapping the resulting data to the 16-QAM constellation symbols at the transmitter, and then to perform the inverse operations in at the receiver.

We also developed a numerical model that allows to predict the theoretical upstream BER as a function of system parameter. The model is directly taken from [10] and uses the parameter shown in the following Table III, which are directly taken from the experimental setup.

TABLE III
NUMERICAL PARAMETERS FOR THE THEORETICAL MODEL TAKEN FROM [10] AND USED FOR FIG. 6 AND TABLE IV

Parameter	Value
SOA gain @ONU	15 dB
SOA Noise figure @ONU	7 dB
SOA Output saturation power @ONU	+8 dBm
Polarizing beam splitter loss	1 dB
R-MZM insertion loss	4.6 dB
RF electrical drive level	Optimized
Raised cosine spectrum roll-off	0.1
CW power in downstream, per λ	+9 dBm
Wavelength	Around 1550 nm

It turned out that the ultimate BER of this system is limited by the ONU SOAs ASE noise and by the noise of the OLT coherent receiver.

In Fig. 6 we report the resulting theoretical BER curve compared with the ones obtained real-time and off-line processing experiments; it is evident that there is almost no difference between the three curves above 10^{-4}, while below 10^{-4} (well below FEC threshold) the real-time system has some higher penalty due to onset of error floors that are anyway below BER=10^{-5}: this is related to second order effects due to the finite mathematic accuracy that we implemented on the FPGA DSP, as demonstrated by the curve obtained forcing the same FPGA DSP accuracy to the off-line processing routine (green circles).

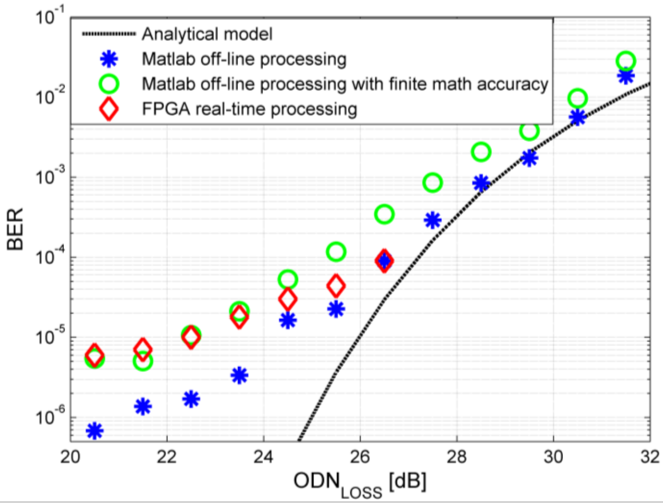

Fig. 6 Performance of the channel under test in terms of BER vs ODN loss when post-processed in Matlab© and real-time processed in FPGA. For how the real-time BER measurement is implemented, we did not report BER values above FEC threshold because they are not meaningful.

IV. Discussion on Potential Evolution

The results presented so far in this paper assumed an R-MZM electrical bandwidth of 11 GHz, corresponding to the available bandwidth of the modulator we used in the experiments. The integrated SiP modulator that is being realized inside the project [4] will also have similar bandwidth, mostly determined by the MZM electronic driver. The intrinsic bandwidth of the SiP modulator could anyway be even higher, as it was recently shown in some Silicon Photonic modulator demonstrations for high speed optical interconnects. In this section, we thus speculate on the system level advantage that would derive from a higher bandwidth modulator inside the FABULOUS upstream architecture.

To perform this study, we used the previously mentioned numerical model derived in [10] that closely matches the experimental performance we obtained so far (such as those shown in Fig. 2, 3 and 4, with parameters shown in previous Tab. III). We report in Table IV some results derived from this analysis for different bandwidths, number of ONUs per wavelength and modulation formats. The first row of the Table matches the experimental results, and it is thus to be taken as a reference. The other rows derive from the same numerical model but do not yet have experimental evidence. The table assumes a pre-FEC BER=10^{-2}.

In order to comment the result in Table IV, we start by assuming that the modulator has twice the bandwidth of the current experimental modulator, i.e. 22 GHz. Under this assumption, our model predicts for instance that 64 users can be supported each using 16-QAM at a net data rate per user equal to 1 Gbps up to ODN loss equal to 30.1 dB. This is a first very interesting result: in a typical 1x64 split PON, this would mean using one wavelength only for all the 64 ONUs, and still reach 1 Gbps per ONU. Interestingly, this setup would avoid using WDM in the upstream, a very promising feature to reduce overall system complexity, and the resulting maximum ODN loss is still 30.1 dB, which would satisfy ODN class N1 (with some margin). The performances are even more impressive when using a 33 GHz modulator, reaching for example 72 Gbps satisfying class N2, depending on the number of users.

TABLE IV
Performances obtained by numerical model for different modulator electrical bandwidths.
Results assume a target pre-FEC BER=10^{-2}

Modulator bandwidth	Number of ONUs per λ	Net Bit-rate per ONU and modulation format	Total upstream net Bit-rate per λ	Maximum ODN loss
11 GHz (reference)	32	1 Gbps (16-QAM)	32 Gbps	31.4 dB
22 GHz	32	2 Gbps (16-QAM)	64 Gbps	29.3 dB
22 GHz	32	2.5Gbps (32-QAM)	80 Gbps	25.1 dB
22 GHz	64	1 Gbps (16-QAM)	64 Gbps	30.1 dB
33 GHz	32	3 Gbps (16-QAM)	96 Gbps	28.1 dB
33 GHz	32	2.25 Gbps (8-QAM)	72 Gbps	32.0 dB
33 GHz	64	1.5Gbps (16-QAM)	96 Gbps	28.7 dB
33 GHz	64	1.1Gbps (8-QAM)	72 Gbps	33.0 dB

A global analysis of all the rows of Table III shows the system flexibility that can be achieved using the proposed upstream architecture; an even higher level can be obtained if, as shown in [10], one assumes that the modulation format and bit rate per ONU is adapted on the actual ODN loss seen by each specific ONU.

V. Conclusions

We have shown that the FDMA-PON architecture proposed in FABULOUS, in its WDM configuration with 4 wavelengths, can provide great performances in terms of aggregate and per user bit-rate, when focusing on high capacity, or very long reach or splitting ration, when 10 Gbps per wavelength are target; WDM+FDM in then a credible solution to be considered for future generations of access networks. In addition, we have demonstrated the real-time feasibility of the DSP needed for achieving such performances, and theoretically analysed possible system upgrades.

References

[1] Project web site: www.fabulous-project.eu

[2] S. Straullu et al., "Optimization of Reflective FDMA-PON Architecture to Achieve 32 Gbps per Upstream Wavelength over 31 dB ODN Loss", J. Lightwave Technol., Vol. 33; no. 2, p. 474 (2015).

[3] B. Charbonnier, N. Brochier, P. Chanclou, "Reflective polarisation independent Mach-Zenhder modulator for FDMA/OFDMA PON," Electronics Letters, Vol. 46, no. 25, p. 1682 (2010).

[4] S. Menezo, B. Charbonnier, G.B. de Farias, D. Thomson, P. Grosse, A. Myko, J.M. Fedeli, B. Ben Bakir, G.T. Reed, A. Lebreton, "Reflective silicon Mach-Zehnder modulator with Faraday rotator mirror effect for self-coherent transmission", in *Proc. Opt. Fiber Commun. Conf. Expo, Nat. Fiber Opt. Eng.*, Anaheim, CA, USA, Mar. 17-21, 2013, Paper JTh2A.30.

[5] *10-Gigabit-Capable Passive Optical Networks (XG-PON): Physical Media Dependent (PMD) Layer Specification*, ITU-T Recommendation G.987.2, Oct. 2010.

[6] *40-Gigabit-capable passive optical networks (NG-PON2)*, ITU-T Recommendation G.989.1, Mar. 2013.

[7] S. Straullu et al., "Demonstration of upstream WDM+FDMA PON and real time implementation on an FPGA platform", ECOC 2015, Valencia, Spain, Mo.3.4.3.

[8] *Transmission characteristics of optical components and subsystems*, ITU-T Recommendation G.671, Feb. 2012.

[9] S. Abrate, S. Straullu, A. Nespola, P. Savio, J. Chang, V. Ferrero, B. Charbonnier and R. Gaudino, "Overview of the FABULOUS EU Project: Final System Performance Assessment With Discrete Components", J. Lightwave Technol., In publication (2015), DOI: 10.1109/JLT.2015.2482226.

[10] B. Charbonnier, A. Lebreton, L. Le Masson, "FDMA PON theoretical model and capacity evaluation", Optical Communications and Networking, IEEE/OSA Journal of, Volume:6, Issue: 10, 2014.

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