Toward 20 Gbps upstream FDMA-PON real-time and low-speed DSP demonstrator

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Abstract: We experimentally demonstrate a FDMA-PON system targeting 20 Gbps per wavelength in the upstream, using a real-time FPGA-based transmitter and low-speed baseband DSP, in the framework of the EU research project FABULOUS.
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1. Introduction

During 2011-2012, FSAN opened a broad investigation on the best options for NG-PON2, i.e., the new PON standard after ITU-T G.987 XG-PON. The final FSAN decision is to adopt the so-called TWDM-PON, soon to be released by ITU-T as G.989, which consists in the stacking of four XG-PON streams over a 100 GHz WDM grid. TWDM-PON can be seen as an "evolutionary" upgrade to XG-PON, since most of the physical and network layers are identical. All the other more "revolutionary" proposals analyzed by FSAN in 2011-2012 have been discarded, likely because the complexity/cost was perceived as too high for today access network requirements. However, we believe that, at a research level, it is today still reasonable to investigate on some of these more advanced proposals, that may become interesting if, in the medium term, PON network will be used for application different from the traditional FTTx residential user target, such as for bandwidth-hungry mobile front-hauling based on CPRI [1]. The EU research project FABULOUS [2] works on one of these FSAN options, and in particularly on the Frequency Division Multiple Access (FDMA-PON) approach. In this paper, we show recent experimental results from this project focusing, for space limitations, only on the upstream (US) transmission, whose details can be found in [2], [3] and can be summarized as follows:

- reflective US modulation: each US wavelength is generated as a CW at the central office, and modulated back at the ONU with an advanced reflective Mach-Zehnder Modulator (R-MZM), suitable for Silicon Photonic integration [3]. The resulting ONU does not need tunable lasers for US, which is on the contrary one of the criticalities in TWDM-PON;
- FDMA spectral allocation, that assigns to each ONU a given electrical spectral slot around a central electrical subcarrier. Each ONU is assigned a given central subcarrier frequency f_c and a given bandwidth B_{el} around it, on top of a wavelength that is FDMA-shared among several ONUs;
- M-QAM modulation around each f_c, with raised cosine spectrum, to obtain higher spectral efficiency than the more traditional OOK used today in all PON standards;
- US coherent detection at the OLT using digital signal processing (DSP).

The novelties of this paper compared to other works already published by the FABULOUS consortium, but also more in general by other research groups working on FDMA-PON are:

- experimental demonstration of 1 Gbps per user (gross bit-rate) over a splitter-based (no AWG) Optical Distribution Network (ODN) with 30 dB loss and 37 km of installed fibers using 16-QAM and approximately 300 MHz of required electrical bandwidth per user (including proper spectral guard-bands);
- demonstration of operation under noise loading conditions that emulates more than 20 ONUs in FDMA over the same wavelength, compatible with the 6-7 GHz electrical bandwidth that we expect for the Silicon Photonic R-MZM currently under development in the project [3], thus allocating 20 users with 300 MHz each;
- using an FPGA-based real-time transmitter that generates a raised cosine 16-QAM with roll-off equal to 0.1, implementing a 128 tap up-sampling filter starting from internal PRBS15 random generators;
- using electrical up- and down-conversions around subcarrier frequency f_c thus allowing the DSP to handle directly the 16-QAM baseband processing, and in particular running the ADC and DAC at 1 GSample/s to cope with a 16-QAM baud-rate equal to 250 MBaud processed at 4 samples per symbol;
- implementation of algorithms that are suitable for a real-time implementation on an FPGA running again at 1 GSample/s (even though results shown here are still due to off-line processing at the OLT receiver, since FPGA transporting of the algorithms is scheduled for the second year of the project), based on a sample-rate down-converting stage, reducing the sampled signal to 2 SpS, a 41-taps equalizer that adjusts its coefficient

through a blind radius-directed CMA algorithm, and a Maximum-Likelihood carrier phase-recovery (CPE) stage [4].

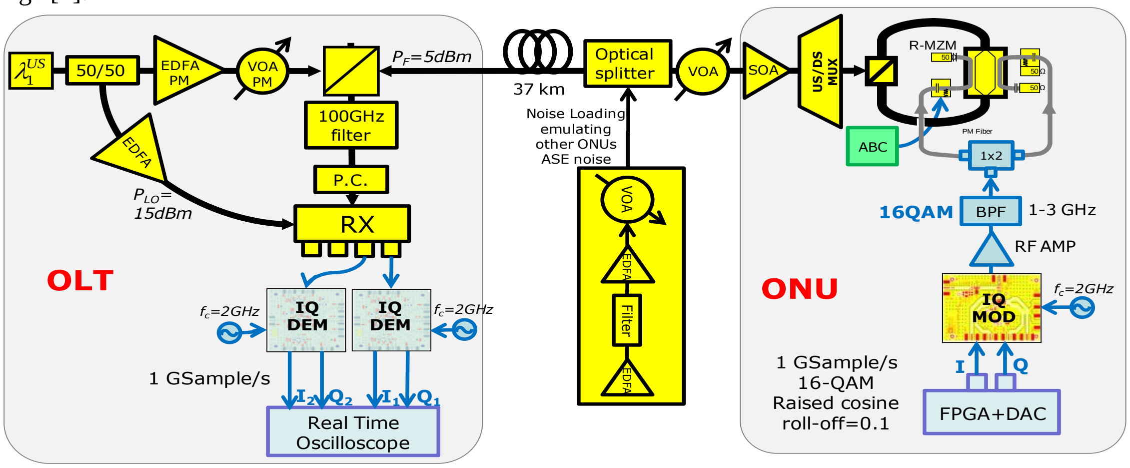

Fig. 1: Experimental setup

Overall, we thus envision an US capacity of approximately 20 Gbps per wavelength, to be compared with TWDM-PON (that we consider as our natural benchmark), which is expected to give 2.5 Gbps per wavelength in its first version. The price we have to pay for this four-fold increase in spectral efficiency per wavelength is in the need to use DSP for both the transmitter and the receiver, but having a complexity that is not very different from several chipset used for modern RF consumer-electronic applications, such as for instance the UWB WiMedia.

More in general, the FABULOUS US FDMA approach, considering a top-level request of 1 Gbps per user, would satisfy 20 users per wavelength over ODN losses suitable for 1x64 split. Using four wavelengths (such as in the first version of TWDM PON) we would thus reach a (sustained) upstream capacity of 64 Gbps (with margins). These results are somehow the complement of those presented on the same architecture in [3], which was focused on one wavelength operation only, and thus assigned a similar capacity (20 Gbps overall) to all 64 users, giving approximately 300 Mbit/s per user.

2. Experimental setup and results

Our experimental setup, shown in Fig.1, considers only US transmission. A CW wavelength (+5 dBm, 1550 nm) generated at the OLT is modulated and reflected back by the ONU. We generate a 16-QAM, square-root raised cosine (roll-off=0.1) baseband electrical IQ signal pair by a real-time FPGA platform. The gross bit-rate is 1 Gbps (generated by two independent PRBS15 in parallel), corresponding to 250 MBaud. We use a DSP running at 4 samples per symbol, so that the two FPGA DACs runs at 1 Gsample/s; the DSP section has been implemented using only Block RAM based LUTs and adders to save processing resources. The IQ signals are applied to a commercial RF IQ modulator, with a central frequency equal to f_c =2 GHz (we envision to use f_c in the range from 1 to 7-8 GHz), whose RF output is sent to the optical modulator structure described in [3] and in the upper right part of Fig. 1. In the current experiment, the R-MZM is assembled using discrete components, but one of the most important targets of the FABULOUS project will be its implementation in Silicon Photonics, including an embedded Semiconductor Optical Amplifier (SOA). The ODN is made of 37 km of installed SMF fibers plus an optical attenuator to change the ODN loss. Inside the ODN, a noise loading system can add a variable amount of ASE noise in order to emulate the noise generated by the SOAs of other ONUs in the network that, though working on different electrical bands thanks to FDMA, would anyway contribute to ASE noise, that turns out to be one of the main limiting factors for our system US capacity. The OLT receiver is a single polarization optical coherent receiver followed by electrical RF IQ demodulators whose baseband outputs are sampled by a real-time oscilloscope with ADCs running at 1 GSample/s (i.e., at 4 samples per symbol, just like the transmitters). The single polarization operation, and thus the use of an input Polarizing Beam Splitter (PBS), is made possible by the Faraday rotation, that is intrinsic in the adopted R-MZM structure (see [2] for further details).

We start in Fig. 2: (left) by showing the resulting BER vs. the received OSNR (measured over 0.1 nm at the output of the OLT PBS). The system shows a floor at BER=10^{-4} that we surely need to further investigate, but we believe is due to cross-gain nonlinear effects inside the SOA used bi-directionally. We assume to use low complexity FEC, such as the RS(248, 232) standardized for US XG-PON that requires a pre-FEC BER≤10^{-3}, which is reached in Fig. 2: (left) for OSNR better than 12 dB. In Fig. 2: (right) we show the BER vs. the number of other

ONUs working in FDMA on the same wavelength, that are emulated by adding their equivalent ASE noise. Measurements are presented for ODN loss equal to 20 and 30 dB, in both cases after 37 km of fiber (using the XG-PON terminology, we are targeting length DD40 and class N2). We see that we can have up to 32 equivalent ONUs up before reaching the FEC threshold. This is the key result of our paper, that we interpret as follows: in terms of ASE noise, 32 ONU's can simultaneously transmit over the same wavelength at 1 Gbps. The limitation can actually come from the available R-MZM electrical bandwidth to be FDMA-shared. If we conservatively assume to have 6 GHz and considering that in this setup each ONU uses less than 300 MHz (250 MHz baud-rate plus 0.1 raised cosine roll-off plus some guard-band), we can satisfy 20 users at 1 Gbps per wavelength.

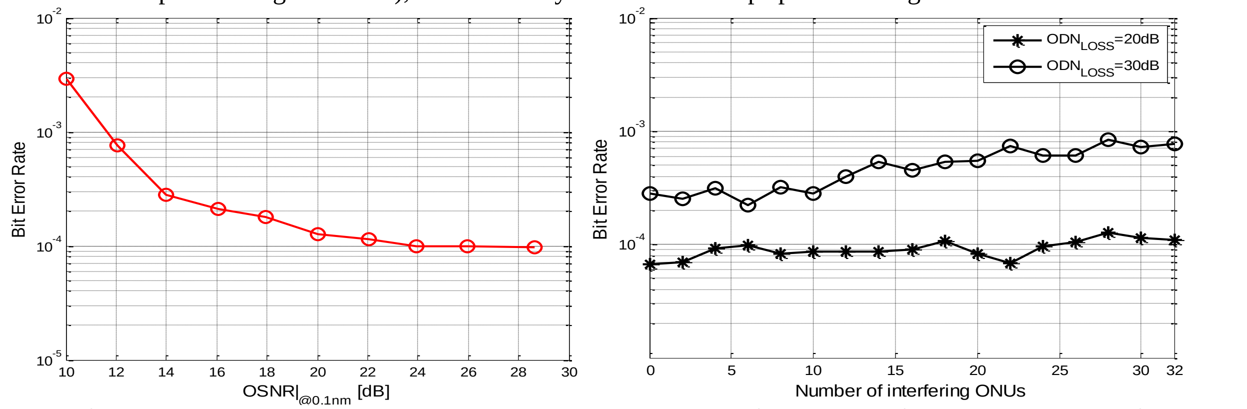

Fig. 2: Left: BER vs. received OSNR (0.1 nm bandwidth). Right: BER vs. the number of equivalent interfering ONU. In both cases: fiber length= 37 km, m_{index}=0.2

The results were obtained for a modulation index m_{index}=0.2, which was defined as the ratio between the RF peak voltage applied to the R-MZM electrodes and its $V_\pi \approx 5$ V. In Fig. 3 (right) we report the BER contour plots at ODN loss=30 dB and 37 km vs. SOA biasing current and m_{index}, a measurement that was done to obtain the optimal values of these two parameters that are key to the result of the previous Fig. 2: . The system is quite sensitive on m_{index}, likely due to non-linearities in the electrical part of the R-MZM when the driving signal is too high.

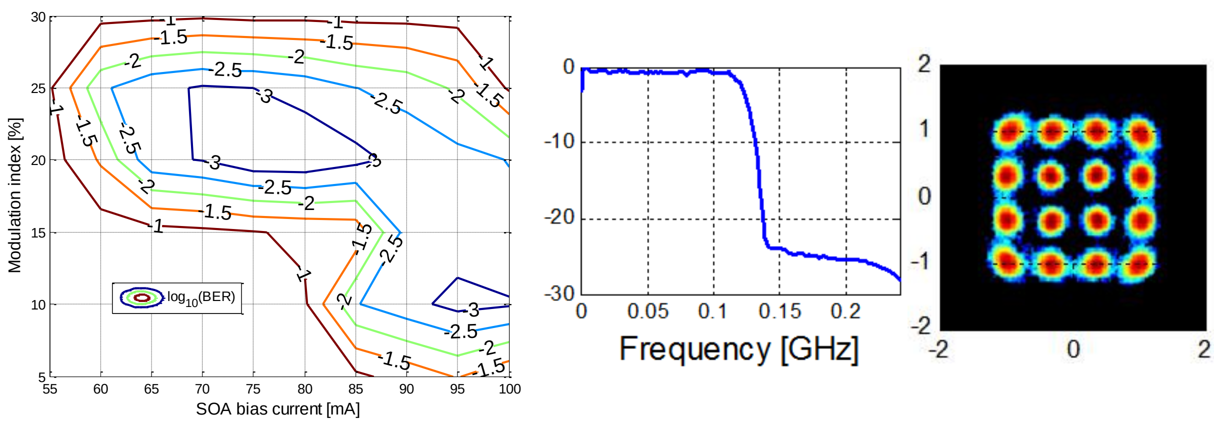

Fig. 3: BER vs. SOA biasing current and 16-QAM modulation index, fiber length= 37 km, ODN loss=30 dB. On the right: received electrical baseband spectrum and scattering diagram after the DSP equalizer for the optimal condition I_{bias}=85 mA and m_{index}=20%

3. Conclusion and future works

We presented new results from the currently ongoing project FABULOUS, whose next goals will be a further optimization of system parameters, and on the implementation of the R-MZM in Silicon Photonics.

4. Acknowledgments

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