System aspects of the FDMA PON conceived within the FABULOUS European project (Invited)

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S. Straullu[1], A. Nespola[1], P. Savio[1], J. Chang[2], V. Ferrero[2], A. Lebreton[3-4], J. Le Masson[4-5], R. Dong[4], P. Chanclou[3], B. Charbonnier[3], S. Abrate[1] and R. Gaudino[2]

[1] *Istituto Superiore Mario Boella, Via Boggio 61, 10138 Torino, Italy – abrate@ismb.it*

[2] *Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy – roberto.gaudino@polito.it*

[3] *Orange Labs, 2 av. Pierre Marzin, 22307, Lannion, France, benoit.charbonnier@orange.com*

[4] *Lab-STICC, Universié de Bretagne-Sud, Lorient, France, rongping.dong@univ-ubs.fr*

[5] *Ecoles de Saint-Cyr Coëtquidan, Guer, France, jerome.lemasson@st-cyr.terre-net.defense.gouv.fr*

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, and 39 Gbps in the downstream using a new resources allocation algorithm with 11.5GHz electrical bandwidth, in the framework of the EU research project FABULOUS.

Keywords: Fiber optics and optical communications; Coherent communications; FDMA; Next Generation PON.

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 **Errore. L'origine riferimento non è stata trovata.**. 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 on both the upstream (US) and downstream (DS) transmission, whose details can be found in [2] 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 a 39 Gbps DS capacity using 11.5 GHz electrical bandwidth with 20 km of Single Mode Fiber (SMF);
- experimental demonstration of 1 Gbps US capacity 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 [5].

2. UPSTREAM TRANSMISSION

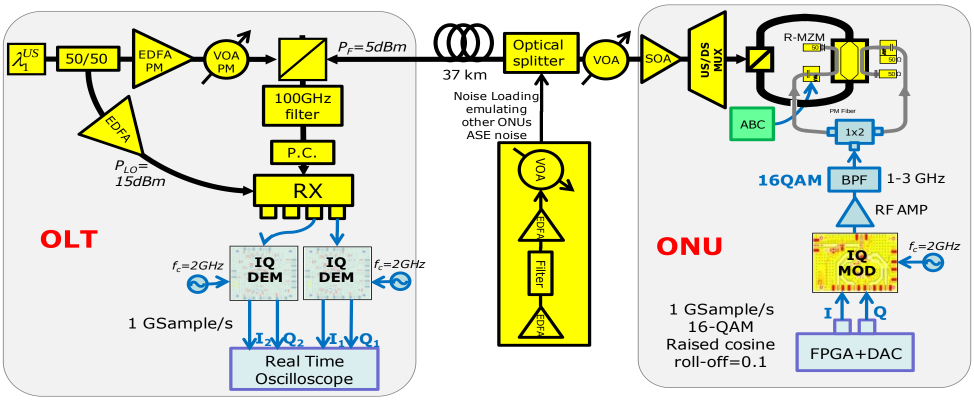

Figure 1. US experimental setup

Our US experimental setup is depicted in Fig.1. 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 run at 1 GSamples/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 GSamples/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 Figure 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 Figure 2. (left) for OSNR better than 12 dB. In Figure 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. 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_π≈5 V.

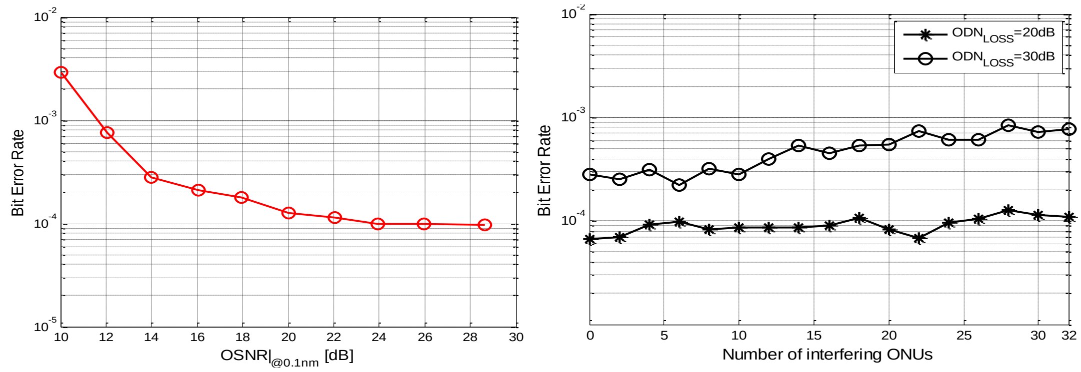

Figure 2. Left: BER vs. received OSNR (0.1 nm bandwidth). Right: BER vs. the number of equivalent interfering ONU. In both cases: fiber length= 37 km, m_{index}=0.2

3. DOWNSTREAM TRANSMISSION

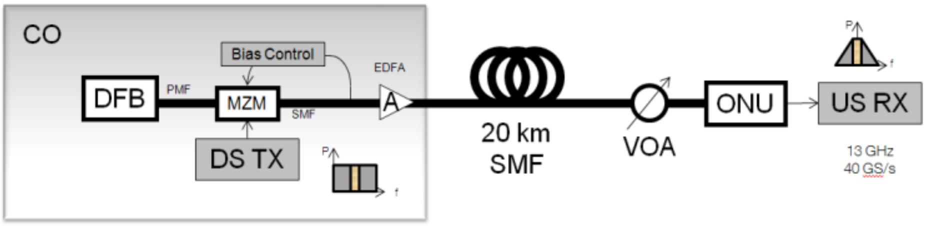

Figure 3. DS experimental setup

To evaluate the performance and the global capacity of our DS system, we first probe the transmission channel for different frequencies and optical budgets with a QPSK reference signal of 250 MHz electrical bandwidth, covering the range of parameters that we will use.

Our experimental test bed for downlink performance evaluation is represented in Fig. 3. A Distributed Feed-Back (DFB) laser at 1.5 µm emitting +9 dBm of continuous optical power is externally modulated by a Mach Zehnder Modulator (MZM) with 10 GHz electrical bandwidth biased at quadrature. The modulating signal is generated by the Downstream Transmitter and is a broadband signal whose spectrum extends from 500 MHz to 12 GHz. We evaluate the transmission quality by measuring the Error Vector Magnitude (EVM) that we convert into Signal to Noise Ratio (SNR) for different center frequencies, Optical Budgets and RF power modulating the MZM.

The main challenge of using a large electrical bandwidth RF signal is to generate a constant power spectral density in low as well as in high frequencies bands. Because of the roll-off of the arbitrary waveform generator (AWG), there is power attenuation for users situated at the top of the spectrum. To overcome this issue, as depicted in Fig. 4, we use 3 AWGs. AWG 1 generates a signal for users situated between 500 MHz to 6 GHz. AWG 3 generates the signal of the user we want to evaluate performance when it is situated after 6 GHz. Finally AWG 2 generates the complementary signal of AWG 3 between 6 and 12 GHz.

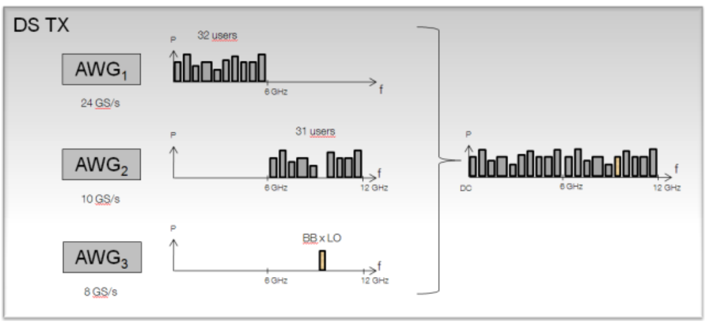

Figure 4. DS spectrum generation

Figure 5 shows an example of spectrum generated by each AWG. In this case, the user we want to evaluate performance is situated at 7.1GHz.

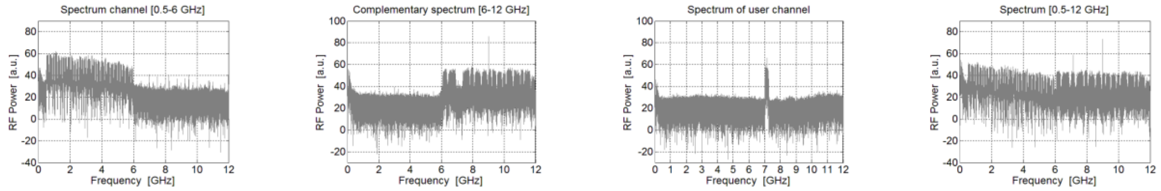

Figure 5. DS spectrum of AWG1out, AWG2out, AWG3out and whole DS spectrum

Because the user signal is realized in base band and transposed, thanks to a RF local oscillator at the correct RF frequency, there is no power attenuation of the signal. By this way, it is now possible to generate and demodulate a correct signal over the full band. With the results of the resources allocation algorithm, we create with Matlab® the corresponding 48 channels.

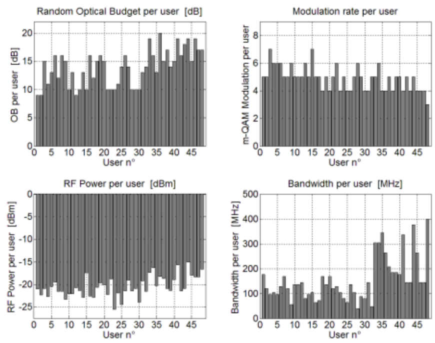

Figure 6. Results of the resources allocation for 48 users

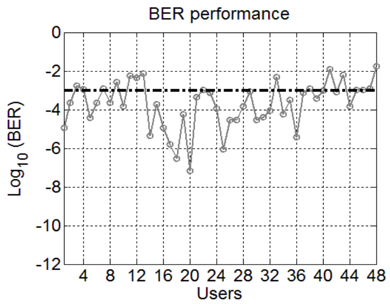

Figure 7. BER performances for each DS user

Figure 6 shows the modulation rate, RF power, bandwidth and optical budget for each user. With the method described above, we demodulate each sub-band and evaluate the transmission performance by measuring the BER (Fig. 7). To assign the correct optical budget, we tune the VOA to the correct value.

To calculate the total capacity, we multiply the bandwidth by the modulation rate for each channel and sum all data rate per user. Finally we found a reachable capacity of 39 Gbps, using 11.5 GHz electrical bandwidth by allocating 48 users.

4. CONCLUSIONS

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.

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