Overview of the FABULOUS EU Project: final system performance assessment with discrete components
(Invited Paper)

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Abstract — **In this paper we present the most comprehensive system demonstrator realized so far inside the FABULOUS project, an EU 7th Framework Program European research project. The architecture proposed in FABULOUS is based on frequency division multiplexed PON and uses a self-coherent and reflective approach in the upstream. The demonstration presented in this paper uses discrete optoelectronics components. We will show system experiments realized with 5 active Optical Network Units, together with the emulation of other 27 ONUs ASE noise, demonstrating that such network is capable of an upstream transmission of 32 Gbps over 40 Km of dark fiber and an attenuation of 31 dB, in compliancy with ODN class N2 of the latest PON standards. In addition, we will demonstrate, thanks to the flexibility of frequency multiplexing, that the network can adapt its performances to the link conditions, achieving higher aggregate bit rates or higher losses depending on the link quality that every user in the network experiences. To conclude, we will investigate on the feasibility of the required Digital Signal Processing onto FPGA or ASIC platforms.**

Index Terms — **FDMA, Next Generation Passive Optical Networks; Reflective Mach-Zehnder Modulator; Self-coherent detection.**

I. INTRODUCTION

Several recent advanced research projects on next generation Passive Optical Networks (PON) proposed a complete change in the transmission paradigm, moving from the "traditional" Time-Division Multiple Access (TDMA) approach ubiquitously used in all PON standards so far, to an (electrical) Frequency Division Multiple Access (FDMA) approach. The Pros and Cons of the two approaches have already been explained at length in previous papers, and will not repeated here; the interested reader can refer to [1]-[3]. The EU STREP project "FABULOUS" (FDMA Access By Using Low-cost Optical network Units in Silicon photonics) [4] investigates these kinds of solutions, proposing an innovative self-coherent reflective FDMA approach for the upstream (US) transmission [5], [6] and a simple FDM approach for the downstream (DS) [7]. In both US and DS directions, each Optical Network Unit (ONU) is assigned a portion of the available electrical spectrum over which spectrally efficient Multilevel Quadrature and Amplitude Modulation (M-QAM) is used on electrical subcarriers. FABULOUS results have been widely disseminated so far. The target of this new paper is to extend previously published results, showing a more extensive experimental setup that will be the basis for the project final real-time demonstrator. The paper is organized as follows:

- in Section II we give a short summary of the proposed architecture, with an insight on how the FABULOUS concept impacts on ONU and Optical Line Termination (OLT) realization;
- in Section III we describe the new experimental setup that extends our previous results (achieved with 2 active and 30 emulated ONUs) to a new configuration using 5 active ONUs and other 27 ONUs emulated in terms of ASE noise-loading. In addition, we will for the first time show the extension to Wavelength Division Multiplexing (WDM) operation. Finally, we experimentally demonstrate how the intrinsic flexibility of FDMA allows FABULOUS to adapt to the link conditions. Focus of these experiments is on the US direction, where most of the innovation of the project resides;
- in Section IV we will analyze the feasibility of the Digital Signal Processing (DSP) implementation on Field Programmable Gate Array (FPGA) or Application-Specific Integrated Circuit (ASIC);
- in Section V we will then draw some conclusions.

II. OVERVIEW OF THE FABULOUS ARCHITECTURE

The FABULOUS project was initially proposed in 2013 taking into account the general requirements set by the Full Service Access Network (FSAN) for NG-PON2. Even though FSAN recently released the NG-PON2 standard (that will still be based on TDMA [8]) we believe that the FABULOUS project targets are still relevant for the discussion that is

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opening today on what will come after NG-PON2. As previously mentioned we propose a splitter based self-coherent reflective PON, capable of WDM at the optical level and FDM/FDMA at the electrical level, through sub-carrier modulation over each wavelength. The choice for FDM, instead of the more traditional TDM-PON approach ([8], [9]), is due to the following advantages:

- electronic simplification at the ONU side, due to the fact that each user needs to detect only its portion of the electrical spectrum and can run at its own baud-rate rather than at the aggregate baud-rate, providing cost and power consumption savings;
- possibility to use complex DSP and long Forward Error Correction (FEC) schemes, for increasing the power budget, thanks to the continuous data-stream;
- network flexibility and adaptability to the link conditions, thanks to the option of adapting modulation format and electrical spectrum width on a per-user bases, as shown in [10] and further investigated in Section III.

The rationale of proposing reflective ONU is the will of leaving the accuracy control on any wavelength (including for the US) to the OLT. The advantage of ONU and wavelength handling simplification comes with the requirements of employing, at the OLT side, coherent detection and External Cavity Lasers (ECL) to seed the US direction, in order to meet the target power budget. In fact, the US wavelengths generated at the OLT and then modulated and reflected back by the ONUs, travels back and forth in the Optical Distribution Network (ODN), thus experiencing increased attenuation compared to a non-reflective architecture.

Fig. 1 shows the signal flow inside the FABULOUS ONU, where the modulated DS wavelength is provided to the ONU receiver, while the un-modulated US wavelength, generated at the OLT, is reflected back and modulated with the US data by a dedicated reflective Mach-Zehnder (R-MZM) depicted in the lower part of Fig. 2. In brief, this reflective ONU structure implements the following features:

- reflective modulation over a generic electrical subcarrier frequency, as described in details in [5];
- optical amplification, using a Semiconductor Optical Amplifier (SOA) on each arm of the loop that follows the Polarizing Beam Splitter (PBS);
- wavelength tunability, using a tunable filter on both the arms of the loop to select the desired wavelength among the set of CW seed wavelengths generated at the OLT side;
- when the two MZM branches are perfectly symmetrical, and for frequencies over 1 GHz, the device turns out to be independent of the input polarization and implements a 90° polarization rotation in reflection. Such polarization rotation is preserved along the whole US path, thus allowing a simplified single polarization homodyne coherent detection at the OLT side, in the Central Office (CO), without using any polarization controller. It can be demonstrated [11] that, with this setup, the penalty due to spurious optical reflections (one of the key drawbacks of reflective PON) is greatly reduced.
- the R-MZM, depicted in the lower part of Fig. 2 is completely polarization independent towards the ODN side, but internally requires handling only one polarization, to be propagated by the waveguide TE-mode only (apart from the input PBS). This feature turns out to be key on a silicon photonics platform that can be only be based on single-polarization waveguides.

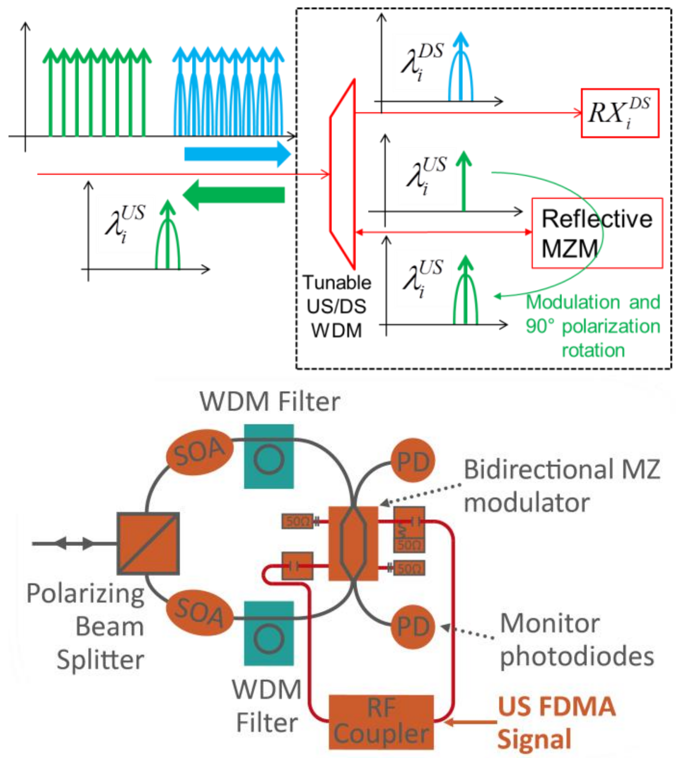

Fig. 1: Architecture of the proposed FDMA-PON ONU for the general case including both WDM and FDM (upper) and details on the Reflective MZM (lower).

We suggest the interested reader to refer to [12], [13] in order to gain more details on the global architecture and on the structures of ONU and OLT. In this paper, we use and refer to experiments carried out with discrete optoelectronic components. The resulting experimental ONU may appear quite complicated and expensive; anyway, the FABULOUS ONU is specifically conceived to allow an unprecedented level of integration on silicon photonic platform, but details on this topic are not in the scope of this paper since the integrated devices will be available only at the end of the project (end of 2015).

III. Experimental Results

A. *Achieving 1 Gbps per user with 31 dB of ODN loss*

For what concerns the US, in [12] we have already reported in detail on an experimental campaign conducted with 2 ONUs implemented with discrete components transmitting an electrical signal and 30 ONUs emulated with the noise-loading mechanism. In [12], we demonstrated the transmission of 32 Gbps to 32 users with an ODN loss of 31,5 dB. It can anyway be argued that using the electrical signal coming from 2 users only doesn't put the system in the worst working condition and thus doesn't provide the lower bound to the transmission performances, that is in the end the meaningful parameter for all specifications. We then organized a more complete setup with 5 complete ONUs equipped with all the optical and electrical components (referred to as "active ONUs" in the following). We also emulated the remaining 27 ONU interference in terms of noise via noise-loading, according to the setup shown in Fig. 2. The experimental ODN encompasses a 37 Km dark fiber test-bed running in the city of Turin and a Variable Optical Attenuator (VOA) for spanning different loss values.

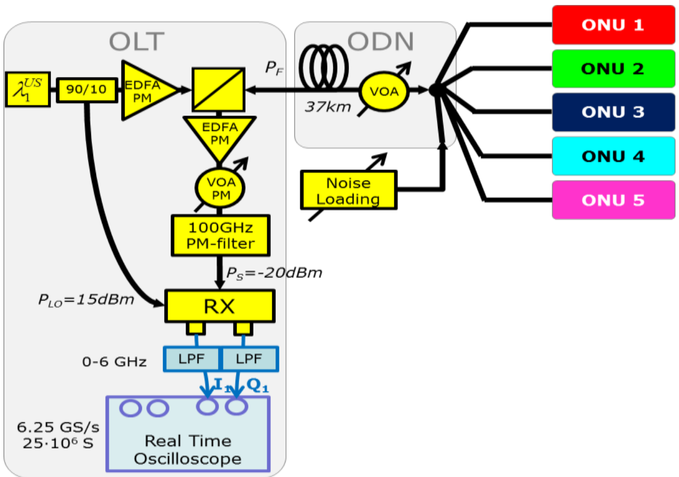

Fig. 2: Experimental US setup with five ONUs and equivalent noise loading for a total of 32 users (ABC: Automatic Bias Controller, EDFA: Erbium-Doped Fiber Amplifier, PM: Polarization-Maintaining, LPF: Low Pass Filter, RX: Receiver, VOA: Variable Optical Attenuator).

The main parameters and features for both (with 2 and 5 ONUs) classes of experiments are:

- 16-QAM modulation format for every electrical subcarrier, using Square-Root Raised Cosine (SRRC) shaping with roll-off factor 0,1;
- 250 Mbaud transmission, 20% overhead taking into account FEC and no guard-band among channels, yielding 330 MHz per channel and 11 GHz of total electrical bandwidth for the 32 users;
- optimized band allocation plan for the electrical subcarrier in terms of absolute positioning of the FDM electrical comb;
- optimized SOA biasing point depending on the ODN loss value;
- optimized modulation index over each R-MZM electrode;
- +9 dBm of OLT side fiber launch power.

We adopted the typical off-line processing approach, using a Real-Time Oscilloscope (RTO) to emulate the OLT and the following DSP and error correction algorithms:

- a Feed-Forward adaptive Equalizer (FFE), with 31 complex taps adapted by Constant Modulus Algorithm (CMA) [14];
- a Carrier Phase Estimation (CPE) using the Viterbi-Viterbi algorithm [14];
- a FEC scheme with hard-decoding capable of correcting up to an incoming Bit Error Rate (BER) of 10^{-2} [15].

As previously mentioned, the rationale for this set of experiments with 5 active ONUs is to determine the lower bound to the absolute maximum performances of this architecture. We have then carefully chosen the central frequencies of such ONUs in order to maximize the electrical interference experienced by the Channel Under Test (CUT) (solid line in Fig. 3). Considering that we already demonstrated in [12] that third and higher harmonic interference does not impact significantly the system performance, such condition is achieved when the CUT is joined by its two adjacent channels plus the two channels generating second harmonic interference.

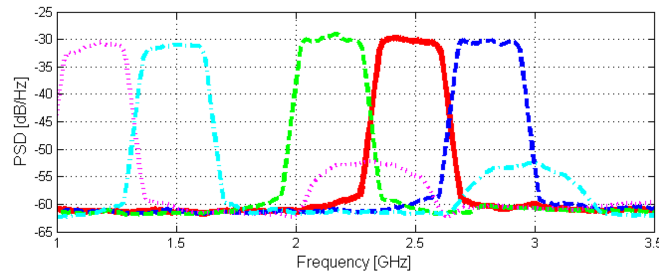

Fig. 3: Experimental upstream electrical spectrum for 5 ONUs. Channel under test at 2.475 GHz is shown with solid line. Maximum electrical interference is provided by the two adjacent channels and the two second harmonics.

We measured the system performances in terms of BER of the channel under test (which was the one with the previously described worst-case interference) as a function of the ODN loss assumed the same for all ONUs, as reported in Fig. 4. Every measurement was performed with the optimum value of the SOA bias current of the ONU under test, as reported in [12]. The SOA bias currents of the other ONUs have been set in order to force the interfering channels to emit the same electrical signal power of the channel under test. Fig. 4 shows that the system supports 31 dB of ODN loss before reaching the pre-FEC BER outage threshold: a 0,5 dB penalty with respect to the experiments carried-out with 2 active ONUs, still satisfying ODN loss specifications set by ITU-T class N2.

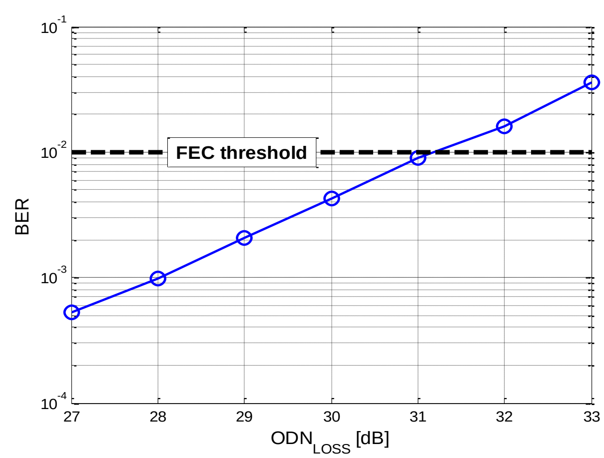

Fig. 4: Performance of the upstream transmission in terms of BER vs ODN loss with 5 active ONUs (32 emulated channels using optical noise loading).

In order to demonstrate that FABULOUS also supports a Differential Optical Path Loss (DOPL) up to 15 dB, as again required by ITU-T standards, we changed the ODN path loss experienced by the ONU under test with respect to the one experienced by the other four interfering ONUs. In this way, we have evaluated the BER of the ONU under test as a function of both its ODN loss and the DOPL (with respect to the interfering ONUs), from 0 to 15 dB, as reported in Fig. 5. Without specific countermeasures, 15 dB of DOPL would mean up to 30 dB received power variation among FDM channels (due to the reflective approach, the ODN loss counts twice on the upstream path), which would create problems to any practical coherent receiver used in the channel detection. Therefore, we propose an OLT-centralized automatic control algorithm on the ONUs SOA gain, whose target is to equalize the received electrical power of the FDM channels at the OLT. We have implemented this algorithm by first measuring each ONU's SOA biasing current required for all ODN loss values, in order to obtain a constant received power of all the channels at the OLT side. The measurement results are given in Fig. 5 as BER contour plots vs. ODN loss and DOPL. We can observe that the BER contour plots are almost vertical, showing that they mostly depend on the ODN loss related to the ONU under test, while they are practically independent of the interfering ONUs ODN loss. This demonstrates that our system supports at least up to 15 dB of DOPL and that our SOA gain control strategy is effective. As a second observation, the graph shows that the area up to BER=10^{-2} pre-FEC is guaranteed for all the ODN losses combinations up to 31 dB, confirming the N2 class compliance.

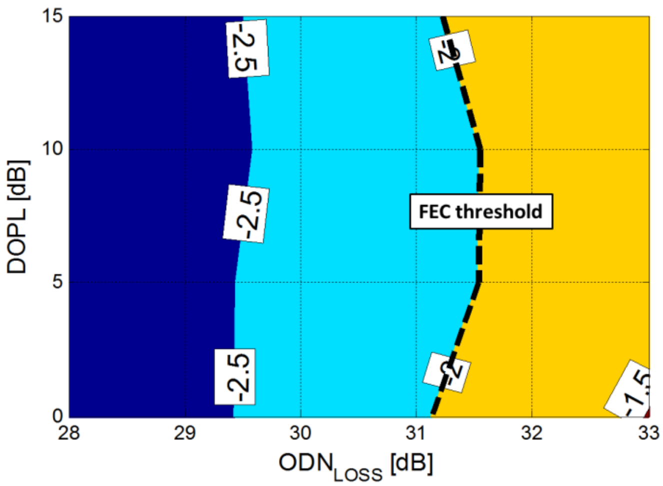

Fig. 5: Performance of the upstream transmission in terms of BER vs ODN loss vs DOPL with 5 active ONUs, 32 emulated channels.

For what concerns the DS direction, it is worth mentioning that in [7] we demonstrated that, with a launch power of +16 dBm plus laser dithering and a FEC with outage threshold of 2.17*10^{-3}, a power budget of 33 dB with a capacity of 32 Gbps can be achieved, allowing us to claim that the FABULOUS architecture is symmetrical.

B. WDM operation

Since the FABULOUS architecture supports multi-wavelength operation, thanks to the tunable filter foreseen at the ONU and the OLT, we modified the experimental setup requiring the OLT to send 4 seed wavelengths through the ODN (in particular, at 1549.32, 1550.12, 1550.92 and 1551.72 nm, +9 dBm launch power each). The CUT is generated by a full-fledged FABULOUS ONU, that selects an operating wavelength and modulates it with one electrical channel. In addition, all four wavelengths are modulated by a Reflective Electro-Absorption Modulator (R-EAM), on a different PON leaf after the power splitter, with 7 channels surrounding the CUT according to the maximum interference condition described in the previous paragraph. As a result, the wavelength under test contains 8 electrical channels, while the three interfering wavelengths contain 7 electrical channels, as evident from Fig. 6.

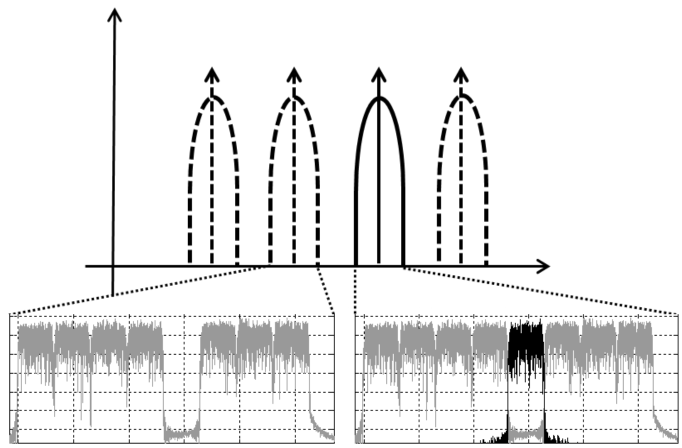

Fig. 6: optical and electrical spectra received by the OLT. The electrical spectrum on the three interfering wavelengths, on the left, has 7 channels, while the electrical spectrum of the wavelength under test, on the right, has 8 channels.

The ODN loss of the different paths (CUT on test wavelength, interfering channels on all wavelengths) has been set in order to have the same power per electrical channel at the OLT. Results are summarized in Fig. 7, in comparison with the single wavelength operation, showing that WDM operation doesn't introduce, as expected, any additional penalty.

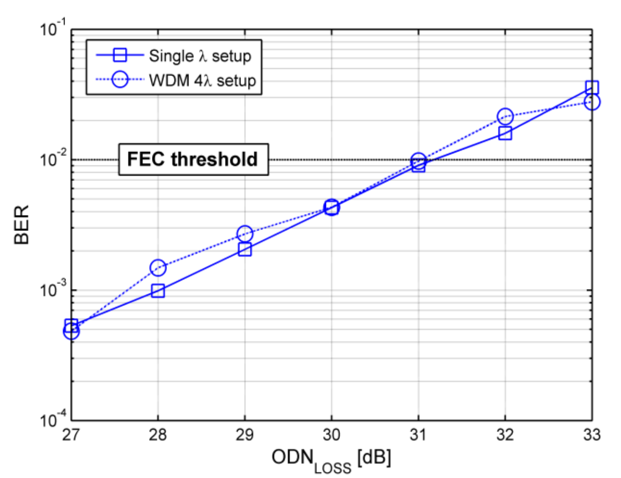

Fig. 7: WDM (dashed line) vs. single wavelength (solid line). No penalty is observed.

C. Physical layer reconfigurability options

The FDM / FDMA PON concept allows the capacity to be reattributed dynamically to respond to the customer demand which understandably varies over time depending on the services requested, hours of day and night, etc… Indeed, when a customer requests a transmission capacity (e.g. in order to download a film from his remote data storage), the system will identify an available frequency channel from the 32 channels possible and associate that frequency channel to that customer for the duration of the data exchange. During that time, the transmission is performed at the maximum available speed until completion in order to free the frequency channel for another request or another customer. The experimental results presented in the previous Sections showed that it is possible to transmit 16-QAM at 1 Gbps net bit rate per frequency channel (i.e. per user) over an ODN having up to 31 dB loss in both uplink and downlink. It should be noted that, in our experiment, we emulated a worst case situation in which all ONUs see the worst case ODN loss. Anyway, on realistic PONs, users typically see different losses [16], so the quality of the transmission channel is dependent upon the physical parameters of the user requesting capacity. As the (de)modulation is performed in DSP, it is possible to implement various levels of QAM modulation coding (from e.g. QPSK to 128-QAM) which will lead to different transmission capacity per RF channel. For instance, we can range from 500 Mbps in QPSK to 1.75 Gbps in 128-QAM over the same electrical bandwidth we used in the previous experiment to deliver 16-QAM at 1 Gbps, while other values can be obtained also varying the electrical bandwidth per channel. For each transmission to a specific user, the QAM modulation level can be adapted to achieve the maximum transmission speed and hence the minimum time occupation of that channel. The traffic towards (or from) different users sharing the same RF channel can be, for instance, multiplexed also in the time domain. Using the model derived in [10] to infer the performance of the FDM/FDMA PON over a broader range of user losses, we showed for instance that a standard class B+ PON with an average user loss of 21.4 dB should be able to transport 48 Gbps in US (64-QAM for each user) and 56 Gbps in the DS (128-QAM per user).

Sticking back to the experimental validation, we then assessed the performances of the FABULOUS architecture varying modulation format and electrical bandwidth, still using the same setup and optical parameters (link length, launch power, etc.). It is important to point out that no hardware modification was necessary to make these adaptations, that only requested intervention on the DSP and on the electrical signal generation (to be performed on FPGA or ASIC platform in a final version). Table I reports the results of these experiments, where we assumed that every user employs the same electrical bandwidth. In a more general case in which every user could also adopt a different bandwidth, that is a possibility foreseen by FDM approaches, such values provide only a rough estimation, since in that case the interference at the electrical level can be quite variable depending on the overall spectrum shape. As an approximate indication, we estimated that, a user experiencing for example an attenuation greater than 40 dB can still be connected to the network at 250 Mbps using BPSK modulation with a bandwidth of 330 MHz or at 100 Mbps using QPSK modulation with a bandwidth of 66 MHz. On the contrary, users experiencing a lower attenuation can increase their bit-rate; for instance, in case all users are below 23 dB of attenuation, the network could grant an aggregate bit-rate close to 50 Gbps using 64-QAM.

TABLE I
PERFORMANCES FOR DIFFERENT MODULATION FORMATS AND BANDWIDTHS

Modulation format	Electrical bandwidth per channel	Net bit-rate per user	Maximum ODN loss
64-QAM	660 MHz	3 Gbps	23.0 dB
64-QAM	1320 MHz	6 Gbps	23.0 dB
16-QAM	330 MHz	1 Gbps	31.0 dB
16-QAM	1650 MHz	5 Gbps	30.5 dB
16-QAM	3300 MHz	10 Gbps	28.0 dB
QPSK	66 MHz	100 Mbps	41.0 dB
QPSK	330 MHz	500 Mbps	38.0 dB
QPSK	1650 MHz	2.5 Gbps	34.5 dB
QPSK	3300 MHz	5 Gbps	32.5 dB
BPSK	330 MHz	250 Mbps	40.5 dB
OOK	6250 MHz	10 Gbps	38.5 dB

We also like to mention that 64-QAM operation with 330 MHz is not possible due to phase-noise affecting the coherent detection, linked to the laser linewidth (< 100 KHz with the ECL unit used in this setup), and for the same reason we did not perform any campaign employing 128-QAM.

IV. FEASIBILITY OF DSP IMPLEMENTATION

The proposed FDMA architecture, besides innovative optoelectronic components for the ONU, will also require DSP at both the ONU and OLT sides that will have to adapt Ethernet digital streams to the specific physical layer algorithms proposed in FABULOUS. In this Section we focus on estimating the cost (expressed in terms of required Silicon area) of an ASIC chip that could implement ONU DSP functionalities, since only ASIC integration can potentially reach the low-cost requirement of ONU customer premises equipment. For performing this task, we obtained detailed information on DSP complexity from our experience on the FPGA-based real-time DSP demonstrator that we are currently developing inside the FABULOUS project.

Focusing on the DS channel, for example purposes, the ONU receiver has to perform the following steps to convert the received optical signal to Ethernet data for the user: after the optoelectronic front end, the electrical signal is filtered and demodulated with an I/Q demodulator (to select the wanted FDMA channel). The two baseband I/Q components are sampled with a two channel A/D Converter (ADC) and enters the DSP domain, were the full FABULOUS physical layer and the Ethernet interface should be implemented. For mass production purposes, it is fundamental to include as many as these functionalities as possible in a single companion ASIC.

In the following, we estimate the Silicon Area required for implementing the DSP, the Ethernet PHY and the converters. For the DS receiver section, the ONU chip should include:

- a two channel 600 MHz ADC;
- an adaptive low-pass down-sampling filter, to reduce noise and interferences from adjacent subcarriers. After careful optimization simulation, this filter is implemented as a FIR filter with 32 complex taps;
- the CPE, implemented following [14] and whose area is estimated on the bases of the off-line implementation;
- the differential decoder;
- a FEC decoder based on ITU G.975 I.4 EFEC, with area estimation based on Altera FEC datasheets.

For the US section, our analysis considered three main blocks:

- a FEC encoder using a 20.5% overhead FEC [15]. Such code is composed by a Reed Solomon RS(781,765) outer code and a concatenated QC-LDPC code as inner code. The resulting area occupation of both RS and LDPC FEC encoders is negligible with respect to DSP area occupation ([17]);
- a SRRC up-sampling filter, made of 128 complex taps;
- a dual 600 MSps DAC.

It is worth pointing out that the complexity of the US FEC resides mostly at the OLT, for the FEC decoding phase, where computational complexity is less of an issue compared to the ONU side since the overall cost can be shared by all users.

TABLE II
AREA ESTIMATION FOR SUB-BLOCKS AT THE ONU

IP	Description	Size	Reference
DS ADC	2 channels, 600 MSps	0.1 mm^2 each	Cadence IP
US DAC	2 channels, 600 MSps	0.1 mm^2 each	Cadence IP
PLL	At least 3, 600 MHz or 1.2 GHz	0.1 mm^2 each	[18]
Gb Ethernet PHY	1 instance	<0.5 mm^2	
DS DSP (down-sampling filter + CPE)	Look-Up Tables: 82627 Flip Flops: 132967 DSP48 cells: 192	2.22 mm^2 total	800 kgates/mm^2 TSMC reports
DS FEC decoder	Look-Up Tables: 46980 Flip Flops: 44675 9 kb RAM: 114 144 kb RAM: 8	2 mm^2 total	Altera 975 I.4 EFEC
US up-sampling filter	18 kb RAM: 160	0.5 um^2 per cell 1.5 mm^2 total	TSMC reports
Total estimation		7 mm^2	

Considering a 65 nm process (optimized for power and for analog components) for the ASIC migration, Table II reports the silicon area estimation of the various blocks. The last column reports the references we used to obtained such values.

Our estimation leads to a more than reasonable 7 mm^2 required area. It should be mentioned that, as of today, 65 nm process mask costs are high, so that they can be justified only by mass production.

V. CONCLUSION

Using off-line processing and discrete optoelectronic components, we have demonstrated the full potential of the FABULOUS FDMA PON architecture, capable of transmitting 32 Gbps per wavelength in ODN class N2, and of supporting WDM transmission and rate adaptability.

We have also demonstrated that the DSP needed for achieving such performances can fit onto commercial FPGA. Moreover, we have estimated the cost of an ASIC implementation in terms of silicon area.

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