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***Abstract* — We discuss the use of frequency division multiplexing in next-generation PON. We start by discussing pros and cons of FDMA compared to traditional TDMA approach, then present the latest results from the EU project FABULOUS.**

Keywords — Optical Access Networks, Passive Optical Networks, Multiplexing Technologies.

I. Introduction

At the end of last year (December 2014) ITU-T finally released the physical layer specifications of the most advanced standard so-far for Passive Optical Networks (PON), under Recommendation G.989.2. Focusing on the so-called TWDM-PON part of the standard (Time and Wavelength multiplexed PON), ITU-T introduced the concept of using N_W wavelengths per direction, each transmitting a traditional On-Off Keying (OOK) modulation, for a resulting total capacity of $N_W \cdot 10$ Gbps in the downstream (DS) and $N_W \cdot 2.5$ Gbps in the upstream (US). The number of used wavelength N_W should likely be 4 in the first commercial releases, justifying the G.989 title "40-Gigabit-capable passive optical networks (NG-PON2)" (Next Generation PON).

In our opinion, this new ITU-T standard sets a "benchmark" for any future research activities on PON, in the sense that any further research work should propose to outperform TWDM-PON in some clear direction. One of the upgrades foreseeable for a future "NG-PON3" is the increase of the bit rate per wavelength (in US and/or DS). Anyway, going above the current 10 Gbps per wavelength poses at least two issues:

- the traditional binary OOK modulation has shown to be extremely critical above 10 Gbps when the distances to be covered are up to 20-40 km of SMF fibers (as requested in ITU-T PON) for the joint effects of chromatic dispersion and polarization mode dispersion;
- apart from pure transmission aspects, a binary OOK approach above 10 Gbps requires extremely fast digital electronic receivers, which in turns are difficult to be implemented at the extremely low target price of Optical Network Unit (ONU, the optoelectronic front-end at the user side).

For all these reasons, several recent research projects have proposed a new approach based on Frequency Division Multiple Access FDMA-PON as an interesting alternative to TDMA-PON: the interested reader can refer to the vast available literature for recent projects like the EU projects ACCORDANCE [1], O-TONES [2], FABULOUS [3], or in the NEC works on OFDM-PON [4]. All these projects share most of the following ideas/technologies/advantages:

- the traffic coming from several users is multiplexed over each wavelength using an electrical FDM (or OFDM) in which each user is allocated a portion of the available electrical spectrum, through electrical subcarrier multiplexing;
- over each subcarrier, some high order modulation format such as M-QAM is used, in order to obtain bit rate per wavelength higher than 10 Gbps thanks to the higher spectral efficiency of M-QAM compared to binary OOK. This is one of the key advantages of the proposed FDM-PON solutions, even though it requires advanced digital signal processing (DSP) to implement it;
- at the user side, each ONU should detect only its portion of the electrical spectrum. Thus, thanks to the use of electrical sub-band processing (such as those proposed in [2], [3]), the DSP required at the ONU side can run at relatively low sample rate. On the contrary, the more traditional TDMA approach requires the ONU to run at the aggregate rate. This is another key advantage of FDMA compared to TDMA;.
- more in general, some recent studies [5] have shown that an FDMA approach can give a great flexibility in satisfying very different data rate requirements, as it is typical for access networks, and different Optical Distribution Networks (ODN) characteristics (such as very sparse ODN loss values).

In the following Sections, we present the most recent result for the EU project FABULOUS [3], an example of a FDMA-PON architecture targeting 32 Gbps per wavelength per direction. In particular, we describe in Sect II the proposed architecture, while in the following Sect. III we present the system performance through a set of experimental results. Sect. IV then draws some final comments.

II. FABULOUS GENERAL ARCHITECTURE

The FABULOUS EU project proposes an FDM/FDMA PON architecture based on the following concepts:

1) two multiplexing levels are envisioned: WDM at the optical level and FDM/FDMA on each wavelength using electrical subcarrier multiplexing, were we can use different modulation format, depending on the requested performances;

2) in order to avoid any problem related to uncontrolled upstream wavelengths in the network when a ONU switches on, which is one of the current issues still to be solved in TWDM-PON, the architecture uses a reflective PON approach. To achieve power budgets compatible with ITU-T G987.2, coherent detection at the OLT is envisioned;

3) in order to target a low-cost solution for massive deployment, the ONU should be conceived in a manner to allow a high level of integration on a Photonic Integrated Circuit (PIC).

As aspects 1) and 2) are straightforward, the real innovating factor of FABULOUS resides in the ONU, especially for its behavior in the US direction, that is conceived to be realized on a silicon-photonics platform, flip-chipping on top the electrical driver and InP-over-silicon SOAs. The schematic of the US part of the ONU is depicted in figure 1, and in the following we will refer only to the US direction of the FABULOUS architecture, since it constitutes the real innovation brought by the project.

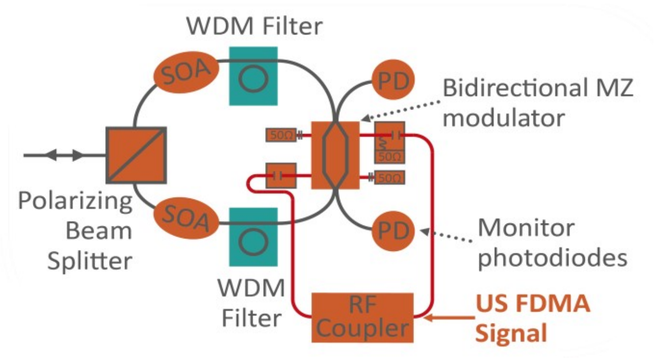

Fig. 1. Schematic of the US part of the ONU.

The two input polarizations of the seed CW signal, coming from the OLT, are split by the Polarizing Beam Splitter (PBS) and travel within the rest of the ONU in opposite directions, being amplified, filtered by a tunable filter for WDM operation, and then modulated by the interferometer. The two branches of the interferometer need to be independently driven by the same modulating signal. Under these conditions, when combined again after the PBS, the upstream signal is rotated by 90° with respect to its seed signal, and this polarization orthogonality is maintained in every point of the network, allowing simplified coherent detection at the OLT. Such ONU structure is ideal for being realized in silicon photonics, due to the fact that this technology is intrinsically single-polarization only. However, since the realization of a prototype ONU PIC is foreseen at the end of the project only, we had for the moment to demonstrate the architecture using discrete optoelectronic components, performing careful polarization management and obtaining a custom-made $LiNbO_3$ MZ Modulator due to the need to access both electrodes.

Since our target is to deliver 1 Gbps to 32 users on each used wavelength, we performed a simulation campaign and optimized a set of physical layer parameters:

- multilevel modulation formats. After a detailed study, we selected 16-QAM with raised-cosine spectral shaping with roll-off factor of 0.1, that turned out to be the best compromise among performances, complexity and bandwidth requirements. In particular, the resulting baud rate below 300 Mbaud allows the DSP, and particularly the required Digital-to-Analog (DAC) and Analog-to-Digital (ADC) converters, to run at a speed of the order of 600 MSample/s, compatible with the today commercial Field Programmable Gate Array (FPGA) platforms and lower-cost CMOS DAC and ADC;
- optimized band plan for the electrical subcarrier in terms of both frequency spacing and absolute positioning of the FDMA electrical comb;
- optimized modulation index (defined as the ratio between the modulated electrical peak voltage and the modulator V_π) over each R-MZM dual electrode;
- optimized SOA biasing point depending on the ODN loss.

We also considered the opportunity to use a recent Forward Error Correction (FEC) encoding/decoding mechanism, able to correct the incoming Bit Error Rates (BER) of 10^{-2} and requesting approximately a bit rate overhead of 20% ([6]): this yielded a bandwidth per subcarrier $B_{RF}=330\ MHz$ (including the raised cosine); for 32 users, the total requested electrical bandwidth, considering a channel spacing equal to B_{RF}, is around 11 GHz, achievable both with the discrete MZM used in our experiments, but also in the soon to be released prototype in Silicon Photonics.

For what concerns the DSP to be realized at the OLT, implemented in Matlab™ for post-processing but taking into account the limitations (such as finite number of bits for AD and DA conversions, limited computational resources, etc.) of a practical implementation over FPGA, it consists of:

- a feed-forward adaptive equalizer, with 31 complex taps updated by Constant Modulus Algorithm (CMA);
- a Carrier Phase Estimation (CPE) using a Viterbi-Viterbi algorithm.

III. EXPERIMENTAL RESULTS

The experimental activity has been carried out with one only optical wavelength, but can be extended without loss of generality to a multi-wavelength case adopting for example the same wavelength allocation plan of NG-PON2 due to the presence of the tunable WDM filter in the ONU. Five active

ONUs where realized, while the effect of the other users has been emulated in terms of optical noise thanks to a noise-loading mechanism. Besides being, to the best of our knowledge, the most extensive FDMA-PON demonstration, the experimental campaign was carried out in order to test US transmission in the worst possible situation in terms of inter-channel interference among adjacent electrical subcarrier-multiplexed ONUs. The ODN is composed by 37 Km of dark-fiber installed in the city of Turin and a variable optical attenuator.

An off-line post-processing approach was adopted so far, generating the electrical signals with an Arbitrary Waveform Generators feeding the five MZM and then sampling, at the OLT, the received signal after the coherent receiver with a real-time oscilloscope, for feeding the Matlab™ DSP. After two years of extensive off-line processing experiments, first real-time experiments, with DSP implemented over an FPGA platform, are taking place at the time of writing this paper.

We also evaluated the Differential Optical Path Loss (DOPL) that FABULOUS can accommodate, proposing 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.

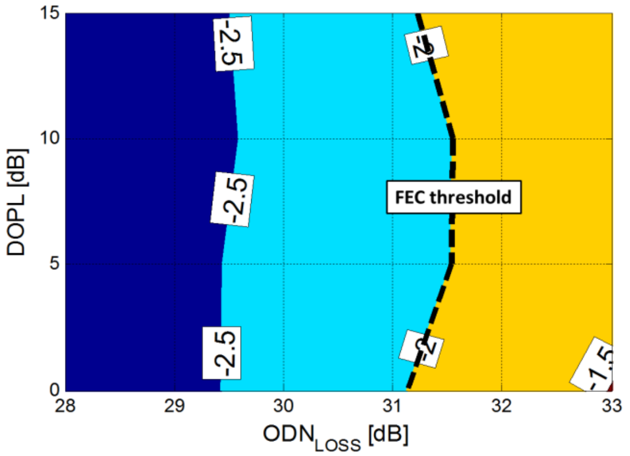

Fig. 2. Performance of the upstream transmission in terms of BER vs ODN loss vs DOPL with 5 active ONUs, 32 emulated channels.

The final results of this extensive campaign are reported in Fig. 2, in the form of BER contour plots vs. ODN loss and DOPL, where the modulation index is set to 0,2. From such graph we can then conclude that:

- FABULOUS can transmit an aggregate capacity of 32 Gbps, organized as 1 Gbps to 32 users, withstanding an ODN loss of 31 dB, as specified by XG-PON class N2;
- FABULOUS supports at least up to 15 dB of DOPL.

We decided to evaluate also other application scenarios, such as PON with extended reach, PON with 128 users, vertical-PON for LAN applications, varying modulation format, channel bandwidth, transmitted power, splitting ratio, FEC scheme, and the results are summarized in Table I.

TABLE I
US PERFORMANCES FOR THE DIFFERENT APPLICATION SCENARIOS

	PON	PON	PON	LAN
Modulation format	16-QAM	QPSK	QPSK	QPSK
B_{RF}	330 MHz	330 MHz	66 MHz	60.5 MHz
Users	32	32	128	128
P_{TX}	9 dBm	9 dBm	9 dBm	0 dBm
Link length	37 Km	37 Km	37 Km	1 Km
FEC threshold	10^{-2}	10^{-2}	10^{-2}	$2{,}17\cdot10^{-3}$
Bit-rate per user	1 Gb/s	500 Mb/s	100 Mb/s	100 Mb/s
ODN Loss	31 dB	38 dB	41 dB	31 dB

IV. DISCUSSION AND CONCLUSION

We have demonstrated that a FDMA approach can provide a feasible and high-performing solution for next generation PON and we have evaluated the cost of mass-production of the fully silicon-photonic integrated ONU to be in the order of 80 €, thus acceptable for mass-market customer premises equipment also for other applications than very-high-speed access.

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