Review and comparative assessment of FDMA-PON vs. TDMA-PON for next-generation optical access networks

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***Abstract**: We present in this paper a comparative assessment of Time Division Multiple Access Passive Optical Networks (TDMA-PON) and Frequency-Division Multiple Access Passive Optical Networks (FDMA-PON). We try to point out the pros and cons of the two different approaches in the context of very high capacity next-generation PON mainly in terms of physical layer transmission performances, but also introducing some comparison in terms of complexity, cost and power consumption.*

1. Introduction

As any other communication systems, Passive Optical Networks (PON) are continuously evolving at the standardization, commercial and research levels in order to keep up with increasing traffic demands. The PON solutions that are massively deployed today worldwide (mostly using ITU-T GPON and IEEE EPON) start to show their limitations in terms of aggregated available bit rates for traditional residential access, but even more for the expected PON evolution towards supporting new mobile networks requirements (front-hauling and back-hauling [2]) and for high-end business applications.

In this paper, we review the current situation, by comparing the most advanced PON standards with some of the recent proposals in the area of Frequency Division Multiple Access Passive Optical Networks (FDMA-PON). We will mostly address the physical layer (usually called Physical Media Dependent PMD layer in the PON standards).

We organized the paper as follows: in Section 2, we review the status of the art in next-generation PON standardization, mainly reviewing the ITU-T NG-PON2 standard [1]. Then in Section 3, we present the FDMA-PON main principles and compare it to TDMA-PON. In the following Section 4, we review some of the existing research proposals on FDMA-PON, then we give a specific example in Section 5. We finally draw some conclusions in Section 6.

2. Current status of the art in next-generation PON standardization

The current benchmark for any research proposal in the area of very high capacity PON is the ITU-T NG-PON2 standard [1], as defined in the G.989 set of Recommendations. This is because ITU-T NG-PON2 is

now the PON standard that grants the highest bit rate, since for the moment IEEE has not yet proposed a standard that upgrades its 10GEPON (even though it is working on it).

The new ITU-T NG-PON2 standard, recently released for its general part as G.989.1 but still under final revision for the details of the physical layer (that should appear soon as Recommendation G.989.2) will generate a "revolution" in PON, by introducing for the first time the use of dense wavelength division multiplexing (DWDM) in both transmission directions. Concisely, the ITU-T NG-PON2 standard builds around two type of services:

- the so-called TWDM-PON service (Time and Wavelength Division Multiplexed PON) in which N_{TWDM} wavelength pairs are used to carry N_{TWDM} XG-PON channels [3], i.e. 10 Gbps in the downstream (DS) direction and 2.5 Gbps and 10 Gbps in the upstream (US) direction (other bit rates are also possible). The first releases are expected to use N_{TWDM}=4 wavelengths per direction, thus giving an overall capacity equal to 40 Gbps in DS and 10 Gbps in US. Each wavelength traffic is organized exactly like the previous GPON and XG-PON standards, so that a given pair of DS/US wavelengths is shared among several ONUs, and multiplexing among these ONUs is organized according to the same TDMA approach used by GPON and XG-PON;
- the so-called P2P-WDM, in which N_{P2P} wavelengths are used to setup very high capacity point-to-point logical links between a given ONU and the OLT. In P2P-WDM each wavelength is thus dedicated to a given ONU, so that no multiplexing is needed at the physical layer. The P2P links are not meant to serve residential customers, but mobile front-hauling and back-hauling for 4G and 5G mobile cellular networks and high-end business applications.

ITU-T recommendation G.989 has also set some other very important keypoints which we will often use in our following considerations:

- the telecom operators see backward compatibility as a key issue in PON. As a consequence:
    - The PON outside plant for NG-PON2 (the so-called Optical Distribution Network, or ODN) should remain exactly as it was defined for previous GPON and XGPON standard, so it must be splitter based (with splitting ration up to 64) and with fiber length up to 20 km (40 km in the extended range versions).
    - The wavelength plan for NG-PON2 should be compliant with previous standards, which include the aforementioned GPON and XGPON but also the RF-Video channel. Thus, ITU-T envisions that GPON, XGPON, RF-Video channel, TWDM-PON and P2P-WDM should coexist on the same PON;
- because of the previous point, the new wavelengths for TWDM-PON and P2P-WDM should be allocated well outside the already occupied optical bands (for GPON, XGPON and RF-Video). The available optical spectrum in the commonly used optical bands turned out to be full, and consequently it is decided that TWDM-PON and P2P-WDM will use the L-band (around 1600 nm) for DS, and in an unusual band (around 1530 nm) for US. Other wavelength allocations are still under discussion. In these new bands, the wavelength channel spacing is expected to be 100 GHz;
- the 100 GHz spacing will generate completely new requirements for PON-grade lasers and optical filters: while all previous PON generation were specified using wide tolerances on wavelength accuracy, of the order of 10 nm, TWDM-PON and P2P-WDM will require optical components having optical spectral accuracy of the same order of long-haul DWDM components, but at much lower

target price. Moreover optics at the ONU will be wavelength tuneable for both transmitter and receiver, again a very new requirement for PON components;

- from a transmission point of view, ITU-T NGPON2 will still use traditional modulation format, and will thus still be based on binary On-Off Keying (OOK) intensity modulation (IM) and direct detection (DD). This decision maintains backward compatibility at almost all layers with XG-PON. For OOK IM-DD systems, the 10 Gbps is a sort of "natural" maximum bit rate since higher bit rates are extremely critical due to attenuation and chromatic dispersion of PON ODN.

3. FDMA-PON and its potential advantages vs. TDMA PON

Several research proposals, as reviewed in the next Section 4, foresee a completely new approach to PON transmission based on Frequency Division Multiple Access. In most of these architectures, an electrical FDM/FDMA multiplexing approach applies on the electrical spectrum available on each used wavelengths (in both DS and US). In most of these proposals, the available electrical spectrum, typically in the range from 0 to 8-9 GHz is used as an "analog" available spectrum which is divided in spectral slices that are allocated one per each ONU. Each electrical spectral slice typically uses some form of M-QAM modulation, sometimes mapped using an OFDM approach (Orthogonal Frequency Division Multiplexing).

Apart from the details of each different research activity, the FDMA-PON approach has in general the following disadvantages:

- The optoelectronic components should have a high-level linearity, an unusual requirements for standard OOK optical systems. It is anyway a well know requirement for any Radio-over-Fiber (RoF) applications and, specifically in PON, for the RF-Video channel (as defined in ITU-T G.984.4)
- The use of advanced modulation formats such as M-QAM (and obviously M-QAM over OFDM) mandates the introduction of fast digital-to-analog (DAC) converters at the transmitter and analog-to-digital (ADC) converters at the receivers, both followed by high-speed digital signal processing (DSP) for M-QAM (or OFDM) modulation and demodulation. While ADC+DSP in the optical systems physical layer is today becoming commonplace in the long-haul application, it is not yet significantly used in any of the currently deployed PON standards (GPON and EPON), being all based on simple OOK IM-DD without any equalization algorithms. Related to this point, it should anyway be mentioned that XGPON (and consequently NG-PON), even though it does not require ADC and DAC, has introduced Forward Error Correction (FEC) in the PMD layer based on a relatively simple Reed-Solomon FEC (as specified in G.987.3 clause 10.3). Its implementation at the required speed (10 Gbps in DS, 2.5 Gbps in the US) already requires powerful ASIC circuits for FEC. Thus, XGPON already envisions some substantial DSP support (even though no ADC and DAC).
- FDMA-PON in its most straightforward versions assumes that each ONU transmits a continuous traffic over its allocated spectral slice. This can be a disadvantage for ONU generating a very low traffic, a situation that can be addressed by a mix of FDMA and (slow) TDMA reconfiguration.

- Anyway, many expected applications for NG-PON such as mobile front-haul and back-haul, will be completely "circuit-oriented" since they will require fixed guaranteed bit rates in both directions.

These disadvantages of FDMA-PON vs. the traditional solutions comes anyway in change for a significantly higher bit rate per wavelength, since as we will show in the following Sections 4 and 5 most FDMA-PON research proposals reach a capacity in the range between 30 and 40 Gbps per wavelength. Apart from pure capacity, which is always the key "selling point" of these FDMA-PON proposals, we review in the following other potential FDMA advantages:

- at least in principle, advanced modulation processing can be applied also to TDMA approaches. Anyway, the burst-mode operation required by TDMA-PON in the upstream makes advanced digital signal processing very complex, since usually DSP-assisted receiver algorithms have a training phase. For instance, even a simple adaptive equalizer in a direct detection receiver needs a training phase to find initial values for the equalizer taps. The requirement for initial training is even more relevant for any solution proposing coherent detection that needs relatively long training phases for frequency, phase and equalization. Even though burst-mode coherent receivers have been proposed [2], they are relatively complex, and we believe a continuous mode transmission such as the one requested by the FDMA approach would make DSP-assisted physical layer significantly easier;
- similar considerations applies to FEC: XG-PON introduced FEC so that ONU and OLT should be mandatorily equipped with Reed-Solomon error correcting codes. Anyway, the specified code for US is a relatively simple RS(248,232) block code, and the resulting reference BER is set at 10^{-4}. Due again to burst mode operation, more efficient FEC code cannot be used, since they always require a long memory and thus can only be applied to continuous transmission, as it is anyway possible to realize with FDMA-PON approaches. A continuous transmission FDMA-PON could thus in principle use (also in the upstream) the most efficient FEC codes. For instance, the code proposed in ITU-T G.795.1–I.4 (a RS(1023,1007)+BCH(2047,1952)) has a $2.17 \cdot 10^{-3}$ FEC threshold with only a 6.7% overhead;
- in many FDMA-PON proposals (and even more in OFDMA-PON) proper DSP algorithms can be used to tailor transmission formats to the physical channel conditions and to the ONU traffic request. While traditional OOK in TDMA-PON has little degrees of freedom to be used for channel/traffic adaptation, advanced modulation formats coupled with DSP offer many degrees of freedom such as:
    - Modulation format (i.e. the type of M-QAM constellation)
    - Power levels for each ONU spectral slice
    - Spectral widths of each ONU spectral slice
    - FEC used for each ONU transmission

4. Review of some of the existing research proposals on FDMA-PON

In this section, we present as a reference for researchers working in this field some of what we believe are very significant examples of FDMA-PON or OFDMA-PON that appeared in the literature in the last years. We focused on only a few selected examples, since it was obviously impossible to give an

exhaustive list of all FDMA-PON or OFDMA-PON research projects. We restricted our attention to the proposals that make use of electrical FDMA approach, i.e. those proposals in which the FDMA US and DS signals are generated using electrical DSP approaches.

We did not report some more advanced proposals that make use of some forms of all-optical generation of (O)-FDMA signals, since we believe that only the electrical FDMA approaches allows a closer comparison with ITU-T NG-PON2 goals. The all-optical (O)-FDMA proposals are focused on longer term PON perspectives and in particular on much higher aggregated capacity (some all-optical OFDMA proposal targets even Tbit/s per PON [5]).

We present in the following Subsections 4.1 to 4.4 four proposals at increasing level of aggregated bit rate per ONU and, thus, at increasing complexity. We then review in the following Section 5 the proposal presented by the authors of this paper.

4.1 The "ADVAntage-PON" project

An attractive architecture proposal for OFDMA-PON comes from the Kiel University Communication Group and its partners, which published several scientific works ([6]- [14]), partially carried out under the German project titled "ADVAntage-PON". This proposal is a "true" electrical OFDMA-PON, and some key features demonstrated in the project are listed below:

- The project proposes a first level of multiplexing using WDM, and a second level using electrical OFDM, achieving the following capacities and characteristics:
    - Use of the OFDM format on US and DS [10]
    - DS-path:
        - *Optical capacity*: 12.173 Gb/s (Net bit-rate) per wavelength (up to 40 wavelengths); four ONU for each wavelength, thus giving a very high multi-Gbps capacity per ONU;
        - *Optical Splitting*: mixed use of AWG & Power Splitter is envisioned;
        - *Tested Optical path*: up to 100km SMF followed by a (1:4) Node Splitter;
        - *OLT*: TX with single DSP for 4xONU multiplexing, using Multiband (4xONU)-8QAM-OFDM
            - *Modulation*: Analog I-Q mixer up-conversion, External optical intensity modulation; optical single sideband (OSSB) signal generation;
        - *ONU*: RX for sub-band-OFDMA for single ONU access,
            - *Demodulation*: single polarization direct detection with Analog I-Q mixer down-conversion;
            - *Baseband signal detection*: single-band RX-DSP (1xONU)-8QAM-OFDM Net bit-rate per ONU: R_b=2.97 Gb/s.
    - US-path
        - *Optical capacity*: 6.12 Gb/s (Net bit-rate) per wavelength (up to 40 wavelengths);
        - *ONU*: TX for sub-band OFDM;
            - *Baseband signal*: QPSK-OFDM, Net bit-rate: R_b=1.53 Gb/s,
            - *Modulation*: Analog I-Q mixer, External optical intensity modulation;
        - *OLT*: RX for 4 unsynchronized QPSK-OFDMA signal (one for each ONU)
            - *Demodulation*: 25GHz-IL for OSSB, Polarization diversity Coherent receiver,
            - *Baseband signal*: DSP: multi-band I-Q mixer, multi-band OFDM RX-DSP
- Two main solutions proposed: spectrally separated carriers for the DS and US (through the Band-Splitter, BS) or use of the same wavelength bi-directionally for DS and US, (through re-modulation techniques at the ONU on the single sideband (SSB) modulated carrier generated at the OLT [8]);

- Use of the coherent detection only at the OLT RX [6], while the direct detection can be sufficient for the ONU RX [13];

4.2 The EU project ACCORDANCE

The EU FP7 project ACCORDANCE [15]-[20] proposed a more general approach for the architectural design of an OFDM-based optical access networks. This project identified a PON architecture which can support very heterogeneous access technologies, starting from today copper-based ADSL (Asymmetric Digital Subscriber Loop) to IEEE-100G future standards. The authors defined a network level architecture to provide a segment-based topological organization using a two-node splitting hierarchy, to obtain a convergence between access and metro networks. Besides, a cluster-based division of the WDM spectrum allows a further segmentation of the network capacity to support different services. Furthermore, by using a time division multiplexing within each OFDM frame, the authors proposes a dynamic allocation of the segment data capacity among different ONUs.

In the ACCORDANCE proposal, the optical spectrum division in clusters is used to allow the coexistence of heterogeneous access technologies on the same optical infrastructure without performance budget interferences. The spectral clusters of the different services are generated in different OLTs (at different wavelength) and they are routed by add/drop nodes on specific branches of the PON. Within each cluster, the OFDMA approach is used to share the capacity among different ONUs, properly designing each OLT in order to support the requested access data rate.

The ACCORDANCE general targets are more advanced than the ones proposed in the ADVAntage-PON project and in the FABULOUS project presented in the following Section 5 and. Consequently, the resulting physical and network layer solutions are significantly more complex, and it is thus one of the most advanced proposals we found in the area of electrical-based (O)-FDMA PON.

4.3 The EU project O-TONES

The OTONES ("Optical Access Networking using OFDM Tones") project [21]-[22] is an EU-project (under the PIANO-PLUS framework) that proposed an OFDM/WDM PON architecture with strong emphasis on the realization of the required optoelectronic components on Silicon Photonics technology. This architecture is particularly focused on long distance PON and high splitting ratio, targeting ODN loss budgets as high as 40 dB (an extremely challenging value, considering that the current specification by ITU-T requires 35 dB for its highest ODN loss classes) and long reach. The main features of this proposed architecture are:

- ONU's net data rate fixed on average to 156Mb/s (1Gb/s peak) (in both the DS/US directions);
- channelized optical spectrum fitting the 12.5 GHz DWDM grid (ITU-T G.694.1) with spectral efficiency 1.6 b/s/Hz;
    - Within each 12.5 GHz slice a further subdivision is used to support the pilot tones (P) for the self-coherent demodulation, the uplink bandwidth (U) and downlink bandwidth (D) and a guard band (G). In the U and D bands (set to 3.125GHz each) up to 10 different ONUs can be allocated;
- 16QAM-OFDM with I-Q optical modulation and coherent detection in both OLT and ONU;
- reflective colorless ONU;
- polarization diversity Self-coherent detection for the ONU-RX for the DS link;
- polarization diversity I-Q optical modulation for the ONU-TX for the US link;

- mixed use of Array Waveguides (λ-splitting) and Power Splitters.

The OTONES architecture is in some parts similar to that proposed in ACCORDANCE, providing two level of optical splitting/combining and a very high aggregated capacity.

4.4 Framed OFDMA-PON

As last example of a very advanced OFDMA-PON proposal, we mention the extensive research work carried out by NEC Lab America in a series of successive papers [23]-[32], where a framed OFDMA approach has been proposed to realize flexible optical access network, able to dynamically assign the data capacity to many ONUs. To achieve that, the OFDMA frame was designed to support also a time multiplexing of the OFDM subcarriers, sharing them among different ONUs.

Several DS/US physical layer arrangements were studied by NEC, most of them making use of coherent receivers at both ONU and OLT. Through the use of a WDM and OFDM multiplexing [26]-[30], a network set-up was demonstrated to support up to 800 ONUs over a reach of 90km of SMF, using a mix of wavelength multiplexing and optical splitting of at least 1:32 and a peak data rate in excess of 10Gb/s for each ONUs. In these PON-Terabit architectures, the data rates per ONU are almost one order of magnitude higher than in all previously presented projects, so this solution has a very long-term perspective in the area future Tbit/s PONs.

We believe that these two last proposals are very advanced in the area of PON, and actually would require optoelectronic components that, for the moments, seems really at the boundary of today typical low-cost requirements in PON.

5. An example: the EU project FABULOUS

The author of this paper is involved in a large EU project titled “FABULOUS” [33], fully focused on an electrical FDMA-PON architecture that is trying to overcome some of the ITU-T NGPON2 limitations along the following main trends:

- increasing the bit rate up to 32 Gbps per wavelength, symmetrically in both directions, using M-QAM modulation and DSP at both OLT and ONU;
- sharing of the electrically available bandwidth (approx. 10 GHz) using a pure electrical FDMA multiplexing (and not OFDMA, like in most of the previously described projects), inserting spectral guard-bands between the spectral slices assigned to each ONU.
    - This approach allows for an easy electrical sub-band multiplexing and demultiplexing at the ONU side, that can thus operate its DSP only on relatively small electrical bands after electrical down-conversion [37]. It should be noted that sub-band processing is also possible in an OFDMA approach but, due to the lack of guard-bands, the DSP requirements are more stringent that in FDMA.
- using a reflective and colorless approach for ONU upstream transmission, thus solving the ITU-T NGPON2 problems of wavelength generation at the ONU side. No lasers are required at the ONU side, and tunability is achieved by optical filters that should be automatically tuned on already active wavelengths, so that a simple tuning algorithm that maximizes the filter output power is needed.

We presented our most recent experimental results in [34] for the upstream transmission (which is the real key focus of the FABULOUS project) and in [35] for the downstream, while a very detailed analysis of the architecture capacity is given in [37].

We show in Fig. 1 the general FDMA-PON architecture proposed by the EU FABULOUS project for the Optical Line Terminal (OLT) at the central office side, while in Fig. 2 we show the details of the proposed Optical Network Unit (ONU). In its most complete version, the architecture envisions two hierarchical multiplexing levels: wavelength division multiplexing (WDM) at the optical level and FDM/FDMA (FDM for the downstream, FDMA for the upstream) at the electrical level through subcarrier modulation over each wavelength. The OLT generates both the modulated DS wavelengths and the un-modulated US wavelengths. The last ones are then modulated in reflection by each ONUs for upstream transmission. Each wavelength pair (DS and US) is destined to multiple ONUs, and each ONU uses an electrical spectral slice around a proper electrical subcarrier on the selected wavelength. In order to achieve a good electrical spectral efficiency, we use M-QAM over each electrical sub-carrier, which is more spectrally efficient than the conventional OOK employed in all ITU-T PON standard so far ([1], [3]) thus allowing a greater bit-rate per wavelength over the same electrical available bandwidth.

Compared to the more traditional TDMA-PON approach and to several previous (O)FDMA proposals, the electrical FDM approach proposed in FABULOUS provides several advantages, and in particular:

- electronic simplification at the ONU side, since FDMA allows each ONU to handle only its dedicated electrical spectrum slice, and then to run at the single-user baud rate, providing costs and power consumption savings;
- high allocation flexibility, since (O)FDMA networks can adapt the bit rate to the channel characteristics and to the user requirements, varying the spectrum portion or the modulation format that every sub-carrier employs;
- the specific ONU structure that we propose allows an implementation on silicon photonic platforms, one of the key goal of the project [36].

Fig. 2 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, whose experimental demonstration is the main focus of the EU project, implements the following features:

- reflective modulation over a generic electrical subcarrier frequency;
- 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 that, with this setup, the

penalty due to the spurious reflections (one of the key drawbacks of reflective PON) is also greatly reduced.

- the R-MZM is completely polarization independent towards the ODN side, but internally it 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 straightforward on a silicon photonics platform that is intrinsically single-polarization. Even though it is outside the scope of this paper, we would like to mention that other partners of the FABULOUS project are working on the R-MZM full integration on a Silicon Photonics platform [36].

The US detection at the OLT is based on a coherent optical receiver to detect the full electrical spectrum generated by all ONUs sharing the same wavelength. In our setup, the OLT digital signal processor (DSP) coherently receives all M-QAM signals over the whole spectrum, then receives each subcarrier separately after a bank of DSP bandpass filters and M-QAM demodulators. Thanks to the aforementioned polarization features, all ONU signals sharing the same wavelength are received on a single polarization that is orthogonal to the transmitted CW seed, so a single-polarization self-coherent receiver can be used, greatly simplifying the receiver structure. Moreover, we can implement a self-coherent approach, so that there is no optical frequency offset to be recovered.

As it is clear from the previous presentation, the FABULOUS project targets high-end access networks based on very high capacity PON, envisioning symmetrical links at about 1 Gbps per user, with optical splitter distribution to 32 users, aiming at maximizing the Optical Distribution Network (ODN) loss. In most of our experiments, we obtained this target (32 users per wavelength at approx. 1 Gbps per user symmetrically in US and DS) using the full available electrical spectrum (~ 10 GHz) and 16-QAM modulation. In one of the most complete experiments for the upstream transmission, we had five fully equipped ONUs working on the same wavelength and on worst-case FDMA spectral allocation, and we obtained the results shown in Fig. 4, demonstrating that the transmission works at BER below FEC threshold up to 31 dB of ODN loss (compliant with ITU-T ODN class N2 [3]). Similar results were obtained for the downstream transmission, as shown in Fig. 5. For the interested readers, more details on the experimental results can be found in [34]-[37].

We are also currently performing a techno-economics analysis of the proposed architecture, to study its actual feasibility with the cost and power consumption typical of PON hardware.

For what concerns ONU power consumption, the FABULOUS project partners have analyzes in details all the sub-components required to implement the structure shown in Fig. 2 in a silicon photonic implementation. Table 1 reports the results of this study.

TABLE I
PERFORMANCES FOR THE DIFFERENT APPLICATION SCENARIOS

Device	Power Consumption (W)
Electronic chipset for modulation (Rx and Tx)	1,1
Optoelectronic receiver	1,0
R-MZM driver	1,4
Silicon photonics R-MZM	0,5
Semiconductor Optical Amplifier (SOA)	0,5
Tuneable optical filters	0,5
Thermo electric control (TEC)	3

TOTAL	**8 W**

The maximum power consumption expected from the ONU is about 8 Watts. This is a first order estimate that anyway shows how the FABULOUS ONU power consumption could be similar or even less to the one estimated for TWDM-PON ONU, even though the obtained capacity per wavelength is at least 3 times higher. It may also be interesting to compare these values with those of today ADSL modems, for which the total power consumption is typically in the order of 10 to 18 W, of which approximately 7 - 8 W for the DSL port alone (data taken from study available at [38]). These ADSL power consumption values are expected to decrease, since for instance the latest European Code of Conduct on Energy Consumption of Broadband Equipment (Version 5.0) specified 2.8 W in the On state for the DSL port (WAN interface).

For what concerns the complexity of the DSP processing required in FABULOUS, the following comments can be made:

- at the ONU side, thanks to the option of electrical sub-band processing, the DSP can work at relatively low speed. To obtains the results show in Figg. 3 and 4, the ONU is assigned a spectral slice of about 250 MHz, so that the DSP ADC and DAC converters can work below 1 Gsamples/s. This is a DSP capacity that is already common in some specific consumer electronic devices for completely different areas, such as for Wireless USB (Universal Serial Bus) applications using multi-band OFDM [39] whose chipsets are produced today at very low cost target prices (in the 1-2 USD range). These Wireless USB chipsets implement the same type of DSP complexity that would also be required in a FABULOUS ONU;
- for what concerns the central office side, the OLT should generates and demodulate the full electrical spectrum of about 8-9 GHz. We envision two options:
    - Very high speed ADC and DAC running at about 20 Gsamples/s over the full spectrum and subsequent high speed DSP, which would then have requirements similar to today ASICs for coherent detection in long-haul transmission applications.
    - As an alternative, proper use of sub-band processing can also be applied at the OLT. For instance, using the aforementioned low-cost Wireless USB chipset that can today handle 500 MHz each, the ~10 GHz spectrum can be electrically split and sent to 20/21 parallel chipsets.

6. Conclusions

We reviewed in this paper the Pros and Cons of (O)-FDMA PON and compared them to the current status of the art in PON standardization, giving a detailed list of proposals in this area, and demonstrating how (O)FDMA can be a promising and reasonable approach for PON generations beyond NG-PON2. We believe that (O)-FDMA would require a great change of paradigm in PON standardization, which up to know has considered only TDMA in all its main versions (GPON, XGPON and now TWDM-PON) also to satisfy the stringent backward compatibility requirements coming from PON telecom operators. Clearly, a potential future (O)-FDMA standardization in PON could be backward compatible only in terms of wavelength plan, but would require a completely new PHY specification.

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FIGURES

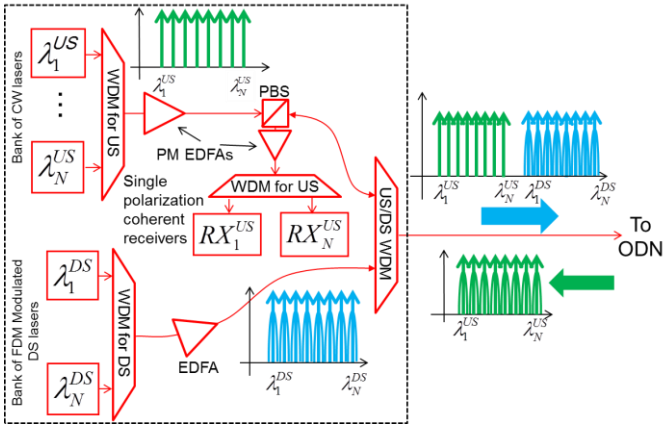

Fig. 1 : Architecture of the proposed FDMA-PON OLT for the general case including both WDM and FDM (EDFA: Erbium-Doped Fiber Amplifier; PM: Polarization Maintaining; PBS: Polarizing Beam Splitter)

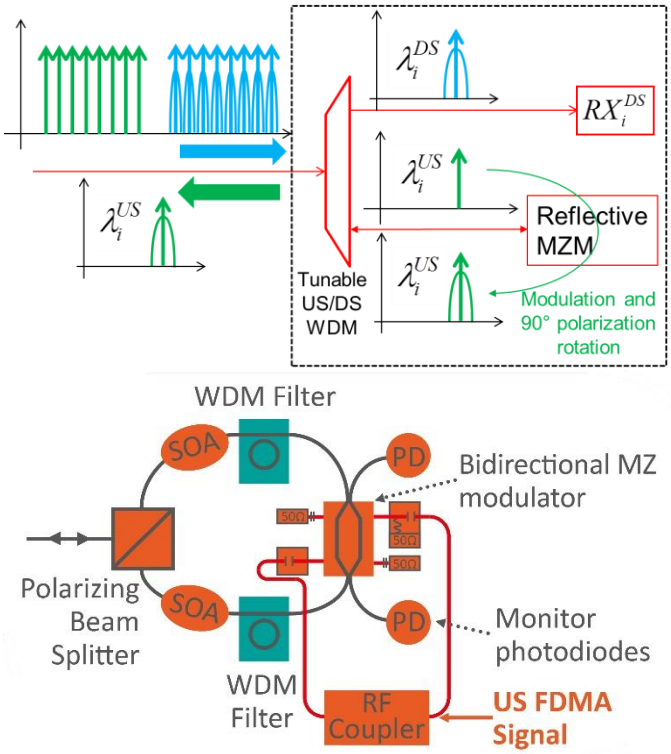

Fig. 2: Architecture of the proposed FDMA-PON ONU for the general case including both WDM and FDM (upper part) and details on the Reflective MZM (lower part)

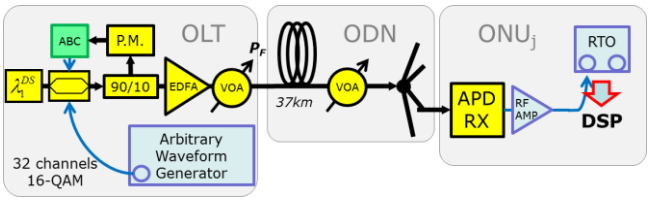

Fig. 3: Experimental DS setup (ABC: Automatic Bias Controller, PM: Power Meter, EDFA: Erbium-Doped Fiber Amplifier, VOA: Variable Optical Attenuator, APD: Avalanche Photo-Diode, RTO: Real Time Oscilloscope, DSP: Digital Signal Processing).

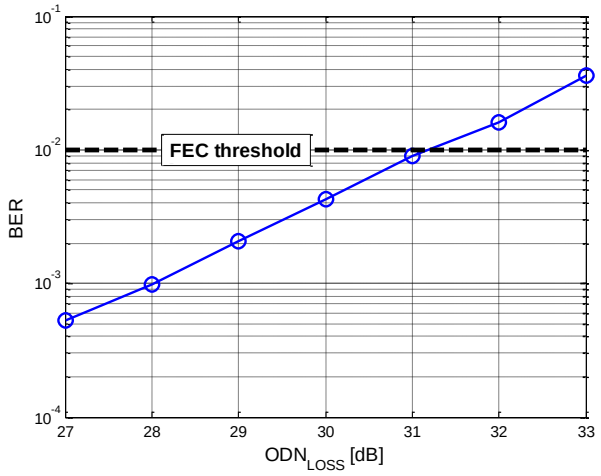

Fig. 4: Performance of the upstream transmission in terms of BER vs ODN loss with 5 active ONUs (32 emulated channels using optical noise loading)

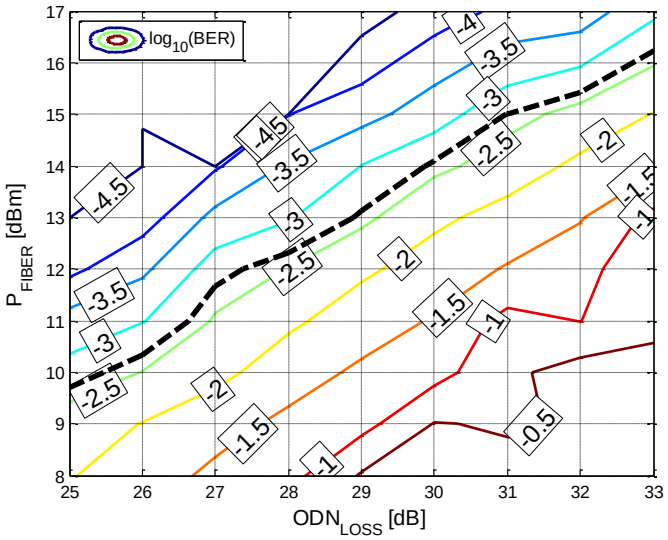

Fig. 5: BER contour plots on the Downstream transmission vs. ODN loss and launched power; the dashed line represents the FEC threshold.