Downstream transmission dimensioning in FDMA-PON architectures: Results from the EU project FABULOUS

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Downstream transmission dimensioning in FDMA-PON architectures:
results from the EU project “FABULOUS”

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***Abstract*— In this paper we present the FDMA-PON (Frequency Division Multiple Access – Passive Optical Network) architecture proposed by the FP7 EU STREP project titled “FABULOUS”, focusing on downstream transmission. We experimentally demonstrate that the proposed architecture allows to reach 16 Gbps aggregated capacity per downstream wavelength over an optical distribution network with 30dB loss, still using direct-detection receivers and requiring relatively low speed digital signal processing at the ONU side.**

Keywords*— *optical transmission, passive optical networks (PON), multiplexing techniques.

I. INTRODUCTION

The EU STREP project “FABULOUS” [1] is experimentally investigating Passive Optical Networks (PON) based on electrical Frequency Division Multiple Access (FDMA) on the architecture described in details in [2] and [3], which is trying to overcome some of the drawbacks of the more traditional TDMA-PON approach deployed nowadays. In particular, TDMA-PON does not scale well above 10 Gbps per wavelength in term of cost/complexity and power efficiency, mostly due to the fact that each ONU should work on the aggregated bit rate. Our proposed FDMA approach allows instead each ONU to handle its dedicated bit rate, and to have a better power allocation and a higher spectral efficiency.

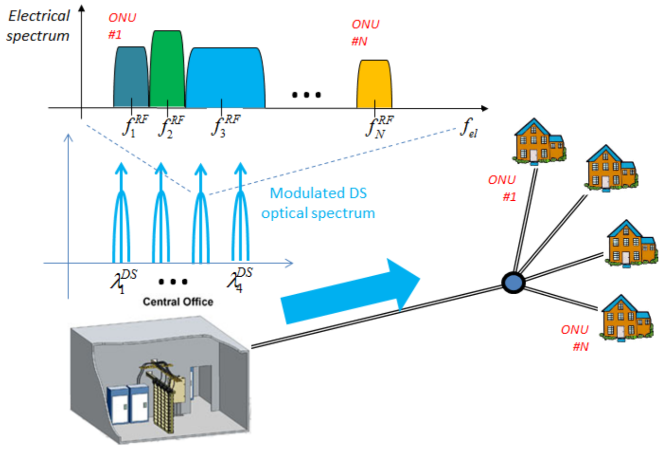

Fig. 1. The downstream architecture

This paper is focused on the downstream transmission, which is based on two levels of multiplexing as shown in Fig. 1, the first one based on Wavelength Division Multiplexing (WDM) and the second one on Frequency Division Multiplexing (FDM), implemented in the electrical domain by means of electrical subcarriers. At the ONU receiver, each ONU will have to detect only its band around its dedicated subcarrier. A detailed description of the transmission in the other direction (i.e. upstream) can be found in [2] and [3].

The downstream multiplexed signals are sent through the Optical Distribution Network (ODN), then are optically filtered and received by the Optical Network Unit (ONU) using direct detection. In our experimental demonstration, we target a 1 Gbps data rate per ONU in the downstream, 16 ONUs per wavelength, achieving a downstream capacity of 16 Gbps per wavelength, which is higher than the 10 Gbps used in the most recent ITU-T PON standards (XG-PON and TWDM-PON). Using a *16-QAM* modulation format over each electrical subcarrier, the resulting baud rate is equal to 250 Mbaud per electrical subcarrier, so that the digital signal processing (DSP) required after the electrical RF down-conversion at the ONU receiver can be basically at 500 Msample/s (i.e, at twice the baud rate). This is the key points for our proposed architecture: despite an aggregated downstream capacity of 16 Gbps, the ONU DSP can run at only 500 Msample/s.

The paper is organized as follows: we start in Sect. II with a description of the downstream setup and physical layer transmission characteristics, then we present the experimental results in Sect. III, and finally we draw our conclusions in Sect. IV.

II. DOWNSTREAM TRANSMISSION CHARACTERISTICS

The downstream transmission from the Optical Light Terminal (OLT) to the ONUs is schematically described in Fig. 3 and 4, where we have focused on a single wavelength. An FDMA electrical multiplexed signal consisting of N electrical subcarriers each carrying an M-QAM modulation is generated through digital signal processing (DSP) techniques at the central office and then directly applied to an external a Mach-Zehnder modulator (MZM). A schematical representation of the resulting electrical spectrum is given in Fig. 2 (Top).

After going through the ODN, the signal is received at the ONU using direct detection, and then it is electrically demultiplexed and processed. As shown in Fig. 4 and as explained in the Introduction Section, it is possible to use an I/Q demodulator after the photodiode to bring the ONU dedicated spectral slice down to baseband before the DSP processing, so that the DSP can run at a low sample rate of about 500 Msamples/s, which is the key aspect of our proposal.

Using this electrical FDMA approach, there are anyway some physical layer disadvantages, similar to those that usually pops up in radio-over-fiber systems, and mostly related to the fact that a high linearity is required in the TX and RX optoelectronic components. Moreover, the electrical signal to be sent to the MZM has a high peak-to-average power ratio (PAPR), similarly to what happens in OFDM systems [5], since the resulting time-domain signal, shown in Fig. 2 (center) has actually a Gaussian-like probability density function (shown in Fig. 2, bottom) with very large tails. Due to these two effect, a proper balance should be obtained between these two opposite requirements:

- In order to preserve sufficient linearity on the FDMA signal when going through the MZM modulator, the signal should have a small peak-to-peak amplitude compared to the MZM half-wave voltage V_π
- Anyway, in order to be resilient to noise at the receiver (and also to quantization effects in the DAC and ADC converters), the root-mean-square amplitude should be as high as possible

As a consequence, an optimized clipping on the electrical signal at the transmitter has to be implemented, as described in the following paragraphs.

The modulator used in our architecture corresponds to a classical MZM biased at its 3dB point, to obtain the maximum electrical-to-electrical linearity in a direct detection system. By setting a maximum level threshold $A_{clipping}$ on the signal applied to the MZM (Fig. 2) and introducing the signal amplitude variance σ^2_{signal}, we have introduced a clipping level defined as:

$$C_{dB} = 10 \cdot \log_{10}\left(\frac{A^2_{clipping}}{\sigma^2_{signal}}\right) \tag{2}$$

This is also often referred as the output back-off, that is defined as the ratio between the maximum possible output power and the transmitted output power average [5]. The C_{dB} clipping parameter turned out to be an important issue in system optimization.

In order to assess system performance, the error vector magnitude (EVM) was evaluated, since it is easily estimated from the scattering diagrams [4], and it can be correlated to the bit error rate (BER). We remind that in order to guarantee BER=10^{-3}, the EVM must be smaller or equal to 10% for the 16-QAM modulation used in the downstream transmission.

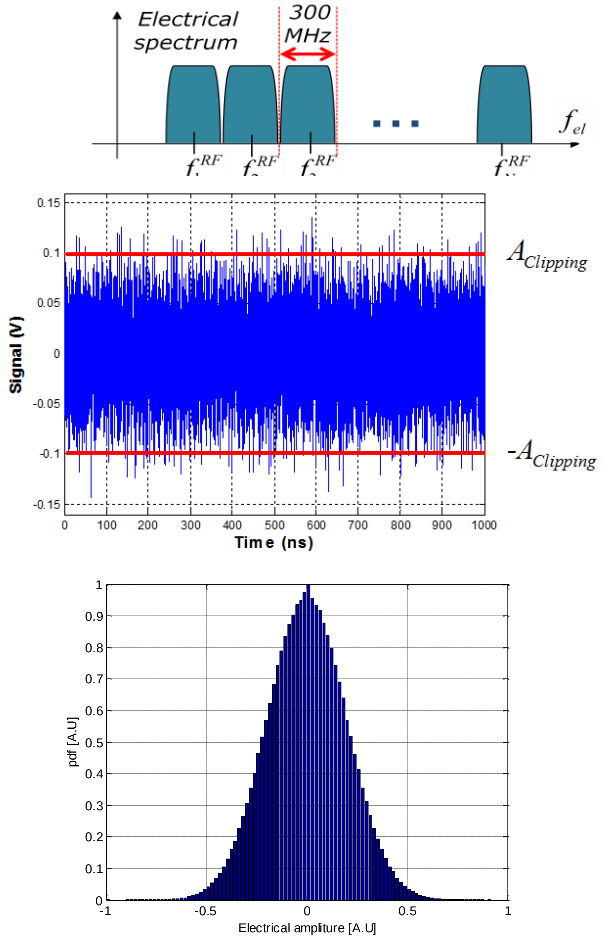

Fig. 2. Top: schematical representation of the transmitted electrical spectrum. Center: resulting signal in the time domain and clipping threshold. Bottom: probability density function of the resulting signal

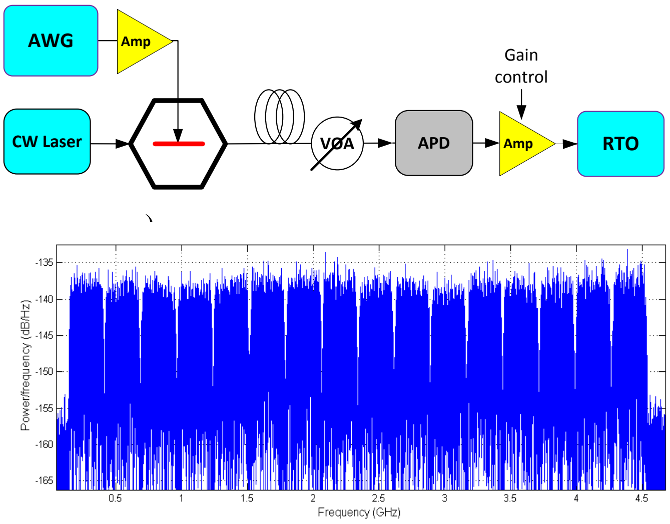

Fig. 3. Top: Experimental setup for the downstream transmission. (AWG: arbitrary waveform generator. APD: avalanche photodiode. RTO: real time oscilloscope). Bottom: spectrum of the electrical signal applied to the MZM input

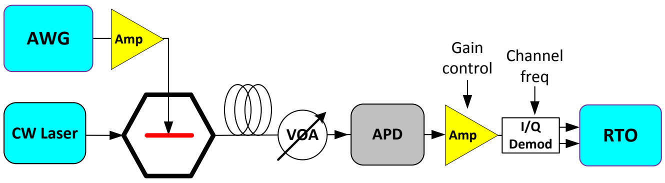

Fig. 4. Downstream Experimental setup with RF down-conversion.

III. EXPERIMENTAL SETUP AND MEASUREMENTS

In this section we present the experiments carried out using commercial optoelectronic components over an installed metropolitan fiber testbed, for two different system configurations.

A. Experimental Setup

The first experimental setup is shown in Fig. 3 (bottom), where 16 transmitted ONU signals are generated in MATLAB, each using a *16-QAM* modulation format and 1 Gbps data rate (250 Mbauds), shaped with a square-root-raised-cosine (SRRC) filter with a roll-off factor 0.1. The 16 signals are FDMA multiplexed without any spectral guard-band (apart from the roll-off, so that each channel occupies 275MHz), to obtain the electrical spectrum shown in Fig. 2 (center), which requires an overall electrical bandwidth of 4.5 GHz.

The signal is then equalized (in DSP) to cope with the actual spectral response of our DAC (a commercial arbitrary waveform generator, or AWG), then clipped according to the previously introduced parameters C_{dB}. The resulting DSP signal sequence is loaded in the AWG (used as a DAC), which generates the resulting FDMA signal at 12 Gsample/s sample rate using its full dynamic range (1 V peak-to-peak for the used AWG instrument), which is then electrically amplified to a given with a given $V_{in,\max}$ peak voltage before being applied to the MZM modulator electrical input.

The TX continuous wave (CW) laser was set to 16dBm in order to have 10dBm average optical power at the optical modulator output (our MZM had an optical insertion loss of approximately 3dB, so the overall optical loss including the modulation effect at the biasing point is about 6 dB). This signal is then sent to the optical distribution network (ODN), consisting of 37km of installed metropolitan fiber (Fastweb testbed in Turin, Italy) and a variable optical attenuator (VOA), used to emulate the optical splitter loss, and in particular to vary the total ODN loss.

The reception is done by using direct detection, through an avalanche photodiode (APD) with a responsivity of 0.7A/W, an electrical linear gain of 7 and an input reference noise density of 11 $pA/\sqrt{Hz}$. We remind that the most recent ITU standard on PON, such as XGPON and TWDM-PON are already envisioning APD receivers to boost sensitivity, so that it is expected that APD for PON devices will soon reach a price compatible with PON ONU constraint. The photo detected electrical signal is then passed through a variable gain amplifier in order to adapt it to the input quantization range of the ADC, which was a 50Gsample/s real time oscilloscope (RTO) in our experiments.

The acquired signal is then handled with DSP algorithms implemented in Matlab, in which the signal is first down-sampled, then filtered through blind equalization and passed through a carrier phase estimator. Afterwards, both the EVM and BER are computed to evaluate the system performance.

In a second experimental setup (Fig. 4), electrical down-conversion for a specific channel is inserted before the ADC and the same set of measurements are taken using anyway a much lower sampling rate for the RTO, emulating the use of a slower DAC at the ONU receiver side.

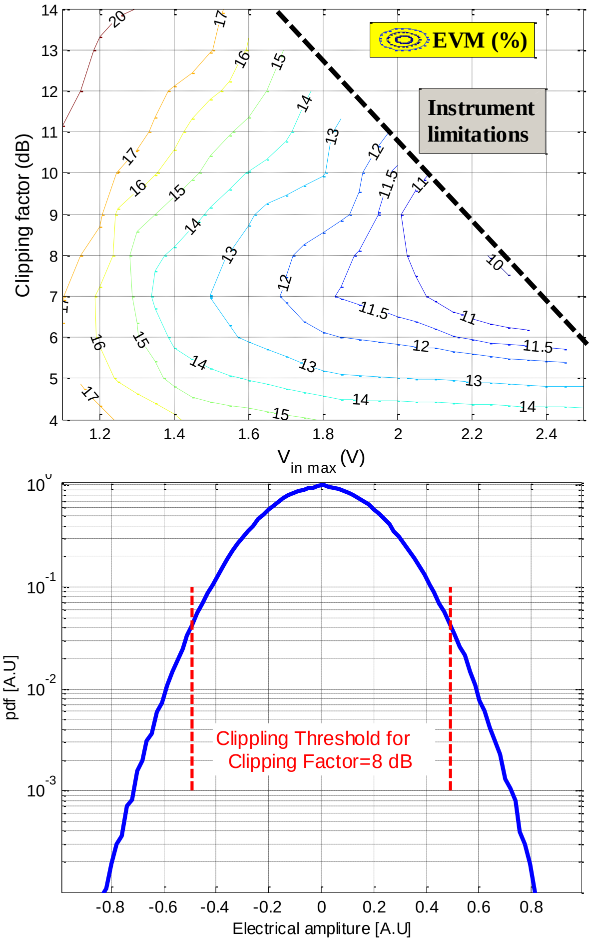

Fig. 5. Top: Performance of the system – EVM vs. Clipping factor and input peak level of the driving RF signal for an ODN loss equal to 30 dB. Bottom: signal probability density function (pdf) and amplitude clipping levels for a clipping factor equal to 8 dB

B. Experimental Results

Due to space and resources limitation, the experimental demonstration shown in this paper uses only on a single wavelength downstream transmission, since we wanted to focus on electrical FDMA transmission and reception.

The first set of measurements consisted on the optimization of the clipping factor and the MZM input peak voltage. For this experiment, we set the ODN loss to 30dB, while we vary the clipping factor and MZM electrical input signal amplitude $V_{in,\max}$ (zero to peak). The results are shown in Fig. 5 (top) in terms of Error Vector Magniture (EVM) contour plots vs. the two free parameters (clipping and $V_{in,\max}$). Unfortunately a portion of the bidimensional parameters space in Fig. 5 (top) could not be achieved due to instruments limitations. This graph clearly shows the relevance of these two parameters, and allowed us to determine that the best configuration for our setup is to have a clipping $C_{dB}= 8dB$ and a $V_{in,\max}$ =2.3 V on the electrical transmitted signal. Fig. 5 (bottom) shows the resulting clipping level in the optimal point on the probability density function of the signal (the same as the one shown in in Fig. 2, Bottom, but represented here on a log-scale to better shows the tails of the Gaussian-like distribution).

After setting the optimal parameters, we proceed with the measurements of EVM and BER versus ODN loss, showing the results in Fig. 6 and 7.

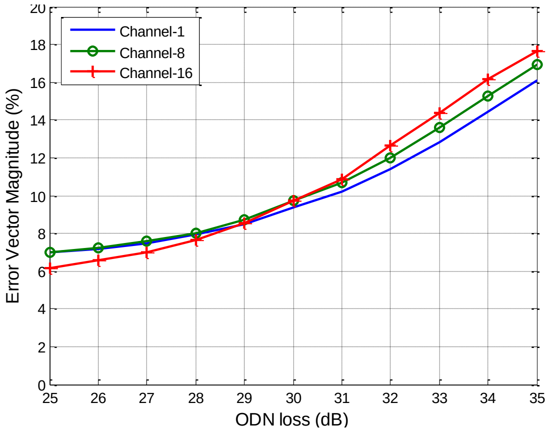

Fig. 6. Performance of the system – EVM vs. ODN loss.

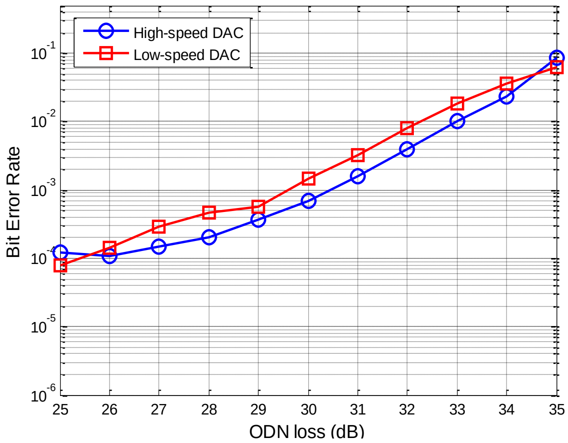

Fig. 7. Performance of the 8th channel – BER vs. ODN loss.

The EVM performance parameter was computed for all the 16 channels, but only three are presented in Fig. 6, since we could observe that all channels have similar performance. Our experimental results shows that at least 30dB of ODN loss is guaranteed in our system at BER=10^{-3}, supporting the 29dB requirements of the “Nominal-1” (N1) optical path loss class set recently by ITU-T for XG-PON and TWDM-PON.

The same set of measurements was taken again by introducing an electrical down-conversion after the photodiode, tuning the electrical local oscillator on the eighth channel at 2.2 GHz central frequency. The resulting baseband signal is then acquired by low-speed ADC sampling. In Fig. 7, we show the resulting performance in terms of BER vs. ODN loss and its comparison with the case without RF down-conversion. By including the I/Q demodulator and a low-speed DAC, we get a penalty of less than 1dB.

IV. CONCLUSIONS

We experimentally demonstrated that 16 Gbps data rate per wavelength for the downstream transmission in a band of 4.5GHz could be achieved over a 30dB ODN loss, which is higher than the current ITU-T standard requirements of 29 dB for PON class N1. This is in itself an interesting results, because it outperforms the XGPON standard (10 Gbps using binary NRZ OOK modulation) in terms of both bit rates and reduced required electrical bandwidth. We have moreover demonstrated, that by adding the RF down-conversion at the ONU side, we can use low-speed DAC and DSP at the ONU receiver, at the expenses of an ODN penalty smaller than 1 dB. To achieve all these results, we showed that optimized clipping and level setting at the transmitter is fundamental.

As further work inside the FABULOUS project, we are working on increasing the used electrical bandwidth up to 9GHz so that, at least in terms of spectral allocation, we could double the number of FDMA channels, therefore envisioning a potential capacity around 32 Gbps per wavelength. This would be a really interesting practical result: today XGPON and TWDM-PON ITU-T standards require the same type of optoelectronic bandwidth for the modulator and photodiodes, but achieve only 10 Gbps (due to the intrinsic constraints of the used binary NRZ OOK modulation), while our proposed FDMA approach would reach about 3 times greater capacity per wavelength, obviously at the expenses of a significantly greater DSP complexity at the OLT side, while requiring a sampling speed of only 2 times the single electrical channel baud rate at the ONU side.

ACKNOWLEDGMENT

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