Single-Wavelength Downstream FDMA-PON at 32 Gbps and 34 dB ODN Loss

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***Abstract*—We propose a PON solution to reach 32 Gbps over a traditional high loss downstream splitter-based optical distribution network (ODN) without using multiple wavelengths at the OLT side nor massive digital signal processing at the ONU side. The achieved 32 Gbps capacity is not too far from the 40 Gbps given by a 4-wavelengths TWDM-PON but completely avoids the handling of multiple wavelengths thanks to a higher electrical spectral efficiency and some system optimization.**

***Index Terms*— Passive Optical Network, FDMA, NG-PON2.**

I. Introduction

THE next generation standard for PONs is currently under ratification by ITU-T under Recommendations G.989.x [1], usually indicated as NG-PON2. In order to reach its initial target of delivering 40 Gbps downstream (DS), G.989 will be based on four wavelengths DS transmission (called TWDM-PON or Time and Wavelength Division Multiplexed PON), where each wavelength will carry 10 Gbps with the same characteristics as the previous XG-PON standard [2]. TWDM-PON will introduce a "revolution" in PONs, since it will require, for the first time, the handling of several dense WDM (DWDM) lasers (the grid will likely be the usual 100 GHz ITU-T grid). These lasers (and the related optical filters) must have a few GHz accuracy, while all lasers used in PONs so far had a very large spectral tolerance masks of the order of several nanometers. The future TWDM-PON lasers will thus have basically the same technical requirements as long-haul 100 GHz grid lasers in terms of wavelength accuracy, but their cost (in terms of both CAPEX and OPEX) should be much smaller to be successfully used in the ultra-low cost PON market. As clearly pointed out in [3], this is for the moment a tremendous engineering task, for which the technological solution is not yet available, since the CAPEX should be reduced by at least one order of magnitude compared to DWDM long-haul lasers [3]. The ITU-T rationale towards using WDM in PONs was strictly connected to the key decision of sticking with the traditional binary On-Off Keying (OOK) modulation with direct-detection, for which it is today well known that the 10 Gbps is a sort of "natural barrier" if the system has to work up to 20-40 km of uncompensated SMF (another must in ITU-T PONs), due to the joint effects of chromatic dispersion and electrical bandwidth limitations of low cost optoelectronic transceivers. In these systems, the available electrical-to-electrical 6 dB bandwidth is hardly above 7-8 GHz, so that sticking with OOK it is really difficult to go above 10 Gbps, also considering the high Optical Distribution Network (ODN) loss requirements, such as the 31 dB or more specified for the highest ITU-T PON classes [2].

In this work we had achieved a solution that largely beat this "10 Gbps per wavelength" barrier using a frequency division multiple access (FDMA) approach considered inside the EU project FABULOUS [4] and the Italian project ROAD-NGN, whose architecture is described in detail in [5],[6].

In particular, this paper shows the transmission of 32 Gbps over a PON DS link with the following characteristics:

- single wavelength transmission: this is the key point of the proposal in this paper. Our benchmark is the TWDM-PON capacity: we show a capacity that are not too far (32 Gbps vs. 40 Gbps) but using only one wavelength in DS;
- available electrical-to-electrical 6 dB bandwidth of less than 7 GHz (using standard optoelectronic components that are currently used for 10 Gbps OOK);
- ITU-T ODN compliant up to very high ODN loss (34dB);
- multiplexing based on FDMA, where each electrical subcarrier is 16-QAM modulated and dedicated to an Optical Network Unit (ONU);
- digital signal processing (DSP) is required for both the OLT and the ONU, to handle the proposed transmission format but, as clearly shown in [6] and in [7], the ONU requires to detect only a sub-band of the received signal, so that the required ONU DSP (and the related analog-to-digital ADC) can run below 1 Gsample/s. Interestingly, the ONU DSP is identical to the one required in the area of the "Wireless USB", whose chipsets, using the UWB technology, are extremely cheap and thus completely compliant with the ONU costs [7]. For what concerns the OLT side, a detailed comparisons of FDMA and TWDM in terms of the techno-economics pros and cons is very complex, and is currently under study.

The novelty of our papers can be summarized as follows:

- compared to previous works inside the same project, such as [6], we found ways to greatly improve the maximum

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achievable ODN loss (from less than 28 dB in [6] up to 34 dB in this paper);

- compared to the many other existing works on FDMA-PON, we believe our downstream architecture has the pros of being compliant with the general ITU-T recent requirements (such as having similar capacity, being splitter-based, high ODN loss compatible) and a very reasonable complexity and thus potential cost.

The paper is organized as follows: in Sect. II we describe the system setup and present the main experimental results. Then in Sect. III we describe in details all the system optimization that were implemented to reach these results.

II. Experimental Setup and Results

In this Section we present the off-line processing experiments carried out using commercial optoelectronic components over an installed metropolitan fiber testbed.

A. Experimental Setup

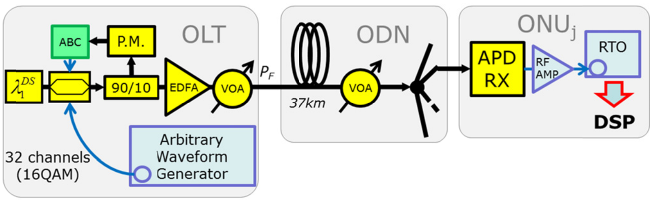

Fig. 1 Experimental setup (ABC: Automatic Bias Controller, PM: Power Meter, EDFA: Erbium-Doped Fiber Amplifier, VOA: Variable Optical Attenuator, APD: Avalanche Photo-Diode, RTO: Real Time Oscilloscope).

The experimental setup is shown in Fig. 1: our target was to deliver 1 Gbps per user to 32 different users, for a total DS capacity of 32 Gbps. To this end, a 32 electrical subcarrier comb was generated in a DSP. Each electrical subcarrier was 16-QAM modulated with a 1 Gbps net data rate, over which we considered a 10% overhead for signaling and FEC. Thus all the data sequences were generated with a gross bit rate of 1.1 Gbps and then they were shaped with a square-root-raised-cosine (SRRC) filter with a 10% roll-off factor, giving a total occupied electrical bandwdth of 302.5 MHz per subcarrier. The 32 subcarriers were multiplexed with a frequency spacing of 302.5 MHz, accounting for the spectral roll-off of subcarriers without any extra guard-band. The FDMA electrical signal resulted to have a bandwidth of 9.8 GHz (including an unused band around DC of 120 MHz, where most spurious back reflections are falling). Each subcarrier was then power equalized (in DSP), for reasons explained in Sect. III. The resulting FDMA signal amplitude was then clipped applying the optimum clipping factor (C_{dB}) described in [8]. As shown in Fig. 1, the resulting signal was loaded in the Tektronix 70001A Arbitrary Waveform Generator (AWG), characterized by a sampling rate of 50 GSample/s and 10-bit amplitude resolution. The generated electrical signal was then amplified before to be fed into the Mach-Zehnder modulator (MZM) RF input. The MZM was biased at the 3 dB point of its electro-optic characteristic, to obtain the maximum linearity of the modulator transfer function. The $V_{in,max}$ and C_{dB} values were jointly optimized, according to the procedure described in [8]. As a result, the maximum amplitude used for the electrical signal sent to the MZM input was $V_{in,max}$=3.9 V (i.e. approximately the full amplitude of the MZM, V_{π}=3.7 V). The TX continuous wave (CW) laser was operated both with and without dithering, for reasons that will be explained in Sect. III. The MZM optical output was amplified from an EDFA to +17 dBm, which was followed by a variable optical attenuator (VOA) to adjust the fiber launched power, P_{FIBER}, in the range from +8 dBm to +17 dBm. The ODN was realized with 37 km of installed and buried fiber (Fastweb metropolitan testbed in Turin, Italy), followed by a VOA, used to change the ODN loss between 25 dB and 36 dB, and a 1x16 optical splitter. The direct detection RX was realized with an avalanche photodiode (APD) having a responsivity of 0.7 A/W, an avalanche gain of 7, a 3 dB O/E bandwidth of 7 GHz and an input referred noise of 11 pA/√Hz. Since the resulting end-to-end system bandwidth was significantly dropping over the 9.8 GHz bandwidth occupied by the FDMA signal (see Fig. 7), a frequency pre-emphasis on the FDMA comb was introduced, as described in Sec. III. The photo-detected electrical signal was then passed through a variable gain amplifier to fitits amplitude into the ADC quantization range. In our experiment, we have used a high speed real time oscilloscope (RTO) as ADC, but it was already shown in the paper [7] that a low-rate processing after RF down conversion is possible, even using commercially available low cost chipsets. In our case, the acquired signal was off-line processed with Matlab® DSP algorithms . Thereafter, the signal was first down-converted to baseband and down-sampled to 2 samples per symbol, then was filtered through a blind equalization stage and finally passed through the carrier phase estimator. Finally, both Error Vector Magnitude (EVM) and Bit Error Rate (BER) were computed to evaluate the system performance.

B. Experimental Results

After having set the optimal TX parameters C_{dB}, $V_{in,max}$ and the frequency pre-emphasis, the EVM and BER measurements were performed as a function of the ODN loss and launched power. We started by evaluating the system performance without dithering the CW laser. The results in terms of the EVM contour plots vs. ODN loss and P_{FIBER} are reported in Fig. 2.

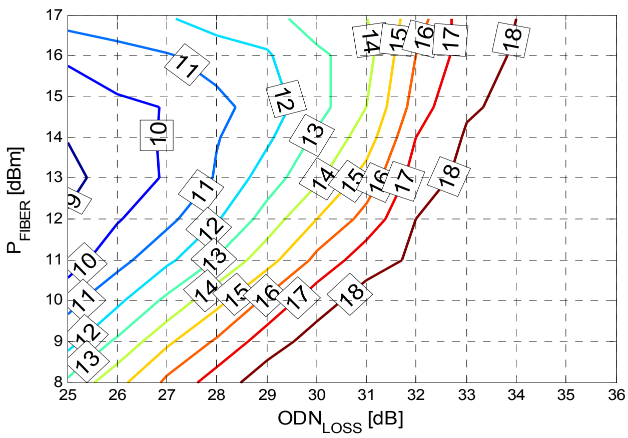

Fig. 2 EVM contour plots vs. P_{FIBER} and ODN loss (no dithering on CW laser).

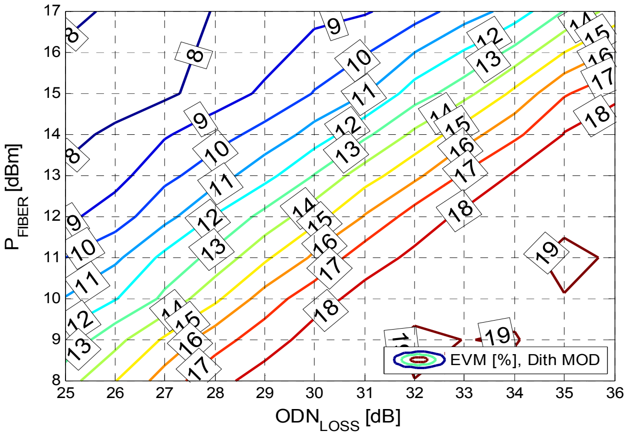

Fig. 3 EVM contour plots vs. P_{FIBER} and ODN loss (dithering on CW laser).

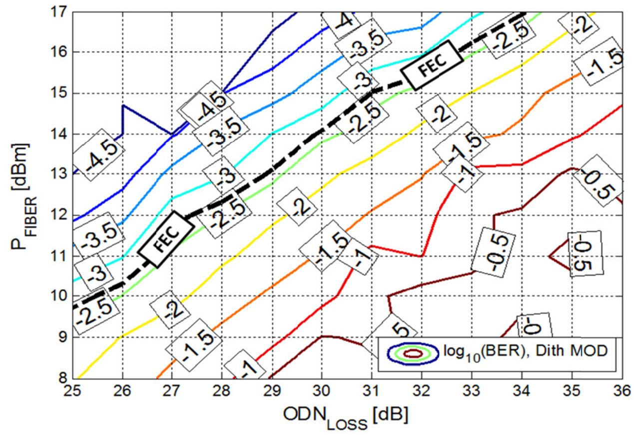

Fig. 4 BER contour plots vs. P_{FIBER} and ODN loss (dithering on CW laser).

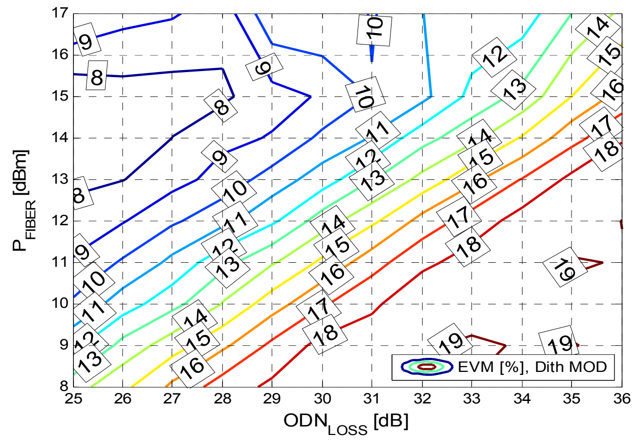

Fig. 5 EVM contour plots vs. P_{FIBER} and ODN loss (dithering on CW laser) using SMF.

In this first situation, we observed alinear dependence of the EVM from the ODN_{LOSS} and P_{FIBER} up to a launched power of about +12 dBm. A further increase of the launched power did not correspond to a system performance improvement, since the nonlinear effects started to be relevant on the transmitted signal, mainly due to the stimulated Brillouin scattering (SBS) effect. Focusing on a target EVM=11% (i.e. a BER≈$2\cdot10^{-3}$ for a 16-QAM), the ODN loss resulted to be limited up to 28 dB. In order to mitigate the effect of such nonlinear phenomena, the dithering option of the CW laser was then activated, achieving the results shown in Fig. 3, where the EVM linear dependence on the ODN loss and P_{FIBER} has allowed to reach a launched power of +17 dBm. The BER was also evaluated in this condition (Fig. 4), verifying that the ODN loss maximum value effectively corresponded to a BER lower than the FEC threshold of $2.17\cdot10^{-3}$ (as required by G.795.1–I.4).

Fig. 4 is the main result of this paper, showing that an ODN loss of at least 34 dB is reachable with standard FEC, thus supporting, with some margin, the 33 dB requirement of the "Extended-1" (E1) optical path loss class, recently set by ITU-T for XG-PON and TWDM-PON, but extending to 32 Gbps the bit rate per wavelength. This figure is also the main novelty of our paper, allowing to envision future multi-Gbps per wavelength PON that are fully compliant with standard splitter-based PON at some of the highest ITU-T ODN losses, without any active device along the ODN. To double check these results in terms of resilience to SBS effect, the same system was also tested using a longer span of standard SMF (50 km), obtaining similar performance, as shown in Fig. 5.

III. Theoretical Analysis on Power Budget and Main Transmission Impairments

The transmission experiments results shown in the previous paragraph has required a careful optimization of some system parameters that will be discussed in this Section. In particular:

- The SBS suppression thanks to laser dithering;
- The frequency-domain equalization using pre-emphasis acting on the modulation index of each subcarrier;
- The TX clipping and amplitude optimization.

The delivery of 32 Gb/s over a single wavelength requires high launch powers if a high ODN loss is a target. In our experiments, it was fundamental to increase the SBS threshold by introducing a dithering technique [9] on the TX laser and optimizing the dithering parameters. After a careful analysis, we found that a dithering signal generating a Δf_{opt}=500 MHz optical frequency deviation was capable of highly suppress SBS, that remained almost negligible even up to +17 dBm per wavelength. For Δf_{opt} significantly lower than 500 MHz, the SBS was not sufficiently suppressed, while for higher Δf_{opt} the FM-AM conversion due to chromatic dispersion started to impact the quality of the FDM subcarriers.

A second fundamental optimization was related to frequency equalization: the overall electrical-to-electrical transfer function has a significant drop towards the higher frequency, mostly due to the RX photodiode and the DAC/ADC pairs. Even the optical fiber span can contribute to the modification of the overall frequency transfer function, due to the combined nonlinear interaction between dispersion and Kerr effects [10], particularly at the highest power level. An optimization process was thus used to equalize the performances of subcarriers. The subcarrier BER is governed to a first degree by the product of the subcarrier modulation index (i.e., the relative subcarrier signal amplitude) and the total launch power, P_{FIBER}. Thus, while P_{FIBER} determines the average BER of the system, the modulation index can individually be used to equalize the BER among the subcarriers, with the introduction of a subcarrier pre-emphasis in the DSP at the TX. In our experiments, this optimization was achieved in two steps. In a first step, we equalize the performances of each subcarrier finding the appropriate modulation index pre-emphasis that leads to a flat received FDMA spectrum. In a second step, we optimize the operating point for the RF modulation voltage and clipping factor of the FDM signal (indicted as $V_{in,max}$ and C_{dB} in Section II). The two steps were then iterated, if the resulting operating point was far from the one chosen in the first optimization step. Fig. 6 shows results of the first equalization process. When transmitting subcarriers having the same modulation index (blue line with stars), the received EVM was unacceptably varying from 5.6% up to 18.8%. Applying our equalization procedure, an EVM around 10% was achieved for all subcarriers (blue line with circles in Fig. 6). The equalized EVM was achieved de-emphasizing and emphasizing the modulation index respectively down to 0.47 times the lower subcarriers and up to 4.5 times the higher subcarriers in the FDM spectrum (Fig. 6, red line). The received signal spectra with and without equalization process can be seen in Fig. 7. This equalization was performed on a system with a 25 dB ODN loss (including the SMF), an optical launching power set to P_{FIBER} = +10 dBm and using a RF modulation voltage of about $V_{in,max}$=3.5 Vpp, without any significant clipping. The second optimization step was then implemented by measuring the EVM of the subcarrier in the middle of the FDM signal as a function of $V_{in,max}$ and C_{dB}, scanning this parameter from 14 dB (i.e. almost no clipping) up to 4 dB (severe clipping). The resulting EVM contour plots vs. $V_{in,max}$ and C_{dB} is reported in Fig. 8. The red bullet in the contour plot indicates the chosen optimal operating point.

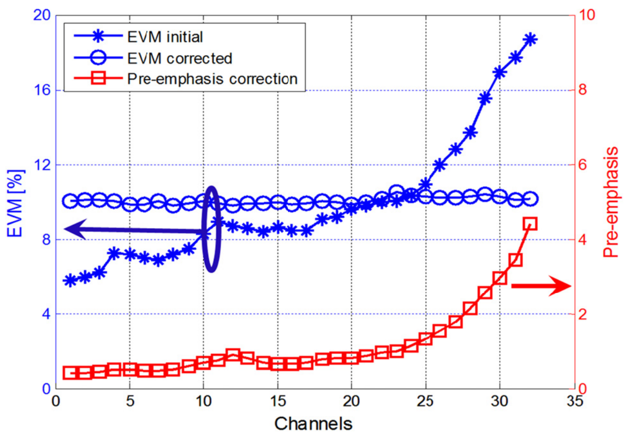

Fig. 6 EVM vs subcarrier number at 25 dB ODN loss (including an optical fiber span of 37km) before and after modulation index optimization.

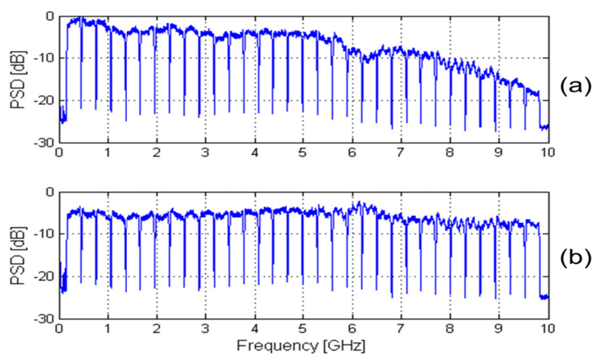

Fig. 7 Received FDM signal spectrum (a) without pre-emphasis, (b) with pre-emphasis (25 dB ODN loss including an optical fiber span of 37km).

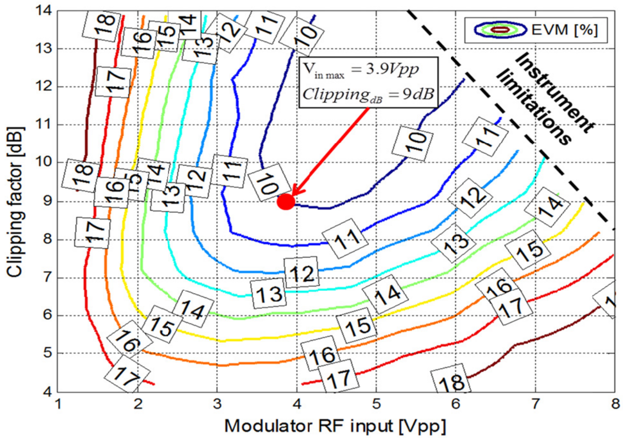

Fig. 8 EVM on the subcarrier #16 vs. Clipping Factor and RF modulation voltage at 25 dB ODN loss (including the optical fiber span of 37km).

After this second step, it was verified that only a further very little adjustment on the modulation indexes pre-emphasis was necessary. This indicates that, after the first two optimization steps, the system performance was mainly dominated by optical receiver noise, while the nonlinear distortions introduced at the transmitter had a limited impact.

IV. Discussion and Conclusions

We have demonstrated the feasibility of 32 Gbps DS link for PONs with a single wavelength approach and capable of sustaining very high ODN losses. These result is achieved multiplexing 32 subcarriers of 1 Gbps net data in a single electrical FDM signal. A relatively low symbol rate per subcarrier was used, which is the key to allow low speed DSP demodulation at the ONU side. In fact, the ONU DS receiver can be equipped with ADC running at less than 1 GSample/s.

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