

# Transmission Performances of 400 Gbps Coherent 16-QAM Multi-Band OFDM Adopting Nonlinear Mitigation Techniques

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**Abstract**—We experimentally study the transmission of a 400 Gbps coherent 16-QAM multi-band OFDM superchannel over a 10x100 km G.652 fibre-based WDM transmission line. We investigate the performance of Volterra-based and digital back-propagation-based nonlinear equalizers over three scenarios with different quantities of inter-channel nonlinearities.

**Keywords**—400 Gbps MB-OFDM; WDM transmission; nonlinear mitigation techniques

## I. INTRODUCTION

Massive deployments are currently under way for 100 Gbps coherent WDM interfaces with more than 2000 km transmission reach [1]. To further increase the capacity of WDM systems, 400 Gbps per wavelength with high spectral efficiency modulation formats, such as 16-QAM, is of primary importance. However, the higher OSNR requirement and increased sensitivity to fibre nonlinear effects of higher-order constellations result in a dramatic reduction of the transmission reach [2]. To counteract the deleterious effects of fibre nonlinearities and improve the transmission distance, nonlinear equalizers based on digital back-propagation split-step Fourier (DBP-SSF) method [3] or on the 3rd-order inverse Volterra series transfer function nonlinear equalization (IVSTF-NLE) [4,5] have been proposed these past few years and extensively studied in conjunction with single-carrier transmission scheme. However, their performance over 400 Gbps coherent orthogonal frequency-division multiplexing (OFDM)-based superchannel [6,7] has not been yet comprehensively investigated experimentally.

In this paper, we experimentally evaluate in a 10x100 km G.652 fibre-based WDM transmission line, for the first time to our knowledge, the performance of IVSTF-NLE [4] over a 400 Gbps coherent 16-QAM multi-band OFDM (MB-OFDM) superchannel composed of 4 sub-bands separated by 2-GHz guard-band. We study three configurations with different

quantities of inter-channel nonlinearities, and demonstrate that, in the scenario with the most severe nonlinearities, IVSTF-NLE is equivalent to DBP-SSF method, with a ~0.3-dB Q<sup>2</sup>-factor improvement after 1,000 km and an extension of the transmission reach of 10%.

## II. EXPERIMENTAL SETUP

Fig. 1 depicts the experimental setup. The 400 Gbps 16-QAM MB-OFDM superchannel comprises four 2-GHz spaced sub-bands of 18 GHz each (see Fig. 1.a). The raw bit rate per sub-band is equal to 144 Gbps. By removing the 20% OFDM overhead (including the cyclic prefix, training sequences and pilot tones) and the 20% soft-decision forward error correction code (SD-FEC), the net bit rate is equal to 100 Gbps per sub-band. The total bandwidth of the superchannel is 78 GHz corresponding to a net spectral efficiency of 5.13 bits/s/Hz.

The OFDM frame is realized with Matlab® using a 1024-point FFT/IFFT among which 576 subcarriers are modulated with 16-QAM. The in-phase and quadrature electrical signals are generated by the 15-GHz bandwidth Keysight® arbitrary waveform generator (AWG) operating at 64 Gsa/s. Four 100 KHz external cavity lasers (ECL), spaced by 20 GHz, are connected to two I/Q modulators (CMZM) for the generation of odd and even sub-bands, respectively, which permits to totally decorrelate the data carried by adjacent sub-bands. The dual-polarization MB-OFDM signal is created using a 1-symbol-delay polarization-multiplexing unit. The OFDM superchannel is then introduced into a multiplex of fifty-eight 50-GHz-spaced wavelengths modulated at 100 Gbps by DP-QPSK. The transmission line is constituted of ten spans of 100 km of G.652 SSMF separated by single-stage EDFAAs with 20 dB gain and ~4.5-dB noise figure. A dynamic gain equalizer (DGE) is introduced in the middle of the link to flatten the multiplex power after 1,000 km. At the end of the link, the optical bandpass filter (OBPF) selects the OFDM sub-band under measurement. This one is detected by a

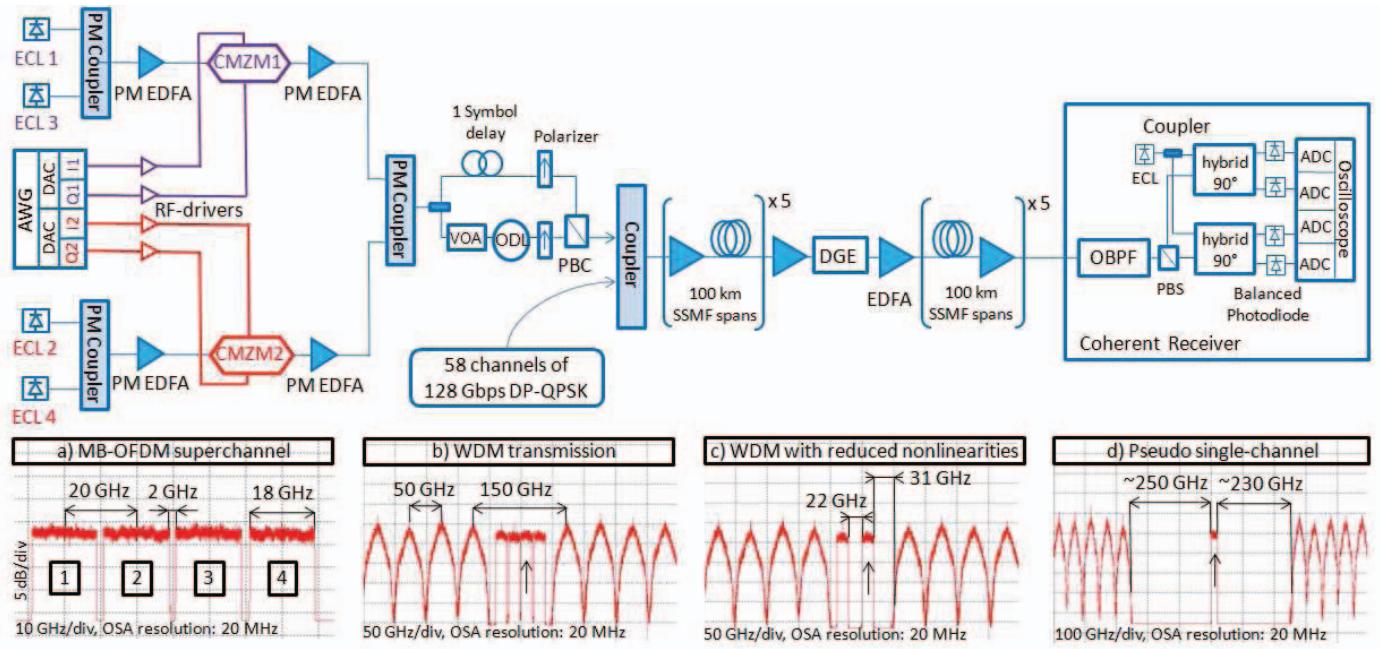


Fig. 1. Experimental setup, with the spectrum of the MB-OFDM superchannel in the inset a), and the spectra corresponding to the three scenarios under study in the insets b), c) and d). The black arrow indicates the sub-band under measurement.

polarization/phase diversity coherent receiver using a 100 KHz linewidth ECL as local oscillator. Hereafter, in order to study the worst case, transmission performances are measured over the third sub-band, which is the most affected among the sub-bands by the various transmission impairments. We use  $10^6$  bits to evaluate the bit error rate (BER). The off-line OFDM signal processing is described in detail elsewhere [8].

To explore the physical limits of the nonlinear equalizers and the configurations where their performance is maximal, three scenarios are studied. First, a purely WDM transmission scheme with 50-GHz channel spacing is investigated. Then, a configuration with relaxed nonlinear effects is created by turning off the sub-bands 2 & 4. Finally, a pseudo single-channel transmission scheme with only one OFDM sub-band surrounded by large guard-bands is studied. Fig. 1.b, 1.c, and 1.d show optical power spectra recorded by means of a high spectral resolution (20-MHz) optical spectrum analyzer (OSA) of the aforementioned configurations. The first study case, depicted in Fig. 1.b, is the one which exacerbates as much as possible non-linear effects coming from the channel itself but also from its nearest neighbors. The second one (highlighted in Fig. 1.c) is an intermediate case, for which nonlinear interplays between the channel under study and its neighbors are relaxed. The last one (shown in Fig. 1.d) corresponds to the pseudo single-channel transmission scenario, for which cross-phase modulation (XPM) and four-wave mixing (FWM) become negligible. As a consequence, the guard-band between the sub-band under measurement and its immediate left/right neighbors are 2/2 GHz, 22/31 GHz and 250/230 GHz for the case 1, 2 and 3, respectively.

### III. RESULTS AND DISCUSSION

The transmission performance is first evaluated without any nonlinear equalization (wo. NLE). The  $Q^2$ -factor vs. span input

power per sub-band is plotted in Fig. 2 for the third sub-band after 1,000 km for each study case shown in Fig. 1.b-d. The optimum  $Q^2$ -factors of all scenarios exceed the 6.25 dB SD-FEC  $Q^2$  threshold (which corresponds to a BER =  $2 \times 10^{-2}$ ). Observations from Fig. 2 show that the optimum span input power per sub-band increases from  $\sim -3.5$  dBm in the case 1 (the worst one) to  $\sim -2$  dBm in the case 3 (the best one) while at the same time the  $Q^2$ -factor is improved by  $\sim 1$  dB. That demonstrates, as expected, that the pseudo single-channel scenario limits the influence of the non-linear crosstalk between the sub-band 3 and its neighbors.

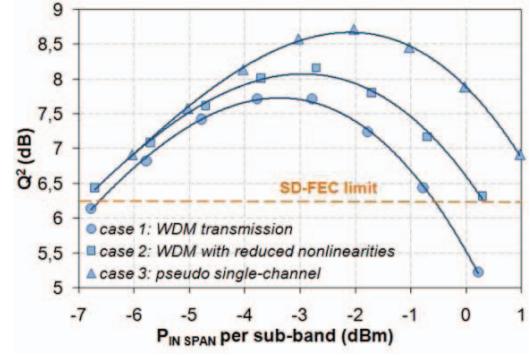


Fig. 2.  $Q^2$ -factor vs. span input power per sub-band for the three configurations under study.

Subsequently, IVSTF-NLE and DBP-SSF equalizers are introduced into the receiver as a first stage of digital signal processing. Their performances are evaluated in the three subplots of Fig. 3. Note that only 1.78 samples per symbol (SpS) is used hereafter for both IVSTF-NLE and DBP-SSF, which corresponds to 32 GSa/s for the sub-band 3 of 18-GHz symbol rate. Further SpS increase provides a marginal performance improvement at the expense of a considerable complexity growth. The abbreviations DBP-SSF1 and DBP-SSF8 denote 1

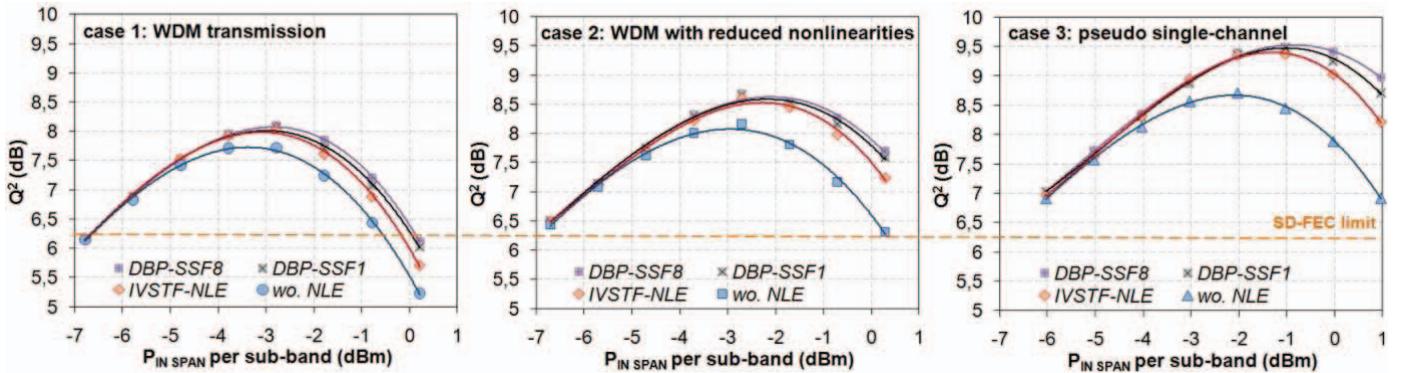


Fig. 3.  $Q^2$ -factor vs. span input power per sub-band without nonlinear equalization (wo. NLE), with IVSTF-NLE and DBP-SSF for the scenario 1, 2 and 3.

step-per-span and 8 steps-per-span digital back-propagation equalization, respectively. Note that the  $Q^2$ -factor improvement reaches its maximum at 8 steps per span. For the first scenario, IVSTF-NLE and DBP-SSF methods yield nearly identical results and provide equivalent  $Q^2$ -factor improvements (i.e.  $\sim 0.3$  dB). At the same time, the optimum span input power per sub-band is increased by  $\sim 0.5$  dB, demonstrating a slight improvement of the nonlinear threshold in the presence of nonlinear equalization. In the second scenario, IVSTF-NLE and DBP-SSF equalizers result in a  $Q^2$ -factor improvement of 0.5 dB and an increase of the span input power per sub-band by  $\sim 1$  dB. Finally, it is in the pseudo single-channel scenario of Fig. 3 that IVSTF-NLE and DBP-SSF equalizers are the most efficient.  $Q^2$ -factors are improved by 0.7–0.8 dB, while the nonlinear threshold is increased by 1–1.2 dB. Fig. 3 shows very clearly that nonlinear equalizers are more effective on the compensation of intra-channel nonlinear effects than on the mitigation of inter-channel nonlinear crosstalk.

DBP-SSF is about 10% of the overall system reach in the WDM scenario.

#### IV. CONCLUSIONS

For the first time, we evaluated the performance of both IVSTF-NLE and DBP-SSF equalizers on a 400 Gbps coherent 16-QAM MB-OFDM superchannel co-propagating with 58 coherent 100 Gbps DP-QPSK channels over a 10x100-km G.652 fibre-based transmission line. We demonstrated a better performance of the nonlinear equalization in the single-channel configuration, even if the  $Q^2$ -factor improvement reaches  $\sim 0.3$  dB after 1,000 km in the WDM scenario, enabling an extension of the transmission reach of 10%.

#### ACKNOWLEDGMENT

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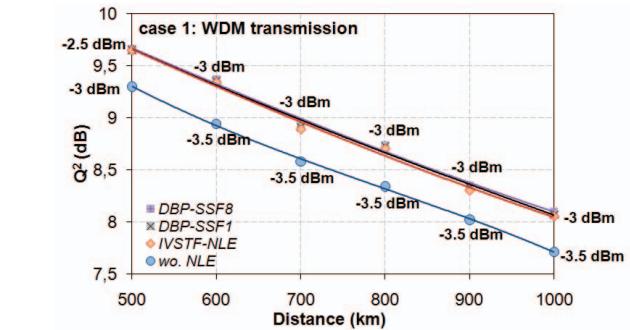


Fig. 4.  $Q^2$ -factor at optimum span input power vs. distance without nonlinear equalization (wo. NLE), using IVSTF-NLE and DBP-SSF for WDM transmission.

Finally, in Fig. 4, we plot the optimum  $Q^2$ -factor as a function of transmission distance (from 500 to 1,000 km) for the first scenario. Whatever the distance, the  $Q^2$ -factor improvement (i.e.,  $\sim 0.3$  dB) is constant between the case where no nonlinear equalization is implemented and the case where either IVSTF-NLE or DBP-SSF is activated into the receiver. We also notice that the  $Q^2$ -factor at 1,000 km with nonlinear equalization is equivalent to the  $Q^2$ -factor obtained at 900 km without any nonlinear processing. As a consequence, the extra transmission reach provided by both the IVSTF-NLE and the