400G Frequency-Hybrid Superchannel for the 62.5 GHz Slot

S. B. Amado[1], F. P. Guiomar[2], N. J. Muga[1], A. Nespola[3], L. Bertignono[2], A. Carena[2] and A. N. Pinto[1]

[1]*DETI, University of Aveiro and Instituto de Telecomunicações, 3810-193, Aveiro, Portugal, sofia.amado@ua.pt*
[2]*DET, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129, Torino, Italy, fernando.guiomar@polito.it*
[3]*Istituto Superiore Mario Boella, via Pier Carlo Boggio 61, 10138, Torino, Italy, nespola@ismb.it*

Abstract: We experimentally demonstrate a PM-16QAM/64QAM triple-carrier 400G superchannel compatible with the 62.5 GHz grid. The optimum power ratio between carriers is analytically determined using the EGN model, enabling a maximum reach of 1700 km.

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1. Introduction

The continuous growth of network data traffic has been pushing the current 100G networks to its limits. One promising solution for the next-generation transport systems comprises the use of superchannel systems capable of increasing the data-rate and spectral efficiency (SE), while using the already available infrastructures [1]. Several superchannel configurations for the 400G transmission systems have been experimentally demonstrated. In [2], dual- and triple-carrier PM-16QAM and PM-64QAM 400G superchannels solutions were proposed for the 75 GHz (SE = 5.33 b/s/Hz) and 50 GHz (SE = 8 b/s/Hz) slots. Given the recently standardized flexible grid of 12.5 GHz, it is also of interest to develop solutions for the 62.5 GHz slot, aiming at a better tradeoff between SE and achievable distance. One option consists in the use of PM-32QAM formats [1]. Other possibility is to use a time-hybrid of PM-16QAM and PM-64QAM carriers, in this case avoiding the use of non-square QAM carriers [3].

In this work, we propose a 400G frequency-hybrid superchannel solution based on PM-16QAM/64QAM carriers for the 62.5 GHz grid slot. The optimum power ratio between carriers is analytically determined through the EGN model and supported by experimental and numerical validations. Two different transmitter operation strategies are evaluated [4]: i) maximum BER (maxBER) where the overall performance is set by the worse performing carrier (the first to hit the forward error correction (FEC) cliff), while the other carriers are practically working error free; ii) mean BER (meanBER) where the overall performance is given by the mean BER of the three carriers. Our results show that taking the meanBER strategy yields the lowest required power ratio and it enables >60% reach increase relatively to the maxBER strategy, at the expense of a higher optimal power and a larger performance imbalance between carriers.

2. Experimental Setup

A scheme of the experimental setup together with the adopted superchannel configuration is depicted in Fig. 1. At the transmitter side, 3 external cavity lasers (ECL) and 24 distributed feedback lasers (DFB) are used to generate 9 WDM optical superchannels, each one composed of two PM-16QAM edge carriers and a central PM-64QAM carrier. The ECLs are used to generate the carriers of the superchannel under test (central superchannel), while DFBs are used to generate the remaining carriers. Each carrier operates at a symbol rate of 18 GBaud, yielding a gross superchannel bit-rate of 504 Gb/s (400 Gb/s net bit-rate considering a FEC and protocol overhead equal to 25%, allowing to work at a bit error rate (BER) of 2×10^{-2}). The frequency separation between carriers and superchannels is 20 GHz and 62.5 GHz, respectively, leading to a net SE of 6.4 b/s/Hz (see the inset of Fig. 1).

The electrical signals used to drive the modulators are obtained from uncorrelated 2^{15}-1 PRBSs, raised-cosine (roll-off 0.05) shaped and pre-emphasized to compensate for the limited bandwidth of the TX components and generated by two digital-to-analog converters (DACs) operating at 64 GSa/s. The central PM-64QAM carrier is digitally generated in the first DAC and optically modulated in a dual-polarization IQ modulator (IQM). In turn, two independent 16QAM electrical carriers are generated by the second DAC. After optical modulation by single-polarization IQMs, polarization multiplexing is applied by means of a PM emulator, yielding the two edge PM-16QAM carriers. Finally, the power ratio (PR) between superchannel carriers, defined as the $P_{\mathrm{PM-64QAM}}/P_{\mathrm{PM-16QAM}}$, is adjusted by a programmable optical filter placed at the optical coupler output, before the Erbium Doped Fibre Amplifier (EDFA), placed at the entrance of the loop. The 9 WDM 400G superchannels are then launched into the recirculating loop, consisting of two Pure Silica Core Fiber (PSCF) spans of 108 km, EDFA amplification with 5.5 dB of noise figure and a loop

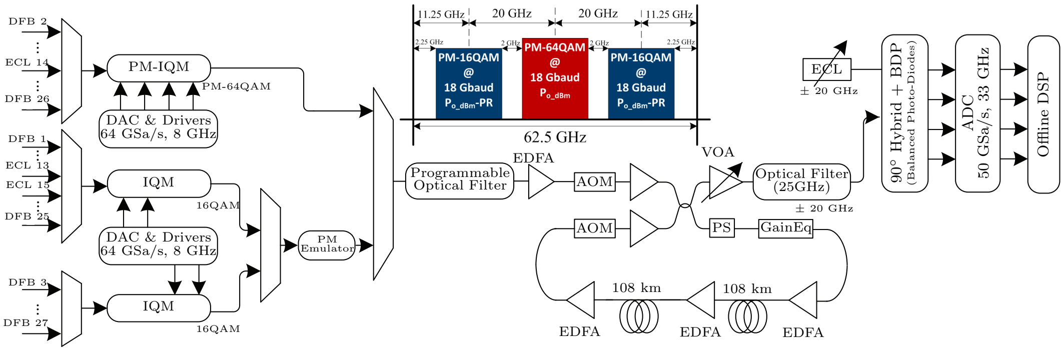

Fig. 1: Experimental setup for the 400G superchannel WDM transmission system. The inset shows the proposed frequency-hybrid superchannel composed of a central PM-64QAM carrier and two edges PM-16QAM carriers.

synchronized polarization scrambler (PS). The fiber attenuation is 0.16 dB/km, chromatic dispersion is 20.6 ps/nm/km, nonlinear coefficient is 0.7 $(\mathrm{W{\cdot}km})^{-1}$ and the total span loss is of 18.75 dB. After the loop, each carrier of the central superchannel is coherently detected by sweeping the frequency of the local oscillator laser. A 25 GHz bandwidth tunable optical filter is inserted at the receiver input, aiming to prevent excessive optical power from reaching the photodetectors. The signal is then sampled by a 50 GSa/s real-time oscilloscope and offline digital signal processing (DSP) is independently applied to each carrier. The DSP starts with the compensation of the optical frontend impairments, low-pass filtering and downsampling to 2 samples per symbol (SpS). Chromatic dispersion is compensated by a static equalizer, which is followed by 2×2 CMA-driven adaptive filtering. After frequency estimation and carrier phase estimation (CPE) an additional 4×4 adaptive equalizer is applied, followed by a downsampling to 1 SpS and by a second fine-tuned CPE stage. Finally, the received signal is decoded and the BER is measured.

3. Theoretical, Numerical and Experimental Results

The 9 WDM 400G superchannels are first analyzed using the EGN model, which allows to consider the different modulation formats assigned to each carrier [5]. The theoretical curves are validated by experimental results (filled markers: ▲, ■, ●) for a set of PR values. The validation is then extended to a wider range of PRs by split-step-based simulations (open markers: △, □, ○) performed with the OptSim simulator. Fig. 2 shows the maximum reach (MR) versus mean power per superchannel for different PRs and for the two modulation formats in the superchannel (for the analysis of the maxBER strategy) as well as the MR resulting from the average BER among all carriers (for the analysis with the meanBER strategy). The obtained results show that increasing the PR involves a compromise between the MR of PM-16QAM and PM-64QAM carriers, triggered by inter-carrier nonlinear interference (NLI). Increasing PR causes a reduction on the MR of PM-16QAM, since its power was reduced relatively to the PM-64QAM, thereby suffering from higher inter-carrier NLI generated by the PM-64QAM carriers. In turn, the MR achieved by PM-64QAM increases due to the reduced NLI induced by the adjacent PM-16QAM carriers.

The B2B penalty, at the defined BER threshold, associated with the PM-64QAM and PM-16QAM carriers was experimentally determined to be 2.5 dB and 0.8 dB, respectively. Taking into account these B2B penalties, and according to the theory for additive white Gaussian noise (AWGN) channels devised in [4], the maxBER and meanBER operation strategies should require a nominal PR of 7.4 dB and 4.8 dB, respectively, to operate at the target BER. However, due to the NLI, this picture may change significantly for nonlinear fiber propagation. Indeed, from Fig. 3a, we observe that the maximum reach for the maxBER and meanBER strategies is achieved for a PR of 8.9 dB and 2.5 dB, respectively. In the maxBER strategy, two different regions of operation can be distinguished: i) at low PR, the system MR and optimum power are set by the worse performing modulation format (PM-64QAM); ii) at high PR,

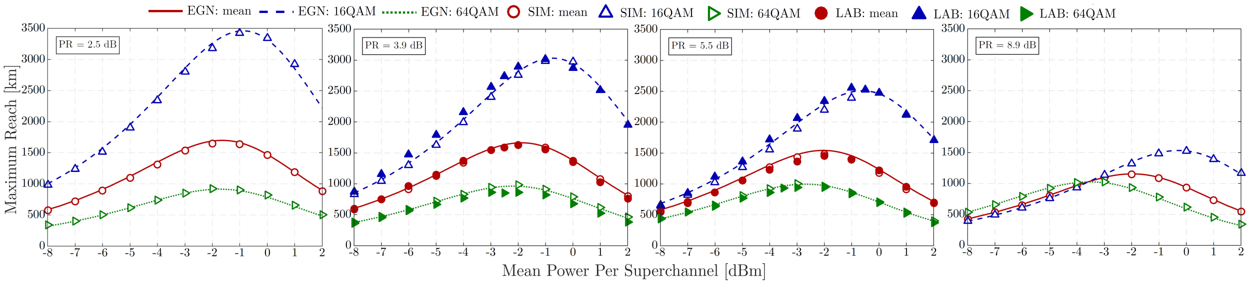

Fig. 2: Maximum transmission distance as a function of the mean power per 400G superchannel for different power ratios between carriers.

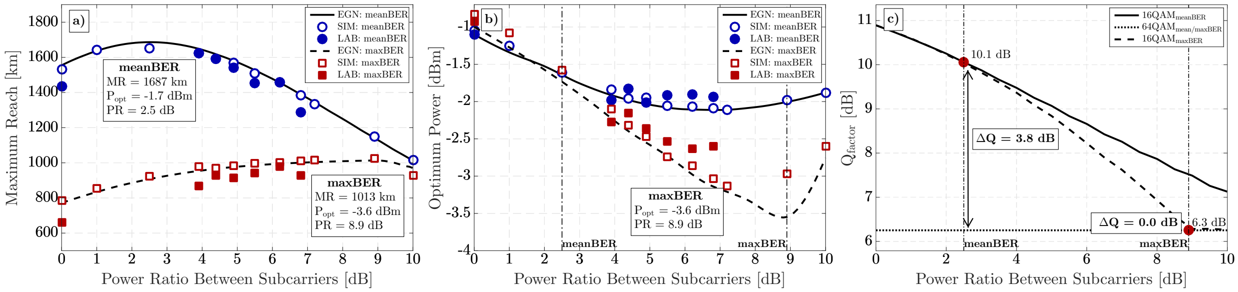

Fig. 3: System performance in terms of a) maximum reach b) optimum power and c) Q factor as a function of power ratio for each operation strategy. Solid/dashed lines correspond to the EGN model, while filled and open markers correspond to the simulation and experimental results, respectively.

the system MR and optimum power are set by the crossing point between the individual MRs of each format, which are consequently operating at the same BER. The best system performance is achieved on the transition between these two regimes, occurring in the considered scenario for a PR of 8.9 dB and optimum power of ∼-3.5 dBm (see Fig. 2). In turn, for the meanBER strategy, the system MR and optimum power require a continuous balanced compromise between the two modulation formats. In the considered scenario, since the PM-16QAM carriers simultaneously enable higher reach and also transport more data (2×4 bits per symbol, against 6 bits per symbol of the PM-64QAM carrier), the maximum performance of the system is achieved for a relatively low PR of 2.5 dB.

The theoretical, simulation and experimental results shown in Fig. 3a prove that the meanBER strategy largely outperforms the maxBER strategy in terms of MR. Operating at the meanBER in the considered scenario enables an extension of 700 km on the reach (1700 km against 1000 km), requiring a much smaller power imbalance between carriers (PR of 2.5 dB against PR of 8.9 dB). On the opposite end, the main drawbacks of this strategy are the higher optimal launched power and the higher BER imbalance between carriers, as highlighted in Figs. 3b and 3c. Indeed, Fig. 3b reveals a gap of almost 2 dB between the optimum powers obtained with the meanBER strategy (PR of 2.5 dB and P_{opt} =-1.7 dBm) and the correspondent maxBER strategy (PR of 8.9 dB and P_{opt} =-3.6 dBm). In addition, Fig. 3c shows that, at its optimum PR of 2.5 dB, the meanBER strategy suffers from a Q_{factor} imbalance of 3.8 dB between the PM-16QAM and PM-64QAM carriers, corresponding to more than two orders of magnitude difference between BERs. In contrast, as previously discussed, the maxBER strategy at its optimum PR inherently ensures zero performance imbalance between the two modulation formats. Nevertheless, taking advantage of the smooth dependence of MR on PR around the optimum operation point of the meanBER strategy, a tradeoff can be applied between MR and performance imbalance. For instance, a 1 dB reduction on Q_{factor} imbalance can be obtained by increasing the PR from 2.5 dB to 5 dB, at the cost of a MR reduction of ∼100 km.

Based on the obtained results, the maxBER strategy can be considered as a lower performance bound providing a constant BER performance among all carriers, which may facilitate the FEC coding. On the other hand, the meanBER strategy presents a better performance at the expense of requiring the application of interleaved FEC between the superchannel carriers, given the performance imbalance between modulation formats.

4. Conclusions

We have experimentally demonstrated a frequency-hybrid PM-16QAM/64QAM 400G superchannel designed to occupy a 62.5 GHz slot with a spectral efficiency of 6.4 b/s/Hz, achieving a maximum reach of ∼1700 km. Supporting the experimental results with complementary simulations and analytical model predictions, we have analyzed the critical issue of power ratio adjustment between the superchannel carriers and its impact on nonlinear propagation performance. Our results show that, using the average superchannel BER as a performance metric yields over 60% extended reach over the worse performing carrier, at the cost of a Q_{factor} imbalance of ∼4 dB between carriers.

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