Investigation of the Dependence of Non-Linear Interference on the Number of WDM Channels in Coherent Optical Networks

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Abstract *We experimentally investigate nonlinearity impact in a multi-span uncompensated coherent optical system, transmitting, in the 50GHz grid, N_{ch}x100G CP-DQPSK channels, varying N_{ch} from 3 to 71. A good agreement was found with an analytical model, confirming the progressive growth of interference with N_{ch}. Impacts on network design are evaluated.*

Introduction

In a DWDM optical network, the transmission systems design requires the balance between optical signal-to-noise ratio (OSNR) at the receiver and transmission margin allocation, where the margin is defined as the extra-OSNR required at the receiver after transmission in order to get the same BER value as in back-to-back. Margins in DWDM transmission are usually dominated by multichannel impairments; this is the reason why multichannel propagation has been widely studied, both experimentally and via simulations. In literature, due to computational cost, split-step simulations often explore multichannel impairments considering a limited number of interfering channels[1,2].

In this work, we study the evolution of multichannel impairments for 100Gb/s CP-DQPSK (Coherent Polarization-Multiplexed Differential QPSK) DWDM signals with 50-GHz channel spacing, over an uncompensated multi-span link composed of 20x125km spans of Ultra Low Loss (ULL) SMF, progressively increasing the number of interfering channels up to the full C-band.

The experimental evaluation of the impairment evolution from 2 to 70 interfering channels is compared to theoretical results based on the analytical model presented in [3] for the nonlinear propagation in uncompensated coherent optical systems, finding a good agreement.

Finally, the impact on network planning of the growth of nonlinear interference with the number of WDM channels is analyzed and analytically extended to other fiber types.

Experimental set-up description

The experimental set-up is shown in Fig. 1. It is a dual-fibers commercial Cisco DWDM system with 12 spans of 125 km of SMF ULL fiber with loss of 22.5 dB each, including patch-cords. The DWDM signal is folded in the terminal site C behaving at optical level as a standard DGE node (Fig. 1). In the terminal site A, a Wavelength Cross-Connect (WXC) has been used as multiplexer and de-multiplexer. On each span, EDFA amplification is adopted and a dynamic gain equalizer (DGE) is used every 6 spans to control tilt and ripple. The maximum available aggregate power at the amplifier output is 20 dBm. In the return path, in the section "DGE D – terminal A", the DWDM signal is dropped after 2 spans, in order to obtain a total of 20 spans (corresponding to 2500 km). The number of spans was limited to 20 in order to keep the measured BER values under the FEC correction threshold of $4 \cdot 10^{-3}$ in the entire range of power levels, even in high-nonlinearity conditions.

The 100Gb/s CP-DQPSK signal is generated and received with a real-time coherent transponder module[4]. The transmitter (TX) runs at 28 Gbaud, including 7% overhead for forward error control (FEC). All internal module parameters, e.g. Mach-Zehnder-modulator (MZM) bias-voltages, are fully automatically controlled. The channel under measure, in the following referred as device under test (DUT), is generated by a transponder module, which uses a tunable external cavity laser (ECL) with a linewidth of ~100kHz. The neighboring channels

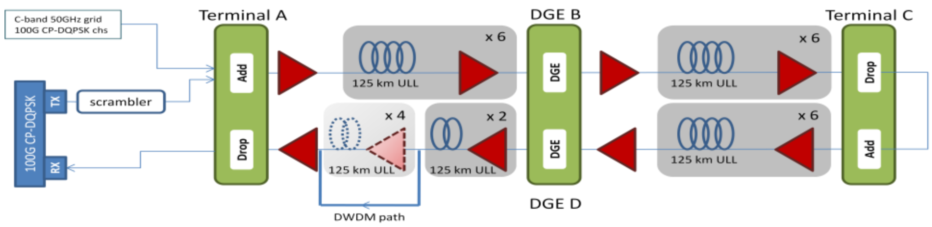

Fig. 1: Transmission system set-up with 20 in-line fiber spans.

are generated from a single TX-module, which modulates the combined light of up to 70 DFB-lasers distributed on a 50-GHz grid in the C-band. The receiver (RX) part of the transponder consists of an integrated coherent RX containing two polarization diverse 90° hybrids, followed by balanced photo-diodes and trans-impedance amplifiers (TIA) with automatic gain control. The local oscillator is an ECL of the same type used for the transmitter. The electrical signals at the output of the TIAs are digitized and processed by a 65 nm CMOS technology mixed-signal ASIC with ~70 MGates. The four ADCs have a sample-rate of 56 Gsamp/s each and ~4 effective bits (ENOB) of resolution. The digital signal processing consists of an ITU-compliant clock-recovery, static filtering for chromatic

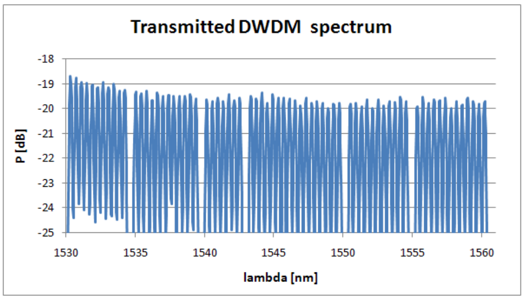

Fig. 2: Transmitted WDM spectrum (71 channels).

dispersion compensation (>70,000 ps/nm), dynamic filtering for time-varying polarization effects such as PMD (17-tap FIR filters, DGD tolerance >100ps) and a Viterbi-&-Viterbi carrier recovery (with adjustable bandwidth and polarization coupling) to mitigate phase deviations due to laser linewidth and non-linear phase noise). The receiver synchronizes blindly onto the received signal and optimizes to the current link scenario (CD, PMD, LO-offset, linewidth and nonlinear phase noise).

Experimental results

The goal of the experiment was the investigation of the influence that the number of DWDM channels has on multichannel impairments affecting the device under test (DUT). To evaluate the contribution to the total impairment of neighboring channels, the DUT was placed at the center wavelength of the DWDM spectrum and the C-band grid was populated with other 70 interfering channels (see Fig. 2, where the full C-band transmitted spectrum is presented). Amplifiers are working in gain control mode, operating with a per-channel target power of 1 dBm and a NF of about 6 dB. Taking into account losses of the patch-cords between amplifier output and fiber input, per-channel power PinF at the fiber input is about 0.5 dBm, while the received OSNR is about 10.5 dB over 0.5 nm.

During the experiment, pre-FEC BER of the DUT has been measured switching off a subset of transmitted channels; the remaining active channels symmetrically populate the 50 GHz grid around the DUT. In each configuration, the DUT pre-FEC BER is obtained as the worst value measured after 60 single acquisitions, each performed over a time frame of 1 s.

Fig. 3 shows the pre-FEC BER vs. the number of channels (with PinF=0.5 dBm): increasing the bandwidth occupation, pre-FEC BER keeps growing without saturating, indicating that also channels at the edges of the DWDM spectrum contribute to multichannel impairments. The Q-penalty, passing from 2 to 14 neighboring channels, is about 0.5 dB, that is only half of the total impairment measured with all 70 interfering channels.

This behavior is also due to the fact that the optimum transmitted power depends on the number of interfering channels. To investigate this dependency, for a subset of configurations, the pre-FEC BER as a function of the transmitted power has been measured. An example of the results is shown in the inset of Fig. 4. Interpolating these curves we can obtain the optimum power P_{opt}, which minimizes the BER, as a function of the number of WDM channels, as shown in Fig. 4. Increasing the

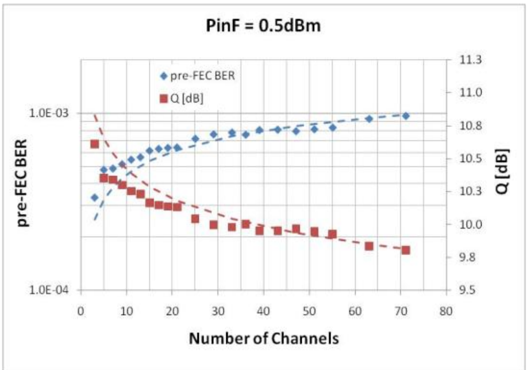

Fig. 3: Pre-FEC BER and Q vs. number of interfering channels with PinF =0.5 dBm (dots: experimental data; lines: analytical model)

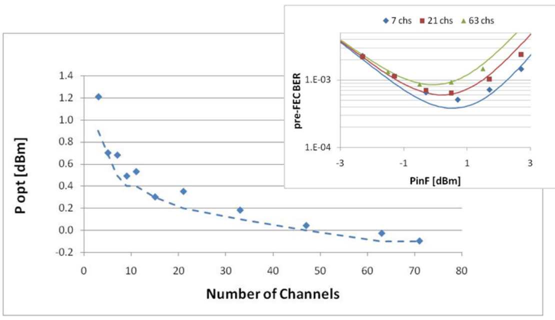

Fig. 4: P_{opt} vs. N_{ch} (dots: experimental data; lines: analytical model). Inset: pre-FEC BER vs. launch power for 7, 21, and 63 channels.

number of channels from 3 to 15, P_{opt} is reduced by about 0.6 dB. The same power reduction is obtained when passing from 15 to 71 channels: this means that channels at a distance equal or greater than 400 GHz from the DUT appreciably affects the DUT transmission performance.

Analytical model and network design

In this section, the experimental measurements are compared to results obtained resorting to an analytical model for nonlinear propagation over uncompensated optical systems proposed in [3]. This model is based on the assumption that the non-linear interference acts as additive Gaussian noise in excess with respect to ASE noise. It can be shown that the non-linear noise power (P_{NLI}) can be analytically evaluated[3] and the system BER can be then directly derived from the equivalent "non-linear" OSNR, defined as: $OSNR_{NL}=(P_{TX})/(P_{ASE}+P_{NLI})$, where P_{TX} is the transmitted power per channel and P_{ASE} is the power of ASE noise introduced by EDFAs.

We applied the analytical model to the experimental setup, obtaining a good agreement with the measurements, as shown in Figs. 3 and 4. When applying the analytical equations, we took into account the measured penalty of the system in linearity with respect to the theoretical matched filter performance, which was about 2.3 dB over the all range of measured BERs. The parameters of the ULL SMF fiber used in the analytical evaluation are: α= 0.17 dB/km, D=15.5 ps/nm/km and γ=1.1 $W^{-1}km^{-1}$. The values of α and D were obtained from experimental measurements, while for γ we used a typical value for ULL SMF fibers derived from the data-sheets. Data from analytical model confirm the experimental trend of growth of multichannel impairments as a function of N_{ch}. The obtained results are also in good agreement with the simulation study performed in [5].

To evaluate the impact of such a behavior in the network design, a theoretical estimation of the OSNR penalty as a function of the bandwidth occupancy was performed (Fig. 5). The full C-band with 100 channels is considered. The OSNR penalty is evaluated using the optimum value of the fiber launch power, i.e. the one minimizing the BER, for 15 transmitted channels. The OSNR penalty is then defined as the increase (or decrease) in OSNR required to obtain the same BER as in the 15 channels case. Note that optimizing the system transmission performances with 15 channels is equivalent to consider as negligible the impairment contributions coming from channels at more than 400 GHz from the DUT.

In the described experimental set-up, the allocation of OSNR margins able to recover the multichannel impairments with N_{ch}=15 implies an underestimation of about 0.95 dB in case of full C-band transmission (see solid line in Fig.5).

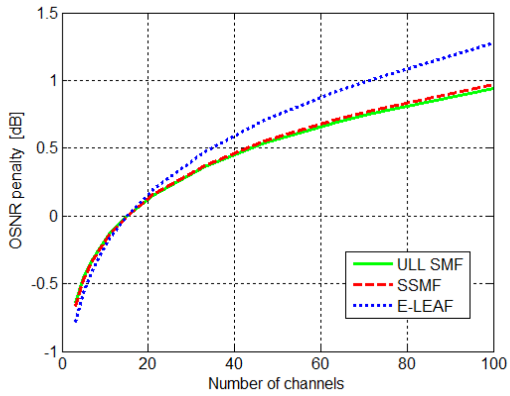

Fig. 5: OSNR penalty vs. N_{ch} using three different fiber types. Fiber launch power is the P_{opt} in case of N_{ch}=15 (ULL SMF: P_{opt}=0.3 dBm, SSMF: P_{opt}=0.2 dBm, E-LEAF: P_{opt}= -2 dBm).

By using the analytical model we extended the study to two other network scenarios with relevant application interest: in the first one the ULL SMF is replaced with SSMF fiber (α= 0.2 dB/km, D=16.7 ps/nm/km and γ=1.3 $W^{-1}km^{-1}$) while in the second one it is replaced with E-LEAF fiber (α= 0.2 dB/km, D=3.8 ps/nm/km and γ=1.5 $W^{-1}km^{-1}$). In both cases, the length of each spool is 106 km, to keep constant the span budget with respect to the ULL SMF set-up. The OSNR penalty has been evaluated as a function of N_{ch} using a fiber launch power equal to the optimum one for the N_{ch}=15 case. As shown in Fig. 5, OSNR margin allocation based on 15 transmitted channels causes an underestimation of the required margin at full channel capacity of 0.95 dB in case of SMF and 1.25 dB in case of E-LEAF transmission fiber.

Conclusions

Both experimental and theoretical results highlight the non saturated growth of the impact of non-linear interference with the number of WDM channels, demonstrating that a network design based on the presence of few WDM channels may underestimate the required OSNR margin in a densely populated WDM configuration.

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