Investigation on WDM Nonlinear Impairments Arising From the Insertion of 100-Gb/s Coherent PDM-QPSK Over Legacy Optical Networks

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***Abstract*—In the perspective of smooth capacity upgrades of legacy systems, we experimentally investigate the performance of one 100-Gb/s coherent polarization-division-multiplexed quaternary-phase-shift-keying (PDM-QPSK) channel inserted in a 10-Gb/s ultra-long-haul (ULH) wavelength-division-multiplexing system relying on nonzero dispersion-shifted fibers. The impact of copropagating 10-Gb/s nonreturn-to-zero (NRZ) channels operating ULH distances onto the operational power range of the inserted 100-Gb/s coherent PDM-QPSK channel is analyzed. Moreover, the performance penalties brought by copropagating 10-Gb/s NRZ channels onto 100-Gb/s PDM-QPSK data are also analyzed depending on the number of channels in the multiplex and on the introduction of guardbands between both type of channels.**

***Index Terms*—Coherent detection, digital signal processing, optical fiber communication, phase-shift keying.**

I. Introduction

IN THE perspective of a future meshed transparent network carrying a mix of 10-, 40-, and 100-G channels, the 10-G channels will probably be used for the longest transmission distances. In contrast, the 40- and 100-G channels could be used for higher capacity links over more moderate distances, because moving to higher bit rates is usually accompanied by a decrease of transmission reach due to physical limitations [1]. Moreover, in the context of progressive upgrade, 100-Gb/s overlaying channels are expected to satisfy the operating conditions designed for 10-Gb/s nonreturn-to-zero (NRZ) channels. On one hand, overlaying channels should have polarization-mode-dispersion (PMD) resilience as high as that defined for most of 10-Gb/s NRZ-based systems. This feature can be provided by using a 100-Gb/s coherent polarization-division-multiplexed (PDM-) quaternary-phase-shift-keying (QPSK) solution [2]–[4]. On the other hand, this solution should operate with copropagating 10-G NRZ channels whose launch power is optimized to reach ultra-long-haul (ULH) distances. Typically, this launch power is at least -1 dBm for 10-G ULH systems operating over more than 20 spans. Provided these conditions are satisfied, 100-G channels may be inserted without any redesign of the system, which is of paramount importance for most carriers. In that respect, the impact of copropagating 10-Gb/s NRZ channels operating ULH distances onto the performance of a 100-Gb/s coherent PDM-QPSK signal has already been assessed in dispersion managed links relying on standard single-mode fiber (SSMF) [5].

In this letter, we focus on smooth capacity upgrades of legacy systems relying on nonzero dispersion-shifted fibers (NZDSFs) in which nonlinear impairments may be exacerbated owing to the low local chromatic dispersion as compared to SSMF. We experimentally investigate the evolution of interchannel nonlinear impairments of a 100-Gb/s coherent PDM-QPSK channel inserted in a 10-Gb/s ULH system and we assess system margins brought by the introduction of guardbands between the 100-Gb/s and the surrounding 10-Gb/s channels

II. Experimental Test-Bed

A. Transmitter Setup

As depicted in Fig. 1, our test-bed consists of 81 distributed-feedback (DFB) lasers, spaced by 50 GHz and separated into two independently modulated, spectrally interleaved combs, plus one narrow linewidth ($\sim$100 kHz) tunable laser (test channel), at 1546.52 nm. The even and odd sets of DFB lasers are modulated with 10-Gb/s NRZ data using Mach–Zehnder modulators fed by $2^{15}-1$-length pseudorandom bit sequences at 10.7 Gb/s. On the contrary, the tunable laser is always modulated with 100-Gb/s RZ-PDM-QPSK data. To produce RZ-PDM-QPSK data, the light from test channel is sent to a QPSK modulator operating at 28 Gbaud, fed by $2^{15}-1$-bit-long sequences at 28 Gb/s, followed by a 50% RZ pulse carver operating at 28 GHz. Polarization multiplexing is finally performed by dividing, decorrelating and recombining the RZ-QPSK data through a polarization beam combiner (PBC) with an approximate 300-symbol delay. A polarization-maintaining delay line is used before the PBC to

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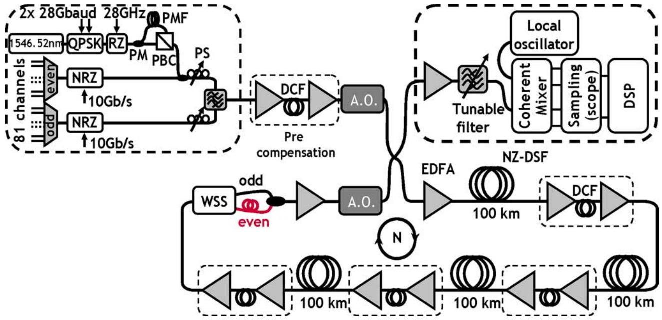

Fig. 1. Experimental setup: transmitter (top-left), receiver (top-right) and transmission link (bottom).

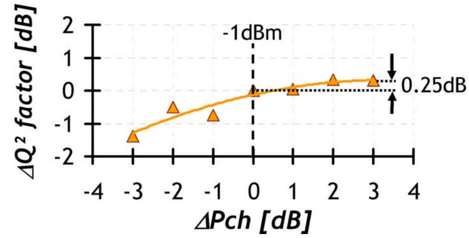

Fig. 2. Performance of the test channel while varying its launch power around that of 10-G NRZ channels (−1 dBm).

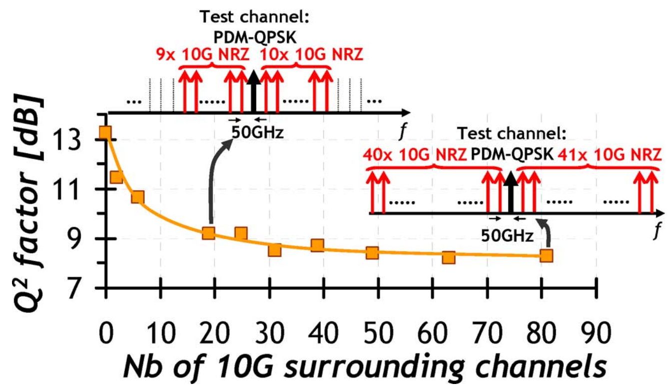

Fig. 3. Tolerance to interchannel nonlinear effects in a hybrid WDM transmission system after 800 km.

temporally interleave orthogonal polarization tributaries by half a symbol (∼18 ps). The light from the test channel is then combined with the light from the odd set of DFBs through a 3-dB coupler. Odd and even sets are passed into separate low-speed (<10 Hz) polarization scramblers (PS) and combined with a 50-GHz interleaver.

B. Link Configuration

The resulting multiplex is boosted through a dual-stage erbium-doped fiber amplifier (EDFA) incorporating dispersion compensating fiber (DCF) for precompensation and sent into the recirculating loop. The recirculating loop incorporates four 100-km-long spans of NZDSF separated by dual-stage EDFA including dispersion-compensating modules for partial under-compensation. The dispersion map, including precompensation, was optimized according to an optimal terrestrial transmission dispersion map [6]. A wavelength selective switch (WSS) is also inserted at the end of the loop to perform channel power equalization and to emulate optical filtering [5]. In all experiments, we measure the performance after two loop round-trips, i.e., after a 800-km transmission.

C. Receiver Setup

At the receiver side, the channel under study is selected by a 0.4-nm bandwidth filter and sent to the coherent receiver already described in detail in previous works [2]. The output signals from this receiver are digitized and stored by sets of 2M of samples using a sampling oscilloscope operating at 50 Gsamples/s with a 16-GHz bandwidth. Due to polarization scrambling, each recording corresponds to an arbitrary received state of polarization (SOP). For each measurement, four sets of 2MSamples are stored and processed off-line to compensate for signal distortions induced by optical-fiber transmission. This is done, as described in more detail in [7], by applying linear filters in the digital domain in five steps: resampling at twice the symbol rate, compensation of cumulated chromatic dispersion, polarization demultiplexing by means of a constant modulus algorithm based adaptive equalizer in a butterfly structure [8], carrier phase estimation and subtraction using the Viterbi and Viterbi algorithm [9], and finally symbol identification to measure the bit-error ratio (BER). The measured BER are averaged over four recordings and subsequently converted into Q^2-factors.

III. Experimental Results

To emulate 10-G systems operating ULH transport, the power per channel, Pch, at each fiber input for all 10-Gb/s NRZ channels is set at the nominal value of −1 dBm. In a first step, we measure the performance evolution of the test channel while varying its launch power around the nominal value of −1 dBm, as depicted in Fig. 2. It can be seen in this figure that only a 0.25-dB performance increase is observed when increasing the launch power by 3 dB beyond the nominal value of −1 dBm. This performance limitation is mainly attributed to the fact that the 100-Gb/s coherent PDM-QPSK channel suffers severe nonlinear penalties arising from the copropagating 10-Gb/s NRZ channels [5] that are not recovered by increasing the received optical signal-to-noise ratio. Therefore, in the following, we choose to set the launch power of the 100-G test channel at the same level as that of 10-Gb/s NRZ channels, i.e., at −1 dBm.

Next, we measure the evolution of nonlinear impairments experimented by the test channel when varying the number of surrounding 10-Gb/s NRZ channels, as depicted in the inset of Fig. 3. According to the previous measurement, we choose to set the launch power of the 100-G test channel at the same level as that of 10-Gb/s NRZ channels, i.e., at −1 dBm. When decreasing the number of copropagating 10-G channels from 82 down to 20, the output power of the amplifiers is successively decreased from 18 to 12 dBm to keep the power per channel to −1 dBm as well as a constant end-of-link optical signal-to-noise ratio. Below the value of 20 copropagating 10-G channels, the output power of the amplifiers is kept at 12 dBm while part of the 10-G channels are progressively substituted by continuous-wave (CW) channels (for constant amplifier loading). When all 20 copropagating channels are CW, the

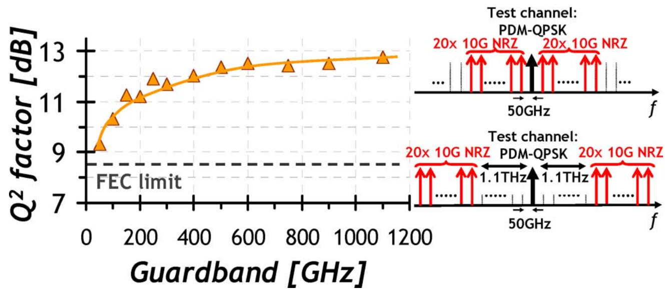

Fig. 4. Performance of the 100-Gb/s test channel versus guardband between the test channel and 10-G NRZ channels.

measure corresponds to the single-channel performance of the 100-Gb/s coherent PDM-QSPK channel at -1 dBm. The measured performance of the test channel is shown in Fig. 3 as a function of the number of surrounding 10-Gb/s NRZ channels. Copropagating 10-G channels induce a maximum penalty of about 4 dB with respect to that obtained in single-channel propagation. Then, when the number of surrounding channels N varies, the Q-factor of the test channel is unchanged (within 0.5 dB) only if N exceeds 40. Our results prove that, contrary to conventional 10-Gb/s NRZ systems using polarization-insensitive detection [10], the PDM-QPSK channel suffers from nonnegligible nonlinear interactions even coming from copropagating channels distant by more than 500 GHz. This result is in fact attributed to the nonlinear cross-polarization scattering induced by surrounding 10-Gb/s NRZ channels, sometimes referred to as cross-polarization modulation [11], [12]. Indeed, this effect is weakly dependent on the channel spacing, and creates sudden changes of the SOP of the signal that are possibly faster than the tracking speed of a polarization-sensitive receiver [13]. Thus, in a polarization-sensitive receiver, sudden changes in SOP may translate into amplitude fluctuations, hence deteriorating the performance of the receiver, whereas they would not affect the performance of a polarization-insensitive receiver. Therefore, measuring the performance of 100-Gb/s coherent PDM-QPSK requires several tens of surrounding wavelength-division-multiplexing (WDM) channels to be accurate. Indeed, the 2-dB performance variation observed between 5 and 20 surrounding channels indicates that the performance penalties brought by legacy channels onto 100-Gb/s coherent PDM-QPSK may significantly depend on the test-bed configuration.

Finally, we investigate the option of introducing guardbands around the 100-Gb/s test channel to increase system margins. As depicted in the inset of Fig. 4, we investigate this option by gradually moving away two sets of 20 adjacent channels modulated at 10 Gb/s on both sides of the test channel for a constant power per channel of -1 dBm. The results of these measurements are depicted in Fig. 4. We observe in this figure a slow decrease of the performance penalties up to 1-THz channel spacing, which is attributed to the effect of nonlinear cross-polarization scattering as previously mentioned. However, we also observe that the largest penalties are induced by the closest adjacent channels, due to the effect of cross-phase modulation. Therefore, this result also demonstrates that a 2-dB increase of system margins can be reached with a 150-GHz guardband. This would provide more than 2.5-dB margins above the forward error correction (FEC) threshold (at a BER of 4×10^{-3}, i.e., 8.5 dB), ensuring error-free transmission after FEC.

IV. Conclusion

We have shown that nonlinearities induced by 10-Gb/s NRZ channels designed for ULH transmission distance strongly constrain the operational power range of overlaying 100-Gb/s PDM-QPSK channels. In addition, we have shown that up to 40 surrounding 10-G NRZ channels have to be considered for the characterization of nonlinear penalties onto a 100-Gb/s coherent PDM-QPSK channel propagating over NZDSF-based transmission links. Moreover, we have shown that a 150-GHz guardband will ensure sufficient system margins for the insertion of 100-Gb/s coherent PDM-QPSK channels onto 10-G ULH systems.

References

[1] S. Bigo, G. Charlet, O. Bertran-Pardo, and J. Renaudier, “Overlaying coherent-detection channels over direct-detection channels in multi-bit-rate systems,” in *OFC'09*, San Diego, CA, 2009, Paper OTuD1.

[2] T. J. Xia, G. Wellbrock, M. Pollock, W. Lee, and D. Peterson, “92-Gb/s field trial with ultra-high PMD tolerance of 107-ps DGD,” in *OFC/NFOEC'09*, San Diego, CA, 2009, Paper NthB3.

[3] O. Bertran-Pardo, J. Renaudier, G. Charlet, P. Tran, H. Mardoyan, M. Salsi, and S. Bigo, “Experimental assessment of interactions between nonlinear impairments and polarization-mode dispersion in 100-Gb/s coherent systems versus receiver complexity,” *IEEE Photon. Technol. Lett.*, vol. 21, no. 1, pp. 51–53, Jan. 1, 2009.

[4] C. R. S. Fludger, T. Duthel, D. van den Borne, C. Schulien, E.-D. Schmidt, T. Wuth, J. Geyer, E. De Man, G.-D. Khoe, and H. de Waardt, “Coherent equalization and POLMUX-RZ-DQPSK for robust 100-GE transmission,” *J. Lightw. Technol.*, vol. 26, no. 1, pp. 64–72, Jan. 1, 2008.

[5] J. Renaudier, O. Bertran-Pardo, H. Mardoyan, P. Tran, G. Charlet, S. Bigo, M. Lefrançois, B. Lavigne, J.-L. Augé, L. Pirou, and O. Courtois, “Performance comparison of 40 G and 100 G coherent PDM-QPSK for upgrading dispersion managed legacy systems,” in *OFC/NFOEC '09*, San Diego, CA, 2009, Paper NWD5.

[6] J.-C. Antona, M. Lefrançois, S. Bigo, and G. LeMeur, “Investigation of advanced dispersion management techniques for ULH transmissions,” in *ECOC'05*, Glasgow, Scotland, 2005, Paper Mo.3.2.6.

[7] G. Charlet, “Coherent detection paired with digital signal processing for fiber optics communication,” *Comptes Rendus Phys.*, vol. 9, no. 9–10, pp. 1012–1030, Nov. 2008.

[8] D. N. Godard, “Self-recovering equalization and carrier tracking in two-dimensional data communication systems,” *IEEE Trans. Commun.*, vol. COM-28, no. 11, pp. 1867–1875, Nov. 1980.

[9] A. J. Viterbi and A. M. Viterbi, “Nonlinear estimation of PSK-modulated carrier phase with application to burst digital transmission,” *IEEE Trans. Inf. Theory*, vol. IT-29, no. 4, pp. 543–551, Jul. 1983.

[10] C. Fürst, J.-P. Elbers, C. Scheerer, and C. Glingener, “Limitations of dispersion managed DWDM systems due to cross-phase modulation,” in *LEOS'00 Ann. Meet.*, Rio Grande, Puerto Rico, 2000, Paper MB3.

[11] D. Van den Borne, N. E. Hecker-Denschlag, G.-D. Khoe, and H. De Waardt, “Cross phase modulation induced depolarization penalties in 2×10 Gb/s polarization-multiplexed transmission,” in *ECOC'04*, Stockholm, Sweden, 2004, Paper Mo.4.5.5.

[12] M. R. Phillips and S. L. Woodward, “Cross-polarization modulation: Theory and measurement of a two-channel WDM system,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 10, pp. 2086–2088, Oct. 2005.

[13] B. C. Collings and L. Boivin, “Nonlinear polarization evolution induced by cross-phase modulation and its impact on optical transmission systems,” *IEEE Photon. Technol. Lett.*, vol. 12, no. 11, pp. 1582–1584, Nov. 2000.