Optical Solutions to Improve PDM-QPSK Resilience Against Cross-Channel Nonlinearities: A Comparison

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***Abstract*—We compare by simulation different optical methods to improve the resilience of coherent 112-Gb/s polarization-division multiplexing (PDM)–quadrature phase-shift keying (QPSK) wavelength-division-multiplexing (WDM) transmissions against cross-channel nonlinearities. Such methods consist of 1) increasing the line group velocity dispersion (GVD), or 2) the line polarization-mode dispersion (PMD), or 3) inserting in-line cross-phase modulation (XPM) suppressors. Such methods are tested using nonreturn-to-zero (NRZ), aligned return-to-zero (aRZ), and interleaved RZ (iRZ) pulse formats. We show that the nonlinearity-mitigating effect underlying all three methods is an increase of the interchannel decorrelation, obtained by either increasing walk-off (methods 1 and 3) or by depolarizing the WDM channels (method 2). Interchannel decorrelation improves performance and reduces the difference among the three pulse formats. We find that the best performance is achieved by iRZ-PDM-QPSK in a dispersion-managed link with an XPM suppressor at each span.**

***Index Terms*—Fiber nonlinear optics, optical fiber communication, optical polarization, optical pulse shaping.**

I. Introduction

POLARIZATION division multiplexing (PDM)–quadrature phase shift keying (QPSK) has emerged as one of the most attractive solutions for 100 Gb/s transmissions. While single-channel linear impairments can be almost completely compensated by means of digital signal processing (DSP) based coherent detection, the performance of wavelength division multiplexing (WDM) transmissions on a 50 GHz grid is still significantly affected by cross-channel fiber nonlinearities [1]. As a way to mitigate cross-channel effects in dispersion-managed (DM) systems, some experiments [2] and simulations [1] verified the benefits of the interleaved return-to-zero (iRZ) pulse format, in which the polarization tributaries are 50%-RZ shaped and delayed by half a symbol time. Polarization mode dispersion (PMD) should reduce the iRZ benefits by partially time realigning the polarization tributaries. However, PMD makes the states of polarization (SOPs) of different channels follow different paths over the Poincaré sphere, thus reducing their cross-interaction [3]. Hence a quantitative analysis of the PMD impact on iRZ transmission is of great interest.

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Both cross-phase modulation (XPM) and cross-polarization modulation (XPolM) are reduced by increasing channel walk-off [4]. Hence cross-channel nonlinearities can be mitigated by the fiber group velocity dispersion (GVD), which, especially in nondispersion managed (NDM) links, induces substantial channel walk-off [1], [5]. Another efficient way to increase channel walk-off is to use passive devices that introduce different delays on adjacent channels at specific points of the line: such devices efficiently suppress XPM in on-off keying (OOK) [6] and PDM-QPSK systems [7], [8] and should prove to be effective also against XPolM [4]. In [9] all such nonlinearity mitigation techniques have been discussed.

In this letter, for the first time, we provide a direct quantitative comparison of the effectiveness of PMD, of GVD, and of the XPM suppressor in mitigating cross-channel nonlinearities in 100 Gb/s PDM-QPSK transmissions for three different pulse formats: iRZ, nonreturn to zero (NRZ) and aligned RZ (aRZ).

II. System Setup

We simulated with the open-source software Optilux [10] the transmission of a 19-channel 112 Gb/s PDM-QPSK homogeneous WDM system with 50 GHz channel spacing. All lasers had first their SOP independently randomized over the Poincaré sphere, and were then modulated by nested Mach-Zehnder modulators with independent random sequences of 1024 symbols each. During multiplexing, each channel was filtered by a 2nd order super-Gaussian optical filter of bandwidth 0.4 nm. The simulated link was composed of 20×100 km spans of single mode fiber (SMF), with zero overall cumulated dispersion obtained with an ideal linear postcompensating fiber. Two different setups were considered: 1) a DM link with precompensation of -650 [ps/nm] and a residual dispersion per span (RDPS) of 30 [ps/nm], and 2) a NDM link without pre- and in-line compensation. PMD was emulated only in the DM link, since in NDM links the interaction between PMD and Kerr nonlinearity is known to be negligible [3].

The XPM suppressor, optionally used only in DM links, was implemented by a demultiplexer followed by a bank of delay lines and a multiplexer, as sketched in Fig. 1. Each channel in the suppressor was delayed by D [ps] with respect to its smaller-wavelength neighbor [6].

Fiber propagation was obtained by solving the Manakov-PMD equation through the split step Fourier algorithm. Fiber birefringence and PMD were emulated by using 50 random waveplates per span. We assumed flat gain amplifiers with 6 dB noise figure at each span end, although the entire link noise was loaded as a unique noise source before detection. Such an approach neglects nonlinear phase noise, which is here negligible [11]. Before detection, we perfectly compensated optical linear impairments (GVD and PMD) by applying the

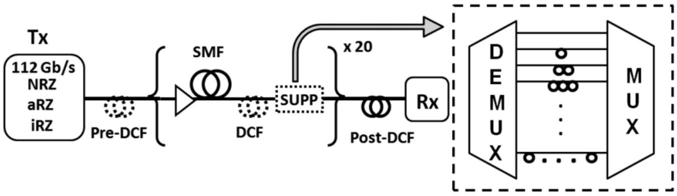

Fig. 1. The 20 × 100-km SMF 28-Gbaud PDM-QPSK coherent system simulation setup. Nineteen WDM channels, 50-GHz spacing.

inverse Jones matrix of the optical line, which allows us to focus entirely on the extra penalty coming from the interplay of linear and nonlinear distortions along the link [3].

The central channel was extracted by a 2nd order super-Gaussian optical filter (bandwidth 0.25 nm (NRZ) and 0.22 nm (aRZ and iRZ) to have same Q-factor in the linear regime) and then detected with a DSP based coherent receiver including: mixing with an ideal local oscillator, low pass filtering over a bandwidth of 17 GHz, polarization recovery through a least-mean-square algorithm [12], sampling, phase-recovery with the Viterbi algorithm using 7 taps, decision, and finally differential decoding [5]. We estimated the bit error rate (BER) through the Monte Carlo algorithm by counting on average 100 errors, and then converting the estimated BER to Q-factor [11]. To take into account the stochastic nature of PMD, each BER was averaged over 40 different runs with different random seeds. Each seed corresponded to selection of different WDM random data patterns, SOPs, and fiber waveplates realizations. For a fair comparison, we used the same random realizations when testing different formats.

III. Results and Discussion

We first investigated the impact of the XPM suppressor on the performance of the NRZ, aRZ and iRZ-based systems in a 19-channel PDM-QPSK DM link without PMD. We estimated the Q-factor for each pulse format by varying the suppressor delay D. Unless otherwise noted, a suppressor was inserted at every span. Fig. 2(a) shows the Q-factor versus D. Error bars indicate the Q-factor standard deviation. In the NRZ and aRZ case we set the power to 0 dBm while for iRZ we used 1 dBm. With this choice, all formats work 1 dB beyond the power of maximum Q-factor at $D = 0$ ps and $DGD = 0$ ps (cfr. Fig. 3). We note that the XPM suppressor is effective for all formats, with an increasing Q-factor for increasing D. The best choice is thus to maximize D such that cross-channel perturbations are uncorrelated from span to span [6]. Q-factor is seen to saturate after a delay of roughly 4 symbols (142.8 ps). Unlike the OOK case, where a value of D of about one symbol time is found to be optimal [6], here we did not find such a feature, even when increasing the delay resolution.

We next studied the impact of PMD on the same three pulse formats and DM link without suppressor. In Fig. 2(b) we show the Q-factor versus average differential group delay (DGD), obtained at the same powers as in Fig. 2(a). This figure shows that DGD improves Q-factor for all pulse formats, and that Q-factor saturates at an average DGD larger than 20 ps, in agreement with [3]. The stochastic fluctuations of the Q-factor are mostly due to XPolM and are related to the random, symbol-dependent SOP orientation of the PDM-QPSK signals. In fact, the standard deviation is larger at small DGD, where XPolM is stronger

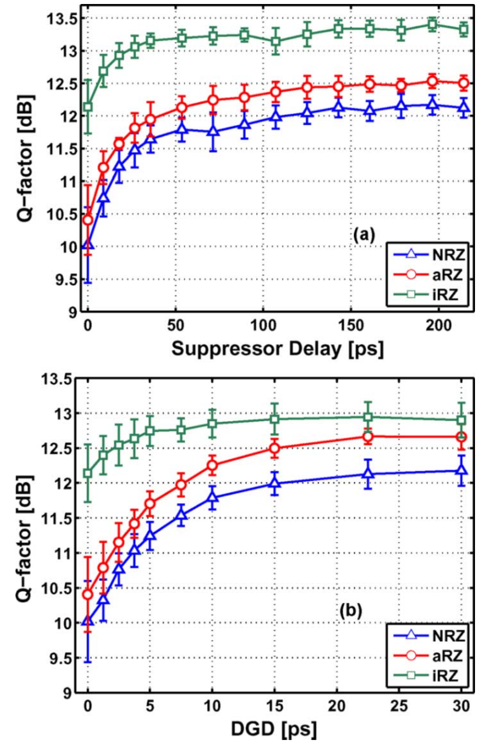

Fig. 2. Q-factor versus: (a) suppressor delay D at zero DGD, and (b) average DGD without suppressor, for a 19-channel PDM-QPSK 20 × 100-km SMF DM link with pulse formats NRZ, aRZ and iRZ (symbol time $= 35.7$ ps).

[3]. It is worth noting that iRZ has a smaller standard deviation than aRZ and NRZ at DGD $= 0$, since iRZ channels induce a weaker XPolM in absence of PMD [1]. Note that the iRZ Q-factor increases for increasing DGD, even if PMD degrades the iRZ pulses time-interleaving, because the PMD-induced depolarization is more effective in reducing XPolM.

For the same WDM DM link and each pulse format, we also report in Fig. 3 the Q-factor versus power in absence/presence of either PMD (average DGD $= 0$ or 22.5 ps) or XPM-suppressor (delay D equal to 0 or 10 symbols, both at DGD $= 0$ ps). As a reference, in the same graphs we also report the single channel DM-case and the WDM NDM case (both in absence of DGD). The figure confirms that in absence of DGD the WDM NDM link largely outperforms the DM one. However, PMD improves the DM performance yielding Q-factors very close to the NDM case. Again, we note for iRZ that the PMD-induced depolarization compensates for the degraded time-interleaving. From the figures, we also note that for aRZ and NRZ the DM link with XPM suppressor has similar performance as the NDM link, while for iRZ the DM link with XPM suppressor is slightly superior to the NDM link. Reason is that the XPM suppressor reduces cross-channel interactions, but does not degrade pulse time-interleaving. It is thus the best option for a PDM-QPSK link with iRZ pulses.

In a final test we investigated more in detail the performance of the DM link with XPM suppressor.Fig. 4(a) shows Q-factor versus power for all pulse formats either in absence of PMD, or with an average DGD $= 22.5$ ps. A suppressor with $D = 10$ symbols is present at each span. From the figure, we note that PMD improves performance except for iRZ, where we observe a small decrease of the Q-factor in the nonlinear regime (descending region of Q-factor) making iRZ performance similar

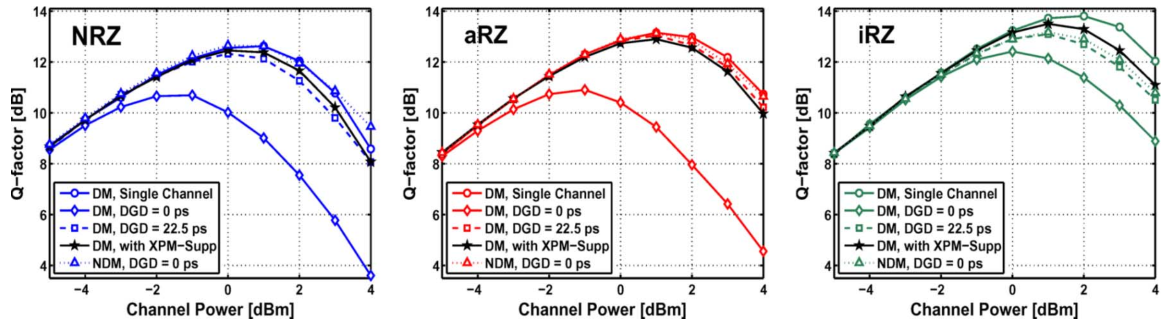

Fig. 3. Average Q-factor versus channel power for a 19-channel PDM-QPSK 20 × 100 SMF link for different pulse formats and average DGD values. Black curves (stars) for XPM-suppressor calculated with $D = 10$ symbols, DGD $= 0$ ps.

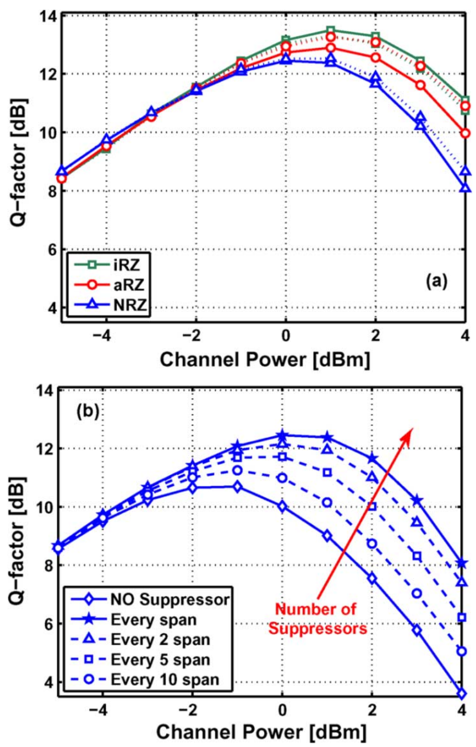

Fig. 4. Q-factor versus power for a 19-channel PDM-QPSK DM link with (a) XPM suppressor at all spans (ten-symbol delay) with average DGD $= 0$ ps (solid line) and 22.5 ps (dotted line). (b) NRZ-PDM-QPSK: DM link, DGD $=$ 0 ps and XPM suppressor at all spans (stars), every ten spans (circles), every four spans (squares) and every other span (triangles).

to aRZ. We ascribe such a worsening to the PMD-induced deterioration of the pulses' time-interleaving.

Fig. 4(b) shows Q-factor versus power at DGD $= 0$ ps, and the $D = 10$ symbols suppressors are inserted every ten spans (circles), every four spans (squares), every other span (triangles) and at all spans (stars) for the NRZ pulse format. By comparison with Fig. 3 we note that a DM link with suppressors is roughly as effective as an NDM link only when suppressors are inserted at every span, with a quick performance deterioration as the number of suppressors is reduced.

IV. Conclusion

We compared the effectiveness of different optical mechanisms that mitigate cross-channel nonlinearities in 112 Gb/s PDM-QPSK transmissions. We showed that decorrelating the WDM channels through either PMD (intrinsic to the fiber or possibly deliberately introduced at compensating stages), or delay-line XPM suppressor, or by removing dispersion management, improves performance and reduces the difference among iRZ, NRZ, and aRZ. We also showed that in iRZ-PDM-QPSK the worsening of the pulses' time-interleaving due to PMD is more than offset by the positive PMD-induced depolarization that reduces XPolM. The best option is to use iRZ-PDM-QPSK in a DM link with an XPM suppressor at each span to decorrelate channels without neither compromising time-orthogonality of the PDM tributaries, as with PMD, nor inducing more nonlinear self-effects, as with NDM. However, a quick Q-factor degradation is observed when reducing the number of in-line XPM suppressors.

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