Impact of nonlinear signal-noise interactions on symbol-aligned and -interleaved formats in dispersion managed coherent PM-QPSK systems

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Abstract: Using numerical simulations, the impact of nonlinear signal-noise interactions (NSNI) between the amplified spontaneous emission noise (ASE) and the information signal on polarization-multiplexed quadrature phase-shift keying (PM-QPSK) systems at 42.8 (112)-Gbit/s is investigated over dispersion-managed (DM) link. Both symbol-aligned and symbol-interleaved formats are considered and compared. We find that for symbol-aligned PM-QPSK systems, the impact of NSNI on system performance seems rather weak due to the strong inter-channel cross-polarization modulation (XPolM). However, when the symbol-interleaved format is used, in which the XPolM is suppressed significantly, the system performance is seriously degraded by NSNI, especially at low bit-rate. Results of 1000-km transmission employing standard single-mode fiber (SSMF) over DM link show that for 42.8-Gbit/s coherent PM-QPSK systems, the nonlinear threshold (NLT) will decrease from 5.8dBm to 0.6dBm due to the nonlinear signal-noise interactions when symbol-interleaved RZ format is used.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications; (060.4370) Nonlinear optics, fibers.

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1. Introduction

As a key technique for the implementation of 40G and 100G optical networks, polarization-multiplexed quadrature phase-shift keying (PM-QPSK) modulation based on coherent detection has been the subject of intensive research by many groups worldwide [1,2]. Combined with powerful digital signal progressing (DSP) technology, coherent receivers have ability to almost fully compensate the linear distortions in the electrical domain, such as chromatic dispersion (CD) and polarization-mode dispersion (PMD) [3,4] and therefore PM-QPSK modulated signals are only fundamentally limited by nonlinear transmission impairments.

Dispersion uncompensated transmission (i.e., no inline optical dispersion compensation) has been proved to be helpful to mitigate nonlinear impairments for wavelength-division multiplexing (WDM) PM-QPSK systems and hence improved system performance significantly compared with that systems using inline dispersion compensated units (DCU) [5,6]. However, in order to upgrade presently installed 10G transmission systems (typically OOK) to 40G and/or 100G PM-QPSK, it is necessary to evaluate as well the transmission performance of PM-QPSK modulation over dispersion managed (DM) transmission link on which pre-existing 10G systems are based. Some previous studies have shown that over DM link, symbol-interleaved return-to-zero (RZ) format, where the symbols of the two polarizations are shifted by half a symbol in time, outperform symbol-aligned non-return-to-zero (NRZ)-PM-QPSK format due to the former's reduction of inter-channel nonlinearities such as cross-phase modulation (XPM) and cross-polarization modulation (XPolM) [7,8].

Another source of nonlinear distortions due to fiber Kerr effects comes from the nonlinear interactions between amplified spontaneous emission (ASE) noise and information signal [9,10]. One important distortion incurred from these nonlinear signal-noise interactions (NSNI), for modulation formats using phase coding to transmit data, is nonlinear phase noise. So far, many studies of NSNI in coherent and non-coherent QPSK systems have been carried out, focusing on symbol-aligned format or single-polarization systems [9–14]. However, the impact of NSNI on the symbol-interleaved PM systems may be different with that on the symbol-aligned format due to the significant reduction of inter-channel nonlinearities in the symbol-interleaved PM systems and this case has not clearly been studied yet.

In this paper, we investigate the impact of NSNI on WDM 42.8-Gbit/s and 112-Gbit/s PM-QPSK systems over DM link. Both symbol-aligned and symbol-interleaved formats are considered and compared. We show that although the impact of NSNI on system performance seems weak for aligned PM-QPSK systems, NSNI degrades the system performance seriously when the interleaved RZ-PM-QPSK format is used. We find that the main reason why the symbol-aligned format is insensitive to NSNI compared with symbol-interleaved format is inter-channel cross-polarization modulation (XPolM), which is the dominant source of the

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signal degradation in symbol-aligned PM systems and insensitive to NSNI. For symbol-interleaved PM-QPSK systems, in which the XPolM is suppressed significantly and the other nonlinear effects such as inter-channel XPM and intra-channel nonlinear effects are the dominant nonlinearities, the system performance is degraded seriously by NSNI.

2. System model

The system scenarios we analyzed are shown in Fig. 1. We use standard I-Q transmitter (Tx) based on nested Mach-Zehnder modulator (MZM) driven by 21.4-Gbit/s or 56-Gbit/s NRZ signals. In order to generate RZ-QPSK signals, a 50% duty cycle RZ pulse carver is used after the QPSK modulator. The symbol-interleaved format is obtained by time interleaving the two polarizations by half a symbol period. Each WDM channel is then spectrally shaped by a 4th order super-Gaussian (SG) optical filter, whose −3dB bandwidth is set to 40GHz. In our simulations, nineteen WDM channels are considered with frequency spacing of 50GHz.

The investigated transmission link, as shown in Fig. 1(a), is periodical and composed of 10 spans, each including 100km-long standard single-mode fiber (SSMF), optical dispersion compensating units (DCU), and an erbium-doped fiber amplifier (EDFA) whose gain completely recovers the span loss. As far as the noise figure of the inline EDFA is concerned, two situations are included. One is that when considering NSNI, the noise figure of inline EDFA for a given launch power is determined through the algorithm shown in Appendix. The other is that for the case without NSNI, inline EDFAs are assumed noiseless and noise is only added before the receiver (see Section 3). The DCUs are assumed to be linear and lossless, a condition which is approximately obtained in practical systems by using the dual-stage EDFAs and/or Fiber Bragg Grating (FBG)-based dispersion compensation modules. Since we focus on the signal-noise interactions due to the fiber nonlinearities, in this paper, no PMD is assumed in the fiber.

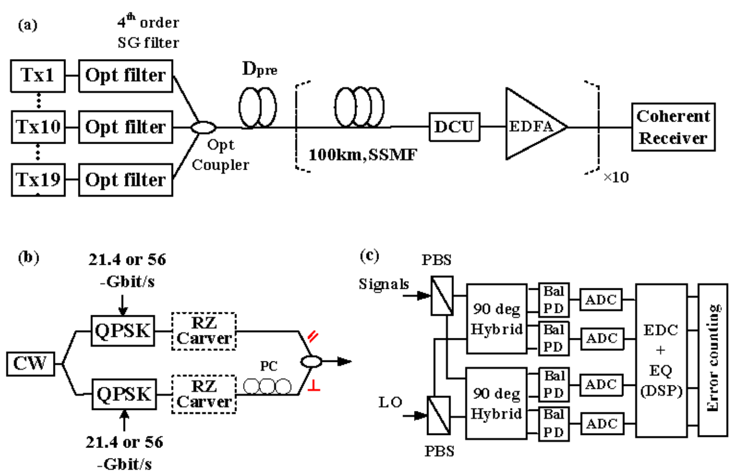

Fig. 1. System configurations in our simulations. (a)Transmission line; (b) block diagram of the PM-QPSK transmitter; (c) block diagram of the coherent receiver based on DSP technology.

The parameters of transmission fiber are as follows: loss coefficient α = 0.22dB/km, dispersion D = 16.7ps/nm/km, dispersion slope S = 0.07ps/nm^2/km, and nonlinear coefficient γ = 1.3/W/km. All the dispersion parameters of the transmission fiber are referenced at 1553.33nm. A typical distributed dispersion map is selected, where the DCU is chosen to under-compensated the transmission fiber dispersion by + 50ps/nm at each span. This residual dispersion per span (RDPS) allows for some walk-off of the WDM channels between each channel, which helps to reduce the impact of inter-channel nonlinear effects such as XPM; this walk-off effect due to RDPS also helps to reduce XPolM for PM-QPSK systems

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since XPolM also results from XPM. The cumulated dispersion of pre-compensating fiber is set to D_{pre} = -470ps/nm. The total residual dispersion at the end of the link is always compensated back to zero by electronic dispersion compensation (EDC) stage based on finite impulse response (FIR) filters at receiver. In our simulations, both the DCUs and the pre-compensation fiber are modeled as FBG-based dispersion compensation modules, which have zero dispersion slope and the cumulated dispersion values of them are referenced at 1553.33nm.

At the coherent receiver (Rx), as shown in Fig. 1(c), after mixed with a local oscillator (LO) in two 90-degree hybrids, the signals are detected by four balanced photo-detectors (BPD). The linewidth of both Tx and Rx lasers is equal to 100kHz. No optical filtering is present at the Rx: the tested channel is selected by changing the frequency of the LO. Each signal component is then filtered by a five-pole Bessel filter with −3dB bandwidth of half of symbol rate (i.e., 5.35GHz or 14GHz). Passing through the EDC, the signals are then processed by a “butterfly” second stage equalizer using four 15-taps FIR filters, whose coefficients are adjusted through a least-mean-square (LMS) algorithm. After an initial training period, during which a first estimation of the FIR coefficient is performed, the equalizer moves into decision directed mode. Bit-error-rate (BER) is evaluated using direct error counting over 131072 symbols (522488 bits). Each WDM channel encodes four uncorrelated pseudo-random binary sequence (PRBSs) of degree 16. PRBSs are also uncorrelated among the different channels. We probe the performance of the center channel (the 10-th) set at 1553.33nm. In our simulations, fiber propagation is simulated using a variable step-size split-step Fourier method (SSFM) to solve dual-polarization Schrödinger equations.

The receiver sensitivity for the WDM symbol-aligned and -interleaved PM-QPSK systems at 42.8 (112)-Gbit/s is shown in Fig. 2. Focusing on the target BER = 10^{-3}, the required optical signal-noise-ratio (OSNR) for these systems is displayed in Table 1.

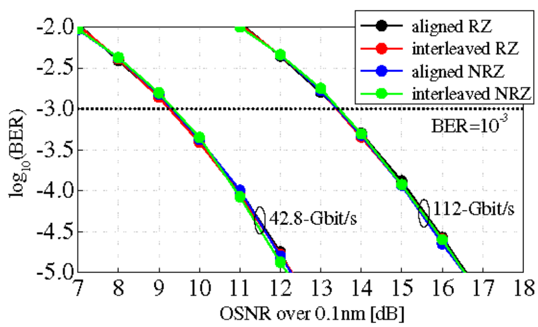

Fig. 2. Back-to-back receiver sensitivity for 42.8-Gbit/s and 112-Gbit/s WDM PM-QPSK systems.

Table 1. Required OSNR for the analyzed systems at BER = 10^{-3}

	NRZ		RZ	
	aligned	interleaved	aligned	interleaved
42.8Gbit/s	9.35dB	9.3dB	9.31dB	9.28dB
112Gbit/s	13.43dB	13.44dB	13.5dB	13.47dB

3. Results and discussions

In order to investigate the impact of NSNI on system performance, we consider two situations: one is noisy signal propagation with distributed ASE generating at each amplifier (with NSNI). In this case, information signal and ASE noise will co-propagate along the transmission link and hence NSNI can be observed due to fiber nonlinearities. The other is noiseless SSFM

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propagation and an equivalent ASE noise source added before the receiver (without NSNI). In doing so, there is no interaction between fiber nonlinearities and ASE noise along the transmission link. Therefore, there are no nonlinear signal-noise interactions in this case.

The transmission performance of the WDM 42.8-Gbit/s symbol-aligned and -interleaved PM-QPSK are given in Fig. 3, which shows the OSNR penalty at BER = 10^{-3} after 1000-km transmission for the system with and without NSNI. The pulse shapes studied include NRZ and 50% duty cycle RZ. The launch power per channel is defined as the input power per the single wavelength and the OSNR penalty is measured with reference to the system at back-to-back (b2b) operation. The nonlinear threshold (NLT) for the four analyzed system configurations is also displayed in Table 2. When considering NSNI along the transmission link, the NLT is obtained based on the algorithm presented in [14]. Here, the NLT is defined as the allowed launch power per channel that gives 1-dB of OSNR penalty at BER = 10^{-3}.

As shown in Fig. 3(a), the system using symbol-interleaved format is less tolerant to NSNI than that using symbol-aligned format. For the symbol-aligned NRZ systems the allowed launch power at 1-dB penalty is almost same for the system with or without NSNI. But for the symbol-interleaved NRZ format, the system performance is degraded obviously by NSNI. The allowed launch power at 1-dB penalty decreases from + 0.4dBm to −0.5dBm due to NSNI. One possible explanation is that for symbol-aligned signals transmitted over DM link, the nonlinearities are dominated by XPolM which is insensitive to NSNI [9,10], whereas for the symbol-interleaved format, XPolM is suppressed and the other nonlinear effects such as inter-channel XPM and intra-channel nonlinear effects are the dominant nonlinearities, which make contributions to NSNI. This effect is more pronounced for the RZ pulse. As shown in Fig. 3(b), for the aligned RZ format, only 0.9dB decrease of NLT could be observed due to NSNI (decreases from −0.6dBm to −1.5dBm, see Table 2). But for the interleaved RZ pulse, the NLT decreases from + 5.8dBm without NSNI to + 0.6dBm with NSNI, indicating a 5.2dB reduction of NLT due to the nonlinear signal-noise interactions. It is interesting to note that the performance difference of interleaved NRZ format with and without NSNI is reduced compared with that for the interleaved RZ format. We attribute this to the fact that the inter-channel XPolM, which is insensitive to NSNI, is suppressed more significantly for interleaved RZ pulse than that for interleaved NRZ pulse [8] and thus other nonlinearities, which make contributions to NSNI, dominate the system performance.

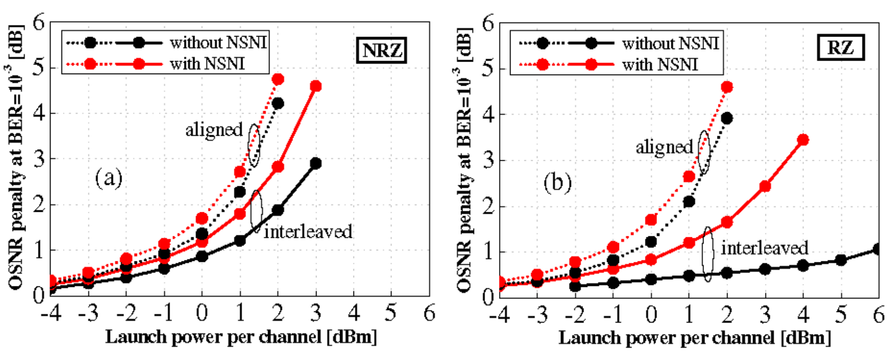

Fig. 3. OSNR penalty at BER = 10^{-3} after 1000-km transmission versus launch power per channel for the WDM 42.8-Gbit/s PM-QPSK coherent system with and without NSNI. (a) NRZ pulse; (b)50% duty cycle RZ pulse.

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Table 2. NLT for the analyzed systems with and without NSNI at 42.8-Gbit/s

		without NSNI	with NSNI
NRZ	aligned	-0.9dBm	-1.3dBm
	interleaved	+0.4dBm	-0.5dBm
RZ	Aligned	-0.6dBm	-1.5dBm
	interleaved	+5.8dBm	+0.6dBm

As shown in Fig. 3(b), a large performance difference of symbol-interleaved RZ format with and without NSNI is observed. To confirm the performance difference, a set of simulations are carried out with a system setup according to Fig. 1 except that a variable optical attenuator (VOA) is inserted before the inline EDFA. The VOA is used to change the span loss A_{span}. The minimum span loss is A_{span} = 22dB, obtained when the VOA is set to 0dB. In this test, the noise figure of the inline EDFA is 7dB and A_{span} is set to 35dB by means of VOA. We then vary the launch power in [-1, + 9] dBm and measure the corresponding BER. The results are depicted in Fig. 4 where the measured BER is plotted as a function of the launch power per channel (or received OSNR) after 1000-km nonlinear transmission for the system with and without NSNI. For comparison, the b2b case is also reported. As shown in Fig. 4, the system performance of symbol-interleaved RZ-PM-QPSK format is degraded seriously by NSNI, which is consistent with the results in Fig. 3. The BER of the system with NSNI is worst more than two orders compared with that without NSNI. At the same time, the optimum launch power, at which the best performance is obtained, decreases from P_{in} = 7dBm to P_{in} = 5dBm. Again, we can see that compared with symbol-interleaved format, the NSNI have a rather weak impact on system performance for symbol-aligned format.

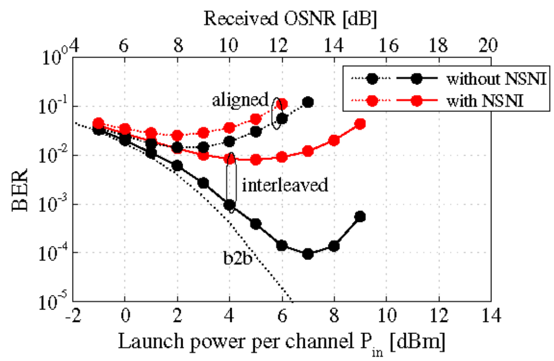

Fig. 4. BER as a function of launch power per channel (or received OSNR) after 1000-km nonlinear transmission for 42.8-Gbit/s RZ-PM-QPSK systems. The noise figure of each inline EDFA is set to 7dB and the span loss A_{span} is equal to 35dB.

From discussed above, we can see that inter-channel XPolM plays an important role in PM systems when considering nonlinear signal-noise interactions. To verify the impact of XPolM on NSNI-induced penalty, we use a model similar to [7,15]. The performance of a 42.8-Gbit/s symbol-aligned NRZ-PM-QPSK channel surrounded by eighteen 21.4-Gbit/s NRZ single-polarization QPSK channels (NRZ-SP-QPSK, nine channels at each side) and that by eighteen 42.8-Gbit/s symbol-aligned NRZ-PM-QPSK channels is analyzed and compared. The bit rate of the SP-QPSK is half that of the PM-QPSK so that they have the same symbol rate. The transmission performance of the two analyzed system configurations is given in Fig. 5. Note that the power per polarization for SP channel is 3dB higher than that for PM channel in this test.

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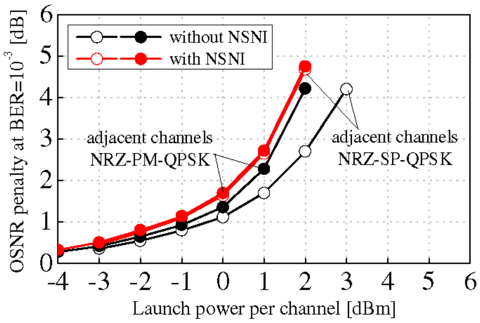

Fig. 5. OSNR penalty at BER = 10^{-3} after 1000-km transmission versus launch power per channel for a 42.8-Gbit/s symbol-aligned NRZ-PM-QPSK channel surrounded by eighteen 42.8-Gbit/s symbol-aligned NRZ-PM-QPSK or 21.4-Gbit/s NRZ-SP-QPSK channels. The results are given with and without NSNI. Solid dots: the tested channel surrounded by NRZ-PM-QPSK; hollow dots: the tested channel surrounded by NRZ-SP-QPSK.

As shown in Fig. 5, the tested signals are degraded considerably by NSNI when the surrounding channels are NRZ-SP-QPSK signals. Due to the NSNI, the NLT decreases from −0.5dBm to −1.5dBm in this case. Figure 5 clearly shows that the tested channel surrounded by SP-QPSK channels is more sensitive to NSNI than that surrounded by PM-QPSK channels. Since the PM-QPSK channel and the SP-QPSK channel have the same power in this test, on average they impose similar XPM on the tested channel, indicating that the performance difference of the two system configurations with and without NSNI are caused not by XPM, but by XPolM [15]. As PM-QPSK channels impose stronger XPolM on the reference channel than SP-QPSK channels do, we can conclude from Fig. 5 that it is inter-channel XPolM that makes PM-QPSK signals insensitive to NSNI. When the XPolM is suppressed and the other nonlinearities become dominant, the system performance is degraded seriously by NSNI. Figure 6 depicts the received signal constellation diagram of one polarization after equalization and carrier phase estimation for the tested 42.8-Gbit/s aligned NRZ-PM-QPSK signals after 1000-km WDM transmission. The launch power per channel and OSNR are same for all the configurations and set to + 3dBm and 14dB, respectively. As shown in Figs. 6(a) and 6(b), the tested signals are degraded obviously by NSNI when the surrounding channels are NRZ-SP-QPSK signals; whereas when the surrounding channels are NRZ-PM-QPSK signals, the impact of NSNI seems rather weak, as shown in Fig. 6(c) and 6(d). In fact, the measured BER for the case of Figs. 6(a)–6(d) is 5.17×10^{-4}, 3.14×10^{-3}, 2.77×10^{-3} and 4.61×10^{-3}, respectively.

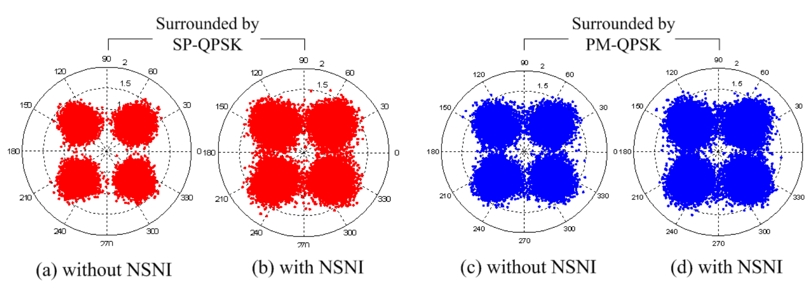

Fig. 6. Signal constellation diagram of X polarization after equalization and phase estimation for a 42.8-Gbit/s symbol-aligned NRZ-PM-QPSK channel after 1000-km nonlinear transmission at OSNR = 14dB. (a,b):surrounding channels are 21.4-Gbit/s NRZ-SP-QPSK(red dots); (c,d): surrounding channels are 42.8-Gbit/s NRZ-PM-QPSK(blue dots). The launch power per channel is same for all the WDM channels and set to + 3dBm.

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Similar simulations have been also carried out according to the system setup shown in Fig. 1 for 112-Gbit/s PM-QPSK systems, with the results depicted in Fig. 7. We can draw from Fig. 7 a similar conclusion as for 42.8-Gbit/s PM-QPSK discussed above. Note that the performance difference of 112-Gbit/s interleaved RZ-PM-QPSK with and without NSNI is reduced compared with that for the 42.8-Gbit/s systems (see Fig. 3(b) and Fig. 7(b)). For example, the NLT decreases from about + 2.2dBm without NSNI to about + 1dBm with NSNI for interleaved RZ format at 112-Gbit/s (Table 3). Only about 1.2dB difference could be observed (in contrast, it is about 5.2dB for 42.8-Gbit/s systems). We attribute this to two reasons. One is that with the increase of symbol rate, the inter-channel nonlinearities such as XPM become smaller. This is due to the fact that nonlinear phase shift introduced by XPM from neighboring channels becomes constant over several symbols of the tested channel when the symbol time becomes relatively shorter (i.e., higher symbol rate) [7,16,17]. Therefore, weaker NSNI between signal and ASE noise occur during propagation since XPM also makes contribution to NSNI. On the other hand, carrier phase recovery at coherent receiver can mitigate the phase noise coming from NSNI due to XPM more effectively for higher symbol rate because more slowly varying phase is more easily tracked [17]. The other reason is that when symbol rate is higher, optical pulses significantly broaden and overlap with neighboring pulses during propagation and thus intra-channel nonlinearities become dominant. In this case, the nonlinear phase noise coming from NSNI is much reduced since the fast pulse spreading distributes nonlinear phase noise over the entire pulse in highly dispersive environment which partially averages out the nonlinear contributions [18].

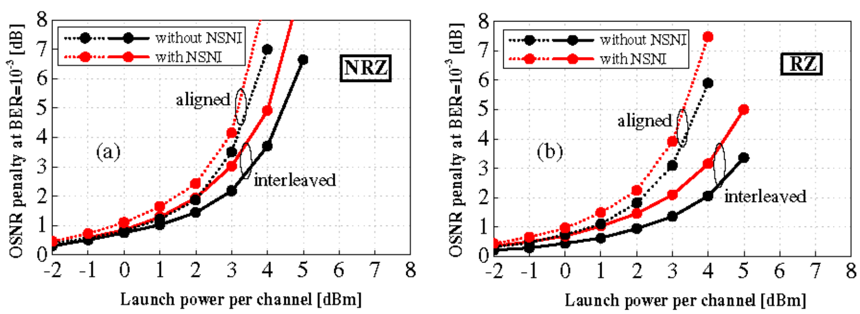

Fig. 7. OSNR penalty at BER = 10^{-3} after 1000-km transmission versus launch power per channel for the WDM 112-Gbit/s PM-QPSK coherent system with and without NSNI. (a) NRZ pulse; (b) 50% duty cycle RZ pulse.

Table 3. NLT for the analyzed systems with and without NSNI at 112-Gbit/s

		without NSNI	with NSNI
NRZ	aligned	-0.5dBm	-0.1dBm
	interleaved	+1dBm	-0.3dBm
RZ	Aligned	-0.7dBm	-0.3dBm
	interleaved	+2.2dBm	+1dBm

4. Conclusions

When considering NSNI-induced penalty in PM systems over DM link, XPolM that is insensitive to nonlinear signal-noise interactions plays an important role. For symbol-aligned format, in which XPolM dominates the system performance, the impact of NSNI seems rather weak. But for symbol-interleaved format, in which XPolM is suppressed and the other nonlinearities such as XPM and intra-channel nonlinearities become dominant, the system performance is degraded seriously by NSNI. This effect is more pronounced for RZ pulse and low bit rate. Our results show that about 5.2dB decrease in NLT could be observed due to NSNI for 42.8-Gbit/s symbol-interleaved RZ-PM-QPSK systems.

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Appendix: Calculation of the OSNR penalty when considering NSNI for nonlinear transmission

In this paper, the NSNI-induced impairments are characterized by the OSNR penalty at BER=10^{-3}. So we need to calculate the required OSNR at BER=10^{-3} in this case. The procedure for the measurement of the OSNR penalty when considering NSNI is detailed here:

1. Measure the required OSNR ($OSNR_{b2b}$) at back-to-back operation that gives BER=10^{-3}.
2. For each given transmitted power P_{in}, we vary noise figure (NF) of inline EDFA so that BER=10^{-3} is obtained at NF_0 after nonlinear transmission. The required OSNR ($OSNR_R$) at BER=10^{-3} can be obtained $OSNR_R=P_{in}/P_{ASE}$, being P_{ASE} the cumulated ASE power at the end of the link, generated from the inline EDFAs. P_{ASE} can be obtained from NF_0.
3. The OSNR penalty at the given launch power is obtained $OSNR_{penalty}=OSNR_R\text{-}OSNR_{b2b}$.

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