PDM-QPSK: on the system benefits arising from temporally interleaving polarization tributaries at 100Gb/s

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Abstract: We experimentally study, over a dispersion-managed link relying on low chromatic dispersion fibre, the origins of the system benefits provided by temporally interleaving the polarization tributaries of 100Gb/s coherent RZ-PDM-QPSK by half a symbol period. Hence, we demonstrate that the amount of benefits provided by this technique is dependent on the configuration of the WDM transmission system.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications, (060.5060) Phase modulation.

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#115018 - $15.00 USD
Received 29 Jul 2009; revised 30 Sep 2009; accepted 6 Oct 2009; published 19 Oct 2009

1. Introduction

The increasing demand for capacity will require in the future to upgrade current 10-Gb/s-based networks in order to carry 100Gb/s channels. Therefore, a growing interest arises from research works and carriers' deployment plans onto 100-Gb/s technologies compliant with existing networks. Polarization division multiplexed (PDM) quaternary phase shift keying (QPSK) paired with coherent detection is found very promising for upgrading current optical systems based on 50GHz wavelength slots thanks to its high spectral efficiency (2bit/s/Hz) and its high resilience to linear effects, such as optical noise [1], chromatic dispersion [2], optical filtering [3] and polarisation mode dispersion (PMD) [4]. On the other hand, transmission reach of WDM systems is a major concern for the deployment of such a solution and is usually mainly limited by optical noise and nonlinear effects. The use of temporally interleaving polarization tributaries by half a symbol period of return-to-zero (RZ-) PDM-QPSK has been studied to partially contain interchannel nonlinearities in optically dispersion-managed WDM coherent systems in which all channels are identically modulated [5,6] or not [7,8].

In this letter, we give further insight onto the origin of the performance improvements observed when the technique of interleaving polarization tributaries of RZ-PDM-QPSK data at 100Gb/s is used. Over a dispersion-managed 1200km-long transmission link made of non-zero dispersion shifted fibers (NZDSF), we compare the impact of this technique to mitigate nonlinear impairments over different WDM system configurations and we demonstrate how the system benefits brought by this technique strongly depend on the WDM system configuration.

2. Experimental test-bed

2.1 Transmitter setup

As depicted in Fig. 1 and similar to the test-bed used in [8], our transmitter consists of 81 DFB lasers, spaced by 50GHz and separated into two independently modulated, spectrally interleaved combs, plus one narrow linewidth (~100kHz) tuneable laser (test channel), at 1546.52nm. The light from each set is sent into a different QPSK modulator operating at 28Gbaud (or 56Gb/s). The modulators are fed by 2^{15}-1-bit-long sequences at 28Gb/s. The QPSK data are then passed through a 50% RZ pulse carver in order to produce 28Gbaud RZ-QPSK signals. A 3dB polarisation maintaining (PM) coupler then splits the output from each modulator along two different PM paths. The length of these paths is different in order to decorrelate both polarisation tributaries by thousands of symbols before being polarization-multiplexed through a polarization beam combiner (PBC) Thus RZ-PDM- QPSK data at 112Gb/s is obtained. Here, by tuning a polarization-maintaining delay line before the PBC, the two orthogonal polarization tributaries can be either temporally aligned or interleaved by half a symbol period (~18ps). In the rest of the paper, iRZ-PDM-QPSK stands for orthogonal RZ-QPSK polarization tributaries interleaved by half a symbol and aRZ-PDM-QSPK refers to the case when orthogonal RZ-QPSK polarization tributaries are pulse-to-pulse aligned. In both cases of aligned and interleaved polarization tributaries, the two generated combs are passed into respective low-speed (<10Hz) polarisation scramblers (PS) and combined with a 50GHz interleaver.

#115018 - $15.00 USD Received 29 Jul 2009; revised 30 Sep 2009; accepted 6 Oct 2009; published 19 Oct 2009

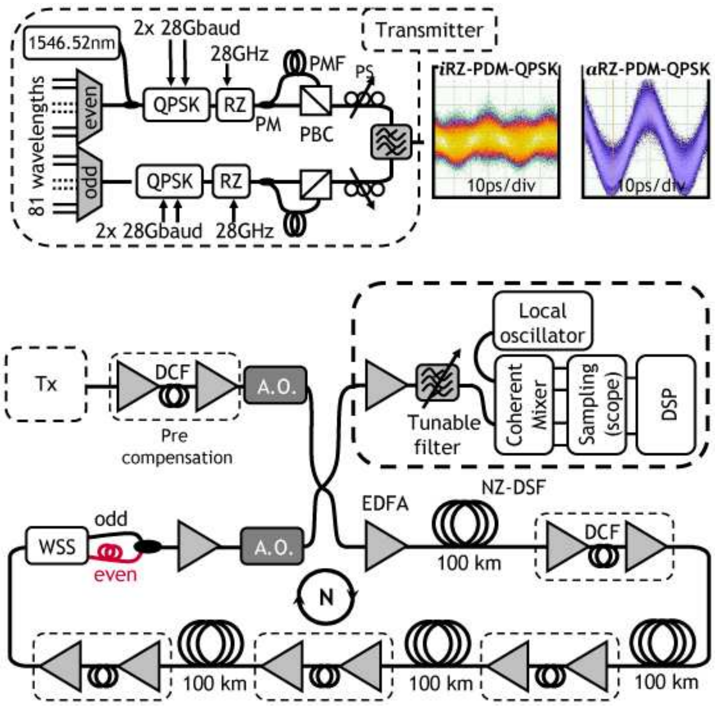

Fig. 1. Experimental test bed: transmitter set up (top left), eye diagrams at the transmitter side (top right insets) and recirculating loop set-up (lower figure)

2.2 Link configuration

The resulting multiplex is boosted through a dual-stage EDFA incorporating dispersion compensating fibre DCF for pre-compensation and sent into the recirculating loop. The recirculating loop incorporates four 100km-long spans of NZ-DSF which are separated by dual-stage EDFA including an adapted spool of DCF for partial dispersion compensation, according to an optimal terrestrial transmission dispersion map [9]. A wavelength selective switch (WSS) is also inserted at the end of the loop to perform channel power equalization and to emulate optical filtering and crosstalk stemming from nodes in a transparent network. This is done by passing odd and even channels through distinct output ports, introducing an additional optical path to even channels for further decorrelation before recombining them through a 3-dB coupler. On top of that, pre-compensation introduces a decorrelation between data carried by the different wavelength channels before being sent into the loop whereas the emulation of optical nodes introduces further decorrelation at the end of each round-trip. Thus a transmission system in which channels are temporally misaligned is emulated.

We measure the performance at a transmission distance of 1,200km, i.e. after three loop round-trips. We vary the power per channel, Pch, at each fiber input by changing the output power of the amplifiers from 12dBm to 18dBm while keeping the number of channels constant. Since the maximum output power of the amplifiers is 18dBm we reduce the number of channels to extend the studied power range, when necessary. In all experiments, we chose to set the launch power of the test channel at the same level as all the co-propagating channels

2.3 Receiver setup

At the receiver end, described in Fig. 1 (top right inset), each channel is isolated from the rest of the multiplex by a tunable filter and sent to the polarisation-diversity coherent mixer. The mixer combines the selected channel with a CW (unlocked) local oscillator. The phase offset between each of its four output ports is 90° so as to supply the in-phase and quadrature components of the beat terms between the incoming signal and the LO. These components are converted into electrical waveforms using four balanced photodiodes. The resulting electrical waveforms are digitized thanks to four analog-to-digital converters (ADC) operating at 50Gsamples/s with 16-GHz electrical bandwidth and subsequently stored by sets of 2,000,000 samples (which correspond to a time slot of 40µs). Due to polarization scrambling, each recording corresponds to an arbitrary state of polarization at the input of the link.

Digital signal processing done within the coherent receiver compensates for signal distortions induced by optical-fibre transmission. This is done, as described in more detail in [10], 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 [11], carrier phase estimation (CPE) and subtraction using the Viterbi and Viterbi algorithm [12], and finally symbol identification. Then, the BER is measured and averaged over 4 recordings and is subsequently converted into the Q^2 factor.

3. Experimental results

We first measure and compare the tolerance to nonlinear effects of both aligned- and interleaved- RZ-PDM-QPSK signals after a single channel transmission (i.e. with cw neighbouring channels) and in a WDM configuration when surrounded by neighbours of the same format. Figure 2 shows the performance of 100Gb/s iRZ- (triangles) and aRZ- (circles) PDM-QPSK signals versus launched power for the test channel in these two configurations. To ease comparisons, we choose to represent in x-axis the relative channel power and we set as a reference the power corresponding to the optimum of performance in single channel configuration. We can see that the technique of interleaving polarization tributaries of RZ-PDM-QPSK signals does not bring significant advantage in the single channel transmission indicating that intrachannel effects impact similarly iRZ and aRZ-PDM-QPSK. Moving to homogeneous WDM system configuration implies a decrease of the performance due to interchannel nonlinear impairments for both iRZ and aRZ-PDM-QPSK. Nevertheless, these performance penalties are different depending on the WDM configuration. In fact, compared to the single channel transmission we observed a reduction in terms of optimum Q^2 factor of 2dB and 3dB respectively for iRZ- and aRZ-PDM-QPSK data. The 1dB higher tolerance of iRZ-PDM-QPSK data is attributed to the fact that interleaving polarization tributaries of WDM channels enables the reduction of cross nonlinear impairments, as demonstrated for 10Gbaud signals with differential detection [13], thanks to the nearly constant power profile of the channels (depicted in the eye diagram of Fig. 1).

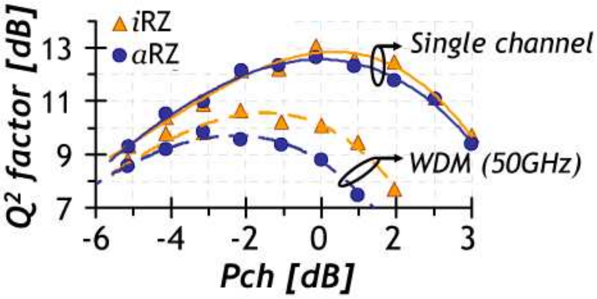

Fig. 2. Tolerance to intrachannel (solid lines) and interchannel (dashed lines) nonlinear effects of iRZ-PDM-QPSK and aRZ-PDM-QPSK after 1,200km. The reference power corresponds to optimum of performance in single channel configuration

To get more insight into this mechanism for coherent systems operating at 28Gbaud, we perform three extra experiments involving only the even set of DFB sources and the test channel (for practical reasons). This yields a multiplex of 41 channels spaced by 100GHz. DFB sources are either modulated with 100Gb/s aRZ-PDM-QPSK or iRZ-PDM-QPSK or 10Gb/s NRZ, whereas the 100Gb/s test channel, which is independently modulated, can be

Received 29 Jul 2009; revised 30 Sep 2009; accepted 6 Oct 2009; published 19 Oct 2009

tuned from temporally aRZ- to iRZ-RZ-PDM-QPSK. Using this experimental setup, the nonlinear effects induced by neighbour channels onto the test channel are unchanged in each experiment, whether polarization tributaries of the test channel are temporally aligned or interleaved. In each experiment, the resulting multiplex is sent to the recirculating loop as previously described to measure the performance of the test channel after a 1,200km WDM transmission.

Figure 3 depicts the performance evolution versus the relative launched power per channel for the three WDM configurations (the reference power is the same as in Fig. 2). Similar performance evolution is observed whether polarisation tributaries of the test channel are time-interleaved or aligned, regardless of the modulation type of the surrounding channels in contrast with the results presented in Fig. 2 for homogeneous WDM configuration. This suggests that iRZ- and aRZ-PDM-QPSK are also equally affected by interchannel impairments. On the other hand, compared to the results obtained when test channel is surrounded by aRZ-PDM-QPSK channels (depicted in Fig. 3 a), slightly better performance is observed when surrounding channels are iRZ-PDM-QPSK (Fig. 3 b) indicating that the nearly constant power profile of the iRZ-PDM-QPSK neighbouring channels induces smaller cross nonlinear impairments onto the test channel.

Given these results, we investigate the insertion of 100Gb/s RZ-PDM-QPSK channels into legacy systems carrying 10Gb/s NRZ channels. As it can be observed in Fig. 3 c, nonlinearities stemming from 10Gb/s NRZ co-propagating channels impact similarly the test channel whether its polarisation tributaries are time-interleaved or aligned in accordance with previous results shown in Fig. 3 a) b). More precisely, 10Gb/s NRZ co-propagating channels cause more than 1dB penalty in terms of optimum Q^2 factor compared to the results depicted in Fig. 3 a. These results indicate that the benefits of temporally interleaving the polarisation tributaries primarily come from a reduction of the impact of neighbouring channels onto the test channel. In other words, this technique brings maximum benefits when it is applied to the full multiplex.

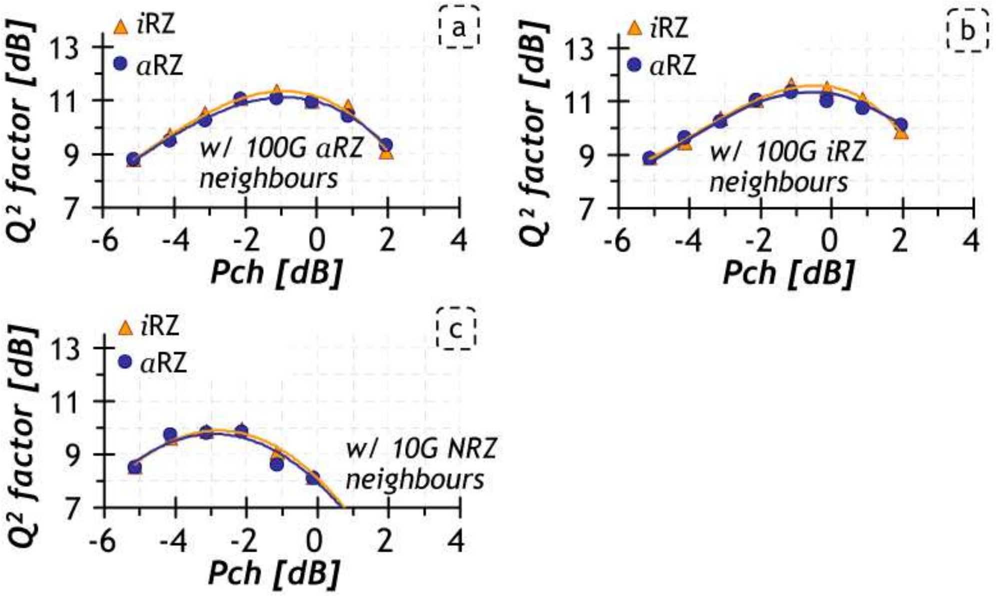

Fig. 3. Performance evolution versus launched power for interleaved and aligned RZ-PDM-QPSK measured after 1,200km with identical interchannel impairments in a WDM configuration with 100GHz spacing. The reference power is the same than in Fig. 2.

4. Conclusions

We have studied the origin of the benefits brought by temporally interleaving polarization tributaries of coherent 100Gb/s RZ-PDM-QPSK signals over a dispersion-managed link relying on low dispersion fibre. We have shown that RZ-PDM-QPSK with time-aligned polarization tributaries and with interleaved polarization tributaries are equally affected not only by intrachannel effects but also by interchannel effects. Hence, the benefits of interleaving polarization tributaries of coherent 100Gb/s RZ-PDM-QPSK does not come from come an enhanced tolerance to nonlinear effects of the channels themselves. Indeed, these benefits come more from the fact that the power profile of the channels is nearly constant which enables the reduction of cross nonlinear impairments onto co-propagating channels.

#115018 - $15.00 USD Received 29 Jul 2009; revised 30 Sep 2009; accepted 6 Oct 2009; published 19 Oct 2009