Insertion of 100Gb/s Coherent PDM-QPSK Channels over Legacy Optical Networks Relying on Low Chromatic Dispersion Fibres

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Abstract— **We investigate the potential of 100Gb/s polarization division multiplexed (PDM-) quadrature phase shift keying (QPSK) paired with coherent detection to enable the future capacity upgrade of current networks designed for 10Gb/s non-return to zero (NRZ) on-off keying data. We experimentally assess the tolerance to nonlinear effects of such a solution over optical systems based on low chromatic dispersion fibres. We particularly study the performance penalties brought by co-propagating channels (either PDM-QPSK or 10Gb/s NRZ) onto 100Gb/s PDM-QPSK data, in which both polarisation tributaries are over-modulated with return-to-zero and temporally interleaved by half a symbol period. Besides, we investigate one option to overcome these limitations: introducing band-gaps in the multiplex.**

I. Introduction

Most of deployed backbone systems are working with wavelengths at a bit rate of 10Gb/s modulated with non-return to zero (NRZ) on-off keying. Up to approximately 100 wavelengths can be multiplexed into a single fibre, using wavelength division multiplexing (WDM), with a channel spacing of 50GHz. This corresponds to a total system capacity of 1Tb/s. 40Gb/s transmission systems are under active development as a way to increase the total transmitted capacity by increasing the spectral density from 0.2bit/s/Hz to 0.8bit/s/Hz. The cost of 40Gb/s transponders is on the way to be competitive with the one of 4x10Gb/s and their deployment has progressively begun since one to two years on the carrier's network to cope with the growing demand of increasing total capacity. At the same time, a growing interest arises from research works onto 100Gb/s technologies and carriers, who require their networks to be compliant with future upgrade at 100Gb/s for supporting the predicted traffic growth of about 50% per year. One likely scenario for 10Gb/s infrastructure upgrade is to design so-called hybrid systems. In these systems, several channels at 40Gb/s and/or 100Gb/s bit-rate are progressively inserted in wavelength slots with 50GHz spacing, originally designed for NRZ channels at 10Gb/s, and transmitted over dispersion-managed links (i.e. incorporating periodically dispersion compensating module to compensate for the accumulated dispersion along the line). Thus channels at both bit-rates will propagate simultaneously over the same fibre.

However, fibre transmission becomes more and more challenging as the bit-rate increases since the tolerance to fibre linear effects is reduced. More precisely, if we consider the same modulation format when moving from one bit rate to a greater one, the sensitivity to optical noise and the maximum tolerable amount of polarisation mode dispersion (PMD) are reduced by the ratio of both bit-rates and the minimum filter bandwidth is increased by the same amount. Moreover, the maximum tolerable amount of chromatic dispersion (CD) is reduced by the square of the same ratio. Among all different solutions proposed to meet this challenge, the use of multilevel modulation formats paired with coherent detection seem to be the most promising. Contrary to direct and differential detection schemes, coherent receivers provide access to the amplitude, the phase and the polarization of the optical field and they offer the possibility to compensate for linear impairments, thanks to appropriated digital signal processing (DSP) [1][2]. Unparalleled tolerance to some of these linear impairments have been already pointed out with polarization division multiplexed (PDM-) quadrature phase shift keying (QPSK) at 100Gb/s, such as PMD [3], chromatic dispersion [4] and optical filtering [5], allowing long-haul transmissions at 100Gb/s fully compliant with the 50GHz-spacing grid and yielding a spectral density of 2bit/s/Hz [4][5][6][7].

On top of linear fibre effects and optical noise, optical communication may be limited by nonlinear fibre effects originating mainly from the Kerr effect. Nonlinear impairments may cause penalties depending on bit rates, modulation formats and detection techniques. As an example, on the one hand, it has been demonstrated that the coherent PDM-QPSK solution suffers from large penalties at 40Gb/s arising from inter-channel effects [8][9], severely limiting the

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maximum achievable transmission reach. On the other hand, the increase of bit rate from 40 to 100Gb/s helps reducing inter-channel related impairments [10]. Several research works have studied the feasibility of 100Gb/s coherent PDM-QPSK long-haul transmission especially over dispersion-managed systems relying on standard single mode fibre (SSMF), having a CD of 17ps/nm/km [11][12][13]. Recently, the transmission of 100Gb/s coherent PDM-QPSK was investigated over non-zero dispersion-shifted-fibre (NZ-DSF) based systems, i.e. having a CD around 4ps/nm/km, in a homogenous WDM system, where all channels are uniformly carry PDM-QPSK [14].

In this paper, we focus on smooth capacity upgrades over the same NZ-DSF fibre. In these upgrades, 100Gb/s channels are transmitted along with 10Gb/s NRZ channels. Compared to SSMF, the use of this fibre emphasizes nonlinear effects owing to its low chromatic dispersion. More precisely, we study the tolerance to intra-channel and inter-channel nonlinear impairments of PDM-QPSK in which both polarisation tributaries are over-modulated with return to zero (RZ) and temporally interleaved by half a symbol period. We evaluate cross nonlinear penalties in a homogenous WDM system as well as in a hybrid one. Moreover, we investigate one possible solution to reduce the distortions induced by the 10Gb/s channels onto the 100Gb/s ones, namely the introduction of band-gaps between them. Finally, we verify the potential of this solution at 100Gb/s compared with the results obtained at 40Gb/s.

II. Experimental set-up

A. Transmitter setup

The experiments carried out here involve single-channel transmission, homogenous WDM transmission and also hybrid WDM transmission. Three configurations are thus used successively at the transmitter side as shown in Fig. 1 a), b) and c). In all configurations, the test channel (at 1546.52nm) is PDM-QSPK modulated at 100Gb/s. On the contrary, the surrounding channels can be either kept continuous, PDM-QPSK modulated at 100Gb/s or NRZ modulated at 10Gb/s corresponding to single-channel, homogenous WDM and hybrid WDM transmissions respectively.

As depicted in Fig. 1, our transmitter consists of 82 DFB lasers, spaced by 50GHz and separated into two spectrally-interleaved combs which are independently modulated. To generate the PDM-QPSK data, the light from each comb is sent to a different QPSK modulator operating at 28Gbaud (i.e. 56Gb/s). The modulators are fed by 2^{15}-1-bit-long pseudo-random bit sequences (PRBS) at 28Gb/s, including forward error correction (FEC) and protocol overhead. When considered, the QPSK data are then passed through a 50% RZ pulse carver operating at 28GHz in order to produce 28Gbaud RZ-QPSK signals. Polarization multiplexing is finally performed by dividing, decorrelating and recombining the (RZ-) QPSK data through a polarisation beam combiner (PBC) with an approximate 300 symbol delay, yielding (RZ-) PDM-QPSK data at 112Gb/s.

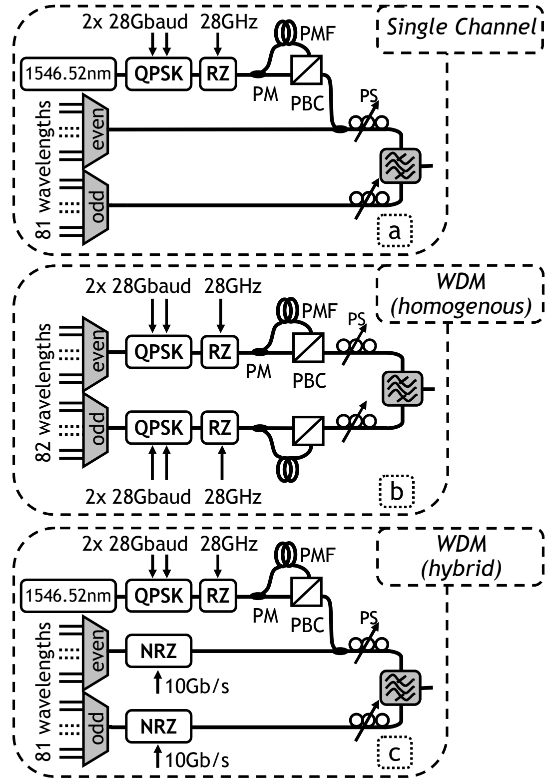

Fig. 1. Experimental transmitter set-up for three different configurations: single-channel (a), homogenous WDM (b) and hybrid WDM (c).

Here, by adjusting polarization-maintaining delay line with appropriate lengths before the PBC, the two orthogonal polarization tributaries can be either temporally aligned or interleaved by half a symbol (~18ps). In the rest of the paper, iRZ-PDM-QPSK stands for orthogonal RZ-QPSK polarization tributaries interleaved by half a symbol and NRZ-PDM-QSPK refers to the case when orthogonal NRZ-QPSK polarization tributaries are pulse-to-pulse aligned. The corresponding schematic forms of the signals in the time domain and eye diagrams are shown in Fig. 2. In iRZ-PDM-QPSK configuration, when polarisation tributaries are interleaved by half a symbol, a nearly almost constant channel power is measured, as shown in the upper-right inset. On the contrary, when the NRZ-QPSK tributaries are temporally aligned, the eye diagram clearly defines intensity transitions between different phase states, characteristic of LiNbO3-based nested QPSK modulators, as shown in the lower-right inset. To generate the 10Gb/s NRZ data required for the hybrid WDM transmission experiment, the light from each comb is sent into a Mach-Zehnder modulator, fed by 2^{15}-1-length PRBS at 10.7Gb/s.

In any case, the two generated combs are passed into a low-speed (<10Hz) polarisation scrambler (PS) and combined with a 50GHz interleaver.

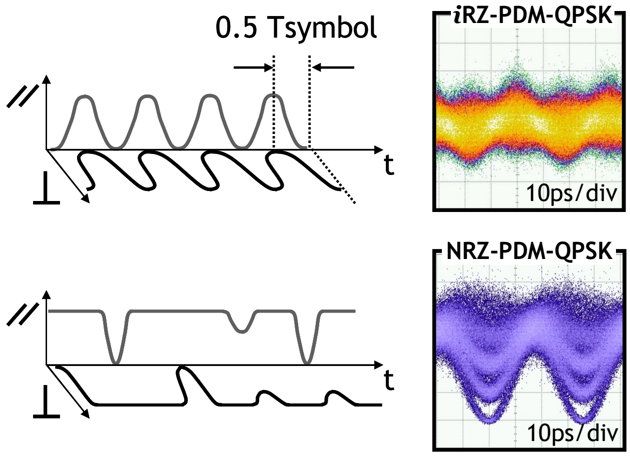

Fig. 2. Typical shape of the signal in the time domain (left) and experimental eye diagrams (right) for iRZ-PDM-QPSK (upper figures) and NRZ-PDM-QPSK (lower figures).

B. *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 a typical terrestrial transmission map [15]. A commercially-available wavelength selective switch (WSS), from Optium, is also inserted at the end of the loop to perform channel power equalization and can also 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.

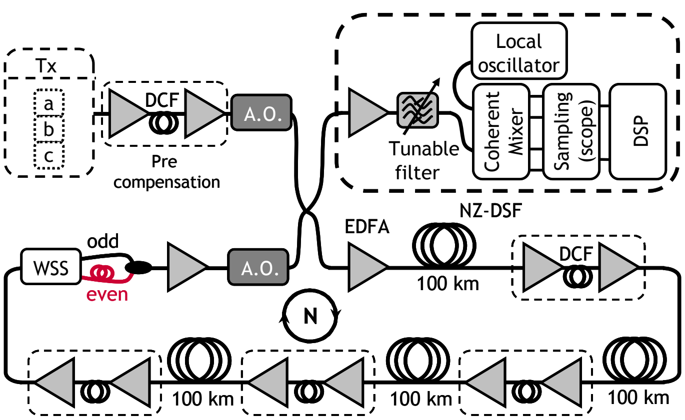

Fig. 3. Experimental recirculating loop set-up

We measure the performance after different transmission distances by changing the number of loop round-trips and we vary the power per channel, Pch, at each fiber input by changing the output power of the amplifiers from 13dBm to 18dBm while keeping the number of channels constant at 82 channels. 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.

C. *Receiver setup*

At the receiver side, the channel under study is selected by a 0.4nm bandwidth filter and sent into the coherent receiver. Such a receiver consists of a polarization beam splitter (PBS) followed by two coherent mixers, one for each received polarization state. Coherent mixers then combine the signal with a narrow linewidth (~100kHz) tuneable continuous wave (cw) laser achieving a phase offset of 90º between each of their four outputs, so as to supply the in-phase and quadrature components of the signal. These waveforms are detected by four balanced photodiodes, digitized by four Analog-to-Digital Converters (ADC) of an oscilloscope at 50Gsamples/s with a 16GHz electrical bandwidth, and stored by sets of 2,000,000 of 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. Afterwards, the waveforms are processed off-line, as explained with more details in [16], for resampling at twice the symbol rate, digital chromatic dispersion mitigation, polarization demultiplexing by means of a constant modulus algorithm based adaptive equalizer in a butterfly structure [17], and carrier phase recovery (CPE) using the Viterbi and Viterbi algorithm [18]. According to previous works showing the importance of varying the length of the averaging window for CPE optimization [8][9], this parameter has been optimized for all the results presented in this paper. Finally, symbols are discriminated for the measurement of bit error ratios (BER) which are subsequently transformed into Q^2-factors after averaging over at least four recordings.

III. EXPERIMENTAL RESULTS

A. *Impact of intra-channel effects*

One of the primary advantages of PDM-QPSK paired with coherent detection is that its sensitivity to optical noise is very close to the lowest value recorded among all modulation schemes. Fig. 4 (top) depicts the optical noise sensitivity measured for 100Gb/s iRZ-PDM-QPSK (with orange triangles) and NRZ-PDM-QPSK (with blue circles). As it can be seen, both solutions provide very similar sensitivity to optical noise. Contrary to directly-detected systems in which RZ pulse carving can sometimes improve sensitivity to optical noise, coherent systems perform a digital equalization which compensates for non-perfectly matched filtering, so that the benefit of using RZ pulse carving with respect to NRZ pulse shaping vanishes [7].

We now study and compare the tolerance of 100Gb/s iRZ-PDM-QPSK and NRZ-PDM-QPSK to intra-channel nonlinear effects through a single-channel transmission, i.e., keeping surrounding channels continuous (as seen in Fig. 1 a). Fig. 4 (bottom) shows the performance of the test channel measured after a transmission distance of 1200km as a function of the power launched per channel, Pch, for iRZ-PDM-QPSK (with triangles) and NRZ-PDM-QPSK (with circles). In both cases, for low values of Pch, performance is limited by optical noise and improves as far as optical signal-to-noise ratio (OSNR) is increased when increasing Pch. The intra-channel effects, mainly self-phase modulation (SPM) and nonlinear phase noise here, arises for both studied solutions as soon as the launch power exceeds -1dBm. However, the performance of NRZ-PDM-QPSK reaches an optimum for a launch power of 0dBm whereas the one of iRZ-PDM-QPSK keeps increasing up to +1dBm launch power. This higher tolerance of iRZ-PDM-QPSK against intra-channel nonlinear effects brings a 1dB Q^2-factor benefit as compared to NRZ-PDM-QPSK. This improvement of the tolerance to intra-channel nonlinearities is attributed to the low peak-to-average power ratio obtained by combining polarization interleaving and RZ pulse-carving that reduces nonlinear impairments induced by Kerr effect. It must be pointed out that this benefit was found maintained in WDM transmission [12] and was not been observed when both polarizations were (NRZ-) QPSK-interleaved [7] or RZ-QPSK pulse-to-pulse aligned [11].

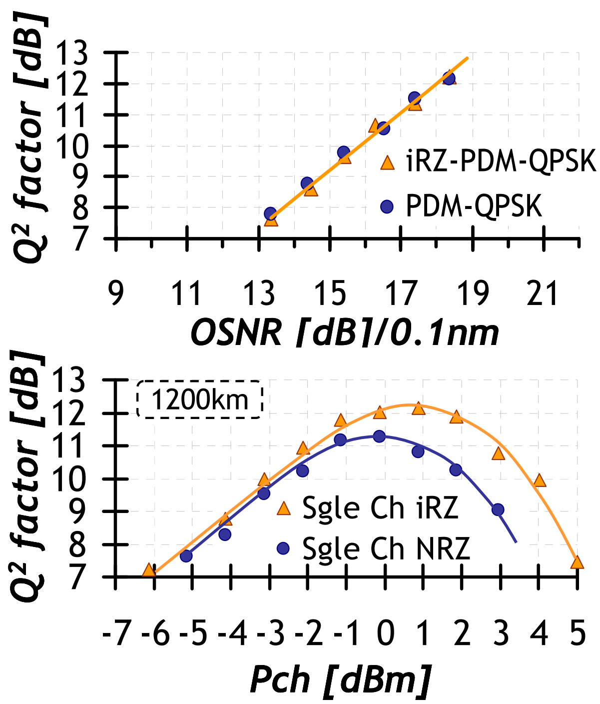

Fig. 4. Optical noise sensitivity (top) and performance comparison between PDM-iRZ-QPSK (orange triangles) and PDM-NRZ-QPSK (blue circles) after 1200km of single-channel transmission (bottom).

The following experiments now focus on the tolerance of iRZ-PDM-QPSK solution against inter-channel nonlinear effects in both homogeneous and hybrid WDM systems.

B. *Impact of inter-channel effects*

Here, we measure the performance of one 100Gb/s iRZ-PDM-QPSK channel surrounded either by other 100Gb/s iRZ-PDM-QPSK or by 10Gb/s NRZ channels (corresponding transmitter configurations depicted in Fig. 1 b and c, respectively) while varying the channel power launched per span. Fig. 5 shows the performance evolution of the test channel versus the power launched per channel in both homogeneous and hybrid WDM configurations. Full symbols depict the performance when optical filtering and crosstalk steaming from nodes is emulated whereas empty symbols depict the results without this emulation. It must be stretched that, to ease comparison, the transmission distance was decreased from 1200km to 800km when moving from homogeneous to hybrid WDM configuration to obtain performance in the same range of Q^2-factor around 10dB.

In the upper figure, it can be seen on one hand that neither optical filtering nor crosstalk induce any penalty on the performance. On the other hand, it demonstrates that the presence of iRZ-PDM-QPSK neighbour channels reduces the optimum Q^2-factor of about 1.5dB compared to the single-channel optimum performance. Despite the low chromatic dispersion of the NZ-DSF, the penalty brought by cross nonlinear effects is small due to the relatively high symbol rate (28Gbauds) which reduces the efficiency of cross nonlinearities [20]. In the lower figure, it can be clearly seen that inter-channel nonlinear effects brought by neighbouring 10Gb/s NRZ channels further reduce the transmission performance and reach as compared with that obtained with 100Gb/s iRZ-PDM-QPSK neighbouring channels. Firstly, the reach is reduced from 1200km to 800km and secondly the optimum performance is just below 10dB of Q^2-factor.

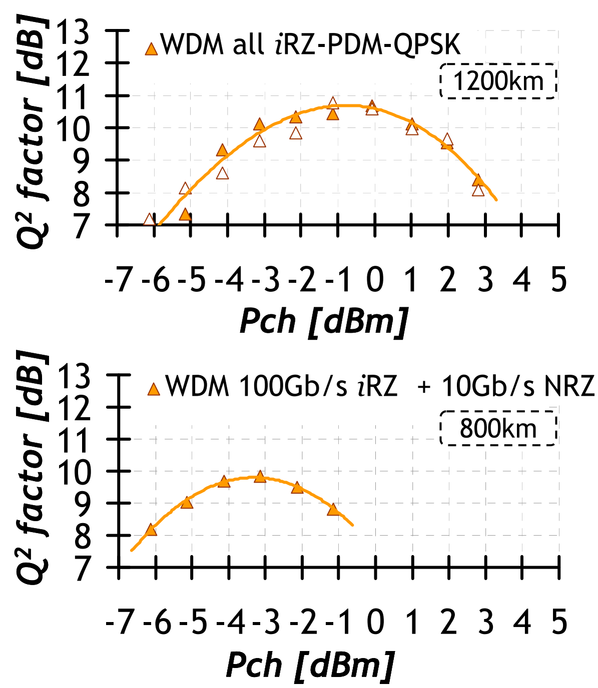

Fig. 5. Tolerance to cross nonlinear effects in a homogenous WDM transmission after 1200km, with (full symbols) and without (empty symbols) emulation of optical filtering and crosstalk (top). And tolerance to cross nonlinear effects in a in a hybrid WDM transmission after 800km with such an emulation (bottom).

C. *Containing inter-channel effects in hybrid WDM systems*

One option to improve the performance of a 100Gb/s coherent iRZ-PDM-QPSK channel in hybrid WDM

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configuration is to introduce band-gaps between iRZ-PDM-QPSK and 10Gb/s NRZ channels to contain inter-channel nonlinear impairments. This option was already investigated in [8] to overcome penalties brought by 10Gb/s NRZ channels onto a coherent PDM-QSPK channel operating at 40Gb/s over a SSMF based system. However, a limited band-gap as large as 300GHz was not sufficient to recover the penalties due to inter-channel effects induced by 10Gb/s NRZ channels in that experiment. Since inter-channel effects appear to be less penalizing when increasing bit rate from 40Gb/s to 100Gb/s, we aim here at measuring and comparing the required band-gap for the insertion of a coherent PDM-QPSK channel at both 40Gb/s and 100Gb/s with only 1dB performance penalty.

As depicted in Fig. 6 a, we investigate this option by gradually moving away two sets of 20 adjacent channels (up to 1.1THz) on both sides of the 100Gb/s test channel. Ideally, when surrounding channels are far enough from the test one, the performance of the test channel should be the same as in a single channel transmission. The total number of channel is kept constant and the output power of inline amplifiers is set at 15dBm, corresponding to a launch power of -1dBm per channel.

Fig. 6 b shows the OSNR sensitivity for both 100Gb/s and 40Gb/s iRZ-PDM-QPSK. 40Gb/s shows a 4-dB better noise sensitivity according to the ratio between the bit rates, 10log(40/100). Therefore, to ease comparison between both bit rates, we contain the power of the 40Gb/s test channel at -5dBm (4 dB lower than that of the 100Gb/s channel), in order to obtain approximately the same performance in single channel transmission. In the meantime, the power of the 10Gb/s NRZ channels is kept at -1dBm to ensure that the test channel at 40Gb/s experiments the same amount of inter-channel effects as at 100Gb/s.

The results of these measurements are depicted in Fig. 6 c after 800km for both 40Gb/s and 100Gb/s coherent iRZ-PDM-QPSK channels. It can be seen that 100Gb/s iRZ-PDM-QPSK is clearly less impacted by impairments brought by 10G/s NRZ neighbours than 40Gb/s iRZ-PDM-QPSK. The maximum penalty is observed, as expected, when no band-gap separate the 10G NRZ channels from the test channel, corresponding to a minimum 50GHz-spacing. This penalty is about 4dB at 100Gb/s whereas it exceeds 5dB at 40Gb/s, thus highlighting the lower tolerance of the 40Gb/s solution against inter-channel effects [10][19]. Moreover, the band-gap required to ensure less than 1dB penalty in the performance of the 100Gb/s channel is of 400GHz, whereas at 40Gb/s a band-gap 200GHz larger is required, i.e. 600GHz of band-gap.

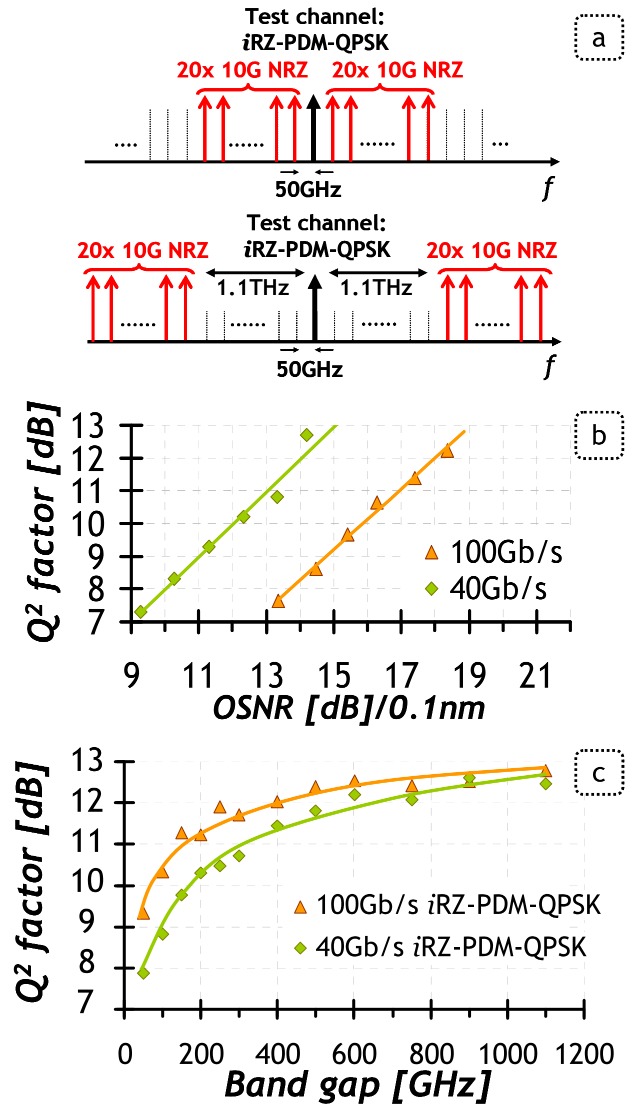

Fig. 6. Channel allocation used when moving away neighbour channels (a), optical noise sensitivity comparison between 40Gb/s and 100Gb/s (b) and performance evolution versus band-gap around iRZ-PDM-QPSK channel (c) after 800km transmission for 100Gb/s (orange triangles) in a hybrid WDM configuration and 40Gb/s (green diamonds).

The better behaviour against nonlinearities of iRZ-PDM-QPSK at 100Gb/s compared to that at 40Gb/s is attributed to the equivalent filter of the phase estimation process in the coherent receiver that becomes more effective as the baud rate of the coherent-detected signal increases with respect to that of neighbouring channels [10]. Indeed, the baud rate increase naturally introduces a longer correlation of induced phase noise over consecutive symbols, thus enabling a more accurate recovery of the carrier phase and a reduction of the inter-channel related impairments.

Finally, the total transmitted capacity of the system should be drastically reduced to ensure performance of 40Gb/s iRZ-PDM-QPSK in a hybrid 10G/40G WDM system whereas at 100Gb/s a narrower band gap could be considered.

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IV. CONCLUSION

We have investigated the penalties caused by intra-channel and inter-channel nonlinear impairments onto 100Gb/s coherent PDM-QPSK channels over a NZ-DSF based transmission test-bed. We have firstly shown that temporally interleaving polarisation tributaries of coherent RZ-PDM-QPSK channels at 100Gb/s is attractive for long-haul transmission of 100Gb/s data. Moreover, we have studied the potential of the introduction of band-gaps in the multiplex to contain nonlinear penalties caused by neighbouring 10Gb/s NRZ channels when upgrading legacy optical networks and demonstrated that leaving a 150GHz band-gap would provide 2dB improvement of Q^2-factor margins for industrial operation.

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