DIMINISHED NONLINEAR IMPACT OF BIT-ALIGNED POLARIZATION MULTIPLEXING WITH ADVANCED MODULATION FORMATS ON SUBSEA CABLES

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Abstract: Investigations from subsea field trials and simulations demonstrate that the choice of using bit-interleaved or bit-aligned polarization multiplexing changes as baud rates are increased, even for an increase from 11.4 Gbaud to 15.3 Gbaud. Polarization bit-aligned formats save in receiver complexity; however past publications have shown that polarization bit-aligned formats are more susceptible to nonlinearities (10 Gb/s, 40 Gb/s and RZ 100 Gb/s). This paper provides data to support that this is not the case for 100 Gb/s NRZ PM-BPSK and therefore polarization bit-aligned formats may be used without compromise.

1 INTRODUCTION

Modulation formats and their respective tolerance to nonlinearities are of particular importance for subsea cable systems. Due to the fast rate of bandwidth growth and high deploy cost, the field of submarine transmission places ultimate capacity as a primary design goal along with ultra-long reach. Legacy submarine cable systems are faced with the challenge of doubling or tripling the initial designed capacities in order to meet demand and extend the life of expensive subsea fiber plants. Moving to advanced modulation systems is highly beneficial for prolonging the service life of existing cable systems, but must be flexible and robust to close all challenging trans-oceanic links. Upgrades often face the problem of higher than optimal power per channel along with ultra-long transmission and therefore the tolerance of modulation formats to nonlinearities is critical.

Polarization multiplexing is a well-known technique to increase spectral efficiency by potentially a factor of two and can be performed either by interleaving or aligning the bits temporally. Past studies have examined the effect of the option on transmission and specifically the tolerance to nonlinearities. Experiments have been performed with a range of formats and baud rates including 10 Gbaud polarization-division-multiplexed RZ DQPSK, DPBSK, and OOK [1], 42.8 Gb/s RZ polarization-multiplexed QPSK [2], and polarization-multiplexed 107 Gb/s RZ-DQPSK [3], all demonstrating an increased nonlinear tolerance from bit-interleaving. Theory and experiment both show that the benefit can be significant for WDM (wavelength-division multiplexed) dispersion-managed links, with up to 5.2 dB increase in nonlinear tolerance [2].

The dispersion map and fiber types used for a particular link have significant effect on the nonlinear tolerance of bit-aligned formats for these susceptible formats and baud rates. This is of particular importance for subsea systems in which the links are dispersion-managed and in-line compensation is implemented and permanent. The sections in this paper will review the relative effect of polarization bit-interleaved and bit-aligned formats for regimes in which inter-channel nonlinearities are dominant and, alternatively, those in which intrachannel nonlinearities are the limiting effect.

Past studies led to the wide adoption of polarization bit-interleaving in order to increase reach. However, this choice was made at the sacrifice of increased receiver complexity and PMD tolerance [3]. The use of bit-aligned formats reduces the PMD for the receiver to compensate and in power-stressed applications when the number of taps is at a premium, bit-aligned can offer an advantage. Presented in this paper are subsea field trial results and simulations demonstrating that this is not the case for WDM 100 Gb/s NRZ PM-BPSK over dispersion-managed links and therefore the choice of polarization bit-aligned versus bit-interleaved can be determined purely by coherent receiver design.

2 TESTING CONFIGURATION

Data is presented herein from two subsea field trials performed on dark fiber pairs. The trial submarine line terminal equipment (SLTE) is capable of full WDM loading on a 25 GHz ITU grid and is shown below in Figure 1. The transmitter's channel under test is fully tunable and modulated with a single IQ modulator driven by a pattern generator (PPG) at 11.4 GBaud for 40 Gb/s testing and 15.3 Gbaud for 100 Gb/s. All of the testing was performed with BPSK formats due to the needed reach for these challenging subsea segments; however the test configuration is additionally capable of QPSK modulation and detection. The baud rate for 100 Gb/s accommodates additional overhead to support soft-decision FEC. The modulated signal is split with a polarization maintaining splitter (PMS) and multiplexed by delaying one arm by approximately 100 symbols and recombining using a polarization beam combiner (PBC).

The aggressor channels are generated using a second IQ modulator operating on a DFB-based WDM comb with 25 GHz spacing across the full bandwidth of the subsea repeaters. The loading channels are decorrelated in time by passing through a de-interleaver and interleaver pair connected with patch cords of varying lengths. The signal is passively combined with the test channel and the entire signal is amplified and transmitted through a dynamic spectral equalizer (DSE) which is used for pre-emphasis and sweeping of power per channel.

In the trial receiver the channel under test is first optically filtered before going into a standard intradyne PM-QPSK optical demodulator with balanced photoreceivers and a 100 kHz linewidth local oscillator (LO). The analog RF outputs are digitized using a 12.5 GHz bandwidth, 50 GSps real-time oscilloscope which provides 4 million sample captures that are processed off-line using the same algorithms as in production line cards.

Performance was characterized using pre-emphasis to sweep the relative power of the test channel and 8 total neighboring channels. Subsea systems use repeaters with constant optical power and thus changing the total launch power can't be

used to sweep power per channel and

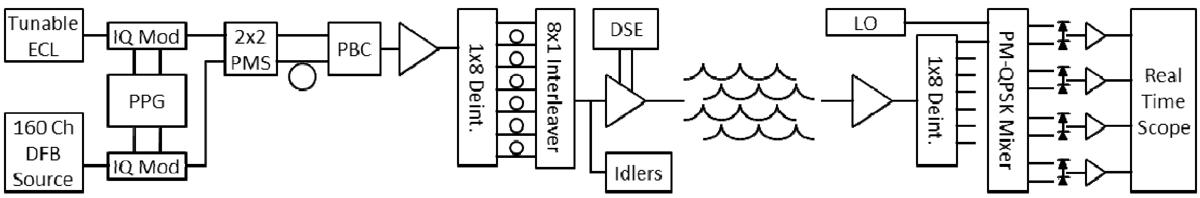

Figure 1: SLTE trial configuration showing the 25GHz-spaced transmitter capable of up to 160 channels and a single channel coherent receiver.

OSNR. However, the OSNR may be swept by raising and lowering a single channel or group of channels relative to the rest of the spectrum. The use of four neighbor channels on each side of the test channel maintains a realistic cross-phase modulation (XPM) penalty. The bit error rate is measured at each power level and converted to a Q factor.

3 SUBSEA LINKS

Two subsea links with similar lengths and different fiber types were analyzed through field trials and simulations to study the differences between using polarization bit-interleaved and polarization bit-aligned formats in a WDM system. Both links are dispersion-managed, as is the case for all legacy subsea repeated links. The first link reviewed has a total transmission distance of 5700 km and consists of NZDSF with NDSF compensation spans. This fiber system has relatively low dispersion as can be seen in Table 1 shown below and also visible from the dispersion map shown in Figure 2. This link will be referred to as the NZDSF link. The second link has a transmission length of over 4200 km and consists of LEAF, RS, and DCF as described in

Fiber Type	Dispersion (ps/nm)	Dispersion Slope (ps/nm-km)	Attenuation (dB/km)	Effective Area (µm2)
DCF	18.55	0.055	0.177	75
LEAF	-4	0.06	0.206	70
LEAF+RS	-3.525	0.088	0.206	50

Table 2 and illustrated by a second dispersion map below in Figure 3. It will be referred to as the LEAF link.

Fiber Type	Dispersion (ps/nm)	Dispersion Slope (ps/nm-km)	Attenuation (dB/km)	Effective Area (µm2)
DCF	19.2	0.055	0.19	72
NZDSF	-1.75	0.07	0.202	50

Table 1: Fiber parameters for NZDSF link.

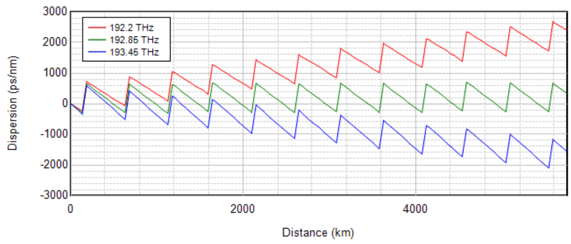

Figure 1: Dispersion map for NZDSF link.

Fiber Type	Dispersion (ps/nm)	Dispersion Slope (ps/nm-km)	Attenuation (dB/km)	Effective Area (µm2)
DCF	18.55	0.055	0.177	75
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Table 2: Fiber parameters for LEAF link.

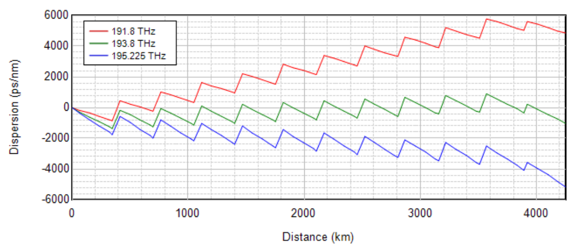

Figure 2: Dispersion map for LEAF link.

4 INTERCHANNEL - DOMINANT REGIME

Polarization-multiplexed formats can experience an increase in nonlinear penalties in comparison to single polarization transmission due to nonlinear polarization scattering and crosspolarization modulation (XPolM). If chromatic dispersion (CD) accumulation is small, as in dispersion-managed links, data dependent nonlinear polarization rotation induces nonlinear polarization scattering [4]. Such depolarization from XPolM leads to crosstalk and can dominate over cross-phase modulation (XPM) [5]. Links and wavelengths with low CD will experience an insufficient walk off between channels and suffer from high nonlinear penalties from XPM and XPolM. Polarization bit-interleaving has been shown to increase nonlinear tolerance in such regimes. The use of interleaving can reduce the number of possible states of polarization (SOP) and thereby cause less nonlinear polarization scattering [4]. In addition, the peak power is reduced in the interleaved format, thus also reducing nonlinear penalties [3,6].

The benefit of bit-interleaving can therefore be most strongly observed on the NZDSF link around the zero-dispersion wavelength where the CD accumulation is low and XPM and XPolM high. The zero-dispersion wavelength corresponds to the part of the spectrum which will repeatedly pass through zero accumulated chromatic dispersion, as illustrated with the green lines in the dispersion maps in Figures 2 and 3. Figure 3 illustrates the higher degree of nonlinearities at this zero-dispersion wavelength (192.85 THz) and the consequent higher benefit from polarization bit-interleaving at that part of the spectrum (0.5 dB of Q at optimal power per channel) for 40 Gb/s NRZ PM-BPSK.

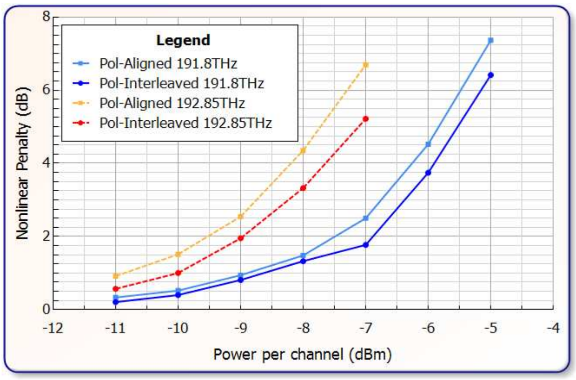

Figure 3: Simulation results over the NZDSF link comparing performance with 40 Gb/s BPSK with polarization bit-aligned and bit-interleaved at an edge and center wavelength

Testing was repeated with 100 Gb/s NRZ PM-BPSK and nonlinear tolerance was examined at the higher baud rate. The shorter bit length leads to a faster channel walk off and therefore a decreased level of XPM and XPoLM [7]. Therefore, the benefit of polarization bit-interleaved formats over polarization bit-aligned formats is also decreased. The simulations shown in Figure 4 illustrate this decrease in benefit. These results were verified during a field trial over the link and resulted in even less difference between polarization bit-interleaving and the bit–aligned format, as shown in Figure 5. The field trial results are expected to show less benefit for polarization bit-interleaved formats as the simulations do not take into account fiber birefringence which serves to randomize the SOP [5].

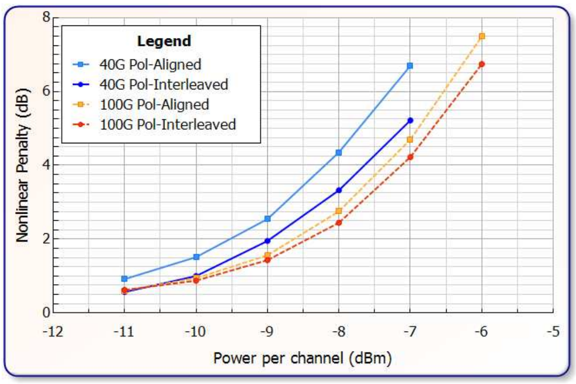

Figure 4: Simulation results over the NZDSF link comparing performance with 40 G BPSK and 100 Gb/s BPSK with polarization bit-aligned

and bit-interleaved at the zero-dispersion wavelength.

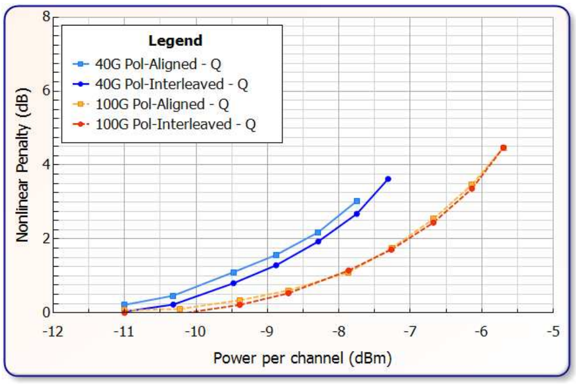

Figure 5: Field trial results over the NZDSF link showing the comparative difference between formats at the zero-dispersion wavelength.

5 INTRACHANNEL - DOMINANT REGIME

The second link examined with these modulation formats falls into a regime in which intrachannel nonlinearities such as self-phase modulation (SPM) and nonlinear phase noise (NLPN) are more dominant than interchannel nonlinearities. Therefore the difference between polarization bit-interleaving and polarization bit-aligning is considerably smaller even at 40G PM-BPSK. The simulation results for 40 Gb/s NRZ PM-BPSK and 100 Gb/s NRZ PM-BPSK are shown below in

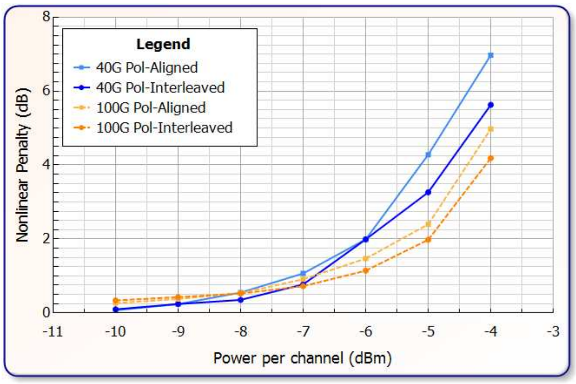

Figure 6.

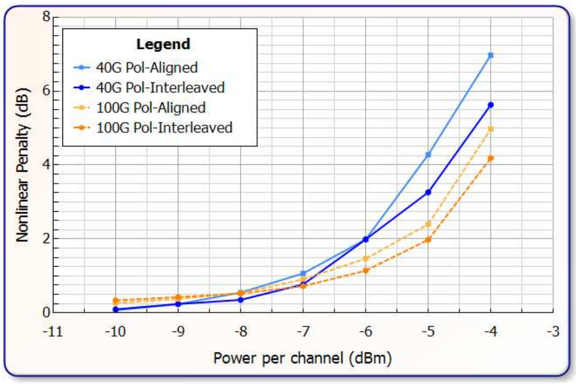

Figure 6: Simulation results over the LEAF link comparing performance with 40 Gb/s BPSK and 100 Gb/s BPSK with polarization bit-aligned and bit-interleaved formats at the zero-dispersion wavelength of 193.4 THz.

These simulation results were verified over the LEAF link and showed even less difference between polarization bit-interleaving and polarization bit-aligning formats. Again, this demonstrates that the difference between the two formats is reduced in practice when compared to theory. The experimental results are shown in Figure 7.

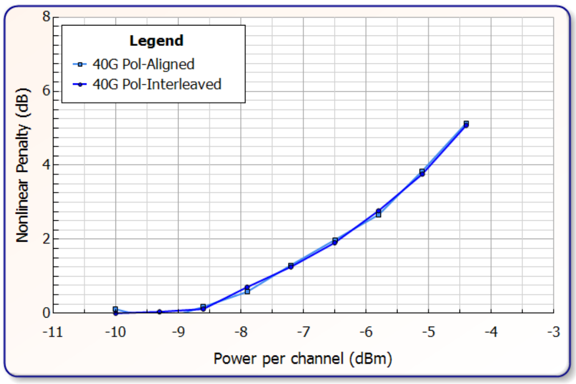

Figure 7: Experimental results over the LEAF link comparing performance with 40 Gb/s BPSK with polarization bit-aligned and bit-interleaved formats at the zero-dispersion wavelength of 193.4 THz.

6 CONCLUSIONS

Simulations and field trial results show that the choice between polarization bit-interleaved formats and polarization bit-aligned formats may be decided solely by the optimal choice for coherent receiver design. Newer fiber types and dispersion maps along with higher baud rates and the use of NRZ formats will lead to highly SPM and nonlinear phase noise - dominant regimes in which polarization bit-interleaving offers negligible benefit for nonlinear tolerance.

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