Experimental Demonstration of a 4D PDL-resilient Signaling for Long-haul Networks

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Abstract: We experimentally demonstrate improvement of the worst-case information rate using the New Spatially Balanced (NSB) signaling recently proposed for PDL mitigation. NSB-coded and dual-polarization QPSK formats are compared over a multi-span link with inline PDL. © 2020 The Author(s)

1. Polarization Dependent Loss in Modern Optical Networks: Modeling

In coherent optical fiber transmission networks, Polarization Dependent Loss (PDL) is a linear, non-unitary impairment expected to have a strong impact in next-generation systems [1]. PDL-mitigating solutions have been proposed including Polarization-time (8-dimensional) Silver coding [2] but it comes with increased equalization complexity. Thus, in previous works we proposed PDL-resilient 4D modulations that make better use of the existing in-phase and quadrature (on 2 orthogonal polarization states) dimensions. Providing diversity or orientation gains, the worst-case performance is significantly enhanced by a joint modulation of information over the 4 dimensions. From all possible 4D unitary transforms, the *New Spatially Balanced* (NSB) signaling [3], is proven to maximize the worst information rate encountered over all possible channel states. This paper aims at experimentally demonstrating the gain on a distributed PDL link compared to the standard Dual-Polarization (DP) scheme.

A memoryless distributed-PDL optical channel model can be simplified as a lumped 2×2 MIMO channel $\mathbf{Y} = \mathbf{HX} + \mathbf{Z}$ where $\mathbf{Z}$ is a Gaussian complex noise with unit covariance, $\mathbf{X}$ is a DP input and $\mathbf{H}$ is the transfer matrix of the PDL channel, unknown at the transmitter. After simplification [3], the channel transfer matrix can be simplified to $\mathbf{H} = \mathbf{D}_\gamma \mathbf{R}_\alpha \mathbf{B}_\beta$ to study PDL penalties. The matrix $\mathbf{D}_\gamma = \mathrm{diag}\left\{\sqrt{1+\gamma}, \sqrt{1-\gamma}\right\}$ captures the PDL-induced gain imbalance, the PDL being $\Lambda = 10\log_{10}(1+\gamma)/(1-\gamma)$ (dB). The complex phase retardance matrix $\mathbf{B}_\beta = \mathrm{diag}\left\{e^{i\beta}, e^{-i\beta}\right\}$ and the real rotation matrix $\mathbf{R}_\alpha$ define the signal incident SOP on the PDL element. In addition to the PDL intrinsic loss, the information rate also strongly depends on the incident SOP [3], and in particular on the angle α. The minimum DP-QAM information rate is met for $\alpha = 0$ modulo $\pi/2$ and any β.

2. Performance of the NSB Signaling on Distributed PDL and Discussion

A rate maximization of a unitary 4D transform $f(\mathbf{X})$ of $\mathbf{X}$ DP-QAM boils down [3] to optimizing the 2-parameter function $f_{\eta\nu}(\mathbf{X}) = \cos\eta\mathbf{X} + \sin\eta e^{i\nu}\mathbf{R}_{-\frac{\pi}{2}}\mathrm{conj}(\mathbf{X})$. The optimum pair $(\hat{\eta}, \hat{\nu}) = (\frac{5\pi}{32}, \frac{\pi}{4})$ defines the NSB signaling.

Adapted Data-Aided Equalization Scheme By construction, the NSB signaling is a 4D encoded modulation, information on one polarization is dependent on the other meaning that the classical 2×2 CMA equalizer is unsuitable as it assumes independent polarizations. Consequently, we choose a pilot-based DSP approach for channel estimation and equalization and compare the performance of standard DP and NSB-coded signals using the same processing. The latter consists in normalization and resampling of the acquired signals, chromatic dispersion compensation when needed, time and frequency synchronization, data-aided channel estimation and multi-tap MMSE equalization, followed by carrier phase noise compensation. Constant Amplitude Zero Autocorrelation (CAZAC)

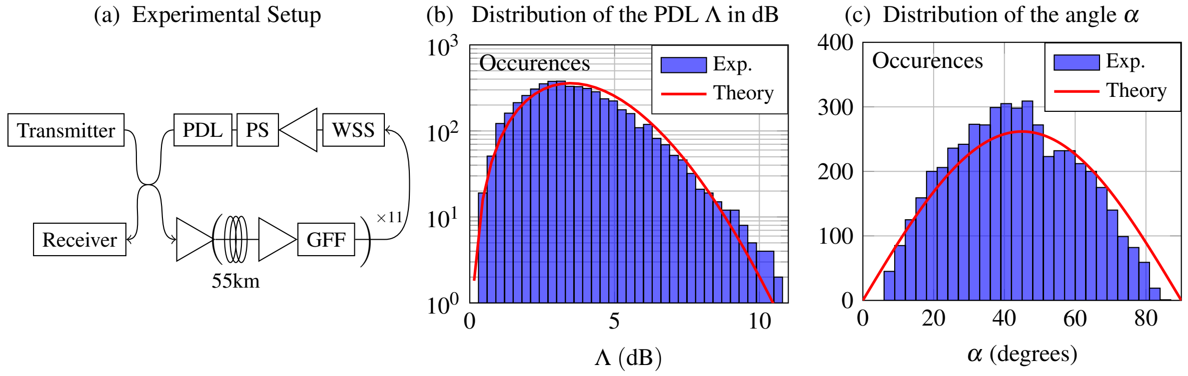
(a) Experimental Setup (b) Distribution of the PDL Λ in dB (c) Distribution of the angle α

Fig. 1: Experimental setup (a): recirculating loop with in-line PDL, 11x55km fiber spools, GFF: Gain Flattening Filters, WSS inserted to ensure a flat spectrum over the C-band, PS: Polarization Scrambler, and EDFA amplifiers. Channel parameters distribution (b and c) of $n = 15$ concatenated, randomly oriented, PDL elements of 1.1dB.

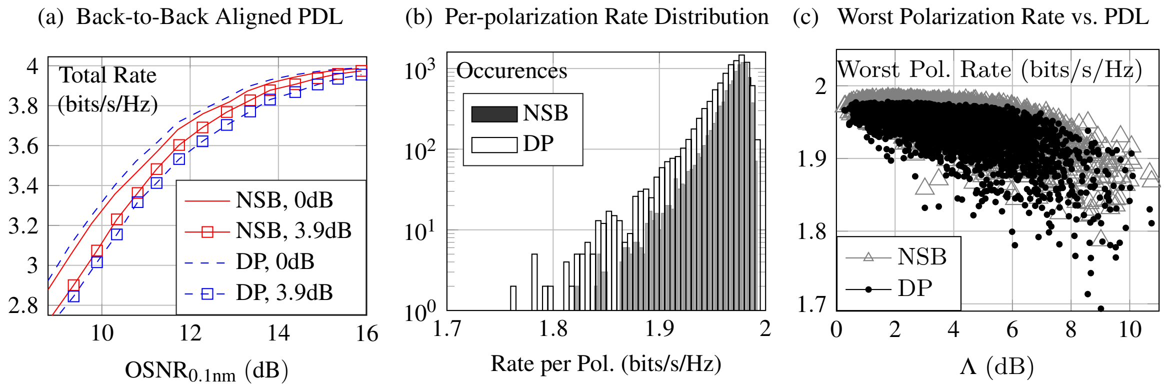
(a) Back-to-Back Aligned PDL (b) Per-polarization Rate Distribution (c) Worst Polarization Rate vs. PDL

Fig. 2: Performance comparison of DP- and NSB-QPSK in back-to-back and distributed scenarii.

sequences of length $l_c = 64$ repeated $n_{\text{rep}} = 10$ times are used for channel estimation. Carrier phase noise estimation is performed via periodically inserted short sequences of 8 random QPSK symbols each 400 payload symbols. Finally, information rates per polarization are computed as the mutual information between the equalized signal and the corresponding transmitted tributary. From the estimated channel, singular value decomposition of the central tap $\mathbf{H_0}$ provides the overall PDL Λ and SOP.

Distributed PDL Experimental Setup The channel under test at 1545.72nm is modulated with polarization-multiplexed 32GBaud signals with 2^{14} symbols where synchronization and channel estimation pilots are at the forefront. Payload symbols are then equally divided in firstly standard DP-QPSK and secondly as NSB-QPSK. This frame structure enables a performance comparison between the two schemes for the same observed channel at each acquisition. The added pilots represent 6.25% of the total frame. Fig. 1a represents the experimental setup. The tested channel at 32GBd is inserted in a recirculating loop along with 87 loading channels modulated at 49GBd covering the C-band. The loop consists of 11 spans of 55km low-PMD fibers as well as a $\Lambda = 1.1$dB PDL emulator preceded by a controllable polarization scrambler. The scrambler randomly changes the SOP for each loop. After 15 loops yielding a total distance of 9075km, the signal is acquired through an80GSa/s scope. To cover different channel states, 5000 acquisitions are recorded. Fig. 1b shows the statistics of the estimated overall Λ that fit well with the theoretical Maxwell distribution [4] of mean $0.92 \times 1.1\sqrt{15} = 3.9$dB. Fig. 1c depicts the rotation angle α statistics defined in section 1. The obtained circular-shaped distribution shows the Poincaré sphere uniform sampling. The retardance angle β uniformally distributed in $[0, 2\pi)$ is not displayed here for space constraints.

After the channel statistics, we compare the information rates of the two modulation schemes. First, we evaluate the total rate over both polarization tributaries in a back-to-back experiment without PDL (no markers). We see in Fig. 2a that the NSB-coded part suffers a small penalty compared to standard DP-QPSK mainly due to imperfect phase estimation. Given that the NSB consists in mixing the I/Q dimensions of the two polarizations, sensitivity to phase recovery imperfections increases. At $\text{OSNR}_{0.1\text{nm}} = 13$dB (the measured value after 15 loops) the penalty is 0.0125bit/s/Hz. While remaining in back-to-back, we add a 3.9dB loss (corresponding to the average PDL after 15 loops) over one polarization at the transmitter to emulate the aligned PDL case where coding gains are expected to be the highest [3] and measure the total rate shown in squared markers. Rate enhancement is clearly illustrated over all the measured OSNR range. Next, we analyze the information rates per polarization after transmission over 9055km for all encountered Λ values and SOP states. For the NSB-coded part, the measured penalty in back-to-back at an OSNR of 13dB is added to assess the PDL-mitigation gain independently of imperfect phase recovery. Fig. 2b displays the measured rates statistics for the two schemes. A net worst case enhancement and a rate fluctuations reduction is observed for the NSB part. Finally we represent in Fig. 2c the measured rates of the most-impaired polarization for NSB- and DP-QPSK modulations as a function of the corresponding estimated PDL. Again, the alleviation of the worst case is well observed when the joint 4D signaling is employed.

3. Conclusion

The novel NSB signaling that guarantees one-timeslot optimal PDL-resilience has been successfully tested and experimentally validated over a distributed PDL link. While suffering from a small implementation penalty, it gives an information rate improvement. First investigations exhibit an implementation penalty due to imperfect carrier phase noise estimation, that has a stronger impact on the NSB 4D signaling than on standard DP scheme.

References

1. H.-M. Chin et al., "Probabilistic Design of Optical Transmission Systems," JLT, vol. 35, no. 4, 2017.
2. S. Mumtaz et al., "Space-time codes for optical fiber communication with polarization multiplexing," ICC 2010, pp. 1-5.
3. A. Dumenil et al., "Rate Optimization Using SO(4) Transforms for PDL Mitigation," 2019 ECOC, Dublin, September 2019, W.2.D.4.
4. L. E. Nelson et al., "Statistics of Polarization Dependent Loss in an Installed Long-Haul WDM System," Opt. Express 19, 2011