Low-Complexity Polarization Coding for PDL-Resilience

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Abstract *We propose a new and low-complexity 4D-signaling that ensures polarization-multiplexed systems to be resilient against polarization dependent loss. For 16QAM modulation above 0.85-coding rate, the required SNR for error-free transmission at 6dB-PDL is relaxed by 0.5 dB or more.*

Introduction

Polarization dependent loss (PDL) is a non-unitary channel impairment that generally affects polarization-multiplexed coherent optical systems. Discrete optical components such as wavelength selective switches (WSSs) cause an SNR imbalance between the two polarization components. This may reach 0.5 dB per WSS. Along a terrestrial network, these impairments add up and lead to possible system outage[1,2]. While polarization mode dispersion (PMD) is well addressed using a linear equalizer, the non-unitary PDL impairment reduces the overall system performance[1]. Current optical systems are designed with extra rate and SNR margins to cope with PDL. For future systems, signaling schemes such as polarization-time codes[3–5] or pairwise coding[6] have been suggested to reduce the rate degradation due to PDL. In this work, we present a new and simple PDL-resilient scheme that recovers the polarization imbalance by performing spatial averaging of the transmitted signal on well-defined orthogonal subspaces. The new polarization code operates at the symbol level and the implementation complexity is similar to standard polarization-multiplexed square QAM. In this paper, we demonstrate the performance of the new scheme with expected SNR gains above 0.5 dB. For illustration purpose, by means of numerical simulations and experimental measurements, a gain of 0.14 bits/cu is reported at SNR = 18dB for dual-polarization-16QAM (DP-16QAM).

PDL Channel Model and Performance

A simple model for tackling PDL is the 2×2-MIMO channel with output $Y = HX + Z$, where X is the polarization-multiplexed input, $H = H(\alpha, \beta, \gamma)$ is the PDL matrix, and Z an additive white Gaussian noise. More precisely, the random PDL matrix decomposes as $H(\alpha, \beta, \gamma) = D_\gamma R_\alpha B_\beta$ where R_α is a real-valued rotation matrix representing the input incident angle $\alpha \in [0, 2\pi)$, D_γ denotes the real-valued eigenvalues $\{\sqrt{1+\gamma}, \sqrt{1-\gamma}\}$ with gain imbalance $\Gamma = 10\log((1+\gamma)/(1-\gamma))$ in dB, and $B_\beta = \mathrm{diag}\{e^{i\beta}, e^{-i\beta}\}$ is the phase birefringence matrix with $\beta \in [0, 2\pi)$. A frequency-flat model is assumed (negligible PMD). In the standard continuous input and power constraint case,

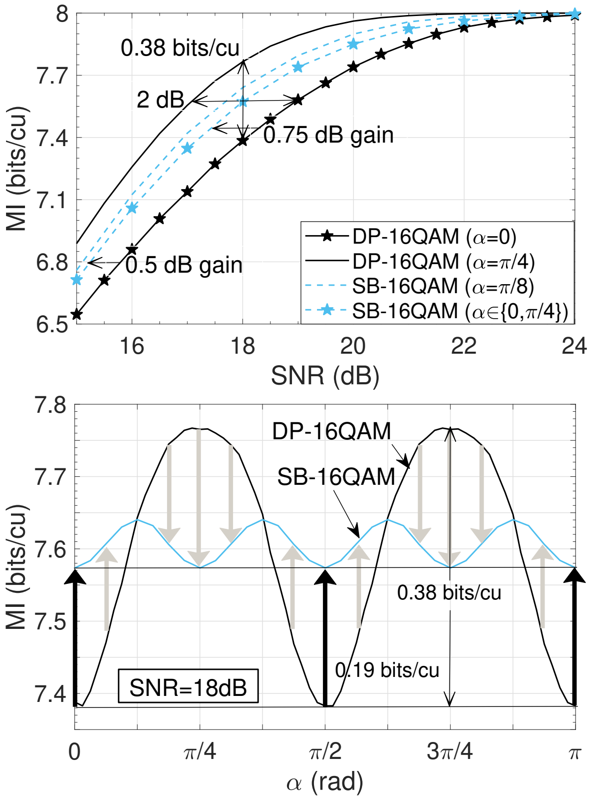

Fig. 1: DP-16QAM and SB-16QAM mutual information (MI) in a 6dB-PDL channel as a function of SNR (top) and α (bottom).

the MIMO channel capacity solely depends on γ. In the discrete case however, it also depends on the two angle α and β. Significant SNR variations are observed as a function of the incident angle α for a given spectral efficiency. They can reach 2 dB for DP-16QAM as shown in Fig. 1 (top picture) where $\beta = 0$. We can see the equivalent variation in α for SNR = 18 dB in Fig. 1 (bottom picture). As later explained, the case $\beta = 0$ turns out to be related to the worst case performance for DP-16QAM. This case is used as a base reference in this paper when constructing efficient polarization codes. Optical systems rely on design margins (in terms of SNR, rate) that guarantee them to be robust against worst case scenarios (PDL, nonlinearities...) and ensure error-free transmission. This work is based on a careful analysis of the MIMO model. It aims at improving the worst case performance in order to relax provisional system margins.

Towards PDL-Resilience

For a given PDL level, the design of efficient polarization-multiplexed modulation reduces to the mitigation of angle dependencies. In the optical literature, the Silver code is shown[3,7] to reach a performance level close to the best uncoded QAM case for any α. The Silver code is a 2-timeslot code whose equalization complexity makes it challenging to implement in practice. Motivated by complexity constraints, emphasis has been drawn on constructing efficient 1-timeslot solutions. Pairwise coding[6] is a first attempt in this direction. Although it may improve the system performance in several instances, it can be shown that the MI minimas are eventually simply shifted in the (α, β) plane: it implies that the overall worst case remains the same. In this work, we propose a low-complexity 1-timeslot modulation scheme that universally leverages the system performance by uniformaly improving the worst case scenarios. Let us give some insight on the proposed construction. Observe that $H(\alpha, \beta = 0, \gamma) = D_\gamma R_\alpha$ is real-valued. The complex output $Y = HX + Z$ decomposes as $Y_{\text{Re}} = HX_{\text{Re}} + Z_{\text{Re}}$ and $Y_{\text{Im}} = HX_{\text{Im}} + Z_{\text{Im}}$ where Re and Im respectively denotes the real and imaginary parts. When using conventional square QAM points on both polarizations, both real and imaginary parts experience the same H with incident angle α. In order to mitigate the dependency in α, let us consider the 2D-projection planes supporting the real (respectively imaginary) parts of the 4D DP-QAM constellation. Exploiting the symmetry and periodicity of the DP-QAM MI as illustrated in Fig.1 (bottom picture), we rotate these planes such that their relative orientation angle corresponds to half the DP-QAM MI period. A simple version for square QAM is to leave the real parts unchanged and rotate the imaginary ones by $\pi/4$, i.e., send $(X_{\text{Re}}, R_{\pi/4} X_{\text{Im}})^T$. Then, the transmitted signal virtually experiences two opposite polarization states, i.e., an averaged case. Fig. 1 (bottom picture) shows the reduced α dependency at SNR 18dB of this spatially balanced (SB) signaling used with 16QAM and denoted by SB-16QAM. Equivalently, 0.75 dB SNR gains are achieved as shown in Fig. 1 (top picture).

Complete Optical Link Simulation

The presented PDL-resilient signaling is based on an mathematical but rather simple MIMO channel model. In order to experimentally validate the new modulation format, we first want to simulate the full communication link. This is the aim of this section, which also permits us to estimate implementation penalties. Compared to usual DP-MQAM-based DSP architecture, a few modifications are required in particular regarding equalization. The constant modulus algorithm (CMA)

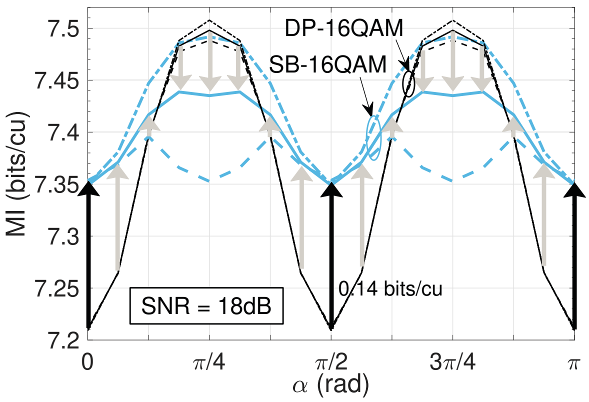

Fig. 2: MI β dependence at SNR 18dB: minimum (at $\beta = 0$), maximum (at $\beta = \pi/8$ for DP, $\beta = \pi/4$ for SB) values in dashed lines, and for an intermediate value in full line. Simulated 6dB-PDL channel with $\alpha \in [0, \pi]$. The arrows depict relative gains ΔMI = $\text{MI}_{\text{SB-16QAM}}$-$\text{MI}_{\text{DP-16QAM}}$ that reach 0.14 bits/cu in the worst case (black arrows).

commonly used for adaptative MIMO equalization assumes that independent input streams are sent on the two polarization components. In the case of SB-MQAM-based architecture, these two components are no longer independent as the imaginary parts are linked by the applied $\pi/4$-rotation. For mimicking the complete fiber channel, birefringence is included in the PDL channel and carrier phase noise is added at the receiver and transmitter side (40kHz-linewidth lasers). We use a pilot-based chain to deal with these impairments. For simplicity and as a proof-of-concept, we partition the signaling frame using as many standard DP-16QAM symbols as PDL-resilient SB-16QAM symbols. The first half of the frame contains the DP-16QAM symbols. The receiver first learns the optical channel using the CMA on the DP-16QAM symbols. Second, the whole frame is equalized with the previously learnt MIMO filter. Every 500 symbols, 12 phase recovering pilots are inserted (2.4% pilots) for carrier phase correction. Time-synchronization symbols are placed at the frame front for pilot identification. In Fig. 2, the lower dashed MI curves for both signaling schemes correspond to $\beta = 0$ (worst case discussed in previous section). Notice that unlike the DP-16QAM modulation, the SB-16QAM exhibits a high dependency on β. The presence of birefringence enhances the performance of our signaling leading to a higher average performance. The new signaling universally improves the link performance as its lowest MI is raised at least to the middle value between the uncoded best and worst cases (black arrows at $\alpha = 0 \bmod \pi/2$).

Experimental Validation of PDL-Resilience

The experimental setup is depicted in the middle picture of Fig. 3. The 32 Gbaud polarization-multiplexed signal is generated by 88 GSa/s digital-to-analog Converters (DAC), modulating a

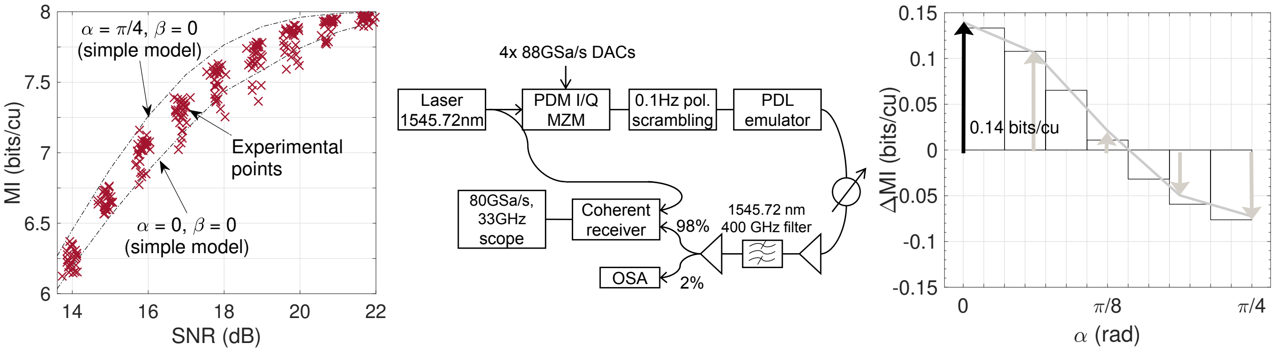

Fig. 3: Left: PDL channel MI against SNR (deduced from the OSNR measured by the OSA) curve for DP-16QAM in a conventional DSP chain. Middle: Experimental setup with an emulated target PDL of 6dB. Right: Experimental gains (quantization over 7 bins) with our pilot-based solution at SNR 18dB compared to simulated gains (arrows indicate the expectation over all β).

PDM-I/Q Mach-Zender modulator and then sent through a PDL channel. The PDL channel is emulated with a polarization scrambler that changes the polarization orientation every 10 seconds, followed by a 6dB polarization gain imbalance device. At the receiver, the signal is retrieved with a coherent mixer and a 33 GHz scope. Offline DSP processing follows. In back-to-back experiments with no PDL, MI measurements present a 0.9dB-SNR implementation penalty at SNR 18dB for the two formats. This is an implementation penalty of our lab setup and is therefore not correlated to the new signaling. Hence, this penalty has been removed from the data shown in Fig. 3 for better understanding. The left picture of Fig. 3 shows the experimental fluctuations of the MI associated with conventional DP-16QAM modulation. This is in accordance with the simple PDL channel model. Having observed that the theoretical model captures the essence of the PDL dependence, let us now focus on Fig. 3 right picture. Out of 100 acquisition points at SNR 18dB, we evaluated the gain of the new signaling (measured as the difference between the MI of SB-16QAM and the DP-16QAM) and ordered the values according to the channel incident angle α. We then classified the values into 7 bins that uniformly partition $[0, \pi/4]$ and represented the average gain value for each bin. The grey arrows represent the predicted simulated gains and can be compared to the experimental values. The incident α angle is retrieved from a Singular Value Decomposition of the CMA equalizer matrix at the null frequency component in the frequency domain. We observe a very satisfying matching between experiments and simulations, which fully validates our approach from theory to real-life scenarios. The new signaling experimentally achieves the original expected gains. This is importantly observed at angles near $\alpha = 0$ where conventional PDL worst cases (and design margins) are located. In this region, experiments report gains of 0.14 bits/cu as predicted by simulations.

Conclusion

This paper presents a new PDL-resilient modulation format defined over a single timeslot. First, the analysis of the underlying MIMO Gaussian channel model permits to construct efficient polarization codes and predict raw gains of 0.19 bits/cu for 16QAM-based system at 18dB SNR. Second, link simulations taking into account physical impairments confirm the expectations with estimated gains of 0.14 bits/cu. Finally, the expected gains of 0.14 bits/cu are measured in experiments. This number transposes to 0.75 dB SNR gain for 16QAM at a coding rate of 0.93. Generally, for 16QAM and above 0.85-coding rate, the SNR margin is relaxed by more than 0.5 dB at 6dB-PDL.

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