



HAL
open science

MIMO Coding Technique for PDL and Crosstalk Mitigation in Optical Transmission Systems

Akram Abouseif, Ghaya Rekaya Ben Othman, Yves Jaouën

► To cite this version:

Akram Abouseif, Ghaya Rekaya Ben Othman, Yves Jaouën. MIMO Coding Technique for PDL and Crosstalk Mitigation in Optical Transmission Systems. Optical Fiber Communication Conference (OFC2023), IEEE, Mar 2023, San Diego (CA), United States. pp.W3E.3, <10.1364/OFC.2023.W3E.3>. <hal-04252941>

HAL Id: hal-04252941

<https://telecom-paris.hal.science/hal-04252941v1>

Submitted on 21 Oct 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

MIMO Coding Technique for PDL and Crosstalk Mitigation in Optical Transmission Systems

Akram Abouseif,^{1,*} Ghaya Rekaya-Ben Othman,^{1,2} and Yves Jaouën²

¹ MIMOPT Technology, France

² Télécom Paris, Institut Polytechnique de Paris, France

*akram.abouseif@mimopt.com

Abstract: We propose new coding technique, called IQ-code, to mitigate PDL and inter-channel crosstalk on optical fiber transmission. We obtain 0.3-0.5 dB OSNR gain at FEC limit for any number of sub-carrier by simple ZF decoding. © 2022 The Author(s)

1. Introduction

The capacity of the deployed optical fibers is reaching the Shannon capacity limit; simultaneously, the degrees of freedom in the conventional fiber are already exploited. Several solutions are proposed in order to cope with fast optical network evolution. One promising candidate is digital sub-carrier multiplexing with Nyquist shaping for achieving spectrum efficiency by approaching the channel spacing close to the baud rate. In [1], the authors demonstrated a real-time 800G DSP ASIC using eight digital sub-carriers (DSC). In this work, we aim to enhance the transmission system for single carrier and DSC systems impaired by linear non-unitary effects such as Polarization Dependent Loss (PDL), which results in a degradation in the transmission performance. Space-Time (ST) codes were previously proposed to mitigate non-unitary effects in several optical systems, such as: PolMux systems [2], Multi-mode fibers [3] and Multi-core fibers [4]. However, these ST solutions remain difficult to be implemented on commercial systems due to the use of OFDM equalization that is incompatible with today's digital signal processing (DSP) solutions. In [5], a coding scheme is proposed for PolMux systems to mitigate the PDL using only a one-time slot (does not need to apply OFDM). This scheme is designed for two data streams and therefore it is not scalable. In this paper, we design a new coding technique, called IQ-code, that improves PDL-impaired transmission systems with crosstalk between the channels. The IQ-code provides several benefits: (i) Improvement in the transmission performance by mitigating simultaneously both PDL and inter-channel crosstalk. (ii) Scalable to any number of channels (sub-carriers), (iii) Does not affect the system performance in presence of nonlinear effects, (iv) Low implementation complexity since it uses a one-time slot to keep its implementation compatible with the existing DSP processing. We demonstrate that the IQ-code achieves pre-FEC optical signal-to-noise (OSNR) gain of 0.3 – 0.5 dB over a 1000 km transmission and dual polarized (DP) 16-QAM modulation for eight sub-carriers while employing a simple Zero-Forcing decoding.

2. IQ-Code Technique

2.1. Principle

The basic principle of the IQ code technique is to average the losses of the two polarizations and the different sub-bands over a one-time slot. In a DSC system, the DP N sub-carriers are equivalent to $2N \times 2N$ MIMO system where $2N$ parallel channels are used on the fiber. The information data bits are mapped to quadrature amplitude modulation (QAM) symbols. The symbol vector $\mathbf{X}_{2N \times 1}$ is separated into two vectors, $\Re(\mathbf{X}_{2N \times 1})$ and $\Im(\mathbf{X}_{2N \times 1})$ composed by the real and imaginary parts of the modulated symbols, respectively. The IQ-code codeword \mathbf{X}_{IQ} is given as follows:

$$\mathbf{X}_{IQ} = R_{2N \times 2N} \cdot \Re(\mathbf{X}_{2N \times 1}) + P \cdot R_{2N \times 2N} \cdot \Im(\mathbf{X}_{2N \times 1}) \quad (1)$$

where $R_{2N \times 2N}$ is real rotation matrix of dimension $2N$ and P is defined as Eq.2. Due to the lack of space, we show in Eq.3 an example of real rotation matrix of dimension $2N = 2$ which corresponds to the case of DP single carrier. In the case of eight sub-carriers, we apply a real rotation matrix of dimension $2N = 16$ constructed as proposed in [6]. Fig. 1 illustrates the general structure of the IQ-code codeword.

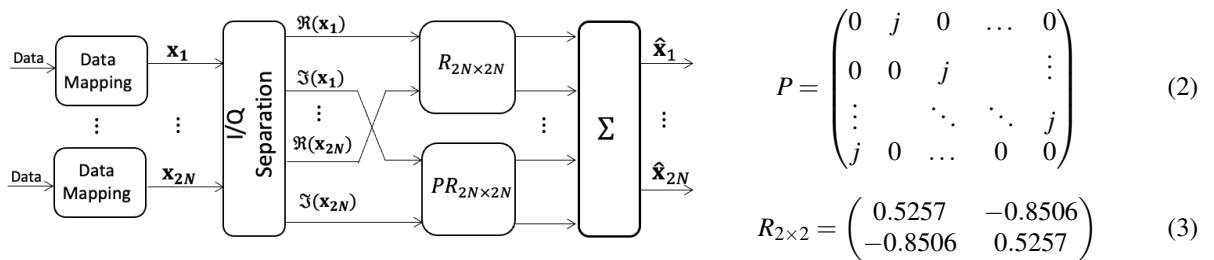


Fig. 1: IQ-code structure

2.2. Validation in Lumped PDL Channel Model

First, we evaluate the IQ-code performance in a single carrier transmission system. In Fig. 2, we illustrate the constellation of the IQ-code (BLUE points) that results from an input of DP-16-QAM modulation (RED points). In this section, a constant lumped PDL channel model is considered as $\mathbf{H}_{PDL} = D_\gamma R_\theta B_\beta$, where R_θ is the rotation matrix and B_β is the birefringence matrix, θ, β in $[-\pi, \pi]$. The total gain matrix $D_\gamma = \text{diag}\{\sqrt{1+\gamma}; \sqrt{1-\gamma}\}$, where $\gamma \in [0, 1]$ that defines the PDL value as $\Gamma_{dB} = 10 \log_{10}(\frac{1+\gamma}{1-\gamma})$. Fig. 3 shows the pre-FEC bit-error-rate (BER) performance function of the optical signal-to-noise-ratio (OSNR). We consider a lumped PDL channel model at the transmitter side with fixed rotation angles $\theta = \{0^\circ, 45^\circ\}$. In Fig. 3(a), we plot the BER performance with PDL $\Gamma_{dB} = 3$ dB. We observe that the uncoded transmission performance has an OSNR penalty of 0.7 dB at FEC limit range = $[3 \cdot 5 \times 10^{-2}]$ compared to back-to-back (B2B) transmission. The IQ-code provides an OSNR gain of 0.3 dB for $\theta = 0^\circ$ and 45° at the FEC limit. Moreover, we notice that the IQ-code is tolerant to the variation of θ , since the OSNR difference between the two angles is equal to 0.1 dB compared to 0.4 dB in the uncoded system at BER = 10^{-2} . In Fig. 3(b), we plot the BER performance with $\Gamma_{dB} = 6$ dB. The uncoded transmission performance has an OSNR penalty of 2 dB at the FEC limit compared to B2B transmission. The IQ-code provides an OSNR gain of 0.4 dB for $\theta = 0^\circ$ and 45° at the FEC limit. We notice that the IQ-code benefits from a high PDL level by providing more gain to the transmission performance. In addition, the obtained results are based on 2×2 MIMO ZF decoding, with more sophisticated MIMO decoding we can have up to 1 dB gain.

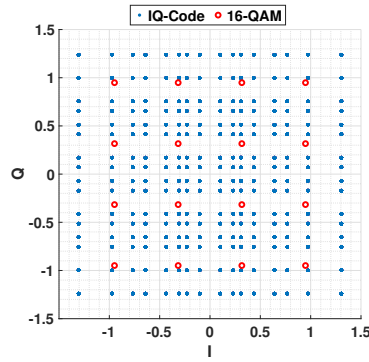


Fig. 2: IQ-Code constellation for DP-16QAM

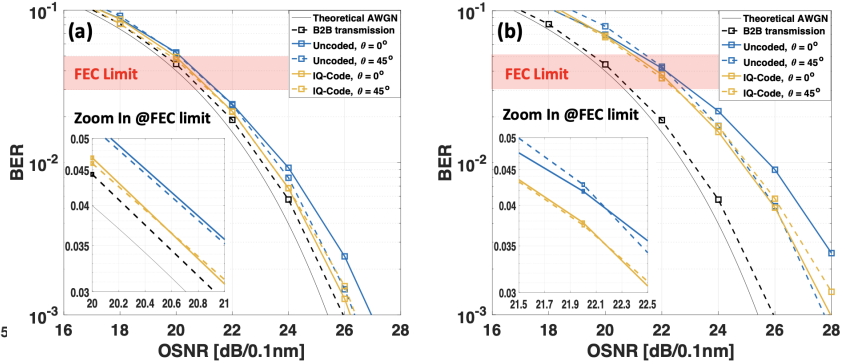


Fig. 3: BER performance for single-carrier, with lumped PDL:(a) $\Gamma_{dB} = 3$ dB, (b) $\Gamma_{dB} = 6$ dB.

3. Application for 800G DSC Transmission Systems

3.1. System Setup

We consider the implementation of 96 GBaud DP-16QAM system using eight sub-carriers ($2N = 16$) with baud rate equal to 12 GBaud, as shown in Fig.4. The sub-carriers are multiplexed at near Nyquist spacing. The signal is shaped by an RRC shaping filter with roll-off values equal to 0.1. Before signals multiplexing, the N sub-bands enter the IQ-code block. We consider 10-span single mode fiber (SMF) of 100 km length (total transmission length $L = 1000$ km), each span followed by a flat gain optical amplifier. Chromatic dispersion coefficient is set to 17 ps/nm/km and PMD coefficient 0.05 ps/ $\sqrt{\text{km}}$. At the receiver side, an RRC filter is employed for inter-symbol-interference (ISI) and inter-carrier-interference (ICI) mitigation. Then chromatic dispersion compensation (CD^{-1}) is done in frequency domain. 2×2 MIMO equalization is used to compensate the PMD in the frequency domain (FDE) thanks to Constant Amplitude Zero Auto Correlation (CAZAC) training sequences as defined in [7]. Then, a carrier phase estimation is applied. A Zero-Forcing (ZF) decoder is applied by multiplying the signal by the inverse of the channel \hat{H}^{-1} , where \hat{H} is the channel estimation (CE). Finally, IQ-code decoder is implemented by applying the inverse of the rotation matrix to retrieve the original QAM symbols. The ZF decoding is considered due to its low implementation complexity. In this system, we have considered a distributed PDL channel model along the transmission link that is equivalent to a Maxwellian distribution. We consider a PDL element after each span (10 PDL elements) with random state-of-polarization (SOP).

3.2. Simulation Results

We evaluate the IQ-code pre-FEC transmission performance for eight sub-carriers. In Fig. 5(a), we plot the BER function of the OSNR with an average PDL $\bar{\Gamma}_{dB} = 3$ dB at the transmission end. In the first case, we consider a channel spacing higher than the baud rate to ensure no overlap between the sub-bands (without ICI), as shown in Fig. 4(b). The IQ-code provides an OSNR gain of 0.5 dB at the FEC limit. In the second case, we consider channel spacing between the sub-bands equal to the baud rate (with ICI), as shown in Fig. 4(c). We observe that the uncoded transmission performance has an OSNR penalty of 2.5 dB compared to the B2B system. The IQ-code

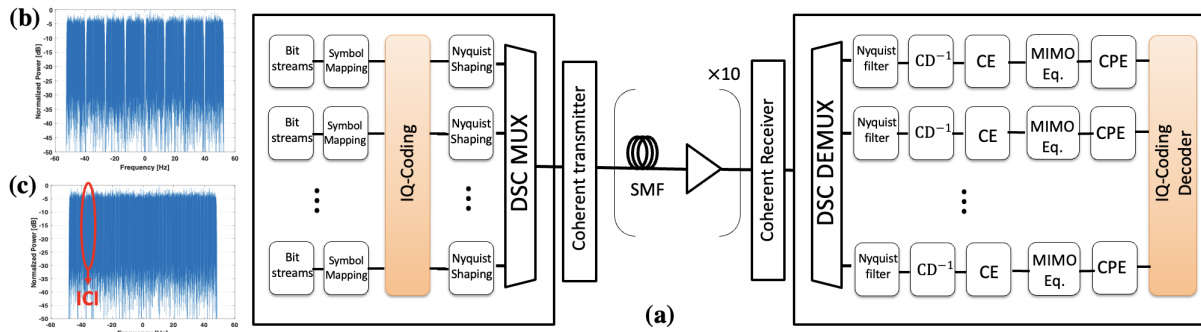


Fig. 4: (a) IQ-code transmission system scheme, (b) 8 sub-carrier spectrum without ICI. (c) 8 sub-carrier spectrum with ICI

still provides an OSNR gain of 0.5 dB at the FEC limit. Fig. 5(b) shows the BER performance with an average PDL $\bar{\Gamma}_{dB} = 6$ dB at the transmission end. We notice that the IQ-code provides 0.4 dB gain without ICI and 0.5 dB gain with ICI at the FEC limit. Lastly, we evaluate the performance of the IQ-code on the non-linear regime for eight sub-carriers and distributed PDL channel model. Fig. 6 shows the Q-factor function of the total launch power. We notice that the IQ-code does not change the transmission performance behavior with non-linearity. Also, we obtain 0.5 dB Q-factor gain compared to the uncoded system at launch power = 4 dBm.

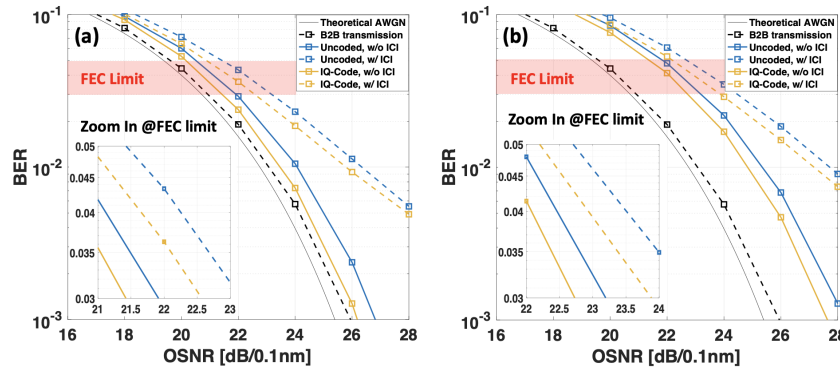


Fig. 5: BER performance for eight sub-carrier with and without ICI, and distributed PDL elements: (a) average $\bar{\Gamma}_{dB} = 3$ dB, (b) average $\bar{\Gamma}_{dB} = 6$ dB.

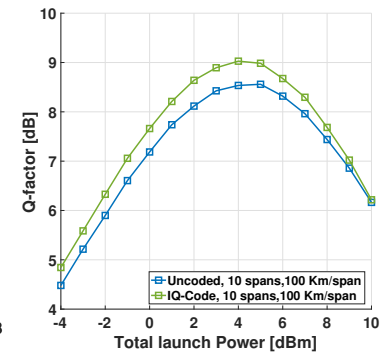


Fig. 6: Q-factor v.s launch power

4. Conclusion

We proposed IQ-code technique to improve the optical transmission performance affected by PDL and crosstalk. The IQ-code uses a one-time slot to be compatible with today's implemented DSP solutions. The performance of the IQ-code is evaluated based on a single carrier and eight sub-carriers transmission systems. We showed that the proposed solution achieves OSNR gain of 0.3-0.5 dB at the FEC limit with and without ICI. In addition, the IQ-code is more tolerant to the variation of PDL angle rotation while keeping the system behavior with non-linearity similar to the uncoded system. Moreover, The shown results are obtained using MIMO ZF decoder based on channel estimation that can be directly integrated into current DSP solutions. Using maximum-likelihood MIMO decoding based on a full $2N \times 2N$ channel estimation IQ-code can achieve an OSNR gain of up to 1 dB.

References

1. H. Sun, et al., "800G DSP ASIC Design using Probabilistic Shaping and Digital Sub-carrier Multiplexing." *Journal of lightwave technology*, vol. 38, no. 17, pp. 4744–4756, 2020.
2. E. Awwad, et al., "Polarization-time Coding for PDL Mitigation in Long-haul PolMux OFDM Systems," *Opt. Express*, 22773–22790, 2013.
3. A. El-Mehdi et al., "Concatenation of Space-Time Coding and FEC for Few-Mode Fiber Systems." *IEEE Photonics Technology Letters* 29, 603–606, 2017.
4. A. Abouseif, et al., "Space-Time Coding Performance Analysis for CDL-impaired Multi-Core Fiber Transmission," *ICT*, pp. 1–5, 2020.
5. A. Dumenil, et al., "Rate optimization using SO (4) Transforms for PDL Mitigation," *ECOC*, pp. 1–3, 2019.
6. E. Bayer-Fluckiger, et al., "New Algebraic Constructions of Rotated Z^n -Lattice Constellations for the Rayleigh Fading Channel," *IEEE Transactions on Information Theory*, vol.50, n.4, pp. 702–714, 2004.
7. F. Pittalà, et al., "Training-Aided Frequency-Domain Channel Estimation and Equalization for Single-Carrier Coherent Optical Transmission Systems," *Journal of Lightwave Technology*, vol. 32, no. 24, pp. 4849–4863, 2014.