PDL Monitoring based on the Eigenvalues Spread of a Data-Aided Zero-Forcing Frequency Domain Equalizer

Fabio Pittalà[1,2,3], Fabian N. Hauske[1], Yabin Ye[1], Neil G. Gonzalez[1], Idelfonso T. Monroy[2], Josef A. Nossek[3]
1: European Research Center, Huawei Technologies Duesseldorf GmbH, Riesstrasse 25, D-80992 Munich, Germany,
2: DTU Fotonik, Technical University of Denmark, Ørsteds Plads 343, DK-2800 Kgs. Lyngby, Denmark.
3: Institute for Circuit Theory and Signal Processing, Technische Universität München, Arcisstr. 21, D-80290 Munich, Germany
E-mail: fabio.pittala@huawei.com

Abstract: Precise and robust PDL monitoring is demonstrated over a wide range of combined channel impairments. The PDL value is extracted from the zero forcing filter matrix estimated by using short CAZAC training sequences.
OCIS codes: (060.1660) Coherent Communications; (060.4261) Network, protection and restoration.

1. Introduction

Polarization dependent loss (PDL) is an important impairment to be monitored in high-speed (≥100Gb/s) dynamically reconfigurable meshed networks [1]. PDL may cause optical power variations due to polarization fluctuations leading to optical-signal to noise-ratio (OSNR) degradations and requires a fine estimation.

However, in coherent optical receiver with digital signal processing (DSP), like for chromatic dispersion (CD) and polarization mode dispersion (PMD), PDL monitoring can be performed from the equalizer filter matrix [2].

Traditionally, blind non-data-aided (NDA) equalizers have been converged by algorithms which lead to the minimum-mean-square-error (MMSE) [3]. In contrast to NDA methods, data-aided (DA) channel estimation can also provide the zero-forcing (ZF) solution which is required for PDL monitoring [4].

In this paper, we present a PDL monitoring technique based on the eigenvalues spread of a ZF DA frequency domain equalizer (FDE) and show the detrimental effect of MMSE filter taps to the PDL estimation.

2. Theory

The transfer function: $\mathbf{K} = \mathbf{R}^{-1}(\theta)\mathbf{A}\mathbf{R}(\theta) = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & PDL_{\text{coef}} \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$ describes a single PDL element, where $\mathbf{R}$ and $\mathbf{R}^{-1}$ define the rotation matrices with rotation angle θ and $\mathbf{A}$ refers to the Hermitian PDL attenuation matrix [5]. The matrix $\mathbf{A}$ contains the PDL coefficient, $0 < PDL_{\text{coef}} < 1$, defined by the attenuation between the orthogonal lossy axis and the lossless axis, which is expressed in dB as: $PDL_{dB} = -20\log(PDL_{\text{coef}})$.

3. PDL Estimator

Once the optical channel $\mathbf{H}(f)$ has been estimated with the aid of short constant amplitude zero autocorrelation (CAZAC) sequences, the ZF filter transfer function $\mathbf{W}_{\text{ZF}}(f)$ simply refers to the inverse of the linear channel transfer function: $\mathbf{W}_{\text{ZF}}(f) = \mathbf{H}^{-1}$, while the MMSE is obtained by $\mathbf{W}_{\text{MMSE}}(f) = \mathbf{H}^{\text{H}}\{\mathbf{H}\mathbf{H}^{\text{H}}+\boldsymbol{\sigma}_{\mathbf{n}}^2/\ \boldsymbol{\sigma}_{\mathbf{s}}^2\}^{-1}$, where $(\cdot)^{\text{H}}$ and $(\cdot)^{-1}$ denote the complex-conjugate (Hermitian) transpose and the inverse respectively.

After normalizing the equalizer matrix $\mathbf{W}$ by the square root of its determinant: $\boldsymbol{W}_N(f) = \frac{\boldsymbol{W}}{\sqrt{det\,(\boldsymbol{W})}}$, the effective frequency dependent PDL can be calculated from the eigenvalues of $\boldsymbol{W}_N(f)$, as: $PDL_{dB}(f) = -20\,log\left(\frac{\lambda W_{N_{max}}}{\lambda W_{N_{min}}}\right)$.

The estimated PDL value is averaged over the central taps of the filter matrix, Fig. 1. The ZF filter only compensates for inter-symbol interference (ISI), therefore in Fig. 1.a the impact of PDL is clearly visible, whereas the MMSE filter jointly optimizes the mitigation of ISI and noise attenuating the eigenvalue spread of the filter taps, Fig. 1.b.

TABLE 1
Parameter Range and Distribution for Channel Simulations

Impairment	Distribution	Value range
PMD	Maxwellian	Mean 25 ps
CD	Linear	[-1000: 1000] ps/nm
α	Linear	[0: 2π] rad
φ	Linear	[0: 2π] rad
PDL	Linear	[0:10] dB
θ	Linear	[0: 2π] rad
Timing phase τ_s	Linear	[0:T] s
OSNR (0.1 nm bandwidth)	Constant	14 dB

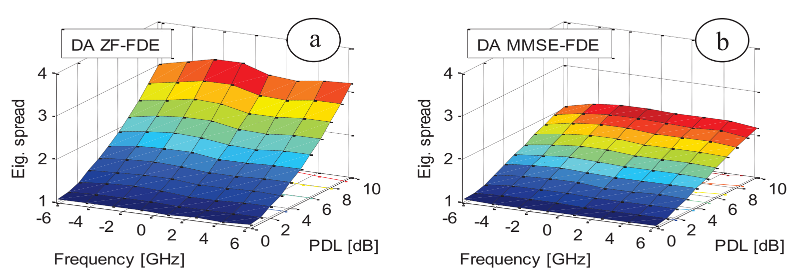

Fig1. Eigenvalues spread of the central taps of the Data-Aided Zero-Forcing (a) and Minimum-Mean-Square-Error (b) Frequency Domain Equalizers as function of the PDL variation.

4. Simulation Results

PDL estimation is demonstrated based on a simulated 28 GBaud polarization-division multiplexed (PDM) system with quaternary phase-shift keying (QPSK) leading to a transmission rate of 112 Gb/s. Simulations of the linear channel include CD, higher-order PMD, polarization rotation angle α, polarization phase ϕ, PDL with rotation angle θ and sampling phase deviation τ_s. In total, 1000 random channels have been generated at a constant OSNR of 14 dB (0.1 nm bandwidth) with parameters randomly chosen from the distributions specified in Table 1.

At the receiver, white Gaussian noise is loaded onto the signal, followed by an optical Gaussian band-pass filter (2^{nd}-order, double-sided 35 GHz), the polarization-diverse 90°-hybrid and an electrical Bessel filter (5^{th}-order, 19 GHz). Finally, an analog-to-digital converter (ADC) stage digitalizes the received signal at 2 samples per symbol.

The channel was estimated using CAZAC sequences of length equal to 16 symbols. Averaging over 1 to 30 channel estimates has been applied before extracting the PDL value from the resulting filter matrix, Fig. 2.a-b-d-e. To obtain accurate and precise PDL monitoring, the estimation should be based on ZF filters, Fig. 2.a-b-c-f.
Fig. 2.d-e show the fail of the MMSE based PDL monitoring which leads to biased and underestimated PDL values. For both, ZF and MMSE filter solution, in absence of PDL the estimator detect some PDL which is due to the impact that noise and dispersive effects have on the eigenvalue spread of the filter matrix, Fig. 2.a-d. For ZF filters calculated after 30 channel estimates, in absence of losses the PDL is overestimated with a mean error around 0.75 dB, while in presence of PDL the maximum estimation error is within ± 0.6 dB with zero mean error, Fig. 2.f.

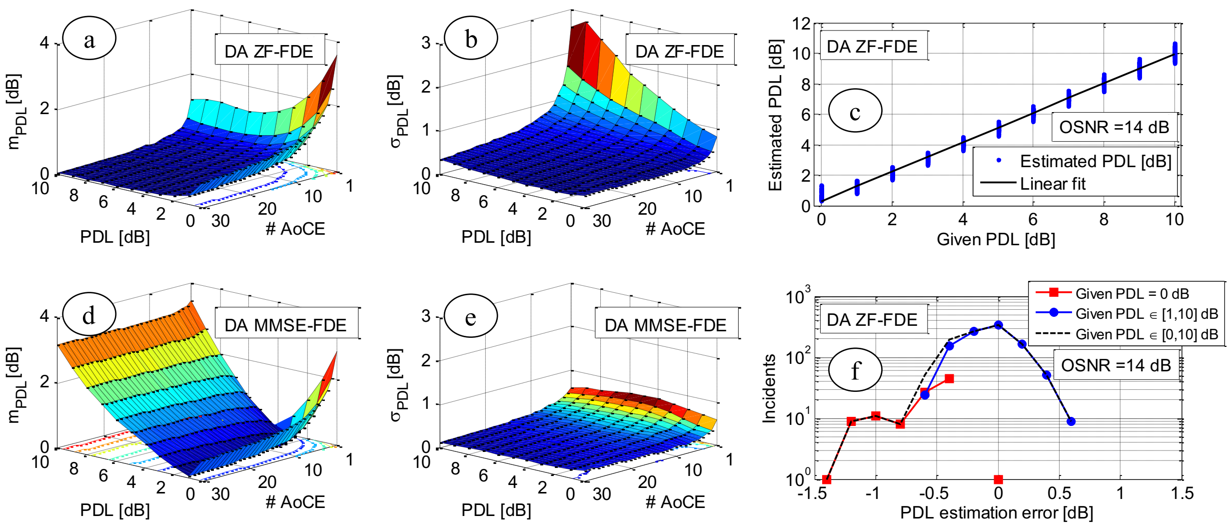

Fig. 2. PDL estimation performance: mean value (a, d) and standard deviation (b, e) of the PDL estimation error versus given PDL and number of averages over channel estimations (# AoCE). Estimation based on the Zero-Forcing (a, b) and Minimum-Mean-Square-Error filter solution (d, e). Given PDL versus estimated PDL (c) and histogram of the PDL estimation error (f) based on Zero-Forcing Frequency Domain Equalizer.

5. Conclusions

Due to the nature of MMSE filters to suppress noise enhancement, accurate PDL monitoring requires zero forcing filter implementation which is obtained by inverting the data aided channel estimation. In presence of combined linear channel impairments and losses, the PDL estimation proves a zero mean error and accuracy within ±0.6 dB.

6. Acknowledgement

The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 258644, CHRON project.

7. References

[1] D. Dahan, U. Mahlab, A. Teixeira, I. Zacharopoulos, I. Tomkos, "Optical performance monitoring for translucent/transparent optical networks," IET Optoelectronics **5**, 1-18 (2011).

[2] J.C. Geyer, C.R.S. Fludger, T. Duthel, C. Schulien and B. Schmauss, "Performance monitoring using coherent receivers", in Opt. Fiber Commun. Conf. (OFC, 2009), OThH5.

[3] C.R.S. Fludger, T. Duthel, D. Van Den Borne, et al., "Coherent Equalization and POLMUX-RZ-DQPSK for Robust 100-GE Transmission" J. of Lightwave Technol., **26**, 1, 64-72, (Jan. 2008).

[4] F. Pittalà, F. N. Hauske, Y. Ye, N. G. Gonzalez, I. T. Monroy, "Joint PDL and In-band OSNR Monitoring Supported by Data-Aided Channel Estimation" in OFC/NFOEC 2012, OW4G.2.

[5] Chan, Calvin C. K., *Optical Performance Monitoring - Advanced Techniques for Next-Generation Photonic Networks*, Elsevier, 2010.