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Published in:
OFC/NFOEC Technical Digest

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Pittalà, F., Hauske, F. N., Ye, Y., Guerrero Gonzalez, N., & Tafur Monroy, I. (2012). Joint PDL and In-band OSNR Monitoring Supported by Data-Aided Channel Estimation. In *OFC/NFOEC Technical Digest* (pp. 3). Optical Society of America.

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Joint PDL and In-band OSNR Monitoring Supported by Data-Aided Channel Estimation

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Abstract: Employing a known training sequence robust and precise PDL and OSNR monitoring is demonstrated over a wide range of combined distortions. The proposed in-service monitoring technique is insensitive to CD, PMD and SOP rotation.

OCIS codes: (060.1660) Coherent communications; (060.4261) Networks, protection and restoration.

1. Introduction

The optical-signal-to-noise ratio (OSNR) is one of the prime parameters to monitor in reconfigurable optical networks with higher-order modulation, flexible switching and wavelength routing. In such networks, optical channels are dynamically switched in the optical domain and data are carried over pre-established paths. An efficient OSNR monitoring would provide direct information about the channel quality allowing for early fault analysis with fast switching to a protection path. Recently, even rate-adaptive transponders have been discussed, which allow to switch between different higher-order modulation formats depending on the required OSNR and the demanded channel capacity, introducing efficient traffic growth-oriented transportation platform of any type of data traffic.

Coherent receivers with advanced digital signal processing (DSP) allow mitigation of all optical impairments in a linear channel. Chromatic dispersion (CD), polarization-mode dispersion (PMD) and polarization-dependent loss (PDL) estimation based on analyzing the finite impulse response (FIR) filter coefficients seems to be one of the most promising optical performance monitoring (OPM) techniques for next generation optical networks [1].

However, the widely considered time-domain (TD) filtering with “blind” non-data-aided (NDA) channel acquisition by gradient algorithms like constant-modulus algorithm (CMA) or decision-directed (DD) least mean square (LMS) is influenced by the properties of the modulation format [2-4] and suffers from a relatively slow convergence with potential sub-optimum acquisition and even failures [5], preventing the receiver from fast switching protection, and finally delays OPM based on the converged digital filter taps. In contrast, frequency-domain (FD) equalization combined with data-aided (DA) channel estimation based on a periodically transmitted training sequence (TS) [6], allows instantaneous filter acquisition and immediate OPM. Furthermore, the modulation format can be altered arbitrarily in between the fixed training patterns. Overhead below 2% is sufficient in dual-stage FD equalizer (FDE) receivers where a FD CD compensation is followed by a DA 2×2 multi-input multi-output (MIMO) FDE. Fast and robust CD and PMD monitoring based on DA 2×2 MIMO FDE has been demonstrated [7].

Unfortunately, the OSNR cannot be directly estimated from the filter transfer function. Techniques based on polarization nulling, spectral analysis, asynchronous histograms, neural networks [1,8] and signal equalization [9] have been presented. However, these methods are not applicable to polarization-division multiplexing (PDM) with amplitude and phase modulation or have not been evaluated with combined deterministic and statistic channel impairments proving reliable estimation under realistic conditions.

In this paper, we propose a method for joint PDL and OSNR monitoring based on DA 2×2 MIMO FDE and on the properties of the equalized TSs. This technique is insensitive to dispersive impairments and polarization effects.

2. Operating Principle

Two orthogonal Zadoff–Chu sequences (one per polarization), framed by guard intervals (GI) are regularly repeated in the transmitted signal [5]. After coherent detection, with the aid of the received spectra and the known transmitted

Fig. 1. Coherent receiver with simplified DSP based on data-aided channel estimation for joint PDL and OSNR estimations.

spectra of the TS, a low-complexity channel estimation can be obtained by simply inverting the estimated channel transfer function. From the filter transfer function CD, PMD and PDL information can be retrieved [10,11]. Although CD and PMD estimation provides same performance for both DA zero-forcing (ZF) and minimum-mean square-error (MMSE) filter implementation [7], PDL estimation should be based on the ZF solution. Due to the nature of MMSE filters to suppress noise enhancement, the estimation based on MMSE filter taps is impaired by OSNR [1]. As shown in Fig. 2.a, the condition number of each tap of the ZF filter transfer function is not influenced by the received OSNR. The eigenvalue spread of the ZF filter matrix is caused by dispersive effects and PDL. However, the impact of CD and PMD can be observed only in absence of PDL. In this case the PDL is overestimated with a mean value around 0.5 dB, Fig. 2.b. However, in presence of PDL the impact of CD and PMD on the eigenvalues spread becomes negligible and the PDL estimation very accurate. We consider 20 channel averages (20 TSs) as the convergence point for PDL estimation, Fig. 2.c.

As depicted in Fig. 1 the estimated PDL value drives the OSNR monitoring which in addition requires knowledge about the statistics of the equalized signal. Differently to [9], to make the OSNR estimation more robust to highly noisy channels we only take into account the equalized TSs, which in FD can be described by:

$$TS_{Eq.}(f) = H_{AF}(f) \left(TS_{Tran.}(f) \sum_{i=1}^N K_i + \eta(f) \right) \quad (1)$$

where $H_{AF}(f)$ is an amplitude filter (AF) function accounting for any band-pass filtering during transmission or low-pass filtering after demodulation in the receiver, $TS_{Tran.}(f)$ contains the transmitted TSs in the x- and y-polarization, $\eta(f)$ is the noise, and K_i is the transfer function of a single PDL element defined by:

$$K_i = R^{-1}(\theta_i) A_i R(\theta_i) = \begin{bmatrix} \cos \theta_i & \sin \theta_i \\ -\sin \theta_i & \cos \theta_i \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & k_i \end{bmatrix} \begin{bmatrix} \cos \theta_i & -\sin \theta_i \\ \sin \theta_i & \cos \theta_i \end{bmatrix} \quad (2)$$

here θ_i is the PDL orientation angle and k_i is the PDL coefficient [1].

After equalization, the pdf of the QPSK clouds can be described by a multivariate Gaussian distribution:

$$\mathcal{N}(p_{j,l} | \mu_{j,l}, \Sigma_{j,l}) = \frac{1}{2\pi \det(\Sigma_{j,l})^{1/2}} \exp \left\{ -\frac{1}{2} (p_{j,l} - \mu_{j,l})^T \Sigma_{j,l}^{-1} (p_{j,l} - \mu_{j,l}) \right\} \quad (3)$$

where p is a constellation point, μ is a 2-dimensional mean vector and Σ a 2-dimensional covariance matrix with $j \in \{x, y\}$ accounting for the polarization axis and $l \in \{1, 2, 3, 4\}$ for the constellation cloud.

The first term in Eq. 1 has a major affect on μ , whereas the second term has a major impact on Σ . Both, μ and Σ are influenced by PDL, PDL orientation and OSNR. We consider the PDL orientation varying between 0 rad. (*worst-case PDL*) and $\pi/4$ rad. (*best-case PDL*) and we equalize the received signal by an MMSE filter updated after 20 channel averages. However, as depicted in Fig. 2.d considering OSNR values $> \sim 10$ dB, for a given PDL value, only the PDL orientation affect μ . Due to the MMSE properties, for lower OSNR values the AF function strongly influences μ . Fig. 2.e-f clearly shows the behavior of Σ as function of the OSNR and PDL orientation for a fixed PDL value. The two standard deviations converge to the same value at the *best-case PDL*. For an estimated PDL value the best match between the estimated statistic of the equalized TSs and a lookup table gives the estimated OSNR value, Fig. 1. For low OSNR values an error in the PDL orientation estimation can be tolerated by the parameter Σ . For high OSNR values an accurate PDL angle estimation is required due to the slow varying of Σ .

Fig. 2. Joint PDL and OSNR monitoring: a) condition number of each filter tap for different values of PDL and OSNR; b) mean value and c) standard deviation of the PDL estimation error versus given PDL and number of averages over channel estimations (# AoCE); d) mean value of the equalized training sequences in the y-polarization for different OSNR values and PDL orientation angles; standard deviation of the equalized training sequences in the e) x- and f) y-polarization for different values of OSNR and PDL orientation angles.

3. Combined PDL and OSNR Monitoring Performance

Joint PDL and OSNR estimation performance investigation is based on a 28 GBaud PDM system with QPSK modulation format, leading to a transmission rate of 112 Gbit/s. The linear optical channel includes additive white Gaussian noise (AWGN), CD, higher-order PMD, PDL, polarization rotation angle α and polarization phase ϕ defining the state of polarization (SOP). After an optical Gaussian band-pass filter (2nd-order, double-sided 35 GHz), a polarization-diverse 90°-hybrid and an electrical Bessel filter (5th-order, 19 GHz), an ADC stage digitalizes the received signal at 2 samples per symbol. A total number of 21.000 random channels (100 for each combination of PDL and OSNR) have been generated with parameters randomly chosen from the distributions specified in Table 1. The channel was estimated with the aid of TSs of length 24 symbols, including 4-symbols GIs at the beginning and end of each sequence. The TS follows a QPSK constellation. The OPM is based on the estimated ZF filter matrix, whereas the signal equalization is based on the MMSE filter solution updated after 20 channel estimation averages. Fig. 3.a-b shows that the accuracy of the PDL estimation. The maximum error is always within ± 1 dB. Fig. 3.c-d shows that the OSNR estimation has accuracy better than 1 dB when the given OSNR ranges between 10 and 20 dB. Although the OSNR estimation slight degrades outside this range, no estimation failures are observed.

Fig. 3. PDL and OSNR estimations. Histogram of the PDL (a) and OSNR (c) estimation error, PDL (b) and OSNR (d) estimation performance.

4. Conclusions

Robust and accurate joint PDL and in-band OSNR monitoring supported by data-aided FD channel estimation employing very short training sequences has been demonstrated in presence of combined linear channel impairments. Both PDL and OSNR estimations prove a zero mean value and accuracy within ± 1 dB.

5. 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.

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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: $\pi/4$] rad
OSNR (0.1 nm bandwidth)	linear	[5:25] dB