Performance Monitoring in Optical OFDM Systems

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Abstract: We investigate performance monitoring within coherent optical OFDM systems. Estimates for CD and instantaneous DGD can be extracted from the result of channel estimation. The method can also provide information about OSNR and non-linear distortion.

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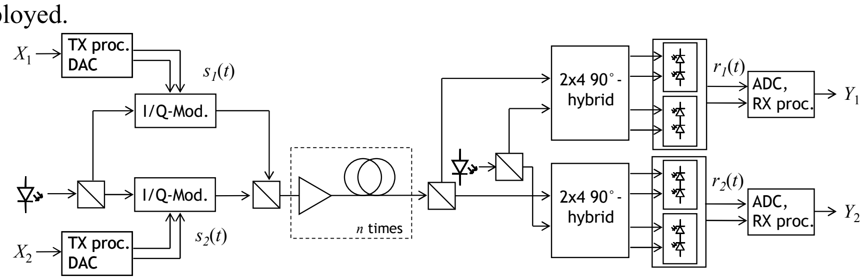
1. Introduction

Performance monitoring is an important feature in optically transparent networks. There are several techniques proposed to identify various sources of degradation accumulated during propagation in optical fiber and components. The emergence of coherent optical transmission systems changes requirements and potential for the monitoring task. These systems allow for equalization of dispersive effects of the optical channel with the help of digital signal processing. Polarization diversity along with joint processing of the samples of both receive branches allow for polarization multiplexing and thus for increased spectral efficiency. At the receiver the signal distortion caused by the channel is compensated. Therefore the equalizer settings give information about channel parameters which are interesting with respect to performance monitoring [1].

In conjunction with coherent optical systems, orthogonal frequency division multiplexing (OFDM) has gained much interest as this scheme allows for efficient equalization of chromatic dispersion (CD) and polarization mode dispersion (PMD). The used frequency band is sub-divided in narrow-band orthogonal sub-carriers, which are all affected by flat fading. The respective set of channel coefficients is a discrete frequency representation of the channel transfer function. Once estimated it can deliver channel parameters like CD, PMD and signal-to-noise power ratio (SNR).

2. OFDM system

Fig. 1 depicts the investigated OFDM transmission system. Two independent baseband signals modulate the orthogonally polarized parts of the TX laser signal. At the receiver, polarization diverse coherent detection is deployed.



Parameters:
Data-rate 100 Gb/s
256 sub-carriers, 16 QAM
12.5 % relative cyclic prefix length
12 spans:
80 km single mode fiber (D = 17 ps/nm/km), mean PMD 10 ps

Fig. 1: Investigated OFDM system.

A compact transmission model describes the system as a set of Q orthogonal narrow band 2x2-MIMO-channels

$$\begin{bmatrix} Y_1(d) \\ Y_2(d) \end{bmatrix} = \begin{bmatrix} H_{11}(d) & H_{12}(d) \\ H_{21}(d) & H_{22}(d) \end{bmatrix} \cdot \begin{bmatrix} X_1(d) \\ X_2(d) \end{bmatrix} + \begin{bmatrix} n_1(d) \\ n_2(d) \end{bmatrix}, \quad d = 1..Q$$

The matrix entries $H_{ij}(d)$ represent linear distortion of the sub-carriers; $n_1(d)$ and $n_2(d)$ denote additive noise samples within both receive branches. The pilot symbol based estimation of the channel coefficients necessitates orthogonal vectors of symbols, which are known to the receiver. A straightforward variant is transmitting pilot symbols $X_p(d)$ in just one polarization while the other branch transmits 0, i.e. successive transmission of $\begin{bmatrix} X_p(d) \\ 0 \end{bmatrix}$ and $\begin{bmatrix} 0 \\ X_p(d) \end{bmatrix}$ [2].

With the help of this operation one can determine all entries of the channel matrix, which then can be decomposed – assuming negligible polarization dependent loss (PDL):

$$\mathbf{H}(d)=\begin{bmatrix} H_{11}(d) & H_{12}(d) \\ H_{21}(d) & H_{22}(d) \end{bmatrix} = a(d)\cdot e^{j\phi(d)}\cdot \underbrace{\begin{bmatrix} U_{11}(d) & U_{12}(d) \\ U_{21}(d) & U_{22}(d) \end{bmatrix}}_{\mathbf{U}(d)} \qquad (1)$$

Here $a(d)$ and $\phi(d)$ are the common attenuation and phase. From $\phi(d)$ one can extract the path's accumulated chromatic dispersion, e.g. with the help of a regression parabola [3]. In [4] the authors demonstrate accurate CD monitoring in a wide dispersion range.

The matrix $\mathbf{U}(d)$ is a special unitary matrix exhibiting the properties $U_{22}(d)=U_{11}^{*}(d),\quad U_{21}(d)=-U_{12}^{*}(d)$. As the OFDM channel estimation delivers a discrete frequency representation of the channel, we can obtain estimates for the differential group delay (DGD) on sub-carrier basis using the difference quotient [5]

$$\Delta\tau(d)=2\sqrt{\left|\frac{U_{11}(d+1)-U_{11}(d)}{2\pi\Delta f}\right|^{2}+\left|\frac{U_{21}(d+1)-U_{21}(d)}{2\pi\Delta f}\right|^{2}}. \qquad (2)$$

Here Δf denotes the sub-carrier bandwidth.

3. Simulations

First simulations have been carried out without amplified spontaneous emission (ASE) noise in order to obtain reference results. The optical link consisted of twelve spans of 80 km SSMF. Each fiber span is assumed to be selected randomly from fiber representations where the whole set has 10 ps PMD. Further system parameters are summarized in Fig. 1.

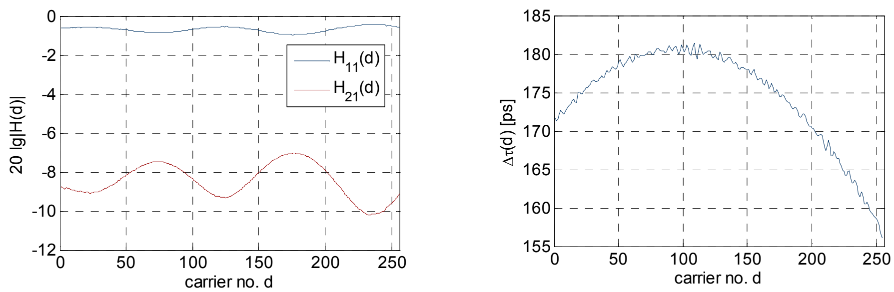


Fig. 2: Amplitudes of channel coefficients; estimated DGD versus OFDM sub-carrier number.

The left hand side diagram in Fig. 2 depicts the magnitudes of the channel coefficients H_{11} and H_{21}. There are no distinct transmission zeros, i.e. the results differ from a scenario where there is pure first order PMD and where the polarization multiplex tributaries are aligned with the principle states of polarization. Instead of measuring the distance between transmission minima we decompose the matrix $\mathbf{H}(d)$ according to (1) and use (2) for DGD estimation. The result is shown on the right hand side of Fig. 2. We obtain the instantaneous DGD characteristic of the optical link – the simulated fiber representation exhibits differential group delays in the range from 155 to 180 ps within the used frequency band. This example is chosen as it comprises a certain amount of higher order PMD. However, at the presence of ASE noise this analysis becomes rather imprecise. One can smooth the estimated transfer matrix by averaging over a number of pilot symbols but there still remain slight fluctuations which result in quite large disturbance for the estimated DGD as the numerical differentiation is very sensitive to additive noise.

Savitzky-Golay filters offer a way to improve accuracy. These filters are FIR smoothing filters and can be treated as a generalization of moving average filters [6]. For the description of the principle we start with W data samples (W shall be an odd number) centered on index $d = 0$:

$$\mathbf{u}=[U(-\tfrac{W-1}{2}),\ldots U(0)\ldots U(\tfrac{W-1}{2})]^{T}$$

It should be noted that the subscripts of $U(d)$ are omitted; respective entries of $\mathbf{U}(d)$, i.e. U_{11} and U_{21}, have to be inserted here. These data samples shall then be fitted by a polynomial of degree p:

$$\hat{U}(d)=c_0+c_1 d+\ldots+c_p d^{p}, \qquad -\tfrac{W-1}{2}\le d\le \tfrac{W-1}{2}$$

Obviously, at $d = 0$ we get c_0 as the smoothed value of $U(0)$. Moreover, we can determine derivatives of the fitting polynomials, especially $\left.\frac{\partial \hat{U}(d)}{\partial d}\right|_{d=0}=c_1$. One can find the coefficients of the polynomial which minimize the squared error, i.e. the squared difference between data samples and the polynomial itself, by $c_i=\mathbf{g}_i^{T}\mathbf{u}$, where $\mathbf{g}_i^{T}$ are trans-

posed columns of $\mathbf{G} = [\mathbf{g}_0, \mathbf{g}_1, \dots \mathbf{g}_p] = \mathbf{F}(\mathbf{F}^T\mathbf{F})^{-1}$. The matrix **F** depends on the window length W and the polynomial degree p; it has the dimension $W \times (p+1)$ and its entries F_{ij} are $F_{ij} = (-\frac{W-1}{2} + i)^j, \quad i = 0 \dots W-1,\ j = 0 \dots p$. For arbitrary values of d substitutions in **u** are necessary, while $\mathbf{g}_i^T$ stay unchanged. The derivatives of (2) can be estimated with the help of FIR filters with coefficients $\mathbf{g}_1^T$.
Fig. 3 depicts simulation results which were obtained at an OSNR of 20 dB.

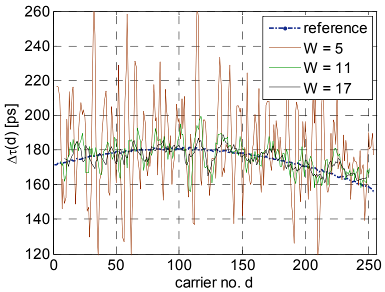


Fig. 3: Estimated DGDs at OSNR = 20 dB using Savitzky-Golay filtering; p = 1.

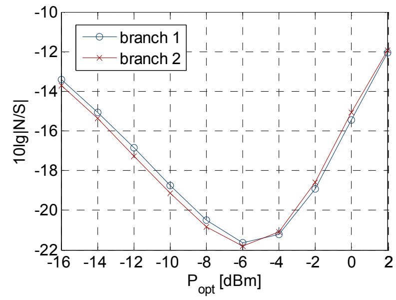


Fig. 4: Estimated inverse SNR versus optical input power.

Polynomial degree p = 1 – which equals linear regression within the observation window – along with W = 17 results in relatively accurate estimation of the instantaneous DGD within the used frequency band.

4. ASE noise and distortion due to self phase modulation

In order to estimate the power of the total additive noise we first subtract known data symbols which have been affected by linear distortion through the channel from the received symbols; then we determine the inverse Signal-to-Noise-Ratio for both receive branches:

$$\begin{bmatrix} n_1(d) \\ n_2(d) \end{bmatrix} = \begin{bmatrix} Y_1(d) \\ Y_2(d) \end{bmatrix} - \mathbf{H}(d) \begin{bmatrix} X_1(d) \\ X_2(d) \end{bmatrix}; \qquad \frac{N_i}{S_i} = \frac{\sum_{d=1}^{Q} |n_i(d)|^2}{\sum_{d=1}^{Q} |H_{i1}(d)X_1(d) + H_{i2}(d)X_2(d)|^2}, i \in \{1,2\}$$

This operation is related with the q-factor method used in [4]. The advantage of the description as an inverse SNR is the observation that the noise power may be a sum of different kinds of distortion; under certain conditions the individual contributions can be determined. Fig. 4 summarizes the resulting estimated inverse SNR versus optical input power. For low optical powers N/S is dominated by ASE noise and decreases by 1 dB per 1 dB power increment. Thus an estimate for the OSNR can be deduced directly [4]. At higher signal power levels distortion due to self phase modulation comes into play which increases by 2 dB per 1 dB input power raise. These observations allow us to separate the estimated N/S into a sum of two noise power contributions, if we are able to obtain estimates for two different input power levels [7].

5. Conclusions

Optical OFDM receivers allow estimating linear channel properties like chromatic dispersion and instantaneous DGD for online monitoring purposes. Savitzky-Golay filters have been used for determining first derivatives of channel coefficients, leading to smoothed instantaneous DGD estimates. Furthermore non-linear signal degradation can be identified with some additional effort by intentionally inserted signal power variations.

6. References

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