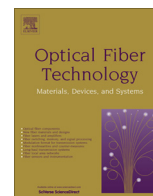




Contents lists available at ScienceDirect

Optical Fiber Technology

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Experimental demonstration of the maximum likelihood-based chromatic dispersion estimator for coherent receivers



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ARTICLE INFO

Article history:

Received 14 November 2013

Revised 16 January 2014

Available online 13 February 2014

Keywords:

Chromatic dispersion

Optical performance monitoring

Maximum likelihood

Digital signal processing

16 QAM

QPSK

ABSTRACT

We perform an experimental investigation of a maximum likelihood-based (ML-based) algorithm for bulk chromatic dispersion estimation for digital coherent receivers operating in uncompensated optical networks. We demonstrate the robustness of the method at low optical signal-to-noise ratio (OSNR) and against differential group delay (DGD) in an experiment involving 112 Gbit/s polarization-division multiplexed (PDM) 16-ary quadrature amplitude modulation (16 QAM) and quaternary phase-shift keying (QPSK).

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1. Introduction

Linear impairments, in particular chromatic dispersion (CD) and polarization-mode dispersion (PMD) resulting from fiber transmission are now routinely mitigated by digital signal processing (DSP) in coherent receivers. This advancement allows for fiber-optic networks that no longer require dispersion compensating modules (DCMs) and two-stage amplification to perform reliable transmission. The major benefits of uncompensated links include: decrease in the noise figure (due to decrease in linear and nonlinear optical noise), reduction in link loss and latency, lower deployment capital expenditures.

As optical networks adopt flexibility and dynamic lightpath switching [1], the CD accumulated in the signal may change between two different connection requests, even if a source and destination are the same. Therefore a conventional approach, where a coherent receiver uses a static CD filter, does no longer apply. This makes an accurate adaptive CD estimation for dispersion unmanaged coherent photonic backbones indispensable.

Various approaches to non-data aided CD estimation in digital coherent receivers have been presented. One of the methods is based on parameter extraction from equalizer taps [2]. Due to a

limited number of filter taps in the receiver, this solution might only be used to monitor relatively small CD, roughly corresponding to a stretch of one fiber span in long haul network. To support longer links, other methods, based on CD scanning are used. In those techniques, the space of possible CD values is searched in small steps (20–200 ps/nm [3]) and a metric value is computed for each step. A characteristic feature of this metric, often global minimum or maximum, is used to indicate successful mitigation of CD. Diverse variants of this procedure, each using a different metric, have been shown so far. A method derived from constant modulus algorithm (CMA), where the metric is based on a departure from a fixed power threshold, is used in Refs. [3,4], delay-tap sampling estimator [5,6], autocorrelation of signal power waveform [7,8], clock tone search [9–11], Gardner time error detector variance [12]. Recently, another technique have been demonstrated, where the sweep over CD values is performed automatically when applying FFT on the autocorrelation of discrete spectrum [13].

In this paper we present an experimental investigation of a method for CD estimation based on the maximum likelihood (ML) criterion [14]. The approach is experimentally verified in a transmission experiment using 112 Gbit/s polarization division multiplexed (PDM) 16-ary quadrature amplitude modulation (16 QAM) and quaternary phase-shift keying (QPSK) optical signals and its performance is compared, and found better, to an alternative (reference) method derived from constant modulus algorithm

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criterion from [4]. (Please notice that this is not the CMA commonly used for polarization demultiplexing.)

2. CD estimator

In this section we shortly present the maximum likelihood CD estimator. The full derivation can be found in [14].

We consider a coherent optical communication system using polarization multiplexing. The data, phase, and polarization state of the received signal are unknown, as is the differential group delay (DGD) along an unknown axis. The received signal can be expressed in the frequency domain as

$$\mathbf{R}(f) = H(f)e^{-j2\pi f\tau}\mathbf{T}(f)\mathbf{S}(f) + \mathbf{N}(f) \equiv \mathbf{X}(f) + \mathbf{N}(f),$$

where $H(f)$ is the transfer function of the CD, τ is an unknown propagation delay, the Jones matrix $\mathbf{T}(f)$ describes the polarization scrambling and DGD, $\mathbf{S}(f)$ is the Fourier transform of the transmitted signal, and $\mathbf{N}(f)$ is complex additive white Gaussian noise (AWGN) with power spectral density $N_0/2$ per each of the four real dimensions. The CD all-pass filter is described by

$$H(f) = \exp\left(-j\frac{\pi f^2 \lambda^2}{c} \int_0^L D(z) dz\right) = e^{j\pi\eta T^2 f^2},$$

where λ is the carrier wavelength, c is the speed of light, $D(z)$ is the dispersion parameter, L is the total system length, and η is the CD parameter to be estimated. The likelihood for the received signal is

$$p(r|\eta, \tau, \mathbf{T}, \mathbf{a}) \propto \exp\left[-\frac{1}{N_0} \int \|\mathbf{R}(f) - \mathbf{X}(f)\|^2 df\right],$$

where we used Parseval's theorem to write the likelihood in the Fourier domain and denoted a vector representation of received signal in time domain, $\mathbf{r}(t)$, by r . This expression depends on the data, represented by the sequence of transmitted symbols \mathbf{a} . To remove the dependency on \mathbf{a} , we use the second order Taylor expansion of $p(r|\eta, \tau, \mathbf{T}, \mathbf{a})$ and take the expectation with respect to \mathbf{a} . We thus find an approximate expression for $p(r|\eta, \tau, \mathbf{T})$. Further approximations allow us to remove the dependence on τ . However, the objective function still depends on \mathbf{T} . We solve this by optimizing over a small number of polarization states and DGD values. We formulate the final result in terms of the received signal after matched filtering. Thus, we introduce $\mathbf{Y}(f) = P^*(f)\mathbf{R}(f)$, where $P^*(f)$ is the transfer function of the filter matched to the transmitted pulse shape. For any M -ary quadrature amplitude modulation or M -ary phase-shift keying modulation format for $M > 2$, the final estimator turns out to be

$$\hat{\eta} = \arg \max_{\eta} \max_{\mathbf{M} \in \mathcal{S}} \left| \int_{-\infty}^{\infty} \mathbf{Y}^H(f) \mathbf{M} \mathbf{Y}(f + 1/T) e^{-j2\pi\eta T f} df \right|, \quad (1)$$

where the set of matrices to test is

$$\mathcal{S} = \left\{ \begin{pmatrix} 1 & 0 \\ 0 & \pm 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 \\ \pm 1 & 0 \end{pmatrix} \right\}.$$

3. Experimental setup

Fig. 1 shows the experimental setup, which can generate optical 16 QAM signal at 14 Gbaud or QPSK at 28 Gbaud. A pulse pattern generator (PPG) generates four copies of decorrelated electrical signals carrying binary pseudorandom bit sequences of length $2^{15} - 1$ (PRBS-15) which are then amplified. For 16 QAM, the PPG operates at 14 GHz and the resulting four signals are grouped in pairs, one signal from each pair is attenuated by 6 dB, and each

pairs is combined in a resistive combiner. This results in two four-level signals: in-phase (I) and quadrature (Q) components for the double-nested Mach-Zehnder modulator. In the optical domain, a 16 QAM signal at 56 Gbit/s is obtained. For QPSK, two amplified PPG outputs operate at 28 Gbit/s, generating two-level I and Q signals, which results in an optical QPSK signal at 56 Gbit/s. The light source used in the transmitter is an external cavity laser (ECL) with a linewidth of 100 kHz. Polarization division multiplexing is emulated by multiplexing the signal with its delayed copy in the orthogonal polarization, creating, respectively PDM-16 QAM and PDM-QPSK optical signals at 112 Gbit/s. An erbium-doped fiber amplifier is used at the transmitter to compensate for the insertion losses.

The signal is launched into a link without dispersion compensating fiber using a commercial wavelength division multiplexing (WDM) equipment with all other WDM channels turned off. An amplified spontaneous emission (ASE) noise loading stage is used only for back-to-back performance measurements. The transmission experiment is performed over links of 240, 400, 640, and 800 km lengths by using 3, 5, 8, and 10 spans, respectively of 80 km-long standard single-mode fiber, with nominal dispersion of 16.25 ps/(nm km) at the operating wavelength. Unless stated otherwise, the input power to the first span is 0 dBm and the optical signal-to-noise ratio (OSNR) is measured at the receiver in 0.1 nm bandwidth. A variable optical attenuator before the receiver is used to keep the power ratio between the signal and the local oscillator (LO) constant. For QPSK back-to-back measurements a DGD emulator is used to introduce delays of 20, 40, 60, and 80 ps.

3.1. Digital coherent receiver

The signal is received with a phase- and polarization-diversity digital coherent receiver whose structure is outlined in Fig. 2. The receiver consists of an opto-electronic front-end and a digital signal processing (DSP) stage.

3.1.1. Opto-electronic front-end

The front-end includes two polarization beam splitters (PBS) splitting the received signal and the local oscillator into two orthogonal polarizations (H – horizontal, V – vertical), two 90° hybrids for each polarization, a set of transimpedance amplifiers (TIAs) and analog-to-digital converters (ADCs). The ADCs are provided inside a real-time digital storage oscilloscope (DSO) with a 50 GS/s with 16 GHz bandwidth. The data is sampled by the DSO and the acquired traces are processed offline.

3.1.2. Digital signal processing

The offline processing stage begins with signal resampling to two samples per symbol by spline interpolation. The downsampled signal is then fed into the CD monitor and CD equalizer block, where the signal is first divided into blocks of fixed length and transformed to frequency domain. Dispersion mitigation is then performed blockwise by a transversal frequency domain equalizer due to low, logarithmically increasing, computational complexity for increasing dispersion magnitude, as compared to time domain equalization [4]. The variable transfer function generator, $H^{-1}(CD)$, is responsible for generating an inverse of the transfer function of fiber dispersion, according to the CD value supplied by the CD monitor. The CD value is swept with a resolution of 3 ps/nm until an optimum value indicated by the metric algorithm (estimator) is found. Depending on the specific test case, either an ML-based algorithm or the reference method is implemented inside CD monitor block in Fig. 2. To avoid aliasing when evaluating Eq. (1), ML CD estimator shall operate with four samples per symbol. Therefore the downsampled signal is again upsampled to four samples per symbol before entering ML CD monitor. Upsampling is necessary

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