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Reduced-Complexity Blind Chromatic Dispersion Estimation for Digital Coherent Systems

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Abstract: We propose an enhancement to the fast blind CD estimation method based on auto-correlation of signal power. The use of Hartley and Cosine transform allow 30% and 70% complexity reductions, within a maximum loss of 2% in accuracy.

OCIS codes: (060.1660) Coherent communications, (060.2330) Fiber optics communications

1. Introduction

The combination of coherent detection and advanced digital signal processing (DSP) is a key technology for present and future optical transmission systems due to its capability to digitally compensate for chromatic dispersion (CD), polarization mode dispersion (PMD), nonlinearities, hardware and other imperfections. To enable tracking of time-varying accumulated CD in future flexible and dynamic scenarios, an accurate, fast and low-complexity CD estimation scheme is desired. Blind CD estimation is often employed to avoid increment in the receiver complexity and system overhead due to large training sequences [1–5]. Blind CD estimation based on modified constant-modulus algorithm (CMA) aims to estimate the accumulated CD by scanning over a preset range, resulting in high complexity and time consuming operations for long distances of fiber links [1, 6]. The auto-correlation of signal power (ACSPW) [7] estimation is based on evaluation of the peak of the auto-correlation of the signal power. Start-up time and complexity are reduced due to the single operation nature of the ACSPW. Even so, this solution requires large size in fast Fourier transform (FFT) that results in high implementation complexity [8, 9].

In this paper we investigate the use of Fast Hartley Transform (FHT) and Fast Cosine Transform (FCT) in the ACSPW method. These schemes preserve the accuracy of the original method, with considerable reduction in complexity. The accuracy of the proposed solutions is validated for polarization-division multiplexed quadrature phase-shift keying (PDM-QPSK) with different pulse shapes.

2. Operating principle of ACSPW estimation scheme

The ACSPW scheme estimates the accumulated CD by using information of the signal power auto-correlation function following the Wiener-Khintchine theorem. Due to CD-induced inter-symbol interference, the aforementioned auto-correlation exhibits a peak whose location is indicative of the accumulated CD. The auto-correlation function of the digital signal is defined as

$$P[n] = \mathrm{IFFT}\left[\left|\mathrm{FFT}[|E_{\mathrm{in}}[n]|^2]\right|^2\right], \tag{1}$$

where E_{in} is the digital signal and $P[n]$ is the auto-correlation function of E_{in}, FFT and IFFT denote the forward and inverse Fourier transform, respectively. The location τ_0 of the peak in $P[n]$, when a long-haul transmission system is considered, and the accumulated CD can be approximated by

$$\tau_0 = -\frac{2\pi\beta_2 z}{T} \qquad \text{and} \qquad \mathrm{CD}_{\mathrm{acc}} = \frac{\tau_0 T c}{\lambda^2},$$

where β_2 is a group velocity dispersion (GVD), z is the fiber length, T is the symbol period, c is the speed of light, and λ is the carrier wavelength.

2.1. Discrete Hartley transform (DHT)

The Hartley transform is a real trigonometric transform. The N-th order discrete Hartley transform (DHT) of a sequence $x(n)$ is defined as

$$h(k) = \frac{1}{\sqrt{2}}\sum_{n=0}^{N-1} x(n)\Big(\cos(2\pi kn/N) + \sin(2\pi knN)\Big) \quad \text{with} \quad k = 0, 1, \ldots, N-1. \tag{2}$$

The real $R(k)$ and imaginary $I(k)$ parts of the DFT coincide with the even and negative odd parts of the DHT as

$$f(k) = R(k) + jI(k) = E(k) - jO(k), \tag{3}$$

$$E(k) = [h(k) + h(N-k)]/2 \qquad \text{and} \qquad O(k) = [h(k) - h(N-k)]/2.$$

The Hartley transform is therefore a suitable alternative for power spectrum evaluation. The power spectrum is

$$S^2(k) = R^2(k) + I^2(k) = [h^2(k) + h^2(N-k)]/2, \tag{4}$$

$$R(k) = [h(k) + h(N-k)]/2 = \sum_{n=0}^{N-1} x(n)\cos(2kn\pi/N) \quad \text{and} \quad -I(k) = [h(k) - h(N-k)]/2 = \sum_{n=0}^{N-1} x(n)\sin(2kn\pi/N).$$

The auto-correlation can then be evaluated applying an inverse Fourier (IFFT) or Hartley transform (IFHT)

$$P[n] = \mathrm{IFFT}\left[h^2(k) + h^2(N-k)/2\right] \quad \text{and} \quad P[n] = \mathrm{IFHT}\left[h^2(k) + h^2(N-k)/2\right]. \tag{5}$$

2.2. *Discrete cosine transform (DCT)*

Since the quantity $|E_{\mathrm{in}}[n]|^2|$ is always real and positive, we can substitute the FFT/IFFT with the cosine transform, i.e., a real trigonometric transform. The N-th order discrete cosine transform (DCT) of a sequence $x(n)$ is defined as

$$z(k) = \sqrt{\frac{2}{N}}\, b(k) \sum_{n=0}^{N-1} x(n)\cos[(\pi(2n+1)k/2N] \quad \text{with} \quad k = 0, 1, \ldots, N-1, \tag{6}$$

with $b(k) = 1/\sqrt{2}$ if $k = 0$ and $b(k) = 1$ if $0 < k \leq N-1$. The auto-correlation can then be evaluated with

$$P[n] = \mathrm{IFCT}\left[\left|\mathrm{FCT}[|E_{\mathrm{in}}[n]|^2]\right|^2\right], \tag{7}$$

where FCT and IFCT are the forward and inverse cosine transform, respectively.

2.3. *Complexity evaluation*

The main computation consumption depends on the transform operation and auto-correlation calculation. In the AC-SPW, referred as FFT case from here after, the required complexity in complex-valued multiplications is $N\log(N) + N$, with N being the FFT size [10]. Assuming that single complex-valued multiplication corresponds to four real-valued multiplications, the total complexity is $4N\log(N) + 4N$. In all the cases radix-2 and Fast implementation of the Transforms have been considered. In the FHT/FFT case, the routine includes 2 FHT operations and 1 FFT operation for power spectrum and auto-correlation calculations, respectively, with a total complexity of $4N\log(N)$. For the FHT case, 2 FHT operations are needed to calculate the power spectrum and 1 FHT operation for the auto-correlation for a $3Nlog(N)$ total complexity [11]. Last in the FCT case, 2 FCT operations and 1 complex multiplication are required for a total complexity of $N\log(N) + 4N$ [12]. Operation requirements and total complexity in terms of real multiplication for the four different schemes are summarized in Table 1, where the complexity reduction is also present. A comparison between the four different schemes is shown in Fig. 1(a) in terms of real-valued multiplication as a function of the transform size N.

Fig. 1(b) shows a comparison of the schemes in terms of estimation of the τ_0 peak. The FHT/IFFT case provides equal results to the FFT case for both auto-correlation and peak estimation. In the FHT and FCT case the auto-correlation produces different result, but equal and comparable estimations in terms of peak location respectively.

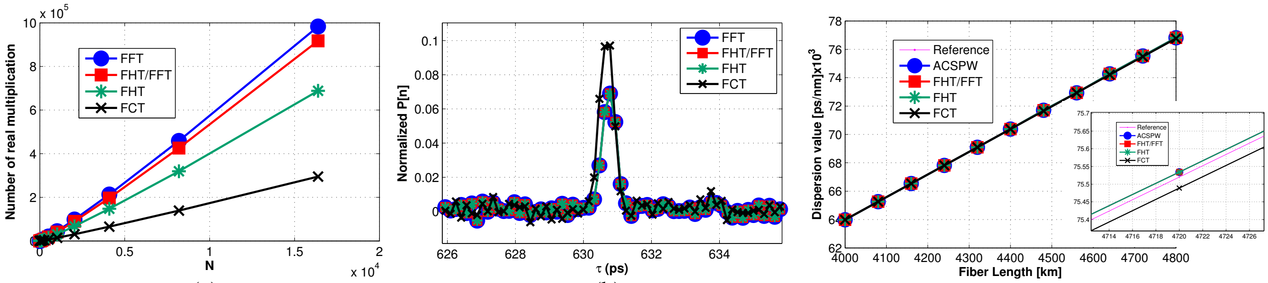
Table 1: Comparison of the three proposed methods with the reference FFT case (ACSPW)

Transform	Operations	Number of multiplications	Complexity reduction
FFT	2FFTs+1 complex multiplication	$4N\log(N) + 4N$	Baseline
FHT/IFFT	2FHTs+1FFT	$4N\log(N)$	10%
FHT	3FHTs	$3N\log(N)$	30%
FCT	2FCTs+1 complex multiplication	$N\log(N) + 4N$	70%

3. Simulation results

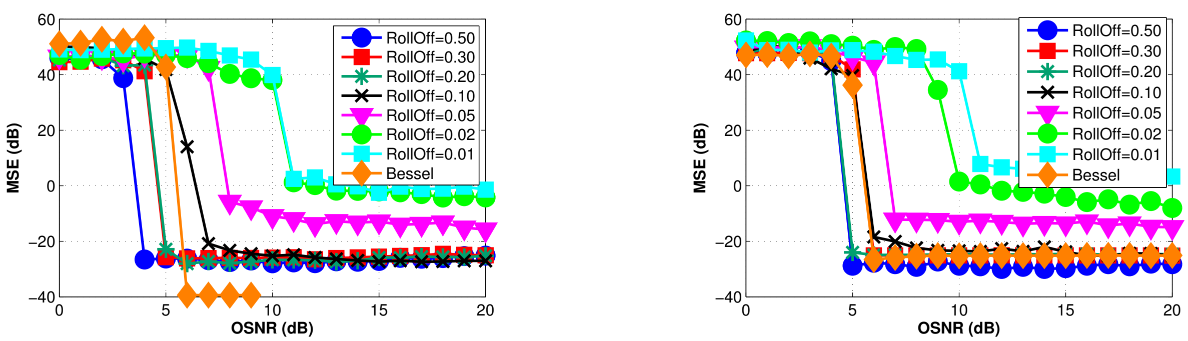
The performance is tested for a single channel 32GBaud PDM-QPSK uncompensated link system with a dispersion parameter of $D = 16$ ps/nm/km, attenuation $\alpha = 0.2$ dB/km, and nonlinear coefficient $\gamma = 1.3$ /W/km. Launch power is fixed at 0 dBm. The received signal is sampled at twice the symbol rate. A total of 50 random data independent trials are conducted and, for each, a random window of 32768 samples, for consistency with [7], is considered for CD estimation. Both non-return-to-zero (NRZ) pulses with Bessel filter (5^{th}order with bandwidth of $\sim$45GHz) and root-raised-cosine (RRC) shaping with roll-off factor ≤ 0.5 are considered. To guarantee peak estimation, delay subtract operation and digital bandpass filter [7] are employed respectively. Fig. 1(c) depicts the estimation value obtained with the four schemes for different link length. FFT, FHT/FFT and FHT show equal behavior, while FCT slightly underestimates the accumulated CD, as appreciable in the zoom. It is found that the maximum accuracy error is 2% compared to FFT case.

We then evaluate the accuracy of the CD estimation in terms of mean-square error (MSE) in dB for a linear regime transmission with different optical signal-to-noise ratio (OSNR) and an accumulated CD of ~ 250000 ps/nm. The effect of OSNR and RRC roll-off factor are shown in Fig. 2(a) for FFT (or FHT/IFFT or FHT, as they provide equal estimation) and Fig. 2(b) for FCT case. Values of 0 dB MSE and -40 dB MSE correspond to $\sim$1000 ps/nm and $\sim$10 ps/nm root mean square error respectively. All of the proposed methods are able to estimate the accumulated CD with a roll-off factor down to 0.05, assuming OSNR values around the 7% forward-error correction (FEC) limit, $\sim$10 dB. Further roll-off reduction will result both in higher OSNR requirements and MSE values. The use of FHT/IFFT, FHT or FCT results, thus, in comparable estimation, but with major complexity reductions, as reported in Table 1. The FCT case presents a maximum accuracy loss of 2% compared to FFT in the operational region with MSE < 0 dB.



(a) (b) (c)

Fig. 1: Comparison of the different methods considered in terms of (a) total complexity, (b) peak estimation, (c) nonlinear transmission for different fiber lengths with zoom in the inset.



(a) (b)

Fig. 2: MSE versus OSNR for NRZ signal with Bessel filter and RRC with varying rolloff for (a) FFT, FHT/IFFT, FHT case and (b) FCT case.

4. Conclusions

Fast and blind reduced-complexity CD estimation methods based on ACSPW are proposed and numerically investigated. The employment of Hartley transform delivers a 30% reduction in complexity with no loss in accuracy. The application of cosine transform allows a 70% complexity reduction and a maximum accuracy loss of 2% compared to the original ACSPW in the operational region with MSE values lower than 0 dB.

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