# Fast and Robust Chromatic Dispersion Estimation Using Auto-Correlation of Signal Power Waveform for DSP based-Coherent Systems

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**Abstract:** We propose chromatic dispersion (CD) estimation technique by using auto-correlation of signal power waveform for DSP based-coherent systems. Simulation results demonstrate 10-fold estimation time reduction with comparable CD range and estimation precision reported to date.
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## 1. Introduction

Coherent receiver is capable of compensating linear impairments such as chromatic dispersion (CD). Blind non-data aided CD estimation is often required for initialization of the equalizer especially for links in dynamic optical networks [1]. Traditional chromatic dispersion (CD) estimation techniques rely on compensating the exact CD and have to scanning through the possible CD values. Hence for large CD values, large amount of samples are required for estimation [2]-[4]. For example, around 100000 symbols are necessary to estimate 0-24000 ps/nm CD for 28 G baud systems in [4]. In this paper, we propose a CD estimation technique based on examining the auto-correlation function of the signal power waveform. The location of peaks in the auto-correlation function is analytically shown to be indicative of the transmission link CD. Simulation results for polarization-division-multiplexed (PDM) QPSK as well as PDM-16-QAM systems shows that up to 80000 ps/nm of residual link CD can be estimated in presence of other transmission impairments by using only 8192 symbols with an estimation precision and accuracy comparable or better than other reported results in the literature.

## 2. Operating principle

For simplicity purpose, we will consider a single polarization system without polarization effects in our analysis and note that the results can be generalized to PDM systems. Let the received signal be $s(t) = \sum_{n=-\infty}^{\infty} x_n q(t-nT)$ where $x_n$ denotes independent and identically distributed (i.i.d) information symbols, $T$ is the symbol period and $q(t)$ denotes the pulse shape that is distorted by CD in general. In this case, the received signal power waveform can be expressed as

$$y(t) = |s(t)|^2 = \sum_n |x_n|^2 |q(t-nT)|^2 + \sum_{k \neq m} x_k x_m^* q(t-kT)q^*(t-mT) \triangleq y_0(t) + y_1(t) \qquad (1)$$

In (1), the term $y_0(t)$ represents the component contributed by the sum of the power of the individual symbols while $y_1(t)$ denotes the component contributed by the interference among different symbols. The auto-correlation function of $y(t)$ averaged over one symbol period is given by [5]

$$
\begin{aligned}
\bar{R}_{yy}(\tau) &= \frac{1}{T} \int_0^T E[y(t)y(t-\tau)] dt \\
&= \frac{1}{T} \sum_v \int_{-\infty}^{\infty} |q(t)|^2 |q(t+vT-\tau)|^2 dt + \frac{1}{T} \sum_{v=1}^{\infty} \int_{-\infty}^{\infty} q(t)q^*(t+vT)q^*(t-\tau)q(t+vT-\tau) dt \\
&= \bar{R}_{y_0 y_0}(\tau) + \bar{R}_{y_1 y_1}(\tau).
\end{aligned}
\qquad (2)
$$

When there are substantial amounts of CD, the pulses are widely broadened and $y_0(t)$ and hence $\bar{R}_{y_0 y_0}(\tau)$ will approach a constant value. Assuming Gaussian pulses for simplicity [6] where $q(t) = \frac{T_0}{(T_0^2 - i\beta_2 z)^{1/2}} \exp\left[-\frac{t^2}{2(T_0^2 - i\beta_2 z)}\right]$, $\bar{R}_{y_1 y_1}(\tau)$ will be given by

$$\bar{R}_{y_1 y_1}(\tau) = \frac{T_0^3}{T} \sqrt{\frac{\pi}{2(T_0^4 + \beta_2^2 z^2)}} \exp\left[-\frac{\tau^2 T_0^2}{2(T_0^4 + \beta_2^2 z^2)}\right] \sum_{v=1}^{\infty} \exp\left[-\frac{v^2 T^2 T_0^2}{2(T_0^4 + \beta_2^2 z^2)}\right] \cos\left(\frac{\tau v T \beta_2 z}{T_0^4 + \beta_2^2 z^2}\right) \qquad (3)$$

where $T_0$ is the half-width of Gaussian pulse, $\beta_2$ is the group velocity dispersion (GVD) parameter of the fiber and $z$ is the transmission length.

Fig. 1 shows the auto-correlation function $\bar{R}_{yy}(\tau)$ for a 112 Gb/s PDM-QPSK system with 66% RZ Gaussian pulse and different amounts of CD. It can be seen that there is a pulse in $\bar{R}_{yy}(\tau)$ and the location of the pulse depends on CD. Therefore, the pulse location of $\bar{R}_{yy}(\tau)$ can be used for CD estimation To determine the CD value from the pulse location, one can assume that the first term in the summation in (3) dominates. In this case, the pulse will be located at $\tau_0 = \frac{2\pi(T_0^4 + \beta_2^2 z^2)}{T\beta_2 z}$ and the accumulated CD can be estimated by

$$\beta_2 z = \frac{\tau_0 T + \sqrt{\tau_0^2 T^2 - 8\pi^2 T_0^4}}{4\pi}. \tag{4}$$

While the analysis presented assumes Gaussian pulses, the vertical dashed lines in Fig. 1 indicate the estimated location of the pulse $\tau_0$ calculated using eq. (4) for a 66% RZ-PDM-16-QAM system. The $\tau_0$ and hence CD estimate almost agree perfectly with that using Gaussian pulses and further simulations reveal that the location of the pulse $\tau_0$ remains unchanged for RZ and/or NRZ pulse shapes even though $\bar{R}_{yy}(\tau)$ does vary in general. Therefore, eq. (4) can be used as a pulse shape and modulation format-independent CD estimation technique. At the coherent receiver, the received signal is sampled with frequency $1/T_s$ and squared to produce $y[n] = |s(nT_s)|^2$. The discrete-timed version of the auto-correlation function can be calculated by

$$\bar{R}_{yy}[n] = IFFT\{|FFT(y[n])|^2\} \tag{5}$$

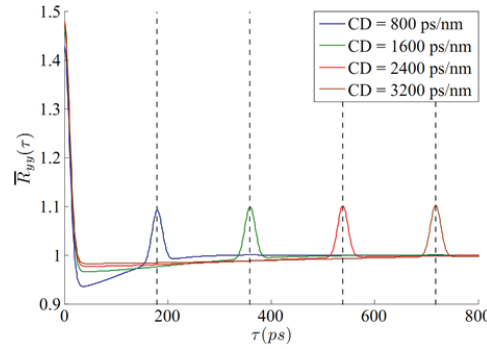and $\bar{R}_{y_1 y_1}(\tau)$ can be recovered by interpolation from which $\tau_0$ can be obtained.



Figure 1. The auto-correlation function $\bar{R}_{yy}(\tau)$ for 28 G baud coherent system with 800, 1600, 2400 and 3200 CD calculated using eq. (3) for Gaussian pulse with $T_0 = 10$ ps. The sampling rate is 56 GSa/s. The vertical dashed lines indicate the estimated location of the pulse $\tau_0$ calculated from eq. (4) using 16384 symbols for a 66% RZ-PDM-16-QAM system. The $\tau_0$ and hence CD estimate almost agree perfectly with that using Gaussian pulses.

## 3. Simulation Results

Simulations are carried out for 66% return-to-zero (RZ) 112 Gb/s PDM-QPSK and 224 Gb/s PDM-16-QAM systems using VPI. A $2^{30}-1$ PRBS sequence is sent into a transmission link and the dispersion coefficient of the fiber is 16 ps/nm-km. The linewidth for both transmitter laser and local oscillator (LO) is 1 MHz and the photo-currents are sampled at 56 GSa/s and processed to obtain $\bar{R}_{yy}(\tau)$. The estimation results in the presence of different impairments such as amplifier noise, frequency offset, polarization-mode dispersion (PMD) and polarization dependent loss (PDL) are shown in Fig. 2. For each combination of various system parameters, the mean errors and standard deviations are calculated from 50 independent simulations. Fig. 2 (a) and (b) show the mean estimation error and standard deviation with only CD. The standard deviation of the estimate is smaller than 10 ps/nm when more than 4096 symbols are used. The effect of optical signal-to-noise ratio (OSNR) and all-order PMD on the proposed CD estimation technique are shown in Fig. 2 (c) and (d). Calculated using 8192 symbols, the standard deviation is 8.8 (9.8) ps/nm with 10 dB OSNR and 34 (30.3) ps/nm with 30 ps mean differential group delay (DGD) for PDM-QPSK (PDM-16-QAM) systems. In addition, Fig. 2 (e) shows that the proposed technique is immune to polarization dependent loss (PDL) up to 10 dB with random polarization state. For a 10-channel WDM system with 50 GHz channel spacing, Fig. 2 (f) shows the CD estimation results for the center channel. The signal power per channel is 0 dBm with random polarization states for each channel. The nonlinear coefficient, OSNR, mean DGD of all order PMD and frequency offset (FO) are 1.32/W-km, 10 dB, 25 ps and –2 ~ 2 GHz. As shown in the figure, the

standard deviation of the CD estimate is always kept within 40 ps/nm. Overall, the maximum estimation error among all the 13800 independent simulations in this paper with different channel conditions is 224 ps/nm. It should be noted that the mean error, standard deviations and maximum estimation error obtained are comparable or better while the number of symbols required is at least 10 times less than that reported in the literature [1]-[4].
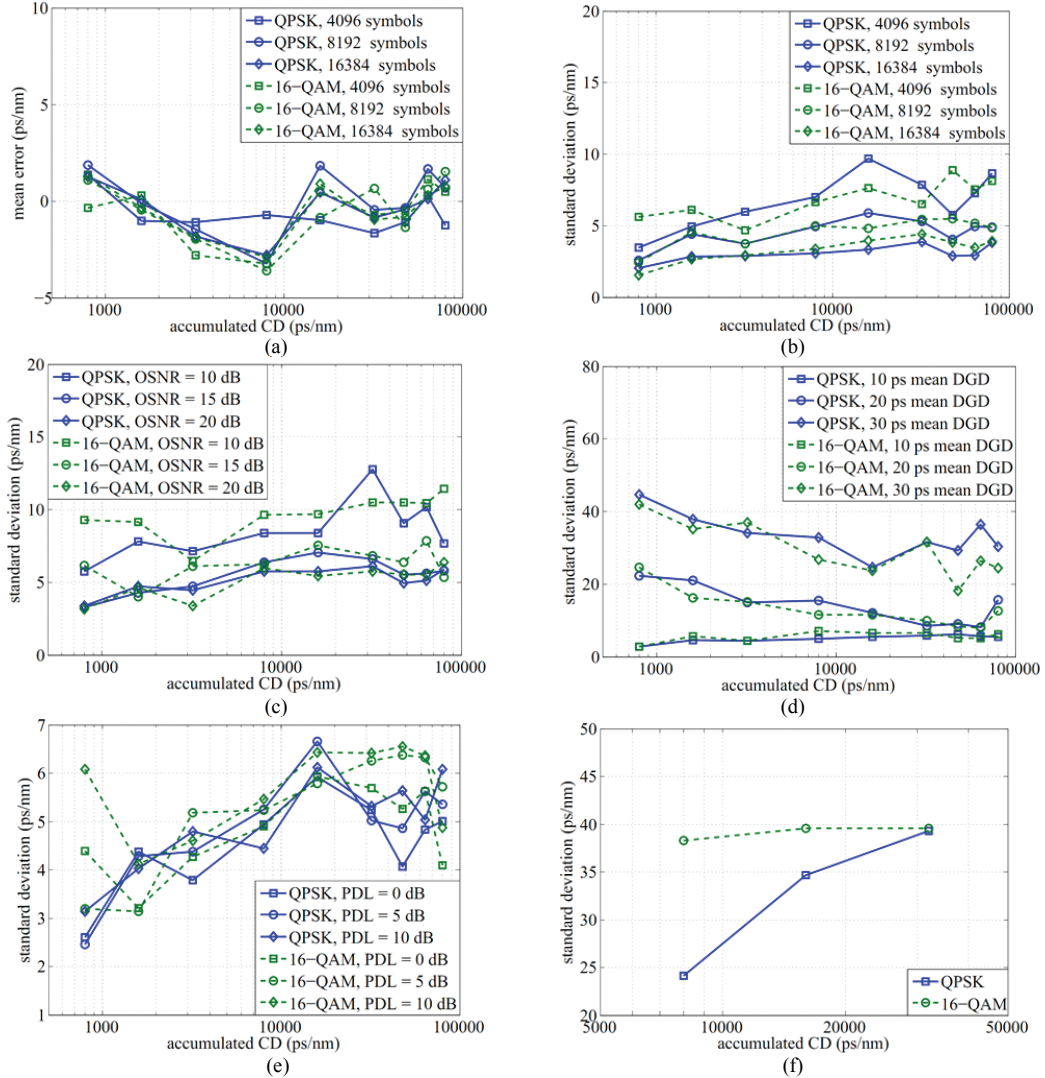


Figure 2. CD estimation results for 66% RZ 112 Gb/s PDM-QPSK and 224 Gb/s PDM-16-QAM systems. (a) mean error and (b) standard deviation of CD estimate when noise, polarization and other effects are absent; Standard deviation of CD estimate for different (c) OSNR (d) all-order PMD and (e) PDL using 8192 symbols; (f) standard deviation in the presence of nonlinearity, 10 dB OSNR, 25 ps mean DGD, -2~2 GHz FO for a 10-channel system with 0 dBm signal power per channel.

## 4. Conclusion

We have proposed a simple CD estimation technique that demonstrates high estimation accuracies, large dynamic range, short estimation time and insensitive to other impairments. It can also be implemented as an optical performance monitor with simple direct detection for intermediate nodes of fiber optic systems.

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