A Chromatic Dispersion Estimation Method for Arbitrary Modulation Formats

John Zweck[(1)] and Curtis Menyuk[(2)]

[(1)]Department of Mathematics and Statistics

[(2)]Department of Computer Science and Electrical Engineering

University of Maryland, Baltimore County

http://www.math.umbc.edu/~zweck/

zweck@umbc.edu

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Overview

We introduce a method to estimate the chromatic dispersion in a coherently received signal with an *unknown* modulation format.

Potential Applications

- Reconfigurable heterogeneous optical networks
- General purpose coherent receiver systems

Main Ingredient

Formula for chromatic dispersion in terms of the phase of the signal at 4 frequencies

Current State-of-the-Art Approach

Commonly, dispersion estimation algorithms

- Use electrical equalization filters
- Continuosly optimize filter coefficients
- Require *a priori* knowledge of modulation format
- Are slow to converge

Features of New Method

- Essentially a one-shot method
- Does not involve optimization
- Completely independent of modulation format
- Requires $\approx$ 5 ns of data (for noise averaging)

Formats for Verification of Algorithm

We have verified that the algorithm performs well at a 10 Gb/s baud rate for the formats:

RZ33	**NRZ**
RZ50	**BPSKPM**
CSRZ	**QPSKPM**
BPSKMZ	
QPSKMZ	

Theoretically justified for the blue formats.

Must know of symbol period, T, and central freq.

$$u(t) = \sum_{n=0}^{N-1} b_n v(t - nT) \qquad \text{(for theory)}$$

Formula for Chromatic Dispersion

- Measure the phase of the coherently received signal, $\widetilde{u}$, at four frequencies, $\pm\omega_1$, $\pm\omega_2$ with

$$\omega_1 = \frac{\pi}{T} + \delta\omega \qquad \text{and} \qquad \omega_2 = \frac{\pi}{T} - \delta\omega.$$

- Set $\varphi(\omega) = \arg[\widetilde{u}(\omega)]$. Calculate

$$\Theta = [\varphi(\omega_1) + \varphi(-\omega_1)] - [\varphi(\omega_2) + \varphi(-\omega_2)].$$

- If the total dispersion, β, satisfies

$$|\beta| < \beta_{\max} = \frac{T}{4\,\delta\omega},$$

then (ignoring noise)

$$\beta = \frac{T\Theta}{4\pi\,\delta\omega}, \qquad \text{where } -\pi \le \Theta < \pi.$$

Why Does the Formula Work?

- After the local oscillator in the coherent receiver,

$$\widetilde{u}(\omega) = \widetilde{v}(\omega) \left(\sum_{n=0}^{N-1} b_n \exp(i\omega T n) \right) \exp(i\theta_0 + it_0\omega + i\beta\omega^2/2).$$

- **Goal:** Extract dispersion, β, from phase of $\widetilde{u}$.
- **Assumption:** The phase of $\widetilde{v}$ is constant. So

$$\varphi \;=\; \varphi_b + \varphi_q.$$

- **Main Obstacle:** The phase of the random data,

$$\varphi_b(\omega) \;=\; \arg\left[\sum_{n=0}^{N-1} b_n \exp(i\omega T n) \right].$$

Why Does the Formula Work?

- The deterministic phase is quadratic in ω:

$$\varphi_q(\omega) = \theta_0 + t_0\omega + \beta\omega^2/2.$$

- Determine β from $\varphi_q(\pm\omega_1)$ and $\varphi_q(\pm\omega_2)$.
- Remove the odd term using

$$\varphi_q(\omega_k) + \varphi_q(-\omega_k) = 2\theta_0 + \beta\omega_k^2, \qquad k = 1, 2.$$

- Remove constant term using

$$\left[\varphi_q(\omega_1) + \varphi_q(-\omega_1)\right] - \left[\varphi_q(\omega_2) + \varphi_q(-\omega_2)\right] = \beta(\omega_1^2 - \omega_2^2).$$

Why Does the Formula Work?

- **Final Step:** Remove the phase of the random data:

$$\varphi_b(\omega) \;=\; \arg\left[\sum_{n=0}^{N-1} b_n \exp(i\omega T n)\right].$$

- **Fundamental Observation:** If

$$\omega_1 + \omega_2 = \frac{2\pi}{T},$$

then

$$\varphi_b(-\omega_2) \;=\; \varphi_b(\omega_1), \qquad \varphi_b(-\omega_1) \;=\; \varphi_b(\omega_2).$$

- **Upshot:** Θ is **independent of the data!**

Noise averaging

To mitigate for estimation errors due to noise:

- Calculate Θ_m for M time segments, $u_m(t)$, of duration

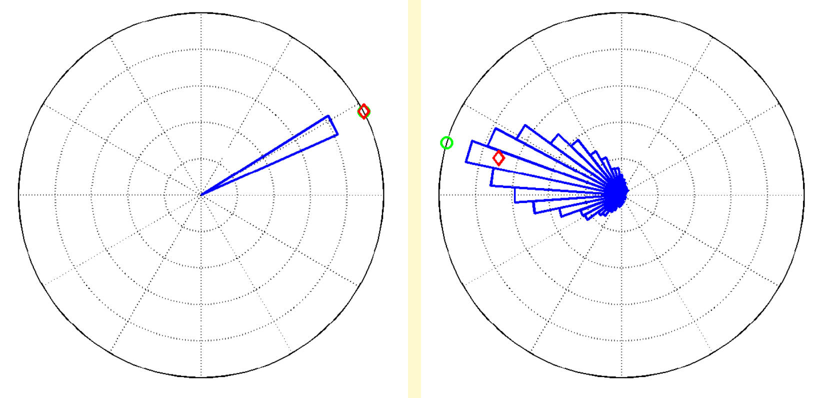
$$T_{\text{seg}} = N_{\text{seg}} T.$$

- Average the Θ_m's over the circle using

$$\langle \Theta \rangle := \arg [\langle \exp(i\Theta) \rangle].$$

- **Problem:** $\tilde{u}_m$ is filtered by a sinc.
- **Solution:** Choose N_{seg} and $\delta\omega$ large enough.

Polar Histograms of Θ



Noise-free QPSKMZ ($\beta = 3000$ ps/nm)

Periodic (left) and non-periodic (right) segments

Simulation Results: System Parameters

- 8 formats generated using MZMs and PMs
- Baud rate: 10 Gb/s
- OSNR: 10, 15 dB
- Total dispersion: $\beta = 500$, 3000 ps/nm
- $M = 8192$ *non-periodic* segments with $T_{\text{seg}} = 3200$ ps
- Measurement frequencies: $f_1 = 4$ GHz, $f_2 = 6$ GHz
- Maximum dispersion: $\beta_{\text{max}} = 3120$ ps/nm

Algorithm Verification

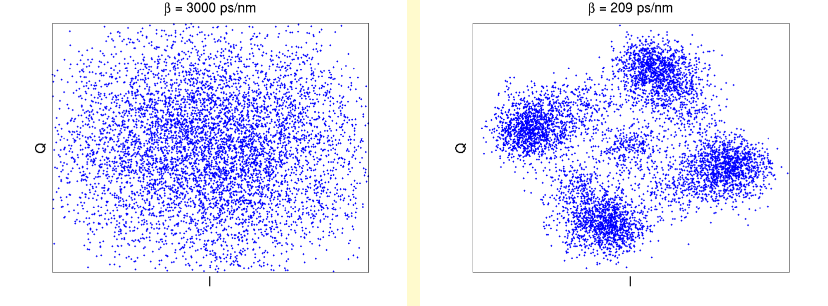
Table: Error in estimated dispersion [ps/nm]. Actual dispersion was 500 ps/nm (left) and 3000 ps/nm (right).

Format	10 dB	15 dB
RZ33	42	48
RZ50	29	38
CSRZ	49	34
BPSKMZ	36	49
QPSKMZ	36	34
NRZ	72	65
BPSKPM	62	55
QPSKPM	62	42

Format	10 dB	15 dB
RZ33	176	182
RZ50	218	199
CSRZ	191	224
BPSKMZ	189	204
QPSKMZ	140	209
NRZ	226	215
BPSKPM	221	210
QPSKPM	199	204

If apply algorithm $\times 2$, can reduce error to < 3%.

Constellation Diagrams for QPSKMZ



Before (left) and after (right) dispersion estimation and compensation (OSNR = 15 dB)

Conclusions

- We devised an algorithm to estimate the chromatic dispersion in a coherently received noisy signal.
- **Novelty:** The method is **blind to the format**.
- We verified the method for a wide range of formats.
- The algorithm is simple and fast.

Initial experimental validation results are very encouraging.[1]

[1] Experimental data from M. Dennis, R. Sova, J. Sluz @ JHU-APL.