Expanding Measurement Range for Chromatic Dispersion Estimation Using Auto-Correlation of Signal Power Waveform

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Abstract By using auto-correlation of signal power waveform (ACSPW) for coherent systems, an improved method for chromatic dispersion (CD) estimation is proposed. In order to overcome the limitation of ACSPW, the ACSPW scheme is extended by artificially adding CD to the received signal using a finite impulse response filter in the estimation phase, moving the pulse to the range that can be measured, and finally subtracting the known added value after the estimation. This method will be essentially unaffected by amplified spontaneous emission noise, pulse shapes and polarization mode dispersion. Mean error of monitoring results is 127 ps/nm.

Key words optical communications; chromatic dispersion; auto-correlation of signal power waveform; spectral shift

OCIS codes 060.2330; 060.2630; 060.1660; 060.4510

扩大基于信号功率谱自相关函数的色散监测范围的研究

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摘要 提出了改进的利用信号功率谱的自相关函数(ACSPW)监测相干系统中色散(CD)的方案。在链路中加入更大的色散值来克服传统使用 ACSPW 监测 CD 方法的限制。扩大监测范围的方式为人为添加已知的较大 CD 值，对接收到的信号使用有限脉冲反应滤波器的估计阶段，移动功率谱自相关函数到可以测量的范围内，最后减去已知的添加的 CD 值即为估计值。此方法基本上不受放大的自发辐射噪声、脉冲的形状和偏振模色散的影响。监测结果平均误差为 127 ps/nm。

关键词 光通信；色度色散；自相关函数；频谱搬移

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1 Introduction

Digital coherent optical communication is the main technology for optical transport networks 100-Gb/s technologies using polarization-division-multiplexed quadrature-phase-shift-keying (PDM-QPSK)[1]. In a digital coherent optical communication system, no optical dispersion compensation is required and the large amount of chromatic dispersion (CD) accumulated along the link can be compensated by digital signal processing (DSP) in a coherent optical receiver[2]. Recently, estimating CD is an important work based on the signal power auto-correlation.

Auto-correlation of signal power waveform (ACSPW) demonstrates large dynamic range, high estimation accuracy, short estimation time and robustness against other transmission impairments, and it is applicable to single-carrier phase-shift keyed (PSK) and quadrature-amplitude modulation (QAM) systems[3]. Nevertheless,

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the technique has some shortcomings, for example incorrect results for relatively small values of CD, and failure to distinguish between positive and negative dispersion[4]. However, we have to estimate small values of CD in many scenes, such as in short-haul transmission, in LAN and there is some negative dispersion when overcompensation exists. In this paper, a simple way to extend ACSPW is proposed by adding bigger values of CD using finite impulse response (FIR) filter, to estimate small values of CD and distinguish positive and negative dispersion.

2 Improvement for ACSPW

In PDM-QPSK coherent system, $\overline{R}_{yy}(\tau)$ is the average auto-correlation of received signal after analog-digital converter which includes two portions,

$$\overline{R}_{yy}(\tau)=\overline{R}_{y_0y_0}(\tau)+\overline{R}_{y_1y_1}(\tau),\tag{1}$$

where $\overline{R}_{y_0y_0}(\tau)$ is the auto-correlation component produced by the power of the individual symbol which approaches to be a constant value when a larger CD exists in the link, and $\overline{R}_{y_1y_1}(\tau)$ is the auto-correlation contribution of the interference among different symbols. Through inference, we find it is a Gaussian pulse sequence that has the same interval by a Gaussian envelope modulated. Assume that pulse shape is a Gaussian pulse shape[5], $\overline{R}_{yy}(\tau)$ can be calculated by

$$\overline{R}_{y_1y_1}(\tau)=R_{\mathrm{env}}(\tau)\cdot\sum_{v}p(\tau-v\tau_0),\tag{2}$$

where $p(t)=\exp[-t^2/(2T_0^2)]$ and the Gaussian envelope $R_{\mathrm{env}}(\tau)$ is given as

$$R_{\mathrm{env}}(\tau)=\frac{\pi T_0^2}{T^2}\exp\left[-\frac{T_0^2\tau^2}{2(T_0^4+\beta^2z^2)}\right],\tag{3}$$

where the interval of sequence τ_0 which allows to compute the accumulated CD value is

$$\tau_0=\frac{2\pi(T_0^4+\beta_2^2 2z^2)}{T\beta_2 z}.\tag{4}$$

Because of the limitation of $R_{\mathrm{env}}(\tau)$, only zeroth order pulse and first order pulse are usable and the first order pulse is used to estimate the value of CD. However, if CD is very small, the first order pulse may be very close to zeroth order pulse or they even may overlap. In this case, the location of the first pulse in $\overline{R}_{y_1y_1}(\tau)$ will not be ascertained. In addition, if CD is not large enough, $\overline{R}_{y_0y_0}(\tau)$ is a variable value and its influence can't be ignored. This method will be not applicable. So there are incorrect results for relatively small values of CD, and it is failing to distinguish between positive and negative dispersion.

In order to mitigate the limitations and expand the measurement range, the ACSPW scheme is extended by artificially adding CD to the received signal using a FIR filter in the estimation phase[4], moving the pulse to the range that can be measured, and finally subtracting the known added value after the estimation[6]. Fig. 1(a) and Fig. 1(b) illustrate the schematic diagrams of the auto-correlation function $\overline{R}_{y_1y_1}(\tau)$ and $R_{\mathrm{env}}(\tau)$ in the presence of 800 ps/nm CD and 8000 ps/nm CD respectively for 28 G baud PDM-QPSK systems. As is shown, the location of the first order pulse of 800 ps/nm CD is near from zeroth order pulse, so the value of CD is not easily calculated. Then 7200 ps/nm CD is added and the auto-correlation function in the presence of 8000 ps/nm CD is obtained. It can be concluded that if we have to estimate a small CD, a big CD can be added in link so that the location of the first pulse changes and moves back. In this way, the value of CD can be estimated accurately.

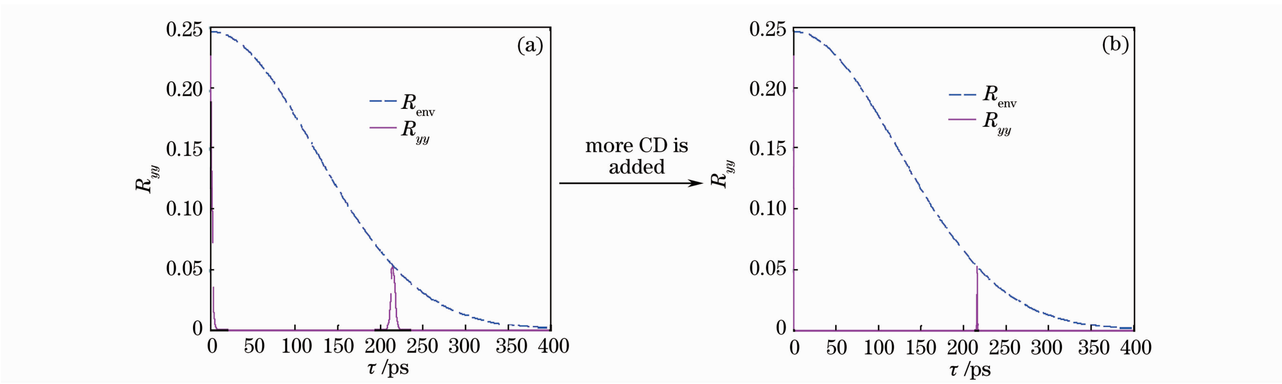

Fig. 1 Auto-correlation function $\overline{R}_{y_1y_1}(\tau)$ and $R_{\mathrm{env}}(\tau)$ in the presence of 800 ps/nm CD with for 28 G baud PDM-QPSK systems

The location of the first pulse in $\overline{R}_{y_1y_1}(\tau)$ as well as $\overline{R}_{yy}(\tau)$ can be employed for CD estimation through equation (3),

$$\arg_\tau\max[\overline{R}_{y_1y_1}(\tau)]=\tau_0=\frac{2\pi(T_0^4+\beta_2^2z^2)}{T\beta_2 z},\tag{5}$$

$$V_{\mathrm{CD\_acc}}=\beta_2 z\frac{2\pi c}{\lambda^2}=\frac{\tau_0T+\sqrt{\tau_0^2 2T^2-16\pi^2T_0^4}}{4\pi}\frac{2\pi c}{\lambda^2}\approx\frac{\tau_0Tc}{\lambda^2}.\tag{6}$$

Moreover, the discrete time version of $\overline{R}_{yy}[n]$ is given by equation (4),

$$\overline{R}_{yy}[n]=\mathscr{F}^{-1}[|\mathscr{F}(y[n])|^2],\tag{7}$$

where $y[n]$ is defined to denote the vector of sampled waveforms in both polarizations after balanced detection.

3 Influences

3.1 Influence of ASE noise

Amplified spontaneous emission (ASE) noise can be modeled as a band-limited Gaussian random process[7]. The power spectral density is

$$P_n(f) = \begin{cases} N_0/2, & |f| \leqslant f_H \\ 0, & |f| > f_H \end{cases}. \tag{8}$$

Auto-correlation function is

$$\begin{aligned} R_n(\tau) &= \int_{-f_H}^{f_H} P_n(f)\exp(j2\pi f\tau)\,df = \\ &\frac{N_0}{2}\int_{-f_H}^{f_H}\exp(j2\pi f\tau)\,df = \\ &\frac{N_0}{2}\frac{\exp(j2\pi f_H\tau)-\exp(-j2\pi f_H\tau)}{j2\pi f\tau} = \\ &\frac{N_0}{2}\frac{2\sin 2\pi f_H\tau}{2\pi\tau} = N_0 f_H\frac{\sin 2\pi f_H\tau}{2\pi f_H\tau}, \end{aligned} \tag{9}$$

$$R_n(\tau) = \sigma_n^2\,\mathrm{Sa}(2\pi f_H\tau), \tag{10}$$

so

$$R_n[k/(2f_H)] = 0,\ k = \pm 1, \pm 2, \pm 3, \cdots. \tag{11}$$

Because $E[n(t)] = 0$, $n(t)$ and $n[t + k/(2f_H)]$ are uncorrelated. $n(t)$ is Gaussian random variable, so statistical independence. Considering the ASE noise which can be modeled as a band-limited Gaussian random process with bandwidth larger than $1/T$, its auto-correlation will essentially be zero for $\tau \geqslant T$. Such correlation property will also hold for the signal-noise beating and noise-noise beating components in the optical intensity. Therefore, $\overline{R}_{yy}(\tau)$ will be essentially unaffected by ASE noise for $\tau > T$. τ_0 and the CD estimate will not be affected as long as $\tau_0 > T$, which translates into 10 km single mode fiber for 28 G baud system.

Fig. 2 illustrates the schematic diagram that CD estimate will not be affected by ASE noise in 28 G baud PDM-QPSK systems with 33% return-to-zero pulses.

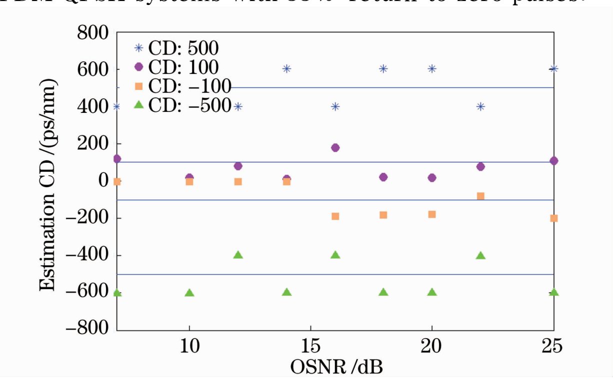

Fig. 2 Monitoring results for 28 G baud PDM-QPSK systems with 33% RZ pulses in different optical signal-to-noise ratios (OSNR)

3.2 Influence of pulse shapes

With respect to non-return-to-zero (NRZ) pulse shape, the pulse located at τ_0 in $\overline{R}_{yy}(\tau)$ is too 'weak' for CD estimation. It makes estimation of NRZ a little worse than other pulse shapes. To cope with this problem, we found that the peak in $\overline{R}_{yy}(\tau)$ can be boosted with high-pass filtering for all the pulse shapes in the research. The technique demonstrates excellent accuracy and precision for all the pulse shapes considered[8]. Therefore, this method is proved to be unacted on different pulse shapes.

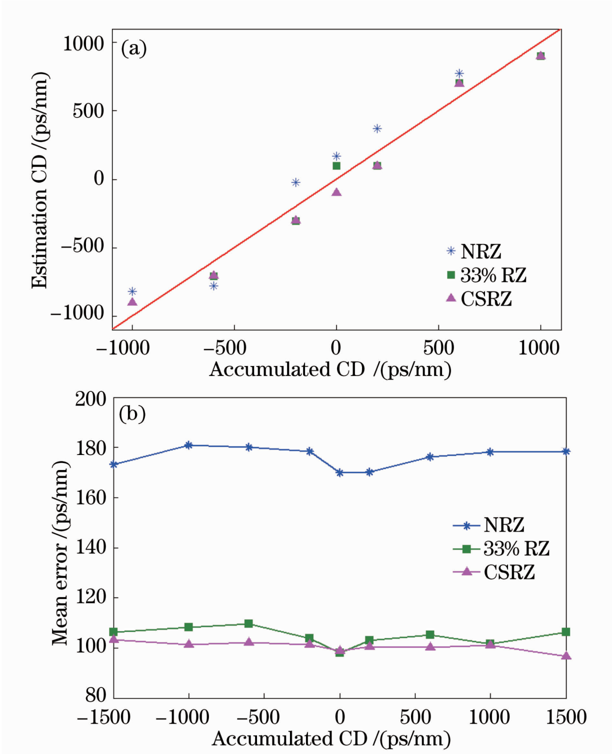

Fig. 3 28 G baud PDM－QPSK systems with NRZ, 33% RZ and CSRZ pulses in the presence of －1500 to 1500 ps/nm accumulated CD (a) and mean error (b)

3.3 Influence of polarization mode dispersion

The signal for a PDM system can be expressed as[9-10]

$$E_t(t) = \sum_n \begin{bmatrix} s_x \\ s_y \end{bmatrix} \cdot p(t - nT), \tag{12}$$

where s_x and s_y denote the information symbols for the two polarizations respectively, satisfying the following constraints

$$E[s_n] = 0, \tag{13}$$

$$E[s_n s_m^{\,*}] = \begin{cases} 1, & n = m \\ 0, & n \neq m \end{cases}. \tag{14}$$

Therefore, in the presence of polarization mode dispersion (PMD), the received signal in the frequency domain can be calculated as

$$\widetilde{E}_{\mathrm{r}}(f)=R_2\begin{bmatrix}\exp(-2\pi \mathrm{i} f\Delta\tau/2), & 0\\ 0, & \exp(-2\pi \mathrm{i} f\Delta\tau/2)\end{bmatrix}R_1 H(f)\widetilde{E}_{\mathrm{t}}(f),\tag{15}$$

where $\Delta\tau$ is differential group delay (DGD), R_1 and R_2 denote the unitary polarization rotation matrices and $H(f)$ is transfer function of a band-pass filter.

The equivalent symbol projected on the two principal state of polarization (PSP) is

$$\begin{bmatrix}s'_x\\ s'_y\end{bmatrix}=\begin{bmatrix}\cos\theta_1\exp(-\mathrm{i}\phi_1/2)s_x+\sin\theta_1\exp(-\mathrm{i}\phi_1/2)s_y\\ \sin\theta_1\exp(-\mathrm{i}\phi_1/2)s_x+\cos\theta_1\exp(-\mathrm{i}\phi_1/2)s_y\end{bmatrix},\tag{16}$$

where s'_x and s'_y are considered as two new signals. Thus, the time-domain received signal is given by

$$E_{\mathrm{r}}(t)=R_2\begin{bmatrix}E_{x'}(t)\\ E_{y'}(t)\end{bmatrix}=R_2\begin{bmatrix}\sum_n s'_x\cdot q(t-nT-\Delta\tau/2)\\ \sum_n s'_y\cdot q(t-nT+\Delta\tau/2)\end{bmatrix},\tag{17}$$

where $E[s'_x]=E[s'_y]=E[s'_x,s'_y]=E[s'_x,s'^{*}_y]=0$, $E[|s'_x|^2]=E[|s'_y|^2]=1$.

Then the intensity is

$$I(t)=|E_{x'}(t)|^2+|E_{y'}(t)^2|=I_{x'}(t)+I_{y'}(t)\approx 2\sqrt{\pi}T_0/T+I'_{x'}(t)+I'_{y'}(t).\tag{18}$$

Since s'_x and s'_y are uncorrelated, and $I_{x'}(t)$, $I_{y'}(t)$ are uncorrelated as well $R_{yy}(\tau)$ is

$$R_{yy}(\tau)=\frac{4\pi T_0^{\,2}}{T^2}+R_{yy_{x'}}(\tau)+R_{yy_{y'}}(\tau).\tag{19}$$

Since the new signal is equal to the original signal, τ_0 is independent of $R_{yy}(\tau)$ and $\Delta\tau$, and the estimated CD is independent of the first order PMD. However, in signal polarization system, $R_{yy_{x'}}(\tau)$ and $R_{yy_{y'}}(\tau)$ are correlated, so $R_{yy}(\tau)$ will change and this method will be influence by PMD.

Fig. 4 illustrates the estimated CD is independent of the first order PMD in 28 G baud PDM-QPSK systems with 33% RZ pulse. With the increase of DGD, estimated error increases when DGD is more than 60 ps.

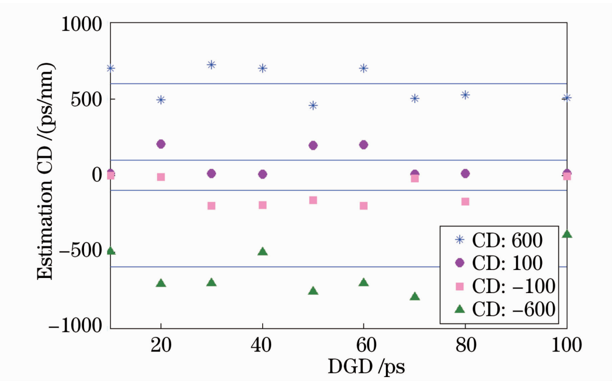

Fig. 4 Monitoring results for 28 G baud PDM-QPSK systems with 33% RZ pulses in different PMD

4 Conclusion

In this paper, a simple method to extend ACSPW is proposed by adding big values of CD using FIR filter. We make analysis of influence of ASE noise, different pulse shapes and the first order PMD. This method will be essentially unaffected by these factors. Mean error of monitoring results is 127 ps/nm.

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