Chromatic Dispersion Estimation for Optical PDM-QPSK Communication System without Symbol Rate Limitation

Junyu Wei, Zhiping Huang, Jing Zhou, Shaojing Su and Yimeng Zhang
School of Mechatronics Engineering and Automation, National University of Defense Technology, Deya Road, Changsha 410073, Hunan Province, China

ABSTRACT: Chromatic dispersion (CD) is one of main channel impairments in the ultra-long optical fiber communication based on polarization-division-multiplexing (PDM) technic. Therefore, CD estimation is an important step during coherent detection in the optical receiver. In this paper, an accurate and fast CD estimation method using two mathematical autocorrelation features of received signal is presented. We firstly use the autocorrelation of signal power waveform (ACSPW) to roughly estimate CD value and scanning range, and then singular value of signal autocorrelation matrix (SVSACM) is utilized to search the maximum value in the estimated CD range for accurate CD estimation. Compared with simply used ACSPW in the PDM-quadrature phase shift keying (QPSK) transmission system, the results of numerical simulations show that the proposed method can effectively expand the symbol rates limitation. Moreover, the scanning efficiency of SVSACM can be improved to be faster than that without coarse estimation, due to the fact that the CD scanning size becomes relatively small.

1 INTRODUCTION

Since the rapid development of wideband internet services and the demand for big data processing at a great capacity, the efficient use of optical signal spectrum and capacity is continuously being enhanced by upgrading the related technics, such as advanced modulation formats, coherent detection, polarization-division-multiplexing (PDM) and digital signal processor (DSP), in the next generation optical transport network (OTN). On the other hand, chromatic dispersion (CD), which is the one of main channel impairments, causes the inter symbol interferences (ISI) in the long or ultra-long OTN. Fortunately, the enhanced DSP using in the coherent detection can effectively compensate large CD in the electrical domain, so optical compensation (For example, dispersion compensation fiber) becomes dispensable for cost saving and uncomplicated system design. Additionally, the flexible and reconfigurable OTN leads to the change of accumulated CD at any time. Thus, it requires the DSP-based CD estimation with fast response and self-adaption.

Up to now, various CD estimation technics have been proposed by scientists and engineers. In [1, 2] training symbols or specific bit sequences are set in advance to identify the value of accumulated CD. These methods not only need extra operation in the optical transmitter and receiver, but also enhance hardware complexity and DSP logical resources. In [3, 4] CD estimation is proposed based on searching the pulse location in the autocorrelation of signal power waveform (ACSPW) without the known data-aid. But its estimation accuracy is limited by the transmission symbol rate [5]. It has been demonstrated that the CD estimation error reach to thousands of ps/nm when the symbol rate is lower than 8 Gsymbol/s. In [6] the average of autocorrelation matrix eigenvalue of received signal is used to search the maximum value by scanning the presetting CD range. However, the CD range depends on many facts such as fiber length and OTN structure. In addition, it can be anticipated that scanning efficiency quickly degrades in the case of large accumulated CD as a result of improper scanning step.

Considering the respective advantages of [4, 6], a CD estimation method with high accuracy and short response time is proposed for optical polarization-division-multiplexing (PDM)-quadrature phase shift keying (QPSK) signals with multiple symbol rates. Essentially, two mathematical autocorrelation features of received signal are used together in this work. The one utilizes ACSPW to coarsely estimate the accumulated CD value and then decide the CD scanning range through the limitation of symbol rate, the other one employs singular value of signal autocorrelation matrix (SVSACM) to scan the previous estimated CD range for accurate CD value. To investigate the influences of impairments on the proposed approach, the numerical simulations are
performed on VPI 9.1 [7] software for simulating 7/14/28 Gsymbol/s PDM-QPSK systems that can vary the size of steps of optical signal to noise ratios (OSNR) and first-order polarization mode dispersion (PMD) in the wide range. The theory analysis and the simulation results show that our approach is fast and sufficient to accurately estimate accumulated CD with good sensitivities.

2 THEORY ANALYSIS OF CHROMATIC DISPERSION ESTIMATION TECHNIQUE

2.1 Autocorrelation of signal power waveform for coarse estimation and scanning range

According to the previous literature [3], the ACSPW can be defined as:

\[ P[n] = \text{IFFT}\left\{\text{FFT}\left\{[R[n]-R[n+1]]^2\right\}^2\right\} \]  

where \( R[n] \) is the received baseband signal, \( \text{FFT} \) is fast Fourier transformation and \( \text{IFFT} \) represents fast Fourier inverse transformation. The differential operation enables the peak point of ACSPW distinctive especially for NRZ pulse shape [4]. The location of ACSPW peak value can be computed as [3]:

\[ \tau_0 = -2\pi(T_0^4 + \beta_z^2z^2)/T\beta_z \]  \[ (2) \]

where \( T_0 \) is the pulse width, \( T \) is the symbol period, \( z \) is the optical fiber length and \( \beta_z \) is the group velocity dispersion (GVD) coefficient. Usually, \( T_0 = \alpha T \) \((0 < \alpha < 1)\). In the classical nonlinear fiber optics theory [8], the accumulated CD is defined as:

\[ CD = -2\pi c\beta_z z / \lambda^2 \]  \[ (3) \]

where \( \lambda \) is the optical carrier wavelength and \( c \) is light velocity in vacuum. Thus the CD estimation value can be obtained by:

\[ CD_{est} = c(\tau_0 T + \sqrt{\tau_0^2 T^2 - 16T_0^4 \pi^2}) / 2\lambda^2 \]  \[ (4) \]

There are two noteworthy points. First, real value can be obtained only when \( \tau_0 \geq 4\pi T_0^2 / T \) in (4). Then \( 4\pi T_0^2 / T \) replaces \( \tau_0 \) in (4), the minimum CD estimation based on ACSPW can be described as:

\[ CD_{est \_\_min} = 2\pi c\alpha^2 T^2 / \lambda^2 \]  \[ (5) \]

Second, it can be predicted that \( \beta_z^2z^2 >> T_0^4 \) in (2) when the long or ultra-long optical fiber is applied, and then (2) can be transformed as:

\[ \tau_0 \approx -2\pi\beta_z z / T \]  \[ (6) \]

Therefore, combining (3) and (6), the CD coarse estimation can be expressed as:

\[ CD_{coarse\_est} = \tau_0 Tc / \lambda^2 \]  \[ (7) \]

Figure 1 (a) shows the relationship between \( CD_{est \_\_min} \) and transmission symbol rate. It can be found that the \( CD_{est \_\_min} \) decreases along with the increase of transmission symbol rate, which is reciprocal of symbol period \( T \). Moreover, the \( CD_{est \_\_min} \) reaches as large as 1250 ps/nm for 7 Gsymbol/s data, 313 ps/nm for 14 Gsymbol/s data and 78 ps/nm for 28 Gsymbol/s data. Hence, more accurate CD estimation using ACSPW can be expected for the high-speed optical signal with large accumulated CD. An example of the CD coarse estimation for 28 Gsymbol/s PDM-QPSK is presented in Figure 1(b). To cope with the symbol rate limitation of ACSPW algorithm, the range \( [CD_{coarse\_est} - CD_{est \_\_min}, CD_{coarse\_est} + CD_{est \_\_min}] \) is used for the next fine CD estimation.
2.2 Singular value of signal autocorrelation matrix for accurate estimation

According to the nonlinear fiber optics theory [8], we can obtain the CD response function in time domain given by:

\[
h_{CD}(z,t) = \sqrt{\frac{c}{jDA^2z}} \exp\left(\frac{j\pi c}{D\lambda^2 z} t^2\right)
\]

where \(t\) is the sampling time, \(D\) represents the dispersion coefficient of fiber calculated as:

\[
D = -2\pi c\beta_2/\lambda^2
\]

Consequently, the finite impulse response (FIR) filter can be designed through equation (10) to complete the CD equalization in time domain. The \(k\)-th tap coefficient of FIR filter is expressed as:

\[
a_k = \sqrt{\frac{cT^2}{D\lambda^2 z}} \exp\left(-\frac{j\pi cT^2}{D\lambda^2 z} k^2\right), -\left\lfloor \frac{U}{2} \right\rfloor \leq k \leq \left\lceil \frac{U}{2} \right\rceil
\]

\[
U = 2 \sqrt{\frac{|D|\lambda^2 z}{2cT^2}} + 1
\]

where \(\lfloor \cdot \rfloor\) is the arithmetic of downward round-off number, \(T\) is the sampling period of optical receiver, and \(U\) is the number of filter tap.

In the practical application, the CD value in the channel is unknown and the range of CD depends on many factors. Hence, a large range of CD and the scanning step should be carefully preset to scan the metric through sweeping over the range to search a special characteristic, such as the minimum and the maximum points of scanning waveform. In addition, the metric is varied by updating the tap coefficients of FIR filter. In [6, 9], the mathematical autocorrelation matrix of sampled signal has been proven to illustrate the distortion or ISI in the optical fiber communication. Hence, it is anticipated that the singular value of autocorrelation matrix could be potentially utilized for CD estimation with high stability, low complexity and less computational time. The autocorrelation matrix of received optical signal can be defined as below:

\[
M = \begin{bmatrix}
C[0] & C[1] & \cdots & C[L-1] \\
\vdots & \vdots & \ddots & \vdots \\
C[L-1] & C[L-2] & \cdots & C[0]
\end{bmatrix}
\]

where “*” represents the complex conjugate, \(C\) is the correlation of received signal \(R[n]\) and computed as:

\[
C[m] = \sum_{k=L}^{(N/2)-1} R[2k]R^*[2(k-m)]
\]

where \(N\) is the number of samples and \(L\) can be computed by [9]:

\[
L = (CD_{\text{max}} - CD_{\text{min}}) / 75
\]

where \(CD_{\text{max}} - CD_{\text{min}}\) is the CD scanning range. Consequently, the singular value of autocorrelation matrix is given by:

\[
S = \text{SVD}(M)
\]

where ‘SVD’ is the singular value decomposition of autocorrelation matrix, and \(S\) is the singular vector: \(\{s_i, 1 \leq i \leq N\}\). As a result, we can utilize the position of a ratio value to estimate the CD value. The singular value ratio (SVR) can be calculated as:

\[
SVR[n] = s_{\text{max}}[n] / \sqrt{\frac{L}{2}} s_{\text{min}}[n]
\]

where \(L\) is the matrix size, \(s_{\text{max}}[n]\) and \(s_{\text{min}}[n]\) are the 1-order and \(\sqrt{\frac{L}{2}}\)-order singular values of \(M\) with the largest and the smallest amplitudes in the CD scanning range, respectively. Figure 2 shows the singular value ratio versus the CD scanning range for 28 Gsymbol/s PDM-QPSK modulated data. It can be predicted higher CD estimation accuracy using SVR rather than 1-order singular value, because the impulse near CD = 1400 ps/nm is distinct.

![Figure 2. Singular value ratio versus the scanning CD for 28 Gsymbol/s PDM-QPSK signal.](image)

2.3 The operation of combined CD estimation

From above results, the flow chart of the proposed method is shown in Figure 3. In the first step, the sampling digital signal \(R[n]\) is processed in the ACSPW module, and then the location of maximum pulse \(P[n]\) is searched for the CD coarse estimation and the CD scanning range is determined. In the second step, to save the computational time and improve the efficiency in the SVACM module, we can utilize the previous estimation range of \([CD_{\text{ coarse est. min}}, CD_{\text{ coarse est. min}} + CD_{\text{ coarse est. max}}]\) obtained from equations (5) and (7). Thus, equation (13) can be transformed as
where $CD_{\text{resolution}}$ is the minimum step of CD estimation. In this work, $CD_{\text{resolution}} = 16$ ps/nm is utilized because of the typical optical fiber coefficient in the most cases. Moreover, singular value ratio of autocorrelation matrix is adopted to enhance the estimation accuracy and expand the symbol rate limitation. In the third step, the location of the maximum $SVR[n]$ is directly used for fine CD value estimation.

$$L = \frac{2CD_{\text{est min}}}{CD_{\text{resolution}}}$$  \hspace{1cm} (16)

Figure 3. Flow chart of the CD estimation proposed.

3 STRUCTURAL PROCESS OF SIMULATION SYSTEM AND RESULTS ANALYSIS

Based on the VPI simulation platform, the 7/14/28 Gsymbol/s PDM-QPSK optical signals are transmitted with about 100 kHz linewidth. The transmitted data is pseudo random bit sequence (PRBS) and the laser power is 1mW. The CD and differential group delay (DGD) are changed by a CD and first-order PMD emulator, while OSNR is regulated by an erbium doped fiber amplifier (EDFA) and a variable optical attenuator (VOA). At the coherent receiver side, the received signal and referenced signal, which is generated by local oscillator (LO), are combined by an optical 90° hybridizer. The hybrid signals are coherently detected by four balanced photodiodes and electrically filtered by low pass-band filters to eliminate the out-band noise. The analog-to-digital converted (ADC) signals are processed using MATLAB code in the off-line DSP module. CD estimation algorithms, including ACSPW, SVSACM and ACSPW+SVSACM, are utilized to estimate the accumulated CD.

Figure 4 shows the mean absolute estimation error using ACSPW and ACSPW+SVSACM two different algorithms for PDM-QPSK modulated signal with multiple symbol rates. Here, 8192 symbols are utilized to estimate the CD value, while 30 independent tests are performed to compute the absolute mean estimation error. It can be found that the estimation error based on ACSPW+SVSACM algorithm is frequently much lower than ACSPW-based for the symbol rates from low to high, especially 28 Gsymbol/s rate, about 10-time accuracy improvement compared to that of ACSPW. Thereby, we believe that more accurate CD value can be obtained using ACSPW+SVSACM algorithm in the coherent optical receiver.

Figure 4. Mean absolute estimation error versus actual CD for 7/14/28 G symbol/s PDM-QPSK signal using ACSPW and ACSPW+SVSACM algorithm, respectively.

Figure 5. The variations of SER versus the step number using SVSACM and ACSPW+SVSACM, respectively.

It is noted that the size of computational autocorrelation matrix only depends on the symbol rate of received signal for ACSPW+SVSACM algorithm. For example, when CD scanning range is from 0 to 16,000 ps/nm for 14 Gsymbol/s PDM-QPSK signal, $39 \times 39$ autocorrelation matrix based on ACSPW+SVSACM is much smaller than SVSACM-based $213 \times 213$ autocorrelation matrix. Figure 5 displays the step number of CD scanning versus the symbol error rate (SER), when the actual CD is 8,000 ps/nm for 14 Gsymbol/s PDM-QPSK signal. It can be found that the minimum SER
appears within 10 steps based on ACSPW-SVSACM algorithm, while about 70 steps are required for SVSACM-based algorithm. Although the proposed approach needs extra operation using ACSPW for the coarse CD estimation, it is unnecessary to blindly scan in the large CD range. Hence, it can be expected that the computational time and logical resources can be effectively saved in the DSP.

To evaluate the influences of OSNR and PMD on the proposed method, OSNR is varied in the range of (10, 30) dB and PMD is changed from 0 to 30 ps. According to the Figure 6(a), it is noted that the mean estimation error slightly decreases along with the increase of OSNR value for the three different data rates. This implies that the proposed approach is insensitive to the variation of OSNR. Figure 6(b) shows mean estimation error versus the variations of PMD for PDM-QPSK signal with different symbol rates. It is clear that the mean estimation error can keep within 50 ps/nm when the symbol rate is larger than 14 Gsymbol/s. However, the PMD increases to be more than 10 ps, the estimation error begin to obviously enhance, due to PMD significant impairment on 7 Gsymbol/s signal. As 10 ps PMD is tantamount to tens of thousands kilometers of fiber transmission distance with typical PMD coefficients of 0.1 ps/√km, the estimation error of the proposed method is still acceptable level for the long or ultra-long fiber communication in reality.

4 CONCLUSIONS

In this paper, a competitive method using ACSPW combined with SVSACM is proposed for accurate and fast CD estimation of PDM-QPSK optical signal. Compared with some existing methods, it is demonstrated that the proposed method has low complexity and not need consideration of symbol rate limitation. Moreover, this method is insensitive to OSNR and has large tolerance to PMD impairment. Thanks to its excellent performance, this method can be utilized in coherent receivers based on DSP as well as the intermediate transmission node of ultra-long cognitive optical communication in optical networking.

REFERENCES