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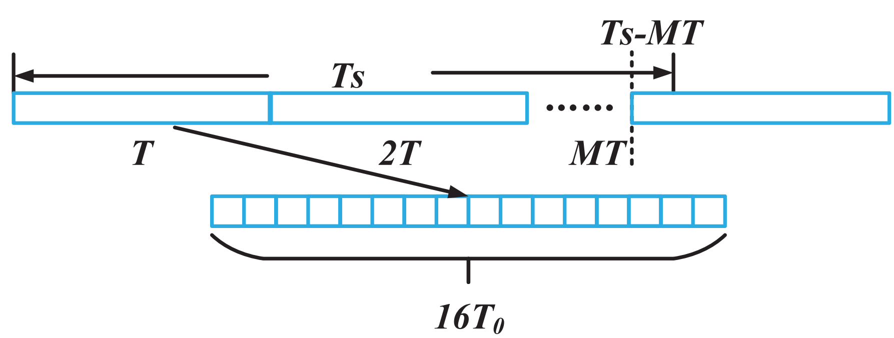

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Training Sequence-Based Chromatic Dispersion Estimation With Ultra-Low Sampling Rate for Optical Fiber Communication Systems

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Abstract: We present a novel method to estimate chromatic dispersion with ultra-low sampling rate based on training sequence. The under-sampling can be equivalent to over-sampling by splicing points with periodic sequence. The functional relationship between equivalent over-sampling rate and symbol rate, actual sampling rate and sequence period is deduced. To demonstrate the feasibility of the method, the simulation of a 28 GBaud QPSK optical fiber communication system is carried, in which 76 MSa/s sampling rate is equivalent to 66.5 GSa/s sampling rate. The results show that maximum estimation error is less than 160 ps/nm after 100 km to 2300 km SSMF transmission. We also demonstrate the robustness of the proposed method to amplified spontaneous emission and nonlinear noise in a three-channel optical fiber communication system. Moreover, the proposed method has been experimentally verified with a 20.5 GBaud QPSK system, 1.25 GSa/s sampling rate is equivalent to 51.25 GSa/s sampling rate, and estimation error is less than 100 ps/nm and 150 ps/nm after 100 km and 200 km SSMF transmission, respectively. The proposed method eliminates the requirement of high speed ADC and is cost effective, which can be used for optical performance monitoring.

Index Terms: Metrology, fiber non-linear optics, fiber optics systems.

1. Introduction

With the development of the optical transmission networks, coherent optical communication has been widely used, and it becomes the mainstream trend in high capacity transmission [1]. The performance of optical networks operating strongly depends on the fiber link impairments such as chromatic dispersion (CD) and nonlinearity [2]. These impairments affect the signal quality, raising the need for optical performance monitoring (OPM). However, the costs for OPM are increasing with the increase of the symbol rate. In order to reduce the operating costs, OPM at ultra-low sampling rate is necessary. Meanwhile, CD monitoring is the basis for nonlinearity monitoring, and it's essential to estimate CD firstly.

Traditional CD estimation method depends on the exact CD compensation by scanning preset CD interval [3], [4]. To ensure estimation accuracy, 200 ps/nm to 1000 ps/nm scanning steps are generally used. However, it takes a long time for CD estimation. For the auto-correlation of signal power (ACSPW) method, it doesn't require the CD scanning, and only 8192 symbols are needed for QPSK and 16QAM systems [5]. Recently, the FrFT-based blind CD estimation method was proposed. The accumulated CD is estimated by scanning different fractional orders, and the robustness to ASE and nonlinearity noise is verified by simulations and experiments [6], [7]. However, for the above methods, it's unavailable to estimate CD in ultra-low sampling rate conditions, and the demands for receiver performance is higher with the increase of the symbol rate.

The fractional Fourier transform (FrFT) is the generalization of traditional Fourier transform (FT) and represents the time-varying frequency distribution [8]–[11]. In traditional FT, the signals are expanded in cosine wave with different frequency to represent the whole spectrum of signal. However, for FrFT, the signals are expanded in a set of chirp basis signal, which can be used for non-stationary signal. Since a linear frequency modulation (LFM) signal has good energy convergence with the fractional optimal order, FrFT is used to estimate a signal's chirp characteristics, CD and nonlinearity in an optical fiber transmission system [6], [7], [12]–[15].

In this paper, we propose a novel method to estimate CD with ultra-low sampling rate based on training sequence. The training sequence is periodic, so under-sampling can be equivalent to over-sampling by splicing sampled points. The equivalent over-sampling rate can be calculated by symbol rate, sampling rate at receiver and sequence period. After equivalent sampling, signals are filtered by the low-pass filter to obtain the low frequency parts. When the signals are transformed into fractional domain, the energy concentration can be represented by energy concentration (EC) function with different transform order, and the extremum of EC function is searched to obtain the optimal order [16]. Finally, the optimal order in fractional domain can be utilized to estimate the accumulated CD [6], [7], [13].

This paper is organized as follows: In Section 2, we introduce the CD estimation method with equivalent sampling, and calculate the maximum measurable accumulated CD for training sequence. In Section 3, we discuss the lowest measurable sampling rate for FrFT-based blind CD estimation method. And the simulation of a 28 GBaud QPSK optical fiber communication system is carried with VPI software to demonstrate the feasibility and robustness in the condition of amplified spontaneous emission (ASE) and nonlinear noise for the proposed method. In Section 4, we performed experiments with a 20.5 GBaud QPSK system after 100 km and 200 km transmission. In Section 5, the applicability of the equivalent sampling method is discussed. The conclusions are drawn in Section 6.

2. Chromatic Dispersion Measurement Method With Equivalent Sampling

2.1 Definition of FrFT

FrFT is the generalization of traditional FT with different transform order $\alpha \in [0, 2\pi)$. The signal $x(t)$ in time domain can be mapped into $X_\alpha(u)$ in fractional domain by Eq. (1) [10].

$$X_\alpha(u) = \int_{+\infty}^{-\infty} K_\alpha(u, t)x(t)\, dt. \tag{1}$$

where $K_\alpha(u, t)$ is the transform kernel as represented by Eq. (2).

$$K_\alpha(u, t) = \begin{cases} \sqrt{\frac{1-j\cot\alpha}{2\pi}}\ exp[j(\frac{1}{2})\, u^2 \cot\alpha - ut\csc\alpha + \frac{1}{2}t^2 \cot\alpha] & \alpha \neq n\pi \\ \delta(u-t), & \alpha = 2n\pi \\ \delta(u+t), & \alpha = (2n\pm 1)\pi \end{cases} \tag{2}$$

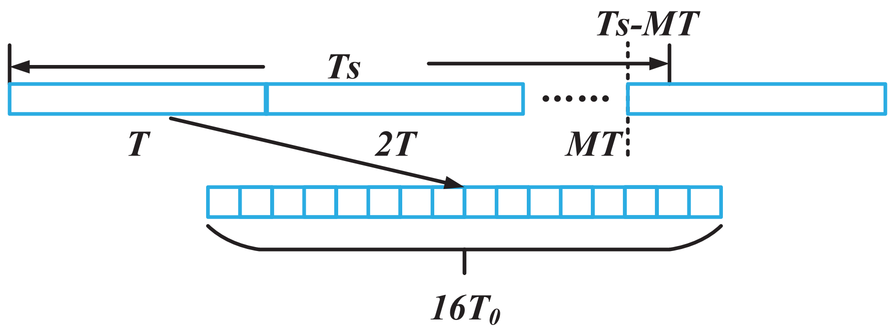

Fig. 1. Equivalent sampling principle.

where α is the rotation angle, the transform order p can be represented by $p = 2\alpha/\pi$, exp is the exponential function, n is the arbitrary integer.

On the basis of energy conservation law, optimal order can be calculated by the extremum of EC function as expressed by Eq. (3) [16].

$$EC(p) = \int_{+\infty}^{-\infty} |X_p(u)|^4 \, du. \tag{3}$$

where $X_p(u)$ is the FrFT with p order.

2.2 Time Domain Pilot With Training Sequence

The general signal is expressed by Eq. (4).

$$x(t) = A\cos(\omega t + \theta) \tag{4}$$

where A is the amplitude, ω is the signal frequency, θ is the initial phase.

The phase of signal is controlled to generate the training sequence, which rotates anticlockwise, then rotates clockwise from the first quadrant. For 16 symbols per cycle, the phase migration trajectory can be expressed by 11223344-11443322 in the quadrant. And the generated training sequence can be used to estimate CD in optical fiber communication systems as the time pilot of the payload.

The maximum measurable accumulated CD for training sequence can be calculated by Eq. (5).

$$DL = \frac{c\Delta\phi}{2\pi f_m^2 \lambda^2} \tag{5}$$

where DL is the accumulated CD, c is the light speed, $\Delta\phi$ is the first sideband phase difference, f_m is the first sideband frequency. When symbol rate is 28 GBaud, f_m equals to 1.75 GHz. Let $\Delta\phi = 2\pi$, the maximum measurable accumulated CD is 40770 ps/nm according to Eq. (5).

2.3 Operation Principle of Equivalent Sampling

Although the training sequence can't be fully sampled for ultra-low sampling rate, it can be equivalent to over-sampling by using its periodic characteristics. The equivalent sampling principle is shown in Fig. 1 with the symbol duration of T_0, so the period of training sequence T equals to $16T_0$. To assume the under sampling rate at receiver is f_s ($T_s = 1/f_s$), the equivalent sampling time interval is $T_s - MT$, where M is expressed by Eq. (6). With the equivalent sampling time interval, the under-sampling points of training sequence are spliced into an over-sampled signal when T_s is not the

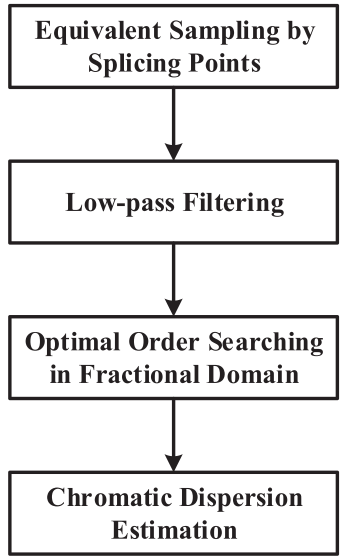

Fig. 2. The flow chart of the CD estimation with equivalent sampling method.

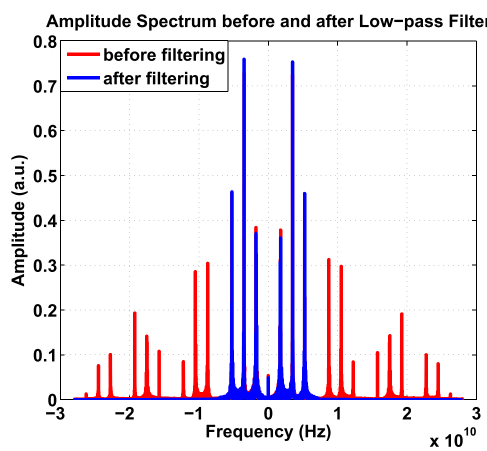

Fig. 3. Amplitude spectrum before and after low-pass filter.

integer multiple of the T. And the equivalent over-sampling rate is expressed by Eq. (7).

$$M = \left\lfloor \frac{T_s}{T} \right\rfloor \tag{6}$$

$$f_{eqv} = \frac{1}{(T_s - MT)} \tag{7}$$

The flow chart of the CD estimation method with equivalent sampling is shown in Fig. 2. Firstly, the under-sampling points of training sequence are spliced into an over-sampled signal. Then, the harmonic components of the training sequence are dropped out by a low-pass filter as in [17]. The blue line of Fig. 3 shows the amplitude spectrum with low-pass filter. EC function of the filtered training sequence can be calculated by Eq. (3), and the extremum of EC function is searched to obtain the optimal order with the searching step of 0.001. Finally, the accumulated CD can be estimated with optimal order in fractional domain [6], [7], [13].

TABLE 1
Estimation Error with Different Sampling Rate for frft-based Blind CD Estimation

Sampling Rate (GSa/s)	Estimated CD (ps/nm)	Estimation Error (ps/nm)
84	16962.82	37.18
70	16958.09	41.91
56	16890.82	109.18
42	16792.51	207.49
28	190837.2	173837.24
14	706770.5	689770.50

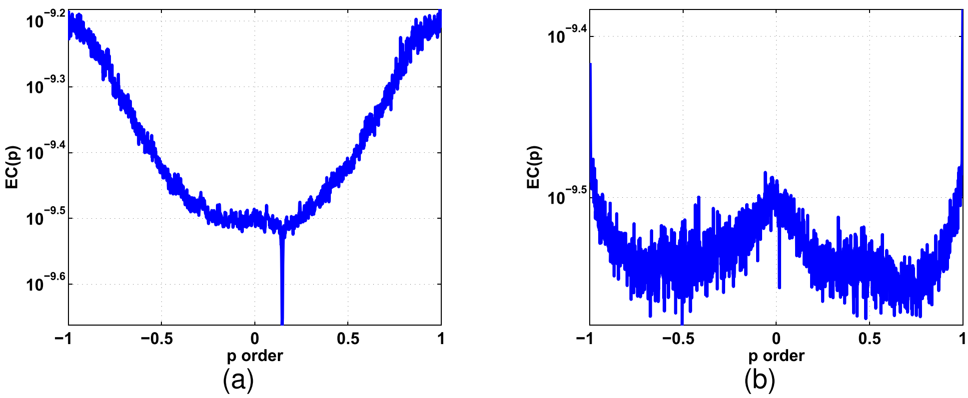

Fig. 4. (a) The optimal order searching graph with 84 GSa/s sampling rate. (b) The optimal order searching graph with 28 GSa/s sampling rate.

3. Simulation

This part discusses the lowest measurable sampling rate for FrFT-based blind CD estimation method. The simulation platform of a 28 GBaud QPSK optical fiber communication system is carried, in which the span length is 100 km, the transmission distance is 10 spans, the dispersion coefficient is set to 17 ps/(nm $\times$ km) for SSMF, the OSNR is set to 20 dB, the launch power is set to 0 dBm, the nonlinear index is set to 2.6 $\times 10^{-20}$ s/m^3, and the bandwidth of the filter is set to 40 GHz. 4096 sampling points are used to search the optimal order with 14 GSa/s, 28 GSa/s, 42 GSa/s, 56 GSa/s, 70 GSa/s and 84 GSa/s sampling rate. The simulation results shown in Table 1 demonstrate that the estimation error increases gradually with the decrease of the sampling rate. And the accumulated CD can't be estimated when sampling rate is less than 28 GSa/s. The optimal order searching graph is shown in Fig. 4(a) and Fig. 4(b) with 84 GSa/s and 28 GSa/s sampling rate respectively. The extremum of EC function is obvious when sampling rate is 84 GSa/s; however, the pit disappears when sampling rate is 28 GSa/s. Therefore, the FrFT-based blind CD estimation method is not available when sampling rate is less than symbol rate.

In order to verify the feasibility of the proposed method, the simulation platform is conducted for a single carrier with 28 GBaud QPSK signal as shown in Fig. 5. The black arrow represents the electrical signals and the red arrow represents the optical signals. At the transmitter side, the optical signals are mapped into QPSK format and modulate two orthogonal linearly polarized laser by Mach-Zehnder modulator (MZM). The polarization beam coupler (PBC) is used to combine the signal for transmission. The modulated optical signals are amplified to a fixed power and launched into the optical fiber links. Considering the effects of ASE noise in fiber links, OSNR is specified by an OSNR setting module after transmission. At receiver, the signals are coherently detected, and the digital signal processing (DSP) is used to process the coherently detected signal off-line. The training sequence is the time domain pilot signal. The center frequency of the laser is set to 193.1 GHz; the linewidth of the laser is set to 100 kHz. The dispersion parameter is set to 17 ps/(nm $\times$ km) for SSMF, therefore the maximum measurable transmission distance is 2300 km.

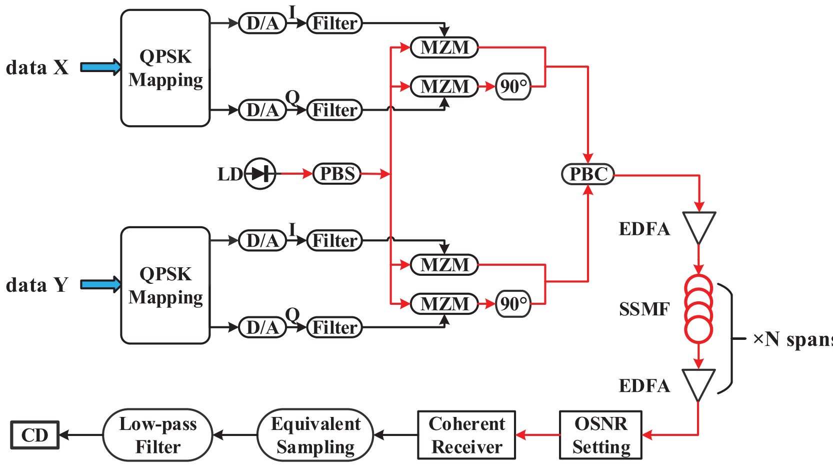

Fig. 5. Diagram of optical fiber transmission system.

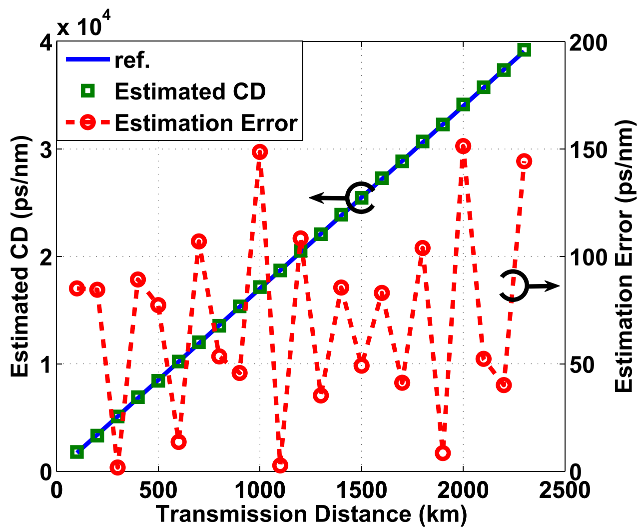

Fig. 6. Estimated CD and estimation error when transmission distance is from 100 km to 2300 km in ideal conditions.

The fiber attenuation is set to 0.2 dB/km, span length is 100 km, and the nonlinear index is set to 2.6×10^{-20} s/m^3 when the nonlinear effect is considered. The EDFA in the fiber link compensates the energy loss caused by the optical fiber attenuation. The sampling rate is set to 76 MSa/s at receiver. For DSP, equivalent sampling method is used to obtain the equivalent over-sampling signal by splicing sampled points firstly. Then, passing through the low-pass filter to drop out the high frequency beyond 7 GHz bandwidth. The extremum of EC function of the filtered signal is searched to calculate and obtain the optimal order with 4096 sampling points and 0.001 searching step. Finally, accumulated CD is estimated with the optimal order in fractional domain.

The equivalent over-sampling rate is 66.5 GSa/s, which can be calculated by Eq. (6) and Eq. (7) with 28 GBaud symbol rate, 16 symbols per cycle and 76 MSa/s sampling rate at receiver. In the ideal case (only CD in the link), the estimated CD and estimation error is shown in Fig. 6 after 100 km to 2300 km SSMF transmission. The blue line represents the reference of accumulated CD, the green label represents the estimated CD, and the red line represents the estimation error. The results show that the estimation error fluctuates with different transmission

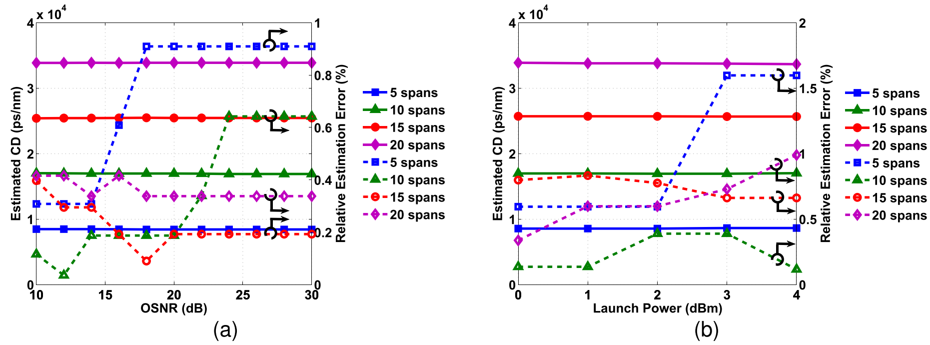

Fig. 7. (a) CD Estimation for 5, 10, 15 and 20 spans transmission when OSNR is from 10 dB to 30 dB. (b) CD Estimation for 5, 10, 15 and 20 spans transmission when launch power is from 0 dBm to 4 dBm per channel and OSNR is 20 dB.

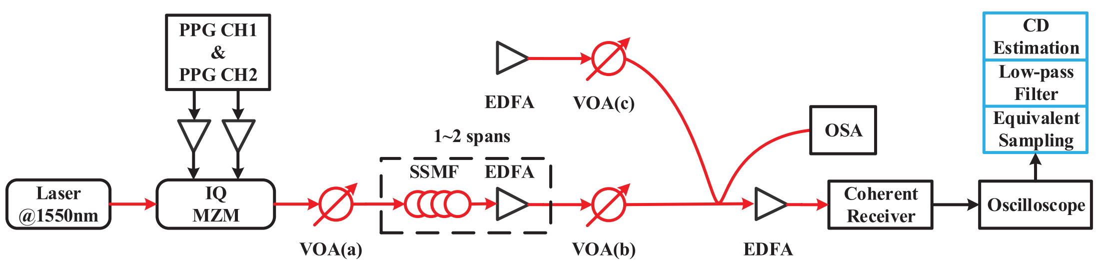

Fig. 8. Experimental platform for 20.5 GBaud QPSK transmission.

distance, and the maximum estimation error is less than 160 ps/nm. Therefore, the feasibility of the equivalent sampling method is demonstrated by the simulation.

In order to verify the robustness to amplifier ASE noise, the estimated CD and relative estimation error with different OSNR is shown in Fig. 7(a) after 5, 10, 15 and 20 spans transmission. The OSNR is set by "OSNR Setting" module to change ASE noise in optical fiber communication systems. The relative estimation error is $|CD_{esti} - CD_{real}|/CD_{real}$, where CD_{esti} is the estimated CD, CD_{real} is the real CD, which is within 1% with OSNR from 10 dB to 30 dB.

Furthermore, we also investigate the nonlinearity's impacts on the proposed method by using three channels with 50 GHz grid. The middle channel is selected at receiver to estimate the accumulated CD value. The estimated CD and relative estimation error with different launch power is shown in Fig. 7(b) with 5, 10, 15 and 20 spans transmission. The relative estimation error is within 1.6% with launch power from 0 dBm to 4 dBm per channel when OSNR is 20 dB.

4. Experimental Verifications

In order to investigate the practical performance of the proposed method, the experimental platform is set up is shown in Fig. 8. The center frequency of the laser is 1550 nm, which is modulated by IQ modulator. The 20.5 GBaud QPSK signals are generated by driving 2-level electrical signals. Then the signals are modified by variable optical attenuator (VOA) (a) and launched into SSMF. The launch power is 1 dBm. The span length is 100 km. The dispersion coefficient is 16.7 ps/(nm $\times$ km). By adjusting VOA(b) and VOA(c), the OSNR of the system is varied from 12 dB to 26 dB. The optical input power is 0 dBm at coherent receiver. And the sampling rate is 1.25 GSa/s at oscilloscope. Finally, the signals are processed off-line for CD estimation.

According to Eq. (6) and Eq. (7), the equivalent over-sampling rate is 51.25 GSa/s when symbol rate is 20.5 GBaud, sampling rate is 1.25 GSa/s at receiver. After equivalent sampling method, 4096

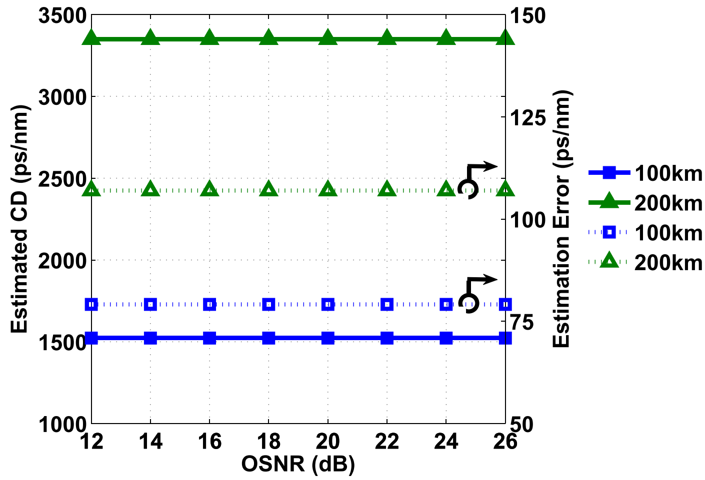

Fig. 9. CD Estimation with different OSNR when transmission distance is 100 km and 200 km.

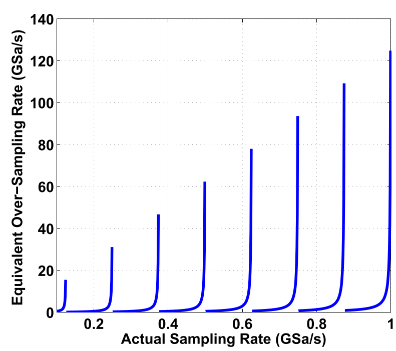

Fig. 10. The relationship between actual sampling rate and equivalent over-sampling rate when symbol rate is 28 GBaud, sequence period is 16.

samples of the received signals and 0.001 searching step were used for optimal order searching in fractional domain. The performance of the proposed method is evaluated for various OSNR is shown in Fig. 9. The estimation results are stable with different OSNR. And the estimation error is less than 100 ps/nm and 150 ps/nm after 100 km and 200 km transmission respectively.

5. Discussion

This section discusses the applicability of the equivalent sampling method. The proposed method is verified by QPSK training sequence in QPSK optical fiber communication systems, other modulation formats can use the related training sequence. And the relationship between actual sampling rate and equivalent over-sampling rate is shown in Fig. 10 when symbol rate is 28 GBaud, sequence period is 16. The proposed method is not available when sampling rate is an integer multiple of the symbol rate, however, which can be slightly offset to equal to the high sampling rate in practical applications.

6. Conclusions

In this paper, we present a novel method to estimate CD with equivalent sampling based on the training sequence in optical fiber transmission systems. Compared with FrFT-based blind CD estimation method, the proposed method is available for ultra-low sampling rate conditions. The feasibility of the method is confirmed by the simulation of a 28 GBaud QPSK optical fiber communication system, in which the 76 MSa/s sampling rate at receiver is equivalent to the 66.5 GSa/s sampling rate. The results show that the maximum estimation error is less than 160 ps/nm after 100 km to 2300 km SSMF transmission. The robustness to ASE and nonlinear noise are also verified after 500 km, 1000 km, 1500 km and 2000 km SSMF transmission, the relative estimation error is within 1% and 1.6% with OSNR from 10 dB to 30 dB and launch power from 0 dBm to 4 dBm of three channels respectively. Furthermore, the proposed method has been experimentally verified. A 20.5 GBaud QPSK system is generated for transmission, 1.25 GSa/s sampling rate is equivalent to the 51.25 GSa/s sampling rate, the estimation error is less than 100 ps/nm and 150 ps/nm with OSNR from 12 dB to 26 dB after 100 km and 200 km SSMF transmission respectively.

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