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Simple and robust symbol rate estimation method for digital coherent optical receivers

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ABSTRACT

A novel symbol rate estimation (SRE) technique utilizing the clock tone (CT) obtained by Godard timing recovery algorithm is proposed. By this technique, the known sampling rate of the analog-to-digital converter (ADC) in digital coherent optical receivers can used as a reference to directly determine the unknown signal symbol rate. The impact of polarization mode dispersion (PMD) on the CT magnitude can be mitigated by using the hybrid correlation function (HCF) consisting of both auto-correlation function (ACF) and cross-correlation function (XCF) of the received signal spectrum, while the chromatic dispersion (CD) impact can be mitigated by adaptive CD compensation techniques. This technique is simple, accurate, applicable to advanced modulation formats commonly used, and robust to various link impairments. Numerical simulations and experimental results are presented to validate this technique.

1. Introduction

Optical networks are nowadays becoming more heterogeneous and may accommodate optical signals with different modulation formats and data rates to support a wide range of data traffic and various services [1–5]. Therefore it cannot be guaranteed any longer that signals arriving at a specific receiver unit will have the same, known in advance, modulation format and date rate. For this reason, optical signal recognition (OSR) techniques for digital coherent optical receivers have been intensively studied recently [6–11]. OSR function is essential to ensure that the signals are properly demodulated and the link impairments, such as the PMD, are properly compensated [12]. But the OSR function often requires the receiver to identify the signal symbol rate first, so that the clock rate and the ADC oversampling rate can be determined [10,11]. Thus it is essential to explore a SRE method which is modulation format transparent and robust to link distortions. By now several SRE methods based on direct-detection (DD) [6–9] and coherent-detection (CoD) [10,11] have been proposed. The DD based methods require additional optical devices, like optical tunable delay line (TDL), and cannot tolerate relatively large CD and PMD distortions, which restricts their applications in long-haul or un-dispersion-managed transmission systems. The CoD based SRE methods can operate without additional optical devices and exploit electrical CD compensation techniques to tolerate large CD distortions [10,11]. One CoD based SRE technique [10] utilized the weighted version of the classical SRE method used in wireless systems which exploits the cyclostationary random process nature of the signal [13,14]. But the corrective weights must be pre-estimated for the specific transmitters in practice [13], making the technique inconvenient to use in dynamic networks. Another CoD based method determined the symbol rate by scanning the all of the possible frequency bands to search the clock signal [11]. In each frequency band the compensated CD is linearly scanned throughout the possible range, then the clock signal is tentatively detected by applying quartic nonlinearity and FFT. So it is time consuming and computation expensive. In this paper the clock tone (CT) obtained by the Godard timing recovery algorithm [15] is exploited for SRE. The signal symbol rate can be directly determined from the ADC sampling rate of the receiver without any knowledge of the transmitter or many times of tentative CT detections. This technique is robust to CD, PMD and amplified spontaneous emission (ASE) noise. Simulation and experimental results are presented to demonstrate the efficiency and effectiveness of this method.

2. Principle

In digital coherent optical receivers the received signal spectrum $r_p(m)$ can be obtained by

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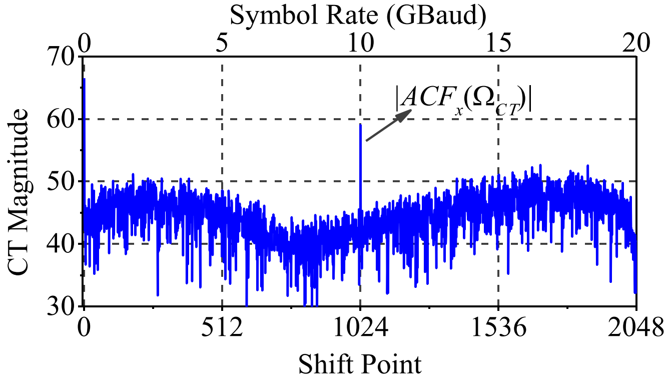

Fig. 1. The curve of $|ACF_x(\Omega)|$ obtained when $R_s = 2B$, N=2048, and CD and PMD distortions are not present. The optical signal used is 10 GBaud DP-QPSK signal.

$$r_p(m) = FFT\{r_p(n)\} = \sum_{n=0}^{N} r_p(n)\exp(-j2\pi mn/N), \tag{1}$$

where $r_p(n)$ is the received signal field samples obtained by the ADC, N is the *FFT* size and p=x, y denotes the x or y polarization signals. The Godard timing recovery technique employs the CT information obtained from the complex auto-correlation function (*ACF*) or cross-correlation function (*XCF*) of $r_p(m)$ given by [14,16]

$$ACF_x(\Omega) = \sum r_x{}^*(n) r_x(n + \Omega), \tag{2}$$

$$XCF_{x,y}(\Omega) = \sum r_x{}^*(n) r_y(n + \Omega) \tag{3}$$

where Ω is the frequency shift parameter and * refers to the complex conjugate. The CT can be observed at [17]

$$\Omega = \Omega_{CT} = \pm N\cdot(1 - B/R_s), \tag{4}$$

where B and R_s are the signal baud rate and ADC sampling frequency. When CD and PMD distortions are not present, the magnitude of the CT element represented by $|ACF_x(\Omega_{CT})|$ is much larger than the other elements with $\Omega \neq \Omega_{CT}$. Thus $|ACF_x(\Omega)|$ shows as a sharp pulse at $\Omega = \Omega_{CT}$ as shown in Fig. 1(a). The figure is obtained by numerical simulations using VPI Transmission Maker 9.0. The optical signal is 10 GBaud dual polarization quadrature phase shift keying (DP-QPSK) signal. It is obvious that Ω_{CT} can be easily obtained from maximal peak of the $ACF_x(\Omega)$ curve (the zero delay ACF peak always exits and should be neglected). As R_s is known in advance, B can be directly obtained from Eq. (4).

When CD and PMD distortions are present the SRE method utilizing only $|ACF_x(\Omega)|$ may fail because the CT and the pulse at $\Omega = \Omega_{CT}$ will be severely suppressed by CD and PMD distortions [16]. The CD impact can be nearly mitigated by using frequency domain CD compensation algorithm [18] combined with the fast CD estimation algorithm which is robust to PMD distortions and can determine the CD accurately and directly in a modulation format and data rate transparent manner [19]. To deal with the PMD impact on the CT, we can utilize the *HCF* given by

$$HCF(\Omega) = |ACF_x(\Omega)| + |XCF_{x,y}(\Omega)|, \tag{5}$$

which contains the pulse corresponding to the hybrid CT magnitude (*HCTM*)

$$HCTM = HCF(\Omega_{CT}) = |ACF_x(\Omega_{CT})| + |XCF_{x,y}(\Omega_{CT})|. \tag{6}$$

The impact of PMD distortions on the CT element magnitudes scaled by their expectancy can be expressed by [16]

$$|ACF_x(\Omega_{CT})|' \approx \left| \cos\left(\frac{\pi\tau}{T}\right) + j\cos(2\theta)\sin\left(\frac{\pi\tau}{T}\right) \right| \tag{7}$$

$$|XCF_{x,y}(\Omega_{CT})|' \approx \left| \sin(2\theta)\sin\left(\frac{\pi\tau}{T}\right) \right|, \tag{8}$$

where T, θ and τ are the symbol period, polarization angle and differential group delay (DGD), respectively. Fig. 2 shows the variations of the two CT element magnitudes against θ and τ. As we can see $|ACF_x(\Omega_{CT})|$ is suppressed severely when $\tau = T/2$ and $\theta = 45^\circ$, while the corresponding $|XCF_{x,y}(\Omega_{CT})|$ reaches its maximum. Because the two are complementary, the *HCTM* can always be maintained for various PMD distortions, making the SRE technique based on $HCF(\Omega)$ robust to PMD effects.

3. Simulation

Based on VPI Transmission Maker 9.0, numerical simulations are first performed to investigate the performance of the proposed SRE technique for DP-QPSK and DP-16QAM with different pulse duty cycles and distortions. The simulation setup is shown in Fig. 3. ASE noise is added at the fiber output to change the optical signal to noise ratio (OSNR). Fig. 4 shows the variations of $|ACF_x(\Omega_{CT})|$ and *HCTM* against θ and τ for 10 GBaud NRZ-DP-QPSK signals. In this figure $R_s = 2B$ and CD=0 ps/nm. As predicted by the analytical expressions, $|ACF_x(\Omega_{CT})|$ drops sharply when $\tau = T/2$ and $\theta = 45^\circ$, while *HCTM* maintains a relatively large value regardless of the PMD distortions, proving that the SRE technique based on $HCF(\Omega)$ is robust to PMD distortions.

To validate that the SRE method based on $HCF(\Omega)$ is robust to other impairments, extensive numerical simulations are carried. Fig. 5 shows PAR (peak to average ratio) of $HCF(\Omega)$ against residual CD and OSNR. We note that high PAR is of great significance for robust and accurate SRE. The number of signal samples used to calculate $HCF(\Omega)$ is N=4096 and the ADC sampling rate $R_s = 2B$. The residual CD may come from the estimation error of the CD

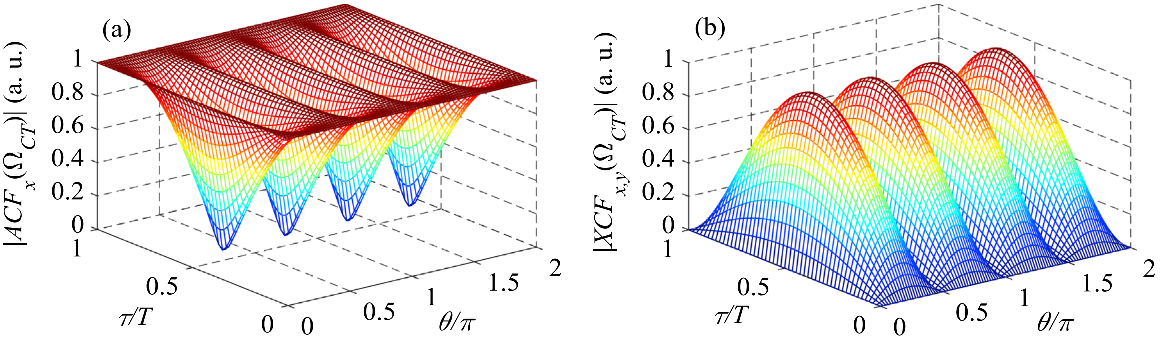

Fig. 2. Clock-tone magnitude of obtained from $|ACF_x(\Omega_{CT})|$ (a) and $|XCF_{x,y}(\Omega_{CT})|$ (b).