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单载波数字相干接收系统中基于导频的自适应色散补偿技术

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摘　要:提出一种用于单载波数字相干光通信系统的自适应色散补偿方法.在发射机端,利用强度光调制器在光信号两侧加入脉冲幅度调制导频光信号.搜索信号谱的峰值确定光信号两侧的 PAM-PTs 线状谱.在色散估计之前,通过其中一个 PAM-PTs 的频率漂移来估计激光器发射频偏,并将信号谱线沿着频率轴反向平移,补偿发射频偏,实现信号谱频域均衡.在接收机端,利用幅度脉冲调制导频信号脉冲时延估计色散大小,在色散补偿之前通过幅度脉冲调制导频信号频移补偿,并消除接收机本振频偏对频域色散补偿的影响.最终,幅度脉冲调制导频的光场信息被充分用来精确进行色散估计和色散补偿.数值仿真表明:每次色散估计的误差小于±65 ps/nm,而且距离从 200 km 到 1 000 km 之间的平均色散估计误差小于±10 ps/nm.该方法色散补偿精度高,计算量小.

关键词:相干通信;色散估计;自适应补偿;色散频域均衡;反馈控制

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Fast and Accurate Adaptive Chromatic Dispersion Compensation Method Utilizing Pilot Tones for Digital Coherent Single Carrier Systems

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Abstract: A novel adaptive chromatic dispersion (CD) compensation method was proposed for digital coherent single carrier systems. Two pulse amplitude modulated pilot tones (PAM-PTs) were inserted at both sidebands of the signal in the transmitter. The two line spectra of the PAM-PTs can be found by searching the spectrum peaks in the upper and lower sideband. Before CD estimation (CDE), the laser frequency offset (LFO) can be directly estimated from the frequency drift of one of the PAM-PTs. Then the signal spectrum was shifted on the reverse of the frequency axis to adjust the received spectrum of OFDE and compensate LFO. After that, the relative time delay between the two line spectra of the PAM-PTs was recovered at the receiver and used for CD estimation, while the frequency of the PAM-PT recovered was used for spectrum pre-adjustment of frequency domain CD equalization, Therefor by using this method, the field information of the PAM-PTs was fully utilized for accurate CDE and CDC. Numerical simulations show that the CDE error is less than ±65 ps/nm for single time CDE and the averaged error is below ±10 ps/nm for all the distances from 200 to 1 000 km. The method enables much

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faster and more accurate CD adaptive compensation and reduces computational complexity.

Key words: Coherent communication; Chromatic dispersion estimation; Adaptive compensation; Frequency domain CD equalization; Feedback control

OCIS Codes: 060.1660; 060.2330; 060.4510; 070.4340; 070.6020

0 Introduction

Coherent optical communications based on Digital Signal Processing (DSP) has been considered as the most efficient method to fulfill a set of different requirements for future optical networks, such as high capacity, better spectral efficiency and long-haul transmission[1]. The main advantage of the DSP-based coherent detection is its capability to compensate various distortions[1]. Among the various distortions CD has important impact on system performance and is generally time-variant because of temperature variations or fast switching in flexible networks[2,3]. Thus adaptive modules consisting of CD Estimation (CDE) and Compensation (CDC) is indispensable for the systems designed for practical applications and future flexible networks[3-8]. Although different adaptive schemes have been proposed over the last years, processing in a real time mode and responding fast enough to optical link reconfiguration is still a difficult issue to be solved because of the DSP hardware limitations[6]. For CDE gradient algorithms or scanning through the possible CD values are often used, which are unstable or slow to converge[8]. In contrast the pilot-aided methods are more stable, robust, and more importantly, have much lower computation load and faster response time, especially for the methods with which CDE can be realized by an analytical procedure[5,7]. With the estimated CD, OFDE can be applied for CDC, which has much lower computation load compared to time domain equalization methods, especially for long-haul systems[9]. But OFDE is sensitive to the frequency offset of the Local Oscillator Laser (LFO) which leads to the drift of the received signal spectrum, and thus the degradation of CDC performance. Former LFO estimation module can only work after CDC and adjust the spectrum to which the OFDE is applied in a feedback way, which is complex, slow and not efficient[1]. To solve this problem we propose a method based on PAM-PTs to improve the accuracy and response time of the adaptive module. Numerical simulations are used to demonstrate the effectiveness and efficiency of this method.

1 Operation principles

The principle of the method is demonstrated in Fig. 1. The optical source (ω_c) is split for generating both the signal and the PAM-PTs. An external Mach-Zehnder Modulator (MZM) driven by a Radio Rrequency (RF) signal (ω_p) modulated with a low frequency periodic pulse signal $A_p(t)$ is used to generate the PAM-PTs. The PAM-PTs are jointed with the signal at the second splitter and transmitted into the fiber. The insertion can be written as

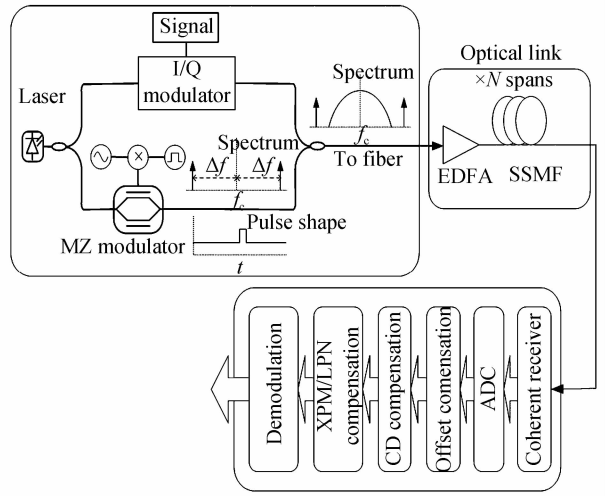


Fig. 1 Configuration of PAM-PT aided coherent transmission system

$$E_p(t)=E_{p_1}+E_{p_2}=A_p(t)\exp\left[\mathrm{i}(\omega_c-\omega_p)t+\mathrm{i}\varphi_{pm}\right]+A_p(t)\exp\left[\mathrm{i}(\omega_c+\omega_p)t+\mathrm{i}\varphi_{pm}\right] \tag{1}$$

The duty cycle and Modulation Index (MI) of the PAM-PT are determined by $A_p(t)$ which can be easily controlled. The CD accumulated in the transmission introduces a relative time delay ($\Delta\tau$) between the two line spectra of pilots. The time delay $\Delta\tau$ is related to CD as follows,

$$\Delta\tau=2\frac{\mathrm{CD}\cdot f_p c}{f_c^2} \tag{2}$$

where $f_{c,p}=\omega_{c,p}/2\pi$ and c is the vacuum light speed.

At the coherent Rx the field of the signal with the inserted PAM-PT is recovered in the electrical domain and the output signal is digitalized by the Analog to Digital Converters (ADCs). The digitalized signal $I(k)$ is processed by the DSP as shown in Fig. 2. First, N-point Discrete Fourier Transform (DFT) is used to convert the signal into the frequency domain. The two line spectra of the PAM-PTs are then found by searching the spectrum peaks in the upper and lower sideband. The LFO ($\Delta\omega$) can be directly estimated from the frequency drift of one of the PAM-PTs as shown in Fig. 2. The signal spectrum is then shifted along the frequency axis by $-\Delta\omega$ to adjust the received

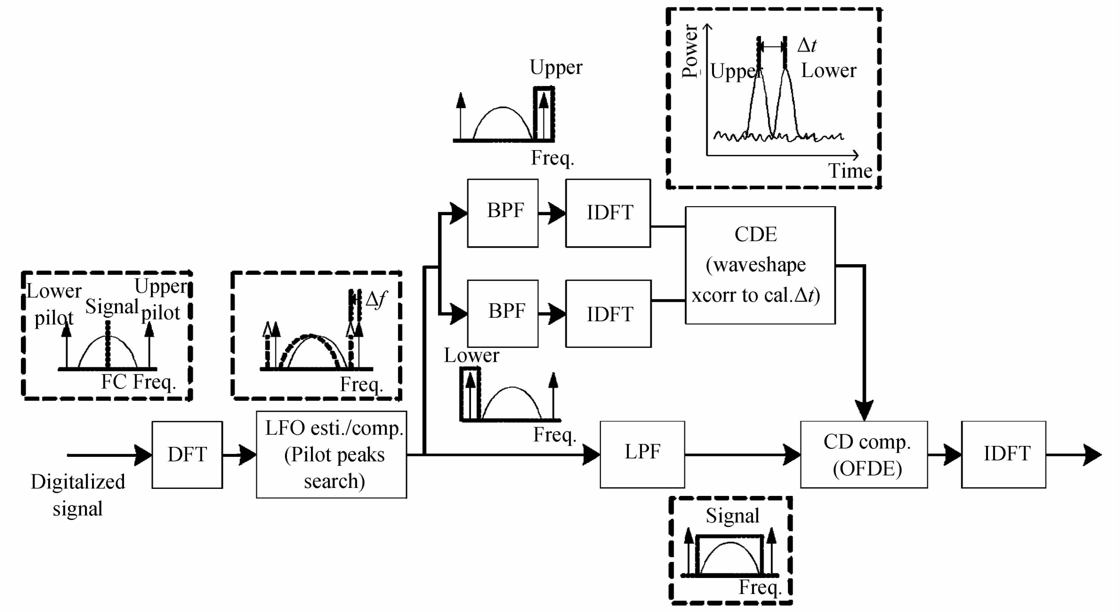


Fig. 2 DSP block diagram of the adaptive CDC module at receiver

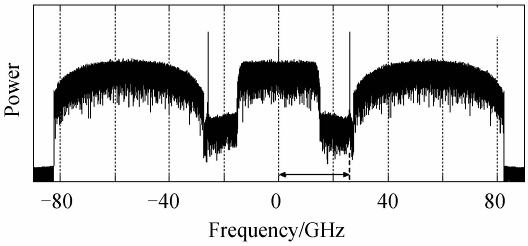
spectrum of OFDE and compensate LFO. Then digital Band-Pass Filters (BPFs) with center frequency and bandwidth equal to $\pm\omega_p$ and $\Delta\omega_p$ are used to Extract the two line spectra of the PAM-PTs. After that Inverse DFT (IDFT) is applied to recover the two PAM-PTs in the time domain. Then cross correlation (XC) can be used to find $\Delta\tau$ as follows

$$\begin{cases}\mathrm{XC}(m)=E[|I_{p_1}(k)|^2\cdot|I_{p_2}(k-m)|^2]\\ \Delta\tau=m_{\max}T_s\end{cases}\tag{3}$$

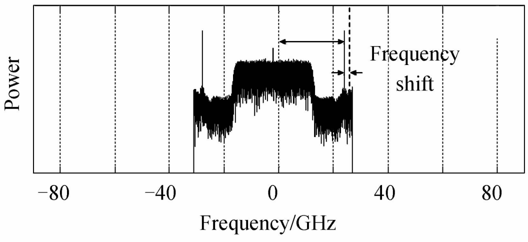
where $\mathrm{XC}(m_{\max})$ is the maximal XC value that can be obtained and T_s is the ADC sampling time interval. CD can then be estimated using Eq. (2) and is compensated by Overlap Frequency Domain Equalization (OFDE) algorithm[9]. With this method the field information of the PAM-PT is fully utilized for CDE and pre-spectrum-adjust for efficient OFDE. Because the method uses XC instead of pulse peak interval measurement which is sensitive to wave shape distortions for CDE the accuracy is also improved compared to the CDE method proposed before[5,7].

2 Simulation results

The setup of the transmission system is shown in Fig. 1. Using the commercial software VPI Transmission Maker 8.6, we simulated a homogeneous Non Dispersion Managed (NDM) Wavelength-Division Multiplexed (WDM) transmission system with a central 1 550 nm 28Gbaud Non-Return-to-Zero (NRZ) 16QAM test channel. The WDM channels were spaced by 50 GHz while the interval between signal and PAM-PTs was 25 GHz. The transmission link consists of N spans of 100 km of Standard Single-Mode Fiber (SSMF) and Erbium Doped Fiber Amplifier (EDFA) with noise figure of 6 dB for complete span loss compensation. The dispersion coefficient, attenuation, fiber nonlinearity refractive index, and effective area of SSMF at the signal wavelength were 16 ps/(nm · km), 0.2 dB/km, 2.6×10^{-20} m^2/W, and 80 $\mu\mathrm{m}^2$ respectively. At the Tx raised cosine filter for the signal with a roll-off factor of 0.1 was employed to ensure that the PAM-PT insertion has neglectable impact on the main signal. At the Rx the ADC sampling rate is set at 2 times the baud rate. Fig. 3 shows the transmitted and received spectrum of the test channel. The Rx ADC sampling rate is 56GSamples/s. The frequency drift of the pilot tones equal to LFO ($\Delta\omega$) can be easily obtained after the PAM-PTs have been found by searching spectrum peaks on the left and right sideband. The power spectrum is then shifted along the frequency axis by $-\Delta\omega$ to compensate LFO.



(a) T_x side



(b) R_x side

Fig. 3 The transmitted and received spectrum

The following results are reported for the case where all PAM-PT parameters are optimal. Among them, we would like to mention: the Pilot-to-Signal Ratio (PSR), the PAM-PT filter bandwidth ($\Delta\omega_p$), duty cycle and MI. From Fig. 4 we found the optimal PSR and $\Delta\omega_p$ was about -7 dB and 300 MHz. Similar numerical simulations show that the optimal τ_w and MI is about 200 T_s and 0.8. Considering that the CD variation speed is much lower than the baud rate of the signal, the duty cycle of the PAM-PT is set at a very small value of 0.003 in the simulation which means the CDE update period is 2^{16} T_s and the CDE can be performed every 1.17 μs.

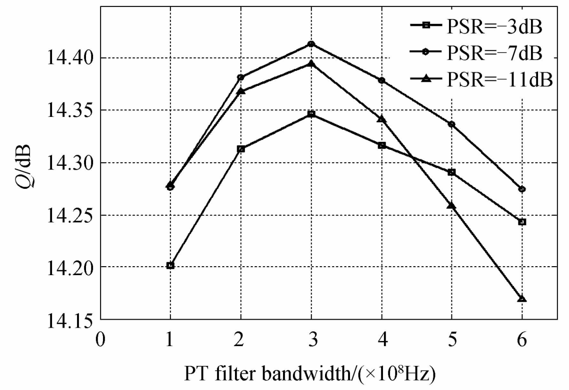
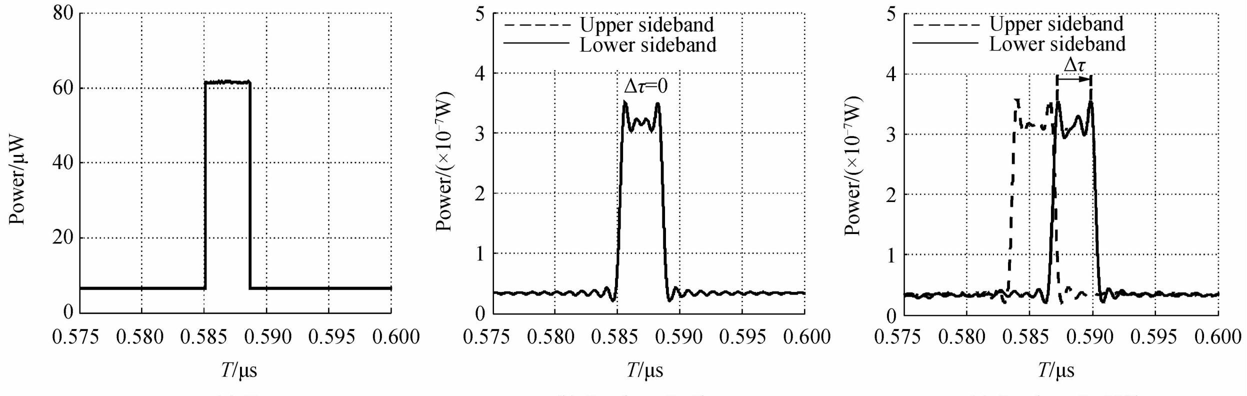
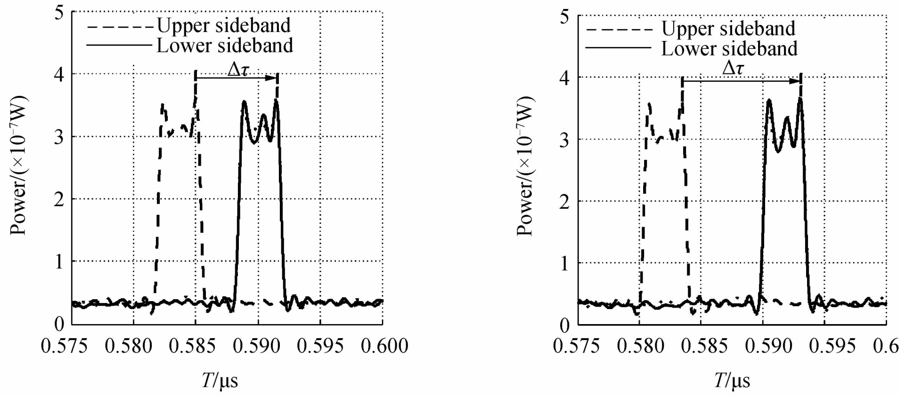


Fig. 4 The optimization of the PSR and the PT filter bandwidth $\Delta\omega_p$

Fig. 5 (a)~(e) show the four samples of the received wave shapes of the upper and low sideband PAM-PT when the transmission fiber length L is set at 0 km, 500 km, 1 000 km and 1 500 km, respectively. Because of the distortion induced by the accumulated ASE noise and fiber nonlinear effects the pulse shape recovered in the Rx is different from that transmitted. The difference exits even between the two PAM-PTs because of the same reason. It is noteworthy that the difference between the transmitted and received one with $L=0$ km is due to the narrow band PT filtering. In Fig. 5 (a)~(e) the dashed lines represent the time-shifted version of the upper sideband PAM-PT pulse leading to the maximal cross correlation value XC ($m_{\max}$) between the two PAM-PTs. Thus the time delay $\Delta\tau$ can be obtained and the CD value can be obtained with Eq. (3). Fig. 6 shows CDE results which are obtained by 400 times of independent simulations at each transmission distance. In each simulation the PRBS pattern transmitted and ASE noise seed of the EDFA is randomly changed. The CDE error is less than ± 65 ps/nm for all the distances. The results show the CDE accuracy achieved with the proposed method is better than that obtained by CDE schemes based on Training Sequence (TS)[5,7] (CDE error not



(a) T_x (b) R_x where L=0km (c) R_x where L=500km



(d) R_x L=1000km (e) R_x L=1500km

Fig. 5 The transmitted and recovered sideband PAM-PT pulses with $L=0$, 500, 1000 and 1 500 km smaller than ±90 ps/nm) for the same transmission length. We note that average over the estimate can further improve the CDE accuracy especially in low OSNR applications. As shown in Fig. 6 the average CDE error is within ±10 ps/nm much lower than ±65 ps/nm. With the PAM-PT aided method proposed much more times of CDE can be performed within the same time interval compared to TS-aided method which has to reduce the TS time interval or wait longer time to receive more TS frames at the cost of transmission efficiency or response time.

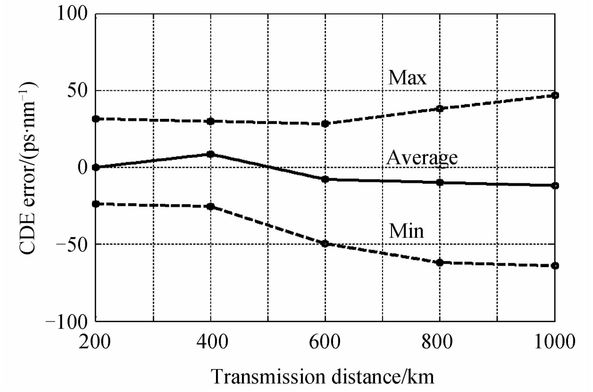


Fig. 6 The CD estimation error for different distance

3 Conclusion

We propose a method to compensate CD adaptively and accurately with PAM-PTs. The field information of the PAM-PTs is fully utilized for accurate CDE and CDC. Compared to other similar methods the PAM-PTs aided method proposed has higher CDE accuracy and reduced computational complexity. Numerical simulations show that the CDE error is less than ±65 ps/nm for single time CDE and the averaged error is below ±10 ps/nm for all the distances from 200 to 1 000 km.

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