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Suppression of laser phase noise in direct-detection optical OFDM transmission using phase-conjugated pilots

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ABSTRACT

Due to the unique phase noise (PN) characteristics in direct-detection optical OFDM (DDO-OFDM) systems, the design of PN compensator is considered as a difficult task. In this paper, a laser PN suppression scheme with low complexity for DDO-OFDM based on coherent superposition of data carrying subcarriers and their phase conjugates is proposed. Through theoretical derivation, the obvious PN suppression is observed. The effectiveness of this technique is demonstrated by simulation of a 4-QAM DDO-OFDM system over 1000 km transmission length at different laser line-width and subcarrier frequency spacing. The results show that the proposed scheme can significantly suppress both varied phase rotation term (PTR) and inter-carrier interference (ICI), and the laser line-width can be relaxed with up to 9 dB OSNR saving or even breakthrough of performance floor.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a promising high-speed transport technology in both broadband wired and wireless communication systems, and has been extensively investigated over the last decade for fiber optics communications [1,2]. Though OFDM has advantages of the flexible data rate and the high spectral efficiency, it suffers from the PN severely due to its very long symbol duration. The PN will degrade the performance of both the coherent optical OFDM (CO-OFDM) and DDO-OFDM, which are currently the primary schemes for the implementation of optical OFDM systems. In CO-OFDM, the PN typically comes from the phase incoherency between the laser source and the local oscillator [3,4]. Several effective methods have been proposed for combating this kind of PN in CO-OFDM [3,5]. On the other hand, because the requirement for the laser line-width can be relaxed and a only simple receiver is needed, DDO-OFDM systems can accept a low-priced distributed feedback (DFB) laser with a MHz-level line-width [6], and could be considered as an alternative choice for metropolitan and long-haul terrestrial transmission. But because of fiber chromatic dispersion (CD), the transmitted carrier and the data sideband would gradually walk off with the increased transmission length and eventually lose their phase coherency and result in significant PN in DDO-OFDM. The PN effect on performance in DDO-OFDM system has been firstly identified in [7] with 12.5 Gb/s (32-QAM) data rate and 320-km standard single mode fiber (SSMF) transmission. Wei-Ren Peng et al. [8,9] characterized the impact of laser PN in DDO-OFDM and found that the PN had two significant differences from those in CO-OFDM: (1) the power and bandwidth of PN in DDO-OFDM are functions of both the subcarrier frequency and the transmission distance. The zero-order PN interference, previously the common phase error (CPE), is no longer common to all subcarriers in DDO-OFDM. (2) The PN has a broad bandwidth, which might range from hundred MHz to several gigahertz (GHz), so significant intercarrier interference (ICI) is introduced. To mitigate the laser PN impact in DDO-OFDM, Wei-Ren Peng et al. [10] also developed a digital compensator based on a key assumption that all OFDM subcarriers suffer the same PN. For Radio-over-Fiber (RoF) system at 60-GHz band, Chia-Chien Wei et al. [11,12,25] developed a post PN suppression (PNS) algorithm to estimate and suppress both PRT and ICI without the requirement of pilot tones, but common PN for all subcarriers is also assumed. Moreover, their PNS algorithm is iterative, which increases the complexity of digital signal processing (DSP). The assumption of common PN for all subcarriers is inappropriate for low frequency RoF systems and baseband optical OFDM systems considering the fact that fiber CD also de-correlates the PN of subcarriers [13,14]. However, in W-band (75–110 GHz) direct-detection OFDM RoF systems, the OFDM bandwidth is relatively small compared to the RF frequency, and the PN can be treated as common for all OFDM

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subcarriers, thus, a RF pilot tone PNS algorithm is proposed for such W-band systems [13,15]. This kind of algorithm obtains the filtered pilot tone at the price of either additional discrete Fourier transform (DFT) and inverse DFT (IDFT) in digital domain or a analog filter and additional analog-to-digital converter (ADC), which all increase the DSP complexity and cost.

Considering the unique feature that the PN's power spectral density (PSD) is different for each individual subcarrier and bandwidth is more broader, suppression of the PN in DDO-OFDM is considered as a complicated task, and to date the effective PN suppression technique is very few. And being inspired by performance improvement profiting from phase-conjugated pilots (PCPs) in fiber nonlinearity compensation [16–19], in this paper, a PN suppression scheme based on coherent superposition of phase-conjugated pilots pairs, which needs minimal additional optical hardware or DSP, is proposed in DDO-OFDM transmission. In this scheme, 33% or 50% of data carrying OFDM subcarriers are transmitted with their phase conjugates, which experiences highly correlated PN as the original subcarriers after propagation over a fiber link. At the receiver the PN can be canceled by simple superposition of the phase-conjugated pairs. The effectiveness of this technique is demonstrated by simulation of a 4-QAM DDO-OFDM system over 1000 km transmission length at different laser line-width and subcarrier frequency spacing. With this technique at least 0.5 dB OSNR can be saved, moreover, in other cases 4 dB, 6 dB, 9 dB performance gain, or even breakthrough of performance floor can be achieved. This technique makes a laser with line-width of 1 MHz, 5 MHz or even 10 MHz acceptable in DDO-OFDM systems, which can further lower the cost of DDO-OFDM systems. Furthermore, the proposed technique can also be effectively applied to both W-band and low frequency RoF systems.

2. Chromatic dispersion induced phase noise

In DDO-OFDM, a low-priced distributed feedback (DFB) laser with a MHz-level line-width, in general, is considerably feasible because of its better phase coherency between the carrier and data sideband [6,9]. However, due to fiber CD, the phase coherency is eventually lost after long distance transmission because the carrier and the sideband would gradually walk off with the increased transmission length, significant PN is induced. In DDO-OFDM, the phase fluctuation of a laser is $\Phi(t)$, after transmitting through fiber link, at the receiver end there are $\rho_k(n) = \left[\Phi\left(t - T_k\right) - \Phi(t)\right]$ and $\theta_k = \left(-2\pi\left(k + N_d\right)\Delta f T_k\right)$ [9], which is the converted phase fluctuation and CD-induced phase rotation on kth subcarrier respectively. $T_k = \left[DL\lambda^2\left(k + N_d\right)\Delta f \cdot c\right]$ is the relative time delay between the kth subcarrier and the optical carrier, and D is the dispersion parameter, L is the fiber length, λ is the operating wavelength, and c is the light speed in vacuum, Δf is the subcarrier frequency spacing, N_d is the number of data subcarriers. Therefore $\exp\left(j\rho_k(t)\right)$ stands for the converted PN (CPN) on kth subcarrier. After the OFDM signal is sampled and FFT demodulated, the kth subcarrier symbol $R(k)$ can be represented as [9]

$$\begin{aligned} R(k) &= D_k\left(\frac{1}{N}\sum_{n=0}^{N-1} e^{j\rho_k(n)}\right) \\ &\quad + \sum_{m=1,m\neq k}^{N_d} D_m \cdot \left(\frac{1}{N}\sum_{n=0}^{N-1} e^{j[2\pi(m-k)n/N+\rho_m(n)]}\right) \\ &= D_k\psi_k(0) + \sum_{m=1,m\neq k}^{N_d} D_m \cdot \psi_m(k-m), \end{aligned} \tag{1}$$

where N is the FFT size, $D_k = A^* d_k \exp\left(j\theta_k\right)$ is the kth subcarrier symbol in the absence of CPN, $\rho_k(n)$ is the discrete-time converted phase fluctuation, and $\psi_k(p)$ is the FFT of $\rho_k(n)$, representing the frequency-dependent interferences from kth subcarrier

$$\psi_k(p) = \frac{1}{N}\sum_{n=0}^{N-1} e^{j[2\pi pn/N+\rho_k(n)]}. \tag{2}$$

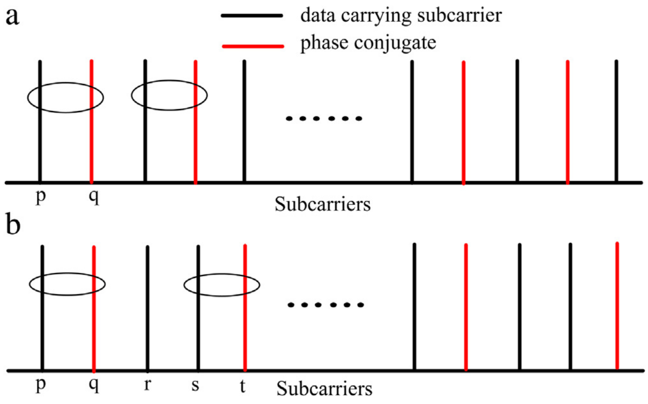

Fig. 1. PCPs insertion for PN suppression in DDO-OFDM. (a) 50% PCPs; (b) 33% PCPs.

The received kth subcarrier symbol includes not only the transmitted symbol D_k, which is corrupted by $\psi_k(0)$, but also the ICI terms from adjacent symbols D_m where $m \neq k$. In [9], $\psi_k(0)$ is called as PRT to distinguish it from its conventional name of common phase error (CPE) in CO-OFDM systems. The PN power on subcarrier can be expressed as

$$\beta_k \approx \sigma_{PRT}^2 + \sigma_{ICI}^2, \tag{3}$$

where σ_{PRT}^2 and σ_{ICI}^2 are PRT power and ICI power on kth subcarrier respectively. Without loss of generality, we can rewrite Eq. (1) as

$$\begin{aligned} R(k) &= \sum_{m=0}^{N} d_m \cdot e^{j\theta_m} \cdot \left(\frac{1}{N}\sum_{n=0}^{N-1} e^{j[2\pi(m-k)n/N+\rho_m(n)]}\right) \\ &= \frac{1}{N}\sum_{n=0}^{N-1} d_m \cdot \left(\sum_{m=0}^{N-1} e^{j\theta_m} \cdot e^{j[2\pi mn/N+\rho_m(n)]}\right) \cdot e^{-j2\pi kn/N} \\ &= \frac{1}{N}\sum_{n=0}^{N-1}\left(\sum_{m=0}^{N-1} d_m \cdot e^{j[2\pi mn/N+\rho_m(n)+\theta_m]}\right) \cdot e^{-j2\pi kn/N}, \end{aligned} \tag{4}$$

where $k = 0, 1, \dots, N-1$.

3. Proposed PN suppression scheme using phase-conjugated pilots

In DDO-OFDM, PN suppression based on single RF-Pilot tone is just effective for W-band RoF systems, where the PN could be approximated to common one irrelevant to the frequencies of subcarriers [13]. For low frequency RoF systems and baseband optical OFDM systems, the PN on each subcarrier is different, which makes the PN compensator more difficult to design. But fortunately the frequency spacing in an OFDM system is often narrow (tens of megahertz) compared to the broad PN bandwidth (∼several GHz [10]), making PN on adjacent subcarriers strongly correlated. This implies that PN experienced on one subcarrier may be used to estimate the PN on other neighboring subcarriers. Due to the varied PRT and significant ICI, to maximize the level of correlation of the PN between data carrying subcarriers and their phase conjugates, the data carrying subcarriers and their PCPs should be closely spaced in frequency. Consequently, in this paper we propose a scheme with 50% PCPs or 33% PCPs insertion for different FFT size to suppress PN induced by fiber CD in DDO-OFDM. 50% or 33% PCPs insertion means 50% or 33% of the subcarriers are transmitted as phase-conjugates of other subcarriers. The method of inserting 50% and 33% PCPs is illustrated in Fig. 1.

To simplify the exposition, we assume that the adjacent subcarriers of p and q are PCP pairs. The information symbol carried by the subcarrier is supposed to $d_p = A_p \cdot e^{j\phi_p}$ where A_p and ϕ_p are the amplitude and the phase of this information symbol, then the phase conjugated symbol is transmitted in the qth subcarrier, $d_q = d_p^* = A_p \cdot e^{-j\phi_p}$, where $(\cdot)^*$ represents complex conjugation. At the receiver end, according to