High Performance, Low Overhead CO-OFDM for Next Generation Fiber Transmission Systems

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Abstract: We present novel channel equalization and phase estimation approaches to reduce overhead in reduced-guard-interval (RGI) CO-OFDM systems. We also discuss the tolerance of RGI CO-OFDM to laser phase noise and fiber nonlinearity.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications; (060.4080) Modulation.

1. Introduction

In order to satisfy the ever-increasing capacity demand in optical communications, high spectral efficiency modulation formats such as coherent optical (CO) orthogonal frequency-division multiplexing (OFDM) have been actively investigated [1, 2]. In spite of the compact spectrum shape, conventional OFDM is not spectral efficient due to the large overhead [1]. The main overhead arises from the long cyclic prefix (CP) length required to accommodate the accumulated chromatic dispersion (CD). Reduced-guard-interval (RGI) OFDM compensates CD exclusively using a separate equalizer before the OFDM demodulation [2]. By doing so, it dramatically reduces the required CP length and improves the spectral efficiency. Many RGI CO-OFDM based spectral efficient transmissions have been demonstrated [2, 3]. In this paper, we first show a zero-guard-interval (ZGI) equalization scheme [4] and a pre-emphasized pilot subcarrier (PEPS) based phase estimation [5] to further reduce the overhead for OFDM systems. Then, we discuss the dispersion-enhanced phase noise (DEPN) [5-7] and the intra-channel nonlinearity tolerance of RGI CO-OFDM systems [8].

2. Channel equalization and phase estimation

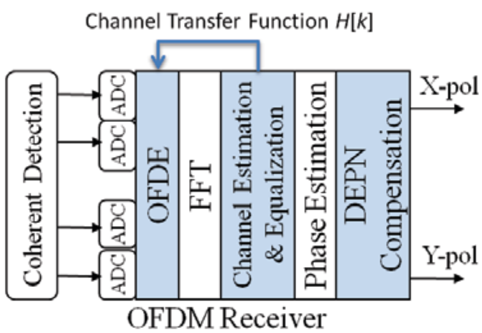

Fig. 1. Block diagram of ZGI CO-OFDM receiver.

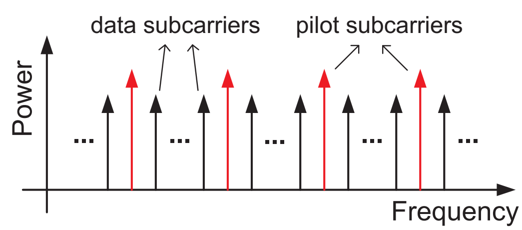

Fig. 2. Illustration of pre-emphasized pilot subcarriers.

In RGI CO-OFDM systems, the first stage equalizer which typically employs an overlap frequency domain equalizer (OFDE) compensates only CD, and the residual inter-symbol interference (ISI) is left to the OFDM channel estimation and equalization. Therefore, it still requires some CP to avoid ISI between OFDM symbols. In order to completely remove CP from data symbols, we proposed a ZGI CO-OFDM system in [4] which uses the OFDE to compensate all the ISI. The block diagram of the ZGI OFDM receiver is depicted in Fig. 1. Particularly, we estimate the residual ISI using conventional OFDM channel estimation and the obtained channel transfer function $H[k]$ is subsequently applied to update the equalizer coefficients of the OFDE. For the following data symbols no CP is required to avoid ISI when demodulating the signal since the OFDE is now able to compensate not only the CD but also the residual ISI such as polarization mode dispersion (PMD). This further reduces the overhead and improves the spectral efficiency. It has been numerically demonstrated in [4] that ZGI CO-OFDM with no CP can achieve the same performance as RGI CO-OFDM with 4 samples CP.

In addition to the CP overhead, the pilot subcarriers induced overhead for phase estimation is also non-negligible, especially in RGI CO-OFDM systems where the total number of subcarriers is typically small (e.g. 80). We proposed a PEPS based phase estimation in [5], aiming to reduce the number of pilot subcarriers while preserving the performance. In this approach the pilot subcarriers are pre-emphasized as shown in Fig. 2 and their signal-to-noise ratio (SNR) is increased. Therefore, the accuracy of the phase estimated from those pilot subcarriers is improved. The analytical and numerical results in [5] show that the number of pilot subcarriers can be reduced from 4 to 1 using PEPS. It should be noted that no complexity is added in this approach.

3. Dispersion-enhanced phase noise and intra-channel nonlinearity tolerance

Due to the CD-induced walk-off, OFDM subcarriers will experience different phase noise from the local oscillator (LO) laser, which is referred to as DEPN [6]. With conventional common phase error (CPE) compensation, since only one phase is estimated and applied to all subcarriers [9] the residual phase shift induced by the DEPN will degrade the performance. When using a large linewidth laser as the LO, the DEPN has to be compensated as shown in the block diagram in Fig. 1. Fig. 3 shows the measured BER versus distance with different lasers in a dual-polarization 28 Gbaud QPSK RGI CO-OFDM transmission experiment. The number of subcarriers N_s is 112. Compared to the system with two external-cavity lasers (ECLs), the transmission distance at BER=3.8×10^{-3} of the system with a distributed feedback (DFB) laser at the transmitter is reduced by 21%. This degradation is due to the laser phase noise induced inter-carrier interference (ICI). But when we put the DFB laser at the receiver the distance is reduced by 53% due to the effect of both DEPN and ICI. However, after using the grouped maximum-likelihood (GML) algorithm proposed in [6, 7] to compensate for DEPN, the performance of using the DFB laser as the LO becomes very close to that of using the DFB laser at the transmitter. This improvement demonstrates the effectiveness of our algorithm in compensating for DEPN. We have also shown in [10] that with DEPN compensation RGI OFDM can achieve better laser linewidth tolerance than Nyquist single carrier (SC) systems for high baudrate and long-haul transmissions because the latter suffers from the equalization-enhanced phase noise (EEPN) which is difficult to compensate [11].

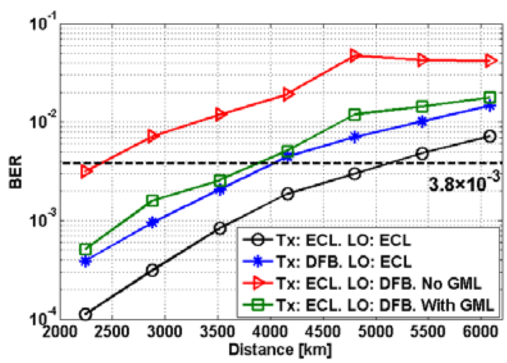

Fig. 3. Experimental investigation of DEPN-induced penalty and its compensation. Tx: transmitter.

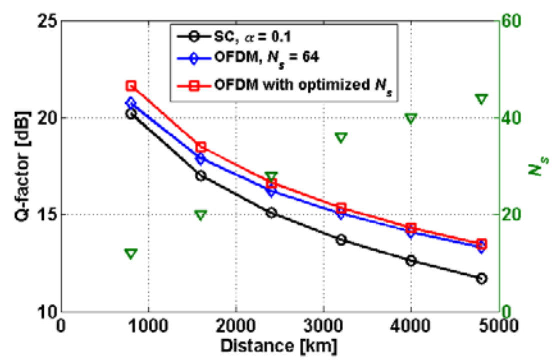

Fig. 4. Comparison of the intra-channel nonlinearity tolerance between RGI OFDM and Nyquist single carrier systems.

OFDM is conventionally considered to be vulnerable to fiber nonlinearities due to the high peak-to-average power ratio (PAPR). However, we showed in [8] that RGI CO-OFDM with a small number of subcarriers can improve the intra-channel nonlinearity tolerance compared with the Nyquist SC system. We explained this phenomenon by the fact that OFDM subcarriers are de-correlated by the CD-induced walk-off during the transmission, whereas the SC pulses are highly correlated by the CD-induced pulse broadening. Fig. 4 shows the Q-factor versus distance for 56 Gbaud QPSK signal of Nyquist SC with a roll-off factor α=0.1 and OFDM with different N_s. For OFDM the optimal N_s increases as the transmission distance becomes longer. And with the optimal N_s, OFDM achieves >1.4 dB larger Q-factor than SC attributed to the improved intra-channel nonlinearity tolerance.

4. Conclusions

In this paper, we presented the improved channel equalization and phase estimation scheme based on the RGI CO-OFDM structure to reduce the overhead and improve the spectral efficiency. We also discussed the performance of RGI CO-OFDM with respect to laser phase noise and intra-channel fiber nonlinearity.

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