Channel Estimation Using Superimposed Training for Coherent Optical OFDM Systems

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Abstract: We demonstrate by simulation that the superimposed training based channel estimation scheme can achieve similar performance as compared with conventional schemes, without any loss in bandwidth. An iterative decision feedback algorithm is also developed to enhance the channel estimation.

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1. Introduction

Coherent optical orthogonal frequency division multiplexing (CO-OFDM) [1] is considered to be one of the promising modulation formats for 100-Gb/s and beyond optical transmission systems, due to its high spectral efficiency, high flexibility and its natural combination with digital signal processing (DSP). In recent DSP based CO-OFDM systems, pilot symbols (preambles) and pilot subcarriers are used for channel estimation (CE) [2-3], which consumes valuable bandwidth and degrades the spectrum efficiency. Here, we propose an overhead free channel estimation method for CO-OFDM systems based on superimposed training (ST), and show that, channel estimation can be performed without any loss in bandwidth. Superimposed training has been well studied in recent literatures [4-6], [8]. In ST based channel estimation schemes, periodic training sequences are arithmetically added on to the data streams in either time-domain or frequency domain prior to transmission, hence the channel state information (CSI) can be extracted by exploiting the first-order statistics of the received signal at receiver. In this way, no extra bandwidth is lost. To further enhance the performance of channel estimation, a decision feedback (DF) method is adopted at the receiver. Simulation results demonstrate that the proposed ST based CE approach offers similar performance to that of the preamble based schemes without sacrificing any bandwidth.

2. System Model

Consider an OFDM system using ST, the transmitted symbol $\mathrm{X_k}$ at the *k*-th subcarrier is a linear superposition of a training symbol $\mathrm{p_k}$ and a data symbol $\mathrm{x_k}$, i.e.,

$$\mathrm{X_k} = \sqrt{\phi_k p_k} + \sqrt{1-\phi_k p_k}, k = 0, 1, \ldots, N-1 \tag{1}$$

where ϕ_k is the power of pilot symbols of the k-th subcarrier. For simplicity, the total transmission power is normalized. Hence, the signal-to-pilot power ratio (SPR) of the k-th subcarrier is $\mathrm{SPR_k} = \mathrm{SPR} = 1/\phi$. The periodic ST sequence $\mathrm{p_k}$ adopted in this paper may refer to that of ref. 6. An inverse Discrete Fourier Transformation (IDFT) is applied to generate the discrete time domain signal $\mathrm{x_n}$. A cyclic prefix (CP) is then added before transmission to prevent inter-symbol-interference (ISI). At the receiver, after removing CP and performing DFT demodulation, the modulated signal can be expressed as [4], [7]:

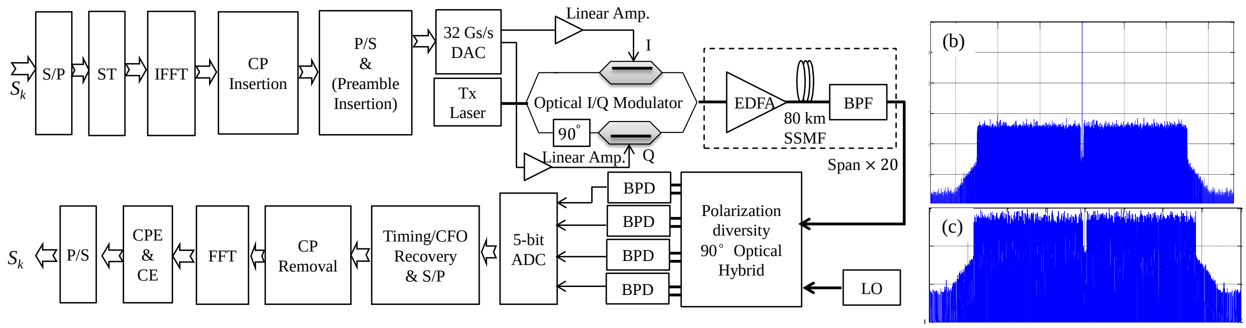
$$Y_k = X_k H_k \Phi_{k,t} + W_k, k = 0, 1, 2, \ldots, N-1 \tag{2}$$

where H_k is the channel frequency response (CFR), $\Phi_{k,t}$ is the phase drift of the *k*-th subcarrier induced by the lasers at both transmitter and receiver, and $\mathrm{W_k}$ is the additive white Gaussian noise with zero mean and a variance of σ^2. Prior to CE, the carrier phase drift $\Phi_{k,t}$ should be estimated due to its time-variant property, and then the ST based CE method can be applied to estimate the CSI [4]. Generally, the channel coefficients $\mathrm{H_k}$ can be considered as time-invariant within one OFDM frame, and the data symbols $\mathrm{s_k}$can be assumed as zero mean with independent and identical distribution. Hence, the statistical mean of $\mathrm{Y_k}$ after carrier phase estimation and compensation, can be expressed as:

$$\mathrm{E(Y_k)} = \mathrm{E(X_k H_k} + W_k) = E\left(\sqrt{\phi_k} p_k H_k\right) + E\left(\sqrt{1-\phi_k}\, s_k + W_k\right) = \sqrt{\phi_k} p_k H_k \tag{3}$$

where $\mathrm{E(.)}$ denotes the expectation operator. Accordingly, the CFR $\mathrm{H_k}$ can be estimated using the ST sequence $\mathrm{p_k}$. It is observed from (3) that the term $E\left(\sqrt{1-\phi_k}\, s_k + W_k\right)$ acts as additive noise to channel estimation. Clearly, such interference is approximately white, and thus can be reduced by increasing the OFDM frame size. Alternatively, to reduce the number of required OFDM symbols in ST based CE, an iterative DF scheme[8] can be adopted at receiver. The detection process is described as follows: First, the data symbols are recovered using the CFR obtained through

Eq. (3). Second, the recovered data symbols are removed from the received signal to cancel the data symbol interference, and thus enhance the channel estimation.



(a)

Fig. 1. (a) The schematic of the ST based CO-OFDM system architecture and simulation setup; (b) Spectrum of the Tx. Signal; (c) Spectrum of the Rx. Signal after pilot extraction.

3. ST based CO-OFDM System Architecture

Single polarization CO-OFDM systems are considered in this contribution. The schematic of the ST based CO-OFDM system is shown in Fig. 1. The FFT size is 1024, of which 896 subcarriers are used for QPSK signal mapping, the 1st subcarrier is reserved as pilot tones used for carrier phase estimation [2], and others are remain unfilled for oversampling. Chromatic dispersion (CD) is compensated using frequency domain equalization [9] to decrease the number of samples of CP. Each OFDM frame has 1-symbol overhead for timing and frequency offset recovery and 1000 payload symbols. After IFFT and CP insertion, the time-domain signal is then parallel/serial converted and D/A converted by two DACs operating at a sample rate of 32 GHz with 5-bit resolution. The net rate of the transmitted signal is 56 Gb/s. The extinction ratio of the optical I/Q modulator used for optical up-conversion is 30 dB. The lasers at both transmitter and receiver have a linewidth of 100 KHz. The fiber link consists of 20 spans of standard single mode fiber (SSMF), each span have 80-km of fiber with a span loss of 20 dB, an EDFA with a noise figure of 5 dB, and a 50-GHz optical band-pass filter. At the receiver, coherent detection with polarization diversity receiver is used for signal reception. The resolution of the ADC is assumed to be 5 bits. The timing and frequency offset recovery is performed after CD compensation. Carrier phase estimation is then performed by extracting the phase of the pilot tone using a low pass filter (LPF) [2]. Channel coefficients are then extracted using Eq. (3) for frequency domain equalization. Preamble based CE is also considered to compare and evaluate the estimation performance of the proposed ST scheme. For both CE schemes, the signal to pilot (preamble) power ratio are 0.01.

4. Simulation Results and Discussion

We first consider the peak-to-average power ratio (PAPR) of the ST based CO-OFDM signals. Fig.2(a) shows the CCDF of the PAPR before and after clipping for different SPR values. As the periodic training sequences in frequency domain result in discrete impulses in time domain, when the pilot power is high, the PAPR can be significantly increased, as shown in Fig. 2(a). As the DAC and ADC both have limited resolution, clipping is necessary in order to get the optimum performance. The optimum value of clipping ratio (CR) for QPSK-OFDM signals is found to be around 2.

Fig. 2(c) shows the back-to-back performance of the CO-OFDM system using both ST and preamble based CE methods. The calculated theoretical OSNR (defined with 0.1 nm noise bandwidth) at BER value of 1E-3 is 12.72 dBm (without CP). One can see from fig. 2(c) that, the BER performance of the ST based CE method in AWGN channels is very close to the theoretical value (with about 0.04 dB OSNR penalty), which proves the effectiveness of the ST based CE approach. For optical channels, when no phase noise is added, both methods exhibit the same performance, with an OSNR penalty of about 0.7 dB resulted from the influence of the AD/DA effect. When 100-KHz linewidth is added to the lasers, the penalty increases to 1 dB for ST based approach, while for preamble based approach, the penalty is 1.3 dB.

As the ST based CE uses the first order statistics of the received OFDM signal, the number of symbols used for averaging is crucial for accurate channel estimation. Fig. 2(b) shows the Q factor as a function of number of symbols per OFDM frame with an OSNR of 15 dBm. The iterative DF algorithm is used to enhance the channel estimation. It can be seen that, for the initial estimation, increasing the average window always helps to enhance the estimation. However, when the iterative DF algorithm is used, only a small number of symbols (> 10) are needed to achieve the upper bound of the Q factor performance. One can also see from Fig.2(b) that most of the gain of using the iterative DF algorithm is obtained in the very first iteration.

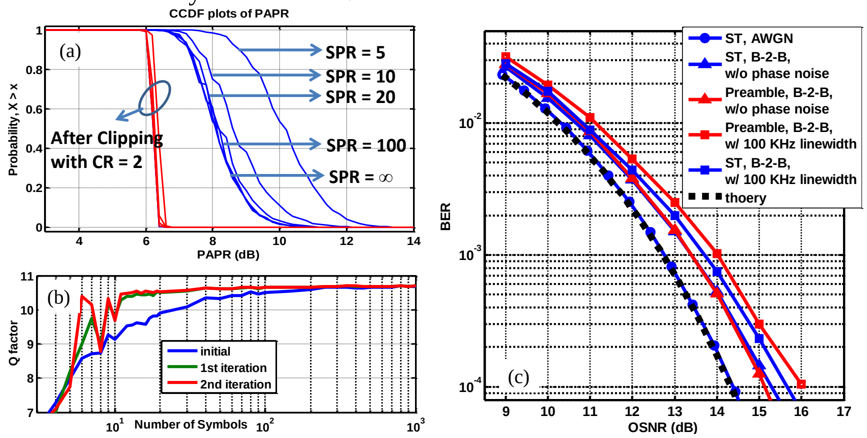


Fig. 2. (a) CCDF plots of PAPR; (b) Q factor as a function of number of symbols used for averaging (at 15 dBm b-2-b OSNR); (c) Simulated BER of the ST based CO-OFDM signal vs. OSNR in the back-to-back case.

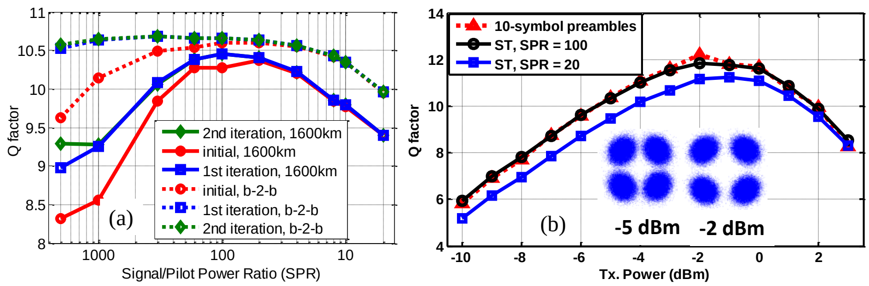


Fig. 3. (a) Q factor as a function of the signal-to-pilot power ratio. The OSNR is set to 15 dBm (-5 dBm of Tx. Power); (b) Q factor vs. transmitter power for both ST and preamble based CE approaches.

We also considered the nonlinear tolerance of the ST based CE approach after fiber transmission. A transmission link of 20 spans of standard single mode fiber (SSMF) is used. The span length is 80 km, with a span loss of 20 dB. The CD coefficient is 16 ps/nm/km. The fiber nonlinear refractive index is 2.6e-20 m^2/W. The polarization mode dispersion (PMD) coefficient is $0.1\mathrm{ps}/\sqrt{\mathrm{km}}$. Random polarization rotation during transmission is taken into account. Coherent detection with polarization diversity receiver is used. Fig. 3(b) shows the Q factor as a function of the transmitter power. It can be seen that the ST and preamble based CE approach shows similar Q factor performance. The optimum power observed is around -2 dBm, with a nonlinear penalty of around 1.4 dB. One can also see from Fig. 3(a) and Fig. 3(b) that the optimum SPR value is around 100. When an SPR value of 20 is used, a 0.7-dB penalty can be observed.

5. Conclusions

We have presented a bandwidth efficient CE method. It is shown through simulations that the ST based CE method can achieve similar performance as that of the preamble based approaches without sacrificing any bandwidth. Furthermore, by using an iterative decision feed-back algorithm, the performance of CE can be further improved.

6. References

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