A channel estimation algorithm for optical orthogonal frequency division multiplexing systems*

WANG Dong (王东)[1]**, **ZOU Nian-yu** (邹念育)[2], **WANG Wei-dong** (王卫东)[1], and **ZHANG Ying-hai** (张英海)[1]

1. Laboratory of Information and Electronics Technology, Beijing University of Posts and Telecommunications, Beijing 100876, China

2. Research Institute of Photonics, Dalian Polytechnic University, Dalian 116034, China

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A simple channel estimation (CE) scheme, which is pilot-aided with just a little number of pilots inserted in the first half part of the subcarriers, is proposed and simulated for resisting the fiber dispersion in optical orthogonal frequency division multiplexing (OFDM) systems. The simulation results verify that the receiver sensitivity is improved by 2–3 dBm for bit error rate (BER) of 10^{-3} with the proposed CE algorithm than that with other kinds of CE algorithms based on linear square principle. The good constellation performance for a 40 Gbit/s transmission system can be also obtained by the proposed scheme.

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Orthogonal frequency division multiplexing (OFDM) technology has shown its usefulness to the next-generation passive optical networks (PONs)[1-5]. The use of optical OFDM (O-OFDM) in PONs has attracted much research interest[6,7].

The OFDM means that data is transmitted on a number of different parallel subcarriers, hence, the total data rate is divided by the number of subcarriers, and high-speed data transmission can be achieved. However, it has been shown that OFDM is sensitive to the phase noise, which can cause common phase error (CPE) noise and inter-carrier interference (ICI)[8]. In addition, the fiber dispersion and sample time shift in discrete Fourier transformation (DFT) processing also can rotate the constellations of the received OFDM signals. Pilot-aided channel estimation (CE) is an effective procedure in O-OFDM to mitigate the chromatic dispersion, polarization mode dispersion and phase noise[9-12].

The least square (LS) and the linear minimum means square error (LMMSE) are two main methods to estimate the channel transfer functions (CTFs) of the pilots. LS is commonly used in the O-OFDM systems, due to its simple realization and low complexity. On contrast, LMMSE is more accurate than LS, but it is complex in computation[11,12]. Based on those two methods, various interpolation algorithms are proposed[13] to estimate CTFs. In this paper, a simple CE scheme, which is pilot-aided with just a little number of pilots inserted in the first half part of subcarriers, is proposed and simulated.

The principle of OFDM is to transmit the data through numbers of parallel orthogonal subcarriers. The nth sample of the typical OFDM signal can be written as[8,9]

$$S_n = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} C_k \exp(\mathrm{j}2\pi\frac{kn}{N}),\ \ n=0\cdots N\text{-}1, \tag{1}$$

where k is the subcarrier number, C_k represents the modulated mary quadrature amplitude modulation (mQAM) or mary phase shift keying (mPSK) symbol, N is the number of the subcarriers, and n is the sample point of the OFDM signal. After the radio to optical converting, the upper sideband of the O-OFDM signal can be represented as

$$E_\mathrm{s} = \exp[\mathrm{j}2\pi(f_\mathrm{LD} + f_\mathrm{LO})t]S_n, \tag{2}$$

where f_LD and f_LO are the frequencies for optical carrier and the local oscillator (LO), respectively. The received optical OFDM signal after propagating through the fiber link, in which just the chromatic dispersion is considered, is approximated as

$$E_\mathrm{s} \approx \exp[\mathrm{j}2\pi(f_\mathrm{LD} + f_\mathrm{LO})t]\times \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} C_k \exp(\mathrm{j}2\pi\frac{kn}{N})\exp[\mathrm{j}\phi_\mathrm{D}(f_k)], \tag{3}$$

$$\phi_\mathrm{D}(f_k) = \pi c D_\mathrm{t} f_k^2 \big/ f_\mathrm{LD}^2, \tag{4}$$

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** E-mail: wangdong0607@163.com

where $\phi_{\mathrm{D}}(f_k)$ is the phase dispersion of the kth subcarrier owing to the fiber chromatic dispersion, f_k is the frequency for the kth subcarrier, D_{t} is the total chromatic dispersion assuming that it is quadratically dependent on frequency but in general can be arbitrary function of the frequency, and c is the speed of the light. Then, the detected signal by PIN is further down-converted to baseband with LO. Based on the above analysis, a parallel subcarrier system model of OFDM is shown in Fig.1.

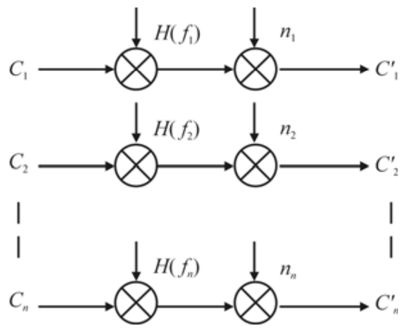


Fig.1 The O-OFDM system described as a set of matrices

As is shown, the received symbol in each subcarrier is then given by

$$C_k^{'} = C_k H(f_k) + n_k \,, \tag{5}$$

$$H(f_k) = \exp[\mathrm{j}\phi_{\mathrm{D}}(f_k)] \,, \tag{6}$$

where $H(f_k)$ is the channel response for the kth subcarrier, n_k is the noise, and C_k and $C_k^{'}$ are the transmitted and received symbols for the kth subcarrier, respectively.

The proposed CE scheme is based on the LS principle and the frequency domain interpolation (FDI). Fig.2 shows the pilot insertion principle of the proposed interpolation scheme. The information carried by the first subcarrier locates at zero frequency after the process of inverse fast Fourier transform (IFFT). In order to avoid the spectrum overlapping between the center optical carrier and the first subcarrier in the modulation process of the modulator, the first subcarrier is set to null. Then, pilots are interpolated in the first half part of subcarriers at the same interval. Other subcarriers are for data transmission. In this case, only half number of pilots are needed in our proposed interpolation scheme compared with the traditional comb interpolation scheme, and high spectral efficiency is achieved.

Based on the LS principle, the CTF for OFDM pilots is deduced as

$$H_{\mathrm{LS}} = X^{-1} Y \,, \tag{7}$$

where X stands for the transmitted pilot symbol, and Y is the received symbol of the pilots. Then the CTF $H_{\mathrm{LS}}(f_k)$ of the subcarriers $1-N/2$ can be obtained by the linear interpolation. Consider the CTF of subcarrier k ($1<k<N/2$) and $k+N/2$,

$$\frac{H_{\mathrm{LS}}(f_k)}{H_{f_{k+128}}} = \frac{\exp[\mathrm{j}\phi_{\mathrm{D}}(f_k)]}{\exp[\mathrm{j}\phi_{\mathrm{D}}(f_{k+128})]} \,. \tag{8}$$

Then the CTFs $H_{f_{k+128}}$ ($1<k<128$) are obtained from Eq.(8). In this case, a simple CE is achieved and accurate transmitted symbols can be recovered, in which the CTFs are closely based on the fiber transmission model.

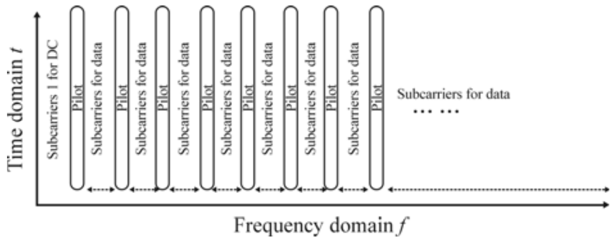


Fig.2 The pilot insertion principle of the proposed interpolation scheme

In order to evaluate the performance of the proposed CE scheme, some simulations are done. Fig.3 illustrates the block diagram for O-OFDM system with 25 km fiber transmission. Firstly, the incoming 40 Gbit/s data is modulated into mQAM or mPSK format. Then, pilots are inserted before the IFFT process. After being upconverted to the intermediate frequency, the OFDM signals are modulated into optical domain through a dual-drive Mach-Zehnder modulator (D-MZM). The distributed feedback laser diode (DFB-LD) is located at 193.1 THz with 5 mW. The channel is modeled as fiber transmission channel corrupted by dispersion, nonlinearity and thermal noise. The signal is turned into electrical domain and demodulated into binary data through a PIN diode and an OFDM receiver whose block diagram is the inverse flow of the OFDM transmitter.

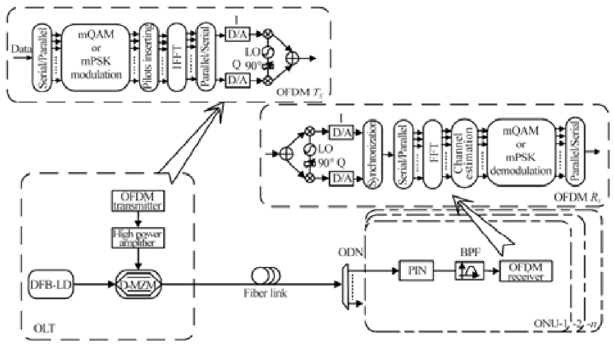


Fig.3 Block diagram of the O-OFDM system for the proposed channel estimation

Fig.4 shows the downstream single sideband (SSB) O-OFDM signal. In order to avoid the spectrum overlapping between the O-OFDM signal band and the center optical carrier, a 15 GHz radio is mixed with the OFDM baseband signal. When double sideband (DSB) modulation is used in O-OFMD system, the dispersion can affect those two optical sidebands. Then, after the detection of a PIN, the upper sideband (USB) and the lower sideband (LSB) can generate two beat-frequency signals with the optical carrier. And those two signals affect each other and lead to cross interference. Compared with DSB modulation, SSB modulation which only has one useful sideband can highly resist the dispersion and the cross interference. As a result, in our work, SSB modulation is used.

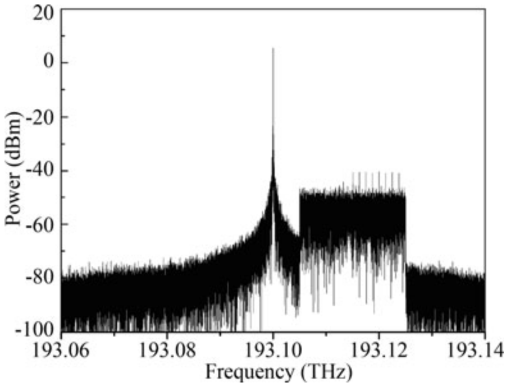
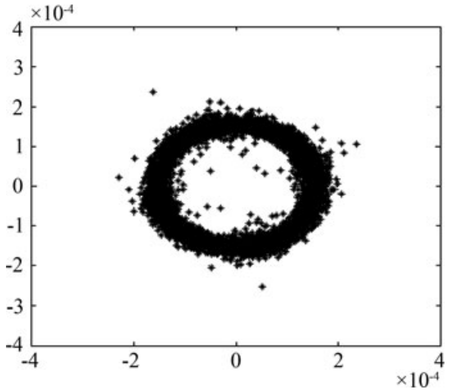
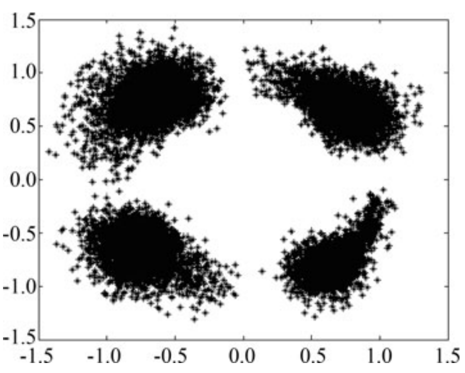


Fig.4 Downstream O-OFDM signal with SSB modulation

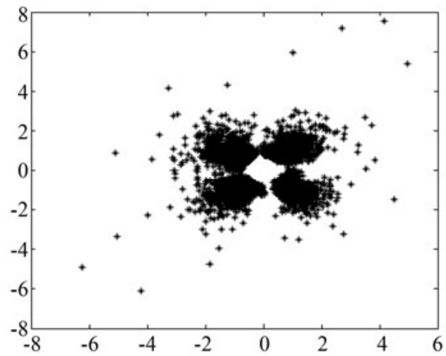
Three received constellations are illustrated in Fig.5. As shown in Fig.5(a), the received constellation without CE illustrates that the transmitted data can't be recovered correctly at all. Fig.5(b) and (c) are the constellations after the proposed CE and comb LS-linear CE. It shows that the proposed CE scheme owns a better and decided constellation than the comb LS-linear CE.



(a) Constellation without channel estimation



(b) Constellation corrected with the proposed CE



(c) Constellation corrected with the comb LS-linear CE

Fig.5 Received constellations without channel estimation and corrected with the proposed CE and the comb LS-linear CE

In order to estimate the transmission performance of the proposed CE scheme, BERs with different CE schemes are calculated. It is well known that cyclic prefix (CP) is a key technique in OFDM, which can highly resist the fiber dispersion. In order to deeply reflect the performance of the proposed CE scheme, LS-const and LS-linear CE schemes with or without CP also are simulated. As is shown in Fig.6, with the increase of the received optical power, the BER gets better. It is clear that the CE schemes with CP get a better BER than those without CP. And among those three kinds of CE algorithms, LS-const CE gets the worst BER performance. Later is the LS-linear scheme. Our proposed CE algorithm obtains the best BER performance.

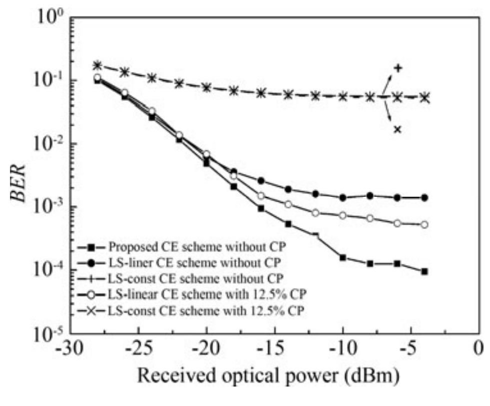


Fig.6 BER versus the received optical power

CE is an effective technique to resist the fiber dispersion in O-OFDM transmission system. In this paper, a CE scheme which is based on the LS and FDI is presented. The proposed scheme is pilot-aided, in which just a little number of pilots are inserted in the first half part of the subcarriers and high spectral efficiency is achieved. Numerical mathematic models of the proposed CE scheme are analyzed. Simulation results show that the proposed scheme achieves 40 Gbit/s data transmission and offers good BER performance. It is believed that the proposed CE scheme will play an important role in the next-generation PONs.

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