TWA-based channel estimation for CO-OFDM systems*

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An efficient channel estimation method called time-domain weighted average (TWA) algorithm is proposed for coherent optical orthogonal frequency division multiplexing (CO-OFDM) systems. On the premise of calculating the associated weight of channel transfer function, a more exact channel characteristic is obtained by calculating the weighted average of the pilot transfer function in this algorithm. Compared with time-domain average (TA) algorithm, the TWA algorithm can reach the same bit error rate (BER) with fewer pilots, and it improves the performance of CO-OFDM systems.

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Orthogonal frequency division multiplexing (OFDM) technology was firstly applied to wireless communication. However, considering its robustness to the fiber transmission impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD), recently it has attracted great attention in optical communications[1,2]. Coherent optical orthogonal frequency division multiplexing (CO-OFDM) technology can effectively reduce the effects of CD and PMD in the optic fiber transmission channel, and improve the spectrum efficiency[3,4]. The CO-OFDM is being considered as a promising technology for future high-speed optical transmission systems.

Channel estimation is an important procedure in CO-OFDM systems[5-7]. With channel estimation, the physical effects of the fiber transmission link are obtained, and channel equalization can be performed to restore the signal quality. In the pilot-based channel estimation methods, the transmitted signal is known at the receiver, and this estimation method has two kinds of working modes: the block pilot mode and the comb pilot mode. The estimation of the channel for this block-type pilot arrangement can be based on least square (LS) or minimum mean-square error (MMSE). The LS estimation is relatively easy since it does not need any channel apriority probability. However, the performance of LS is not very good due to the presence of noise. The MMSE estimation has better performance since it uses the channel statistical properties, including the channel autocorrelation matrix and the noise variance, whereas the computational complexity of MMSE is higher. Several improved methods based on LS algorithm have been discussed. To enhance the channel estimation accuracy, a time-domain averaging (TA) method that averages the transfer function estimated by multiple training symbols is used for CO-OFDM system in Refs.[8,9]. This method can further compensate for the impact of CD in CO-OFDM system. In this letter, we present a time-domain weighted average (TWA) channel estimation algorithm, which is an improvement of TA algorithm. On the premise of calculating the associated weight of channel transfer function, a more exact channel characteristic is obtained by calculating the weighted average of the pilot transfer function in TWA algorithm. Simulation results show that the TWA algorithm can reach the same bit error rate (BER) with fewer pilots compared with the TA algorithm, and it improves the performance of CO-OFDM systems.

The TA algorithm is a kind of pilot-aided channel estimation. Fig.1 is an illustration of a frame structure for pilot-aided channel estimation. 4 pilot OFDM symbols and 8 data OFDM symbols are included in Fig.1. There are two transmission modes in the block pilot estimation: the pilot transmission mode and the data transmission mode. In the pilot transmission mode, one or more predefined (known at the receiver) training sequences are transmitted, and then the receiver would be able to obtain the channel information from the received pilots. The LS algorithm channel transfer function by multiple training symbols is[10-12]

$$H_{\mathrm{LS},i}(k)=\frac{Y_i(k)}{X(k)},\qquad 1\le i\le L,\ \ 0\le k\le N-1,\tag{1}$$

where $X(k)$ is the known training sequence, $Y_i(k)$ is the received OFDM signal for the ith training sequence, $H_{\mathrm{LS},i}(k)$ is the channel matrix (or the channel transfer function) for the ith training sequence, L is the number of

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training sequences, and N is the total number of subcarriers.

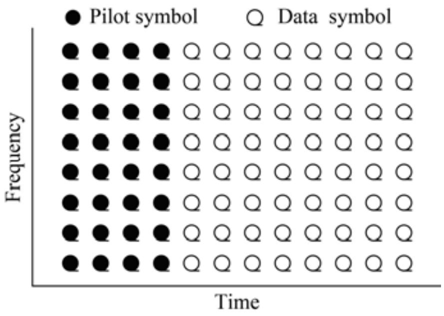


Fig.1 An illustration of a frame structure for pilot-aided channel estimation

In order to eliminate the influence of the random noise, and then enhance the accuracy of channel estimation, the time averaging is done on all the training sequences. The TA algorithm channel matrix is

$$\hat{H}(k)=\frac{1}{L}\sum_{i=1}^{L}H_{\mathrm{LS},i}(k) \quad . \tag{2}$$

TA algorithm removes the random noise interference and improves system's noise immunity through a great deal of training sequences. The more training sequences are used, the more accurate the channel transfer function will be. While the training sequence is useless information, it increases the redundancy of system. OFDM symbol itself has introduced the cyclic prefix and some other redundant information, and too much useless information will affect the performance of the system. To solve this problem, we propose the TWA channel estimation algorithm.

The L channel matrices are not simply averaged in TWA algorithm. The main idea of the TWA algorithm is to calculate the associated weight of the channel transfer function, and then compute the weighted average of the transfer function according to the associated weight, so channel information is obtained which can reflect channel characteristic more exactly.

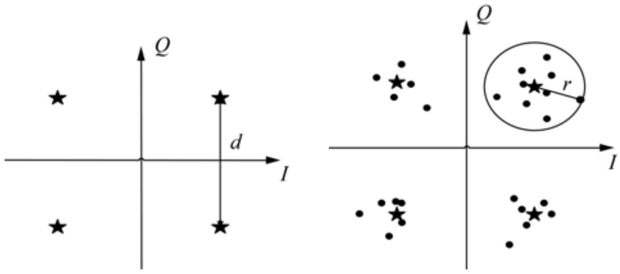
TWA algorithm and its implementation are considered next. Firstly, the binary information is grouped and mapped to quadrature phase shift keying (QPSK) symbols by the constellation mapper as shown in Fig.2(a), and then the serial to parallel converter rearranges the QPSK symbols to OFDM symbols where the number of subcarriers is N in the frequency domain. L pilot symbols are contained in an OFDM frame, and all the pilots are the same. In the receiving end, $Y_i(k)$ is received correspondingly, and L estimated channel matrices $H_{\mathrm{LS},i}(k)$ are obtained by Eq.(1).

In order to obtain the exact channel information, two associated restored pilot signals are defined

$$\hat{X}_{i,i-1}(k)=\frac{Y_{i-1}(k)}{H_{\mathrm{LS},i}(k)}, \tag{3}$$

$$\hat{X}_{i,i+1}(k)=\frac{Y_{i+1}(k)}{H_{\mathrm{LS},i}(k)}, \tag{4}$$

where $\hat{X}_{i,i-1}(k)$ is the $(i-1)$th restored pilot symbol by the ith channel information $H_{\mathrm{LS},i}(k)$, and $\hat{X}_{i,i+1}(k)$ is the $(i+1)$th restored pilot symbol. The constellation diagram of each subcarrier data for $\hat{X}_{i,i-1}(k)$, $\hat{X}_{i,i+1}(k)$ is shown in Fig.2(b).



(a) Standard constellation mapper (b) Associated restored signal constellation diagram

Fig.2 Standard constellation diagram and the restored signal constellation diagram

Due to the presence of the fiber chromatic dispersion and electrical noise in CO-OFDM system, the constellation points of restored pilot signal are not central to the standard constellation. According to the concept of the variance in mathematics, we propose a factor α to express channel transfer function's discrete degree as

$$\alpha=\frac{\frac{1}{N}\sum_{i=1}^{N}\left|r_i\right|^2}{\left(0.5d\right)^2}, \tag{5}$$

where d denotes the distance between two standard constellation points (shown in Fig.2(a)), and r_i is the distance between constellation points of restored pilot signal and standard constellation points (shown in Fig.2(b)). By Eq.(5), we can know that $\alpha\in(0,1)$, and the smaller the α is, the more centered the restored pilot signal will be on standard constellation restored constellation.

Considering channel discrete degree α, the channel matrix of TWA algorithm is depicted as

$$\hat{H}(k)=\sum_{i=1}^{L}\frac{\lambda_i}{\lambda_1+\lambda_2+\cdots+\lambda_L}H_{\mathrm{LS},i}(k), \tag{6}$$

where

$$\lambda_i=\frac{1}{\alpha_{i,i+1}+\alpha_{i,i-1}}, \tag{7}$$

where $\alpha_{i,i+1}$ denotes channel discrete degree of signal $\hat{X}_{i,i+1}(k)$, and $\alpha_{i,i-1}$ denotes channel discrete degree of signal $\hat{X}_{i,i-1}(k)$. λ_i combines three pilot channels' information circularly. By Eq.(6), $\lambda_i/(\lambda_1+\lambda_2+\cdots+\lambda_L)$ is the associated weight of channel transfer function, and the bigger the λ_i is, the more the ith associated pilot channel estimation will affect the final channel estimation. Therefore, the TWA algorithm can get more accurate channel information than the TA algorithm.

We carry out Monte Carlo simulations to verify the TWA algorithm in CO-OFDM system by Optisystem and MATLAB. Fig.3 shows the simulation block diagram of CO-OFDM system. OFDM modulation, OFDM demodulation, analog to digital converter (ADC) and digital to analog converter (DAC) are realized by MATLAB. Optical transmitter, optical receiver and optical fiber are realized by Optisystem. In the OFDM modulation module, random binary sequences generated by Optisystem are all mapped to 16 quandrative amplitude modulation (16-QAM) in the MATLAB. The time-domain signal is formed after inverse fast Fourier transform (IFFT) operation, and inserted with a guard interval. The I and Q components of the time signal are loaded into Optisystem after they are converted to analog signals. The optical transmitter module, comprising of two Mach-Zehnder modulators with 90^{o} phase shift, directly converts OFDM baseband signals from the radio-frequency (RF) domain to the optical domain. The optical OFDM signal is launched into 2-span of fiber link emulated with a recirculation loop. The recirculation loop consists of 100-km single mode fiber (SMF) and a fiber amplifier to compensate the link loss. In the optical receiver module, direct optical-to-RF conversion is employed. We tune the local oscillator (LO) laser frequency close to that of the incoming signal. Both signal and LO are fed into an optical 90^{o} hybrid. Two balanced receivers are used to detect the I and Q components. The detected RF signals are exported to MATLAB. In the OFDM demodulation module, after CP is removed, the received electrical signals are converted into the frequency domain by FFT. Next, in the pilot transmission mode, the channel estimation is finished by TA or TWA algorithm. In the data transmission mode, data symbols are recovered by estimated channel information. The simulation parameters are indicated in Tab.1.

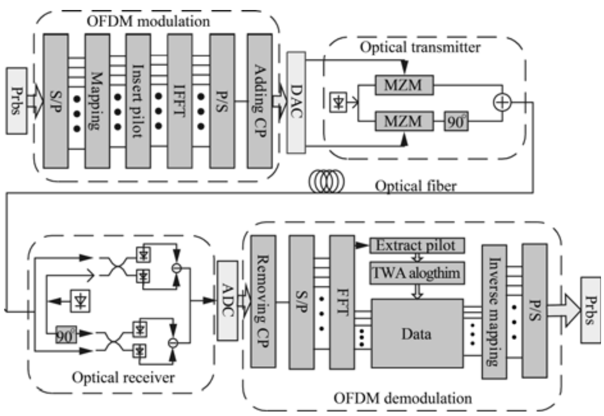


Fig.3 Simulation block diagram of CO-OFDM system

In order to evaluate the transmission performance for the proposed TWA algorithm, BERs with different optical signal-to-noise ratios (OSNRs) are calculated. Fig.4 shows the BER performance of LS, MMSE and TWA algorithms with different OSNRs. In simulation, there are 4 pilot symbols and 8 data symbols in an OFDM frame. Because of the effects of the noise and CD, the BER performance of LS algorithm is the worst, TWA algorithm is better than LS algorithm, while the MMSE algorithm has the best performance. When BER is 10^{-4}, TWA algorithm can save OSNR of 2 dB compared with LS algorithm for CO-OFDM system. Obviously, TWA algorithm eliminates the influence of random noise and CD, and improves the performance of CO-OFDM system compared with LS algorithm.

Tab.1 Simulation parameters

Parameter	Value
FFT size	256
CP size	32
Data rate	40 Gbit/s
Modulation	16QAM
Laser linewidth	1 MHz
Fiber	G-652
MZM extinction ratio	20 dB
PMD	0.2 ps / $\sqrt{\text{km}}$
Accumulation chromatic dispersion	17000 ps/nm
Transmission distance	100 km

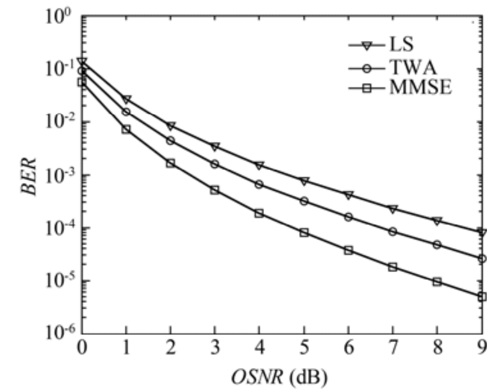


Fig.4 BERs of LS, MMSE and TWA algorithms vs. OSNR

In TA algorithm, a great deal of training sequences are used to remove random noise interference, the more training sequences used, the more accurate the channel transfer function is, whereas it also increases the redundancy of systems. In TWA algorithm, the channel characteristics are obtained through fewer training sequences. Compared with TA algorithm, the system overhead is reduced in TWA algorithm.

In order to estimate the performance of TWA algorithm, simulations are performed at OSNR of 10 dB. TWA and TA bit error rate curves with different symbol-to-pilot ratios (SPRs) are calculated in Fig.5, where SPR is the ratio of the number of data symbols to the number of pilot symbols in dB. When *SPR*=0 dB, the number of data symbols equals the number of pilot symbols. When *SPR*=3 dB, the number of data symbols is twice as big as the number of pilot symbols. As can be seen in Fig.5, with SPR is decreasing, the BERs of TWA and TA algorithms are both reduced, but under the same SPR, the BER of TWA is lower than that of TA. In terms of bit error rate, in order to get the same BER performance, TWA algorithm requires lower SPR, namely, requires less pilots.

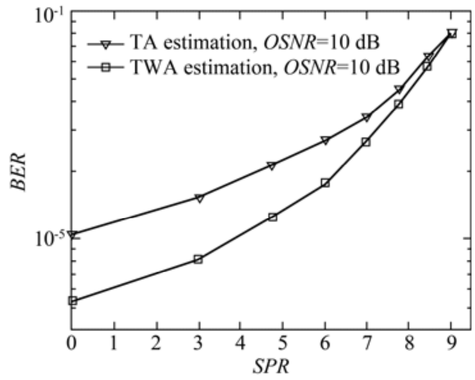


Fig.5 TWA and TA bit error rate curves with different SPRs

In this letter, we have presented an efficient TWA algorithm for CO-OFDM system. TWA and TA algorithms are both based on LS estimator, and TWA algorithm has an improvement compared with TA. There are two advantages in TWA algorithm: one is that BER is lower than that of TA and LS algorithms, and the other is that the efficiency is higher relative to TA. On the other hand, TWA algorithm has a disadvantage that computation complexity is slightly larger compared with TA, but all the additional operations are numerical computations. This numerical computation can be solved easily by DSP at present. So it is worthy of doing some calculations to get a lower BER and higher efficiency.

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