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Timing Offset Estimation Method for DD-OOFDM Systems Based on Optimization of Training Symbol

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Abstract: We have theoretically and experimentally investigated the timing offset estimation methods based on training symbol with three different structures (Two-segments, Four-segments and Eight-segments) in direct-detection (DD) optical orthogonal frequency division multiplexing (OOFDM) systems. The performance of the proposed method is evaluated in terms of mean and mean-square error (MSE) of timing offset estimation in one experimental system with 4 Gbits sec^{-1} DD-OOFDM signal transmission over 100 km standard Single Mode Fiber (SMF). The experimental results show that the two-segments timing offset estimation method has smaller MSE than the other methods and achieves higher acquisition probability of timing synchronization in DD-OOFDM transmission system.

Key words: Orthogonal frequency division multiplexing, training symbol, direct-detection, timing offset estimation, acquisition probability

INTRODUCTION

Optical Orthogonal Frequency Division Multiplexing (OOFDM) has been proposed as a promising technology to significantly improve the optical transmission system performance due to its high spectral efficiency and good resistance to the chromatic dispersion (CD) (Armstrong, 2009; Cao *et al*., 2010). Timing synchronization is one of the major research topics in OFDM systems since its sensitivity to symbol timing offset and carrier frequency offset (Pollet *et al*., 1995). The realization of high-speed OOFDM synchronization with excellent accuracy is extremely vital for implementation of the OOFDM technique in cost-effective, next-generation, high-capacity transmission systems (Giddings and Tang, 2011).

Several approaches have been proposed to estimate time and frequency offset either jointly or individually in the wireless communication systems (Moose, 1994; Schmidl and Cox, 1997; Van de Beek *et al*., 1997; Kim *et al*., 1999; Minn *et al*., 2000; Park *et al*., 2003). In these approaches, the synchronization signal is achieved by correlating samples one or half a training symbol apart. Timing synchronization is achieved when the amplitude of the correlated output exceeds a certain threshold. Compared with other methods (Moose, 1994; Schmidl and Cox, 1997; Van de Beek *et al*., 1997; Kim *et al*., 1999; Minn *et al*., 2000), Park's method (Park *et al*., 2003) can achieve the best timing synchronization performance in the wireless channel. (Hao *et al*., 2009) have demonstrated that Park's method was not suitable for the non-coherent OOFDM systems. The main reasons are that only real valued signal is transmitted in DD-OOFDM systems and the conjugate symmetric property of Park's training symbol is destroyed. Besides, there exists the Fiber channel non-linearity and its intricate interaction with fiber dispersion in optical fiber, which are nonexistent in the wireless systems.

In this study, we presented a modified method by using non-conjugate symmetric training symbol which is more suitable for optical fiber channel and experimentally investigate timing synchronization methods based on training symbols. According to the period of sub-sequence, the training symbol is divided into two segments, four segments and eight segments respectively. The experimental results demonstrate that the timing offset estimation method with the 2-segments training symbol can obtain the best performance of timing synchronization.

DD-OOFDM PRINCIPLE

Figure 1 shows the principle of Intensity Modulation (IM) DD-OOFDM transmission system. The

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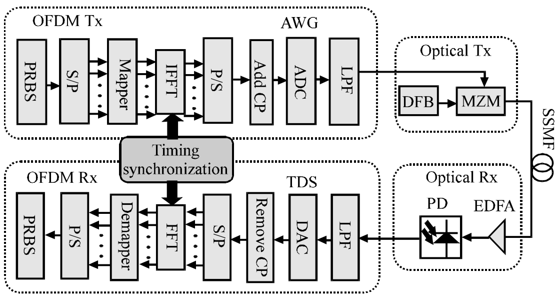

Fig. 1: Principle of DD-OOFDM transmission system. Tx: Transmitter, LPF: Low-pass filter, Rx: Receiver

pseudorandom binary sequence (PRBS) bits are changed to OFDM baseband signal through OFDM modulation as shown in the OFDM transmitter (Tx) in Fig. 1. The OFDM modulation contains serial-to-parallel (S/P) conversion, QPSK modulation, pilot insertion, inverse fast Fourier transform (IFFT), parallel-to-serial conversion (P/S) and adding Circle Prefix (CP). The digital data sequence is converted to an analogue electrical signal waveform by an Arbitrary Waveform Generator (AWG) serving as a digital to analogue converter (DAC). The electrical baseband OFDM signal is directly modulated on optical carrier. After transmission over standard single-mode fiber (SSMF), the OOFDM signal is converted to a baseband OFDM electrical signal after detection by a photodiode (PD). The received electrical signal is then sampled by a real-time oscilloscope and is processed off-line for demodulation which is the inverse of the transmitter.

COMPARISON OF OFDM TIMING SYNCHRONIZATION METHODS

OFDM systems are much more sensitive to synchronization errors than single carrier systems (Gudmundson and Anderson, 1996). The goal of OFDM timing synchronization is to find the start of the symbol. According to the characteristics of OOFDM systems using IM/DD, we proposed a new training symbol with centrosymmetric structure. We use a training symbol for timing offset estimation. The training symbol P with length N is composed of real valued sub-sequences A and B. According to the period of the sub-sequences, we divided the training symbol into three types as Two-segments, Four-segments and Eight-segments training symbol. Following, we briefly describe the timing synchronization methods using these training symbols.

Two-segments method: The form of the time-domain training symbol is as follows:

$$P_{Two} = [A_{N/2}\ B_{N/2}]$$

where, $A_{N/2}$ represents samples of length N/2 and $B_{N/2}$ is designed to be symmetric with $A_{N/2}$. This symbol patter can be easily obtained by using the properties of IFFT.

The timing offset estimator finds the starting point of the symbol at the maximum point of the timing metric given by:

$$M_{Two}(d) = \frac{|P_1(d)|^2}{(R_1(d))^2} \quad (1)$$

Where:

$$P_1(d) = \sum_{n=0}^{N/2-1} r^*(d+n)\, r(d-n) \quad (2)$$

$$R_1(d) = \frac{1}{2}\sum_{n=0}^{N/2-1}\left[|r(d+n)|^2 + |r(d-n)|^2\right] \quad (3)$$

The P_1 (d) is designed so that there are different pairs of product between two adjacent values. It has its maximum different pairs of product. Therefore, the proposed timing metric has its peak value at the correct symbol timing points, while the values are almost zero at other positions.

Four-segments method: The training symbol has the following form:

$$P_{Four} = [A_{N/4}\ B_{N/4}\ A_{N/4}\ B_{N/4}]$$

where, $A_{N/4}$ represents a PN sequence of length N/4 and $B_{N/4}$ is symmetric with $A_{N/4}$. Similar with the Two-segments algorithm, we defined timing metric as follows:

$$M_{Four}(d) = \frac{|p_2(d)|^2}{R_2^{\,2}(d)} \quad (4)$$

Where:

$$P_2(d) = \sum_{n=0}^{N/2-1} r^*(d+n)\, r(d-n) \quad (5)$$

$$R_2(d) = \sum_{n=0}^{N/4-1}\left[|r(d+n)|^2 + \left|r(d+n+\frac{N}{4})\right|^2\right] \quad (6)$$

Eight-segments method: The Eight-segments training symbol is designed to be of the form:

$$P_{Eight} = [A_{N/8}\ B_{N/8}\ A_{N/8}\ B_{N/8}\ A_{N/8}\ B_{N/8}\ A_{N/8}\ B_{N/8}]$$

where, $A_{N/8}$ represents samples of length N/8, generated by IFFT of a PN sequence and $B_{N/8}$ is designed to be symmetric with $A_{N/8}$.

To make use of the property that $A_{N/8}$ is symmetric with $B_{N/8}$, we defined the timing metric as follows:

$$M_{Eight}(d) = \frac{|p_3(d)|^2}{R_3^2(d)} \quad (7)$$

Where:

$$P_3(d) = \sum_{n=0}^{N/2-1} r^*(d+n)\, r(d-n) \quad (8)$$

$$R_3(d) = 2\sum_{n=0}^{N/8-1}\left[|r(d+n)|^2 + \left|r(d+n+\frac{N}{8})\right|^2\right] \quad (9)$$

From the timing metric we can obtains that the Eight-segments synchronization method will leads to some uncertainty due to the existence of CP.

EXPERIMENTAL SETUP

Figure 2 shows the experimental setup for DD-OOFDM system. In this experiment, the number of OFDM subcarriers is 256 while the subcarriers used for data, pilots and guard intervals are 192, 8 and 56, respectively. The CP is 1/8 of an OFDM period which would be 32 samples in every OFDM frame. QPSK modulation scheme is employed for subcarriers modulation scheme. The OFDM modulation of the digital data is implemented offline using MATLAB program. The required analog electrical signals to be transmitted are generated by a Tektronix AWG. The bit rate in our experiment is 4 Gb sec^{-1}. The CW lightwave with the output power of 7 dBm is generated from a commercial distributed-feedback (DFB) laser at 1543.52 nm and then is modulated by analog electrical OFDM signals to generate the OOFDM signal by an optical intensity modulator. The optical OFDM signal is amplified to 8.3 dBm by one EDFA before transmission. After transmission over 100 km SMF-28, the optical signal is preamplifier by the anther EDFA to 6.3 dBm and then filtered by a 1 nm bandwidth optical band-pass filter. At the receiver, the optical OFDM signal gets optical-to-electrical (O/E) conversion via a commercial optical receiver of HP83433 which is the type of PIN with a 3-dB bandwidth of 10 GHz. The power of the detected optical signal can be changed with a tunable attenuator (ATT). The converted electrical OFDM signal is sampled by the Tektronix real-time oscilloscope and stored for processing off-line in MATLAB.

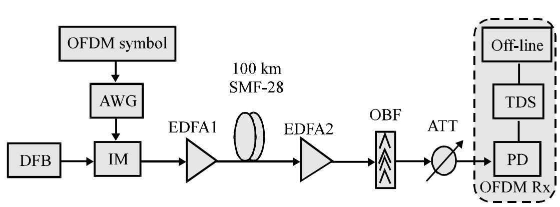

Fig. 2: Experimental setup of DD-OOFDM transmission system, EDFA: Erbium-doped optical fiber amplifier, OBF: Optical band-pass filter, ATT: Attenuator, TDS: Real-time storage oscilloscope, Off-line: Off-line process in MATLAB

EXPERIMENTAL RESULTS

The performance of the proposed timing estimator is evaluated by mean and MSE. The measured means and MSE curves versus the received optical signal power are shown in Fig. 3 and 4. We compared the means and variances for the timing offset estimators after 100 km SMF-28 transmission.

We can see from the mean and MSE curve in Fig. 3 and 4 that the Two-segments timing offset estimator has much smaller mean and MSE than the other estimators when the receiving power is low.

We took 400 times tests in each receiving power points, then recorded the correct number of timing synchronization. Figure 5 shows the probability of obtaining accurate timing offset estimation after 100 km SMF transmission. It is clearly shown that the acquisition probability of the Two-segments method is 100% when

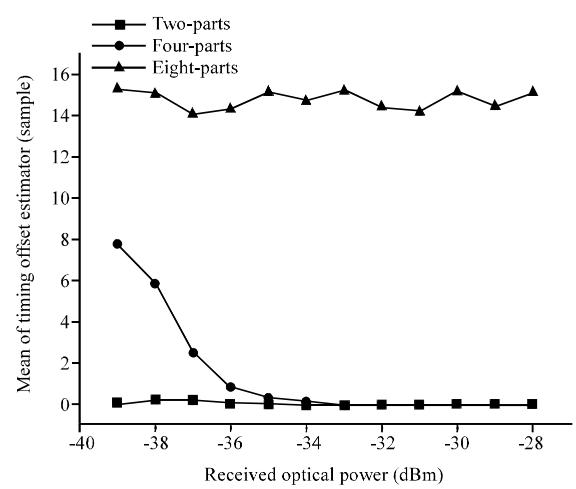

Fig. 3: Mean of timing offset estimators vs. the received power after transmission over 100 km SMF-28

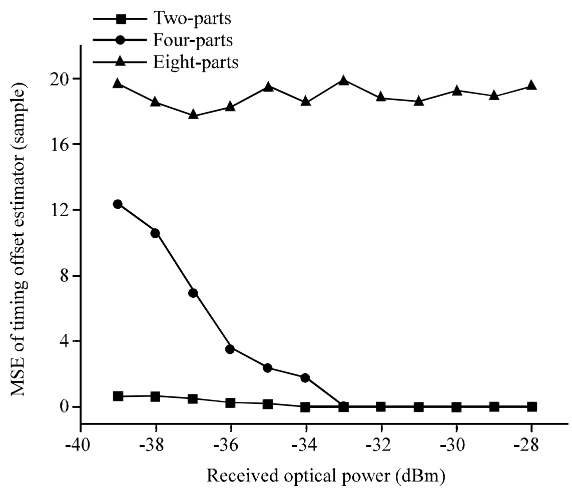

Fig. 4: MSE of timing offset estimators vs. the received power after transmission over 100 km SMF-28

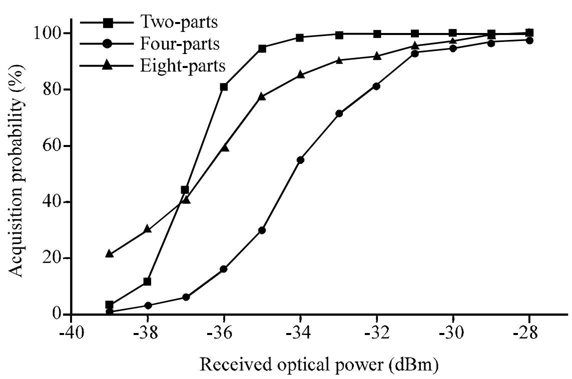

Fig. 5: Curves of acquisition probability of timing synchronization vs. the received power after transmission over 100 km SMF-28

the receiving power is larger than 33 dB and it's acquisition probability is higher than the other two methods though it will drop with the decreasing receiving power.

CONCLUSION

We have theoretically and experimentally investigated timing synchronization methods based on training symbol with different symmetrical structure in DD-OOFDM system. The experimental results show that the timing synchronization method which divided the training symbol into two segments makes it possible to estimate symbol timing offset with much smaller mean and MSE. The Two-segments estimator is suitable for the timing synchronization of DD-OOFDM systems due to its higher timing offset estimation accuracy and acquisition probability.

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