An OFDM Timing Synchronization Method Based on Averaging the Correlations of Preamble Symbol

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Abstract. In this paper, we propose a novel timing synchronization method for orthogonal frequency division multiplexing (OFDM) systems with a single-symbol preamble. The proposed method has an impulsive timing metric and outperforms the conventional methods in multipath fading channels by averaging M_0 differential correlations of the preamble. Using this method, the system will achieve accurate timing synchronization and keep low out-of-band radiation. Performances of the proposed estimator with different M_0 values are evaluated in terms of bias and mean square error (MSE). Simulation results validate the effectiveness of the proposed timing synchronization method.

Keywords: OFDM · Timing synchronization · Differential correlation

1 Introduction

Orthogonal frequency division multiplexing (OFDM) technique has received much attention in the last decade owing to its effective transmission capability and robustness over multipath fading channels. Currently, OFDM is employed intensively in various satellite and mobile communication systems, such as digital video broadcasting-Satellite to Handheld systems (DVB-SH) [1, 2], and wireless local area network (WLAN) systems [3].

The principal weakness of OFDM is its sensitivity to carrier and frequency offsets. OFDM exhibits some tolerance to timing offsets when the guard interval length is longer than the maximum channel delay spread. However, when the timing error positions the fast Fourier transform (FFT) window to include samples of either preceding or succeeding symbols, it will result in inter-symbol interference (ISI). Several timing offset estimation schemes for OFDM systems have been investigated in [4–8]. The conventional OFDM timing synchronization methods can be divided into four categories [4]: those that use the periodic structure of cyclic prefix (CP), those that utilize null subcarriers, those that take the advantage of the special structure of preamble symbols, and those that use a preamble symbol but work independent of its structure.

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Schmidl proposed using the autocorrelation of a preamble containing two repetitive patterns to estimate timing offset in the time-domain [5]. However, the timing metric plateau inherent in this method leads to a large variance of the timing estimate. Minn presented two methods as modifications to Schmidl's method to avoid the timing metric plateau [6]. Minn's methods achieve a smaller estimator variance than that of Schmidl's method. In [7], for having an impulse-like timing metric, Ren multiplied the constant envelop preamble containing two identical parts by a pseudo-random noise (PN) sequence. Exploiting the differential cross-correlation of a randomized sequence [8], Ren's method improves the accuracy of the timing offset estimator and achieves a smaller MSE than that of Minn's method. It is noted that the weighted preamble will increase the out-of-band radiation of OFDM signals and produce interference to the adjacent band users.

Considering those above problems in the literature, we propose a novel timing synchronization method in the time-domain for the OFDM system with a single-symbol preamble. Performance of the proposed estimator is evaluated in terms of bias and MSE. Computer simulations are employed to validate the effectiveness of the proposed timing method.

2 System Model and Timing Synchronization

In this section, we describe briefly an OFDM system and then analyze the advantages and weaknesses of conventional timing synchronization methods. Thereby, the motivation of the novel timing synchronization is drawn.

2.1 OFDM System Model

In the OFDM system, the samples of complex-valued baseband OFDM symbol in the time-domain can be expressed by

$$x_i(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N_u-1} X_i(k) \cdot e^{j2\pi nk/N}, \quad n = -N_g, \ \cdots, \ N-1, \tag{1}$$

where $x_i(n)$ denotes the ith OFDM symbol, $X_i(k)$ represents the data sequence modulated on the kth subcarrier, which may assume any modulation format such as quadrature amplitude modulation (QAM) or quadratic phase-shift keying (QPSK), N is the size of inverse fast Fourier transform (IFFT) with N_u active subcarriers, and N_g is the CP length.

In the OFDM digital transmitter, firstly, the preamble sequence is inserted into the channel-coded data according to the frame structure. Then, an OFDM signal is generated by taking the IFFT of QAM or PSK symbols and it is preceded by a cyclic prefix that is longer than the channel impulse response. Due to the equivalent rectangular pulse shaping in modulation, OFDM has high levels of out-of-band (OOB) radiation [9]. In order to make the amplitude go smoothly to zero at the symbol boundaries, windowing is often applied to individual OFDM symbols [10],

$$\bar{x}_i(n) = \begin{cases} c_1(n+N_g)\cdot x_i(n) + x_{i-1}(n+N_g)\cdot c_2\,(n+N_g)\,, & -N_g \le n < -N_g + \alpha N \\ x_i(n)\,, & -N_g + \alpha N \le n \le N-1 \end{cases}, \tag{2}$$

where $c_1(n)$, $c_2(n)$ represents respectively the prefix and postfix coefficients of window function. The raised-cosine window is usually employed and expressed by

$$c_1(n) = 0.5 + 0.5\cos\left(\pi + \frac{n\pi}{\alpha N}\right),\ c_2(n) = 0.5 + 0.5\cos\left(\frac{n\pi}{\alpha N}\right), \tag{3}$$

where α is the roll-off factor of the raised-cosine window.

In the OFDM digital receiver, after removing the cyclic prefix, the nth sample of the received OFDM baseband signal $r(n)$ [11] is given by

$$r(n) = y(n-\varepsilon)e^{j(2\pi vn/N)} + w(n) = \sum_{m=0}^{L-1} h(m)x(n-\varepsilon-m)e^{j(2\pi vn/N)} + w(n), \tag{4}$$

where ε represents the integer-valued unknown arrival time of a symbol, v represents the frequency offset normalized by the subcarrier spacing, $h(m)$ is the channel impulse response whose memory order is L-1, and $w(n)$ is the zero-mean complex additive white Gaussian noise (AWGN).

2.2 Timing Synchronization

Schmidl proposed a preamble-aided timing synchronization method [5]. Ren presented a synchronization method based on a constant envelope preamble [7]. We briefly describe these two methods as follows.

A. Schmidl's Method. Schmidl exploits a preamble containing two identical halves in the time-domain, and the form of preamble is described as

$$a_1 = [A_{N/2}\,A_{N/2}], \tag{5}$$

where $A_{N/2}$ represents a random sequence consisting of $N/2$ samples in the time-domain. Schmidl's preamble can be generated via direct repetition of a suitable pseudo-noise (PN) sequence in the time-domain or an IFFT of the odd-numbered subcarriers in the frequency-domain. This method estimates the starting point of the received signal at the maximum point of the timing metric given by

$$M_1(d) = \frac{|P_1(d)|^2}{(R_1(d))^2}, \tag{6}$$

where

$$P_1(d) = \sum_{n=0}^{N/2-1} r^*(d+n) \cdot r(d+n+N/2), \tag{7}$$

$$R_1(d) = \sum_{n=0}^{N/2-1} |r(d+n+N/2)|^2, \tag{8}$$

where $r^*(n)$ represents the complex conjugate of the received OFDM signal $r(n)$. The timing offset of Schmidl's method can be estimated from

$$\hat{\varepsilon}_1 = \arg\max_d \left(M_1(d)\right). \tag{9}$$

B. Ren's Method. The timing metric of Schmidl's method suffers from a plateau which has a length equal to the length of the guard interval minus the length of the channel impulse response in frequency selective channel. In order to reduce some uncertainty of the timing estimate, Ren proposed a timing offset estimation method with a scrambled preamble weighted by PN sequence, which can be defined as

$$x'(n) = s(n) \cdot x(n),\ n = 0, \cdots, N-1, \tag{10}$$

where $s(n)$ represents the PN sequence weighted factor of the nth sample of the original preamble and the value is $+1$ or -1. The timing metric in [7] is defined as

$$M_2(d) = \frac{|P_2(d)|^2}{\left(R_2(d)\right)^2}, \tag{11}$$

where

$$P_2(d) = \sum_{n=0}^{N/2-1} s(n) \cdot s(n+N/2) \cdot r^*(d+n) \cdot r(d+n+N/2), \tag{12}$$

$$R_2(d) = \frac{1}{2}\sum_{n=0}^{N-1} |r(d+n)|^2. \tag{13}$$

The timing offset of Ren's method can be estimated from

$$\hat{\varepsilon}_2 = \arg\max_d \left(M_2(d)\right). \tag{14}$$

The timing metric of Ren's method has an impulsive shape only at the exact timing point [7]. Therefore, Ren's method eliminates the plateau of Schmidl's method under the same channel condition, and achieves a smaller MSE than Schmidl's estimator (9). However, the preamble weighted by PN sequence will lead to high levels of out-of-band radiation, as illustrated by the simulation results in Fig. 1. In the following section, we will address this problem and develop a novel timing synchronization method.

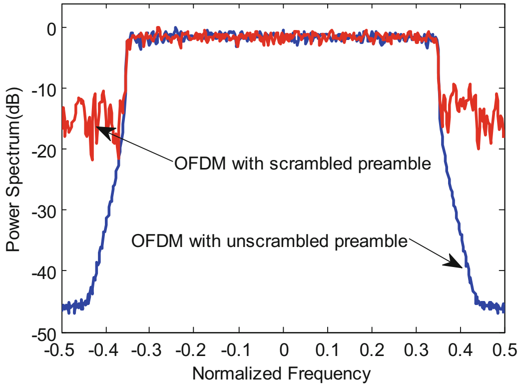

Fig. 1. Power spectrum of OFDM signals with the scrambled/unscrambled preamble

3 Correlation-Based Timing Synchronization

In this section, we will propose a timing synchronization method which works independent of the preamble structure in the time-domain and discuss a frequency offset estimator when the proposed timing method is used.

3.1 Proposed Timing Synchronization Method

Considering that the preamble $x_i(n) = a(n)$ is known at the OFDM receiver, we can make full use of the characteristics of the correlation to eliminate the modulation information of the preamble. We multiply the samples of the received signal $r(n)$ by the samples of the known preamble $a(n)$, which can be described as

$$r_0(n,d) = r(n+d)a^*(n) \ , n = 0, 1, \cdots, N-1, \tag{15}$$

where d is the timing index corresponding to the first sample in a window of N samples. Then, define the differential correlation function of $r_0(n, d)$ as

$$p(m,d) = \sum_{k=m}^{N-1} r_0(k,d) \cdot r_0^*(k-m,d) \, , \ m = 1, \cdots, M_0 \, , \tag{16}$$

where N-m is the number of summation items in the differential correlation function, and M_0 is an adjustable parameter, which should be carefully evaluated. For $M_0 = 1$, a single-lag differential correlation function can be directly used to produce the timing metric. For $M_0 > 1$, M_0 differential correlation values can be summed together with different weighted factors. Therefore, we derive a reasonable solution with their weights as

$$P(d) = \sum_{m=1}^{M_0} \frac{(N-m) \cdot |p(m,d)|}{M_0 N - M_0(1+M_0)/2}. \tag{17}$$

For simplicity, when M_0 is small, we suggest averaging M_0 differential correlation values, that is, each of weighted factors equal to $1/M_{0.}$ The corresponding timing metric of the proposed method is derived as

$$M(d) = \frac{P(d)^2}{(R(d))^2}, \tag{18}$$

where

$$P(d) = \frac{1}{M_0} \sum_{m=1}^{M_0} |p(m,d)| = \frac{1}{M_0} \sum_{m=1}^{M_0} \left| \sum_{k=m}^{N-1} r_0(k,d) \cdot r_0^*(k-m,d) \right|, \tag{19}$$

$$R(d) = \sum_{n=0}^{N-1} |r(n+d)|^2. \tag{20}$$

The timing offset of proposed method can be estimated from

$$\hat{\varepsilon} = \arg\max_d (M(d)). \tag{21}$$

3.2 Timing Metric with Different Preambles

The timing metric proposed in (19) for OFDM systems will be examined with two different preamble structures: (1) preamble-1 is a single symbol preamble with no repetitive patterns; (2) preamble-2 is a particular preamble containing two identical halves, which can be generated in the frequency-domain by mapping a PSK PN sequence to the odd numbered subcarriers. For the OFDM system, we assume using $N = 256$ subcarriers and the signal-to-noise ratio being SNR = 10 dB in AWGN channel.

In Fig. 2, we can find that, for the larger value of M_0 (e.g. $M_0 = 5$), the noise of the timing metric will get smaller for both kinds of preambles. There is a major peak in the middle at the starting point of the preamble corresponding to a full-symbol pattern match. However, for the preamble-2 with repetitive structure, besides this major peak, there are two minor peaks at the $N/2$ samples left and right corresponding to a half-symbol pattern match. In complicated wireless transmission channel, the values of the minor peaks may exceed the major peak, which will result in a large timing error.

An alternative solution is to employ a window function. The autocorrelation metric (6) of the preamble is a feasible window [8]. Therefore, we take the product of the window (6) and the proposed timing metric (18) as the modified timing metric for timing offset estimate, that is, the timing offset can be estimated from

$$\hat{\varepsilon} = \arg\max_d \left(M(d) \cdot M_1(d)\right). \tag{22}$$

After the timing synchronization, the starting point of the received signal can be determined. In the next section, we will discuss the frequency synchronization when the proposed timing synchronization method is employed in OFDM digital receiver.

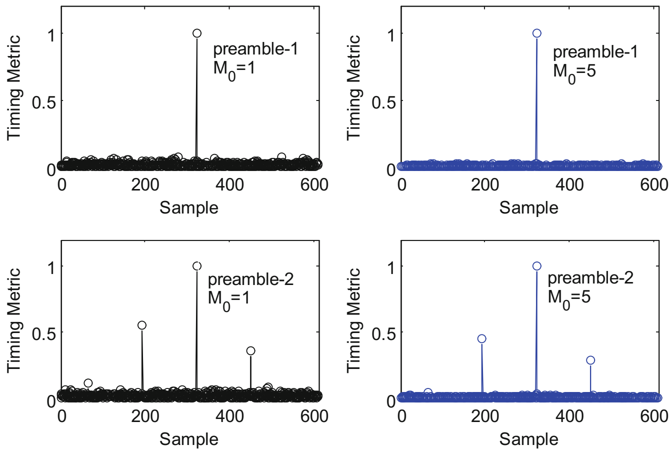

Fig. 2. The timing metric for the proposed method

3.3 Corresponding Frequency Estimation

Similar to the frequency synchronization in [7], the frequency offset v is divided into fractional part q and integer part ξ, $v = q + \xi$. In order to estimate the frequency offset, the preamble containing two identical halves (5) is exploited. The fractional frequency offset estimation is given as

$$\hat{\xi} = \frac{1}{\pi} angle\left(\sum_{n=0}^{N/2-1} r^*(\varepsilon + n) \cdot r(\varepsilon + n + N/2) \right). \tag{23}$$

After compensating the fractional frequency offset of the preamble signal, we multiply the received preamble by $a_1{}^*(n)$ in (5) as

$$r_1(n) = r(n) \cdot \exp\left[-j\left(2\pi\hat{\xi}n/N\right)\right] \cdot a_1^*(n). \tag{24}$$

The integer frequency offset is then estimated by

$$\hat{q} = \arg\max_q \left(\Gamma(q)\right), \tag{25}$$

where

$$\Gamma(q) = \left| \sum_{n=0}^{N-1} r_1(n) \cdot e^{-j2\pi qn/N} \right|^2, \ q = -\frac{N}{2}, \ \cdots, \ \frac{N}{2}. \tag{26}$$

Therefore, the total frequency offset estimate can be estimated as

$$\hat{v} = \hat{q} + \hat{\xi}. \tag{27}$$

As shown in (26), the range of the frequency offset estimation method in (27) is $\pm N/2$. The accuracy of different timing estimation methods (9), (14) and (22) will affect the succeeding frequency estimation in (23)–(27). In the following section, the performance of timing synchronization will be studied, whereas that of frequency estimation still keeps with the results in [7].

4 Simulation Results and Discussions

In this section, we will investigate the performance of the proposed timing estimation method in terms of bias and MSE by simulations. The results are further compared with those of the conventional methods.

These estimators work in the OFDM system with QPSK modulation, $N_u = 180$ active subcarriers, $N = 256$ size of IFFT/FFT, and $N_g = 32$ samples of cyclic prefix. The OFDM system bandwidth is 3 MHz, and the subcarrier spacing is 15 kHz. The channel conditions are described in the following. The Rayleigh fading channel has an exponential power delay profile given by $A_i = e^{-(i/3)}$. In our simulation, the corresponding time delays of a multipath channel with 6 taps are set as [0 0.333 0.667 1.0 1.333 1.667] μs. A normalized carrier frequency offset of $v = 1.2$ is considered, and 10000 simulation runs are applied.

Figure 3 shows the estimation means of the timing offset, which reflect the bias of timing estimates. It can be found that both of the proposed method (22) and Ren's method (14) have smaller bias values than those of Schmidl's method. Furthermore, adopting different M_0 values for the differential correlations, the proposed method (22) achieves approximate estimation bias values. For example, for $M_0 = 3, 8$, as given in Fig. 3, the proposed method (22) achieves much smaller bias values than those of Ren's methods for SNR < 10 dB.

Figure 4 illustrates the MSE performance of timing offset estimation. We find that both of the proposed method and Ren's method outperform Schmidl's method. And the proposed method will achieve better MSE performance for increasing M_0 especially at low SNRs. What's more, for $M_0 \geq 2$, the MSEs of the proposed method are smaller than those of Ren's method for SNR < 10 dB, whereas their MSEs get tight for SNR ≥ 10 dB.

It is noted that the performance improvements become tiny for $M_0 \geq 3$, whereas the computational complexity will grow continuously. Therefore, in practical OFDM system, the parameter M_0 should make a compromise between estimation performance and implementation complexity and $M_0 = 1, 2, 3$ are recommended here.

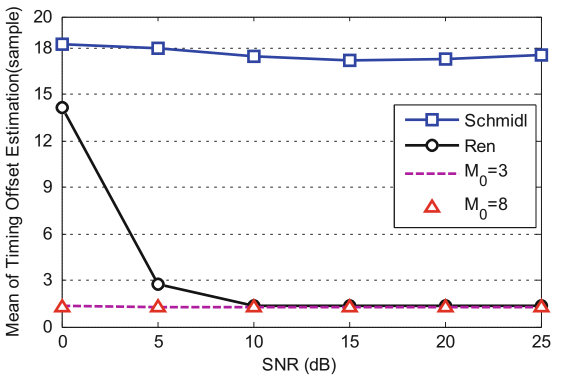

Fig. 3. Mean of timing offset estimate in a Rayleigh fading channel

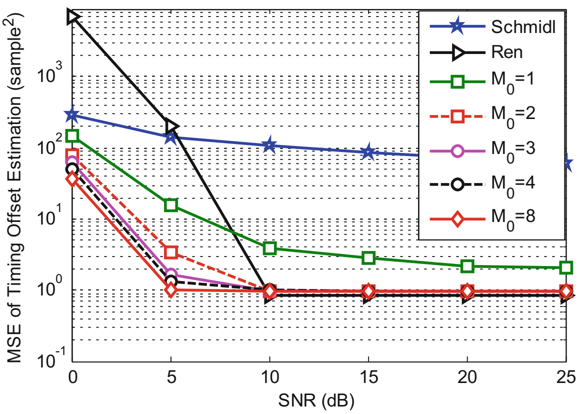

Fig. 4. MSE of timing offset estimate in a Rayleigh fading channel

5 Conclusions

In this paper, we firstly describe an OFDM system and then analyze the advantages and weaknesses of conventional timing synchronization methods. Then, we propose a novel timing synchronization method in the time-domain for OFDM systems with a single-symbol preamble. The proposed timing synchronization method has an impulse-shaped timing metric and outperforms the conventional methods in multi-path fading channels by averaging the M_0 differential correlations of a conjugate structure preamble. Furthermore, performances of the proposed estimator are evaluated by simulations in terms of bias and MSE. This work may be helpful for designing OFDM wireless transceivers.

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