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A NOVEL SYNCHRONIZATION METHOD BASED ON TRAINING SEQUENCE FOR OFDM SYSTEMS

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Abstract. *In this paper, a new training sequence structure is designed and a novel synchronization method is proposed for OFDM systems, which aim to overcome fuzzy timing problem in the low SNR environment and the low precision of frequency synchronization. The proposed method can achieve accurate timing according to the conjugate property of training sequence sampling points in the time domain. Then, fractional frequency offset (FFO) can be estimated by the phase angle of training sequence in the time domain, and integer frequency offset (IFO) can be estimated in the frequency domain. Theoretical analysis and simulation results show that the symbol timing synchronization algorithm can achieve the sharp correlation peak and zero side lobe, the correct detection probability of symbol timing offset (STO) is higher in the low SNR, the correct detection probability of the IFO is higher and carrier frequency offset (CFO) estimation has good MSE performance.*
Keywords: OFDM, Training sequence, Symbol timing synchronization, Frequency synchronization, Correct detection probability

1. **Introduction.** OFDM systems are very sensitive to symbol timing offset (STO) and carrier frequency offset (CFO). STO and CFO estimation are two main synchronization operations in OFDM systems. Estimation methods can be classified into the following two categories: 1) non-data-aided/blind [1]. Blind methods exploit the periodic structure of cyclic prefix (CP) to accomplish the estimation task; 2) data-aided [2-8]. The most classic synchronization method of data-aided method is proposed by Schmidl and Cox in [2] (S&C method), S&C method uses a training sequence containing two identical halves to estimate STO and CFO; however, the CP leads to a plateau in the timing metric, which causes a large variance in STO estimation. Minn et al. proposed negative-valued samples at the second half of training sequence in [3] to eliminate the peak plateau of the timing metric, but it still has many side lobes. When estimating fractional frequency offset (FFO), the mean square error (MSE) is large. To improve the performance of timing synchronization and reduce side lobes, Park et al. proposed another modified training sequence in [4]. The timing metric of Park's method has its peak value at the correct symbol timing. However, it still has a side lobe, which will affect STO estimation. Moreover, the frequency offset estimation range of Park's method is small, and aims to correct the integer frequency offset (IFO), the even training sequence must be a geometric series, and this kind of method has high algorithm complexity. Guo et al. proposed using the real training sequence in [5], and this method can achieve timing synchronization based on the conjugate characteristic of the training sequence structure after IFFT. Since there is no repetitive structure in the training sequence, FFO can be estimated by ML method [1], and the estimation range is small. IFO estimation is obtained by calculating the maximum value of nonzero part energy of the training sequence after demodulation. The correct detection probability of the IFO estimation is low. The authors in [6-8] propose CAZAC sequence to be the

training symbols, but they all use the local sequence in the timing synchronization, so there is still a large computational complexity. In this paper, a new training sequence structure is designed, according to the conjugate characteristics of the training sequence in the time domain to achieve accurate timing. The correct detection probability of STO is higher than that of other methods, and timing is more accurate in multipath channel. Then we can obtain FFO by the phase angle of training sequence in the time domain, and IFO can be estimated in frequency domain. The CFO estimation range of the proposed method is expanded, and the proposed method has better estimation performance.

The rest of this paper is organized as follows. In Section 2, we describe the OFDM system model. In Section 3, the synchronization method is proposed and described in detail. Simulation results are presented in Section 4. Finally, conclusions are made in Section 5.

2. **System Model.** CP is used as guard interval between two consecutive OFDM symbols to understand ISI effect of the multipath channel. As shown in Figure 1, CP is to extend the OFDM symbol by copying the last samples of the OFDM symbol into its front.

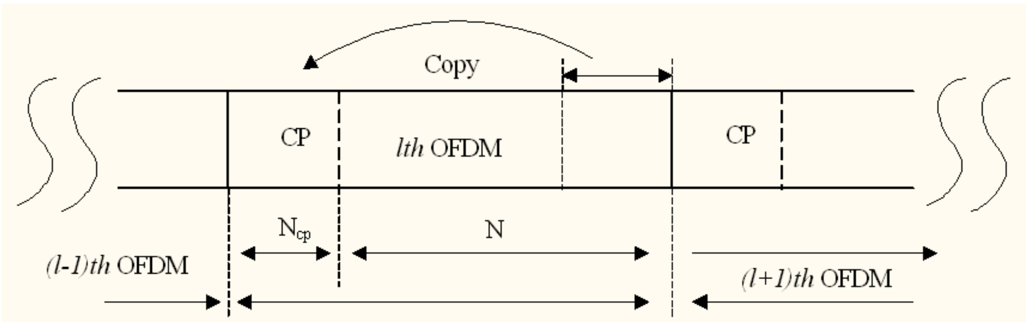


Figure 1. OFDM symbols with CP

An OFDM symbol includes lots of modulated sub-carrier synthesis signals, and each sub-carrier can be modulated by 16QAM modulation. $X[k]$ is denoted the zero-padding data constellation point in the k-th subcarrier of the OFDM symbol. $x[n]$ is denoted the time domain sample signal of the OFDM symbol. Define the transmitted signal as $x[n]$, and received signal as $y[n]$. Then the time domain transmitted signal with CP can be defined as

$$x_n = IFFT[X_k] = \frac{1}{N}\sum_{k=0}^{N-1} X_k e^{j\frac{2\pi nk}{N}}, \quad -N_{cp} \le n \le N-1 \tag{1}$$

In the following analysis, we assume that the channel is non-dispersive and that the transmitted signal $x[n]$ is only affected by complex AWGN. Consider two uncertainties in the receiver of this OFDM symbol, the uncertainty in the arrival time of the OFDM symbol and the uncertainty in carrier frequency. The first uncertainty is modeled as a delay in the channel impulse response $\delta(n-\theta)$, where θ is the integer-valued unknown arrival time of a symbol. Let f_{offset} denote their difference between the carrier frequencies in the transmitter and receiver. Let us define the normalized CFO as a ratio of the CFO to subcarrier spacing Δf, shown as $\varepsilon = f_{offset}/\Delta f$. The received signal $y[n]$ can be given by

$$y[n] = x[n-\theta]e^{2\pi j\varepsilon n/N} + w[n], \quad -N_{cp} \le n \le N-1 \tag{2}$$

Let ε_i and ε_f denote the integer part and fractional part of ε; therefore, $\varepsilon = \varepsilon_i + \varepsilon_f$. There will be the amplitude and phase distortion of the subcarrier frequency component due to ε_f. ε_i leads to the signal of $e^{j2\pi\varepsilon_i n/N}x[n]$ in the receiver. Due to the IFO, the transmit signal $X[k]$ is cyclic shifted by ε_i in the receiver, thus producing $Y[k] = X[k-\varepsilon_i]$ [9] in the k-th subcarrier.

3. **The Proposed Synchronization Method.** The goal of OFDM timing and frequency synchronization is to estimate θ and ε. To achieve accurate timing and improve the CFO estimation performance, a training sequence is designed and an STO and CFO estimation method is proposed.

3.1. **The proposed training sequence.** In the transmitter, design a new training sequence in frequency domain. Define a sequence, $C[k] = [C_1/2, C_2/2, \ldots, C_{N/2}/2, 2C_1, 2C_2, \ldots, 2C_{N/2}]$, where N is the number of subcarriers, $C_1, C_2, \ldots, C_{N/2-1}, C_{N/2}$ is a real-valued PN sequence, and the samples in second half of $C[k]$ are 4 times as much as the corresponding first half (spaced $N/2$ samples apart). So the samples of the new training sequence in frequency domain are designed to be of the form, $X[k] = C[k]e^{-j\frac{3\pi}{4}k}$. The corresponding time domain complex baseband training symbol samples are, $x_{preamble} = [x_0, x_1, \ldots, x_{N-1}]$. The training sequence as the first OFDM symbol is used to estimate the STO and CFO, to achieve synchronization. In the transmitter, the time domain training sequence structure is shown in Figure 2.

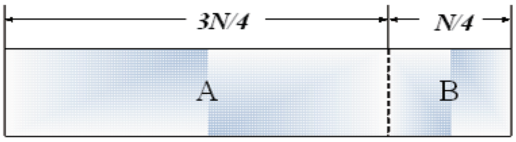


Figure 2. The structure of the training sequence in time domain

In Figure 2, N is the number of subcarriers, the length of A is $3N/4$, and the length of B is $N/4$. According to Equation (1), we can obtain

$$x\left[\frac{3}{4}N - n\right] = \frac{1}{N}\sum_{k=0}^{N-1} X[k]e^{j2\pi\left(\frac{3}{4}N-n\right)k/N} = x^*[n] \tag{3}$$

and, $x[N-n] = x^*\left[\frac{3N}{4} + n\right]$. The training symbol A shows conjugate relationship $x\left[\frac{3}{4}N - n\right] = x^*[n]$.

3.2. **The proposed STO estimation method.** In the receiver, the structure of received signal with CP is shown in Figure 3.

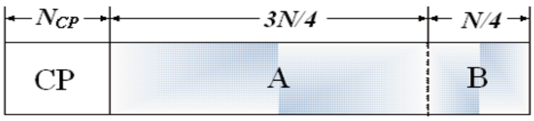


Figure 3. The structure of the training sequence with CP in time domain

In Figure 3, N_{CP} represents the length of CP samples, and $N_{CP} = N/4$. The received signal $y[n]$ can be given by

$$y[n] = x[n-\theta]e^{2\pi j\varepsilon n/N} + w[n], \quad -N_{cp} \le n \le N-1 \tag{4}$$

$$y\left[\frac{3N}{4} - n\right] = x\left[\frac{3N}{4} - n - \theta\right]e^{2\pi j\varepsilon\left(\frac{3N}{4}-n\right)/N} = e^{\frac{3}{2}\pi j\varepsilon}x\left[\frac{3N}{4} - n - \theta\right]e^{-2\pi j\varepsilon nN} \tag{5}$$

Define a function

$$P_1(d) = \sum_{n=1}^{3N/8-1} y(d+n)y\left(d + \frac{3}{4}N - n\right) \tag{6}$$

where d is a time index corresponding to the first sample in a window of $3N/4$ samples. A timing metric can be defined as

$$M(d) = \frac{|P_1(d)|^2}{(R(d))^2} \tag{7}$$

where $P_1(d) = \sum_{n=1}^{3N/8-1} y(d+n)y\left(d+\frac{3}{4}N-n\right)$, $R(d) = \sum_{n=1}^{3N/8-1} |y(d+n)|^2$. The value of the $M(d)$ is the largest in the accurate symbol start position, and the STO estimation can be obtained by

$$\hat{\theta} = \arg\max_{d} M(d) \tag{8}$$

3.3. **The proposed CFO estimation method.** Use the above method to achieve symbol timing synchronization to detect the starting point of each OFDM symbol, and FFO estimation in time domain; transform the compensated signal from the time domain to frequency domain, IFO estimation in frequency domain [9,10].

A. ***FFO estimation***

After symbol timing synchronization, FFO estimation in time domain, the structure of received signal is shown in Figure 3. There is conjugate relationship in A and B, respectively.

$$y\left[\frac{3N}{4}-n\right] = e^{\frac{3}{2}\pi j\varepsilon}y^*[n] \tag{9}$$

$$y[N-n] = e^{\frac{7}{2}\pi j\varepsilon}y^*\left[\frac{3N}{4}+n\right] \tag{10}$$

Define two auxiliary functions

$$P_1 = \sum_{n=1}^{3N/8-1} y[n]y\left[\frac{3N}{4}-n\right] = e^{\frac{3}{2}\pi j\varepsilon}\sum_{n=1}^{3N/8-1} y[n]y^*[n] \tag{11}$$

$$P_2 = \sum_{n=1}^{N/8-1} y\left[n+\frac{3N}{4}\right]y[N-n] = e^{\frac{7}{2}\pi j\varepsilon}\sum_{n=1}^{N/8-1} y\left[n+\frac{3N}{4}\right]y^*\left[n+\frac{3N}{4}\right] \tag{12}$$

The estimation of the FFO ε_f can be obtained by

$$\hat{\varepsilon}_f = \frac{1}{2\pi}angle({P_1}^*(n)P_2(n)) \tag{13}$$

The estimation range of the proposed method is only $|\hat{\varepsilon}_f| \le 0.5$; when the actual FFO $|\varepsilon_f| > 0.5$, we can get the estimated value $\hat{\varepsilon}_f = \varepsilon_f - 1$. Compensate the received signal with the estimation of the CFO $\hat{\varepsilon}_f$, $y_c(n) = y(n)e^{-j2\pi\hat{\varepsilon}_f n/N}$. When the actual FFO exceeds the estimated range, it can be corrected by the IFO estimation in frequency domain.

B. ***IFO estimation***

After FFO estimation and compensation, the received signal has only IFO. The received signal with ε_i can be given by $y_{\varepsilon_i} = e^{j2\pi\varepsilon_i n/N}x[n]$. After FFT, due to the IFO, the transmit signal $X[k]$ is cyclic shifted by ε_i in the receiver, $Y[k] = X[k-\varepsilon_i]$. We can get

$$Y[k] = X[k-\varepsilon_i] = C[k-\varepsilon_i]e^{-j\frac{3\pi}{4}k}e^{j\frac{3\pi}{4}\varepsilon_i} \tag{14}$$

Multiply the demodulation signal $Y[k]$ by factor $e^{j\frac{3\pi}{4}k}$, it can be simplified as $Y'[k] = C[k-\varepsilon_i]e^{j\frac{3\pi}{4}\varepsilon_i}$, and $e^{j\frac{3\pi}{4}\varepsilon_i}$ is constant value. The samples in the second half of $C[k]$ are 4 times as much as the corresponding first half (spaced $N/2$ samples apart). Cyclic shift the sequence $Y'[k]$ and get the ratio of the second half of the samples to the first half of the samples (spaced $N/2$ samples apart). When the value of the ratio multiplication is the largest, the position of the shift number is the IFO

$$\hat{\varepsilon}_i = \arg\max_d \left\{ \prod_{k=d}^{d+N/2-1} [Y'(k+N/2)/Y'(k)] \right\} \tag{15}$$

$Y[k]$ is the cyclic-shift of $X[k]$; therefore, $X[k]$ cyclic shift left ε_i and cyclic shift right $X[N-\varepsilon_i]$ have the same effect, and the IFO estimation range is $|\hat{\varepsilon}_i| \leq N/2$. Comprehending the range of FFO estimation, the range of CFO estimation for the proposed method is $|\hat{\varepsilon}| \leq N/2$.

4. **Simulation Results.** The performance of the proposed method is investigated by the computer simulation under the AWGN channel and the multipath channel. The OFDM parameters used here are 256 subcarriers with 64 cyclic prefix, and modulation is 16QAM. Figure 4 shows the comparison of the timing metric of different algorithms in the AWGN channel and SNR = 20dB.

As shown in Figure 4, Minn method can prevent the peak plateau of the timing estimation effectively, but it produces a lot of side lobes which will affect correct timing. Park and Guo methods are similar to reducing the number of side lobes, but due to the influence of CP, there still will be a side lobe, and it will affect the timing in low SNR. The proposed method has removed the effect of CP and achieved accurate timing.

Figure 5 is the comparison of correct detection probability of STO estimations in multipath channel. As shown in Figure 5, the correct detection probability of the proposed method is higher than that of the Minn, Park and Guo methods, and timing is more accurate in multipath channel.

Figure 6 compares IFO estimation performance of the proposed method with that of the Guo methods. As shown in Figure 6, the proposed method has higher correct detection probability of IFO estimation in the low SNR, and it has better synchronization performance.

Figure 7 shows comparison of the CFO estimation range and the performance of MSE for different methods in the multipath channel and SNR = 10dB. The estimation range of the Minn method is $|\hat{\varepsilon}| \leq 2$, and MSE performance is inferior to Park method, but estimation range of Park method is only $|\hat{\varepsilon}| \leq 1$. The CFO estimation range of the proposed method is $|\hat{\varepsilon}| \leq N/2$, and the proposed method has better estimation performance.

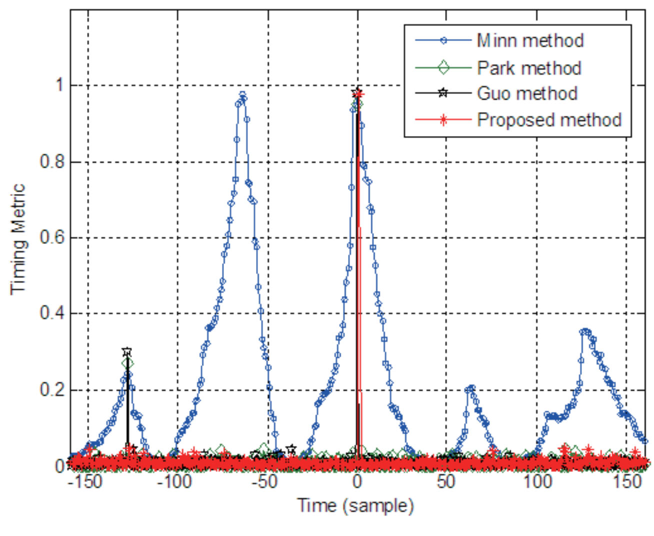


Figure 4. The timing metric of different methods

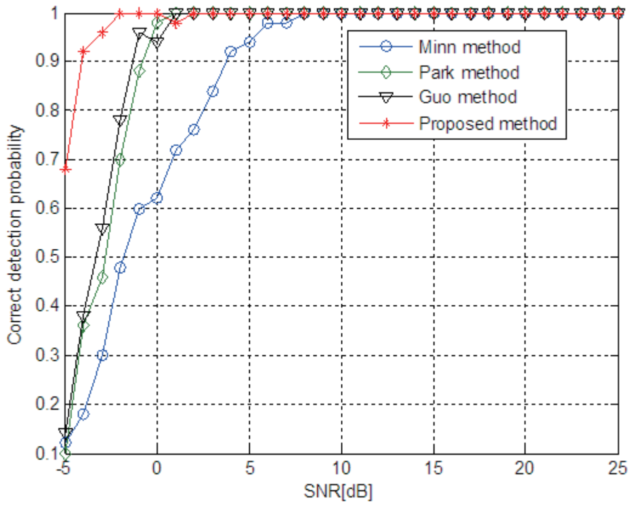


FIGURE 5. Correct detection probability

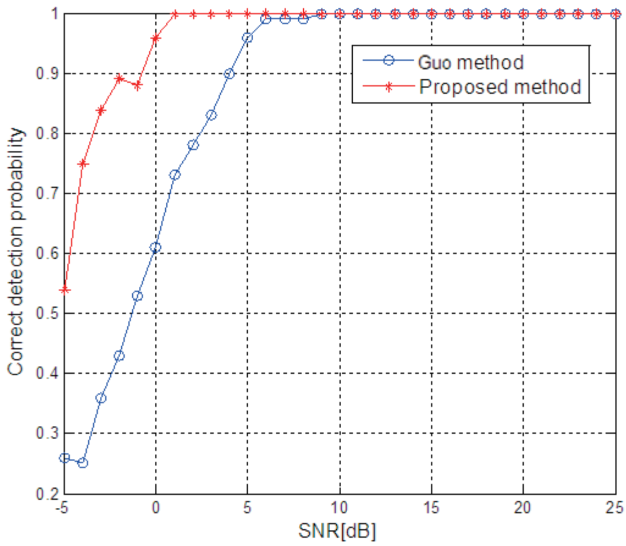


FIGURE 6. Correct detection probability

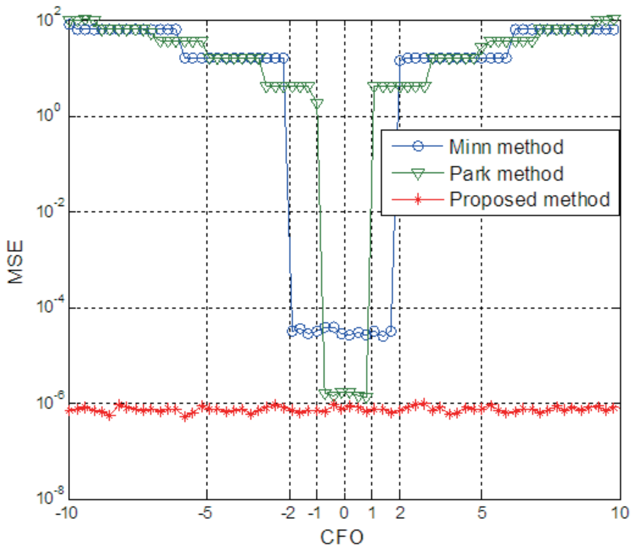
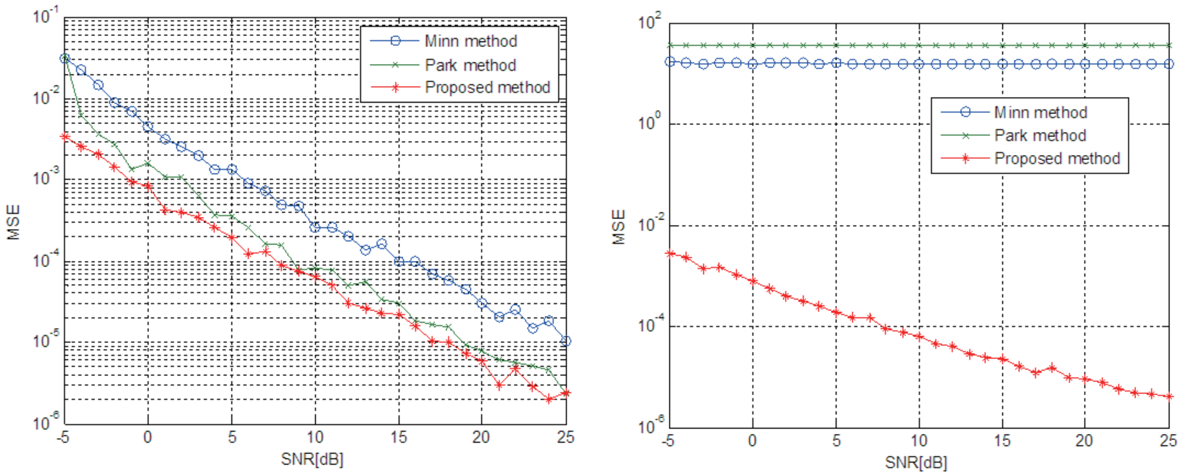


FIGURE 7. CFO estimation range and MSE



(a) CFO $\varepsilon = 0.7$ (b) CFO $\varepsilon = 5.7$

Figure 8. Comparison of the MSE with different CFO

As shown in Figure 8, it is the MSE comparison in different CFO. In Figure 8(a), $\varepsilon = 0.7$, the performance of the proposed method is better than Minn method and Park method. In Figure 8(b), $\varepsilon = 5.7$, Minn and Park methods cannot be used for CFO estimation. The proposed method still has good MSE performance.

5. **Conclusions.** This paper presents new STO estimation and CFO estimation methods for OFDM system using a training sequence. The performance of the proposed method is better than that of other methods. The timing metric of the proposed method has removed the effect of CP, and achieved zero side lobe to accurate timing in the time domain. Simulation results show that the STO estimation has a higher correct detection probability in the low SNR. FFO can be estimated in the time domain, and FFO estimation has a good MSE performance. IFO estimation can be achieved in the frequency domain, and has a higher correct detection probability than other methods. Simulation results show that the proposed method has good performance in both AWGN and multipath channel, and it is more practical.

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