Performance of Coarse Timing Synchronization in Orthogonal Frequency Division Multiplexing System

BRUNO¹,* and Zhai Xuping¹

¹Key laboratory of Specialty Fiber Optics and Optical Access Networks Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, Shanghai, China

*bruso167@gmail.com

Abstract. A novel symbol timing synchronization based on training symbols for OFDM system was designed and presented in this paper. The performance of the proposed method is tested in terms of the timing metric and mean square error (MSE), indoor no-noise, and Rayleigh fading channel, obtained by simulation. The over the air transmission of the proposed timing metric is evaluated by implementing a software defined radio based on the GNU Radio and universal software radio peripheral communication platforms. The simulation results show that the proposed timing metric indexed at the correct time point, which has smaller MSE than others methods, particularly at high signal-to-noise ratio. Therefore the proposed method works well, even in transmission through the air indoor laboratory environment.

1. Introduction
At present, orthogonal frequency division multiplexing (OFDM) has become the most popular modulation technique in wireless communication, owing to its high data rate transmission capability and high bandwidth efficiency. OFDM has been widely applied in practice, such as in digital audio broadcasting (DAB) and digital video broadcasting for terrestrial television (DVB-T) [1], [2], wireless local area network (WLANs), long-term evolution (LTE) [3], [4] and WiMAX. OFDM systems are considerably more sensitive to synchronization error due to the symbol timing and carrier frequency offset [5]-[7], which leads to the degradation of the system performance.

Different symbol timing offset estimation-based training symbols were proposed in literature. A well-known example is the Schmidl and Cox [8] method. This method uses a training symbol, which has identical halves in the time domain to estimate the symbol timing offset. However, its timing metric gives a plateau, which results in some uncertainty in determining the start of the OFDM frame. To avoid the ambiguity due to the timing metric, Minn et al. [9] modified the Schmidl and Cox method and proposed identical preambles in the time domain with the opposite signs. The Minn method performs well, but it still has a high mean square error in the inter-symbol interference (ISI) channel. To improve symbol timing synchronization, Park et al. [10] proposed another method, which causes an impulse-like timing response. This method is assumed to be a better estimator, but its timing metric has large sidelobes that lead to worse detection at the low SNR. Seung et al. [11] have designed a new time domain preamble to give a smaller MSE than the previous estimators, even in a multipath fading channel. To reduce the sidelobes in the Park estimator, A. M Khan et al. [12] modified the Park
method and proposed a new preamble scheme that has a PN sequence of value 1 and -1, which performs better at low SNR.

The aim of this work is to design a new training symbol for coarse timing synchronization in OFDM receiver and compare it with three popular conventional existing estimators, which are the Schmidl and Cox, Minn and Park estimators. The proposed method is also used in real-time Transmission-based universal software radio peripheral (USRP) and GNU Radio as shown in Figure 3 to verify its performance by transmitting a text file from a laptop acting as a transmitter, through the air. At the receiver, the text file received by the antenna feeds into a PC to perform the synchronization task. Note that in this scenario, the complete OFDM system is needed, including channel coding and channel estimation.

2. System model
A general case of OFDM systems using the standard complex-valued baseband equivalent signal model can be expressed as

\[ y(n) = \sum_{m=0}^{L-1} h(m)x(n-m) \]  

where \( h(n) \) is the channel response, which has number of channels \( L \). \( x(n) \) is the time domain signal, which can be expressed

\[ x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} c_k \exp \left( j \frac{2\pi nk}{N} \right) \]  

where \( N \) is number of IFFT points and \( c_k \) are the complex information symbols. At the receiver, the timing offset is modelled as a delay in the received signal and the frequency offset as a phase distortion of the received data in the time domain. These two offsets and additive white Gaussian noise (AWGN) \( w(n) \) yield received signal:

\[ r(n) = y(n - \tau) \exp(j(2\pi\Delta f n + \phi)) + w(n) \]  

where \( \tau \) is the integer unknown arrival time of a symbol, \( \Delta f \) is the frequency offset and \( \phi \) is the initial phase. Therefore, the target of the timing synchronization is to estimate \( \tau \) [13].

3. Conventional synchronization technique

3.1. Schmidl and Cox method
Schmidl and Cox proposed a training sequence that has identical halves in the time domain. Those identical halves can be generated by transmitting the zero on odd frequencies and PN sequence on the even frequencies. Then, by taking the IFFT, we obtain the halves in the time domain. Let \( N \) be the number of IFFT points in one OFDM symbol. Schmidl used the following preamble.

\[ P_{SC} = \begin{bmatrix} A_{N/2} & A_{N/2} \end{bmatrix} \]  

where \( A \) represents the sample length \( N/2 \).

3.2. Minn method
In order to avoid uncertainty produced by timing metric of the Schmidl and Cox estimator, Minn proposed new training preamble is as follows

\[ P_{MN} = \begin{bmatrix} B_{N/4} & B_{N/4} & -B_{N/4} & -B_{N/4} \end{bmatrix} \]  

where \( B \) represents the sample length \( N/4 \).

3.3. Park method
In this method, the real value of PN sequence is transmitted on the even frequencies and zeros are transmitted on the odd frequencies and applied to the IFFT operation in the sequence. Park achieves an impulse-like timing response. The training symbol used in this method is given by

\[ P_{Park} = [C_{N/4} \quad D_{N/4} \quad C^*_{N/4} \quad D^*_{N/4}] \]  

(6)

where \( C \) represents a sample length of \( N/4 \) generated by \( N \) number of IFFT of a PN sequence and \( C \) is symmetric to \( D \). \( C^* \) and \( D^* \) are the conjugates of \( C \) and \( D \) respectively.

4. Proposed method

As is known, OFDM timing synchronization using preamble technique depends on the structure of the training symbol and definition of the timing metric. A sample of the proposed pattern preamble can be designed as follows:

\[ P_{Pro} = [E_{N/2} \quad -E_{N/2}] \]  

(7)

where the real value \( E \) represents a sample of length \( N/2 \) generated by IFFT of a PN sequence.

This symbol pattern can be easily obtained by using the properties of the FFT. The training symbol can be produced by transmitting the complex values of the PN sequence on the odd frequencies and zeros on the even frequencies, as shown in following:

\[ X = [0 \quad x_0 \quad 0 \quad x_1 \ldots x_{N/2-1} \quad 0 \quad x^*_1 \quad 0 \quad x^*_0] \]  

(8)

where \( x_k = a + ib \); \( a \), \( b \) are real values and \( x^*_k \) is the conjugate of \( x_k \). Let \( N \) be the number of IFFT points in one OFDM symbol. Then, by applying the IFFT operation to expression (8) will produce the output signal in the time domain, as shown in (7). The timing metric for the proposed method can be written as follows:

\[ P_{Pro} = \left| P_4(d) \right|^4 \left( R_4(d) \right)^4 \]  

(9)

where the terms \( P_4(d) \) and \( R_4(d) \) can be expressed, respectively, as follows:

\[ P_4(d) = \sum_{n=0}^{N/2-1} r(n+d) r(n+d+N/2) \]  

(10)

\[ R_4(d) = \sum_{n=0}^{N/2-1} \left| r(n+d) \right|^2 \]  

(11)

and \( r(n) \) is the received signal. Here, the 4th power is needed to reduce the subpeaks beside the main peak instead of the 2nd power (in Experimental). However, they yielded almost the same result in a Matlab simulation.

The timing metric defined in (9) creates a plateau, causing ambiguity in determining the correct symbol start position. To improve the proposed method, a new timing metric is defined. The key point of this improved method is to reduce the length of the plateau to achieve a shaped peak, which indicates the precise start of the FFT windows at the receiver. The plateau is a window with length equal to the cyclic prefix in the AWGN channel where the timing metric reaches a maximum; the start of the symbol can then be taken to be any point within the window. The length of the window could change in the frequency-selective channel. Therefore, to realize this concept, it is necessary to examine the output of the timing metric to find the exact length of the plateau. Let \( m \) be the length of the plateau and keep the preamble the same as that designed in (7) and (8); the only change here is the timing metric. The timing metric for the improved method can be defined as follows:
\[ M_{\text{pro}} = \frac{|P_s(d)|^4}{(R_s(d))^4} \]  \hspace{1cm} (12)

where the terms \(P_s(d)\) and \(R_s(d)\) can be written, respectively, as

\[ P_s(d) = \sum_{n=-L}^{N-2-L} r(n+d) \left( r(n+d+\frac{N}{2}) \right) \]  \hspace{1cm} (13)

\[ R_s(d) = \sum_{n=1}^{N/2+L} |r(n+d)|^2 \]  \hspace{1cm} (14)

Here, \(L = m-1\) and \(r(n)\) is the received signal.

5. Simulation results
This section investigates the performance of the proposed estimator by comparing it with three existing estimators in terms of timing metric and MSE using the indoor Rayleigh fading channel obtained by Matlab simulations. On the other hand, the performance of proposed method has been evaluated in terms of the timing metric in real-word transmission with the USRP and GNU Radio as the software defined radio (SDR) in an indoor laboratory environment; the OFDM parameters for this experiment setup are chosen as OFDM parameters for the IEEE 802.11a standard, as shown in Table 1.

**Table 1.** OFDM parameters for simulation and testbed.

| OFDM Parameters          | Simulations | Testbed |
|--------------------------|-------------|---------|
| Number of FFT points     | 512         | 64      |
| Number of subcarriers    | 256         | 52      |
| Cyclic Prefix length     | 128         | 16      |
| Number of taps           | 6           |         |
| Number of simulation runs| 50000       |         |
| Centre frequency         | 2.412 GHz   |         |
| Gain [dB]                | 38 dB       |         |
| Distance between two USRP N210 | 3 m |         |

5.1. Timing metric
Figure 1 shows the performance of the proposed algorithm with those of the Schmidl and Cox, Minn, and Park methods under the condition no noise and no channel distortion. The correct point is indexed 0 in the figure. The Schmidl and Cox method creates a plateau which causes ambiguity when estimating the correct time. The Minn method reduced the timing metric plateau, but when data is transmitted in the ISI fading channel, the adjacent samples to the metric peak have almost the same values as the main peak. This causes incorrect estimation and increases the MSE. The Park method achieves the impulse-like timing response. It is assumed to be the better estimator, but its timing metric has subpeaks which result in worse estimation in the fast fading channel. The proposed method achieved a shaped peak indexed at the correct timing point which indicates the precise starting point of the OFDM symbol.
5.2. Means square error (MSE)

Figure 2 shows the MSE of the estimators versus SNR in the Rayleigh fading channel. The results for the Schmidl and Cox method are the worst, and it has the greatest uncertainty in the calculated timing offset point owing to the plateau in the timing metric. The proposed method has a lower MSE than the Minn and Park methods. Therefore, the proposed method outperforms the Minn and Park methods.

5.3. Testbed description

This section describes the real-time testbed SDR implementation, based on the GNU Radio and USRP platforms, to investigate the performance of the proposed timing synchronization method. The experimental setup consists of one laptop, one PC, and two USRP N210 produced by Beijing Highmesh. Each USRP is equipped with one antenna and controlled by UHD software from the laptop. The daughter boards used for this experiment are RFX 2400, which could cover the frequency range between 2.3 – 2.9 GHz. Moreover, the center frequency was set at 2.412 GHz.

As seen in Figure 3, during the transmission, the baseband signal from the host laptop is sent to the first USRP by an intermediate Gigabit Ethernet cable to ensure communication between the laptop and USRP device, where it is converted to an RF signal and transmitted through the air. At the receiver side, the analog signal from the air is captured by the antenna and gets processed in the second USRP board. Then, it is fed to the PC with GNU Radio installed to perform synchronization tasks and other signal processing.
5.4. Testbed results
The coarse timing synchronization is implemented in block called synchronization. Its inputs are the samples from the USRP device in the form of a stream. As seen in in Figure 4, the first peak marks the start of the first OFDM frame; it feeds a fixed number of samples into the rest of the signal processing blocks and the second peak indicates another new frame that has been detected. If the second frame arrives shortly after the first one, it will be ignored.

6. Simulation results
In this paper, we presents a different symbol timing synchronization based on a preamble technique. The proposed timing offset estimator reduces the plateau that leads to the uncertainty estimation in the Schmidl timing offset estimation method. The simulation results show that the proposed method performs better than other methods in the indoor Rayleigh fading channel, particularly at high SNR. The proposed method can also detect the precise starting point of the FFT windows, even in real-time transmission through the air in an indoor laboratory environment.

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