A Novel Timing Estimation Method for OFDM Systems

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***Abstract*—In this letter, we present a novel timing offset estimation method for orthogonal frequency division multiplexing systems. The estimator proposed here is designed to avoid the ambiguity which occurs in Schmidl's timing offset estimation method. The performance of the proposed scheme is presented in terms of mean and mean-square error (MSE) obtained by simulations. The simulation results show that the proposed estimator has a significantly smaller MSE than the other estimators.**

***Index Terms*—Orthogonal frequency division multiplexing (OFDM), preamble, timing offset estimation.**

I. Introduction

SYNCHRONIZATION has been a major research topic in orthogonal frequency division multiplexing (OFDM) systems due to the sensitivity to symbol timing and carrier frequency offset [1]. Several approaches have been proposed to estimate time and frequency offset either jointly or individually [2]–[4].

The most popular of the pilot-aided algorithms is the method proposed by Schmidl [5]. His method uses a preamble containing the same two halves to estimate the symbol timing and frequency offset. Schmidl's estimator provides simple and robust estimates for symbol timing and carrier frequency offset. However, the timing metric of Schmidl's method has a plateau, which causes a large variance in the timing estimate.

To reduce the uncertainty arising from the timing metric, Minn proposed a method as a modification to Schmidl's approach [6]. Minn's preamble yields a sharper timing metric and smaller variance than Schmidl's. While Minn's estimator provides accurate estimation, the variance of estimation is quite large in ISI channels.

This letter contains our proposal for a new timing synchronization method for OFDM timing estimation which produces an even sharper timing metric than Schmidl's and Minn's.

In Section II we introduce the OFDM signal model and describe the existing timing estimation methods. Section III covers the proposed preamble and timing offset estimation method. In Section IV, the performances of the proposed estimator and the other estimators are compared in terms of mean-square error using computer simulation results. Finally conclusion is drawn in Section V.

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II. System Description

A. OFDM Signal Description

Consider a general case of a OFDM system, using the standard complex-valued baseband equivalent signal model. The nth received sample has the standard form

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

where $h[n]$ is the channel impulse response, whose memory is denoted by L. $x[n]$ is the time-domain OFDM signal expressed by

$$x[n] = \sum_{k=0}^{N-1} c_k e^{j(2\pi/N)kn} \tag{2}$$

where N is the number of sub-carriers and the c_k's are the complex information symbols.

At the receiver, timing offset is modeled as a delay in the received signal and frequency offset is modeled as a phase distortion of the received data in the time domain. These two uncertainties and the AWGN $w[n]$ yield the received signal

$$r[n] = y[n-n_\epsilon]e^{j(2\pi\theta_\epsilon n/N+\phi)} + w[n] \tag{3}$$

where n_ϵ is the integer-valued unknown arrival time of a symbol, θ_ϵ is the frequency offset and ϕ is the initial phase.

B. OFDM Timing Synchronization

The goal of OFDM timing synchronization is to estimate n_ϵ. Before we proceed, let us briefly describe the timing offset estimation methods presented in [5] and [6].

1) Schmidl's Method: The form of the time-domain preamble proposed by Schmidl is as follows:

$$P_{\mathrm{Sch}} = [A_{N/2} \quad A_{N/2}]$$

where $A_{N/2}$ represents samples of length $N/2$ and is generated by the method in [5].

The Schmidl's timing estimator finds the starting point of the symbol at the maximum point of the timing metric given by

$$M_{\mathrm{Sch}}(d) = \frac{|P_1(d)|^2}{(R_1(d))^2} \tag{4}$$

where

$$P_1(d) = \sum_{k=0}^{N/2-1} r^*(d+k) \cdot r\left(d+k+\frac{N}{2}\right) \tag{5}$$

$$R_1(d) = \sum_{k=0}^{N/2-1} \left|r\left(d+k+\frac{N}{2}\right)\right|^2. \tag{6}$$

The timing metric of Schmidl's method has a plateau which leads to some uncertainty regarding the starting point of the OFDM symbol. To reduce this effect, Schmidl proposes an averaging method which takes the timing estimate as the average of the two 90% of maximum timing metric point. Nevertheless, the mean-square error of the Schmidl's estimator is quite large.

2) Minn's Method: In order to alleviate the uncertainty caused by the timing metric plateau and to improve the timing offset estimation, Minn proposed a modified preamble. Minn's preamble has the following form:

$$P_{\text{Minn}} = [\, B_{N/4} \quad B_{N/4} \quad -B_{N/4} \quad -B_{N/4} \,]$$

where $B_{N/4}$ represents a PN sequence of length $N/4$.

Then the timing metric is expressed as

$$M_{\text{Minn}}(d) = \frac{|P_2(d)|^2}{(R_2(d))^2} \tag{7}$$

where

$$P_2(d) = \sum_{m=0}^{1} \sum_{k=0}^{N/4-1} r^*\left(d+\frac{N}{2}m+k\right) r\left(d+\frac{N}{2}m+k+\frac{N}{4}\right) \tag{8}$$

$$R_2(d) = \sum_{m=0}^{1} \sum_{k=0}^{N/4-1} \left|r\left(d+\frac{N}{2}m+k+\frac{N}{4}\right)\right|^2. \tag{9}$$

In Schmidl's method, the timing metric has its peak for the entire interval of the cyclic prefix. The Minn's method has its peak at the correct starting point for the OFDM symbol, since correlation of some samples results in negative values. For this reason, Minn's method eliminates the peak plateau of the timing metric, hence resulting in a smaller MSE.

III. Proposed Symbol Timing Method

Minn's method uses negative-valued samples at the second-half of training symbols to reduce the timing metric plateau. Correlation of these negative samples results in a decrease of the timing metric at an incorrect OFDM symbol starting point. However, in spite of the reduction of the timing metric plateau, it is observed that the MSE of Minn's estimator is quite large in ISI channels from the results in [6]. This is because the values of the timing metric around the correct starting point are almost the same. Therefore, in order to increase the performance of the estimator, a method which enlarges the difference between peak value of the timing metric and the other values is required.

Observation of two adjacent values of the timing metric clearly shows that they have all the same sum of the pairs of product, with the exception of only two pairs of product. This fact makes the difference between the peak value and the following value slight. Therefore, to enlarge the difference between the two adjacent values of the timing metric, it is needed to maximize the different pairs of product between them. This is dependent on the structure of the training symbol and the definition of the timing metric. For this reason, we propose a new preamble and correlation method to obtain an impulse-shaped timing metric.

The samples of the proposed preamble are designed to be of the form

$$P_{\text{Pro}} = \left[\, C_{N/4} \quad D_{N/4} \quad C^*_{N/4} \quad D^*_{N/4} \,\right] \tag{10}$$

where $C_{N/4}$ represents samples of length $N/4$ generated by IFFT of a PN sequence, and $C^*_{N/4}$ represents a conjugate of $C_{N/4}$. To get impulse-shaped timing metric, $D_{N/4}$ is designed to be symmetric with $C_{N/4}$ in this letter.

This symbol pattern can be easily obtained by using the properties of FFT. The training symbol is produced by transmitting a real-valued PN sequence on the even frequencies, while zeros are used on the odd frequencies. This means that one of the points of a BPSK constellation is transmitted at each even frequency. Then result of IFFT will produce the time-domain sequence as shown in (10).

To estimate frequency offset using the same preamble, the basic form of proposed preamble is same that of Schmidl. Therefore, Schmidl's frequency offset estimation algorithm can be also applied to the proposed preamble.

To make use of the property that $D_{N/4}$ is symmetric with $C_{N/4}$, let us define a new timing metric as follows:

$$M_{\text{Pro}}(d) = \frac{|P_3(d)|^2}{(R_3(d))^2} \tag{11}$$

where

$$P_3(d) = \sum_{k=0}^{N/2} r(d-k) \cdot r(d+k) \tag{12}$$

$$R_3(d) = \sum_{k=0}^{N/2} |r(d+k)|^2. \tag{13}$$

The $P_3(d)$ is designed such that there are $N/2$ different pairs of product between two adjacent values. It is maximum different pairs of product. Therefore, the proposed timing metric has its peak value at the correct symbol timing, while the values are almost zero at all other positions.

Fig. 1 shows an example of the timing metric under no noise and no channel distortion with 1024 subcarriers and 128 cyclic prefix. The correct timing point is indexed 0 in the figure. The proposed timing metric is compared to those of Schmidl's and Minn's. As seen in the Fig. 1, Schmidl's method creates a plateau for the whole interval of cyclic prefix. The timing metric from Minn's method reduces the plateau, and yields a sharp timing metric. As expected, the proposed method has an impulse-shaped timing metric, allowing it to achieve a more accurate timing offset estimation.

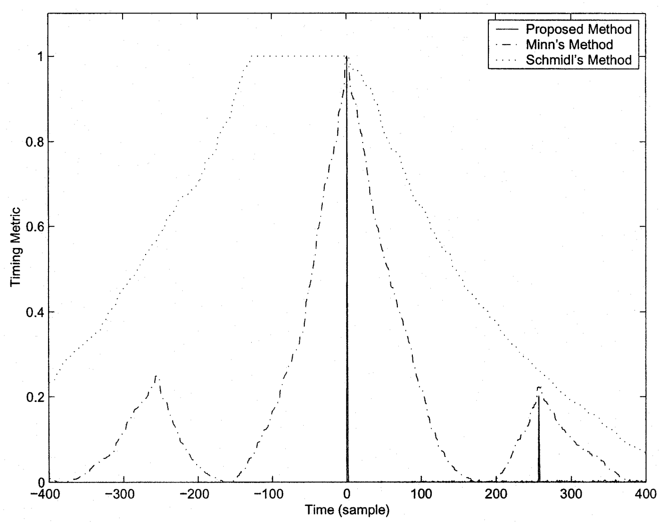

Fig. 1. Comparison of the timing metric of estimators.

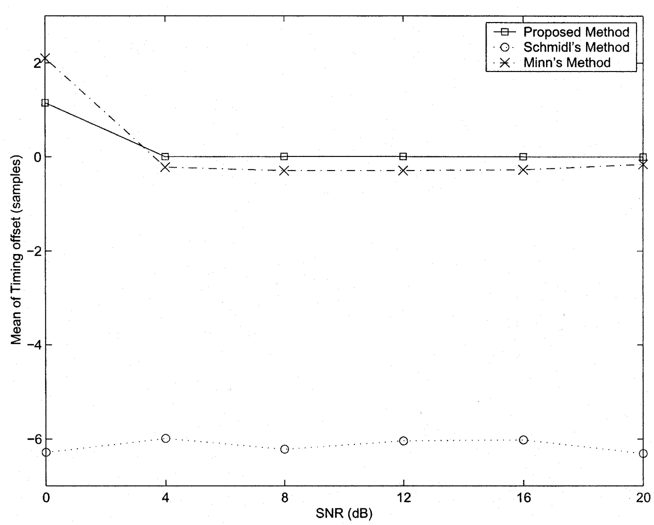

Fig. 2. Mean of estimators in HIPERLAN/2 indoor channel A.

IV. Simulation Results

The performance of the proposed estimator is evaluated by computer simulations. OFDM system with 64 subcarriers and 16 cyclic prefix is considered and HIPERLAN/2 indoor channel model [7] is used for simulations. We assume that frequency offset is 0.1. The performance of the proposed timing estimator is evaluated by mean and mean-square error (MSE), and is compared with those of Schmidl's and Minn's methods.

Figs. 2 and 3 show the means and variances for the timing offset estimators in HIPERLAN/2 indoor channel A. Fig. 2 shows that the mean value of Schmidl's method has shifted to the middle of the cyclic prefix, whereas the mean value of both the proposed estimator and Minn's estimator is at roughly the correct timing point. This graph demonstrates that reduction of the timing metric plateau yields a more accurate estimation.

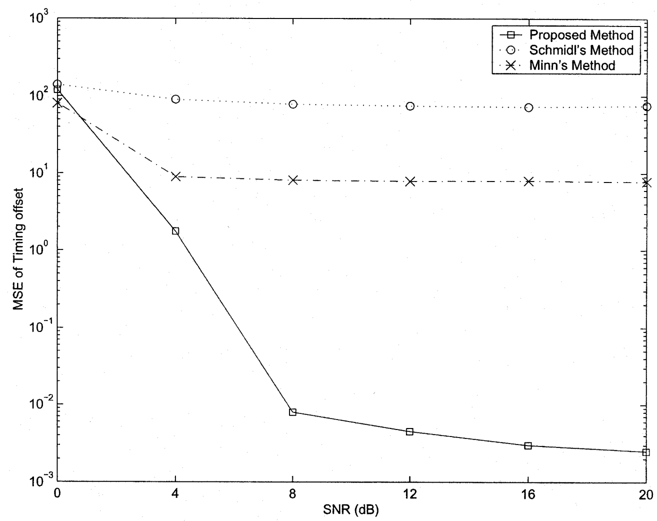

Fig. 3. MSE of estimators in HIPERLAN/2 indoor channel A.

We can see from the MSE curve in Fig. 3 that the proposed timing offset estimator has a much smaller MSE than the other estimators. This improvement can be inferred from the impulse-like shape of the timing metric of proposed estimator.

The simulation results make it clear that the performance of the proposed estimator performs better than the other two estimators, making it a more favorable option for the initial timing synchronization of OFDM systems.

V. Conclusions

A preamble and a timing offset estimator are presented in this letter. The proposed timing offset estimator reduces the plateau, which makes the uncertainty of estimation in Schmidl's timing offset estimation method. The proposed timing synchronization method makes it possible to estimate symbol timing offset with a much smaller MSE. Therefore, the proposed estimator is suitable for the initial timing synchronization of OFDM systems.

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