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A Robust Frequency Offset Estimator for Orthogonal Frequency Division Multiplexing

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***Abstract*—We address the integer frequency offset (IFO) estimation under the influence of the timing offset (TO) in orthogonal frequency division multiplexing (OFDM) systems. Incorporating the IFO and TO into the symbol set used to represent the received OFDM symbol, we investigate the influence of the TO on the IFO, and then, propose a combining method between two consecutive OFDM correlations, reducing the influence. The proposed scheme has almost the same complexity as that of the conventional schemes, whereas it does not need the TO knowledge contrary to the conventional schemes. From numerical results it is confirmed that the proposed scheme is insensitive to the TO, consequently, yielding an improvement of the IFO estimation performance over the conventional schemes when the TO exists.

***Keywords*—Estimation, integer frequency offset, OFDM, timing offset.

I. Introduction

THE orthogonal frequency division multiplexing (OFDM) system has attracted much interest in a variety of wireless communications such as European digital video broadcasting (DVB) [1], IEEE 802.11a [2], IEEE 802.16 [3], and Long Term Evolution (LTE) [4], since it provides various advantages including high spectral efficiency and immunity to multipath fading [5]. In OFDM systems, the frequency offset (FO) estimation is one of the most important technical steps [6], because most of the advantages in OFDM come from the orthogonality among subcarriers and the orthogonality is very vulnerable to the FO [7]. The FO consists of the fractional FO (FFO) and integer FO (IFO). The absolute value of the FFO is less than the half of the subcarrier spacing and the IFO is an integer multiple of the subcarrier spacing. In this paper, we focus on the IFO estimation based on preambles [8].

Conventionally, the TO has not been considered in the IFO estimation [9]; however, it was presented that the TO is an unavoidable and has a large influence on the IFO estimation in [10]. In addition, [10] proposed a method to reduce the influence, and yet, the scheme needs the knowledge on the possible maximum value of the timing offset, resulting in a complexity increase.

Thus, in this paper, we propose a new scheme to reduce the TO influence on the IFO. We first investigate how the TO affects the IFO, and then, find that the TO decreases the correlation between the preamble and fast Fourier transform (FFT) outputs, resulting in a significant degradation in the IFO estimation performance. Thus, we propose to combine two consecutive correlations and then to use it as the demodulator input instead of the single correlation. Numerical results demonstrate that the IFO estimation performance offers a significant improvement over the conventional schemes in terms of the robustness to the TO and the correct estimation probability.

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II. System Model

In the presence of timing and frequency offsets, the mth received OFDM sample can be expressed as [11], [12]

$$y(m) = z(m-\tau)e^{j2\pi\Delta(m-\tau)/N} + w(m), \tag{1}$$

for $m = 0, 1, \cdots, N-1$, where Δ is the FO normalized to the subcarrier spacing, τ is the TO normalized to the sample interval, $w(m)$ is the mth additive white Gaussian noise (AWGN) sample [13]-[15] with mean zero and variance σ_w^2, and $z(m)$ is the mth sample of the transmitted OFDM symbol generated by inverse FFT of size N as

$$z(m) = \sum_{k=0}^{N-1} Z_k e^{j2\pi km/N}, \tag{2}$$

where Z_k is a preamble data for the kth subcarrier. The FO Δ can be expressed as the sum of IFO Δ_I and FFO Δ_F. In this paper, we focus on estimation of IFO assuming that FFO is perfectly estimated and compensated (i.e., $\Delta_F = 0$) as in other literatures [16]-[20].

The FFT output Y_l corresponding to the lth subcarrier can be expressed as

$$Y_l = Z_{l-\Delta} e^{-j2\pi(l-\Delta)\tau/N} + W_l, \tag{3}$$

where W_l is the FFT output of $w(m)$ corresponding to the lth subcarrier. From (3), we can see that the FFT output is shifted by the IFO and its phase is rotated by the TO.

III. The Effect of TO on Conventional Schemes

The conventional IFO estimation scheme without considering the TO in [9] obtains the IFO estimate as

$$\hat{\Delta}_{c1} = \arg\max_d \left\{ \left| \sum_{k=0}^{N-1} Z_k^* Y_{(k+d)_N} \right| \right\}, \tag{4}$$

where d is the IFO candidate in $\{-N/2, -N/2+1, \cdots, N/2-1\}$ and $(\cdot)_N$ is the modulo-N operator [21]-[23]. In the case that $d = \Delta$, the normalized correlation value in (4) becomes $\left| e^{\frac{-j\pi\tau(N-1)}{N}} \frac{\sin(\pi\tau)}{\sin(\pi\tau/N)} \right|$ in the absence of noise, which

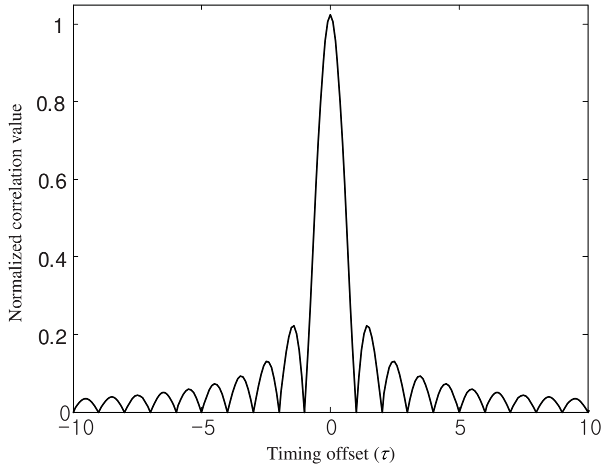

Fig. 1: The normalized correlation value of the scheme in [9].

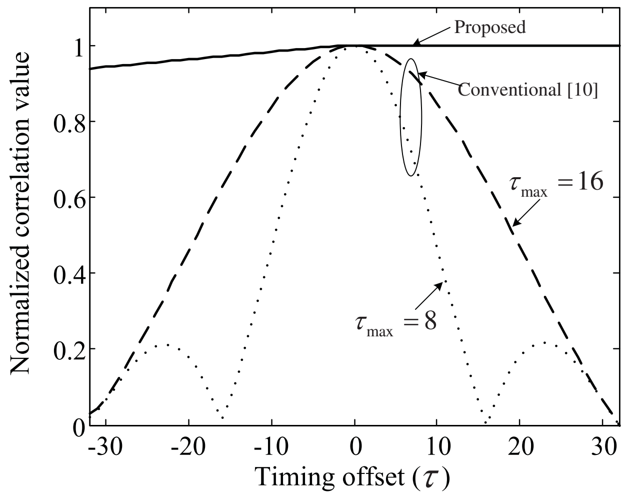

Fig. 2: The normalized correlation value of the proposed scheme and the conventional scheme in [10].

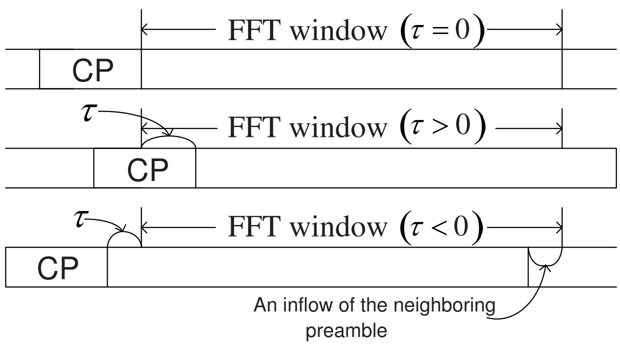

Fig. 3: The location of the FFT window in the absence and presence of the timing offset.

is depicted as a function of TO τ in Fig. 1. From the figure, we can clearly observe that the correlation value used in the IFO estimation is very sensitive to the variation of the TO, which implies that the correlation value could be reduced significantly due to the FO even if the FO is correctly estimated, resulting in considerable degradation in FO estimation performance (note that a large correlation value when $d = \Delta$ is essential for the detection of the correct FO estimate).

The conventional scheme in [10] can estimate an IFO in the presence of TO using the coherence phase bandwidth (CPB) defined as

$$B_c \triangleq \frac{N}{2\tau_{\max}}, \tag{5}$$

where $\tau_{\max}$ is the possible maximum value of TO. Using the CPB, the scheme in [10] estimates the IFO as

$$\hat{\Delta}_{c2} = \arg\max_d \left\{ \sum_{m=0}^{K-1} \left| \sum_{k=0}^{B_c-1} Z^*_{k+mB_c} Y_{(k+mB_c+d)_N} \right| \right\}, \tag{6}$$

where $K = N/B_c$ is the number of blocks. The dashed and dotted lines in Fig. 2 show the normalized correlation value in (6) in the absence of noise when $\tau_{\max} = 16$ and 8, respectively. From the figure, we can see that the scheme in [10] reduced decrease of the correlation value compared with the scheme in [9], yet, the correlation value still decreases rapidly as the TO becomes larger than $\tau_{\max}$, which would result in the significant performance degradation in estimating Δ. That is, the scheme in [10] requires the knowledge on the TO for its proper operation.

IV. Proposed Scheme

To reduce the effect of the TO on the IFO estimation, we perform the differential combining between two successive FFT outputs multiplied by the preamble, and then, estimate IFO as

$$\hat{\Delta}_p = \arg\max_d \left\{ \left| \sum_{k=0}^{N-1} \left\{ Z^*_k Y_{(k+d)_N} \right\} \left\{ Z^*_{k+1} Y_{(k+1+d)_N} \right\} \right| \right\}. \tag{7}$$

In the conventional schemes, the correlation value decreases in the presence of TO because the schemes add correlation values with different phases. However, in the proposed scheme, the phase differences between the subcarriers are the same. Thus, a large correlation value can be obtained by adding the outputs.

In Fig. 2, we can observe that the normalized correlation value is almost constant regardless of the TO value, as expected. Although the correlation value of the proposed scheme slightly decreases when τ is negative, it is caused by the interference from the neighboring preamble as shown in Fig. 3. On the other hand, in the case that τ is positive, the correlation value is constant since other OFDM symbols are not flowed in the FFT window.

V. Numerical Results

We compare the IFO estimation performances of the proposed and conventional schemes in terms of the correct estimation probability defined as the probability that the chosen IFO candidate is the correct one. We assume the following parameters: $N = 1024$, cyclic prefix of 100 samples, an AWGN channel with a fixed frequency offset 10 and TOs

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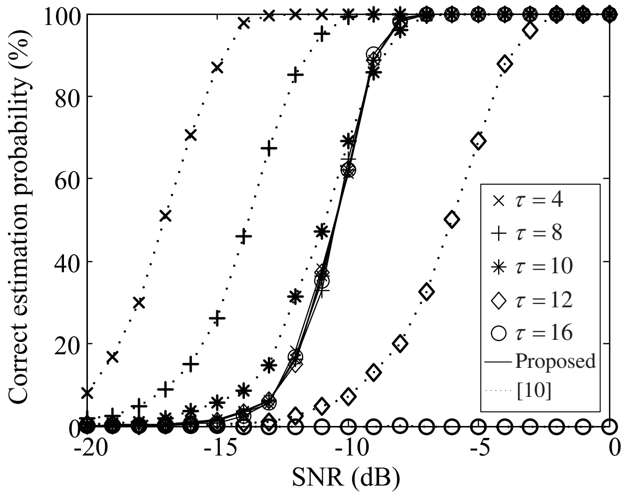

Fig. 4: Correct estimation probabilities of the proposed and conventional schemes when $\tau = 4, 8, 10, 12,$ and 16.

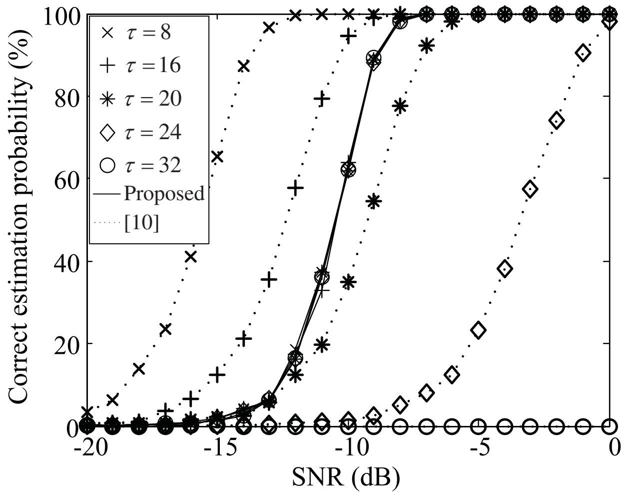

Fig. 5: Correct estimation probabilities of the proposed and conventional schemes when $\tau = 8, 16, 20, 24,$ and 32.

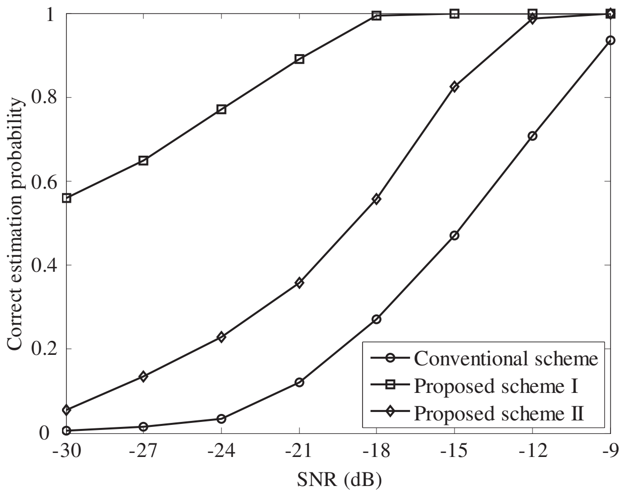

Fig. 6: Correct estimation probabilities in the AWGN channel model.

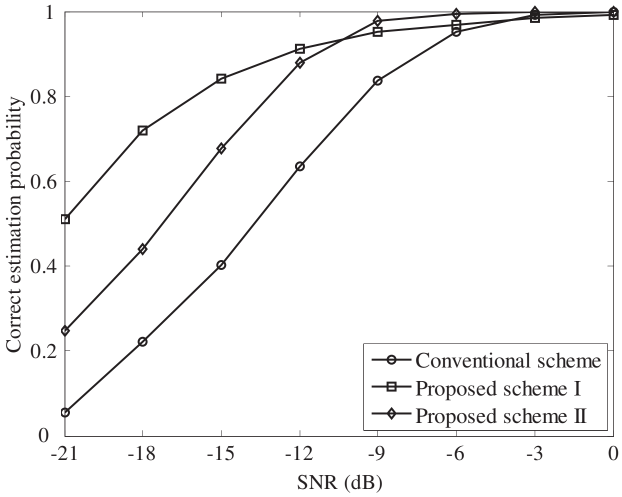

Fig. 7: Correct estimation probabilities in the multipath fading channel model.

4, 8, 10, 12, and 16 for Fig. 4 and 8, 16, 20, 24 and 32 for Fig. 5, respectively.

Figs. 4 and 5 show the correct estimation probabilities of the proposed and conventional schemes as a function of signal-to-noise ratio (SNR) when $\tau_{\max} = 8$ and 16, respectively. From figures, we can observe that the conventional scheme in [10] performs better than the proposed scheme when τ is equal to or less than $\tau_{\max}$; however, the performance of the conventional scheme significantly degrades as τ becomes larger than $\tau_{\max}$, and eventually, becomes much worse than that of the proposed scheme. That is, the conventional scheme can not operate properly without the knowledge on $\tau_{\max}$. In addition, we can see that the proposed scheme is robust to the TO variation.

Fig. 6 shows the correct estimation probabilities of the conventional and two proposed schemes in the AWGN channel model whose coherence bandwidth is infinity. As shown in Fig. 6, the proposed schemes outperform the conventional scheme. Especially, the correct estimation probability of the proposed scheme I is close to 1 at low SNRs such as -18 and -15 dBs, since the proposed scheme I fully exploits the pilot signal energy. Otherwise, the proposed scheme II has some performance degradation compared with that of the proposed scheme I, however, the proposed scheme II has better performance than the conventional scheme based on its efficient combinations.

Fig. 7 shows the correct estimation probabilities of the conventional and two proposed schemes in the multipath fading channel model whose coherence bandwidth size is 34. Unlike in Fig. 6, it is shown that the performances of the proposed scheme I has worse performance than the conventional scheme and proposed scheme II in the SNR range above -4 dB and -10 dB, respectively. This is due to the fact that the influence of the noise becomes larger than that of the channel as the SNR decreases, thus, the performance of the proposed scheme I is the best in the low SNR range. On the other hand, as the SNR increases, the influence of the channel becomes larger than that of the noise, thus, the performance of the proposed scheme I becomes worse than those of other schemes. The proposed scheme II has the best performance above the SNR value of -10 dB, since the proposed scheme II considers the influence of the channel by using the distance parameter B.

VI. Conclusion and Future Works

In this paper, we have proposed an integer frequency offset estimation scheme robust to the timing offset variation, where two consecutive OFDM correlations are differently combined, reducing the influence of the timing offset variation on the integer frequency offset. Contrary to the conventional schemes, from numerical results, it has been confirmed that the proposed integer frequency offset estimation scheme with the differently combined correlation is insensitive to the timing offset variation and performs well even when the timing offset knowledge is unavailable. However, the proposed scheme may suffer from a performance degradation in a fast time-varying fading environment, where the timing offset is changing very fast and two consecutive OFDM correlations could have a significant phase difference. Oversampling might be a solution to the phase difference; yet, it could require a increase in complexity. Thus, we will consider a trade-off between performance and complexity for oversampling based schemes, and also, will pursue additional methods for the integer frequency offset estimation in a fast time-varying fading environment in our future work.

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