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Abstract — In this paper, a new integer frequency offset estimation method is proposed for orthogonal frequency division multiplexing (OFDM)-based digital video broadcasting (DVB) systems. Several pilot-aided frequency offset estimation methods have been proposed for OFDM-based DVB systems. In the conventional methods, however, the information of some combinations that pilots provide is used only. Thus, in this paper, we propose a new integer frequency offset estimation method exploiting the information of all combinations that pilots provide. The simulation results show that the proposed method outperforms the conventional method in terms of the probability of integer frequency offset estimation failure.

Keywords — Orthogonal frequency division multiplexing (OFDM), digital video broadcasting (DVB), frequency offset, synchronization.

1. Introduction

Due to its immunity to impulsive noise and multipath fading and optimum use of spectrum, orthogonal frequency division multiplexing (OFDM) has been widely used in digital video broadcasting (DVB) and digital audio broadcasting (DAB) systems, wireless local area networks (WLANs), and HIPERLAN/2 as a modulation method in wireless communications [1], [2].

As well known, however, OFDM system is very sensitive to the frequency synchronization error, the frequency offset caused by Doppler shift or a misalignment between the oscillators in the transmitter and receiver, resulting in significant performance degradation. Therefore, the frequency offset estimation is one of the most important procedures for OFDM-based systems. In this paper, we focus on OFDM-based DVB systems.

The frequency offset can be divided into the integer part and the fractional part. If the frequency offset is not precisely estimated and compensated before data demodulation, a cyclic shift of the subcarrier indices of demodulated OFDM symbol is produced by the integer part of the frequency offset and an inter-carrier interference (ICI) is introduced by the fractional part of the frequency offset after the fast Fourier transform (FFT) in the receiver [3].

Recently, several methods have been proposed for frequency offset estimation for OFDM-based DVB systems [2], [4], [5]. In the conventional methods, however, the information of some combinations that pilots provide is used only.

Therefore, in this paper, we propose a new integer frequency offset estimation method for OFDM-based DVB systems exploiting the information of all combinations that continual pilots (CPs) and scattered pilots (SPs) provide in frequency domain. This proposed method is highly accurate and outperforms the conventional method in terms of the probability of integer frequency offset estimation failure. And we regard the performance of the proposed method as the highest priority at the expense of the complexity of the proposed method.

To propose the new frequency offset estimation method, some modified numerical expressions of the conventional method in [2] are presented. The conventional method uses combinations only of two CPs and of a CP and an SP nearest to it. That is, only some parts of all combinations among CPs and SPs are used in the conventional method. So, we propose a new method that uses all combinations of pilots, which should offer better performance than the conventional method as a result of more information being used.

The rest of this paper is organized as follows. Section 2 describes the system model. In the Section 3, the conventional method is presented. In the Section 4, the new integer frequency offset estimation method for OFDM-based DVB systems using the information of all combinations that pilots provide is proposed. In the Section 5, the simulation results show that the performance of the proposed integer frequency offset estimation method in additive white Gaussian noise (AWGN) and multipath Rayleigh channels. Then the Section 6 is the conclusion of this paper.

2. System Model

A DVB system operates in 2K or 8K mode, depending on the total number of subcarriers. In this paper, we consider a DVB system with 2K mode, where 1705 subcarriers among 2048 total subcarriers are used to transmit data and 45 continual pilots (CPs) and 142 or 143 scattered pilots (SPs) are
used to estimate the channel and timing and frequency offsets. The pilot value is +4/3 or -4/3, which is randomly decided by a pseudo random binary sequence (PRBS). Fig. 1 describes a pilot arrangement in a DVB system with 2K mode, where \( K_{\text{min}} \) and \( K_{\text{max}} \) are the smallest and largest carrier numbers of the carriers that transmit the complex-valued symbols respectively in OFDM-based DVB system [6].

The values of CPs within a subcarrier are the same. The SPs are periodically inserted every twelve subcarriers and their locations are periodic for every four OFDM symbols.

Assuming that \( 2N_0 + 1 \) subcarriers among \( N \) total subcarriers are used to transmit data, we can express the \( n \) th sample \( x_i(n) \) of the \( l \) th transmitted OFDM symbol as

\[
x_i(n) = \frac{1}{\sqrt{N}} \sum_{k=-N_0}^{N_0} P_k \exp(j2\pi nk/N),
\]

for \( l = 0,1,\ldots, N - 1 \), \( n = 0,1,\ldots, N-1 \), \( k \) is the subcarrier index, \( P_k \) is a pilot or data symbol transmitted through the \( k \) th subcarrier of the \( l \) th OFDM symbol, and \( N \) is the size of the inverse fast Fourier transform (IFFT).

Then, the \( n \) th sample \( y_i(n) \) of the \( l \) th received OFDM symbol is obtained as

\[
y_i(n) = \frac{1}{\sqrt{N}} \sum_{k=-N_0}^{N_0} H_{l,i}(k) P_k \exp(j2\pi nk/N)
\cdot \exp(j2\pi n\Delta l(N_0 + N)) + N_i(n),
\]

where \( \Delta \) is the frequency offset normalized to subcarrier spacing, \( N_i(n) \) is the zero-mean complex additive white Gaussian noise (AWGN), \( H_{l,i}(k) \) is the channel response on the \( k \) th subcarrier of the \( l \) th symbol, and \( N_0 \) is the guard interval length.

In the receiver, we assume that the symbol timing and the fractional frequency offsets are precisely measured and compensated before the integer frequency offset estimation. Thus, in the receiver, the FFT output \( Y_l(k) \) corresponding to the \( k \) th subcarrier of the \( l \) th symbol is

\[
Y_l(k) = \exp(j2\pi(l\Delta N_0/N)H_{l,i}(k-\Delta))P_{l,i}(k-\Delta) + N_{i,l}(k),
\]

where \( N_{i,l}(k) \) is zero-mean complex AWGN in frequency domain and \( \Delta \) is the integer frequency offset.

### 3. Conventional Method

The conventional method uses the following two templates for estimation \( \Delta \), [2]:

\[
X_l(k) = \frac{P_{l,i}(k)}{P_l(k)}, \quad \text{for } k \in C_{\text{cp}}, \tag{4}
\]

and

\[
\hat{X}_l(k) = \frac{P_{l,i}(k)}{P_l(k)}, \quad \text{for } k \in C_{\text{cp}}, \tag{5}
\]

where \( C_{\text{cp}} \) is the set of CP indices and \( k' \) is a subcarrier index of the SP nearest to \( P_l(k) \).

Then, an estimate \( \hat{\Delta}_l \) of \( \Delta_l \) can be obtained as

\[
\hat{\Delta}_l = \arg \max_{f \in \{f, f', \ldots, f_D\}} \left\{ \Re \left[ \sum_{k \in C_{\text{cp}}} D \sum_{l=0}^{N_l-1} Z_{l}(k+f)X_l(k) \right] + \sum_{l \in C_{\text{sp}}} \sum_{j=0}^{D-1} \hat{Z}_{l}(k+f) \hat{X}_l(k) \exp(j2\pi fN_0/N) \right\}, \tag{6}
\]

where \( f \) is a trial value of \( \Delta_l \), which is selected among the most reliable \( \alpha \) trial values obtained based on \( Z_{l}(k+f)X_l(k) \), \( D + 1 \) is the number of symbols used in estimation of \( \Delta_l \), and \( Z_{l}(k+f) \) and \( \hat{Z}_{l}(k+f) \) are defined as \( Z_{l}(k+f)Y_{l,i}(k+f) \) and \( Y_{l}(k+f)Y_{l,i}(k+f) \), respectively.

### 4. Proposed Method

As shown in the previous section, the conventional method uses combinations only of two CPs and of a CP and an SP nearest to it. That is, only some parts of all combinations among CPs and SPs are used in the conventional method. So, we propose a new method that uses all combinations of pilots, which should offer better performance than the conventional method as a result of more information being used.

First, we create the following template.

\[
d_{l,i}(n,i) = \frac{P_{l,i}(i)}{P_l(i)}, \tag{7}
\]

for \( n \in P_i, i \in P_{n}, l \leq m \in \{0,1,\ldots,D\}, m-l = 1 \) or \( 0 \), \( (\text{7}) \)

where \( P_i \) and \( P_{n} \) are the sets of subcarrier indices allocated for CPs and SPs in the \( l \) th and \( m \) th symbols, respectively.

Then, exploiting all combinations among pilots on two consecutive symbols of \( D + 1 \) OFDM symbols, we can obtain an estimate \( \hat{\Delta}_l \) of \( \Delta_l \) as follows.

\[
\hat{\Delta}_l = \arg \max_{\{f\}^{D+1}} \left\{ \Re \left[ \sum_{n \in P_i \cup P_{n}, l \leq m \in \{0,1,\ldots,D\}} d_{l,i}(n,i)Y_l(n+f)Y_{l,i}(i+f) \right] \cdot \exp(j2\pi fN_0(m-l)/N) \right\}, \tag{8}
\]

where \( M \) is a maximum allowable value of \( f \), we refer to the method shown in (7) as proposed I method.

As shown in (8), the proposed method uses all information that can be obtained from all combinations of pilots. However,
the proposed method may be complex for practical usage. Thus, we form a group centering a pilot and the group is set to contain 25 subcarriers, considering the period of SP insertion.

Then, all combinations of pilot symbols within the group are used to estimate $\Delta_i$, which is referred to as proposed II method.

5. Simulation Results

In this section, the proposed methods are compared with the conventional method in terms of the probability of integer frequency offset estimation failure.

![Figure 2. The probability of estimation failure with the AWGN channel](image1)

![Figure 3. The probability of estimation failure with a multipath channel](image2)

We consider a DVB system with 2K mode and QPSK data transmission. The system parameters used in the simulation as follows: $M = 2$, $\alpha = 5$, $D = 1$, and a guard interval length of $28\mu$s. Two channel models are employed: additional white Gaussian noise (AWGN) and multipath Rayleigh with an exponential power delay profile channels. The number and maximum delay of multipaths, and maximum Doppler frequency are set to 9, 8.75$\mu$s, and 100$Hz$, respectively.

Figs. 2 and 3 show the probability of integer frequency offset estimation failure of the conventional, proposed I, and proposed II estimation methods in AWGN and Rayleigh channels.

As shown in the figures, the proposed I and II methods dramatically outperform the conventional method both in AWGN and Rayleigh channels. This stems from the fact that the proposed methods employ more information than the conventional method.

In Fig. 3, we can observe that the performance of the two proposed methods become reverse in the SNR range, more than -7dB. This implies that the proposed II method can be used in the SNR range, instead of the proposed I method, resulting in a decrease in computation complexity.

6. Conclusion

OFDM system is very sensitive to frequency synchronization error, the frequency offset. Therefore, in this paper, the new pilot-aided frequency offset estimation methods have been proposed for OFDM-based DVB systems by exploiting the information of all combinations that pilots provide in frequency domain. From the simulation results, as a result of more information being used, we have observed that the proposed methods are highly accurate and outperform the conventional method in terms of the probability of integer frequency offset estimation failure.

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