Novel Schemes of Pilot-Aided Integer Frequency Offset Estimation for OFDM-Based DVB-T Systems

Youngyoon Lee, Dahae Chong, Myungsoo Lee, Seongho Chae, and Seokho Yoon

Abstract—This paper proposes two novel schemes for pilot-aided integer frequency offset (IFO) estimation in orthogonal frequency division multiplexing (OFDM)-based digital video broadcasting-terrestrial (DVB-T) systems. The conventional scheme proposed for estimating the IFO uses only partial information of combinations that pilots can provide, which stems from a rigorous assumption that the channel responses of pilots used for estimating the IFO change very rapidly. Thus, in this paper, we propose the novel IFO estimation schemes exploiting all information of combinations that pilots can provide to improve the performance of IFO estimation. The simulation results show that the proposed schemes are highly accurate in terms of the IFO detection probability.

Keywords—OFDM, DVB-T, pilot, IFO, estimation

I. INTRODUCTION

DUE to its immunity to impulsive noise and multipath fading and the optimum use of spectrum, orthogonal frequency division multiplexing (OFDM) has been widely used as a modulation scheme in wireless communication systems such as digital audio broadcasting (DAB) and digital video broadcasting-terrestrial/handheld (DVB-T/H) systems, wireless local area networks (WLANs), and high performance radio LAN type 2 (HIPERLAN/2) [1]-[4].

As well known, however, OFDM-based systems are very sensitive to the frequency offset (FO) caused by a mismatch between the oscillators in the transmitter and receiver or a Doppler shift, resulting in a significant performance degradation. Therefore, the FO estimation is one of the most important procedures in the OFDM-based systems. The FO normalized to subcarrier spacing can be divided into integer and fractional parts, which bring on a cyclic shift of the subcarrier indices of the OFDM symbols and an intercarrier interference (ICI), respectively [5]. In this paper, we focus on the integer FO (IFO) estimation for the OFDM-based DVB-T systems.

Recently, an efficient IFO estimation scheme has been proposed for the OFDM-based DVB-T systems [3]. In the conventional scheme, partial information of combinations that pilots can provide is used for IFO estimation, based on the assumption that channel responses of pilots used for estimating the IFO change very rapidly. However, this assumption is so rigorous.

Thus, in this paper, we propose two novel schemes for IFO estimation that use all information of combinations provided by pilots. The rest of this paper is organized as follows. Section

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II describes the system model. In Section III, the conventional scheme is addressed and two novel pilot-aided schemes for IFO estimation are proposed in Section IV. Section V compares the performance of the conventional and proposed IFO estimation schemes in the additive white Gaussian noise (AWGN) and multipath fading channels. Finally, Section VI concludes this paper.

II. SYSTEM MODEL

The DVB-T system operates in 2K or 8K mode, depending on the total number of subcarriers. In this paper, we consider the DVB-T system with 2K mode, where 1705 subcarriers among 2048 total subcarriers are used to transmit data, 45 continual pilots (CPs), and 142 or 143 scattered pilots (SPs). The pilots can be used for frequency and timing synchronization and channel response estimation. The value of pilot is $+4/3$ or $-4/3$, which is randomly decided by a pseudo random binary sequence (PRBS). Fig. 1 describes the pilot arrangement in the DVB-T system with 2K mode, where K_{min} and K_{max} are the smallest and largest numbers of the active subcarriers that transmit the complex-valued symbols, respectively [6]. The values of pilots with the same subcarrier index in all OFDM symbols are the same. The SPs are periodically inserted every twelve subcarriers in an OFDM symbol and their locations are periodic for every four OFDM symbols.

In the OFDM system, the n-th sample of the l-th OFDM symbol is generated by taking the inverse fast Fourier transform (IFFT) and can be expressed as

$$x_l(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} P_l(k) e^{j2\pi kn/N},$$

$$\text{for } l = 0, 1, ..., \text{ and } n = 0, 1, ..., N-1, \quad (1)$$

where k is the subcarrier index, $P_l(k)$ is a pilot or data transmitted through the k-th subcarrier of the l-th OFDM symbol, and N is the size of the IFFT. After the guard interval
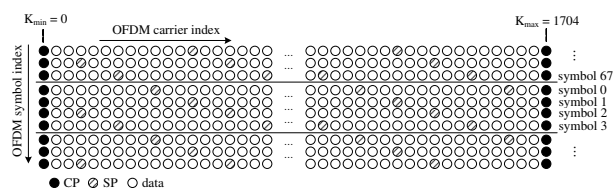

Fig. 1. Pilot arrangement in the DVB-T system with 2K mode.

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is inserted, the output sequence including the guard interval is

$$x_l^g(n) = x_l(n + N - N_g)_N, \quad \text{for} \ \ 0 \le n \le N + N_g - 1, \ (2)$$

where $(n)_N$ denotes the residue of n modulo N. Then, the n-th sample of the l-th received OFDM symbol $y_l(n)$ in the time domain is obtained as

$$\begin{aligned} y_l(n) &= \mathrm{e}^{j2\pi\Delta(n+lN_T)/N}[h_l(n) \otimes x_l^g(n)] + w_l(n) \\ &= s_l(n) + w_l(n), \end{aligned} \quad (3)$$

where Δ, N_T, $h_l(n)$, $\otimes$, and $w_l(n)$ denote the FO normalized to subcarrier spacing, the length of the OFDM symbol including the guard interval, the channel impulse response, the convolution operation, and an AWGN sample with zero-mean and variance $\sigma_w^2 = \mathbf{E}\{|w_l(n)|^2\}$, respectively. The signal to noise ratio (SNR) ρ is defined as $\rho \triangleq \sigma_s^2/\sigma_w^2$ with $\sigma_s^2 = \mathbf{E}\{|s_l(n)|^2\}$.

In the receiver, we assume that the timing offset and the fractional FO (FFO) are precisely measured and compensated before the IFO estimation. Then, the FFT output corresponding to the k-th subcarrier of the l-th received OFDM symbol is represented as

$$Y_l(k) = \mathrm{e}^{j2\pi\Delta_i lN_T/N}H_l(k-\Delta_i)P_l(k-\Delta_i) + W_l(k), \ \ (4)$$

where Δ_i is the IFO, $H_l(k)$ is the channel response on the k-th subcarrier of the l-th OFDM symbol, and $W_l(k)$ is the zero-mean complex AWGN sample in the frequency domain. From (4), we can observe that the IFO introduces the cyclic shift of the subcarrier indices in the OFDM symbol.

III. CONVENTIONAL SCHEME

The conventional scheme uses two templates $X_l(k)$ and $\hat{X}_l(k)$ related to the indices and values of the pilots in order to estimate the IFO [3].

$$X_l(k) = \frac{P_l(k')}{P_l(k)}, \quad \text{for} \quad k \in C_{cp} \quad (5)$$

and

$$\hat{X}_l(k) = \frac{P_{l+1}(k)}{P_l(k)}, \quad \text{for} \quad k \in C_{cp}, \quad (6)$$

where C_{cp} is the set of CP indices and k' is a subcarrier index of the SP nearest to the CP with index of k. As shown in (5) and (6), $X_l(k)$ and $\hat{X}_l(k)$ are expressed by the combinations of a CP and its nearest SP in an OFDM symbol and of two CPs located on the same indices in the two consecutive OFDM symbols, respectively. The value that templates have is either +1 or -1.

Assuming that the channel responses of two pilots used in combinations are the same and the SNR is high, an estimate $\hat{\Delta}_i$ of Δ_i can be obtained as

$$\begin{aligned} \hat{\Delta}_i = \arg \max_{f \in \{f_1, \ldots, f_\alpha\}} &\Big\{ \mathbf{Re}\Big(\sum_{k \in C_{cp}} \sum_{l=0}^{D} Z_l(k+f)X_l(k) \\ &+ \sum_{k \in C_{cp}} \sum_{l=0}^{D-1} \hat{Z}_l(k+f)\hat{X}_l(k)\mathrm{e}^{j2\pi f N_T/N} \Big) \Big\}, \end{aligned} \quad (7)$$

where f is a trial value of Δ_i, which is selected among the most reliable α trial values obtained based on $Z_0(k+f)X_0(k)$,
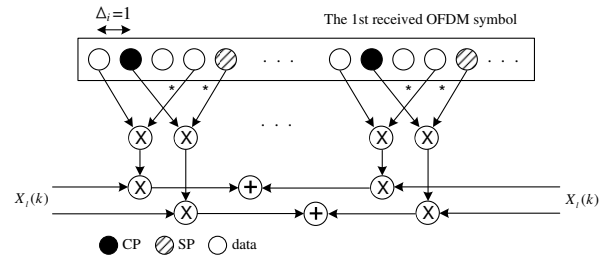

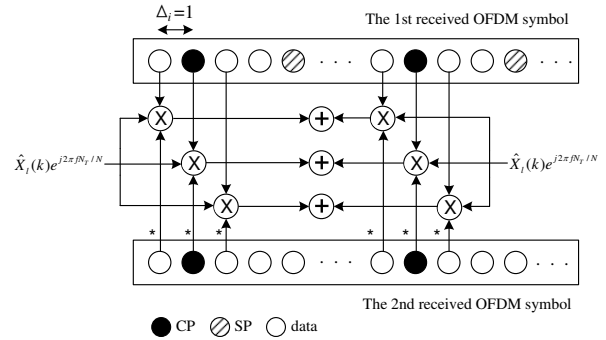Fig. 2. The structure of the conventional scheme exploiting the first template.

Fig. 3. The structure of the conventional scheme exploiting the second template.

$D+1$ is the number of the OFDM symbols used for estimation of Δ_i, and $Z_l(k+f)$ and $\hat{Z}_l(k+f)$ are defined as $Y_l(k+f)Y_l^*(k'+f)$ and $Y_l(k+f)Y_{l+1}^*(k+f)$, respectively. If α is set to 1, the conventional scheme estimates the IFO without the template defined in (6).

Figs. 2 and 3 illustrate the structures of the conventional scheme exploiting the two templates, when $\Delta_i = 1$. In the figures, $*$ denotes the complex conjugate. Fig. 2 explains the structure using the first template defined in (5). In Fig. 3, the structure using the second template defined in (6) related to the combinations of the two CPs located on the same indices in the two consecutive OFDM symbols is shown.

IV. PROPOSED SCHEMES

As shown in the previous section, the conventional scheme uses only combinations of two CPs and of a CP and its nearest SP. It means that partial parts of all combinations among CPs and SPs are only used in the conventional scheme. However, this stems from a rigorous assumption that channel responses of a CP and an SP related to the templates change very rapidly. Thus, we consider the additional combinations that pilots provide, which is not used in the conventional scheme, to improve the performance of IFO estimation.

First, we create the following template.

$$d_{l,m}(n,i) = \frac{P_m(i)}{P_l(n)}, \quad (8)$$

where $n \in p_l$, $i \in p_m$, $l, m \in \{0, 1, \ldots, D\}$, and $|m - l| \le 1$. p_l and p_m are the sets of subcarrier indices allocated for pilots in the l-th and m-th OFDM symbol, respectively. Then, exploiting all combinations among pilots in the two

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consecutive symbols of $D+1$ OFDM symbols, we can obtain a correlation function as

$$M(f) = \sum_{n,i \in p_l, p_m} d_{l,m}(n,i) Y_l(n+f) Y_m^*(i+f)$$
$$\times \, e^{j2\pi f(m-l)N_T/N}. \qquad (9)$$

When the SNR is high and the channel responses of the n-th subcarrier of the l-th OFDM symbol and the i-th subcarrier of the m-th OFDM symbol are the same, we can have the approximation of (9)

$$M(f) \simeq \sum_{n,i \in p_l, p_m} d_{l,m}(n,i) |H_l(n+f-\Delta_i)|^2$$
$$\times \, P_l(n+f-\Delta_i) P_m^*(i+f-\Delta_i)$$
$$\times \, e^{j2\pi(f-\Delta_i)(m-l)N_T/N}. \qquad (10)$$

If the IFO Δ_i is estimated exactly, (10) has a real number. Thus, finally, we obtain the estimate of IFO $\hat{\Delta}_i$ as

$$\hat{\Delta}_i = \arg\max_f \{ \mathbf{Re}(M(f)) \}, \qquad (11)$$

where f is a trial value of Δ_i. In the following, this scheme is called the proposed scheme I. As shown in (8), the proposed scheme I uses information of all combination provided from pilots. Thus, the computational load of the proposed scheme I will be relatively high. Also the assumption that the channel responses of a pilot and other pilots remote from it are same is not reasonable.

Taking into consideration the channel responses of pilots and the complexity issue, we propose a modified IFO estimation scheme. In the DVB-T system, the SP is periodically inserted every twelve subcarriers in an OFDM symbol. Considering this period of SP insertion, we can form a group centering every pilot with 25 subcarriers. If two consecutive OFDM symbols are used, the first pilot of the first OFDM symbol is the first center pilot and the last pilot of the second OFDM symbol is the last center pilot. Since there are many pilots in the two consecutive OFDM symbols, many groups are also formed. Focusing on all combinations of pilots within this group, we can modify the template (8) as

$$\hat{d}_{l,m}(n,i) = \frac{P_m(i)}{P_l(n)}, \qquad (12)$$

which satisfies the condition $|n-i| \le 12$. Substituting (12) into (10), we can obtain the modified correlation function as

$$M(f) = \sum_{n,i \in p_l, p_m} \hat{d}_{l,m}(n,i) Y_l(n+f) Y_m^*(i+f)$$
$$\times \, e^{j2\pi f(m-l)N_T/N}. \qquad (13)$$

The IFO estimation scheme employing this modified correlation function is referred to as the proposed scheme II. Fig. 4 shows an example of a group whose center pilot is the second pilot of the first OFDM symbol.

V. SIMULATION RESULTS

In this section, the proposed schemes are compared with the conventional scheme in terms of the IFO detection probability. We consider the DVB-T system with 2K mode and quadrature
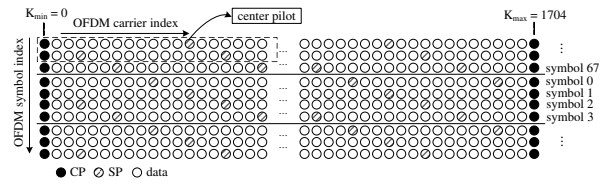

Fig. 4.   An example of a group in the proposed scheme II.

phase shift keying (QPSK) data transmission. The system parameters used in the simulation are as follows: $\alpha = N$, $D = 1$, $\Delta_i = 1$, and a guard interval length of 256 samples. Two channel models are employed: AWGN and multipath fading channels. The multipath fading channel has 9 paths with path delays of 0, 10, 20, 30, 40, 50, 60, 70, and 80 samples, respectively. The amplitude A_l of the l-th path varies independently from the others according to a Rayleigh distribution with exponential power delay profile such that $\mathbf{E}\{A_l^2\} = \exp(-0.8l)$ and the maximum Doppler frequency is set to 100 Hz. Figs. 5 and 6 show the IFO detection probabilities of the conventional scheme and proposed schemes I and II in the AWGN and the multipath fading channels, respectively. As shown in Fig. 5, both proposed schemes I and II outperform the conventional scheme in the AWGN channel. Especially, the proposed scheme I shows dramatic performance improvement. This stems from the fact that the proposed schemes employ more combinations of pilots than those of the conventional scheme. From the figure, we can observe that more combination of pilots can give higher accuracy in the IFO estimation in the AWGN channel and thus, the performance of the proposed scheme I employing all combination of pilots is the best. On the other hand, in the multipath fading channel, the performance of the two proposed schemes is reversed above the SNR value of -10 dB and the performance of the proposed scheme I and conventional scheme becomes reverse in the SNR range, more than -4 dB, respectively as shown in Fig. 6. This is because that the channel responses of pilots used for making the templates have influence on the performance of IFO estimation. The
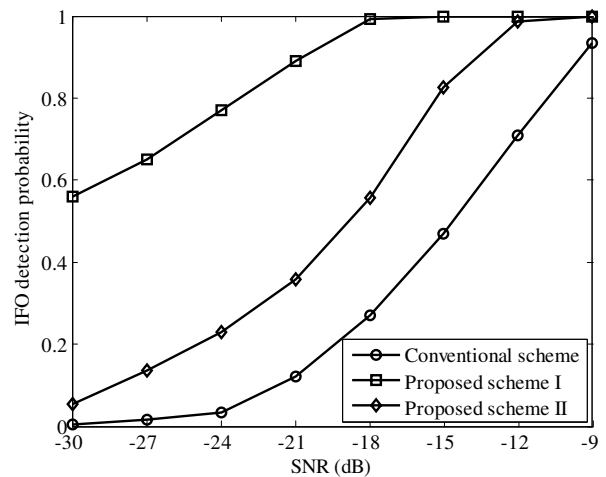

Fig. 5.   IFO detection probabilities in the AWGN channel.

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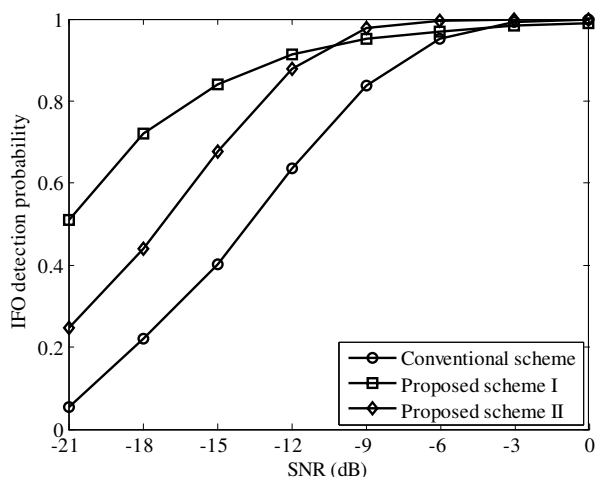Vol:3, No:11, 2009

Fig. 6.   IFO detection probabilities in the multipath fading channel.

proposed scheme II considers the channel responses of pilots so that the performance of proposed scheme II is better than that of proposed scheme I in that SNR range. Also pilots used for making the template in the proposed scheme I can be affected by the channel responses than those of the conventional scheme in that SNR range.

VI. CONCLUSION

In this paper, we have proposed two novel pilot-aided schemes for IFO estimation in the OFDM-based DVB-T systems, where all information of combinations that pilots provide is exploited. From the simulation results, we have confirmed that IFO estimation performance of two schemes proposed in this paper is better than that of the conventional scheme in the AWGN channel. Also IFO estimation performance of the proposed scheme I outperforms other schemes in the SNR range, less than -10 dB and the performance of the proposed scheme II is the best in the SNR range, more than -4 dB, respectively in the multipath channel.

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