Estimation Schemes of OFDM Integer Frequency Offset for DVB-T Systems

Youngpo Lee, Jong In Park, and Seokho Yoon[†]

School of Information and Communication Engineering, Sungkyunkwan University, South Korea
[†]Corresponding Author (e-mail: syoon@skku.edu)

Abstract— **In this paper, we propose two estimation schemes of orthogonal frequency division multiplexing (OFDM) integer frequency offset (IFO) for digital video broadcasting-terrestrial (DVB-T) systems. In the conventional scheme, the decision variable is based on the limited number of the correlations and ratios of pilots of the received samples, and thus, the decision variable contains only a small portion of the signal energy, resulting in performance degradation. On the other hand, the propose schemes combine the correlations and ratios of pilots of the received samples efficiently. Numerical results demonstrate that the proposed schemes provide a better performance compared with that of the conventional scheme in terms of the correct estimation probability.**

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

I. INTRODUCTION

Recently, driven by the demand for high quality mobile broadcasting services, digital video broadcasting-terrestrial (DVB-T) systems have been highlighted due to its high data rate [1]-[3]. DVB-T systems are able to maintain its high data rate by employing an orthogonal frequency division multiplexing (OFDM) as the modulation scheme [4], [5], however, the frequency offset (FO) caused by the mismatch between the oscillators in the transmitter and receiver or Doppler frequency severely degrades the overall performance of the OFDM-based systems [6], [7]. Thus, the FO estimation and compensation processes are essential for the reliable DVB-T systems. The FO normalized to the subcarrier spacing of the OFDM symbol can be divided into the integer and fractional parts, which bring on a shift of the subcarrier indices of the OFDM symbol and an intercarrier interference, respectively. In this paper, we focus on the integer FO (IFO) estimation for OFDM-based DVB-T systems.

Several IFO estimation schemes have been proposed for the DVB-T systems [8], [9]. In [8], the IFO is estimated using the decision variable generated by combining the correlations and ratios of pilots of the received samples with the same subcarrier indices of two consecutive OFDM symbols. In order to improve the IFO estimation performance, the scheme in [9] uses not only the correlations in [8], but also some additional correlations between the received samples in each OFDM symbol to form the decision variable. However the decision variables in [8] and [9] are still based on the limited number of the correlations and ratios of pilots, and thus, the decision variables contain only a small portion of the signal energy, resulting in performance degradation.

In this paper, thus, we propose two novel IFO estimation schemes combining the correlations and ratios of pilots of the received samples efficiently. In the proposed scheme I, all possible correlations and ratios of pilots of the received samples are combined to form the decision variable. In the proposed scheme II, the number of combinations between the correlations and ratios of pilots are combined efficiently to form a decision variable using a distance parameter considering the influence of the channel. Numerical results demonstrate that the proposed schemes provide a better performance compared with that of the conventional scheme in [9] in terms of the correct estimation probability.

II. SYSTEM MODEL

DVB-T systems operate in 2K or 8K mode, depending on the total number of the subcarriers. In this paper, we consider DVB-T systems 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). Fig. 1 describes the pilot arrangement in DVB-T systems with 2K mode, where K_{min} and K_{max} are the smallest and largest subcarrier indices of the active subcarriers that transmit the complex valued symbols, respectively [4]. The subcarrier indices of the CPs in an OFDM symbol are fixed and their subcarrier indices are the same for all OFDM symbols, on the other hand, the SPs are periodically inserted every twelve subcarriers in an OFDM symbol and their locations are periodic for every four OFDM symbols.

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

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

for $l = 0, 1, \cdots, \infty$ and $0 \le n \le N-1$, where N is the size of the IFFT, k is the subcarrier index, and $X_l(k)$ is a pilot or data transmitted through the k th subcarrier of the l th OFDM symbol. After the guard interval is inserted, the output sequence including the guard interval is

$$x_{l,g}(n) = x_l \left(n + N - N_g \right)_N \qquad (2)$$

for $0 \le n \le N + N_g - 1$, where N_g is the length of the guard interval and $(u)_v$ denotes the result of u modulo v. Then, the n th sample of the l th received OFDM symbol $y_l(n)$ in the time domain is obtained as
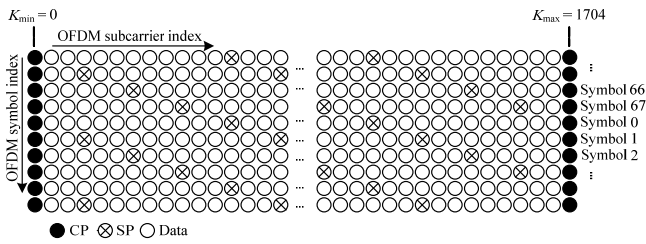
Fig. 1. Pilot arrangement in DVB-T systems with 2K mode.

$$y_l(n) = e^{j2\pi\Delta n/N} \left[h_l(n) \otimes x_{l,g}(n) \right] + w_l(n)$$
$$= s_l(n) + w_l(n) \tag{3}$$

for $0 \le n \le N + N_g - 1$, where Δ, $h_l(n)$, $\otimes$, and $w_l(n)$ denote the FO normalized to the subcarrier spacing, the channel impulse response, the convolution operation, and an additive white Gaussian noise (AWGN) sample with zero mean and variance of $\sigma_w^2 = E\left\{ |w_l(n)|^2 \right\}$, respectively. The signal-to-noise ratio (SNR) is defined as σ_s^2 / σ_w^2 with $\sigma_s^2 = E\left\{ |s_l(n)|^2 \right\}$.

In the receiver, the guard interval is first removed, and then, the estimation and compensation processes for the fractional FO (FFO) are generally performed before the IFO estimation [9]. Assuming the perfect estimation and compensation for the FFO, the FFT output corresponding to the k th subcarrier of the l th received OFDM symbol is represented as

$$Y_l(k) = H_l(k - \Delta_I) X_l(k - \Delta_I) + W_l(k), \tag{4}$$

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 shift of the subcarrier indices in the OFDM symbol.

The ratio between SP and CP of the l th OFDM symbol is defined as

$$C_l(k) = \frac{X_l(k')}{X_l(k)}, \text{ for } k' \in S_{SP} \text{ and } k \in S_{CP}, \tag{5}$$

where S_{SP} and S_{CP} are the sets of the subcarrier indices of the SPs and CPs, respectively, k' is the index of the SP nearest to the CP with the index k, and the ratio between CP of the l th OFDM symbol and CP of the $l+1$ th OFDM symbol are defined as

$$D_l(k) = \frac{X_{l+1}(k)}{X_l(k)}, \text{ for } k \in S_{CP}. \tag{6}$$

The value of $C_l(k)$ is -1 or 1 depending on the value of l and k and that of $D_l(k)$ is 1 regardless of the value of l and k.

Using the ratios between pilots, the conventional scheme in [9] obtains an estimate $\hat{\Delta}_{I,conv}$ of Δ_I as

$$\hat{\Delta}_{I,conv} = \underset{f_c \in \{f_1, \ldots, f_\alpha\}}{\arg\max} Z_{conv}(f_c) \tag{7}$$

and

$$Z_{conv}(f_c) = \text{Re}\left(\sum_{l=0}^{L-1} \sum_{k \in S_{CP}} U_l(k + f_c) C_l(k) \right.$$
$$\left. + \sum_{l=0}^{L-2} \sum_{k \in S_{CP}} V_l(k + f_c) D_l(k) \right), \tag{8}$$

where f_c is a trial value to estimate Δ_I, which is selected among the most reliable α trial values obtained based on $U_0(k+f)C_0(k)$, L is the number of the OFDM symbols exploited to estimate Δ_I, and $U_l(k+f_c)$ and $V_l(k+f_c)$ are defined as the correlations between the received samples $Y_l(k+f_c)Y_l^*(k'+f_c)$ and $Y_l(k+f_c)Y_{l+1}^*(k+f_c)$, respectively. When $L = 1$, the decision variable $Z_{conv}(f_c)$ is rewritten as $Z_{conv}(f_c) = \text{Re}\left(\sum_{k \in S_{CP}} U_0(k+f_c)C_0(k) \right)$, and when $\alpha = 1$, the conventional scheme estimates the IFO as

$$\hat{\Delta}_{I,conv} = \underset{|f| \le N/2}{\arg\max} \left\{ \text{Re}\left(\sum_{k \in S_{CP}} U_0(k+f)C_0(k) \right) \right\}. \quad \text{The}$$

conventional scheme would not have enough signal energy to perform reliable IFO estimation since the signal energy in the decision variable depends on the number of CPs as shown in (7) and (8).

III. PROPOSED SCHEMES

In this section, we propose novel IFO estimation schemes using the decision variable generated by combining the correlations and ratios of pilots efficiently. First, we define the new ratio between pilots as

$$G_{q,m}(n,i) = \frac{X_m(i)}{X_q(n)}, \text{ for } n \in S_{P_q} \text{ and } i \in S_{P_m}, \tag{9}$$

where S_{P_q} and S_{P_m} are the sets of the subcarrier indices of the pilots in the q th and m th OFDM symbols, respectively. Then, using the new ratio $G_{q,m}(n,i)$, we make the decision variable $Z_{prop\,I}(f)$ as

$$Z_{prop\,I}(f) = \sum_{q=0}^{L-1} \sum_{m=0}^{L-1} \sum_{n \in S_{P_q}} \sum_{i \in S_{P_m}} G_{q,m}(n,i) Y_q(n+f) Y_m^*(i+f). \tag{10}$$

Finally, the IFO can be estimated by

$$\hat{\Delta}_{I,prop\,I} = \underset{|f| \le N/2}{\arg\max} \left\{ \text{Re}\left(Z_{prop\,I}(f) \right) \right\}, \tag{11}$$

referred to as the proposed scheme I. As shown in (10) and (11), the proposed scheme I uses every possible combinations between the correlations and ratios of pilots, thus, it is expected that the proposed scheme I has a good estimation performance averaging the noise components out. However, in the frequency selective channel with small coherence bandwidth, the proposed scheme I would experience some performance degradation due to some correlations and ratios
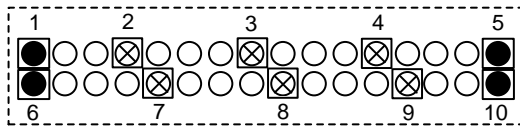
● CP   ⊗ SP   ○ data   □ pilots used in the combination

Fig. 2. An example of the pilot combinations for correlations $Y_q(3+\Delta_I)Y_q^*(i+\Delta_I)$ and $Y_q(3+\Delta_I)Y_{q+1}^*(i+\Delta_I)$ $(1 \le i \le 10)$ for the proposed scheme I when indices of the received OFDM symbols are q and $q+1$.
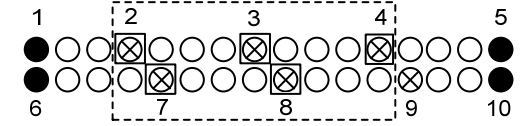
● CP   ⊗ SP   ○ data   □ pilots used in the combination

Fig. 3. An example of the pilot combinations for correlations $Y_q(3+\Delta_I)Y_q^*(i+\Delta_I)$ and $Y_q(3+\Delta_I)Y_{q+1}^*(i+\Delta_I)$ $(1 \le i \le 10)$ for the proposed scheme II when $B=4$ and indices of the received OFDM symbols are q and $q+1$.

of pilots whose absolute difference of subcarrier indices is larger than the coherence bandwidth.

Taking the coherence bandwidth of the channel into consideration, we define the modified ratio between pilots as

$$Q_{q,m}(n,i) = \frac{X_m(i)}{X_q(n)}, \text{ for } n \in S_{P_q} \text{ and } i \in S_{P_m}, \quad (12)$$

which satisfies the condition $|n-i| \le B$, where the distance parameter B is not larger than the coherence bandwidth normalized to the subcarrier spacing of the channel. Then, the modified decision variable $Z_{\text{prop II}}(f)$ is generated using the ratio in (12) as

$$Z_{\text{prop II}}(f) = \sum_{q=0}^{L-1}\sum_{m=0}^{L-1}\sum_{n \in S_{P_q}}\sum_{i \in S_{P_m}} Q_{q,m}(n,i)Y_q(n+f)Y_m^*(i+f), \quad (13)$$

and we obtain the estimate for $\hat{\Delta}_I$ as

$$\hat{\Delta}_{I,\text{prop II}} = \arg\max_{|f| \le N/2}\left\{\text{Re}\left(Z_{\text{prop II}}(f)\right)\right\}, \quad (14)$$

which is referred to as the proposed scheme II.

Figs. 2 and 3 show the examples of the pilot combinations for correlations $Y_q(3+\Delta_I)Y_q^*(i+\Delta_I)$ and $Y_q(3+\Delta_I)Y_{q+1}^*(i+\Delta_I)$ $(1 \le i \le 10)$ for proposed scheme I and II, respectively, when $B=4$ and indices of the received OFDM symbols are q and $q+1$. In Fig. 2, the number of the available correlations is 10, and they are combined with $G_{q,q}(3,i)$ and $G_{q,q+1}(3,i)$, meanwhile in Fig. 3, the number of the available correlations is 5, and they are combined with $G_{q,q}(3,i)$ and $Q_{q,q+1}(3,i)$. If the coherence bandwidth of the channel is sufficiently large, the decision variable of the proposed scheme I can fully exploit the pilot signal energy. However, if the coherence bandwidth of the channel is small, the decision variable of the proposed scheme I includes
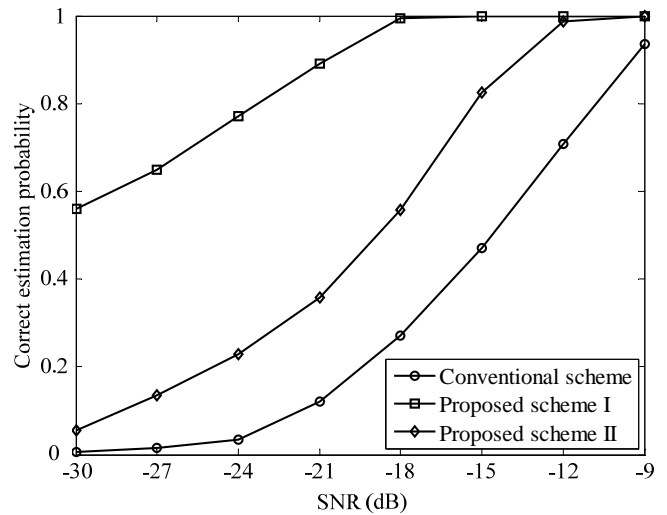

Fig. 4. Correct estimation probabilities in the AWGN channel model.
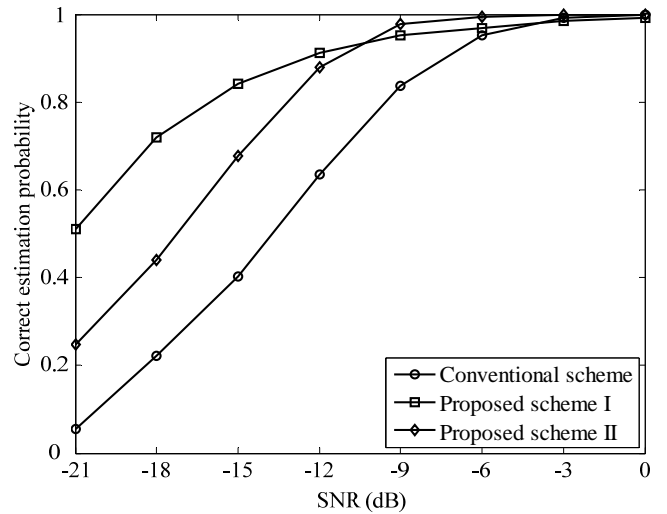

Fig. 5. Correct estimation probabilities in the multipath fading channel model.

undesirable correlations between the pilots whose distance is larger than the coherence bandwidth, which would lower the signal energy of the decision variable, thus in this case, the proposed scheme II would be preferred to the proposed scheme I.

IV. NUMERICAL RESULTS

In this section, the performance of proposed schemes are compared with the conventional scheme in [9] in terms of the correct estimation probability defined as the probability that the estimated IFO is the same as Δ_I. We consider DVB-T systems with 2K mode. The parameters are as follows: $\alpha = N = 2048$, $L = 2$, $N_g = 256$, and $B = 12$. For simulations, we employ the multipath fading channel with 9 paths. The distance between paths is set to 10 samples and the amplitude of each path has a Rayleigh distribution with average power $E\{A_j^2\} = \exp(-0.8j)/\sum_{j=0}^{8}\exp(-0.8j)$, where j is the index of the path. The coherence bandwidth of

the channel for the simulation is set to approximately 34 (normalized to the subcarrier spacing) [10].

Fig. 4 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. 4, 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. 5 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 the case in Fig. 4, it is shown that 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 .

V. CONCLUSION

In this paper, we have proposed novel IFO estimation schemes for OFDM-based DVB-T systems. In the proposed scheme I, the decision variable is formed by combining all available correlations and ratios of pilots, on other hand, in the proposed scheme II, the number of combinations between the correlations and ratios of pilots are combined efficiently to form a decision variable using a distance parameter considering the influence of the channel. From numerical results, we have confirmed that the proposed schemes provide a better performance compared with that of the conventional scheme in terms of the correct estimation probability. When the coherence bandwidth of the channel is sufficiently large,

the proposed scheme I shows the best performance, on the other hand, when the coherence bandwidth of the channel is small, the proposed scheme II shows the best performance by using the distance parameter at high SNR range.

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