Low-overhead sampling clock frequency synchronization for OFDM-based DRM systems

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Abstract: In this paper, an improved and low-complexity sampling clock frequency offset (SFO) estimation scheme is proposed for orthogonal frequency division multiplexing (OFDM) based digital radio mondiale (DRM) systems. In order to devise the low-complexity SFO estimator, some modifications on the conventional estimator are highlighted with an emphasis on the selection of pilot subcarrier.

Keywords: OFDM, digital radio mondiale, sampling frequency offset

Classification: Science and engineering for electronics

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1 Introduction

Orthogonal frequency division multiplexing (OFDM) is commonly used for wireless transmission nowadays because of the ability of combating the multi-path channel problem and is used in broadcast media like digital audio broadcasting (DAB), digital radio mondiale (DRM), and digital video broadcasting (DVB) [1, 2, 3]. Since DRM uses OFDM modulation which is very sensitive to frequency offsets, frequency synchronization has an important influence on the performance of the receiver. So far, a number of algorithms to combat the carrier frequency offset (CFO) and sampling clock frequency offset (SFO) for DRM systems, which use frequency reference cells (FRCs), are presented in [4, 5, 6, 7]. In DRM systems, only a few FRCs are embedded for frequency tracking. Therefore, increasing the accuracy of frequency estimation with the limited number of pilots is one of the major concerns for the DRM system.

This paper proposes an improved SFO estimation algorithm for the OFDM-based DRM system that can achieve a much lower computational burden than the conventional SFO estimators. The new scheme is tested and verified under simulations carried out within the framework of DRM systems.

2 Conventional estimation scheme

For the purposes of comparison, we introduce two conventional SFO estimation algorithms that exploit the differential relation among the FRCs. In the DRM system [3], three FRCs are put in subcarriers $\{k_1, k_2, k_3\}$, depending on transmission modes.

A frequency offset Δ_f between the transmit signal and the received signal can be introduced by inaccuracies of the receiver’s local oscillator. After compensating the CFO with estimated CFO $\hat{\Delta}_f$ at the acquisition stage, there might still be a residual CFO $\Delta_r = \hat{\Delta}_f - \Delta_f$ and possible SFO Δ_s . Thus, the received OFDM symbol after FFT demodulation is given by [8]

$$R_l(k) \approx H_l(k)X_l(k)e^{j2\pi(\Delta_r+k\Delta_s)(lN_u+N_g)/N}e^{j\pi(N-1)(\Delta_r+k\Delta_s)/N} + Z_l(k) \quad (1)$$

where N is the number of subcarriers, N_g is the number of guard interval (GI) samples, $N_u = N + N_g$, $H_l(k)$ is the channel’s frequency response, and $Z_l(k)$ is a zero-mean complex Gaussian noise during the l -th symbol period.

2.1 Method A

The SFO estimation scheme in [4] uses the difference between two neighboring FRCs in the frequency direction, producing the form

$$\hat{\Delta}_s = \frac{1}{4\pi\rho} \sum_{i=2}^3 \frac{\vartheta(k_i) - \vartheta(k_1)}{k_i - k_1} \quad (2)$$

where $\rho = N_u/N$, $\vartheta(k_i) = \arg \left\{ \sum_{l=1}^{N_a} R_l^*(k_i) R_{l+1}(k_i) \right\}$, and $\arg\{x\}$ stands for the angle of a complex number x . From above, N_a is the number of averaging in the time direction and $\vartheta(k_i) = 2\pi(\Delta_r + k_i\Delta_s)\rho + z_l(k_i)$, where $z_l(k_i)$ refers to a noise which vanishes in absence of the additive noise $Z_l(k_i)$ and when the inter-carrier interference (ICI) is neglected.

2.2 Method B

In [5], an estimator based on the differential relation among pilot subcarrier indexes provided in the DRM system, i.e., $k_2 - k_1 = 2(k_3 - k_2)$ and $k_3 - k_1 = 3(k_3 - k_2)$, is proposed. The resulting expression is

$$\hat{\Delta}_s = \frac{1}{4\pi\rho(k_3 - k_2)} \arg \left\{ \sum_{l=1}^{N_a} \sum_{m=1}^3 \sum_{\substack{n=1 \\ n < m}}^3 \hat{R}_l(k_m) \hat{R}_l^*(k_n) \right\} \quad (3)$$

where $\hat{R}_l(k) = R_l^*(k) R_{l+1}(k)$.

3 Proposed estimation scheme

In this section, we suggest an improved SFO estimation scheme for DRM systems by employing FRCs, which is consistent on a modification of the estimator (2).

3.1 Algorithm description

In order to reduce the effect of noise, the difference between two pilot frequencies is designed to produce the following form

$$k_{f_1}\vartheta(k_{g_1}) - k_{f_2}\vartheta(k_{g_2}) = 2\pi\Delta_s(k_{f_1}k_{g_1} - k_{f_2}k_{g_2})\rho + 2\pi\Delta_r(k_{f_1} - k_{f_2})\rho + k_{f_1}z_l(k_{g_1}) - k_{f_2}z_l(k_{g_2}) \quad (4)$$

where $f_i \in \{1, 2, 3\}$ and $g_i \in \{1, 2, 3\}$ that satisfies $k_{f_1}k_{g_1} - k_{f_2}k_{g_2} \neq 0$. Additionally, to exploit the statistically independent correlation samples, it should be $k_{g_1} \neq k_{g_2}$ so that $\vartheta(k_{g_1}) \neq \vartheta(k_{g_2})$.

Based on (4), the following estimator is eventually derived

$$\hat{\Delta}_s = \frac{1}{2\pi\rho} \frac{k_{f_1}\vartheta(k_{g_1}) - k_{f_2}\vartheta(k_{g_2})}{k_{f_1}k_{g_1} - k_{f_2}k_{g_2}}. \quad (5)$$

The mean square error (MSE) of (5) is expressed by

$$E[|\hat{\Delta}_s - \Delta_s|^2] = \left(\frac{1}{2\pi\rho} \right)^2 \left[\frac{k_{f_1}^2\sigma_{z_1}^2 + k_{f_2}^2\sigma_{z_2}^2}{(k_{f_1}k_{g_1} - k_{f_2}k_{g_2})^2} + E[|\hat{\Delta}_f - \Delta_f|^2] \left(\frac{k_{f_1} - k_{f_2}}{k_{f_1}k_{g_1} - k_{f_2}k_{g_2}} \right)^2 \right] \quad (6)$$

where $\sigma_{z_i}^2$ is the variance of $z_l(k_i)$, the first term is the noise variance caused by AWGN, and the second term is the bias introduced by residual CFO.

If we assume that the second term is negligible at high SNRs, equivalently $E[|\hat{\Delta}_f - \Delta_f|^2]$ is very small, (6) can be simplified as

$$E[|\hat{\Delta}_s - \Delta_s|^2] \approx \left(\frac{1}{2\pi\rho} \right)^2 \frac{k_{f_1}^2\sigma_{z_1}^2 + k_{f_2}^2\sigma_{z_2}^2}{(k_{f_1}k_{g_1} - k_{f_2}k_{g_2})^2} \quad (7)$$

Table I. Complexity comparison of SFO estimators

Estimator	Real multiplication	Real addition	$\arg(\cdot)$
Method A	$12N_a + 3$	$6N_a - 3$	3
Method B	$24N_a + 1$	$6N_a - 2$	1
Proposed	$8N_a + 2$	$4N_a - 3$	2

Table II. DRM robustness modes

Parameter	Mode A	Mode B	Mode C	Mode D
N	288	256	176	112
N_g	32	64	64	88

where the above approximation depends on the accuracy of initial frequency synchronization. For the estimation part of the initial frequency synchronization, a method based on GI correlation can be used [9, 10]. If the correlation value is calculated over several symbols, $E[|\hat{\Delta}_f - \Delta_f|^2]$ becomes much smaller. Note from (7) that MSE performance of (5) is a function of indexes of FRCs, thereby the choice of the sets $\{f_1, f_2\}$ and $\{g_1, g_2\}$ heavily affects (7). By a simple search, it is found that (7) is minimum when $\{f_1, f_2\} = \{g_1, g_2\} = \{1, 3\}$ or $\{3, 1\}$, which is true for all DRM operation modes.

With the searched configurations $\{f_1, f_2\} = \{g_1, g_2\} = \{1, 3\}$ or $\{3, 1\}$, the range of $(k_{f_1} - k_{f_2})^2 / (k_{f_1}k_{g_1} - k_{f_2}k_{g_2})^2$ in (6) is calculated by

$$10^{-4} < \left(\frac{k_{f_1} - k_{f_2}}{k_{f_1}k_{g_1} - k_{f_2}k_{g_2}} \right)^2 < 8 \times 10^{-4} \quad (8)$$

which says that the second term in (6) can be negligible. Note that the minimum and maximum values occur at DRM mode A and DRM mode D, respectively. In the next section, we resort to simulations to verify that the approximation (7) is reasonable.

3.2 Computational complexity

Now, we consider the computational complexity of calculating (2), (3) and (5). Table I shows the complexity comparison of SFO estimators in terms of the number of real multiplications and additions. It is evident that the proposed SFO scheme can be implemented with low complexity over the conventional methods, while two computations of inverse tangent to find the phase angle are required.

4 Simulation results

In this section, simulations are performed to verify the usefulness of the proposed estimator in DRM channel models, taking into account different DRM robustness modes [3], whose main parameters are summarized in Table II. For CFO and SFO, $\Delta_f = 10^{-1}$ and $\Delta_s = 20$ ppm were used. The initial CFO

Fig. 1. MSE of the SFO estimation schemes versus SNR in channel 1 and channel 3

Fig. 2. MSE of the SFO estimation schemes versus N_a when SNR = 15 dB: (1) solid line - channel 4 (2) dashed line - channel 6

Δ_f is estimated and compensated by using GI-based one-shot estimation scheme [9, 10].

Figure 1 shows the MSE of the SFO estimation schemes in channel 1 and channel 3 when $N_a = 3$. From this figure, it is found that the performance of the proposed estimation scheme is better than that of the conventional methods, while the computational cost of the proposed estimator with $\{f_1, f_2\} = \{g_1, g_2\} = \{1, 3\}$ is shown to be kept minimum.

Figure 2 presents the MSE of the SFO estimation schemes versus N_a in channel 4 and channel 6. It is clear that the performance enhancement of three SFO estimators is proportional to an increase in N_a . Regardless of the channel used, the proposed SFO estimator outperforms the conventional SFO estimators.

5 Conclusion

This paper proposed a simple way to implement a low-complexity SFO estimator with improved performance in OFDM-based DRM systems. By modifying the conventional estimator, the proposed estimator was made computationally efficient, with a performance that outperforms the existing estimators.

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