A Common Symbol Timing Offset Synchronization (post FFT) Method for OFDM System

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Abstract. As we know, synchronization issues are of great importance in OFDM receiver especially symbol timing offset synchronization. Synchronization errors not only cause inter-symbol interference (ISI) but also introduce inter-carrier interference (ICI) duo to the loss of orthogonally among all sub-carriers. In this paper, we proposed an improved method which can not only get better estimation performance but also decrease computation complexity that never needs any analogy timing loops for better ASIC area cost and power consumption.

Keywords: OFDM, synchronization, symbol timing offset.

1 Introduction

OFDM technique has been used in many audio and video broadcasting systems, because of high-quality video audio services and reliable stability transmission demand. Unfortunately, the OFDM systems are much more sensitive to carrier frequency offset (CFO) and symbol timing offset (STO).Therefore many synchronization algorithms have been proposed to solve these problems, but it has been shown that the performance may be great deteriorated due to synchronization errors [1]. In this paper, we mainly discuss the STO issues, which consist of fine symbol offset and sampling clock offset synchronization method. First, we will discuss a conventional synchronization algorithm [3] based on analogy timing loop. Second, we will introduce an improved method which use scatter pilots to estimate timing and clock offset errors post FFT (Fast Fourier Transform), and use NCO (Numerical Control Oscillator) to realize tracking loop. Simulation results show the improved method has the much better performance as the conventional method in multi-path channels. This method is also more flexible in receiver, because it supports multiply baseband symbol rate by using a fixed sampling frequency DAC (Digital to Analogy Convert).

2 Common Synchronization Procedure

In most OFDM systems, synchronization procedure includes: transmission mode detection, symbol timing synchronization pre FFT, carrier frequency synchronization, symbol timing synchronization post FFT.

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Symbol timing synchronization post FFT consists of fine symbol timing offset and sampling clock offset synchronization. Fine symbol timing offset synchronization can estimate residual timing offset after coarse symbol timing synchronization, and adjust FFT windows to proper position. Sampling clock offset leads to sample rob/stuff phenomenon that must be estimated post FFT. It works in the tracking stage and needs a symbol timing tracking loop.

3 Conventional Symbol Timing Synchronization for OFDM System

A symbol timing synchronization method is proposed by Dong Kyu Kim[3] that may be used for OFDM system with two-dimensional (frequency-domain and time-domain) interleaving, and enough pilots. For example the DRM+[2] system has the transmission frame pilot format as shows in figure 1.

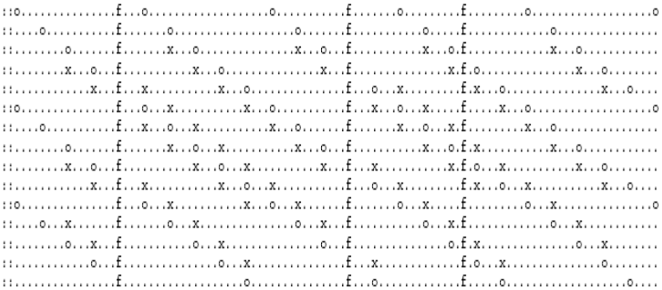

Fig. 1. DRM+ frame structure

Figure 1 shows the frame structure of DRM+ transmission in frequency domain, each OFDM symbol has frequency reference cells character “f”, scattered pilots character “o”, and FAC(Fast Access Channel) cells character “x”. Frequency reference cell is a kind of pilot mainly used for frequency synchronization. The FAC is used to provide information on the channel parameters required for de-multiplex as well as basic service selection information for fast scanning. Scattered pilots (SPs) are used for timing synchronization and channel estimation.

In this method, a joint estimation method based scatter pilots is used. Fine symbol timing offset synchronization can be performed with sampling clock offset synchronization using phase difference between the SPs carriers. Detailed algorithm can be summarized as follows:

1) First, the phase rotation occurred at the k-th subcarrier of the j-th OFDM symbol is

$$\phi_{k,j} = Arg[\hat{SP}_{k,j} SP^{*}_{k,j}] = 2\pi k \frac{T_d + \Delta t(j)}{T_u} + \phi_0 + 2\pi \Delta f T_{sym} \qquad (1)$$

Where $\hat{SP}_{k,j}$ and $SP^{*}_{k,j}$ are the transmitted and received SP cells indexed with carrier indices k and symbol number j respectively. $Arg[\cdot]$ is the arctangent function. And Td, $\Delta t(j)$, ϕ_0 and Δf are fine symbol timing offset, sampling clock offset, phase offset , frequency offset in the the j-th OFDM symbol, respectively. They are all related to the synchronization errors. T_u, T_s and T_{sym} are the useful data duration, nominal sampling period and the total OFDM symbol duration, respectively. T_{sym} is the sum of the useful data duration and the guard interval. The difference of the phase rotation between $k = k_1$ and $k = k_2$ SP carriers of the j-th symbol is expressed as in (2).

$$\Delta\phi_{k_{2,1}}(j) = \phi_{k_2}(j) - \phi_{k_1}(j) = 2\pi\Delta k \frac{T_d + \Delta t(j)}{T_u} \tag{2}$$

Where Δk is frequency spacing between two scattered pilots carriers.

2) From (2) the difference of phase rotation between the two scattered pilots in a symbol is the function of the frequency spacing $k_2 - k_1$, the normalized fine symbol timing offset Td/Ts, and the normalized sampling clock offset Δt(j)/Ts. The synchronization error $\varepsilon_{k_{2,1}}(j)$ is the sum of fine symbol offset and sampling clock offset and can be obtained as (3). The average phase difference can be obtained using all the scattered pilots in one OFDM symbol, as in (4). Then the average phase difference can be divided into an integer part and a fractional part as in (5).

$$\varepsilon_{k_{2,1}}(j) = \frac{T_d + \Delta t(j)}{T_s} = \frac{N}{2\pi} \times \frac{\Delta\phi_{k_{2,1}}(j)}{\Delta k} \tag{3}$$

$$\varepsilon(j) = \frac{1}{L}\sum_{n=0}^{L-1} \varepsilon_{k_{2n+1,2n}}(j) \tag{4}$$

$$\varepsilon(j) = \mathrm{int}[\varepsilon(j)] + \{\varepsilon(j) - \mathrm{int}[\varepsilon(j)]\} \tag{5}$$

Where L is the carrier number of the SPs in symbol j, N is the length of FFT. int[z] means the largest integer not exceeding z. The value of the integer is the fine symbol timing offset and the value of the fraction can be used for correcting the sampling clock offset.

Figure 2 shows the block diagram of the algorithm. There needs an analog timing loop which uses the fraction part as the input to the phase detector of PLL. The symbol timing offset can be tracked by PLL to adjust ADC's sampling frequency and the FFT widow controller. Thus the ADC sampling clock will be adjusted to output correct sampling frequency and the fine timing offset will also be compensated.

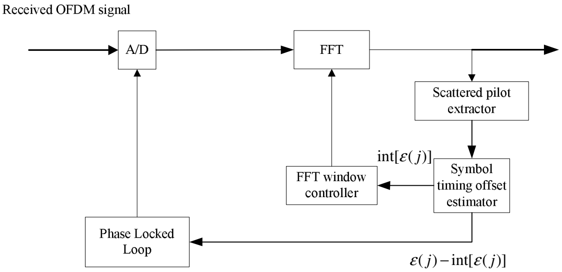

Fig. 2. Block diagram of timing loop

The symbol timing offset synchronization method post FFT for DRM+ has the following drawbacks:

1. It is based on the difference of phase rotations between the two SPs, there are L SPs used in one OFDM symbol, so there will be L-1 estimations of the phase difference according (4). Otherwise, we need calculate L times the phase angle for the arctangent function in one OFDM symbol duration. As we know, in real system or hardware realization, the arctangent function is a class of iterative computations, which needs much processing timing, either for the arctan() look-up table or for the ORDIC algorithm. In DRM+ system, there are 23 SPs in one OFDM symbol for robustness mode A and spectrum occupancy 20kHz [2], and repeated every five symbols, so too much processing time and power consumption are needed. However for mobile reception, the power consumption is a key problem that needs to be considered. In addition, the power characteristic is utilized in the algorithm. It is well known that, power characteristic is much more sensitive to the multi-path fading channels. So the performance of the method is not good under multi-path fading channels.

2. From figure 2, a fine symbol timing tracking loop is combined with sampling synchronization loop. In the method, the symbol timing synchronization which decided the FFT window position can be achieved by adjusting the ADC's sampling frequency and phase and the FFT window controller. However, it needs an analog timing loop which covers some analog components. As we know, analog timing loop is difficult to integrate in ASIC design, which will increase the ASIC area and power consumption. In many OFDM systems, such as ISDB-T [6], there must be at least two sampling rates for reception mode, the ADC's sampling clock must be changed corresponding to the reception mode that means the analog timing loop needs 2 VCOs. It will increase the ASIC area and power consumption.

Taking the above two drawbacks into consideration, more suitable method needs to be developed.

4 The Proposed Method

The above symbol timing synchronization method must calculate a number of arctangent functions in one OFDM symbol and need an analog timing loop to track the symbol timing offset. An improved method which decreases the arctangent functions is proposed based on the method above. At the same time, the symbol timing offset can be tracked by a NCO controlled loop.

The proposed new symbol timing offset synchronization method and tracking loop can be summarized as follows:

1) The improved method also utilizes the joint operation between fine symbol timing recovery and sampling clock adjustment based on the method above. First, we do the correlation operation between the local and received SPs.

$$\phi_{k,j} = S\hat{P}_{k,j} \cdot SP_{k,j}^{*} \tag{6}$$

The symbol timing offset is expressed:

$$\varepsilon(j) = \frac{N}{2\pi\Delta k} Arg\left[\frac{\sum_{k=0}^{L-1} \mathrm{Im}(\phi_{k+1,j}\phi_{k,j}^{*})}{\sum_{k=0}^{L-1} \mathrm{Re}(\phi_{k+1,j}\phi_{k,j}^{*})}\right] \tag{7}$$

The integer part of the symbol timing offset is:

$$\varepsilon_i = \mathrm{int}[\varepsilon(j)] \tag{8}$$

Where, int[z] means the largest integer not exceeding z. The value of the integer ε_i can also be used for estimating the sampling clock offset.

$$\varepsilon_i = \mathrm{int}[\varepsilon(j)]\eta(j) = \frac{\varepsilon(j) - \varepsilon(j-1)}{N + N_g} \tag{9}$$

Where Ng is the length of guard interval and η is the relative sampling clock offset. The basic block diagram of improved method is illustrated in the figure 3.

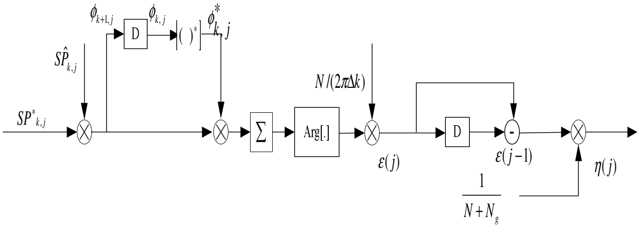

Fig. 3. The block diagram of the improved method

In the figure 3, the received SPs and local SPs are used to estimate the fine symbol timing offset by a series of correlation operation every symbol. The output signal $\varepsilon(j)$ is used to estimate the sampling clock offset by the differential operation every two symbols. The improved method firstly gets the sum of the correlation operation, and then calculates phase angle. This method just needs a calculation for arctangent function every OFDM symbol. Because the phase characteristic is less sensitive to the multi-path channels than power characteristic, so the utilized phase characteristic can get better performance than that of the method proposed by Dong Kyu Kim[3].

2) Since many systems are multimode and have multi-rate. In reception, the ADC input signal should be sampled at a free running clock regardless transmission mode and transmitting rate. In the improved method, we use a differential operation for sampling clock offset estimation, which can be tracked by a NCO controlled interpolation loop as shown in figure 4. For a non-synchronized sampling receiver system, symbol timing loop includes mainly interpolator, and interpolation controller (NCO) and FFT window controller.

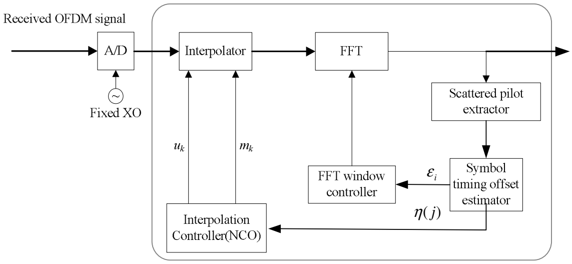

Fig. 4. Block diagram of NCO controlled timing loop

Refer to the figure 4, the ADC input signal is digitized under a fixed XO, which is commonly about 2 times or 4 times upsample. As we know, the fixed XO sampling rate must be converted to the IFFT sampling rate to carry out correct FFT computation. As shown in the figure, an interpolation loop is used for rate conversion and sampling clock offset tracking. The fine symbol timing offset ε_i will be used to feedback to FFT window controller to adjust the FFT start position. While $\eta(j)$ can be used to compensate and track the sampling clock offset through the interpolation loop based NCO.

3) The sampling rate conversion can be realized by interpolation. The interpolating equation can be written as:

$$y(kT_i) = \sum_{I=I_1}^{I_2} x[(m_k - i)T_s]h_I[(i+\mu_k)T_s] \tag{10}$$

Where $h_I(t)$ is the pulse response of interpolating filter, $x(k)$ is input sample, m_k is a base point index and μ_k is the timing offset, $0 \le \mu_k < 1$ .The interplant $y(kT_i)$ is computed from (10) using adjacent samples $x(k)$ and I samples of the interpolating filter. The correct set of signal samples is identified by the base point index m_k and the correct set of filter samples is identified by the μ_k .

In consideration of implementation complexity, a Farrow structure polynomial-based filter is more desirable [4]. It can be expressed as:

$$y(k) = \sum_{l=0}^{N} u_k^l v(l), \qquad v(l) = \sum_{i=I_1}^{I_2} b_l(i) x(m_k - i) \tag{11}$$

Where, the coefficients $b_l(i)$ are fixed numbers, independent of μ_k . For a cubic interpolation:

$$y(k) = [\{v(3)u_k + v(2)\}u_k + v(1)]u_k + v(0) \tag{12}$$

A block diagram for interpolator is shown in figure 5. The cubic interpolator consists of 4 fir branches and 3 multipliers.

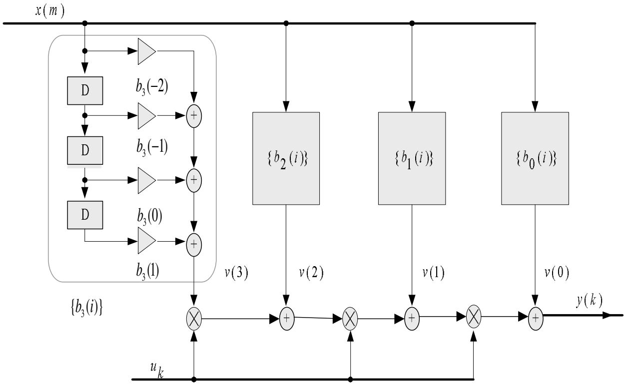

Fig. 5. Farrow structure of cubic interpolator

4) The interpolation controller determining m_k and μ_k , and making that available to do the interpolate calculation. The necessary control can be provided by a number-controlled oscillator (NCO), m_k and μ_k can be expressed as:

$$m_{k+1} = \mathrm{int}[T_i / T_s + u_k] + m_k \tag{13}$$

$$u_{k+1} = \left[u_k + \frac{T_i}{T_s} \right] \bmod 1 \tag{14}$$

Here T_i is sampling rate after interpolator, T_s is sample rate before interpolator. The structure of the NCO is shown in the figure 6. And $frac[\cdot]$ means get the fractional part. The Interval is mean value and decided by the upsample times.

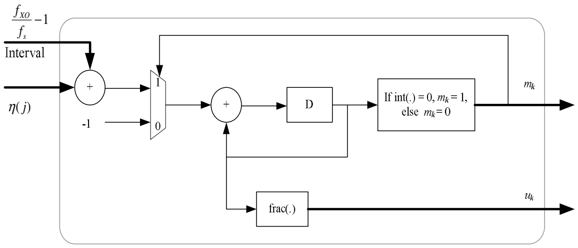

Fig. 6. NCO structure

We evaluate the performance of the proposed symbol timing offset estimation post FFT by computer simulation with the results given in figure 7 and figure 8. In figure 7, the MSE is a metric of the difference between the actual symbol timing offset and the estimation result. The simulation was run for 100 frames under multi-path channel with a Doppler frequency spread of 20Hz. From the simulation we can see that the performance of the improved method is much better than that of the conventional method. In Figure 8, the estimation probability is the probability that the estimation result locates the (0, +1) range of the actual symbol timing offset. At the same simulation condition, we can see the estimation probability is much close to 1 with the improved method, even in lower SNR.

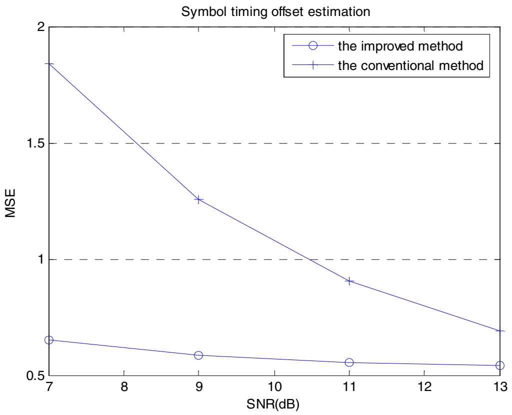

Fig. 7. Performance comparison of the two symbol timing offset synchronization methods

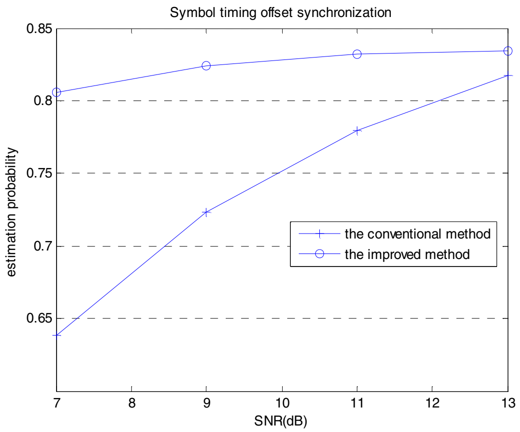

Fig. 8. Estimation probability comparisons of the two methods

5 Conclusion

We have proposed a new symbol timing offset synchronization method with all tracking loop digitally in OFDM reception systems. For the improved and conventional symbol timing offset synchronization methods, some conclusions showed as follows:

(1) The common ground is that both of them are based on phase difference of the scattered pilots to estimate the symbol timing offset post FFT.

(2) The key point is the conventional method firstly calculates every phase difference between the two SPs, and then average the estimation. It uses the power characteristic. In fact, we can use the phase characteristic to estimate the offset, which justly need calculate a phase difference.

(3) The main difference is that they adopt different cost functions for symbol timing offset synchronization and different timing tracking loop to track symbol timing offset.

Compared with the conventional method, the advantages of the improved method are:

(1) Better estimation performance and lower computation complexity. Simulation results show the improved method has the much better performance as the conventional method in multi-path channels. As far as computation complexity is concerned, the conventional method needs calculate a number of arctangent functions in one OFDM symbol duration. This causes higher computation complexity since arctangent operation is a time-consuming and complex process, and need much more processing timing. The proposed method gets the sum of the correlation operation and justly need calculate an arctangent function.

(2) Much less resources and good compatibility. The conventional method need an analog timing loop for tracking the symbol timing offset, which increase the ASIC area and the power consumption. The improved method uses an all digitally timing loop and adapt to multi-mode and multi-rate receivers in multimode and multi-rate OFDM systems.

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