Chapter 4
Investigation of OFDM Synchronization Techniques

In this chapter, basic function blocks of OFDM-based synchronous receiver such as: integral and fractional frequency offset detection, symbol timing synchronization, frame timing synchronization, will be discussed.

4.1 Eureka 147 DAB System

The synchronization scheme of Eureka 147 DAB system is illustrated in Figure 4.1. In the figure the dotted-line blocks are functions not discussed in this thesis. The synchronization scheme may perform the following operation sequence:

Stage 1: Detect the null symbol to find the start of a frame.

Stage 2: Acquire symbol timing and fractional frequency offset.

Stage 3: Use the phase reference signal to find the integral frequency offset after the end of a null symbol.

Stage 4: Keep tracking the fractional frequency offset and compensate it.

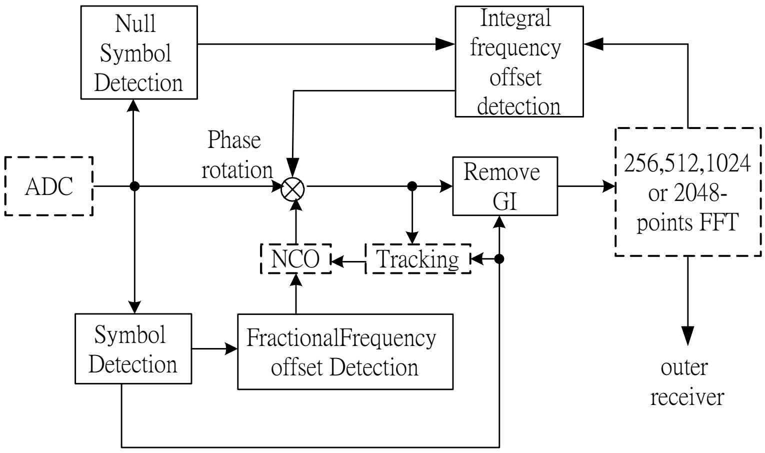

Figure 4.1 Block diagram of the adopted Eureka 147 DAB synchronization scheme.

4.1.1 Frame Detection

Initially, we lack the frame information. So, we have to use null symbol to detect the start of a frame. In the Eureka 147 DAB system, a null symbol precedes a phase reference symbol in an OFDM frame. During the null symbol period, no signal is transmitted. Thus, a power estimation circuit can be used to detect the occurrence of an OFDM frame. In this stage, we use the double-sliding-window packet detection algorithm [13] and calculate the energies of the received signals windowed by these two consecutive sliding windows. The basic principle is to form the decision variable $m(n)$ as a ratio of the total energy contained inside the two windows. If the null symbol length is L, this method can be expressed as:

$$A(n) = \sum_{m=0}^{L-1} \left| r_{n-m} \right|^2 \tag{4.1}$$

$$B(n) = \sum_{l=1}^{L} \left| r_{n+l} \right|^2 \tag{4.2}$$

$$m(n) = \frac{A(n)}{B(n)} \tag{4.3}$$

Both A and B are the windowed signal energies due to the sliding windows, implicitly shown in equations (4.1) and (4.2). When the null symbol falls within the windows, B will be very small. This particular signal position indicates a frame start, as shown in Figure 4.2. When $m(n)$ reaches its maximal value, $A(n)$ contains the frame energy S within the corresponding window, plus the noise energy N, while $B(n)$ equals to noise energy N in the corresponding window:

$$m_{peak} = \frac{S+N}{N} = \frac{S}{N} + 1 \tag{4.4}$$

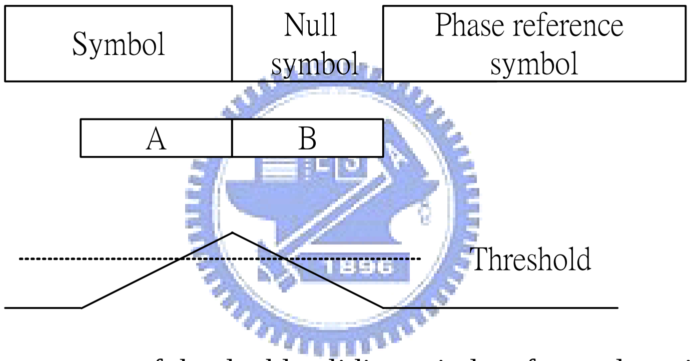

Figure 4.2 The response of the double-sliding-window frame detection algorithm

4.1.2 Detection of Symbol Timing and Fractional Frequency Offset

We have already used the null symbol to detect the start of a frame. In this stage, guard interval may be used to search the symbol boundary and estimate the fractional frequency offset. We know that OFDM signals have particular auto-correlation property. This is a consequence of the cyclic prefix insertion in between each consecutive OFDM symbol pair. The maximum likelihood (ML) estimation algorithm [14], [15] is adopted to estimate the symbol boundary and fractional frequency offset under the assumption that received samples are jointly Gaussian. It is assumed that one transmitted OFDM symbol contains N subcarriers and L samples in the cyclic prefix. The transmitted signal is $s(k)$ and the received signal is $r(k)$. The estimators are based on the observation of $2N+L$ samples of $r(k)$. These samples contain one complete $(N+L)$-sample OFDM symbol. Thus, the ML estimate of timing offset θ is given by

$$\hat{\theta}_{ML} = \arg\max_{\theta}\{|\gamma(\theta)| - \rho\Phi(\theta)\} \tag{4.5}$$

where

$$\gamma(m) \equiv \sum_{k=m}^{m+L-1} r(k)r^*(k+N)$$

$$\Phi(m) \equiv \frac{1}{2}\sum_{k=m}^{m+L-1} |r(k)|^2 + |r(k+N)|^2$$

$$\rho \equiv \frac{\sigma_s^2}{\sigma_s^2+\sigma_n^2} = \frac{SNR}{SNR+1}, \qquad SNR = \frac{\sigma_s^2}{\sigma_n^2}$$

In the equations, $\sigma_s^2 \equiv E\{|s(k)|^2\}$, and $n(k)$ is additive complex white zero-mean Gaussian noise, θ is the integer-value arrival time of the symbol and ε is the fractional frequency offset normalized to the carrier spacing. While in the conventional method, ρ is set to zero, only the correlation part is performed in order to reduce complexity. Then the symbol time offset estimator becomes

$$\hat{\theta} = \arg\max_{\theta}\{\left|\sum_{k=\theta}^{\theta+L-1} r(k)\cdot r^*(k+N)\right|\} \tag{4.6}$$

In AWGN channel, the received sample in guard interval is

$$r(k) = s(k-\theta)e^{j2\pi k(\varepsilon+\varepsilon_i)/N} + n(k) \tag{4.7}$$

$$r(k)r^*(k+N) = |s(k)|^2 e^{-j2\pi\varepsilon} \tag{4.8}$$

where ε_i is the integer frequency offset.

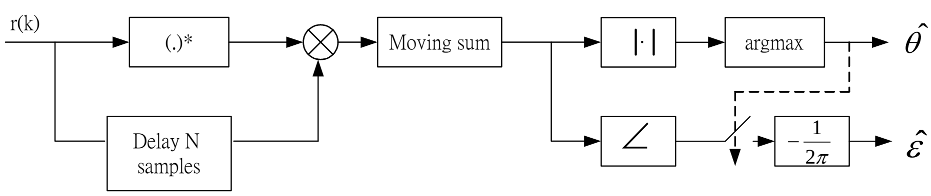

Figure 4.3 Structure of the symbol time and the fractional frequency offset estimator.

Based on estimation of symbol timing, the estimated fractional frequency offset $\hat{\varepsilon}$ is given by

$$\hat{\varepsilon} = -\frac{1}{2\pi}\angle\gamma(\hat{\theta}) \tag{4.9}$$

Since the phase rotation of integer frequency offset is integer multiples of 2π, this estimator is merely able to detect fractional frequency offset.

4.1.3 Integral Frequency Offset Estimation

Since the phase reference symbol (PRS) in Eureka 147 has the property that it is orthogonal to itself with any integral frequency offset (IFO), which can be estimated by a matched filter using the received PRS (whose fractional frequency offset is already compensated). However, two imperfect conditions must be considered. One is that the channel estimation is not performed yet. Another is the phase rotation in frequency domain due to inexact symbol synchronization. Therefore, conventional matched filter with PRS as reference data is not suitable here. The phases of the adjacent subchannels are strongly correlated, and the phase rotation due to timing offset increases linearly. Hence the uncertain phase can be eliminated by multiplying the two adjacent symbols. The integral frequency offset estimation $\hat{i} = i$ can be obtained by maximizing the metric $D(i)$ [16]:

$$D(i) = \frac{\left|\sum R_{k+i}C_k^* R_{k+1+i}^*\right|^2}{(\sum_k \left|R_{k+i}\right|^2)^2} \tag{4.10}$$

where k is the subcarrier index, , X_k is the k-th subcarrier data of the transmitted phase reference symbol, and R_k is the corresponding FFT output.

The one that most closely matches the FFO-compensated PRS produces peaks in its output, while the others produce noise-like outputs. Thus, the IFO can be estimated and compensated.

4.1.4 Tracking Mode

After finishing the initial synchronization, the symbol time can be predicted. However, the subscriber shall track the frequency changes and shall defer any transmission if synchronization is lost. Small frequency changes can be tracked by the phase part of the cyclic prefix correlator output. These changes are averaged over a period of time then compensated.

4.2 DVB-T

Figure 4.4 shows the synchronization scheme for DVB-T, where the FFT block is 2048-point if it is operated in 2K mode, 8192-point if 8K mode. The operation sequence for the received DVB-T signal can be stated as:

Stage 1: Find symbol timing and fractional frequency offset.

Stage 2: Detect and compensate integral frequency offset.

Stage 3: Find the frame timing by using synchronization word.

Stage 4: Keep tracking and compensating the fractional frequency offset.

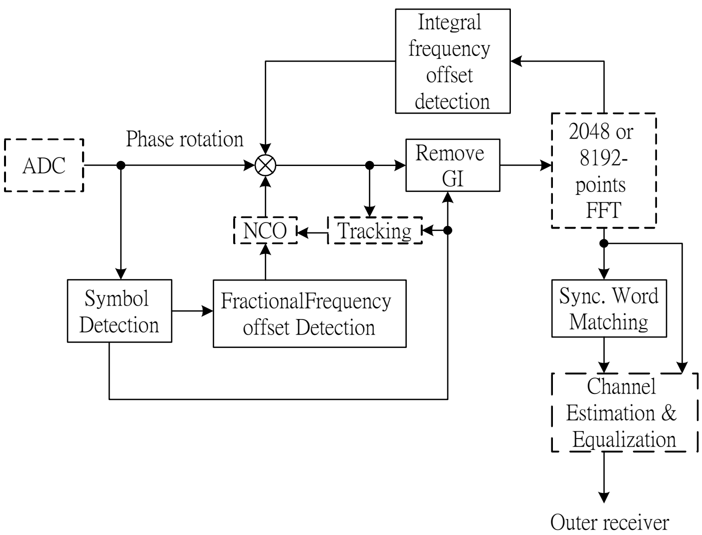

Figure 4.4 Synchronization structure of DVB-T

4.2.1 Detection of the Symbol Timing and Fractional Frequency Offset

In this stage, the detection algorithm is same as that used in the Eureka 147 DAB. Guard interval is used to detect the symbol boundary and fractional frequency offset.

4.2.2 Integral Frequency Offset Estimation

After solving the fractional frequency offset, integral frequency synchronization stage is performed after FFT by utilizing the continual pilots [16], [17], [18]. The continual pilots in every symbol have the same positions and data. A block diagram of the integral frequency synchronization scheme is shown in Figure. 4.5. The position of the FFT outputs can be different from their original positions due to integral frequency offset. In the scheme, the algorithm calculates the correlation between two continual pilots with the same subcarriers for two successive symbols in the frequency domain based on the shifted pilot positions. We propose two algorithms for DVB-T IFO synchronization task here. The first algorithm can be expressed as:

$$C(m) = \max\{\left|\sum_{k=P_m} Y_{j-1,k} \cdot Y_{j,k}^{*}\right|\} \tag{4.11}$$

and algorithm 2 can be expressed as:

$$C^{'}(m) = \min\{\sum_{k=P_m}\left|\frac{Y_{j-1,k}}{Y_{j,k}} - 1\right|\} \tag{4.12}$$

where $P_m = [p_1 + m, p_2 + m, ..., p_L + m]$, p is the continual pilot location. In 2K mode, $p = \{p_1, p_2, ..., p_{45}\}$. In 8K mode $p = \{p_1, p_2, ..., p_{177}\}$. m is the subcarrier offset from P_0.

The integral part $\hat{m} = m$ of the carrier frequency offset is estimated by algorithm 1 which maximizes metric while it is estimated by algorithm 2 which minimizes metric

$C^{'}(m)$.

Given that a DVB-T system with 2K mode, and positions of the continual pilots are at subcarrier 0, 48, 54…. If the maximum value $C(m)$ is obtained from subcarriers 2, 50, 56..., then the estimated integral frequency offset is 2, because the position of maximum correlation is achieved two subcarrier positions away from the original continual pilots.

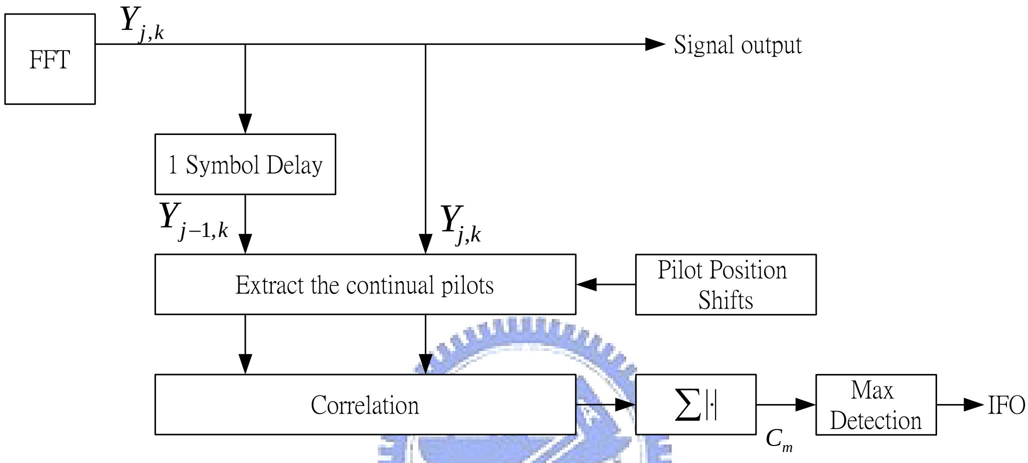

Figure 4.5 Block diagram of the first integral frequency offset synchronization algorithm.

4.2.3 Frame Detection

Synchronization word consists of 1~16 bits of TPS, which carriers a pseudo random binary sequence, and are placed in 1~16 symbols of a frame (i.e., there are 68 symbols and a 68-bit TPS signals in a frame).

The first and third TPS blocks in each super-frame have the following synchronization word:

$$s_1 - s_{16} = 0011010111101110.$$

The second and fourth TPS blocks have the following synchronization word:

$$s_1 - s_{16} = 1100101000010001.$$

Thus, if the synchronization TPS in the received signal is found, the correct symbol count of a frame can be known, and the frame synchronization can be achieved.

Since every TPS carrier in a frame is DBPSK modulated and conveys the same message, the TPS subcarriers can be extracted by:

$$S_l = Sign\{\mathrm{Re}[\sum_{k\in\Omega_T} Y_{l,k} \cdot Y^*_{l-1,k}]\} \tag{4.13}$$

where N is the number of the subcarriers in a symbol, k denotes the subcarrier number in a symbol, Ω_T denotes the subcarriers which carry the TPS signals, and l denotes the symbol number in a frame.

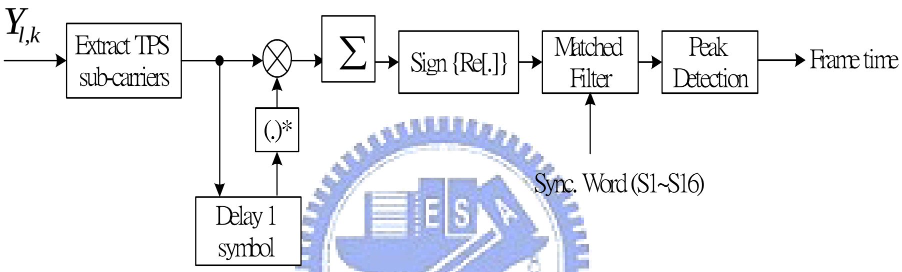

Figure 4.6 Frame synchronization structure for DVB-T

Once the TPS signal is extracted, a peak correlation between the demodulated TPS and known synchronization word reveals the correct frame timing. The correlation can be easily implemented by a matched filter, as illustrated in Figure 4.6.

4.3 IEEE 802.16a

4.3.1 Synchronization Requirements

For both TDD and FDD realizations, it is recommended (but not required) that all BSs be time synchronized to a common timing signal. In the event of the loss of the network timing signal, BSs shall continue to operate and shall automatically resynchronize to the network timing signal when it is recovered. The synchronization reference shall be a 1pps timing pulse and a 10 MHz frequency reference. These signals are typically provided by a GPS receiver.

Frequency references derived from the timing reference may be used to control the frequency accuracy of base stations. This applies during normal operation and during loss of timing reference.

BS:

The transmitter center frequency, receiver center frequency and the symbol clock frequency shall be derived from the same reference oscillator. At the BS, the reference frequency tolerance shall be $+/-$ 2ppm.

SS:

DL: At initial acquisition, a SS which wants to join the transmission network must detect the start of a DL frame. At the SS, both the transmitted center frequency and the symbol clock frequency shall be synchronized to the BS with a tolerance of maximum 2% of the carrier spacing. After initial acquisition, the SS can extract the transmission parameters from the DL_MAPs and UP_MAPs. Thus, the SS can successfully join the network.

UL: For any duplexing, all SSs shall acquire and adjust their timing such that all uplink arrival times of OFDM symbols coincide at the Base-Station within an accuracy of $+/-$ 25% of the minimum guard-interval or better.

4.3.2 DL Synchronization Scheme

The techniques in [14], [15], [17] and [20] are employed for IEEE 802.16a DL synchronization. Figure 4.7 shows the synchronization scheme for IEEE 802.16a DL TDD system. The proposed synchronization scheme is divided into several stages. In the first stage, we utilize the guard interval, which has strong correlation with the tail part of the associated OFDM symbol, to detect the symbol boundary and fractional frequency offset. In the second stage, variable-location pilots of a preamble are used to find the residual integer frequency offset and to detect the DL frame starts. We will describe the operations of each stage in detail.

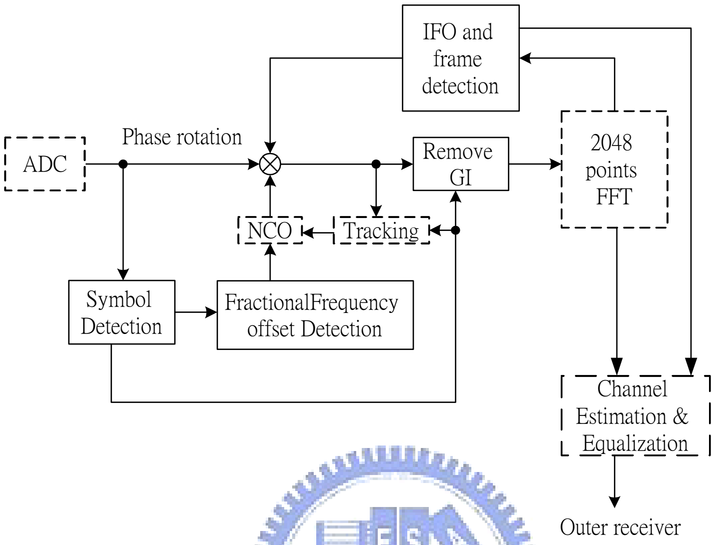

Figure 4.7 Synchronization structure of IEEE 802.16a DL TDD system.

4.3.3 Symbol Timing and Fractional Frequency Offset Synchronization

In this stage, the adopted algorithm is same as that of the Eureka 147 DAB. Guard interval is used to detect the symbol boundary and fractional frequency offset.

4.3.4 Integral Frequency Offset and Frame Synchronization

The task of this stage is to detect the integer frequency offset and the first symbol of a DL frame. It is performed by utilizing the variable-location pilots of the preamble. 802.16a DL preamble contains the first three symbols that have different pilot modulations from the other symbols. Those unique and known pilots in the first symbol of a DL frame are differential-coded in the frequency domain [17]. The coded data is used as the reference data to match the received data after FFT to detect to integer frequency offset and the start of a DL frame.

The differential-coded matched filter $F(g)$ is defined as

$$F(g) = \frac{\left|\sum_{k\in K'} R_{k+g} C_k^* R_{k+1+g}^*\right|^2}{(\sum_{k\in K'} \left|R_k\right|^2)^2} \tag{4.14}$$

Let K' be the set of indices for the variable-location pilot carriers, $K' = \{0,1,....,141\}$ $k \in K'$, and C_k be defined as

$$C_k = \begin{cases} \dfrac{X_k}{X_{k+1}}, & k = 0,....141 \\ 0, & otherwise \end{cases} \tag{4.15}$$

where k is the variable-location pilot carrier index, X_k is the kth pilot-carrier data and R_k is the FFT output.

The metric is a robust measure against symbol timing offset and channel phase effect. If $F(\hat{g})$ is larger than a predefined threshold, it declares $\hat{g}$ to be the integer frequency offset and the current symbol to be the start of a DL frame.

In order to tradeoff between performance and complexity, number of pilots used in the matched filter should be carefully determined. In the next chapter, we will perform simulations and get the information as how many pilots we needs and how to choose those pilots.

4.3.5 Tracking Mode

After the initial synchronization, an SS already compensated the frequency offset and found the frame information from the frame duration code in the MAPs. According to IEEE 802.16a standard, the SS shall track the small frequency changes and detect the correct boundary of each received symbol. These small offsets can be tracked in stage I. If synchronization is lost, the SS must restart the initial synchronization scheme.