Synchronization Acquisition Methods for DRM Systems

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Abstract—In this paper, we report DRM receiver synchronization methods at the acquisition stage. Synchronization process consists of robustness mode detection, coarse symbol timing estimation, coarse fractional carrier frequency offset estimation, integer carrier frequency offset estimation, and frame timing estimation. These detection and estimation methods exploit the characteristics of DRM signal structure and pilot cells. Their performance is assessed by simulation with DRM full link simulator and verified with DRM hardware platform based on FPGA.

Keywords—Digital broadcasting; Digital radio mondiale; synchronization; acquisition

I. INTRODUCTION

DRM (Digital Radio Mondiale) is the only universal nonproprietary digital radio broadcasting system for the frequency bands below 30 MHz. DRM systems can provide a high quality of audio and various data services by adoption of advanced OFDM modulation technique and multilevel coding scheme [1][2][3].

As we know, synchronization is the key problem of an OFDM receiver system. The Synchronization of an OFDM system can be divided into carrier frequency synchronization, symbol timing synchronization, and sampling clock synchronization. For DRM systems, robustness mode detection and frame timing synchronization processes are required.

The rest of this paper is organized as follows. Section II introduces DRM systems and its signal parameters. The methods for DRM synchronization at the acquisition stage are discussed in section III. Finally, we conclude the paper in Section IV.

II. SYSTEM AND SIGNAL PARAMETER

For DRM systems, there are four robustness modes. These modes vary from a high capacity but low robustness (mode A) to low capacity but high robustness (mode D). Various sets of OFDM symbol parameters are defined for different robustness modes in Table 1.

Table 1. OFDM symbol parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Robustness mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>list</td>
<td>A</td>
</tr>
<tr>
<td>( T_u (\text{ms}) )</td>
<td>24</td>
</tr>
<tr>
<td>( T_g (\text{ms}) )</td>
<td>( \frac{3}{5} )</td>
</tr>
<tr>
<td>( T_g/T_u )</td>
<td>1/9</td>
</tr>
<tr>
<td>( T_f= T_u+T_g (\text{ms}) )</td>
<td>( \frac{28}{5} )</td>
</tr>
<tr>
<td>( \Delta F (\text{Hz}) )</td>
<td>( \frac{41}{5} )</td>
</tr>
</tbody>
</table>

In Table 1, \( T_u \) is the duration of an OFDM symbol, \( T_g \) is the duration of the guard interval, and \( T_u \) is the duration of the useful part of an OFDM symbol (i.e. excluding the guard interval). \( \Delta F \) is the subcarrier spacing, and \( \Delta F = 1/T_u \). In the DRM receiver system we designed, 48KHz is chosen as the sample rate of baseband signal which is equal to \( 4/T \), where \( T \) is an elementary time period of 83(1/3) \( \mu \)s. The corresponding FFT size of \( N \), the guard interval of \( N_g \) (unit: sample), and the useful part of \( N_u \) are shown in Table 2.

Table 2. Values of system parameters used in a real system

<table>
<thead>
<tr>
<th>Parameters list</th>
<th>Robustness mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>list</td>
<td>A</td>
</tr>
<tr>
<td>( N_g ) (sample)</td>
<td>128</td>
</tr>
<tr>
<td>( N ) or ( N_u ) (sample)</td>
<td>1152</td>
</tr>
<tr>
<td>( N_c=N_o+N_g ) (sample)</td>
<td>1280</td>
</tr>
</tbody>
</table>

In DRM systems, the transmitted signal is organized in transmission super frames. Each transmission super frame consists of three transmission frames. Each transmission frame has duration \( T_f \) and consists of \( N_c \) OFDM symbols. An OFDM frame contains pilot cells, control cells, and data cells. For frame, frequency and time synchronization, we need to utilize the pilot cells. The signal information in pilot cells are known at the receiver side, and used as frequency, time, and gain references, respectively. Every OFDM symbol of a transmission frame contains three frequency reference cells, whereas only the first OFDM symbol contains time reference cells. The signal information in gain reference cells are mainly used by the receiver to estimate the channel response for coherent demodulation and are allocated throughout the time and frequency domains.
III. SYNCHRONIZATION ACQUISITION METHODS

A. Robustness mode detection (RMD)

Robustness mode detection is the first task of DRM synchronization. Its purpose is to detect the robustness mode of current transmitted signal. As shown in Table 1, different robustness modes have different OFDM parameters. By using this information, we can detect robustness mode of the transmitted signal. A RMD method for DRM systems was proposed in [4] and it is based on employing guard interval correlations across the whole guard interval. The correlation function is defined as:

$$\lambda(\theta) = |\gamma(\theta)| - \rho \Phi(\theta).$$  \hspace{1cm} (1)

It is well known that Eq. (1) is based on maximum likelihood technique [5] with

$$\gamma(\theta) = \sum_{k=0}^{N_s-1} r(k) \cdot r^*(k - N_s)$$ \hspace{1cm} (2)

$$\Phi(\theta) = \frac{1}{2} \sum_{k=0}^{N_s-1} |r(k)|^2 + |r(k - N_s)|^2,$$ \hspace{1cm} (3)

where \(r(k)\) is the received baseband signal at the \(k\)-th sample. \(\rho\) is a weighting factor, and its value depends on the signal-to-noise ratio (SNR). At high SNR, \(\rho\) can be assumed to 1. \(L\) is the length of correlation window which is equal to \(N_g\).

From the equation (1), it is observed that if the OFDM parameters in a particular robustness mode match with current transmitted OFDM parameters, distinct correlation peaks appear periodically with one OFDM interval apart in an observation window of \(N_s\). As a result, the period of the correlation peaks can be used for distinguishing current transmitted robustness mode.

To detect periodic correlation peaks, we use the cost function in [4] as follows

$$C(\theta) = \sum_{\theta=\frac{\theta_0}{L}}^{\theta_0+\frac{L N_g}{N_s}-1} \lambda(\theta) \cos \left( \frac{2\pi}{N_s} \theta \right),$$ \hspace{1cm} (4)

where \(N_{RMD}\) is the number of symbols used for mode detection. Therefore, any robustness mode whose OFDM signal parameters maximize the cost function \(C(\theta)\) will be chosen as the detected robustness mode. As shown in equation (4), correlation result is multiplied by a cosine function with the frequency \(f = 4/(N_s T)\). Since the cosine operation is time consuming and complex, it is not easy to be realized by hardware such as FPGA. Thus we propose a new detection criterion to decrease the computation complexity.

The relative error of the distance between two consecutive peaks is defined as:

$$\varepsilon_r = |d - N_s|/N_s,$$ \hspace{1cm} (5)

where \(d\) is the distance (unit: sample) between two consecutive peaks and \(|\cdot|\) represents absolute value operation. If the transmitted OFDM parameters match with those in a particular robustness mode, the distance \(d\) is equal to \(N_s\) of an OFDM symbol. Then \(\varepsilon_r\) becomes to zero consequently. Otherwise, any two consecutive peaks appear aperiodic. Thus the value of \(\varepsilon_r\) becomes larger.

Based on the above discussion, a new detection criterion can be determined that any robustness mode whose OFDM signal parameters can minimize \(\varepsilon_r\) will be chosen as the detected robustness mode. Since this new detection criterion only deals with multiplication and subtraction operations, the computation complexity can be much reduced compare to the detection criterion in [4] which needs more complex cosine operation. Furthermore, in order to decrease error probability of detection, two additional control strategies are adopted in the new criterion as follows: first, if a particular robustness mode is selected, the corresponding correlator should output at least \(N\) consecutive \(\varepsilon_r\) which are minimum values among all modes; second, all these values of \(\varepsilon_r\) should be smaller than the threshold \(th\). Both \(N\) and \(th\) can be determined through simulations.

B. Combined coarse symbol timing (CST) and coarse fractional carrier frequency offset (CFCFO) estimation

After the RMD, the next task is to achieve CST and CFCFO synchronization based on guard interval correlation. The correlation function is the same as equation (1) for robustness mode detection.

The CST estimation method in [5] uses the whole guard interval information that the correlation window length \(L\) is equal to whole guard interval length \(N_g\). The estimation criterion for the CST estimation method in [5] is expressed as

$$\hat{\theta} = \arg \max_{\theta} \lambda(\theta).$$ \hspace{1cm} (6)

This estimation criterion can be described that the timing \(\theta\) which maximizes the correlation function \(\lambda(\theta)\) is chosen as the estimate \(\hat{\theta}\) of CST.

In our design scheme, to mitigate effects of various channel impairments such as delay spread, three key strategies are adopted as following:

1. In correlation function (1), the correlation window length \(L\) is chosen to be smaller than the guard interval length \(N_g\);
2. The weighting factor \(\rho\) is assumed to be smaller than 1;
3. The timing instant with corresponding correlation function value by (1) smaller than the threshold 0 for the first time is chosen as the estimated timing \(\hat{\theta}\) for each OFDM symbol.

The third strategy is illustrated with Figure 1. In Fig. 1., \(L\) equals to \(N_g/4\) with \(\rho = 0.85\). Other simulation parameters are mode B, channel 3 [1], 10KHz bandwidth, and SNR = 25.4dB.
The purpose of CFCFO synchronization is to estimate and correct fractional carrier frequency offset as well as to decrease the error probability of integer carrier frequency offset estimation. The CFCFO estimation formula is expressed as
\[ \hat{\epsilon} = -\left(\frac{1}{2\pi}\right)\gamma(\hat{\theta}_{ML}), \]  
where \(\gamma(\theta)\) is given by (2) and 
\[ \hat{\theta}_{ML} = \max_{\theta} \lambda(\theta). \]

In CFCFO estimation, it is assumed that correlation length \(L = N_g/4\) and \(\rho = 1\).

Compared to conventional CST estimation method in [5], decreasing the length of correlation window can effectively mitigate the effects of various channel impairments. In addition, proposed scheme can ensure that estimated symbol timing positions are located in ISI-free field with smaller fluctuation.

The performances of the conventional and proposed CST estimation method are compared in Fig. 2. and 3 with different simulation conditions. The probability distribution of estimated symbol timing position is chosen as performance metric.

Simulation parameters are chosen that the spectrum occupancy = 3 (i.e. 10KHz bandwidth), carrier frequency offset = 2.45\(\Delta F\), sampling clock frequency offset = 50ppm, and baseband sample rate 48KHz. For the proposed CST estimation method, we use decreased correlation length \(L = N_g/4\), \(\rho = 0.85\), and the threshold = 0.

Fig. 2. shows that estimated symbol timing positions of the conventional estimation method converges at the timing position 0 in AWGN channel (i.e. channel 1). Though conventional estimation method has good convergence performance, almost half of estimated timing positions are located in the data field of preceding OFDM symbol. Fig. 2. also shows that proposed estimation method not only has good convergence performance, but also ensures that estimated timing positions are located in ISI-free field.

From Fig. 3., it is shown that the convergence performance of the conventional method becomes poor in multi-path channel, such as channel 3. Moreover, estimated symbol timing positions by conventional method are not acceptable for synchronization because they are mainly located in ISI field. In Fig. 3., it is noted that if we decrease the correlation length, the effect caused by multi-path channel can be mitigated. In addition, estimated symbol timing positions of conventional method with decreasing correlation length are mainly located in ISI-free field. This is a great improvement compared to conventional method with correlation length that is same as guard interval. However, timing positions estimated by conventional method with decreasing correlation length are located in broad range, such as from 64th to 192nd samples as shown in Fig. 3. This indicates that the fluctuation of estimated positions is very large. Compare to conventional scheme, our proposed method can overcome this drawback effectively. As shown in Fig. 3., the timing positions estimated by proposed method are located in relatively small range, such as from 192nd to 256th samples. This implies that our proposed estimation method has smaller fluctuation of estimated positions than conventional method.
as a combined process. When the estimate of FT is obtained, the estimate of ICFO can be obtained at the same time. Both of them use time reference cells that are inserted at the beginning of each DRM transmission frame. These time reference cells are located in groups such that they can be divided into many pairs of pilots being direct neighbors. A key observation is that the channel can be regarded as being identical at adjacent pilot positions in frequency domain [6] [7]. With this observation, we define the estimation function for combined FT and ICFO estimation as

$$C(s, m) = \text{Re}\left\{\sum_{l=0}^{L_{t}-1} \sum_{i=0}^{N_{f}} z_{r, p(l)+m} z_{s, q(l)+m} c_{0, p(l)} c_{0, q(l)}\right\}, \quad (9)$$

where $z_{r, k}$ denotes the received cell for carrier $k$ of symbol $s$ at receiver and $c_{r, k}$ denotes the transmitted cell for carrier $k$ of symbol $s$ at transmitter. $s$ denotes the symbol number for $s = i$, $i+1$, ..., $i+N$, where $N_f$ is the number of symbol in a transmission frame and $i$ is an arbitrary symbol number. $k$ denotes the carrier number for $k = 0, 1, ..., N$, where $N$ is the size of FFT as shown in Table [2]. $m$ denotes the trial value of integer carrier frequency offset for $m = -M, -M+1, ..., M$, where $M$ is the maximum estimation range. $p(l)$ and $q(l)$ denote the carrier number of a pair of time reference cells, where $p(l)$ denotes the position of the first time reference cell of a pair and $q(l)$ denotes the position of the second time reference cell of a pair. Hence, $c_{0, p(l)}$ and $c_{0, q(l)}$ actually denote a pair of time reference cells of the first symbol of each transmission frame, where $s = 0$. $L_{t}$ denotes the number of time reference cell pairs.

Note that $s$ and $m$ can be regarded as trial positions in time and frequency direction respectively. The estimation criterion can be defined as:

- The position $s$ corresponding to the greatest value of estimation function (9) gives the estimate of the starting position of a transmission frame;
- The position $m$ corresponding to the greatest value of estimation function (9) gives the estimate of integer carrier frequency offset.

To decrease the error probability of estimation, gain reference cells located within 0–4.5KHz bandwidth of the first symbol of each transmission frame can be used with time reference cells for combined FT and ICFO estimation. For example, for mode B, there are 19 time reference cells and 15 gain reference cells that are located within 0–4.5KHz bandwidth of the first symbol of each transmission frame. Hence, 34 known pilots are used for combined estimation. The selection criterion is that the interval of two carrier numbers of all pairs of pilots is equal to a fixed value, such as 1. For example, pilots with carrier number 13 and 14 for mode B can be chosen as a pair of pilots. Due to additional gain reference cells, more pairs of pilots can be obtained. Thus better estimation performance can be achieved.

In practical application, control strategies are used with the combined FT and ICFO estimation method to obtain satisfied performance. Two control strategies are adopted as following:

Let $F_{\text{max}}$ be the greatest value and $F_{\text{max}1}$ be the second greatest value of the estimation function given by (9).

1. **Control strategy 1**: If the value of $F_{\text{max}1}$ divided by $F_{\text{max}}$ is greater than threshold $th$, i.e. $F_{\text{max}1}/F_{\text{max}} > th$, then the estimate obtained from the current frame is valid. Otherwise, the estimate is invalid.

2. **Control strategy 2**: If two valid and consecutive estimates have same values, then FT&ICFO estimation is assumed to be completed.

The performance of FT estimation method is evaluated by computation simulation. The error probability of estimation is chosen as performance metric and is defined as the probability of estimated frame timing position that is not the beginning of a transmission frame.

For this simulation, we assumed that carrier frequency offset = 2.05F (F is the subcarrier spacing), sampling clock frequency offset = 50ppm, symbol timing offset = $N_0/8$, and baseband sample rate = 48KHz. In addition, we assume that the maximum carrier frequency offset of both positive and negative direction is 3KHz. As we know, before the frame timing synchronization stage, coarse symbol timing recovery and fractional carrier frequency offset estimation and compensation are need to be performed. Hence, the above simulation parameter settings are consistent with the actual conditions. For DRM systems, there are four modes and six channel models. We choose typical case that consists of mode B, Channel model 3, and spectrum occupancy 3 (i.e. 10KHz bandwidth).

![Fig. 4. Comparison between proposed and conventional estimation method](Image)

Simulation result is shown in Fig. 4, with the threshold value $th = 0.8$. It is shown that the method exploiting the information of time and gain reference cells together has smaller error probability of estimation than the method only using time reference cells. Two simple and practical control algorithms can greatly improve the performance of combined estimation method.

**IV. CONCLUSION**

We have proposed synchronization acquisition methods for DRM systems. The synchronization processes of DRM receiver include robustness mode detection to find propagation related transmission conditions. The proposed
synchronization acquisition methods exploit the characteristics of DRM signal structure in time and frequency domain. In addition, it utilizes the information of various pilot cells. From an implementation point of view, they are also easy to be realized by hardware such as FPGA chipset.

The proposed synchronization acquisition methods for DRM systems have been assessed in a full link software simulator which consists of transmitter, shortwave channel model, and receiver. They also have been realized and verified in a DRM prototype receiver based on Altera StratixII EP2S130 chipset. Simulation and experiment results show that our proposed synchronization acquisition scheme has better performance than conventional method.

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REFERENCES