A Novel Fine Frequency Synchronization Technique for OFDM Wireless Systems

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Abstract

A novel frequency tracking algorithm for OFDM systems based on pilot symbol tracking has been developed. This algorithm significantly reduces the complexity of traditional OFDM receivers by eliminating the need to have two separate algorithms for coarse frequency estimation (pre FFT synchronization) and fine frequency tracking (post FFT synchronization). The proposed algorithm updates the frequency estimate at every sample of the input signal compared to frequency update available only at OFDM symbol rate by the traditional algorithms. This feature allows compensation of rapid frequency variations in the input signal (due to cheaper RF front ends).

1. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is the most widely used technique in modern communication systems today. OFDM not only provides a bandwidth efficient way of information transmission but it is also very effective in multipath fading in wireless communications. This is achieved in OFDM by dividing the main data stream into lower rate parallel streams each occupying its own sub-channel bandwidth without interfering others and by the insertion of guard interval to absorb any channel dispersion [8]. OFDM has been also attractive to provide the flexibility to choose digital modulation technique for its subcarriers to achieve power-bandwidth trade-offs in given channel conditions thus allowing *adaptive modulation*.

OFDM has equally found its applications in narrowband wireless systems such as DRM, DAB and broadband system like WiMax, DVB-T, due to above mentioned features. In broadcast systems OFDM provides the key advantage of single frequency network (SFN), resulting in large bandwidth savings.

However the performance of OFDM is very sensitive to carrier frequency and sampling clock offsets and very much dependent on the reliability and quality of the synchronization algorithms. It is therefore focused to develop these synchronization algorithms to have optimum performance and at the same time with minimal computational effort to minimize power requirement for portable applications.

In the following pages DRM system example has been used, however this algorithm may be employed in any OFDM wireless system with pilot symbols.

2. DRM OFDM System

Digital Radio Mondiale (DRM) is digital broadcast standard for the HF band below 30MHz [1]. It is a narrowband system with bandwidth up to 20 KHz to replace existing AM analog transmission. The DRM system supports high data rates up to 72Kbits/s to provide both voice and data streams. The higher data rates are aimed to provide near FM quality sound in the HF band which is notorious for its fading and multipath effects. DRM provides various robustness modes to combat radio wave propagation conditions for different frequency bands within HF spectrum.

DRM OFDM parameters are summarized in the following table;

Table 1 DRM System Parameters

Mode	Propagation Channel Type	Symbol Length (ms)	Guard Interval (ms)	Carrier Spacing (Hz)	Active Carriers in Channel Bandwidth(KHz)		
					5	10	**20**
A	Ground Wave *LF/MF*	26.66	2.66	41.67	113	226	**458**
B	Sky Wave *MF/HF*	26.66	5.33	46.875	102	206	**410**
C	Sky Wave *HF* Difficult	20	5.33	68.18	-	138	**280**
D	Sky Wave *HF* Most Difficult	16.66	7.33	107.14	-	88	178

2.1 Pilot Carriers

DRM system provides reference pilot carriers (or cells as they are called in the standard itself) for the purpose of synchronization and equalization. The following Figure 1 illustrates distribution of pilot cells and data cells for the robustness mode B.

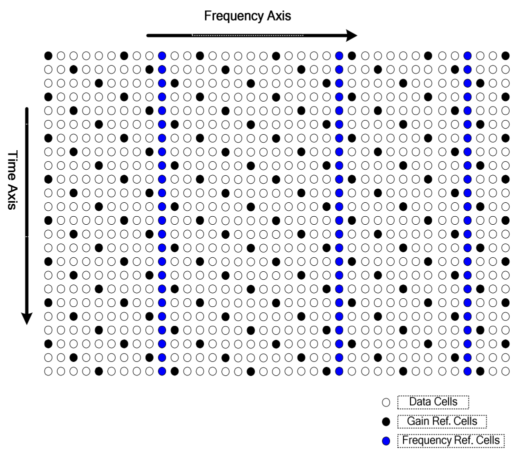

Figure 1 Reference Pilots Distribution in DRM (Mode B)

The scattered reference pilots are used for channel estimation while frequency reference pilots may be used for frequency synchronization. These frequency pilots as can be seen in Figure 1 have a fixed-position in frequency domain and their location is independent of the robustness mode and the channel bandwidth. These pilots are also boosted in gain (compared to data cells) and their phase is chosen to provide continuous tones. These features of frequency pilots are exploited to develop a robust and efficient fine frequency synchronization algorithm described in the following sections.

3. Synchronization Algorithms and the Receiver Structure

Frequency offset in OFDM system has two effects; first it attenuates and rotates data symbols at the output of FFT demodulator and the second, it destroys the orthogonality of the OFDM carriers resulting in Inter Channel Interference (ICI). The SNR degradation caused by ICI due to frequency offset has been studied [2] and is given by Figure 2. It can be seen that the frequency offset needs to be less than 1% of the carrier spacing to have a degradation of less than 0.5 dB at input SNR of 25dB.

This condition puts very strict requirements on frequency synchronization algorithms, especially in consumer-oriented applications where carrier and clock frequencies may not only have large offsets but also larger fluctuations due to cheaper analog front ends.

There are a number of algorithms studied by Speth *et al* [2-3] for frequency synchronization for OFDM systems falling into pre and post FFT categories, the former being used for coarse estimation while the later for fine tracking. The pre-FFT algorithms are time domain and are based on the cyclic prefix whereas post-FFT algorithms are in frequency domain. The performance of the time-domain guard interval based algorithms is generally not sufficient that's the reason these are used only for the coarse estimation.

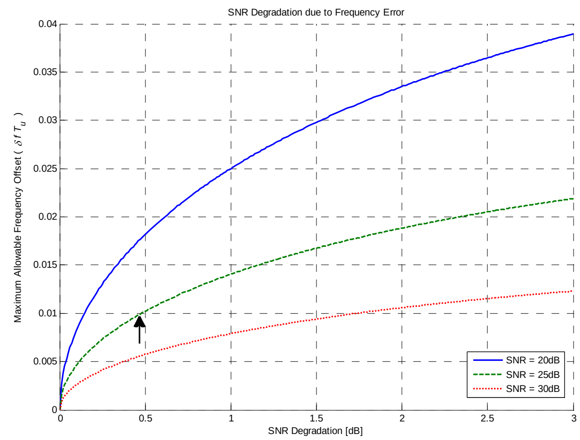

Figure 2 Frequency Offset and OFDM Degradation

This arrangement works well if the channel variations and RF front end phase noise is not causing rapid frequency variations such as in fixed wireless access. However in the mobile wireless applications with cheaper RF front ends and mobility this arrangement does not allow to compensate faster frequency variations (related to the RF Oscillator's PPM and phase noise). This is due to the fact that the post FFT frequency estimate is used in the long feedback loop for compensation as shown in the OFDM receiver structure proposed by Speth *et al* [2].

The switching between the pre and post FFT synchronization is based on some form of statistical information which may also result in burst errors due to occasional erroneous switching decisions.

The synchronization technique which is proposed here simplifies the receiver architecture to avoid the need of switching and only one algorithm is used. This simplified receiver structure reduces the computational load significantly (no need to run two different algorithms simultaneously) and is therefore more suitable for low power portable applications.

4. SDFT Frequency Synchronization

The basic principle of SDFT frequency synchronization is to track frequency pilot tones provided in the DRM standard as described in the previous section. These frequency pilots have been used for frequency acquisition by Fisher [4] using spectral estimation and correlation techniques. However, these pilots have not been used for fine frequency tracking in the pre-FFT stage. The new approach has been developed to make use of these frequency pilots for fine frequency tracking as well as using them during acquisition.

In this new technique DRM frequency pilots are extracted using Sliding Discrete Fourier Transform (SDFT) algorithm. This algorithm is more efficient in extracting the pilots than using any other kind of narrowband filtering. SDFT algorithm provides frequency components of the input signal at every new input sample compared to DFT or

FFT where frequency components are only available after block of samples (size of DFT length). This makes SDFT very suitable to estimate rapid frequency variations.

In the following sections SDFT algorithm is described and explained how SDFT is used for the tracking of DRM frequency pilots

4.1 The SDFT

Sliding DFT algorithms comes from the observation that at two consecutive time instants n-1 and n, the windowed sequence **x**(n-1) and **x**(n) contain essentially identical elements. This similarity along with the DFT time shift property is exploited to compute the DFT of the sliding window sequence for computational efficiency. If N point DFT of **x**(n) is X(k) then;

$$\mathbf{x}(n-m) \leftrightarrow X(k)e^{-\frac{j2\pi km}{N}} \qquad (1)$$

The above expression shows the DFT of a circularly shifted sequence. Now if a sequence is circularly shifted by one sample (to the left), then the DFT value X_k becomes;

$$X_k \rightarrow X_k e^{j2\pi k/N} \qquad (2)$$

Thus the spectral components of a shifted windowed sequence are the original (unshifted) spectral components multiplied by $e^{j2\pi k/N}$. This process is expressed by the following equation [5];

$$X_k(n) = X_k(n-1)e^{j2\pi k/N} - x(n-N) + x(n) \qquad (3)$$

Where $X_k(n)$ is the new spectral component and $X_k(n-1)$ is the previous spectral component. The subscript k is the DFT bin index. It can be observed from the above equation that its computational requirements are independent of the DFT size N.

A single DFT bin implementation using SDFT equation is given by the following Figure 3.

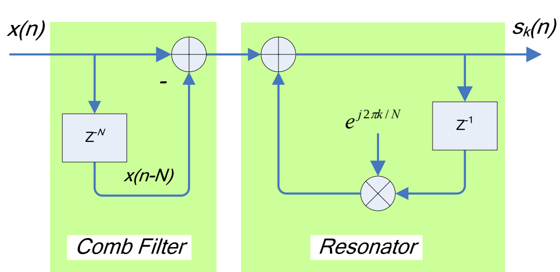

Figure 3 Sliding DFT Filter

The above implementation is simply a comb filter and a resonator in cascade. There are two features of the above structure;

1. The output frequency sample $S_k(n)$ is not equal to $X_k(n)$ for $n < N$ due to comb filter delay.
2. If more than one bin is to be calculated it will require only one comb filter section with parallel resonators for each bin.

The computational requirements of the SDFT algorithm are far less than those of DFT or FFT functions when new spectral components are needed for each time step.

The Transfer function of the above SDFT filter for kth DFT bin is given as;

$$H_k(z) = \frac{1-z^{-N}}{1-e^{j2\pi k/N}z^{-1}} \qquad (4)$$

This complex filter has N zeros due to the comb filter equally spaced around the unit circle and a single pole cancelling the zero at $z = e^{j2\pi k/N}$.

The SDFT filter's complex sinusoidal unit impulse response is finite in length due to the comb filter and truncated in time to N samples. This property makes the frequency magnitude response of the SDFT filter identical to the sin(Nx)/sin(x) response of a single DFT bin centered at a normalized frequency of $2\pi k/N$ [5]. This leads to the development of an efficient frequency error detection algorithm described in the following section.

4.2 Frequency Error Detector (FED)

The frequency response of the SDFT filter tuned to the pilot tone is shown in the following figure with samples marked with circles at the pilot frequency $2\pi k_0/N$ and at $2\pi(k_0\pm1)/N$. In the case of k_0 matching exactly with the tone frequency then the middle frequency sample will be at the maximum while the two side frequency samples will have zero value. When there is a frequency error, these samples are no more at maximum and zero locations any more, as illustrated by Figure 4.

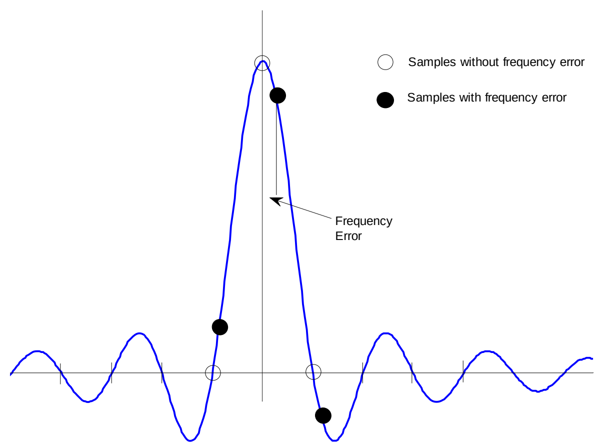

Figure 4 SDFT Filter Response

This frequency error can be estimated using the following expression;

$$e_k(n) = s_k(n)\left[s_{k-1}(n) - s_{k+1}(n)\right] \qquad (5)$$

Similar type of error detector has been used in timing error estimation in single carrier systems [6-7]. However according to the author, this is the first frequency domain application employing this type of detector for frequency synchronization of OFDM signals.

The above FED given by the expression (5) assumes real input frequency samples. In case of complex samples of SDFT filter output, it will be applied to both real and imaginary parts separately as given by the following expression;

$$e_k(n) = Sr_k(n)\left[Sr_{k-1}(n) - Sr_{k+1}(n)\right] + Si_k(n)\left[Si_{k-1}(n) - Si_{k+1}(n)\right] \quad (6)$$

Where $Sr_k(n)$ is the real part and $Si_k(n)$ is the imaginary part of the kth frequency sample $S_k(n)$ at time instant n.

This frequency error detector requires three frequency samples to be computed at each time step. The S-curve of this frequency error detector is given in the following figure for the case of $N = 512$ (it does not need to be power of 2).

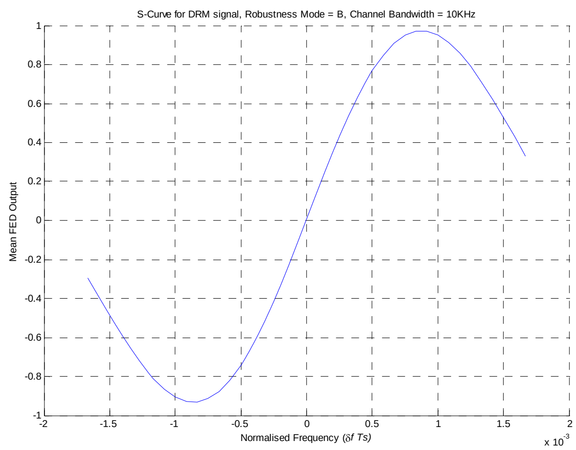

Figure 5 Frequency Error Detector S-Curve

The frequency tracking range of this algorithm is $\pm\pi/N$ as can be seen from the above frequency response of SDFT filter and FED S-curve. A smaller value of N will provide larger tracking range at the expanse of reduced noise performance due to increased SDFT filter bandwidth.

This frequency error detector is used in the tracking loop for DRM pilots and is explained in the following section.

4.3 SDFT AFC

In the Automatic Frequency Correction (AFC) loop, three pilot tones embedded in the DRM OFDM signal are tracked using above mentioned FED. The requirement of the frequency samples is three per pilot. In total nine frequency samples are calculated at each time instant as shown in the following Figure 6.

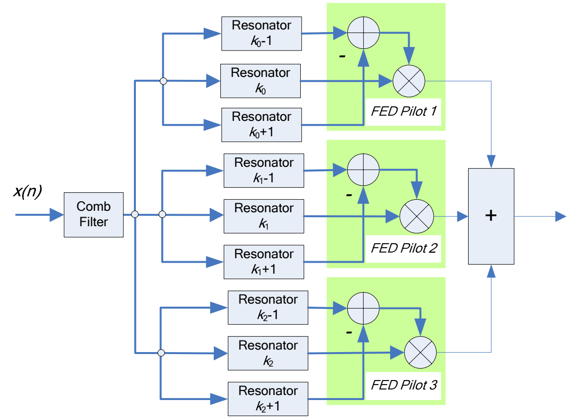

Figure 6 SDFT Filters and FED for DRM System

The frequency error detectors configuration given in the above figure makes use of all three DRM frequency pilots, however only one or two pilots may be used to reduce the processing load. However it may reduce performance especially in frequency selective fading channels.

The complete AFC loop for DRM signal is shown in Figure 7. The AFC loop response is controlled by the loop filter which has the following transfer function;

$$H_L(z) = k_p + \frac{k_f}{1 - z^{-1}} \quad (7)$$

Where k_p and k_f are proportional gain and integral gain. These filter constants are calculated for a given loop bandwidth and the damping factor as given by the following equations;

$$k_p = 4\frac{B_L T}{1 + \frac{1}{4\zeta^2}} \quad (8)$$

$$k_f = 4\left(\frac{B_L T}{\zeta + \frac{1}{4\zeta}}\right)^2 \quad (9)$$

Where ζ is the damping factor and $B_L T$ is the normalized loop bandwidth.

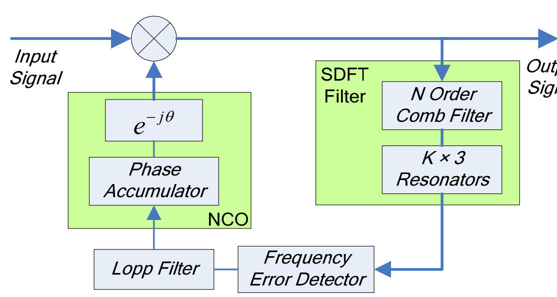

Figure 7 DRM AFC Loop

The NCO in AFC loop generates complex sinusoidal signal for the estimated frequency offset. It has been implemented using Taylor series approximation.

The response of the AFC loop is given in the following figure for two values of loop bandwidth.

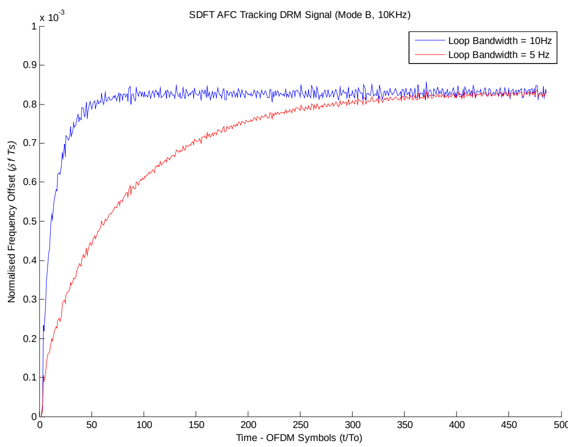

Figure 8 SDFT AFC Loop Response

An application has been filed for the patent of this frequency synchronization technique for OFDM broadcast systems.

5. Conclusions

It has been shown that sliding DFT algorithm can be used for the synchronization of OFDM pilots in DRM system. A novel computational efficient carrier frequency offset (CFO) detector is developed and used in the tracking loop. The characteristic curve of the CFO detector has been given along with the tracking loop response. The key feature of this SDFT tracking technique is that it is used in pre-FFT stage of an OFDM system and avoids the need for the post-FFT synchronization stage used in traditional OFDM receivers. This simplifies the receiver structure and reduces computational load and hence most suitable for mobile portable applications.

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