

Frequency Offset Estimation and Cell Search Algorithms for OFDMA Based Mobile WiMAX

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Abstract— Frequency offset estimation is an important issue in digital transceiver design, especially for coherent wireless transmission such as in WiMAX systems based on the IEEE 802.16e orthogonal frequency-division multiple access (OFDMA). The downlink synchronization, in WiMAX systems, involves synchronization of carrier frequency and timing as well as identification of the preamble index. This paper introduces synchronization algorithms for frequency offset estimation and cell search. The performance of these algorithms was tested using simulation under adaptive white Gaussian noise and fading channel for different values of signal to noise ratio. Simulation provided accurate results and the frequency offset in the received frame was successfully estimated.

Keywords—Mobile WiMAX; Synchronization; OFDMA; IEEE 802.16e; Cell search

I. INTRODUCTION

Mobile WiMAX systems are based on the IEEE 802.16e-2005 specifications which define a physical (PHY) layer and a medium access control (MAC) layer for mobile and broadband wireless access systems operating at microwave frequencies below 6 GHz [1]. The IEEE 802.16e-2005 specifications actually define three different PHY layers single-carrier transmission, orthogonal frequency-division multiplexing (OFDM), and orthogonal frequency division multiple access (OFDMA). WiMAX systems based on the IEEE 802.16e orthogonal frequency-division multiple access (OFDMA) physical layer specifications; synchronization is an essential issue for the OFDMA system. OFDMA inherits from OFDM the ability to compensate channel distortions in the frequency domain without the need of time domain equalizers. Thus without accurate synchronization algorithms, it is not possible to reliably receive the transmitted. Mobile WiMAX downlink (DL) synchronization involves synchronization of carrier frequency and timing as well as identification of the preamble index. Carrier frequency offset (CFO) may arise from the difference in natural oscillator frequencies between the base station (BS) and the mobile station (MS). However, OFDMA is extremely sensitive to timing errors and carrier frequency offsets between the incoming signal and the local oscillator used for signal demodulation.

Frequency offset in an OFDM system is introduced from two sources mismatch between the transmitted and the received sampling clocks and misalignment between the reference frequencies of transmit and receive stations. Both impairments and their effects on performance are analysed [2].

Carrier frequency errors between the transmitter and the receiver of any digital communication system increase the number of errors in the received bits. These errors result from the mismatch between the carrier frequency oscillators of the transmitter and the receiver in the RF section. Also, Doppler frequency due to the receiver's motion (up to 125 Km/hr) contributes to frequency offset [5] [6]. Carrier frequency offset has a great effect on OFDMA systems. The OFDMA symbol depends on the subcarriers being orthogonal. Each signal of a certain subcarrier should be detected at the frequency of its maximum in the frequency domain which is exactly the value of this subcarrier, which meets a zero from the signal carried on all other subcarriers. A frequency offset will distort the signal leading to incorrect decision and interference from all other subcarriers. If the timing window slides to the left or the right, a unique phase change will be introduced to each of the subcarriers. In the frequency domain, if the carrier frequency synchronization is perfect, the receiver samples at the peak of each subcarrier, where the desired subcarrier amplitude is maximized, and the inter carrier interference (ICI) are zero. However, if the carrier frequency is misaligned by some amount d , some of the desired energy is lost, and more significantly, inter carrier interference is introduced. So it's important to detect the frequency offset that occur on the OFDM signal. The frequency offset-shift-can be:

- **Fine frequency offset:** It's a shift within one subcarrier spacing.
- **Coarse frequency offset:** It's a shift of multiple integer number of subcarrier spacing [3] [4].

II. CYCLIC-PREFIX-BASED FINE FREQUENCY OFFSET ESTIMATION

The cyclic-prefix-based estimation technique depends on the repeated time samples of the guard time. As shown in Fig.1, The cyclic prefix samples are compared to their repeated part of the preamble OFDMA symbol in the form of a correlation in time domain [8].

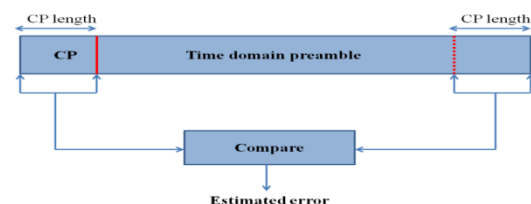


Figure 1. Cyclic-prefix-based frequency estimation.

The estimated frequency offset is proved by the following equations [7]:

$$-rn = sn \cdot \exp(j2\pi\Delta f n Ts) \quad (1)$$

If the number of time samples between the first time sample of the guard band and its corresponding time sample inside the OFDMA symbol is $D=1024$ which is the complete

FFT size of course. Then to estimate the frequency offset, the following algorithm may be applied.

$$z = \sum_{n=0}^{L-1} r(n) * r(n + D) \quad (2)$$

Where L is the number of compared time samples, which must be lower than the guard time. n is the index time sample. Then,

$$Z = \sum_{n=0}^{L-1} S(n) \exp(j2\pi\Delta f n Ts) [S(n D) \exp(j2\pi\Delta f (n D) Ts)]^* \quad (3)$$

and

$$Z = \exp(j2\pi\Delta f D Ts) \sum_{n=0}^{L-1} |S(n)|^2 \quad (4)$$

Then, the estimated frequency offset takes the form

$$\Delta f = -\frac{1}{2\pi D Ts} \text{angle}(Z) \quad (5)$$

The number of samples used for the estimation process is chosen to be less than half the guard band interval, starting from the beginning of its second quarter, to avoid the transient part affected by the channel. The complete guard band cannot be used because the errors in timing synchronization may lead not to exactly determine the start of the guard band. Taking more samples did not improve anything in the simulation results. The minimum number of correlation to give acceptable performance is determined. The limitation in this estimator is the angle (Z) which has the range from π to $-\pi$.

$$-\pi < \text{angle}(Z) < \pi; \quad (6)$$

$$-\pi < 2\pi D Ts \Delta f < \pi; \quad (7)$$

$$\frac{-1}{2 D Ts} < \Delta f < \frac{1}{2 D Ts}; \quad (8)$$

$$\frac{-fs}{2D} < \Delta f < \frac{fs}{2D}; \quad (9)$$

$$\frac{-\text{subcarrier spacing}}{2} < \Delta f < \frac{\text{subcarrier spacing}}{2}; \quad (10)$$

Where fs is the sampling frequency and D equals to the FFT size = 1024 samples. The limitation on the angle from $-\pi$ to π makes it impossible for the algorithm to estimate the coarse frequency offset which is multiple from the $\frac{fs}{D}$, which means it is multiples of $-\pi$ or π . Another conclusion from the implementation point of view is that the use of this correlation based algorithm will allow a hardware reuse as it's the same correlation needed for symbol start algorithm. Then both fine frequency estimation and symbol start needs same basic operation, which is correlation [9]. To prepare the received preamble for correlation with stored preambles, the following steps are executed:

- 1) The channel effect on the received preamble must be reduced. This is done by multiplying each sample by the conjugate of its predecessor with 3 samples apart. For illustration, examine the following equation:

If $Q(k)$ is the received preamble in frequency domain, $G(k) = R\{Q(k)Q^*(k-1)\}$. This is on the assumption that the angles added by the channel on each 2 consecutive active subcarriers are nearly the same, then multiplying by the conjugate eliminate the channel's effect.

- 2) In case of using the second method hard decision is to be done to $G(k)$.

After estimating the fine frequency offset through the angle of maximum correlation -see equation "(5)", compensating the offset is through multiplying the preamble samples by $\exp(-j2\pi\Delta f n Ts)$ to correct the frequency offset.

III. JOINT DETECTION OF INTEGRAL CARRIER FREQUENCY OFFSET AND CELL SEARCH

This algorithm considers joint detection of integral CFO and preamble index, under the assumption OFDM symbol boundaries and fine frequency offset have been acquired to reasonable accuracy. This assumption is valid with the timing and fine frequency offset simulation results. Based on an optimization formulation, a number of detection methods are driven of different complexity and optimization methods. The methods exploit the quasi-orthogonality among the OFDMA WiMAX preamble sequences as well as the organization of the nonzero subcarriers in the preambles [4]. Simulation results are presented to illustrate the performance of the methods, see section IV. This algorithm detect the integer frequency offset in range [-9 9 frequency offset pins] by the correlation in frequency domain between the received preamble -that is one of the 114 preambles- and the 114 preambles stored in the receiver. The max correlation indicates the most probable preamble sent, and then we can use it to calculate the integer frequency offset.

If the spacing of the nonzero subcarriers in the preamble is much smaller than the coherence bandwidth of the channel, then the channel responses at neighbouring preamble subcarriers are approximately equal, mathematically, this can be given by:

$$H(K+1) = H(K) + \Delta H(K) \quad (11)$$

Where $|\Delta H(K)| \ll |H(K)|$ and K is an index for nonzero preamble subcarriers.

and,

$$\begin{aligned} R\{Q(k)Q^*(k-1)\} \\ = R\{H(k)P_j(k+n)H^*(k-1)P_j^*(k+n-1)\} \\ \approx |\Delta H(K)|^2 D_j(k+n) \end{aligned} \quad (12)$$

Where,

- $Q(k)$ is the received preamble in the frequency domain.
- $P_j(k)$ the stored preamble of index (j) in the frequency .
- $D_j(k) = P_j(k) \times P_j^*(k-1)$ Preamble (j) multiplied by a shifted version of one active subcarrier
- n is the integral frequency offset normalized to the subcarrier spacing.

The normalized integral frequency offset means that multiplying each active subcarrier by the conjugate of its predecessor will cancel the channel-added phase and then we can correlate the preamble patterns shifted by the expected values of the integral carrier frequency offset and select the maximum correlation as follows:

$$M_n^{n,j} = \sum_{k=0}^{N_p-1} D_j(k+n) R\{Q(k)Q^*(k-1)\} \quad (13)$$

Where $R\{Q(k)Q^*(k-1)\}$ is called the differential signal. The estimated integral CFO -carrier frequency offset- and preamble index are given by:

$$(\hat{n}, \hat{j}) = \underset{n,j}{\operatorname{argmax}} M_{n,j}^n \quad (14)$$

IV. ALGORITHMS SIMULATION RESULTS

This section provides a detailed explanation and discussion of the simulation results of each algorithm. Those algorithms are simulated in ideal, AWGN, and dispersive fading channel with fixed point analysis. Each algorithm was simulated under fixed point analysis with the minimum number of bits achieved for each operation with acceptable performance. The parameters used are tabulated in Table 1.

TABLE 1. WiMAX OFDM parameters.

Symbol	Description	Relation	Used value
B	Nominal bandwidth	$B = 1/T_s$	10 MHz
L	Number of subcarriers	Size of <i>IFFT/FFT</i>	1024
G	Guard fraction	% of <i>L</i> for <i>CP</i>	¼
F_s	Sampling frequency	$1/T_s$	11.2 MHz
T_s	Sample time	$1/F_s$	89.2 nano sec
N_g	Guard band	$N_g = GL$	256
T_g	Guard time	$T_g = T_s N_g$	22.8 sec
T	OFDM symbol time	$T = T_s(L + N_g)$	114.2 sec
B_{sc}	Subcarrier spacing	$B_{sc} = B / L$	10.94 KHz.

A. Cyclic-Prefix-Based Fine Frequency Offset Estimation

To compute the percentage of errors the following conditions have been applied:

- Runs for x-axis = number of runs for y-axis = 1000 runs.
- The area of consideration ($-f_s/2$ to $f_s/2$) is estimated 500 times for each dB, where f_s is subcarrier spacing.
- The upper line at 2% represents the end range of error stated by the standard, for frequency offset error in estimation.

As shown in Fig.2, Fig.3 and Fig.4 the estimated error percentage is less than half of the maximum allowed error, this means the cyclic prefix based fine frequency algorithm have acceptable performance in frequency offset estimation.

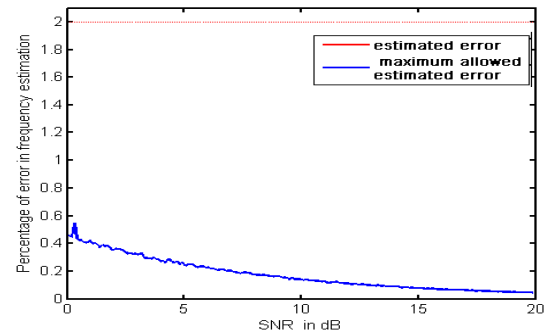


Figure 2. Fine frequency offset estimation with different SNR under AWGN.

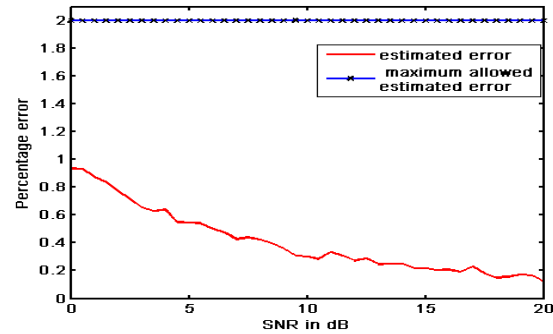


Figure 3. Fine frequency offset estimation with different 18bit fixed point analysis.

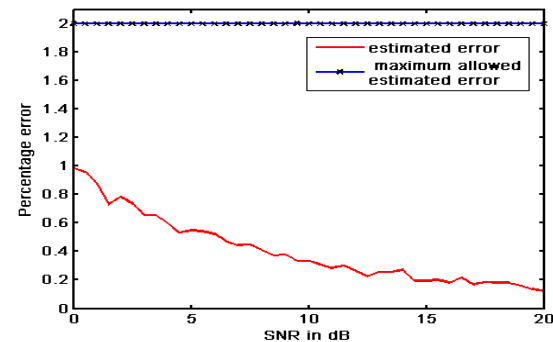


Figure 4. Fine frequency offset estimation with different 20 bit fixed point analysis.

B. Joint-Based Coarse Frequency Offset Estimation

The following figures illustrate the performance of the coarse frequency offset algorithm through histograms under fading and AWGN.

- Number of runs = 250 run.
- Number of integral carrier frequency offset tested = 6
- In these histograms, it's taken into consideration to try preambles of different segments, to make sure it works for all 114 preamble patterns, thus different segments.

From the simulation result of joint based frequency coarse offset figures shown below, when the algorithm applied under fading at 2dB the estimated coarse frequency shift is equal to 6 and preamble number is equal to 90 at 246 run. This means that the algorithm was accurate at 246 runs; this is illustrated in Fig. 5 and Fig. 6. In Fig. 7 and Fig. 8 SNR was increased to 10dB and the performance increased to 250 run.

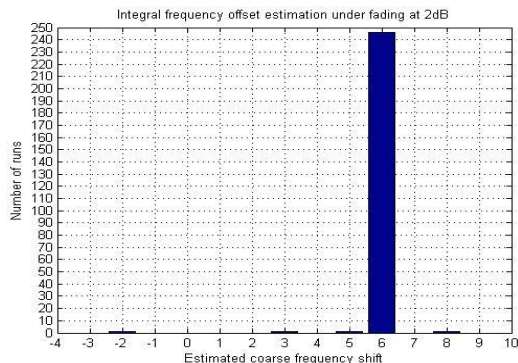


Figure 5. Integral frequency offset estimation under fading at 2dB.

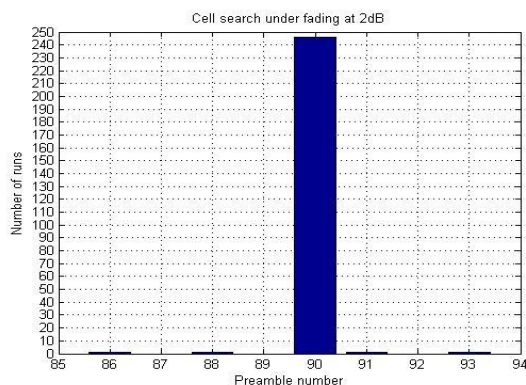


Figure 6. Cell search results under fading at 2dB.

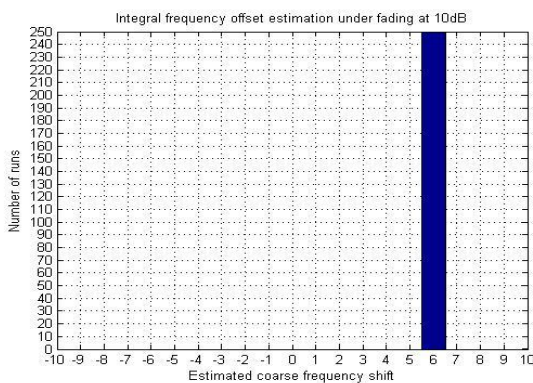


Figure 7. Integral frequency offset estimation under fading at 10dB.

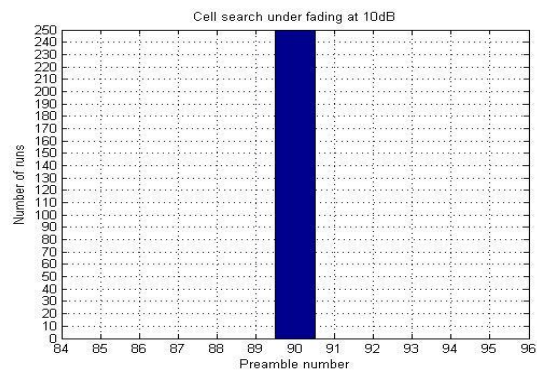


Figure 8. Cell search results under fading at 10dB.

V. CONCLUSIONS

In OFDMA based mobile WiMAX, the receiver must align its carrier frequency as closely as possible to the transmitted carrier frequency. In this paper, the fine and coarse frequency offset estimation algorithms have been simulated. Joint detection of the coarse frequency offset and the cell search under fading and AWGN was obtained. The simulation results of these algorithms accurately estimated the frequency offset in the received frame. For future work, the whole transceiver system of the WiMAX can be simulated and implemented applying the same parameters.

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