An Adaptive Cell Search and Integral Frequency Offset Estimation in Mobile WiMAX

Jieun Choi, Minjae Park, Suhyun Cha and Hwang Soo Lee
Department of EECS, Division of Electrical Engineering,
KAIST 373-1,
Guseong-dong, Yuseong-gu, Daejeon, Republic of Korea
{roziel, mjpark, suhyuncha}@mcl.kaist.ac.kr, hwanglee@ee.kaist.ac.kr

Abstract— **In the orthogonal frequency division multiplexing (OFDM) based cellular wireless communication systems such as the Mobile WiMAX system, the communication between a mobile station (MS) and a base station (BS) starts with synchronization that includes time and frequency synchronization, and cell search. During the initial synchronization process in the Mobile WiMAX system, the cell search and the integral carrier frequency offset (CFO) estimation require computational complexity that consumes much of computational resources in downlink synchronization block. Therefore in this paper, we propose an efficient method to reduce the computational complexity of the synchronization process without performance degradation. The simulation result shows that the proposed method reduces computational complexity up to 1/16 compared with a conventional method.**

Keywords-adaptive, cell search, Integral CFO, Mobile WiMAX, synchronization

I. Introduction

In wireless communication systems, when the receiver starts communication, it can decode the data signal after estimating a starting sample point of a frame and compensating a frequency offset of the local oscillator. For cellular systems, the downlink synchronization block of the mobile station (MS) should also include cell search for distinguishing cells. Recently, the orthogonal frequency division multiplexing (OFDM) technique is widely used in the cellular wireless systems due to the advantages such as high bandwidth efficiency and robustness to frequency selective fading. However, OFDM is very sensitive to synchronization error, which leads to severe system performance degradation [1]. Therefore, in the OFDM based cellular wireless communication systems such as the Mobile WiMAX, precise time and frequency synchronization, and cell search is required.

The synchronization block of the Mobile WiMAX is composed of time synchronization [2][3][4], fractional frequency synchronization [5][6][7] and cell search and integral frequency synchronization [8][9]. Several cell search and integral frequency offset estimation methods in Mobile WiMAX have been proposed in the papers [8][9]. Lim and kwon [8] used the receiver signal strength information (RSSI) for synchronization of Mobile WiMAX. However, it requires high computational complexity since this method uses a whole data in time domain. To reduce the computational complexity, Hung and Lin [9] used a 2-taps low pass filter having a sync function in frequency domain. However, at the cost of the computational complexity reduction it resulted in performance degradation. Therefore in this paper, we present an adaptive cell search and integral carrier frequency offset (CFO) estimation method, which significantly reduces the computational complexity without performance degradation.

A brief description of the preamble structure in Mobile WiMAX is given in Section II. In Section III, the initial synchronization algorithm except cell search and integral CFO estimation is described. A conventional method and the proposed method for cell search and integral CFO estimation are explained in Section IV. Performance results are shown in Section V, and conclusions are made in Section VI.

II. Preamble Structure in Mobile WiMAX

OFDM based systems usually have a preamble located at the first symbol of the frame for reducing synchronization error. Generally a preamble is designed to have a repetitive pattern in time domain, because a good autocorrelation property of the repetitive pattern helps reliable and rapid frame timing estimation [10]. OFDM systems usually have only one fixed preamble. However, for cellular systems, neighboring cells should use different preamble sequences for distinguishing cells. There are 114 different preamble sequences that help distinguish cells in Mobile WiMAX. The preamble sequences are defined in the IEEE 802.16e standard [11]. Each sequence is BPSK modulated on every third subcarrier, so the preamble has a pattern that repeats itself 3 times. The preamble structure is shown in Fig. 1. The transmitted preamble symbol in time domain is given by

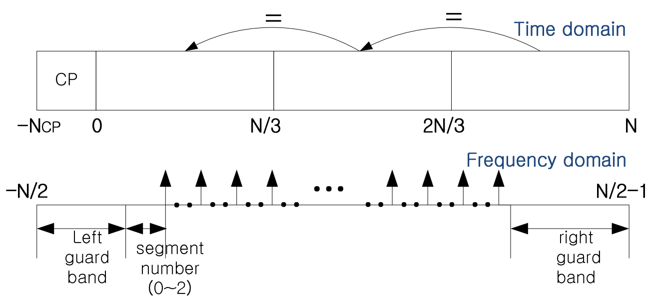

Figure 1. Preamble structure

This work was supported in part by the IT R&D program of MKE/IITA under Contract number 2005-S-609-04 in Korea.

$$s(n)=\frac{1}{N}\sum_{k=-N/2}^{N/2-1}P(k)\cdot e^{j2\pi n\frac{k}{N}},\ \ n=0,\ldots,N-1 \qquad (1)$$

where $P(k)$ is BPSK modulated preamble sequence on k-th subcarrier and N is the fast Fourier transform (FFT) size.

III. Initial Downlink Synchronization

In this section, we introduce initial synchronization algorithms except cell search and integral CFO estimation. The initial downlink synchronization process for Mobile WiMAX is shown in Fig. 2.

A. Frame Timing Synchronization

Let the sampled received signal be r(n). Then, the starting sample point of the frame is given by [2]

$$\hat{d}=\left\{\arg\max_{d}\sum_{n=0}^{N_{window}-1}\left(\begin{array}{l}r^{*}(n+d)\\ \cdot r(n+N/3+d)\end{array}\right)\right\}+N_{CP} \qquad (2)$$

$$d=0,\ldots,\ frame\ length$$

where N_{CP} is the number of the samples in cyclic prefix (CP) and N_{window} is equal to (2N/3) + N_{CP} as a correlation window size. To estimate the starting sample point of the frame, an autocorrelation method is used due to the fact that the preamble has a pattern that repeats itself 3 times.

B. Fractional CFO Estimation

The CP correlation c_m is defined as

$$c_m=\sum_{n=-\frac{3N_{CP}}{4}}^{-\frac{N_{CP}}{4}}\begin{array}{l}r^{*}(\hat{d}+m\cdot N_s+n)\\ \cdot r(\hat{d}+m\cdot N_s+n+N)\end{array} \qquad (3)$$

where N_S is equal to N + N_{CP} as a symbol size. Then fractional part of CFO normalized to subcarrier spacing is estimated using M OFDM symbols [7].

$$\vartriangle\hat{f}_f=\frac{1}{2\pi}\angle\sum_{m=0}^{M}c_m \qquad (4)$$

A CP is a copy of the last portion of data symbol. Therefore, the transmitted CP and the last portion of the data symbol are exactly same. The received CP and last portion of the data symbol have a phase difference, which is proportional to CFO.

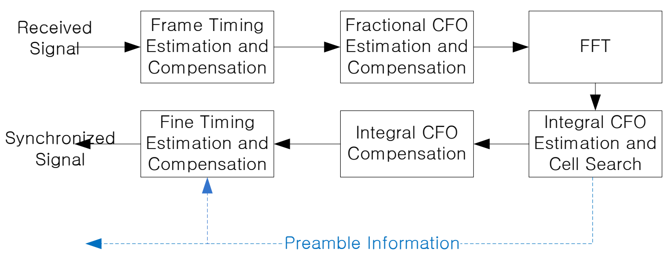

Figure 2. Block diagram of the downlink initial synchronization for Mobile WiMAX

Therefore, fractional CFO can be estimated using the phase difference. The correlation region is set as (-3N_{CP}/4, -N_{CP}/4), not the whole CP duration, due to residual frame timing estimation errors and multipath delay.

C. Fine Timing Estimation

Let the estimated channel impulse response be $r_I(n)$,

$$\begin{aligned}r_I(n)&=\ IFFT(P_{\hat{c}}^{*}(k)\cdot R(k))\\ &=IFFT[\ \textstyle\sum_i\alpha_i\cdot|P_{\hat{c}}^{*}(k)|^2\cdot e^{-j2\pi n_d k/N}\cdot e^{-j2\pi n_i k/N}\,]\\ &=IFFT[\ \textstyle\sum_i\alpha_i\cdot P^2\cdot e^{-j2\pi n_d k/N}\cdot e^{-j2\pi n_i k/N}\ ]\\ &\approx\textstyle\sum_i\alpha_i\cdot P^2\delta(n-n_d-n_i),\quad n=0,\ldots,N/3-1\end{aligned} \qquad (5)$$

where the estimated preamble sequence is $P_{\hat{c}}(k)$, which can be obtained in cell search block. The channel impulse response is $h(n)=\sum_i\alpha_i\cdot\delta(n-n_i)$, the propagation delay is n_d, received signal in time domain is $r(n)=\sum_i\alpha_i\cdot s(n-n_d-n_i)$, and the received preamble in frequency domain is $R(k)=\sum_i\alpha_i\cdot P_c(k)\cdot e^{-j2\pi(n_d+n_i)k/N}$.

Then there are impulse signals at n_d + n_i in $r_I(n)$. The fine timing offset $\hat{d}_{fine}$ is thus given by [4]

$$\hat{d}_{fine}=\arg\max_{n}(r_I(n)) \qquad (6)$$

IV. Integral CFO Estimation and Cell Search

A. The Conventional Method

In Mobile WiMAX system, the preamble sequence is BPSK modulated on every third subcarrier between left and right guard band as shown in Fig. 1. When the detection of preamble index and integral CFO is obtained in time domain, it is required to calculate a correlation sum for samples in a symbol. On the other hand, when it is obtained in frequency domain, it is required to calculate a correlation sum only for modulated subcarriers. Therefore, in a conventional method, it is obtained in frequency domain. The estimated preamble index $\hat{c}$ and integral CFO $\vartriangle\hat{f}_i$ can be expressed as

$$(\vartriangle\hat{f}_i,\hat{c})=\arg\max_{\vartriangle f_i,c}\left|C(\vartriangle f_i,c)\right| \qquad (7)$$

$$\text{where}\ \ C(\vartriangle f_i,c)=\sum_{l=0}^{Np-1}\left(\begin{array}{l}R(\vartriangle f_i+k_l)\cdot P_c^{*}(k_l)\\ \cdot R^{*}(\vartriangle f_i+k_{l+1})\cdot P_c(k_{l+1})\end{array}\right) \qquad (8)$$

$$c=0,\ldots,113,\ \ \Delta f_i\ \in\{\text{CFO Range}\}$$

$P_c(k)$ is the k-th value of the preamble which of index c, k_l is N_{left_offset} +3·l as the l-th modulated signal (N_{left_offset} = -N/2 + left guard + segment number), and the received signal with residual timing offset in frequency domain R(k) will be

$$R(k) = P(k)H(k)e^{-j2\pi\varepsilon\frac{k}{N}} + W(k),\ k = 0,...N-1 \qquad (9)$$

where H(k) is the frequency channel response on the k-th subcarrier, ε is residual timing offset, and W(k) is complex Gaussian noise.

When $(\triangle \hat{f}_i, \hat{c})$ is correct, $C_{\triangle f_i, c}$ can be approximated

$$C(\triangle f_i, c) \approx \left| \sum_{k=0}^{Np-1} \left| H(\triangle f_i + k_l) \right|^2 \cdot P^4 \cdot e^{\frac{-j2\pi\varepsilon(3)}{N}} + \tilde{W} \right|$$

$$\approx \left| \sum_{k=0}^{Np-1} \left| H(\triangle f_i + k_l) \right|^2 \cdot P^4 \right| + \left| \tilde{W} \right| \qquad (10)$$

where $|P_c(k_l)|$ is constant P, $\tilde{W}$ is defined noise and we can suppose that $H(k_l) \approx H(k_{l+1})$ due to the very narrow subcarrier spacing. The result from (10) indicates this algorithm is not affected by residual timing offset.

For practical applications, the computational complexity is very important. In this stage we calculate the number of multiplications (MULs#) and additions (ADDs#) needed in the synchronization block.

- Frame timing estimation:

  MULs# : $4 \cdot (N_{window} + 2 \cdot N_{frame}) \approx 4.51 \times 10^5$

  ADDs# : $4 \cdot (N_{window} + 2 \cdot N_{frame}) \approx 4.51 \times 10^5$

- Fractional CFO estimation:

  MULs#: $2 \cdot N_{CP} \cdot M \approx 2.56 \times 10^3$

  ADDs#: $2 \cdot N_{CP} \cdot M \approx 2.56 \times 10^3$

- Fine timing estimation:

  MULs#: $2 \cdot N_{CP} + (2N) \cdot \log_2 N \approx 2.16 \times 10^4$

  ADDs#: $(2N) \cdot \log_2 N \approx 2.05 \times 10^4$

- Cell search and integral CFO estimation using a conventional method:

  MULs#: $7 \cdot Np \cdot 114 \cdot (\text{CFO Range}) \approx 1.36 \times 10^7$

  ADDs#: $4 \cdot Np \cdot 114 \cdot (\text{CFO Range}) \approx 7.77 \times 10^6$

In the above calculation, we assume N=1024samples, N_{frame}=56000samples, N_{CP}=128samples, Np=284, M=10 and CFO Range = 60 subcarrier spacings.

According to the analysis above, the computational complexity of cell search and integral CFO estimation block is about twenty times than that of all other synchronization block. In other words, the computational complexity of the whole synchronization block is heavily dependent on that of the cell search and integral CFO estimation. Therefore, it is important to reduce the computational complexity of cell search and integral CFO estimation for rapid initial synchronization.

B. The Proposed Method

In the conventional method, Np bits are used for calculating

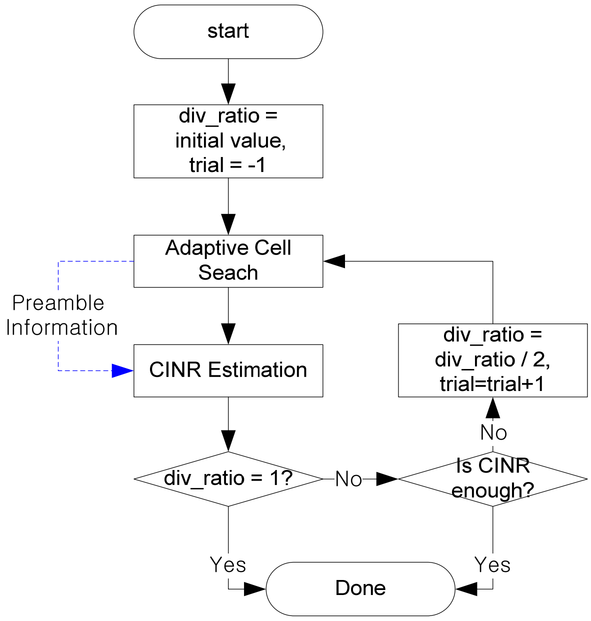

Figure 3. The flow chart of the proposed method

a correlation. However, to use a fraction of Np bits for calculating a correlation doesn't affect the performance of cell search and integral CFO when CINR is high enough. We implement this idea in a proposed method as shown in the following procedure and Fig. 3.

1) A MS initializes div_ratio, which determines correlation window size, Np/div_ratio, for adaptive cell search. Also, trial is set as -1. Generally, div_ratio is larger than 1.

2) The preamble index and integral CFO are estimated by (11) , adaptive cell search equation.

3) CINR is calculated using the result of 2) by (14).

4) If div_ratio is not equal to 1, it goes to 5). Else this procedure is over and a MS accepts current estimated preamble index and integral CFO. Because div_ratio is equal to 1, which implies that Np bits are used such as the conventional method.

5) If minimum required correlation window size for estimated CINR is bigger than the current window size (Np/div_ratio), we decide estimated result is not enough to trust and it goes to 6). Else this procedure is over and a MS accepts current estimated preamble index and integral CFO.

6) The div_ratio is set as a half of div_ratio to increse the correlation window size and the trial is increased by one, and it goes to 2) and repeats.

In 5), if one of the estimated preamble index or integral CFO is wrong, the estimated CINR obtained by the wrong information will be very low. Then, go to 6) and increase the correlation window size. Though both of them are correct, if the estimated CINR is lower than the reliable CINR of the current correlation window size, go to 6) and increase the correlation window size. Therefore, the proposed method reduces computational complexity without performance degradation compared with the conventional method. The adaptive cell search equation is given by

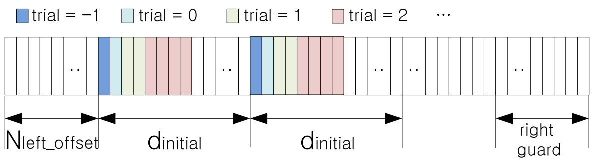

Figure 4. The calculated signals for each trial

$$(\triangle \hat{f}_i, \hat{c}) = \underset{\triangle f_i, c}{\max \arg}\, C_{trial}(\triangle f_i, c) \tag{11}$$

where

$$C_{trial}(\triangle f_i, c) = \begin{cases} \displaystyle\sum_{l=0}^{\frac{Np}{initial\_value}-1} \begin{pmatrix} R(\triangle f_i + k_{-1}(l)) \cdot P_c^*(k_{-1}(l)) \cdot \\ R^*(\triangle f_i + k_{-1}(l+1)) \cdot P_c(k_{-1}(l+1)) \end{pmatrix}, & trial = -1 \\ C_{(trial-1)}(\triangle f_i, c) + & \\ \displaystyle\sum_{t=0}^{2^{trial}-1} \sum_{l=0}^{\frac{Np}{initial\_value}-1} \begin{pmatrix} R(\triangle f_i + t + k_{trial}(l)) \cdot \\ R^*(\triangle f_i + t + k_{trial}(l+1)) \cdot \\ P_c^*(t + k_{trial}(l)) \cdot P_c(t + k_{trial}(l+1)) \end{pmatrix}, & o.w. \end{cases} \tag{12}$$

$$k_{trial}(l) = \begin{cases} N_{left\_offset} + 3 \cdot (initial\ value) \cdot l, & trial = -1 \\ N_{left\_offset} + 2^{trial} + 3 \cdot (initial\ value) \cdot l, & o.w. \end{cases} \tag{13}$$

It is shown ((12) and Fig. 4) that, even when the trial is -1, $C_{trial}(\triangle f_i, c)$ yields the diversity gain because the calculated signal is spread over a wide spectrum that is affected by frequency selective fading. The Np/div_raio is the correlation window size of each trial. Since the MS keeps the correlation sum of the previous trial, it is required to calculate the subcarriers that are not calculated before. Therefore, the adaptive cell search has the same computational complexity as that of conventional method even though the div_ratio is 1. Of course, the computational complexity of the adaptive cell search is lower than the conventional method when the div_ratio is bigger than 1. In the proposed method, the computation for estimating CINR is additionally needed, but the estimated CINR can be used for the channel quality information (CQI) feedback. Then CINR can be calculated by [12]

$$CINR_{data}(dB) = 10\log_{10}\left(\frac{A-B}{B}\right) - 9 \tag{14}$$

where $A = \sum_{l=0}^{Np-1} |U_l|^2$, $B = \frac{1}{2}\sum_{l=0}^{Np-1} |U_{l+1} - U_l|^2$

$$U_l = R(\Delta \hat{f}_i + k_l) \cdot \hat{P}_c^*(k_l), \qquad l = 0, \ldots, Np \tag{15}$$

V. Simulation Result

The simulation parameters are selected from Mobile WiMAX system parameters [11]; N=1024, N_{cp}=256 and Np=284. The residual timing offset ε is randomly selected in the range of [-10, 10] samples and the residual fractional CFO is 0.02 subcarrier spacing. The integral CFO range is selected

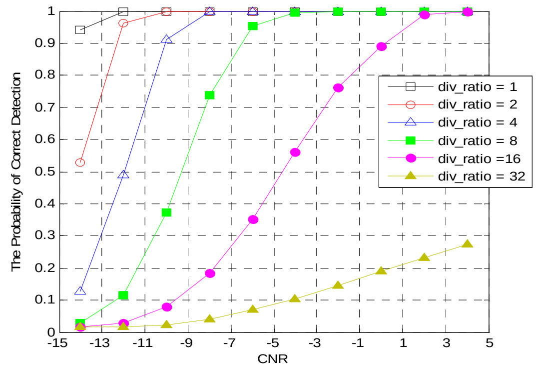

Figure 5. The probability of correct detection for each div_ratio in AWGN channel

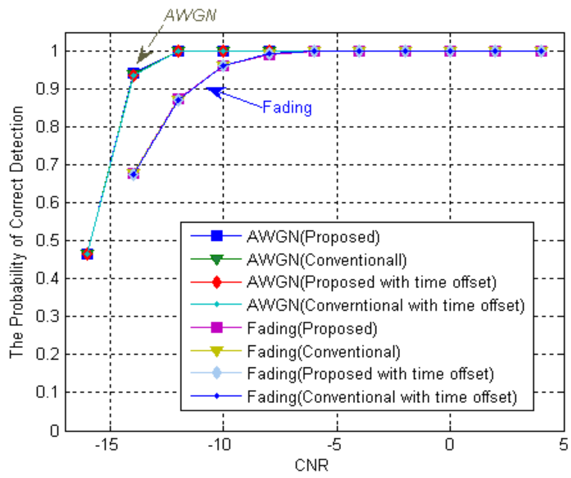

Figure 6. The probability of correct detection

from -50 subcarrier spacing to 50 subcarrier spacing. $CINR_d$ is CINR in the data region and set as from -20dB to 15dB. Therefore, CINR in the preamble region is -11dB to 24dB since the power of preamble is 9dB higher than the power of data. Fig. 5 shows the probability of correct detection for different div_ratios. The initial value of the div_ratio is set as 16, because it is impossible to find the exact preamble index among the preamble set despite of the high CINR when the div_ratio is 32. The CINR thresholds of different div_ratios used for 'Is CINR enough?' block in Fig. 3 are determined according to the CINR that the probability of correct detection goes to 100% from Fig. 5. The condition of 'Is CINR enough?' block is as follows

$$\begin{Bmatrix} (CINR > 2\ and\ div\_ratio \geq 16)\ \text{or}\ (CINR > 0\ and\ div\_ratio \geq 8)\ \text{or} \\ (CINR > -4\ and\ div\_ratio \geq 4)\ \text{or}\ (CINR > -8\ and\ div\_ratio \geq 2) \end{Bmatrix} \tag{16}$$

In Fig.6 shows the probabilities of correct detection in an AWGN channel and a fading channel conditions, respectively. The fading channel is the vehicular A 30km/h model [13]. The correct detection means to detect both preamble index and integral CFO correctly. From the Fig. 6, it can be observed that the proposed and the conventional method reveal the same performance in each channel model. When CINR is -10,

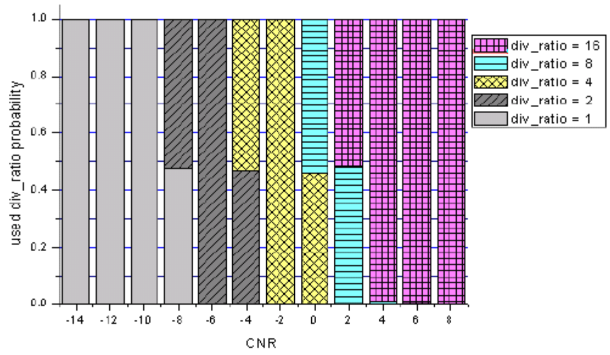

Figure 7. Used div_ratio probability in AWGN channel

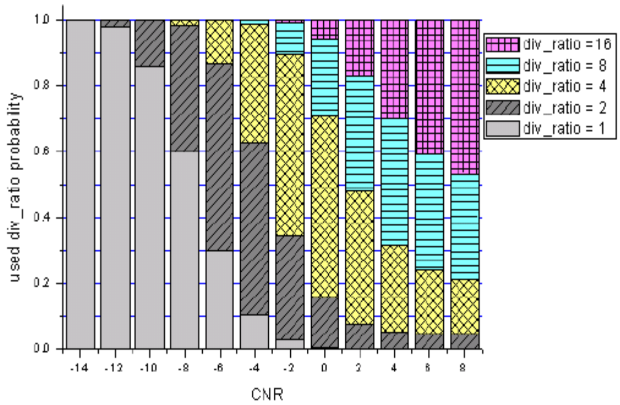

Figure 8. Used div_ratio probability in Fading channel

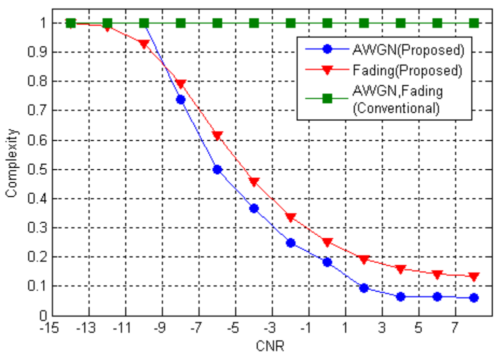

Figure 9. Complexity

a MS is not able to decode data but we can detect the preamble index and integral CFO almost. Synchronization is necessary, even CINR is very low. The simulation result is satisfied this condition. The Figs. 7 and 8 shows the ratio of the div_ratio used to detect the preamble index and integral CFO versus CINR in an AWGN channel and a fading channel, respectively. The CINR value from (14) is reliable, because the Fig. 7 matchs well with the condition of (16). Finally Fig. 9 shows the overall computational complexity. From the Fig. 9, When CINR is high enough, the computational complexity is reduced up to 1/16 by the proposed method compared to the conventional method. We can get almost accurate detection and low computational complexity simultaneously in general communication environment that has channel condition to decode data. Also, the proposed method does not show any degradation when CINR is very low.

VI. Conclusions

A computationally efficient cell search and integral CFO estimation method for Mobile WiMAX is presented in this paper. To detect preamble index and integral CFO, MS has to calculate correlation for all preamble sequences in the integral CFO range. In the conventional method, the computational complexity of the cell search and integral CFO estimation block is about twenty times higher than that of all other synchronization block. Considering practical implementation, initial synchronization performance depends not only on the accuracy of estimation but also the computational complexity. Therefore, it is necessary to reduce the computational complexity of cell search and integral CFO estimation block. The simulation results show that the proposed method satisfies two conditions, accuracy and low computational complexity, simultaneously.

References

[1] T. Pollet, "The BER performance of OFDM systems using nonsynchronized sampling," in proc. Of GLOBCOM'94, pp.253-257,1994.

[2] T. M. Schmidle and D. C. Cox, "Robust Frequency and Timing Synchronization for OFDM," IEEE Trans. Commun., vol. 45, pp.242-244, Dec. 1997

[3] T. Bhatt, V. Sundaramurthy, J Zhang and D McCain, "Initial Synchronization for 802.16e Downlink," in proc. Of ACSSC'06, pp701-706, Nov. 2006.

[4] K. Taura, M. Tsujishta, M. Takeda, H. Kato, M. Ishida and Y. Ishida, "Digital AudioBroadcasting(DAB) Receiver," IEEE Trans. Consumer Electronics vol. 42, no. 3, pp.322-326, Aug. 1996

[5] P. H. Moose, "A technique for orthogonal frequency division multiplexing frequency offset correction," IEEE Trans. Commun., vol. 42, pp.2908-2914, Oct. 1994.

[6] H. Zhou, H. Hayashi, T. Kubo and J. Zhang, "A novel carrier frequency offset estimation method for IEEE 802.16E systme," in proc. Of GLOBCOM'07, pp.2826-2830, Nov. 2007.

[7] J. Beek, M. Sandell and P.O. Borjesson, "ML estimation of Time and Frequency Offset in OFDM Systems," IEEE Trans. Signal Processing, vol 45, pp 1800-1805, July 1997.

[8] H. S. Lim and D. S. Kwon, "Initial Synchronization for WiBrao," Asia-Pacific Conference on Communications, pp.284-288, Oct.2005.

[9] K. C. Hung and D. W. Lin, "Joint Detection of Integral Carrier Frequency Offset and Preamble Index in OFDMA WiMAX Downlink Synchronization," in proc. Of WCNC'07, pp.1959-1964, March 2007

[10] T. H. Sun, S. W. Kang, K. H. Kim and K. H. Chang, "Optimizaztion of Link-level performance and Complexity for the Floating-point and Fixed-point Designs of IEEE 802.16e OFDMA/TDD Mobile Modem," KICS, vol.47, pp95-117, Nov. 2007.

[11] K. S, Kim, S. W. Kim, Y. S. Cho and J. Y. Ahn,"Synchronization and Cell-Search Technique Using Preamble for OFDM Cellular Systems," IEEE Trans.Vehicular Technology, vol. 56, pp.3469-3485, Nov. 2007.

[12] IEEE LAN/MAN Standard Committee, "IEEE Standard for Local and Metropolitian Area Networks – Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Ststems," IEEE Std 802.16e-2005 and IEEE Std 802.16-2004/Cor1-2005, 2006.

[13] R. Srinivasan, J. Zhuang, L. Jalloul, R. Novak and J. Park, "Draft IEEE 802.16m Evaluation Methodology," IEEE 802.16m-07/037r2