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

Fakher Eldin M. Suliman, Nuha M. Elhassan, Tertiel A. Ibrahim

Sudan University of Science and Technology, Khartoum, Sudan

fakhereldinmohamed@sustech.edu, nohamohamed3@gmail.com, terteil88@yahoo.com

***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) due to inherited frequency and timing offset problems which contribute to the loss of the transmitted data. To overcome these problems, the transmitter and receiver must be well synchronized. In WiMAX systems, the downlink synchronization 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*-Carrier frequency, Cell search, Mobile WiMAX, Orthogonal frequency-division multiplexing (OFDM), Synchronization; Wireless metropolitan area network (WMAN)**

I. INTRODUCTION

In view of the requirement of providing sufficient data rate when the user is moving at high speed, the Institute of Electrical and Electronic Engineers (IEEE) has proposed the IEEE 802.16e standard to achieve a high speed broadband wireless access network for future mobile wireless communication systems [1]. The standard is widely known as WiMax, which is an acronym for Worldwide Interoperability for Microwave Access.

The WiMAX network is considered as a Wireless Metropolitan Area Network (WMAN) and is one of the Broadband Wireless Access (BWA) techniques that have emerged as a promising solution for last mile access technology. Fig.1 shows positions of different existing wireless access technologies in terms of mobility and data rate.

The IEEE 802.16e-2005 specifications 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 [2]. Actually, three different PHY layers are defined: single-carrier transmission, orthogonal frequency-division multiplexing (OFDM), and orthogonal frequency division multiple access (OFDMA). OFDMA inherits from OFDM the ability to compensate channel distortions in the frequency domain without the need of time domain equalizers. In WiMAX systems based on the IEEE 802.16e orthogonal frequency-division multiple access (OFDMA) physical layer specifications; synchronization is an essential issue. Thus without accurate synchronization algorithms, it is not possible to reliably receive the transmitted signal. Mobile WiMAX downlink (DL) synchronization involves synchronization of carrier frequency and timing as well as identification of the preamble index.

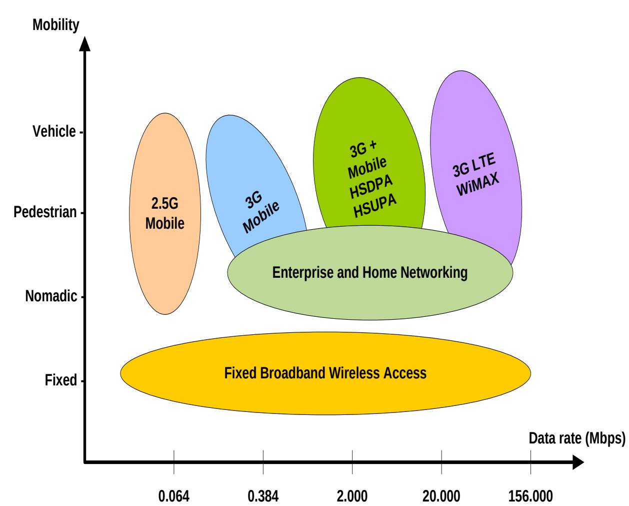

Fig. 1. Positioning of different wireless access technologies in terms of mobility and data rate.

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.

Manuscript received 30 April, 2012.
F. M. Suliman is now with the Department of Electrical Engineering, King Khalid University, Abha, KSA (Tel: 00966551792532; e-mail: fmsuliman@kku.edu.sa)
N. M. Elhassan is with the Department of Electronics Engineering, Sudan University of Science and Technology, Khartoum, Sudan.
(e-mail: nohamohamed3@gmail.com)
T. A. Ibrahim is with the Department of Electronics Engineering, Sudan University of Science and Technology, Khartoum, Sudan.
(e-mail: terteil88@yahoo.com)

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 [3].

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 [4] [5]. 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 [6] [7]:

- 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.

II. Cyclic-Prefix-Based Fine Frequency Offset Estimation

There are a number of well-known methods that are used to estimate the frequency offset, the most efficient of which is based on exploiting time domain periodicity in the preamble. For all OFDM systems, there is always the periodicity involving the cyclic prefix. However, as will be shown later in the paper, there is a performance degradation if the system uses the cyclic prefix(CP) periodicity in estimating the frequency offset in frequency selective fading channels. That's one of the main reasons preambles are periodic in OFDM based systems. However, the preamble of the OFDMA mode of Mobile WiMAX does not have a periodic portion if it is sampled at the commonly employed Fast Fourier Transform (FFT) sampling rate. The OFDM theory requires the addition of a CP at the beginning of the OFDM symbol to allow the receiver to absorb the delay spread due to the multipath much more efficiently and to maintain frequency orthogonality. The CP occupies a duration called the guard time and is a temporal redundancy that must be taken into account in data rate computations. The CP-based estimation technique depends on the repeated time samples of the guard time. As shown in Fig.2, 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].

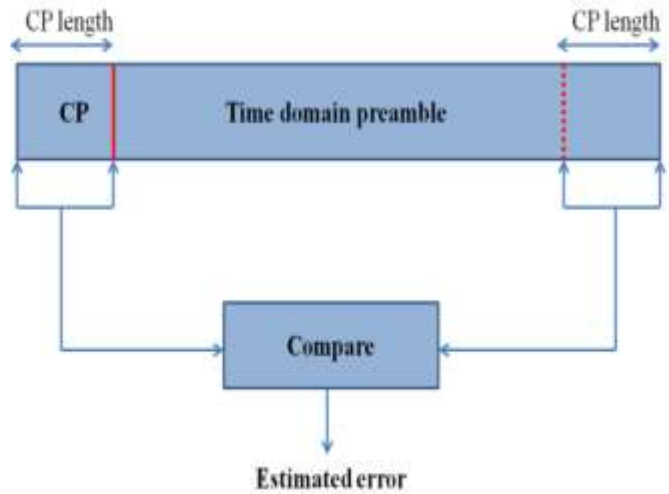

Fig. 2. Cyclic-prefix-based frequency estimation.

The proposed symbol timing technique depends on the CP nature of the OFDMA symbols. The incoming packet slides over two windows separated by fixed distance. The size of each window is the same as the used CP. When the packet is detected, the estimated start of the packet is shifted back and a correlation between the fixed windows is turned on for certain period within which the maximum correlation gives an estimate for the true symbol timing. Fig. 3 shows the illustration of this technique.

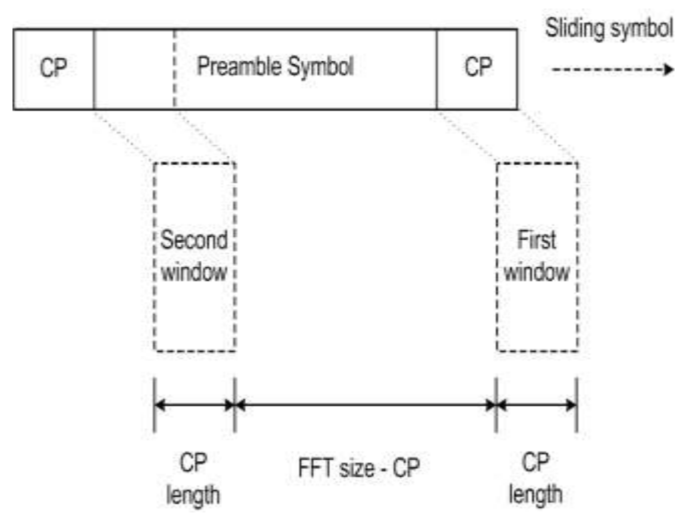

Fig. 3. Symbol timing technique.

The estimated frequency offset is proved by the following equations [9]:

$$-r_n = Sn.\exp(j2\pi\Delta fnTs) \quad (1)$$

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, Then to estimate the frequency offset, the following algorithm may be applied:

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

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

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

and

$$Z = exp(j2\pi\Delta fDTs) \sum_{n=0}^{l-1} |Sn|^2 \tag{4}$$

Then, the estimated frequency offset takes the form

$$\Delta f = -\frac{1}{2\pi DTs} angle(Z) \tag{5}$$

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 to not 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$-\pi$.

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

$$-\pi < 2\pi DTs\Delta f < \pi; \tag{7}$$

$$\frac{-1}{2DTs} < \Delta f < \frac{1}{2DTs}; \tag{8}$$

$$\frac{-fs}{2D} < \Delta f < \frac{fs}{2D}; \tag{9}$$

$$\frac{-subcarrier\ spacing}{2} < \Delta f < \frac{subcarrier\ spacing}{2}; \tag{10}$$

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. Also both fine frequency estimation and symbol start need the same basic operation, which is correlation [10]. 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 $exp(j2\pi\Delta fnTs)$ to correct the frequency offset.

However, there are some issues that should be noticed [11]:
(i) The efficiency of the estimator is directly proportional to the length of the repeated part.
(ii) The presence of multipath fading channel will significantly reduce the accuracy of the estimator. The presence of multipath will alter the cyclic prefix values of the preamble with respect to the corresponding values in the symbol. As a result, one would either consider a shorter duration of the preamble which will decrease the estimation accuracy or accept the distortion caused by the fading channel.
(iii) The phase rotation between the identical samples used to estimate the frequency offset should be in the range $[-\pi, \pi)$, otherwise angle Z will fold by multiples of 2π and the estimate will be incorrect.

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 [5]. 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:

$$H(K+1) = H(K) + \Delta H(K) \tag{11}$$

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

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

Where,
Q (k) is the received preamble in the frequency domain.
$P_j(k)$ is 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 and preamble index are given by:

$$\widehat{(n,j)} = argmax_{n,j} M_{n,j}^n \quad (14)$$

It should be noted that, the coarse frequency offset is usually estimated during the Cell-ID detection phase. Cell-ID detection is used to detect the preamble sequence being transmitted by the operating base station. Cell-ID detection is usually performed after fine frequency offset detection and correction. The Cell-ID detection block correlates the received frequency domain signal with the possible sequences. The correlators should take into consideration the possible shift, the range of which is determined by the allowed frequency offset defined in the standard. The Cell-ID detection block estimates the coarse frequency offset value and the detected preamble sequence [11].

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 for simulation are tabulated in Table 1.

A. *Cyclic-Prefix-Based Fine Frequency Offset Estimation*

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

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

TABLE I
WiMAX OFDM Parameters

Symbol	Description	Relation	Used value
B	Nominal bandwidth	*B = 1/Ts*	0 MHz
L	Number of subcarriers	Size of *IFFT/FFT*	1024
G	Guard fraction	$\%\ of\ L\ for\ CP$	$1/4$
Fs	Sampling frequency	$1/_{Ts}$	11.2 MHz
Ts	Sample time	$1/_{Fs}$	89.2 nano sec
Ng	Guard band	$Ng = GL$	256
Tg	Guard time	$Tg = TsNg$	22.8 sec
T	OFDM symbol time	$T = Ts(L + Ng)$	114.2 sec
Bsc	Subcarrier spacing	$Bsc = B / L$	10.94 KHz.

As shown in Fig.4, Fig.5, Fig. 6 and Fig.7 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.

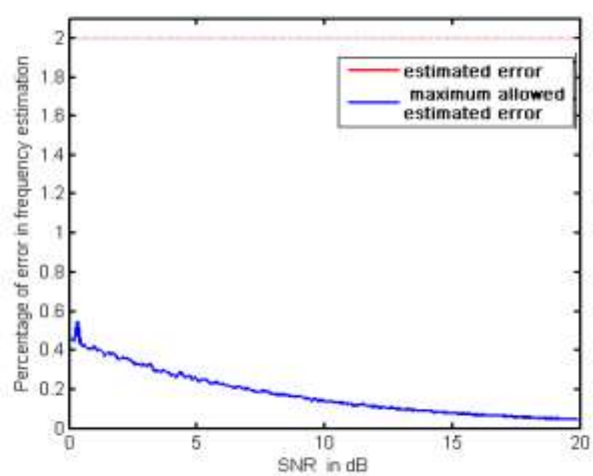

Fig. 4. Fine frequency offset estimation with different SNR under AWGN.

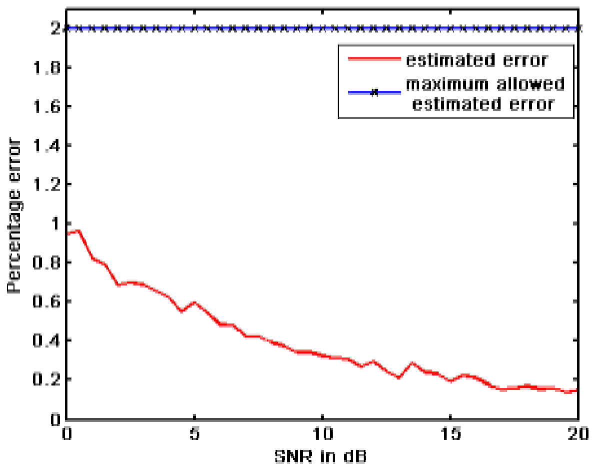

Fig. 5. Fine frequency offset estimation with different 16-bit fixed point analysis.

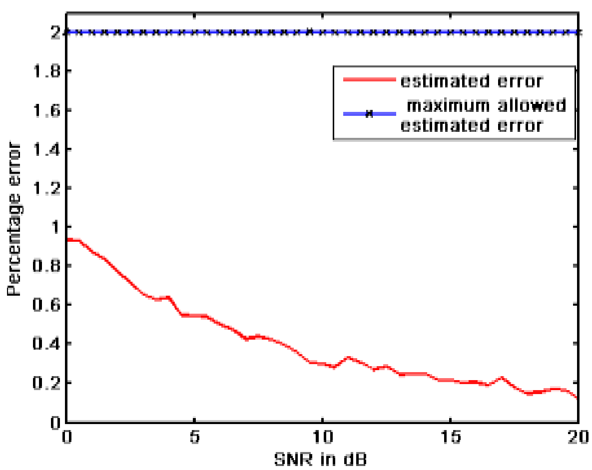

Fig. 6. Fine frequency offset estimation with different 18-bit fixed point analysis.

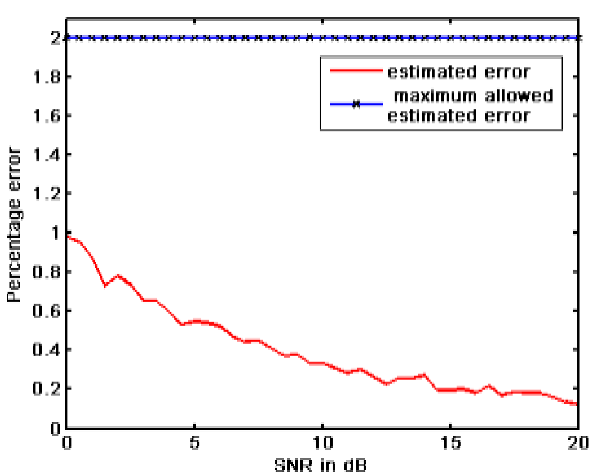

Fig. 7. Fine frequency offset estimation with different 20-bit fixed point analysis.

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. The conditions applied here are:

- 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 is applied under fading at 2 dB the estimated coarse frequency shift is equal to 6. This means that the algorithm was accurate at 246 runs; this is illustrated in Fig. 8 and Fig. 9. In Fig. 10 SNR was increased to 10 dB and the performance increased to 250 runs. Cell search results under fading at 2dB, 5 dB, and 10 dB are given in Fig. 11, Fig. 12, and Fig. 13 respectively. The preamble number is equal to 90 at both 246 and 250 runs.

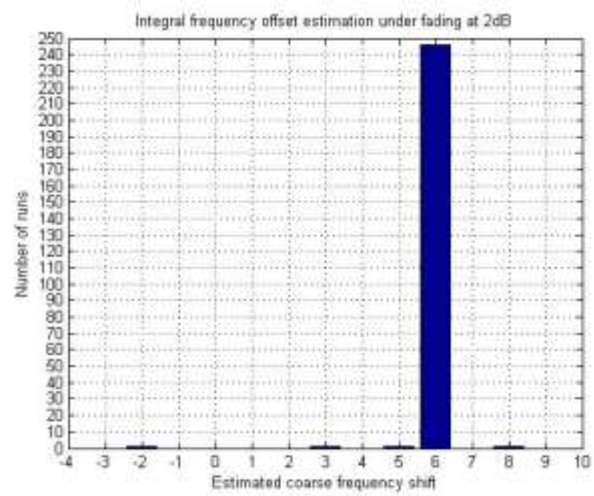

Fig. 8. Integral frequency offset estimation under fading at 2dB.

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 by using the packet preamble structure adopted by the IEEE 802.16 standardization workgroup have been presented and 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. Also, the performance of these algorithms can be tested under different types of noise and channels.

ACKNOWLEDGMENT

Authors would like to thank the Department of Electronics Engineering, Faculty of Engineering, Sudan University of Science and Technology where this work has been carried.

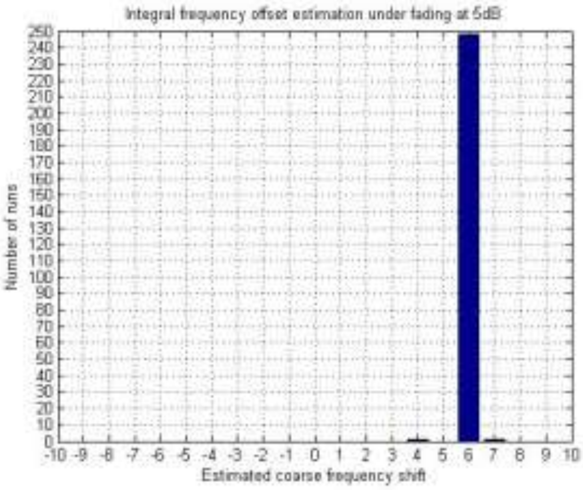

Fig. 9. Integral frequency offset estimation under fading at 5 dB.

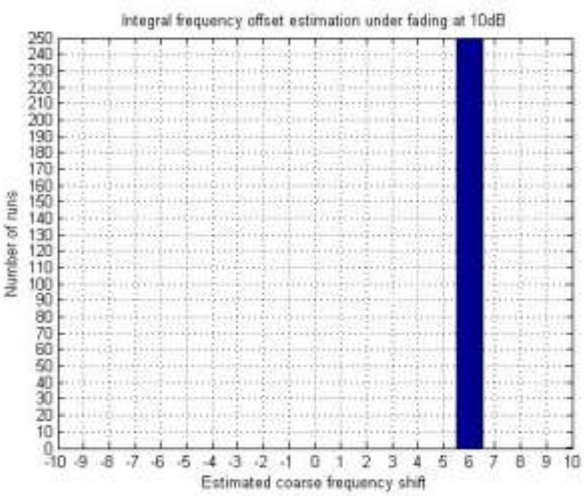

Fig. 10. Integral frequency offset estimation under fading at 10 dB.

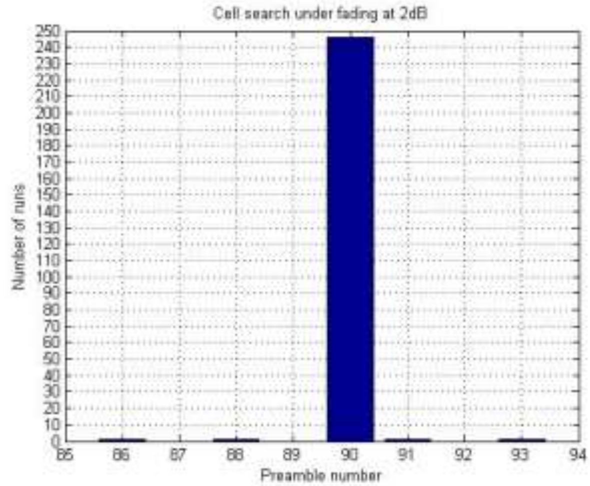

Fig. 11. Cell search results under fading at 2dB.

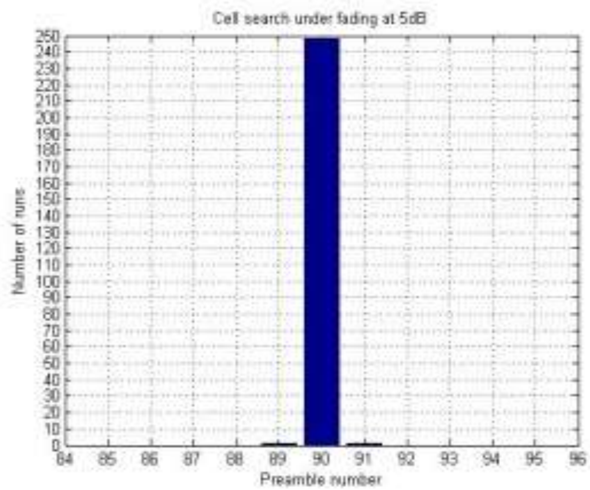

Fig. 12. Cell search results under fading at 5 dB.

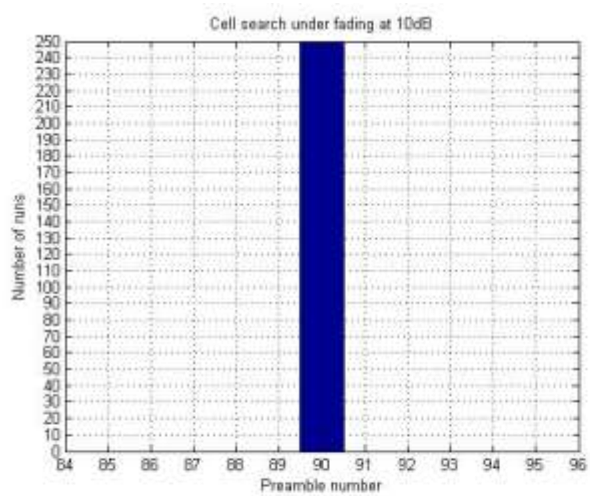

Fig. 13. Cell search results under fading at 10dB.

REFERENCES

[1] C. Ball, *LTE and WiMax Technology and Performance Comparison, Nokia Siemens Networks*, EW2007 Panel, 2007.

[2] B. Sidhu, H. Singh,, and A. Chhabra, *Emerging Wireless Standards WiFi, ZigBee and WiMax,* WASET.ORG, 2007.

[3] Jeffrey G. Andrews, Arunabha Ghosh, and Rias Muhamed, *Fundamentals of WiMAX: understanding broadband wireless networking*, Pearson Education. Inc, 2007.

[4] Juha Heiskala and John Terry, *OFDM wireless LANs A theoretical and practical Guide, Sams Publishing, 2002.*

[5] Kun-Chien Hung and David W. Lin,Joint "Detection of integral carrier frequency offset and preamble index in OFDMA WiMAX downlink synchronization" , *IEEE Proc, WCNC2007*.pp. 1959-1964.

[6] Kwang-Cheng Chen and J. Roberto B. de Marco, *Mobile WiMAX* , John Wiley & Sons. Ltd, 2008.

[7] kwang-cheng chen, *Introduction to Mobile Wimax*, Taiwan university, 2007.

[8] Loutfi Nuaymi, *WiMAX technology for broadband wireless access*, John Wiley and Sons Ltd, 2007.

[9] M. Morelli and M. Pun, "Synchronization Techniques For Orthogonal Frequency Division Multiple Access (OFDMA) A Tutorial Review", *Proc. IEEE*, July 2007, Vol. 95, no. 7. pp. 1394 – 1427, doi: 10.1109/JPROC.2007.897979.

[10] Mohamed Ismail Ali, "Simulation and implementation of the frequency synchronization and Viterbi decoding for the OFDMA-based Mobile WIMAX 802.16e", a thesis submitted to the Faculty of Engineering at Cairo University, 2007.

[11] Khairy, M. M., "A novel frequency offset estimation technique for Mobile WiMAX", Eur. Trans. Telecomm., 2011, Vol. 22. pp. 45–50. doi: 10.1002/ett.1462

Dr. Fakher Eldin Mohamed Suliman was born in Sudan in 1966.
He did his PhD, MSc, and BSc in 2004, 1999, and 1989 respectively, all in Electrical Engineering.
He is an assistant professor in the Electronics Engineering Department, College of Engineering, Sudan University of Science and Technology (SUST) since 2004.
He is the General manager of the Electronics System Research Center (ESRC) at SUST.
He is the coordinator of the postgraduate studies in his college.
He published a number of technical papers in international conferences and has two books under publication process.
His research interest includes; performance analysis and performance enhancement for Optical fiber systems, Wireless communications systems, and Switching systems.
Dr. Suliman is a Specialist Engineer in the Sudan Engineering Council and a Full Member of the Sudan Engineering Society.

Nuha M. Elhassan was born in Jeddah, Kingdom of Saudi Arabia, in 1988. She received the B.S. degrees in communication engineering from SUST in 2009 .
From 2010 up to now, she is a Teaching Assistant in SUST, University of Medical Science and Technology and Khartoum Collage of Technology.
Her Research Interest includes: performance analysis and performance enhancement for wireless Communications systems
Ms Elhassan is an Engineer in the Sudanese Engineering Council
Email: nohamohamed3@gmail.com
Tel: +249912493098

MS.Terteil Abdalla Abrahim was born in Sudan on Dec,28, 1987
She did her Bsc. In 2009 in Electronics Engineering (Communications), College of Engineering SUST
Since 2012 she is a Teaching Assistant in the School of Electronics, College of Engineering, SUST and a part time teaching assistant at the Electrical and Electronic Department, College of Engineering, International Of Africa University since 2013 until now.
She published two technical papers in international conferences.
Her Research Interest includes: performance analysis and performance enhancement for the following:
Wireless Communications and Embedded Systems.
Ms.Terteil A. Abrahim is an Engineer in the Sudanese Engineering Council.
Email: terteil88@yahoo.com.
Tel: (+249) 922272954