DYNAMIC CFO REDUCTION IN VARIOUS MOBILITIES BASED ON EXTENDED KALMAN FILTER FOR BROADBAND WIRELESS ACCESS TECHNOLOGY

Asri Diliyanzah
School of Electrical Engineering
Telkom University
Bandung, Indonesia
asridiliyanzah@gmail.com

Rina Pudji Astuti
School of Electrical Engineering
Telkom University
Bandung, Indonesia
rina_pudjiastuti@yahoo.com
rinapudjiastuti@telkomuniversity.ac.id

Budi Syihabuddin
School of Electrical Engineering
Telkom University
Bandung, Indonesia
budisyihab@telkomuniversity.ac.id

Abstract—**Alteration of user's speed and direction to the base station cause Carrier Frequency Offset (CFO). CFO is able to damage orthogonality among subcarriers and decrease system performance significantly. There are several researches already focused on ICI mitigation, however most of them only employed restricted inputs for CFO in order to generate Inter Carrier Interference (ICI). This research proposes modified dynamic CFO resulted from Doppler shift and oscillator accuracy tolerance. The CFO value takes user's velocity and random user's direction as well as involving oscillator instability. The main purpose of this research is to reduce CFO in dynamic propagation nature in various users' velocities using Extended Kalman Filter (EKF) method. The result showed that those dynamic CFO values can be reduced using EKF method and thereby enhance OFDM system performance, in this case Mobile WiMAX 802.16e. Besides, this proposed system has the adaptability upon different CFO values by adjusting better improvement for higher speed and worse oscillator's quality.**

Keywords—**OFDM, CFO, ICI, PPM, EKF, BWA**

I. INTRODUCTION

Several benefits of OFDM system are the capability to overcome frequency selective fading effectively and able to support high data rate [1]. These points bring OFDM to be adopted by various Broadband Wireless Access technologies, one of them is Mobile WiMAX (IEEE 802.16e) [2]. However, the performance of OFDM-based technology is vulnerable against frequency shifting. This is caused by the occurance of CFO as a consequence of carrier frequency inexpediency both in transmitter and receiver [1,2]. Basically, CFO value is influenced by inaccuracy frequency generated by oscillator to send and receive information signal [2]. For instance, an oscillator has an accuracy tolerance up to 0.1 ppm (parts per million) employed at 3 GHz would produce maximum frequency shifting up to 300Hz [2]. Although it is very low, it has high effect to reduce system performance. It is due to OFDM that consist of subcarriers using narrow bandwidth and composed orthogonally [1]. Hence, even a little frequency shifting is able to wreck orthogonality among subcarriers and reduces system performance. In some cases of mobile communication, CFO value becomes higher and creates bigger damage [2]. Doppler shift results frequency shifting which is directly proportional to velocity and depends on user's direction of mobility [3]. Nowadays, in terms of high mobility user, for example user's speed of 300 km/h (e.g. fast train, airplane) will experience bigger CFO effect and lead to high error bit. Therefore, an effective method is required to suppress CFO effect which one of them is studied in this research.

Several methods are already explained in order to overcome ICI problem. Gupta and Mehra [4] proposed channel estimation technique based on Kalman Filter to suppress ICI effect for high-mobility user. Afterwards, in [5], Zhao, Yang, Li, and Men developed EKF method to be UKF (Unscented Kalman Filter) in high mobility environment as well. So did it with [6] and [7] in which the former employed PEKF method using less redundant bit and the latter introduced dynamic CFO value. However, those researches only involved incomplete CFO that affected by Doppler shift (f_d) to generate ICI without taking oscillator accuracy tolerance (f_o) into account. Different from [8], Simon et al estimated CFO value generated from f_d and f_o. In addition, they applied channel estimation at fast time-varying to improve system performance. However, because generated CFO value was still set statically and also using limited input parameters, it required more detail model in order to approach substantive propagation circumstance.

In order to improve those drawbacks, this research generates dynamic CFO value resulted by f_d in various user velocities with random direction and f_o with different oscillator accuracy tolerances. It has the main purpose to observe the influence on various user mobility conditions whose dynamic CFO value could decrease system performance. EKF method is also choosen based on [7] to approach substantive CFO value and reduce its effect.

This paper is organized as follows: Section II explains about Carrier Frequency Offset. Descriptions of EKF method to estimate and correct CFO value is in section III. In section IV, there are analysis and discussion about simulation result. Final conclusion is drawn in section V.

II. CARRIER FREQUENCY OFFSET

CFO is formed by frequency shifting resulted from miss synchronization of carrier frequency both in transmitter and receiver. This causes the instability of oscillator accuracy and/or mobility of sender and/or receiver. The frequency shifting is represented by normalized CFO [5]:

$$\varepsilon = \frac{f_{offset}}{\Delta f} \qquad (1)$$

where Δf refers to subcarrier spacing and f_{offset} is frequency shifting accumulated from f_d dan f_o. Those refer to Doppler shift and oscillator accuracy tolerance and they can be expressed as [2,3] :

978-1-4799-5303-5/14/$31.00 ©2014 IEEE

$$f_d = \frac{v}{\lambda}\cos\theta \qquad (2)$$

$$f_o \approx f_c X \qquad (3)$$

where in (2), v is denoted as user velocity, λ refers to wavelength, and θ indicates the angle between signal propagation direction and user movement direction. According to (3), f_c is carrier frequency in OFDM system, and X is oscillator accuracy tolerance in unit ppm.

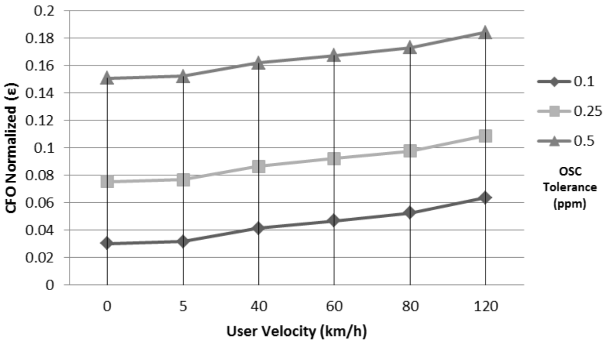

Fig.1: Influence of oscillator accuracy tolerance and user velocity against normalized CFO

Figure 1 depicts relationship between user velocity and oscillator accuracy tolerance in order to determine CFO value. High mobility and less quality of oscillator with bigger tolerance would worsen system performance because of increasing normalized CFO value.

Next, the normalized CFO becomes an input for emerging ICI effect. In this paper, ICI model adopts the equation from [5,6,7] using normalized CFO (ε) as an input. The equation is given by:

$$S(l-n) = \frac{\sin(\pi(l+\varepsilon-n))}{N.\sin(\frac{\pi(l+\varepsilon-n)}{N})} e^{j\pi\left(1-\frac{1}{N}\right)(l+\varepsilon-n)} \qquad (4)$$

where $S(l-k)$ refers to ICI coefficient and N is denoted as total subcarriers. The following illustration shows ICI coefficient caused of either f_o only or $f_o + f_d$. These following figures are modified from [7].

ICI coefficient illustration in figure 2 conveys ICI effect experienced by 128th subcarrier in OFDM system using 256 subcarriers. This system also has QPSK mapper, along with various types of velocity and different quality of oscillators. On the first figure (upper-left), it only considers f_o using oscillator with ppm=0.1 in accuracy tolerance. It is shown that maximum ε is about 0.32. Otherwise,on the second figure (upper-right) after calculating f_o and f_d with v=40 km/h, it is able to reach maximum ε equals to 0.41. The value of ε is getting higher together with the increasing of user velocity and the decreasing of oscillator quality. The third (lower-left) with ppm=0.5 and the forth (lower-right) by adding the calculation with v=120 km/h indicate the raising level of ε in about 0.17 and 0.23 respectively.

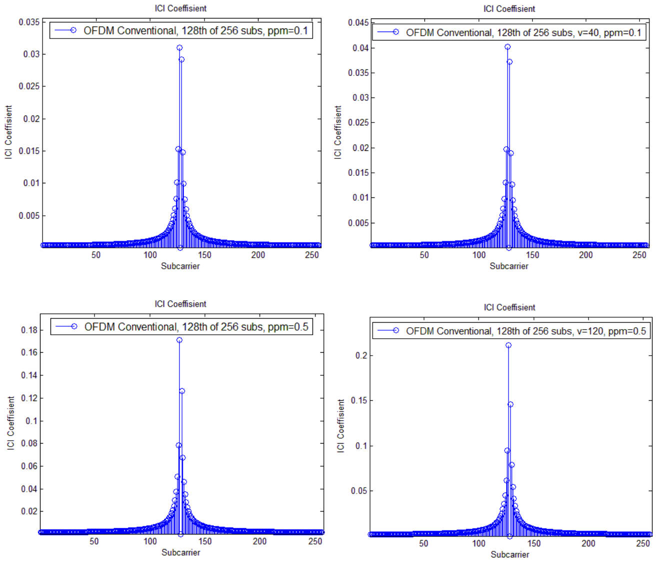

Fig.2: Illustration of ICI Coeffisient caused of f_o and $f_o + f_d$

Henceforth, the ICI coefficient would be involved in receiving signal. The equation of received signal can be derived as follows [5,6,7] :

$$Y(\mathrm{n}) = \mathrm{X(n).S(n)} + \sum_{\mathrm{l=0,l\neq k}}^{\mathrm{N-1}} \mathrm{X(l).S(l-n)} + \mathrm{W_n} \qquad (5)$$

where the received signal Y(n) refers to X(n) (symbol of OFDM) affected by S(n) (Rayleigh fading), $\mathrm{S(l-n)}$(ICI coefficient), and $\mathrm{W_n}$(Noise AWGN) all at once.

III. DYNAMIC CFO REDUCTION USING EKF

In this research, due to random user's direction and oscillator accuracy tolerance, the frequency output taken from transmitter and receiver will be changed in realtime on each subcarrier depends on how fast user move and how well oscillator to be used. The major purpose is to observe dynamic CFO influences plus to analyze OFDM using EKF system performance in order to deal with ICI effect caused by those various CFO values.

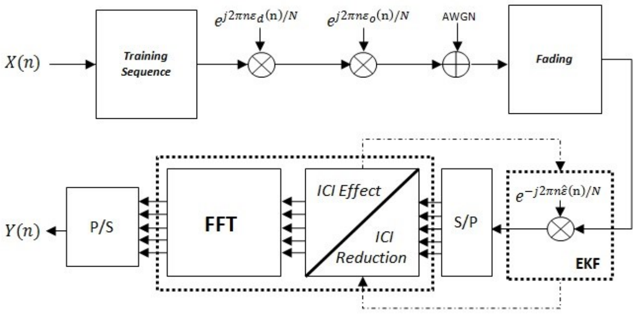

Fig.3: OFDM Using EKF Model System
(This figure is modified from [5] and [7])

Normalized CFO will be generated based on ε_d and $\varepsilon_o$which are calculated from f_d and f_o. Furthermore, the main feature is the various types of f_d caused by operating band

and random user's direction, plus dynamic f_o generation because of instability oscillator according to its accuracy tolerance. This feature depicts more substantive condition since mobile user would create unstatic effect of frequency shifting. Otherwise, most of the previous studies [5,6,7] only assume static CFO in ICI occurrence. In other words, they assumed only immobile user.

According to system model in figure 3, OFDM using EKF comprises iteration processs in order to estimate the substantive ε. Afterward, it utilizes the estimation result ($\hat{\varepsilon}$) to alleviate ICI effect. Generally, EKF method derives from Kalman Filter development for the purpose of non-linear system [5,6]. This method consists of two stages i.e estimation stage and correction stage [5,6,7].

A. EKF Estimation Stage

Commonly, EKF method requires training sequence bits to send for initial process before transmitting information bits. These training sequence bits generally put in the beginning frame early estimation. Its objective is to approach the happening CFO. There are some equations substantially needed for EKF computation process [5,6,7]. Firstly, it is required to determine measurement value and initial state before starting iteration process. Those equations are given by:

$$y(n) = x(n)e^{j\frac{2\pi n\varepsilon(n)}{N}} + W(n) \qquad (6)$$

$$\varepsilon(n) = \varepsilon(n-1) \qquad (7)$$

$$P(n) = P(n-1) \qquad (8)$$

Equation (6) refers to measurement value using $x(n)$ as the transmitting OFDM symbol, ε is denoted as real normalized CFO experienced by OFDM, as well as Noise AWGN. N is the total subcarriers. Afterwards, equation (7) and (8) refers to ε estimation dan error covarian for initialization purpose. Final preparation determines the number of desirable iteration to this method.

Next, computation process of iteration in order to estimate ε is described as follows [5,6,7] :

1. Calculate H(n), the derivative of y(n) with respect to $\varepsilon(n)$ at $\varepsilon(n-1)$.

$$H(n) = \left.\frac{\partial y(\mathrm{x})}{\partial \mathrm{x}}\right|_{\mathrm{x}=\varepsilon(\mathrm{n})} \qquad (9)$$

$$H(n) = j\frac{2\pi n}{N}e^{-j\frac{2\pi n\varepsilon(\mathrm{n})}{N}}x(n) \qquad (10)$$

2. Calculate the Kalman Gain $K(n)$.

$$K(n) = \frac{P(n-1).H^*(n)}{P(n-1)+W(n)} \qquad (11)$$

3. Calculate the estimation of $\varepsilon(n)$ using $\varepsilon(n-1)$, $y(n)$, and $x(n)$ in order to update the ε estimation state.

$$\varepsilon(n) = \varepsilon(n-1) + Re\left\{K(n)\left[y(n) - x(n)e^{j\frac{2\pi n\varepsilon(\mathrm{n}-1)}{N}}\right]\right\} \qquad (12)$$

4. Update the state of error covariance $P(n)$ using Kalman Gain $K(n)$, $H(n)$, and the previous state of error covariance $p(n-1)$.

$$P(n) = [1 - K(n)H(n)]P(n-1) \qquad (13)$$

5. If $n < N_p$, set the increment of n by 1 and go to the next recursive process. Otherwise, stop the process.

In this section, OFDM system is using training sequence in the beginning frame to achieve steady state while approaching substantive value of ε. Besides, due to the dynamic CFO employed on each subcarrier, then user velocity would create a significant impact. User's mobility direction doesn't produce constant angle toward signal propagation direction, therefore it keeps making various Doppler shifts in realtime.

The OFDM system uses training sequence in the beginning frame to achieve steady state while approaching substantive ε value. Besides, due to the research employs dynamic CFO on each subcarrier, then user velocity would create a significant impact. User's mobility direction doesn't produce constant angle toward signal propagation direction therefore it keeps making various Doppler shift.

The following figure informs EKF estimation stage for several user velocities with different direction. The oscillator has accuracy tolerance 0.5 ppm, along with carrier frequency as 3.3 GHz.

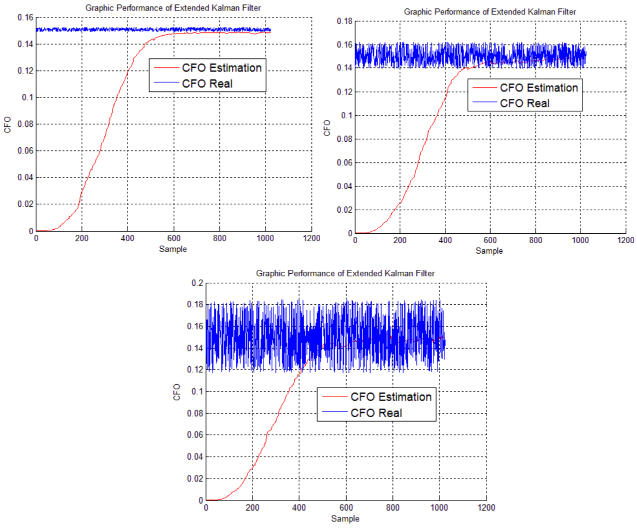

Fig. 4: Normalized CFO Estimation Stage untuk v=5, v=40, dan v=120 (ppm = 0.5)

As illustrated in figure 4, the substantive CFO creates higher fluctuation value together with the increasing of user velocity. This fluctuation is randomly generated in order to reflect user's direction. A higher velocity, oscillator tolerance, and more unpredictable motion would produce more fluctuative CFO. For instance, oscillator in the manner of ppm=0.5 and fc=3.3 GHz occurs maximum frequency shifting by its tolerance equals to ±1650 Hz. Therefore, according to equation (3) for spacing carrier 10.94 KHz, it results maximum ε equivalent to 0.15. Users with 5 km/h, 40 km/h, and 120 km/h, based on equation (2) contribute the ε value as 0.001, 0.01, and 0.03 respectively.

B. *EKF Correction Stage*

In this stage, according to previous procedure of transmitting bit, training sequence bit would be delivered first to execute initial estimation. In this case, as many as 3 OFDM symbols with each of them consists of 256 subcarriers [6]. Then, after reaching steady state, it would start to send information bit. The following figure shows EKF process that calculates CFO estimation toward substantive CFO. This figure is modified from [7].

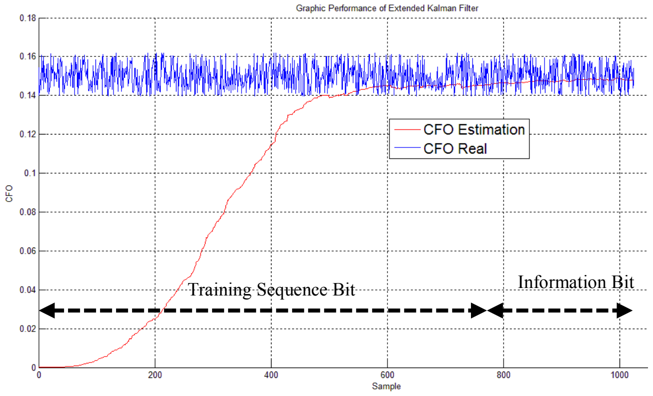

Fig. 5: Differentiation between Training Sequence Bit and Information Bit Transmission

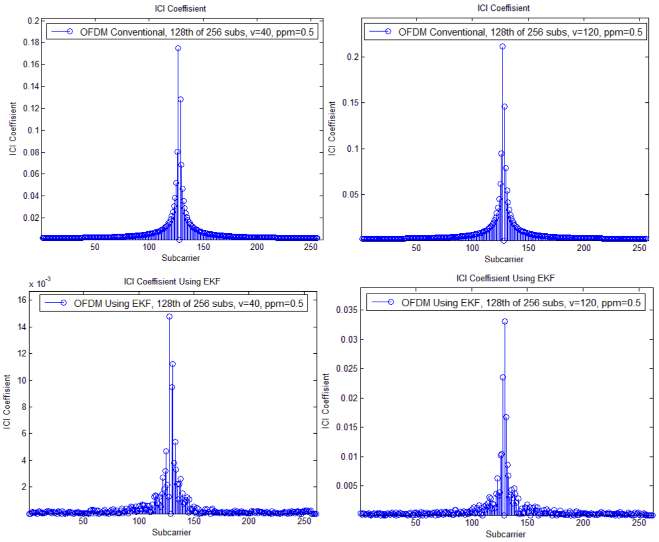

Fig.6: ICI coefficient reduction before (up) and after (down)

Figure 5 shows the beginning frame process while sending early data toward receiver. In this study, as many as 256 last samples are formed by information bit. Those samples would become the input of correction equation later. This stage has a purpose to reduce normalized CFO value using equation as follows [5,6,7] :

$$Y(n) = FFT\{X(n)e^{-j\frac{2\pi n\hat{\varepsilon}(n)}{N}}\} \qquad (14)$$

Normalized CFO in information bit sample refers to $\hat{\varepsilon}$ with expected value is close by the real one (ε). Afterwards, those inputs would be multiplied by its conjugationas depicted in (14). Then, CFO value in OFDM symbol that experienced carrier shifting (caused of f_d and f_o) would be reduced significantly.

Figure 6 indicates the output from EKF process. OFDM system influenced by Doppler shift while having velocity 40 km/h and 120 km/h would produce different coefficient ICI. The contribution of maximum interference subcarrier level is located exactly next to it. In the early condition, user with speed 40 km/h has maximum coefficient ICI about 0.16, otherwise for 120 km/h resulted 0.22. However, after applying EKF method, coefficient ICI turns to 0.012 and 0.034 for the same user velocity and oscillator quality.

IV. ANALYSIS AND SIMULATION RESULT

This research adopts several input parameters derived from one of BWA technology, Mobile WiMAX (IEEE 802.16e). These parameters is describes as follows [2] :

1. Spacing carrier Mobile WiMAX is 10.94 KHz.
2. FFT size is 256 subcarriers and QPSK Mapper.
3. Frequency Carrier Mobile WiMAX is 3.3 GHz.
4. Channel Models are AWGN, Rayleigh Fading, and ICI Model [5,6,7].
5. Normalized CFO in ICI Model is generated based on Doppler shift (f_d) and oscillator accuracy tolerance (f_o).

Several circumstances using different combinations of user velocity and oscillator quality are applied. The major purpose is to observe EKF method performance in order to reduce ICI effect with dynamic CFO and various scenarios. On behalf of analyzing performance comparison in every circumstance, the observed parameter would be BER against Eb/No.

In order to analyze simulation result, there are two user velocity categories; they are low mobility environment and high mobility environment. In addition, it also considers usage of different kinds of oscillator based on its accuracy tolerance.

A. *Analysis of the low mobility user environtment using different kinds of oscillator in OFDM system*

There are a lot of things which affect OFDM performance. However, in this research, it is limited to the influence of user velocity and oscillator quality. Low mobility environment includes fixed user (0 km/h), pedestrian user (5 km/h), and low-speed urban user (40 km/h). These types of users are major in large cities and dense residences. This part analyzes OFDM using EKF system performance using different kinds of oscillator, they use accuracy tolerance 0.1 ppm, 0.25 ppm, and 0.5 ppm. The higher the user's speed and the worse the quality of oscillator, then the worse system performance would be. This condition is obviously caused by the damage of orthogonality subcarrier.

For particular cases, utilizing of low tolerance oscillator does not result in a significant difference, neither for conventional system nor system using EKF method. It is because both oscillator in transmitter and receiver has worked very well to maintain frequency shifting. However, this type of oscillator is commonly more expensive. Figure 7 depicts OFDM using EKF and conventional system performance that are not too different. The most basic variance is only affected by user's velocity. The fixed and pedestrian users only have a few dissimilarities. Both of them require Eb/No about 14 dB to reach BER performance 10^{-5}. Meanwhile, low-speed urban user requires 18 dB to reach same BER performance. It is caused by higher user velocity which creates bigger Doppler shift and able to wreck orthogonality among subcarriers.

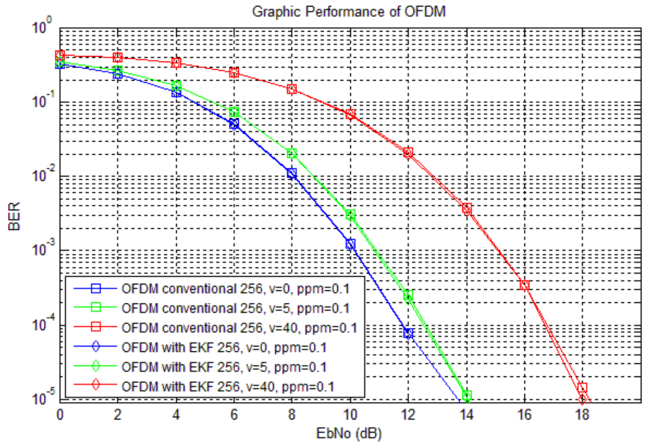

Fig.7 : OFDM performance for low mobility environtment with oscillator accuracy tolerance 0.1 ppm

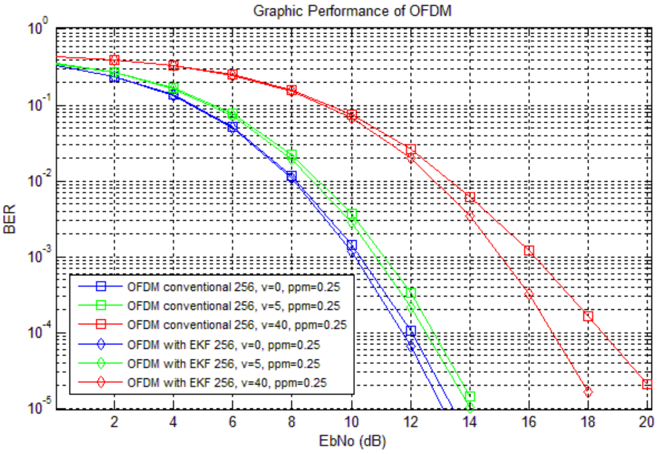

Fig.8 : OFDM performance for low mobility environtment with oscillator accuracy tolerance 0.25 ppm

Degradation of quality oscillator in OFDM system is able to change the system performance thoroughly. Figure 8 shows Conventional OFDM performance which is decreasing as a consequence of bigger oscillator tolerance which is 0.25. Although fixed and pedestrian users are not too different (Eb/No is about 14 dB for BER 10^{-5}), however low-speed urban user with OFDM using EKF is able to produce system gain as 2 dB Eb/No from 20 dB to 18 dB for BER 10^{-5}.

This circumstance is caused by higher speed user in random direction thereby resulted in bigger normalized CFO fluctuation as shown in figure 4. Therefore, lower quality of oscillator (Accuracy tolerance is 0.5 ppm) as shown in figure 9 creates worse system performance compared to accuracy tolerance 0.1 ppm and 0.25 ppm. Figure 8 depicts fixed and pedestrian users with OFDM using EKF are able to produce system gain about 1 dan 2 dB respectively. Even for low-speed urban user, OFDM using EKF is able to improve BER performance from $10^{-2.7}$to $10^{-4.9}$for Eb/No 18 dB.

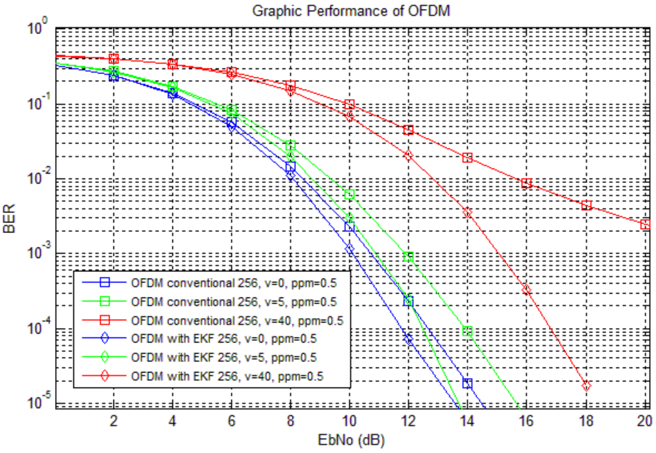

Fig.9 : OFDM performance for low mobility environtment with oscillator accuracy tolerance 0.5 ppm

B. Analysis of the high mobility user environtment using different kinds of oscillator in OFDM system

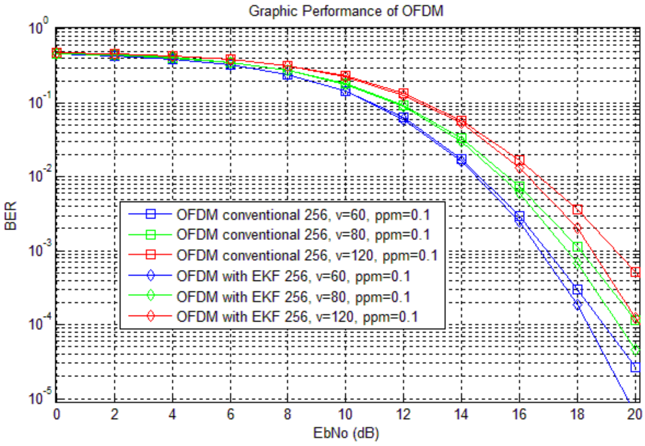

Fig.9 : OFDM performance for high mobility environtment with oscillator accuracy tolerance 0.1 ppm

The similar condition is in line for high mobility user, where higher user speed would lead to worse OFDM system performance. High mobility environment in this section comprises medium-speed urban user, high-speed urban user, and very high-speed urban user. These user categories are spread in areas of high mobility, namely toll road, train, etc. However, they are different from previous result in low-mobility environment. In this manner, eventhough users already use a better quality of oscillator (ppm=0.1), it is known that both conventional OFDM and OFDM using EKF have different result.

As illustrated in figure 9, OFDM system using EKF is able to improve BER performance until $10^{0.5}$ for Eb/No=20 dB in each category of high mobility user (oscillator tolerance=0.1 ppm). In contrast, figure 10 depicts higher BER performance improvement about $10^{1.5}$ to 10^{2} still for the same Eb/No and for every category using oscillator tolerance=0.25. The highest BER performance improvement among all simulations is resulted from the worst oscillator tolerance (0.5), it's about $10^{2.5}$ - 10^{3} for all categories of user in Eb/No=20 dB. It's shown in figure 11.

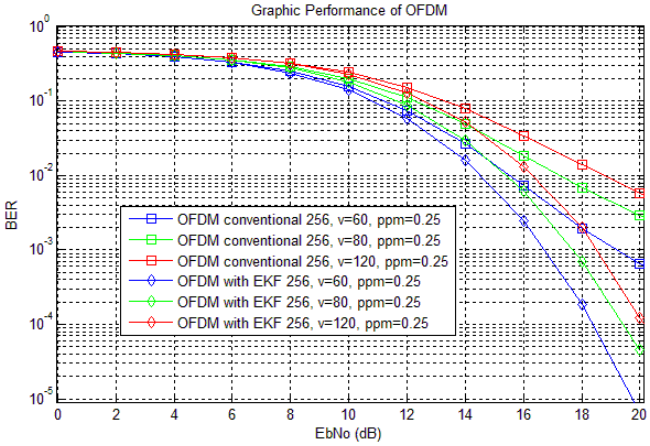

Fig.10 : OFDM performance for high mobility environtment with oscillator accuracy tolerance 0.25 ppm

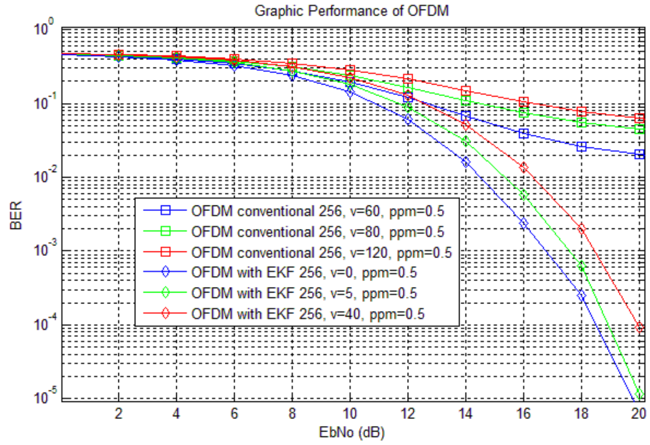

Fig.11 : OFDM performance for high mobility environtment with oscillator accuracy tolerance 0.5 ppm

C. Discussion

This section informs OFDM performance using EKF method in dynamic CFO Environment caused by Doppler shift and oscillator accuracy tolerance. Those factors are the causal of frequency shifting. Although its value only a few hundred Hz, it could influence the whole system performance by ICI. Orthogonality among subcarriers using narrow spacing bandwidth on each of them might be damaged caused by CFO. Several previous researches [4,5,6,7] are in line with this study. They show better performance of OFDM using EKF system or its modification compared to other methods. However, those ones have restrictions parameter particularly in input which only consider Doppler shift in ICI effect.

The other researches [8] proposed computation CFO was caused by Doppler shift together with oscillator shifting frequency. However, they only put static CFO without taking into account user direction and oscillator instability. This research applies comprehensive method to overcome those drawbacks. As a result, EKF method is able to enhance system performance even in dynamic environment. It is also able to maintain system stability by adjusting system gain appropriate to particular condition, including the matter of user velocity and oscillator condition.

V. CONCLUSION

There are several conclusions based on the analysis result. First, OFDM using EKF is able to work optimally starting from user speed in 40 km/h and oscillator quality in 0.25 ppm. For fixed and pedestrian users whose speed under 40 km/h, this method does not assess a clear result because the occurred CFO is not too high. Besides, this research is in line with [7] which shows the capability of EKF method in order to overcome dynamic CFO, and is able to maintain system stability both for low-mobility and high-mobility. It is proved by similar output adaptations eventhough they use different kinds of input, in this case user velocity and oscillator accuracy tolerance.

REFERENCES

[1]. A. J. Goldsmith. *Wireless Communication*. Cambridge University Press 2005.

[2]. J. G. Andrews, A. Ghosh, and R. Muhamed. *Fundamentals of WiMAX : Understanding Broadband Wireless Networking*. Prentice-Hall, 2007.

[3]. T. S. Rappaport.*Wireless Communication : Principles and Practice*, 2d ed. Prentice-Hall, 2002.

[4]. P. Gupta, and D. K. Mehra. "Kalman Filter based Channel Estimation and ICI Suppression for High Mobility OFDM Systems," *IEEE International Conference on Industrial Technology ICIT*, pp. 612-615, Dec. 2006.

[5]. X. Zhang, B. Yang, S. Li, and A. Men. "An Unscented Kalman Filter for ICI Cancellation in High-Mobility OFDM System," *Vehicular Technology Conference (VTC Spring) 2011 IEEE 73rd*, pp. 1-5, May. 2011.

[6]. Q. Shi. "ICI Mitigation for OFDM Using PEKF," *IEEE Signal Processing*, vol. 17, no. 12, pp. 981-984, Dec. 2010.

[7]. A. Diliyanzah, R. P. Astuti, B. Syihabuddin. "Inter-Carrier Interference Reduction In Broadband Wireless Access Technology Using Extended Kalman Filter," 2nd *International Conference of Information and Communication Technology (ICoICT)*, May. 2014.

[8]. E. P. Simon, et al. "Joint CFO and channel acquisition and tracking based on parametric channel modeling for OFDM systems in the presence of high mobility," *11th International Conference on ITS Telecommunications (ITST)*. pp. 565-570, Aug. 2011.