INTER-CARRIER INTERFERENCE REDUCTION IN BROADBAND WIRELESS ACCESS TECHNOLOGY USING EXTENDED KALMAN FILTER

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—**OFDM technology in Broadband Wireless Access has some disadvantages, one of which is Intercarrier Interference (ICI) caused by carrier frequency offset (CFO). Moreover, in high-mobility communication, Doppler effect from user shift causes CFO that affects the impairment of orthogonality among subcarriers, and obviously degrades OFDM performance. This research used Extended Kalman Filter (EKF) as scheme of ICI reduction by deploying CFO estimation and making CFO correction using estimation value in earlier iteration. This method requires preamble in every beginning of frame for estimation purpose prior to the delivery of the information. This method works optimally in slow time varying channel. Differing from other researches, this research sets CFO dynamically using certain stretches of CFO value in order to approach real condition. The result of the research shows that OFDM with EKF is able to improve OFDM system performance significantly by reducing ICI coefficient value in the system and maintain the stability of system, even under dynamic CFO condition. For instance, in condition CFO = 15% with QPSK mapper, the system gain improves as high as 2 dB for BER performance 10^{-5}. Whereas, under worse condition (i.e. CFO = 30%) and with similar parameters, OFDM system is able to produce almost 6 dB gain. Besides, EKF scheme can deliver reliable performance in different mappers.**

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

I. INTRODUCTION

OFDM technique is able to handle ISI effectively since bandwidth of subcarrier produced is smaller than coherence bandwidth [1]. Besides, OFDM has high spectral efficiency by setting overlapping subcarriers orthogonally [2,3]. However, beyond the superiority of OFDM, it has high sensitivity particularly on frequency synchronization as the drawback. This multicarrier modulation technique is susceptible of frequency offset between transmitter and receiver, which is known as Carrier Frequency Offset (CFO). CFO occurs due to the imperfection of oscillator used to generate the frequency of either transmitter or receiver. For example [4], for a frequency oscillator with up to 0.1 ppm (parts per million) accuration and frequency band of 3GHz, the CFO will be 300 Hz. In addition, especially for mobile communication, user mobility may cause Doppler Shift effect where frequency offset is directly proportional to velocity [1]. Thereby, OFDM subcarrier with much smaller spacing carrier will result in damaged received signal orthogonality. This is the effect of subcarrier with interference from another subcarrier, and this perturbation is known as ICI. A lot of ICI mitigation methods have been researched, one of which is ICI Self Cancellation [5]. However, the drawback of this method demonstrates low spectral efficiency because only half of the bandwidth can be used to send information data.

Therefore, in order to overcome the drawback, a method called Extended Kalman Filter (EKF) is employed to reduce the ICI effect. EKF is a method used to estimate desired value optimally (i.e. Normalized CFO) in a dynamical system [6]. The main purpose of this method is to minimize error covariance, or the relationship between two variables of a non-linear system by using recursive method [6]. The expected result is a normalized CFO estimation value that is close to observation CFO value so that frequency offset will be reduced.

One of previous research related to EKF method is Low-Complexity CFO Estimation and Tracking [7]. This research does not require any training sequence or prior knowledge, therefore it extends more advantages compare to other methods. Beside that, PEKF (Planar EKF) method [8] is also introduced, which addresses better enhancement of system gain. This method increases complexity in order to overcome ICI. However, neither these researches nor most of previous studies [9,10] apply their methods into commonly OFDM-implemented technology and apply dynamic CFO value.

In this paper, there are several comparative modifications differing from most studies. First, this paper applies EKF method into one of BWA technology, Mobile WiMAX, as the simulation environment to test the commonly-used wireless technology. Secondly, it also implements particular dynamic CFO as the modified perturbation system in order to approach real condition.

In addition, the analysis of research is focused on the influences of ICI parameters toward OFDM system and the method of EKF scheme to reduce ICI effect and consequently enhance OFDM system performance. The EKF scheme

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applied in this research has two phases [9,10]; estimation phase using preamble, and correction phase in order to come up to normalized CFO value that varies in every subcarrier.

The paper is organized as follows: the explanation about ICI effect is in section II; in section III, there is description about EKF scheme implemented into OFDM system including how it works to reduce ICI; analysis and simulation are presented in section III; and final conclusion is drawn in section V.

II. INTER CARRIER INTERFERENCE

ICI is a perturbation in subcarrier signal detection because of the interference from another subcarrier involved in the detection process. Some causal factors of ICI are CFO between transmitter and receiver and also Doppler Shift caused by user mobility. Illustration of ICI caused by CFO is drawn below [4]:

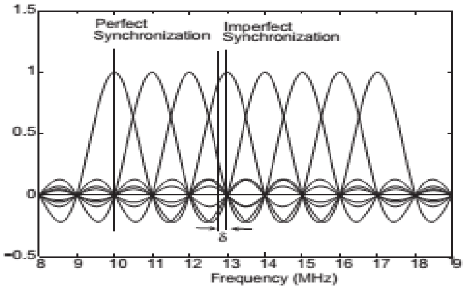

Fig.1: Illustration of ICI Effect in OFDM System [4]

The presence of ICI results in signal distortion caused by the energy of another subcarrier that is also detected by the receiver. In this research, propagation disturbance model is based on the following formula [5,8] :

$$Y(\mathrm{k}) = \underbrace{\mathrm{X(k).S(k)}}_{Fading} + \underbrace{\sum_{\mathrm{l=0,l\neq k}}^{\mathrm{N-1}} \mathrm{X(l).S(l-k)}}_{ICI} + \underbrace{\mathrm{W_k}}_{Noise} \qquad (1)$$

This model consist of three components; fading, ICI, and AWGN noise. However, the object of this research is ICI effect as the main part of processing by EKF method [5,8].

$$ICI = \sum_{\mathrm{l=0,l\neq k}}^{\mathrm{N-1}} \mathrm{X(l).S(l-k)} \qquad (2)$$

A given equation (2) describes how a *k*-th subcarrier encounters interference caused by *l*-th subcarriers, where $\mathrm{S(l-k)}$ functions as ICI coefficient with input ε or normalized CFO. Further details of Normalized CFO is described below [5,8] :

$$S(l-k) = \frac{Sin(\pi(l+\varepsilon-k)}{N.Sin(\frac{\pi(l+\varepsilon-k)}{N})} e^{j\pi\left(1-\frac{1}{N}\right)(l+\varepsilon-k)} \qquad (3)$$

Thereby, it can be concluded that ICI effect is influenced by ε (Normalized CFO) and amount of subcarriers. The higher the value of normalized CFO and/or the amount of subcarriers, the higher the ICI effect will be. The following figure is an illustration of ICI coefficient experienced by the 128th subcarrier of 256 subcarriers.

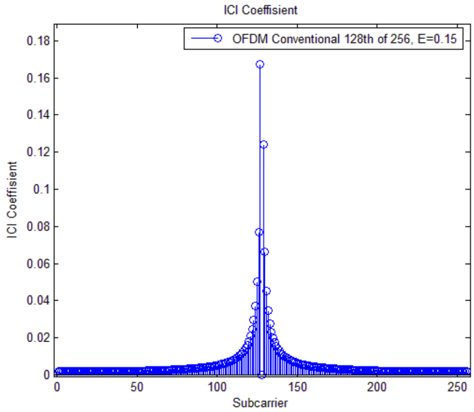

Fig.2: Illustration of ICI effect in OFDM system (CFO = 0.15)

III. OFDM SYSTEM USING EKF

While previous studies [9,10] assumed that CFO normalized is constant in every subcarrier, this research assumes that normalized CFO value experienced by subcarriers is dynamic for all of subcarriers. Normalized CFO in this research is set dynamically using particular stretches of value to move toward real condition.

In this research, OFDM system using EKF scheme requires additional blocks. They are Training Sequence block in OFDM transmitter, and EKF block in OFDM receiver. The main purpose of adding these two blocks is to reduce ICI coefficient caused by CFO. The following block diagram is modified from the previous studies [9,11,12].

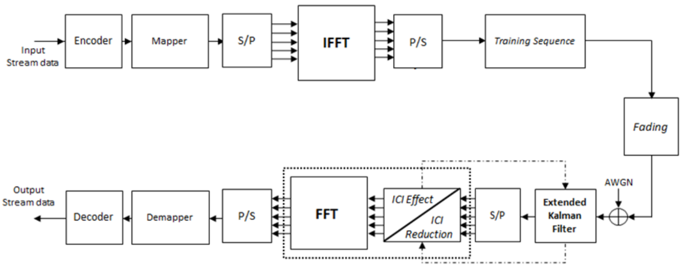

Fig.3: Block Diagram of OFDM System using EKF

There are two phases in EKF scheme to reduce ICI effect. They are Normalized CFO Estimation Phase and Normalized CFO Correction Phase [8,9,10].

A. Normalized CFO Estimation Phase

In this research, normalized CFO is set dynamically with 2.5% instability of value set (Fig. 4 describes CFO equal to 30% ± max 2.5%). These value shows that 30% refers to the frequency offset value resulted from the dissimilarity of oscilator in transmitter and receiver, and 2.5% stretches of value refers to the instability of oscillator plus the influence from Doppler Shift effect caused by user mobility. This value corresponds to user maximum velocity of about 128 km/h based on the equation of Doppler Shift in [1]. This parameter setting is intended to get close to real propagation condition in which EKF scheme can calculate CFO value varied in every subcarrier.

Thereby, the formula for received signal OFDM called observation value is as follows [8,9,10] :

$$y(n) = x(n)e^{j\frac{2\pi n\varepsilon(\mathrm{n})}{N}} + w(n) \qquad (4)$$

where $x(n)$ refers to transmitted signal of the n^{th} sample, ε(n) refers to normalized CFO experienced by n^{th} sample, w(n) denotes noise in the system, and N represents total number of subcarriers in OFDM system.

In the process of normalized CFO estimation or (ε), a number of preambles (Np) are required in the beginning of frame, before transmitting OFDM information symbol (N). For example, OFDM system with 256 subcarriers requires at least three *preambles* (i.e. 768 *samples*) to reach steady state condition. Then, next 256 samples are used to transmit information symbols.

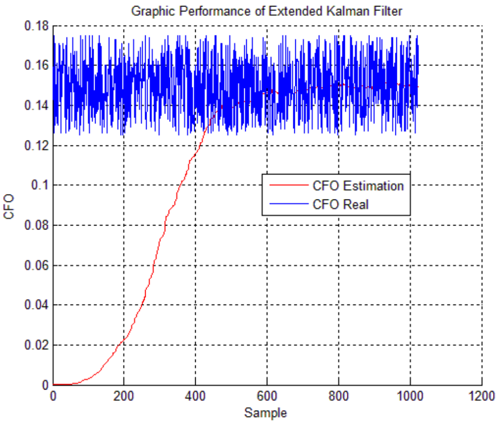

Fig. 4: Normalized CFO Estimation Phase (CFO = 0.15)

The computation procedure in order to perform estimation based on EKF method is describe as follow [8,9,10] :

1. Initialize the condition of original estimation or $\varepsilon(0)$ and initial covariance error or P(0).

$$\varepsilon(n) = \varepsilon(n-1) \qquad (5)$$
$$P(n) = P(n-1) \qquad (6)$$

2. Compute H(n), the derivative of y(n) with respect to $\varepsilon(n)$ at $\varepsilon(n-1)$, the estimation obtained in the previous iteration.

$$H(n) = \left.\frac{\partial y(\mathrm{x})}{\partial \mathrm{x}}\right|_{\mathrm{x}=\varepsilon(\mathrm{n})} = j\frac{2\pi n}{N}x(n)e^{-j\frac{2\pi n\varepsilon(\mathrm{n})}{N}} \qquad (7)$$

3. Compute the time-varying Kalman Gain $K(n)$, using error covariance or $p(n-1)$, $H(n)$, and AWGN noise W(n).

$$K(n) = \frac{P(n-1).H^{*}(n)}{P(n-1)+W(n)} \qquad (8)$$

4. Compute the estimation of $\hat{y}$(n) using x(n) dan $\varepsilon(n-1)$. Based on observation up to time n-1, compute the error between the true observation y(n) and $\hat{y}(n)$, and then update the estimation of $\varepsilon(n)$ by adding $K(n)$ weighing error value between the observation of $y(n)$ and $\hat{y}(n)$ to the previous estimation value of $\varepsilon(n-1)$.

$$\varepsilon(n) = \varepsilon(n-1) + Re\left\{K(n)\left[y(n) - x(n)e^{j\frac{2\pi n\varepsilon(\mathrm{n}-1)}{N}}\right]\right\} \qquad (9)$$

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

$$P(n) = [1-K(n)H(n)]P(n-1) \qquad (10)$$

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

It is observed that the actual errors of the estimation $\hat{\varepsilon}(n)$ from the ideal value $\varepsilon(n)$ are computed in each recursive step and adjusted for the estimation in the next step [8,9,10].

B. *Normalized CFO Correction Phase*

After passing through normalized CFO estimation phase, the next step is correction phase using the result of estimation from earlier phase. The equation to describe Normalized CFO Correction phase in OFDM using EKF is given below [8,9,10].

$$X(N) = FFT\{\, y(n)e^{-j\frac{2\pi n\hat{\varepsilon}(n)}{N}} \} \qquad (11)$$

In this research, the value of normalized CFO estimation ($\hat{\varepsilon}$) becomes an input for equation (11). Therefore, it is expected that the value of ICI coefficient using EKF scheme becomes smaller than that using conventional method.

The accurate value of normalized CFO estimation is able to support OFDM system performance, so that it may only be affected by AWGN noise and fading. This estimation is the factor that decreases ICI coefficient value and improves system performance.

The following figure is the illustration of ICI coefficient experienced by the 128th out of 256 subcarriers using EKF scheme.

As illustrated in Fig. 2 and Fig. 5, the value of maximum amplitude of ICI coefficient by the biggest interfered component in Fig. 2 compared to Fig. 5 decreases significantly for the normalized CFO value in the same subcarriers. In Fig.2, maximum ICI coefficient affecting the 128th subcarrier is given by exactly the next subcarrier, which is about 0.17. Whereas after we use EKF scheme, Fig.5 shows the biggest ICI effect, which is only about 0.01.

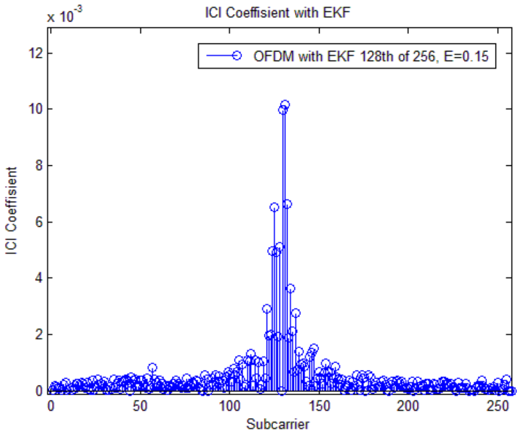

Fig.5: The influence of ICI coefficient using EKF scheme (CFO = 0.15)

IV. ANALYSIS AND SIMULATION RESULT

The main purpose of this research is to analyze how successful EKF scheme improves system performance in overcoming ICI in respect of the conventional method by employing several varying input scenarios. The result of this research is presented in a comparison chart between Bit Error Rate (BER) and Energy Bit per Noise (Eb/No).

In the simulation of this research, there are some assumptions described as follows:

a) Normalized CFO as the input of OFDM system is dynamic in a particular value set with 2.5% instability.
b) ICI is only caused by miss synchronization resulted from offset frequency between transmitter and receiver oscillators, and by Doppler shift affected by *user* mobility. All of them are represented by CFO.
c) The characteristic of channel in this simulation is slow time varying, and therefore, channel impulse response is considered almost constant in a frame.

In addition to those assumptions, this research employs some specifications of OFDM system referring to 802.16e IEEE standard or Mobile WiMAX.

TABLE I. WIMAX SPECIFICATION (IEEE 802.16E) [4,13]

Parameter	**Specification**
FFT size	256
Mapper	QPSK, 16QAM, 64QAM
Operating Band	2.3 GHz
Subcarrier spacing	10.94 kHz
Normalized CFO	0.15, 0.3, 0.4
Channel Model	AWGN + *fading* + *ICI Effect*
Eb/No	0 dB - 20 dB

A. *Analysis of the influence of normalized CFO (ε) against the degree of ICI in OFDM system*

Normalized CFO (ε) is the ratio of carrier frequency offset from proper value to subcarrierspacing. Thereby, the increase of ε value describes the difference of frequency between the frequency of transmitted signal and frequency of local oscillator generated in the receiver and getting higher. It will ruin the orthogonality of OFDM system and lead to worse performance due to higher ICI coefficient on equation (3).

The value of $\varepsilon = 0.15$ informs that there is frequency offset equal to 15% from subcarrier spacing. This research employs Mobile WiMAX specification so that subcarrier spacing is set in 10.94 KHz. Then, the approximate CFO is 1.641 KHz. The condition is similar for $\varepsilon = 0.3$ and $\varepsilon = 0.45$ with respective CFO value are 3.282 KHz and 4.923 KHz. Thus, signal of a subcarrier detected by FFT will be interfered by the signal caused by another subcarrier and detected in receiver. So that, the bigger the CFO value is, the bigger the ICI value is going to occur in subcarrier.

Fig. 6 shows that the greater the CFO occurs, the worse the OFDM system performance will be. When Eb/No is equal to 18 dB, OFDM system is able to reach BER 10^{-6} for 15% CFO. Whereas, for 30% CFO, OFDM system is able to obtain BER $10^{-3.9}$, and for 45% CFO, OFDM system could only reach about BER $10^{-2.8}$.

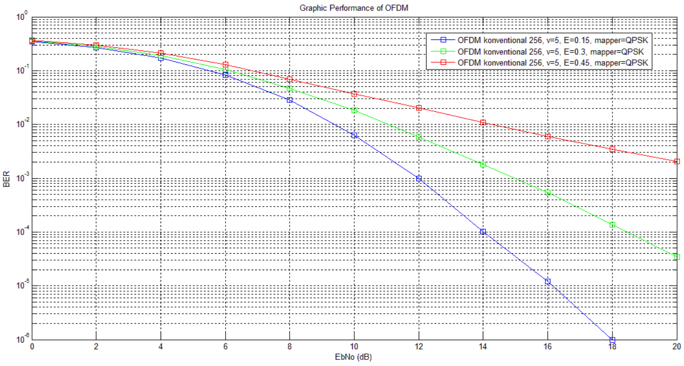

Fig. 6: Influence of Normalized CFO in OFDM system performance

B. *Analysis of the influence of EKF scheme for ICI mitigation due to Normalized CFO (ε) in OFDM system*

EKF scheme is able to reduce ICI effect by estimating the observation value of CFO and then employing the result to produce new offset that is smaller than that with conventional system. In that way, ICI Coefficient will be reduced significantly.

Fig. 7 indicates that the performance of OFDM using EKF is better than that using conventional method. By setting ε = 15% and Eb/No equal to 14 dB, OFDM with EKF is able to demonstrate BER $10^{-4.9}$. In the same degree of Eb/No, conventinal OFDM could only reach BER about 10^{-4}, meaning that EKF scheme can conduct error correction for about 7 - 8 bits for each $10^{4.9}$ bit of information. In the other point of view, OFDM using EKF is able to increase system gain as big as 2 dB against conventional OFDM.

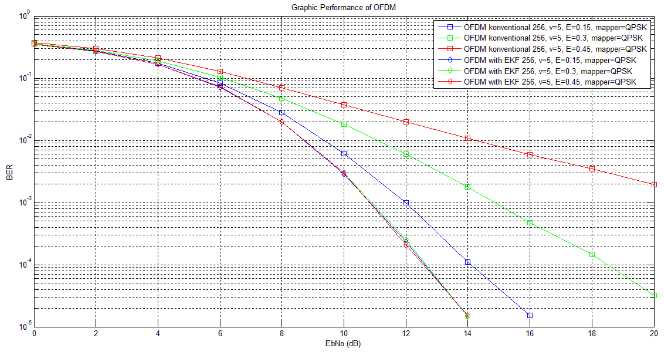

Fig.7: Influence of EKF scheme in OFDM System Performance

Furthermore, conventional OFDM with ε = 30% can obtain BER performance = $10^{-4.9}$ by requiring Eb/No in about 20 dB. While for similar ε, by using EKF scheme, system OFDM can also obtain similar performance only by requiring 14 dB of Eb/No. In conclusion, power efficiency using EKF scheme goes up to 6 dB or 4 times lower than power for conventional OFDM. This 6 dB power efficiency is reached in ε = 30% condition, and this power efficiency could be increasing as the value of ε become higher. For example, when ε = 45%, power efficiency by using EKF scheme is almost 10 dB or 10 times lower than OFDM conventional require to reach performance in BER =10^{-3}.

C. Analysis of EKF scheme reability in OFDM system using different mappers

EKF scheme is also reliable for different use of mappers. As example, below is the performance simulation of three kinds of mappers; QPSK, 16QAM, and 64QAM, in OFDM conventional and OFDM using EKF.

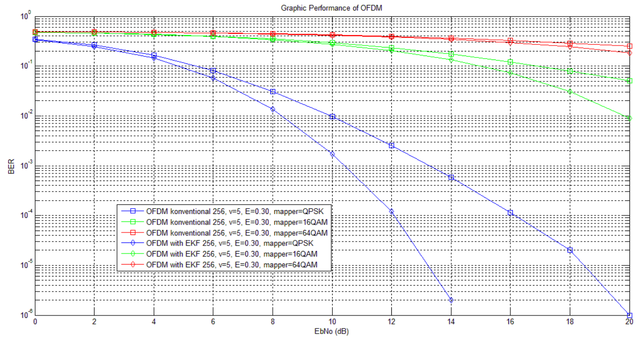

Fig. 8: Influence of different mappers in OFDM system performance

Fig. 8 shows how OFDM using EKF enhance performance when normalized CFO = 0.3 and subcarrier = 256. The use of EKF scheme in OFDM system is relatively reliable for the use QPSK and 16QAM mappers. However, 64QAM mapper only gives a little improvment on conventional OFDM performance. For example, QPSK mapper with Eb/No = 14 dB, OFDM using EKF is able to obtain BER improvement in $10^{-1.2}$. Next, 16QAM mapper with Eb/No=16 dB, is able to gain BER improvement as big as $10^{-0.4}$. Finally, 64QAM mapper with Eb/No = 20 dB is able to reach BER improvement as big as $10^{-0.1}$.

D. Discussion

In order to reduce ICI, OFDM using EKF demonstrates better adaptive capability to work under worse CFO condition. As illustrated in Fig. 9 and Fig. 10, Performance of OFDM is reliable to be used with many kinds of mapper under the conditions of 15% and 30% CFO.

In Fig. 9 and Fig. 10, OFDM using EKF is able to maintain the stability of system, even under dynamic CFO condition. For instance, in condition CFO = 15% with QPSK mapper, the system gain improves as high as 2 dB for BER performance 10^{-5}. Whereas, under worse condition (i.e. CFO = 30%) and with similar parameters, OFDM system is able to produce almost 6 dB gain.

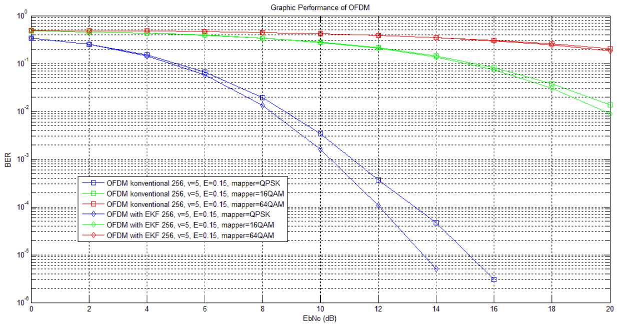

Fig. 9: Influence of different mappers in OFDM System Performance (CFO = 15%)

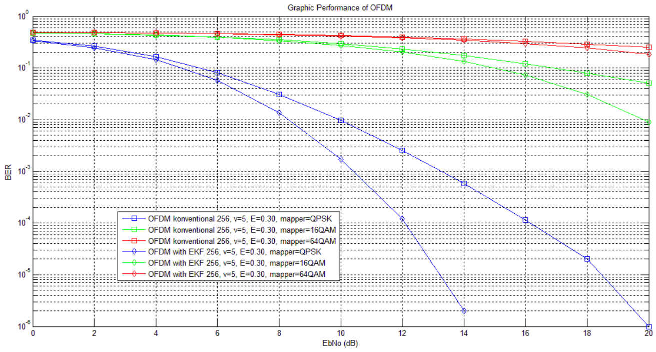

Fig. 10: Influence of different mappers in OFDM System Performance (CFO = 30%)

The result of previous studies [8,9,10,11,12] address EKF method outperforms another methods in order to against ICI. However, this research affirms EKF method is able to overcome ICI effect even under dynamic channel impulse response by modification using various CFO value. Besides, most of simulations in previous studies are only performed in limited specifications as well. This paper brings particular specifications related to technology which adopt OFDM. Therefore, this research is able to bring an impact as the reference to adopt EKF method into OFDM-implemented technology in future.

V. CONCLUSION

Based on the result of analysis and simulation explained in previous section, the conclusions about the implementation of EKF scheme for OFDM system are given as follows:

1. The bigger the value of normalized CFO caused by frequency synchronization failure between transmitter and receiver is, the bigger the impact of ICI will be. Certainly, it will also degrade OFDM system performance. OFDM system with ε =0.15 can obtain BER performance value of 10^{-4} using about 14 dB Eb/No, but OFDM system under ε=0.30 requires about 18 dB Eb/No to obtain similar result.
2. EKF scheme is able to improve OFDM system performance significantly by reducing ICI coefficient value in the system. This method is implemented by performing estimation phase using preamble in the beginning of frame, and then carrying out correction phase to reduce the value of normalized CFO. To illustrate, conventional OFDM with CFO = 0.15 results in maximum amplitude of ICI coefficient about 0.13 experienced by the 128th subcarrier out of 256 subcarriers. On the other hand, the use of EKF scheme shows that the value of ICI coefficient is only about 0.035 on *subcarrier* basis and as normalized CFO remains the same.
3. OFDM using EKF scheme is relatively realiable to be implemented in different kinds of mappers. For example, in the conventional OFDM system using QPSK mapper and 0.3 normalized CFO, this system is able to obtain BER performance about 10^{-6} with 20dB Eb/No. Whereas, OFDM using EKF scheme only requires about 14dB Eb/No. Thereby, EKF scheme can improve gain for 6 dB.
4. The ability of OFDM using EKF scheme is more adaptive on varied values of normalized CFO. For example, this scheme is able to give better improvement when normalized CFO (ε) is more than 30%, rather than 15%. As illustrated, in order to reach BER performance of 10^{-5}, OFDM system using EKF scheme with QPSK mapper under ε = 15% is able to improve system gain for 2 dB. Moreover, in worse condition, with ε = 30%, the system is also able to yield improvement for about 6 dB.

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