

A Fast and Accurate ICI Cancellation with Feedback Correction for the LTE-Advanced Uplink System

Haeseong Jeong, Heung-Gyoon Ryu

Department of Electronic Engineering, Chungbuk National University, Korea

haeseongz@gmail.com, ecomm@cbu.ac.kr

Abstract— In this paper, we propose a fast and accurate ICI cancellation with feedback correction algorithm against phase noise and frequency offset for LTE-advanced uplink system. The purpose of this paper is to describe a method to effectively compensate for ICI. In this paper, we use a fast ICI compensation algorithm, feedback correction algorithm in order to compensate ICI with adaptive channel estimation. We reduce computational complexity by decreasing overlapping computation or unnecessary computation. Therefore, this algorithm is feasible for use in systems requiring fast speed. Also, we can reduce burden of equalizer by using feedback correction algorithm. In order to cancel phase noise and carrier frequency offset, we adapt comb type pilot because the characteristic of phase noise is random. We use an adaptive channel estimation method in order to effectively compensate ICI for multipath channel. The BER performance of the proposed method is better by about 0.3dB than the conventional method in the Vehicular A channel.

Keywords—Carrier frequency offset, ICI cancellation, Phase noise, SC-FDMA, LTE-advanced.

I. INTRODUCTION

In multicarrier system, there are many studies in order to remove phase noise and CFO (Carrier Frequency Offset). In [1] and [2], PNS which is effectively equalizer in order to remove only phase noise is suggested, but if this algorithm is applied to I/Q imbalance and multipath channel, system performance get worse. In [3], the technique that compensates phase noise and I/Q imbalance at same time is introduced, but it compensates only CPE component of phase noise in frequency domain. [4] is FDE (Frequency Domain Equalizer) that can compensate RF impairments by using adaptive ICI cancellation with comb type pilot.

In this paper, we suggest a fast ICI cancellation algorithm against phase noise and frequency offset with adaptive channel estimation for multipath channel at SC-FDMA system. Proposed algorithm has low complexity than PNFS algorithm. Therefore, proposed algorithm can speed up the processing system and we can expect the reduction effect for computational complexity. We reduce computational complexity by decreasing overlapping computation or unnecessary computation. Therefore, this algorithm is feasible to fast data process. Also, we use comb type pilot in order to effectively remove phase noise and carrier frequency offset effect at time-varying channel. And we use an adaptive

channel estimation method in order to effectively compensate ICI for multipath channel.

II. SYSTEM MODEL

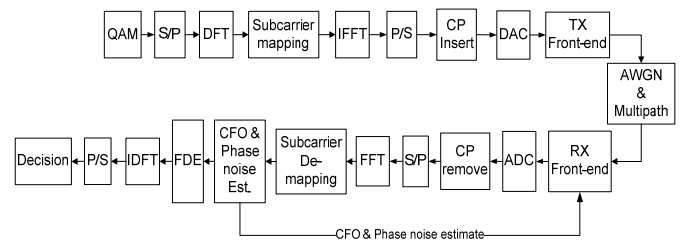


Figure 1. Block diagram of overall system model

Fig. 1 is block diagram of overall system model. In this paper, we use a fast ICI cancellation algorithm and feedback correction algorithm in order to compensate ICI components. In this system model, we consider CFO and phase noise. ICI is occurred by phase noise and carrier frequency offset. Phase noise is a noise component that originate frequency synthesizer. And CFO is occurred by frequency differences of oscillators between receiver and transmitter. In order to reduce burden of FDE, we use a feedback correction algorithm in this paper. At receiver front-end, a feedback algorithm can reduce ICI components by controlling frequency. A feedback correction algorithm use comb type pilot because phase noise is random. The structure of feedback correction algorithm estimate effect of CFO and phase noise by using received pilot at frequency domain, and then we correct CFO and phase noise by using feedback at time domain. After CFO and phase noise correction algorithm, we use a fast ICI cancellation algorithm.

III. FEEDBACK CORRECTION ALGORITHM WITH A FAST ICI CANCELLATION ALGORITHM

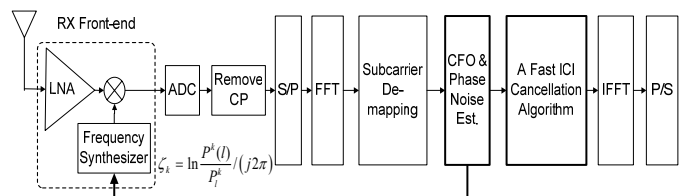


Figure 2. Block diagram for a feedback correction algorithm with a fast ICI cancellation algorithm

We apply a feedback correction algorithm in order to reduce burden of equalizer. Fig. 2 is block diagram for a feedback correction algorithm with a fast ICI cancellation algorithm.

After FFT, the received signal is as follows.

$$\begin{aligned} Y_l^k &= \frac{1}{\sqrt{N_k}} \sum_{n=0}^{N_k-1} r(n) \cdot e^{-j\frac{2\pi nl}{N_k}} \\ &= \frac{1}{N_k} \sum_{n=0}^{N_k-1} \sum_{i=0}^{N_k-1} d_i^k \cdot H_i^k \cdot e^{j\frac{2\pi(\varepsilon_k + \phi(n))}{N_k}} \cdot e^{j\frac{2\pi ni}{N_k}} \cdot e^{j\frac{2\pi n(\varepsilon_k + \phi(n))}{N_k}} \cdot e^{-j\frac{2\pi nl}{N_k}} + V_l^k \quad (1) \\ &= \frac{1}{N_k} \sum_{n=0}^{N_k-1} \sum_{i=0}^{N_k-1} d_i^k \cdot H_i^k \cdot e^{j\frac{2\pi(\varepsilon_k + \phi(n))}{N_k}} \cdot e^{j\frac{2\pi n[(i-l) + (\varepsilon_k + \phi(n))]}{N_k}} + V_l^k \\ &= \frac{1}{N_k} \sum_{n=0}^{N_k-1} d_l^k \cdot H_l^k \cdot e^{j\frac{2\pi(\varepsilon_k + \phi(n))}{N_k}} \cdot e^{j\frac{2\pi n(\varepsilon_k + \phi(n))}{N_k}} \\ &\quad + \frac{1}{N_k} \sum_{n=0}^{N_k-1} \sum_{\substack{i=0, \\ i \neq l}}^{N_k-1} d_i^k \cdot H_i^k \cdot e^{j\frac{2\pi(\varepsilon_k + \phi(n))}{N_k}} \cdot e^{j\frac{2\pi n[(i-l) + (\varepsilon_k + \phi(n))]}{N_k}} + V_l^k \end{aligned}$$

Where, ε_k is CFO and $\phi(n)$ is phase noise. To analyse the CFO and phase noise effects independently, we use as follows to denote the interference factor caused by CFO and phase noise.

$$Q_L^k = \frac{1}{N_k} \sum_{n=0}^{N_k-1} e^{j\frac{2\pi \zeta_k n}{N_k}} \cdot e^{j\frac{2\pi n[(i-l) + \zeta_k]}{N_k}}, \quad (\zeta_k = \varepsilon_k + \phi(n)) \quad (2)$$

Therefore, the received signal can be written as follows.

$$\begin{aligned} Y_l^k &= \frac{1}{N_k} \sum_{n=0}^{N_k-1} d_l^k \cdot H_l^k \cdot e^{j\frac{2\pi \zeta_k n}{N_k}} + \frac{1}{N_k} \sum_{n=0}^{N_k-1} \sum_{\substack{i=0, \\ i \neq l}}^{N_k-1} d_i^k \cdot H_i^k \cdot e^{j\frac{2\pi n[(i-l) + \zeta_k]}{N_k}} + V_l^k \quad (3) \\ &= d_l^k \cdot H_l^k \cdot Q_0^k + \sum_{\substack{i=0, \\ i \neq l}}^{N_k-1} d_i^k \cdot H_i^k \cdot Q_{i-l}^k + V_l^k \\ &= d_l^k + d_l^k \cdot (H_l^k \cdot Q_0^k - 1) + \sum_{\substack{i=0, \\ i \neq l}}^{N_k-1} d_i^k \cdot H_i^k \cdot Q_{i-l}^k + V_l^k \end{aligned}$$

In the first contribution, d_l^k corresponds to the data transmitted on the l th subcarrier. In the second contribution, Q_0^k denotes the CPE (Common Phase Error), which is generated by the CFO and phase noise and will cause a constant phase rotation for all subcarriers. The third contribution corresponds to the summation of interference from the data transmitted on the other subcarriers of the k th component band. The fourth contribution corresponds to AWGN noise and it is also affected by CFO, phase noise.

The received pilot can be written as

$$\begin{aligned} P^k(l) &= P_l^k \cdot H_l^k \cdot Q_0^k + \sum_{\substack{i=0, \\ i \neq l}}^{N_k-1} P_l^k \cdot H_l^k \cdot Q_{i-l}^k + V_l^k \quad (4) \\ &= P_l^k \cdot H_l^k \cdot Q_0^k + W_{ICI+AWGN} \end{aligned}$$

And we estimate CFO and phase noise by comb type pilot. Phase noise is random. But, phase noise is quasi-static in each symbol. Therefore, we can reduce effect of phase noise by feedback correction method.

$$\begin{aligned} P^k(l) &= P_l^k \cdot H_l^k \cdot Q_0^k + \sum_{\substack{i=0, \\ i \neq l}}^{N_k-1} P_l^k \cdot H_l^k \cdot Q_{i-l}^k + V_l^k \quad (5) \\ &= P_l^k \cdot H_l^k \cdot Q_0^k + W_{ICI+AWGN} \end{aligned}$$

The CFO and phase noise effects are as follows.

$$\zeta_k = \ln \frac{P^k(l)}{P_l^k} / (j2\pi) \quad (6)$$

And then, we can reduce the effect of CFO and phase noise by controlling frequency through fractional PLL. And we can effectively compensate ICI components by using a fast ICI cancellation algorithm.

IV. A FAST ICI CANCELLATION ALGORITHM

Fig. 3 is block diagram of a fast ICI cancellation algorithm. This algorithm is FDE. So, we use a fast ICI cancellation algorithm after FFT in frequency domain. At first, we compensate effect of CPE by using pilot, and then compensate effect of ICI by using decision method and MMSE at same time. CPE is component that affects their signal and its effect is same in all OFDM symbols. And CPE is rotated constellation of OFDM symbol. Also, pilot symbol is rotated by CPE.

Therefore, we remove CPE by using pilot. CPE component is compensated as follows.

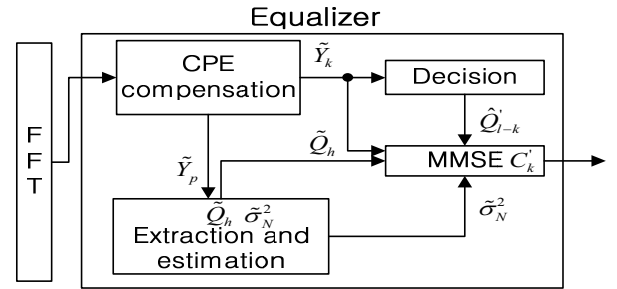


Figure 3. Block diagram of a fast ICI cancellation algorithm

$$CPE_k = \frac{Y_k}{X_k} = Q_0 + \frac{ICI + N_k}{X_k} = Q_0 + W_k \quad (7)$$

And in order to compensate CPE component, we compute mean value of CPE. And then we estimate and compensate CPE component through process to divide CPE.

$$r_{cpe} = \frac{1}{N_p} \sum_{k \in S_p} CPE_k = Q_0 + \frac{1}{4} \sum_{k \in S_p} W_k \quad (8)$$

where, N_p is the number of pilot symbol, S_p is pilot symbol.

In this paper, we use 4 comb type pilots. The received signal after CPE compensation is as follow.

$$\tilde{Y}_k = \left(X_k \cdot Q_0 + \sum_{\substack{l=0 \\ l \neq k}}^{N-1} X_l \cdot Q_{l-k} + V_k \right) / r_{cpe} = X_k \tilde{Q}_0 + W_{ICI+AWGN} \quad (9)$$

In (9), ICI component is only remained after CPE compensation. In order to compensate ICI component, fast ICI cancellation algorithm have process of MMSE and decision method. And we calculate MMSE criterion and then we compensate the data.

In order to make equalization criterion by using extract power because phase noise and carrier frequency offset exist at same time in system, we suggest as follow by pilot symbol that is removed CPE.

$$\tilde{Q}_h = \left(\frac{1}{N_p} \sum_{k \in S_p} (Y_k - \tilde{Y}_k) \right)^2 = \left(\frac{1}{N_p} \sum_{k \in S_p} \varepsilon \right) = E[\varepsilon] \quad (10)$$

In conventional PNFS algorithm, we use decision feedback process as follows.

$$\hat{Q}_{l-k} = \tilde{Q}_h \tilde{Q}_{l-k} + (1 - \tilde{Q}_h) \tilde{Q}_{l-k}', \quad (11)$$

where, $\tilde{Q}_{l-k}$ is phase noise value according to each subcarrier interference. In order to calculate sample of $\tilde{Q}_{l-k}$, we use pilot symbol. But, in (11), characteristic of $\tilde{Q}_{l-k}$ is similar to characteristic of $\tilde{Q}_{l-k}'$. So, in fast ICI cancellation algorithm, we use only decision method. Therefore, (11) writes over again as follow.

$$\hat{Q}_{l-k} = \tilde{Q}_h \tilde{Q}_{l-k}' + (1 - \tilde{Q}_h) \tilde{Q}_{l-k} = \tilde{Q}_{l-k}'. \quad (12)$$

And we calculate average power and adapt to fast ICI cancellation algorithm.

$$\tilde{Q}_{l-k} = \frac{\sum_{k \in S_p} \tilde{Y}_p X_p^*}{\sum_{k \in S_p} |X_p|^2}, \quad \tilde{Q}_{l-k}' = \frac{\sum_{k \in S_d} \tilde{Y}_d D_d^*}{\sum_{k \in S_d} |D_d|^2}, \quad (13)$$

where, X_p is pilot symbol, S_p is the number of pilot symbol, D_d is preamble, and S_d is the number of preamble.

(14) is cost function for MMSE.

$$\min_{\tilde{Q}_{l-k}} \sum_{k \in S_p} |\tilde{Y}_k - X_k \tilde{Q}_{l-k}|^2 \quad (14)$$

And equation for MMSE criterion is finally as follow.

$$C_k' = \frac{\tilde{Q}_{l-k}^* \cdot H_k^*}{|\tilde{Q}_{l-k}^* \cdot H_k^*|^2 + \frac{\sigma_{ph}^2}{E_x}}, \quad (15)$$

where, σ_{ph}^2 is power of $\mathcal{W}_{ICI+AWGN}$. In equalization process, because the effect of ICI is big enough than noise power after FFT in equalization process, we use error power from pilot symbol without dividing between phase noise and carrier frequency offset for optimization tap weighting value of equalizer. And E_x is useful power through the channel estimation.

$$\tilde{\sigma}_{ph}^2 = \frac{1}{N_p} \sum_{k \in S_p} |\tilde{Y}_k|^2. \quad (16)$$

A fast ICI cancellation algorithm goes through decision process. And then a fast ICI cancellation algorithm compensates effect of CPE and ICI that is caused phase noise and carrier offset by using MMSE criterion that is updated by (12). The signal which is removed CPE pass through MMSE equalizer in order to remove effect of ICI. And final signal is as follow.

$$\hat{X}_k' = \tilde{Y}_k \cdot C_k'. \quad (17)$$

If we use (7) ~ (17), equalizer with MMSE compensate effectively ICI when there's a problem of ICI by phase noise and CFO.

In proposed algorithm, we can compute MMSE criterion by using $\tilde{Q}_{l-k}'$ which is calculated just by decision instead of $\tilde{Q}_{l-k}$ which is calculated by decision feedback process. And proposed algorithm is to satisfied same performance by using just decision without decision feedback. Proposed algorithm has low complexity than conventional PNFS algorithm because proposed algorithm is not decision feedback.

The operation process of proposed algorithm is as follows.

- 1) We calculate to r_{cpe} of average CPE component by using (7) and (8) like conventional algorithm.
- 2) And then, we get received signal after CPE compensation by using (9).
- 3) We calculate $\tilde{Q}_h$ by using (10) in order to make equalizer criterion using extract power as pilot symbol that is removed CPE. And we compute $\hat{Q}_{l-k}$ by using (11). And we calculate $\tilde{\sigma}_{ph}^2$ that is estimation value by ICI and AWGN channel by using (16).
- 4) We calculate equalization coefficient C_k' about N sample per each symbol by substituting (12) to (15).
- 5) By using (17), we estimate final output signal.
- 6) We estimate and compensate about total symbol by using repetitive 1) ~ 5) process.

Difference between conventional PNFS algorithm and proposed algorithm is (11) and (12). Difference is to make equalization coefficient about N sample per each symbol by using just decision without decision feedback.

Table I is comparison of computational complexity between conventional PNFS algorithm and proposed algorithm. In order to compare computational complexity to conventional PNFS algorithm, we compare the amount of computation on algorithm.

And we make comparison between conventional PNFS algorithm and proposed algorithm by using the amount of computation for addition and for multiplication. In table 1, k is the number of pilot in each symbol, d is the number of preamble, m is the number of symbol.

In table 1, we compare computational complexity at 3 aspects. At first, we compare with computing part of phase value $\tilde{Q}_{l-k}$ which is generated to interference for subcarriers. Proposed algorithm doesn't calculate $\tilde{Q}_{l-k}$ by using pilot symbol separately because characteristic of $\tilde{Q}_{l-k}$ is similar to characteristic of $\tilde{Q}_{l-k}'$. And we compare computational complexity of decision feedback part. We don't calculate $\hat{Q}_{l-k}$ like (5) separately. Finally, we compare part of MMSE criterion. Proposed algorithm just uses decision when we compute MMSE criterion C_k as table 1. Therefore, proposed algorithm has low computational complexity because there is no part of computation by using pilot.

TABLE 1. COMPUTATIONAL COMPLEXITY COMPARISON

		PNFS Algorithm	Proposed Algorithm
$\tilde{Q}_{l-k}$	A ^a	$\sum_{k=1}^k \sum_{m=1}^{2m} (k \times m - 1)$	-
	M ^b	$\sum_{k=1}^k \sum_{m=1}^{2m} (k \times m)$	-
C_k	A	$\sum_{k=1}^k \sum_{m=1}^m (k \times m - 1) + \sum_{d=1}^d \sum_{m=1}^m (d \times m - 1)$	$\sum_{d=1}^d \sum_{m=1}^m (d \times m - 1)$
	M	$\sum_{k=1}^k \sum_{m=1}^{4m} (k \times m) + \sum_{d=1}^d \sum_{m=1}^{4m} (d \times m)$	$\sum_{d=1}^d \sum_{m=1}^{4m} (d \times m)$
$\hat{Q}_{l-k}$	A ^c	$\sum_{k=1}^k \sum_{m=1}^{2m} (k \times m - 1) + \sum_{d=1}^d \sum_{m=1}^{2m} (d \times m - 1)$	-
	M	$\sum_{k=1}^k \sum_{m=1}^m (k \times m)^2 \cdot \left(\sum_{k=1}^k \sum_{m=1}^{3m} (k \times m) + \sum_{d=1}^d \sum_{m=1}^{3m} (d \times m) \right)$	-

^a Addition; ^b Multiplication; ^c Decision Feedback Equalizer

V. ADAPTIVE CHANNEL ESTIMATION FOR A FAST ICI CANCELLATION ALGORITHM

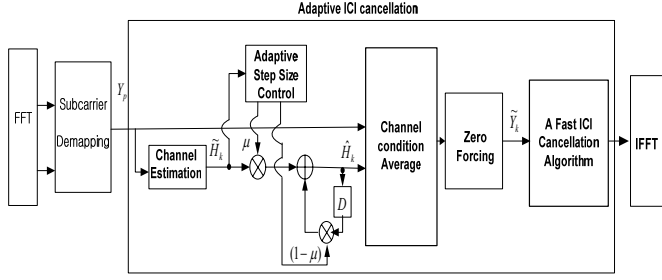


Figure 4. Adaptive channel estimation for a fast ICI cancellation algorithm

In multipath channel, the system performance will get worse. Therefore, we introduce an adaptive channel estimation algorithm for effectively channel estimation. Fig. 4 is adaptive channel estimation for a fast ICI cancellation algorithm. First, we estimate channel by using preamble and control step size adaptively in order to estimate multipath channel according to variation of channel impulse response. But there is a problem that we can't accurately estimate channel impulse response if change of channel impulse response is big. Therefore, we use channel condition average block in Fig. 4. In this paper, when we estimate channel by controlling step size, we estimate channel and make average channel condition by estimating odd subcarrier and even subcarrier respectively. μ is step size.

$$\mu = \left| \frac{1}{N_p} (1 - \sum_{k \in s_p} \tilde{H}_k) \right|, \quad (18)$$

where, μ is $0 < \mu \leq 1$. And we estimate channel impulse response by using (19) and (20).

$$\hat{H}_k = \mu \tilde{H}_k + (1 - \mu) \hat{H}_{k-1}, \quad (19)$$

$$\text{if } |\tilde{H}_k - \hat{H}_k| < \mu, \quad \tilde{H}_k = \hat{H}_{k-1}. \quad (20)$$

We perform the channel condition average process by using adaptive estimated channel impulse response. The channel condition average process is as follows.

$$\hat{H}_{k_CCA} = \frac{2}{N} \sum_{i=1}^{N/2} \hat{H}_i + \hat{H}_{i+1}, \quad (21)$$

where, $\hat{H}_i$ is odd channel response, $\hat{H}_{i+1}$ is even channel response of estimated channel. After channel condition average process, we compensate multipath by using ZF (zero forcing). And we cancel phase noise and CFO by using an error correction method and a fast ICI cancellation algorithm.

VI. SIMULATION RESULTS

TABLE 2. SIMULATION CONDITIONS

Modulation	16QAM
The number of sub-carrier	64(data=60, pilot=4)
Oversampling rate	4
Channel	AWGN, Multipath channel(Vehicular A)
Carrier frequency offset	CFO = 0.01, 0.1
Phase noise	-15dBc, -20dBc, cut-off freq.=10kHz, 100kHz

In this study, we check performance between PNFS algorithm and proposed algorithm. Fig. 5 is BER comparison between PNFS algorithm and proposed algorithm according to phase noise and CFO. In Fig. 5, the diamond markers are that total power of phase noise is -20dBc, cut-off frequency of phase noise is 100kHz, and normalized CFO is 0.01. And the square markers are that total power of phase noise is -20dBc, cut-off frequency of phase noise is 10kHz, and normalized CFO is 0.01. The dot lines are without compensation algorithm between simulation conditions of phase noise and CFO. And the dash-dot lines are with compensation algorithm between conventional PNFS algorithm and proposed algorithm at each simulation conditions. And the solid lines are also with compensation algorithm between conventional PNFS algorithm and proposed algorithm at each simulation conditions. Fig. 6 is comparison of channel impulse estimation between conventional method and proposed method at Vehicular A channel. The performance of proposed method is better than conventional method if we use adaptive channel average algorithm. Fig. 7 is BER comparison between proposed method and conventional method according to adaptive channel estimation method at Vehicular A channel. In Fig. 7, ACE is adaptive channel estimation and FICA is a fast ICI cancellation algorithm. In Vehicular A channel, if we use an adaptive channel estimation, the performance is better than conventional method such Fig. 7. Also, we set the parameter that total power of phase noise is -20dBc, cut-off frequency is 10kHz, and the normalized CFO is 0.01. The BER performance of proposed method is better about 0.5dB than conventional method. Fig. 8 is BER comparison between proposed algorithm and feedback correction method at 4QAM. In Fig. 8, the diamond maker is with feedback correction algorithm. If we use a feedback correction algorithm, the effects of CFO and phase noise are mitigated. Therefore, we get the diamond maker in Fig. 8. And the pentagram maker is BER performance by using a fast ICI cancellation algorithm and a feedback correction algorithm.

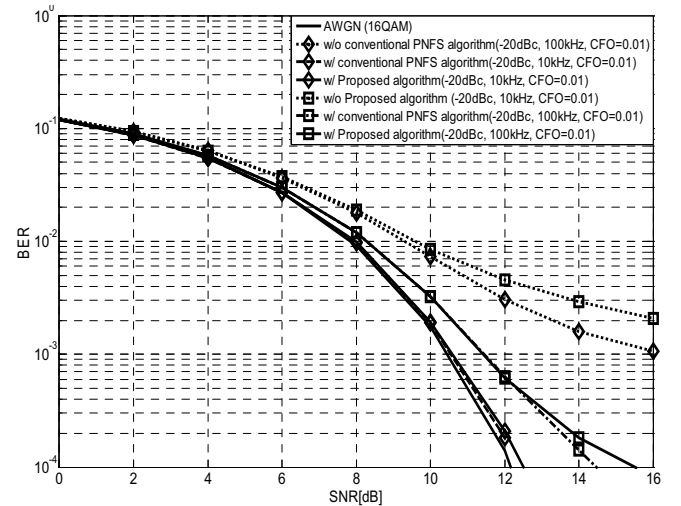


Figure 5. BER comparison between PNFS algorithm and proposed algorithm according to phase noise and CFO at 16QAM (AWGN)

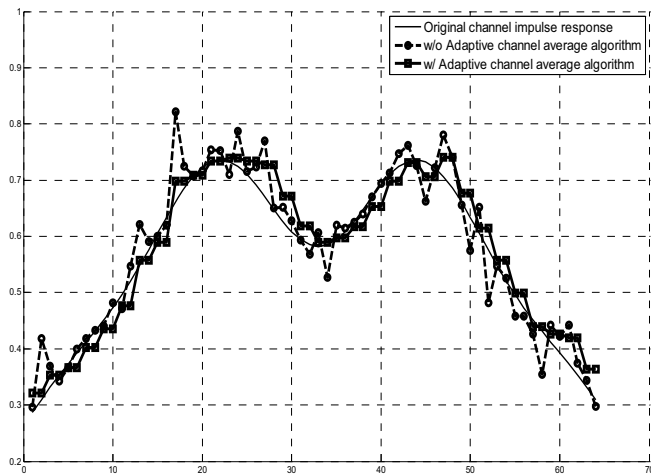


Figure 6. Comparison of channel impulse estimations(Vehicular A channel)

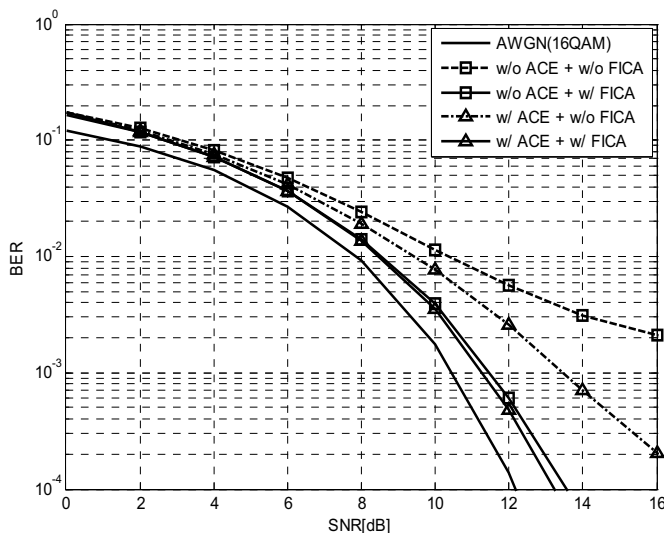


Figure 7. Comparison of BER between proposed method and conventional method(Vehicular A channel)

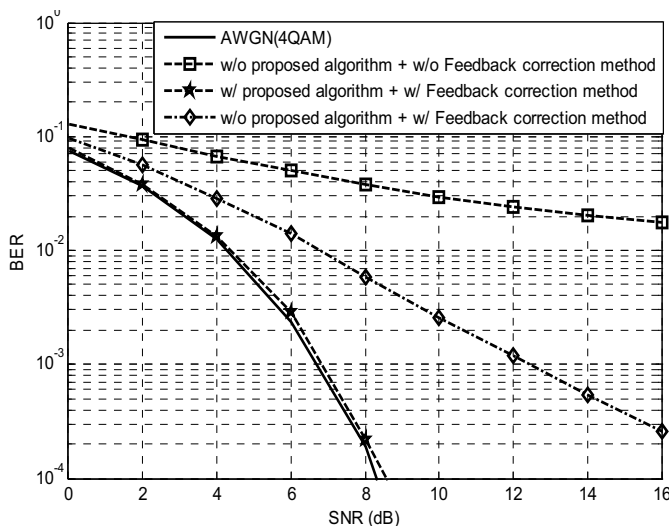


Figure 8. BER comparison between proposed algorithm and feedback correction method at 4QAM (CFO=0.1, PN=-20dBc, 100kHz, AWGN)

VII. CONCLUSIONS

In this paper, the purpose is to describe a method to effectively compensate for ICI. In this paper, we use a fast and accurate ICI cancellation with feedback correction algorithm against phase noise and frequency offset for LTE-advanced uplink system. Proposed algorithm compensates the effect of phase noise and CFO by using decision without decision feedback. Therefore, proposed algorithm can speed up the processing system and we can expect the reduction effect for computational complexity. The improvement of data processing speed can be suitable at multiband communication system or high speed communication system. Also, we can reduce burden of equalizer by using feedback correction algorithm. In order to cancel phase noise and carrier frequency offset, we adapt comb type pilot because the characteristic of phase noise is random. We use an adaptive channel estimation method in order to effectively compensate ICI for multipath channel. The BER performance of the proposed method is better by about 0.3dB than the conventional method in the Vehicular A channel.

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology(No. 2010-0007567)

REFERENCES

- [1] S. Wu and Y. Bar-Ness, "A phase noise suppression algorithm for OFDM-based WLANs," *IEEE Transactions on Communication Letters*, vol. 6, no.12, pp. 535 – 537, 2002.
- [2] S. Wu and Y. Bar-Ness, "OFDM systems in the presence of phase noise: consequences and solutions" *Communications, IEEE Transactions*, vol. 52, Issue 2, pp.1988 - 1996, Nov. 2004.
- [3] J. Tubbax, L. V. Perre and S. Donnay, "Compensation of IQ imbalance and phase noise in OFDM systems," *IEEE Transactions on Wireless communications*, vol. 4, Issue 3, pp. 872-877, May 2005.
- [4] S. B. Ryu, J. Kim and H. G. Ryu, Y. Li, "PNS Algorithm for the SC-FDMA Communication System with Phase Noise," *Wireless and Optical Communications Networks, 2009 IFIP International Conference*, April 2009.
- [5] H. G. Ryu and Y. S. Li, "Phase noise analysis of the OFDM communication system by the standard frequency deviation," *IEEE Transactions on Consumer Electronics*, vol. 49, no.1, pp.41 - 47, Feb 2003.
- [6] H. G. Ryu and H. S. Lee, "Analysis and minimization of phase noise of the digital hybrid PLL frequency synthesizer," *IEEE Transactions on Consumer Electronics*, vol.48, no.2, May 2002.
- [7] B. Wu, S. Cheng and H. Wang, "Clipping effects on channel estimation and signal detection in OFDM," *Personal, Indoor and Mobile Radio Communications*, vol. 1, pp.531 - 534, 7-10, Sept 2003.