Novel Pilot-Assisted Channel Estimation Techniques for 3GPP LTE Downlink with Performance-Complexity Evaluation

Yang Qin* *Associate Member*, Bing Hui* *Regular Member*, KyungHi Chang* *Lifelong Member*

ABSTRACT

In this paper, various of pilot-assisted channel estimation techniques for 3GPP LTE downlink are tested under multipath Rayleigh fading channel. At first, the conventional channel estimation techniques are applied with linear zero-forcing (ZF) equalizer, such as one dimensional least square (1-D LS) linear interpolation, two dimensional (2-D) wiener filter, the time and frequency dimension separate wiener filter and maximum likelihood estimator (MLE). Considering the practical implementation, we proposed two channel estimation techniques by combining time-dimension wiener filter and MLE in two manners, which showed a good tradeoff between system performance and complexity when comparing with conventional techniques. The nonlinear decision feedback equalizer (DFE) which can show a better performance than linear ZF equalizer is also implemented for mitigating inter-carrier interference (ICI) in our system. The complexity of these algorithms are calculated in terms of the number of complex multiplications (CMs) and the performances are evaluated by showing the bit error rate (BER).

Key Words : 3GPP LTE, Channel estimation, Computational complexity, Two 1-dimension wiener filters, MLE

Ⅰ. Introduction

The third generation partnership project (3GPP) has considered the long term evolution (LTE) of 3G to ensure its competitiveness in the future. And LTE offers a smooth evolutionary path to higher speeds and lower latency communication, specified in 3GPP Release 8. The downlink of the new air interface would be orthogonal frequency division multiple access (OFDMA) based and the uplink would be single carrier frequency division multiple access (SC-FDMA) based. OFDMA is an extension of OFDM in which the user allocation can be multi-plexed both in the time and frequency domains [1].

OFDM technique has advantages in high-bit-rate transmissions over frequency selective fading channels. In OFDM system, the knowledge of wireless channel is unknown, and the Doppler spread can destroy the orthogonality between sub-carriers, which causes inter-carrier interference (ICI) and results in data distortion. So the fading channel estimation and equalization are necessary for the demodulation of OFDM symbols. Usually, the channel are estimated by using the pilot signals which are known to transmitter and receiver. One dimensional Least Square (1-D LS) and two dimensional (2-D) wiener filter are well known channel estimation techniques [2-3]. The 2-D wiener filter is the optimal solution based on minimum mean square error (MMSE) criteria with a huge

※ This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) (KRF-2007-331-D00296).

* Mobile Telecommunications Research Lab, The Graduate School of Information Technology & Telecommunications, Inha University (vickiloving_qin@hotmail.com, huibing_zxo@163.com, khchang@inha.ac.kr).

논문번호 : KICS2010-03-100, 접수일자 : 2010년 3월 11일, 최종논문접수일자 : 2010년 7월 1일

computational complexity[4]. In order to reduce the complexity, the scheme which uses two 1-dimensional (2×1-D) wiener filters in the frequency and the time dimension respectively has been proposed in [4-5]. The maximum likelihood estimator (MLE), which is an efficient algorithm without any correlation matrix computation, has been investigated by Morelli M. in [6]. In this paper, we try to estimate the channel by using time-dimension wiener filtering and MLE in frequency dimension in a different order. By doing this, the computational complexity will stay low and the performance is maximized for practical implementation. Also, we apply some equalizers after channel estimation, such as linear zero-forcing (ZF) and nonlinear decision feedback equalizer (DFE).

The remaining part of this paper is organized as follows. At first, we introduce the 3GPP LTE Downlink system and pilot pattern in Section II, and in Section III, various channel estimation and equalization algorithms are presented. The computational complexity analysis is shown in Section IV. In Section V, the performance and complexity evaluation are shown and discussed. Finally, conclusions are given in Section VI.

Ⅱ. System Description in 3GPP LTE Downlink

2.1 OFDM System Model

The system block diagram of 3GPP LTE Downlink is shown in Fig. 1, where *x(k)* is the transmitted data, $h_{l,n}$ is the channel impulse response and *w(n)* is a complex additive white Gaussian noise (AWGN). *y(k)* is the received data. The binary information bits are first grouped and mapped to the QPSK symbols. Before applying N-point IDFT to modulated symbol *X(k)*, which is the data symbol on the *k*-th sub-carrier, pilots should be inserted into fixed positions among the information data. The *n*-th sample after IDFT in the OFDM symbol is *x(n)=IDFT{X(k)}*. A cyclic prefix (CP) with length N_{cp} should be larger than channel length *L* for avoiding Inter-symbol interference and then is added

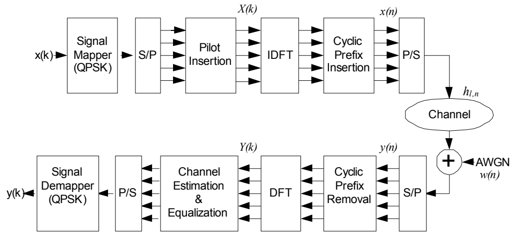

Fig. 1. OFDM system block diagram

to form an OFDM symbol. At last, the transmitted OFDM symbols are sent through the Rayleigh fading multipath wireless channels.

At the receiver, the CP is removed from received symbols first. Before DFT, the received signal in time domain is *y(n)*, and then the signal in frequency domain *Y(k)* is given as

$$Y(k) = X(k)H(k) + I(k) + W(k), \quad (1)$$

where $0 \le k \le N$-1 and $H(k)=DFT\{h_{l,n}\}$, $h_{l,n}$ stands for channel impulse response at the *l*-th channel tap and *n*-th sample[7], $W(k)=DFT\{w(n)\}$, and *I(k)* is the ICI part due to Doppler spread,

$$I(k) = \sum_{i=0; i \ne k}^{N-1} H(i, k-i) X(i), \quad (2)$$

where

$$H(i, k-i) = \frac{1}{N} \sum_{n=0}^{N-1} \sum_{l=0}^{L-1} h_{l,n} e^{-j2\pi li/N} e^{-j2\pi n(k-i)/N}. \quad (3)$$

Channel estimation is performed after DFT block. The pilot signals are extracted and used to estimate channel. The channel matrix is a banded matrix in which most of the channel energy is located on the main diagonal and on a few diagonals distributed around it[8]. After channel equalization process, the transmitted binary information bits can be recovered by performing symbol demapping.

2.2 Pilot Pattern

In 3GPP LTE downlink, OFDM symbol used in LTE comprises a maximum of 2048 and minimum of 128 different sub-carriers with the spacing of

15Khz. All sub-carriers are split into physical resource blocks (PRBs), and each PRB comprises 12 sub-carriers and covers one slot duration[1].

These pilots in specification are named as reference signals, which are usually embedded in the PRBs and transmitted during the first and the fifth (or fourth, depending on whether the normal or extended CP is employed.) OFDM symbols. In this paper, Fig.2 shows the position of reference signals in each PRB and the reference signals value is assumed as

$$P_v = \frac{1+j}{\sqrt{2}}. \tag{4}$$

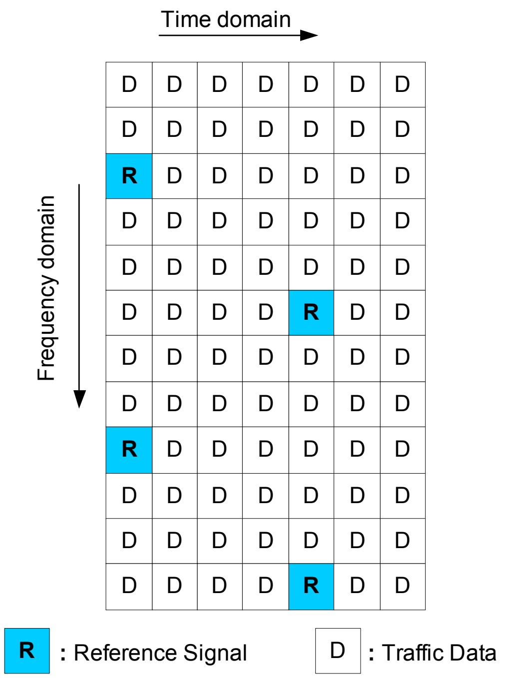

Fig. 2. Pilot position of a PRB in 3GPP LTE downlink

Ⅲ. Channel Compensation Techniques for 3GPP LTE Downlink

Channel estimation scheme, which is applied at the receiver side, is to form an estimate of the channel attenuation caused by wireless channel from the available reference signals. With the estimated channel information, the channel equalization scheme is performed to compensate the distortion of the received signals.

3.1 Conventional Channel Estimation Techniques

Usually the conventional channel estimation scheme is performed based on reference signals by using 1-D LS linear interpolation or 2-D wiener filter[2]. As we know, the 1-D LS linear interpolation is the simplest algorithm with the worst system performance and 2-D wiener filter can avoid noise amplification very well. However, the 2-D wiener filter includes the matrix inversion which can dramatically increase computational complexity. In [9], the simplified 2×(1-D) wiener filter estimator is suggested. In this simplified version, the complexity is further reduced by computing all correlation matrixes in time and frequency dimension, respectively.

Also in [10], we have studied the other efficient less complexity technique named as MLE. A briefly introduction is given below.

3.1.1 2×(1-dimension) Wiener Filter

In the case of 2×(1-dimension) wiener filter, frequency dimension wiener filter is performed at first to enable channel estimation immediately. *d(i)* and *p(j)* denote the positions of *i*-th data and *j*-th reference signal sub-carrier in frequency dimension respectively. R_{hp} and R_{pp} are cross-correlation and auto-correlation fuctions. r_t and r_f are the correlation functions in time and frequency, respectively as defined in [4]. $\widehat{H}_p$ is the channel information of reference signals' position.

$$[R^f_{hp}]_{i,j} = r_f(|d(i)-p(j)|), \tag{5}$$

$$[R^f_{pp}]_{j,j'} = r_f(|p(j)-p(j')|). \tag{6}$$

According to (5) and (6), the estimated channel in frequency dimension $\widehat{H}_f$ can be given as

$$\widehat{H}_f = R^f_{hp}\left(R^f_{pp}+\sigma^2 I\right)^{-1}\widehat{H}_p. \tag{7}$$

Then, the time-dimension wiener filter is applied with the result of frequency dimension estimated channel to get the whole estimated channel matrix. T_s is the duration of each OFDM symbol, the elements of auto-correlation and cross-correlation matrixes are given as

$$\left[R_{hp}^{t}\right]_{i,j}=r_t(|d(i)-p(j)|T_s), \quad (8)$$

$$\left[R_{pp}^{t}\right]_{j,j'}=r_t(|p(j)-p(j')|T_s). \quad (9)$$

After wiener filtering in time-dimension, the estimated channel is shown as

$$\hat{H}=R_{hp}^{t}\left(R_{pp}^{t}+\sigma^2 I\right)^{-1}\hat{H}_f. \quad (10)$$

Through (10), we can get the whole estimated channel.

3.1.2 Maximum Likelihood Estimator

This method is also a low complexity estimator. It can be interpreted as a translation of the frequency response of reference signals position channel information to the time domain, followed by a linear transformation, and retranslation to the frequency domain[12].

In [6] and [10], based on maximum likelihood algorithm and the channel information at the reference signals position, we can get the channel information of one OFDM symbol which contains reference signals.

$$\widehat{H_{MLE}}(n)=\sum_{m=0}^{N_p-1}\hat{H}_p(m)p_{MLE}(n,m), \quad (11)$$

the maximum likelihood matrix p_{MLE} is as follow:

$$p_{MLE}(n,m)=\sum_{k=0}^{L-1}\left[\left(B^H B\right)^{-1}B^H\right]_{k,m}e^{-j2\pi nk/N}, \quad (12)$$

$$[B]_{n,k}=e^{-j2\pi kp_j/N}, \quad (13)$$

where $0\le n\le N_p$-1, $0\le k\le N$-1, **B** is the Fourier transform matrix of reference signals position and p_j is the index of reference signals' sub-carrier. Hence, after we get the channel information of some OFDM symbols, many methods can be applied to get other unknown channel information, such as interpolation and so on.

3.2 Proposed Channel Estimation Techniques

Due to the requirement of high efficiency and less complexity in practical implementation, we try to propose two channel estimation strategies by combining above two schemes in a different order.

3.2.1 Proposed Strategy 1: Time-dimension Wiener Filter Followed by Frequency-dimension MLE

At first, time-dimension wiener filtering is implemented to get the channel information of all sub-carriers for all OFDM symbols in each PRB, as shown in Fig. 3. Then, MLE is applied to get the whole channel matrix for each OFDM symbol. From (10)~(13), we can get the estimates of channel as shown below,

$$\hat{H}_t=R_{hp}^{t}\left(R_{pp}^{t}+\sigma^2 I\right)^{-1}\hat{H}_p, \quad (14)$$

$$\hat{H}_{s1}=\sum_{m=0}^{2N_p-1}\hat{H}_t(m)p_{MLE}(n,m), \quad (15)$$

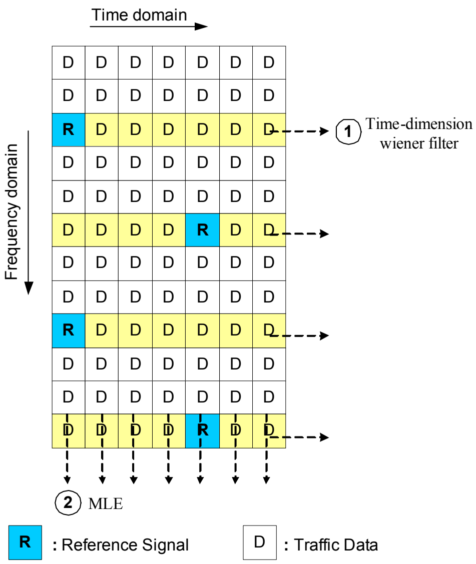

Fig. 3. Strategy 1: Time-dimension wiener filter + MLE

where $0 \le n \le 2N_p$-1 and $\widehat{H_{s1}}$ is the final estimated channel from proposed strategy 1.

3.2.2 Proposed Strategy 2: Frequency-dimension MLE Followed by Time-dimension Wiener Filter

In this strategy, we apply MLE in frequency dimension at first to get the channel information for some OFDM symbols which contains reference signals, as shown in Fig. 4. Then, time-dimension wiener filtering is performed to get the whole channel matrix.

$$\widehat{H_p} = \sum_{m=0}^{N_p-1} \widehat{H_p}(m) p_{MLE}(n,m), \qquad (16)$$

$$\widehat{H_{s2}} = H_{hp}^t \left(H_{pp}^t + \sigma^2 I\right)^{-1} \widehat{H_p}, \qquad (17)$$

where $0 \le n \le N_p$-1, $\widehat{H_{s2}}$ is the final estimated channel from proposed strategy 2 and $\widehat{H_p}$ is the channel information of some OFDM symbols containing reference signals. Due to the special scattered reference signal pattern in Fig. 2, the proposed channel estimation strategy 2 shows a slightly better bit error rate (BER) performance.

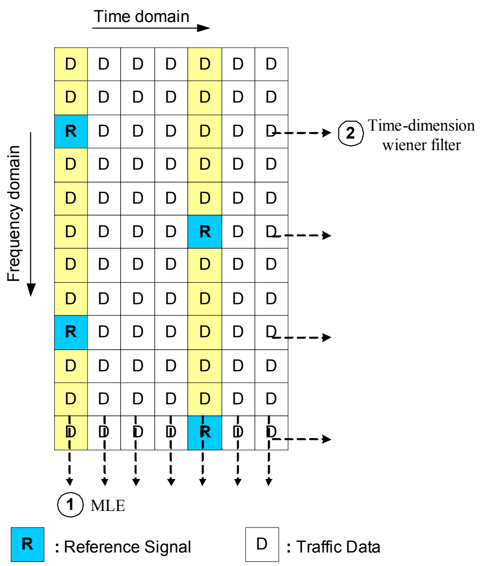

Fig. 4. Strategy 2: MLE + Time-dimension wiener filter

3.3 Conventional Channel Equalization Techniques

The well-known equalizer in real system is the simplest linear ZF equalizer. After ZF equalization, the output of received signal is

$$Y_{eq}(k) = \frac{Y(k)}{\widehat{H}(k)}, \qquad (18)$$

where $0 \le k \le N$-1. In [7] and [11], nonlinear DFE has been introduced to suppress the ICI in OFDM system. As shown in Fig. 5, It consists of a forward filter with the received signals as input and a feedback filter with the previously detected signals as input, $G_{k,i}$ denotes the entry (k,i) of the N frequency domain channel matrix **G**, and $H_{i,n}$ is the FFT of $h_{l,n}$.

$$G_{k,i} = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} H_{i,n} e^{j2\pi n(i-k)/N}, \qquad (19)$$

where $0 \le k \le N$-1, $0 \le i \le N$-1.

Supposing the effective symbol is s_m, the symbol filtered by the first filter β that follows Zero Forcing criterion as ZF equalizer is given as

$$\widehat{s_m} = \beta_{ZF}^H y_m. \qquad (20)$$

Taking hard decision based on ^, and then removing ICI with the feedback filter, so the received symbol is

$$r = r_{old} - \widehat{s_m^{HD}} \gamma_m, \qquad (21)$$

where γ_m is the m-th column of the channel matrix **G**.

Usually, the nonlinear equalizer can present better BER performance than linear equalizer in wireless communication systems.

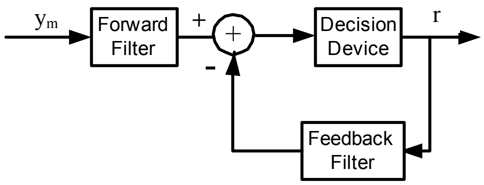

Fig. 5. Decision feedback equalizer

Ⅳ. Computational Complexity Analysis of Channel Estimation Techniques for 3GPP LTE Downlink

In 3GPP LTE specifications, the number of PRBs has been defined. The maximum number of PRBs is 100 and the minimum number of PRBs is 6. It is well known that the computational complexity of channel estimation scheme increases significantly as the number of PRBs increasing. Therefore, we will measure the complexities of all the channel estimators in terms of calculating the number of complex multiplications (CMs) by considering the system bandwidth (The different number of PRBs) in each slot[12].

According to the descriptions of existing and two proposed channel estimation algorithms, the block diagrams of various channel estimation techniques in this paper are given as follows:

- 1-D LS Interpolation

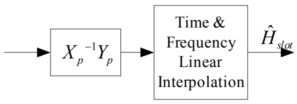

Fig. 6. Block diagram of 1-D LS estimator

- 2-D Wiener Filter

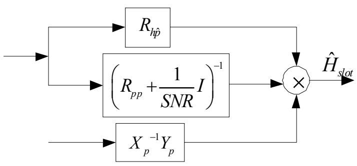

Fig. 7. Block diagram of 2-D wiener filter estimator

- 2×(1-D) Wiener Filter

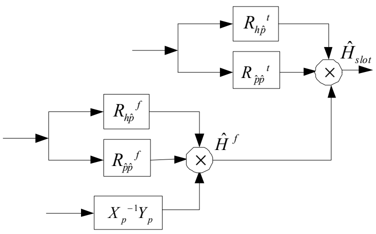

Fig. 8. Block diagram of 2×(1-D) wiener filter estimator.

- Maximum Likelihood Estimator

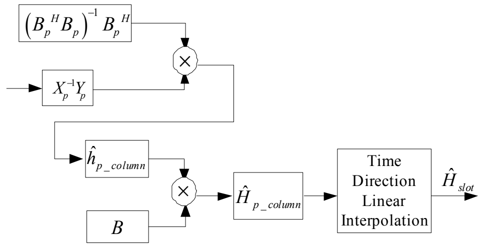

Fig. 9. Block diagram of MLE estimator

- Time-dimension Wiener Filter + MLE

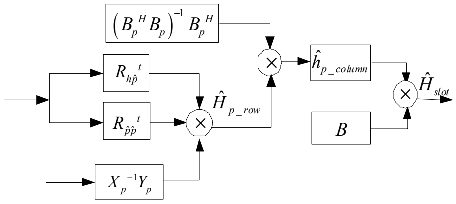

Fig. 10. Block diagram of proposed strategy 1 estimator

- MLE + Time-dimension Wiener Filter

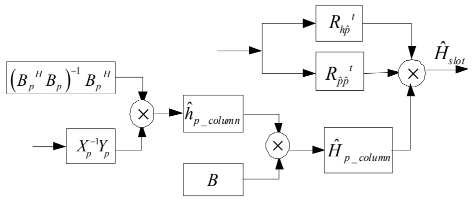

Fig. 11. Block diagram of proposed strategy 2 estimator

In Table 1, analysis of computational complexity for various channel estimation scenarios are represented by adopting three parameters: L, N_p, N_s, where L is the channel length, N_p is the number of pilots and N_s is the number of subcarriers. In our system, since the bandwidth is fixed, we can use a common parameter N_{PRB}, where N_{PRB} is the number of physical resource blocks to represent all three parameters, as show in Table 2.

In Fig. 12, we find that LS algorithm shows the lowest complexity, and 2-D wiener filter shows the highest complexity. MLE scheme is less complex than 2×(1-D) wiener filter when the number of PRBs is larger than 15. Also, we can see that both of two proposed combining schemes have higher complexity than MLE scheme with any number of PRBs.

However, our two proposed strategies have much lower complexity than 2-D wiener filter and 2×(1-D) wiener filter schemes when the number of PRBs is larger than 20 and 30, respectively.

Table 1. Analysis of computational complexity for various channel estimation scenarios.

Channel Estimation methods	The number of CMs in each slot
1-D LS Interpolation	$9N_s$
MLE	$4L\left[\frac{N_p}{2}(L+1)+N_s+\frac{L^2}{2}\right]+7N_s$
MLE + Time Wiener Filter	$4L\left[\frac{N_p}{2}(L+1)+N_s+\frac{L^2}{2}\right]+68N_s$
Time Wiener Filter + MLE	$7L\left[L^2+2LN_p+(2N_p+N_s)\right]+23N_p$
2×(1-D) Wiener Filter	$N_p\left[\left(\frac{N_p}{2}\right)^2+(N_s+1)\frac{N_p}{2}+2N_s\right]+68N_s$
2-D Wiener Filter	$N_p\left[N_p^2+3N_p+(28+N_p)N_s\right]$

Table 2. Analysis of computational complexity in 3GPP LTE downlink.

Channel Estimation methods	The number of CMs in each slot
1-D LS Interpolation	$108N_{PRB}$
MLE	$14436N_{PRB}+118638$
MLE + Time Wiener Filter	$15168N_{PRB}+118638$
Time Wiener Filter + MLE	$90728N_{PRB}+415233$
2×(1-D) Wiener Filter	$16N_{PRB}^3+200N_{PRB}^2+816N_{PRB}$
2-D Wiener Filter	$256N_{PRB}^3+1392N_{PRB}^2$

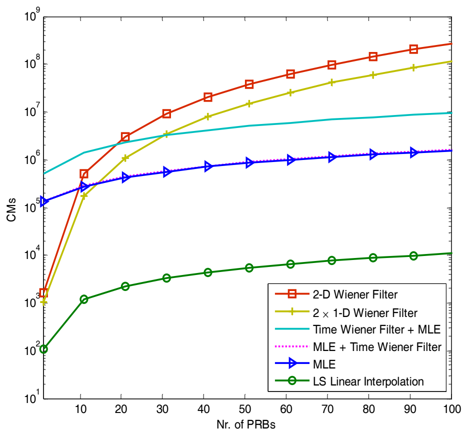

Fig. 12. Computational complexity comparison between various channel estimation techniques

V. Simulation Results

5.1 Simulation Environment

In this paper, 10 MHz bandwidth is used from 3GPP LTE specification and other parameters are listed as follows: an FFT size of 1024, the number of reference signals is 200 in one slot, CP length is 73 and modulation scheme is QPSK. We assume perfect synchronization in the system and the channel model is the ITU-R M.1225 vehicular channel model A as shown in [12].

5.2 BER Performance Evaluation and Comparison

Fig. 13 compares the BER performance of all channel estimation algorithms in this paper with linear ZF equalizer. It is obvious that the best performance is achieved by using '2-D winer filter', and 'LS estimation' gives the worst performance. Because only a few number of reference signals are inserted in each PRB, the correlation only in time or frequency direction is not good at all, and '2×(1-D) wiener filter' shows a serious performance degradation and just a little complexity reduction comparing with '2-D wiener filter' scheme. 'MLE

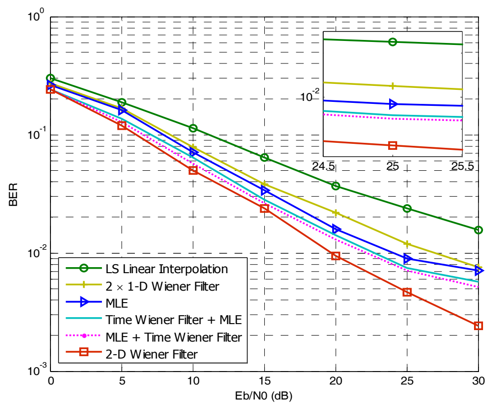

Fig. 13. Performance of channel estimation methods with ZF equalizer

scheme' has a lower computational complexity and shows a better performance than '2×(1-D) wiener filter', but still about 4 dB worse than '2-D wiener filter' at BER of 10^{-2}. Our proposed new strategies have nearly the same performance, and they are both about 1.5 dB better than 'MLE scheme' when the BER is 10^{-2}. By comparing the first step estimator of two proposed strategies, MLE is more accurate than separated wiener filter in Fig. 13, and in frequency direction, there are two reference signals, but there is only one reference signal in time direction, so the first estimator in strategy 2 is more accurate than that in strategy 1. So the performance of our first strategy 'Time wiener filter + MLE' is a little worse than the second strategy 'MLE + Time wiener filter'.

In Fig. 14, we compare the BER performance of the channel estimation algorithms of two combining methods with linear ZF equalizer and nonlinear DFE. We have known that '2-D wiener filter & ZF equalizer' is the optimal method in our system from Fig. 13. So we will compare the channel estimation techniques of our two strategies by using DFE with '2-D wiener filter & ZF equalizer'. From the magnified figure, we can see that both of two combining strategies, 'Time wiener filter + MLE & DFE' and 'MLE + Time wiener filter & DFE', perform slightly better than ZF equalizer, since nonlinear equalizer DFE can mitigation ICI

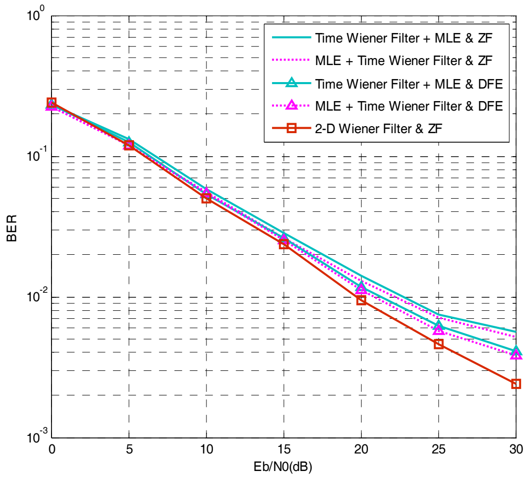

Fig. 14. BER comparison for linear ZF equalizer and nonlinear DFE

efficiently in the fading channel. Also the performance of 'MLE + Time wiener filter & DFE' is a little better than 'Time wiener filter + MLE & DFE'.

Ⅵ. Conclusions

Some fundamental channel estimation techniques and two novel schemes have been performed and compared by considering the BER performance and computational complexity for 3GPP LTE Downlink in this paper.

In the practical implementation, to achieve a better performance but with low computational complexity is very important. Therefore, we tried to estimate channel by combining time-dimension wiener filter with maximum likelihood estimator in different orders. Due to the specific pilot position in the system, the proposed strategy 2 shows a slight better performance than proposed strategy 1. Then we applied linear and nonlinear equalization techniques to the two proposed channel estimation schemes. The results show that nonlinear equalizer performs slightly better than linear equalizer due to ICI mitigation. Based on the BER performance and computational complexity analysis, we can realize that the 2-D wiener filter outperforms all the other algorithms but requires huge computational complexity. In contrast, the proposed channel estimation strategies can achieve good balances between performance and complexity for practical implementation.

References

〔1〕 Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Physical Layer–General Description, 3GPP Std. TS 36.201. Release 8, March 2009.

〔2〕 J. Beek, O. Edfors, M. Sandell, S. K. Wilson, and P. O. Börjesson, "On channel estimation in OFDM systems," in *Proc. of IEEE 45th Vehicular Technology Conference*, July 1995, pp.815-819.

〔3〕 Y. Qin, B. Hui, and K. H. Chang,

"Performance evaluation of pilot-based channel estimation and equalization techniques in 3GPP LTE downlink," in *Proc. of KICS Summer Conference*, November 2009.

〔4〕 R. Nee and R. Prasad. OFDM for Wireless Multimedia Communications, Ch.5, Boston London: Artech House Publishers, 2000.

〔5〕 P. Hoeher, S. Kaiser, and P. Robertson, "Pilot symbol aided channel estimation in time and frequency," in *Proc. of Communication Theory Mini-Conference within IEEE Global Telecommunications Conference*, November 1997, pp.90-96.

〔6〕 M. Morelli and U. Mengali, "A comparison of pilot-aided channel estimation methods for OFDM systems," *IEEE Transactions on Signal Processing*, Vol.49, No.12, pp.3065-3073, December 2001.

〔7〕 I. Ivan and B. Muquet, "Reduced complexity decision feedback equalizer for supporting high mobility in Wimax," in *Proc. of IEEE Vehicular Technology Conference*, April 2009, 7E-5.

〔8〕 X. Cai and G. B. Giannakis, "Bounding performance and suppressing intercarrier interference in wireless mobile OFDM," *IEEE Transactions on Communications*, Vol. 51, No.12, December 2003.

〔9〕 A. R. Varma, C. R. N. Athaudage, L. L. H. Andrew, and J. H. Manton, "Optimal superimposed pilot selection for OFDM channel estimation," in *Proc. of IEEE 7th Workshop on Signal Processing Advances in Wireless Communications*, Vol., No., July 2006, pp.1-5.

〔10〕 W. Jiang and W. Weiling, "A comparative study of robust channel estimators for OFDM systems," in *Proc. of International Conference on Communication Technology*, April 2003, pp. 1932-1935.

〔11〕 C. Shaoping, D. Guangfa, and T. Hongwen, "Low complexity DFE for OFDM systems over time-varying channels," *IEEE Transactions on Consumer Electronics*, Vol.53, No.2, pp.289-293, May 2007.

〔12〕 O. Edfors and M. Sandell, "A comparative study of pilot-based channel estimators for wireless OFDM," Research Report TULEA, September 1996.

칭 양 (Yang Qin) 준회원

2008년 7월 중국 정주대학교 정보통신공학과(공학사)
2008년 9월~현재 인하대학교 정보통신 대학원 석사과정
<관심분야> OFDM / MIMO Systems, Channel estimation and equalization algorithms, 3GPP LTE

휘 빙 (Bing Hui) 정회원

2005년 7월 중국 동북대학교 정보통신공학과(공학사)
2009년 8월 인하대학교 정보통신 대학원(공학석사)
2009년 9월~현재 인하대학교 정보통신 대학원 박사과정
<관심분야> OFDM / MIMO Systems, MIMO Detection algorithm, WiMAX, 3GPP LTE

장 경 희 (KyungHi Chang) 종신회원

1985년 2월 연세대학교 전자공학과(공학사)
1987년 2월 연세대학교 전자공학과 (공학석사)
1992년 8월 Texas A & M Univ., EE Dept. (Ph.D.)
1989년~1990년 삼성종합기술원 주임연구원
1992년~2003년 한국전자통신연구원, 이동통신연구소 무선전송방식연구팀장 (책임연구원)
2003년~현재 인하대학교 정보통신대학원 교수
<관심분야> 4세대 이동통신 및 3GPP LTE 무선전송방식, WMAN 및 DMB 시스템 무선전송기술, Cognitive Radio, Cross-layer Design, Cooperative Relaying System, RFID / USN Systems, Mobile Ad-hoc Network, 해상/수중 통신 등