A Low Complexity ICI Cancellation Method for High Mobility OFDM Systems

Kwanghoon Kim and Hyuncheol Park
School of Engineering
Information and Communications University (ICU)
119 Munjiro, Yuseong-gu, Daejeon, 305-714, KOREA
E-mail :{hoon0217 and hpark}@icu.ac.kr

***Abstract*— Orthogonal frequency division multiplexing (OFDM) can significantly reduce a receiver complexity using one-tap frequency domain equalizer in a frequency-selective fading channel. However, the channel variation due to high mobility gives a time-selectivity in one OFDM symbol. As a result, each OFDM subcarrier experiences inter-carrier interference (ICI) that makes the equalization process very complicate. We propose a low complexity ICI cancellation method that takes advantage of the ICI power distribution. Instead of computing the inversion of the whole channel frequency response (CFR) matrix, we split the matrix into several small sub-matrices that contain significant channel information and perform a linear minimum mean squared error (LMMSE) equalization. We also propose an efficient successive interference cancellation (SIC) method that can effectively utilize a time diversity resulting from the mobility. Simulation results show that the performance improvements is remarkable even though the sub-matrix size is much smaller than that of the whole CFR matrix while taking high computational efficiency.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) has the most promise as a future high data rate wireless communication system due to its advantage of high-bit-rate transmission over a frequency-selective fading channel [1]. However, a next generation wireless communication systems require high mobility that makes the channel significantly different in single OFDM symbol. This introduces a time-selectivity as well as frequency selectivity to the fading channel, resulting in doubly selective channel. In this environment, the OFDM-based system loses its strength since the symbol period is extended. As the mobility introduces the Doppler spread, the orthogonality between each sub-channel is destroyed [2] [3]. This is called inter-carrier (or channel) interference (ICI), the main challenge of future high mobility OFDM systems.

Compensating for the effect of ICI, there are many literatures to cancel and equalize the ICI with low complexity [4]-[6]. In [4], they introduce several high performance equalization methods including the linear minimum mean square error (LMMSE) method with successive interference cancellation for doubly selective Rayleigh fading channel. However, it requires very high computational complexity over $\mathcal{O}(N^3)$ causing impractical to implement for large number of subcarrier N. As an effort of reducing the complexity, Cai *et al.* [6] analyze the generating mechanism and power distribution of ICI, and propose the low complexity LMMSE equalization method. They use the idea that actual ICI power is concentrated in several neighboring subcarriers.

In this paper, we propose an efficient LMMSE equalizer utilizing this ICI distribution more effectively. We split the channel frequency response (CFR) matrix into relative small sub-matrices that contain most information about the channel gain and ICI effect. With these matrices, we perform the LMMSE equalization to detect each subcarrier data. Moreover, we propose an efficient SIC method that can dramatically improve the system performance. This method can be implemented with asymptotic complexity $\mathcal{O}(NlogN)$ as the number of subcarriers increases while achieving a remarkable performance improvement.

The rest of paper is organized as follows. The next section describes the basic model for high mobility OFDM systems. We introduce some previous works for ICI cancellation and propose a low complexity ICI cancellation method including SIC method in Section III. Section IV shows the simulation results that make sure the performance of our ICI-cancellation method. We conclude this paper in Section V.

II. System model

We consider an OFDM system depicted in Fig. 1 that consists of *N* subcarriers. After taking an inverse fast Fourier transformation (IFFT), the transmitted discrete time signal vector can be expressed as:

$$\mathbf{x} = \mathbf{F}_N^H \mathbf{s} \quad (1)$$

where $\mathbf{F}_N$ is N point discrete Fourier transformation (DFT) matrix and $(\cdot)^H$ represents the conjugate transpose (Hermitian). In order to avoid ICI and inter-symbol interference (ISI) caused by multipath environments, a cyclic prefix (CP) is appended to each OFDM symbol.

The discrete time channel impulse response (CIR) $h^t(l,m)$ that the OFDM signal undergoes in high mobility environment can be defined as the l-th received time response experienced at $(l-m)$-th transmitted impulse. After passing through this channel and removing the CP, the received discrete time signal vector can be represented by:

$$\mathbf{r} = \mathbf{h}\mathbf{x} + \mathbf{n}, \quad (2)$$

0-7803-9392-9/06/$20.00 (c) 2006 IEEE

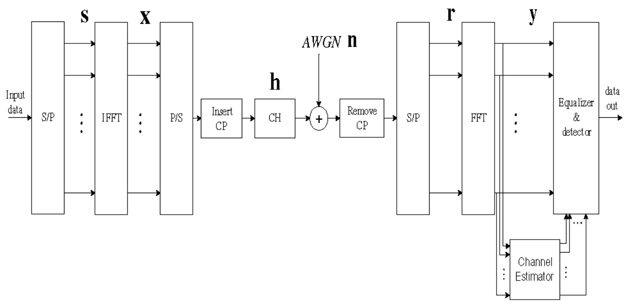

Fig. 1. Structure of base-band high mobility OFDM system

where $\mathbf{h}$ represents the $N \times N$ multipath convolution matrix whose component is:

$$h(l,m) = h^t(l,(l-m)_N), \tag{3}$$

and $\mathbf{n}$ is a vector of additive white gaussian noise (AWGN) with variance σ^2. The receiver then conventionally performs fast Fourier transform (FFT) that produces

$$\mathbf{y} = \mathbf{F}_N \mathbf{r}. \tag{4}$$

Using (1) and (2), this signal can be expressed as :

$$\begin{aligned} \mathbf{y} &= \mathbf{F}_N \mathbf{r} \\ &= \mathbf{F}_N(\mathbf{hx}+\mathbf{n}) \\ &= (\mathbf{F}_N \mathbf{h} \mathbf{F}_N^H)\mathbf{s} + \mathbf{F}_N \mathbf{n} \end{aligned} \tag{5}$$

Defining the CFR matrix $\mathbf{H}$:

$$\mathbf{H} \equiv (\mathbf{F}_N \mathbf{h} \mathbf{F}_N^H), \tag{6}$$

then, the received frequency domain signal can be written as:

$$\mathbf{y} = \mathbf{Hs} + \mathbf{w} \tag{7}$$

where $\mathbf{w}$ is a frequency domain AWGN vector. It is not hard to show that the components of $\mathbf{H}$, $H(d,k) \equiv H^f(d-k,k)$, where

$$H^f(d,k) = \frac{1}{N}\sum_{l=0}^{N-1}\sum_{m=0}^{N-1} h^t(l,m)e^{-j\frac{2\pi(mk+ld)}{N}}. \tag{8}$$

This frequency domain channel component can be interpreted as the channel gain of k-th subcarrier if $d=0$, and ICI contribution of k-th subcarrier on $(k+d)_N$-th subcarrier, otherwise. It is straightforward to confirm that if the channel is time-nonselective then $h^t(l,m)$ is constant over received discrete time l and off-diagonal components of $\mathbf{H}$, $H^f(d-k,k)$ for $d \neq k$ are zero and consequently the matrix $\mathbf{H}$ is diagonal. However, high mobility makes the channel time selective and the matrix may not be diagonal anymore.

III. ICI CANCELLATION METHOD

A. LMMSE equalizer

Classical LMMSE equalizer [9] for (7) is:

$$\mathbf{G}^H = \mathbf{H}^H(\mathbf{HH}^H + \sigma^2\mathbf{I}_N)^{-1}. \tag{9}$$

If the channel is time-nonselective, this equalizer only needs to compute the inversion of diagonal matrix since the off-diagonal coefficients of $\mathbf{H}$ are zero. In this case, the computational complexity is $\mathcal{O}(N)$ and this is the classical motivation for the use of OFDM. However, time-selective channel makes the matrix in (6) non-diagonal and the computation requires the inversion of $N \times N$ matrix with $\mathcal{O}(N^3)$ complexity resulting in impractical implements for a large N.

In [6], they show that effective subcarriers that contribute the ICI to specific subcarrier are actually much smaller than the number of subcarriers in one OFDM symbol. Using the fundamental observation, they use only partial information for generating LMMSE equalizer. If we want to detect transmitted k-th subcarrier data s_k, they use only partial received vector and channel matrix defined as:

$$\mathbf{y}_k \equiv \mathbf{y}[(k-D):(k+D)], \tag{10}$$

$$\mathbf{H}_k \equiv \mathbf{H}[(k-D):(k+D),:] \tag{11}$$

where $\mathbf{y}[n:m]$ represents the partial vector whose elements are consecutive from y_n to y_m and $\mathbf{H}[n:m,:]$ means the partial matrix that takes consecutive all row vector from n-th vector to m-th vector. In here, D is effective ICI depth that is defined as a half number of significant contributed subcarriers to ICI. With this partial matrix, the LMMSE equalizer for k-th subcarrier s_k is:

$$\bar{\mathbf{G}}^H[k,k-D:k+D] = \mathbf{H}_k^H[:,k](\mathbf{H}_k\mathbf{H}_k^H + N_0\mathbf{I})^{-1} \tag{12}$$

where $\mathbf{H}_k[:,k]$ is the k-th column vector of $\mathbf{H}_k$. However, this LMMSE equalizer has still $\mathcal{O}(N^2)$ complexity [6] since they do not utilize the ICI power distribution in channel matrix $\mathbf{H}$.

We propose an equalizer that takes advantage of ICI power distribution in $\mathbf{H}$. Since the number of effective subcarriers is much smaller than N, we assume that the channel coefficients $H^f(d,k)$ is almost negligible where d is large. Let D be the maximum d such that $H^f(d,k) \approx 0$ where $d \geq D$. We transform $\mathbf{H}$ to $\bar{\mathbf{H}}$ with following rule:

$$\begin{aligned} if \quad |(d-k)| &\leq D \ or\ |(d-k)| \geq N-D+1 \\ \bar{H}(d,k) &= H(d,k) \\ else & \\ \bar{H}(d,k) &= 0. \end{aligned} \tag{13}$$

This is equivalent to zero padding at corresponding $H^f(d,k)$ where $|d| > D$. The resulting modified CFR matrix $\bar{\mathbf{H}}$ has sparse structure like Fig. 2. Using the sparse structure of $\bar{\mathbf{H}}$, we reduce a size of the partial channel matrix from $(2D+1)\times N$ to $(2D+1)\times(4D+1)$ as Fig. 2. The remaining process of generating LMMSE equalizer using the partial CFR matrix is straightforward and resulting low complexity LMMSE equalizer for s_k is:

$$\begin{aligned} \mathbf{g}_k^H &= \bar{\mathbf{G}}_{prop.}^H[k,k-D:k+D] \\ &= \bar{\mathbf{H}}_k^H[:,k](\bar{\mathbf{H}}_k\bar{\mathbf{H}}_k^H + N_0\mathbf{I})^{-1}. \end{aligned} \tag{14}$$

Since we reduce the size of partial channel matrix, the computational complexity also can be reduced. Contrary to

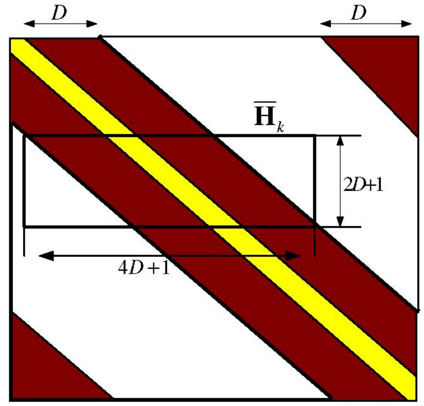

Fig. 2. Structure of modified channel matrix $\bar{\mathbf{H}}$ and proposed partial channel matrix $\bar{\mathbf{H}}_k$

previous method in [6], the size of partial matrix does not depend on the number of subcarrier N. As a result, the complexity of generating $\mathbf{g}_k^H$ is independent to N as N increases. As a result, the asymptotic complexity of proposed method is $\mathcal{O}(N)$.

B. Successive Interference Cancellation (SIC)

A SIC method is popular for the system that is distorted by a significant interference such as a multiple-antenna system [7] [8]. In [4], they adopt the SIC method to detect the signal for high mobility multi-carrier system. However, this method cannot be applied without modification to our low complexity LMMSE since they only consider the classical LMMSE method.

In [4], they use a post signal-to-interference-plus-noise ratio (SINR) criterion for deciding the detection order. However, the computation of the post-SINR is a large burden and almost impossible to apply our scheme since they require all LMMSE equalizer coefficients. Instead, the proposed SIC method first detects the subcarrier data s_k that has highest channel gain among the undetected data, that is, maximum diagonal coefficient of $\bar{\mathbf{H}}$. After equalizing s_k, we cancel the interference of s_k from received signal $\mathbf{y}$ as follows:

$$\mathbf{y}_{new} = \mathbf{y}_{previous} - \bar{\mathbf{H}}[:, k]\hat{s}_k. \tag{15}$$

The column $\bar{\mathbf{H}}[:, k]$ that contains the channel gain and ICI contribution of s_k is now replaced by $\mathbf{0}$ vector. This procedure continues until all subcarrier data are detected. The whole procedure is described in Table I.

Since our ordering criterion is just finding the largest diagonal coefficients of $\bar{\mathbf{H}}$ that is equivalent to sort the N items, the proposed SIC scheme only requires $\mathcal{O}(N log N)$ computational complexity that is much more efficient than that of [4] or [6].

IV. Simulations

We investigate the performance of the proposed low complexity LMMSE equalization over doubly selective channels. An OFDM system with symbols modulated by QPSK is used on multipath channel. The system bandwidth is 1MHz, which is divided into 64 tones with 16 time samples for cyclic prefix (CP) and the carrier frequency is 2.4GHz.

At first, we investigate the ICI power distributions of $\mathbf{H}$. We use exponential decaying power delay profiles whose maximum delay spread is sufficiently smaller than the length of CP for ignoring the effect of ISI. Also, we adopt the classical Jake's method [10] to implement the high-mobility fading channels. As we expect, the ICI power of $\mathbf{H}$ is very concentrated in a few neighboring subcarriers as shown in Fig. 3 even though the normalized Doppler frequency F_dT_s is 0.1 that exceeds the equivalent mobility of 300 km/h for IEEE 802.16e system [11].

Before demonstrating the performance of proposed method, we also show the performance bound when we adopt the various effective ICI depth D. This bound is called matched filter (MF) bound [6],[12] and can be obtained by transmitting only one subcarrier data for one OFDM symbol duration. Instead of calculating the theoretical bound, we show the MF bound using simulation when F_dT_s is 0.10667. Fig. 4 shows that the performance of MF bound at $D = N$ (full) is not much different to that of the case, $D = 2$. The result implies that we do not have to consider the case for large $D \gg 2$.

We compare the proposed method with the classical

TABLE I

Low complexity LMMSE procedure with SIC

Step	Process
1	$k = \arg\max_i\{\bar{H}(i,i)\}$
2	$\hat{s}_k = hard\ decision\{\mathbf{g}_k^H \mathbf{y}_k\}$
3	$\mathbf{y}_{new} = \mathbf{y}_{previous} - \bar{\mathbf{H}}[:, k]\hat{s}_k$
4	$\bar{\mathbf{H}}[:, k] = \mathbf{0}$
5	$if\ \bar{\mathbf{H}} = \mathbf{0}, stop.\ Else\ go\ 1.$

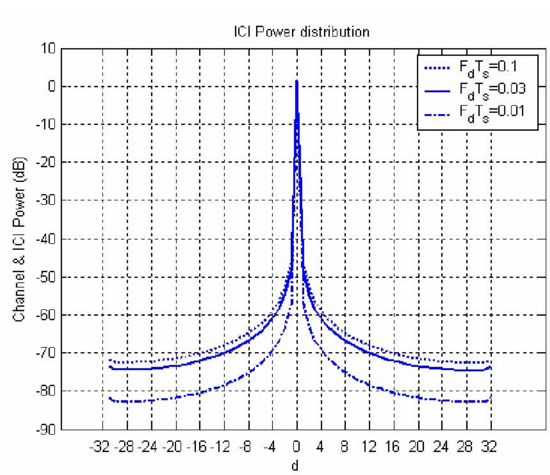

Fig. 3. ICI Power distribution of various F_dT_s

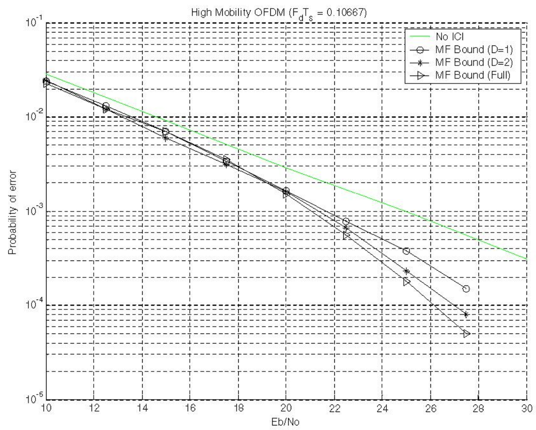

Fig. 4. Performance of MF bound for various effective ICI depth D, F_dT_s = 0.10667

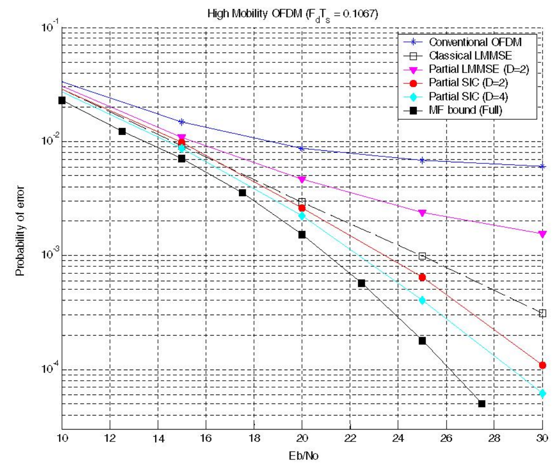

Fig. 6. Performance of the proposed method, F_dT_s = 0.10667

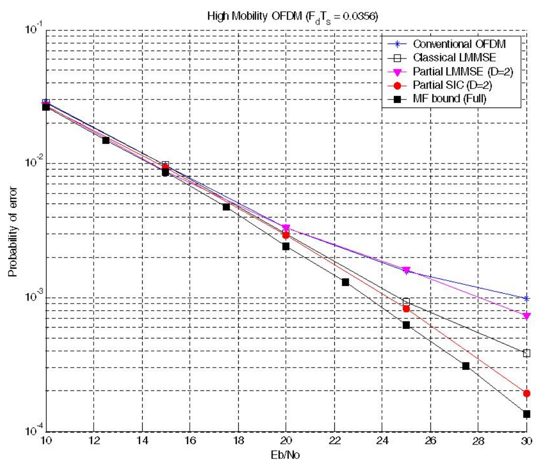

Fig. 5. Performance of the proposed method, F_dT_s = 0.0356

LMMSE method when F_dT_s is 0.0356 and 0.10667 in Fig. 5 and Fig. 6, respectively. Fig. 5 shows that the low complexity LMMSE method without SIC (Partial LMMSE) does not give remarkable performance improvement. However, the method with SIC (Partial SIC) can achieve higher performance than that of classical LMMSE method and can have almost similar performance to that of MF bound in high E_b/N_0 region, because of the time diversity. These phenomena are similar when the mobility increases as shown in Fig. 6. In this case, the proposed method without SIC can gives more performance improvement. Of course, we can achieve higher performance according to larger D.

V. Conclusions

We investigate the channel equalization method for OFDM systems in doubly selective fading channel. Proposed low complexity LMMSE equalization method can reduce the computational complexity of classical LMMSE method significantly. This method can be enhanced with the aid of SIC method that can utilize a time diversity induced by the high mobility. With proper simplification rule, the performance improvement with mobility at F_dT_s = 0.10667 equivalent to 300km/h for IEEE 802.16e system is remarkable even when D = 2. Actually, D is only dependent on F_dT_s. Thus the proposed method has advantages both in performance and complexity for wideband multimedia OFDM systems that adopt large number of subcarrier, N.

Acknowledgments

This research was supported by the MIC (Ministry of Information and Communication), Korea, under the ITRC (Information Technology Research Center) support program supervised by the IITA (Institute of Information Technology Assessment)

References

[1] S. Weinstein and P. Ebert, "Data transmission by frequency-division multiplexing using the discrete Fourier transform," *IEEE Transaction on Communications*, vol. 19, pp. 628-634, Oct. 1971.

[2] M. Russell and G. Stuber, "Interchannel interference analysis of OFDM in a mobile environment," *Proc. VTC 95*, pp. 820-824, 1995.

[3] P. Robertson and S. Kaiser, "The effects of Doppler spreads in OFDM(A) mobile radio systems," *Proc. VTC 99Fall*, pp. 329-333, 1999.

[4] Y.S. Choi, P. J. Voltz, and F. A. Cassara, "On channel estimation and detection for multicarrier signals in fast and selective Rayleigh fading channels," *IEEE Transaction on Communications*, vol. 49, pp. 1375-1387, Aug. 2001.

[5] S. Chen, T. Yao, "Low complexity ICI cancellation for OFDM systems in doubly-selective fading channel," *IEEE International Conference on Communications*," vol. 5, pp. 2535 - 2538, June 2004.

[6] X. Cai, G. B. Giannakis, "Bounding performance and suppressing intercarrier interference in wireless mobile OFDM," *IEEE Transaction on Communications*, vol. 51, pp.2047-2056, no.12, Dec. 2003.

[7] G. Wang, D. Wang, and D. Li, "An efficient ZF-SIC detection algorithm in MIMO CDMA system," *Proc. IEEE PIMRC*, pp. 1708-1711, 2003.

[8] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, "V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel," *Proc. IEEE ISSSE-98*, pp. 295-300, Sep. 1998.

[9] L. L. Scharf, *Statistical Signal Processing*, U.S.A, Addison-Wesley Publishing Company, 1991.

[10] W.C. Jakes, *Microwave Mobile Communications*, New York, Wiley, 1974.

[11] IEEE 802.16 TGe Working Document, (Draft Standard) - Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands, 802.16e/D4, Aug. 2004.
[12] F.Ling, "Mateched filter-bound for time-discrete multipath Rayleigh fading channels," *IEEE Transaction on Communications*, vol. 43, pp.710-713, no.2/3/4, Feb./Mar./Apr. 1995.