A Comparison of New and Previous Methods of ICI Canceller for Mobile OFDM Receivers

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Abstract—**While OFDM achieves a high spectral efficiency by using multiple orthogonal sub-carriers, it is sensitive to frequency offset. Especially, for OFDM mobile receivers, Doppler effect causes frequency offset. Consequently, inter-carrier interference (ICI) occurs and results in a serious degradation of received signal. In this paper, we implement a combination of Linear MMSE (LMMSE) channel estimation and ICI canceller in a simple manner. By using output from ICI canceller, we implement LMMSE without knowledge of statistical characteristic of channel. This method can achieve a slightly better performance than an iterative ICI canceller that we proposed in [1]. In addition, we implement a combination of 2D channel estimation and ICI canceller to deal with serious channel conditions in which high delay and high Doppler happen simultaneously.**

Keywords—OFDM, ICI, LMMSE

I. INTRODUCTION

OFDM utilized a large number of orthogonal subcarrier to achieve high-spectral efficiency. The long duration symbol and guard interval protect useful part of OFDM symbols from inter-symbol-interference (ISI). Guard interval (GI) is implemented by cyclic prefix (CP). This scheme keeps OFDM symbols smoothly in time domain, and reduces out of band power of OFDM. Moreover, cyclic prefix keeps convolution of channel and OFDM symbol is circular convolution. However, in mobile environment, GI or CP could not avoid Doppler-effect. Doppler-effect spreads energy of one subcarrier to many other subcarriers. This is called ICI. On other word, in time-varying channel, the orthogonality among subcarriers is lost. Thus performance is degraded severely.

Many researches are conducted to deal with ICI caused by Doppler. In [2] and [3], an efficient approach is to linearly approximate time-varying channel within one OFDM symbol. Then we should solve a large ICI matrix equation. In [4], a method is proposed to solve the large ICI matrix equation. As most ICI power concentrated near the diagonal of ICI matrix, [4] considered D lines that are closest to the diagonal. Instead finding invert of $N \times N$ matrix, [3] find invert of N matrix of order $(2D+1) \times (2D+1)$. This still requires heavy computation. In addition, As pilot symbols are suffered ICI, the estimated values of the diagonal also is corrupted by ICI. In addition, the diagonal is the most important element. Therefore, performance of [2], [3] is limited, even we solve the full ICI matrix equation exactly. In order to deal with these problems, we proposed an iterative ICI canceller as in [1]. By using Jacobi iteration method, we solve the ICI matrix equation without calculating inverse matrix. Moreover, at 2nd iteration, ICI is removed from pilot symbol and channel is re-estimated. As a result, the performance is improved significantly.

However, the iterative ICI canceller needs to re-estimate channel. This increases latency of OFDM mobile receivers. So, in this paper we combine LMMSE channel estimation and ICI canceller. Because LMMSE is robust to random noise and ICI impact in frequency domain, it can estimate channel accurately without re-estimating as the iterative ICI canceller does. Furthermore, the auto-correlation in frequency domain is measured from ICI output. Thereby, LMMSE can be implemented without statistical knowledge of channel. In addition, to deal with serious channel in which channel suffer high delay and high Doppler simultaneously, we implement a combination of 2D channel estimation and ICI canceller. The 2D channel estimation ensures that channel can be estimated even high delay and high Doppler occurs simultaneously.

The rest of paper is organized as follows: Section II reviews ICI canceller. Section III describes the combination of LMMSE channel estimation and ICI canceller. In section IV, we implement the combination of the 2D channel estimation and ICI canceller. Simulation results are shown in section V. Finally, section VI shows conclusion.

II. REVIEW OF ICI CANCELLER

First, in this section, we present the derivation of ICI equation, and how to solve this equation. As in [2], the received signal in frequency domain can be written as follows:

$$Y(k) = X(k).H_{k,k} + \underbrace{\sum_{l=0,l\#k}^{N-1} X(l).H_{k,l}}_{ICI} + W(k) \tag{1}$$

$$H_{k,l} = \frac{1}{N}\sum_{n=0}^{N-1}\sum_{m=0}^{N-1} h(m,n).e^{-j\frac{2\pi lm}{N}}.e^{-j\frac{2\pi}{N}n(k-l)} \tag{2}$$

$$\begin{bmatrix} Y(0) \\ Y(1) \\ \vdots \\ Y(N-2) \\ Y(N-1) \end{bmatrix} = \overbrace{\begin{bmatrix} H_{0,0} & \Phi_{-1}\overline{V_1'} & \cdots & \Phi_{-N+2}\overline{V_{N-2}}' & \Phi_{-N+1}\overline{V_{N-1}}' \\ \Phi_1\overline{V_0'} & H_{1,1} & \cdots & \Phi_{-N+3}\overline{V_{N-2}} & \Phi_{-N+2}\overline{V_{N-1}}' \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \Phi_{N-2}\overline{V_0'} & \Phi_{N-3}\overline{V_1'} & \cdots & H_{N-2,N-2} & \Phi_{-1}\overline{V_{N-1}}' \\ \Phi_{N-1}\overline{V_0'} & \Phi_{N-2}\overline{V_1'} & \cdots & \Phi_1\overline{V_{N-2}}' & H_{N-1,N-1} \end{bmatrix}}^{ICI\ Matrix\ [H]} \times \begin{bmatrix} X(0) \\ X(1) \\ \vdots \\ X(N-2) \\ X(N-1) \end{bmatrix} + \begin{bmatrix} W(0) \\ W(1) \\ \vdots \\ W(N-2) \\ W(N-1) \end{bmatrix} \tag{3}$$

Where $X(k)$ and $Y(k)$ is transmitted and received signal respectively. l, and k are subcarrier indexes. $h(m,n)$ is channel impulse response of path m at instant time n. N is number of subcarrier. W denotes random noise.

$V_l(n)$ denotes Fourier Transform of channel impulse response $h(m,n)$ at n instant time. In [2] and [3], by approximating $V_l(n)$ or channel impulse response $h(m,n)$ as a linear function within an OFDM, the ICI equation is defined as (4). For more detail about the linear approximation of time varying channel, please refer to [2] and [3].

$$V_l(n) = \sum_{m=0}^{N-1} h(m,n) e^{-j\frac{2\pi}{N}lm} \tag{4}$$

Where

$$\Phi_\Delta = \frac{1}{e^{j\frac{2\pi}{N}\Delta} - 1} \tag{5}$$

$$\overline{V_l}' = \frac{H_{l,l}^{(next\ symbol)} - H_{l,l}^{(pre\ symbol)}}{2N_s} \tag{6}$$

From (3), in order to recover the transmitted signal $X(k)$, we have to estimate the ICI matrix $[H]$ and solve a big ICI matrix equation. In [1], we proposed an iterative method in which we solved the big ICI matrix in a simple manner without calculating an inverse of $[H]$. Moreover, we removed ICI from pilot symbols and then re-estimated channel at 2nd iteration. As a result, we achieved a significant improvement. In the next section, we will present a combination of LMSSE and ICI canceller.

III. A COMBINATION OF LMMSE CHANNEL ESTIMATION AND ICI CANCELLER

While LMMSE is robust to random noise, it requires statistical knowledge such as the auto-correlation of channel in frequency domain and time domain. In fact, we do not know exactly the auto-correlation of channel. By assuming that power delay profile is an exponential function or rectangular function as in [5], then the auto-correlation in the frequency domain can be determined. However, this method will not work well because the mismatch between assumed channel model and the real channel. In this paper, we measure the auto-correlation in frequency domain using output of ICI canceller The detailed steps are presented as follow.

First, as shown in Fig. 1, channel transfer function at sub-carrier m is given by

$$\widehat{H}(m) = C_1.\widehat{H}(P_1) + C_2.\widehat{H}(P_2) + C_3.\widehat{H}(P_3) + C_4.\widehat{H}(P_4) \tag{7}$$

$$e(m) = \left|H(m) - \widehat{H}(m)\right|^2 \tag{8}$$

Where $\widehat{H}(P)$ is the channel transfer function at pilot position, and $\widehat{H}(m)$ is the estimated channel at m^{th} subcarrier. We should find the coefficient C so that the error e is minimized. According to LMMSE principle, e should be orthogonal with the space vector formed by $[C_1\ C_2\ C_3\ C_4]$. Thus, the coefficients are found as

$$\begin{aligned} &[C_1(m) \quad C_2(m) \quad C_3(m) \quad C_4(m)] \\ &= \frac{[R(m-P_1) \quad R(m-P_2) \quad R(m-P_3) \quad R(m-P_4)]}{\begin{bmatrix} \mathrm{R}(0) & \mathrm{R}(-12) & \mathrm{R}(-24) & \mathrm{R}(-36) \\ \mathrm{R}(12) & \mathrm{R}(0) & \mathrm{R}(-12) & \mathrm{R}(-24) \\ \mathrm{R}(24) & \mathrm{R}(12) & \mathrm{R}(0) & \mathrm{R}(-12) \\ \mathrm{R}(36) & \mathrm{R}(24) & \mathrm{R}(12) & \mathrm{R}(0) \end{bmatrix} + \sigma^2 I} \end{aligned} \tag{9}$$

$$\mathrm{R_{HH}} = \begin{bmatrix} \mathrm{R}(0) & \mathrm{R}(-12) & \mathrm{R}(-24) & \mathrm{R}(-36) \\ \mathrm{R}(12) & \mathrm{R}(0) & \mathrm{R}(-12) & \mathrm{R}(-24) \\ \mathrm{R}(24) & \mathrm{R}(12) & \mathrm{R}(0) & \mathrm{R}(-12) \\ \mathrm{R}(36) & \mathrm{R}(24) & \mathrm{R}(12) & \mathrm{R}(0) \end{bmatrix} \tag{10}$$

Second, in order to find the coefficients we should calculate the auto-correlation $R(\Delta f)$. From definition of auto-correlation,

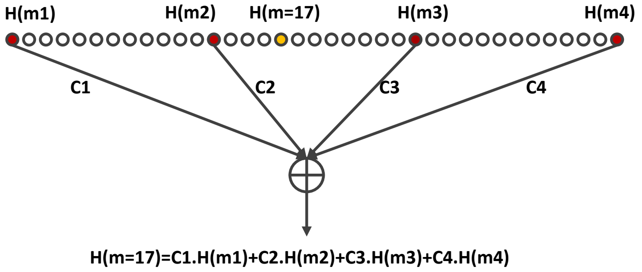

Fig. 1 LMMSE channel estimation

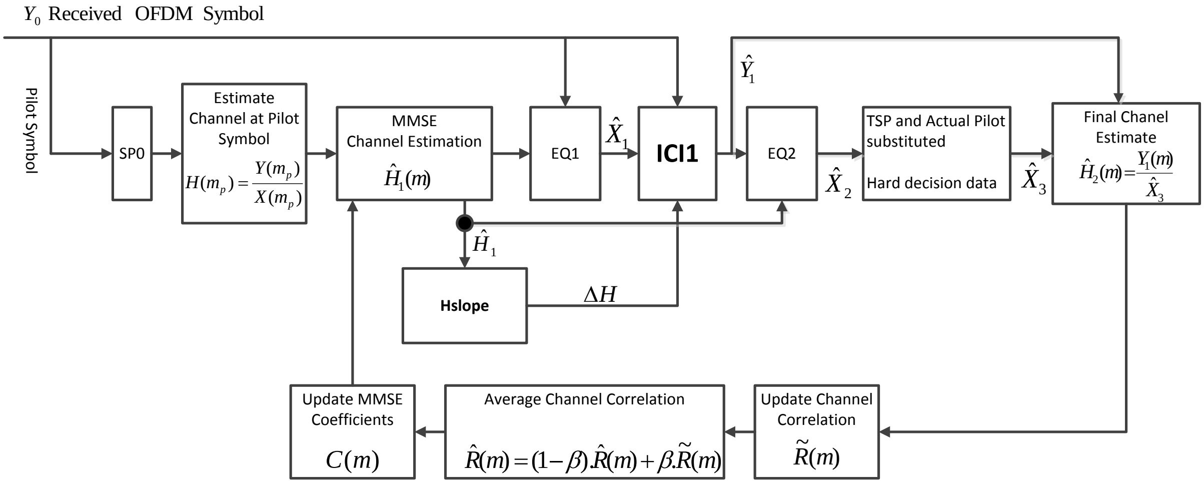

Fig. 2 Combination of LMMSE channel estimation and ICI canceller

$$R(\mathrm{m}) = E[H(k)^*H(k+m)] = \frac{1}{K}\sum_{k=0}^{N-1} H(k)^*.H(k+m) \tag{11}$$

Where N is the total number of subcarriers. As equation, a estimation of the auto-correlation as given as

$$\hat{R}(m) = \frac{1}{K}\sum_{k=0}^{N-1} \hat{H}(k)^*.\hat{H}(k+m) \tag{12}$$

Where $\hat{H}(k)$ is the estimated channel transfer function at k^{th} subcarrier.

Third, (12) is used to calculate the initial value of the auto-correlation. Then, after a new OFDM arrive the receiver, we have new information about the real channel. So we use output of ICI canceller to update the auto-correlation function as follow

$$\hat{R}(m) = (1-\beta).\hat{R}(m) + \beta.\breve{R}(m) \tag{13}$$

Where $\breve{R}(m)$ is calculated from the current OFDM symbol using output of ICI canceller. The factor β can be interpreted as a memory factor that adjust the correlation function R at each iteration. When a new OFDM symbol comes, we have new information about channel that is a random process in both frequency and time domain. The new information is $\breve{R}(m)$. So we use the new information to update the correlation function $\hat{R}(m)$. The more OFDM symbol come, the more accurate the auto-correlation is. The β factor can be defined exactly as in [6]. However, it requires the complicated computation. In this case, we set $\beta = 1/8$. For more detail about β, please refer to [6].

IV. AN IMPLEMENTATION OF 2D CHANNEL ESTIMATION AND ICI CANCELLER

As we know, the 1D interpolation that consists of 1D carrier interpolation and 1D time interpolation can estimate channel as long as number of pilots fulfill Nyquist law. Otherwise, it fails to estimate channel. For example, if the transfer function changes faster than a haft of sampling speed of pilots in frequency domain, 1D carrier interpolation is not available to estimate the transfer function. Similarity, in time domain, if channel changes faster than sampling speed of pilots, 1D time interpolations will fail to estimate channel. Therefore, in order to estimate in serious channel conditions in which high delay and high Doppler happen simultaneously, we implement a 2D channel estimation.

The process of 2D channel estimation is shown in Fig. 3. To estimate channel transfer function for an OFDM symbol we use 20 OFDM symbols. It is noted that there are three zeros points between two pilots in the frequency domain, so after FFT, we receive four copied versions of the Delay-Doppler Profile that provide information of both Doppler profile and Delay profile. We should choose one of these copied versions and remove three others. Then, we convert the chosen copied version to obtain channel transfer function.

Basically, in 2D interpolation, channel is measured by pilots from 20 OFDM symbols instead of from 1 OFDM symbol as in the case of 1D carrier interpolation. Additionally, pilots are scattered. As a result, 2D interpolation has more samples to interpolate channel than the case of 1D carrier interpolation or 1D time interpolation. For example, assuming that channel is not changing in time domain, scattered pilots from 20 OFDM symbols measure channel at all sub-carrier. Thereby, in this case, 2D interpolation can estimate exactly the transfer function. In contrast, with 1D carrier interpolation, the distance between two pilots is 12. Consequently, it is not available to estimate channel transfer function that changes faster than 1/24.

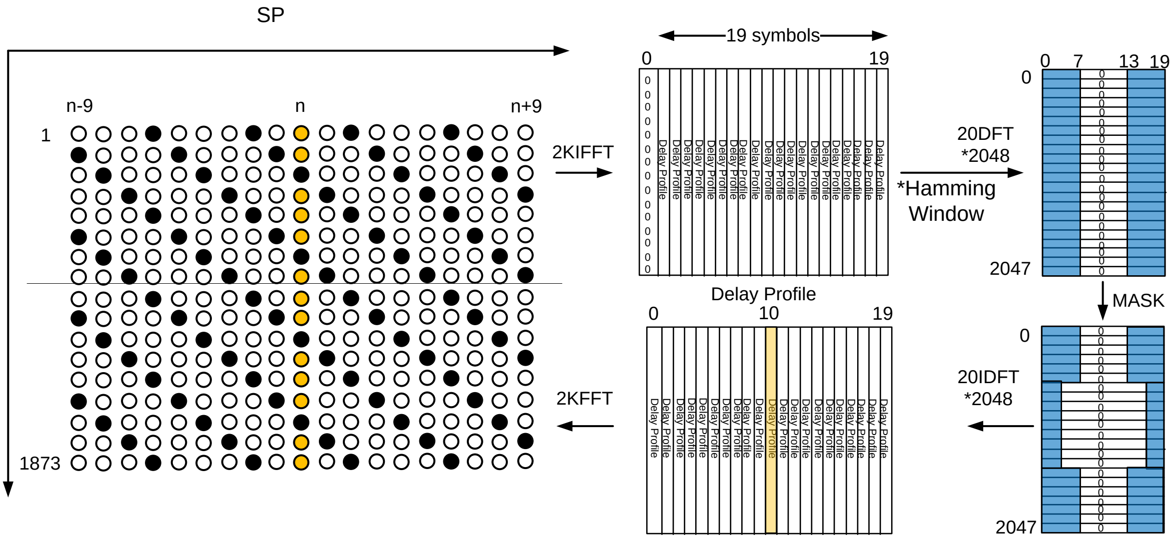

Fig. 3 Implementation of 2D channel estimation

In the next section, we will compare 1D separated iteration with 2D interpolation by simulation. After channel is estimated by 2D interpolation, ICI is implemented as previous method in [1], [2] and [3].

V. SIMULATION RESULT

In this section, we evaluate performance the combination of ICI canceller and LMMSE channel estimation, and a combination of 2D channel estimation and ICI canceller. The parameters of OFDM system are set as ISDB-T mode 3, and these parameters are shown in table I. Different channel conditions are shown in table II and III.

TABLE I. ISDB-T MODE 3 PAREMETERS

Parameters	Values
FFT size	8192
Number of sub-carrier	5617
Carrier interval	992.06 (Hz)
Effective Sym. Duration	1008μs
Guard interval	126 μs
Modulation	64QAM

TABLE II. TU-6 CHANNEL

Tap number	Delay (μs)	Power (dB)	Doppler Spread (Hz)
1	0.0	-3.0	[0 200]
2	0.2	0.0	[0 200]
3	0.5	-2.0	[0 200]
4	1.6	-6.0	[0 200]
5	2.3	-8.0	[0 200]
6	5.0	-10.0	[0 200]

TABLE III. TWO PATHS DOPPLER CHANNEL

Tap number	Delay (μs)	Power (dB)	Doppler Spread (Hz)
1	0.0	0.0	[0 200]
2	12.3	-3.0	[0 200]

A. *Comparison of the iterative ICI cancelelr and the combination of LMMSE channel estimation and ICI cancelelr*

This section investigates performance of the combination of ICI canceller and LMMSE channel estimation. Actually, LMMSE can be implemented in both frequency domain and time domain, but in this section we implement only in frequency domain. As a result, this method will work well under channel conditions that suffer low relative delay.

Since LMMSE is robust to random noise and impact of ICI in frequency domain, the estimated channel accuracy is improved. As a result, the ICI cancellation is improved compared with ICI canceller using normal interpolation channel, or iterative ICI canceller at 1st iteration. Moreover, the combination of ICI and LMMSE channel estimation achieve a slightly better performance in compared with iterative ICI canceller at 2nd iteration. Fig. 4 and Fig. 5 show a comparison of iterative ICI canceller and the combination of ICI canceller with LMMSE channel estimation.

B. *Comparation ICI using 2D channel estimation and ICI using 1D channel estimation*

As mentioned in section 3.3, in the high delay or Doppler conditions, the separated 1D interpolation or LMMSE in the frequency domain does work well. Hence, it is needed to find a method that can estimate channel at such conditions. Simulation in Fig. 6 and Fig. 7 demonstrate that 2D interpolation can work better than 1D separated interpolation in both high delay and high Doppler conditions.

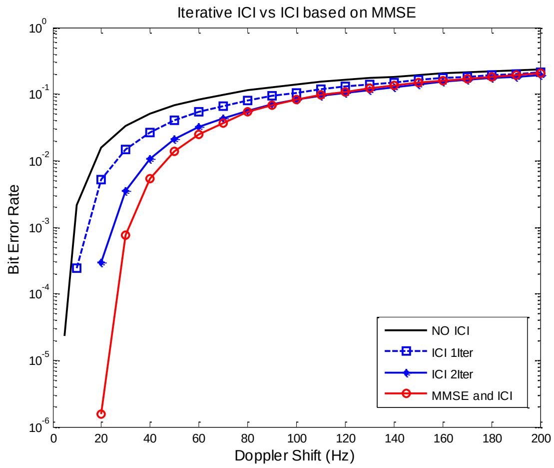

Fig. 4 Comparison of Iterative method and combination of LMMSE and ICI canceller with TU-6 channel

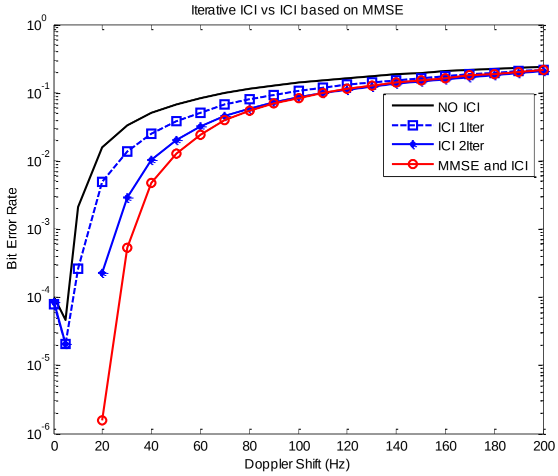

Fig. 5 Comparison of Iterative method and combination of LMMSE and ICI canceller with two paths channel

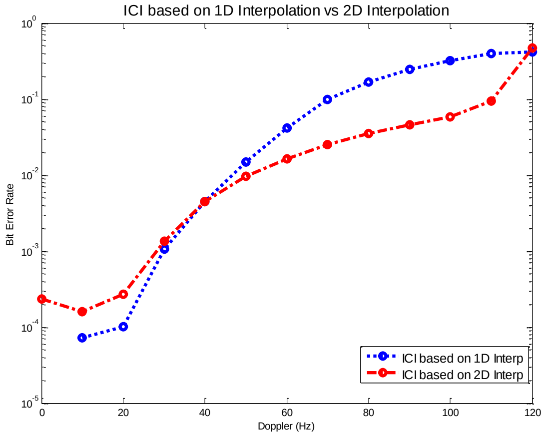

Fig. 6 Comparison of ICI canceller using 1D and 2D channel estimation

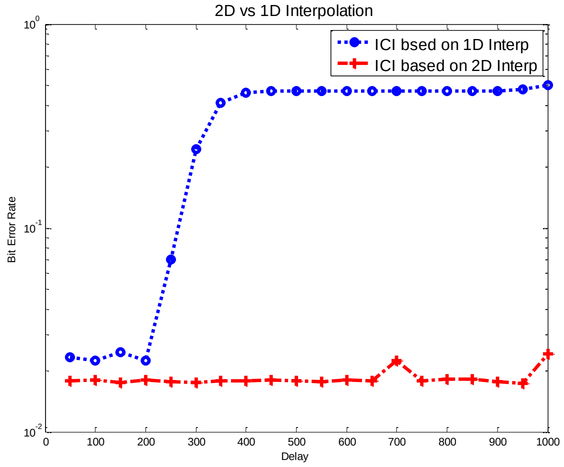

Fig. 7 Comparison of ICI canceller using 1D and 2D channel estimation

VI. CONCLUSION

In paper, we proposed a combination of ICI canceller and LMMSE channel estimation. In this method, by using output of ICI canceller, LMMSE can be implemented in a simple manner without requiring statistical knowledge of channel. The estimated channel that results from LLMSE is more accurate than the conventional interpolation channel estimation. As a result, the combination of LMMSE and ICI canceller achieved a better performance compared with the iterative method at 1st iteration, and achieved a slightly better performance compared with the iterative method at 2nd iteration. In addition, we implemented a 2D interpolation for channel estimation that can estimate serious channel in which high delay and high Doppler occurs simultaneously.

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