On ICI Canceller for Mobile OFDM DTV Receivers

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***Abstract*— In mobile environment, the performance of OFDM mobile receivers is degraded severely because of Inter-Carrier-Interference (ICI) caused by Doppler Spread. So ICI canceller is an important task for designers of mobile OFDM receivers. [1] and [2] proposed an efficient method to reduce ICI. The main idea of this method is to linearly approximate time varying channel within one OFDM symbol. Then a large ICI matrix equation is given. However, in [1] and [2], the estimated values of the channel transfer function—the diagonal of the ICI matrix is corrupted by ICI. Consequently, the equalized signal still is distorted. In this paper, we propose an iterative method to improve performance of the conventional method in [1] and [2]. We implement Jacobi iteration method to solve the big ICI matrix equation. Thereby, we are able to implement ICI canceller by a simple FIR filter rather than finding the inverse of ICI matrix. Next, at second iteration of Jacobi method, we improve the accuracy the diagonal by removing ICI from pilot symbols and re-estimating the channel transfer function. Simulation results for ISDB-T mode 3 demonstrated that our method could double performance of the conventional method under TU-6 channel and Doppler Spread. The improvement is better for two paths and one path Doppler channel.**

***Keyword*— Digital television (DTV), Inter-Carrier Interference (ICI), Jacobi Iteration, Orthogonal frequency-division multiplexing (OFDM).**

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 sub-carriers to many other subcarriers. This is called ICI. In 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 [1] and [2], an efficient approach is to linearly approximate time-varying channel within one OFDM symbol. Then we should solve a large ICI matrix equation. In [3], a method is proposed to solve the large ICI matrix equation. As most ICI power concentrates near the diagonal of ICI matrix, [3] considered D lines that are closest to the diagonal. Instead finding invert of $[N \times N]$ matrix, [3] find inverse of N matrix of order $[(2D+1) \times (2D+1)]$. This still requires heavy computation.

As pilot symbols suffer from ICI, the estimated values of the diagonal also is corrupted by ICI. In addition, the diagonal has the most important rule. Therefore, performance of [1], [2] is limited, even we solve the full ICI matrix equation. In this paper, we apply Jacobi iteration method to solve the large ICI equation, so we do not need calculate any inverse matrix. The simulation result shown that performance of Jacobi iteration at first iteration is the same as [3]. It is noted that Jacobi iteration method also is considered in [4]. However, in our method, we improve the diagonal of ICI matrix at second iteration of Jacobi method. By using output of the first iteration, we remove ICI from pilot symbols. Then, we re-estimate the diagonal of ICI matrix. As the diagonal is reliable, our method achieved a good improvement at second iteration.

The rest of paper is organized as follows: Section II reviews the conventional method. Section III shows our proposed method. Section IV presents implementation of the proposed method. Simulation result is shown in section V. Finally, conclusion is presented in section VI.

II. REVIEW OF THE CONVENTIONAL METHOD

A. A Linear Approximation of Time Varying Channel

Time varying channel causes ICI. Therefore, we need characterizing time varying channel to define the ICI effect. By a linear approximation of time varying channel, the ICI is defined.

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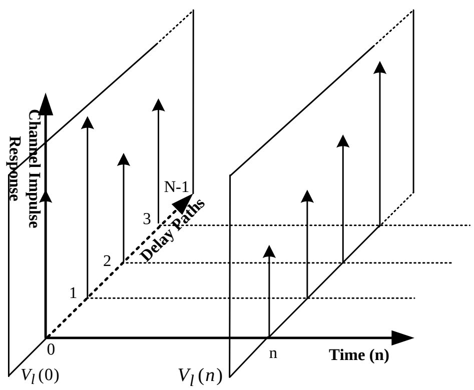

Figure 1. $\boldsymbol{V_l(n)}$ in Time Domain

As in [1], the received signal in frequency domain can be written as follows:

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

$X(k)$ and $Y(k)$ is transmitted and received signal respectively. l, and k are subcarrier indexes. N is number of subcarrier. W denotes random noise. The channel transfer function from l^{th} to k^{th} subcarrier is calculated as

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

$h(m,n)$ is channel impulse response, with m and n are delay path and time index, respectively. $H_{k,l}$ should be determined. However, we do not know $h(m,n)$ at all (m,n). By assuming $h(m,n)$ changes linearly in time domain and within an OFDM symbol, $H_{k,l}$ can be determined.

$V_l(n)$ denotes Fourier Transform of channel impulse response $h(m,n)$ at n instant time.

$$V_l(n) = \sum_{m=0}^{N-1} h(m,n).e^{-j\frac{2\pi}{N}lm} \quad (3)$$

$$H_{k,l} = \frac{1}{N}\sum_{n=0}^{N-1} V_l(n).e^{-j\frac{2\pi}{N}n(k-l)} \quad (4)$$

If $k = l$, we have

$$H_{k,k} = \frac{1}{N}\sum^{N-1} V_l(n) = \overline{V_l(n)} \quad (5)$$

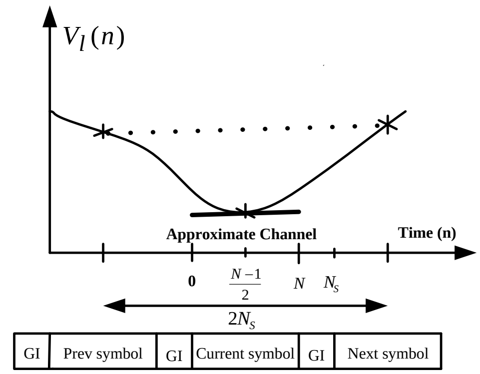

Figure 2. Approximation of $\boldsymbol{V_l(n)}$

If $h(m,n)$ is linear in time domain, then $V_l(n)$ also is linear in time domain. Instead of linear approximating $h(m,n)$, it is equivalent to linearly approximate $V_l(n)$. The two first terms of Taylor series for $V_l(n)$ is

$$V_l(n) \approx \bar{V}_l + \left(n - \frac{N-1}{2}\right).\bar{V}_l{}' \quad (5)$$

The first central difference at $\left(\frac{N-1}{2}\right)$ is approximated as

$$\bar{V}_l{}' \approx \frac{\bar{V}_l^{(next)} - \bar{V}_l^{(pre)}}{2N_s} \quad (6)$$

It is noted that error of the first central difference is $O(h^2)$, while the error of the first backward or forward difference is $O(h)$ [5]. Therefore, $\bar{V}_l{}'$ is approximated by the first central difference. From (1), (4), and (5) we have the ICI equation:

$$Y(k) = X(k)H_{k,k} + \sum_{l=0,l\#k}^{N-1} X(l)\bar{V}_l{}'\Phi_{\Delta_l} + W(k), \quad \Delta_l = l - k \quad (7)$$

$$\Phi_{\Delta_l} = \frac{1}{e^{j\frac{2\pi}{N}\Delta_l} - 1}, l\#k \quad (8)$$

For more detail about capability of linear approximating time varying channel, please refer to [1] and [2].

B. The Large ICI Matrix Equation

Equation (7) can be represented in matrix form as (9). In this paper, we assumed $[W] = [0]$.

$$\begin{bmatrix} Y(0) \\ Y(1) \\ \vdots \\ Y(N-2) \\ Y(N-1) \end{bmatrix} = \overbrace{\begin{bmatrix} H_{0,0} & \Phi_{-1}\overline{V_1'} & \cdots & \Phi_{-N+2}\overline{V_{N-2}'} & \Phi_{-N+1}\overline{V_{N-1}'} \\ \Phi_1\overline{V_0'} & H_{1,1} & \cdots & \Phi_{-N+3}\overline{V_{N-2}} & \Phi_{-N+2}\overline{V_{N-1}'} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \Phi_{N-2}\overline{V_0'} & \Phi_{N-3}\overline{V_1'} & \cdots & H_{N-2,N-2} & \Phi_{-1}\overline{V_{N-1}'} \\ \Phi_{N-1}\overline{V_0'} & \Phi_{N-2}\overline{V_1'} & \cdots & \Phi_1\overline{V_{N-2}'} & H_{N-1,N-1} \end{bmatrix}}^{ICI\ Matrix\ [H]} \times \begin{bmatrix} X(0) \\ X(1) \\ \vdots \\ X(N-2) \\ X(N-1) \end{bmatrix} + \begin{bmatrix} W(0) \\ W(1) \\ \vdots \\ W(N-2) \\ W(N-1) \end{bmatrix} \quad (9)$$

In order to recover the transmitted signal, we should solve a very lager matrix equation. In ISDB-T mode 3, as number of subcarrier is $(N = 8192)$, finding inverse of $[H]_{8192\times8192}$ is a heavy task. Therefore, it is necessary to reduce complexity of (9).

To solve the larger matrix equation, we investigate characteristics of matrix $[H]$. Firstly, we consider ICI power distribution. Absolute value of Φ_{Δ_l} indicates ICI power from l^{th} subcarrier to k^{th} subcarrier, $\Delta_l = (l-k)$ is distance between l^{th} and k^{th} subcarrier.

$$\Phi_{\Delta_l} = \frac{1}{2e^{j\frac{\pi\Delta_l}{N}}\sin\left(\frac{\pi\Delta}{N}\right)} \quad (10)$$

$$|\Phi_{\Delta_l}| = \frac{1}{\left|2\sin\left(\frac{\pi\Delta}{N}\right)\right|} = \begin{cases} \frac{0.5N}{\pi\Delta_l} & if\ \Delta_l \to 0 \\ \frac{0.5N}{\pi(N+\Delta_l)} & if\ \Delta_l \to -N+1 \end{cases} \quad (11)$$

$\Delta_l \to 0$ means that the subcarriers that are near l^{th} subcarrier causes a big ICI power on l^{th} subcarrier. $\Delta_l \to (-N+1)$ means the subcarriers that are far l^{th} subcarrier may generate a big ICI power on l^{th} subcarrier. For example, Fig.1 shows ICI power from $(N-1)$ subcarrier to 1^{st} subcarrier. In matrix form, ICI power concentrated on the elements that near the diagonal and the elements that at low-left corner or upper-right corner of $[H]$ matrix.

Because ICI power concentrates on near diagonal of $[H]$ matrix, in paper [1], [3] researchers considered D elements that closest the diagonal and solve $[(2D+1)\times(2D+1)]$ matrix size equation instead for $[N\times N]$ matrix equation. For example, $D = 1$, we have $[3\times3]$ matrix equation as

$$\begin{bmatrix} Y_0 \\ Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} H_{0,0} & \phi_1\overrightarrow{V_1} & \phi_2\overrightarrow{V_2} \\ \phi_{-1}\overrightarrow{V_0} & H_{1,1} & \phi_1\overrightarrow{V_2} \\ \phi_{-2}\overrightarrow{V_0} & \phi_{-1}\overrightarrow{V_1} & H_{2,2} \end{bmatrix} \times \begin{bmatrix} X_0 \\ X_1 \\ X_2 \end{bmatrix} \quad (12)$$

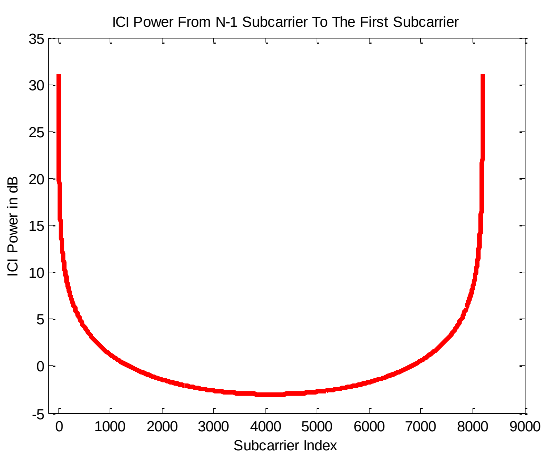

Figure 3. ICI Power From Other Subcarriers to First Subcarrier

By increasing D, we can achieve more improvement, but the computational complexity also is increased. Even $(D = 1)$ we should find N invert matrix size of $[3\times3]$. In next section, by using Jacobi iteration we do not need calculate inverse of any matrix, while performance is remaining.

III. The Proposal Method

As section II, through linearly approximating time varying channel, the conventional method can define the ICI matrix equation. However, we face with two challenges. First, the given ICI matrix is very big such as $[H]_{8192\times8192}$ for ISDB-T mode 3. Second, the diagonal of the ICI matrix-the conventional channel transfer function is not accurate because of pilots were corrupted by ICI. To deal with the two challenges, we first apply Jacobi iteration method for solving the big ICI matrix. By this way, we do not need calculate any inverse matrix. Next, we re-estimate channel at 2^{nd} iteration to improve accuracy of the diagonal of the ICI matrix.

A. Jacobi Iteration Method for The Large ICI Matrix

In this section, we apply Jacobi iteration method for the large ICI matrix equation. First we separate the ICI matrix into two parts. The first part is the diagonal of ICI matrix as

$$[P] = diag\left[H_{0,0}\ H_{1,1} \ldots H_{N-2,N-2}\ H_{N-1,N-1}\right] \quad (13)$$

The remained part of ICI matrix is

$$[T] = [H] - [P] \quad (14)$$

Equation (9) can be re-written as

$$[Y] = [P].[X] + [T].[X] \quad (15)$$

$$[P].[X] = [Y] - [T].[X] \quad (16)$$

According to Jacobi method, the approximate solution at $(k+1)$ iteration is updated as:

$$[P].[X_{k+1}] = [Y] - [T].[X_k] \quad (17)$$

Because $[P]$ is diagonal matrix, it is easy to solve (17). The initial value X_0 is calculated from 1 tap equalizer. For example, k^{th} subcarrier is initiated as

$$X_0(k) = \frac{Y(k)}{H_{k,k}} \quad (18)$$

At each iteration, error is

$$e_{k+1} = [X]_{k+1} - [X] = ([I] - [P^{-1}][H])e_k = [M]e_k$$

$$e_{k+1} = [M]^k e_1 \le |\lambda_M|^k e_1, \quad (19)$$

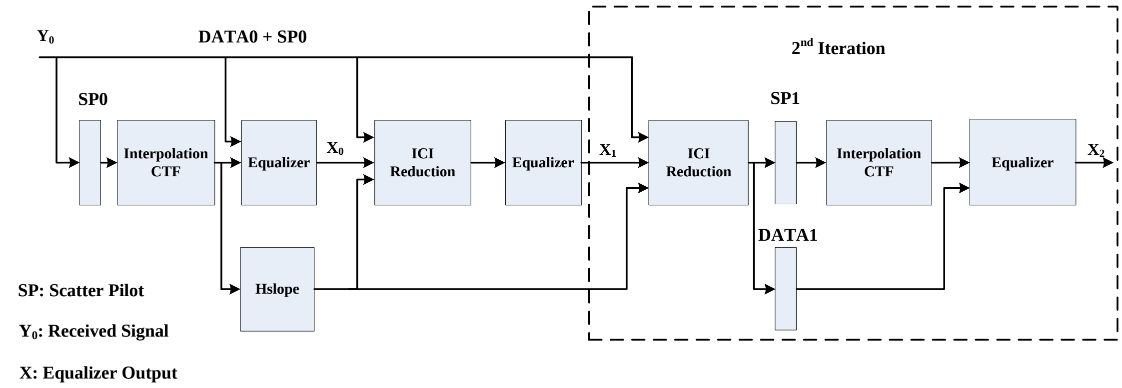

Figure 4. Two Iterations with Improved The Diagonal of The ICI Matrix

λ_M is the biggest engine value of $[M]$. In this case, as the diagonal is dominated, Jacobi iteration method is effective. For more detail about Jacobi iteration, please refer to [4], [5].

Since most ICI power concentrated near the diagonal, we can reduce size of $[T]$ to get the low complexity. We form $[T]$ by 30 elements that are nearest the diagonal. k^{th} subcarrier is updated at first iteration as

$$X_1(k) = \frac{Y_k - \sum_{\Delta=-15}^{15} X_0(\Delta+k).\overline{V_{\Delta+k}'}.\Phi_\Delta}{H_{k,k}} \quad (20)$$

$\Phi_\Delta,\ \Delta = -15, -14, \dots, 15$ is fixed coefficient as (11). We can implement iteration equation by a FIR filter with 31 taps.

B. Two Iterations with Re-estimating Channel Transfer Function

Normally, the approximate solution at 2nd iteration of Jacobi method is

$$X_2(k) = \frac{Y_k - \sum_{\Delta=-15}^{15} X_1(\Delta+k).\overline{V_{\Delta+k}'}.\Phi_\Delta}{H_{k,k}} \quad (21)$$

We should remind that $H_{k,k}$ is estimated from pilots that were corrupted by ICI. Consequently, $X_k^{(2)}$ still is distorted. In order to improve performance, we re-estimate channel $H_{k,k}$ at 2nd iteration.

Firstly, we remove ICI from pilot symbols by using output at 1st iteration as

$$Y_1(m) = Y(m) - \sum_{\Delta=-15}^{15} X_1(\Delta+\mathrm{m}).\overline{V_{\Delta+\mathrm{m}}'}.\Phi_\Delta \quad (22)$$

m is pilot symbol index. Secondly, the channel transfer function is re-estimated using $Y_1(m)$. Therefore, $H_{k,k}^{(re-estimate\ )}$ is more accurate. Finally, the recover signal at second iteration is updated as (23). The channel transfer function -the diagonal of ICI matrix is the most important element of the ICI matrix. As the channel transfer function is refined at 2nd iteration, we could achieve a significant improvement. The all above procedures are shown in Fig. 4.

$$X_k^{(2)} = \frac{Y_k - \sum_{\Delta_k=-15}^{15} X_{\Delta+k}^{(1)}.\overline{V_{\Delta+k}'}.\Phi_\Delta}{H_{k,k}^{(re-estimate\ )}} \quad (23)$$

IV. Implementation of the Proposal Method

A. Implementation of ICI Canceller using FIR Filter

In this section, we present an implementation of ICI canceller using a FIR filter. By using linear approximating time varying channel, the ICI matrix is obtained. In addition, interestingly, the ICI coefficient Φ_Δ is constant. As Φ_Δ is constant, we can implement ICI canceller by using a FIR filter.

From (1) the transmitted signal can be recovered as

$$X(k) = \frac{Y(k) - \sum_{l=0, l\neq k}^{N-1} X(l).H_{k,l}}{H_{k,k}} \quad (24)$$

We separate (24) into two steps. At first step, ICI power is subtracted from the received signal, so the clean ICI signal is obtained. At second step, the clean ICI signal is equalized by dividing by conventional channel transfer function. At first step, we consider W nearest subcarrier to k^{th} subcarrier.

$$W = 2.Q + 1$$

The ICI term that impacts on k^{th} subcarrier is re-written as follow

$$ICI(k) = \sum_{\Delta=-Q}^{Q} X(k+\Delta).\overline{\mathrm{V}_{\Delta+\mathrm{k}}'}.\Phi_\Delta \quad (25)$$

$$ICI(k) = conv\left(\Phi_\Delta, \quad X(k).\overline{\mathrm{V}_{\Delta+\mathrm{k}}'}\right) \quad (26)$$

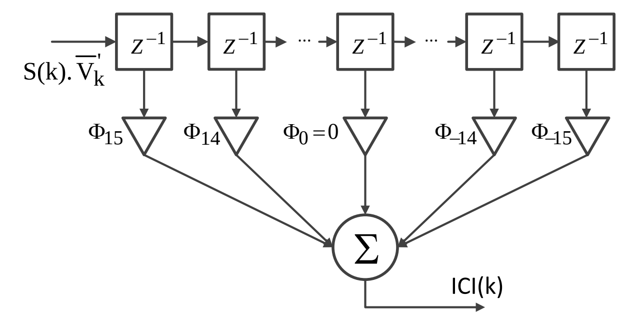

Figure 5. Implement ICI Canceller Using FIR Filter

As (26), $ICI(k)$ is output of a FIR filter with the coefficients are Φ_{Δ}, and input is $\left(X(k+\Delta).\overline{\mathrm{V_k}'}\right)$. The input $X(k+\Delta)$ is calculated by conventional 1 tap equalizer as (17). This value is called the initial value of ICI canceller. The FIR filter causes delay, so we have to locate and extract the ICI term from the FIR output. If the FIR filter has W taps, the extracted signal is within the range of

$$\left[\left(\frac{W-1}{2}+1\right)\left(N-\frac{W-1}{2}\right)\right]$$

.

For example $W=31$, we have

$$ICI(k)=\sum_{\Delta=-15}^{\Delta=15} S(k+\Delta).\Phi_{\Delta}.\overline{V_{\Delta+k}{}'} \tag{26}$$

Fig. (5) illustrates calculating $ICI(k)$ using a FIR with 31 taps Φ_{Δ}.

After the ICI term is calculated, we subtract the ICI term from the received signal. Thus, the clean ICI signal is obtained. Next, the clean ICI signal is equalized by only one tap equalizer as follow

$$X(k)=\frac{Y(k)-ICI(k)}{H_{k,k}} \tag{27}$$

The number of FIR coefficients is W, it means we consider ICI from the W closest subcarriers to the interest subcarrier k. Therefore, the value W determines how much ICI is removed from the received signal. The bigger W, the more ICI is removed. However, the big W increases FIR implementation cost. In next section, we show how to find a reasonable W.

B. *Finding a Reasonable ICI Window Size*

In this section, we explain how to choose a reasonable W, the number taps of FIR filter. We can choose a maximum $(W=N)$ to ensure the best ICI canceller performance. However, that is not necessary, even a big W increases FIR implementation cost.

Φ_{Δ} quantifies ICI from l^{th} subcarrier to k^{th} subcarrier. We exam $|\Phi_{\Delta}|$ to know how strong the ICI from l^{th} subcarrier to k^{th} subcarrier is.

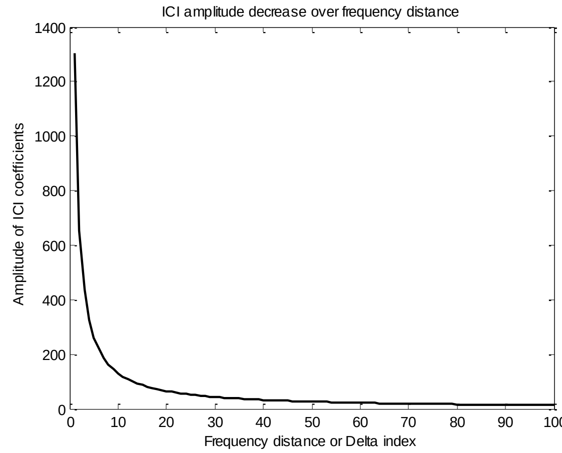

Figure 6. ICI Amplitude Decays over Frequency Distance

$$\Phi_{\Delta}=\frac{1}{2je^{j\frac{\pi}{N}\Delta}.\sin\left(\frac{\pi\Delta}{N}\right)} \tag{28}$$

$$|\Phi_{\Delta}|=\frac{0.5}{\left|\sin\left(\frac{\pi\Delta}{N}\right)\right|} \tag{29}$$

From (29), the ICI amplitude decays over the distance from l^{th} subcarrier to k^{th} subcarrier. It decays quickly with the rate of $\left|\sin\left(\frac{\pi\Delta}{N}\right)\right|$. Fig. (6) shows the ICI amplitude $|\Phi_{\Delta}|$ decreases over frequency distance Δ.

More specifically, we compare the ICI power is removed by W coefficients with the total ICI. The removed ICI power is numerator of (30), and the total ICI is the denominator.

$$ICI_{considered}=\frac{\sum_{n=1}^{\frac{W-1}{2}}\left(\frac{0.5}{\sin\left(\frac{\pi\Delta}{N}\right)}\right)^2}{\sum_{n=1}^{\frac{N}{2}}\left(\frac{0.5}{\sin\left(\frac{\pi\Delta}{N}\right)}\right)^2} \tag{30}$$

If $W=31$ and $N=8192$, we have

$$ICI_{considered}=\frac{\sum_{\Delta=1}^{15}\left(\frac{0.5}{\sin\left(\frac{\pi\Delta}{N}\right)}\right)^2}{\sum_{\Delta=1}^{4096}\left(\frac{0.5}{\sin\left(\frac{\pi\Delta}{N}\right)}\right)^2}=96.0793\% \tag{31}$$

If $W=63,\ N=8192$

$$ICI_{considered}=98.0071\% \tag{32}$$

From (31), we conclude that, $W=31$ results in 96.0793%

ICI is removed. If we increase W to 63, the removed ICI is 98.0703%. Obviously we can $(W = 31)$ to keep implementation at low cost. In section IV, we will compare bit error rate with different values of W.

V. SIMULATION RESULT

In this section, firstly, we compare Jacobi iteration method and direct solving the ICI matrix in [3]. Secondly, we evaluate and compare our proposed method with the conventional method. Finally, we investigate our proposal method with different value of ICI window size W. We apply our proposal method for ISDB-T mode 3. The parameter of OFDM system is shown in table I. We evaluate our proposal method under three different channel conditions. These are the TU-6 channel, two path Doppler channel, and one path Doppler channel. The detail channel parameters are shown in table II, III, IV.

A. Comparison of Jacobi Iteration Method and Direct Solving ICI Matrix

As section I, [3] proposed a method to solve the large ICI matrix equation. Instead finding inverse of $[N \times N]$ matrix, [3] find inverse of N matrix order of $[(2D + 1) \times (2D + 1)]$. We set $D = 2,\ 7,\ 15$ and solve matrix order of $[5 \times 5]$, $[15 \times 15]$, $[31 \times 31]$, respectively. As shown in Fig. 5, under TU-6 channel condition, as D increases, the performance is improved. Because most ICI energy concentrated near the diagonal, improvement by increasing $(D = 2)$ to $(D = 7)$ or $(D = 15)$ is small.

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]

TABLE IV ONE PATH DOPPLER CHANNEL

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

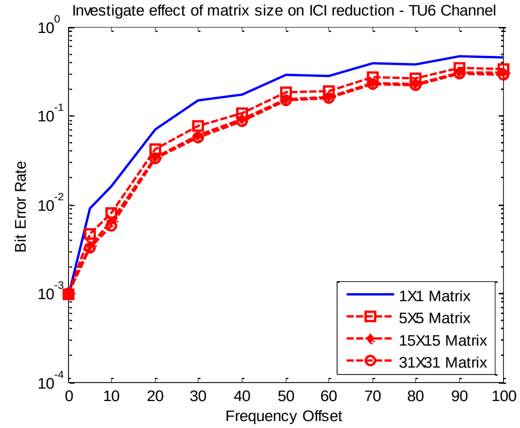

Figure 5. The Original Method with different value of D under TU-6 Channel

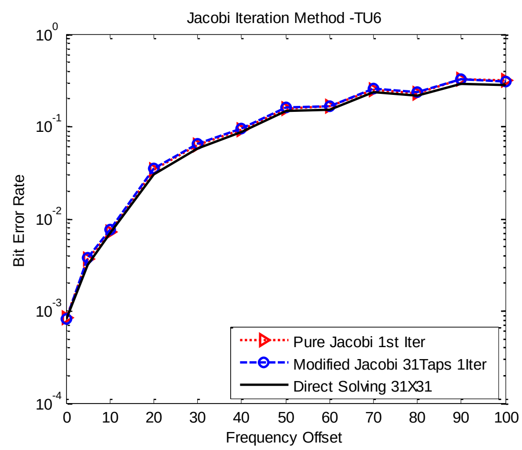

Figure 6. Jacobi Iteration Method with TU-6 Channel

Next, we compared Jacobi iteration method and method in [3] with $(D = 15)$. In Fig 6, pure Jacobi means $[T] = [H] - [P]$, and $[P]$ is the diagonal of $[H]$. Modified Jacobi 31 taps used 30 lines that closest the diagonal of ICI matrix for $[T]$. In Fig. 6, under TU-6 channel, the modified Jacobi with 31 taps achieved a performance as $(D = 15)$ or pure Jacobi iteration.

B. Comparison of Our Proposed Method and the Conventional Method

In this section, we compare our proposal method with the conventional method under three different channel conditions. We investigate improvement of our proposal method with re-estimating channel at 2nd and 3rd iteration.

By removing ICI from pilot symbols and re-estimating channel at 2nd iteration, the re-estimate channel is more accurate. Thereby, our proposal method improved performance significantly. In Fig. 7, under TU-6 channel, the proposed method doubles performance of 1st iteration-the conventional method over a wide range of frequency offset. Moreover, the proposed method achieved more improvement for two paths and one path Doppler channel. This is because the residual ICI in two paths and one path Doppler channel is less than that in TU-6 channel.

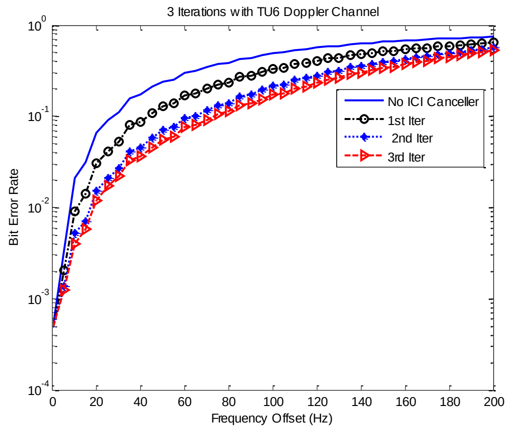

Figure 7. The Propsed Method with TU-6 Channel

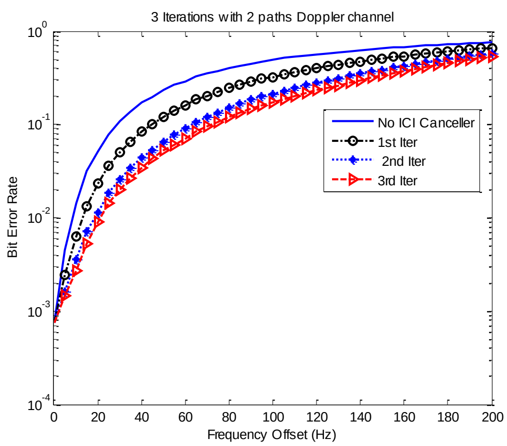

Figure 8. The Proposed Method with Two Paths Doppler Channel

In more detail, at 2^{nd} iteration, by reducing ICI effect in pilot symbols, the diagonal is improved. However, the residual ICI in pilot symbols still degrade reliability of the diagonal. As number of paths channel decreases, the residual ICI becomes smaller and the diagonal suffer less effect of the ICI residual. Therefore, the proposed method got more improvement for one and two paths channel.

In order to get more improvement, we extend our proposed method to 3 iterations. The signal is derived from 2^{nd} iteration is clearer and closer to real transmitted signal. The output at 2^{nd} iteration is utilized to remove ICI from pilot symbols. Then, the channel transfer function $H(k,k)$ is re-estimated. As a result $H(k,k)$ is more accurate, and output at 3^{rd} iteration is better. In Fig. 7, 8, 9, simulation results show 3^{rd} iteration achieved better performance than 2^{nd} iteration.

C. ICI Canceller with Different ICI Window Size W

As our above analysis, the bigger W the more ICI is removed. In addition, $(W = 31)$ and $(W = 63)$ provide similar performance, and almost ICI is considered. We evaluate bit error rate with different W at 1^{st} iteration, and 2^{nd} iteration. In Fig. 10 and Fig. 11, $W = 3, 5, 15, 31, 63$. The bit error rate confirmed the bigger W, the better performance. In addition, it is a slightly different between $W = 31$ and $W = 63$. Therefore, $W = 31$ is a reasonable choice for ICI window size.

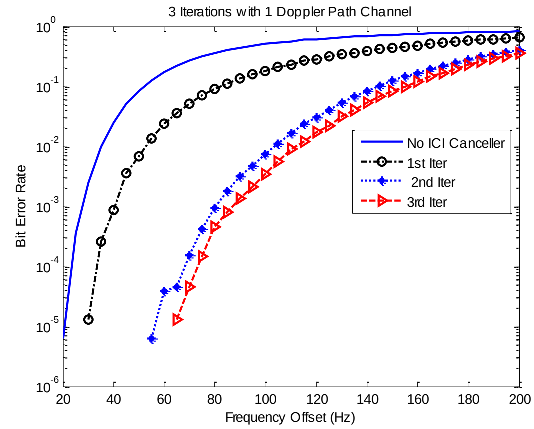

Figure 9. The Proposed Method with One Path Doppler Channel

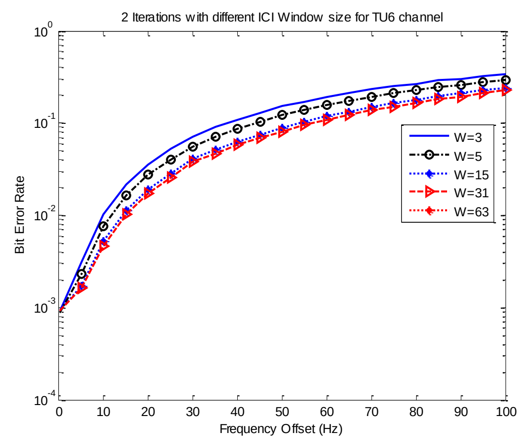

Figure 10. The Proposed Method with Different ICI Window Size

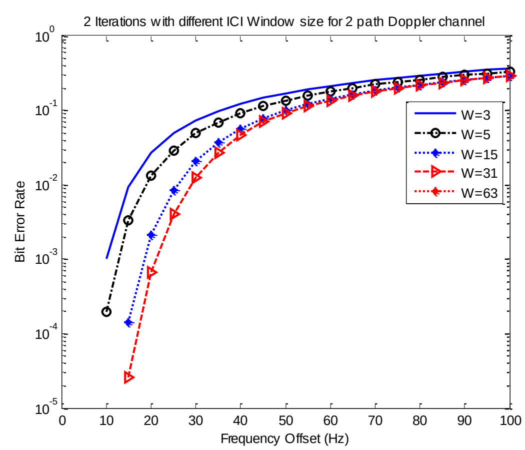

Figure 11. The Proposed Method with Different ICI Window Size

VI. CONCLUSION

In this paper, we achieved a good improvement by removing ICI from pilots and re-estimating channel transfer function-the diagonal of ICI matrix at 2^{nd}, and 3^{rd} iteration. The performance of our method is evaluated and compare with original method. As simulation result, our method doubled performance of original method for TU-6 channel. The improvement is better for two paths and one path Doppler channel.

In addition, instead of direct solving ICI matrix, we applied Jacobi iteration with low complexity. We also present a simple and beautiful implementation of ICI canceller using FIR filter. This method is easy for hard-ware implementation. Moreover, we prove that 96% the ICI is considered by only 31 FIR taps. It is not necessary to choose a big number FIR taps such as maximum N taps. Therefore, we can keep the FIR at low cost. The simulation with different W also is consistent with our numerical analysis.

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