Investigation on Performance of ICI Canceller for OFDM Mobile Receiver

Genta Izumi
Graduate School of Engineering and Science,
University of The Ryukyus
Okinawa, Japan
Email: izumi@lsi.ie.u-ryukyu.ac.jp

Tran Minh Hai
Graduate School of Engineering and Science,
University of The Ryukyus
Okinawa, Japan
Email: haitran@lsi.ie.u-ryukyu.ac.jp

Tomohisa Wada
Department of Information Engineering,
University of The Ryukyus
Okinawa, Japan
Email: wada@ie.u-ryukyu.ac.jp

Abstract—**In order to improve a mobile reception performance in OFDM communication system, Doppler-shift induced inter-carrier interference (ICI) is the biggest obstacle. Then ICI canceller is one of key technology to improve mobile reception performance. Nakamura et al. have proposed their ICI cancelling method[1]. In this study, we have evaluated the proposed ICI canceller for Japan Digital TV reception system. Not only multipath Doppler-shift condition but also more than guard interval delay condition are evaluated. Although the paper[1] suggested the ICI cancelling method is applied only to less than GI delay condition, it realizes better DUR ratio under more than GI delay conditions.**

Index Terms—**OFDM, ICI, ISDB-T, Equalization.**

I. Introduction

In wideband digital broadcasting, OFDM (Orthogonal Frequency Division Multiplexing) is used as modulation systems in order to realize efficient spectrum utilization. However Doppler-shift induced ICI severely degrades the OFDM mobile reception performance.

In this paper, we have evaluated the Nakamura's Zero-forcing ICI canceller[1][2] performance for more than guard interval delay condition.

II. Fundamental Knowledge

A. Received signal

OFDM passband signal $s(t)$ can be expressed as (1).

$$
\begin{aligned}
s(t) &= \sum_{m=-\infty}^{\infty} g(t-mT_s) \\
&\quad \sum_{n=0}^{N-1} d(m,n) e^{j2\pi n f_0 (t-mT_s)} e^{j2\pi f_c t} \qquad (1)
\end{aligned}
$$

where, N is the number of subcarriers, f_0 is the carrier interval, f_c is the lowest carrier frequency, T_s is the symbol length, $d(m,n)$ is the data symbol on the carrier whose frequency is f_c+nf_0 in the m^{th} OFDM symbol. By assuming the transmission channel has N_p delay paths, the received OFDM signal can be written as (2).

$$
s_r(t) = \sum_{i=1}^{N_p} r_i s(t-\tau_i) e^{j2\pi\Delta f_i (t-\tau_i)} \qquad (2)
$$

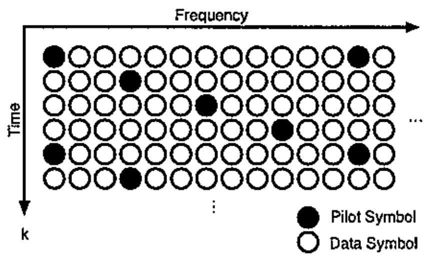

Fig. 1. Scattered pilot configuration

where, r_i, τ_i and Δf_i are attenuation, relative delay and Doppler-shift of i^{th} path respectively. After the down-conversion and samplig of $s_r(t)$ at the receiver, the block of samples are transformed by DFT to generate the data symbol $\hat{d}(k,l)$ as expressed in (3).

$$
\begin{aligned}
\hat{d}(k,l) &= h(k,l,l) d(k,l) \\
&\quad + \sum_{\substack{n=0 \\ n\neq l}}^{N-1} h(k,l,n) d(k,n) + w(k,l) \qquad (3)
\end{aligned}
$$

where $w(k,l)$ is additive noise that corresponds to the l^{th} carrier in the k^{th} OFDM symbol and $h(k,l,n)$ is the transfer function from symbol $d(k,n)$ to the l^{th} carrier. If $l \neq n$, h(k,l,n) represents the influence of ICI. $h(k,l,n)$ can be expressed as:

$$
\begin{aligned}
h(k,l,n) &= \sum_{i=1}^{N_p} \frac{1}{N} \frac{\sin\{\pi(n-l+\alpha_i)\}}{\sin\frac{\pi(n-l+\alpha_i)}{N}} \\
&\quad \times e^{j\frac{\pi(N-1)(n-l+\alpha_i)}{N}} e^{j2\pi\alpha_i f_0 T_s k} \\
&\quad \times r_i e^{-j2\pi(f_c+nf_0+\alpha_i f_0)\tau_i} \qquad (4)
\end{aligned}
$$

where, $\alpha_i (\alpha_i = \Delta f_i / f_0)$ is normalized frequency offset of i^{th} path.

B. Scattered pilot

Scattered pilot symbols are used to estimate the channel parameters. In ISDB-T, scattered pilot symbols are inserted among the data symbols as shown in Fig.1. Scattered pilot symbols are used for channel estimation in the standard of

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digital terrestrial television broadcasting in Japanese ISDB-T system.

III. ICI CANCELLER

A. Cost function

The parameters of channel transfer function is estimated so as to minimize the mean square error shown in (5).

$$\begin{aligned} E(N_p) &= \sum_{\mathbf{P}_k} |x(k,l) \quad h(k,l,l)d(k,l)|^2 \\ &+ \sum_{\mathbf{P}_{k \; 1}} |x(k \quad 1,l) \quad h(k \quad 1,l,l)d(k \quad 1,l)|^2 \end{aligned} \tag{5}$$

where $\sum_{\mathbf{P}_k}$ means that the summation is performed as long as $d(k,l)$ is a pilot symbol. In (5), the received symbols and the locally generated replicas of the received symbols against pilot symbols are compared and channel parameters such as r_i,τ_i and α_i are estimated to minimize this criterion.

B. Estimation the first path

In order to simplify this problem, it is suppose that the channel model only contains one path at the first. In this case, criterion is rewritten as (6).

$$\begin{aligned} E_1(k) &= \sum_{P_k} |x(k,l) \quad f(\alpha_1) \\ &\qquad \times r_1 e^{\;j2\pi(f_c+\alpha_1 f_0 + l f_0)\tau_1} d(k,l)|^2 \\ &+ \sum_{P_{k \; 1}} |x(k \quad 1,l) \quad f(\alpha_1) e^{\;j2\pi\alpha_1 f_0 T_s} \\ &\qquad \times r_1 e^{\;j2\pi(f_c+\alpha_1 f_0 + l f_0)\tau_1} d(k \quad 1,l)|^2 \end{aligned} \tag{6}$$

$f(\alpha_i)$ is written as (7).

$$f(\alpha_i) = \frac{1}{N} \frac{\sin \pi\alpha_i}{\sin \frac{\pi\alpha_1}{N}} e^{j\frac{N \; 1}{N}\pi\alpha_i} e^{j2\pi\alpha_1 f_0 T_s k} \tag{7}$$

One of the necessary conditions to minimize $E(1)$ with regard to r_1,τ_1 and α_1 is that its partial derivative of r_1 has zero value. This condition is shown as

$$r_1 = \frac{S_k + e^{j2\pi\alpha_1 f_0 T_s} S_{k \; 1}}{f(\alpha_1) e^{\;j2\pi(f_c+\alpha_1 f_0)\tau_1} \{D_k + D_{k \; 1}\}} \tag{8}$$

where,S_k and D_k are shown as follows:

$$S_k = \sum_{P_k} e^{\;j2\pi l f_0 \tau_1} d(k,l) x \; (k,l) \tag{9}$$

$$D_k = \sum_{P_k} |d(k,l)|^2 \tag{10}$$

When (8) is satisfied, (6) can be re-written as

$$\begin{aligned} E_1(k) &= \sum_{P_k} |x(k,l)|^2 + \sum_{P_{k \; 1}} |x(k \quad 1,l)|^2 \\ &\quad |f(\alpha_1)|^2 |r_1|^2 \{D_k + D_{k \; 1}\} \end{aligned} \tag{11}$$

Equation (11) indicates that $E(1)$ has the minimum value if $|f(\alpha_1)|^2|r_1|^2$ has the maximum value. $|f(\alpha_1)|^2|r_1|^2$ is written in (12).

$$|f(\alpha_1)|^2|r_1|^2 = |S_k + e^{j2\pi\alpha_1 f_0 T_s} S_{k \; 1}|^2 \tag{12}$$

Since $|f(\alpha_1)|^2|r_1|^2$ is the function of τ_1 and α_1, the necessary condition to maximize this is derived by partially differentiating this by τ_1 and α_1 and assuming the obtained partial derivatives to be zero.

$$\begin{aligned} & W_k S_k + W_{k \; 1} S_{k \; 1} \quad W_k S_k \quad W_{k \; 1} S_{k \; 1} \\ + \; & e^{\;j2\pi\alpha_1 f_0 T_s} W_k S_{k \; 1} + e^{j2\pi\alpha_1 f_0 T_s} W_{k \; 1} S_k \\ & e^{j2\pi\alpha_1 f_0 T_s} W_k S_{k \; 1} \quad e^{\;j2\pi\alpha_1 f_0 T_s} W_{k \; 1} S_k = 0 \end{aligned} \tag{13}$$

$$e^{j2\pi\alpha_1 f_0 T_s} S_{k \; 1} S_k \quad e^{\;j2\pi\alpha_1 f_0 T_s} S_{k \; 1} S_k = 0 \tag{14}$$

where,

$$W_k = \sum_{\mathbf{P}_k} l e^{\;j2\pi l f_0 \tau_1} d(k,l) x \; (k,l) \tag{15}$$

From (14)), α_1 is calculated from τ_1 as

$$\alpha_1 = \frac{\arctan\left[\frac{\Im[S_{k \; 1} S_k]}{\Re[S_{k \; 1} S_k]}\right]}{2\pi f_0 T_s} \tag{16}$$

By changing τ_1 within the assumed delay spread range (this is usually guard interval length), it is possible to calculate the value of $|f(\alpha_1)|^2|r|^2$. By changing τ_1 with an appropriate step, τ_1 that maximizes the value of $|f(\alpha_1)|^2|r|^2$ of derived and τ_1 is regarded to be the estimation of the relative delay. If τ_1 is determined r_1 and α_1 are easily obtained from (8) and (16) respectively. In the proposed method, τ_1 is changed by $1/(2Nf_0)$(twice of sampling frequency) and rough estimation is first obtained. And this rough estimation is modified to more precise value using Newton method using the conditions in (13).

C. Newton Method

In order to increase accuracy of rough estimation in previous section, Newton Method is used. Roughly estimated value of τ_1 satisfies only (14), but doesn't always satisfy (13). In the Newton method, τ_1 is modified by using (17) iteratively.

$$\tau_{1,n+1} = \tau_{1,n} \quad \frac{g(\tau_1, n)}{g'(\tau_1, n)} \tag{17}$$

where $g(\tau_1)$ is left part of (13) which is obtained by substituting α_1 in (16) into (13). By using (17) the roughly estimated value can be made to be more precise value, and only several iterations are sufficient to converge.

D. Estimation when multiple path exist

In this section, when $N_p \quad 2$ is considered. In this method, it is assumed that the influence to the mean square error from each path is approximately independent. Therefore, if the case of $N_p = 1$ is assumed and the parameters of this path is estimated by previously mentioned method, the influence of this path can be removed from the mean square error $E(1)$. After this, there remains the influence of other paths in the mean square error, Actually, because of the approximation and estimation error, the influence of the first estimated path still remains in $E(1)$. In this method, this is neglected.

By removing the influence of the first estimated path from the mean square error, the following criterion, $E(2)$ is obtained. Since $E(2)$ contains the influence of other paths, the second path is estimated from $E(2)$ using the same procedure in the previous section.

$$\begin{aligned} E(2) &= \sum_{P_k} |x(1,k,l) \quad f(\alpha_2) \\ &\quad \times r_2 e^{\quad j2\pi(f_c+\alpha_2 f_0+l f_0)\tau_2} d(k,l)|^2 \\ &+ \sum_{P_{k \quad 1}} |x(1,k \quad 1,l) \quad f(\alpha_2) e^{\quad j2\pi\alpha_2 f_0 T_s} \\ &\quad \times r_2 e^{\quad j2\pi(f_c+\alpha_2 f_0+l f_0)\tau_2} d(k \quad 1,l)|^2 \end{aligned} \tag{18}$$

where,

$$x(1,k,l) = x(k,l) \quad \sum_{P_k} h(1,k,l,n) d(k,n) \tag{19}$$

$$\begin{aligned} h(1,k,l,n) &= \frac{1}{N} \frac{\sin\{\pi(n \quad l+\alpha_1)\}}{\sin\frac{\pi(n \quad l+\alpha_1)}{N}} \\ &\times \; e^{j\frac{\pi(N \quad 1)(n \quad l+\alpha_1)}{N}} e^{j2\pi\alpha_1 f_0 T_s k} \\ &\times \; r_1 e^{\quad j2\pi(f_c+n f_0+\alpha_1 f_0)\tau_1} \end{aligned} \tag{20}$$

By repeating this operation by the number of paths in the channel model, all r_{N_p}, τ_{N_p}, and α_{N_p} can be obtained. In this method, it is considered that the estimated path whose $|r_{N_p}|^2$ is very small doesn't much contribute to the criteria. Therefor such a path is not used in equalization. This reduces the influence of additive noise and estimation error. Actually, the estimated paths whose $|r_{N_p}|^2$ is smaller than the predefined threshold value is not used.

E. Zero-Forcing ICI canceller

Equation of received symbols is shown as follows.

$$\hat{\mathbf{D}} = \mathbf{H}\mathbf{D} + \mathbf{W} \tag{21}$$

where,

$$\begin{aligned} \hat{\mathbf{D}} &= \left[\hat{d}(k,0), \quad ,\hat{d}(k,N \quad 1)\right]^T \\ \mathbf{D} &= [d(k,0), \quad ,d(k,N \quad 1)]^T \\ \mathbf{W} &= [w(k,0), \quad ,w(k,N \quad 1)]^T \\ \mathbf{H} &= \begin{bmatrix} h(k,0,0) & & h(k,0,N \quad 1) \\ \vdots & \ddots & \vdots \\ h(k,N \quad 1,0) & & h(k,N \quad 1,N \quad 1) \end{bmatrix} \end{aligned} \tag{22}$$

In order to obtain $\mathbf{D}$, it is necessary to calculate inverse the channel matrix $\mathbf{H}$. Since $\mathbf{H}$ can often have large dimension, it is necessary to simplify the calculation of matrix inversion.[2]

F. Reduce the inverse calculation

Since most energy of ICI is concentrated in the neighborhood of the diagonal line in (22), the ICI terms which do not significantly affect $\hat{d}(k,l)$ in (22) can be neglected and it is assumed as:

$$h(k,l,n) = 0 \qquad (|l \quad n| > q/2) \tag{23}$$

where q means the number of dominant ICI terms against l^{th} symbol. Then, input-output relationship corresponds to the l^{th} carrier is written as:

$$\hat{\mathcal{D}}_l = \mathcal{H}_l \mathcal{D}_l + \mathcal{W}_l \tag{24}$$

where,

$$\begin{aligned} \hat{\mathcal{D}}_l &= \left[\hat{d}(k,l \quad \tfrac{q}{2}), \quad ,\hat{d}(k,l+\tfrac{q}{2})\right]^T \\ \mathcal{D}_l &= \left[d(k,l \quad \tfrac{q}{2}), \quad ,d(k,l+\tfrac{q}{2})\right]^T \\ \mathcal{W}_l &= \left[w(k,l+\tfrac{q}{2}), \quad ,w(k,l+\tfrac{q}{2})\right]^T \\ \mathcal{H}_l &= \begin{bmatrix} h(k,l \quad \frac{q}{2},l \quad \frac{q}{2}) & & h(k,l \quad \frac{q}{2},l+\frac{q}{2}) \\ \vdots & \ddots & \vdots \\ h(k,l+\frac{q}{2},l \quad \frac{q}{2}) & & h(k,l+\frac{q}{2},l+\frac{q}{2}) \end{bmatrix} \end{aligned} \tag{25}$$

Compensation of both multiplicative distortion and ICI is accomplished by multiplying the inverse of $\mathcal{H}_l$ to (25). The resulting signal can be expressed as follows:

$$\tilde{\mathcal{D}}_l = \mathcal{H}_l^{\quad 1} \hat{\mathcal{D}}_l \tag{26}$$

The transmitted symbols $d(k,l)$ are obtained by selecting the elements in the middle of $\tilde{\mathcal{D}}_l$.

IV. SIMULATION RESULT

In this section, the performance of ICI canceller is analyzed by the computer simulation. The parameters used in the simulation are shown Table.I. ISDB-T mode3 of the digital broadcasting system in japan is assumed.

In this simulation, two waves multipath condition with $+\alpha_1$ and $\quad \alpha_1$ ($\alpha_2 = \quad \alpha_1$) normalized Doppler-shift condition. Here $\alpha_1 = \quad \alpha_2 = f_d/f_0$. In these figure, 'TIME and FREQ interp' means characteristic of equalizer that doesn't perform ICI cancellation when channel transfer function is interpolated in time and frequency domain.

In Fig.2, the bit error rate characteristic against normalized frequency offset α_1 is shown. The more Number of dominant ICI terms q is increased, the smaller BER is obtained.

In Fig.3, the bit error rate characteristic against carrier to noise ratio is shown. The conventional 'TIME and FREQ interp' and all ICI ($q = 0, 2, 4$) cancelling method showed similar BER performance.

TABLE I
SIMULATION PARAMETERS

FFT size		8192 points
Number of Subcarrier	(N)	5167 points
Length of guard interval		1024 points
Carrier interval	(f_0)	0.992[kHz]
Modulation		64QAM
Iteration number of Newton method		8
Number of dominant ICI terms	(q)	0, 2, 4
Multi-path channel		2 path environment
DUR		-6[dB]
delay (points)		200, 800
normalized frequency offset	(α)	$\pm$0.01

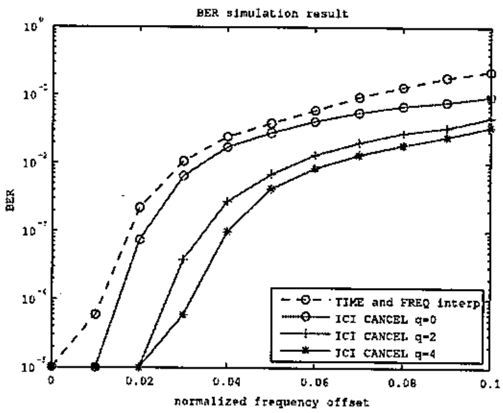

Fig. 2. BER against normalized frequency offset

In Fig.4, the bit error rate characteristic against relative delay over guard interval is shown. While the first wave delay is fixed to 200 point, the second wave delay was changed. Since GI length is 1024 point in this simulation, delay more than 1024 corresponds to more than GI delay condition. During over guard interval region, BER value of ICI cancellation is reduced.

In Fig.5, desired to undesired signal ratio (DUR) characteristic against relative delay when BER is equal to 10 ^{3} is shown. During over GI region, ICI canceller has shown better DUR performance than conventional method.

V. CONCLUSION

In this study, paper[1]'s ICI canceller for ISDB-T japan DTV system was evaluated. The ICI cancellation method showed improved performance even for over GI delay multipath condition as well as less than GI condition.

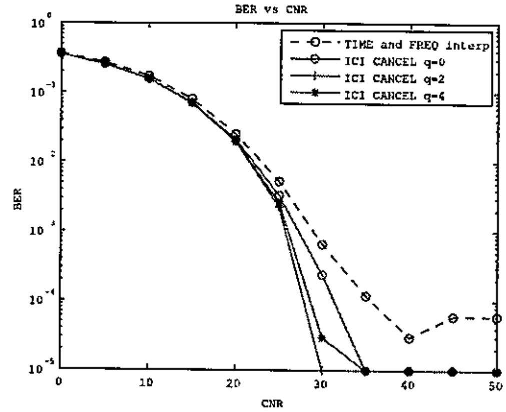

Fig. 3. BER against CNR

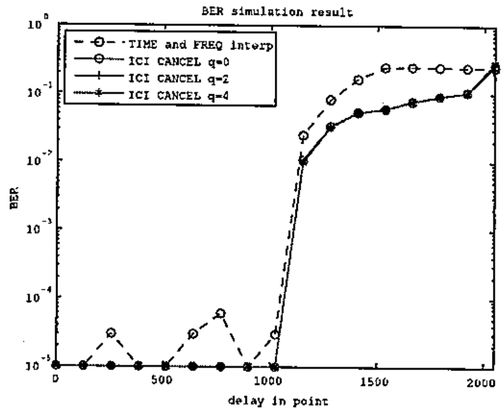

Fig. 4. BER against delay

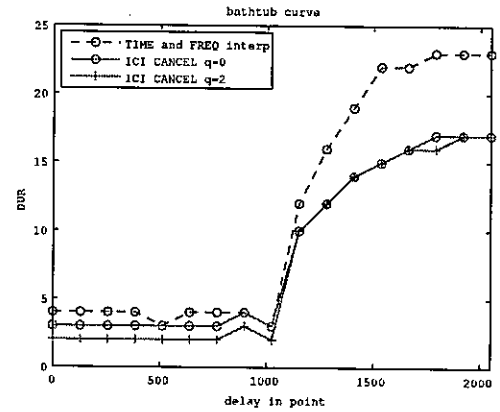

Fig. 5. DUR against delay

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