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An Improved Channel Impulse Response Estimation for OFDM System with Virtual Subcarriers

Se-Bin Im*[1], Sungsoo Kim[2], Hynung-Jin Choi[1]
[1]School of Information and Communications Engineering, Sungkyunkwan University, Korea, yuner@ece.skku.ac.kr
[2]Telecommunication R&D Center, SAMSUNG Electronics, CO., LTD, Korea, sungsoo04.kim@samsung.com

***Abstract-* We introduce a novel channel impulse response (CIR) estimation method to improve performance of conventional frequency-domain pilot and time-domain processing (FPTP) algorithm. In practical OFDM system with virtual subcarriers, the conventional FPTP algorithm can effectively reduce CIR estimation error caused by band-limitation effect but it has a limit on reducing the error if the first estimation error of CIR with maximum power is large. In order to overcome the problem, the proposed method estimates the CIR using a modified pilot sequence not to induce the correlation error in contrast with the conventional cancellation processing. Simulation results show that the proposed method outperforms the CEC method of the conventional FPTP algorithm.**

Keywords: OFDM, Channel Estimation, Virtual Subcarriers

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has many well known advantages such as robustness in frequency-selective fading channels, high bandwidth efficiency, efficient implementation, and so on. Hence, OFDM has been widely applied to wireless communication system and broadcasting. Some of well known examples include digital audio broadcasting (DAB), digital video broadcasting-terrestrial (DVB-H), IEEE 802. 11a wireless local area network (WLAN), and 802.16e wireless broadband (WiBro) [1]-[3].

In practical OFDM systems, some virtual sub-carriers are reserved as guard band for easing the requirements on the filter. In this case, the absence of pilot subcarriers in the virtual subcarriers results in the spectral leakage effect in CIR estimated through discrete Fourier transform (DFT)-based approach [4-6] or time-domain (TD) correlation-based approach [7-8]. Consequently, the channel power is distributed in the whole CIR sample vector. If several main paths in the estimated CIR are chosen to obtain channel frequency response (CFR), a significant estimation error floor will appear at high SNR. However, if all samples in the estimated CIR are chosen, the performance of noise suppressing will be reduced [7-8]. In order to solve the problem, recently, a FPTP algorithm is proposed in [8]. Its major advantage is the correlation error cancellation (CEC) and the effective path detection. However, the CEC method still has the estimation error and the path detection method needs main information of time varying multi-path channel. In this paper, we propose a novel CIR estimation method to improve the performance of the conventional FPTP algorithm. The proposed method is based on time-domain cyclic correlation similar to the conventional method but the key point is that we use a modified time-domain pilot sequence not to induce the correlation error.

The remainder of this paper is as follows. In section 2, the OFDM system model for baseband signal processing is introduced. The multipath channel model and the proposed CIR estimation algorithm are investigated in section 3. The simulation results and some analysis are given in section 4. The concluding remarks can be found in the last section.

II. OFDM SYSTEM MODEL

We consider an OFDM system employing N subcarriers for the parallel transmission of N_D data symbols and N_P pilot symbols. The total number of used subcarriers is N_U (=N_D+N_P) and N_V (=$N-N_U$) subcarriers (virtual subcarriers) at the edge of the spectrum are not used to make the transmission filter physically realizable. After OFDM modulation, N_{CP} samples of cyclic prefix are padded at the beginning of the N samples of inverse discrete Fourier transform (IDFT). The $N+N_{CP}$ samples of each OFDM symbol are given as

$$x[n] = \frac{1}{N}\sum_{k=0}^{N-1} X[k]\cdot e^{j2\pi nk/N} = x_d[n] + x_p[n],\ \ (-N_{CP} \le n < N) \quad (1)$$

$$\begin{cases} x_d[n] = \dfrac{1}{N}\sum_{k\in \mathbf{S}_d} X_d[k]\cdot e^{j2\pi nk/N},\ \ \mathbf{S}_d : \text{set of data subcarriers} \\ x_p[n] = \dfrac{1}{N}\sum_{k\in \mathbf{S}_p} X_p[k]\cdot e^{j2\pi nk/N},\ \ \mathbf{S}_p : \text{set of pilot subcarriers} \end{cases}$$

where $X_d[k]$ and $X_p[k]$ represent the data and pilot symbols, respectively. $x[n]$ is transmitted over a time-varying multi-path fading channel with the following CIR

$$h(n,\tau) = \sum_{l=0}^{N_{path}-1} h_{l,n}\cdot\delta(\tau-\tau_l) \quad (2)$$

where $h_{l,n}$ is the channel impulse response of path l at time n, τ_l is the corresponding path delays normalized by the sampling interval, and N_{path} is the total number of channel paths. The maximum path delay L is assumed not to exceed the length of guard interval ($L<N_{CP}$). To simplify analysis, we assume that synchronization is perfect at the receiver and the channel does not change during one OFDM symbol period, then the received signal can be written by

$$\begin{aligned} y[n] &= \sum_{l=0}^{L-1} h[l]\cdot x[n-l]_N = h[n]*x[n]+w[n] \\ &= h[n]*\left(x_d[n]+x_p[n]\right)+w[n],\ \ (0\le n<N) \end{aligned} \quad (3)$$

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where $w[n]$ is the complex-valued additive white Gaussian noise (AWGN) with zero mean and variance σ_w^2. $[\cdot]_N$ and $*$ denote modulo N and cyclic convolution. $h(n)\left(=\sum_{l=0}^{N_{path}-1} h_l \cdot \delta(\tau-\tau_l)\right)$ means CIR function with complex gain h_l during one OFDM symbol period.

III. CIR ESTIMATION

Since the data sequence $x_d[n]$ and the pilot sequence $x_p[n]$ are orthogonal, the initial CIR estimation $h_c[n]$ can be performed by cyclic correlation between $y[n]$ and $x_p[n]$ as follows:

$$\begin{aligned} h_c[n] &= \frac{1}{P}\cdot\left(x_p[n]\otimes y[n]\right), \left(P=\sum_{n=0}^{N-1}\left|x_p[n]\right|^2\right) \\ &= \frac{1}{P}\cdot\left\{x_p[n]\otimes\left(h[n]*x_p[n]+w[n]\right)\right\} \\ &= h[n]+\sum_{l=0,l\neq n}^{L-1} h[l]\cdot R_{pp}[n-l]+w'[n] \end{aligned} \quad (4)$$

where $\otimes$ represents the cyclic autocorrelation and $R_{pp}[n]$ means cyclic auto-correlation function of $x_p[n]$ as follows:

$$R_{pp}[n]=\frac{1}{P}\left(x_p[n]\otimes x_p[n]\right)=\frac{1}{P}\sum_{l=0}^{N-1} x_p^*[l-n]_N\cdot x_p[l] \quad (5)$$

If all subcarriers are used for transmission without virtual subcarriers and the pilots are inserted into every N_{PS} subcarrier, the autocorrelation function becomes the ideal Kronecher function with period N_{PS}. In this case, the estimated CIR $h_c[n]$ can be expressed by $h_c[n]=h[n]+w'[n]$, $(0\le n<L,\ L<N/N_{PS})$ where $w'[n]=x_p[n]\otimes w[n]/P$ is AWGN with zero mean and variance σ_w^2/P. However, if the unused virtual subcarriers are considered, the autocorrelation function cannot be ideal Kronecher function due to the band limitation effect of frequency-domain pilot. Consequently, each path estimated by the cyclic correlation contains not only the effective component of itself but also the correlation error components coming from other paths.

A. Conventional CIR estimation method

The CEC method of the conventional FPTP algorithm is summarized in Table I and the path detection of CIR is performed by path-to-noise power ratio (PNR) threshold as follows[7-8]:

$$\hat{h}[n]=\begin{cases}\tilde{h}^{[M]}[n], & \left|\tilde{h}^{[M]}[n]\right|^2\ge\Gamma \\ 0, & \left|\tilde{h}^{[M]}[n]\right|^2<\Gamma\end{cases},\ \left(\begin{aligned}\Gamma&=\frac{\rho P\sqrt{2N_{av}}}{SNR}\\ \rho&=J_0(2\pi f_D\Delta m T_s)\end{aligned}\right) \quad (6)$$

where, f_D , Δm , T_s and N_{av} are maximum Doppler frequency, OFDM symbol interval, sample duration and the number of OFDM symbols for PNR averaging, respectively.

As represented in Table I, the CEC method corrects the cyclic correlation error using reference function $R_{pp}[n]$ in the order of maximum CIR, and thus it causes error propagation if the correlation error of the first path with maximum power is large.

TABLE I
CEC METHOD OF THE CONVENTIONAL FPTP ALGORITHM

Step1: Set the initial CIR. $\tilde{h}^{[0]}[n]=h_c[n]$

Step2: Search the path with maximum power except for the previous paths,

$$n_{\max}^{[1]}=\max_n\left|\tilde{h}^{[0]}[n]\right|^2$$

$$n_{\max}^{[i]}=\max_n\left|\tilde{h}^{[i]}[n]\right|^2,\ \left(n\neq n_{\max}^{[u]},\ 0\le u<i<L\right)$$

Step3: Cancel the correlation error.

$$\tilde{h}^{[i]}[n]=h^{[i-1]}[n]-h^{[i-1]}[n_{\max}^{[i]}]\cdot R_{pp}[n-n_{\max}^{[i]}],\ \left(n\neq n_{\max}^{[i]}\right)$$

Step4: Calculate the difference of the CIR between before and after the cancellation in the *i*-th iteration.

$$e(i)=\sum_{n=0}^{L-1}\left|\tilde{h}^{[i]}[n]-h^{[i-1]}[n]\right|^2$$

Step5: Finish the CEC if $e(i)>e(i-1)$ or $i>N_{path}$. Otherwise, return to step 2.

[a] Superscript $[\cdot]$ represents the number of iterations.

B. Proposed CIR estimation method

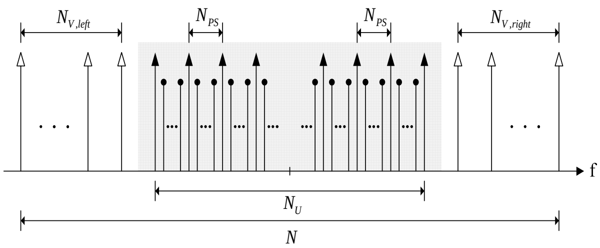

Figure 1. Frequency-domain mapping structure of OFDM system with virtual pilot subcarriers

In order to avoid the original cyclic correlation error caused by band-limited subcarrier allocation, we consider virtual pilot subcarriers as shown in Fig. 1. The virtual pilot subcarriers are allocated in the unused guard band and the pilot spacing is identical to the original pilot spacing. For the virtual pilot $X_v[k]$, the corresponding time-domain sequence $x_v[n]$ is expressed by

$$x_v[n]=\frac{1}{N}\sum_{k\in \mathbf{S}_{vp}} X_v[k]\cdot e^{j2\pi nk/N} \quad (7)$$

where $\boldsymbol{S}_{vp}$ denotes the set of virtual pilot subcarriers.

After the initial CIR estimation is performed as (4), we extend the limited band of the received signal to the overall band including unused virtual subcarriers as follows:

$$y_s[n]=y[n]+\sum_{l=0}^{N_{path}-1} h_c[\tau_l]\cdot x_v[n-\tau_l] \quad (8)$$

Since the band-extended signal $y_s[n]$ contains inaccurate channel components due to the initial CIR error, we consider an iterative estimation processing with the following pilot sequence $x_s[n]$

$$x_s[n]=x_p[n]+x_v[n] \quad (9)$$

TABLE II
PROPOSED CIR ESTIMATION ALGORITHM

Step1: Set the initial CIR. $\tilde{h}^{[0]}[n] = h_c[n]$

Step2: Sort the path in the order of the CIR power $(0 \le l < N_{path})$

$$n_{\max}^{[l]} = \max_n |h_c[n]|^2, \quad \begin{pmatrix} n \ne n_{\max}^{[u]}, \quad 0 \le u < l, \quad 0 \le n < L, \\ n_{\max}^{[0]} = \max_n |h_c[n]|^2 \end{pmatrix}$$

Step3: Generate the virtual signal $y_v^{[i]}[n]$ using $x_v[n]$ and $\tilde{h}^{[i-1]}[n]$.

$$y_v^{[i]}[n] = \sum_{l=0}^{M-1} \tilde{h}^{[i-1]}[n_{\max}^{[l]}] \cdot x_v[n - n_{\max}^{[l]}]$$

Step4: Modify the received signal

$$y_s^{[i]}[n] = y[n] + y_v^{[i]}[n]$$

Step5: Re-estimate the CIR using the modified signal $y_s^{[i]}[n]$.

$$\tilde{h}^{[i]}[n] = \frac{1}{P_s} \cdot \left(x_s[n] \otimes y_s^{[i]}[n] \right)$$

Step6: Calculate the difference of the CIR between before and after re-estimation in the *i*-th iteration.

$$e(i) = \sum_{n=0}^{L-1} \left| \tilde{h}^{[i]}[n] - h^{[i-1]}[n] \right|^2$$

Step7: Finish the CEC if $e(i) > e(i-1)$.

Otherwise, return to step 2.

The proposed CIR estimation method is summarized in Table II. Note that the virtual pilot $X_v[k]$ and the modified pilot sequence $x_s[n]$ are generated for only CIR estimation at the receiver.

In case of the proposed method, the cyclic auto-correlation function of the modified pilot sequence becomes ideal Kronecher function with period N_{PS}, thus the threshold fcor path detection can be simplified by $\Gamma = \sigma_w^2 / P$ in (6).

IV. Simulation Results

Table III summarizes major OFDM system para-meters for performance evaluation. The multipath fading channel is generated by GSM TU 6 model and channel coding scheme is not considered. The performance comparison of the CIR estimation methods is performed by mean square error (MSE) of CFR, detection error rate (DER) of CIR path, and uncoded bit error rate (BER) where the CFR is obtained by discrete Fourier transform of the estimated CIR. For simplicity of expression, we use FPTP 1 and FPTP 2 as meaning 'before' and 'after' the path detection.

TABLE III
MAJOR OFDM SYSTEM PARAMETERS

Parameters	values
Center frequency	2GHz
Bandwidth	10MHz
FFT size (N)	1024
Number of used subcarriers (N_U)	768
Number of unused subcarriers (N_V)	256
Pilot spacing	6
CP ratio (N_{CP} / N)	1/8

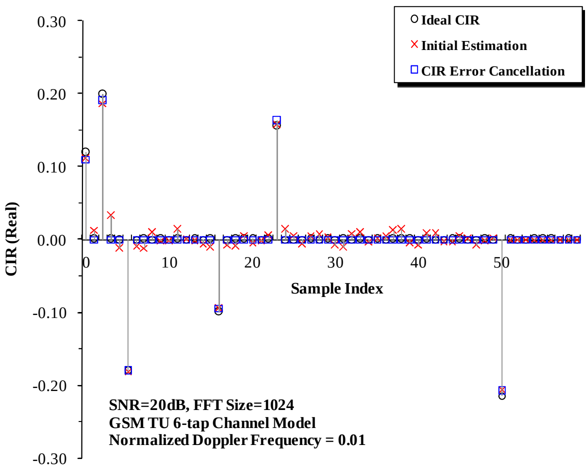

Figure 2. An example of error compensation effect of the proposed CIR estimation method. Compared with the ideal CIR, the conventional FPTP 1 shows inaccurate compen-sation result due to the error of the estimated CIR with maximum power (sample index=3) but the proposed FPTP 1 has small side lobe around the peak values and each peak value is very close to ideal CIR.

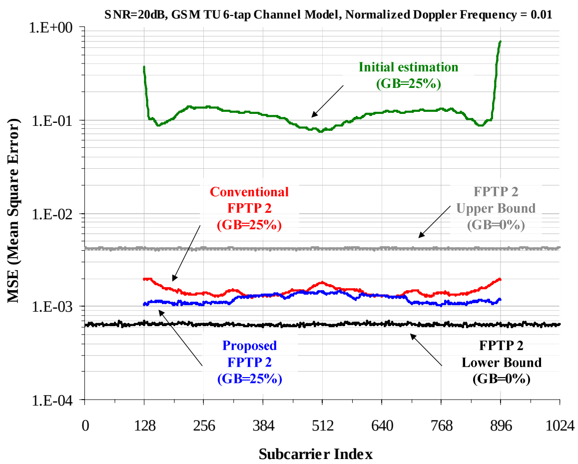

Figure 3. MSE performance in each subcarrier index. This shows that the initial estimation performance is significantly degraded at the spectrum edge but FPTP algorithm can reduce the error effectively. In case of the proposed FPTP 2, it has better performance than the conventional FPTP 2 at the edge.

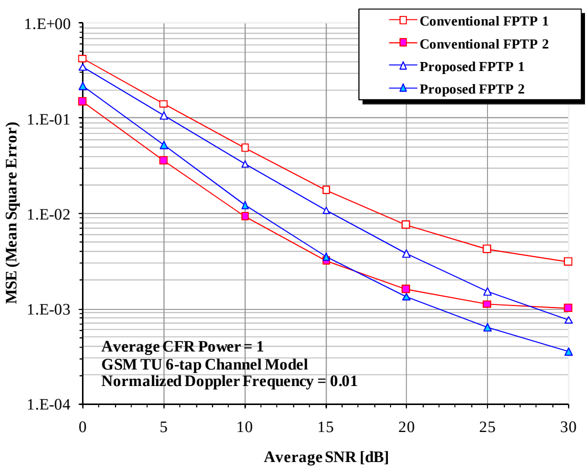

Figure. 4. MSE performance versus average SNR. We can know that the proposed method outperforms the conventional method except for the proposed FPTP 2 at low SNR less than 17dB. Notice that the proposed FPTP 1 has similar performance to the FPTP 2 because the proposed pilot sequence does not induce the correlation error due to the band-limitation effect.

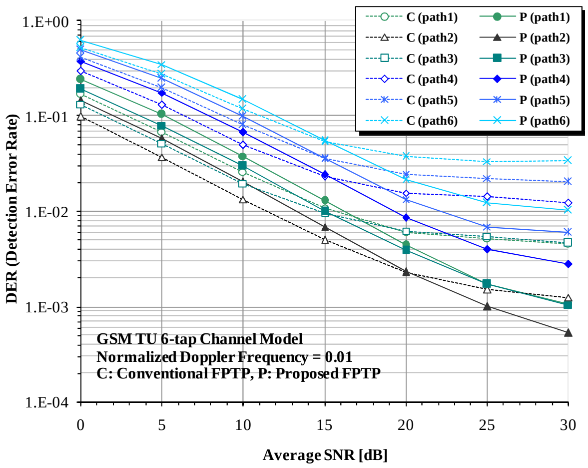

Figure 5. DER performance versus average SNR. This shows that the proposed method provides better performance of the path detection than conventional method at high SNR. (C: conventional method, P: proposed method)

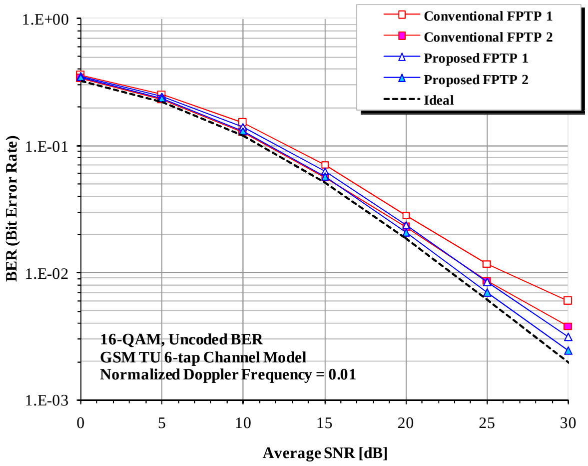

Figure 6. Uncoded BER performance versus average SNR. We can see that the proposed method outperforms the conventional method and the proposed FPTP 1 displays sufficiently good performance.

V. Conclusions

In this paper, a novel CIR estimation method has been proposed. Compared with the conventional CEC method, the proposed compensation method has three significant points. First, it can avoid the error propagation due to initial path error with maximum power. Second, it provides relatively simple path detection scheme. Finally, it improves the performance of the conventional FPTP algorithm owing to above two advantages.

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