A simple ICI pre-suppression Method for OFDM Systems

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Abstract: In orthogonal frequency division multiplexing (OFDM) systems, channel variations within an OFDM symbol destroy orthogonality among subcarriers, resulting in inter-carrier interference (ICI), and performance of one-tap equalizer is degraded as maximum Doppler frequency increases. In this paper, we propose a simple ICI pre-suppression method to mitigate the effect of channel variations. The proposed method consists of three steps; average channel impulse response (CIR) estimation, time-varying CIR estimation by Gaussian interpolation, and time-domain suppression. Since the proposed method utilizes CIR estimation scheme, we can also obtain noise reduction effect by zero-padding such as in traditional discrete Fourier transform (DFT)-based channel estimation. Simulation results show that the proposed method can sufficiently reduce the ICI-induced performance degradation of the frequency-domain one-tap equalizer.

1. Introduction

OFDM is an attractive technique for high-speed data transmission in mobile communications since it can prevent inter-symbol interference (ISI) by inserting a guard interval and can mitigate frequency selectivity of time-invariant multi-path channel using a simple 1-tap equalizer [1]. However, request for communications with high mobility suggests that future OFDM designs should take into account the large Doppler spread associated with time-varying channels. This scenario complicates the equalization, because time-varying channel induces ICI, thus destroying orthogonality among OFDM subcarriers [2]. Recently, various techniques have been proposed to cancel out such ICI effects in OFDM systems [3]-[9], and they have shown that nonlinear equalizers based on ICI cancellation generally outperform linear approaches [4]-[7].

In spite of that, linear schemes still preserve their importance. First, linear equalizers are usually simpler, and thus less complex. Second, nonlinear schemes usually employ a linear equalizer to obtain the temporary decisions that they use to cancel out the ICI. In this paper, for computational efficiency, we introduce a simple ICI pre-suppression method in time domain before one-tap equalization in frequency domain, and show that this scheme is very effective in large Doppler spread channel.

This paper is organized as follows. In section 2, we introduce an OFDM signal model. Receiver structure for the ICI pre-suppression method and ICI analysis are described in section 3. Simulation results and analysis are given in section 4 and we draw conclusions in section 5.

2. OFDM Signal Model

We consider an OFDM system employing N subcarriers for the parallel transmission of N_D data symbols and N_P pilot symbols with spacing N_{ps}, as shown in Figure 1.

After OFDM modulation, N_G samples of guard interval are inserted at the beginning of N samples of inverse discrete Fourier transform (IDFT). The $N+N_G$ samples of the m-th OFDM symbol are given as

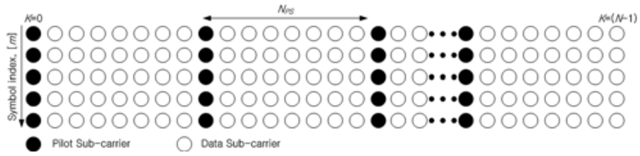


Figure 1. OFDM pilot allocation

$$x_m(n) = \frac{1}{N}\sum_{k=0}^{N-1} X_m(k) e^{j2\pi nk/N} = d_m(n) + p_m(n), (-N_G \le n < N) \quad (1)$$

where $d_m(n)$ and $p_m(n)$ are time-domain data signal and pilot signal, respectively, in the m-th OFDM symbol. $x_m(n)$ is transmitted over a time-varying multi-path fading channel with the following CIR

$$h_m(n,\tau) = \sum_{l=0}^{L-1} h_{m,l,n} \cdot \delta(\tau - \tau_l) \quad (2)$$

where $h_{m,l,n}$ is a complex gain of the τ_l -path at time n of the m-the OFDM symbol and the maximum path delay L is not to exceed the length of guard interval.

Assuming that timing and frequency synchronization are perfect, the received signal can be written by

$$y_m(n) = x_m(n) * h_m(n,\tau) + w_m(n) \quad (3)$$

where * denotes the convolution operator and $w_m(n)$ represents additive white Gaussian noise (AWGN) with zero-mean and variance δ^2.

3. Proposed Method

3.1 Receiver Structure

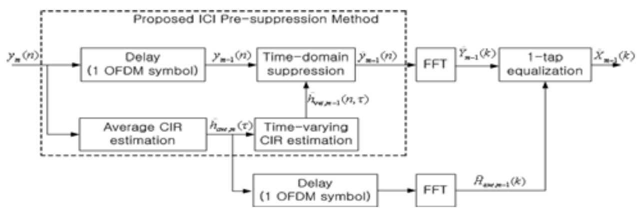


Figure 2. Receiver structure

The receiver structure for the proposed ICI pre-suppression method is shown in Figure 1. After removing guard interval of the received signal, the proposed method is performed by the following three steps. The first step is the average CIR estimation. The second step is the time-varying CIR estimation. The final step is time-domain suppression to reduce the ICI-induced components. After the above three steps, non-effective paths are eliminated by zero-padding for noise reduction effect and channel frequency response (CFR) is obtained by DFT of CIR with only effective paths.

3.2 Proposed Time-varying CIR Estimation

Since the CIR can be divided into average components and time-varying components as Eq. (4), we first estimate the time-invariant average CIR in the m-th received signal as Eq. (5)

$$h_m(n,\tau) = h_{\mathrm{var},m}(n,\tau) = h_{ave,m}(\tau) + \left\{ h_{\mathrm{var},m}(n,\tau) - h_{ave,m}(\tau) \right\} \qquad (4)$$

$$\hat{h}_{ave,m}(\tau) = \frac{1}{P}\sum_{n=0}^{N-1} y_m(n-\tau)\, p_m^*(n), \quad \left(P = \sum_{n=0}^{N-1} \left| p_m(n) \right|^2 \right) \qquad (5)$$

Figure 3 shows the estimated time-invariant average CIR with N_{PS} repetition pattern. Since each pattern is identical except for phase rotation due to pilot position, we can select only the first N/N_{PS} samples.

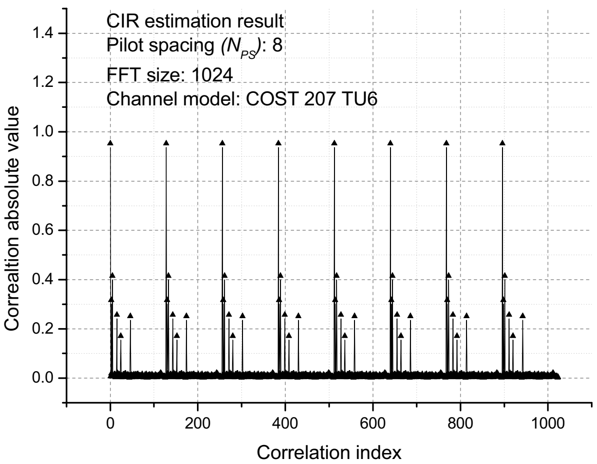


Figure 3. Time-invariant average CIR

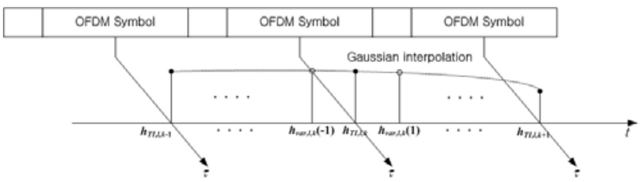


Figure 4. Interpolation processing for the second step

The time-varying CIR estimation generally requires very high computational complexity of $O(N^2L)$ for an accurate estimation [2]. However, if we assume that the channel fluctuation is not severe within an OFDM symbol, the time-varying CIR can be estimated by using a simple interpolation scheme. There are many methods for the interpolation but we consider the 2nd order Lagrange interpolation called Gaussian interpolation because the average CIR is approximately an instantaneous value at time $N/2$ and thus the time-varying CIR estimation requires three OFDM symbols at least. The following equation and Figure 4 represent the interpolation processing for the second step.

$$\begin{gathered} \hat{h}_{\mathrm{var},m}(n,\tau) = \alpha_n \hat{h}_{ave,m-1}(\tau) + \beta_n \hat{h}_{ave,m}(\tau) + \gamma_n \hat{h}_{ave,m+1}(\tau) \\ \left(\begin{matrix} \alpha_n = (\rho^2 - \rho)/2 \\ \beta_n = 1 - \rho^2 \\ \gamma_n = (\rho^2 + \rho)/2 \end{matrix} \quad , \quad \rho = \frac{n - N/2}{N + N_G} \right) \end{gathered} \qquad (6)$$

where α_n, β_n, and γ_n means interpolation coefficients.

3.3 Analysis of ICI Effect

In general, the time-varying CIR causes ICI and the interference power of adjacent subcarrier is approximately proportion to the variation. Assuming that the channel variation, in terms of magnitude and phase, is linear and the average interference power of two adjacent subcarriers is dominant, we can simply analyze the ICI effect.

The gradient values $G_{mag}(\tau)$ of the time-varying CIR magnitude expressed by Eq. (7).

$$\left| h_{\mathrm{var},m}(n,\tau) \right| = G_{mag}(\tau) \cdot (n - N/2) + \left| h_{ave.m}(\tau) \right| \qquad (7)$$

Since the minimum magnitude is zero, the maximum gradient is $2\left| h_{ave,m}(\tau) \right| / N$. Note that the absolute interference power does not vary though the magnitude of the average CIR $h_{ave}(\tau)$ increases because the constant component $\left| h_{ave,m}(\tau) \right|$ is transformed into frequency-domain impulse signal as follows:

$$\begin{aligned} &\frac{1}{N} DFT\left\{ \left| h_{\mathrm{var},m}(n,\tau) \right| \right\} \\ &= G_{mag}(\tau) \cdot \sum_{n=0}^{N-1} (n - N/2) \cdot \exp\left(j2\pi nk/N \right) + \left| h_{ave.m}(\tau) \right| \end{aligned} \qquad (8)$$

In Figure 5 represent ICI-induced function expressed by Eq. (8), ICI-induced function of time-varying magnitude, and ICI power ratio normalized by peak power, respectively. Here, the peak power means maximum power of the ICI-induced function and the ICI power is calculated by average power of the adjacent two subcarrier signals on the basis of peak subcarrier. The figure demonstrates that the ICI depends on the magnitude variation regardless of the average CIR power.

In addition, the ICI power is related to phase variation. Assuming that the phase variation does not exceed 2π because the linear phase variation is a kind of frequency offset and the phase variation of 2π means one subcarrier shift, time-varying phase component with the gradient $G_{pha}(\tau)$ can be expressed by

$$\arg\left\{ h_{\mathrm{var},m}(n,\tau) \right\} = G_{pha}(\tau) \cdot (n - N/2) + \arg\left\{ h_{ave.m}(\tau) \right\} \qquad (9)$$

And the corresponding DFT is

$$\begin{aligned} &\frac{1}{N} DFT\left[\exp\left(j \arg\left\{ h_{\mathrm{var},m}(n,\tau) \right\} \right) \right] \\ &= \sum_{n=0, n\neq k}^{N-1} \frac{\sin \pi (n - k + \varepsilon)}{N \sin \frac{\pi}{N}(n - k + \varepsilon)} \cdot \exp\left\{ j\frac{\pi}{N}(N-1)(n - k + \varepsilon) + \theta_0 \right\} \\ &, \left(\varepsilon = \frac{N}{2\pi} G_{pha}(\tau), \quad \theta_0 = -\frac{N}{2} G_{pha}(\tau) + \arg\left\{ h_{ave}(\tau) \right\} \right) \end{aligned} \qquad (10)$$

In Figure 6 represent ICI-induced function expressed by Eq. (10). From the figure, we can see that the phase variation affects peak power as well as adjacent interference power.

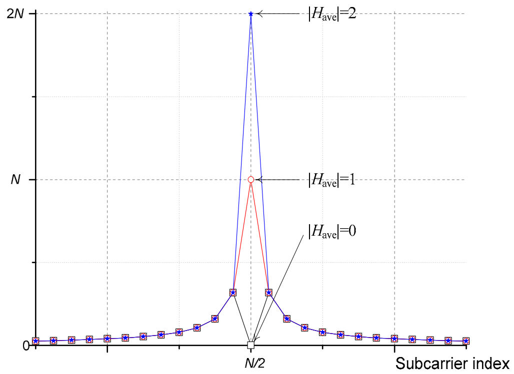


Figure 5. ICI-induced function of time-varying magnitude

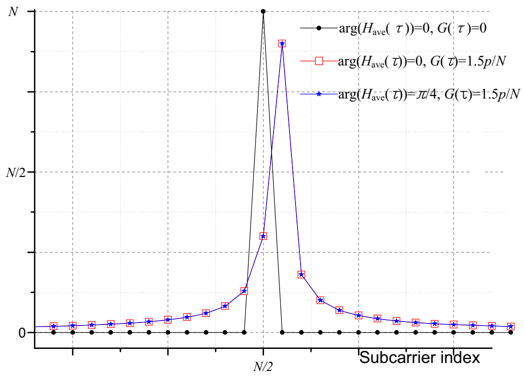


Figure 6. ICI-induced function of time-varying phase

3.4 Proposed Pre-suppression Method

For an optimal compensation of the time-varying channel, frequency-domain multi-tap equalizer is required but it entails high complexity of $\mathrm{O}(N \cdot N_{\mathrm{tap}}^{3})$ for the number of taps N_{tap} [2]. For simple implementation, however, we simply use one-tap equalizer and add time-domain supplementary processing as the final step.

In single path fading channel, the effect of time-varying CIR can be simply compensated by the interpolated $\hat{h}_{\mathrm{var},m}(n,\tau)$ as follows:

$$\begin{aligned}\hat{y}_m(n) &= y_m(n)\cdot\frac{\hat{h}_{ave,m}(0)}{\hat{h}_{\mathrm{var},m}(n,0)} \\ &\approx x_m(n)\cdot\hat{h}_{ave,m}(0)+w_m(n), \quad (0\le n<N)\end{aligned} \tag{11}$$

In case of multi-path fading channel, since the received signal is expressed by sum of several path signals, time-domain multi-tap equalization is required for independent compensation of each path. But it complicates the OFDM receiver similar to frequency-domain multi-tap equalizer. Thus we propose an efficient suppression method using average channel variation of effective paths as follows:

$$\hat{y}_m(n) = y_m(n)\cdot g_m(n), \quad (0\le n<N) \tag{12}$$

where $g_m(n)$ is the suppression coefficient and each magnitude and phase is given in Eq. (13) and Eq. (14), respectively.

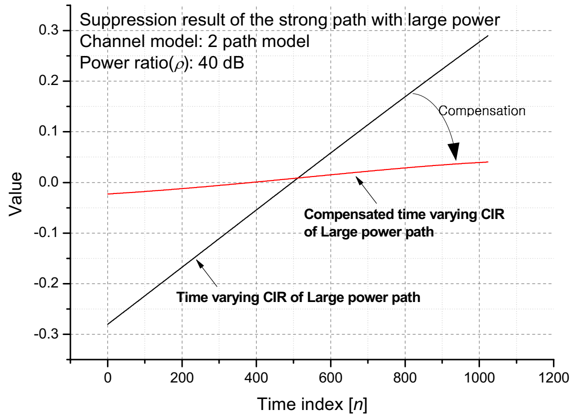
$$|g(n)| = \sum_{l=0}^{N_{path}-1}\left|\frac{\hat{h}_{ave,m}(\tau_l)}{\hat{h}_{\mathrm{var},m}(n,\tau_l)}\right|\cdot\chi_l \tag{13}$$

$$\arg\{g(n)\} = \sum_{l=0}^{N_{path}-1}\arg\left\{\frac{\hat{h}_{ave,m}(\tau_l)}{\hat{h}_{\mathrm{var},m}(n,\tau_l)}\right\}\cdot\chi_l \tag{14}$$

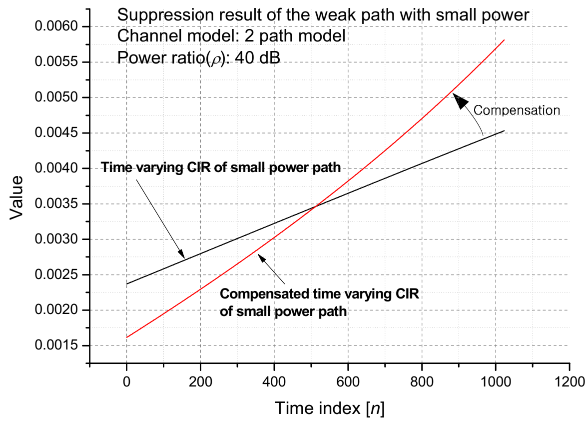
Here, χ_l denotes the weight of the τ_l-th path for averaging of each path and τ_l denotes the effective path with CIR power larger than noise power. The weight α_l of each path is calculated by power and phase of the time-varying CIR as

$$\chi_l = \frac{\gamma(\tau_l)}{\sum_{i=0}^{N_{path}-1}\gamma(\tau_i)}, \quad \left(\gamma(\tau_l)=\left|\hat{h}_{\mathrm{var},m}(N-1,\tau_l)-\hat{h}_{\mathrm{var},m}(0,\tau_l)\right|^2\right) \tag{15}$$

where $\gamma(\tau_l)$ denotes the absolute difference of the τ_l-th time-varying CIR and it represents a kind of complex gradient including both magnitude and phase variations.



(a) Suppression of strong path with large power



(b) Suppression of strong path with weak power

Figure 7. An example of the proposed pre-suppression

Figure 7 shows an example of the proposed pre-suppression method in time-varying Rayleigh fading channel with two paths. If $\rho(>0)$ denotes power ratio of two paths, one strong path with relatively large power and another weak path are suppressed as shown in Figure 7 (a), (b), respectively. From the results, we can see that CIR suppression results in reducing the variation of the strong path though the variation of the week path increases. Because ICI is dominantly affected by the strong path with relatively large variation of power, the suppression effect is enhanced as the power ratio increases, which is verified by simulation results in section 4.

3.5. CFR Estimation and Equalization

After DFT of the ICI-suppressed signal $\hat{y}_m(n)$, a simple DFT-based channel estimation and one-tap equalization are performed in frequency domain.

Note that the proposed suppression method of Eq. (12) requires no additional CIR estimation and thus the CFR can be simply obtained by DFT of the detected CIR as given by the following equation [9].

$$\hat{H}_{ave,m}(k) = DFT\left[\hat{h}_{ave,m}(\tau)\right] \tag{16}$$

If the pilot sub-carrier is equally spaced, the average CIR of Eq. (5) is repeated N_{PS} times within N. For noise reduction of the CFR, we take only the first N/N_{PS} samples of CIR and insert zero to the rest of the samples. Then noise variance of CFR is reduced by N_{PS}. If we can detect the accurate path position of the CIR, the noise reduction effect increases in proportion to the number of zero-padded samples except for the detected path. Lastly, the equalization of the received signal is given by.

$$\hat{X}_m(k) = \hat{Y}_m(k) / \hat{H}_{ave,m}(k) \tag{17}$$

4. Simulation Results

Major OFDM system parameters for performance evaluation are as following, FFT size N=1024, CP length N_G=256, number of data N_D=896, number of pilot N_P=128, Pilot spacing N_{PS}=8, modulation method is QPSK, bandwidth is 10 MHz. We consider Rayleigh fading channel model with normalized maximum Doppler frequency 0.1 and the number of the paths is 1 and 2.

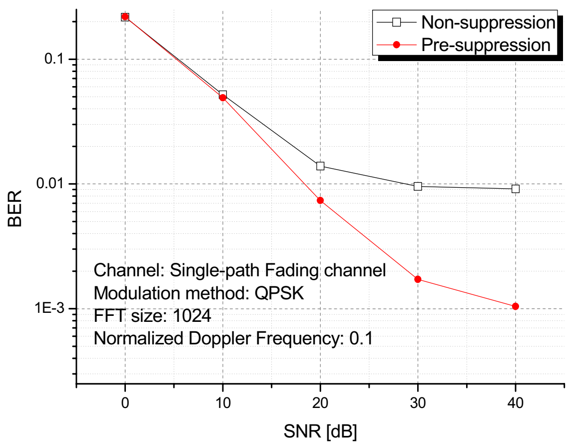


Figure 8. BER performance (single path)

Figure 8, 9 shows bit error rate (BER) performance of the proposed method in Rayleigh fading channel. Since the proposed method utilizes only one time-varying suppression component, we can see that it has relatively good performance in comparison with the non-suppressed one-tap equalization in single-path channel of Figure 8. In case of two-path channel of Figure 9, BER performance of the proposed method is improved in proportion to power ratio $\rho(>1)$ of the two paths.

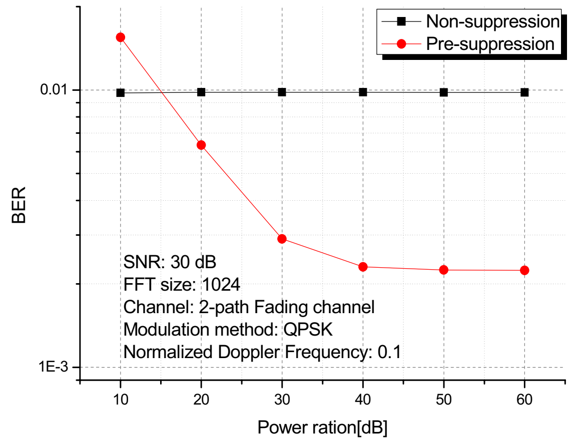


Figure 9. BER performance (two paths)

5. Conclusions

In this paper, we have proposed the ICI pre-suppression method with low complexity. Considering a practical OFDM receiver with high mobility, requirement of the conventional optimal equalizer places a burden on system designer because of high computational complexity and non-real time process. For this reason, the proposed pre-suppression method using simple multiplication can be efficiently applied to various OFDM systems.

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