Optimum Frequency-Domain Partial Response Encoding in OFDM System

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Abstract—Time variance of wireless channels destroys the orthogonality among subchannels in orthogonal frequency-division multiplexing (OFDM) systems and causes interchannel interference (ICI), which results in an error floor. In this letter, we study frequency-domain partial-response coding (PRC) for reducing the effect of the ICI. Based on the general expression of the ICI power for OFDM with PRC, the optimum weights for PRC that minimize the ICI power are derived. From the numerical and simulation results, optimum PRC for OFDM can reduce the ICI effectively by 4.0 dB for two-tap PRC and 6.2 dB for three-tap PRC, respectively.

Index Terms—Interchannel interference (ICI), orthogonal frequency-division multiplexing (OFDM), partial-response coding (PRC).

I. INTRODUCTION

AS A promising technique for high data-rate transmission [1], orthogonal frequency-division multiplexing (OFDM) has been successfully used in many environments, such as digital audio broadcasting (DAB), digital video broadcasting (DVB), and HyperLAN-II. In a classical OFDM system, the entire channel is divided into many orthogonal subchannels, and information symbols are transmitted in parallel over these subchannels with a long symbol duration to deal with the frequency-selective fading of wireless environments. However, it has been shown [2]–[5] that time variation of wireless channels over an OFDM symbol period destroys orthogonality among subchannels and causes the interchannel interference (ICI). If not compensated for, the ICI will result in an error floor, which increases with Doppler frequency and symbol duration. Several methods [6]–[16] have been proposed to reduce the effect of the ICI. One of the most commonly used methods is frequency-domain equalization [6], [7]. In [6], a pilot symbol assisted frequency-domain equalizer was proposed. In [7], an equalization technique suitable to time-varying multipath channel has been developed. The antenna diversity is an effective way to combat the effects of time variation of wireless channels, hence, can reduce the ICI as shown in [2]. Another way to deal with the ICI is the time-domain windowing in [8] and [9]. In [10], ICI suppression in multiple-input multiple-output (MIMO) OFDM is studied. Recently, a self-ICI-cancellation approach [11] has been proposed, which transmits each symbol over a pair of adjacent subchannels with a 180° phase shift. This method can suppress the ICI significantly with a reduction

Fig. 1. OFDM system with PRC.

in bandwidth efficiency. Partial-response coding (PRC) in the time domain has been studied for single-carrier systems to reduce the sensitivity to time offset [12] without sacrificing the bandwidth. In the frequency domain, the PRC with correlation polynomial $F(D) = 1 - D$ was used to mitigate the ICI caused by carrier frequency offset in [13]. In this letter, we study general frequency-domain PRC for suppressing the ICI caused by Doppler frequency shift or carrier frequency offset.

This letter is organized as follows. In Section II, we describe an OFDM system with PRC and derive the exact ICI expression. With the expression, we obtain the optimum weights of PRC based on minimizing the ICI and analyze its performance in Section III. Then, in Section IV, the numerical and simulation results are presented to demonstrate the performance improvement of OFDM systems with optimum PRC.

II. ICI FOR OFDM WITH PRC

The baseband model of OFDM with PRC is shown in Fig. 1. At the transmitter, the modulated signal is encoded by PRC. Let x_k be the symbols to be transmitted and c_i be the weights for PRC with unit norm, i.e.,

$$\sum_{i=0}^{K-1} c_i^2 = 1$$

where K is the number of weights of PRC. Without loss of generality, we assume $E|x_k|^2 = 1$ and $E(x_k x_l^*) = 0$ for $k \neq l$. Then the transmitted signal at the k th subchannel can be expressed as

$$s_k = \sum_{i=0}^{K-1} c_i x_{k-i}. \quad (1)$$

The coded signals can be recovered by a maximum-likelihood (ML) sequence detector [14] at the receiver. The OFDM signal in time domain is

$$y(t) = \sum_k s_k e^{j2\pi f_k t}, \quad 0 \leq t < T_s \quad (2)$$

where $f_k = f_0 + k\Delta f$ is the frequency of the k th subchannel, $\Delta f = 1/T_s$ is the subchannel spacing, and T_s is the symbol

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duration. After passing through a time-varying channel with the impulse response $h(t, \tau)$, the received signal is

$$\tilde{y}(t) = \int h(t, \tau) y(t - \tau) d\tau. \quad (3)$$

The channel impulse response for the frequency-selective fading channel can be described by

$$h(t, \tau) = \sum_l \gamma_l(t) \delta(\tau - \tau_l) \quad (4)$$

where τ_l is the delay of the l th path, and $\gamma_l(t)$ is the corresponding path gain. Here, we assume that the complex stochastic processes $\gamma_l(t)$ are independent for different l 's and have the same statistics but different variance ε_l . For simplicity, we first consider the flat-fading channel and omit the subscription l . Then the received signal becomes

$$\tilde{y}(t) = \gamma(t) y(t).$$

The demodulated signal can be written as

$$\tilde{s}_m = \frac{1}{T_s} \int_0^{T_s} \tilde{y}(t) e^{-j2\pi f_m t} dt. \quad (5)$$

Here, the integration is used instead of the discrete Fourier transform (DFT). As indicated in [5], the difference is negligible. It has been derived in [5] that the demodulated signal can be expressed as

$$\tilde{s}_m = a_0 s_m + \sum_{k \neq m} a_{m-k} s_k \quad (6)$$

where a_l is defined as

$$a_l = \frac{1}{T_s} \int_0^{T_s} \gamma(t) e^{-j2\pi l \Delta f t} dt. \quad (7)$$

Here, a_0 is the gain of the desired signal and a_l , for $l \neq 0$, represents the gain of the interfering signals from other subchannels. For time-invariant channels, $\gamma(t)$ is a constant and $a_l = 0$ for $l \neq 0$; consequently, there is no ICI. In general, for time-varying channels, $a_l \neq 0$ for some $l \neq 0$, the ICI exists.

The total ICI power is defined as

$$P_{\text{ICI}} = E \left| \sum_{l \neq 0} a_l s_{m-l} \right|^2. \quad (8)$$

For OFDM without PRC [5], it is

$$\tilde{P}_{\text{ICI}} = 1 - 2 \int_0^{f_d} P(f) \text{sinc}^2(f T_s) df \quad (9)$$

where f_d is the maximum Doppler frequency shift, $P(f)$ is the power spectral density of $\gamma(t)$, and $\text{sinc}(x) = \sin(\pi x)/(\pi x)$.

It is derived in the appendix that P_{ICI} for OFDM with PRC can be expressed as

$$P_{\text{ICI}} = 1 - 2 \int_0^{f_d} P(f) \text{sinc}^2(f T_s) df + I_{\text{PRC}}(\mathbf{c}_K, f_d T_s) \quad (10)$$

where

$$\begin{aligned} I_{\text{PRC}}(\mathbf{c}_K, f_d T_s) &= \int_0^{f_d} \frac{8 \sin(\pi f T_s)^2 P(f)}{\pi^2} \left(\sum_{k=1}^{K-1} \sum_{i=0}^{K-1-k} \frac{c_i c_{i+k}}{k^2 - f^2 T_s^2} \right) df \\ &= \int_0^{f_d} \frac{8 \sin(\pi f T_s)^2 P(f)}{\pi^2} I(\mathbf{c}_K, f T_s) df \end{aligned} \quad (11)$$

with

$$\mathbf{c}_K = [c_0, c_1, \dots, c_{K-1}]^T$$

and

$$I(\mathbf{c}_K, f T_s) = \sum_{k=1}^{K-1} \sum_{i=0}^{K-1-k} \frac{c_i c_{i+k}}{k^2 - f^2 T_s^2}.$$

III. OPTIMUM PRC FOR OFDM

In the previous section, we have introduced OFDM with PRC and derived the expression of the ICI power. In this section, we will investigate optimum PRC weights and analyze its performance.

A. Optimum Weights for PRC

From (10), the ICI power includes two parts: the ICI power for OFDM without PRC; and $I_{\text{PRC}}(\mathbf{c}_K, f_d T_s)$ contributed by PRC. Therefore, the only way to reduce the ICI power is to minimize $I_{\text{PRC}}(\mathbf{c}_K, f_d T_s)$ with respect to $\mathbf{c}_K$. In the integral of $I_{\text{PRC}}(\mathbf{c}_K, f_d T_s)$, the first part, $(8 \sin(\pi f T_s)^2 P(f)/\pi^2)$, is always positive. So we need only make the last part as small as possible. When $f^2 T_s^2 \ll 1$, the last part can be approximated as

$$I(\mathbf{c}_K, f T_s) \approx g(\mathbf{c}_K) = \sum_{k=1}^{K-1} \sum_{i=0}^{K-1-k} \frac{c_i c_{i+k}}{k^2} = \mathbf{c}_K^T \mathbf{R}_K \mathbf{c}_K \quad (12)$$

where $\mathbf{R}_K$ is defined as

$$\mathbf{R}_K = \begin{bmatrix} 0 & \frac{1}{2} & \frac{1}{8} & \cdots & \frac{1}{2(K-1)^2} \\ \frac{1}{2} & 0 & \frac{1}{2} & \cdots & \frac{1}{2(K-2)^2} \\ \frac{1}{8} & \frac{1}{2} & 0 & \cdots & \frac{1}{2(K-3)^2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{1}{2(K-1)^2} & \frac{1}{2(K-2)^2} & \frac{1}{2(K-3)^2} & \cdots & 0 \end{bmatrix}.$$

From (12), it is clear that the optimum $\mathbf{c}_K$ that minimizes the ICI is the normalized eigenvector of $\mathbf{R}_K$ corresponding to the smallest eigenvalue. In this case

$$I_{\min}(\mathbf{c}_K, f T_s) \approx g_{\min}(\mathbf{c}_K) = \lambda_0^{(K)}$$

where $\lambda_0^{(K)} \leq \lambda_1^{(K)} \leq \dots \leq \lambda_{K-1}^{(K)}$ are the ordered eigenvalues of $\mathbf{R}_K$.

When $K \rightarrow \infty$, we can obtain the limit of $g_{\min}(\mathbf{c}_K)$ using [17, Corollary 4.2]

$$\lim_{K \rightarrow \infty} g_{\min}(\mathbf{c}_K) = \min_{\lambda \in \mathcal{R}} f(\lambda) \quad (13)$$

where $f(\lambda)$ is defined as

$$f(\lambda) = \sum_{k \neq 0} \frac{1}{2k^2} e^{jk\lambda}. \quad (14)$$

The minimum of $f(\lambda)$ can be found by setting its derivative with respect to λ to be zero, that is

$$\frac{d}{d\lambda} f(\lambda) = - \sum_{k=1}^{\infty} \frac{1}{k} \sin(k\lambda) = 0. \quad (15)$$

Solving (15) for λ and substituting it into (13) leads to

$$\lim_{K \rightarrow \infty} g_{\min}(\mathbf{c}_K) = \sum_{k=1}^{\infty} \frac{(-1)^k}{k^2} = -\frac{\pi^2}{12}. \quad (16)$$

Once $g_{\min}(\mathbf{c}_K)$ is found, the total ICI power for OFDM with optimum PRC can be calculated using (10).

B. Performance Analysis

The exact expression of the ICI is too complicated to provide much insight. In many cases, it is difficult to calculate the ICI because the exact power spectrum is not available. Here, we derive an approximate expression using a similar method to [5].

If $fT_s \ll 1$, we have the following approximation:

$$\sin^2(\pi f T_s) \approx (\pi f T_s)^2. \quad (17)$$

Substituting (12) and (17) into (11), we can obtain the following expression:

$$\begin{aligned} I_{\text{PRC}}(\mathbf{c}_K, f_d T_s) &\approx \int_0^{f_d} \frac{8(\pi f T_s)^2}{\pi^2} P(f) g(\mathbf{c}_K) df \\ &= 4\alpha g(\mathbf{c}_K) (f_d T_s)^2 \end{aligned} \quad (18)$$

where α is defined as

$$\alpha = \frac{2}{T_s^2} \int_0^{f_d} f^2 P(f) df \quad (19)$$

which is dependent on the spectral density of $\gamma(t)$. It is calculated in [5] that $\alpha = 1/2$ for the classical Doppler spectrum (Jakes' model) and $\alpha = 1$ for OFDM with carrier offset.

Using [5, eq. (3.10)] and (18), we can get an approximate expression of the ICI for PRC signals as

$$P_{\text{ICI}} \approx \left[\frac{\pi^2}{3} + 4g(\mathbf{c}_K) \right] \alpha (f_d T_s)^2. \quad (20)$$

The expression is much simpler than the exact one. From (18), the total ICI is decided by three factors: α ; $f_d T_s$; and $g(\mathbf{c}_K)$. $f_d T_s$ can be regarded as the normalized Doppler frequency shift. $g(\mathbf{c}_K)$ represents the ICI reduction due to PRC. For OFDM without PRC [5]

$$\tilde{P}_{\text{ICI}} \approx \frac{\pi^2}{3} \alpha (f_d T_s)^2. \quad (21)$$

Then, the performance gain of PRC is

$$\begin{aligned} \text{Gain(dB)} &= \tilde{P}_{\text{ICI}}(\text{dB}) - P_{\text{ICI}}(\text{dB}) \\ &\approx -10 \log_{10} \left[1 + \frac{12}{\pi^2} g(\mathbf{c}_K) \right]. \end{aligned}$$

Table I lists the optimum weights, the corresponding $g(\mathbf{c}_K)$, and the performance gain, according to the above results. From the table, the value of $g(\mathbf{c}_K)$ is close to the limit when $K = 4$.

In the above discussion, we obtained the optimum PRC and analyzed its performance for flat-fading channels. For frequency-selective fading channels, it is usually assumed that a cyclic extension is inserted ahead of each OFDM symbol to combat the interblock interference (IBI). Then, the expression of the ICI for frequency-selective fading channels can be derived in a similar way

$$P_{\text{ICI}} = 1 - 2 \int_0^{f_d} P(f) \sin^2(f T_s) df + \tilde{I}_{\text{PRC}}(\mathbf{c}_K, f_d T_s) \quad (22)$$

where

$$\tilde{I}_{\text{PRC}}(\mathbf{c}_K, f_d T_s) = \int_0^{f_d} \frac{8 \sin(\pi f T_s)^2 P(f)}{\pi^2} \tilde{I}(\mathbf{c}_K, f T_s) df \quad (23)$$

TABLE I

K	$\mathbf{c}_K$	$-g(\mathbf{c}_K)$	Gain(dB)
1	1	0	0
2	0.7071, -0.7071	0.5000	4.066
3	-0.4775, 0.7376, -0.4775	0.6474	6.719
4	-0.3501, 0.6144, -0.6144, 0.3501	0.7137	8.786
∞		0.8225	—

Fig. 2. Comparison of the ICI power due to Doppler frequency shift.

and

$$\tilde{I}(\mathbf{c}_K, f T_s) = \sum_{k=1}^{K-1} \sum_{i=0}^{K-1-k} \sum_l \varepsilon_l e^{j2\pi k \Delta f \tau_l} \frac{c_i c_{i+k}}{k^2 - f^2 T_s^2}. \quad (24)$$

Usually, the path delay τ_l is much smaller than an OFDM symbol duration. Then for small-size PRC, the term $\varepsilon_l e^{j2\pi k \Delta f \tau_l}$ approximates to constant. Therefore, the optimum PRC with small size obtained for flat-fading channels are applicable to the frequency-selective fading channel.

IV. NUMERICAL AND SIMULATION RESULTS

In this section, we present some numerical and simulation results to show the performance improvement of OFDM with optimum PRC.

A. Numerical Results

To examine the performance improvement, we compare the ICI value of OFDM with and without PRC.

Fig. 2 presents a comparison of ICI power for the classical Doppler spectrum (Jakes' model)

$$P_J(f) = \begin{cases} \frac{1}{\pi f_d} \frac{1}{\sqrt{1 - (f/f_d)^2}}, & \text{if } |f| < f_d \\ 0, & \text{else.} \end{cases} \quad (25)$$

From the figure, the ICI power is reduced by about 4.0 dB for two-tap and about 6.2 dB for three-tap PRC, respectively.

The optimum PRC can also reduce the ICI due to carrier offset as shown in Fig. 3. There is about 4.5-dB improvement for two-tap PRC.

Fig. 3. Comparison of the ICI power due to carrier offset.

 Fig. 4. WER of OFDM with and without PRC ($f_d T_s = 0.1$).

B. Simulation Results

Here, we present our simulation results for the performance of PRC. The system model and parameters used in our simulation are the same as those in [20]. The entire channel bandwidth (800 kHz) is divided into 128 subchannels. 120 tones at the middle are used to transmit data. The rest tones on each side are used as guard tones. Quaternary phase-shift keying (QPSK) with coherent demodulation is used. A (40,20) Reed–Solomon (R–S) code, with each code symbol consisting of three QPSK symbols grouped in frequency, is used so that each block forms an R–S codeword. The noise is assumed to be white Gaussian with zero-mean and variance σ_n^2 , then the signal-to-noise ratio (SNR) is $1/\sigma_n^2$. The time-varying fading channel is generated using Jakes' model. A cyclic prefix of length larger than the delay spread is used to avoid IBI.

Fig. 4 shows word-error rate (WER) versus SNR for a hilly-terrain (HT) channel. From the figure, OFDM with PRC has some performance loss at lower SNR. However, for the system at a high SNR, the ICI is the dominant impairment and PRC has better performance than without PRC. And the error floor

Fig. 5. Error-floor comparison for OFDM signal with and without PRC.

due to Doppler frequency shift is reduced from 10^{-2} to 10^{-3} . Because PRC has some performance loss when $K > 2$, as for time-domain PRC [12], the performance of three-tap PRC is not as good as that of two-tap PRC, though three-tap PRC has better performance for ICI suppression.

The error floors versus normalized Doppler frequency shift are shown in Fig. 5. From the figure, to ensure WER below 1%, the maximum tolerable Doppler frequency shift for OFDM without PRC is about 10% of subchannel spacing, and it is relaxed to be 15% for OFDM with two-tap or three-tap PRC.

V. CONCLUSION

In this letter, we investigated frequency-domain PRC to reduce the ICI caused by time variation of wireless channels. The optimum weights for PRC that minimizes the ICI power are obtained. The numerical and simulation results show that PRC effectively reduces the error floor caused by Doppler frequency shift or carrier offset. Even though our discussions are for flat-fading channels, the obtained optimum PRCs are also applicable to the frequency-selective channels.

APPENDIX DERIVATION OF ICI

Here, we derive the ICI power due to Doppler frequency shift for OFDM with PRC. First, we calculate the autocorrelation of a_l , that is

$$E(a_m a_n^*) = E \left\{ \frac{1}{T_s} \int_0^{T_s} \gamma(t) e^{-j2\pi m \Delta f t} dt \frac{1}{T_s} \int_0^{T_s} \gamma^*(\tau) e^{-j2\pi n \Delta f \tau} d\tau \right\} \quad (\text{A.1})$$

where $m \neq n$. By (7) and [18, eq. (10–50)]

$$E(a_m a_n^*) = \int_{-1}^1 r(T_s x) \frac{-\sin[\pi(m-n)x]}{\pi(m-n)} e^{-j2\pi(m+n/2)x} dx \quad (\text{A.2})$$

where $r(\tau)$ is the autocorrelation of $\gamma(t)$. Then the ICI power is then

$$\begin{aligned}
 P_{\text{ICI}} &= E \left| \sum_{l \neq 0} a_l s_{m-l} \right|^2 \\
 &= E \left| \sum_{l \neq 0} a_l \sum_{i=0}^{K-1} c_i x_{m-l-i} \right|^2 \\
 &= \sum_{n \neq i} \sum_{i=0}^{K-1} c_i^2 E |a_{n-i}|^2 \\
 &\quad + 2 \sum_{\substack{n \neq i \\ n \neq i+k}} \sum_{k=0}^{K-1} \sum_{i=0}^{K-1-k} c_i c_{i+k} E(a_{n-i} a_{n-i-k}^*) \\
 &= \sum_{l \neq 0} E |a_l|^2 + 2 \sum_{k=1}^{K-1} \sum_{i=0}^{K-1-k} c_i c_{i+k} T_k
 \end{aligned}$$

where we have used the identity $\sum_{i=0}^{K-1} c_i^2 = 1$ and the definition

$$T_k = \sum_n E(a_{n-i} a_{n-i-k}^*) - E(a_0 a_{-k}^*) - E(a_k a_0^*). \quad (\text{A.3})$$

Substituting (A.2) into (A.3), we have

$$\begin{aligned}
 T_k &= \int_{-1}^1 r(T_s x) \frac{-\sin(\pi k |x|)}{\pi x} \\
 &\quad \times \left[\sum_n e^{-j2\pi(2(n-i)-k/2)x} - 2 \cos(\pi k x) \right] dx. \quad (\text{A.4})
 \end{aligned}$$

From [19, eqs. (3.2) and (3.5)]

$$\sum_{n=-\infty}^{\infty} e^{-j2\pi n x} = \sum_{m=-\infty}^{\infty} \delta(x - m).$$

Consequently

$$\begin{aligned}
 T_k &= \int_{-1}^1 r(T_s x) \frac{-\sin(\pi k |x|)}{\pi k} \left[\sum_m \delta(x-m) e^{j\pi k x} - 2 \cos(\pi k x) \right] dx \\
 &= \int_{-1}^1 r(T_s x) \frac{2 \sin(\pi k |x|) \cos(\pi k x)}{\pi k} dx \\
 &= \int_{-1}^1 \frac{\sin(2\pi k |x|)}{\pi k} \left[2 \int_0^{f_d} P(f) \cos(2\pi f T_s x) df \right] dx \\
 &= \int_0^{f_d} \frac{4 \sin^2(\pi f T_s) P(f)}{\pi^2 (k^2 - f^2 T_s^2)} df. \quad (\text{A.5})
 \end{aligned}$$

From [5]

$$\sum_{l \neq 0} E |a_l|^2 = 1 - 2 \int_0^{f_d} P(f) \text{sinc}^2(f T_s) df \quad (\text{A.6})$$

$$P_{\text{ICI}} = 1 - 2 \int_0^{f_d} P(f) \text{sinc}^2(f T_s) df + I_{\text{PRC}}(c_K, f_d T_s) \quad (\text{A.7})$$

where

$$\begin{aligned}
 I_{\text{PRC}}(c_K, f_d T_s) &= \\
 &\int_0^{f_d} \frac{8 \sin(\pi f T_s)^2 P(f)}{\pi^2} \left(\sum_{k=1}^{K-1} \sum_{i=0}^{K-1-k} \frac{c_i c_{i+k}}{k^2 - f^2 T_s^2} \right) df. \quad (\text{A.8})
 \end{aligned}$$

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