A Novel ICI Triple Cancellation Scheme in Fast Time-varying Environment for OFDM Systems

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Abstract. In fast time-varying environment, orthogonal frequency division multiplexing (OFDM) systems lose the orthogonality between subcarriers due to the Doppler effect, resulting in inter-carrier interference (ICI), which greatly affects the performance of the communication system. Based on the analysis of the principle of ICI generation in time-varying environment, an ICI triple cancellation scheme is proposed to reduce the ICI of the OFDM systems in fast time-varying environment. In the scheme, the ICI self-cancellation modulation is performed at the transmitter of the OFDM system. Then, the time-varying channel is modeled as a linearly time-varying (LTV) model for ICI dual cancellation. Finally, the ICI self-cancellation demodulation is executed at the receiver of the system. Simulation experiment results show that the proposed ICI triple cancellation scheme can achieve a better effect of ICI cancellation than ICI self-cancellation scheme and ICI dual cancellation scheme, improving the performance of the communication system.

1. Introduction
Orthogonal frequency division multiplexing (OFDM) is widely used in wireless communication systems due to its advantages of high-speed data transmission capability, high spectral efficiency, robustness to the multi-path interference, flexible modulation mode and low price, etc., and it has become the main transmission technology of high-speed wireless communication systems and the core technology of many standards. Because the subcarriers of the OFDM are orthogonal to each other, the frequency spectrum of the subcarriers is allowed to overlap each other, so that OFDM has higher spectral efficiency.

However, in practical applications, the OFDM system is often in a mobile environment, and the resulting Doppler effect leads to the loss of orthogonality among the subcarriers of OFDM, which inevitably brings about inter-carrier interference (ICI). ICI seriously affects the performance of the communication system, especially in the high-speed mobile environment. Therefore, it is of great significance to study the ICI cancellation scheme in the OFDM system.

At present, the more commonly used ICI cancellation schemes mainly include frequency-domain equalization scheme [1], time-domain windowing scheme [2], and the ICI self-cancellation scheme [3]-[4], and so on. Frequency-domain equalization scheme is too complex to implement relatively. Time-domain windowing scheme has the defect of spectral leakage. The self-cancellation method is an easy and effective way to cancel ICI compared with other methods.

To further improve the performance of the OFDM systems in fast time-varying environment, an ICI triple cancellation scheme is proposed in this paper. ICI dual cancellation is achieved by modeling
the time-varying channel as a LTV model, and ICI self-cancellation modulation and demodulation are performed at the transmitter and the receiver of the OFDM system, respectively, to enhance the ICI cancellation effect of the system. Simulation experiment results show that compared with the ICI self-cancellation scheme and dual cancellation scheme, the system after ICI triple cancellation can better suppress the impact of ICI and improve the performance of the OFDM systems in fast time-varying environment.

2. Related work

The ICI self-cancellation scheme is a simple way for ICI reduction. Zhao et al. [4] propose for the first time the ICI self-cancellation scheme, and its core idea is that the transmitted data and its opposite number are modulated onto the adjacent subcarrier at the transmitter to cancel part of the ICI, and then the data on the odd subcarriers are inverted and plused on the even subcarriers at the receiver to further cancel the ICI.

Since then, many more improved ICI self-cancellation schemes have been put forward in succession [5]-[7]. ICI self-cancellation scheme has the advantages of simple implementation and better effects of ICI cancellation, but its spectral efficiency is low. In order to improve the spectral efficiency of ICI self-cancellation algorithm, Liu et al. [8] put forward an ICI self-cancellation scheme based on differential coding, by differential encoding the data on all subcarriers at the transmitter and making the corresponding differential decoding at the receiver. The scheme can improve the spectral efficiency, but the differential encoding and decoding exacerbate the influence of channel Gaussian noise, so the performance of the scheme is poor when the signal to noise ratio (SNR) is low. Mostofi et al. [9] firstly come up with an ICI cancellation scheme based on LTV model, which is named as single cancellation scheme, but the effect of cancellation is poor. Kwak et al. [10] improve the single cancellation scheme, introducing the ICI pre-cancellation process by using the first sending OFDM header or the last OFDM symbol to obtain the channel information and pre-cancel the received signal by ICI, which improves the accuracy of subsequent cancellation.

In recent years, some ICI joint cancellation schemes have been proposed one after another. Liu et al. [11] combine the ICI self-cancellation scheme with the time-domain windowing scheme, by using the cosine window multiplied by the transmitted data after IFFT. ICI is effectively cancelled and the band-shaped frequency domain channel matrix is estimated by complex exponential basis expansion model (CE-BEM), which improves the performance of bit error rate (BER) of the system. Li et al. [12] put forward an ICI self-cancellation scheme based on symmetric subcarriers, which is combined with the time-domain cosine windowing scheme to improve the BER of the system. However, it has the disadvantage of poor performance in low SNR environment and low spectral efficiency. Singh et al. [13] come up with a joint cancellation scheme based on ICI self-cancellation and maximum likelihood estimation method. The performance of the system in this scheme has been improved compared with the ICI self-cancellation scheme and the maximum likelihood estimation scheme alone.

3. System Model

Assuming that the number of subcarriers in an OFDM system is $N$ and the inter symbol interference (ISI) is canceled by inserting a cyclic prefix, the time domain form of the signal received at the receiver can be expressed as:

$$y = hx + w$$  \hspace{1cm} (1)

where $\mathbf{x} = [x_0, x_1, ..., x_{N-1}]^T$, $\mathbf{y} = [y_0, y_1, ..., y_{N-1}]^T$, respectively, represent the collection of all transmitted data and received data in the OFDM symbol, $w$ denotes the additive Gaussian white noise in the time domain, and $h$ represents a time-domain channel matrix with a size of $N \times N$, which specifically can be expressed as:
where \( L \) represents the number of multi-path, and \( h(n, l) \) denotes the channel response of the \( l^{th} \) tap at the \( n^{th} \) sampling point, \( 0 \leq n \leq N - 1, 0 \leq l \leq L - 1 \). With FFT on the Eqn. (1), the input-output relationship in the frequency domain of the OFDM system can be represented as:

\[
Y = Fy = Fh^H X + Fw = HX + W
\]

where \( F, F^H \) represent the FFT matrix and IFFT matrix of the \( N^{th} \) point, respectively, and \( (\mathbf{H})^H \) represents the Hermitian conjugate transpose of the matrix. The elements in \( F \) are given by:

\[
F(n, m) = \frac{1}{\sqrt{N}} e^{-j \frac{2\pi nm}{N}}
\]

If the channel is not time-varying, the condition \( h(0, l) = h(1, l) = \cdots = h(N - 1, l) \) is established. The channel frequency domain matrix \( H \) is a diagonal matrix with a size of \( N \times N \), and the diagonal elements represent the frequency domain response of the channel, which means that at this time each subcarrier in the OFDM system is orthogonal without ICI. However, in practice, the assumption \( h(0, l) = h(1, l) = \cdots = h(N - 1, l) \) generally cannot be established due to following reasons such as high-speed movement, so the channel comes to be a time-varying one. In this case, the channel frequency domain matrix becomes an approximately banded matrix, resulting in ICI.

For an approximately banded channel frequency domain matrix \( H \), it can be decomposed into a channel matrix without ICI composed of diagonal elements of \( H \) and a channel matrix with ICI composed of off-diagonal elements of \( H \). Without loss of generality, the frequency domain input-output relationship of the \( n^{th} \) symbol in the OFDM system can be expressed as:

\[
Y_n = H_n^{ave} X_n + H_n^{ICI} X_n + W_n
\]

where \( H_n^{ave} \) denotes the no ICI channel matrix with a size of \( N \times N \), its diagonal elements are equal to the diagonal elements of channel frequency domain matrix \( H \), and its remaining elements are equal to zero. \( H_n^{ICI} \) denotes the ICI channel matrix with a size of \( N \times N \), its diagonal elements are equal to zero, and its remaining elements are equal to the off-diagonal elements of channel frequency domain matrix \( H \).

### 4. ICI Triple Cancellation Scheme

The basic principle of the ICI self-cancellation scheme is to perform ICI self-cancellation modulation on the transmitted signal at the transmitter end and perform corresponding ICI self-cancellation demodulation on the received signal at the receiver to suppress the impact of ICI. The classic ICI self-cancellation scheme is to perform the data-conversion on adjacent subcarriers, which can be expressed as:

\[
\begin{align*}
X_n' &= X_n, & n &= 0, 2, 4, \cdots, N - 1 \\
X_n' &= -X_n, & n &= 0, 2, 4, \cdots, N - 1
\end{align*}
\]

Then many other self-cancellation schemes, such as the weighted conjugate of the complex number of adjacent data, and the conjugate of the symmetric data-conversion scheme, has been put forward in succession. Considering the existence of ICI, the received signal of the OFDM system can be represented as:

\[
Y_m = \sum_{n=0}^{N-1} X_n^* S(n - m) + W_m
\]

where \( N \) denotes the number of subcarriers, \( Y_n \) represents the received signal, \( X_n \) denotes the transmitted signal, \( W_m \) represents the noise interference, and \( S(n - m) \) denotes the ICI coefficient,
which represents the interference caused by the data of the $n$th subcarrier on the data of the $m$th subcarrier, $0 \leq m \leq N - 1, 0 \leq n \leq N - 1$. If data-conversion is performed on the adjacent subcarriers, only one symbol is transmitted for each pair of subcarriers, and the received signals on the $m$th subcarrier and the $(m+1)$th subcarrier can be derived as:

$$Y'_m = \sum_{n=0,2,4,...}^{N-2} X_n [S(n-m) - S(n+1-m)] + W_m$$

(8)

$$Y'_{m+1} = \sum_{n=0,2,4,...}^{N-2} X_n [S(n-m-1) - S(n-m)] + W_{m+1}$$

(9)

Therefore, the ICI coefficient after ICI self-cancellation modulation is given by:

$$S(n-m) = S(n-m) - S(n+1-m)$$

(10)

Since the ICI coefficient $S(n-m)$ has little change in adjacent subcarriers, the data on the $(m+1)$th subcarrier can better offset the ICI generated by the $m$th subcarrier.

Although ICI self-cancellation scheme is easy to implement and has a good effect of ICI cancellation, its spectral efficiency is very low due to the reason that one symbol is transmitted by two subcarriers. In this regard, ICI self-cancellation scheme based on differential coding can be utilized, it perform the transmitted data as differential encoding instead to perform data-conversion on its adjacent subcarriers at the transmitter of the system, and the transmitted signal can be expressed as:

$$X'_n = \begin{cases} X_0, & n = 0 \\ X_n - X_{n-1}, & 1 \leq n \leq N - 1 \end{cases}$$

(11)

Then the signal received by the system can be represented as:

$$Y'_m = \sum_{n=0}^{N-1} X'_n S(n-m) = \sum_{n=0}^{N-1} S(n-m)(X_n - X_{n-1})$$

(12)

Because the interference between adjacent subcarriers is the largest, the ICI can be suppressed to a certain extent by differential coding.

For the $n$th OFDM symbol, the relationship between the channel response $h_n(m,l)$ of the $l$th path at the $m$th sampling point and the channel response $h_n(m_0,l)$ of the $l$th path at the $m_0$th sampling point in the LTV model is given by:

$$h_n(m,l) = h_n(m_0,l) + a_n(l)(m - m_0)$$

(13)

where $a_n(l)$ represents the envelope of the channel, characterizing the time-varying characteristic of the channel.

In the LTV model, a better effect of ICI cancellation is obtained by modeling three consecutive OFDM symbols [10], then the time-domain input-output relationship of the OFDM system can be expressed as:

$$y_n = h_n^{mid}f_{th}X_n + (b_p a_{n,p} + b_f a_{n,f} + e_n)f_{th}X_n + w_n$$

(14)

where $h_n^{mid}$ denotes the Toeplitz matrix composed of the channel response of all paths at the $(\frac{N}{2} - 1)$th sampling point of the $n$th OFDM symbol, and the first column of the Toeplitz matrix is $[h_n(\frac{N}{2} - 1, 0), h_n(\frac{N}{2} - 1, 1), \cdots, h_n(\frac{N}{2} - 1, L - 1), 0, \cdots, 0]$, $a_{n,p}$ represents the time-varying characteristic of the channel from the midpoint of the previous symbol to the midpoint of the current symbol, similarly, $a_{n,f}$ denotes the time-varying characteristic of the channel from the midpoint of the current symbol to the midpoint of the next symbol, $e_n$ represents the modeling error, $b_p$ and $b_f$ both are diagonal matrices, represent the interval between each sample point in the current OFDM symbol and the midpoint, the elements of which are given by:

$$b_p(m,n) = \begin{cases} m - \frac{N}{2} + 1, & 0 \leq m \leq \frac{N}{2} - 1 \\ 0, & else \end{cases}$$

(15)

$$b_f(m,n) = \begin{cases} m - \frac{N}{2} + 1, & \frac{N}{2} - 1 \leq m \leq N - 1 \\ 0, & else \end{cases}$$

(16)
If the signal at the transmitter has been ICI self-cancellation modulated, then perform the FFT on Eqn. (14). The frequency domain form of the received signal can be derived as:

$$Y'_n = H_n^{mid}X'_n + (B_p A_{np} + B_f A_{nf} + E_n)X'_n + W_n$$

(17)

where $X'_n$ represents the data after ICI self-cancellation modulation, and $Y'_n$ denotes the received data at the receiver.

In this paper, the ICI triple cancellation scheme uses the ICI channel matrix estimated from the previous OFDM symbol to perform ICI pre-cancellation at first. The first OFDM symbol can obtain the ICI channel matrix from the first transmitted header. The header in this paper is derived from [14], Schmidl and Cox propose a sequence for estimating time and frequency shift, and the data "0" is transmitted on the odd subcarriers and the PN sequences are transmitted on the even subcarriers. Next, the ICI channel matrix at this time is re-estimated by using the received signal after ICI pre-cancellation to cancel the ICI again. The structure of the OFDM frame in the ICI triple cancellation scheme is shown in figure 1.

**Figure 1.** ICI triple cancellation scheme used in the structure of OFDM frame.

The ICI matrix estimated by the last OFDM symbol or header can be expressed as:

$$\hat{H}_n^{IC{\text{pre}}} = C\hat{A}_{n-1,p}$$

(18)

where $C$ is $Fb_p F^H$ whose $s(m,n)$ element is given by:

$$C(m,n) = \begin{cases} 
\frac{1}{1 - e^{-j\frac{2\pi}{N}m}}, & m \neq n \\
\frac{1}{2}, & m = n 
\end{cases}$$

(19)

The received signal after the ICI pre-cancellation is given as follows,

$$Y_n^{IC,pre} = Y'_n - \hat{H}_n^{IC{\text{pre}}}X'_n$$

$$= H_n^{ave}X'_n - CA_{n-1,p}X'_n$$

$$- CA_{n-1,p}X'_n + W_n + E_nX'_n$$

(20)

where channel matrix without ICI $H_n^{ave} = \Phi \hat{H}_n^{LS}$, $\Phi$ denotes an interpolation matrix, and $\hat{H}_n^{LS}$ denotes a frequency domain channel response matrix at the pilot position, which can be obtained by using a transmitted pilot through least squares (LS) estimation. $\hat{H}_n^{LS}$ can be expressed as:

$$\hat{H}_n^{LS}(k) = \frac{Y_n^{IC,pre}(pk)}{X_n(pk)}$$

(21)

Using the estimated channel matrix without ICI of three consecutive OFDM symbols, the envelope of the channel of the adjacent symbols can be derived as:

$$\hat{A}_{n,p} = \frac{\hat{H}_n^{ave} \hat{H}_{n-1}^{ave}}{N + N_g}$$

(22)

$$\hat{A}_{n,f} = \frac{\hat{H}_n^{ave} \hat{H}_{n+1}^{ave}}{N + N_g}$$

(23)

where $N_g$ represents the length of the cyclic prefix. After the ICI pre-cancellation, ICI re-cancellation matrix can be expressed as:

$$\hat{H}_n^{IC,post} = C_p \hat{A}_{n,p} + C_f \hat{A}_{n,f}$$

(24)
To achieve an accurate pre-demodulation at the receiver, the received signal after the ICI dual cancellation can be derived as:

$$Y^{IIC, pos}_n = Y'_n - H^{IIC, pos}_n \hat{X}'_n$$

$$= H^\text{ave}_n X'_n - (H^{IIC}_n - H^{IIC, pos}_n)X'_n + W'_n + E'_nX'_n$$  \hspace{1cm} (25)

The received signal $\hat{X}^{IIC}_m$ can be obtained by direct equalization with $Y^{IIC, pos}_n$.

The receiver then performs ICI self-cancellation demodulation on the received signal, and subtracts the data on the adjacent subcarriers to further cancel the ICI, which can be represented as:

$$\hat{X}^*_{m} = \frac{1}{2} \left[ \hat{X}^{IIC}_m - \hat{X}^{IIC}_{m+1} \right]$$

$$= \sum_{m=0, 2, 4, \ldots}^{N-2} X_n \left( -S(n - m - 1) + 2S(n - m) - S(n - m + 1) \right) + W_m - W_{m+1}$$  \hspace{1cm} (26)

The ICI coefficient after the ICI self-cancellation demodulation can be expressed as:

$$S^*(n - m) = -S(n - m - 1) + 2S(n - m) - S(n - m + 1)$$  \hspace{1cm} (27)

For the three ICI coefficients, it has proved that $|S^*(n - m)|$ is the smallest and $S(n - m)$ is the largest of the three [1]. Therefore, the signals are performed as the ICI self-cancellation modulation and the ICI self-cancellation demodulation in the OFDM system to better suppress ICI.

If the ICI self-cancellation modulation using a differential coding at the transmitter, then the signals should be performed as receiving decision and forward feedback to realize the differential decoding at the receiver, which is given as follows,

$$\hat{X}^*_{m} = \begin{cases} \text{Dec}(\hat{X}^{IIC}_m), & m = 0 \\ \text{Dec}(\hat{X}^{IIC}_m + \hat{X}^*_{m-1}), & 1 \leq m \leq N - 1 \end{cases}$$ \hspace{1cm} (28)

where $\text{Dec}(\bullet)$ represents the receiving decision of the data at the receiver, and $\hat{X}^*$ represents the output data after the ICI triple cancellation. According to the Equ. (28), it can be seen that the noise on each subcarrier is superimposed by differential coding and decoding, which increases the interference of channel noise on the signal and reduces the performance of the scheme, especially at low SNR. However, the ICI self-cancellation scheme based on differential coding can improve the spectral efficiency of self-cancellation scheme and has better performance in high SNR environment.

Because the ICI self-cancellation scheme can choose the way of differential coding or adjacent data-conversion, so the ICI triple cancellation scheme includes two methods, one is the ICI self-cancellation modulation and demodulation module using differential coding and differential decoding (hereinafter referred to as method 1 proposed), and the other is that the ICI self-cancellation modulation and demodulation module adopting adjacent data-conversion and data-subtraction (hereinafter referred to as method 2 proposed). The remaining modules of the two methods are the same.

5. Simulation Experiment and Analysis

Table I shows the setting of simulation parameters.

Figure 2 depicts the symbol error rate (SER) comparison of each ICI cancellation scheme at different SNR. It can be seen that the performance of the differential coding self-cancellation scheme is the worst. According to Equ. (28), differential coding and decoding exacerbate the interference on the data by the noise and suffer more serious in the low SNR environment.

The performance of the single cancellation scheme is better than that of the differential coding self-cancellation scheme. However, owing to the lack of ICI pre-cancellation, the estimation accuracy of the channel matrix without ICI is low, which in turn influences the effect of subsequent ICI cancellation.
Table 1. Simulation parameters.

| Parameter            | Specification |
|----------------------|---------------|
| Number of subcarriers| 256           |
| Length of cyclic prefix | 30           |
| Length of pilot       | 32            |
| Modulation type       | 16QAM         |
| Sampling interval     | 5μs           |
| Number of multi-paths | 5             |
| Carrier frequency     | 2GHz          |

\[
\text{SNR when the } f_{nd}\text{ is changed} = 0.1 \quad \text{SNR when the } f_{nd}\text{ is changed} = 40\text{dB}
\]

Figure 2. SER comparison at different SNR.

The performance of the adjacent data-conversion self-cancellation scheme is much better than the single cancellation scheme, but its spectral efficiency is low.

As a result of the addition of ICI pre-cancellation, the performance of dual cancellation scheme has been improved to some extent, especially in the high SNR environment, compared with the adjacent data-conversion self-cancellation scheme.

Due to the use of differential coding and decoding in self-cancellation modulation and demodulation, the performance of method 1 proposed in this paper is poor when the SNR is low, but its performance is obviously improved compared with the dual cancellation scheme when the SNR is more than 35dB.

The spectral efficiency in method 2 proposed in this paper is low at the expense of spectral resources, but its performance is optimal among the ICI cancellation schemes.

Figure 3. SNR comparison at different \( f_{nd} \).
Based on the results shown in figure 3, it can be seen the SER comparison of each ICI cancellation scheme at different normalized Doppler frequency shift $f_{nd}$. Because the SNR is $40dB$, the method 1 proposed in this paper has less interference by noise, and its performance is better.

6. Conclusion
The OFDM system inevitably generates ICI under high-speed mobile environment due to Doppler effect, which greatly affects the performance of the communication system. In this paper, an ICI triple cancellation scheme is proposed to reduce the ICI of the OFDM systems in fast time-varying environment.

In view of the defect of low spectral efficiency of traditional ICI self-cancellation scheme, this paper introduces differential coding and decoding method into ICI self-cancellation modulation and demodulation, which improve the spectral efficiency of the system. Through the simulation experiment and analysis, it can be seen that when the spectral resources of the system are tight and the SNR is relatively high, method 1 can be adopted, and the ICI self-cancellation modulation and demodulation module using differential coding and differential decoding. When the spectral resources of the system are sufficient, method 2 proposed in this paper has a better effect of ICI cancellation, and the ICI self-cancellation modulation and demodulation module adopting adjacent data-conversion and data-subtraction.

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