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Repeated correlative coding scheme for mitigation of inter-carrier interference in an orthogonal frequency division multiplexing system

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Abstract: In this study, a repeated correlative coding scheme is proposed to combat the inter-carrier interference (ICI) caused by the frequency offset in orthogonal frequency division multiplexing (OFDM) communication systems. This proposed scheme combine two ideas of the well-known methods, which are the coding of adjacent subcarriers with antipodal of the same data symbol (ICI self-cancellation) and correlative coding. A mathematical expression for the carrier-to-interference ratio (CIR) by using this proposed repeated correlative coding scheme is derived. The simulated result of CIR for the proposed scheme is significantly improved compared to the correlative coding as well as a self-cancellation scheme. The bit-error-rate (BER) of the proposed scheme is also compared with the ICI self-cancellation scheme and correlative coding scheme, which is comparable to that of the ICI self-cancellation scheme and better than the correlative coding scheme.

1 Introduction

Orthogonal frequency division multiplexing (OFDM) is a multi-carrier modulation technique, which is widely used in various communication systems and standards because of its high data rate, high spectral efficiency and robustness to the frequency selective channels [1–18]. However, the OFDM is susceptible to the phase-noise and multi-carrier frequency offset between the transmitter and receiver local oscillator, which causes number of impairments including disrupting the orthogonality among subcarriers and introduces inter-carrier interference (ICI) that would significantly degrade the system performance [3–9]. Currently, five different approaches for reducing the ICI have been developed including: ICI self-cancellation [4], frequency-domain equalisation [1], time-domain windowing scheme [2], frequency offset estimation and compensation techniques [6, 8, 17, 18], correlative coding [5, 12–15] and the conjugate cancellation scheme [11, 19]. The most commonly used ICI counter measure methods are frequency-domain equalisation [1], which uses training signal that is one of the most commonly used methods and time-domain windowing [2]. However, the use of training symbol or redundant subcarriers reduces the bandwidth efficiency. A simple and most effective method, called the self-cancellation scheme, has been proposed by Zhao and Haggman [4], which greatly reduces the ICI with little additional computational complexity. This scheme significantly reduces the ICI at the cost of reducing the transmission rate. Besides its low-computational complexity, another very important advantage of the self-cancellation scheme is that since the frequency shift is not estimated, this technique can also be useful to mitigate ICI created by a spread of frequency shifts in the signal, such as a Doppler spread resulting from a time-variable channel. Zhao *et al.* [5] proposed the correlative coding between the signals modulated on subsequent subcarriers in binary phase-shift keying OFDM but this scheme does not improve carrier-to-interference ratio (CIR) significantly. The conjugate cancellation scheme is proposed in [6]. In this scheme, two sequences are transmitted in each data symbol. First, sequence is original received sequence and another sequence is conjugate of the original sequence. Thus, the two sequences are conjugate of each other rather than adjacent subcarriers with opposite polarities in order to cancel the ICI.

In this paper, an expression for the ICI power of OFDM systems using repeated correlative coding as a function of the frequency offset is derived and further evaluated the CIR power. The average CIR power is used as the ICI level indicators and theoretical CIR expression is derived for the proposed scheme. The CIR performance of the proposed system is compared with that of CIR of ICI self-cancellation scheme [4], correlative coding scheme [5] and normal OFDM system. The bit-error-rate (BER) of the proposed scheme is also compared with the ICI self-cancellation scheme [4] and correlative coding scheme [5], which shows that the CIR obtained using the repeated correlative coding method, is significantly enhanced. The rest of the paper is organised as follows. Section 2 discusses about the system model of the OFDM with repeated correlative coding. Section 3 concerns with the ICI mechanism. In Section 4, the proposed ICI cancellation technique is discussed. In Section 5, analysed and simulated of the proposed ICI cancellation technique is discussed. Finally, Section 6 concludes the work.

2 System model

Fig. 1 shows a simplified block diagram of the binary phase-shift keying (BPSK) OFDM system using repeated correlative coding scheme. The binary signal sequence after BPSK modulation is expressed as m_k, where k is the subcarriers index. m_k can take values of 1, -1 that fulfil the zero-mean and independence condition. The symbols on two adjacent subcarriers have an 180° phase difference between them such that $m_1 = -m_0,\ m_3 = -m_2,\ \ldots,\ m_{N-1} = m_{N-2}$ [4]. The correlative coding is performed using $F(D) = (1 - D)$ [5], where D denotes the unit delay, which generates new sequence.

$$g_k = m_k - m_{k-1} \tag{1}$$

Then the coded symbols g_k, $k \in [0, N/2 - 1]$ are modulated on $N/2$ subcarriers. Equation (1) introduces correlation between the adjacent symbols (g_k, g_{k-1}), which implies that the independence condition is no longer maintained. The error propagation in decoding procedure can be avoided using the pre-coding technique [20]. The normal OFDM system can be achieved by removing the repeating code, correlative code and decoding blocks from Fig. 1.

3 ICI mechanism

In the OFDM communication system, the received signal on subcarrier k is written as [4]

$$Y_k = m_k S_0 + \sum_{l=0, l \neq k}^{N-1} m_l S_l + n_k \quad k = 0, 1, \ldots, N-1 \tag{2}$$

where N is the total number of subcarriers and n_k is an additive white Gaussian noise. The first term in the right-hand side of (2) represents the desired signal and second term is the ICI components. The sequence S_k is defined as the ICI coefficient between lth and kth subcarriers, which can be expressed as [16]

$$S_k = \frac{\sin \pi(k + \varepsilon)}{N \sin(\pi/N)(k + \varepsilon)} \exp\left(j\pi\left(1 - \frac{1}{N}\right)(k + \varepsilon)\right) \tag{3}$$

The variable ε is the normalised frequency offset (ratio of the actual frequency offset to inter-carrier spacing). The desired signal power on the kth subcarrier can be represented as

$$E(|C_k|^2) = E(|m_k S_0|^2)$$

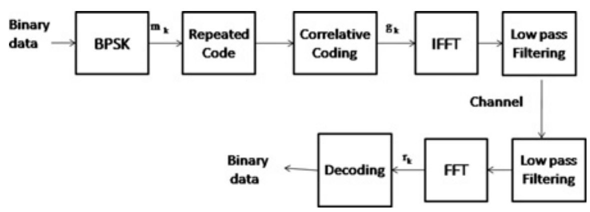

Fig. 1 *Block diagram of the repeated correlative coding OFDM communication system*

and the ICI power is

$$E(|I_k|^2) = E\left(\left|\sum_{l=0, l \neq k}^{N-1} m_l S_l\right|^2\right)$$

It is assumed that the transmitted data have zero-mean and statistically independent therefore the CIR expression for BPSK OFDM system without self-cancellation for subcarriers $0 \leq k \leq N-1$ can be derived as [4, 5]

$$\text{CIR} = \frac{|S_0|^2}{\sum_{l=1}^{N-1} |S_l|^2} \tag{4}$$

4 CIR improvement using repeated correlative coding

The average CIR power is used as the ICI level indicator [7]. CIR is defined as the desired received signal power on the kth subcarrier divided by ICI power to other subcarriers. The impact of ICI power on OFDM system can be evaluated by computing the CIR. The received signal at the receiver can be expressed by using (2).

$$r_k = Y_k - Y_{k+1}, \quad k = 0, 1, \ldots, N-1$$

For the proposed OFDM system with repeated correlative coding, if the channel frequency offset normalised to the subcarrier separation is denoted by $\in$, then the received signal on subcarrier k can be expressed as given in [16]

$$r_k = (2S_0 - S_{-1} - S_1)g_k + \sum_{\substack{l=0 \\ l \neq k}}^{N/2-1} (2S_{2l} - S_{2l-1} - S_{2l+1})g_l + (n_{2k} - n_{2k+1})$$

The first term of the received signal is the desired signal and the second term is the undesired ICI signal. Most types of the noise present in radio communication systems can be modelled accurately by using additive white Gaussian noise. This noise has a uniform spectral density (making it white) and Gaussian distribution in amplitude. OFDM signals have a flat spectral density and Gaussian amplitude distribution provided that numbers of carriers are large [10]. In the following derivations, without loss of generality an additive white Gaussian noise is assumed to be zero because we calculate CIR power [4, 5].

$$r_k = C_k + I_k \tag{5a}$$

where

$$C_k = (2S_0 - S_{-1} - S_1)g_k \tag{5b}$$

and

$$I_k = \sum_{\substack{l=0 \\ l \neq k}}^{N/2-1} (2S_{2l} - S_{2l-1} - S_{2l+1})g_l \tag{5c}$$

Since the $E[m_k] = 0$ for BPSK signals, which implies that the $E[g_k] = 0$ from (1), which leads to $E[c_k] = 0$ and $E[I_k] = 0$.

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Since m_k fulfils the independence condition, we have

$$E[m_k m_{k-1}] = \begin{cases} E[(m_k)^2], & k = l \\ 0, & k \neq l \end{cases} \tag{6}$$

Therefore we have

$$E((g_k)^2) = E((m_k - m_{k-1})^2) = 2E((m_k)^2) \tag{7}$$

The average carrier power $E(|C_k|)^2$ can be derived as

$$E(|C_k|^2) = 2(|2S_0 - S_{-1} - S_1|^2)(E(m_k)^2) \tag{8}$$

and the average ICI power $E(|I_k|)^2$ can be calculated a

$$\begin{aligned} E(|I_k|^2) &= E\left(\left|\sum_{l=0,l\neq k}^{N/2-1}(2S_{2l} - S_{2l-1} - S_{2l+1})g_l\right|^2\right) \\ &= \sum_{\substack{l=0 \\ l\neq k}}^{N/2-1}\sum_{\substack{p=0 \\ p\neq k}}^{N/2-1}(2S_{2l} - S_{2l-1} - S_{2l+1}) \\ &\quad \times (2S^*_{2p} - S^*_{2p-1} - S^*_{2p+1})E[g_l g_p] \end{aligned} \tag{9}$$

Taking the correlation between g_k and $g_{k\pm 1}$ into account as given in [5]

$$E(g_l g_p) = \begin{cases} 2E((m_k)^2), & l = p \\ E((m_l - m_{l-1})(m_p - m_{p-1})) & \\ \quad = -E((m_k)^2), & l = p \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

Using (9) and (10), we obtain

$$\begin{aligned} E(|I_k|^2) = \Bigg(& 2\sum_{l=1}^{N/2-1}|2S_{2l} - S_{2l-1} - S_{2l+1}|^2 \\ & - \sum_{l=2}^{N/2-1}(2S_{2l} - S_{2l-1} - S_{2l+1}) \\ & \times (2S^*_{2(l-1)} - S^*_{2(l-1)-1} - S^*_{2(l-1)+1}) \\ & + (2S_{2(l-1)} - S_{2(l-1)-1} - S_{2(l-1)+1}) \\ & \times (2S^*_{2l} - S^*_{2l-1} - S^*_{2l+1})\Bigg)E((m_k)^2) \end{aligned} \tag{11}$$

Thus, the average CIR of the proposed repeated correlative coded OFDM system is obtained by using (8) and (11). (see (12))

5 Results and discussion

In order to minimise the ICI in the OFDM communication system, a novel repeated correlative coding scheme is proposed. The normalised frequency offset is introduced in order to analyse the performance of the system where subcarrier frequency offset is used to measure the IC1 in the system. The CIR power levels against normalised frequency offset is calculated by using (4) and (12) for the ICI self-cancellation scheme [4] and proposed repeated correlative coding scheme are plotted for $0 < \varepsilon < 0.5$. The above simulations have been performed for the BPSK OFDM system by using the repeated correlative coding scheme for normalised frequency offset, where $N = 64$, and guard band is seven. Fig. 2 shows the CIR as a function of the normalised frequency offset. The CIR values for BPSK OFDM system at $\varepsilon = 0.1$ for the repeated correlative

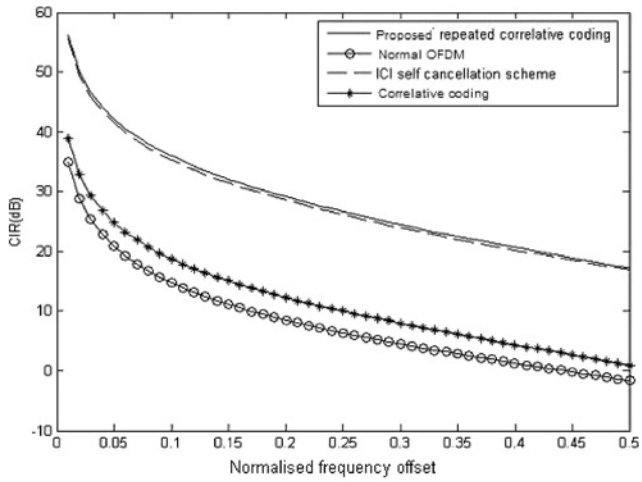

Fig. 2 *CIR characteristics of the BPSK OFDM communication system with the normalised frequency offset*

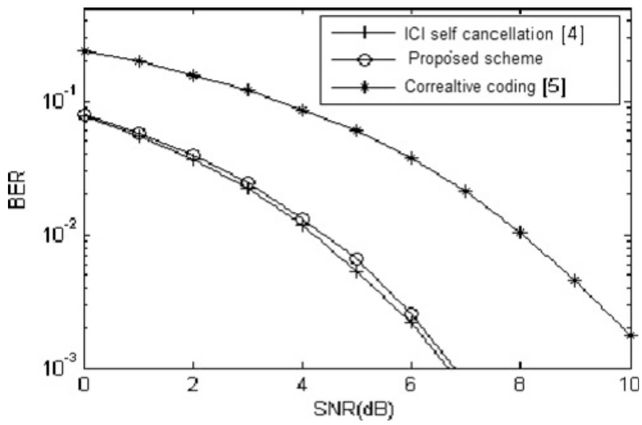

Fig. 3 *BER comparison for $\in = 0.05$ of the proposed BPSK OFDM system with ICI self-cancellation method in [4] and correlative coding scheme [5]*

$$CIR = \frac{(|2S_0 - S_{-1} - S_1|^2)}{\left\{\sum_{l=2}^{N/2-1}|2S_{2l} - S_{2l-1} - S_{2l+1}|^2 - (1/2)\left[\sum_{l=2}^{N/2-1}(2S_{2l} - S_{2l-1} - S_{2l+1})(2S^*_{2(l-1)} - S^*_{2(l-1)-1} - S^*_{2(l-1)+1}) + (2S_{2(l-1)} - S_{2(l-1)-1} - S_{2(l-1)+1})(2S^*_{2l} - S^*_{2l-1} - S^*_{2l+1})\right]\right\}} \tag{12}$$

Table 1 BER for different normalised frequency offsets for different ICI cancellation schemes

ICI cancellation scheme	BER for $\varepsilon = 0.05$	BER for $\varepsilon = 0.1$	BER for $\varepsilon = 0.15$
ICI self-cancellation	0.0059	0.0056	0.0055
correlative coding	0.0597	0.0686	0.0836
repeated correlative coding	0.0066	0.0079	0.0107

coding scheme is 35.7 dB, for the ICI self-cancellation scheme is 35.2 dB, for the correlative coding scheme is 18.7 dB and for the normal OFDM system is 14.7 dB. Comparative study of the CIR with various proposed schemes as well as for the normal OFDM system is shown in Fig. 2, which reveals that the proposed repeated correlative coding scheme improves the CIR power significantly. Although, the proposed repeated correlative coding scheme is not much better than the ICI self-cancellation scheme because the number of ICI component reduces half by using repeated symbols for adjacent subcarriers in the frequency domain. Thus, it reveals that the proposed repeated correlative coding scheme is able to reduce ICI significantly and improve the performance of the OFDM system.

Equation (4) suggests that the CIR is the function of total number of subcarriers and frequency offset normalised by the subcarrier separation. However, the CIR power varies very little as a function of total number of subcarriers. In [4], it is also clearly shown that the CIR for a given ε, results in a maximum change of 0.068 dB when $N \geq 8$. Therefore the CIR of the OFDM systems depends on the normalised frequency offset ε approximately. Thus, it is not easy to reduce the ICI unless the ε value is decreased [4]. For a certain channel frequency offset, smaller ε values can be obtained by increasing the subcarriers separation. Thus, the bandwidth efficiency will be reduced and, therefore the guard interval will take a relatively larger portion of the useful signal. The spectral efficiency of the proposed method should be taken into account when comparing BER performance with the correlative coding scheme.

Fig. 3 shows the BER comparison between proposed repeated correlative coding scheme, ICI self-cancellation scheme [4] and correlative coding scheme [5]. With the ICI self-cancellation scheme, only the half-subcarriers could be used to carry the information symbols, therefore the frequency spectral efficiency of the system will decrease to half. The BER compression with the ICI self-cancellation schemes for different normalised frequency offset ($\varepsilon = 0.05$, 0.1 and 0.15) at SNR = 6 dB is also given in Table 1. Here, the BER of the proposed methods is approximately same as the ICI self-cancellation method as discussed in [4], but is much better than the correlative coding scheme given in [5].

6 Conclusion

In this paper, we have explored a novel repeated correlative coding scheme to combat the ICI problem in the OFDM communication system. By the use of this repeated correlative coding scheme, the CIR of OFDM system has been analysed and compared with ICI self-cancellation scheme, correlative coding and normal OFDM system. The proposed scheme enhanced the CIR power up to 0.45, 16 and 20 dB with respect to the ICI self-cancellation scheme, correlative coding scheme and normal OFDM system, respectively, at frequency offset ($\varepsilon = 0.1$) without increasing system complexity. For the frequency offset, $\varepsilon = 0.05$, the BER for both repeated correlative coding and ICI self-cancellation scheme [4] is comparable. For the frequency offset, $\varepsilon = 0.1$, there is a very small increase in the BER for the proposed scheme but it increases slightly with the increase of the numerical value of the frequency offset. However, in all these cases, the BER of the proposed scheme is comparable to that of the ICI self-cancellation scheme [4] and significant improvement can be seen as compared with the correlative coding scheme [5]. The proposed theoretical analysis and simulation results prove that the ICI caused by multi-carrier frequency offset can be cancelled efficiently by using the proposed repeated correlative coding scheme for the OFDM communication system.

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