CHAPTER – 3

REPEATED CORRELATIVE CODING BASED ICI CANCELLATION TECHNIQUE

3.1 INTRODUCTION

Future wireless communication systems are expected to offer extremely high data rates with appropriate link quality over poor transmission environments. One efficient way to achieve this is by using OFDM communication technique because of its sufficient robustness to handle the radio channel impairments and its bandwidth efficiency due to overlapping orthogonal subcarriers. Despite its benefits, its major disadvantage is its sensitivity to frequency offset. The frequency offset results from a Doppler shift due to a mobile environment as well as from carrier frequency synchronization error. Such a frequency offset causes the loss of carrier’s orthogonality, therefore ICI occurs. Currently, several approaches have been suggested for ICI cancellation such as frequency-domain equalization [51], time-domain windowing scheme [52], ICI self-cancellation [54], conjugate cancellation scheme [61, 69], and correlative coding [55]. The most commonly used ICI counter measure methods are frequency-domain equalization [51], which uses training signal. Another most commonly used method is time-domain windowing [52], which uses redundant subcarrier. However, the use of training symbol or redundant subcarriers reduces the bandwidth efficiency. The self-cancellation scheme proposed in [54] requires to modulate one data symbol on to the next subcarrier with predefined inversed weighting coefficients “-1”. This concept of predefined weighting coefficients makes the ICI component in the received signal to cancel among them and bandwidth efficiency for this technique becomes half. The scheme proposed in [61, 69] requires data to be sent on two paths. The first path employs a regular OFDM algorithm and the second path uses the conjugate transmission of the first path. Due to the duplication, the bandwidth efficiency becomes half for conjugate cancellation.
scheme is also. Most of the techniques discussed in [51, 52, 54, 61, 69, 130] for ICI cancellation, are bandwidth inefficient, but correlative coding based ICI cancellation technique [55] is bandwidth efficient. However, the main problem of this technique is its very low value of carrier-to-interference ratio, which is important parameter for the performance analysis of OFDM communication system.

In this Chapter, we have discussed about one of the important issues of OFDM system that is carrier-to-interference ratio. For improvement of the carrier-to-interference ratio, we have proposed repeated correlative coding scheme in this chapter. 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 carrier-to-interference ratio power. The average carrier-to-interference ratio power is used as the ICI level indicators and theoretical carrier-to-interference ratio expression is derived for the proposed scheme. The carrier-to-interference ratio performance of the proposed system is compared with that of ICI self-cancellation scheme [54], correlative coding scheme [55], and standard OFDM system. The BER of the proposed scheme is also compared with the ICI self-cancellation scheme [54] and correlative coding scheme [55], which shows that the CIR obtained by using repeated correlative coding scheme is significantly enhanced.

3.2 Repeated Correlative Coding Scheme for Mitigation of ICI in OFDM System

3.2.1 System Model

Figure 3.1 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 subcarriers index. $m_k$ can take values of $\pm 1$ that fulfill the zero mean and independence condition. The symbols on two adjacent subcarriers have an $180^\circ$ phase difference between them such that $m_1 = -m_0, m_3 = -m_2, \ldots, m_{N-1} = -m_{N-2}$ [54]. The correlative coding is performed using $F(D) = (1-D)$ [55], where $D$ denotes the unit delay, which generates new sequence.

$$g_k = m_k - m_{k-1}$$  \hspace{1cm} (3.1)
Then the coded symbols $g_k$, $k \in [0, N/2-1]$ are modulated on $N/2$ subcarriers. The Equation (3.1) 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 by using pre-coding technique [130]. The standard OFDM system can be achieved by removing the repeated code, correlative code and decoding blocks from the Figure 3.1.

**Figure 3.1** Block diagram of the repeated correlative coding OFDM communication system.

### 3.2.2 ICI MECHANISM

In the OFDM communication system, the received signal on subcarrier $k$ is written as [54]:

$$Y_k = m_k S_0 + \sum_{l=0, l \neq k}^{N-1} m_l S_l + n_k$$  \hspace{1cm} (3.2)

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 Equation (3.2) represents the desired signal and second term is the ICI components. The sequence $S_k$ is defined as the ICI coefficient between $l^{th}$ and $k^{th}$ subcarriers, which can be expressed as [56]:

$$S_k = \frac{\sin \pi (k + \varepsilon)}{N \sin \frac{\pi}{N}(k + \varepsilon)} \exp( j \pi (1 - \frac{1}{N})(k + \varepsilon))$$  \hspace{1cm} (3.3)

The variable $\varepsilon$ is normalized frequency offset (ratio of the actual frequency offset to inter carrier spacing). The desired signal power on the $k^{th}$ subcarrier can be represented as:
\[ E(|c_k|^2) = E(|m_k s_0|^2) \]

and the ICI power is:

\[ E(|I_k|^2) = E\left( \left| \sum_{j=0, j \neq k}^{N-1} m_j s_j \right|^2 \right) \]

It is assumed that the transmitted data have zero-mean and statistically independent, therefore, the expression for carrier-to-interference ratio for BPSK OFDM system without self-cancellation for subcarriers \( 0 \leq k \leq N - 1 \) can be derived as [54]:

\[ CIR = \frac{|S_0|^2}{\sum_{l=1}^{N-1} |S_l|^2} \]  

(3.4)

### 3.2.3 CIR IMPROVEMENT BY USING REPEATED CORRELATIVE CODING

The average carrier-to-interference ratio (CIR) power is used as the ICI level indicator [57]. The CIR is defined as the desired received signal power on the \( k \)th 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 as given by Equation (3.2).

\[ r_k = y_k - y_{k+1} \]

\[ k = 0, 1, \ldots, N-1 \]

For the proposed OFDM system with repeated correlative coding, if the channel frequency offset normalized to the subcarrier separation is denoted by \( \nu \), then the received signal on subcarrier \( k \) can be expressed as given in [66]:

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

The first term of the received signal is desired signal and the second term is the undesired ICI signal. In the following derivations, without loss of the generality an additive white Gaussian noise is assumed to be zero. The received signal \( r_k \) can be written as:
\[ r_k = C_k + I_k \] (3.5)

where
\[ C_k = (2S_0 - S_{-1} - S_1)g_k \] (3.6)

and
\[ I_k = \sum_{l=0, l \neq k}^{N/2-1} (2S_{2l} - S_{2l-1} - S_{2l+1})g_l \] (3.7)

Since the \( E[m_k] = 0 \) for BPSK signals, which implies that the \( E[g_k] = 0 \) from Equation (3.1) which leads to \( E[c_k] = 0 \) and \( E[I_k] = 0 \). Since \( m_k \) fulfills the independence condition, so we have:

\[ E[m_km_{k-1}] = \begin{cases} E[(m_k)^2], & k = l \\ 0, & k \neq l \end{cases} \] (3.8)

Therefore, we have

\[ E \left( (g_k)^2 \right) = E \left( (m_k - m_{k-1})^2 \right) = 2E \left( (m_k)^2 \right) \] (3.9)

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

\[ E \left( |C_k|^2 \right) = 2E \left( |2S_0 - S_{-1} - S_1|^2 \right) \left( E \left( (m_k)^2 \right) \right) \] (3.10)

and the average ICI power \( E(|I_k|^2) \) can be calculated as:

\[ E \left( |I_k|^2 \right) = E \left( \left| \sum_{l=0, l \neq k}^{N/2-1} (2S_{2l} - S_{2l-1} - S_{2l+1})g_l \right|^2 \right) \]

\[ = \sum_{l=0}^{N/2-1} \sum_{p=0}^{N/2-1} \sum_{l \neq k}^{1} (2S_{2l} - S_{2l-1} - S_{2l+1})(2S_{2p} - S_{2p-1} - S_{2p+1}) E[gg_p] \] (3.11)

Taking the correlation between \( g_k \) and \( g_{k+1} \) into account as given in [55]:

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\[ E(g_l g_p) = \begin{cases} 2E((m_k)^2), & l = p \\ E((m_l-m_{l-1})(m_p-m_{p-1})) = -E((m_k)^2) & p = l \pm 1 \\ 0, & \text{Otherwise} \end{cases} \] (3.12)

By using Equation (3.11) and (3.12), we get:

\[
E(\mid I_k \mid^2) = \left(2 \sum_{l=1}^{N/2-1} |2 S_{2l} - S_{2l-1} - S_{2l+1}|^2 - \sum_{l=2}^{N/2-1} (2 S_{2l} - S_{2l-1} - S_{2l+1})(2 S_{2(l-1)}^* - S_{2(l-1)-1}^* - S_{2(l-1)+1}^*) + (2 S_{2(l-1)} - S_{2(l-1)-1} - S_{2(l-1)+1})(2 S_{2l}^* - S_{2l-1}^* - S_{2l+1}^*) \right) E((m_k)^2) \] (3.13)

Thus, the average CIR of the proposed repeated correlative coded OFDM system is obtained by using Equation (3.10) and (3.13).

\[
CIR = \frac{\left(2 S_0 - S_{-1} - S_{1}\right)^2}{\left\{ \sum_{l=2}^{N/2-1} |2 S_{2l} - S_{2l-1} - S_{2l+1}|^2 - \sum_{l=2}^{N/2-1} (2 S_{2l} - S_{2l-1} - S_{2l+1})(2 S_{2(l-1)}^* - S_{2(l-1)-1}^* - S_{2(l-1)+1}^*) + (2 S_{2(l-1)} - S_{2(l-1)-1} - S_{2(l-1)+1})(2 S_{2l}^* - S_{2l-1}^* - S_{2l+1}^*) \right\}} \] (3.14)

### 3.3 Results and Discussion

In order to minimize the ICI in the OFDM system, a novel repeated correlative coding method is proposed. The normalized frequency offset is introduced in order to analyze the performance of the system where subcarrier frequency offset is used to measure the ICI in the system. The CIR power levels versus normalized frequency offset is computed by using Equation (3.4) and (3.14), for the ICI self-cancellation method [54] and proposed repeated correlative coding method are plotted for range of normalized frequency offset \(0 < \varepsilon < 0.5\). This simulation has been performed for BPSK OFDM system by using repeated correlative coding for normalized frequency offset, where \(N = 64\) and guard band is 7. Figure 3.2 shows the CIR as a function of the normalized frequency offset. The CIR values for BPSK OFDM system at \(\varepsilon = 0.1\) for proposed repeated correlative coding is 35.7 dB, for ICI self-cancellation scheme.
is 35.2 dB, for correlative coding is 18.7 dB and for normal OFDM) system is 14.7 dB. For comparison, the CIR of the conventional scheme and proposed scheme is shown in Figure 3.2. Comparing with conventional scheme, the proposed scheme improves the CIR power remarkably. Although, the new $0 < \varepsilon < 0.5$ scheme is not in the range of ICI-self cancellation scheme because the number of ICI component reduces a half by using repeated symbols for adjacent subcarriers in frequency domain. Thus, it reveals that the new scheme is able to reduce ICI due to frequency offset and improve the performance of OFDM communication system.

![Graph showing CIR characteristics](image)

**Figure 3.2** The CIR characteristics of the BPSK OFDM communication system with the normalized frequency offset.

The Equation (3.4) suggests that the CIR is a function of total number of subcarriers and frequency offset normalized by the subcarrier separation. However, the CIR power varies very small as a function of total number of subcarriers. Therefore, the CIR of the OFDM systems depends on the normalized frequency offset $\varepsilon$ approximately. Thus, it is not easy to reduce the ICI unless the normalized frequency offset $\varepsilon$ value is decreased [54]. For a certain channel frequency offset, smaller $\varepsilon$ 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 bit-error-rate performance with the correlative coding scheme. Figure 3.3 shows the bit-error-rate comparison between the proposed repeated correlative coding scheme, ICI self-cancellation scheme [54], and correlative coding scheme [55]. With the ICI self-cancellation scheme, only the half subcarriers could be used to carry information symbols and the frequency spectral efficiency of the system will decrease to half. The bit-error-rate comparison of the proposed scheme with the ICI self-cancellation scheme for different normalized frequency offset ($\epsilon = 0.05, 0.1$ and $0.15$) at SNR = 6 dB is given in table 1. Here, the bit-error-rate of the proposed scheme is approximately same with that of the ICI self-cancellation scheme [54], but far better than correlative coding scheme in [55].

![Graph showing BER comparisons for $\epsilon = 0.05$ of proposed BPSK OFDM system with ICI-self cancellation method and correlative coding scheme.](image)

**Figure 3.3** BER comparisons for $\epsilon = 0.05$ of proposed BPSK OFDM system with ICI-self-cancellation method and correlative coding scheme.

<table>
<thead>
<tr>
<th>ICI Cancellation Scheme</th>
<th>BER for $\epsilon = 0.05$</th>
<th>BER for $\epsilon = 0.1$</th>
<th>BER for $\epsilon = 0.15$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICI self-cancellation</td>
<td>0.0059</td>
<td>0.0056</td>
<td>0.0055</td>
</tr>
<tr>
<td>Correlative coding</td>
<td>0.0597</td>
<td>0.0686</td>
<td>0.0836</td>
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<td>Repeated correlative coding</td>
<td>0.0066</td>
<td>0.0079</td>
<td>0.0107</td>
</tr>
</tbody>
</table>

**Table 3.1** Comparison of bit-error-rate for various normalized frequency offset with different ICI cancellation scheme.
3.4 CONCLUSION

In this chapter, a novel solution for the ICI problem for OFDM communication systems is presented. The use of repeated correlative coding in BPSK OFDM system has been analyzed and compared with ICI self-cancellation scheme [54], correlative coding [55], and normal (un-coded) OFDM system. The proposed scheme enhances the CIR power with 0.45dB by ICI self-cancellation scheme, 16dB by correlative coding scheme, 20dB by normal OFDM system at frequency offset ($\nu = 0.1$) without increasing system complexity, respectively. For $\nu = 0.05$, the BER for both the repeated correlative coding and ICI self-cancellation scheme [54] is comparable. For $\nu = 0.1$, there is a slight increase in the BER for the proposed scheme. This increment widens more for $\nu = 0.15$. However, in all the cases, the bit-error-rate of the proposed scheme is comparable to that of the ICI self-cancellation scheme and is much improved from correlative coding scheme [55]. All the theoretical analysis and simulation results prove that the ICI caused by multicarrier frequency offset can be cancelled efficiently by proposed repeated correlative coding scheme for the OFDM communication system.