

A Survey of ICI Self-Cancellation Techniques for OFDM Systems

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Abstract: *Inter-carrier Interference (ICI) is a severe problem in orthogonal frequency division multiplexing (OFDM) systems. Any offset between the subcarrier frequencies of the transmitter and receiver ruins the orthogonality of OFDM subcarriers and introduces ICI to an OFDM system. There are various methods to mitigate the effects of ICI. In this paper various ICI self-cancellation (ICI-SC) techniques to minimize ICI are studied and reviewed. Those techniques are described in this paper and a comprehensive comparison is made of all the techniques. It is found that Weighted Conjugate Transformation technique (WCT) is better than all other conventional ICI-SC schemes.*

Keywords: OFDM, ICI, ICI-Self Cancellation, Data-Conversion, Data-Conjugate.

1. Introduction

With the evolution of internet the need for wireless technology that can deliver data at high speed in a spectrally efficient manner is increased. For supporting such high data rates with sufficient robustness to radio channel demands a careful selection of modulation or multiple access techniques is required. By the usage of FDM, FDMA, TDMA and CDMA we are facing certain problems. By the usage of FDM there could be loss in bandwidth and by the usage of FDMA and TDMA there could be a chance of occurring the problems like multipath fading, time dispersion which leads to Inter Symbol Interference (ISI), lower bit rate capacity, requirement of large transmit power for high bit rates and less spectral efficiency. For this reason most of the wireless technologies uses CDMA and OFDM. But CDMA has more multipath fading and complexity than the OFDM. So, OFDM appears to be most suitable than all the remaining technologies. OFDM is considered as a digital multicarrier modulation technique that provides high data rates and now it is used in many communication systems. IEEE802.11, IEEE802.16, DVB-T and DAB are some of the examples of OFDM which provides high data rates for wireless LANs and it is also used in ADHOC networks. The wireless LAN standards of OFDM supports a bit rate of 6 to 54 Mbps [1].

1.1 OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier transmission technique, which divides the bandwidth into many carriers [2, 3], each one is modulated by a low rate data stream. OFDM uses the spectrum much more efficiently by spacing the channels much closer together. This is achieved by making all the carriers orthogonal to one another, preventing interference between the closely spaced carriers. OFDM can be seen as either a modulation technique

or a multiplexing technique. One of the main reasons to use OFDM is to increase the robustness against frequency selective fading or narrowband interference. In a single carrier system, a single fade or interferer can cause the entire link to fail, but in a multicarrier system, only a small percentage of the subcarriers will be affected. Error correction coding can then be used to correct for the few erroneous subcarriers. The concept of using parallel data transmission and frequency division multiplexing was published in the mid-1960s [4, 5]. In a classical parallel data system, the total signal frequency band is divided into N non overlapping frequency up channels. Each sub channel is modulated with a separate symbol and then the N sub channels are frequency-multiplexed. It seems good to avoid spectral overlap of channels to eliminate inter channel interference. However, this leads to inefficient use of the available spectrum. To cope with the inefficiency, the ideas proposed from the mid-1960s were to use parallel data and FDM with overlapping sub channels. To realize the overlapping multicarrier technique, however crosstalk needs to be reduced between subcarriers, which mean that we want orthogonality between the different modulated carriers. Frequency spectrum of OFDM subcarrier transmission is represented below.

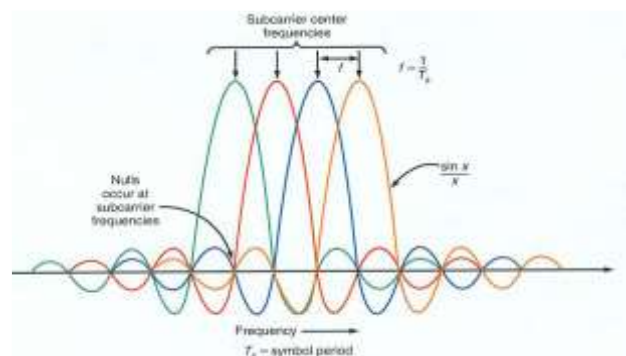


Figure 1: Frequency Spectrum of OFDM Transmission

If two signals are said to be orthogonal then their dot product is zero. As the subcarriers are orthogonal then the spectrum of each subcarrier has a null at the centre frequency of the other subcarrier in the system.

1.2 Problems in OFDM

The received signal consists of a combination of attenuated, reflected, refracted, and diffracted replicas of the transmitted signal [6]. On top of all this, the channel adds noise to the signal and can cause a shift in the carrier frequency if the transmitter or receiver is moving (Doppler Effect). In a multipath environment, an OFDM system faces many problems like Multipath Fading, Delay Spread, Doppler spread, Frequency selective fading, Intersymbol Interference (ISI) and Inter Carrier Interference (ICI). But Inter-Carrier Interference is proved in [7] and [8] to be the most severe problem which highly degrades the performance of the OFDM systems.

1.3 Inter-Carrier Interference (ICI)

OFDM systems are very sensitive to frequency and phase offsets [9]. The front-end distortion disturbs the orthogonality between the subcarriers and cause intercarrier interference (ICI). The performance of OFDM is maintained by removing ICI. Various researchers followed different methods to mitigate the effect of ICI, such as frequency-domain equalization [10], time-domain windowing [11], self-cancellation [12]-[16], frequency offset estimation and correction technique [17]-[18], correlative coding [19] etc.

1.3.1 Frequency Domain Equalization

The fading distortion in the channel causes ICI in the OFDM demodulator. Compensation for fading distortion in the time domain introduces the problem of noise enhancement. So frequency domain equalization process is used for reduction of ICI by using suitable equalization techniques. We can estimate the ICI for each frame by inserting frequency domain pilot symbols in each frame as shown in Figure 2.

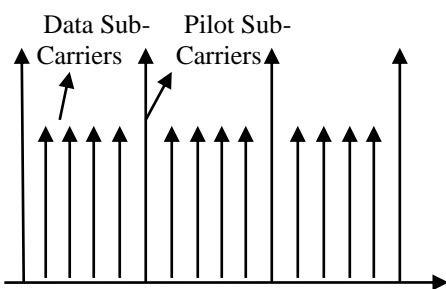


Figure 2: Pilot Subcarrier Arrangements

The Equalizer co-efficient for eliminating ICI in the frequency domain can be derived from the pattern of the pilot symbol and hence a suitable equalizer can be constructed. It can only reduce the ICI caused by fading distortion but it does not deal the problems of frequency mismatch between transmitter and receiver and Doppler shift which is the main source of ICI. Again it is only suitable for flat fading channels, but in mobile communication the channels are frequency selective fading in nature because of multipath components. Here also the channel needs to be estimated for every frame. Estimation of channel is

complex, expensive & time consuming. Hence this method is not effective one.

1.3.2 Time Domain Windowing

Windowing is the process of multiplying the transmitted signal waveform with a suitable function i.e., window function. The same window is used in the receiver side to get back the original signal. The widely spread power spectrum of OFDM signal is when transmitted in a band limited channel, a certain portion of the signal spectrum will be cut-off, which leads to ICI. This technique reduce that type of ICI and it also does not deal with the frequency mismatch between the transmitter and the receiver, and the Doppler shift..Windowing is done frame by frame and hence it reduces spectral efficiency. Thus this method is also not efficient method.

1.3.3 Pulse Shaping

In the OFDM spectrum that each carrier consist of a main lobe followed by a number of side lobes with reducing amplitudes .Some power of the side lobes exists at the centre of the individual subcarrier which is called ICI power. The purpose of this technique is to reduce the side lobes [20]. If the side lobe reduces then the ICI power will also be reduce significantly. But the drawback is complexity in implementation

1.3.4 Maximum Likelihood Estimation

In this technique, the frequency offset is first statistically estimated using a maximum likelihood algorithm and then cancelled at the receiver. Before transmission replication of OFDM symbol is done and then comparison of the phases of each of the subcarriers between the successive subcarriers are made. It is unbiased estimate of the frequency offset and can be computed by using received data

The maximum likelihood estimate of the normalized frequency offset is given by

$$\hat{\epsilon} = \frac{1}{2\pi} \tan^{-1} \left[\frac{\sum_{k=-K}^K \text{Im} Y_2(k) Y_2^*(k)}{\sum_{k=-K}^K \text{Re} Y_2(k) Y_1^*(k)} \right] \quad (1)$$

Once the frequency is known, the ICI distortion in the data symbol is reduced by multiplying the received symbols with a complex conjugate of the frequency shift and applying the FFT.

$$X(n) = FFT\{Y(n)e^{-j2\pi n\epsilon/N}\} \quad (2)$$

1.3.5 ICI Self-Cancellation

The ICI self-cancellation scheme is a very simple way for suppressing ICI in OFDM. The difference between the ICI coefficient of two consecutive sub-carriers are very small. This makes the basis of ICI self cancellation. The main idea [12] is to modulate one data symbol onto a group of subcarriers with predefined weighting coefficients. One data symbol is not modulated in to one sub-carrier, rather at least in to two consecutive sub-carriers. If the data symbol 'a' is modulated in to the 1st sub-carrier then '-a' is modulated in to the 2nd sub-carrier. Hence the ICI generated between the two sub-carriers almost mutually cancels each other. This method is suitable for multipath fading channels as here no channel estimation is required. Because in multipath case, channel estimation fails in the channel changes randomly. After the ideas proposed in [21], the further discussions of ICI Self-Cancellation schemes are presented in [22] and [23]. The self-cancellation (SC)

method is not very complex and is an easy way to cancel ICI compared to other methods. Because the scheme needn't to estimate frequency offsets. Figure 3 represents a typical block diagram of ICI Self-Cancellation OFDM system [24].

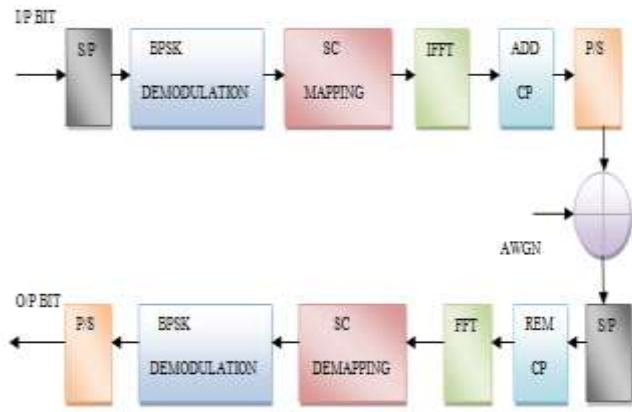


Figure 3: Block Diagram of ICI SC OFDM system

2. ICI Mechanism of Standard OFDM System

In an OFDM communication system, assuming the channel frequency offset normalised by the subcarrier separation is ϵ , the received signal on subcarrier k can be written as:

$$r(k) = X(k)S(0) + \sum_{l=0, l \neq k}^{N-1} X(l)S(l-k) + n_k \quad (3)$$

where N is the total number of subcarriers $X(k)$ denotes the transmitted symbol for the k^{th} subcarrier and n_k is noise. The first term in the right hand side of (3) is the desired signal. The second term is the ICI components. The sequence $S(l-k)$ is defined as the ICI coefficient between l^{th} and k^{th} subcarriers, which can be expressed as:

$$S(l-k) = \frac{\sin(\pi(l+\epsilon-k))}{N \sin(\frac{\pi}{N}(l+\epsilon-k))} \cdot \exp\left(j\pi\left(1 - \frac{1}{N}(l+\epsilon-k)\right)\right) \quad (4)$$

2.1 ICI Cancellation Modulation

For a certain channel frequency offset, smaller ϵ values can be obtained by increasing the subcarrier separation. Consequently, the bandwidth efficiency will be reduced since the time-domain symbol length is reduced and therefore, the guard interval will take a relatively larger portion of the useful signal. For the majority of $l-k$ values, the difference between $S(l-k)$ and $S(l+1-k)$ is very small. Therefore if a data pair $(a, -a)$ is modulated onto two adjacent subcarriers $(l, l+1)$, where a is complex data, then the ICI signals generated by the subcarrier l will be cancelled out significantly by the ICI generated by subcarrier $l+1$. This method proposed and simulated in [12].

Assume the transmitted symbols are constrained so that:

$$X(1) = -X(0), X(3) = -X(2), \dots, X(N-1) = -X(N-2)$$

Then the received signal on subcarrier k becomes

$$Y'(k) = \sum_{l=0, l \neq k}^{N-2} X(l)[S(l-k) - S(l+1-k)] + n_k \quad (5)$$

And on subcarrier $k+1$ is

$$Y'(k+1) = \sum_{l=0, l \neq k+1}^{N-2} X(l)[S(l-k-1) - S(l-k)] + n_k \quad (6)$$

In such case, ICI coefficient is denoted as:

$$S'(l-k) = S(l-k) - S(l+1-k) \quad (7)$$

It is found that ICI component $S'(l-k)$ is less than the ICI component of standard OFDM System $S(l-k)$.

2.2 ICI Cancellation Demodulation

To further reduce ICI, ICI cancellation demodulation is done [12]. The demodulation is suggested to work in such a way that each signal at the $(k+1)^{th}$ subcarrier is multiplied by -1 and then summed with the one at k^{th} subcarrier. Then the resultant data sequence is used for making symbol decision. It can be represented as:

$$Y''(k) = Y'(k) - Y'(k-1) \quad (8)$$

$$Y''(k) = \sum_{l=0, l \neq k}^{N-2} X(l)[-S(l-k-1) + 2S(l-k) - S(l-k+1)] + n_k - n_{k+1} \quad (9)$$

The corresponding ICI coefficients then become

$$S''(l-k) = -S(l-k-1) + 2S(l-k) - S(l-k+1) \quad (10)$$

The magnitude of $S''(l-k)$ has less value than $S'(l-k)$ and $S(l-k)$. Thus, the ICI signal becomes smaller after applying ICI cancellation modulation. On the other hand, the ICI cancellation demodulation can further reduce ICI in the received signal. The combined ICI cancellation modulation and demodulation is called ICI Self-Cancellation Scheme [12].

3. DIFFERENT ICI-SC SCHEMES

Several SC methods are presented, such as data-conversion [12], symmetric data-conversion [13], weighted data-conversion [13]-[14], data-conjugate [15] and weighted conjugate transformation (WCT) [16]. In SC scheme, at transmitter side one data symbol is mapped onto two subcarriers with predefined weighting coefficients. At receiver, the received signal is determined by the difference between the adjacent subcarriers.

3.1 Data-Conversion Scheme

The data-conversion self-cancellation scheme for ICI mitigation based on the data symbol allocation of $X'(k) = X(k)$, $X'(k+1) = -X(k)$ ($k=0,2,4,\dots,N-2$). The received signal $Z(k)$ is determined by the difference between the adjacent subcarriers. This self-cancellation scheme relies on the fact that the real and imaginary parts of the ICI coefficients change gradually with respect to the subcarrier index k .

Therefore, the difference between consecutive ICI coefficients $S(l-k)$ and $S(l+1-k)$ is very small. Then the resultant data sequence is used for making symbol decision can be represented as:

The desired signal is recovered in the receiver as

$$Z(k) = \frac{1}{2}(Y'(k+1)) \quad (11)$$

where $X'(k)$ is the transmitted data symbol at k^{th} subcarrier after SC mapping, $Y'(k)$ is the $2k^{th}$ subcarrier data after FFT

in the receiver and $Z(k)$ is the desired received signal after SC demapping.

The CIR of data-conversion is given by [12] and expressed as:

$$\text{CIR} = \frac{|-S(1) + 2S(0) - S(-1)|^2}{\sum_{l=2, l=\text{even}}^{N-2} |-S(l-1) + 2S(l) - S(l+1)|^2} \quad (12)$$

(a) Symmetric Data- Conversion Scheme

This scheme is based on data allocation of $X'(k) = X(k)$, $X'(N-k-1) = -X(k)$ ($k = 0, 2, 4, \dots, N-2$). The desired signal given is recovered in the receiver as:

$$Z(k) = \frac{1}{2} (Y'(k) - Y'(N-k-1)) \quad (13)$$

The CIR is given by [13] and expressed as:

$$\text{CIR} = \frac{|-S(N-1) + 2S(0) - S(12-N)|^2}{\sum_{l=2, l=\text{even}}^{N-2} |-S(N-l-1) + S(l) + S(-l) - S(l-N+1)|^2} \quad (14)$$

(b) Real Constant Weighted Data-Conversion Scheme

This scheme is based on the data symbol allocation of $X'(k) = X(k)$, $X'(k+1) = -\mu X(k)$ ($k=0, 2, 4, \dots, N-2$), where μ is a real constant in (0,1). The desired signal given by [14] is recovered as:

$$Z(k) = \frac{1}{1+\mu} (Y'(k) - Y'(k+1)) \quad (15)$$

The CIR is given by [14] and expressed as:

$$\text{CIR} = \frac{|-\mu S(1) + (1+\mu)S(0) - S(-1)|^2}{\sum_{l=2, l=\text{even}}^{N-2} |-S(l-1) + (1+\mu)S(l) - \mu S(l+1)|^2} \quad (16)$$

(c) Plural Weighted Data- Conversion Scheme

This scheme is based on the data symbol allocation of $X'(k) = X(k)$, $X'(k+1) = e^{-j\frac{\pi}{2}} X(k)$ ($k = 0, 2, 4, \dots, N-2$). The desired signal given by [15] is recovered as:

$$Z(k) = \frac{1}{2} (Y'(k) - e^{-j\frac{\pi}{2}} Y'(k+1)) \quad (17)$$

The CIR is given by [15] and expressed as:

$$\text{CIR} = \frac{|2S(0) + e^{-j\pi/2} [S(1) - S(-1)]|^2}{\sum_{l=2, l=\text{even}}^{N-2} |2S(l) + e^{-j\pi/2} [S(l+1) - S(l-1)]|^2} \quad (18)$$

3.2 Data-Conjugate Scheme

This scheme is based on the data symbol allocation of $X'(k) = X(k)$, $X'(K+1) = X^*(k+1)$ ($k=0, 2, 4, \dots, N-2$). The desired signal given is recovered in the receiver as:

$$Z(k) = \frac{1}{2} (Y'(k) - Y^*(k+1)) \quad (19)$$

The CIR is given by [16] and expressed as:

$$\text{CIR} = \frac{|S(0) + S^*(0)|^2 + |S(1) + S^*(-1)|^2}{\sum_{l=2, l=\text{even}}^{N-2} |S(l) + S^*(l)|^2 + |S(l+1) + S^*(l-1)|^2} \quad (20)$$

(a) Weighted Conjugated Transformation

This scheme is based on the data symbol allocation of $X'(k) = X(k)$, $X'(k+1) = e^{j\pi/2} X^*(k)$ ($k=0, 2, 4, \dots, N-2$). The desired symbol is recovered as:

$$Z(k) = \frac{1}{2} (Y'(k) - e^{-j\frac{\pi}{2}} Y^*(k+1)) \quad (21)$$

The CIR is given by [17] and expressed as:

CIR=

$$\frac{|S(0) + S^*(0)|^2 + \left| e^{j\frac{\pi}{2}} S(1) - e^{-j\frac{\pi}{2}} S^*(-1) \right|^2}{\sum_{l=2, l=\text{even}}^{N-2} |S(l) + S^*(l)|^2 + \left| e^{j\frac{\pi}{2}} S(l+1) - e^{-j\frac{\pi}{2}} S^*(l-1) \right|^2} \quad (22)$$

The data modulated within the $(k+1)^{th}$ subcarrier is the rotated phase $\pi/2$ of the conjugate of the modulated data within k^{th} subcarrier. The CIR and BER of WCT scheme are much better than other conventional ICI-SC schemes explained in [16], [24] and [25]. It is suggested that this method should be used to reduce the effect of ICI in OFDM systems.

4. Conclusion

In this paper, it has been concluded that ICI is the main problem which minimizes the performance of the OFDM systems. To cancel the effect of ICI in OFDM systems different ICI self-cancellation techniques like data conversion scheme, symmetric data-conversion scheme, real constant weighted data-conversion scheme, plural weighted data-conversion scheme, data-conjugate scheme and weighted conjugate transformation scheme has been studied theoretically. These schemes have two major advantages over other ICI cancellation methods. One is that they are less complex as compared to the other estimation and correction schemes. The other advantage is that they can combat the impact of frequency offset at low frequency offsets. In addition, no channel estimation is needed for reducing ICI. After learning all above techniques it has been concluded that Weighted Conjugate Transformation technique (WCT) is better than other conventional ICI-SC schemes.

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