An Overview of ICI Self Cancellation Techniques in OFDM systems

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***Abstract*—Intercarrier interference (ICI) is one of the critical problems faced in orthogonal frequency division multiplexing (OFDM) systems which is caused mainly due to frequency impairment of local oscillators, Doppler spread of time varying channels which results in carrier frequency offset (CFO). ICI destroys the orthogonality of OFDM signals and degrades the system performance. Many ICI reduction techniques like frequency domain equalization, time domain windowing, pulse shaping and ICI self cancellation have been developed. ICI self cancellation is an efficient technique in terms of bit error rate, computational complexity. Interference in adjacent subcarriers is self cancelled by modulating the same data on adjacent subcarriers with predefined weighting coefficients. This paper gives a brief overview of various ICI self cancellation techniques based on this principle.**

Keywords—carrier frequency offset , inter-carrier interference, ICI reduction, ICI self cancellation, OFDM.

I. INTRODUCTION

The present wireless communication systems require high speed data streaming. OFDM is a promising technique which fulfills this requirement [1]. OFDM has been widely accepted as a data transmission technique in communication media such as asymmetric digital subscriber line (ADSL), digital audio broadcasting (DAB), digital video broadcasting (DVB), wireless local area network (WLAN), worldwide interoperability for microwave access (WiMax) and ultra wideband (UWB) systems.

OFDM is a parallel data transmission technique in which data symbols are modulated and transmitted on orthogonal sub-carriers but due to frequency mismatch of local oscillator of transmitter and receiver, there is a gap in the transmission and reception frequency. This frequency gap is called carrier frequency offset which shatters the orthogonality of the subcarriers which induce ICI and causes a error floor at receiver side and degrades the system performance. Different approaches to mitigate the effect of adjacent carrier frequency offset are frequency domain equalization [2], time domain windowing [3], frequency offset estimation and removal [4] and ICI cancellation [5]. This paper mainly focuses in ICI self cancellation (ICI SC) techniques.

There are two types of techniques to eliminate ICI in OFDM systems. First technique is to design a system that can estimate and remove carrier frequency offset [6-7]. But it is quite complex and have high cost of implementation. Second technique is to design a system that can process an OFDM symbol in such a way that it is less sensitive to carrier frequency offset. In 2001 Zhao and Haggman [5] gave an ICI self cancellation scheme which can be considered as a basic building block for ICI reduction techniques because of its simplicity and efficiency which is widely accepted. The main idea is to modulate a same data sample on adjacent subcarrier with specific weighting coefficients and at the receiver side these samples are linearly combined with predefined weighting coefficients and reduction in the residual ICI in the received signal is obtained up to a significant level. The weighting coefficients are designed in such a way that the effect of carrier frequency offset on subcarriers can be minimized. Banwidth efficiency reduced since same data sample is modulated on the adjacent subcarriers. Interference in adjacent subcarriers can also be reduced by shaping the spectra of OFDM signals such that main lobe coincide with spectral null of adjacent subcarriers. This is achieved by performing a windowing function in time domain [8]. This idea can be further extended to decrease computational complexity at receiver side [9]. In this technique, instead of using two windows i.e. one at transmitter and another on receiver, only one window is used at the transmitter side with no compromise in system performance.

The rest of the paper is organized as follows: section II represent a conventional OFDM system, section III describe problem of ICI in OFDM. Different ICI self reduction techniques are explained and summarized in section IV and V respectively. Finally the last section concludes the paper.

II. BASIC OFDM SYSTEM

In OFDM systems, the wideband channel is splitted into a number of parallel narrowband channels which are orthogonal to each other. Fig. 1 shows the block diagram of OFDM system which is discrete time and FFT based. Transmitter side involve data generator, modulator, IFFT and cyclic prefix adder, while receiver side consists of cyclic prefix remover, DFT block, demodulator. The data symbol to be transmitted are mapped with M-ary PSK scheme and then modulated on N subcarriers by using IFFT. In order to avoid intersymbol interference, a cyclic prefix of sufficient length is also added. The complete OFDM symbol is transmitted through a discrete time channel. At the receiver end, the received symbol is demodulated and remapped to retrieve the original symbol.

978-1-4799-6023-1/15 $31.00 © 2015 IEEE
DOI 10.1109/CICT.2015.113

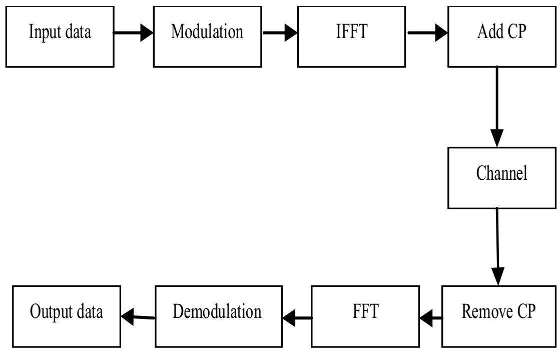

Fig. 1: Block diagram of OFDM system

In OFDM systems, the transmitted signal is represented in time domain as

$$x(n) = \frac{1}{N}\sum_{i=0}^{N-1} X(i)e^{j2\pi in/N} \qquad (1)$$

Where x(n) denotes the n^{th} sample of the OFDM transmitted signal, N is the total number of subcarriers, X(i) denote the modulated symbol on i^{th} subcarrier which are assumed to be zero mean and independent random variables. The carrier frequency offset is assumed to be normalized by sub-carrier frequency spacing and denoted as ε. The received signal in time domain is represented as

$$y(n) = [x(n) + w(n)]e^{j2\pi\varepsilon n/N} \qquad (2)$$

where w(n) is the additive white Gaussian noise (AWGN).

III. Problem of ICI in OFDM

The received signal on k^{th} sub-carrier in frequency domain is given by

$$Y(k) = X(k)S(0) + \sum_{i=0,i\neq k}^{N-1} X(i)S(i-k) + n(k), \quad \text{where}, k = 0,1,\dots,N-1 \qquad (3)$$

Where X(k) is the transmitted symbol on k^{th} sub-carrier, $n(k)$ is the added noise while the sequence S(*i-k*) denotes the inter-carrier interference or ICI coefficients between i^{th} and k^{th} sub carriers , which is represented as

$$S(i-k) = \frac{\sin(\pi(i-k+\varepsilon))}{N\sin(\pi(i-k+\varepsilon))}\exp\left(j\pi(1-\frac{1}{N})(i-k+\varepsilon)\right) \qquad (4)$$

The CIR is used as a measure of inter-carrier interference or ICI. The CIR is defined as the ratio of average power of carrier component to the power of interference component, The received signal power on desired k^{th} subcarrier is given as

$$E[|C(k)|^2] = E[|X(k)S(0))|^2] \qquad (5)$$

And ICI power is given as

$$E[|I(k)|^2] = E\left[\left|\sum_{i=0,i\neq k}^{N-1} X(i)S(i-k)\right|^2\right] \qquad (6)$$

So CIR is written as

$$CIR = \frac{E[|C(k)^2|]}{E[|I(k)|^2]} = \frac{E[|X(k)|^2]E[|S(0)|^2]}{E[|X(i)|^2]\sum_{i=0,i\neq k}^{N-1}|S(i-k)|^2} \qquad (7)$$

All the modulated data symbols i.e. X(k) are statistically independent and identically distributed , so

$$CIR = \frac{|S(k)|^2}{\sum_{i=0,i\neq k}^{N-1}|S(i)|^2} = \frac{|S(0)|^2}{\sum_{i=1}^{N-1}|S(i)|^2} \qquad (8)$$

The above equation shows that CIR depends upon number of subcarrier i.e. *N* and carrier frequency offset ε.

IV. ICI Reduction Techniques

Various ICI self cancellation technique to mitigate the effect of frequency offset and reduce ICI are as follows

A. ICI self cancellation scheme :

Zhao and Haggman [5] proposed a very simple and effective ICI self cancellation technique . The basic idea is to modulate a same data block on adjacent subcarriers i.e. if data 'a' is modulated on one subcarrier then '-a' will be modulated on adjacent subcarrier. The transmitted signal constrained can be given as

X(1) = -X(0), X(3) = -X(2)…..X(N-1)=X(N-2)

At the receiver side, the signal is demodulated by linearly combining the adjacent subcarriers by multiplying odd number of subcarriers by '-1'. If $Y'(k)$ is received signal on k^{th} subcarrier, then data sequence used for decision symbol will be represented as:

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

The theoretical CIR of the ICI self cancellation technique is given as

$$CIR = \frac{|-S(-1) + 2S(0) - S(1)|^2}{\sum_{l=even,l=2}^{N-2}|-S(l-1) + 2S(l) - S(l+1)|^2} \qquad (10)$$

The performance of OFDM system will further be improved if we use data allocation on adjacent subcarriers as follows X(k+1)= $e^{\frac{-j\pi}{2}}$X(k). With this data allocation scheme [8] CIR is given as

$$CIR = \frac{\left|2S(0)+e^{-j\pi/2}[S(1)-S(-1)]\right|^2}{\sum_{l=even,l=2}^{N-2}\left|2S(l)+e^{-j\pi/2}[S(l+1)-S(l-1)]\right|^2} \qquad (11)$$

OFDM system performs better with this data allocation scheme even at higher frequency offset and phase error will be mitigated without any coding scheme.

B. ICI SC using windowing in time domain:

Zhao's ICI SC scheme mitigate the effect the frequency offset by signal processing in frequency domain, the same function is performed by windowing in time domain [9]. The block diagram for this scheme is given in fig. 2.

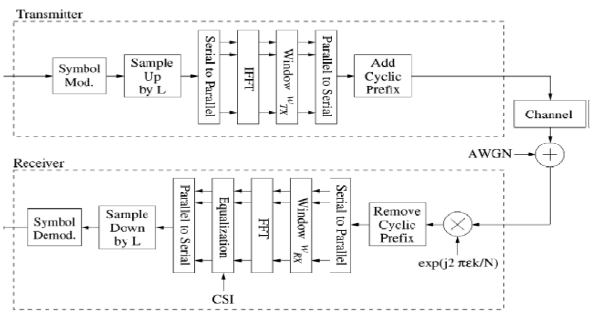

Fig. 2 block diagram of ICI SC with windowing [9]

In this technique *N-1* numbers of zeros are inserted between each pair of symbols by the sample up block. We can say that one data symbol is placed on N^{th} sub carrier and other *N-1* subcarriers are set to zero. After IFFT operation, the OFDM symbols are windowed by transmitter window $w_{TX,k}$, k=0, 1,..., N-1. At the receiver side, the received symbols are first passed through the receiver window $w_{RX,k}$, k=0, 1,.. , N-1, after that FFT operation is performed. An equalizer is used to design optimum filter coefficients at which highest CIR is attained. The main advantage of this scheme is that it works efficiently in fast fading environment since it does not require frequency offset to be a single valued. Further signal processing at receiver will be simplified if we use five weighing coefficients to design window in frequency domain instead [10] which is used only at the transmitter side without degrading system performance, where OFDM symbols are equalized in frequency domain, samples at the even sub-carriers are used to estimate the transmitted symbol. The main advantage of this technique is reduced complexity at receiver side and can mitigate ICI in AWGN channel as well as in frequency selective Rayleigh channel.

C. ICI SC based on symmetric conjugate property :

In frequency domain, the received signal is considered as the circular convolution of transmitted signal and weighting coefficients [11]. The weighting coefficients are symmetric conjugate of each other so this inherent property of weighting coefficients is used to eliminate the effect of phase noise. The weighting coefficients are given by the expression

$$S_k = \frac{1}{N}\sum_{n=0}^{N-1} e^{j\varphi_n} e^{-j2\pi nk/N} \quad k=1\ldots N-1. \tag{12}$$

Here φ_n is the phase noise generated by local oscillators.

Symmetric conjugate property of ICI weighting coefficients is explained as follows

$$S_k + S_k^* = \frac{1}{N}\sum_{n=0}^{N-1}(e^{j\varphi_n} + e^{-j\varphi_n})e^{-j2\pi nk/N} \tag{13}$$

$$= \frac{2}{N}\sum_{n=0}^{N-1}(\cos\varphi_n)e^{-j2\pi nk/N} \tag{14}$$

$$\approx \frac{2}{N}\sum_{n=0}^{N-1} e^{-j2\pi nk/N} \quad k = 0, \ldots, N-1. \tag{15}$$

Therefore, $S_0 + S_0^* = 2$ and $S_k + S_{-k}^* = 0$, k≠0

So N/2 data symbol are transmitted on half of the subcarriers of an OFDM data block and their complex conjugate with inverted phase are symmetrically transmitted on remaining half subcarriers. The data modulation constrained for this scheme is given as

$$X_{N-1} = -X_0^*, \ldots, X_{N-1-k} = -X_k^*; 0 \le k \le \frac{N}{2} - 1 \tag{16}$$

The main advantage of this technique is that under flat fading channel CIR is improved and system can tolerate a phase noise of 7 deg with a BER of 10^{-3} . CIR performance of this scheme is enhanced if an artificial phase rotation φ is introduced with transmitted data [12]. With this data allocation scheme, data symbol with a phase rotation of $e^{-j\varphi}$ are modulated on half of the subcarrier and their complex conjugate with a phase inversion are transmitted symmetrically on the remaining half subcarriers. This artificial phase rotation helps to combat the effect of phase noise caused by frequency offset and this minimizes ICI.

D. ICI SC based on repeated symbols :

ICI self cancellation technique in [13] is based on transmission of repeated symbol in time domain in OFDM system. At the transmitter side, two data blocks are transmitted in which first data block is generated by inserting an zero to the tail of an conventional OFDM symbol block and second data block is generated by right cyclic shift with a phase inversion in first data block. To generate second data block transmitter require some additional circuit such as shifter and shift register for cyclic right shift. At the receiver end, the received signal is divided into two data blocks and then data streams are added to estimate the transmitted data block. There is additional complexity of few circuits such as symbol block shifter, shift registers, frame synchronizer, divider, symbol register and adder at the receiver side. Despite of some additional circuitivity, this scheme can efficiently combat the sensitivity of OFDM system to carrier frequency offset and provide better CIR performance over an conventional OFDM system.

V. OVERVIEW OF VARIOUS ICI SELF CANCELLATION

Zhao-Haggman's [5] ICI self cancellation is considered as basic building block for comparison because of its low complexity and good performance. All the techniques discussed gives better performance over conventional OFDM systems in terms of carrier to interference ratio and bit error rate. There is always a trade of between system performance and computational complexity. Now depending upon the system requirement user can choose any of ICI self cancellation technique.

TABLE I. OVERVIEW

ICI SC schemes	Modulation constrained	CIR, BER	Complexity	
			TX	*RX*
Zhao's	X(k+1)= -X(k)	better	No	No
Y.H. Peng's	$X(k+1) = e^{-j\pi/2}X(k)$	better	No	No
A.Sayedi's	Window w_{TX}, w_{RX}	better	Slight Increase	Slight Increase
Oscar real's	Only w_{TX}	better	Increase	No
S.Tang's	X(N-1-k)= $-X(k)^*$	better	Slight Increase	Slight Increase

VI. CONCLUSION

Various ICI suppression techniques are studied which are based on self cancellation techniques and can eliminate the inter-carrier interference. At the cost of reduced bandwidth efficiency, ICI SC techniques can suppress the effect of frequency offset caused by channel impairment efficiently and at a very low cost. All ICI self cancellation techniques perform well in AWGN and fast fading environment which is a better option.

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