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Reduction of ICI Using ICI Self Cancellation Scheme in OFDM Systems

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Abstract - **OFDM is a multicarrier modulation technique in which a high rate bitstream is split into N parallel bit-streams of lower rate and each of these are modulated using one of N orthogonal sub-carriers. In a basic communication system, the date is modulated onto a single carrier frequency. The available bandwidth is then totally occupied by each symbol. This kind of system can lead to inter-symbol-interference (ISI) in case of frequency selective channel. The basic idea of OFDM is to divide the available spectrum into several orthogonal sub channels so that each narrowband subchannels experiences almost flat fading. Orthogonal frequency division multiplexing (OFDM) is becoming the chosen modulation technique for wireless communications. A well known problem of OFDM is its sensitivity to frequency offset between the transmitted and received signals, which may be caused by Doppler shift in the channel, or by the difference between the transmitter and receiver local oscillator frequencies. This carrier frequency offset causes loss of orthogonality between sub-carriers and the signals transmitted on each carrier are not independent of each other. The orthogonality of the carriers is no longer maintained, which results in inter-carrier interference (ICI). The undesired ICI degrades the performance of the system. This paper investigates an efficient ICI cancellation method termed ICI self-cancellation scheme for combating the impact of ICI on OFDM systems.**

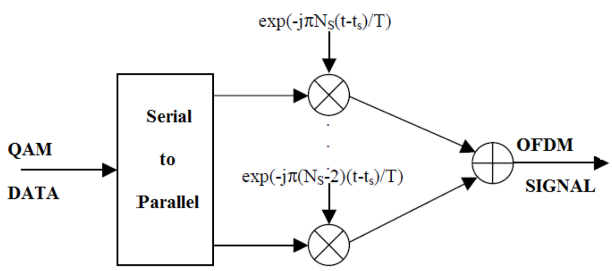
Keywords - **Inter symbol interference, Inter carrier interference, orthogonality, Doppler shift, Self cancellation, CIR, BER etc.**

I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a technique in which the total transmission bandwidth is split into a number of orthogonal subcarriers so that a wideband signal is transformed in a parallel arrangement of narrowband 'orthogonal' signals. In this way, a high data rate stream that would otherwise require a channel bandwidth far beyond the actual coherence bandwidth can be divided into a number of lower rate streams. Increasing the number of subcarriers increases the symbol period so that, ideally, a frequency selective fading channel is turned into a flat fading one. In other words, OFDM handles frequency selective fading resulting from time dispersion of multipath channels by expanding the symbol duration [1].

Very high data rates are consequently possible and for this reason it has been chosen as the transmission method for many standards from cable-based Asymmetric Digital Subscriber Line (ADSL), to wireless systems such as the IEEE 802.11a/g local area network, the IEEE 802.16 for broadband metropolitan area network and digital video and audio broadcasting. The fact that the OFDM symbol period is longer than in single carrier modulation, assures a greater robustness against Inter-Symbol Interference (ISI) caused by delay spread. On the other hand, this makes the system more sensitive to time variations that may cause the loss of orthogonality among subcarriers thus introducing cross interference among subcarriers. Other possible causes of this loss may be due to frequency or sampling offsets emerging at the local oscillator, phase noise and synchronization errors: the combination of all these factors forms the frequency domain OFDM channel response that can be summarized in an ICI matrix. Estimation of this channel matrix is crucial to maximize performance, but in real world OFDM systems this task can be very tough, since the size of the ICI matrix depends on the number of OFDM subcarriers which can be in the order of hundreds or thousands. Several channel estimation algorithms and methods to obtain ICI cancellation have been reported in the literature in both frequency and time domain: although blind techniques are possible without reduction of Spectrum efficiency, commercial systems include pilot patterns to improve the estimation process. These are exploited for example in [2] where a pilot-symbol-aided estimation in the time domain is proposed. Other approaches tend to exploit some other redundancy in the signal structure. In [3][4], training symbols are used to estimate the frequency offset, in [5] the authors propose to use the cyclic-prefix and then Independent Component Analysis (ICA) is applied to the received subcarriers. In [6] frequency offset estimation is obtained by repeated information symbols. The paper is organized as follows. In Section II the formulation of the OFDM channel in frequency domain is introduced together with the ICI matrix approximation. In Section III the problem due to inter carrier interference is analyzed and In Section IV the proposed method is described and in Section V the simulations results are analyzed. Finally conclusions and some perspectives are given.

II. System Model



In an OFDM system, the input bit stream is multiplexed into N symbol streams, each with symbol period T, and each symbol stream is used to modulate parallel, synchronous sub-carriers [1]. The sub-carriers are spaced by 1 in frequency, thus they are orthogonal over the interval (0, T).

A typical discrete-time baseband OFDM transceiver system is shown in Figure 2.1. First, a serial-to-parallel (S/P) converter groups the stream of input bits from the source encoder into groups of $\log_2 M$ bits, where M is the alphabet of size of the digital modulation scheme employed on each sub-carrier. A total of N such symbols, X_m, are created. Then, the N symbols are mapped to bins of an inverse fast Fourier transform (IFFT). These IFFT bins correspond to the orthogonal sub-carriers in the OFDM symbol. Therefore, the OFDM symbol can be expressed as

$$X(n)=1/N\sum_{m=0}^{N-1} X(m)\exp\left(\frac{j2\pi nm}{N}\right) \text{-------}(2.1)$$

where the X(m)'s are the baseband symbols on each sub-carrier. The digital-to-analog (D/A) converter then creates an analog time-domain signal which is transmitted through the channel.

At the receiver, the signal is converted back to a discrete N point sequence y(n), corresponding to each sub-carrier. This discrete signal is demodulated using an N-point fast Fourier transform (FFT) operation at the receiver. The demodulated symbol stream is given by:

$$Y(m)=\sum_{m=0}^{N-1} y(n)\exp\left(\frac{-j2\pi nm}{N}\right) + W(m) \text{---}(2.2)$$

where, W(m) corresponds to the FFT of the samples of w(n), which is the Additive White Gaussian Noise (AWGN) introduced in the channel.

The high speed data rates for OFDM are accomplished by the simultaneous transmission of data at a lower rate on each of the orthogonal sub-carriers. Because of the low data rate transmission, distortion in the received signal induced by multi-path delay in the channel is not as significant as compared to single-carrier high-data rate systems. For example, a narrowband signal sent at a high data rate through a multipath channel will experience greater negative effects of the multipath delay spread, because the symbols are much closer together [3]. Multipath distortion can also cause inter-symbol interference (ISI) where adjacent symbols overlap with each other. This is prevented in OFDM by the insertion of a cyclic prefix between successive OFDM symbols. This cyclic prefix is discarded at the receiver to cancel out ISI. It is due to the robustness of OFDM to ISI and multipath distortion that it has been considered for various wireless applications and standards[3].

2.1 *DERIVATIONS OF ICI COEFFICIENTS:*

Say Y(k) is the Discrete Fourier Transform of y(n). Then we get,

$$Y(k) = \sum_{n=0}^{N-1} x(n)\exp\left(\frac{j2\pi n\pounds}{N}\right)\exp\left(\frac{-j2\pi nk}{N}\right)$$

$$=\sum_{n=0}^{N-1} 1/N\left(\sum_{n=0}^{N-1} X(m)\exp\left(\frac{j2\pi nm}{N}\right)\exp\left(\frac{j2\pi n(\pounds-k)}{N}\right)\right.$$

$$=\frac{1}{N}\sum_{m=0}^{N-1} X(m)\sum_{n=0}^{N-1}\exp\left(\frac{j2\pi n(m+\pounds-k)}{N}\right) = \frac{1}{N}\sum_{m=0}^{N-1} X(m)\sum_{n=0}^{N-1}\exp\left(\frac{j2\pi n(m+\pounds-k)}{N}\right) \text{(B.1)}$$

We can expand $\frac{1}{N}\sum_{n=0}^{N-1}\exp\left(\frac{j2\pi n(m+\pounds-k}{N}\right)$ using the geometric series as ,

$$\frac{1}{N}\sum_{n=0}^{N-1}\exp\left(\frac{j2\pi n(m+\pounds-k)}{N}\right) = \frac{1}{N}\frac{1-\exp(j2\pi(m+\pounds-k))}{1-\exp(j2\pi(m+\pounds-k))/N)}$$

$$=\left(\frac{1}{N}\right)\frac{\exp\left(\frac{j2\pi(m+\pounds-k)}{2}\right)\left(\exp\left(-\frac{j2\pi(m+\pounds-k)}{2}\right)-\exp\left(\frac{j2\pi(m+\pounds-k)}{2}\right)\right)}{\exp\left(\frac{j2\pi(m+\pounds-k)}{2N}\right)\left(\exp\left(-\frac{j2\pi(m+\pounds-k)}{2N}\right)-\exp\left(\frac{j2\pi(m+\pounds-k)}{2N}\right)\right)}$$

(B.2)

$$=\frac{1}{N}.\exp(j2\pi(m+\pounds-k)(1-\frac{1}{N})\frac{SIN(\pi(m+\pounds-k))}{\sin\left(\frac{\pi(m+\pounds-k)}{N}\right)}$$

Substituting (B.2) in (B.1) , we get,

$$Y(k) = \sum_{m=0}^{N-1} X(m)S(m-k) \text{ Where ,}$$

$$S(m-k) = \exp(j2\pi(m+\pounds-k)(1 - -\frac{1}{N})\frac{\sin(\pi(m+\pounds-k))}{N\sin\left(\frac{\pi(m+\pounds-k)}{N}\right)}$$

These are the required ICI coefficients.

III. Analysis of Inter Carrier Interference

The main disadvantage of OFDM, however, is its susceptibility to small differences in frequency at the transmitter and receiver, normally referred to as frequency offset. This frequency offset can be caused by Doppler shift due to relative motion between the transmitter and receiver, or by differences between the frequencies of the local oscillators at the transmitter and receiver. In this project, the frequency offset is modeled as a multiplicative factor introduced in the channel[10].

The received signal is given by

$$Y(n)=x(n)\exp\left(\frac{j2\pi n\pounds}{N}\right) + W(n) \text{----}(3.1)$$

where ε is the normalized frequency offset, and is given by ΔfNT_s. Δf is the frequency difference between the transmitted and received carrier frequencies and T_s is the subcarrier symbol period. w(n) is the AWGN introduced in the channel.

The effect of this frequency offset on the received symbol stream can be understood by considering the received symbol Y(k) on the k^{th} sub-carrier.

$$Y(k)=x(k)S(0) + \sum_{l=0,l\#k}^{N-1} X(l)S(l-k) + n_k \text{--}(3.2)$$

K=0,1,----N-1

where N is the total number of subcarriers, X(k) is the transmitted symbol (M-ary phase-shift keying (M-PSK), for example) for the k^{th} subcarrier, is the FFT of w(n), and S(l-k) are the complex coefficients for the ICI components in the received signal. The ICI components are the interfering signals transmitted on sub-carriers other than the k^{th} sub-carrier. The complex coefficients are given by

$$S(l-k)=\frac{\sin(\pi(l+\pounds-k))}{N\sin\left(\frac{\pi(l+\pounds-k)}{N}\right)}\exp(j\pi(1-1/N)(l+\pounds-k) \text{---}(3.3)$$

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The carrier-to-interference ratio (CIR) is the ratio of the signal power to the power in the interference components. It serves as a good indication of signal quality. It has been derived from (3.2) in [7] and is given below. The derivation assumes that the standard transmitted data has zero mean and the symbols transmitted on the different sub-carriers are statistically independent.

$$CIR=\frac{|S(k)|^2}{\sum_{l=0,l\neq k}^{N-1}|S(l-k)|^2}=\frac{|S(0)|^2}{\sum_{l=0}^{N-1}|S(l)|^2} \text{---(3.4)}$$

IV. ICI SELF-CANCELLATION SCHEME

ICI self-cancellation is a scheme that was introduced by Yuping Zhao and Sven-Gustav Häggman in 2001 in [8] to combat and suppress ICI in OFDM. Succinctly, the main idea is to modulate the input data symbol onto a group of subcarriers with predefined coefficients such that the generated ICI signals within that group cancel each other, hence the name self- cancellation[6].

4.1 ICI Canceling Modulation

The ICI self-cancellation scheme shown in figure 4.1.1 requires that the transmitted signals be constrained such that X(1)= -X(0), X(3)= -X(2),----X(N-1)= -X (N-2), Using (3.3), this assignment of transmitted symbols allows the received signal on subcarriers k and k + 1 to be written as

$$Y`(K)=\sum_{l=0,l=even}^{N-2}x(l)[S(l-k)-S(l+1-k)] + n_k$$

$$Y`(K+1)=\sum_{l=0,l=even}^{N-2}x(l)[S(l-k-1)-S(l-k)]+ n_k \text{--(4.1)}$$

and the ICI coefficient S'(l-k) is denoted as

S'(l-k)=S(l-k)-S(l+1-k) ----------(4.2)

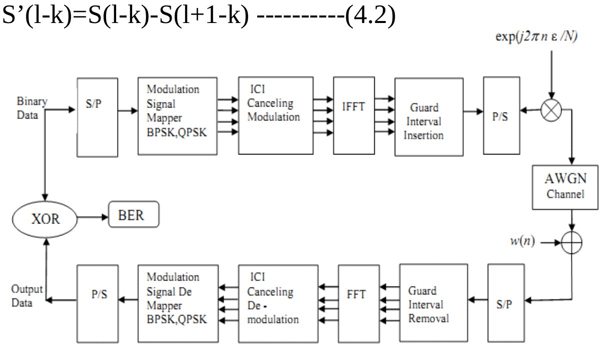

Fig.4.1.1 – OFDM Model with Self cancellation

ICI coefficients S(l-k) Vs subcarrier k is plotted in figure 4.1.2

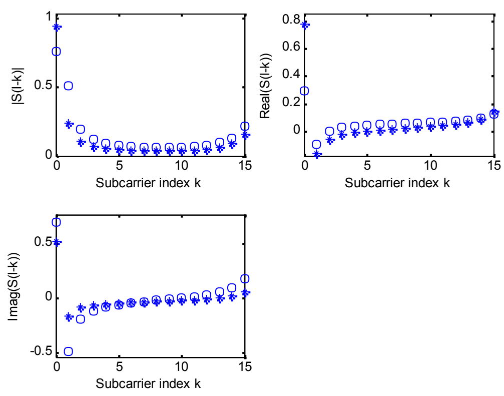

Fig.4.1.2 ICI coefficients S(l-k) Vs subcarrier k

Figure (4.1.3) shows a comparison between |S'(l-k)| and |S(l-k)| on a logarithmic scale. It is seen that |S'(l-k)| << |S(l-k)| for most of the l-k values. Hence, the ICI components are much smaller in (4.2) than they are in (3.3). Also, the total number of interference signals is halved in (4.2) as opposed to (3.3) since only the even subcarriers are involved in the summation.

Comparision of |S(1-k)|,|S"(1-k)|, and |S''(1-k)| for ε=0.2 and N=64

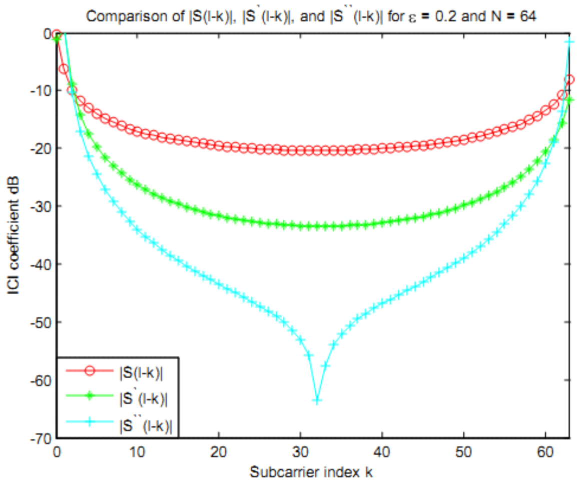

Fig.(4.1.3). comparison of S(l-k),S'(l-k) and S''(l-k) Vs subcarrier k

4.2 *ICI Canceling Demodulation*

ICI modulation introduces redundancy in the received signal since each pair of subcarriers transmit only one data symbol. This redundancy can be exploited to improve the system power performance, while it surely decreases the bandwidth efficiency. To take advantage of this redundancy, the received signal at the (k + 1)th subcarrier, where k is even, is subtracted from the kth subcarrier. This is expressed mathematically as

Y''(k) = Y'(k) – Y'(k+1)

$$= \sum_{l=0,l=even}^{N-2}x(l)[-S(l-k-1)+2S(l-k)-S(l-k+1)] + n_k - n_{k+1}$$

Subsequently, the ICI coefficients for this received signal becomes

S"(l-k)= -S(l-k-1)+2S(l-k)-S(l-K+1) ----(4.4)

When compared to the two previous ICI coefficients |S(l-k)| for the standard OFDM system and |S'(l-k)| for the ICI canceling modulation, |S''(l-k)| has the smallest ICI coefficients, for the majority of l-k values, followed by |S'(l-k)| and |S(l-k)|. This is shown in Figure 4.1.3 for N = 64 and ε = 0.2. The combined modulation and demodulation method is called the ICI self-cancellation scheme.

The reduction of the ICI signal levels in the ICI self-cancellation scheme leads to a higher CIR.

From (4.4), the theoretical CIR can be derived as

$$CIR=\frac{|-S(-1)+2S(0)-S(1)|^2}{\sum_{l=2,4,6--}^{N-1}|-S(l-1)+2S(l)-S(l+1)|^2} \text{----(4.5)}$$

Figure (4.2.1) shows the comparison of the theoretical CIR curve of the ICI self-cancellation scheme, calculated by (4.5), and the CIR of a standard OFDM system calculated by (3.3). As expected, the CIR is greatly improved using the ICI self-cancellation scheme[9]. The improvement can be greater than 15 dB for 0 < ε < 0.5.

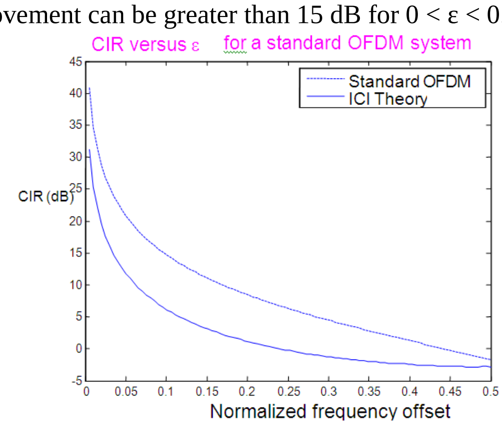

Fig.(4.2.1). CIR Vs Normalized frequency offset

As mentioned above, the redundancy in this scheme reduces the bandwidth efficiency by half. This could be compensated by transmitting signals of larger alphabet size. Using the theoretical results for the improvement of the CIR should increase the power efficiency in the system and gives better results for the BER shown in figure (4.2.2).

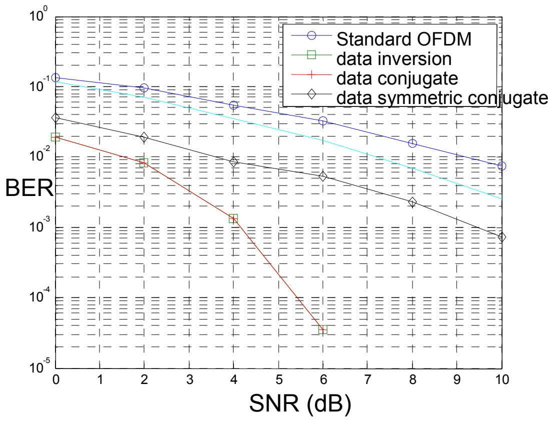

Fig.4.2.2. BER Vs SNR for an OFDM system

Hence, there is a tradeoff between bandwidth and power tradeoff in the ICI self-cancellation scheme.

V. Simulation Results and Discussion

Figure 4.1.1 shows the Fast Fourier transform (FFT) based N-subcarrier OFDM system model used for simulation [1]. The simulation parameters used for the model shown in Figure 4.1 is as given below.

Parameter	Specifications
IFFT Size	64
Number of Carriers in one OFDM symbol	52
Channel	AWGN
Frequency Offset	0, 0.15, 0.3
Guard Interval	12
Modulation	BPSK,QPSK
OFDM symbols for one loop	10000

Table 5.1- Simulation Parameters

5.1 *BER Performance of BPSK OFDM System:*

(a) BER performance of a BPSK OFDM system with & without self cancellation :

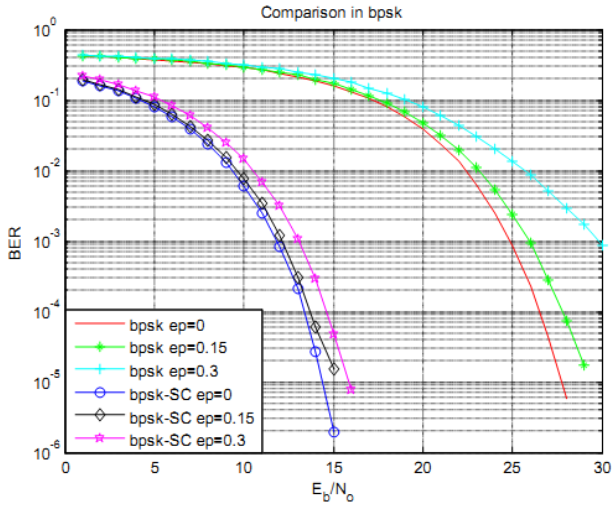

Fig.5.1.1BER performance of a BPSK OFDM system with & without Self Cancellation

BER performance of a BPSK OFDM system with & without Self Cancellation shown in Fig. 5.1.1.This is the plot which shows the comparison between standard OFDM and OFDM with self cancellation technique for different values of frequency offset for the modulation BPSK. From the figure we observe that as the value of carrier frequency offset ε increases, the BER increases. We can infer that self cancellation technique in OFDM has less BER compared to without self cancellation.

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5.2 *BER performance of QPSK OFDM system*

(a) BER performance of a QPSK OFDM system with & without Self Cancellation:

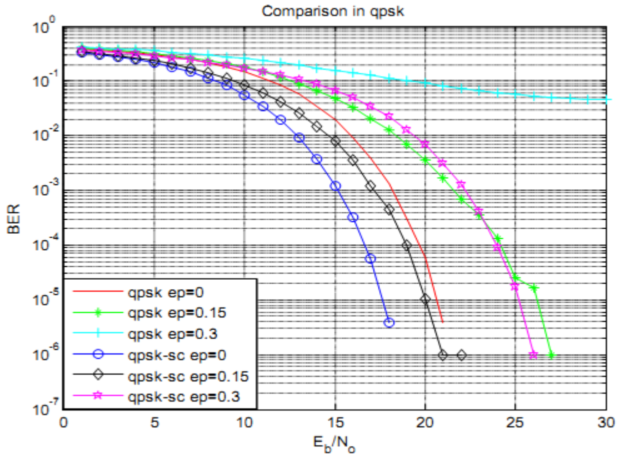

Fig.5.2.1 BER performance of a QPSK OFDM system with & without Self Cancellation

From the figure 5.2.1 we observe that as the value of carrier frequency offset ε increases, the BER increases. As SNR increases QPSK BER curve leans downward which indicates reduction in bit error rate. This is the plot which shows the comparison between standard OFDM and OFDM with self cancellation technique for different values of frequency offset for the modulation QPSK.

We can infer that self cancellation technique in OFDM has low BER compared to standard OFDM.

(b) BER performances of QPSK, BPSK OFDM systems with constant frequency offsets is simulated in figure(5.2.2).

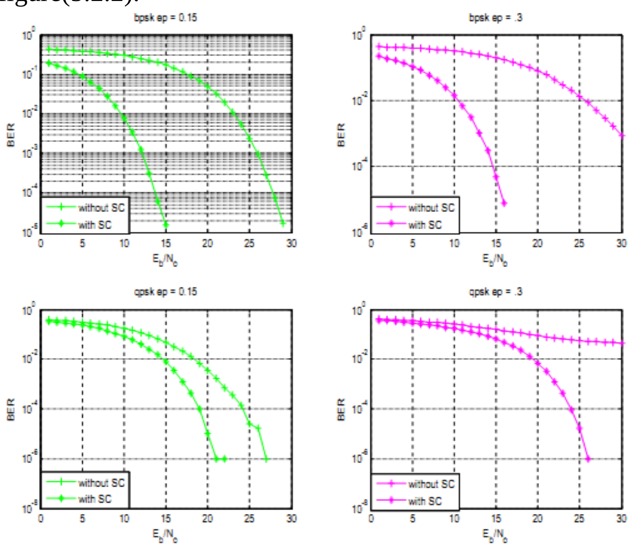

Fig. 5.2.2 BER performances of QPSK, BPSK OFDM systems with constant frequency offsets

5.3 *Comparison of BER performances of BPSK, QPSK OFDM systems*

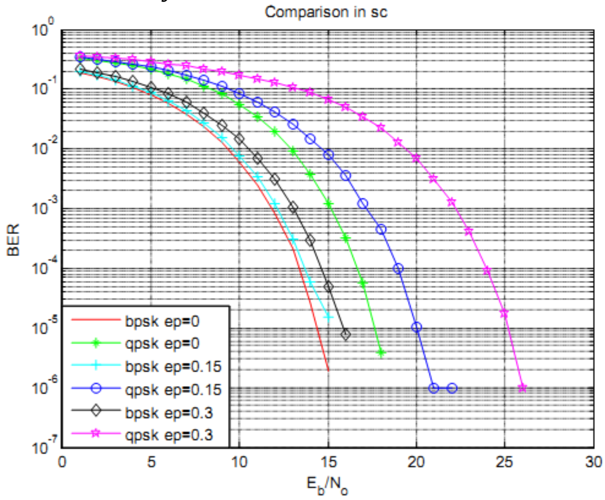

Fig.5.3.1 BER performance of a BPSK, QPSK OFDM systems with Self Cancellation.

This plot shown in figure (5.3.1) is the comparison between two modulation techniques for different values of frequency offset. Here only self cancellation technique is considered. We notice that as the value of carrier frequency offset ε increases, the BER increases. For low frequency offset value BER is less. For constant ε value, BER of BPSK is less than BER of QPSK.

VI. Conclusion

In this paper, the performance of OFDM systems in the presence of frequency offset between the transmitter and the receiver has been studied in terms of the Carrier-to-Interference ratio(CIR).Inter-carrier interference (ICI) which results from the frequency offset degrades the performance of the OFDM system.

One of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes attenuation and rotation of subcarriers, and inter carrier interference (ICI). Orthogonality of the sub-carriers in OFDM helps to extract the symbols at the receiver without interference with each other. This work investigates an ICI self-cancellation scheme for combating the impact of ICI on OFDM systems for different frequency offset values. Different modulation techniques are considered for ICI reduction and compared with each other for their performances. It is also suitable for multipath fading channels. It is less complex and effective. The proposed scheme provides significant CIR improvement, which has been studied theoretically and by simulations. Under the condition of the same bandwidth efficiency and larger frequency offsets, the proposed OFDM system using the ICI self-cancellation scheme performs much better than standard OFDM systems. In addition, since no channel equalization is needed for reducing ICI, the proposed scheme is therefore easy to implement without increasing system complexity.

VII. Scope of Future Work

Following are the areas of future study which can be considered for further research work.

1. Coding associated with frequency (among carriers) and time interleaving make the system very robust in frequency selective fading. Hence Channel coding is very important in OFDM systems. COFDM (Coded OFDM) Systems can be used for ICI reduction using self cancellation technique.
2. This self cancellation technique can also be applied under different multipath propogation mobile conditions such as Rayleigh fading channel, urban, rural area channels etc.
3. This self cancellation scheme can be extended to Multiple input and Multiple output (MIMO) OFDM systems.

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