Effect Of TO & CFO on OFDM and SIR Analysis and Interference Cancellation in MIMO-OFDM

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Abstract: OFDM is a multicarrier modulation technique in which a high rate bit stream 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 data is modulated onto a single carrier frequency. OFDM is a promising candidate for achieving high data rates in mobile environment because of its multicarrier modulation technique. The available bandwidth is then totally occupied by each symbol. The variations in Time Offset (TO) can lead to inter-symbol-interference (ISI) in case of frequency selective channel. 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(CFO) causes loss of orthogonality between sub-carriers and the signals transmitted on each carrier are not independent of each other, which results in inter-carrier interference (ICI).The undesired ICI degrades the performance of the system. ICI mitigation techniques are essential in improving the performance of an OFDM system in an environment which induces frequency offset error in the transmitted signal. In this paper , the focus is on the problem of ICI. We proposed ICI reduction using self cancellation scheme and compared with standard OFDM system. . The simulation of OFDM was done with different digital modulation schemes such as BPSK and QPSK modulation techniques . the performance of the designed OFDM system by finding their bit error rate (BER) for different values of signal to noise ratio (SNR). Later we proposed MIMO diversity technique such as STBC OFDM to enhance the performance of the system by reducing the BER for different values of signal to noise ratio (SNR). BER Analysis for BPSK in Rayleigh channel With two transmit and one receive antenna as well as two transmit and two receive antennas for Alamouti STBC case shows higher performance, which effectively alleviates the effects of ISI and ICI.

Keywords: *TO, CFO, ISI, ICI, Doppler shift, Self cancellation, CIR, STBC, BER etc.*

1. 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 2 the OFDM system model and formulation of the OFDM channel in frequency domain is introduced together with the ICI matrix approximation. In

Section 3 the problem due to inter carrier interference is analyzed. In Section 4 the proposed method is described. Section 5 the simulations results are analyzed. Section 6 the MIMO STBC model is introduced and in Section 7 the BER analysis of proposed STBC method is derived and simulated. Finally conclusions and some perspectives are given.

2. SYSTEM MODEL

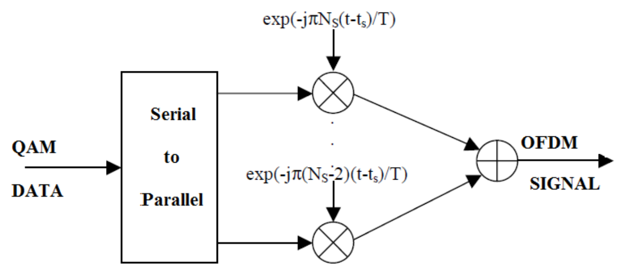

Fig 2.1 OFDM system model

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,

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

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

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

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

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

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

(B.2)

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

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

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

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

Which are the required ICI coefficients.

3. 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

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

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.

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

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

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.

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

4. 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 Fig 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

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

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

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

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

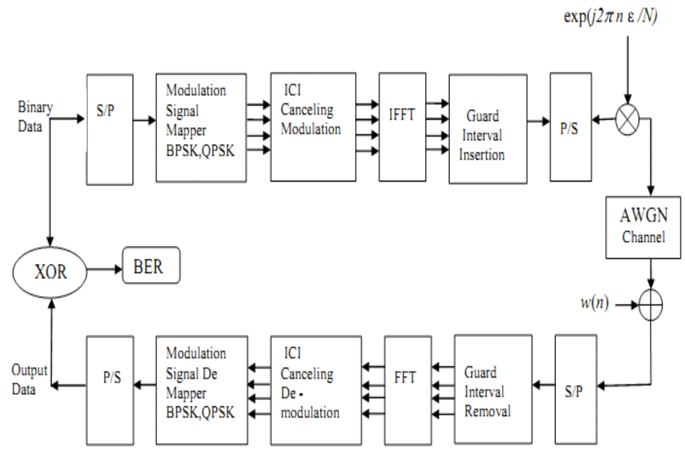

Fig.4.1.1 – OFDM Model with Self cancellation

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

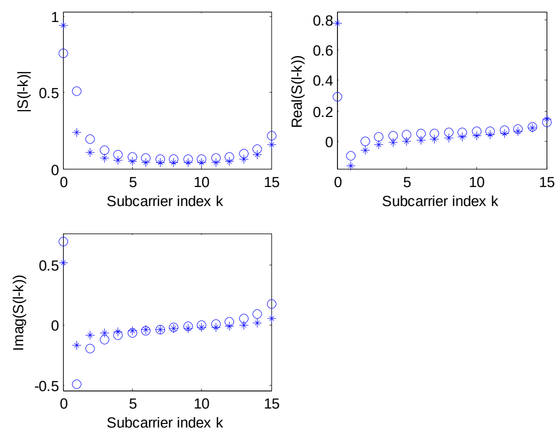

Fig 4.1.2 ICI coefficients S(l-k) Vs subcarrier k

Fig.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

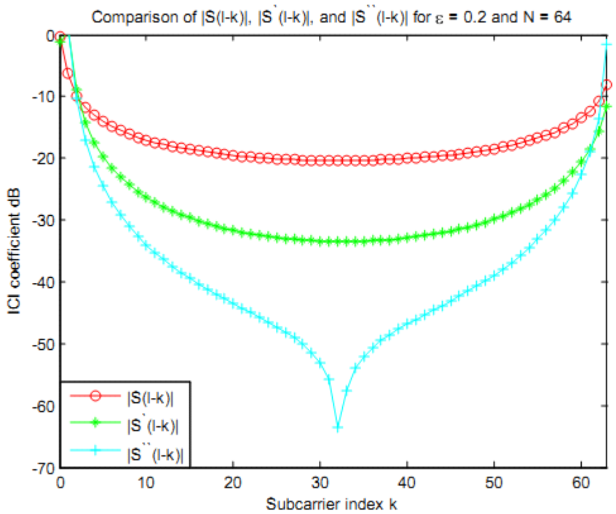

Fig.4.1.3. comparison of S (l-k), S' (l-k) and S''(l-k) Vs subcarrier k

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

$$S''(l-k) = -S(l-k-1)+2S(l-k)-S(l-K+1) \quad \text{----(4.4)}$$

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

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

Fig. (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.

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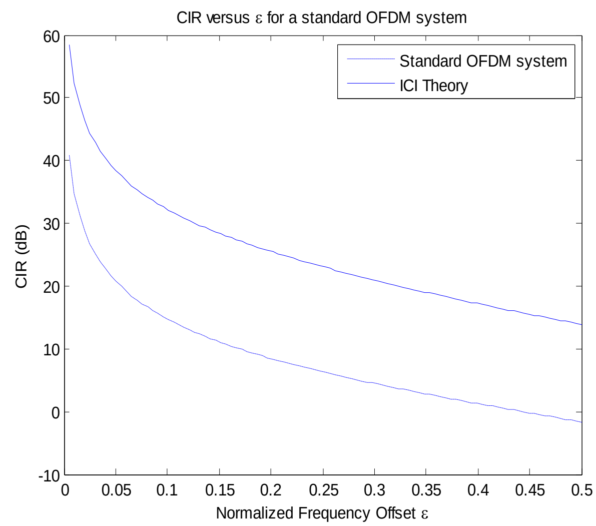

Fig .4.2.1. CIR Vs Normalized frequency offset

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 Fig. 4.2.2.

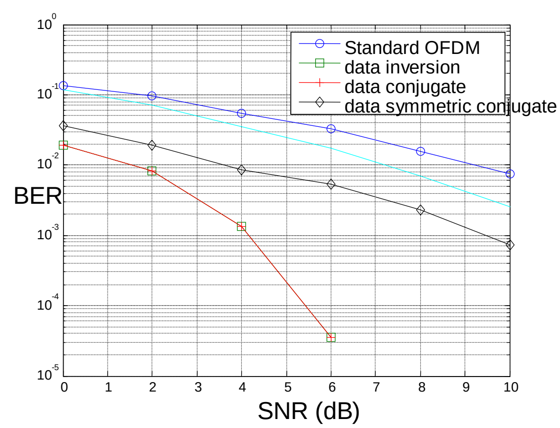

Fig. 4.2.2. BER Vs SNR for an OFDM system

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

5. SIMULATION RESULTS and DISCUSSION

Fig.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 OFDN Symbol	52
channel	AWGN
Frequency Offset	0,0.15,0.3
Guard Interval	12
Modulation	BPSK,QPSK
OFDM Symbols for one loop	1000

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 :

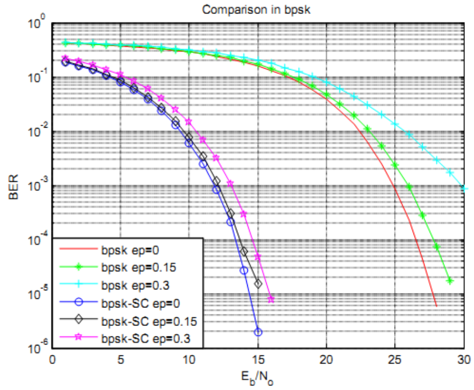

Fig 5.1.1BER performance of a BPSK OFDM system with & without Self Cancellation

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.

5.2 BER performance of QPSK OFDM system

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

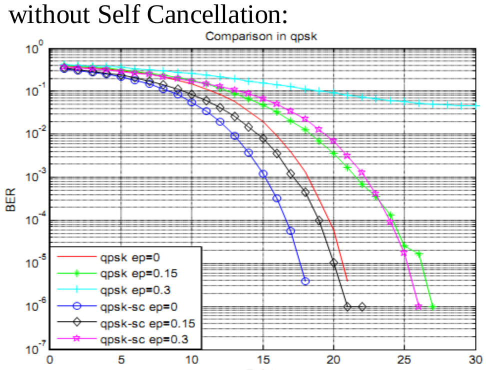

Fig.5.2.1 BER performance of a QPSK OFDM system with & without Self Cancellation

From the Fig. 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 Fig.(5.2.2).

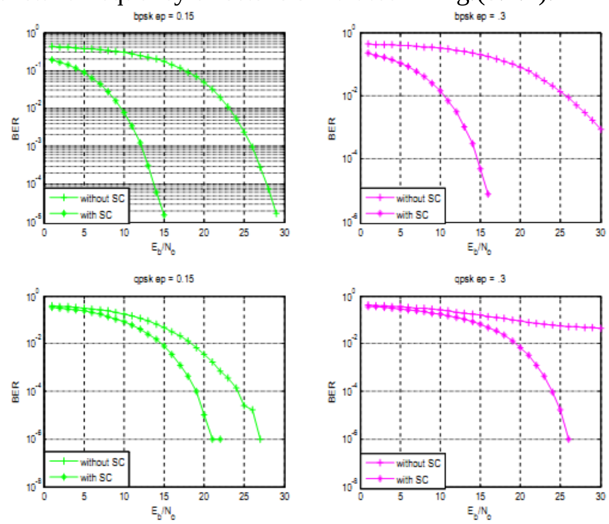

Fig 5.2.2 BER performances of QPSK, BPSK OFDM systems with constant frequency offsets

5.3 Comparison of BER performances of BPSK, QPSK OFDM systems

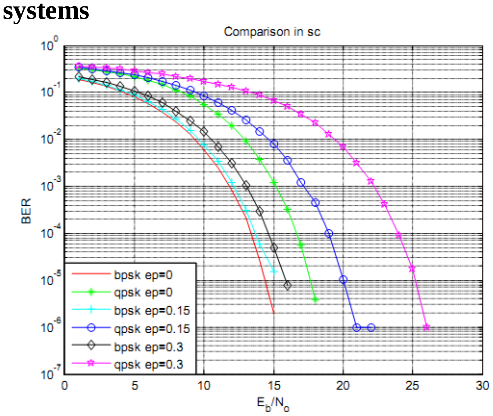

Fig 5.3.1 BER performance of a BPSK, QPSK OFDM systems with Self Cancellation.

This plot shown in Fig.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.

6. ALTAMONTE STBC

6.1 Transmitter with Alamouti STBC

Three receive diversity schemes – Selection combining, Equal Gain Combining and Maximal Ratio Combining. All the three approaches used the antenna array at the receiver to improve the demodulation performance, albeit with different levels of complexity. Time to move on to a **transmit diversity[11]** scheme where the information is spread across multiple antennas at the transmitter. lets discuss a popular transmit diversity scheme called **Alamouti Space Time Block Coding (STBC)[13]**. For the discussion, we will assume that the channel is a flat fading Rayleigh multipath channel and the modulation is BPSK.

A simple Space Time Code, suggested by Mr. Siavash M Alamouti in his landmark October 1998 paper – A Simple Transmit Diversity Technique for Wireless Communication[13], offers a simple method for achieving spatial diversity with two transmit antennas. The scheme is as follows:

1. Consider that we have a transmission sequence, For example $\{x_1, x_2, x_3, \ldots, x_n\}$
2. In normal transmission, we will be sending x_1 in the first time slot, x_2 in the second time slot, x_3 and so on.
3. However, Alamouti suggested that we group the symbols into groups of two. In the first time slot, send x_1 and x_2 from the first and second antenna. In second time slot send $-x_2^*$ and x_1^* from the first and second antenna. In the third time slot send x_3 and x_4 from the first and second antenna. In fourth time slot, send $-x_4^*$ and x_3^* from the first and second antenna and so on.
4. Notice that though we are grouping two symbols, we still need two time slots to send two symbols. Hence, there is no change in the data rate.
5. This forms the simple explanation of the transmission scheme with Alamouti Space Time Block coding shown in Fig.6.1.1.

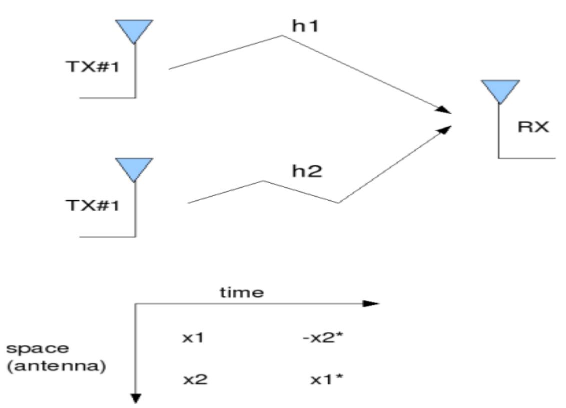

Fig. 6.1.1. Alamouti's 2Tx and 1Rx STBC Scheme

Other Assumptions

1. The channel is flat fading – In simple terms, it means that the multipath channel has only one tap. So, the convolution operation reduces to a simple multiplication.
2. The channel experience by each transmit antenna is independent from the channel experienced by other transmit antennas.
3. For the i^{th} transmit antenna, each transmitted symbol gets multiplied by a randomly varying complex number h_i. As the channel under consideration is a Rayleigh channel, the real and imaginary parts of h_i are Gaussian distributed having mean $\mu_{h_i} = 0$ and variance $\sigma^2_{h_i} = \frac{1}{2}$.

4. The channel experienced between each transmit to the receive antenna is randomly varying in time. However, the channel is **assumed to remain constant over two time slots.**
5. On the receive antenna, the noise n has the Gaussian probability density function with

$$p(n) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(n-\mu)^2}{2\sigma^2}}$$ with $\mu = 0$ and $\sigma^2 = \frac{N_0}{2}$.

6. The channel h_i is known at the receiver.

6.2 Receiver with Alamouti STBC

In the first time slot, the received signal is,

$$y_1 = h_1 x_1 + h_2 x_2 + n_1 = [h_1 \ h_2]\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + n_1.$$

In the second time slot, the received signal is,

$$y_2 = -h_1 x_2^* + h_2 x_1^* + n_2 = [h_1 \ h_2]\begin{bmatrix} -x_2^* \\ x_1^* \end{bmatrix} + n_2.$$

Where

y_1, y_2 is the received symbol on the first and second time slot respectively,

h_1 is the channel from 1^{st} transmit antenna to receive antenna,

h_2 is the channel from 2^{nd} transmit antenna to receive antenna,

x_1, x_2 are the transmitted symbols and

n_1, n_2 is the noise on $1^{st}, 2^{nd}$ time slots.

Since the two noise terms are independent and identically distributed,

$$E\left\{\begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}\begin{bmatrix} n_1^* & n_2 \end{bmatrix}\right\} = \begin{bmatrix} |n_1|^2 & 0 \\ 0 & |n_2|^2 \end{bmatrix}.$$

For convenience, the above equation can be represented in matrix notation as follows:

$$\begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \underbrace{\begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}.$$

Let us define $\boldsymbol{H} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}$. To solve for $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$, we know that we need to find the inverse of $\boldsymbol{H}$ .We know, for a general m x n matrix, the pseudo inverse is defined as,

$$\boldsymbol{H}^+ = (H^H H)^{-1} H^H.$$

The term,

$$(H^H H) = \begin{bmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{bmatrix}\begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} = \begin{bmatrix} |h_1|^2 + |h_2|^2 & \\ 0 & |h_1|^2 + |h_2 \end{bmatrix}$$

. Since this is a diagonal matrix, the inverse is just the inverse of the diagonal elements, i.e

$$(H^H H)^{-1} = \begin{bmatrix} \frac{1}{|h_1|^2 + |h_2|^2} & 0 \\ 0 & \frac{1}{|h_1|^2 + |h_2|^2} \end{bmatrix}.$$

The estimate of the transmitted symbol is,

$$\widehat{\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}} = (H^H H)^{-1} H^H \begin{bmatrix} y_1 \\ y_2^* \end{bmatrix}$$
$$= (H^H H)^{-1} H^H \left(H \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix} \right)$$
$$= \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + (H^H H)^{-1} H^H \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}.$$

By compare the above equation with the estimated symbol following equalization in Maximal Ratio Combining, we can see that the equations are identical.

6.3 Alamouti STBC with two receive antenna

The principle of space time block coding with 2 transmit antenna . With two receive antenna's the system can be modeled as shown in the Fig.6.3.1. below.

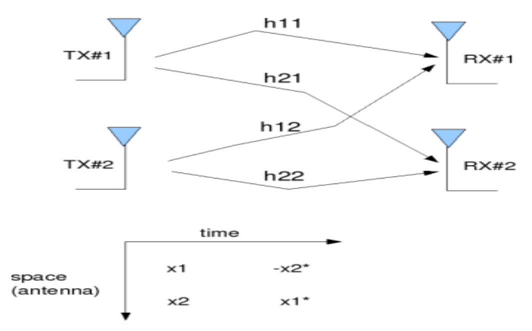

Fig.6.3.1. Transmit 2 Receive Alamouti STBC

The received signal in the first time slot is,

$$\begin{bmatrix} y_1^1 \\ y_2^1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1^1 \\ n_2^1 \end{bmatrix}.$$

Assuming that the channel remains constant for the second time slot, the received signal is in the second time slot is,

$$\begin{bmatrix} y_1^2 \\ y_2^2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}\begin{bmatrix} -x_2^* \\ x_1^* \end{bmatrix} + \begin{bmatrix} n_1^2 \\ n_2^2 \end{bmatrix}$$

where

$\begin{bmatrix} y_1^1 \\ y_2^1 \end{bmatrix}$ are the received information at time slot 1 on receive antenna 1, 2 respectively,

$\begin{bmatrix} y_1^2 \\ y_2^2 \end{bmatrix}$ are the received information at time slot 2 on receive antenna 1, 2 respectively, h_{ij} is the channel from i^{th} receive antenna to j^{th} transmit antenna,

x_1, x_2 are the transmitted symbols,

$\begin{bmatrix} n_1^1 \\ n_2^1 \end{bmatrix}$ are the noise at time slot 1 on receive antenna 1, 2 respectively and

$\begin{bmatrix} n_1^2 \\ n_2^2 \end{bmatrix}$ are the noise at time slot 2 on receive antenna 1, 2 respectively. Combining the equations at time slot 1 and 2,

$$\begin{bmatrix} y_1^1 \\ y_2^1 \\ y_1^{2*} \\ y_2^{2*} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{12}^* & -h_{11}^* \\ h_{22}^* & -h_{21}^* \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1^1 \\ n_2^1 \\ n_1^{2*} \\ n_2^{2*} \end{bmatrix}$$

Let us define

$\boldsymbol{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{12}^* & -h_{11}^* \\ h_{22}^* & -h_{21}^* \end{bmatrix}$,To solve for $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$, we know that we need to find the inverse of $\boldsymbol{H}$.

$\boldsymbol{H}^+ = (H^H H)^{-1} H^H$.The term,

$$(H^H H) = \begin{bmatrix} |h_{11}|^2+|h_{21}|^2+|h_{12}|^2+|h_{22}|^2 & 0 \\ 0 & |h_{11}|^2+|h_{21}|^2+|h_{12}|^2+|h_{22}|^2 \end{bmatrix}$$

Since this is a diagonal matrix, the inverse is just the inverse of the diagonal elements, i.e

$$(H^H H)^{-1} = \begin{bmatrix} \frac{1}{|h_{11}|^2+|h_{21}|^2+|h_{12}|^2+|h_{22}|^2} & 0 \\ 0 & \frac{1}{|h_{11}|^2+|h_{21}|^2+|h_{12}|^2+|h_{22}|^2} \end{bmatrix}$$

The estimate of the transmitted symbol is,

$$\widehat{\begin{bmatrix} x_1 \\ x_2^* \end{bmatrix}} = (H^H H)^{-1} H^H \begin{bmatrix} y_1^1 \\ y_2^1 \\ y_1^{2*} \\ y_2^{2*} \end{bmatrix}$$
.

7. BER analysis with Almouti STBC

Since the estimate of the transmitted symbol with the Alamouti STBC scheme is identical to that obtained from MRC, the BER with above described Alamouti scheme should be same as that for MRC. However, there is a small catch.

With Alamouti STBC, we are transmitting from two antennas. Hence the total transmits power in the Alamouti scheme is twice that of that used in MRC. To make the comparison fair, we need to make the total transmit power from two antennas in STBC case to be equal to that of power transmitted from a single antenna in the MRC case[14]. With this scaling, we can see that **BER performance of 2Tx, 1Rx Alamouti STBC case has a roughly 3dB poorer performance that 1Tx, 2Rx MRC case**.

From the Maximal Ratio Combining, the bit error rate for BPSK modulation in Rayleigh channel [17]with 1 transmit, 2 receive case is,

$$P_{e,MRC} = p_{MRC}^2\left[1+2(1-p_{MRC})\right],$$

where $p_{MRC} = \frac{1}{2} - \frac{1}{2}\left(1+\frac{1}{E_b/N_0}\right)^{-1/2}$.

With **Alamouti 2 transmit antenna, 1 receive antenna STBC** case,

$$p_{STBC} = \frac{1}{2} - \frac{1}{2}\left(1+\frac{2}{E_b/N_0}\right)^{-1/2}$$ and

Bit Error Rate is

$$P_{e,STBC} = p_{STBC}^2\left[1+2(1-p_{STBC})\right].$$

1. There is no cross talk between x_1, x_2 after the equalizer.
2. The noise term is still white.

$$E\left\{H^H \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix} \begin{bmatrix} n_1^* & n_2 \end{bmatrix} H\right\} = H^H \begin{bmatrix} |n_1|^2 & 0 \\ 0 & |n_2|^2 \end{bmatrix} H = \begin{bmatrix} |n_1|^2 & 0 \\ 0 & |n_2|^2 \end{bmatrix} \begin{bmatrix} |h_1|^2+|h_2|^2 & 0 \\ 0 & |h_1|^2+|h_2|^2 \end{bmatrix}$$

Simulation Model for BPSK in Rayleigh channel With two transmit and one receive antenna:

The Matlab simulation performs the following

(a) Generate random binary sequence of +1's and -1's.
(b) Group them into pair of two symbols
(c) Code it per the Alamouti Space Time code, multiply the symbols with the channel and then add white Gaussian noise.
(d) Equalize the received symbols
(e) Perform hard decision decoding and count the bit errors
(f) Repeat for multiple values of E_b/N_0 and plot the simulation and theoretical results.

The simulation results are as shown in the plot below Fig.7.1.1..

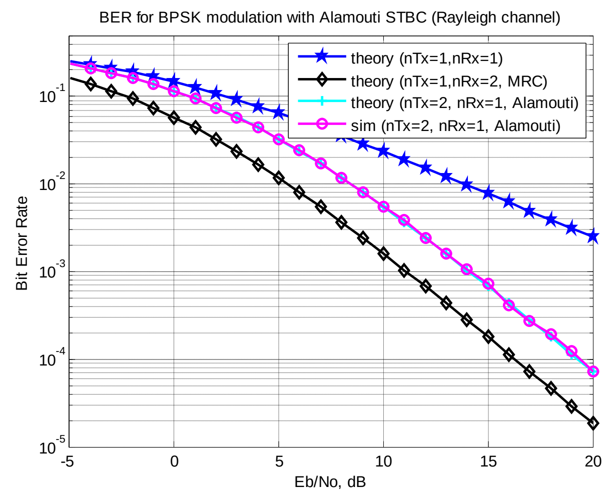

Fig.7.1.1. BER plot for BPSK in Rayleigh channel With two transmit and one receive antenna

Simulation Model for BPSK in Rayleigh channel With two transmit and two receive antenna:

The Matlab simulation performs the following

(a) Generate random binary sequence of +1′s and -1′s.
(b) Group them into pair of two symbols
(c) Code it per the Alamouti Space Time code, multiply the symbols with the channel and then add white Gaussian noise.
(d) Equalize the received symbols
(e) Perform hard decision decoding and count the bit errors
(f) Repeat for multiple values of Eb/No and plot the simulation and theoretical results.

The simulation results are as shown in the plot below Fig.7.1.2.

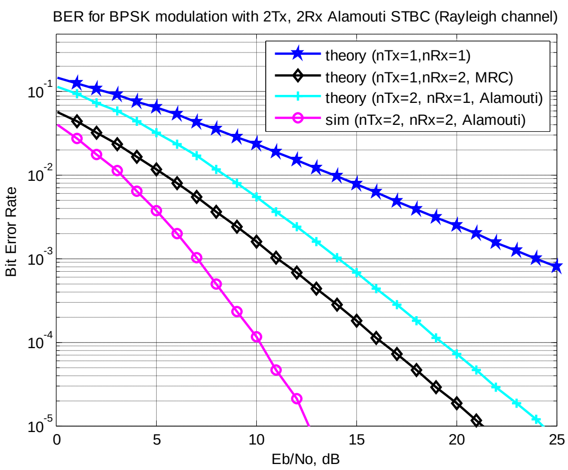

Fig.7.1.2. BER plot for BPSK in Rayleigh channel With two transmit and two receive antenna

6. 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. The variations in Time Offset(TO) can lead to inter-symbol-interference (ISI) in case of frequency selective channel can be reduced by using cyclic prefix as well as diversity in receiver design.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, In this work we develop a generally applicable equalization technique for space-time block coded (STBC) MIMO orthogonal frequency division multiplexing (OFDM) communication systems. We can observe that the BER performance is much better than 1 transmit 2 receive MRC case. This is because the effective channel concatenating the information from 2 receive antennas over two symbols results in a diversity order of 4. In general, with *m* receive antennas, the diversity order for 2 transmit antenna Alamouti STBC is 2*m*.BER plots for BPSK in Rayleigh channel With two transmit and one receive antenna as well as two transmit and two receive antennas for Alamouti case are derived and simulated.

7. 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 for more number of transmitters and receivers..

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