EFFECT OF SYNCHRONIZATION ERROR IN MULTI CARRIER SYSTEMS

a thesis submitted in partial fulfilment of the requirements for the degree of

Bachelor of Technology
in
Electronics and Communications Engineering
by

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NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

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CERTIFICATE

This is to certify that the thesis entitled **“Effect of Synchronization error in Multi Carrier systems”** submitted by **Priyaranjan Swain** and **Goudu J K Chaitanya**, in partial fulfilment of the requirements for the award of Bachelor of technology degree in Electronics and Communication Engineering at National Institute of Technology, Rourkela(Deemed University) is an authentic work carried by them under my guidance during session 2011-2012.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any institute/ university for the award of degree or diploma.

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ABSTRACT

Communications as an important aspect life plays a major role in our daily routine. With the progress in age and growth in its demand, there has been rapid development in the field of communications. Analog signals which were used to send information previously are now sent in digital domain in a much wider range. For better performance in terms of transmissions, single carriers are replaced by multi-carriers

Some of the methods that use multi-carriers for transmission are Orthogonal Division Frequency Multiplexing (OFDM), Code Division Multiple Access (CDMA). In OFDM system, orthogonally placed subcarriers are used to carry the data from the transmitter to the receiver. The guard band present in this system avoids the system from being effected by Inter Symbol Interference (ISI). However, Doppler Shifts and delays induced in the channel due to various reasons impose frequency offset to the carrier. This results in an error in the Synchronization between the transmitter and receiver. This leads to the loss of orthogonally between the subcarriers and thus degrades the performance of the OFDM system.

In this project, the Synchronization error in OFDM is discussed in particular and a technique of estimating the Carrier Frequency Offset (CFO) using Null Subcarriers is studied.

KEYWORDS: OFDM, ISI, ICI, Cyclic Prefix, Synchronization Error, IDFT, CFO, Null Subcarrier, BPSK, NMSE, BER.

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LIST OF ACRONYMS

AWGN	Additive White Guassian Noise
BER	Bit Error Rate
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
ICI	Inter Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
OFDM	Orthogonal Frequency Division Multiplexing
BPSK	Binary Phase Shift Keying
SNR	Signal – to – Noise Ratio
CRB	Cramer Rao Boundary
CFO	Carrier Frequency Offset
NMSE	Normalised Mean square Error
ML CFO	Maximum Likelihood Carrier Frequency Offset

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Modulation is the process of encoding data from a source in a way suitable for transmission. It usually contains translating a base band signal to a band pass signal at frequencies those are high when compared to the baseband frequency .The band pass signal is called the modulated signal and the base band message signal is called the modulated signal. Modulation may be done by changing the amplitude, phase and frequency of a carrier in comparison to the amplitude of the message signal. Demodulation is the process of getting the original message from the carrier so that it may be processed and interpreted by the receiver.

After the start of wireless communication a large change has occurred in the daily routine of people. Wireless communication networks have become much more pervasive than anyone can have imagined when the cellular concept was first developed. The rapid worldwide growth in communication made sure that wireless communication is a robust, information transmission mechanism. The wide spread success of cellular has inspired the development of new wireless models and examples for many other types of communication traffic besides mobile voice telephone calls.

Wireless communication which was dealt with only analogue domain for transferring data is now-a-days implemented in digital domain. There are some data rate issue with the communication with single carrier. To enhance the data rate the multiple carrier system is implemented.

1.2 ADVANCE ELECTRONIC SYSTEM

The world now days are mostly affected by the communication processes. Previously communication with anyone was made through different slow processes. But now a days it is very fast and error free due to the implementation of new modulation techniques. Everything can be done within very less time.

A communication system contains a transmitter which sends the information and a receiver which receives the information. Usually due to error there is a change in data due to the channel impact and due to the noise it gets distorted and affects the medium. Different modulation schemes are used in order to ensure maximum error is removed from an original data can be extracted with no distortion.

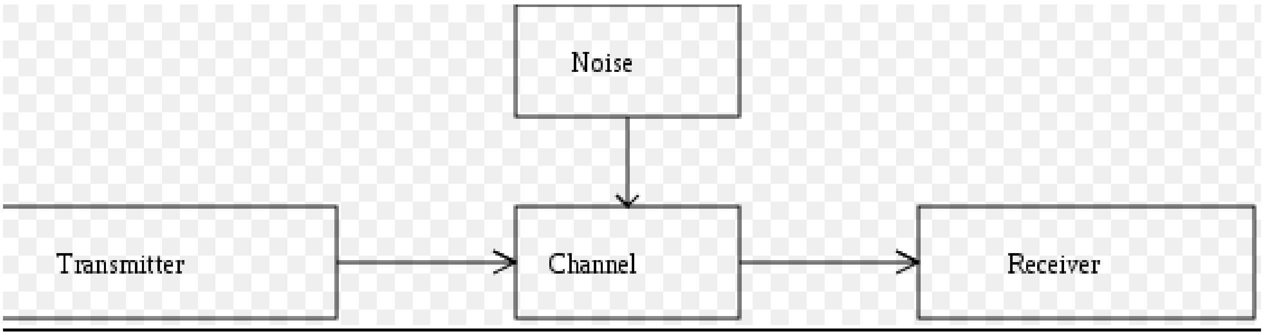


Fig 1.1 Basic Diagram of a Communicative System

CHAPTER 2

FUNDAMENTALS

2.1 INTRODUCTION

Here we explain the basic fundamentals and implementations in order to obtain a strong knowledge on OFDM Systems. These basic terms lay a proper foundation for Digital Communication Systems.

2.2 CONVOLUTION

In this section we will go through some important properties of convolution. It is used to get the output of the process. Channel impulse response and the input are convoluted to give the output. One of the signals can be time reversed, then shifted and multiplied with the other signal to give the output response. Stability of a linear time invariant system can be checked through convolution.

$$y(n) = x(n)*h(n) \equiv \sum_{k=-\infty}^{\infty} x(k)h(n-k)$$

2.3 CORRELATION

A mathematical that closely resemblance is correlation .in correlation we measure the extent to which the signals are similar to each other and to extract information that depend to a large extent on the application.Cross correlation and auto correlation are two different terms which are useful in signal processing applications.

$$y(n) = x(n)*h(n) \equiv \sum_{k=-\infty}^{\infty} x(n)h(n+k)$$

2.4 DISCRETE FOURIER TRANSFORM

Frequency analysis of discrete – time signals is usually performed in a digital signal processor in a most convenient way. If a N sample valued signal observed at regular intervals T_s over a period of T_0.So we must have some generalised idea about the signal's spectral content from its time period and interval space. We assumed that the signal is a periodic signal having period T_0 and the nyquist criteria is satisfied for the whole sampling period. For reducing complexity, even number of samples are taken and placed symmetrically around the origin. The location of sample values are $\pm T_s$ /2, $\pm 3T_s$ /2.....

$$M_n = \frac{1}{T} \int_{-T_0/2}^{T_0/2} m(t) e^{-j\pi n t/T_0} \, dt$$

where waveform to be sampled is m (t) and we get m (t) S (t) after sampling.

S(t) is the sampling function here. The spectral amplitude of the spectrum of m(t)s(t) is expressed by the above expression. The period of the highest frequency component should be 2Ts.

2.5 FREQUENCY SELECTIVE CHANNELS

If channel behaviour differs for different frequencies, it may attenuate some frequency and enhance certain frequency. So it can be called as frequency selective channel. In it the coherence bandwidth is smaller than the signal bandwidth i.e. $T_s \ll \sigma_\tau$. So some frequency components of the signal might experience de-correlated fading

2.6 FLAT FADING CHANNEL

In flat fading, the coherence bandwidth is larger than the signal bandwidth i.e. $T_s \gg \sigma_\tau$. The delay spread is lesser than the symbol duration. So it can not affect the data. So in an OFDM or CDMA scheme we try to convert a frequency selective channel into a flat fading channel.

where T_s is the symbol duration and

σ_τ is the rms delay spread.

CHAPTER 3

ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

3.1 INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) comprises of a broader domain of multicarrier technique in which the information is transmitted over many lower rate subcarriers. Two of the basic benefits of OFDM are its robustness against channel dispersion and its benefit of phase and channel estimation in time varying surrounding. With the benefit of powerful silicon DSP enhancement OFDM has affected a wide variety of implement in the Radio frequency domain from digital audio/video broadcasting (DAB/DVB) to wireless local area networks (LANS). Still, OFDM has intrinsic drawback, like high peak to average power ratio (PAPR) and reactivity to frequency and phase noise. Therefore, a proper explanation of OFDM fundamentals is required for the study of its implementation in the field of communication. In this paper, we present a useful perspective of OFDM and A brief discussion on its usefulness in communication. We then provide an introduction to the basics of OFDM, including its fundamental mathematical formulation, discrete Fourier transformation, cyclic prefix, spectral efficiency, bit error rate and carrier offset estimation using null sub carrier. Wireless communication which was implemented in analogue domain for communication is presently done in digital domain. Instead of a single carrier in the system multiple subcarriers are used.

3.2 FUNDAMENTALS OF OFDM SYSTEM

The fundamentals of OFDM systems consist of multicarrier communication, frequency division multiplexing and orthogonal frequency division multiplexing.

3.2.1 MULTICARRIER COMMUNICATION

To increase the data rate in a channel the signal is divided into a number of signals over a frequency range. Then each signal is modulated and transmitted. At the receiver end, these signals are applied to a demodulator and reconstructed to get the original signal.

3.2.2 FREQUENCY DIVISION MULTIPLEXING

Frequency division multiplexing (FDM) consists of the placing every channel to certain frequency range. This frequency range consists of both the middle frequency and channel width. Below, we show the frequency domain of an OFDM system. We can see that each channel operates a different carrier frequency and that these channels are limited to operate within certain bandwidth. Pulse shaping filter allows each channel to be band limited to a particular frequency range.

3.3 OFDM THEORY

Orthogonal frequency division multiplexing is a multicarrier technique which is used transmission over a dispersive channel. In this the carriers are orthogonal to each other, which make them independent of one another. We are basically using the flat fading channel, where delay spread is less than the symbol duration.

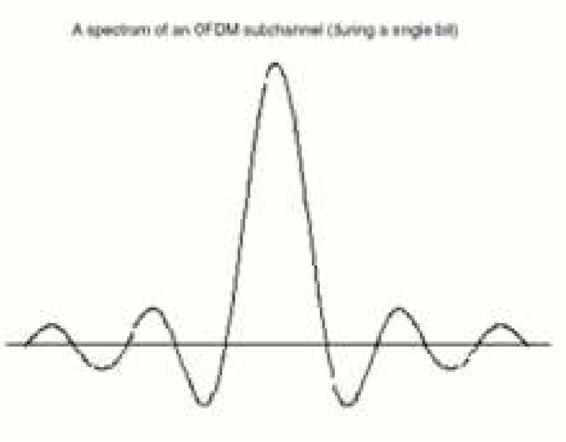


Fig 3.1(a): OFDM sub channel spectrum

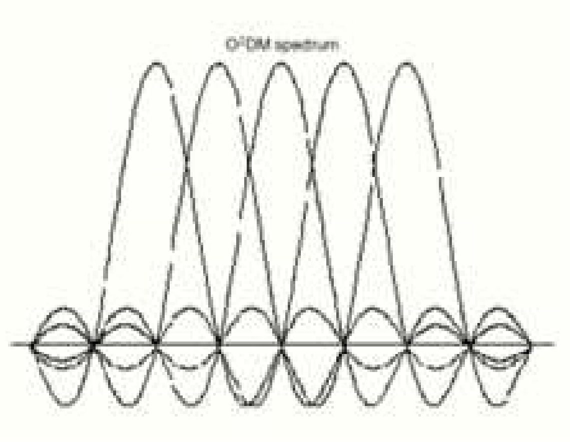


Fig 3.1(b): OFDM spectrum

3.3.1 SUB CARRIERS

Every sub carrier in OFDM system is having frequency that has an integer multiple of a fundamental frequency. Every sub carrier is a Fourier component of the OFDM signal.

Equation for the sub carrier:

$$\begin{aligned} s(t) &= \cos(2\pi f_c t + \theta_k) \\ &= a_n \cos(2\pi n f_0 t) + b_n \sin(2\pi n f_0 t) \\ &= \sqrt{a_n^2 + b_n^2}\cos(2\pi n f_0 t + \varphi_n), \end{aligned}$$

Where $\varphi_n = \tan^{-1}(\frac{b_n}{a_n})$

As the total sum of the sub carriers will make the main OFDM signal so the equation of OFDM will be like-

$$s_B(t) = \sum_{n=0}^{N-1} \{a_n \cos(2\pi n f_0 t) - b_n \sin(2\pi n f_0 t)\}$$

3.3.2 ORTHOGONALITY CONDITION

We can mention that periodic signals are said to be orthogonal if their product over a period is equal to zero.

Equation for checking orthogonality:

$$\int_0^T \cos(2\pi n f_0 t)\cos(2\pi m f_0 t)dt = 0,$$

In discrete domain:

$$s_B(t) = \sum_{n=0}^{N-1} \{a_n \cos(2\pi n f_0 t) - b_n \sin(2\pi n f_0 t)\}$$

where m$\neq$ n for both the cases.

3.3.3 INTER CARRIER INTERFERENCE (ICI)

Due to the presence of Doppler Effect and frequency offset, there might be a chance of loss of orthogonality of sub carriers. So interference occurs between the sub-carriers. This is known as inter carrier interference.

3.3.4 INTER SYMBOL INTERFERENCE

Inter symbol interference (ISI) is an unavoidable outcome of both wired and wireless communication system.It makes a system less efficient.Multipath is a main cause of this kind of problem.It introduces error inside a system.So receiver and transmitter filter must be used to reduce this kind of problem and provide minimum error possible.

3.3.5 CYCLIC PREFIX

This is an addition of guard interval to the end of an OFDM symbol that is added to the front of the symbol in the transmitter, and is removed before demodulation at the receiving end.

Main advantages of cyclic prefixes

- It acts as guard interval, which can eliminate the ISI from the previous symbol.
- It maintains the continuity of a OFDM signal.

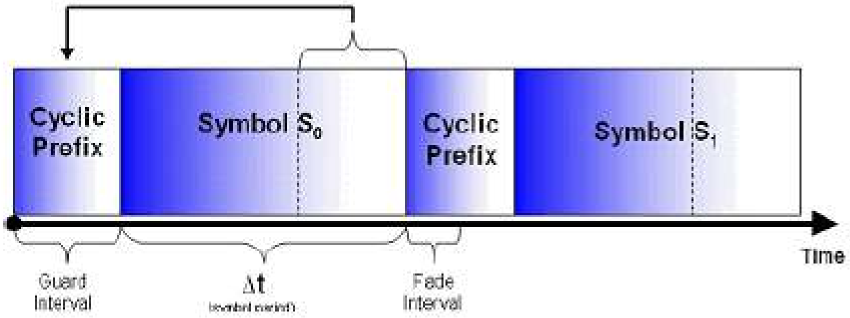


Fig 3.2: Arrangement of cyclic prefix to an OFDM symbol.

3.3.6 INVERSE FOURIER TRANSFORM

In inverse Fourier transform, it takes the signal in frequency domain, and maps it into time domain. The time domain generally consists of a set of real values. The Fourier maps it into a frequency domain series. The IDFT consists of complex value, whose imaginary part is zero.

It is a linear transformation that can be applied at the transmitter end and to get the original signal DFT must be used at the receiver end. We can use IDFT to OFDM signal to get the time domain series.

It also plays a major rule in forming a filter. Generally we can implement fast Fourier transform (FFT) instead of DFT and IDFT to reduce the system complexity and the computation speed will also much faster.

3.4 MODULATION AND DEMODULATION IN OFDM

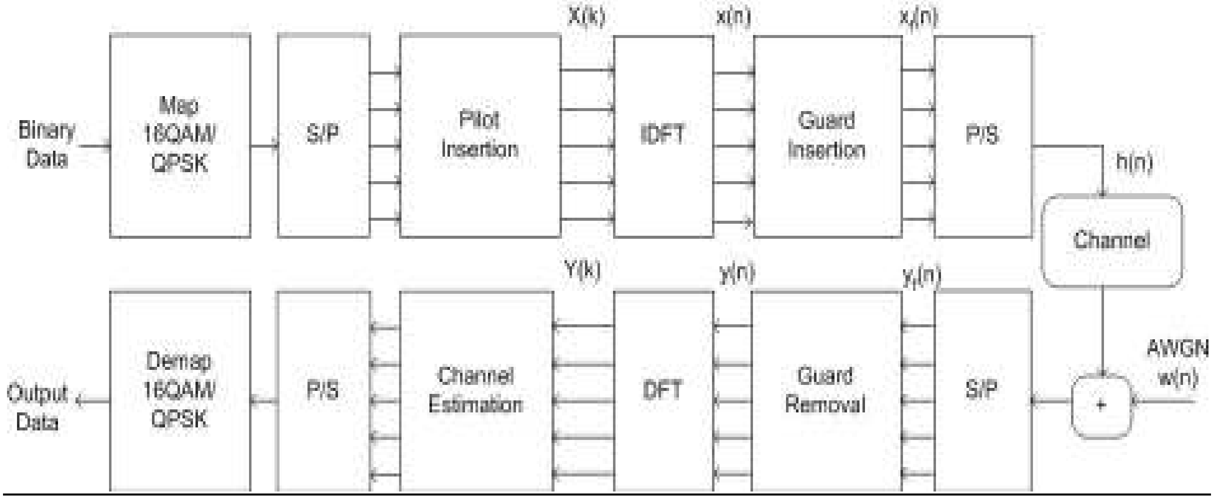


Fig 3.3 Block Diagram of OFDM Technique

3.4.1 MODULATION

By modulation the signal wave is transformed in order to transmit it over the communication channel in order to minimize the effect of noise. This is done to ensure that received data can be demodulated to give back the original data. In an OFDM system, the high data rate information is divided into small sets of data which are placed orthogonal to each other. This is achieved by modulating the data by a desirable modulation technique like BPSK, QPSK, QAM, and MSK. Then, IFFT is performed on the modulated signal which is further processed by passing through a parallel – to – serial converter. In order to avoid ISI we provide a cyclic prefix to the signal.

3.4.2 COMMUNICATION CHANNEL

Channel is required to carry the data through it. Presence of noise may affect the data and make the data signal distorted. There may be addition of additive white Gaussian noise, which affect the signal to noise ratio (SNR).Carrier offset can also be added which may affect the mean square error.

3.4.3 DEMODULATION

It is the technique by which the modulated data signal will be converted to the original data. First the modulated data is passed through a low pass filter. After that the cyclic prefix is removed and FFT is applied to it to convert it into frequency domain. Then a serial to parallel converter is used .The bit error rate and signal to noise ratio is calculated to compare the original signal and the signal received at the receiver end.

3.5 ADVANTAGES OF OFDM SYSTEM

- Introduction of guard band eliminates the chances of inter symbol interference.
- Robustness in multipath environment.
- It can tolerate the effect of delay spread.
- It is resistant to fading.
- Higher data rate. It can be varied using different modulation schemes at the baseband.

3.6 DISADVANTAGES OF OFDM SYSTEM

- Sensitive to frequency offset, need the correction at the receiver.
- Output signal power is less compared to input signal power.
- Complex FFT/IFFT process is going on.
- Use of guard interval makes the system complex.

CHAPTER 4

SYNCHRONIZATION ERROR: AN OVERVIEW

4.1 INTRODUCTION

Synchronization has been one of the most important research topics in Orthogonal Frequency Division Multiplexing (OFDM) system because of its greatly prone sensitivity towards timing and frequency offset errors.

The three main channel parameters required by most receivers are the carrier frequency, the carrier phase and the symbol timing of the received signal. The carrier phase of the received signal is the sum of three major components, namely, the random phase of the transmitter oscillator, the channel phase response, and the phase due to the transmission delay.

Frequency offsets arise from the mismatch in the frequency of the transmitter and the receiver oscillators and the existence of Doppler Shift in the same channel. In addition, due to the delay of signal induced while transmitting in the channel, the receiver on the other side starts sampling a new symbol at the incorrect instant of time. These discrepancies while transmission of an OFDM symbol induces the so called Synchronization Error in the system.

Though the word seems to be lighter, its effects are worse. They mainly affect the system by making the subcarriers lose their orthogonality which is the most important feature in OFDM transmission thus, degrading the performance of the system.

In this particular chapter, we come across the various types of OFDM synchronization and the errors that can occur during the transmission and in the later chapters we shall also see the different techniques for reducing the synchronization error for a given OFDM system thus, improving its performance.

4.2 SYNCHRONIZATION ERRORS IN OFDM

OFDM synchronization error can be divided into two types:

a) Data aided
b) Non Data aided

Data–aided category uses a training sequence i.e. pilot symbol and has high accuracy and less number of calculations involved but reduces the data transmission speed and loss in bandwidth. The non-data aided category uses the cyclic prefix correlation. It has the benefit that, it doesn't reduce the data transmission speed and waste bandwidth. The estimation range is very less, so not suitable for acquisition.

There are two types of synchronizations to be considered:

1) Frequency Synchronization
2) Time Synchronization

Accurate frequency and time synchronization of orthogonal frequency division multiplexing (OFDM) systems is required in order to achieve good performance. The very property that these systems rely on "orthogonality of the subcarriers" will be lost if synchronization is inaccurate. In the uplink of multiple access systems, where several transmitting users must all synchronize to the base station, the need for efficient synchronization algorithms is especially evident.

In "Time Synchronization," the start time of the symbol is not known or even it is known due to the delays induced in the channel the receiver always samples a symbol at the wrong instant of time. Coming to "Frequency Synchronization," the start frequency of the symbol is known and due to the offset introduced by the channel the frequency at the output differs as the orthogonality is lost in the subcarriers.

4.3 FREQUENCY SYNCHRONIZATION IN OFDM

As stated earlier, the synchronization in terms of frequency is a primary necessity for the high-speed non-erroneous transmission of data. The major feature of OFDM system is that the flat-fading channel is converted into a frequency-selective channel by dividing the entire channel into equally spaced (periodic) subcarriers which are "orthogonal" to each other. These subcarriers being orthogonal to each other, whenever data is being multiplied with them, it is transmitted to the receiver without any ISI or ICI. The same property of orthogonality is again used to recover the data without any error or loss in data.

Once, a change in frequency is occurred in the channel of transmission, the frequency of the received channel is changes (either increases or decreases depending upon channel parameters). The reason for this might be the Doppler Shift present in the channel when the transmitter is in relative motion with that of receiver. Also the delays induced in the channel during transmission also account for the frequency offset introduction at the receiver end.

The primary harm, this frequency offset does to an OFDM system, is that ir reduces the orthogonality between the subcarriers allowing them to interfere into the other. Once the orthogonality is lost, the performance of the system is degraded drastically leaving OFDM not so good selection for high-speed data transmission.

Hence, it is our main objective to study about this Frequency Offset in the carriers and though its effect cannot be eliminated completely, it can be estimated through various techniques and can be compensated. By doing so, the performance of the system can be improved by using an appropriate technique. Once such method discussed and studied in detail is the Carrier Frequency Offset estimation using Null Subcarriers. This is an optimal method to improve the performance of a frequency offset effected OFDM system.

CHAPTER 5

SYNCHRONIZATION ERROR REDUCTION TECHNIQUES

5.1 INTRODUCTION

As stated earlier in the previous chapter, the Synchronization error causes a considerable degradation in the performance of any digital system. In particular with an OFDM system which is the topic under discussion, the synchronization error has got a significant effect on the system's performance. This reduction in the performance of the system makes it ineffective to serve its purpose. Hence we take initiatives to reduce this Synchronization error in OFDM systems.

As we know an OFDM system suffers due to "Time" and "Frequency (phase)" offsets, eliminating these will reduce the synchronization errors. Hence, it is important to estimate the frequency offset to reduce its effect and the timing offset at the receiver to recognise the start time of each frame and the position of the FFT Window for each OFDM symbol.

Here in this thesis, our main work deals with the estimation of Frequency Offset of the carriers used in OFDM transmission. The technique we worked was proposed based on the "Null Subcarrier" allocation to the already available subcarriers in transmission of data. In this thesis we mainly focussed on estimation of frequency offset keeping the time frequency portion apart.

The scheme is stated and discussed in detail and furthermore, methods are being stated to obtain good performance using certain specific binary sequences such as proposed m-sequences. Also it is shown by simulations that the same method could be used for Maximum-Likehood CFO (ML CFO) estimation too.

5.2 CARRIER FREQUENCY OFFSET ESTIMATION FOR OFDM SYSTEMS USING NULL SUBCARRIERS

Null Subcarrier allocation for the estimation of Carrier Frequency Offset (CFO) is mainly chosen as this technique is relatively simple to implement when compared to other methods as it involves the usage of a simple correlator as the main component. Moreover, with just only one training symbol of OFDM and accurate allocation of null subcarriers, the estimation range of the suggested scheme can be the inverse of the sampling duration. The same method should also be applied for ML CFO estimation as stated earlier.

5.2.1 ADVANTAGE OF USING NULL SUBCARRIERS

Null Subcarriers as the name suggests are those carriers which practically contain no information or data with them. They are mainly used for Band-Guarding, carrying DC component and sometimes in frequency offset estimation. In training all the subcarriers are not available for transmission always. Hence sometimes null subcarriers are set on either sides of the assigned bandwidth to soften the effect of interferences from adjacent bands.

For example, for IEEE 802.16e standard has got 256 subcarriers out of which 56 of the subcarriers present at the edges of the bandwidth and at the DC component are set as null subcarriers. The existence of null subcarriers makes the design of training preamble for channel estimation complicated. In addition to this, the null subcarriers make the equi-distant and equi-powered pilot symbols impossible to use. Thus eliminates the Inter-symbol interference.

In practice, the guard bands used in OFDM transmission are composed of null subcarriers which naturally deteriorate thereby reducing the severeness of the interferences to the neighbouring channels.

In this way, null subcarriers are used in data-aided OFDM synchronization where in training (pilot) symbols are used for channel estimation. It involves less calculations and higher rates of accuracy but however there is a loss in the band-width and a reduction in the data transmission speed. To eliminate this we use the null subcarriers to estimate the CFO and compensate it to improve the performance of the OFDM system.

5.3 THE SYSTEM MODEL AND ML CFO ESTIMATION USING NULL SUBCARRIERS

We first considered an OFDM system with N subcarriers. One training symbol is taken for the CFO estimation in the OFDM system.

Now, we have

$$\mathrm{N_z} + \mathrm{N_p} = \mathrm{N} \tag{1}$$

where, N_z is the number of null subcarriers and

N_p is the number of pilot tones.

Also we define,

$$\Gamma_\mathrm{z} = \{ a_1, a_2, \dots, a_{N_z}\} \quad \text{with} \quad a_1 < a_2 \dots < a_{N_z} \quad \text{and}$$

$$\Gamma_\mathrm{p} = \{ b_1, b_2, \dots, b_{N_p}\} \quad \text{with} \quad b_1 < b_2 \dots < b_{N_p}$$

as the sets containing all the null subcarrier indexes and all the pilot-tone indexes respectively.

The training OFDM symbol in the time domain is then given by

$$\mathrm{s(n)} = \frac{1}{\sqrt{N}} \sum_{k \in \Gamma_p} d_k \, e^{j2\pi nk/N} \quad , \qquad \mathrm{n = -Ng}, \dots\dots\dots, \mathrm{N-1} \tag{2}$$

where, Ng is the length of the guard interval and

d_k is the pilot symbol at the k^{th} subcarrier.

We also take into assumption that the guard interval is longer than the length of the CIR and the time synchronization is perfect. After sampling and removing the guard interval, the received signal is then given by,

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k \in \Gamma_p} H(k) \, d_k \, e^{j\left(\frac{2\pi k}{N} + 2\pi \phi\right)n} + z(n) \, ,$$

$$\mathrm{n = 0,1,\dots\dots\dots\dots, N-1} \tag{3}$$

where, H(k) is the channel frequency response at the k^{th} subcarrier,

z(n) is thw Additive White Guassian Noise,

$\phi = \Delta f \ . T_s$ is the normalized CFO,

Δf is the CFO,

T_s is the sampling interval.

For convenience, we define the following vectors in Matrix form:

$\mathbf{P} = \text{diag}\ (1, e^{j2\pi\phi},\ldots\ldots\ldots, e^{j2\pi(N-1)\phi})$

$\mathrm{d} = [d_{b1}, d_{b2}, \ldots, d_{bN_p}]$

$\mathrm{z} = [\,\mathrm{z}(0), \mathrm{z}(1), \ldots \ldots, \mathrm{z}(\mathrm{N}-1)]^T$

$\mathrm{H} = \text{diag}\ (H(b_1), H(b_2), \ldots, H(b_{N_p}))$

Where, diag(.) is a diagonal matrix with the elements in the main diagonal given by (.), and $(.)^T$ in the denotes transpose.

(3) can now be written as follows:

$$\mathrm{x} = [x(0), x(1), \ldots, x(N-1)]^T$$

$$= \mathbf{PW}\widetilde{\boldsymbol{d}} + \mathrm{z} \qquad (4)$$

Where, **W** is an *N* x *Np* matrix with $[\mathbf{W}]_{\boldsymbol{n},\boldsymbol{k}} = \frac{1}{\sqrt{N}}\ e^{j2\pi(n-1)b_k/N}$, and

$$\widetilde{\boldsymbol{d}} = [\,\tilde{d}_{b_1}, \ldots, \tilde{d}_{b_{N_p}}] \equiv \mathbf{Hd}$$

Assume that the covariance matrix of z is $\sigma^2\mathbf{I}$, where σ^2 is the noise variance and **I** denotes the identity matrix.

The likelihood function for ϕ and $\widetilde{d}$ is then given by

$$\boldsymbol{L}(\phi, \widetilde{\boldsymbol{d}}) = \frac{1}{(\pi\sigma^2)^N} \exp\{ -\frac{1}{\sigma^2} \left(\mathrm{x} - \mathbf{PW}\widetilde{\boldsymbol{d}}\right)^H \left(\mathrm{x} - \mathbf{PW}\widetilde{\boldsymbol{d}}\right) \} \qquad (5)$$

where $(.)^H$ in the formula denotes conjugate transpose.

For a given $\mathbf{P}$, we can obtain an estimator for $\tilde{d}$ by maximizing the above likelihood function.

The ML estimation of $\tilde{d}$ is then given by

$$\tilde{d}_{ML} = \mathbf{W}^H \mathbf{P}^H \mathrm{x} \tag{6}$$

By substituting (6) in (5) , the estimation of ϕ can be obtained by the minimization of the following expression:

$$\begin{aligned} S(\hat{\phi}) &= \left(\widehat{\boldsymbol{P}}^H \mathrm{x}\right)^H (\mathbf{I} - \mathbf{W}\mathbf{W}^H)\, \widehat{\boldsymbol{P}}^H \mathrm{x} \\ &= \left(\widehat{\boldsymbol{P}}^H \mathrm{x}\right)^H \left(\textstyle\sum_{i \in \Gamma_z} v_i\, v_i{}^H\right) \widehat{\boldsymbol{P}}^H \mathrm{x} \\ &= \textstyle\sum_{i \in \Gamma_z} \left| v_i{}^H \widehat{\boldsymbol{P}}^H \mathrm{x} \right| \end{aligned} \tag{7}$$

where $\widehat{\mathbf{P}} = \operatorname{diag}\left(1, e^{j2\pi\hat{\phi}}, \ldots, e^{j2\pi(N-1)\hat{\phi}}\right)$, and v_i is an N x 1 vector with the n^{th} element given by $(1/\sqrt{N}) e^{j2\pi(n-1)i/N}$.

To estimate the CFO, we have from (7) that $\widehat{\boldsymbol{P}}^H \mathrm{x}$ should be generated with a tentative normalized CFO $\hat{\phi}$. The power of $\widehat{\boldsymbol{P}}^H \mathrm{x}$ at the positions of the null subcarriers is then calculated and summed up. The $\hat{\phi}$ that results in the minimum total power is considered to be the estimated CFO. We also come to know that (7) can also be obtained by the sub-space method [3], as also noted in [4]. Hence, using null subcarriers, the subspace-based CFO estimation and the ML-based CFO estimation, the results obtained are equivalent.

Therefore, we have seen that proposing Maximum Likelihood estimation method for the CFO estimation though provides us a better result but as we look into the equations it is noticed that the entire system is characterized with a bit of complex calculations as the number of symbols increase. Hence, our next aim is to reduce this complexity.

5.4 REDUCED-COMPLEXITY CFO ESTIMATION

Optimal ML-CFO estimation using null subcarriers is generally complex, due to the requirement of global search. In this area, we first show that a closed solution to ϕ can be obtained by making all odd subcarriers as null subcarriers and all even subcarriers as pilot tones. But, the estimation range is limited here in this case within two subcarriers spacing. To extend this estimation range, we need to simplify the system further by proposing a reduced-complexity CFO estimation scheme, with all odd subcarriers as null subcarriers and some of the even subcarriers being null subcarriers.

In an OFDM symbol, when all odd subcarriers are null subcarriers and all even subcarriers are pilot tones, we have the following expression:

$$\sum_{i\in\Gamma_2} v_i\, {v_i}^H = \frac{1}{2}\begin{bmatrix} \mathbf{I} & -\mathbf{I} \\ -\mathbf{I} & \mathbf{I} \end{bmatrix} \qquad (8)$$

where $\Gamma_2 = \{1,3,5,7,\ldots\ldots\ldots,N-1\}$ and N is assumed to be an even number.

For convenience, we define the following vector:

$$\mathbf{x} = \begin{bmatrix} \mathrm{x}_1 \\ \mathrm{x}_2 \end{bmatrix} \qquad (9)$$

where x_1 and x_2 are $(N/2)$ x 1 vectors denoting the first half (positive frequencies) and the second half (negative frequencies) parts of the received symbol, respectively.

Also we can write $\widehat{\mathbf{P}}$ in (7) as follows:

$$\widehat{\mathbf{P}} = \begin{bmatrix} \widehat{\mathbf{P}}_{temp} & 0 \\ 0 & e^{j2\pi N\hat{\phi}}\ \widehat{\mathbf{P}}_{temp} \end{bmatrix} \qquad (10)$$

where $\widehat{\mathbf{P}}_{temp} = \mathrm{diag}(1, e^{j2\pi\hat{\Phi}}, \ldots, e^{j2\pi(N-2)\hat{\Phi}})$.

By putting (8)-(10) in (7), we obtain the following

$$S_2(\hat{\phi}) = \left(\widehat{\boldsymbol{P}}^H \mathrm{x}\right)^H \left(\sum_{i\in\Gamma_2} v_i\, {v_i}^H\right) \widehat{\boldsymbol{P}}^H \mathrm{x}$$

$$= \frac{1}{2}\left({\mathrm{x}_1}^H\mathrm{x}_1 + {\mathrm{x}_2}^H\mathrm{x}_2 - e^{-j\pi N\hat{\Phi}}{\mathrm{x}_1}^H\mathrm{x}_2 - e^{j\pi N\hat{\Phi}}{\mathrm{x}_2}^H\mathrm{x}_1\right) \qquad (11)$$

Minimizing (11) i.e. finding solution for $\frac{dS_2(\hat{\phi})}{d\hat{\phi}} = 0$, gives us $\hat{\phi}$ which is the estimated CFO and the expression for the same can be written as

$$\hat{\phi} = \frac{1}{\pi N} \arg\left(\mathrm{x}_1{}^H \mathrm{x}_2\right) + \frac{k}{N}, \qquad k = 0, \pm 1, \pm 2, \ldots\ldots\ldots$$

When k is an odd number, (11) is maximized rather than minimized. Hence, when $\hat{\phi}$ is limited in the range of [0,1), the closed-form solution to minimizing (11) is given by,

$$\hat{\phi}_k = \frac{1}{\pi N} \arg\left(\mathrm{x}_1{}^H \mathrm{x}_2\right) + \frac{2k}{N}, \quad k = 0, \ldots, \frac{N}{2} \tag{12}$$

We also note here that (12) is the same as the equation for estimated CFO given in [5]. The reason behind this is because an OFDM symbol with two identical components is actually an OFDM symbol with zeros at all subcarriers. Hence, by making all odd subcarriers as null subcarriers, the ML CFO estimation is made very simple in terms of calculations. To extend the estimation range we must find k in (12). In [5], an extra OFDM is used to find the above stated value of k.

Now, it is our turn to propose a reduced-complexity ML CFO estimation scheme where our objective of finding k can be achieved without the requirement of an extra symbol as stated in [5]. For this to accomplish we make use of the even null subcarriers present in the OFDM training symbol.

When all odd subcarriers and some of the even subcarriers are imposed as null subcarriers in an OFDM training symbol, we have

$$\sum_{i \in \Gamma_z} v_i\, v_i{}^H = \sum_{i \in \Gamma_2} v_i\, v_i{}^H + \sum_{\substack{i \in \Gamma_z \\ i \notin \Gamma_2}} v_i v_i{}^H \tag{13}$$

By using (13) in (7), we get the following expression:

$$S(\hat{\phi}) = \left(\widehat{\boldsymbol{P}}^H \mathrm{x}\right)^H \left(\sum_{i \in \Gamma_2} v_i\, v_i{}^H\right) \widehat{\boldsymbol{P}}^H \mathrm{x}$$

$$+ \left(\widehat{\boldsymbol{P}}^H \mathrm{x}\right)^H \left(\sum_{\substack{i \in \Gamma_z \\ i \notin \Gamma_2}} v_i v_i{}^H\right) \widehat{\boldsymbol{P}}^H \mathrm{x} \tag{14}$$

In (14), both the terms will be equal to zero (minima) when there is no noise and the tentative normalized CFO is the actual normalized CFO. Interested by this information, we now minimize the two terms separately which makes the procedure of CFO estimation to be divided into two steps. This method is heuristic type.

As, we already stated that the entire CFO is divided into fractional and integer parts

So, each part must be estimated separately to obtain the entire CFO. In the first step which involves the minimization of the first part yields the fractional normalized CFO. On the other hand, in the second step minimizing the second part gives the integer normalized CFO. If we observe closely, the result in the first step can be obtained from minimizing (11) as both the equations are similar to each other.

Therefore, the solution for the fractional normalized CFO is $\hat{\phi}_0$ given from (12).

$$\hat{\phi}_0 = \frac{1}{\pi N} \arg\left(\mathrm{x}_1{}^{H}\mathrm{x}_2\right) \qquad \text{for } k = 0.$$

For convenience, we define

$$\widehat{\mathbf{P}}_0 \equiv \mathrm{diag}\left(1, e^{j2\pi\widehat{\Phi}_0}, \ldots, e^{j2\pi(N-1)\widehat{\Phi}_0}\right)$$

and

$$\widehat{\mathbf{P}}_k \equiv \mathrm{diag}\left(1, e^{j2\pi\widehat{\Phi}_k}, \ldots, e^{j2\pi(N-1)\widehat{\Phi}_k}\right)$$

$$= \sqrt{\mathrm{N}}\ \mathrm{diag}\left(v_{2k}\right) \widehat{\mathbf{P}}_0 \qquad (15)$$

By replacing $\widehat{\mathbf{P}}$ in the second term of (14) with $\widehat{\mathbf{P}}_k$, we have

$$= \sum_{\substack{i\in\Gamma_z \\ i\notin\Gamma_2}} \left| v^{H}{}_{i+2k}\, \widehat{\mathbf{P}}_0{}^{H}\ \mathrm{x} \right|^2 \qquad (16)$$

For convenience, we also define E_i as follows:

$$E_i = \left| v_i{}^H \, \widehat{\mathbf{P}}_0{}^H \, \mathrm{x} \right|^2 \tag{17}$$

Then in the second step, the integer normalized CFO is found using the criterion stated below:

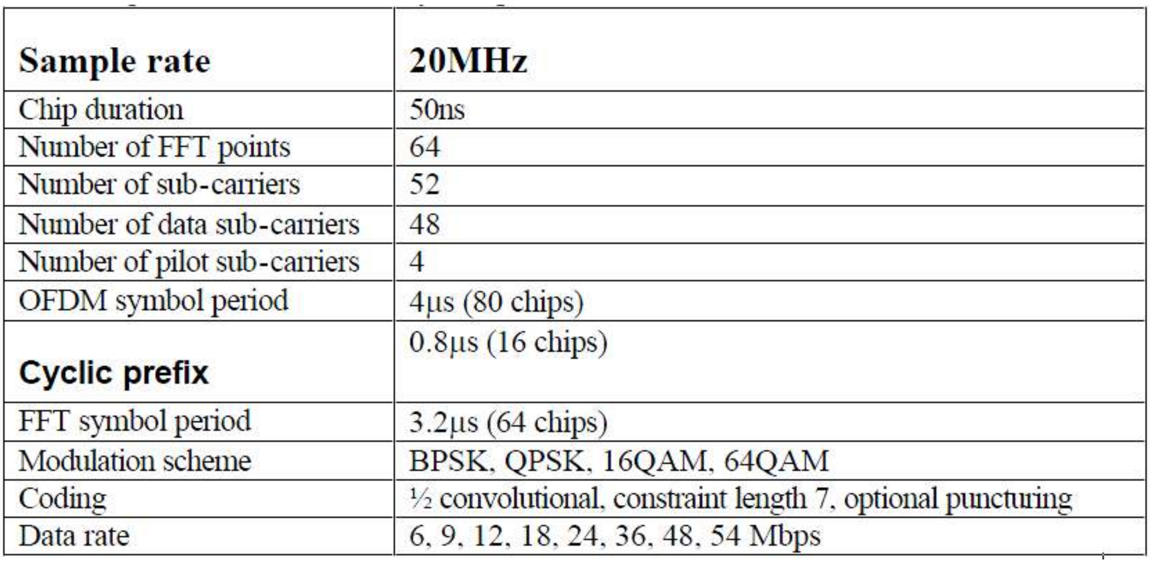
$$\hat{k} = \arg_k \min \sum_{\substack{i \in \Gamma_z \\ i \notin \Gamma_2}} E_{i+2k} \tag{18}$$

From (17) it is noted that, here the fractional normalized CFO is first compensated for in the proposed scheme, and E_i is then obtained using an FFT. As both the fractional CFO compensation and FFT processing are available in the OFDM system, it implies that the second step requires only extra adders. These are of little importance when compared with multiplexers and FFT. Therefore, the complexity of the proposed scheme is comparable (almost similar) to that proposed in [5]. However, the estimation range of our scheme can be much larger provided certain method to be followed.

CHAPTER-6

SIMULATIONS & RESULTS

For observing the results for the OFDM system with a carrier frequency offset ϕ, a channel with the following parameters and properties are considered.



Sample rate	**20MHz**
Chip duration	50ns
Number of FFT points	64
Number of sub-carriers	52
Number of data sub-carriers	48
Number of pilot sub-carriers	4
OFDM symbol period	4μs (80 chips)
Cyclic prefix	0.8μs (16 chips)
FFT symbol period	3.2μs (64 chips)
Modulation scheme	BPSK, QPSK, 16QAM, 64QAM
Coding	½ convolutional, constraint length 7, optional puncturing
Data rate	6, 9, 12, 18, 24, 36, 48, 54 Mbps

Fig 6.1 Parameters considered for SIMULATION 1 and SIMULATION 2

Using these parameters we first find the plot of BER vs SNR for an OFDM system.

Bit Error Rate (BER) can be calculated from the formula:

$$\text{BER} = \frac{1}{2}\, erfc\left(\sqrt{2E_b/N_0}\right)$$

and Signal-to-Noise Ratio (SNR) can be found from E_b/N_0 and is expressed usually in decibels (dB). Using MATLAB, we calculate the ratio ‘ebn0’ from the SNR in dB,’snrdb’ as

ebn0 = 10^(snrdb/10)

where E_b / N_0 is the ratio of energy per bit to noise spectral density ratio.

We used a BPSK modulation in the simulation and AWGN as the noise added by the channel. The results are shown in the pages to be followed.

6.1 SIMULATION 1

AIM: To plot the graph between BER vs SNR for an OFDM system with AWGN added to the channel.

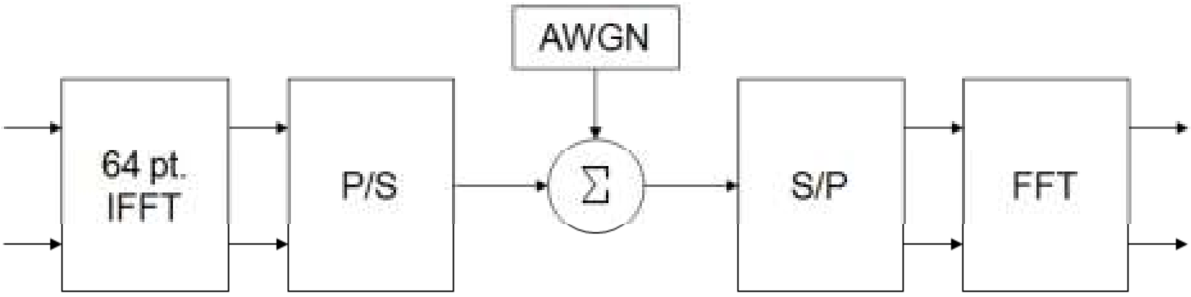


Fig6.2 Simulation Model of an OFDM system

RESULT:

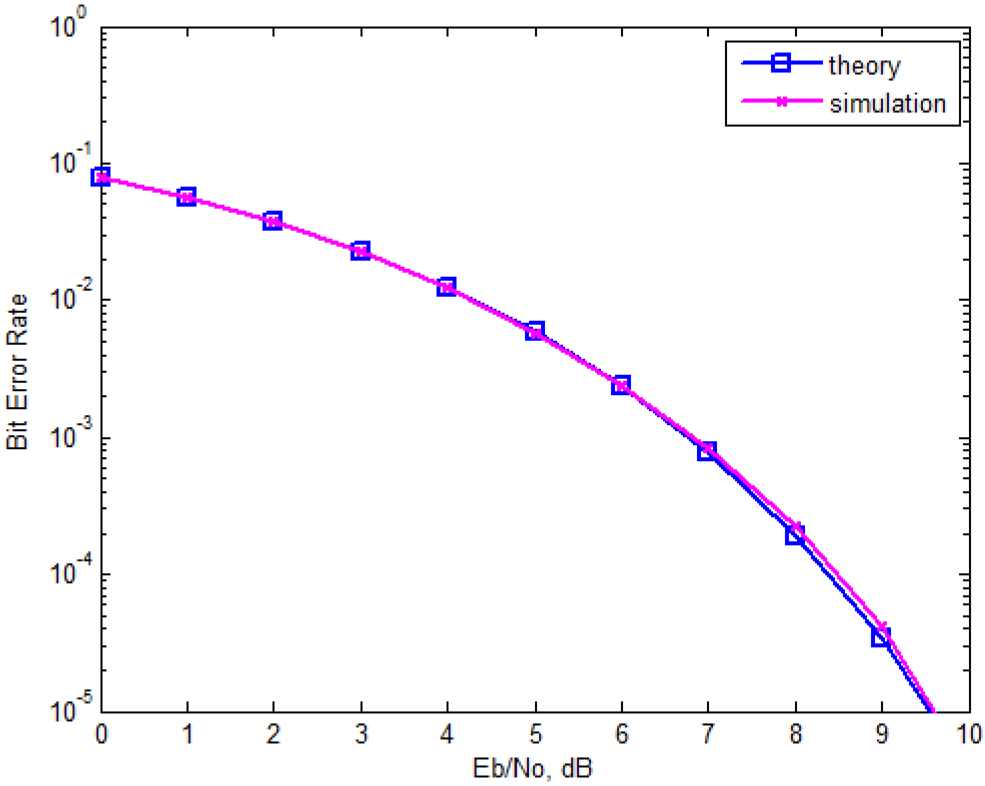


Fig 6.3: BER vs. SNR plot for an AWGN added OFDM symbol

6.2 SIMULATION 2

AIM: To plot the graph between BER vs SNR for a AWGN added OFDM system with frequency 'offset' component introduced to the channel.

RESULT:

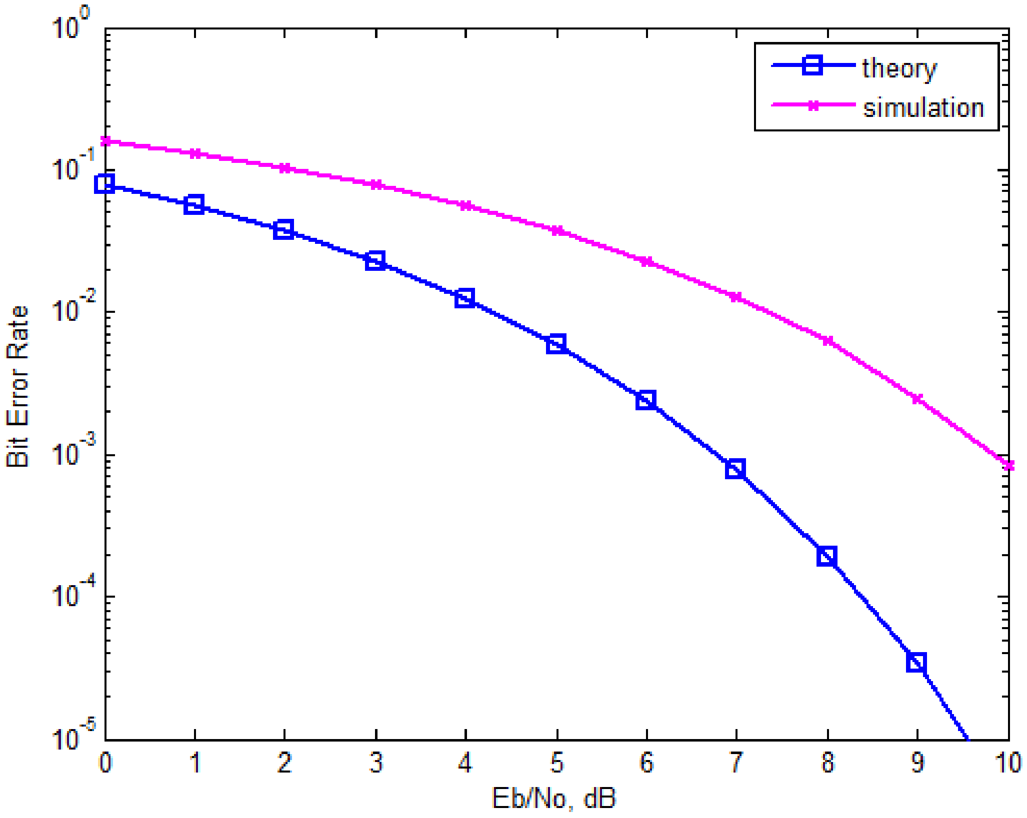


Fig6.4 BER vs SNR plot for offset introduced AWGN added ofdm system

DISCUSSION:

Phase offset $(\theta + \phi) \in [0, 2\pi]$ and without $(\theta + \phi = 0)$. The first expression refers to a system (say S1) and the second refers to system (S2).

For $E_b / N_0 \geq 10$ dB and $2\pi h \leq 0.5$, S1 and S2 are shown to have identical performance and hence the result matches closely for BER<0.01. For $2\pi h = 0.7$, S1 has a loss in performance (about 1 dB) compared to S2. For a large modulation index and low signal-to-noise ratio, the phase demodulator has difficulty demodulating the noisy samples. The performance of S1 is slightly worse than S2 since the output of the phase demodulator has more phase jumps since the received phase crosses the π boundary more frequently. Proper phase unwrapping is therefore required. However, phase unwrapping a noisy signal isdifficult problem and the unwrapper makes mistakes. As a result the performance degrades slightly.

In the next part of our simulation, we use the same channel with 64 subcarriers. The performance measure for the ofdm system is taken to be the Normalized Mean-Square Error (NMSE), which is defined as

$$\text{NMSE} = \frac{N}{N_t} \sum_{t=1}^{N_t} \left(\hat{\phi}_t - \phi \right)^2 \qquad (1)$$

where N_t is the number of Monte Carlo trials,

ϕ is the actual normalized CFO, and

$\hat{\phi}_t$ is the estimated normalized CFO at the t^{th} trial.

The channel model used is same as that in [6]. The CIR is given by

$$h(k) = \sum_{i=0}^{5} A_i g_T \left(kT_s - \tau_i - t_0 \right) \qquad (2)$$

where $\{A_i\}$ and $\{\tau_i\}$ are attenuation and delays of the paths,

t_0 is the timing phase and is equal to $3T_s$ and

g_T (t) is the impulse of the raised-cosine filter with roll-off factor (α) of 0.5.

The normalized delays $\{\tau_i/T_s\}$ = {0, 0.054, 0.135, 0.432, 0.621, 1.135}and

$\{A_i\}$ = {-3, 0, -2, -6, -8, -10}.

As given in [6] the right hand side of (2) takes the significant values only for $0 \leq k \leq 7$.

This implies that the length of CIR is 8. So, in order to avoid Inter-Symbol Interference (ISI),

we chose the guard interval's length (GI) longer than that of CIR's. Here we take GI = 16.

The other parameters we take for the measurement of the system's performance is the Signal-to-Noise Ratio i.e. SNR which is defined as the received instantaneous signal power divided by noise variance. Considering, the power of the transmitted symbol as fixed, we define SNR here as

$$\text{SNR} = \frac{\sum_{k=o}^{N-1} |\text{H}(k)|^2}{N\,\sigma^2} \qquad (3)$$

6.3 SIMULATION 3

AIM: To obtain the plot between SNR and normalized CFO,ϕ.

RESULT:

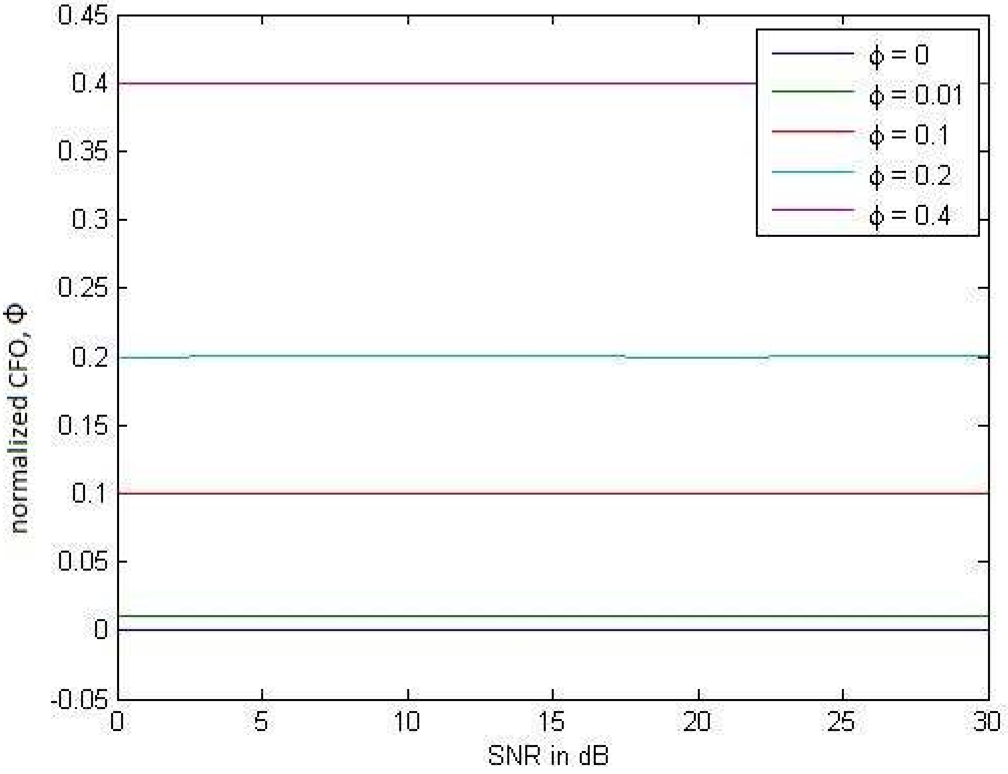


Fig 6.5: Normalized CFO vs SNR plot

DISCUSSION:

The plot shown above has nothing to do with the performance of the system. However, it has got an importance of its own as it shows that the SNR is independent of the normalized CFO,ϕ which implies that the SNR is independent of null subcarrier allocation.

From definition, we must have,

$$\text{SNR}=\frac{\text{Signal power}}{\text{Noise power}}=\frac{\tilde{d}^H\tilde{d}}{N\,\sigma^2} \tag{4}$$

But the use of null subcarriers implies that some of the sub channels may not be excited by the transmitted signal. Therefore, whenever a poor signal power is received, from the definition we cannot know if it is induced either by a poor channel condition or by poor subcarrier allocation. Hence, in order to avoid this confusion, we had already taken the power of the transmitted signal to be fixed. That is

$$\left|d_{b_i}\right|^2 = \frac{N}{N_p}, \ i = 1,2,3,\ldots,N_p \qquad (5)$$

Hence, in order to avoid this confusion, we define SNR according to (3).

Also from the graph we get the information that for the interation process which we obtained for the CFO estimation, the values of normalized CFO, ϕ are taken as

$\{\phi\} = \{ 0, 0{,}01, 0{,}1, 0.2, 0.4\}$

6.3.1 CRAMER RAO BOUNDARY (CRB)

For one training symbol with M identical components in time domain, where CFO estimation within the range of M subcarriers can be achieved using ML CFO estimation, we define

$$var\,(\phi - \hat{\phi}) = \frac{3\,(SNR)^{-1}}{2\pi^2 N^3 (1 - {}^{1}/_{M^2})} \qquad (6)$$

where SNR is the same as defined in (4).

CRB is the lower boundary for the change of variance that can occur between

$\hat{\phi}$ and ϕ in the considered OFDM system. CRB given from above equation is considered as a baseline for the performance measurement of any system.

6.4 SIMULATION 4

AIM: To measure the Normalized Mean-Square Error (NMSE) performance of the proposed reduced-complexity CFO estimator using a periodic training OFDM symbol.

RESULT:

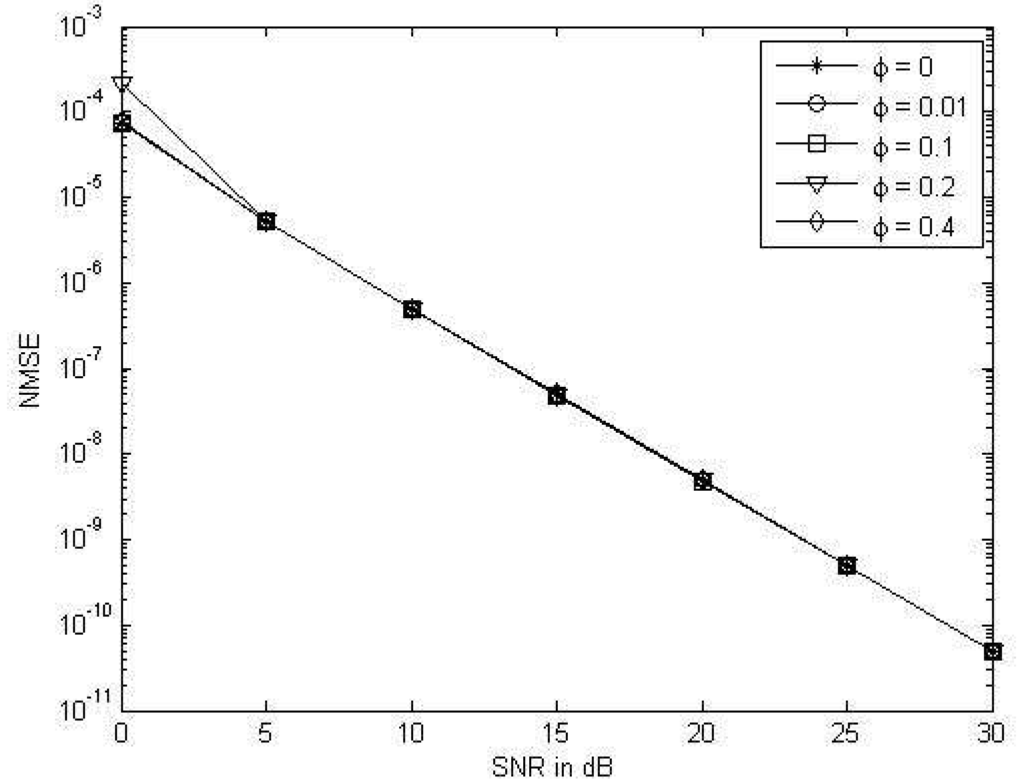


Fig 6.6: NMSE vs. SNR plot for an one training OFDM system

DISCUSSION:

The plot above shows the NSME based performance for one training OFDM symbol. As mentioned earlier, the CRB from (6) is taken as a baseline. The result of (6) with M = 2, is considered to be the best performance achieved by the ML CFO estimator using one training symbol with 2 identical components.

From the plot above, we observe that as SNR increases the NMSE reduces considerably thus, improving the performance of the system. However, at smaller SNR values there is slight performance degradation due to the deep fading of the pilot tone. But, as we increase the number of identical components, a similar and much significant performance is obtained reducing even those degradations observed at lower values of SNR.

As stated earlier, similar optimal performance of the system can be obtained for any number of identical components by putting M = N in (6).

For **Fig 6.4**, we assume that the normalized CFO values are within a limited range. From the given normalized CFO values we considered for our simulation task,

as {ɸ} = { 0, 0,01, 0,1, 0.2, 0.4},

we get *k* values as {k} = { 0, 0, 3, 6, 13} respectively.

These are just the simulation results and are not fixed values. Since. This scheme can further be extended to any number of identical components, the values may vary.

In our case, we considered M = N/2 = 64/2 = 32 in the calculation of CRB.

6.5 Advantages and Disadvantages of ML CFO estimation method

6.5.1 Advantages

The proposed method is simple to implement, easy to calculate and highly cost-effective. The performance of the system can be improved with the available components in the OFDM system itself.

6.5.2 Disadvantages

Care is to be taken in the ML CFO estimation method while null subcarrier allocation due to the fact that one estimator error contributes significantly to the variance of the entire estimation since the preocedure involves iterations in it.

CHAPTER 7

CONCLUSION

In the course of time, OFDM proved to be an efficient and attractive technique in multi-carrier technology. It has become the primary choice for high-speed data transmission over any given channel. We studied both the advantages as well as the disadvantages of OFDM.

Among some of the problems that OFDM faces, is the synchronization error due to the frequency offset which makes the OFDM subcarriers to lose orthogonality, a major feature for effective speed- data transmission with reduced errors.

In this project, we analysed the various properties of an OFDM symbol and studied in detail about the frequency synchronization which is a fundamental necessity for an OFDM system. We observed the performance of a frequency offset effected OFDM system by plotting the BER vs. SNR plot.

We targeted at probing some techniques out of which one was the CFO estimation using Null Subcarriers. We reduced the complexity of the calculations by proposing a Maximum Likelihood criterion for the variables of a training OFDM symbol we considered, thus making the scheme as Maximum Likelihood Carrier Frequency Offset estimation (ML CFO Estimation). Also we plotted the NMSE vs. SNR plot to observe the performance for a one training OFDM symbol with two identical components.

However, we also came across the disadvantages of this scheme too making this method not so perfect for estimation of CFO. But given is simplicity of implementation, this method can be opted and further the performance can be improved in a much better way as mentioned in “Future Scope” by us.

CHAPTER 8

FUTURE SCOPE

The proposed method of ML CFO Estimation using null subcarriers can be extended to any number of identical components using one pilot symbol or more. But, the problem lies in the null subcarrier allocation as the number of identical components increases in the system.

To avail, exact null subcarrier allocation, the even subcarriers must be imposed as null subcarriers just like we did for odd subcarriers. The only difference lies in the method opted for imposing the same. Here comes into play, the usage of some binary correlated sequences for the imposing even subcarriers as null subcarriers.

This can be done by using *m* – correlated sequences for a given channel at any given point of time. If the purpose is served, then the performance of the system is improved greatly as for increasing N and SNR values the plot is close to CRB even at lower SNR values. Usage of almost – perfect autocorrelation sequences makes the performance to lie almost close to CRB for a given M.

Also the performance criterion can be stated by making the even subcarriers as null subcarriers. The impact of the "fractional CFO estimation error" can be studied and also steps can be taken to reduce it. It is represented as

$$\widehat{\phi}_0 = \phi_0 + \phi_e$$

where ϕ_e is the estimation error.

Estimation of this error can be done by following the calculations as proposed in [1].

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