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Enhanced BER Analysis of Mitigation of ICI through SC, ML and EKF Methods 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. Orthogonal Frequency Division Multiplexing (OFDM) is an emerging multi-carrier modulation scheme, which has been adopted for several wireless standards such as IEEE 802.11a and HiperLAN2. 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[2]. 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 The orthogonality of the carriers is no longer maintained, which results in inter-carrier interference (ICI).The undesired ICI degrades the performance of the system[6]. This paper investigates three methods for combating the effects of ICI: ICI self-cancellation (SC), maximum likelihood (ML) estimation, and extended Kalman filter (EKF) method. These three methods are compared in terms of bit error rate performance, bandwidth efficiency, and computational complexity. Through simulations, it is shown that the three techniques are effective in mitigating the effects of ICI. For high values of the frequency offset and for higher order modulation schemes, the ML and EKF methods perform better than the SC method.

Index Terms- Inter symbol interference, Inter carrier interference, orthogonality, Doppler shift, Self cancellation ,CIR,BER etc.

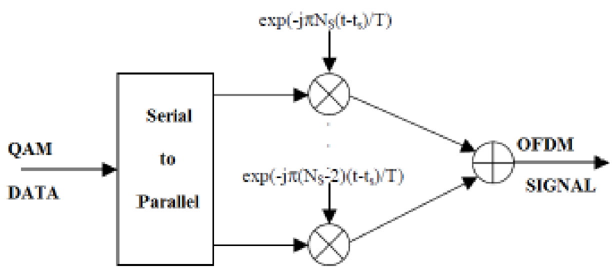
I. Introduction

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.

In this paper, the effects of ICI have been analyzed and three solutions to combat ICI have been presented. The first method is a self-cancellation scheme[1], in which redundant data is transmitted onto adjacent sub-carriers such that the ICI between adjacent sub-carriers cancels out at the receiver. The other two techniques, maximum likelihood (ML) estimation and the extended Kalman filter (EKF) method, statistically estimate the frequency offset and correct the offset [7],using the estimated value at the receiver. The works presented in this paper concentrate on a quantitative ICI power analysis of the ICI cancellation scheme, which has not been studied previously. The average carrier-to interference power ratio (CIR) is used as the ICI level indicator, and a theoretical CIR expression is derived for the proposed scheme.

The paper is organized as follows. In Section 2 the 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 and In Section 4-6 the proposed methods are described and in Section 7 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,

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

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

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

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 ,

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

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

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

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

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

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

Which 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

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

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.

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

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

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

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.

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

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

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

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

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

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

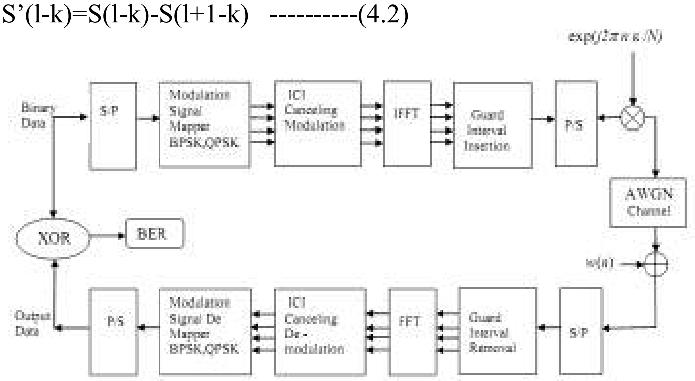


Fig.4.1.1 : OFDM Model with Self cancellation

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

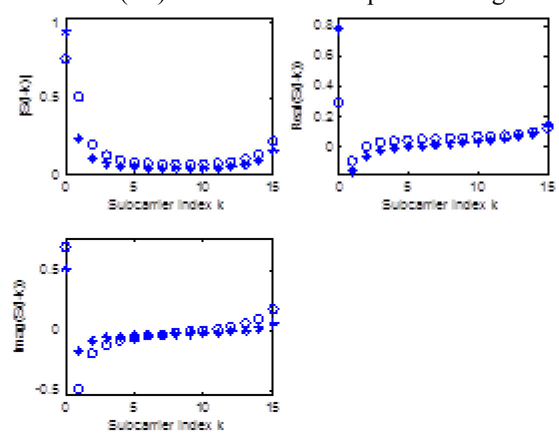


Figure 4.1.2: ICI coefficients S(l-k) Vs subcarrier k

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.

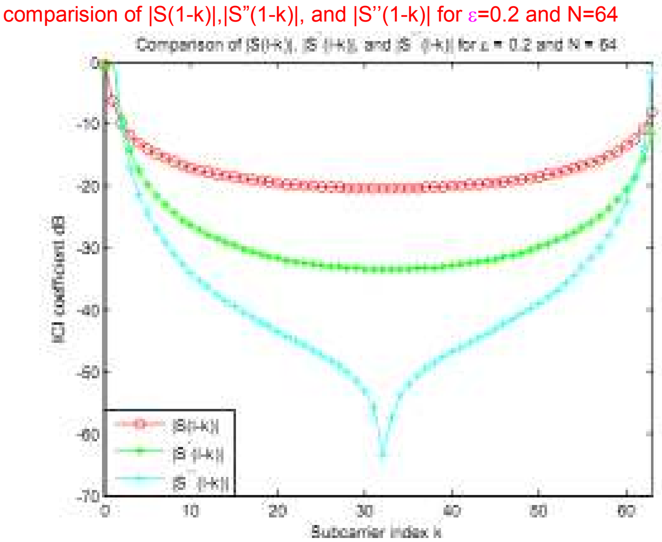


Figure (4.1.3): Comparison of S(l-k),S'(l-k) and S''(l-k) Vs subcarrier k

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

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

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.

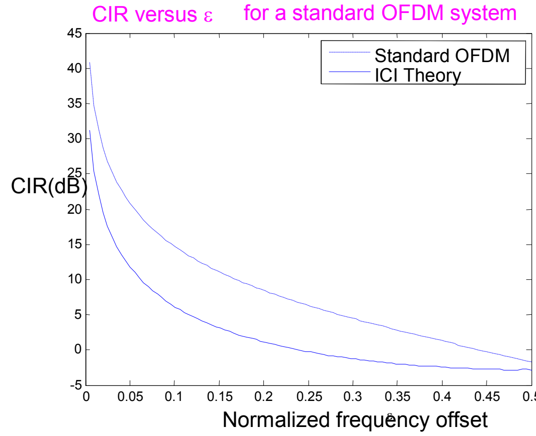


Figure (4.2.1): CIR Vs Normalized frequency offset

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).

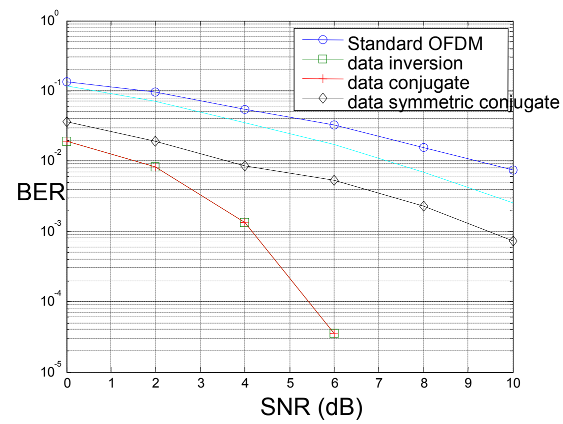


Figure 4.2.2: BER Vs SNR for an OFDM system

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

V. MAXIMUM LIKELIHOOD ESTIMATION

The second method for frequency offset correction in OFDM systems was suggested by Moose in [2]. In this approach, the frequency offset is first statistically estimated using a maximum likelihood algorithm and then cancelled at the receiver. This technique involves the replication of an OFDM symbol before transmission and comparison of the phases of each of the subcarriers between the successive symbols.

When an OFDM symbol of sequence length N is replicated, the receiver receives, in the absence of noise, the 2N point sequence {r(n)} given by

$$r(n) = \frac{1}{N}\left[\sum_{k=-K}^{K} X(k)H(k)e^{\frac{j2\pi n(k+\varepsilon)}{N}}\right]$$

k=0,1,….N-1, $N \geq 2K+1$

where {X(k)} are the 2k+1 complex modulation values used to modulate 2k+1 subcarriers,H(k) is the channel transfer function for the k^{th} carrier and ε is the normalized frequency offset of the channel.

The first set of N symbols is demodulated using an N-point FFT to yield the sequence$R_1(K)$, and the second set is demodulated using another N-point FFT to yield the sequence$R_2(K)$. The frequency offset is the phase difference between

$R_1(k)$ and $R_2(k)$, that is $R_2(k)= R_1(k)e^{j2\pi z}$

Adding the AWGN yields

$Y_1(k)=R_1(k)+W_1(k)$

$Y_2(k)=R_1(k)e^{j2\pi z}+W_2(k)$

k=0,1,….N-1

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

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

This maximum likelihood estimate is a conditionally unbiased estimate of the frequency offset and was computed using the received data [7]. Once the frequency offset is known, the ICI distortion in the data symbols is reduced by multiplying the received symbols with a complex conjugate of the frequency shift and applying the FFT,

$\hat{x}(n)=FFT\{y(n)e^{-j\frac{2\pi\hat{\varepsilon}}{N}}\}$

From Figure 5.1, it can be seen that the results of the maximum likelihood estimation of the frequency offset are quite accurate over a varying range of SNR values.

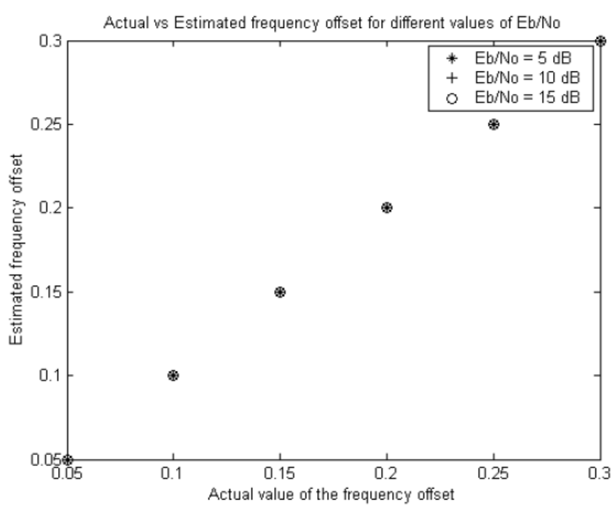


Figure 5.1: Actual vs ML estimation of frequency offset for various values of Eb/No

5.1 MLE SCHEME

Another way of canceling the effect of ICI in OFDM systems is statistically estimating the frequency offset and canceling this offset at the receiver. In this technique, an OFDM symbol stream of *N* symbols is replicated such that the duplicate symbols are *N* positions apart in the symbol stream. These symbols are then modulated using a 2*N*-point inverse discrete Fourier transform (IDFT). At the receiver, the first set of *N* symbols are demodulated using an N-point discrete Fourier transform (DFT) to yield the sequence Y_{1k}, and the second set is demodulated with another N-point DFT to yield the sequence Y_{2k}. The frequency offset is the phase difference between Y_{1k} and Y_{2k}, that is, $Y_{2k} = Y_{1k}e^{j2\pi\varepsilon}$.

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

$$\hat{\varepsilon} = (1/2\pi)\tan^{-1}\{(\sum_{k=-K}^{K}\text{Im}[Y_{2k}Y_{1k}^*])/(\sum_{k=-K}^{K}\text{Re}[Y_{2k}Y_{1k}^*])\} \quad (3)$$

This maximum likelihood estimate is a conditionally unbiased estimate of the frequency offset and will be computed using the received data [7]. Once the frequency offset is known, the ICI distortion in the data symbols can be reduced by multiplying received symbols with a complex conjugate of the frequency shift. To test the accuracy of the estimate, a mean squared error (MSE) metric, calculated between the estimated offset and the actual offset for different values of the frequency offset, will be used.

VI. EXTENDED KALMAN FILTERING

Kalman filters are common in communications and signal processing literature. The Kalman filter is a remarkably versatile and powerful recursive estimation algorithm that has found various applications in communications, such as adaptive equalization of telephone channels, adaptive equalization of fading dispersive channels, and adaptive antenna arrays. As a recursive filter, it is particularly applicable to non-stationary processes such as signals transmitted in a time-variant radio channel. In estimating non-stationary processes, the Kalman filter computes estimates of its own performance as part of the recursion and use this information to update the estimate at each step. Therefore, the estimation procedure is adjusted to the time-variant statistical characteristics of the random process.

6.1 Problem Formulation

A state-space model of the discrete Kalman filter is defined as

$$z(n)=a(n)d(n)+v(n)$$

In this model, the observation z(n) has a linear relationship with the desired value d(n). By using the discrete Kalman filter, d(n) can be recursively estimated based on the observation of z(n) and the updated estimation in each recursion is optimum in the minimum mean square sense.

As illustrated in Figure 3.1, the received symbols are

$$y(n)=x(n)e^{\frac{j2\pi n\varepsilon}{N}}+w(n)$$

It is obvious that the observation y(n) is in a nonlinear relationship with the desired value ϵ(n),

$$y(n) = f(\varepsilon(n)) + \omega(n)$$

where

$$f(\varepsilon(n)) = x(n) e^{j\frac{2\pi n.\varepsilon(n)}{N}}$$

In order to estimate ε(n) efficiently in computation, we build an approximate linear relationship using the first-order Taylor's expansion:

$$y(n) = f(\hat{\varepsilon}(n-1)) + f^{1}(\hat{\varepsilon}(n-1))[\varepsilon(n) - (\hat{\varepsilon}(n-1))] + w(n)$$

where $\hat{\varepsilon}(n-1)$ is the estimation of $\varepsilon(n-1)$

$$f^{1}(\hat{\varepsilon}(n-1)) = \frac{\partial f(\varepsilon(n))}{\partial \varepsilon(n)} \Big|_{\varepsilon(n)=\hat{\varepsilon}(n-1)}$$

Define

$$z(n) = y(n) - f(\hat{\varepsilon}(n-1))$$

$$d(n) = \varepsilon(n) - \hat{\varepsilon}(n-1)$$

and the following relationship:

$$z(n) = f^{1}(\hat{\varepsilon}(n-1))d(n) + \omega(n)$$

which has the same form as (6.1), i.e., z(n) is linearly related to d(n). Hence the normalized frequency offset ε(n) can be estimated in a recursive procedure similar to the discrete Kalman filter. As linear approximation is involved in the derivation, the filter is called the extended Kalman filter (EKF). The derivation of the EKF is omitted in this report for the sake of brevity.)(n

The EKF provides a trajectory of estimation for ε(n). The error in each update decreases and the estimate becomes closer to the ideal value during iterations. It is noted that the actual error in each recursion between ε(n) and $\hat{\varepsilon}(n)$ does not strictly obey (6.8). Thus there is no guarantee of optimal MMSE estimates in the EKF scheme. However it has been proven that EKF is a very useful method of obtaining good estimates of the system state. Hence this has motivated us to explore the performance of EKF in ICI cancellation in an OFDM system.

6.2 EKF SCHEME

The Extended Kalman Filtering (EKF) technique is another method to estimate the frequency offset in the received signal. It is assumed that the channel is slowly time varying so that the time-variant channel impulse response can be approximated to be quasi-static during the transmission of one OFDM frame. Hence the frequency offset is considered to be constant during a frame. The preamble preceding each frame can thus be utilized as a training sequence for estimation of the frequency offset imposed on the symbols in this frame.

Let *s*(*n*) be the training sequence in the time domain, which is generated at baseband by taking the IDFT of the M-QAM modulated preamble. In the case of frequency offset, the signal *s*(*n*) will be distorted by a frequency shift $e^{j2\pi n\varepsilon/N}$ where *ε* is the same normalized frequency offset as defined in the SC method. Without cyclic prefix, the received training sequence is expressed as

$$y(n) = s(n)e^{j2\pi n'\varepsilon/N} + w(n),$$

where *n'* denotes the modulation of the index *n* by *N* and *w*(*n*) the complex white Gaussian additive noise.

To estimate the quantity ε using an EKF, a state-space model is built as

$$\hat{\varepsilon}(n) = \hat{\varepsilon}(n-1)$$

$$y(n) = e^{j2\pi n'/N\cdot\hat{\varepsilon}(n)}s(n) + w(n)$$

Through a recursive iteration procedure, an estimate of the frequency offset can be obtained. Fig. 2 shows the estimates for various normalized frequency offsets . It is observed that the EKF technique offers fast convergence. The ICI distortion in the following data symbols can be mitigated by multiplying the received signal with a complex conjugate of the estimated frequency offset

6.3 ASSUMPTIONS

In the following estimation using the EKF, it is assumed that the channel is slowly time varying so that the time-variant channel impulse response can be approximated to be quasi-static during the transmission of one OFDM frame. Hence the frequency offset is considered to be constant during a frame. The preamble preceding each frame can thus be utilized as a training sequence for estimation of the frequency offset imposed on the symbols in this frame. Furthermore, in our estimation, the channel is assumed to be flat-fading and ideal channel estimation is available at the receiver. Therefore in our derivation and simulation, the one-tap equalization is temporarily suppressed.

6.4 ICI CANCELLATION

There are two stages in the EKF scheme to mitigate the ICI effect: the offset estimation scheme and the offset correction scheme.

6.4.1. Offset Estimation Scheme

To estimate the quantity ϵ(n) using an EKF in each OFDM frame, the state equation is built as

$$\varepsilon(n) = \varepsilon(n-1)$$

i.e., in this case we are estimating an unknown constant ε. This constant is distorted by a non-stationary process x(n), an observation of which is the preamble symbols preceding the data symbols in the frame. The observation equation is

$$y(n) = x(n)e^{\frac{j2\pi n\varepsilon}{N}} + w(n)$$

where y(n) denotes the received preamble symbols distorted in the channel, w(n) the AWGN, and x(n) the IFFT of the preambles X(k) that are transmitted, which are known at the receiver. Assume there are N_p preambles preceding the data symbols in each frame are used as a training sequence and the variance σof the AWGN w(n) is stationary. The computation procedure is described as follows.

1. Initialize $\varepsilon(0)$ the estimate and corresponding state error P(0).

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2. Compute the H(n), the derivative of y(n) with respect to $\varepsilon(n)$ at $\hat{\varepsilon}$(n-1), the estimate obtained in the previous iteration.
3. Compute the time-varying Kalman gain K(n) using the error variance P(n-1), H(n), and , σ^2
4. Compute the estimate $\hat{y}$(n) using x(n) and $\hat{\varepsilon}$(n-1) , i.e. based on the observations up to time n-1, compute the error between the true observation y(n) and $\hat{y}$(n) .
5. Update the estimate by adding the K(n)-weighted error between the observation y(n) and $\hat{y}$(n) to the previous estimation $\hat{\varepsilon}$(n-1).
6. Compute the state error P(n) with the Kalman gain K(n), H(n), and the previous error P(n-1).
7. If n is less than N_p, increment n by 1 and go to step 2; otherwise stop.

It is observed that the actual errors of the estimation $\hat{\varepsilon}$(n) from the ideal value ε(n) are computed in each step and are used for adjustment of estimation in the next step.

Through the recursive iteration procedure described above, an estimate of the frequency offset εˆ can be obtained. It is observed that the EKF technique offers fast convergence.

6.4.2. Offset Correction Scheme

The ICI distortion in the data symbols x(n) that follow the training sequence can then be mitigated by multiplying the received data symbols y(n) with a complex conjugate of the estimated frequency offset and applying FFT, i.e.

$$\hat{x}(n)=FFT\{y(n)e^{-j\frac{2\pi\hat{\varepsilon}}{N}}\}$$

As the estimation of the frequency offset by the EKF scheme is pretty efficient and accurate, it is expected that the performance will be mainly influenced by the variation of the AWGN.

VII. 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 Table 7.1

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 7.1 : Simulation Parameters

7.1 BER performance of BPSK OFDM system:

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

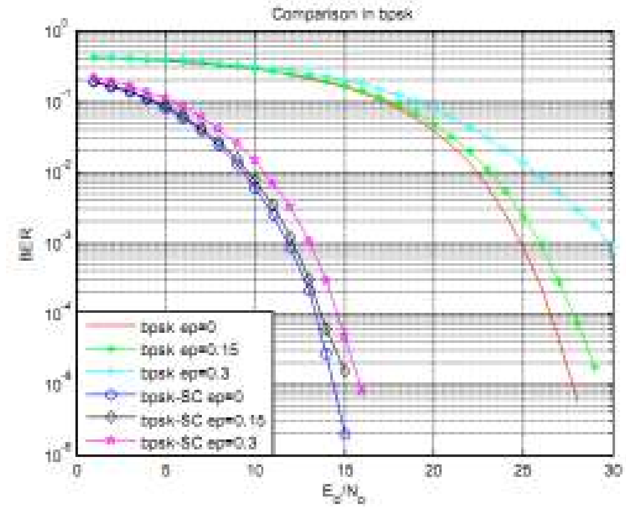

Figure. 7.1.1: BER performance of a BPSK OFDM system with & without Self Cancellation

BER performance of a BPSK OFDM system with & without Self Cancellation shown in Fig. 7.1.1.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:

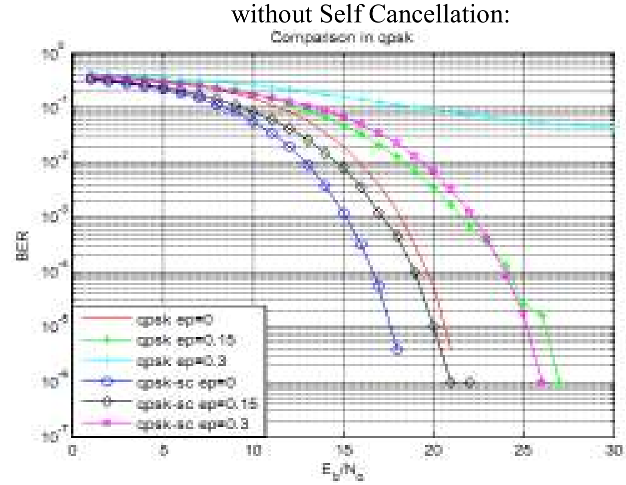

Figure.7.2.1: BER performance of a QPSK OFDM system with & without Self Cancellation

From the figure 7.2.1 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(7.2.2).

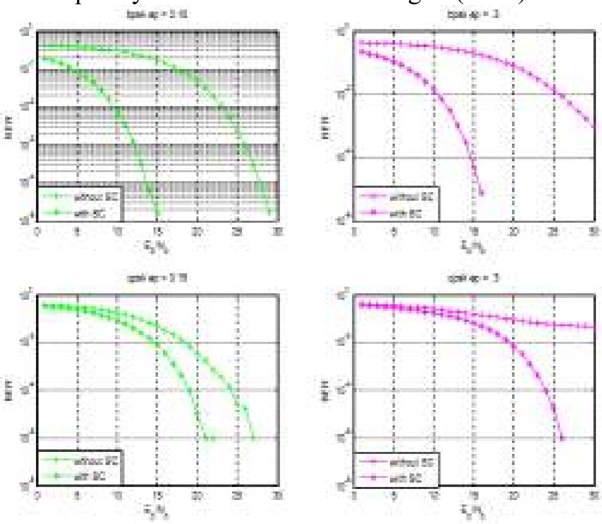

Figure 7.2.2: BER performances of QPSK, BPSK OFDM systems with constant frequency offsets

7.3 Comparison of BER performances of BPSK, QPSK OFDM systems

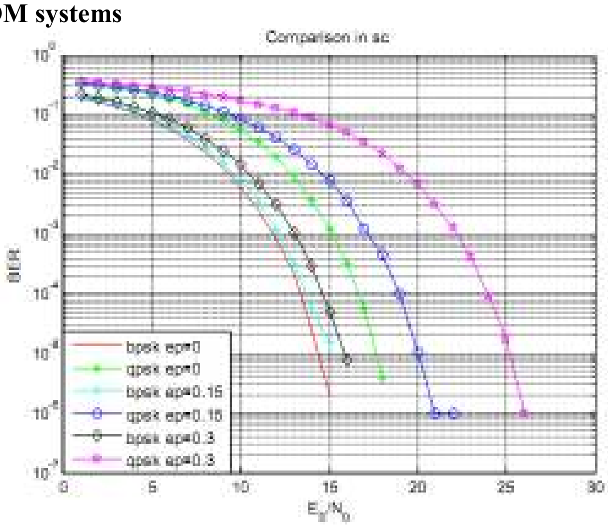

Figure 7.3.1: BER performance of a BPSK, QPSK OFDM systems with Self Cancellation.

This plot shown in figure (7.3.1) 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.

VIII. COMPARISON

In order to compare the three different cancellation schemes, BER curves were used to evaluate the performance of each scheme. For the simulations in this paper, MATLAB was employed with its Communications Toolbox for all data runs. The OFDM transceiver system was implemented as specified by Figure 2.1. Frequency offset was introduced as the phase rotation as given by (3.1). Modulation schemes of binary phase shift keying (BPSK) and 4-ary quadrature amplitude modulation (QAM) were chosen as they are used in many standards such as 802.11a. Simulations for cases of normalized frequency offsets equal to 0.05, 0.15, and 0.30 are given in Figure 8.1.

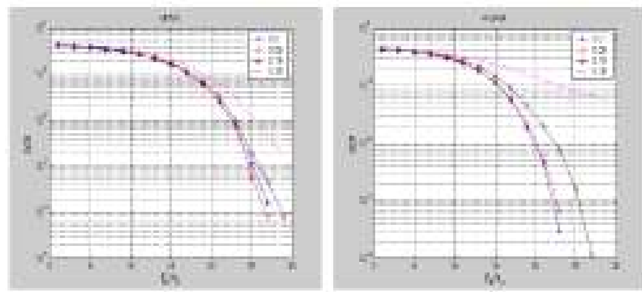

Figure 8.1: Simulations fo normalized frequency offsets equal to 0.05, 0.15, and 0.30

These results show that degradation of performance increases with frequency offset. For the case of BPSK, even severe frequency offset of 0.30 does not deteriorate the performance too greatly. However, for QAM with an alphabet of size 2, performance degrades more quickly. When frequency offset is small, the 4-QAM system has a lower BER than the BPSK system. But the BER of 4-QAM varies more dramatically with the increase the frequency offset than that of BPSK. Therefore it is concluded that larger alphabet sizes are more sensitive to ICI.

Figures 8.2-8.4 provide comparisons of the performance of the SC, ML and EKF schemes for different alphabet sizes and different values of the frequency offset.

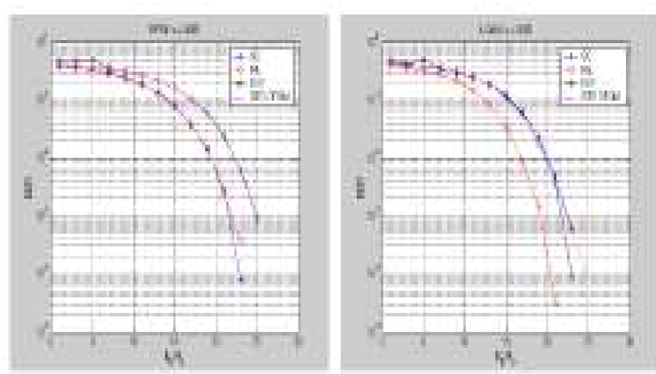

Figure 8.2: Performance of the SC, ML and EKF schemes FOR $\varepsilon = 0.05$

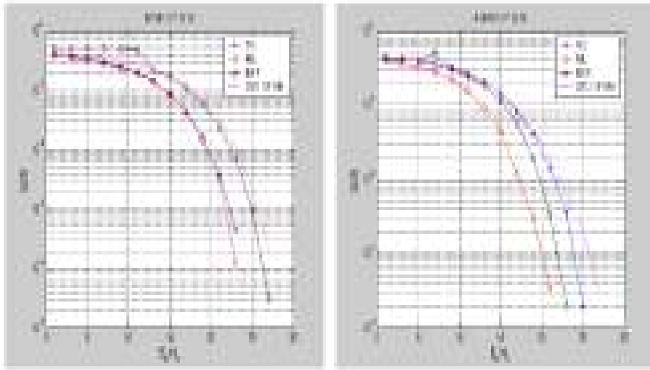

Figure 8.3: Performance of the SC, ML and EKF schemes $\varepsilon = 0.15$

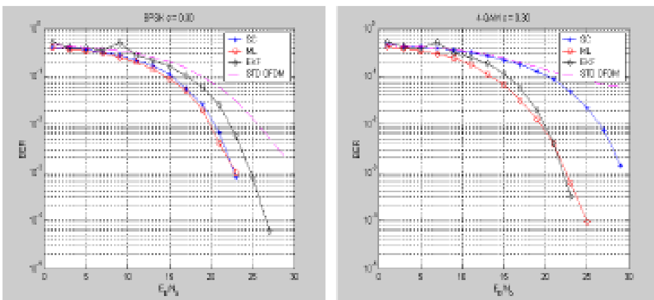

Figure 8.4: Performance of the SC, ML and EKF schemes $\varepsilon = 0.30$

It is observed in the figures that each method has its own advantages. In the presence of small frequency offset and binary alphabet size, self cancellation gives the best results. However, for larger alphabet sizes and larger frequency offset such as 4-QAM and frequency offset of 0.30, self cancellation does not offer much increase in performance. The maximum likelihood method gives the best overall results. The Kalman filter method indicates that for very small frequency offset, it does not perform very well, as it hardly improves BER. However, for high frequency offset the Kalman filter does perform extremely well. It gives a significant boost to performance. Tables 8.1 and 8.2 summarize required values of SNR for BER specified at 10^{-2}. Significant gains in performance can be achieved using the ML and EKF methods for a large frequency offset.

Method	$\varepsilon = 0.05$	Gain	$\varepsilon = 0.15$	Gain	ε=0.30	Gain
None	23 dB		23 dB		26 dB	
SC	18 dB	5dB	18 dB	5 dB	20.5 dB	5.5 dB
ML	18 dB	5dB	18 dB	5dB	20 dB	6dB
EKF	22.5dB	0.5dB	22dB	1dB	23dB	3dB

Table 8.1: Required SNR and improvement for BER of 10^{-2} for BPSK

Method	$\varepsilon = 0.05$	Gain	$\varepsilon = 0.15$	Gain	ε=0.30	Gain
None	20 dB		23 dB		40 dB	
SC	20 dB	0dB	22 dB	1 dB	27dB	13 dB
ML	17 dB	3dB	17dB	6dB	19.5 dB	20.5dB
EKF	20dB	0dB	20dB	3dB	20dB	20dB

Table 8.2: Required SNR and improvement for BER of 10^{-2} for 4-QAM

For small alphabet sizes (BPSK) and for low frequency offset values, the SC and ML techniques have good performance in terms of BER. However, for higher order modulation schemes, the EKF and ML techniques perform better. This is attributed to the fact that the ML and EKF methods estimate the frequency offset very accurately and cancel the offset using this estimated value. However, the self-cancellation technique does not completely cancel the ICI from adjacent sub-carriers, and the effect of this residual ICI increases for larger alphabet sizes and offset values.

8.1. EXPECTED OUTCOME

Numerical simulations of the three ICI mitigation schemes will be performed and their performance will be evaluated and compared in terms of various parameters such as CIR, BER, bandwidth efficiency, and computational complexity. These simulations will be implemented in MATLAB. The normalized frequency offset for these simulations will be in the range of $|\varepsilon| < 0.5$. The EKF technique is expected to be more computationally efficient as compared to the SC and MLE techniques.

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. The comparisons of the three schemes in terms of various parameters will be useful in determining the choice of ICI mitigation techniques for different applications and mobile environments.

IX. 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) and the bit error rate (BER) performance. 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.

Three methods were explored in this paper for mitigation of the ICI. The ICI self-cancellation (SC) and the maximum likelihood (ML) estimation techniques were proposed in previous publications [8]-[9]. The extended Kalman filtering (EKF) method for estimation and cancellation of the frequency offset has been investigated in this project, and compared with these two existing techniques.

The choice of which method to employ depends on the specific application. For example, self cancellation does not require very complex hardware or software for implementation. However, it is not bandwidth efficient as there is a redundancy of 2 for each carrier. The ML method also introduces the same level of redundancy but provides better BER performance, since it accurately estimates the frequency offset. Its implementation is more complex than the SC method. On the other hand, the EKF method does not reduce bandwidth efficiency as the frequency offset can be estimated from the preamble of the data sequence in each OFDM frame. However, it has the most complex implementation of the three methods. In addition, this method requires a training sequence to be sent before the data symbols for estimation of the frequency offset. It can be adopted for the receiver design for IEEE 802.11a because this standard specifies preambles for every OFDM frame. The preambles are used as the training sequence for estimation of the frequency offset.

In this paper, the simulations were performed in an AWGN channel. This model can be easily adapted to a flat-fading channel with perfect channel estimation.

9.1 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.
4. Further work can be done by performing simulations to investigate the performance of these ICI cancellation schemes in multipath fading channels without perfect channel information at the receiver. In this case, the multipath fading may hamper the performance of these ICI cancellation schemes.

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