# COMPARISON OF SOME METHODS INCLUDING USE OF CODING FOR REDUCTION OF ICI IN OFDM CHANNELES

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Abstract - One of the limitations of orthogonal frequency division Multiplexing (OFDM) in many applications is its sensitivity to frequency shifts, errors normally referred to as carrier frequency offset (CFO). Although, this small offset is negligible in conventional single carrier communication systems, it is a severe problem in the OFDM systems. Because, the carriers in OFDM are inherently closely spaced in frequency, the tolerable frequency offset becomes a very small fraction of the channel bandwidth. Besides, for OFDM communication systems, the frequency offset in mobile radio channels distorts the orthogonality between subcarriers, resulting in intercarrier interference (ICI). In this paper, we analyze and compare the performance of some already existing methods for reducing ICI with new ICI cancellation schemes by simulation. Also the advantage of using a coding scheme is shown.

**Keywords** - Intercarrier Interference, OFDM, BPSK Modulation, Extended Kalman Filter, Bit Error Rate, Self Cancellation, Modify Self Cancellation, Maximum Likelihood, Coding, AWGN, CFO, PICR

## INTRODUCTION

Wireless communications is an emerging field, which has witnessed enormous growth in the last several years. The huge uptake rate of mobile phone technology, Wireless Local Area Networks (WLAN) and the exponential growth of the internet have resulted in an increased demand for new methods of obtaining high capacity wireless networks [7].

Researches have just recently begun to develop the 4th generation (4G) mobile communication systems. The commercial rollout of these systems is likely to begin around 2008 - 2012, and will replace the 3rd generation technology. [2,8]

OFDM is a bandwidth efficient signaling scheme for digital communications in which the input bit stream is modulated in parallel on a number of subcarriers which are orthogonal to each other.

OFDM subcarriers exhibit orthogonality on a symbol interval if synthesized such that they are spaced in frequency exactly at the reciprocal of the symbol interval. This synthesis is accomplished perfectly by utilizing Discrete Fourier Transform (DFT). With the evolution of integrated circuit DSP chips, OFDM has become more practical to implement and is being used as an efficient modulation technique in Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB) and wireless LANs [7].

OFDM has been proposed as a modulation technique for the 4th generation wireless communication because of its high data rate transmission capability. It makes efficient use of the spectrum by allowing overlap in spectrum. In addition, OFDM provides an efficient way to deal with multipath effect and hence intersymbol interference (ISI). It is robust in frequency selective channels, because in such channels only a small percentage of the subcarriers are affected.

One of the limitations of OFDM in many applications is that it is very sensitive to frequency errors, normally referred to as 'carrier frequency offset'. This frequency offset can be caused by Doppler shift due to relative motion between the transmitter and receiver, or by frequency drift between the local oscillators at the transmitter and receiver. As a result, there is a loss of orthogonality among subcarriers giving rise to inter carrier interference [4]. Besides, like other wireless communication systems, Multipath phenomena result in severe fading or Rayleigh fading channel, so increasing bit error rate (BER) or symbol error rate (SER) [11,13].

## PEAK INTERFERENCE -TO- CARRIER RATIO (PICR) PROBLEM

The complex baseband OFDM signal may be represented as:

$$x(t)=\sum_{k=0}^{N-1} X(k)e^{j2\pi.k.\Delta f.t} \qquad 0\le t\le T \tag{1}$$

Where $j^2=-1$ and N is the total number of subcarriers. The frequency separation between any two adjacent subcarriers is $\Delta f=\frac{1}{T}$ and T is the OFDM symbol duration. $X(k)$ is the data symbol for the k.th subcarrier. We refer to $X=(X(0), X(1),\ldots, X(N-1))$ as a data frame or codeword. If x(t) is sampled by Nyquist rate, we will have:

$$x(n)=x(\frac{nT}{N})=\sum_{k=0}^{N-1} X(k)e^{j2\pi.k.\Delta f.(\frac{nT}{N})} \qquad 0\le n\le N-1 \tag{2}$$

or

$$x(n)=\sum_{k=0}^{N-1} X(k)e^{j2\pi.k.(\frac{n}{N})}$$

The received OFDM signal is

$$y(t)=\sum_{k=0}^{k=N-1} X(k)e^{j2\pi.(k.\Delta f+f_D)t}+w(t) \qquad 0\le t\le T \tag{3}$$

$$y(n)=y(\frac{nT}{N})=\sum_{k=0}^{N-1} X(k)e^{j2\pi(k\Delta f+\varepsilon.\Delta f).(\frac{nT}{N})}+w(n) \qquad 0\le n\le N-1$$

$$y(n)=\sum_{k=0}^{N-1} X(k)e^{j2\pi(k\Delta f).(\frac{nT}{N})}e^{\frac{j2\pi n.\varepsilon}{N}}+w(n)$$

$$y(n)=x(n)e^{\frac{j2\pi.n.\varepsilon}{N}}+w(n) \tag{4}$$

Where ε is the normalized frequency offset, $f_D$ is frequency shift due to Doppler effect and w(t) is AWGN .In this paper, we assume that x(t) is transmitted on an Additive White Gaussian Noise channel, so the received sample signal of the $k_{th}$ sub carrier ,after Fast Fourier Transform(FFT) demodulation, could be expressed as:

$$Y(k) = X(k)S(0) + \sum_{l=0, l \neq k}^{N-1} X(l)S(l-k) + n_k, \qquad K = 0, 1, 2, 3 \ldots\ldots. N-1 \tag{5}$$

Where $n_k$ is a complex Gaussian noise sample (with its real and imaginary components being independent and identically distributed with variance $\sigma^2$). The second term in (2) is the ICI term attributable to the carrier frequency offset (CFO). The sequence S(k) (the ICI coefficients) depends on the CFO and is expressed as:

$$S(k) = \frac{\sin \pi(k+\varepsilon)}{N \sin \frac{\pi}{N}(k+\varepsilon)} \exp[j\pi(1-\frac{1}{N})(k+\varepsilon)] \tag{6}$$

In the above equation is the normalized frequency offset defined as a ratio between the frequency offset (which remains constant over each symbol period) and subcarrier spacing. For a zero frequency offset *S(k)* reduces to the unit impulse sequence. The ICI term can be separated from equation (2) and is expressed as:

$$I(k) = \sum_{l=0, l \neq k}^{N-1} X(l)\, S(l-k) \quad \text{for } 0 \leq k \leq N-1 \tag{7}$$

Note that *I(k)* is a function of both *X(k)* and ε. The admissible sequence *X* is called codewords, and the ensemble of all possible codewords is a code χ.

We define the Peak Interference-to-Carrier ratio (PICR) as:

$$PICR(X, \varepsilon) = \max_{0 \leq k \leq N-1} \left\{ \frac{|I(k)|^2}{|S(0)\, X(k)|^2} \right\}. \tag{8}$$

PICR is the maximum Interference-to-signal ratio for any subcarrier.In other words, it specifies the worst-case ICI on any subcarrier.

## ICI REDUCTION METHODES

Various algorithms for reducing ICI in OFDM communication systems have been developed. Some of them are as follows:

1. PICR reduction by coding [9,12]
2. ICI self cancellation [10]
3. Modified ICI self cancellation [4]
4. Maximum likelihood offset estimation and cancellation [5]
5. Kalman Filter offset estimation and cancellation [6]

These schemes have their own merits and demerits. In many OFDM standards the system parameters are adaptive. For instance, in Asynchronous digital subscriber line (ADSL), adaptive bit loading and adaptive modulation are used. Also, in new OFDM standards, which are on there way, various issues like subcarrier spacing and type of modulation are yet to be decided. Therefore, a comparative study needs to be done in ICI domain, before the standards are finalized.

This paper concentrates on comparing various ICI cancellation schemes, as they respond differently to different OFDM parameters.

## - PICR REDUCTION BY CODING

To reduce ICI effects, the equation (8) should be minimized. However, we need to know ε to compute PICR at the transmitter. Although the absolute PICR is a function of ε, we can design a coding system in which the amount of PICR reduction is independent of ε. This property is crucial as the exact value of ε is not known a priori.
For a code $\mathcal{X}$, we define:

$$PICR(\mathcal{X}, \varepsilon) = \max_{X \in \mathcal{X}} PICR(X, \varepsilon) \tag{9}$$

to show that PICR reduction code exists, we consider an OFDM system with N=4 and binary phase shift keying (BPSK) modulated subcarrier. The PICR for all data frames are given in Table 1 in ascending order. Ten data frames have a PICR of -12.49 dB for ε =0.1 and four data frames have PICR of -14.67. Clearly, we can choose only these data frames for transmission in order to reduce PICR. This can be done by block coding that 3 bits of data mapped on to 4 best data frames. In Table 1, codewords: 0011,0110,1001 have a PICR of -14.76 dB. Thus, by transmitting only these data frames PICR can be reduced. This can be done by block coding the data, such that 2 data bits are mapped on to 4 best data frames. Thus, this code halves the data throughput. Note also that the complete rank i.e. ordering of all codewords in terms of PICR is independent of the frequency offset. That suggests that this block code's performance is independent of ε.

Table 1: PICR for N=4 and BPSK modulation for ε=.05&ε=.1.

| $d_1$ | $d_2$ | $d_3$ | $d_4$ | PICR(dB) $\varepsilon = 0.1$ | $\varepsilon = .05$ |
|---|---|---|---|---|---|
| 0 | 1 | 0 | 1 | -21.8 | -28.06 |
| 1 | 0 | 1 | 0 | -21.8 | -28.06 |
| 0 | 0 | 1 | 1 | -14.76 | -20.97 |
| 0 | 1 | 1 | 0 | -14.76 | -20.97 |
| 1 | 0 | 0 | 1 | -14.76 | -20.97 |
| 1 | 1 | 0 | 0 | -14.76 | -20.97 |
| 0 | 0 | 0 | 0 | -12.49 | -18.56 |
| 0 | 0 | 0 | 1 | -12.49 | -18.56 |
| 0 | 0 | 1 | 0 | -12.49 | -18.56 |
| 0 | 1 | 0 | 0 | -12.49 | -18.56 |

| $d_1$ | $d_2$ | $d_3$ | $d_4$ | PICR(dB) $\varepsilon = 0.1$ | $\varepsilon = .05$ |
|---|---|---|---|---|---|
| 0 | 1 | 1 | 1 | -12.49 | -18.56 |
| 1 | 0 | 0 | 0 | -12.49 | -18.56 |
| 1 | 0 | 1 | 1 | -12.49 | -18.56 |
| 1 | 1 | 0 | 1 | -12.49 | -18.56 |
| 1 | 1 | 1 | 0 | -12.49 | -18.56 |
| 1 | 1 | 1 | 1 | -12.49 | -18.56 |

## - ICI SELF CANCELLATION

In self cancellation scheme the main idea is to modulate the input data symbol onto a group of subcarriers with predefined self coefficients such that the generated ICI signals within that group cancels each other [14].

The data pair (X,-X) is modulated onto two adjacent subcarriers ($l$, $l$+1). The ICI signals generated by the subcarrier $l$ will be cancelled out significantly by the ICI generated by the subcarrier ($l$+1) [1,6].

By using the ICI cancellation modulation, each pair of subcarriers transmits only one data symbol. The signal redundancy makes it possible to improve the system performance at the receiver side. In considering a further reduction of ICI, an ICI cancellation demodulation scheme is used. In ICI cancellation demodulation scheme, signal at the *(k*+1*)th* subcarrier is multiplied by "-1" and then added to the one at the *kth* subcarrier. Then, the resulting data sequence is used for making symbol decision [14].

## - MODIFIED SELF CANCELLATION SCHEME

The main idea of this scheme is to map each data symbol X(k) which is to be transmitted onto a pair of non-adjacent subcarriers $k$ and ($N$-1-$k$), with weightings "+1" and "-1", rather than to adjacent carriers [10].

As, in the case of self cancellation modulation algorithm, each pair of subcarrier transmits only one data symbol. In considering a further reduction of ICI, an ICI cancellation demodulation scheme is used. The demodulation is suggested to work in such a way that each signal at the (*N*-1-*k)th* subcarrier is multiplied by "-1" and then summed with one at the *kth* subcarrier [10].

## STATISTICAL APPROACH

In statistical approach, the carrier frequency offset (CFO) is first estimated statistically in order to reduce ICI. Once a precise CFO estimate is obtained, it is cancelled at the receiver. Various approaches have been proposed to estimate the CFO. Some of them are:

- Maximum likelihood approach
- Extended Kalman filter approach
- ESPRIT approach

### - MAXIMUM LIKELIHOOD ESTIMATION

In this approach, the frequency offset is first estimated statistically 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 [4].

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

$$r(n) = \frac{1}{N}\left[\sum_{k=-K}^{K} X(k)H(k)e^{j2\pi n(k+\varepsilon)/N}\right] \quad , n=0, 1, 2, \ldots, N-1 \tag{10}$$

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 *kth* carrier. The first set of *N* symbols is demodulated using an *N*-point FFT to yield the sequence $R_1(k)$, which is equal to

$$R_1(k) = \sum_{n=0}^{N-1} r(n)e^{-j2\pi nk/N} \tag{11}$$

The second set is demodulated using another *N*-point FFT to yield the sequence

$$R_2(k) = \sum_{n=N}^{2N-1} r(n)e^{-j2\pi nk/N}$$

$$= \sum_{n=0}^{N-1} r(n+N)e^{-j2\pi nk/N} \quad , k=0,1,2,\ldots\ldots\ldots N-1, \tag{12}$$

From equation (4) we have

$$r(n+N) = r(n)\exp(2\pi j\varepsilon) \leftrightarrow R_2(k)=R_1(k)\exp(2\pi j\varepsilon)$$

That is frequency offset is the phase difference between the sequences $R_1(k)$ and $R_2(k)$. Adding White Gaussian Noise we get

$$Y_1(k) = R_1(k) + W_1(k) \tag{13}$$

$$Y_2(k) = R_1(k)\exp(2\pi j\varepsilon) + W_2(k) \tag{14}$$

We observe that between the first and second FFTs, both the ICI and the signal are altered in exactly the same way, by a phase shift proportional to frequency offset [4]. Therefore, if frequency offset ε is estimated using equation (8) it is possible to obtain accurate estimates even when the offset is too large for satisfactory data demodulation.

It was shown by Moose that CFO (Carrier Frequency Offset) can be estimated using Maximum likelihood (ML) algorithm and is equal to [4]:

$$\hat{\varepsilon} = \left(\frac{1}{2\pi}\right)\tan^{-1}\left\{\frac{\left[\sum_{k=K}^{K} Imag[Y_2(k)Y_1^*(k)]\right]}{\left[\sum_{k=K}^{K} Real[Y_2(k)Y_1^*(k)]\right]}\right\} \quad (15)$$

Where $\hat{\varepsilon}$ is the estimated carrier frequency offset for sub carrier number one i.e. smallest carrier frequency. Of course, for sub carrier number k the offset frequency is k $\hat{\varepsilon}$.This is an intuitively satisfying result since, in the absence of noise, the angle of $Y_2(k)Y_1^*(k)$ is $2\pi\varepsilon$ for each k. This maximum likelihood estimate is a conditionally unbiased estimate of the frequency offset and is computed using the received data. 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 FFT [4,6].

## - EXTENDED KALMAN FILTER

The Kalman filter is a remarkably versatile and powerful recursive estimation algorithm. As a recursive filter, it is particularly applicable to non-stationary processes such as signals transmitted in a time-variant radio channel. Kalman Filter was originally designed for solving linear systems in white gaussian noise. For nonlinear systems there is a method called Extended Kalman Filter (EKF), which is based on regular Kalman filter. Its idea is to linearize the system and then use the same method as in the Kalman filter [3,5]. There are also two stages in the EKF scheme to mitigate the ICI effect: the offset estimation scheme and the offset correction scheme.

### - - OFFSET ESTIMATION SCHEME

To estimate the quantity $\hat{\varepsilon}(n)$ using an EKF in each OFDM frame, the first order state equation is built as:

$$\hat{\varepsilon}(n) = \hat{\varepsilon}(n-1) \quad (16)$$

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:

$$y(n) = x(n)e^{\frac{j2\pi n\varepsilon}{N}} + w(n) \quad (17)$$

Where $y(n)$ denotes the received symbols distorted in the channel, $w(n)$ the AWGN, and $x(n)$ is the IFFT of the transmitted preambles $X(k)$, which are known at the receiver. Through the recursive iteration procedure, an estimate of the frequency offset $\hat{\varepsilon}(n)$ can be obtained [5]. Assume Np preambles preceding the data symbols in each frame are used as a training sequence and the variance $\sigma^2$ of the AWGN w(n) is stationary. The algorithm for computation of frequency offset for $N_p$ iterations is:

1. Initialize Estimate $\hat{\varepsilon}(0)$ *and* corresponding state error $P(0)$
2. Compute the $H(n)$, the derivate of y(n) with respect to $\varepsilon(n)$ at , $\hat{\varepsilon}(n-1)$ the estimate

obtained in the previous iteration.

3. Compute the time-average Kalman gain k(n) using the error variance P(n-1) , H(n), and $\sigma^2$.
4. Compute the estimate using y(n), x(n), k(n) and $\hat{\varepsilon}\ (n-1)$
5. Compute the state error P(n) with Kalman gain k(n), H(n),and the previous error P(n-1)
6. If n is less than Np, increment by 1 and go to step 2; otherwise stop

**- - OFFSET CORRECTION**

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

$$\hat{x}(n) = FFT\left\{ y(n)\, e^{\frac{-j2\pi n \hat{\varepsilon}^*}{N}} \right\} \tag{18}$$

Where $\hat{x}$(n) is the restored data symbol.

**SIMULATION**

Performance of four ICI reduction algorithms namely ICI self cancellation, Modified ICI self cancellation, Maximum likelihood offset estimation and Extended Kalman filter offset estimation were evaluated and compared with an ordinary OFDM system. An OFDM ICI cancellation Test bed was made using Matlab. The front panel of the simulator is shown in Figure 1.

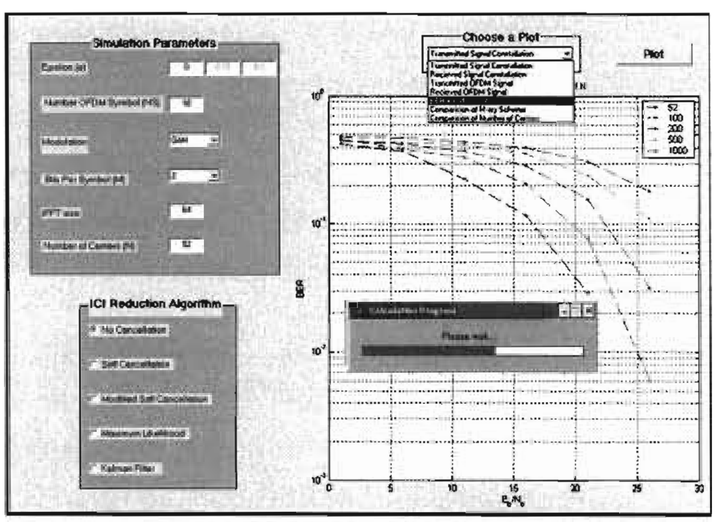


Figure 1: Snapshot of an OFDM ICI cancellation simulator.

The simulator can be used to compare the above algorithms in terms of BER, for any value of alphabet size (M), Number of subcarriers (N), frequency offset ($\varepsilon$) and type of modulation (QAM, PSK). This simulator can also be used to evaluate the performance of an OFDM system in terms of BER for different M and N. A Graphical user interface was also created using Matlab. The Matlab code was changed to C++ in order to get higher simulation speeds and to create standalone software named as OFDM ICI Cancellation Simulator (ICS). The software is compatible with Windows and Linux operating systems.

## SIMULATION RESULTS AND DISCUSSIONS

BER curves are used as the criteria for evaluating the performance of each ICI reduction algorithm. Modulation schemes of BPSK, QPSK and M-ary quadrature amplitude modulation (QAM) are used in simulations, as they are used in many OFDM standards such as 802.11a, Hiperlan/2 and ADSL. Normalized frequency offset values of 0.05, 0.1, 0.2 and 0.3 are used in the simulations. Other simulation parameters are given in Table 1.

Table 2: Basic simulation parameters.

| | |
|---|---|
| Number of subcarriers (N) | 52 |
| IFFT size | 64 |
| Number of OFDM symbols | 100 |
| Normalized frequency offset = $\varepsilon$ | 0.05, 0.1,0.2,0.3 |
| Signal to noise ratio = $E_b/N_o$ | 1,2,3,4.........30 dB |

Comparison of the different algorithms for QPSK and different values of frequency offset are shown in Figures 2(a-d).

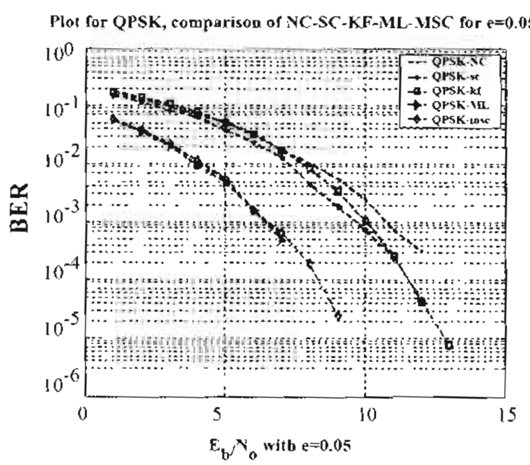


Figure: 2(a).

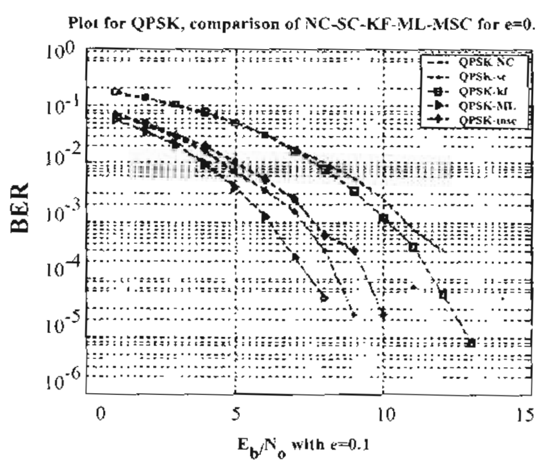


Figure: 2(b).

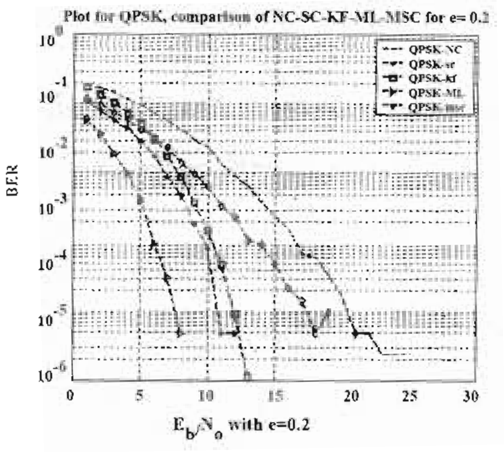


Figure: 2(c)

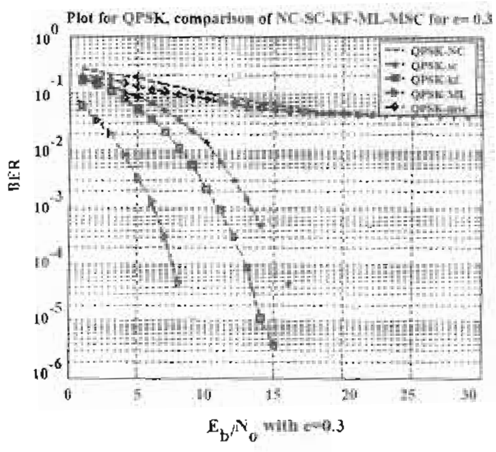


Figure: 2(d)

Figure 2: Comparison of ICI cancellation algorithms for QPSK modulation. (a): ε = 0.05., (b): ε = 0.1., (c): ε = 0.2., (d): ε = 0.3.

Figure 2 (a-d) shows simulation results for QPSK OFDM system. It is seen that for lower values of frequency offset (=0.05, 0.1) BER of self cancellation, modified self cancellation and maximum likelihood methods is lower than normal OFDM system. Also, extended kalman filter approach does not offer much improvement in performance. For higher values of frequency, offset maximum likelihood approach gives the best results. Maximum likelihood method offers 7.2 db improvement in the SNR for BER of $10^{-4}$ and frequency offset value of 0.3 as compared with self cancellation scheme.

Comparison of ICI reduction algorithms for 16 QAM and different values of frequency offset are shown in Figures 3(a-d).

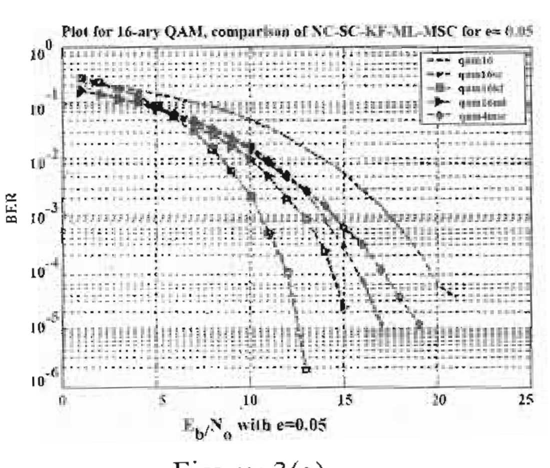


Figure: 3(a)

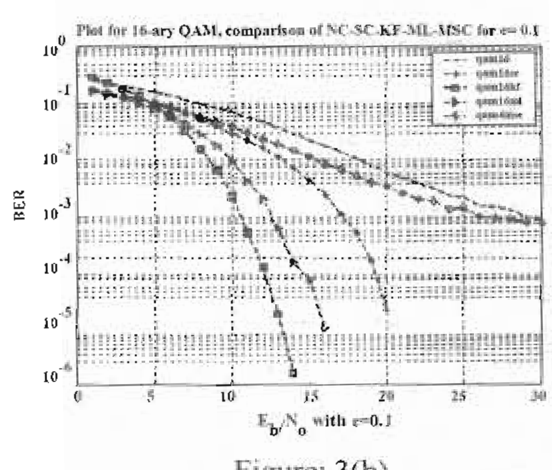


Figure: 3(b)

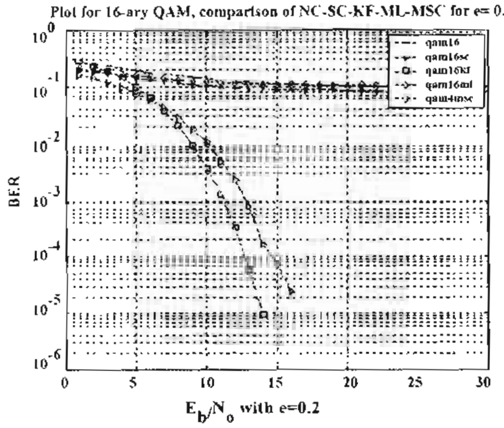


Figure:3(c)

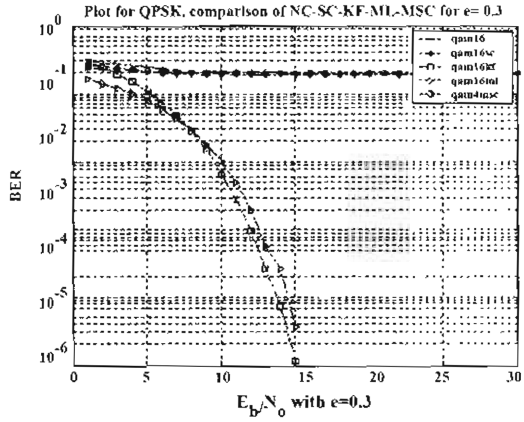


Figure: 3(d)

Figure 3: Comparison of ICI cancellation algorithms for 16-ary QAM modulation.
(a): ε = 0.05., (b): ε = 0.1., (c): ε = 0.2., (d): ε = 0.3.

Figure 3 (a-d) shows simulation results for 16-QAM OFDM system. It is seen that for lower values of frequency offset BER of extended kalman filter was least followed by maximum likelihood method. As we increased frequency offset these two methods give outperformed rest of the methods.

A comparison of the mentioned algorithms for 64 QAM and different values of frequency offset are shown in Figures 4(a-d).

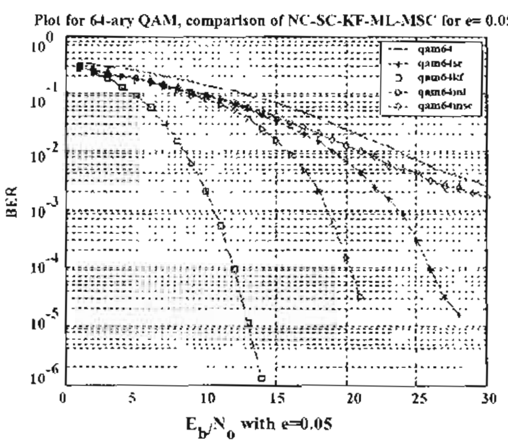


Figure: 4(a)

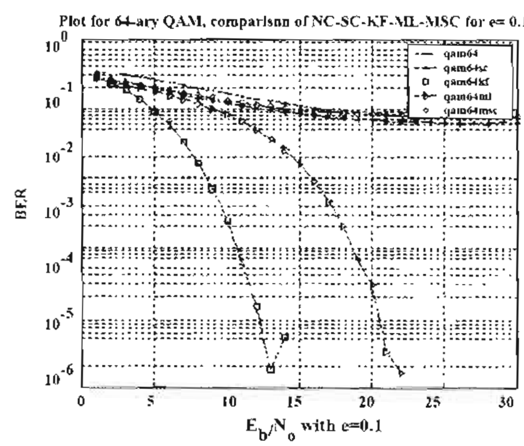


Figure:4(b)

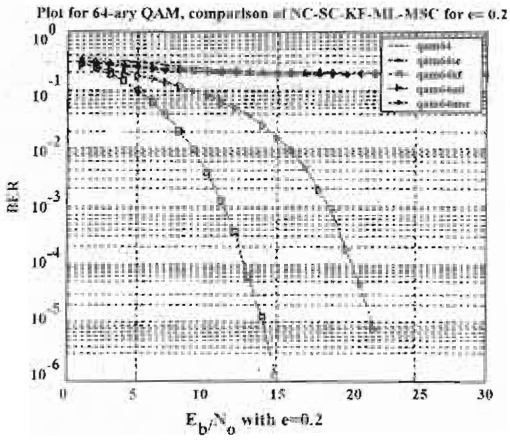


Figure: 4(c)

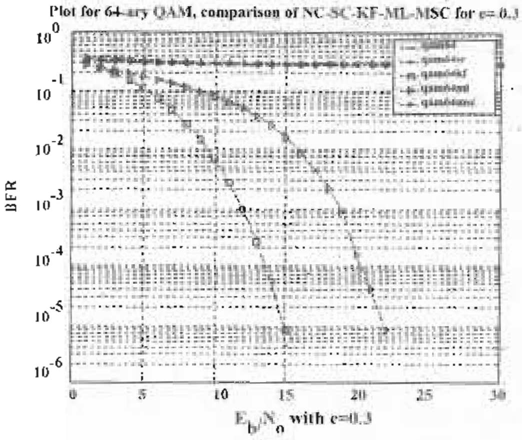


Figure: 4(d)

Figure 4: Comparison of ICI cancellation algorithms for 64-ary QAM modulation.
(a): $\varepsilon = 0.05$., (b): $\varepsilon = 0.1$., (c): $\varepsilon = 0.2$., (d): $\varepsilon = 0.3$.

Figure 4 (a-d) shows simulation results for 64-QAM OFDM system. It is seen that for both lower as well as higher values of frequency, offset extended kalman filter gives best results followed by maximum likelihood method. Self cancellation and modified self cancellation methods do not offer any improvement in the performance. For carrier frequency offset of 0.05 to maintain a BER of $10^{-4}$, there was an 7.5db SNR improvement for extended kalman filter compared with maximum likelihood method and 13.5 db improvement as compared to self cancellation method.

## CONCLUSIONS

It is observed from Figures 2 (a-d), Figures 3 (a-d) and Figures 4 (a-d) that each method has its own merits and demerits. For small alphabet size i:e. for small values of M (2,4) M and for small frequency offset values $\varepsilon$ ($\varepsilon < 0.2$), ICI self cancellation algorithm gives better results than modified self cancellation and Kalman filter algorithms. But for higher values of M (16,64) and $\varepsilon$ ($\varepsilon > 0.2$) it does not offer much increase in performance.

The modified self cancellation algorithm improves performance for small alphabet size and for small values of frequency offset. For higher values of M and $\varepsilon$ its performance does not offer much improvement and is poorer than self cancellation algorithm. This scheme has advantage of frequency diversity effect in a fading channel because the data symbol at subcarriers k and (N-1-k) may not fade together.

The maximum likelihood method gives the best overall results for small values of M and larger values of offset. But for higher values of M it is outperformed by Extended Kalman filter algorithm.

The Extended Kalman filter algorithm does not perform better for small values of alphabet size M. But for higher values of M (16,14) and higher values of offset, it outperforms the rest of the algorithms. This is because extended kalman filter is a recursive algorithm and needs many iterations to have an exact estimate of frequency offset.

Also, in case of self cancellation, modified self cancellation and maximum likelihood methods we use redundant data, so in these methods bandwidth efficiency is reduced. To use a particular inter carrier interference reduction method in OFDM systems there must be a trade off between bandwidth efficiency and bit error rate.

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