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Performance Analysis of ICI in OFDM systems using Self-Cancellation and Extended Kalman Filtering

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***Abstract* - Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation where each sub carrier is orthogonal to other sub carriers. OFDM is widely used in wireless communications as it provides high data rates. The major problem in OFDM is its sensitivity to frequency offset. The causes of frequency offset are differences in local oscillator frequencies at transmitter and receiver and Doppler shift due to relative motion between transmitter and receiver. The effects of frequency offset are reduction of signal amplitude in output of the filters matched to each carriers at the receiver and the introduction of inter carrier interference (ICI) from other subcarriers due to loss of orthogonality. ICI causes power leakage among subcarriers degrading system performance. There are various methods to reduce ICI which can be categorized as frequency domain equalization, time domain windowing, pulse shaping, ICI self cancellation and extended kalman filtering. In this paper ICI self cancellation and extended kalman filtering methods are proposed to reduce ICI. The performance of two methods is analyzed in terms of bit error rate. At higher frequency offsets, Extended Kalman Filtering performs well when compared to Self Cancellation method.**

***Index Terms* - Extended kalman filter, Inter carrier interference, Orthogonal frequency division multiplexing, Self cancellation.**

I. INTRODUCTION

The demand for high data rate wireless transmission technologies has been increasing enormously which indeed needs the efficient utilization of communication resource (time and bandwidth).There are three ways to increase the efficiency of a communication system. They are increasing transmitter power, providing more channel bandwidth and allocating the communication resource in the most efficient way. The third method is the domain of communications where different techniques such as modulation, multiplexing and multiple access schemes are employed. Modulation is defined as the process of variation of the characteristics of the carrier signal according to the message signal. Multiplexing is combining signals from different sources to send through a single channel. Multiple access is allowing more number of users to share a channel by allocating dedicated resources. These three processes are interdependent. Increasing number of users and the requirement of broadband facilities in our daily life at colleges, offices etc need very reliable data transmission technologies that are robust to attenuation, interference, multipath fading, noise, delay spread etc. The multicarrier communication is one such technology that can overcome all these impairments when compared to single carrier communication systems.

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Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation where the available bandwidth is divided into subcarriers which are orthogonal to each other. It is most popular to produce high speed communication. OFDM is similar to FDM but the utilization of the spectrum is more efficient by spacing the sub bands closer together in OFDM. The main disadvantage of OFDM system is its sensitivity to frequency offset which leads to loss of orthogonality among sub carriers. This loss of orthogonality among the sub carriers leads to Inter Carrier Interference (ICI) which degrades the performance of the OFDM system.

II. FUNDAMENTALS OF OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation where the carrier spacing is carefully selected such that each subcarrier is orthogonal to other subcarriers.

Orthogonality principle is very responsible to non overlapping of subcarriers that minimizes interference between the carriers.Two signals are said to be orthogonal if the area under the product of two signals is zero. In time domain the orthogonality of signals is expressed as

$$\int x_i(t) * x_j(t) = 0 \text{ for all } i \neq j$$

$$= K \text{ for } i = j \text{ , K is some constant}$$

A. OFDM system overview

The basic OFDM transceiver is shown in the fig. 1. At the transmitter side, digital data to be transmitted is converted to parallel form using a serial to parallel converter and then

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mapped onto subcarriers amplitude and phase in signal mapper. The modulated data is converted to time domain using IFFT and guard interval is inserted to avoid inter symbol interference(ISI) .the parallel data again converted to serial form and then to analog form using digital to analog converter(DAC) to transmit through free space. Exactly reverse operation is done at the receiver to retrieve transmitted digital data.

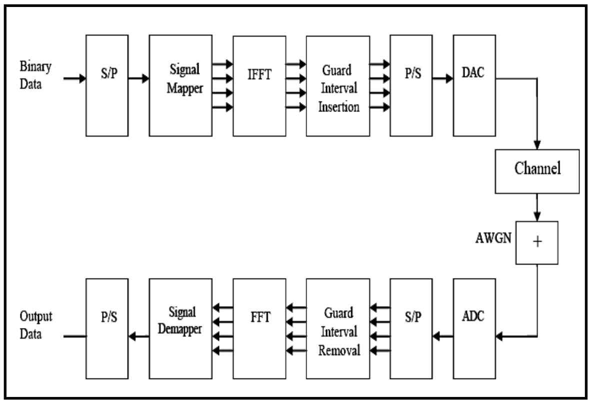


Figure 1: Basic block diagram of OFDM system

Signal mapper

In signal mapper modulation process is performed. The increasing demand of digital transmission channels led to investigation of bandwidth efficient modulation techniques. Two such modulation techniques are m-ary or binary phase shift keying and quadrature amplitude modulation(QAM).Hence OFDM uses these two modulation schemes. Signals are mapped into I (in phase) Q (Quadrature phase) constellation. M-ary modulation schemes are used because they allow the transmission of $k=\log_2 M$ bits during each symbol period which increase data rate by a factor 'k' within same bandwidth as in binary signaling.

Fast Fourier transform

Decomposition of a signal into frequency components is done using DFT. Fast Fourier transform (FFT) is similar to DFT which is algorithm for speedier implementation of DFT. It requires less number of computations.

IDFT $x(n) = \frac{1}{N}\sum_{k=0}^{N-1} X(k)\exp(j\frac{2\pi}{N}kn)$

DFT $X(K) = \sum_{n=0}^{N-1} x(n)\exp(-j\frac{2\pi}{N}kn)$

Guard interval insertion

In order to reduce Inter Symbol Interference (ISI) in OFDM system, guard interval is inserted between two OFDM symbols. This guard period is a cyclic copy that extends the length of the symbol waveform.

The digital data after guard interval insertion is converted to analog signal by using DAC in order to transmit in the free space.

B. Advantages of OFDM

- Efficient spectrum utilization.
- Inter Symbol Interference (ISI) reduction by adding cyclic prefix.
- Robust to frequency selective fading.
- OFDM is computationally efficient by using FFT techniques to implement the modulation and demodulation functions.
- OFDM is highly immune to multipath delay spread that causes inter symbol interference in wireless channels.

C. Drawback of OFDM

The main drawback of OFDM is its sensitivity to frequency offset which leads to Inter Carrier Interference (ICI). The frequency offset occurs due to difference in frequencies at local oscillators of transmitter and receiver and Doppler shift due to relative motion between transmitter and receiver.

Research has been going on to reduce this major problem ICI and many techniques to mitigate ICI have been implemented. They are

- Frequency domain Equalization
- Time domain windowing
- Pulse shaping
- Self Cancellation
- Extended Kalman filtering

The initial three approaches failed to reduce the ICI caused by the frequency offset. Hence in this paper Self Cancellation and Extended Kalman Filtering methods are proposed to mitigate ICI effect.

III. ICI SELF CANCELLATION METHOD

ICI self cancellation was introduced by Zhao and Sven-Gustav in 2001 to reduce ICI in OFDM.

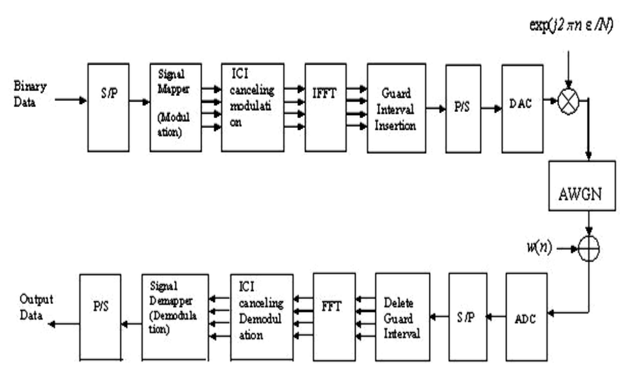


Figure 2: Block diagram of OFDM system implementing Self-cancellation method.

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. The block diagram of OFDM system using ICI self cancellation method is shown in fig. 2. The input binary data is fed to serial to parallel converter so as to convert high data rate stream to low data rate stream. This low data rate stream gets modulated in signal mapper. Bandwidth efficient modulation techniques QPSK, QAM are employed. The modulated data is given to ICI cancelling modulation where ICI coefficients are calculated. The data in frequency domain is converted to time domain by using IFFT, then guard interval is added to reduce ISI(inter Symbol Interference). The parallel data is converted to serial form by using parallel to serial converter and then into analog form using digital to analog converter(DAC) so as to transmit through the channel. At the receiver part exactly reverse operation is performed. ICI cancelling modulation and ICI cancelling demodulation constitute Self-cancellation method.

The received signal is

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

where ε represents the normalized frequency offset, that is, ε =Δf/(1/NT) , where Δf is the frequency difference between the transmitter and the receiver, and *NT* denotes the interval of an FFT period ,w(n) is the AWGN introduced in the channel and T is the subcarrier symbol period.

After applying fast fourier transform to y(n), we get

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

Then after some mathematical manipulations,

$$Y(k) = \sum_{l=0}^{N-1} X(l)S(l-k)$$

Where,

$$S(l-k) = exp\,(j2\pi(l+\varepsilon-k)(1-\frac{1}{N})\frac{\sin(\pi(l+\varepsilon-k))}{N\sin(\frac{\pi(l+\varepsilon-k)}{N})}$$

Which are the required ICI coefficients

The self cancellation method relies on the fact that the real and imaginary parts of the ICI coefficients change gradually with respect to the subcarrier index *k*; therefore, the difference between consecutive ICI coefficients, *S(l-k)-S(l-k+1)*, is very small.

After ICI cancelling modulation, ICI coefficient is

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

At the receiver side after performing ICI cancelling demodulation, ICI coefficient is

$$S''(l-k) = -S(l-k-1) + 2s(l-k) - S(l-k+1)$$

Simulation of ICI coefficients for various values of frequency offset:

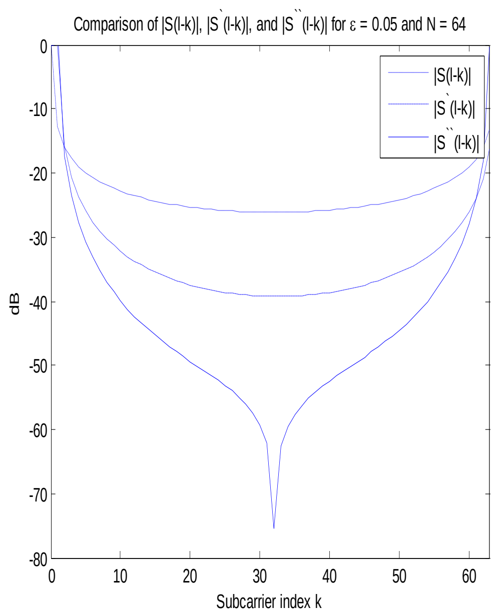


Figure 3: comparison of ICI coefficients for N=64 and ε = 0.05

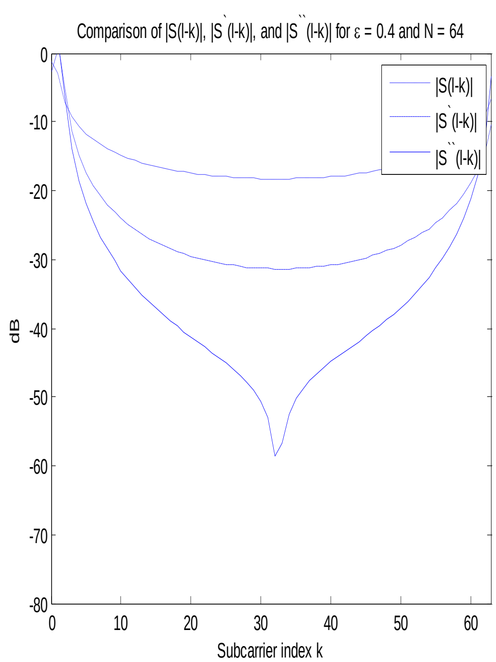


Figure 4 : comparison of ICI coefficients for N=64 and ε=0.4

TABLE I: COMPARISON OF ICI COEFFICIENTS IN SELF CANCELLATION METHOD FOR VARIOUS FREQUENCY OFFSETS

Frequency offset(ε)	ICI coefficient (dB)	ICI coefficient after ICI cancelling modulation (dB)	ICI coefficient after ICI cancelling demodulation (dB)
0.05	-26.11	-39.2	-75.38
0.1	-23.16	-36.25	-69.42
0.15	-21.49	-34.58	-65.98
0.2	-20.37	-33.45	-63.61
0.25	-19.57	-32.65	-61.84
0.3	-18.98	-32.06	-60.46
0.35	-18.56	-31.64	-59.37
0.4	-18.28	-31.36	-58.51

Drawback:

The major drawback of this method is the reduction in band width efficiency as same symbol occupies two sub-carriers and also as frequency offset increases, ICI increases as shown in above table

IV. EXTENDED KALMAN FILTERING

Kalman filter was derived by Rudolf Emil Kalman in the year 1958 and was used for tracking purpose in Apollo project at NASA for the first time in 1960. Kalman filters are mainly used for guidance,

navigation and controlling a system. Kalman filter can be easily implemented on a digital computer as an algorithm. Due to the recursive nature, it can also be applied to non stationary processes such as estimation of a time varying radio channel. It is a linear estimator to estimate the state of a system. The applications of kalman filtering in communications include adaptive equalization of telephone channels etc.

Kalman filter is a linear estimator but here the measurement is varying non linearly. So, we are going for Extended kalman filtering (EKF) where the non linear measurement is linearized using some mathematical methods and same process of estimation as kalman filtering is used.

The state space model of a kalman filter is

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

here desired value d(n) varies linearly with z(n).

The received symbols are given as

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

here y(n) is in non linear relationship with desired value ε(n) so we first linearize the equation and then estimate ε(n).

Hence we use Numerical method analysis from where First Order Taylor's series is employed to linearize above equation

Above can be written as y(n)=f(ε(n))+w(n) where, f(ε(n)) is a non linear function of ε. Using first order taylor's series, f(ε(n)) is given by

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

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

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

we define $z(n) = y(n) - f(\hat{\varepsilon}(n-1))$ = measurement – estimated value

and $d(n) = \varepsilon(n) - \hat{\varepsilon}(n-1)$ = true value – previous estimate

substituting z(n) and d(n) in above equation we obtain

$$z(n) = f'(\hat{\varepsilon}(n-1))\, d(n) + w(n)$$

In above equation d(n) is in linear relationship with the measurement and now we can use the kalman filter procedure to estimate frequency offset 'ε' and the filter is called as Extended kalman filter.

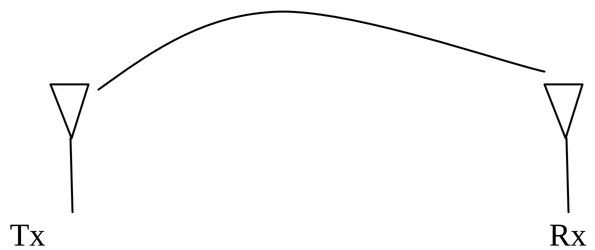
Now to estimate frequency offset 'ε' we have to make following assumptions.

Assume the channel is slowly time varying so that we can also assume that the impulse response of that slowly time varying channel is quasi static.

Quasi static means the channel response is constant for a block of transmission and this constant within the block vary independently. The constant for a block may be different from constant in other block.

Here the constant is frequency offset and it is considered to be constant during a block of transmission i.e., during a single frame. But the frequency offset differ from one frame to the other frame. Hence we insert preamble symbols at the starting of each frame to estimate frequency offset imposed on the symbols in a particular frame. These symbols are applied as a training sequence at the receiver. To generate training sequence s(n), we firstly modulate preamble symbols at the baseband using M-QAM modulation and then using IDFT, the frequency domain symbols are converted into time domain. There are two stages in the Extended Kalman Filter method to reduce ICI effect. They are **Offset Estimation** and **Offset Correction.**

Offset Estimation



preamble	Data symbols	preamble	Data symbols

(preamble, data symbols)

We are transmitting a series of frames which are distorted by frequency offset ε and noise w(n). The constant ε is distorted by non stationary process x(n), an observation of x(n) is preamble symbols preceeding the data symbols in each frame.

The observation equation is given by

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

where y(n) is received preamble distorted in channel,

w(n) is white gaussian noise,

x(n) is IFFT of preambles X(k) known at receiver,

σ^2 is variance of AWGN

Assume there are N_p preambles preceeding data symbols in each frame.

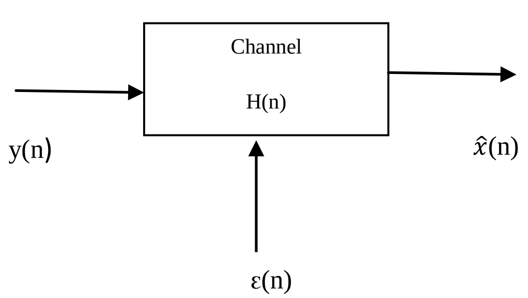
Algorithm:

1. Estimation and detection of error

ε(n) ⟶ ε(0) ⟶ p(0)

To estimate ε(n) it is initialized by equating to some previous estimated offset ε(0) with some corresponding state error p(0)

2. Compute channel sensitivity



y(n) is distorted with some frequency offset ε(n) in the channel, hence derivate y(n) with ε(n) at some previous initialized offset estimate ε̂(n-1).

3. Compute Kalman gain

At present state the offset is ε(n) but in the previous iteration it is ε(n-1) with some corresponding state error p(n-1). We can obtain some gain between the iterations which is computed by using H(n), p(n-1), variance σ^2.

4. Compute the estimate

The true value received is y(n) whose estimate is

calculated as $\hat{y}$(n) by estimating the offset at previous iteration ε̂(n-1).

5. Update offset estimate

Now ε̂(n-1) is updated by adding gain and error between computed estimate and true observation y(n).

6. Compute the state error

The state error p(n) at present state corresponding to frequency offset ε(n) is calculated using kalman gain k(n), channel sensitivity H(n) and previous state error p(n-1).

All the process from step 2 is repeated if $n<N_p$ by incrementing n by 1 ,otherwise stop.

Till now we estimated the frequency offset ε̂(n) in each iteration.

Offset Correction

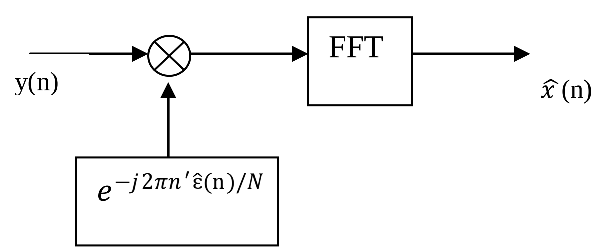


Figure 5: ICI correction

The ICI distortion in the data symbols x(n) that follow the training sequence can be corrected by multiplying with complex conjugate of estimated frequency offset and then applying FFT.

$$\hat{x}(n) = FFT\{\, y(n)\, e^{-j2\pi n'\hat{\varepsilon}(n)/N} \,\}$$

Where

$\hat{x}$(n) is the estimate of the transmitted data symbol,

y(n) is the received data symbol,

$\hat{\varepsilon}(n)$ is the estimated frequency offset.

V. SIMULATION RESULTS

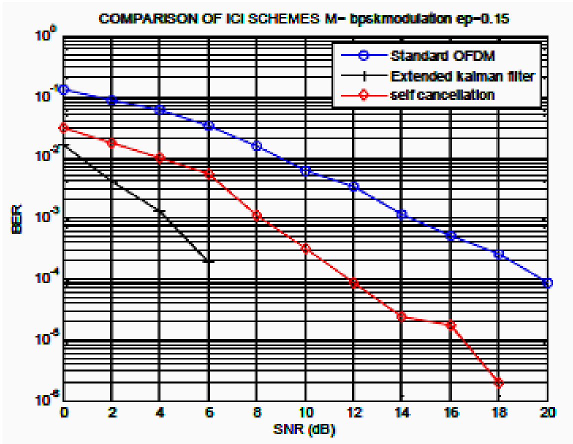


Figure6:BER comparison of standard OFDM, OFDM with ICI schemes for BPSK modulation, ε = 0.15

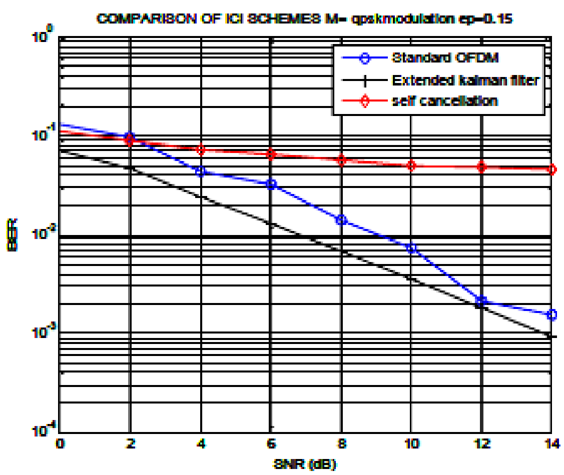


Figure 7: BER comparison of standard OFDM, OFDM with ICI schemes for QPSK modulation, ε = 0.15

VI. CONCLUSION

The major disadvantage in OFDM system is ICI. There are several methods to reduce ICI namely time domain windowing, frequency domain equalisation , Self Cancellation (SC) and Extended Kalman Filtering (EKF) etc. In this paper Bit Error Rates of standard OFDM, SC and EKF are simulated using matlab software. EKF produces an efficient result in mitigating ICI .It performs well even at higher frequency offsets.

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