ISSN No. 0976-5697
Volume 5, No. 1, Jan-Feb 2014
International Journal of Advanced Research in Computer Science
RESEARCH PAPER
Available Online at www.ijarcs.info

Mitigation of ICI in OFDM and Its Techniques

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Abstract: Multi-carrier modulation is an attractive technique for fourth generation wireless communication..Orthogonal Frequency Division Multiplexing (OFDM) is an efficient method of data receiving for high speed communication systems. However, the main drawback of OFDM system is that, it exhibits ICI inter carrier interference of the transmission and receiving signals. Many techniques have been proposed to mitigate the ICI problem. The redundancy based ICI reduction techniques include Frequency domain equalization, Time domain windowing, Pulse shaping, ICI self cancellation, Maximum likelihood Estimation, Extended Kalman Filtering, Optimized Sinc Power Pulse OSPP etc. That information the undesired effects occurring to the distortion techniques can be alleviated with the penalty of the reduced and transmission and receiving rates due to introduction of redundancy.

Keywords: Orthogonal Frequency Division Multiplexing OFDM, Inter carrier interference ICI, Frequency domain equalization, Time domain windowing FTDW, Pulse shaping PS, ICI self cancellation SC, Maximum likelihood Estimation MLE, Extended Kalman Filtering EKF, Optimized Sinc Power Pulse OSPP etc.

I. INTRODUCTION

In OFDM, a high-data rate channel is divided into *N* number of low data-rate sub channels and each sub channel is modulated in different sub-carrier. These low data rate sub channels have bandwidth less than the coherence bandwidth of the channel. By doing so each sub channel experience a flat-fading and equalization at the receiver is less complex. By selecting a special set of (orthogonal) carrier frequencies, high spectral efficiency is obtained because the spectra of the SCs overlap, while mutual influence among the SCs can be avoided.

In an OFDM system, the input bit is multiplexed into N symbol, each with symbol period of T, and each symbol stream is used to modulate the parallel sub carriers. The sub carriers are separated by $1/NTs$ in frequency domain, so they are orthogonal over $(0,Ts)$. A typical OFDM transceiver system is shown in fig.

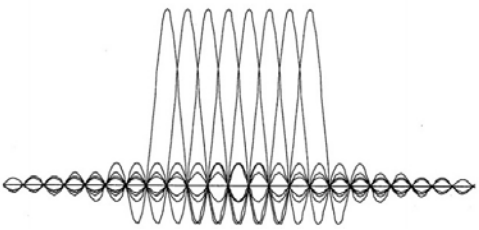


Figure: 1

First, serial to parallel converter converts the input bits stream into groups of $log2M$ bits, Where M is alphabet of size of digital modulation scheme used in different sub-carrier. A total of N such symbols $X(k)$ are created. Then, the N symbols are mapped to IFFT. These IFFT corresponds to the orthogonal sub-carriers in the OFDM symbol[1,2].

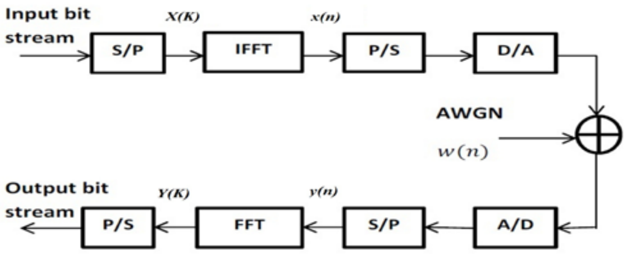


Figure 2: Block diagram of OFDM transceiver

Therefore, the OFDM symbol can be expressed as:

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

The digital-to-analog (D/A) converter produces an analog time domain signal which is transmitted through the channel. Before transmitting the OFDM symbol cyclic prefix must be append at the front end of symbol. At the receiving side, the cyclic prefix is removed then the signal is converted back to a discrete N point sequence $y(n)$, for 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:

$$Y(k) = \sum_{n=0}^{N-1} y(n)e^{-j\frac{2\pi nk}{N}} + W(k)$$

Where, $W(k)$ corresponds to the FFT of the sample of w(n), which is AWGN channel.

In OFDM system, there are mainly two principles as follows:

A. The IFFT and the FFT are used for, respectively, modulating and demodulating the data constellations on the orthogonal SCs [1,3]. These signal processing algorithms replace the banks of I/Q-modulators and demodulators that would otherwise be required.

Note that at the input of the IFFT, *N* data constellation points are present, where *N* is the number of FFT points. (*i* is an index on the SC; *k* is an index on the OFDM symbol).

These constellations can be taken according to any phase shift keying (PSK) or QAM signalling set (symbol mapping). The *N* output samples of the IFFT, being in TD, form the baseband signal carrying the data symbols on a set of *N* orthogonal SCs. In a real system, however, not all of these *N* possible SCs can be used for data.

B. The second key principle is the introduction of a cyclic prefix as a GI, whose length should exceed the maximum excess delay of the multipath propagation channel [1].

Due to the cyclic prefix, the transmitted signal becomes periodic, and the effect of the time-dispersive multipath channel becomes equivalent to a cyclic convolution, discarding the GI at the receiver. Due to the properties of the cyclic convolution, the effect of the multipath channel is limited to a point wise multiplication of the transmitted data constellations by the channel TF, or the FT of the channel IR; that is, the SCs remain orthogonal. The only drawback of this principle is a slight loss of effective transmit power, as the redundant GI must be transmitted. Usually, the GI is selected to have a length of one tenth to a quarter of the symbol period, leading to an SNR loss of 0.5 to 1 dB.[4,5,7] The equalization (symbol demapping) required for detecting the data constellations is an element wise multiplication of the FFT output by the inverse of the estimated channel TF (channel estimation). For phase modulation schemes, multiplication by the complex conjugate of the channel estimate can do the equalization. Differential detection can be applied as well, where the symbol constellations of adjacent SCs or subsequent OFDM symbols are compared to recover the data.

II. ICI PROBLEM IN OFDM SYSTEM

In an OFDM link, if transmitter and receiver frequency exactly matches then only the sub carriers are orthogonal. Any frequency offset results in ICI. A practical oscillator does not produce a carrier at exactly one frequency, but rather a carrier that is phase modulated by random phase jitter. As a result, the frequency, which is the time derivative of the phase, is never constant and hence causing ICI in OFDM system.[6,9]

Factor Causes ICI in OFDM system

A. Phase Noise:

Phase noise has two effects. First, it introduce a random phase variation that is common to all sub carriers. If the oscillator line width is much smaller than the OFDM symbol rate, then the common phase error is strongly correlated from symbol to symbol, so tracking technique is used to minimize the effect of this common phase noise error.

The second which is the most disturbing effect of phase noise is ICI, because the sub carrier are no longer orthogonal. In [5], the amount of ICI is calculated and translated into degradation in SNR that is expressed as:

$$D_{Phase} = \frac{11}{6ln10} 4\pi\beta T \frac{E_s}{N_o}$$

Where β is the -3db one sided bandwidth of the power density spectrum of the carrier.[2,3]

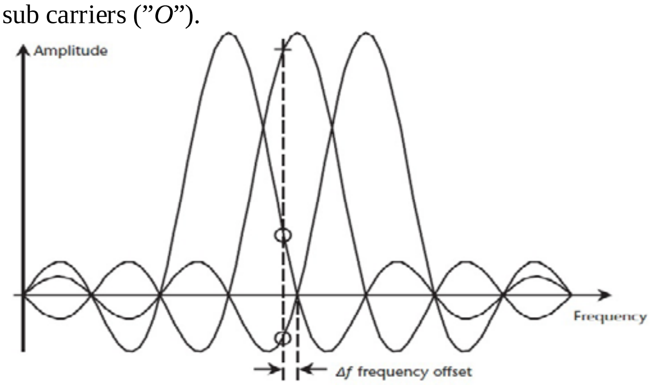
B. Frequency Offset:

OFDM sub carriers are orthogonal only when they all have different integer number of cycles within the FFT interval. if there is frequency offset, then the number of cycles in the FFT interval is not an integer any more and hence causes ICI after FFT.

The FFT output for each sub carrier will contain interfering terms from all other sub carriers. The amount of ICI in the middle sub carrier if OFDM spectrum is approximately double than the sub carriers at the band edges, because the sub carriers in the middle have interfering sub carriers on both sides. In [27], the degradation in SNR due to frequency offset is expressed as:

$$D_{Frequency} = \frac{10}{3ln10} (\pi\Delta f T)^2 \frac{E_s}{N_o}$$

Where Δf is the frequency offset. The impact of frequency offset can be seen as an error in the frequency instants, where the received signal is sampled during demodulation by the FFT. The amplitude of the desired sub carrier is reduced (" + "), and ICI increases from adjacent sub carriers ("*O*").



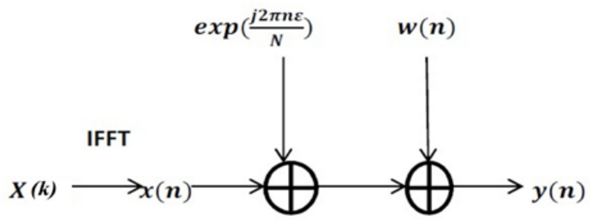


Figure: 3 ICI arises due to frequency offset

The main disadvantage of OFDM, is its susceptibility to small differences in frequency at the transmitter and receiver, 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 report, the frequency offset is modeled as a multiplicative factor introduced in the channel, as shown in Fig. 3.2. The received signal in time domain is given by:

$$y(n) = (x(n)e^{j(\frac{2\pi n\epsilon}{N}+\theta)}) \otimes h(n) + w(n)$$

Where $h(n)$ is the channel parameter, Θ is the convolution in time domain and _ is the unknown original carrier phase error, which is a constant distributed over $(-\pi, \pi)$.[7,8]

The effect of Doppler frequency shift on the received symbol stream can be understood by considering the received symbol $Y(k)$ on the *kth* sub carrier. Assuming the wireless fading channel is flat, the channel frequency response is known and equal to 1. The received signal at the *kth* sub carrier can be expressed as:

$$Y(k) = \sum_{l=0}^{N-1} y(n) e^{-j2\pi kn/N}$$

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

The desired carrier signal and ICI signal is given by first and second term of $W(k)$ is the FFT of $w(n)$. The ICI components are the interfering signals other than the *kth* sub carrier signal. $S(l-k)$ are complex coefficients for the ICI components in received signal and expressed as:

$$S(l-k) = \frac{sin(\pi(l+\epsilon-k))}{N sin(\pi(l+\epsilon-k)/N)} e^{j\pi(1-1/N)(l+\epsilon-k)}$$

III. METHODS OF ICI REDUCTION

A. Self-Cancellation:

ICI self-cancellation is a scheme that was introduced by Yuping Zhao and Sven-Gustav Haggman in 2001 in [6] to combat and suppress ICI in OFDM. In this scheme, at transmitter side one data symbol is mapped onto two sub carriers with predefined weighting coefficients. At receiver, the received signal is determined by the difference between the adjacent sub carriers.

a. ICI cancellation mapping:

In this method the data modulated within the $(k + 1)th$ sub carrier is phase rotated by $-\pi/2$, instead of $\pi/2$ as presented in WCT of the conjugate of the modulated data within *kth* sub carrier. So in proposed method, the data symbol is allocated by $X0(k) = X(k)$,$X0(k + 1)$= $e^{-j\pi/2} X^*(k) \;\; (k{=}0,2,4...,N{-}2)$.

The received signal within *kth* and $(k + 1)th$ sub carrier are given as:

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

$$= X(0)S(0-k) + e^{-j\pi/2} X^*(0)S(1-k) + ... + W(k)$$

$$= \sum_{l=0,even}^{N-2} X(l)S(l-k) + e^{-j\pi/2} X^*(l)S(l+1-k) + W(k)$$

and

$$Y'(k+1) =$$

$$\sum_{l-0,even}^{N-2} X(l)S(l-k-1) + e^{-j\pi/2} X^*(l)S(l-k) + W(k+1)$$

respectively and ICI coefficient $|S'(l-k)|$ is given by

$$S'(l-k) = S(l-k) + e^{-j\pi/2} S(l+1-k)$$

b. Ici Cancellation Demapping:

ICI modulation introduces redundancy in the received signal since each pair of sub carriers 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 $(k+1)th$ sub carrier, where k is even, is subtracted from the *kth* sub carrier. The desired signal is recovered as follows

$$Z(k) = \tfrac{1}{2}(Y'(k) - e^{j\pi/2} Y'^*(k+1))$$

$$= \tfrac{1}{2}\sum_{l=0,even}^{N-2} (X(l)[S(l-k) + S^*(l-k)]$$

$$+ X^*(l)[e^{-j\pi/2} S(l+1-k) - e^{j\pi/2} S^*(l-k-1)]) + W'(k)$$

$$= \tfrac{1}{2}(X(k)[S(0) + S^*(0)] + X^*(K)[e^{\frac{-j\pi}{2}} S(1) - e^{\frac{j\pi}{2}} S^*(-1)]$$

$$+ \sum_{l=0,l\neq k,even}^{N-2} (X(l)[S(l-k) + S^*(l-k)]$$

$$+ X^*(l)[e^{-j\pi/2} S(l+1-k) - e^{j\pi/2} S^*(l-k-1)])) + W'(k)$$

The ICI coefficients for this received signal is given by

$$S''(l-k) = S(l-k) + S^*(l-k) + e^{-j\pi/2} S(l+1-k) + e^{j\pi/2} S^*(l-k-1)$$

B. Pulse Shaping:

In OFDM spectrum the sub carriers consist of a main lobe followed by reducing amplitude side lobes. There is no interference among the sub carrier as long as orthogonality is maintained, because at the peak of every sub carrier there exists a spectral null. Frequency offset leads to loss of orthogonality because the spectral null does not coincide of the individual carriers peak. So some side lobes power exist at the centre of each sub carriers and it is called as ICI power. As frequency offset increases, ICI power increases. So the main purpose of pulse shaping is to reduce the amplitude of side lobes and hence reduce the ICI power[10,11]. The complex envelope of one radio frequency (RF) *N*-sub-carrier OFDM block with pulse shaping is expressed as:

$$x(t) = e^{j2\pi f_c t} \sum_{k=0}^{N-1} a_k p(t) e^{j2\pi f_k t}$$

Where *fc* is carrier frequency, *fk* is the sub carrier frequency of the *kth* sub carrier, $p(t)$ is the time-limited pulse shaping function and *ak* is the data symbol transmitted on the *kth* sub carrier has zero mean and normalized average symbol energy. We also assume that data symbols are uncorrelated as given by

$$E[a_k a_m^*] = \begin{cases} 1 & k = m \\ 0 & k \neq m \end{cases}$$

Where a^* is the conjugate of a.

The following condition must be satisfied to ensure the sub-carrier orthogonality.

$$f_k - f_m = \frac{k-m}{T_s}$$

$$\int_{-\infty}^{\infty} p(t)e^{j2\pi(f_k - f_m)t}dt = \begin{cases} 1 & k = m \\ 0 & k \neq m \end{cases}$$

Where $1/Ts$ is the minimum sub-carrier frequency spacing required.

During transmission; frequency offset, $\Delta f(\Delta f \geq 0)$ and phase error, θ, are introduced because of channel distortion or receiver crystal oscillator inaccuracy. The received signal is given by:

$$r(t) = e^{(j2\pi\Delta fT+\theta)} \sum_{k=0}^{N-1} a_k p(t) e^{j2\pi f_k t}$$

The decision variable for transmitted symbol *am* is given by:

$$\hat{a}_m = \int_{-\infty}^{\infty} r(t)e^{-j2\pi f_m t}dt$$

$$= a_m e^{j\theta} \int_{-\infty}^{\infty} p(t)e^{j2\pi\Delta f t}dt$$

$$+e^{j\theta} \sum_{k\neq m, k=0}^{N-1} a_k \int_{-\infty}^{\infty} p(t)e^{j2\pi(f_k - f_m + \Delta f)t}dt$$

The first term of represent desired signal power and the second term represent
ICI power, so it gives

$$\hat{a}_m = a_m e^{j\theta} P(-\Delta f) + e^{j\theta} \sum_{k\neq m, k=0}^{N-1} a_k P(\frac{m-k}{T_s} + \Delta f)$$

Where $P(f)$ is the Fourier transform of $p(t)$. Hence, the desired signal power is given by:

$$P_m = |a_m|^2 |P(\Delta f)|^2$$

and the ICI power is given by

$$PmICI = \sum_{k\neq m, k=0}^{N-1} \sum_{n\neq m, n=0}^{N-1} a_k a_n^* P(\frac{k-m}{T_s} + \Delta f) P(\frac{n-m}{T_s} + \Delta f)$$

and hence, the average ICI power is expressed as

$$\overline{P_{ICI}^{m}} = \sum_{k\neq m, k=0}^{N-1} |P(\frac{k-m}{T_s} + \Delta f)|^2$$

C. Optimized Sinc Power Pulse:

There have been many pulse shaping technique proposed in literature. In [19], SPP was proposed and given as

$P_{SPP}(f) = sinc^n(fT)$

Where n is the degree of sinc function. In this report, a new method of ICI mitigation known as optimized sinc power pulse (OSPP) is proposed. In this method , optimized parameter *aopt* is define which is the design parameter to adjust the amplitude. The OSPP is given by

$P_{OSPP}(f) = sinc^n(\, aoptf\, T)$.[12,15]

D. Maximum Likelihood Estimation:

The second method for frequency offset correction in OFDM systems was suggested by Moose in [3]. In this approach, the frequency offset is first statistically estimated using a maximum likelihood algorithm and then cancelled at the receiver[13]. 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

$$r(n) = \frac{1}{N} [\sum_{k=-K}^{K} X(k)H(k)e^{\frac{j2m(k+z)}{N}}]$$

$$k=0,1,\ldots.N-1, N \geq 2K+1$$

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 kth 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 sequenceR1(K), and the second set is demodulated using another N-point FFT to yield the sequenceR2(K). The frequency offset is the phase difference between

R1(k) and R2(k), that is R2(k)= R1(k)ej2πz

Adding the AWGN yields

Y1(k)=R1(k)+W1(k)

Y2(k)=R1(k)ej2πz+W2(k)   k=0,1,….N-1

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

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

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

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

E. 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.

a. Offset Estimation Scheme:

To estimate the quantity (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 Np 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.

a) Initialize ε 0 the estimate and corresponding state error P(0).
b) Compute the H(n), the derivative of y(n) with respect to ε n at ε(n-1), the estimate obtained in the previous iteration.
c) Compute the time-varying Kalman gain K(n) using the error variance P(n-1), H(n), and , σ2
d) Compute the estimate y (n) using x(n) and ε(n-1) , i.e. based on the observations up to time n-1, compute the error between the true observation y(n) and y (n) .
e) Update the estimate by adding the K(n)-weighted error between the observation y(n) and y (n) to the previous estimation ε(n-1).
f) Compute the state error P(n) with the Kalman gain K(n), H(n), and the previous error P(n-1).
g) If n is less than Np, increment n by 1 and go to step 2; otherwise stop.

It is observed that the actual errors of the estimation ε(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 $\hat{\varepsilon}$ can be obtained. It is observed that the EKF technique offers fast convergence.

b. 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.[5,7,8]

F. Frequency Domain Equalization, Time Domain Windowing Ftdw:

a. Frequency Domain Equalization:

The fading distortion in the channel causes ICI in the OFDM demodulator. Compensation for fading distortion in the time domain introduces the problem of noise enhancement[14]. So frequency domain equalization process is used for reduction of ICI by using suitable equalization techniques. We can estimate the ICI for each frame by inserting frequency domain pilot symbols in each frame as shown.

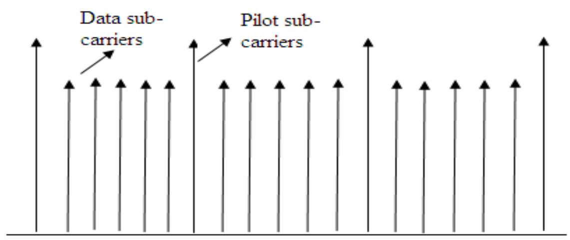


Figure: 4

The equalizer co-efficient for eliminating ICI in the frequency domain can be derived from the pattern of the pilot symbol & hence a suitable equalizer can be constructed. It can only reduce the ICI caused by fading distortion but it does not deal the problems of frequency mismatch between transmitter and receiver and doppler shift which is the main source of ICI. Again it is only suitable for flat fading channels, but in mobile communication the channels are frequency selective fading in nature because of multipath components. Here also the channel needs to be estimated for every frame. Estimation of channel is complex, expensive & time consuming. Hence this method is not effective one.

b. Time Domain Windowing:

We know that OFDM signal has widely spread power spectrum. So if this kind of signal is transmitted in a band limited channel, certain portion of the signal spectrum will be cut off, which will lead to inter carrier interference (ICI). To reduce the interference, the spectrum of the signal wave form need to be more concentrated. This is achieved by windowing the signal. Basically windowing is the process of multiplying the transmitted signal wave form with a suitable function (i.e. with window function). The same window is used in the receiver side to get back the original signal. It can only reduce the ICI caused by band limited channel and it also does not deal with the frequency mismatch between the transmitter and receiver, and the Doppler shift. Windowing is done frame by frame & hence it reduces the spectral efficiency to a large extent. Hence this method is also not an effective one[15,16].

Time domain windowing is used to reduce the sensitivity to linear distortions and frequency errors (ICI). Window may be realized with a raised cosine or other kind of function that fulfills the Nyquist criterion. Raised cosine window is used in order to reduce the ICI effects. However, this intuitive window is shown to be sub-optimum and a closed solution for optimum window coefficients. A condition for orthogonality of windowing schemes in terms of the FFT of the windowing function is derived. The FFT can be considered as a filter bank with N filters where N is the FFT size.[11,17]

The frequency response of the nth filter Hn(F) is

$$|H_n(F)| = \left|\frac{\sin[\pi(F-n)]}{\sin[\pi(F-n)/N]}\right|$$

Where F = N. f/fs and fs is the sampling rate at the receiver.

IV. CONCLUSION

From the study of all EKF will prove to be the best method because EKF is suitable for both multipath fading & flat fading channels where as frequency domain equalization is only suitable for flat fading. Frequency domain equalization needs channel estimation for every frame and the estimation of channel is complex, expensive & time consuming but whereas EKF does not require channel estimation and equalization. Frequency domain equalization reduces the ICI caused by fading distortion and time domain windowing reduces the ICI caused by band limited channel but they do not deal with the major cause for ICI i.e. ICI caused by the frequency mismatch between transmitter and receiver and due to doppler shift which is dealt by ICI self cancellation. Simple in implementation i.e. less complexity and effective when compared to frequency domain equalization, time domain windowing and pulse shaping and self cancellation.

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