

# Study and Analysis of ICI for OFDM System in the Doubly Selective Fading Channel

*A Dissertation Submitted in Partial Fulfillment of the Requirement for the Award of the  
Degree of*

MASTER OF ENGINEERING

in

Electronics and Communication

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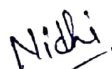
THAPAR UNIVERSITY, PATIALA, PUNJAB

JUNE, 2017

## DECLARATION


I, Nidhi Raheja hereby declare that the work presented in this thesis entitled “Study and Analysis of ICI for OFDM system in doubly selective fading channel” is a record of my own work carried out by me towards the partial fulfillment for the award of degree of Master of Engineering in Electronics and Communication Engineering at Thapar University, Patiala under the supervision of Dr. Hem Dutt Joshi (Assistant Professor), Electronics and Communication Engineering Department, Thapar University from January 2017 to July 2017. The matter presented in this has not been submitted either in part or full to any other university or institute for the award of any other degree.

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It is certified that the above statement made by the candidate is correct to the best of my knowledge and belief.

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## **ABSTRACT**

In recent time, the demand for multimedia data services has grown up rapidly. One of the most promising multi-carrier system, Orthogonal Frequency Division Multiplexing (OFDM) forms basis for all 4G wireless communication systems due to its large capacity to allow the number of subcarriers, high data rate and ubiquitous coverage with high mobility. The propagation of radio waves for communication purpose through the wireless medium is affected by lot of impairments on their way like carrier frequency offset, phase noise. Due to such impairments, signal experience fading which has been an area of significant interest among the research fraternity in order to evaluate the performance of a digital communication system amplitude and phase distortions, which cause loss of orthogonality among the subcarriers, and hence, inter-carrier interference (ICI) is introduced in the transmitted signal. There are various methods to overcome from such impairments like frequency domain equalization, windowing, maximum likelihood estimation and ICI self cancellation scheme.

This thesis mainly emphasis on ICI reduction using windowing technique which is a leading technique to deal with the severity of induced fading in signal transmitted over channel. Various window functions are applied like raised cosine window, better than raised cosine window, sinc pulse, improved sinc pulse. Adopting this windowing technique at transmitter side is effective and has improved performance of OFDM system. Goal of system designer is to reach at a unified set of mathematical models characterized by window functions. As a result there is much interest shown by the research fraternity in using this technique to improve SIR which also proving to be a very powerful tool for minimization of ICI and SIR improvement in communication networks.

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## LIST OF ABBREVIATIONS

ADSL	Assymmetric Digital Subscriber Line
POTS	Plain old telephone services
MOLA	Multimedia over Loan service
DAB	Digital Audio Broadcast
3GPP	3 <sup>rd</sup> Generation Partnership Project
LTE	Longterm Evaluation
DVB	Digital Video Broadcasting
OFDM	Orthogonal frequency division multiplexing
IMT	International mobile telecommunication
PHY	physical layer
MAC	media access control
ARQ	automatic repeat request
ICI	inter carrier interference
CFO	carrier frequency offset
PHN	phase noise
BTRC	better than raised cosine
SOCW	second order
MMSE	minimum mean square error
ISI	inter symbol interference
BER	bit error rate
RC	raised cosine

SLM	selected mapping schemes
PTS	partial transmit sequence
PICR	peak interference to carrier ratio
TWTA	travelling wave tube amplifier
PTS	partial transmit sequence
DSR	distortion to signal power ratio
MBH	modified bartlett hanning
AWGN	additive white Gaussian noise
SP	sinc pulse
ISP	improved sinc pulse
PMSP	phase modulated sinc pulse
HDSL	high bit rate digital subscriber line
ADSL	asymmetric digital subscriber line
VDSL	very high speed digital subscriber line
DAB	digital audio broadcasting
HDTV	high definition television
STO	symbol timing offset

# CHAPTER 1

## INTRODUCTION

### 1.1 Overview

Nowadays there is development in wireless communication market significantly, clients are estimated to achieve 4.77 billion in number. Wireless technology utilize radio waves in which multiple transmission happen at same time therefore receiver should have multipath gathering capacity [1]. Reflected waves from trees, buildings, vehicles and so forth meddle with direct received wave bringing up ISI which affect the entire system antagonistically. Therefore, ISI should be expelled while designing wireless network. High data rate transmission is necessary to meet expanded demand of market which can be accomplished at cost of bandwidth and symbol interval. As higher modulation technique is used which constrict symbol interval and enlarge channel bandwidth, this fast symbol transmission enhance delay time [2]. Ultimately data get corrupted and inadmissible for communication and further leads to fading. To overcome problem of ISI basically OFDM technology is utilized which is more efficient and less complex [3]. This is latest wireless technology which forms basis of 4g communication and has its applications in LTE, wi-max, wifi (802.11a, 802.11ac) [4]. In OFDM system, signal is partitioned into multiple carriers which are orthogonal to each other and this orthogonality annihilate cross talk and no need of guard bands after that even design of transmitter and receiver get streamlined [2]. In this various symbols loaded to corresponding subcarriers using various types of modulation techniques such as PSK, QPSK etc and total bandwidth also get divided acc to number of subcarriers. Then on these symbols, N-point inverse Fourier transform is performed. Then on the resultant samples cyclic prefix is applied and the block is ready for transmission [5]. These symbols are then transmitted downlinks over ISI channel then receiver receive these N compositely transmitted symbols. Received signal is basically obtained with the circular shifting property of channel filter over the samples that is transmitted, signal get circularly convolved with the channel filter to give output. Basically cyclic prefix has converted linear convolution to circular convolution. Ultimately at the receiver N-point Fourier transform is taken to attain output signal and signal is coherently demodulated [1].

## **1.2 History and development of OFDM**

Firstly in 1950's military framework began using the idea of multi-carrier transmission in which multiple data streams are transmitted over non overlapping channels. Such frameworks need analog oscillator and wideband filter with sharp cut-off. Hence in January 1958 a term generated named OFDM which mainly came into practice in 1960s. Due to complexity of large array of sine generators, transmitters and receivers, cost and coherence demodulators, it did not able to accomplish fame around that time and major turn in the use of OFDM appeared when Weinstein and Ebert applied DFT to perform baseband modulation and demodulation and its use totally annihilate oscillators present at the transmitter/receiver side [6]. Accessibility of algorithm (i.e., FFT algorithm) altogether chopped down the execution complexity of OFDM modems. IEEE 802.11a is considered as physical standard for OFDM and now likewise called 4G mobile communication system [7]. Various reviews in regards with the usage of OFDM were made after 1990s HDSL; 1.6 Mbps, ADSL; 6 Mbps, VDSL; 100 Mbps, DAB and HDTV terrestrial broadcasting [8]. Different authors dissect performance of OFDM framework in various channel conditions like flat fading channel, frequency selective fading channel etc. and these channels are impaired with CFO, PHN [9].

## **1.3 Principle of OFDM**

OFDM follows the principle of rupturing high information stream rate into various lower rate data streams and then these numerous information streams are parallely transmitted utilizing diverse orthogonal sub-carriers. Parallel transmission widen symbol duration thus depleting time dispersion due to multipath delay spread in OFDM framework which can act as either multiplexing or modulation technique [10]. OFDM (orthogonal frequency division multiplexing) and FDM (frequency division multiplexing) both have many similarities. OFDM utilizes the standard of FDM to enable transfer of numerous messages over radio channel which provide upgraded spectral proficiency and considerably proves as more controlled route [11].

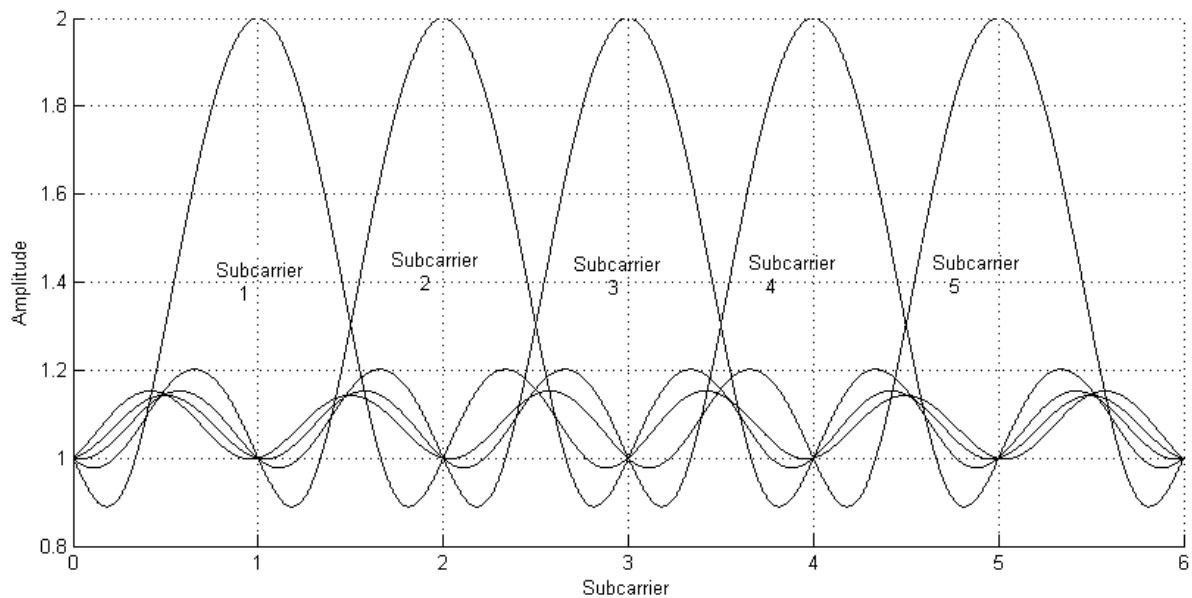


Fig. 1.1 Frequency response of 5 subcarriers of OFDM signal [12]

#### 1.4 Advantages of OFDM system

OFDM system has been utilized by numerous present wireless technologies and further more anticipated for future wireless communication systems because of its numerous advantageous. Various advantages of OFDM framework are:

- Improving bandwidth efficiency-**  
 OFDM framework utilizes bandwidth efficiently in contrast with Frequency Division Multiplexing (FDM). Fig. 1.2(a) depicts comparison of bandwidth utilization in FDM and OFDM technique. All different carriers are dispersed separated to each other i.e. no overlapping in FDM framework whereas in OFDM framework sub-carrier utilizes orthogonality feature to save bandwidth.
- Reducing implementation Complexity:** For a particular defer multipath fading channel spread, the complexity is fundamentally lesser as compared to single tap equalizer in an OFDM framework with an equalizer [1]. The testing issue in an MCM framework is to actualize series of modulators and demodulators at the transmitter and receiver side respectively. The concept of “Information transmission” can be productively actualized utilizing IFFT and FFT rather than bank of modulators and demodulators.

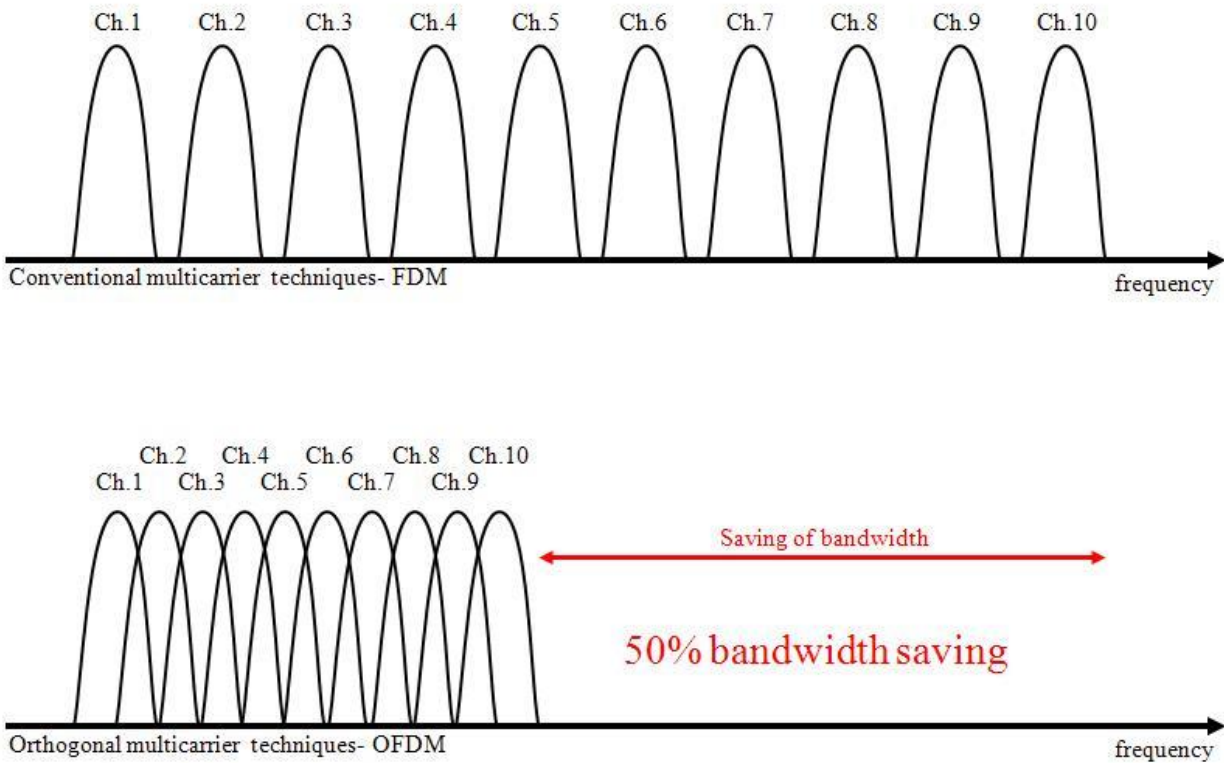


Fig. 1.2 Efficient use of bandwidth [12]

- **Narrowband Interference** – In single carrier system, a single distortion between transmitter and receiver make the whole connection come up short as it generate errors at receiver but in a multicarrier system, small no. of subcarriers will be influenced like OFDM. Therefore OFDM is powerful against narrowband interference [1].
- **Immune to fading** - OFDM is very invulnerable to frequency selective fading on account of transmitting signal parallely (sub-carriers has narrow bandwidth in contrast with overall signal bandwidth).
- **Spectral Efficiency** - Sub-carriers maintain the orthogonal property therefore substantial number of subcarriers can be accommodated in a small spectral region hence improving the spectral efficiency [13].
- **Easy Equalization-** In a single carrier system, equalization convert frequency selective fading channel into flat fading along with noise amplification significantly there is poor reaction in frequency domain. Subsequently, single carrier performance is influenced because of high attenuation in some bands as all used frequencies have equivalent significance. In OFDM framework wideband channel are partitioned into

numerous flat fading sub-channels, which lessen receiver equalization complexity. In this way, it is conceivable to utilize maximum likelihood decoding.

### 1.5 Limitations of OFDM:

- **Symbol Timing Offset (STO):-** In multi carrier system, there are hundreds or thousands of samples tests for every OFDM symbol. The fundamental point of symbol timing estimator is to discover the start of OFDM symbol. Thus begin of frame is computed by evaluating symbol timing offset which present a phase rotation at the yield. This phase rotation can be repaid by channel equalizer. If STO ( $\delta$ ) lies in a range outside the predetermined range it brings about ICI and ISI at the yield.
- **Carrier Frequency Offset (CFO):-** The divergence between transmitted carrier frequency and received carrier frequency is called CFO (carrier frequency offset). CFO is brought about misalignment in the carrier frequencies because of Doppler shift emerges due to multipath fading channel. CFO causes various debilitations. Hence exact frequency estimation method is necessary to perform at the receiver to lessen ICI and enhance BER execution [14]. In DA technique, frequency offset is assessed in two stages, the FFO estimation and IFO estimation.
- **High PAPR:-** The OFDM signal transmission displays high PAPR. This high PAPR decrease the effectiveness of high power amplifier and debases the execution of the framework. PAPR is corresponding to the quantity of sub-carriers utilized for OFDM systems. An OFDM system with tremendous number of sub-carriers will therefore have substantial PAPR when the sub-carriers include logically. Substantial PAPR of any framework makes the execution of DAC and ADC colossal hard [15]. The devise of RF amplifier likewise turns out to be progressively troublesome as the PAPR increases.
- **Inter-Carrier Interference (ICI):-** All above mentioned problems yield ICI at the receiver and ICI lessen SNR and debases BER execution of OFDM framework.
- **Synchronization (timing and frequency) at the receiver:** STO and CFO influences on the execution of OFDM framework. At the receiver side amendment in timing among FFT and IFFT is necessary. OFDM framework is highly susceptible to doppler shifts which influence the CFO and generate ICI.

## 1.6 Applications

Utilization of Fourier transform makes usage of OFDM simple. The uses of OFDM are partitioned into two classifications-wire-line and remote application.

- i. The wire-line application such as-
  - a. ADSL broadband access through POTS copper wiring
  - b. MOCA home system administration
- ii. The wireless application such as-
  - a. Wireless LAN
  - b. IEEE 802.16.
  - c. IEEE 802.20.
  - d. DAB systems.
  - e. HDTV
  - f. LTE and LTE advanced

OFDM is connected to 3GPP UMTS and 3GPP@LTE and furthermore in 4th Generation (4G). Additionally utilized for the improvement in DVB which was generally utilized as a part of Australia and Europe. Currently, number of individuals are still working to adjust the IEEE 802.16 i.e. Wi Max ("Worldwide Interoperability for Microwave Access") standard which might bring out high information transfer speed up to 100 Mbps. Also OFDM has been considered and affirmed by numerous IEEE standard operating in gatherings like IEEE 802.11g/a/n, IEEE 802.15.3a, and IEEE 802.16d/e. These days, OFDM is being explored as standout amongst the most encouraging radio transmission methods for LTE of 3GPP, IMT.

<p><b>1. ADSL</b></p>	<ul style="list-style-type: none"> <li>• Data communication innovation that empower speedier transfer of information over copper cables.</li> <li>• Bandwidth and bit rate are asymmetric i.e. more prominent towards downstream (138KHz-1104KHz) than upstream (26.075KHz-137.825KHz).</li> <li>• Full duplex either by FDD or TDD</li> <li>• At first existed in two versions <ul style="list-style-type: none"> <li>a. CAP- defacto std until 1996</li> <li>b. DMT-first ITU-T ADSL std. and all present day installations are based on DMT modulation scheme.</li> </ul> </li> </ul>
<p><b>2. Multimedia over coax alliance(MOCA)</b></p>	<ul style="list-style-type: none"> <li>• MOCA is a worldwide standard consortium distributing particulars for networking over coaxial cable.</li> <li>• Three renditions of specifications accessible MoCA1.1, MoCA2.0, MoCA2.5</li> <li>• MoCA1.1 – works in the 500 to 1500 MHz frequency range gives 175 Mbit/s net throughput.</li> <li>• MoCA2.0 - Operating frequency range is 500 to 1650 MHz throughputs up to 1 Gbps</li> <li>• MOCA2.5 – offers real information rates up to 2.5 Gbps MoCA Access is proposed for multiple staying units (MDUs) for example lodgings, resorts, hospitals, or educational facilities.</li> </ul>
<p><b>3. HDTV</b></p>	<ul style="list-style-type: none"> <li>• Most broadcasts use standard video format: streaming video, terrestrial broadcasts television DVDs cable television, satellite television.</li> <li>• HDTV may be transmitted in different formats: <ul style="list-style-type: none"> <li>a)1080p:1920X1080p: 2.07MP per frame, full HD</li> <li>b)1080i: 1920X1080i: 1.04MP per field 2.07MP per frame</li> <li>c)720p: 1280X720p: 0.92 MP per frame</li> </ul> </li> </ul> <p>here I refers to interlaced scan and p refers to progressive scan</p>

<p>4. Wireless LAN</p>	<ul style="list-style-type: none"> <li>• Links at least two gadgets utilizing wireless distribution technique and all parts that are associated in a system are called stations and remote stations fall into two classifications: <ul style="list-style-type: none"> <li>a) wireless access points</li> <li>b) clients</li> </ul> </li> <li>• It has two essential modes: <ul style="list-style-type: none"> <li>a) infrastructure- mobile unit communicate through access points that act as bridge for other networks</li> <li>b) adhoc- versatile units transmit straightforwardly shared. Here is no base and nobody permits to talk. This is proficient utilizing IBSS(independent basic service set)</li> </ul> </li> </ul>
<p>5. IEEE 802.16</p>	<ul style="list-style-type: none"> <li>• Family of std. called wireless MAN and popularized under the name “Wi-MAX”</li> <li>• Standardizes two parts of air interface- <ul style="list-style-type: none"> <li>a) PHY <ul style="list-style-type: none"> <li>I. PHY <ul style="list-style-type: none"> <li>• Channel bandwidth between 1.25MHz to 20MHz with upto 2048 subcarriers.</li> <li>• PHY features incorporate support for MIMO antennas to give better non line of sight. Hybrid ARQ and propagation characteristics to correct errors perfectly for better performance.</li> </ul> </li> <li>II. MAC <ul style="list-style-type: none"> <li>• It portrays how technologies for example Ethernet, ATM, IP are typified on air interface and how information is characterized.</li> <li>• Secure communication by utilizing secure key exchange during authentication and encryption utilizing AES or DES.</li> </ul> </li> </ul> </li> <li>b) MAC</li> </ul> </li> </ul>

<p>6. IEEE 802.20</p>	<ul style="list-style-type: none"> <li>• This technology is promoted as burst or HC-SDMA developed by array com and bandwidth is optimized by smart antennas.</li> <li>• Bandwidth of 5,10 and 20MHz</li> <li>• Peak data rate of 80Mbps</li> <li>• Supports low bit rate, can carry upto 100 phone calls per MHz</li> <li>• Interleaving and hybrid ARQ choices with upto 6 transmissions</li> <li>• Slot period of 913 microseconds carrying 8 OFDM symbols.</li> </ul>
<p>7. DAB</p>	<ul style="list-style-type: none"> <li>• Digital radio standard for broadcasting digital audio radio services</li> <li>• DAB has no of specific modes(I,II,III,IV) <ul style="list-style-type: none"> <li>a) mode I-&gt; band III(174-240MHz)</li> <li>b) mode II-&gt; band L-band (1452-1492MHz)</li> <li>c)mode III -&gt; frequencies less than 3GHz</li> <li>d)mode IV -&gt; L-band</li> </ul> </li> <li>• Various services are embedded into one and these services include: <ul style="list-style-type: none"> <li>a) primary services- man radio stations</li> <li>b) secondary services- additional sports commentaries</li> <li>c) data services- IP tunneling, electronic programme guide</li> </ul> </li> <li>• Benefits of DAB <ul style="list-style-type: none"> <li>a) enhanced features for users</li> <li>b) more stations</li> <li>c) reception quality</li> <li>d) variable bandwidth</li> <li>e) transmission cost</li> </ul> </li> <li>• Disadvantages of DAB <ul style="list-style-type: none"> <li>a) audio quality</li> <li>b) signal delay</li> <li>c) power requirements</li> </ul> </li> </ul>

## 1.7 Organization of Thesis

Thesis is well organized in form of chapters. Various chapters include introduction of topic, survey regarding to that topic that developments already have done and what new improvements are to be done, detailed version of the work which has done during my research and then on basis of this results obtained.

Chapter-1 introduces generation of OFDM technique its advantages, disadvantages and its application in different fields.

Chapter-2 provides an overview on OFDM and its significant issues. From that overview, it is discovered that apart of having a large number of benefits of OFDM framework, some real issues are yet present which must be resolved properly to prove advantageous. Loads of work has been accounted for in the writing to tackle these issues. This thesis presents improving SIR of OFDM framework over doubly selective channel when CFO and PHN both are available in the channel.

Chapter-3 begins with basic system model of baseband OFDM containing transmitter, channel and receiver model with the mathematical expression of transmitted and received OFDM signal. The impulse response of multipath fading channel has also been given. ICI and SIR expressions in the presence of CFO and the same expressions are calculated over doubly selective channel in presence of carrier frequency offset and phase noise too. Then improvement in the ICI and SIR values using windowing function is described and their mathematical expressions are also calculated.

Chapter-4 provides the result on basis of calculated expressions.

## CHAPTER 2

### LITERATURE SURVEY

The literature survey of any research field or subject is must required, before contributing in the research of that field. The literature review gives a detailed study of exiting published material for clear understanding of that research area. Therefore, this chapter presents a detail literature survey of the research area taken (i.e., OFDM). The study in this chapter highlights different problems of OFDM framework like PAPR, SIR improvement, ICI reduction and Synchronization. This survey likewise abridges the solutions of the problems appearing in literature.

- **Peng Tan *et al.*** (2004) [16] In this performance of OFDM is affected due to presence of CFO which generate ICI. To combat the effect of inter carrier interference rectangular pulse and raised cosine pulses are applied:

$$p_r(t) = \begin{cases} \frac{1}{T}, & -T/2 \leq |t| \leq T/2 \\ 0, & \textit{otherwise} \end{cases} \quad (2.1)$$

$$p_{rc}(t) = \begin{cases} \frac{1}{T}, & 0 \leq |t| \leq \frac{T(1-\alpha)}{2} \\ \frac{1}{2T} \left\{ 1 + \text{Cos} \left[ \frac{\pi}{\alpha T} \left( |t| - \frac{T(1-\alpha)}{2} \right) \right] \right\}, & \frac{T(1-\alpha)}{2} \leq |t| \leq \frac{T(1+\alpha)}{2} \\ 0, & \textit{otherwise} \end{cases} \quad (2.2)$$

$$p_{btrc}(t) = \begin{cases} \frac{1}{T}, & 0 \leq |t| \leq \frac{T(1-\alpha)}{2} \\ \frac{1}{T} e^{(-2\log 2/\alpha T) \left[ |t| - \frac{T(1-\alpha)}{2} \right]}, & \frac{T(1-\alpha)}{2} \leq |t| \leq \frac{T}{2} \\ \frac{1}{T} \left\{ 1 - e^{(-2\log 2/\alpha T) \left[ \frac{T(1+\alpha)}{2} - |t| \right]} \right\}, & \frac{T}{2} \leq |t| \leq \frac{T(1+\alpha)}{2} \\ 0, & \textit{otherwise} \end{cases} \quad (2.3)$$

In “better than” raised-cosine pulse is employed which gives better results as compared to raised cosine and rectangular pulse. ICI is plotted against normalized frequency offset at different roll off factor. Best performance of OFDM framework is when roll off factor is one.

- **N.C. Beaulieu *et al.*** (2005) [17] The impact of various Nyquist pulse-shaping, including BTRC, Franks pulse, the polynomial pulse SOCW on reducing ICI in OFDM systems with CFO is contemplated which have been presented in the literature. These Nyquist pulse-shapes are created utilizing criteria commonly known as MMSE in an ISI channel. It was demonstrated that Franks pulse creates negligible obstruction in the existence of small carrier phase error and small sampling time and BTRC, which gives improve BER performance than both RC pulse in both co channel interference environment and ISI environment. Then a SOCW shape is proposed and applied on receiver side in an OFDM framework receiver windowing to lessen ICI. ISI-free polynomial pulses are proposed which can be utilized in the OFDM transmitter shaping to lessen ICI. These two pulses can provide better output than RC pulse in the aspect of reduction of ICI in OFDM framework with CFO, by considering a set of properly chosen parameters. In an N-subcarrier OFDM framework, suppose CFO appears between transmitter and receiver oscillator with  $1/T$  as subcarrier frequency spacing. The effects of utilizing various pulses such as RC pulse, BTRC pulse, the Franks pulse, the polynomial pulse and the SOCW pulse on reducing ICI power and improving SIR.
- **HEBAT-ALLAH M. MOURAD** (2006) [18] A novel pulse shape is utilized to minimize the ICI in an OFDM framework in which CFO is considered. For the same purpose furthermore various Nyquist-I pulses are also utilized. For the considered or particular pulse average ICI and SIR are calculated then these are compared with the simulated results. Sensitivity of the ICI to the proposed pulse shape and the effectiveness of pulse under consideration are reported. To lessen ICI in OFDM framework various pulse shapes like four just constructed Nyquist-I pulse shapes are proposed and utilized to diminish the average ICI in OFDM framework. Superiority of the pulse shapes are verified and the proposed one proves itself as the most superior one as compare to all other considered pulse shapes. A tradeoff between gain achieving in minimizing the average ICI and the simplicity of realization of these

pulse shapes must be considered by the system designer. Future work depends on finding various solutions to attain simple realization of all proposed pulses.

- **Norman C. Beaulieu *et al.*** (2007) [19] The impacts of different Nyquist windows, like RC window, BTRC window, the double jump window, the Franks window, and SOCW on the execution of the framework are analyzed in light of measurement of both BER measure and SIR. After applying BTRC window for various values of roll off factor and calculating BER for each one them then BTRC proves to achieve the minimum BER among the five window functions But when the roll-off factor approaches one then the SOCW window or Franks window provides better BER performance

Numerically ICI can be calculated as:

$$\sum_{m_1=0}^{N_u-1} \sum_{m_2=0}^{N_u-1} P_{m_1} P_{m_2} e^{\frac{j2\pi(m_1-m_2)\epsilon}{N}} / \sum_{d=0}^{N-1} \sum_{m_1=0}^{N_u-1} \sum_{m_2=0}^{N_u-1} P_{m_1} P_{m_2} e^{\frac{j2\pi(m_1-m_2)(d-q+\epsilon)}{N}} \quad (2.4)$$

- **Volkan Kumbasar *et al.*** (2007) [20] In this new pulse shape is proposed for average ICI power reduction in OFDM framework. Results reveal the superiority of the proposed pulse over conventional pulse shapes in aspect of ICI power reduction, improved SIR and BER performance. The new pulse is modification of sinc pulse known by the name improved sinc pulse (ISP). So this paper defines each window function in the form of sinc pulse. Performance of each pulse is compared with the other one and improved sinc pulse provide improved result.

$$P_{RT}(f) = Sinc(fT) \quad (2.5)$$

$$P_{RC}(f) = Sinc(fT) * \frac{\cos(\pi\alpha fT)}{1 - (2\alpha fT)^2} \quad (2.6)$$

$$P_{BTRC}(f) = sinc(fT) * \frac{[2\beta fT \sin(\pi\alpha fT) + 2\cos(\pi\alpha fT) - 1]}{1 - (2\beta fT)^2} \quad (2.7)$$

$$\text{where, } \beta = \frac{\pi\alpha}{\ln 2}$$

$$P_{SP}(f) = \text{sinc}^n(fT) \quad (2.8)$$

$$P_{ISP}(f) = \exp(-a(fT)^2) \text{sinc}^n(fT) \quad (2.9)$$

$$P_{PMSP}(f) = \exp(-a(fT)^2) \text{sinc}^n((\pi f - b\sin(c\pi f))T) \quad (2.10)$$

Here  $a$  is design parameter for amplitude adjustment  $b$  and  $c$  to control the phase of sinc function and  $n$  is degree of sinc function.

- **Jing Di *et al.*** (2012) [21] Polynomial class of second order window functions is adopted and according to the frequency offset its window parameter can be calculated adaptively. To optimize average SINR, window suboptimum parameter estimation is to be developed. It is observed that such sub-optimum window parameter yields a better performance close to the optimum one. The average BER and SINR values of different fading Rayleigh channels after applying different Nyquist windows are compared. Numerical and analytical results both give a confirmation that the optimum SOCW outperforms RC and “better than” nyquist window.
- **Jian Zhang *et al.*** (2012) [22] Two multiple signal representation transceiver design schemes are presented that are known as SLM and PTS which are utilized for OFDM in doubly selective channels. In order to decrease ICI because of time-varying characteristics of channel PICR is introduced as a measurement for the resulting ICI, therefore a transmit sequence is serially generated and we have to select the best sequence among all which minimizes the PICR for the adjustment of transmitted data. With all these mentioned methods, low-complexity one-tap equalization could provide adequate performance. Analyzing such schemes theoretically after that Simulation depicts that the performance of the proposed method is good and can effectively stifle ICI. The phase adjustment vector is optimized and acquired by discovering out the sequence with minimal PICR value from a predetermined number of random sequences. As transmitter utilizes SLM or PTS, exploitation of low-complexity one-tap equalization is done by receiver to achieve satisfied performance. In this way the primarily computational operation is performed at transmitter. Simulation results confirm that the proposed methods can provide improved performance gain.

- **Md. Al-Mahadi Hasan *et al.*** (2012) [23] This presents technique to decline inter carrier interference with the help of variety of window functions in frequency domain which are utilized in pulse shaping of OFDM uncorrelated symbols. Five window functions are used here to compare the performance of wireless system. Windows considered are Kaiser window, hamming window, blackman window, gaussian window and hanning window. These window functions are utilized as envelope of OFDM symbol and their relative performance in perspective to power of ICI and SIR.
- **C. C. Tsimenidis *et al.*** (2012) [24] This suggests technique to improve ICI performance of OFDM affected due to TWTA and CFO and refined version of PTS scheme is adopted based DSR instead of PAPR measurements because of less complexity of DSR. Perfect acquaintance of phase coefficients at receiver side for PTS technique is necessary for coherent demodulation.
- **Kun-Yi Lin *et al.*** (2012) [25] Orthogonality between subcarriers get shattered in time varying channels which leads to produce inter carrier interference. This paper provides a method to remove ICI i.e. time domain self cancellation method. A franks window with numerous subcarriers over linear time varying Rayleigh channel is assumed in which set of windowing coefficients are derived which are same as the coefficients of franks window to lessen the equivalent channel time variation and therefore mitigating ICI with the concept of flattening equivalent time variation of channel.
- **Hung Nguyen-Le *et al.*** (2013) [26] This paper has taken into consideration effect of CFO, PHN over doubly selective fading channel and SIR is calculated considering all these factors. SIR is plotted against phase noise by considering various values of carrier frequency offset.
- **P. Hari Krishna Prasad *et al.*** (2014) [27] To minimize ICI in OFDM framework, a novel receiver window function is introduced which is defined as:

$$p(t) = \left(1 - \frac{t}{T_s}\right) \otimes \left(e^{-\frac{\pi^2 \tau^2}{\alpha^2}} \text{sinc}\left(\frac{2dt}{\alpha}\right)\right)$$

The performance of this proposed window is analyzed with RC window, BTRC window, the MBH window and rectangular window by calculating SIR and ICI. After all calculation it has been concluded that ICI power is 17.74 dB for the proposed

window which is much superior than that of BTRC and it has 7.3 dB enhanced value than that of MBH window function at 0.05 as CFO value.

## CHAPTER 3

### MATHEMATICAL MODEL

#### 3.1 OFDM system model

OFDM system model with N subcarriers consisting of transmitter, channel and receiver block is described as:

##### 3.1.1 Transmitter

In this model, M-ary data modulators modulate building block of information bits (symbols) and then, N such symbols are send with the help of serial to parallel converter. It depends on the requirement of system which type of data modulator is to be used like M-QAM, M-PSK etc. [28]. N point IFFT block is provided with the complex parallel data symbols ( $X_K$ ) with the help of modulation techniques are given as shown:

The complex envelope of the baseband transmitted OFDM signal can be defined as:

$$x(t) = \frac{1}{N} \sum_{K=0}^{N-1} X_K e^{j2\pi kt / NT} \quad 0 \leq t \leq NT \quad (3.1)$$

Where

N= number of subcarriers

$X_K$ = number of input symbols

T= original symbol period

Discrete form of the same signal can be represented as:

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{j2\pi kn / N} \quad \text{for } n = 1, 2, 3 \dots \dots \dots N - 1 \quad (3.2)$$

This shows transmitted signal after performing inverse Fourier transform of modulated data symbol  $X_k$ .

##### 3.1.1.1 Addition of Guard band

Benefit of using guard band in OFDM framework is minimizing ISI which is usually developed between successive OFDM symbols due to delay

spread of multipath channel in OFDM symbols. To combat the effect of ISI totally guard interval is introduced with no signal transmission but ICI get generated due to higher spectral components which occurred because of fast varying nature of waveforms [29]. Zero padding (ZP) and cyclic extension uses the concept of guard interval. Cyclic prefix (CP) or cyclic suffix (CS) are two way extension.

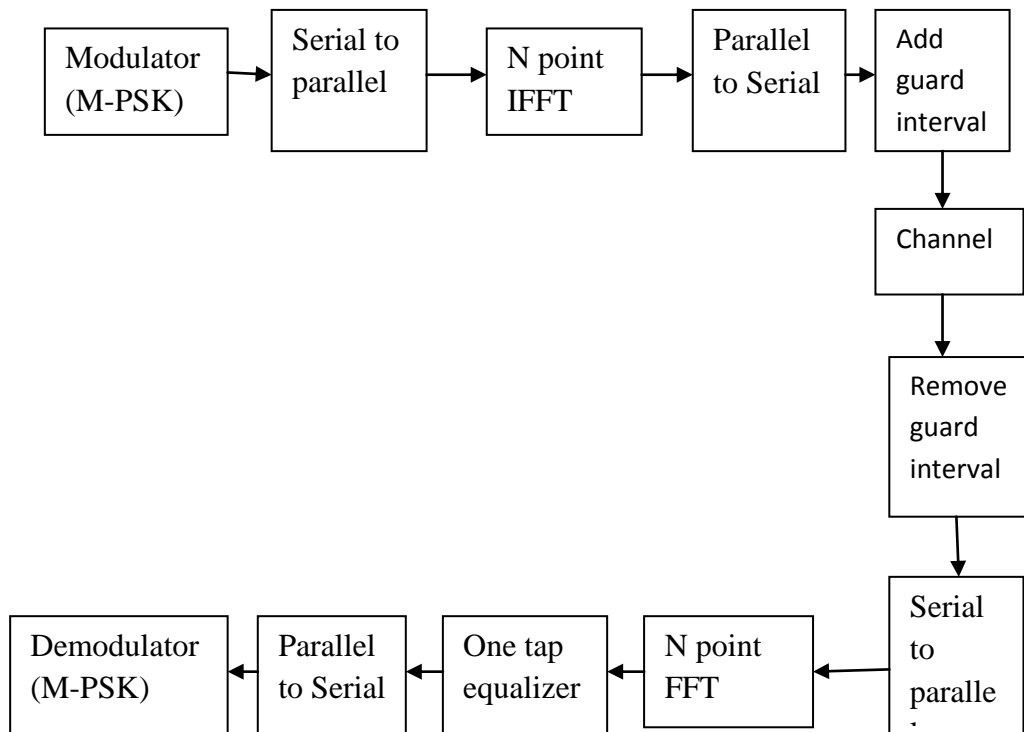


Fig. 3.1 OFDM system model

### 3.1.1.2 Cyclic prefix

In this a symbol is transmitted then some of its portion is taken and repeated again which act as the prefix of next transmitted symbol [30]. Such prefixes are helpful in removing ISI. Insertion of cyclic prefix is shown as:

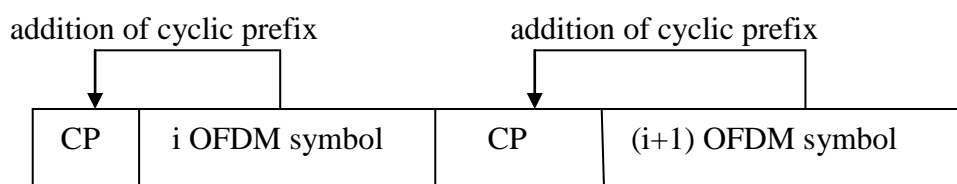


Fig. 3.2 cyclic prefix

Cyclic prefix enhance the symbol duration and mathematically it can be extended as:

$$x(t)_{ext} = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{j2\pi f_k t} \quad -T_p \leq t \leq T_p \quad (3.3)$$

$$x(t)_{ext} = x(t + T) \quad -T_p \leq t \leq 0 \quad (3.4)$$

Cyclic prefix length must be greater than delay spread of a multipath channel. If by chance it gets less than delay spread of multipath channel, then the ending part of previous OFDM symbol overlap the starting part of the next OFDM symbol and ultimately ISI get generated [31]. To maintain the orthogonality among the subcarriers cyclic prefix should be larger than the delay spread of the multipath channel.

If instead of adding small portion of transmitted symbol as prefix add that information as a suffix then it is known as cyclic suffix. This method of insertion of guard interval is used for frequency hopping and radio frequency (RF) convergence.

### 3.1.1.3 Zero Padding

In zero padding (ZP) top and bottom portion of the transmitted symbols are filled with zeros as shown as:

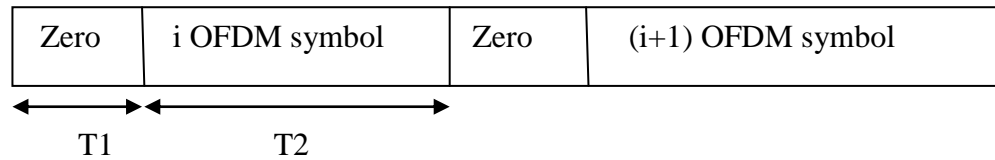


Fig. 3.3 zero padding

### 3.2 Channel model

OFDM is in great demand in wireless technology that is why fading in multipath channel has been taken into consideration. The tap-delay line model is considered with frequency selective fading in the channel and the impulse response  $h(\tau, t)$  is given as –

$$h(\tau, t) = \sum_{l=0}^{L-1} h_l(t)\delta(t - \tau_l) \quad (3.5)$$

$h_l(t)$  - the complex amplitude (or tap coefficient)

$\tau_l$  - the delay in propagation of the  $l^{\text{th}}$  path

The tap coefficients are random complex Gaussian variable  $h_l(t), \{l = 0, 1, 2 \dots, L - 1\}$  are modeled as zero mean with variances  $\{\sigma_l^2\}$  where  $\sigma_0^2 + \sigma_1^2 + \sigma_2^2 + \dots + \sigma_{L-1}^2 = 1$

[32]. The multipath fading channel effect  $h(\tau, t)$  is to be considered to find the  $i^{\text{th}}$  received signal  $r_i(t)$  which can be expressed as :

$$r_i(t) = \sum_{l=0}^{L-1} h_l(t)s_i(t - \tau_l) + w(t) \quad (3.6)$$

Where,  $w(t)$  is the undesired signal at the receiver side i.e. AWGN which has  $\frac{N_0}{2}$  as two sided power spectral density.

If cyclic prefix is greater than the maximum delay spread of multipath channel and if there is no timing and frequency offsets or if the timing and frequency offsets are estimated appropriately and then the received signal extracted from the OFDM symbol perfectly [33]. Assume above said condition are verified then cyclic prefix is removed, and now received signal is fed to the FFT block and the output is achieved after FFT block and represented as :

$$d_{i,k} = H_k d_{i,k} + w_k \quad \text{for } 0 \leq k \leq N - 1 \quad (3.7)$$

Where  $H_k$  denotes the frequency response of the multipath fading channel at the  $k^{\text{th}}$  subchannel and  $w_k$  is the AWGN component in frequency domain. The frequency response of channel is defined as -

$$H_k = \sum_{l=0}^{L-1} h_l(t) e^{-\frac{j2\pi k\tau_l}{N}} \quad (3.8)$$

Based on the availability of estimation techniques in the literature use any of the channel to determine equalizer gain  $G_k$  which is given as-

$$G_k = \frac{1}{H_k} \quad (3.9)$$

### 3.3 ICI AND SIR ANALYSIS:

Consider an OFDM system with N-point Fourier transform for multicarrier transmission. After IFFT transmitted baseband samples in OFDM system

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} X_k \exp\left(\frac{j2\pi kn}{N}\right) \quad (3.10)$$

By assuming data symbols are uncorrelated. That is  $E[X_K X_K^*] = 1$

The OFDM system has a major demand in wireless technology therefore multipath fading channel has been taken into consideration [34]. The tap-delay line model with frequency selective fading as given in with L-path has been considered. The impulse response  $h(\tau, t)$  for this channel is –

$$h(\tau, t) = \sum_{l=0}^{L-1} h_l(t) \cdot \delta(t - \tau_l) \quad (3.11)$$

$h_l(t)$  is tap coefficient

$\tau_l$  is propagation delay

Zero mean and  $\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2 \dots \dots \dots + \sigma_l^2 = 1$

effects multipath fading are considered and then new achieved received signal is:

$$r(i, n) = \sum_{l=0}^{L-1} h_l(\tau) x(i, n - \tau_l) e^{\frac{j2\pi\epsilon(n-\tau_l)}{N}} + w(i, n) \quad (3.12)$$

Put value of  $x(i, n - \tau_l)$  in the above equation

$$r(i, n) = \sum_{l=0}^{L-1} h_l(\tau) \cdot \frac{1}{N} \sum_{k=0}^{N-1} X(i, k) e^{\frac{j2\pi k(n-\tau_l)}{N}} e^{\frac{j2\pi\epsilon(n-\tau_l)}{N}} + w(i, n) \quad (3.13)$$

Interchanging summation terms:

$$r(i, n) = \frac{1}{N} \sum_{k=0}^{N-1} X(i, k) e^{\frac{j2\pi n(k+\varepsilon)}{N}} \sum_{l=0}^{L-1} h_l(\tau) e^{-\frac{j2\pi \tau_l(k+\varepsilon)}{N}} + w(i, n) \quad (3.14)$$

$$\sum_{l=0}^{L-1} h_l(\tau) e^{-\frac{j2\pi \tau_l(k+\varepsilon)}{N}} = H(k, \varepsilon) \quad (3.15)$$

$$X(i, p) = \sum_{n=0}^{2N-1} y(i, n) e^{-\frac{j2\pi pn}{2N}} \quad (3.16)$$

$$X(i, p) = \sum_{n=0}^{2N-1} \frac{1}{N} \sum_{k=0}^{N-1} X(i, k) e^{\frac{j2\pi n(k+\varepsilon)}{N}} H(k, \varepsilon) p(n) e^{-\frac{j2\pi pn}{2N}} + \sum_{n=0}^{2N-1} w(i, n) e^{-\frac{j2\pi pn}{2N}} \quad (3.17)$$

$$X(i, p) = \frac{1}{N} \sum_{k=0}^{N-1} X(i, k) H(k, \varepsilon) \sum_{n=0}^{2N-1} p(n) e^{\frac{j2\pi n(2k-p+2\varepsilon)}{2N}} + \sum_{n=0}^{2N-1} w(i, n) e^{-\frac{j2\pi pn}{2N}} \quad (3.18)$$

After simplification

$$X(i, p) = \sum_{k=0}^{N-1} X(i, k) H(k, \varepsilon) S(k, p, \varepsilon) + w(i, p) \quad (3.19)$$

Comparing from the above equation

$$S(k, p, \varepsilon) = \frac{1}{N} \sum_{n=0}^{2N-1} p(n) e^{\frac{j2\pi n(2k-p+\varepsilon)}{2N}} \quad (3.20)$$

Between even or odd terms one of them contain desired data and that can be retrieved by putting  $p=2q$  in  $X(i, p)$

$$X(i, 2q) = \sum_{k=0}^{N-1} X(i, k) H(k, \varepsilon) S(k, 2q, \varepsilon) + w(i, 2q) \quad (3.21)$$

Breaking summation into 2 parts and those parts representing desired signal and ICI

$$X(i, 2q) = X(i, q)H(q, \varepsilon)S(q, 2q, \varepsilon) + \sum_{k=0, k \neq q}^{N-1} X(i, k)H(k, \varepsilon)S(k, 2q, \varepsilon) \quad (3.22)$$

In this first term is the desired signal and second component is noise. Now ICI can be calculated as:

$$\sum_{k_1=0, k_1 \neq q}^{N-1} \sum_{k_2=0, k_2 \neq q}^{N-1} E[X(i, k_1)X(i, k_2)^*]E[H(k_1, \varepsilon)H(k_2, \varepsilon)^*]E[S(k_1, 2q, \varepsilon)S(k_2, 2q, \varepsilon)^*] \quad (3.23)$$

$$\sigma_{ici}^2 = \frac{\sigma_f^2}{N} \sum_{k=0}^{N-1} \sum_{n_1=0}^{2N-1} \sum_{n_2=0}^{2N-1} p(n_1)p(n_2)e^{\frac{j2\pi(n_1-n_2)(k-q+\varepsilon)}{N}} \quad (3.24)$$

ICI powers can be written as:

$$\sigma_{ici}^2 = \sum_{k=0, k \neq q}^{N-1} P(k - q + \varepsilon)^2 \quad (3.25)$$

When  $k=q$  it defines the desired signal

$$\sigma_s^2 = P(\varepsilon)^2 \quad (3.26)$$

SIR can be defined as:

$$SIR = \frac{\sigma_s^2}{\sigma_{ici}^2} \quad (3.27)$$

Put value of both in this equation

$$SIR = \frac{P(\varepsilon)^2}{P(k - q + \varepsilon)^2} \quad (3.28)$$

### 3.4 ICI and SIR over doubly selective channel

#### 3.4.1 Transmitter

Consider an OFDM system with N-point Fourier transform for multicarrier transmission. After IFFT transmitted baseband samples in OFDM system are:

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} X_k \exp\left(\frac{j2\pi kn}{N}\right) \quad (3.29)$$

Where  $n = \{0,1,2,\dots,N-1\}$

$X_k$  is subcarrier of modulated data OFDM symbol where power of these subcarriers is one.

### 3.4.2 Doubly selective channel

In OFDM transmission, transmitted signal  $x_n$  experiences time and frequency selective fading i.e. traverses through doubly selective channel [35]. Such type of propagation is represented by  $h_{l,n}$  where  $n$  denotes time domain sample. Correlation of channel coefficients for path  $l$  can be described as :

$$E[h_{l,n}h_{l,n+m}] = J_0\left(\frac{2\pi m f_d T_s}{N}\right) \sigma_l^2 \quad (3.30)$$

Where

$f_d$  is doppler spread

$f_d = v f_c / c_0$  where  $v$  is mobile speed

$f_c$  is carrier frequency

$C_0$  is speed of light

$T_s$  is symbol duration

$\sigma_l^2$  is power delay profile of particular channel

In presence of doubly selective channel, CFO and PHN, baseband received signal can be represented by-

$$y_n = e^{\frac{j2\pi\epsilon n}{N}} e^{j\phi_n} \sum_{l=0}^{L-1} x_{n-l} h_{l,n} + z_n \quad (3.31)$$

Where  $\epsilon$  denotes to fractional carrier frequency offset

$\Phi_n$  denotes phase offset

$\epsilon$  denotes fractional carrier frequency offset

### 3.4.3 Phase noise

Phase noise is short term random fluctuations caused by time domain instabilities (jitter).it is continuous Brownian motion [36]. Phase noise and jitter are related to each other with relation-

$$\text{Jitter(seconds)} = \text{phaseerror (degrees)} / (360 * \text{frequency (hz)}) \quad (3.32)$$

Autocorrelation of phase noise can be computed by

$$E[e^{j\phi_n} e^{-j\phi'_n}] = e^{-\frac{\pi\beta T_s(n-n')}{N}} \quad (3.33)$$

Transmitted signal after passing through doubly selective channel which is affected by CFO and PHN i.e. after performing FFT at receiver:

$$Y_k = G_{k,k} X_k + \sum_{k'=0, k' \neq k}^{N-1} G_{k,k'} X_{k'} + Z_k \quad (3.34)$$

by replacing n by n-l in above equation of  $x_n$  put value of  $x_{n-l}$  in above equation

$$y_n = e^{\frac{j2\pi\epsilon n}{N}} e^{j\phi_n} \sum_{l=0}^{L-1} \sum_{k=0}^{N-1} \frac{1}{N} X_k \exp\left(\frac{j2\pi k(n-l)}{N}\right) h_{nl} \quad (3.35)$$

Taking its Fourier transform-

$$Y_q = \sum_{n=0}^{N-1} y_n e^{-\frac{j2\pi qn}{N}} \quad q = 0,1,2 \dots \dots N-1$$

(3.36)

$$\sum_{l=0}^{N-1} \sum_{k=0}^{N-1} \sum_{n=0}^{N-1} \frac{1}{N} \cdot X_{k'} \cdot e^{\frac{j2\pi k(n-1)}{N}} h_{nl} \cdot e^{\frac{j2\pi \epsilon n}{N}} \cdot e^{j\varphi_n} \cdot e^{-\frac{j2\pi qn}{N}}$$

(3.37)

By comparing

$$G_{k,k'} = \sum_{l=0}^{L-1} \sum_{n=0}^{N-1} \frac{1}{N} \cdot h_{nl} \cdot e^{\frac{j2\pi(nk-nq+n\epsilon-lk)}{N}} e^{j\varphi_n}$$

(3.38)

$$\sum_{l=0}^{N-1} \sum_{n=0}^{N-1} \sum_{n'=0}^{N-1} \frac{1}{N} \cdot E[h_{nl} \cdot h_{n'l}^*] \cdot E[e^{j\varphi_n} \cdot e^{-j\varphi_{n'}}] \cdot e^{\frac{j2\pi((nk'-nk-lk'+n\epsilon)-(n'k'-n'k-lk'+n'\epsilon))}{N}}$$

(3.39)

Put  $r = n - n'$  and  $\Delta = k - k'$

$$= \frac{1}{N} \sum_{l=0}^{L-1} \sum_{r=1-N}^{N-1} (N-r) J_0 \left( \frac{2\pi f_d T_s r}{N} \right) \sigma_l^2 e^{-\frac{j2\pi r(\Delta-\epsilon)}{N}} e^{-\frac{\pi\beta T_s r}{N}}$$

(3.40)

$$= \frac{1}{N} \sum_{l=0}^{L-1} \sigma_l^2 \left[ N + 2 \sum_{r=1}^{N-1} (N-r) J_0 \left( \frac{2\pi f_d T_s r}{N} \right) \cos \left( \frac{2\pi r \Delta}{N} \right) \cos \left( \frac{2\pi r \epsilon}{N} \right) e^{-\frac{\pi\beta T_s r}{N}} \right]$$

(3.41)

$$= \frac{1}{N} [N + 2 \sum_{r=1}^{N-1} (N-r) J_0 \left( \frac{2\pi f_d T_s r}{N} \right) \cos \left( \frac{2\pi r \Delta}{N} \right) \cos \left( \frac{2\pi r \epsilon}{N} \right) e^{-\frac{\pi \beta T_s r}{N}}] \quad (3.42)$$

At  $\Delta = 0$  this ICI represents signal

so signal is defined as:

$$= \frac{1}{N} [N + 2 \sum_{r=1}^{N-1} (N-r) J_0 \left( \frac{2\pi f_d T_s r}{N} \right) \cos \left( \frac{2\pi r \epsilon}{N} \right) e^{-\frac{\pi \beta T_s r}{N}}] \quad (3.43)$$

Dividing both to obtain signal to interference ratio:

$$\begin{aligned} SIR &= [N + 2 \sum_{r=1}^{N-1} (N-r) J_0 \left( \frac{2\pi f_d T_s r}{N} \right) \cos \left( \frac{2\pi r \epsilon}{N} \right) e^{-\frac{\pi \beta T_s r}{N}}] / [N \\ &+ 2 \sum_{r=1}^{N-1} (N-r) J_0 \left( \frac{2\pi f_d T_s r}{N} \right) \cos \left( \frac{2\pi r \Delta}{N} \right) \cos \left( \frac{2\pi r \epsilon}{N} \right) e^{-\frac{\pi \beta T_s r}{N}}] \end{aligned} \quad (3.44)$$

This represent signal to interference ratio over doubly selective channel in presence of both carrier frequency offset and phase noise.

### 3.5 Proposed technique for SIR improvement

#### 3.5.1 SIR improvement using window function

OFDM is precise method of multiplexing which is perceptive to carrier frequency offset (CFO) and hence generating ICI at the OFDM receiver [3]. CFO often occurs due to mismatching in frequency of transmitter and receiver oscillators and due to Doppler effect which appears when transmitter and receiver both are moving [8]. This ICI decimate the orthogonality of sub-carriers and deteriorate the performance of OFDM system. There are various method for reducing ICI and improving SIR-

- Frequency domain equalization
- Time domain windowing

- Maximum likelihood estimation
- ICI self cancellation scheme
- Pulse shaping

In this chapter, time domain windowing is proposed for ICI reduction

### 3.5.2 System model for sir improvement

OFDM system model with N subcarriers is shown which consists of transmitter, channel and receiver blocks with an extra block of window is described as [12]

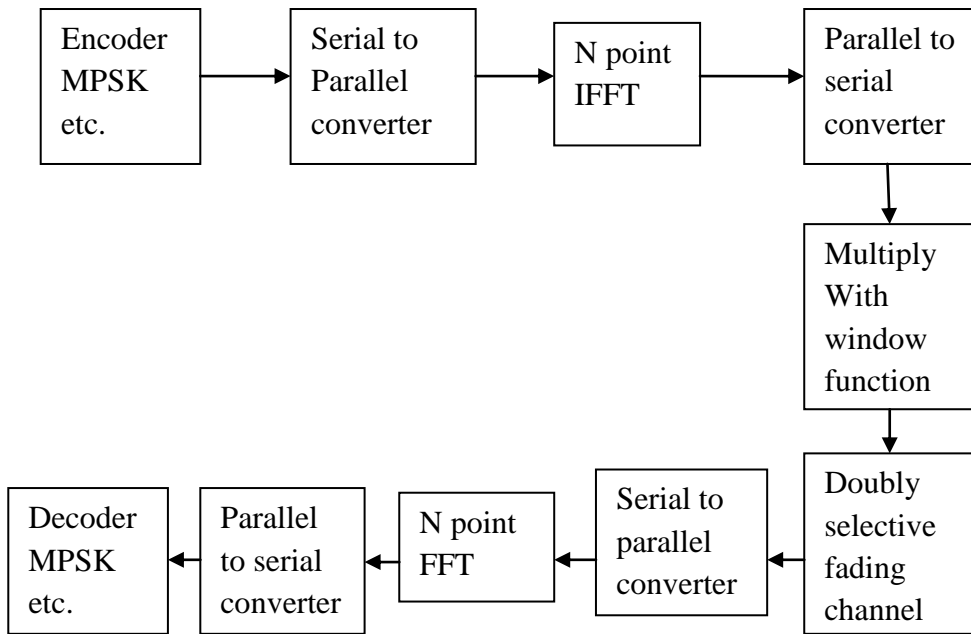


Fig..3.4 OFDM system with windowing

### 3.5.3 Transmitter

Consider an OFDM system with N-point Fourier transform for multicarrier transmission. After IFFT transmitted baseband samples in OFDM system passing through window function can be represented [16]

$$= \frac{p(n)}{N} \sum_{k=0}^{N-1} X_k \exp\left(\frac{j2\pi kn}{N}\right)$$

(3.45)

$X_k$  is subcarrier of modulated data OFDM symbol where power of these subcarriers is one.

### 3.5.4 Doubly selective channel

In OFDM transmission, transmitted signal  $x_n$  experiences time and frequency selective fading i.e. traverses through doubly selective channel. This type of propagation is denoted by  $h_{l,n}$  where  $n$  stands for time domain sample [30].

Correlation of channel coefficients for path  $l$  can be described as-

$$E[h_{l,n}h_{l,n+m}] = J_0\left(\frac{2\pi m f_d T_s}{N}\right) \sigma_l^2 \quad (3.46)$$

Where,

$f_d$  is doppler spread

$f_d = v f_c / c_0$  where  $v$  is mobile speed

$f_c$  is carrier frequency

$c_0$  is speed of light

$T_s$  is symbol duration

$\sigma_l^2$  is power delay profile of particular channel

In presence of doubly selective channel, carrier frequency offset and phase frequency offset, baseband received signal can be represented by-

$$y_n = e^{\frac{j2\pi\epsilon n}{N}} e^{j\phi_n} \sum_{l=0}^{L-1} x_{n-l} h_{l,n} + z_n \quad (3.47)$$

Where  $\epsilon$  denotes to fractional carrier frequency offset

$\phi_n$  denotes phase offset

$\epsilon$  denotes fractional carrier frequency offset

### 3.5.5 Phase noise

Phase noise is short term random fluctuations caused by time domain instabilities (jitter).it is continuous Brownian motion. Phase noise and jitter are related to each other with relation-

$$\text{Jitter (seconds)} = \text{phase error (degrees)} / (360 * \text{frequency (Hz)}) \quad (3.48)$$

Autocorrelation of phase noise can be computed by

$$E[e^{j\phi_n} e^{-j\phi'_n}] = e^{-\frac{\pi\beta T_s(n-n')}{N}} \quad (3.49)$$

### 3.5.6 Received signal

Transmitted signal after passing through doubly selective channel which is affected by phase noise and carrier frequency offset:

$$y_n = e^{\frac{j2\pi\epsilon n}{N}} e^{j\phi_n} \sum_{l=0}^{L-1} x_{n-l} h_{nl} + z_n \quad (3.50)$$

by replacing n by n-l in above equation of  $x_n$  put value of  $x_{n-l}$  in above equation

$$y_n = e^{\frac{j2\pi\epsilon n}{N}} e^{j\phi_n} \sum_{l=0}^{L-1} \sum_{k=0}^{N-1} \frac{p(n)}{N} X_k \exp\left(\frac{j2\pi k(n-l)}{N}\right) h_{nl} \quad (3.51)$$

Taking its Fourier transform-

$$Y_q = \sum_{n=0}^{N-1} y_n e^{-\frac{j2\pi qn}{N}} \quad q = 0,1,2 \dots \dots N-1 \quad (3.52)$$

$$\sum_{l=0}^{N-1} \sum_{k=0}^{N-1} \sum_{n=0}^{N-1} \frac{p(n)}{N} \cdot X_k \cdot e^{\frac{j2\pi k(n-l)}{N}} h_{nl} \cdot e^{\frac{j2\pi \epsilon n}{N}} \cdot e^{j\varphi_n} \cdot e^{-\frac{j2\pi qn}{N}} \quad (3.53)$$

By comparing

$$G_k = \sum_{l=0}^{L-1} \sum_{n=0}^{N-1} \frac{p(n)}{N} \cdot h_{nl} \cdot \frac{\exp(nk - nq + n\epsilon - lk)}{N} \quad (3.54)$$

ICI analysis:

$$\sum_{l=0}^{N-1} \sum_{n=0}^{N-1} \sum_{n'=0}^{N-1} \frac{p(n)}{N} \cdot E[h_{nl} \cdot h_{n'l}^*] \cdot E[e^{j\varphi_n} \cdot e^{-j\varphi_{n'}}] \cdot e^{\frac{j2\pi(n-n')k - (n-n')q + (n-n')\epsilon}{N}} \quad (3.55)$$

$$\sum_{l=0}^{L-1} \sum_{n=0}^{N-1} \sum_{n'=0}^{N-1} \frac{p(n)}{N^2} \cdot J_0\left(\frac{2\pi f_d T_s (n-n')}{N}\right) \cdot \sigma_l^2 \cdot e^{-\frac{\pi\beta T_s (n-n')}{N}} e^{\frac{j2\pi(n-n')k - (n-n')q + (n-n')\epsilon}{N}} \quad (3.56)$$

$$\sum_{l=0}^{L-1} \sum_{n=0}^{N-1} \sum_{n'=0}^{N-1} \frac{p(n)}{N^2} \cdot J_0\left(\frac{2\pi f_d T_s (n-n')}{N}\right) \cdot \sigma_l^2 \cdot e^{-\frac{\pi\beta T_s (n-n')}{N}} e^{\frac{j2\pi(n-n')(k-q+\epsilon)}{N}} \quad (3.57)$$

$$k - q = \Delta, \quad \Delta \neq 0$$

So ICI becomes:

$$\sum_{l=0}^{L-1} \sum_{n=0}^{N-1} \sum_{n'=0}^{N-1} \frac{p(n)}{N^2} \cdot J_0\left(\frac{2\pi f_d T_s (n-n')}{N}\right) \cdot \sigma_l^2 \cdot e^{-\frac{\pi\beta T_s (n-n')}{N}} e^{\frac{j2\pi(n-n')(\Delta+\epsilon)}{N}} \quad (3.58)$$

The desired signal is obtained when  $k=q$  so signal is :

$$\sum_{l=0}^{L-1} \sum_{n=0}^{N-1} \sum_{n'=0}^{N-1} \frac{p(n)}{N^2} \cdot J_0 \left( \frac{2\pi f_d T_s (n' - n)}{N} \right) \cdot \sigma_l^2 \cdot e^{-\frac{\pi \beta T_s (n-n')}{N}} e^{\frac{j2\pi(n-n')(\epsilon)}{N}} \quad (3.59)$$

Signal to interference ratio can be obtained by dividing both equations:

$$\frac{\sum_{l=0}^{L-1} \sum_{n=0}^{N-1} \sum_{n'=0}^{N-1} \frac{p(n)}{N^2} \cdot J_0 \left( \frac{2\pi f_d T_s (n' - n)}{N} \right) \cdot \sigma_l^2 \cdot e^{-\frac{\pi \beta T_s (n-n')}{N}} e^{\frac{j2\pi(n-n')(\epsilon)}{N}}}{\sum_{l=0}^{L-1} \sum_{n=0}^{N-1} \sum_{n'=0}^{N-1} \frac{p(n)}{N^2} \cdot J_0 \left( \frac{2\pi f_d T_s (n' - n)}{N} \right) \cdot \sigma_l^2 \cdot e^{-\frac{\pi \beta T_s (n-n')}{N}} e^{\frac{j2\pi(n-n')(\Delta+\epsilon)}{N}}} \quad (3.60)$$

Here  $p(n)$  is window function at transmitter side and a lot of research has been done about applying window in OFDM system to reduce ICI [7]. These are divided into two groups. One group use pulse shaping or windowing at the initial stage of communication system i.e. at transmitter whereas another groups make use of windowing at the receiver. The groups which use window at the initial stage that lessen the sensitivity to linear distortion [10]. At transmitter side, original signal remains same but the OFDM signal is extended cyclically after IFFT and then the windowing function maintains the prefix part of symbol [37]. The endeavor of windowing at transmitter is to make the spectrum to go down at fast rate. To make the amplitude to reach to zero smoothly window is applied on OFDM symbol at the symbol boundaries [13]. On the other hand if instead of windowing out-of-band spectrum decays rather gradually due to transition in phase sharply at symbol boundaries. IEEE 802.11 standards are provided with utilization of RC window at transmitter side [14]. Some other Nyquist pulse shapes like BTRC, improved sinc power pulse, phase modified sinc pulse, Frank's window and SOCW are also available in the literature [24].

To diminish the sensitivity to frequency errors receiver side windowing is used. This concept of windowing to lessen ICI is very well reported. All such works presented utilization of a proper Nyquist window that will minimize ICI to such a larger extent [36]. The window is applied to the estimated ISI-free part of a received OFDM symbol. Nyquist window is the time-limited window which minimizes the side lobes and conserves the carrier orthogonality [38]. The work reported demonstrate the effects of several Nyquist windows, including SOCW, RC, BTRC, the frank window,

and the double jump window on the performance of OFDM system [26]. The assessment is also measured on basis of parameters like SIR and BER [33].

### **3.6 Different window functions**

Several window functions or pulse shaping function are accessible in the literature to combat the effects of ICI. To make sure about sub-carrier orthogonality pulse shaping function should follow a condition i.e. spectral nulls at various frequencies should be there after taking Fourier transform of the pulse [27]. The pulse shapes which accomplish this condition is known as Nyquist pulse shape. A key Nyquist pulse shape is RC pulse shape, whose utilization in OFDM framework is also mentioned in IEEE 802.11a [21]. The another one like BTRC [12] SP, ISP, PMSP [26], Frank's window (FRANK) and SOCW pulse are also accessible in the literature. Out of these some have been applied at transmitter and some at receiver. Like RC, BTRC, SOCW, and FRANK pulse shapes have been applied at receiver while others like SP, ISP, and PMSP have been applied at transmitter side only [19]. To the best of our acquaintance, time domain expressions i.e. closed-form are not accessible for windows like SP, ISP and PMSP. However, these pulse shapes can be proficiently numerically evaluated in time domain by using IFFT. On the other hand, the expression of RC, BTRC, SOCW, and FRANK are accessible in both frequency and time domain [24]. The expression of different pulse shapes in time domain and frequency domain are already defined in chapter-2.

## CHAPTER 4

### RESULTS AND DISCUSSIONS

In this chapter, derived expressions of inter carrier interference and signal to interference ratio in the above chapter are plotted. These both expressions are calculated by considering CFO, PHN and time selective channels. The time selective multipath fading channel with  $L=5$  resolvable paths, 32 point FFT, carrier frequency  $f_c=3.5\text{GHz}$  and sampling frequency  $f_s=5.6\text{MHz}$ .

Calculated interference with all the above mentioned conditions i.e. expression (3.42) is plotted against phase noise with various values of carrier frequency offset.

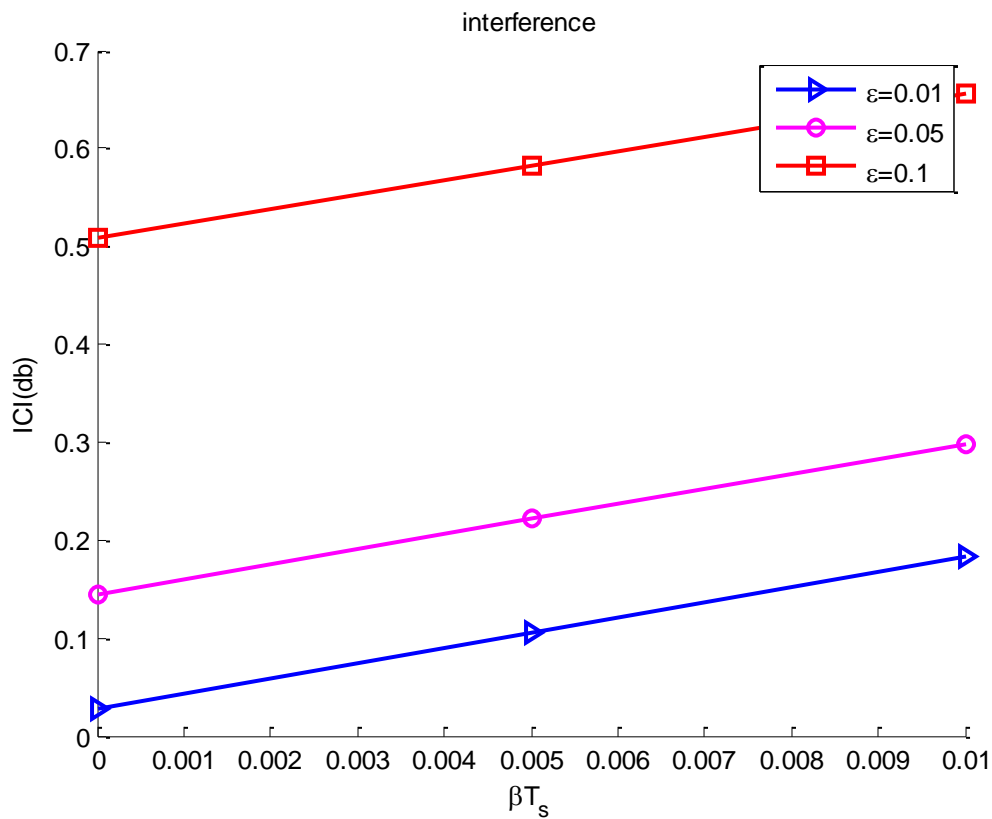


Fig. 4.1 ICI versus PHN level for various CFO values

After calculating expression for interference i.e. (3.42), expression for signal is calculated by applying certain conditions i.e. (3.43) then these two expressions are divided for the same above mentioned conditions and a new expression (3.44) is achieved which is of SIR and then SIR curves are plotted against phase noise under different carrier frequency offset values.

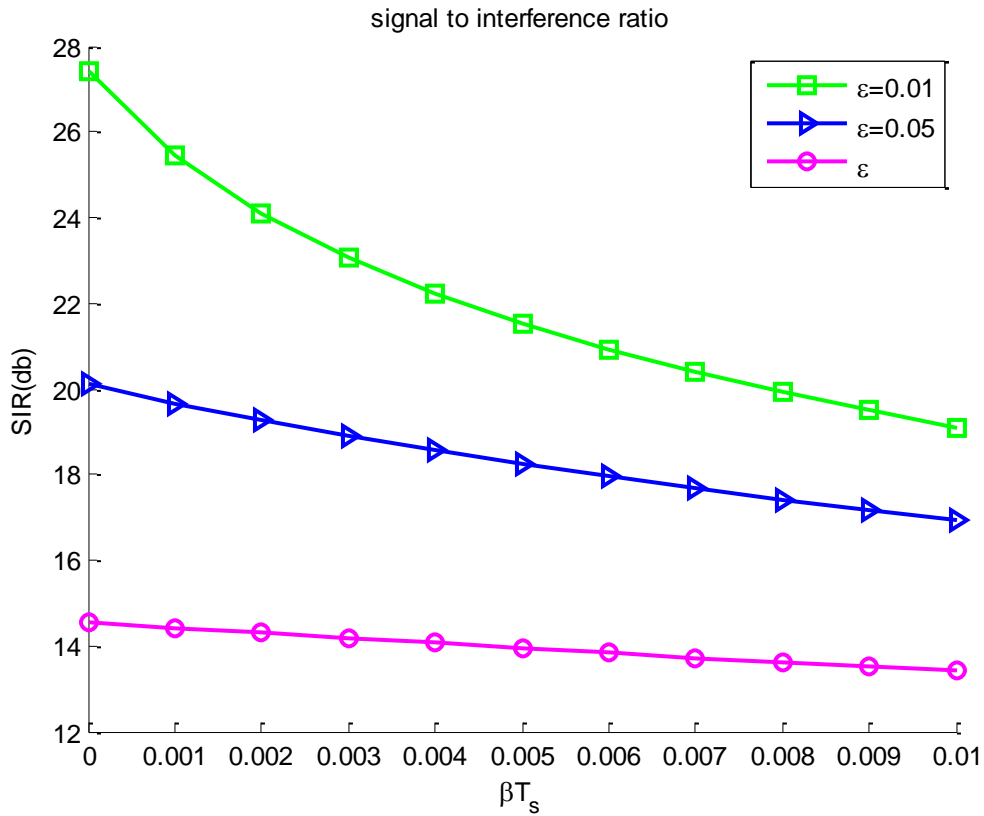


Fig. 4.2 SIR verses PHN level under various CFO values[28]

In this way, interference and signal to interference ratio are plotted. SIR decays as synchronization impairments increases and expressions calculated numerically proves the importance of consideration of CFO,PHN and Doppler spread in SIR analysis. To improve the performance of OFDM system various techniques were applied. Here improvement in performance is shown by improving SIR parameter. Actually pulse shaping enhance the main lobe width by minimizing side lobe level which is main source of ICI power. Pulse shaping and number of subcarriers also determine level of ICI i.e if spectrums of particular window function has lower side lobes then it is expected to give lower ICI as a result. Now various windows are to be applied on transmitter side to decrease ICI and improve SIR. Results with various window functions are shown as:

### **Raised cosine window**

On applying RC window at transmitter side SIR is plotted against PHN for three different values of CFO. It is observed from Fig. 4.3 that values of SIR get improved.

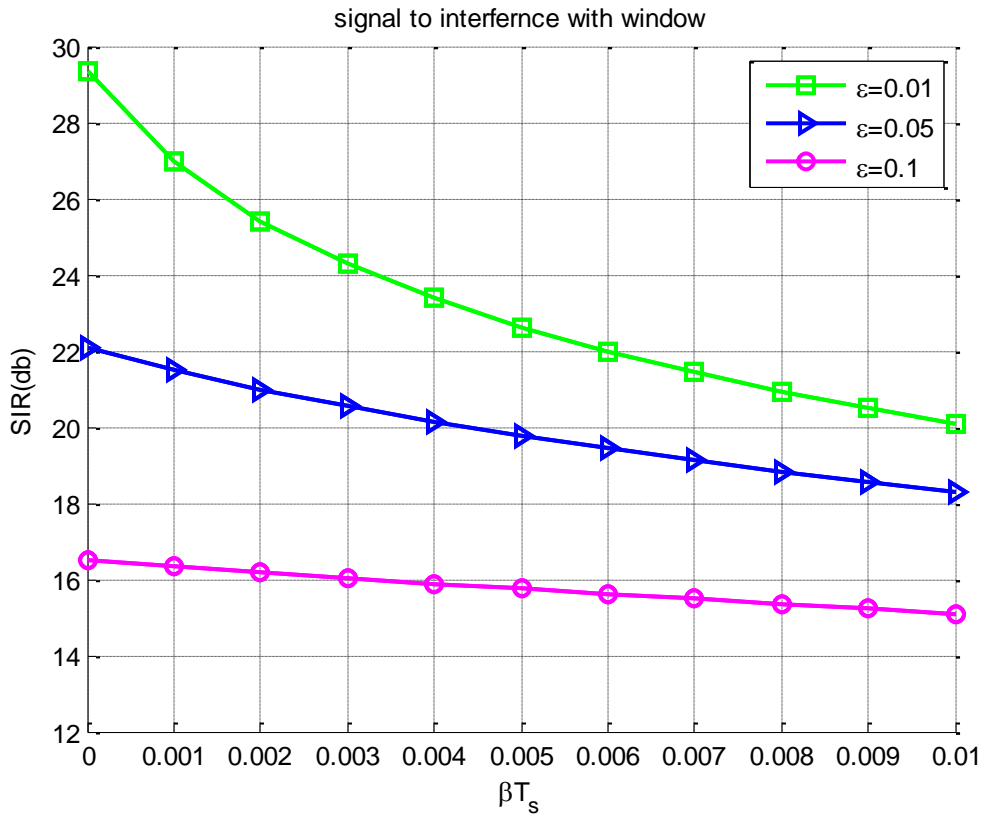


Fig. 4.3 SIR verses PHN under various CFO values with window

To compare the result accurately SIR is plotted against PHN for both cases i.e. SIR without windowing as well as SIR with windowing. So here compared result is calculated and executed by using various types of windows like

- RC window
- BTRC window
- SP window
- ISP window

Various graphs are plotted in which comparison occurs as a single graph contains SIR plots against PHN with and without window. On applying window it can be observed that improvement in value occurs for each value of PHN when CFO is considered. These graphs are plotted for three different values of CFO which is 0.01, 0.05 and 0.1. for each case graph is plotted.

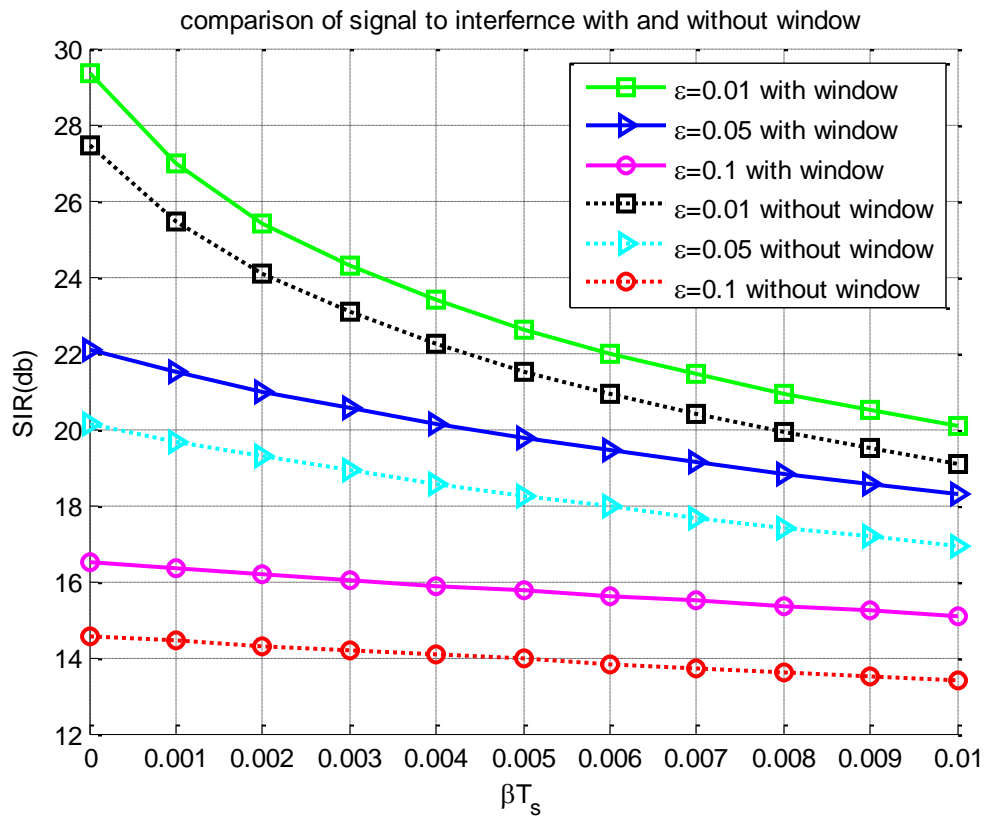


Fig. 4.4 SIR verses PHN using RC window

RC window in time domain is applied at transmitter side where each OFDM subcarrier get multiplied with window function. Its functioning depends upon roll off factor as it increases side lobe power level decreases hence ICI decays and ultimately SIR get improved.

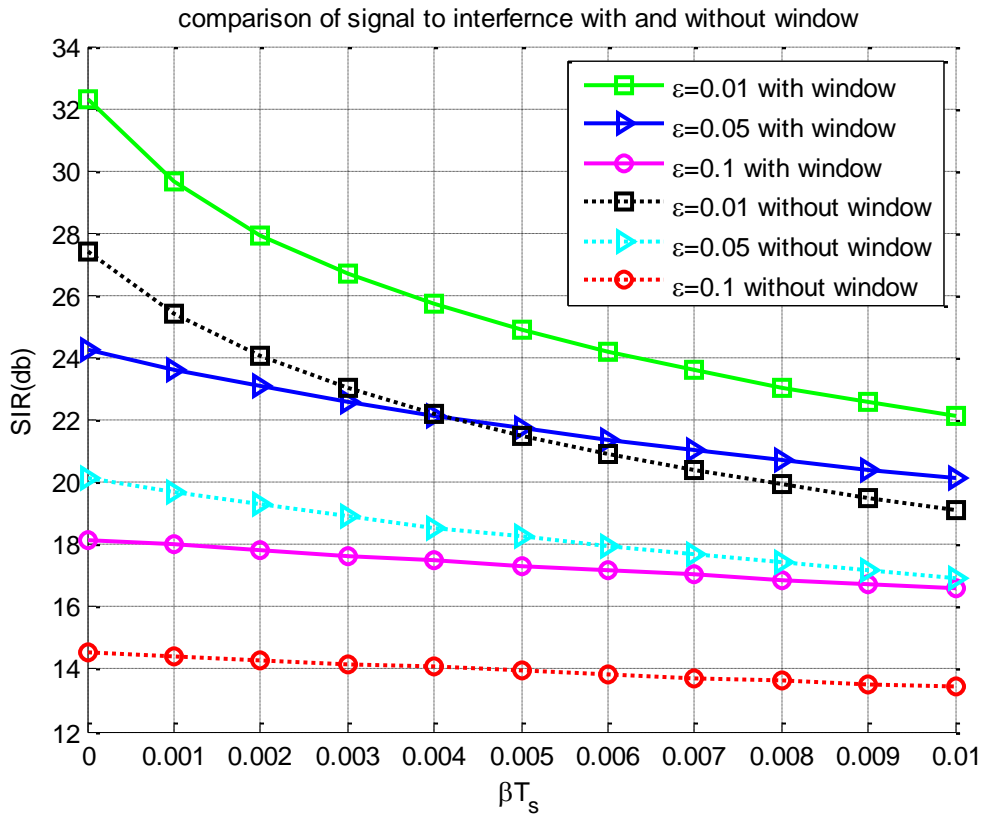


Fig. 4.5 SIR verses PHN using SP window

Fig. 4.5 depicts SP provides better result in ICI reduction and SIR improvement as compare to RC window function. So to improve the effects of RC pulse a new modified RC pulse is generated known as BTRC which further improves the result and prove to make available with better results as compared to SP.

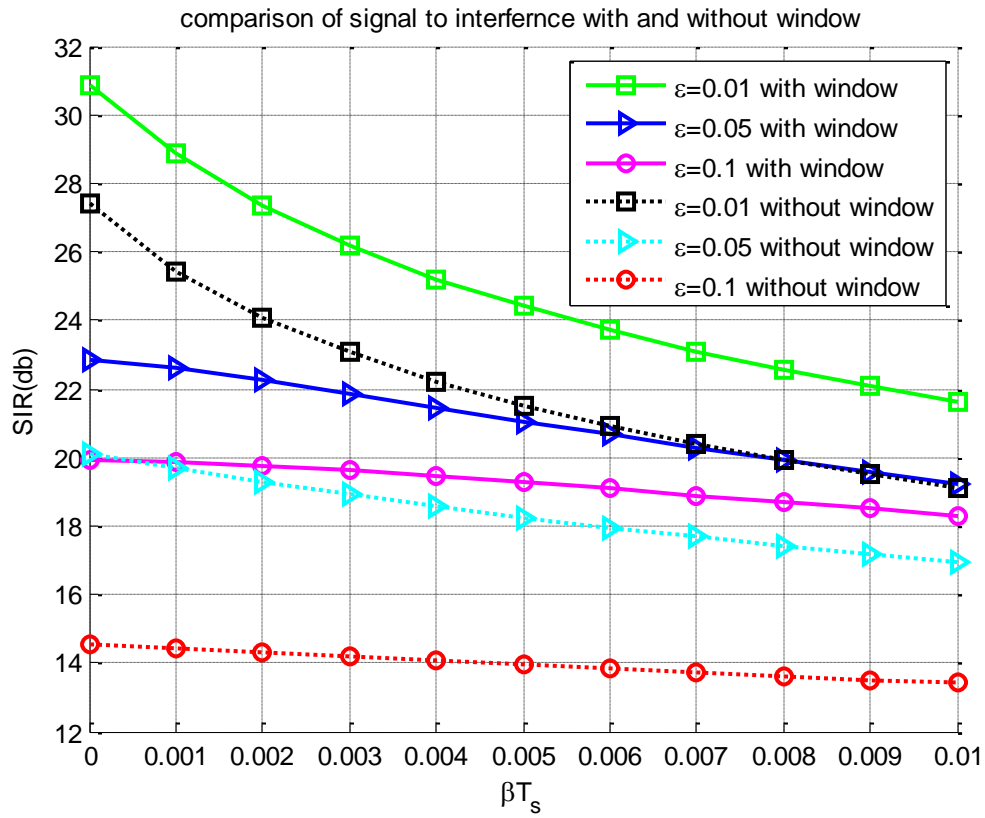


Fig. 4.6 SIR verses PHN using BTRC window

Fig. 4.6 shows improvement in performance of OFDM system in aspect of SIR which is improved version of Fig. 4.5. No doubt SP have maximum amplitude level but the side lobe level of BTRC is minimum that is why it outperforms SP.

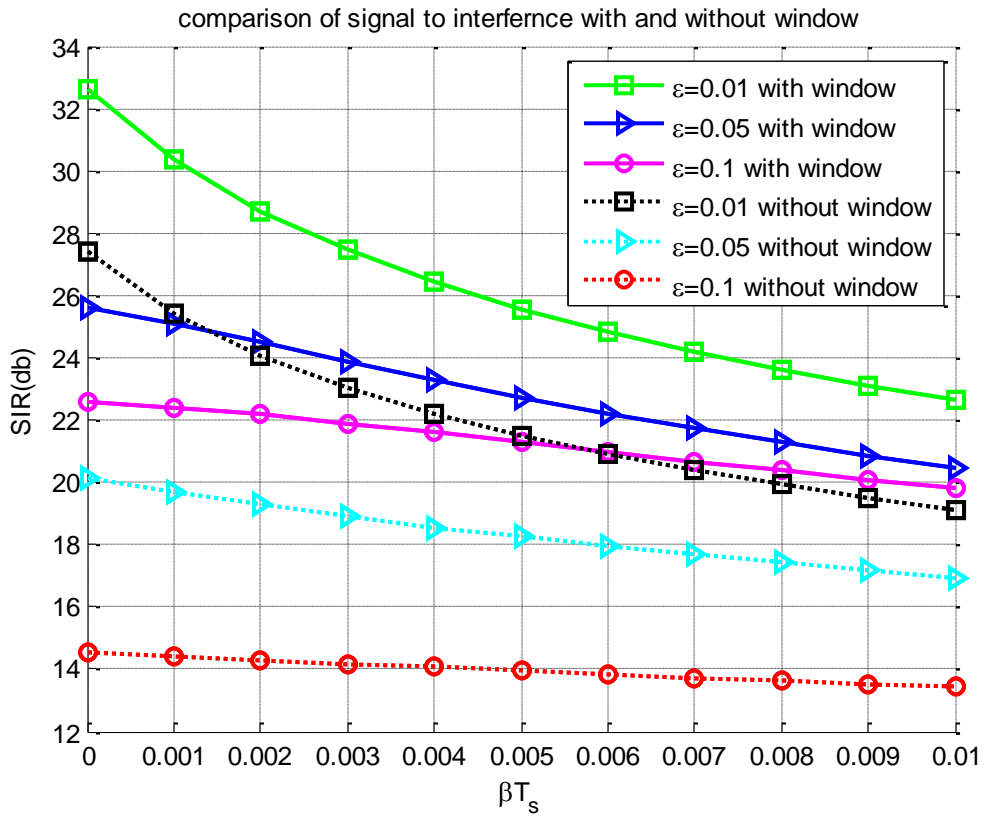


Fig. 4.7 SIR verses PHN using ISP window

Comparison of SIR with and without window is shown in above Figs. Window under consideration are RC, SP, BTRC, ISP. From the above Figs it can be concluded that ISP provide the best result. At all frequencies ISP has least amplitude due to this property of ISP it provides better performance in SIR improvement as compare to other pulses.

## **CHAPTER-5**

### **CONCLUSION AND FUTURE SCOPE**

This chapter concludes the thesis which encloses the method proposed for the enhancement of already obtained results. This also portrays further advanced expansion of the work displayed. OFDM is one of the promising multicarrier technologies in communication systems that have been embraced by various standards because of its well performance in multipath conditions. The transformative history of OFDM, its advantages and disadvantages incorporate its usage in wide areas which are exhibited in first chapter. The fast improvement in OFDM starts when DFT came into implementation rather than using bank of modulators.

Chapter 2 describes the literature review on effect of ICI and SIR on the performance of system and defining various methods of improving SIR over different channels with various conditions.

Chapter 3 lightens up the theory and arithmetic behind OFDM. The role of Fourier transform, guard band, cyclic prefix and zero padding is described and some are numerically dissected in OFDM framework. It clarifies various parts of OFDM framework like transmitter, channel and receiver model. Detailed expression of ICI and SIR are deliberated over doubly selective channel with various impairments like CFO, PHN. To improve the system performance, time windowing technique is embraced which enhances the SIR. OFDM system model with different time window functions like RC window, SP window, BTRC window and ISP window is proposed. Improved results by embracing these techniques are demonstrated in Chapter-4. By observing the results it is concluded that ISP provides best results among all.

In the present situation, the ICI issue is yet difficult issue to handle which cost the OFDM system performance. In this thesis, time domain windowing technique for the enhancement of OFDM system is presented. The system can be made more reliable by improving BER with the adoption of same strategy of time windowing over doubly selective channel. Further enhancement in performance of system will be accomplished. Distinctive techniques as exhibited in the literature survey chapter can be applied. Furthermore, other window functions can be applied to obtain further better results.

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