

# **THROUGHPUT ANALYSIS OF OFDM BASED WIRELESS SYSTEM WITH FrFT**

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# CERTIFICATE

Certified that the thesis entitled **“THROUGHPUT ANALYSIS OF OFDM BASED WIRELESS SYSTEM WITH FrFT”** being submitted by **Mr. Ankush Kansal** to the **Department of Electronics and Communication Engineering, Thapar University, Patiala** in fulfillment of the requirements for the award of degree of **“Doctor of Philosophy”** is a record of bonafied research work carried out by him. He has worked under our guidance and supervision and fulfilled the requirements for the submission of this thesis which has reached the requisite standard. The matter presented in this thesis does not incorporate any material previously published or written by any other person except where due references are made in the text.

The results obtained in this thesis have not been submitted in part or full to any other institute or university for the award of degree or diploma.



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*“Life without thankfulness is devoid of love and passion. Hope without thankfulness is lacking in fine perception. Faith without thankfulness lacks strength and fortitude. Every virtue divorced from thankfulness is maimed and limps along the spiritual road.”*

— *John Henry Jowett*

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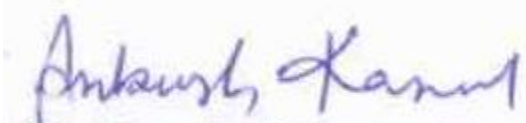
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# ABSTRACT

Fourier Transform (FT) is a well defined transform which has seen wide publicity and advantageous applications in the field of signal processing, optics and image processing. However, the real revolution in signal processing is given by its generalized form Fractional Fourier transform (FrFT) and has been utilized in this research work for wireless systems. The fractional variable ' $\alpha$ ' given the freedom to transform the signal into time-frequency plane and hence FrFT is able to analyze the signal performance more precisely in fast time varying frequency selective channel. The main problem in the existing Orthogonal frequency division multiplexing (OFDM) systems is its inability to detect the change in frequency of signal with time under wireless channel. This non-detection of exact frequency of the signal at any instance of time in a wireless channel increases the bit error rate (BER) of the system. The aim of this research work is to use the FrFT in OFDM wireless system which is based on IEEE 802.11g protocol and capable of delivering 54 Mbps of bandwidth. Here, the throughput analysis of FrFT based OFDM system has been carried out in terms of BER, Signal to Noise Ratio (SNR), Inter Carrier Interference (ICI), Carrier Frequency Offset (CFO) and Peak-to-Average Power Ratio (PAPR) as the performance metrics.

Hence, the contribution of this research work is develop an FrFT based OFDM system by using various modulation techniques for better performance and security of said system using the benefits of FrFT. The security of the signal transmitted on the wireless channel is not taken care in case of conventional OFDM system. Security of OFDM modulated signal in wireless domain has been enhanced as compared to existing OFDM system. In this proposed technique the FrFT is appended with the traditional OFDM system for encrypting the signal before transmitting. Now, instead of transmitting the plain OFDM signal in wireless domain; the OFDM modulated signal is encrypted with fractional variable ' $\alpha$ ' using FrFT before transmission. At the receiver side the FrFT appended OFDM signal must be first of all decrypted with exactly the same value of fractional variable ' $\alpha$ ' as was used for encrypting the signal at the transmitter. For all other values of ' $\alpha$ ' the demodulator intercepts the signal as noise. Further, the results achieved from the FrFT appended OFDM system in terms of BER vs. SNR are much better as compared to the traditional OFDM system. The proposed system has been able to improve the BER as compared to the traditional OFDM system under all the wireless fading channels.

Next, a FrFT based OFDM system has been proposed for higher order modulation techniques namely 1024-PSK and 1024-QAM, where, the IFFT/FFT block of existing OFDM system are replaced with an IFrFT / FrFT block at transmitter and receiver respectively. The said model has been able to give a improved performance in terms of BER as compared to existing FFT based OFDM system for higher order modulation techniques. In addition, the performance of this model has been simulated with various wireless fading channels and compared with existing FFT based OFDM system. The optimum value of fractional variable ' $\alpha$ ' is obtained to get the best performance of the given model. 1024-PSK and 1024-QAM modulation techniques have been proposed for the FrFT based OFDM model; henceforth the proposed model is considered to be very useful in the higher order transmission of data in wireless channels.

The recovery of source data from OFDM modulated signal at the receiver is mainly dependent on the orthogonality between the subcarriers used for modulating OFDM symbols. However, due to Doppler shift caused by mobility of source and destination; there is a change in the carrier frequency of subcarriers and generates CFO. This introduces Inter Carrier Interference (ICI) in OFDM and effects the channel estimation and symbol recovery at the receiver. Ultimately, it will increase in the BER of OFDM system. Another contribution of this thesis is to reduce the effect of CFO with the help of FrFT for further enhancing the performance of the existing OFDM system. The effect of CFO has been mitigated by proposing an FrFT based OFDM system with  $\pi/4$  Differential Quadrature Phase-Shift Keying ( $\pi/4$ DQPSK) modulation technique. The BER of  $\pi/4$  DQPSK modulated FrFT based OFDM system has been derived mathematically with CFO under the frequency selective Rayleigh channel. The BER calculated theoretically is compared with simulated results and found to be same. It has been established that the proposed model outperforms than FFT based OFDM for the optimized value of ' $\alpha$ '.

Gaussian minimum shift keying (GMSK) has also been used as a modulation technique for evaluating the performance of FrFT based OFDM. The problem of ISI and low spectral efficiency of GMSK has been solved by proposing the FrFT based OFDM system using GMSK. The BER is calculated mathematically and also simulated for the proposed model under the presence of CFO. Results obtained has shown that proposed GMSK based FrFT based OFDM system outperforms the existing FFT based OFDM under all wireless frequency selective fading channels.

Finally, the everlasting problem of PAPR in OFDM systems has also been reduced and is a contribution to literature. The PAPR analysis of the FrFT based OFDM system has been carried out for different type of modulation techniques like 1024-PSK, 1024-QAM,  $\pi/4$  DQPSK and GMSK. It can be concluded from the results achieved that the improved OFDM system has been proposed without any additional burden of PAPR. The PAPR can further be improved by using Selective Mapping (SLM) clipping technique. Results achieved in this research work have shown that the FrFT based OFDM system has shown improvement in PAPR for all the modulation techniques discussed above as compared to existing OFDM system.

# ACRONYMS AND ABBREVIATIONS

<b>Abbreviation</b>	<b>Description</b>
AES	Advanced Encryption Standard
AWGN	Additive White Gaussian Noise
BCH	Bose Chaudhuri Hocquenhem
BEM	Basic Exponential Model
BER	Bit Error Rate
BW	Bandwidth
BWC	Broad Band Wireless Communication
CCDF	Complementary Cumulative Distributive Function
CFO	Carrier Frequency Offset
CP	Cyclic Prefix
CS	Compressed Sensing
DAB	Digital Audio Broadcasting
DCS	Distributed Comprehensive Sensing
DCT	Discrete Cosine Transform
DDGMSK	Differential Detected GMSK
DE	Differential Evolution
DFrFT	Discrete Fractional Fourier Transform
DFT	Discrete Fourier Transform
DS-CDMA	Direct Sequence CDMA

DSP	Digital Signal Processing
DVB-T	Terrestrial Digital Video Broadcasting
EDGE	Enhanced Data Rates for GSM
EGT	Equal Gain Transmission
FDMA	Frequency Division CDMA
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FrFT	Fractional Fourier Transform
FT	Fourier Transform
GPRS	General Packet Radio Service
GSM	Global System for Mobile
ICI	Inter Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
LCT	Linear Canonical Transform
LTE	Long Term Evaluation
MB-OFDM	Multiband OFDM
MC	Multicarrier
MC-CDMA	Multicarrier CDMA
MCM	Multicarrier Modulation
MIMO	Multiple Input Multiple Output

MISO	Multiple Input Single Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
M-PSK	M-ary Phase Shift Keying
M-QAM	M-ary Quadrature Amplitude Modulation
MRT	Maximum Ratio Transmission
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Access
PAPR	Peak-to-Average Power Ratio
Pdf	Probability Distribution Function
PLL	Phase Locked Loop
RFBC	Receiver Frequency Block Code
SFBC	Space Frequency Block Code
SINR	Signal to Interference Plus Noise Ratio
SIR	Signal to Interference
SLM	Selective Mapping
SNR	Signal to Noise Ratio
SPI	Search and Partial Interpolation
TDS-OFDM	Time Domain Synchronous OFDM
TVSNR	Time Varying Signal to Noise Ratio
W-CDMA	Wideband CDMA

# GLOSSARY OF SYMBOLS

Symbol	Description
$\alpha$	Fractional parameter
$F_\alpha$	Fractional Fourier Transform at angle ' $\alpha$ '
$F_{-\alpha}$	Inverse Fractional Transform
$\sigma^2$	Variance
$\delta(l)$	Kronecker Delta Function
$f_d$	Doppler Frequency Shift
$w(n)$	AWGN Noise
$J_0$	Bessel Function of 0 <sup>th</sup> order
$\epsilon$	Frequency Offset
$\xi$	Normalized Carrier frequency Offset
$E[X]$	Expectation of random variable $X$
$\gamma_{l-1}[k]$	Phase of symbol modulated on $(l-1)^{th}$ sub-carrier of $k^{th}$ symbol
$N_{CP}$	Cyclic Prefix length
$k$	$k^{th}$ subcarrier
$s_i(k)$	Symbol to be transmitted
$U$	Statistically independent FrFT based OFDM frame

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# CHAPTER 1

## INTRODUCTION

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### 1.1 PREAMBLE

In this world of wireless communication era, there is tremendous increase in demand of spectrum for large data transmission over wireless channel. Wireless technology is widely used globally and still growing [1-3]. Wireless technology has helped in expanding the work of companies outside office premises or in field. People and business are beginning to depend heavily on wireless services. Various advantages of wireless systems are easy installation, low cost, high capacity, and minimum transmission losses [4, 5]. These systems are physically robust as there are no cables in a wireless system, which can be destroyed [6]. The major drawbacks of these networks are security, limited bandwidth and capacity; which is much smaller than optical fiber. However, this problem of limited bandwidth and scarcity of spectrum had greatly dealt with by using Multicarrier Communication (MC) instead of single carrier communication [7-10]. Orthogonal Frequency Division Multiplexing (OFDM) is one of the multicarrier communication techniques [11, 12] which solved the problem of bandwidth in wireless channel by spectrum overlapping of allocated carrier frequencies. OFDM transmits multiple symbols simultaneously over a wireless channel [5, 13-15]. Each symbol is modulated by different subcarrier [16-18]. In OFDM the subcarrier are chosen in such a way that they all are orthogonally separated; but still are overlapped [19-21]. This orthogonality helps demodulators to demodulate the different symbols at receiver corresponding to that particular sub carrier [22, 23].

The major advantage of OFDM is its efficient utilization of bandwidth by overlapping the sub carriers and immunity to multipath fading in wireless domain [24]. This is possible because at receiver the signal is received from various paths it followed in wireless channel [25, 26].

Due to inter symbol interference, it is difficult to extract the original transmitted signal from multiple received signal components [10, 27, 28]. Wireless communication had been developed over IEEE 802.11 standard [29-31]. The IEEE 802.11 standard agency has released various advanced versions of IEEE 802.11 protocol namely 802.11a, 802.11b,

802.11g and 802.11n [32, 33] time to time. Out of these, IEEE802.11g is based on OFDM and can support bandwidth up to 54 Mbps [34-36]. OFDM system could be designed using many modulation techniques. OFDM systems have been developed by using multicarrier communication system and are based on time-frequency domain of the signal; hence it results in high efficiency and gives improved response of wireless networks as compared to traditional systems [37, 38].

## **1.2 ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING**

The demand of higher data rates in wireless domain had generated the use of multicarrier communication systems in mobile communication [2, 33]. The traditional FDMA and TDMA based single carrier communication systems are not capable of handling applications that demand large speed, high bandwidth and large capacity [39, 40]. The communication systems like DS- CDMA and WCDMA systems suffer from multipath fading in wireless channels [41]. The performance of these systems degrades significantly under frequency selective Rayleigh fading channel [42]. With increase in number of users the performance of these systems degrades more. Moreover, the integration of various applications like; video on demand, online gaming and large file sharing in cellular systems could only be catered by multiple access techniques like WCDMA, MC-CDMA, OFDM, MIMO and MIMO-OFDM systems[34, 43, 44]. Hence the wireless technology had been shifted from single carrier to multicarrier communication systems. MC-CDMA and OFDM are the multicarrier communication techniques used in next generation broadband wireless communication networks [1, 36].

Initially, the multicarrier communication systems were working on transmitting the multiple data symbols on multiple carriers without any overlapping of sub carriers. This process was developed by army in the 1960's and was called as multicarrier communication (MCM) [45, 46]. Although, these MCM based systems were able to provide the answer for large data transmission, but the non-overlapping of sub carriers the spectral efficiency of these MCM systems was very poor [47]. In addition, these systems were required very complex system integration like individual oscillator for each sub carrier and that to be synchronized with all other oscillators of sub carrier used at same instance by MCM [48]. However, to recover signal at receiver MCM systems made the sub carriers of adjacent symbols as orthogonal to each other. Hence MCM was named as band limited OFDM system [48]. Later on a time limited orthogonal signals based MCM system was proposed by H.F. Marmuth [49] called as

OFDM system. The major benefit of OFDM in terms of spectrum efficiency was proposed by overlapping the orthogonally separated sub carriers in 1966 by R.W. Chang [47]. Although till date OFDM system was able to use the spectrum very efficiently and transmit data with moderately higher rate as compared to previous single carrier communication systems; but still OFDM systems were suffering from high cost very complex system integration which requires an individual oscillator for each sub carrier at both transmitter and receiver [48, 50]. This problem was solved by Weinstein *et al.* [51] by replacing individual oscillators for sub carriers at both transmitter and receiver with IDFT and DFT at transmitter and receiver respectively. This DFT based OFDM system was very cost effective and less complex as compared to traditional OFDM system. Further, the implementation of FFT had reduced the cost and complexity of OFDM circuits. Henceforth, the first use of OFDM system in industry was done in digital audio broadcasters (DAB) in 1995 [52-55]. Since 1995 to till date the researchers had contributed a lot in the improvement of performance of OFDM systems in terms of BER, PAPR etc. The behavior of OFDM system under wireless fading channel had been carried by [56, 57].

The various applications of OFDM system are given as

- a) OFDM is used in next generation wireless broadband networks like 4G systems [58].
- b) OFDM is used in IEEE 802.11 a/b/g protocol used in Wi-Fi networks [59, 60].
- c) It is used by fixed and wireless mobile systems (Wi Max) using IEEE 802.16 protocol [61, 62].
- d) It is widely used in Digital audio broadcasters (DAB) and terrestrial digital video broadcasters (DVB-T) [1, 63].
- e) OFDM systems have been adopted by HIPERLAN networks to achieve data range of as high as upto 54Mbps [64].
- f) OFDM systems had seen the application in ultra wide band (UWB) systems by using multiband OFDM (MB-OFDM) [40, 65].
- g) Finally, OFDM systems have also been implied by MIMO systems for enhancing the system performance under highly disturbed frequency selective fading channels as MIMO-OFDM systems [40, 66].

The major advantages of OFDM systems are given:

- OFDM systems can provide large capacity, higher data rates and high spectral efficiency as compared to single carrier systems.

- As the data is spread in large frequency spectrum in OFDM, hence the effect of interference is very less in it. Moreover, by using interleaving between the data to be transmitted on different sub carriers the burst error which may occur in channel transmission due to some deeply faded channels may be distributed into different sub carriers and hence is very easy to recover the error free data at receiver by using very less number of bits for Forward Error Correcting (FEC) codes.
- The implementation complexity of OFDM systems are very easy due to use of FFT and IFFT.
- The parallel transmission of data makes OFDM system reduce the effect of frequency selective fading upto large extent. As the large number of subcarriers used in OFDM makes the channel to behave approximately as flat fading channel.

Although there are large number of advantages of OFDM over single carrier communication systems; but it also suffers from certain limitations. All the major shortcomings of OFDM systems are listed below:

- OFDM systems are very prone to ICI. The major reason for generation of ICI is due to carrier frequency offset (CFO) caused by mobility of source, destination or both in wireless networks. The mobility of the users cause Doppler shift which is the source of CFO [22, 67].
- The timing synchronization of start of symbol is very important for the correct processing of symbols by IFFT or FFT at transmitter or receiver respectively [16, 68].
- OFDM signals have very high PAPR. The performance of power amplifiers degrades due to high PAPR and eventually reduces the efficiency of OFDM systems [69-71].

The work has to be carried out to overcome the above stated shortcomings of OFDM systems.

### **1.3 FRACTIONAL FOURIER TRANSFORM (FrFT)**

The role of transformation is to extract the information from signal by changing its domain from time to frequency or vice versa. For e.g. the signal in time domain gives the amplitude of signal at any instance of time but is totally silent about the frequency of that signal at that particular instance of time. The Fourier transform (FT) can give the frequency status of signal by transforming the domain of signal from time to frequency domain [72]. FrFT is the further extension of FT which gives the fractional order response of FT. FrFT is also called as the generalized form of FT. The very first definition of FrFT was given in 1929 by N. Wiener

[73] as a form of solving partial differentiation equations. The real revolution in the development of FrFT was seen after V. Namias [74] gives its definition as transformation method. In 1994 FrFT was widely used in various applications of signal processing and optics [74-77]. As FrFT is used in communication models, the computation of FrFT with computers was the need of hour. So FrFT was discretized and DFrFT was proposed [78, 79]. The FrFT follows unitary property, additive property, and reduces to FT at unity transform order [78, 80]. FrFT has seen various applications in the field of image processing, radar communication and optical science [81-84].

The representation of signal in time or frequency domain does not reveal the complete information about the signal. The solution to this problem is to provide two domain information of signal i.e. time-frequency space. The time-frequency domain gives the exact frequency of the signal at any instance of time. This time-frequency domain can perfectly define the chirp signals which changes frequency with time. A time-frequency domain transforms the one dimensional time or frequency domain signal into two dimensional function of time and frequency [81-83]. The time varying signals can easily and accurately be analyzed using discrete time-frequency transforms. FrFT is the answer for all this time-frequency representation of signal [76, 84]. The FrFT of a signal  $x(t)$  is given by [76]

$$F(x(t)) = X_{\alpha}(q) = \int_{-\infty}^{+\infty} x(t) K_{\alpha}(t, q) dt \quad (1.3.1)$$

where, ' $\alpha$ ' is the fractional transform variable with range from -1 to +1 and is given by

$\alpha = \frac{a\pi}{2}$  and the FrFT kernel  $K_{\alpha}$  is given by [76]

$$K_{\alpha}(t, q) = \begin{cases} \sqrt{\frac{1 - j \cot \alpha}{2\pi}} e^{\frac{j}{2}[(t^2 + q^2) \cot \alpha - 2tq \csc \alpha]} & ; \text{if } \alpha \neq n\pi \\ \gamma(t - q) & ; \text{if } \alpha = 2n\pi \\ \gamma(t + q) & ; \text{if } \alpha = (2n + 1)\pi \end{cases} \quad (1.3.2)$$

FrFT becomes an identical operator at  $\alpha = 0$ , whereas at  $\alpha = \pi / 2$  the FrFT converges to FT. FrFT converges to Inverse FrFT or IFrFT at  $\alpha = \pi$  [76].

There are many methods by which time-frequency two dimensional domain representation of signal can be given like FrFT, Wigner distribution and Short time Fourier Transform (STFT) [85-87]. Each of these methods has its own advantages and applications. It is very important to choose the appropriate method for time-frequency analysis of signal. In this thesis work,

the OFDM system performance is being analyzed, hence FrFT has been selected for analyzing the behavior of OFDM in time-frequency channel. The reason for choosing FrFT is its much better results for multi component signals [88, 89] as compared to Wigner distribution and STFT.

Since the channel frequency response is rapidly time varying, the original FFT based OFDM system fails to demodulate data efficiently at receiver due to loss of orthogonality between subcarriers in wireless channel [76]. The solution for this problem had been proposed by Chen *et al.* [90] by defining FrFT based OFDM system [40, 91, 92]. The FFT based OFDM system security could be enhanced by appending FrFT link immediately before channel at transmitter side and at the beginning of receiver. In this FrFT appended OFDM system, the value of FrFT variable ' $\alpha$ ' is used for encrypting the transmitting data and at receiver side the signal could only be demodulated correctly with exactly the same value of ' $\alpha$ ' as was used at transmitter else for other values of ' $\alpha$ ' receiver will treat all the received signal as noise.

#### **1.4 CONTRIBUTION OF THESIS**

The main contributions of this research work are listed below:

- i. The security of existing OFDM system is enhanced by appending FrFT before and after the wireless channel. In this proposed model, the OFDM modulated signal is encrypted with a particular value of fractional variable ' $\alpha$ ' and then transmitted in radio domain. At the receiver side, the received signal could be decoded only with the exact same value of ' $\alpha$ ' which was used at transmitter. For all other values of ' $\alpha$ ', the receiver will interpret the signal as noise only. This encryption of existing OFDM signal has added a new security level in OFDM transmission. Moreover, it had been analysed that the appending of FrFT has also improved the BER vs. SNR of existing OFDM system.
- ii. It has been established that the symbol rate of existing OFDM system can be enhanced to as high as upto 1024 symbols. An FrFT based OFDM system for 1024-PSK and 1024-QAM modulation technique is proposed. In this proposed model IFFT/FFT is replaced by IFrFT/FrFT at transmitter and receiver respectively. By using the freedom of fraction variable ' $\alpha$ ' of FrFT, improvement in the form of BER has been achieved in proposed system as compared with the existing FFT based OFDM system.

- iii. A new modulation technique namely  $\pi/4$  DQPSK modulation has been proposed for FrFT based OFDM system. The reason for using said modulation technique is its wide application in TDMA cellular systems. The new proposed system could easily be implemented for 4G technology because of the encouraging results achieved in this research work. In this the mathematical analysis of BER for proposed system along with CFO has been presented; which is a contribution to existing literature.
- iv. In this research work another FrFT based OFDM system has been proposed based on GMSK modulation technique. As GMSK modulation technique has widely been used in 2G and 2.5 G cellular systems. It has been established in this thesis that same modulation technique can be adopted in 4G cellular systems on the basis of improvement achieved in BER as compared to existing FFT based OFDM system by using optimized fractional variable ' $\alpha$ '. Further, the proposed system has shown much better improvement in PAPR for different modulation techniques by using SLM clipping technique.

## 1.5 ORGANIZATION OF THE THESIS

**Chapter 1** is introductory and serves the purpose of familiarizing the basic concept needed in the subsequent chapters. It starts with the general overview of wireless communication systems. Then effect of multipath fading, wireless fading channels, multicarrier communication and its benefit over single carrier communication is discussed. Further, an introduction to the FFT based OFDM system and its historic development had explored. Then the introduction and evolution of FrFT is presented. Finally, the chapter wise thesis organisation has given.

**Chapter 2** gives a comprehensive review of related literatures to provide background information on the issues considered in the thesis and to emphasize the relevance of the present study. It presents the preliminaries of wireless communication, single carrier and multicarrier communication, wireless fading channels, OFDM, Fractional Fourier Transform and modulation techniques. It comprises of the definitions and results for existing FFT based OFDM with various modulation techniques and fading channels. In the initial stage, a thorough study of the FFT based OFDM system in the literature has been carried out. The advantages and deficiencies of the FFT based OFDM documented in the literature are highlighted for study of OFDM system. Then literature defining time-frequency analysis of signal in wireless domain is presented. After this, literature defining recent development in

FFT based OFDM and FrFT based OFDM systems is presented. Finally, the papers for improving bit error rate (BER) and reduction of ICI of FFT based OFDM and FrFT based OFDM system are discussed. Critically analyzing the literature, some gaps were formulated. Based upon the gaps found in the literature, objectives and methodology for the current work were decided.

**Chapter 3** discusses the FFT based OFDM along with its mathematical analysis. The use of pilot signal and serial to parallel converter in OFDM is explained in this chapter. Then FrFT was used to calculate the change in frequency with time in OFDM. A new FrFT appended OFDM system is proposed for compensating the effect of frequency shift under wireless channel and providing the security to transmitted signal. In this FrFT had appended before feeding the transmitting signal to wireless channel and at receiver side immediately after wireless channel. The BER vs. SNR analysis of said model had also been shown for various values of fractional transformation coefficient ' $\alpha$ ' from 0.0 to 1.0. Finally, the benefits of appending FrFT before and after channel in traditional FFT based OFDM system have discussed. This will add to security of data in wireless domain. The behaviour of both systems had analyzed for various wireless fading channels.

In **Chapter 4**, the block diagram of proposed FrFT based OFDM system is discussed. The proposed FrFT based OFDM by replacing FFT computation had been analyzed. A comparison of the proposed FrFT based OFDM was done with the literature. The performance of OFDM in the FrFT domain has compared with FFT domain in terms of BER versus SNR. A simulation comparative analysis of proposed FrFT based OFDM under higher order data rate with existing FFT based OFDM has been presented. Finally, the BER analysis of proposed system has been given for various wireless fading channels and compared with traditional FFT based OFDM system. Further, PAPR analysis of FrFT based OFDM system is presented for different modulation technique. Improvement in PAPR for proposed system was shown for different modulation techniques by using SLM clipping technique.

In **Chapter 5**, the effect of ICI due to CFO is presented. Here the  $\pi/4$  DQPSK modulation technique has used for analysing the performance of FrFT based OFDM with CFO. Here after explaining the effect of ICI on OFDM's orthogonality,  $\pi/4$  DQPSK modulation technique has been explained. Subsequently, the mathematical modelling of ICI and BER analysis for  $\pi/4$  DQPSK was derived for proposed system, which has not already been done for said modulation technique and is a contribution towards the literature. In this chapter an

expression of BER of FrFT based OFDM system for  $\pi/4$  DQPSK modulation has been successfully derived. The response of proposed system for ICI and BER was derived and simulated for frequency selective Rayleigh fading channel. Simulation results are shown for the proposed FrFT based OFDM system with  $\pi/4$  DQPSK modulation technique and compared with the traditional FFT based OFDM system for same modulation technique. The effect of CFO on the proposed system has also been analysed. PAPR is another performance metric that had been studied for the proposed model.

In **Chapter 6**, GMSK modulation technique and its applications have been presented. Here implementation of GMSK based FrFT based OFDM system is discussed. The BER vs. SNR analysis of proposed system with GMSK modulation under various fading channels is discussed. The BER of proposed system with GMSK modulation technique has been derived mathematically, which is new and had not been done earlier. Further, the PAPR analysis of FrFT based OFDM system for different modulation techniques like 1024-PSK, 1024-QAM,  $\pi/4$  DQPSK and GMSK has been presented.

Finally, the conclusion of the thesis along with the possible future scope in the area of work is discussed in **Chapter 7**.

# CHAPTER 2

## LITERATURE REVIEW

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This chapter discusses the detailed analysis of work done till date in the area of OFDM. Here the focus is also given to FrFT and the shortcomings of OFDM systems like ICI, ISI and PAPR. It also discuss the solutions for these problem provided by various researchers till date. Based on the literature survey, gaps in the reported study have been reported and objectives for said research work are defined. Finally, the research methodology is defined.

### 2.1 INTRODUCTION

The demand for high speed and larger bandwidth on wireless networks is growing rapidly day by day. Today large amount of data is shared on broadband wireless networks [61]. To satisfy the need of large data transmission over wireless network, one has to use the spectrum very efficiently as the wireless spectrum is band limited and there is tremendous increase in its demand. These higher data transmission requirements had also increased now a day due to large demand of data by multimedia applications on mobile networks [93]. It has been studied and reported in literature that multicarrier systems like OFDM, MC-CDMA are best suitable for efficient use of wireless channels [36]. Moreover, the behaviour of wireless channel can be represented by fast time varying frequency selective channel and are demodulated very efficiently by OFDM systems [43]. OFDM is the best solution for catering the demand of bandwidth (BW) over wireless media. In OFDM, the data had been subdivided into frames and each frame had been modulated on different subcarriers. These modulated frames had transmitted in parallel over overlapped wireless channels and saves the bandwidth. Further, these overlapped subcarriers had separated orthogonally to each other and hence could easily be demodulate at receiver.

FFT based OFDM systems were performing much better as compared to single carrier systems in terms of bandwidth utilization of spectrum [29]. However, when the channel becomes time-frequency selective, this FFT based system fails; because the channel is varying its frequency rapidly with time. To analyze the signal performance in time varying

channel, the FrFT should be used instead of FFT [78]. In this thesis work, FrFT based OFDM system had been evaluated using 1024-PSK, 1024-QAM, GMSK and  $\pi/4$  DQPSK modulation techniques. The reason for using these modulation techniques is that, the current mobile communication systems are deploying modulation techniques like GSM and CDMA systems are based on GMSK and  $\pi/4$  DQPSK modulation techniques respectively. Hence, the proposed FrFT based OFDM system with said modulation techniques could easily be deployed for next generation mobile communication like 4G.

Although OFDM system provides so much benefits for wireless applications but it suffers from certain deficiencies also. The frames of OFDM signal modulated on different subcarriers have different peak powers. This large variation in peak amplitudes of OFDM envelopes is the major drawback of OFDM, because the practical communication amplifiers are peak-power limited [71]. These amplifiers are not able to handle change in instantaneous signal power, which is much larger than signal power. In order to compensate this problem, the amplifiers are required to have large linear operating range. This problem had been defined as PAPR problem [40]. Secondly, the response of OFDM system is largely dependent on orthogonality between subcarriers. Slight deviation in subcarriers under wireless domain due to multipath fading, channel dispersion etc. the performance of OFDM system degrades upto large extent. However, the drift in frequency causes drift in CFO which eventually generates ICI in OFDM system [22]. In this thesis work, emphasis is given to improve the system performance by subsidising ICI effect in proposed FrFT based OFDM system with CFO. The work done by various researchers in the said area is reviewed and reported here.

## 2.2 WIRELESS NETWORKS

A lot of work is done in the development of wireless networks to increase its efficiency and speed. **W. Stallings** [94] described the IEEE 802.11 protocol for wireless networks. Further, the various developments in IEEE 802.11 standard have been issued by development group. The evolution and architecture of IEEE 802.11 protocol had been presented in very simple and understandable manner. **Y. Xiao et al.** [32] had given the maximum throughput and minimum delay limits which can be achieved by IEEE 802.11 protocol. IEEE 802.11 standard can provide maximum of 54 Mbps data speed. **S. C. Sharma et al.** [95] had given the comparison of routing algorithms used for data transmission on wireless networks. The development of these high-speed wireless networks had set the path for accessing internet services over these networks. The ever increasing demand of higher data rates by

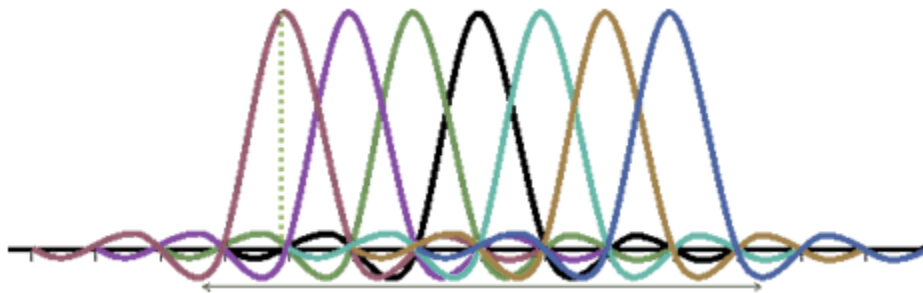
wireless communication industry had remained unanswered due to limitations of limited wireless spectrum, multipath fading in wireless domain and overheads. The system performance cannot be enhanced without reducing these overheads. **H. Woesner** *et al.* [96] provided an outline of system which is utilized for power saving in WLAN networks. These standards address the power saving on the MAC level in a quite different way. Author introduced the mechanism for power saving in ad-hoc networks with some trade offs for optimization of system performance. **D. Niyato** *et al.* [97] discussed the implementation of IEEE 802.16 protocol for telemedicine services and its scope in terms of wireless based applications. **G. Ohta** *et al.* [64] concluded that to support high speed newly introduced wireless broadband networks WLANs are required because of WLANs capability to provide large data rates and seamless mobility which could not be given by traditional cellular systems. **S. Vadivel** *et al.* [98] had proposed new algorithm for interoperability of web services, so that they all are compatible with each other and are able to open at wireless devices. The existing WLANs like OFDM systems can provide data rate as high as upto 2 Mbps that too in running train at speed of 95 km/h. With the advancement in wireless networks and use of internet applications on these networks, it have emerged the need of developing the efficient intrusion detection system. **A. Abraham** *et al.* [99] had developed a hybrid intrusion detection using combination of classifiers in order to make the intrusion detection more efficient. Also hyper cube based architecture had been defined by **D. Kaur** *et al.* [100] for high speed wireless systems. This architecture had based on digital demultiplexing and demodulation algorithms. The major drawback of these networks is its security over wireless channel, limited bandwidth and their capacity is much smaller then optical fiber. The security, integrity and utilization of world's computation and system information access of wireless networks in a more efficient and secured way had defined in cyber security by **P.P. Dey** *et al.* in [101]. Further, **A. Pande** *et al.* [93] detailed challenges in delivery of multimedia content over 4G networks for various applications. Emerging immersive applications, augmented reality, and others are also classified into these categories. Important challenges faced are the design and implementation of robust video quality assessment metrics for mobile stations. Also, **J. S. Park** *et al.* [102] highlighted the new services and security concerns of WLANs as compared to traditional wired local area networks. The security of WLANs can be improved significantly with enhanced technologies, improved standards and service conditions; however the WLANs can never be made fully secured i.e. intrusion may still be possible. **S. Simoens** *et al.* [103] focused on development of wireless networks along with review of physical layer and MAC layer

characteristics of WLANs. Then verification of analytical throughput of physical layer is done. It had been shown by author that the throughput of system could be tripled and its range can be doubled by adding space time code in existing multicarrier communication systems. **S. Peddabachigari** *et al.* [99] worked on intrusion detection and evaluation of WLANs. The author had given Hybrid Decision Tree and Support Vector Machine (DT-SVM) for intrusion detection. **L. Nazaryan** *et al.* [104] proposed IPsec as security protocol for WiMAX networks. The traffic from source to destination was protected by using various cryptographic techniques. After series of simulations it is observed that Advanced Encryption Standard (AES) is the best and easy to implement cryptographic technique for IPsec for WLANs. **K. Manoj** *et al.* [95] evaluated the various routing algorithms adopted by ad-hoc networks using OPNET. The performance of routing algorithms was measured on the basis of traffic, throughput and number of retransmissions. Author proved that WLANs performed well using AODV routing algorithm in terms of received control traffic, and data transmitted. However, DSDV performs well for data received and throughput. **A. S. Zahmati** *et al.* [6] reviewed existing wireless techniques for various applications along with their limitations and conditions. In aerospace industry various wired communication are being considered to be replaced by wireless communication as it guarantees multitude of advantages. Moreover, wireless links are more reliable and secured now days as compared to traditional networks. In addition, non-interference with aircraft electronics, high level of security, anti-jamming property and dedicated resend frequency band requirements are the basic needs of wireless applications in aerospace. **H. Zhai** *et al.* [105] explained the increasing interest in voice over IP (VOIP) in wireless which used enhanced DCP protocol. Due to difficulty of supporting QOS requirements for VOIP, author developed a new scheme for call admission control which is based on MAC layer for providing VOIP. It regulates voice traffic efficiently to coordinate medium combat among voice services. The proposed scheme can well support QOS guarantees for voice traffic. At the same time it provides very high throughput for non voice services.

### **2.3 ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING**

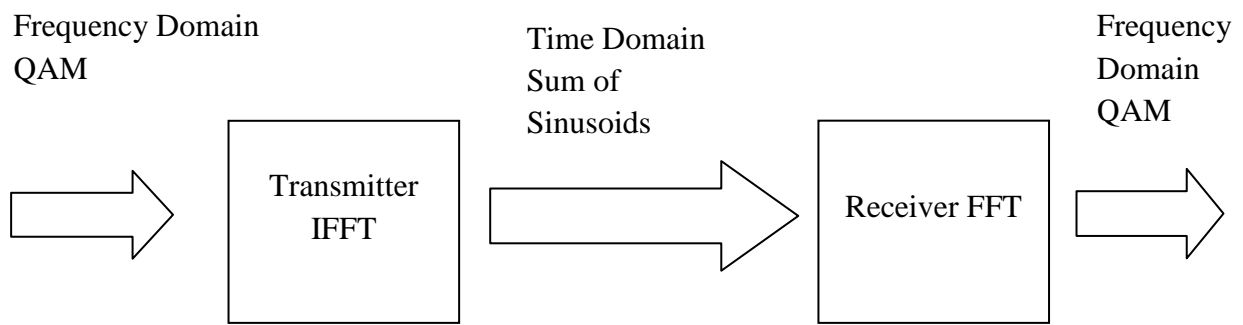
In OFDM, the required data to be transmitted is distributed into number of equally spaced large number of sub-carriers. The detection of these equally spaced sub carriers at receiver side is very easy because of the ‘orthogonality’ maintained between successive sub carriers. Due to this orthogonality between sub carriers, at receiver side, the signals are easily

demodulated without accessing adjacent frequencies, which are not meant for that particular band [106]. The main advantage of OFDM is its efficient use of spectrum due to overlapping of subcarrier frequencies as shown in Figure 2.1. Moreover, the OFDM signal has pliancy to RF interference as well as very low multipath fading distortion [107, 108]. This distribution of transmitted data into different sub carriers make the transmitted signal immune to multipath fading as well as ISI upto great extent [36, 109]. The reason for ISI immunity in the case of OFDM is due to its longer duration of each sub carrier frequency which is much larger than individual symbol duration [1].



**Figure 2-1: OFDM sub carrier overlapping [9]**

OFDM used the time-frequency channels very efficiently which eventually resulted in enhancing the efficiency of OFDM system over other multicarrier systems. Also, this efficient spectrum utilization by OFDM has improved the performance of broadband wireless systems [110]. OFDM helps to transmit large amount of data in wireless domain and has the ability to fulfil the demand of next generation wireless systems. **H. Steendam** *et al.* [92] reviewed about the fading channels in mobile radio communication, which are changing their frequency with time. To prevent the effect of frequency shifting dependency, the OFDM has been kept forward, but its performance is affected by changing time. The author focused on the various parameters like guard interval, sub carriers etc for analysing the system performance. Wideband OFDM is another widely accepted wireless transmission technique. The OFDM systems were possible only after availability of very high speed DSP processors and reduction in its cost [72]. Figure 2.2 shown below gives the basic implementation of OFDM system.



**Figure 2-2: Basic Block diagram of OFDM system**

The traditional communication systems required many oscillators for processing different sub carriers and all the oscillators required to be locked to get exact multiples of frequencies, which was very expensive and difficult to synchronise [5, 30]. **S. Weinstein** *et al.* [51] computed frequency-division multiplexing (FDM) using DFT. Here the authors eliminated the banks of subcarrier oscillators, a complete digital operation can be built around a special-purpose computer, doing the Fast Fourier Transform (FFT). The effects of variations in channel distortion, equalization algorithms and signal design criteria are investigated. DSP processors are considered to be best solution for this problem [72, 80]. Oscillators represent the sine wave subcarriers in numerical domain in digitized form for all sub carriers simultaneously. The outputs of each oscillator are added and hold. Now the signal that is in frequency is to be modulated in time domain. Hence, IFFT is applied on each block. This will convert the frequency domain signal to time domain. At receiver side, the received signal is again digitized and FFT is performed on the said signal. This will again convert the signal in frequency domain. Finally, it is very easy to recover the data from these orthogonally separated sub carriers [36, 111]. As shown in Figure 2.2, it is clear that FFT is one of the important blocks in the implementation of OFDM. FFT which is the digital implementation of Fourier Transform (FT) is a frequently used mechanism in signal processing and analysis [63]. In Coded OFDM (COFDM) some of the carriers are used for only channel estimation along with some extra bits for forward error detection and correction [1, 29]. Traditional radios are using 2.4 GHz spectrum based on DSSS, which is very prone to echoes and multipath fading. This problem can easily be resolved by adopting 5 GHz band for radios, hence they can easily adopt OFDM and avoid echoes and multipath fading effects. One of the outstanding features of an OFDM radio operating in 5 GHz is its ability to overcome hindrances such as mountains, trees and buildings to link between transmitter and receiver for long distance, where, no line of sight link is available [64]. With OFDM, the range of 15 to

50 Km can easily be covered in different geographical areas. Moreover, if line of sight link is available the performance of OFDM system improves significantly [112]. The recent development and performance evaluation of traditional FFT based OFDM reviewed by various researchers is discussed next.

**A. Glavieux** *et al.* [21] studied the performance issues of non-coherent reception over the multipath fading channels using binary frequency shift keying (BFSK) and OFDM modulation with or without channel coding. Channel coding helps in avoiding interference caused due to multiple paths. **A. N. Akansu** *et al.* [1] presented conventional and developing applications of orthogonal synthesis/analysis transform configurations (trans-multiplexer) in communications. It is revealed that orthogonal filter banks (sub band transforms) with appropriate time–frequency features can help to design new systems. Authors also proposed an attempt to raise the visibility of developing communication applications of orthogonal filter banks and to create more research activity in the signal processing community on these topics. Orthogonal synthesis/analysis filter banks (multiplexers) are most widely used for a variety of single and multiuser communication systems. **T. Y. Al-Naffouri** *et al.* [39] proposes that the OFDM system is perfectly suited to deal with frequency selective channels and AWGN, its performance may be vividly impacted by the existence of impulse noise. It proposed an algorithm that makes use of the guard band null subcarriers for the impulse noise estimation and cancellation. This algorithm has reduced the computational complexity to a large extent as compared to sparse signal reconstruction schemes. The proposed methodology makes a collective use of the structure of the sensing matrix (partial DFT matrix) in OFDM systems and prior information of the impulse noise distribution. **S. B. Bulumulla** *et al.* [15] presented that the complexity of the maximum a posterior probability (MAP) receiver is high. Authors analysed a new suboptimal receiver, which is less complex. They derive the MAP receiver for OFDM signal in wireless domain. **K. A. Hmadi** *et al.* [57] proposed that the OFDM based mobile systems are very sensitive to time fluctuation over wireless channels due to Doppler shift. This Doppler shift may lose the orthogonality between subcarriers and cause ICI that eventually will degrade the system performance. The authors proposed a new more accurate method, which provides performance enhancement of OFDM, when the ICI is present. **E. Lawrey** *et al.* [72] provides some potential advantages of the multiuser OFDM and several new techniques to enhance the spectral efficiency and system reliability. It also presents a low bandwidth hardware implementation. Multiuser OFDM allows for highly flexible communications. **A. Bassiouni** *et al.* [113] proposes a novel data-aided CFO

estimator, because OFDM is sensitive to frequency synchronization errors. Here, it is proved that estimating the CFO is correspondent to finding the Eigen values of a two-dimensional ICI coefficient matrix. The Eigen values of the ICI coefficient matrix are the elements of a geometric series distributed on the unit circle of the complex plane. The proposed estimator depends on transmitting the Eigen vectors consistent to a two-dimensional diagonal matrix to estimate the CFO value. Also the proposed estimator has little computational complexity, as it involves no complex operations as compared with existing CFO estimators. **L. J. Cimini** *et al.* [19] discussed the analysis and simulation of a technique for contending the co-channel interference and multipath propagation on a narrow-band digital mobile channel. When this technique is used with pilot-based correction, the effects of Rayleigh fading can be eliminated to a large extent. Under high frequency selective channels, interpolated pilot signals are used. **H. Dogan** *et al.* [114] proposed a new technique for data detection and channel equalization. This algorithm helps in reducing ICI by updating sequence in series and availability of data to users at high speed. The computer simulations have demonstrated that the algorithm can be implemented in Long Term Evaluation (LTE) systems along with full mobility to the users at high speed. **N. Y. Ermolova** *et al.* [115] analysed the sensitivity of OFDM waveforms to the joint distortion effects of coexisting with “dirty” RF problems operating over the double-selective Rayleigh fading wireless channel, joined also with the time variations of the multipath wireless channel. Author proposed a semi analytical technique for the SER evaluation for arbitrary rectangular QAM as subcarrier modulation. The proposed method integrally overcomes the uncertainty caused by an unidentified true non-Gaussian distribution of joint interference. **B. Lin** *et al.* [116] proposed a numerical calculation method for the ML estimator to derive its approximate mean square error (MSE) performance. The results achieved by author had shown that MSEs attained by these methods could be used as SNR estimator for Maximum Likelihood (ML) estimator analysis. **C. Y. Ma** *et al.* [117] optimally derived three sets of combining weights in high mobility multipath fading channels for different aspects of the OFDM systems. The performance may be enhanced if the delay spread is large. The proposed methods are highly compatible with most existing data equalization, detection and channel estimation methods. These methods have low complexity and may be directly applied other communication systems. **M. Mirahmadi** *et al.* [63] proposed that in the OFDM system, impulsive noise can effect the performance of OFDM very badly. Authors used a technique to improve the BER of OFDM, which had been degraded by Impulsive noise and multipath fading in broadband systems. This is a type of interleaving process which is applied after IFFT in OFDM systems; it is also called time

domain interleaving; which can be used to effectively reduce frequency selective fading. **J. Montalban** *et al.* [118] said that the OFDM system is used as transmission scheme for the most important broadcasting methods, like as DVB, DSL, and ISDB-T; which is sensitive in a time domain and it can also lead to selective interference ICI. Mostly, the performance degradation depends upon the maximum Doppler frequency or the existing space between OFDM subcarriers, actually this spacing is inversely proportional to the FFT, if we have smaller FFT size, the bigger carrier will be sub spacing, and so this is the only main reason broadcasting symbols has short lengths. **J. I. Montojo** *et al.* [43] described BER for a non-ideal OFDM system with different modulation techniques. It is operating over a time-frequency varying Rayleigh fading channel. In which author considered imperfections like ICI or ISI, frequency synchronization and noisy channel estimations. Authors have shown that the effect of ICI and ISI on OFDM system increases due to higher order modulation techniques. **S. H. M. Weinfurtnner** *et al.* [119] explained that OFDM does not bother about minor dispersion in channel by ignoring the guard time. This may lose the orthogonality between successive sub carriers. This problem can be answered by using Nyquist window at receiver. With Nyquist window, the orthogonality between sub carriers and FFT can be retained. Moreover, window would lessen the effect of additive noise and ICI among sub carriers. Windowing can reduce the effect of additive noise and inter carrier interference caused due to carrier frequency offset. **T. Keller** *et al.* [29] highlighted the recent thinking behind adaptive allocation and turbo coding in content of OFDM. It is the main objective of the review and a historic view of the OFDM. Its advantage and disadvantage are reviewed, and performance is characterized over highly spread channels. The consequence of both time and frequency domain harmonization errors are measured and a range of solution proposed in the latest literature are reviewed. **D. Linglong** *et al.* [120] reviewed the performance and applications of next generation broadband wireless communication (BWC) systems. Their reliable performance over fast fading channels is becoming more and more important for OFDM-based BWC systems. Authors proved that, although the spectral efficiency of the time domain synchronous OFDM (TDS-OFDM) is higher than the standard cyclic prefix OFDM (CP-OFDM), but it suffers from serious performance loss over high speed mobile channels. **F. P. Campos** *et al.* [112] said that OFDM is implemented with assumption that the frequency selective channel remains invariant in the time span of an OFDM symbol. Under high-speed mobility and higher carrier frequency, the system performance degrades due to ICI. Authors have solved this problem by proposing a new channel estimation algorithm. This algorithm is based on subspace approach. It is independent of the particular channel

scattering function and hence is very robust. **J. Wang** *et al.* [25] defined a method to deal with the spectral nulls by suggesting a DFT codes based signal reconstruction. The OFDM systems have faced eroded performance over the wireless domain. The symbol recovery is assured by Zero-Padded (ZP) OFDM signal by utilizing minimum mean square error (MMSE). However, the said system has very complex equalizer. **Y. Wang** *et al.* [26] gave the comparison of channel estimation of a Discrete Cosine Transform (DCT) based OFDM system over a wireless channel. By allowing coherent demodulation, channel estimation is considered better to improve system throughput and efficiency. To learn the channel response, initially pilot-aided methods are utilized. MMSE and least square (LS) are examined for measuring performance. Authors also analyzed a compressed sensing (CS) based channel estimation, which involves the sparse property of wireless channel into consideration. Simulation results show that the CS based channel estimation has superior performance than LS. However MMSE can attain optimum fulfilment due to its advance command of the channel statistic. **S. Wu** *et al.* [121] provided an exact analysis of OFDM performance in the presence of phase noise. The authors analysed the effect of phase noise on OFDM performance. They derived an exact expression for Signal to Interference plus Noise Ratio (SINR) in terms of phase noise parameters. By providing a general phase noise suppression scheme the performance of OFDM has improved significantly. **M. Yalcin** *et al.* [33] done channel estimation of OFDM systems using time and frequency domain interpolation. Multicarrier transmission is quite popular because of the high data rate requirement of wireless systems. OFDM is considered an effective technique for frequency-selective channels because of its ability of solving inter symbol interference, its robustness in different multipath propagation environments, and its spectral efficiency. Losing sub channel orthogonally causes ICI, but many conventional channel estimators consider that the channel frequency remain same in one symbol duration of OFDM symbol. This assumption often causes error floors along the OFDM symbol for high-mobility cases. This method reduces the complexity of system and reduces delay for channel approximation. **J. Y. Yun** *et al.* [18] proposed an ICI cancelling technique for multiple input single output (MISO) orthogonal frequency division system in wireless channels. This scheme consists of Space Frequency Block Code (SFBC) at the transmitter and Receiver Frequency Block Code (RFBC) at the receiver for MISO systems. The code design is based on the approximated upper bound of the pair wise error probability.

**V. Gogate** *et al.* [44] studied multiple input and multiple output (MIMO) technique for 4G wireless communication system because MIMO systems promise to increase capacity and performance in proportion to the number of antennas. Study shows that performance depends heavily on the path loss exponent, number of antennas and inter-cell interference. Resource allocation plays an important role in deciding the cell loading factor. As the user moves away from base station; path loss increases reducing path gain which decreases ergodic capacity at that path loss exponent. As the sub bands allocated per user goes down, it results in cell loading factor. When all the selected users get maximum number of sub bands for given path loss exponent, cell loading factor approaches one. **R. P Singh** *et al.* [44] had done the performance analyses of MIMO systems for various data traffics. **C. G. Calero** *et al.* [4] presented a new test bed specifically designed for analysing and measuring MIMO system. A flexible and reconfigurable system with multiple antenna configurations was implemented and system parameters such as sampling frequency and power gain are selected. A user interface was developed to simplify testing of algorithm. **T. C. W. Schenk** *et al.* [122] derived expressions for probability of error of an un-coded zero-forcing based MIMO OFDM system. It had been shown that error floor in case of RX impairments depends on number of antennas used for reception while it is not the case for TX impairments.

**M. N. Seyman** *et al.* [66] proposed a differential evolution (DE) algorithm to optimize power for LS channel algorithm and adjustment of pilot tones in MIMO-OFDM systems. Authors concluded that as compared to orthogonal placement of pilot tones, optimization of the location and power of pilot tones based on the DE algorithm offers better performance and robustness to different Doppler shifts. **H. Y. Che** *et al.* [123] said that beam-forming (or pre-coding) techniques have been widely adopted in modern MIMO OFDM systems. Beam-forming can substantially improve the receive SNR of OFDM systems. However, the combination of transmit signals after beam-forming degrades the PAPR, which been considered a major issue of OFDM Systems. Not only High PAPR complicates the design of the power amplifier, but also increases power consumption. Authors theoretically examined the PAPR performance of MIMO- OFDM systems that adopt either one of the two popular beam-forming schemes, i.e. MRT (maximum ratio transmission) and EGT (equal gain transmission). The results may give important reference for practical designs when evaluating the required power amplifiers and power consumption. In terms of PAPR, the theoretical results show that MRT OFDM systems perform worse than EGT OFDM systems. Furthermore, motivated from the derived results, PAPR reduction algorithms are suggested

for both MRT OFDM and EGT OFDM systems. The proposed algorithm can improve both PAPR and bit error rate; for EGT OFDM systems, the proposed algorithm improves PAPR while it only slightly degrades bit error rate.

## 2.4 MODULATION TECHNIQUES

**M. Kalkan** *et al.* [10] concluded that the BER performance of a zero-crossing based MSK demodulator is within 0.8 to 1.0 dB of the theoretical optimum for MSK which is much better than many other MSK receivers. It is also well depicted that location of zero crossing is Gaussian distributed except at low SNR values. **B. Baggini** *et al.* [2] examined a complete CMOS chip supporting GSM/EDGE as well as enhanced audio applications. From various solutions for transmit section, solution based on Laurent's approximation of the nonlinear GMSK modulator is chosen because it enables burst shaping in the I Q domain so in turn solve the problem of power re-sampling. Excellent results having Gaussian distribution with  $3\sigma$  standard deviation of the peak values of less than 1% had given for baseband section. **L. Y** *et al.* [68] proposed noise robust & low-complexity feed forward synchronisation algorithms for GMSK systems in wireless networks. The maximisation of SNR at the receiver had been achieved with improved timing approximation by using matched filter technique. The synchronization of carriers was obtained by estimation of CFO with sample level method. **D. K. Asano** *et al.* [124] analysed the performance of coded GMSK. The code rate optimization had been achieved by function of system bandwidth. The relationship between bandwidth of coding and system had been presented. Authors proved that the BER performance of systems can be improved by using Bose Chaudhuri Hocquenhem (BCH) and convolution codes. **D. C. Dalwadi** *et al.* [125] concluded that in Rician channel MSK performs better in terms of BER as compared to GMSK. ISI is introduced in GMSK due to increase in modulation memory by Gaussian filter. GMSK has high spectral efficiency and is used in cellular systems globally. **X. He** *et al.* [126] focused on the BER evaluation of Differential Detection of Gaussian Minimum Shift Keying (DDGMSK). Authors also derived the formula for the analysis of BER of GMSK. Time varying Signal to Noise Ratio (TVSNR) of m-bit dock tailed had also been derived. **A. Linz** *et al.* [127] describe the efficacy achieved by using symmetry properties of pre-modulation filters in implementation of GMSK modulators. **H. Mathis** *et al.* [128] proposed the combination of Viterbi algorithm along with differential phase detection; which makes the GMSK receiver bit complex as compared to the differential phase detection with feedback, but it will produce more soft decisions. This soft decision will help

in improvement of one to three dB as compared to hard decision. In addition, this soft decision with coding will make spectrum utilization very efficient. **M. Rice** *et al.* [129] derived ML estimator using data to measure signal level at receiver and noise variance for GMSK modulation. For fixed observation length, the probability density function (pdf) estimators were found to be asymptotically unbiased. **P. Varshney** *et al.* [130] analysed the BER performance for discriminator detection of GMSK in a frequency selective fast fading Rayleigh channel corrupted by AWGN and CCI. Performance of GMSK was found to be better compared to  $\pi/4$  QPSK, considering the fact that the  $\pi/4$  QPSK analysis assumed the interfering channel to be synchronous. ISI was also not considered. For same BER SNR is lowered by 10-15 dB without co-channel interference and time dispersion. **P. Tan** *et al.* [131] developed an exact method for calculating the BER of a  $\pi/4$  DQPSK OFDM in the presence of CFO under fast fading Rayleigh channels. Closed-form BER expression can be calculated directly for small number of subcarriers. For large number of subcarriers, the BER performance can be evaluated using modified Monte Carlo method.

## 2.5 EFFECT OF ICI ON OFDM

**Y. Lei** *et al.* [132] analysed the effect of timing jitter and I Q imbalance in OFDM systems. It is observed that ICI had been generated at receiver due to I Q imbalance as well as timing jitter. This will cause ICI in receiver and degrades the OFDM system performance. I Q imbalance add extra ICI in OFDM systems. **J. Li** *et al.* [35] presented a technique for estimation of carrier frequency offset of OFDM systems used by IEEE 802.11 standard family. This CFO estimation enhanced the accuracy level of OFDM symbol estimation at the receivers. **G. Dou** *et al.* [20] presented a new channel estimation technique by superimposing pilot based channels. The improvement in SER performance was achieved by using iterative symbol reconstruction scheme. It also eliminated the interference in channel estimation without any data loss. The simulation results shown by authors proved that the proposed method is better than traditional FDM pilot's method without the need of any extra training bandwidth. **P. Dharmawansa** *et al.* [22] derived an exact closed form symbol error rate (SER) or bit error rate (BER) expressions for OFDM systems having CFO. Authors had shown that the results achieved by proposed methods are very similar to analytical error rate expressions without CFO. The simulation results also proved the accuracy of proposed method. **W. Jingxian** *et al.* [70] proposed an oversampled OFDM (OOFDM) scheme. Authors implemented the linear processing in the frequency domain and oversampling in

time domain at the receiver. In this, the conventional structure of OFDM, was not changed. This method gave two dimensional Doppler frequency grids of the fading channels. The optimum combining ensures the non-coherent combining of ICI components and coherent combining of the data symbols spread over the Doppler frequency. **A. Al-Dweik** *et al.* [13] proposed the BER analysis of OFDM systems under Nakagami-m channel. The logical results confirmed by simulation demonstrated that the pdf for infinite fading parameter 'm' are different from finite 'm'. It was also found that the dependency of the system performance on 'm' depends on the number of multipath components. **B. Chen** *et al.* [133] studied the estimation of the OFDM CFO. Authors proposed that system performance can be enhanced by deploying OFDM blocks. Also to eliminate the effect of CFO receiver divert may be used. **C. Y. Ma** *et al.* [134] proposed an ICI suppression scheme. The proposed scheme reduced the effect of ICI in OFDM which is caused due to time varying channel by combining ISI free path of cyclic prefix along with the corresponding OFDM symbol. Three sets of segment combining weights have been optimally derived in altered aspects for OFDM systems in wireless channels. The proposed methods have very low complexity. They are highly compatible with most existing data detection, equalization, and channel estimation methods. **M. C. Erturk** *et al.* [109] analysed an OFDM based system mainly for aeronautical environment. It is shown that ICI can be alleviated by exploiting the dual Doppler shift features of the aeronautical channel. As the number of paths is probable, parametric spectrum estimation algorithms are used to estimate the Doppler shifts. From the study, it has been seen that increasing the size of autocorrelation matrix or the number OFDM symbols for the estimation could enhance the MSE performance. However, by this the number of computation increases and cause latency of estimation. The compensation & estimation methods projected in this paper can be efficiently applied to the single-carrier system. **K. A. Hamdi** *et al.* [57] presented mathematical analysis of average SNR present in OFDM due to CFO. There is increase in ICI due to presence of CFO, which destroys the orthogonality between different sub carriers. The exact evaluation of ratio of correlated random variables using direct methods has high computational complexity. Authors proposed an indirect exact methodology having mathematical analysis for the average SINR over Rayleigh multipath fading channels. **Ma Jun** *et al.* [135] developed a scheme to cancel ICI under wireless fading channels for reduced rate OFDM transmitter. The reduced rate OFDM transmitter is capable of self-cancelling ICI without knowing channel state information. All the sub channels of OFDM are made to have same average SIR. **Z. Liang** *et al.* [110] proposed ICI cancellation technique, a somewhat low-complexity iterative channel estimation and low complexity

iterative decision-directed ICI cancellation (LC-IDDICI), for OFDM based wireless mobile communication systems and demonstrated its significance by spread over it to a DVB-T receiver. The complexity analysis showed that the very good performance of LC-IDDICI is obtained with low additional computational complexity, which is well within the capability of the today's VLSI technologies for consumer products. **Y. L. Kun** *et al.* [136] presented a method by mitigating time variation using time domain ICI self-cancellation. The effect of ICI is diminished by reducing the variation in channel with time. The theoretical BER and ICI power performance are examined. Authors suggested modified windows for ICI cancellation in OFDM system. These windows perform better than Chang's corresponding windowing method and the 4-step window for ICI cancellation. **C. Y. Ma** *et al.* [117] proposed very simple and operational ICI suppression method in presence of phase noise for OFDM transmission. Utilization of ISI-free samples in CP to derive the optimum combining effects for ICI power maximization. Simulation results show that the proposed system achieved improvement of 0.5 to 1.5 dB better than conventional methods. Authors clearly depicted that an additional performance gain can be achieved by properly exploiting the unused resources in CP. **C. M. Xian** *et al.* [137] said that in OFDM systems, the orthogonality between sub carries is lost due to time varying multipath channels, which limits the BER probability at high SNR. Authors proposed an ICI Self-cancellation algorithm. To add diversity, a pre processor is added in symbol at transmitters as well as a post processor is inserted to cancel the ICI effect at transmitter itself.

**C. Peng** *et al.* [138] said a very challenging aspect of an OFDM broadband system is its channel estimation over a time-frequency doubly selective channel. This time-frequency doubly selective channel (DS) is formed due to Doppler shift. The DS channel has many channel coefficients, which results in ICI. This raised the need for allocating a large number of pilot subcarriers. A novel channel estimation mechanism had been proposed by authors for solving the problem of ICI based on theory of distributed compressive sensing (DCS). Authors transformed the original DS channel into a novel two-dimensional channel model, by taking advantage of the basis expansion model (BEM), where, several jointly sparse BEM coefficient vectors become the estimation goal. Then authors proposed an ICI free structure, because of a special decoupling form originating from a novel sparse pilot pattern which is designed for such estimation. It also enables the DCS application to make joint estimation of these vectors accurately. The proposed scheme, in combination with a smoothing treatment process, can achieve significantly higher estimation accuracy than the existing ones, with a

much smaller number of pilot subcarriers. The performance merits are confirmed by theoretical analysis and simulation results. **Z. Wen** *et al.* [139] innovated various data detection techniques and channel-estimation for OFDM systems over the Rayleigh fading channel. The eroded performance of OFDM systems is due to the production of ICI by the Doppler shift of fast fading channels. Authors developed a new pilot pattern that includes comb type pilot pattern along with grouped pilot pattern. Author represented the MSE analysis of the proposed channel estimation scheme. The results achieved from proposed channel estimation techniques had been thoroughly examined by measuring the MSE performance of channel estimation. A mathematical expression is derived by author for channel estimation, which is dependent on Doppler shift, number of channel paths and polynomial order. The improvement in BER performance of OFDM system in terms of MSE of channel estimation had been proved by authors analytically as well as by simulation results by removing ICI. **T. Y. Ren** *et al.* [140] proposed the technique to improve the performance of the receivers located at the boundary of cell with OFDM combined with coordinated multi-point (CoMP) transmission technique. The system performance can only be enhanced by proper estimation and eliminating the CFO. The problem of CFO increases more because of multiple transmitters carrier frequency mismatch. Mutual interference among the signal from different transmitters, degrade the performance of CFO estimation techniques. They designed an optimal set of training sequences based on ZAD OFF CHU sequences to minimize the mutual interferences. **X. Zhikun** *et al.* [141] derived efficient scheme of Fractional Frequency Reuse (FFR) to mitigate ICI in OFDMA of DMA network. Authors also calculated RR and SINR scheduling to derive the average throughput of users, which are uniformly distributed in cell boundary. Authors proved that the FFR scheme with optimal threshold had significantly improved the performance with the existing fixed threshold. **F. Munier** *et al.* [142] presented an algorithm for estimating channel coefficients. They also reduced the phase noise in OFDM system under wireless channels. The effect of ICI can be reduced to a large extent at the cost of complexity of algorithm used for estimating ICI. It had been observed that for an un-coded system, SNR loss was 1 dB for a BER of  $10^{-2}$  and for a coded system SNR loss was around 1.5 dB for a BER of  $10^{-3}$ . **K. Sathananthan** *et al.* [143] proposed a very precise analytical technique for calculating the effect of the CFO on bit error rate performance of OFDM using various modulation techniques. **S. T. Subha** *et al.* [144] focused on spectrum efficiency of the OFDM system in the presence of adjacent channel interference (ACI) of a wireless communication system. Spectrum efficiency improves with increase in gain (G) with corresponding increase in Signal to Interference Ratio (SIR).

## 2.6 PAPR

**E. Al-Dalakta** *et al.* [111] presented a method for improving the BER performance. BER degradation is caused due to the nonlinear characteristics of the solid-state power amplifiers used in OFDM systems. Authors proposed that the systems PAPR performance can be improved by combining it with distortion less techniques such as Partial Transmit Sequences (PTS) and Selective Mapping (SLM). It had been proved by authors with the help of simulation results that system performance can be improved by reducing amplifier distortion.

**W. C. Liang** *et al.* [71] proposed Search and Partial Interpolation (SPI) scheme for estimating PAPR for OFDM systems. SPI gets sample with power higher than preset threshold level from OFDM samples and then add the surrounding samples with large sampling rate around the pre searched sample. Authors also developed a condition to control the interpolation filter length and the threshold.

**A. D. S. Jayalath** *et al.* [145] discussed the problem of PAPR in OFDM and its remedies. PAPR is the main shortcoming of OFDM symbol. As the high peaks are very rare in occurrence, so the PAPR can be reduced by the clipping of the high peaks, but the clipping leads to out of band radiation and introduction of in-band distortion. PAPR can be reduced by the multiple signal representations; however, it increases the complexity. Coding techniques limit the PAPR at 3 dB, coding rate is generally low.

**J. Jinwei** *et al.* [69] proposed conversion matrices (CMs) for the modified SLM scheme to decrease the computational complexity and to avoid the transmission of the side information. It also derived the signal processing scheme to remove the weighted factors on each sub-carrier for wireless OFDM systems. The proposed new modified SLM scheme can be directly used in practical OFDM systems, such as the DVB system and LTE down-link system.

**K. K. Hoon** *et al.* [146] proposed a new scheme based on the selected mapping (SLM) for reducing PAPR of OFDM. It generates alternative OFDM signal sequence by shifting the connections in each sub-block at an intermediate stage of the IFFT. It proved numerically that the proposed SLM scheme can reduce PAPR upto large extent with very low computational complexity, at the same time it did not affect the BER performance.

**D. W. Lim** *et al.* [106] provided an impression of the conventional PAPR reduction schemes such as clipping, PTS, TI, and SLM, ACE and TR for attaining a low computational complexity. Therefore many of the PAPR reduction schemes have been developed but none of them is adopted as a standard for the wireless communication systems as these may also not satisfy the commercial requirements. These modified techniques can be positively applied to the high data rate OFDM systems.

However, the FT is unable to solve partial differential equations in signal processing and quantum mechanics. The shortcomings of Fourier Transform (FT) were overcome by Fractional Fourier Transform (FrFT) [90, 147]. Also, worth mentioning is the fact that, earlier most of the reported applications on FrFT were in the field of optics [87]. Recently, the FrFT has also made inroad in the digital signal analysis and processing with filtering, encoding, watermarking, phase retrieval being the key application arenas and wireless networks [148].

## 2.7 FRACTIONAL FOURIER TRANSFORMATION (FrFT)

The definition of Fractional Fourier Transform (FrFT) states it as the chirp basis expansion which is defined as the rotation of time-frequency plane. By changing the value of fractional constant ' $\alpha$ ' from 0.0 to 1.0 the signal characteristics can be transformed from time to frequency domain.

The recent development in the area of FrFT development by various researchers is reported below:

**V. Namias** *et al.* [74] presented the concept of Fourier transforms of fractional order, and a transform of order 1 is the ordinary Fourier transform. The table of fractional order FT has been constructed by the integral representation of this transform. A generalized operational calculus is developed, complementing the familiar one for the ordinary transform. **H. M. Ozaktas** *et al.* [75] presented an algorithm for efficient and accurate computation of FrFT. Authors had also discussed the definition of discrete FrFT. **H. M. Ozaktas** *et al.* [86] gave the brief introduction to the concept of FrFT based on the following two concepts;

- a) The relation of Fourier transforms to chirp.
- b) Wavelet transforms.

The Wigner distribution of a signal develops the notion of fractional Fourier domains. FrFT improved the performance of various signal-processing applications like convolution, filtering and multiplexing of signals. **V. N. Mishra** *et al.* [149] proposed the applications of wavelet transform in neural networks and implemented the model for computing the discrimination of gases. **L. B. Almeida** [76] introduced FrFT as the augmentation of FT. The fractional parameter ' $\alpha$ ' represents rotation in the time-frequency plane. The classical FT depends on the value of  $a = \pi/2$  and the identity operator has a value  $\alpha = 0$ . A single FrFT with value  $\alpha + \beta$  can replace two successive FrFTs with angle  $\alpha$  and  $\beta$  respectively. The FrFT also represents signal in the form of chirps which are shifted

versions of one another and are orthogonal. One application of FrFT allows a treatment of swept frequency filters. **S. Chatterji** *et al.* [150] had also done the analysis of integral and fractional order current mode in power converters. **S. Ashutosh** *et al.* [81] dealt with all the aspects of EM wave and channels which are considered to define a new method DDT-FrFT to examine the travelling EM wave for wireless communication. In regard to wireless communication, the travelling EM nature of wave signal is not reported completely in the literature. The travelling EM wave which is actually propagating through the channel has both time and spatial dependencies. However, it is different from the previously reported literature and not defined the nature of signal propagating through the channel in time-frequency domain. Authors proposed the effect of channel variation in terms of time-frequency and spatial dependency, on propagation constant of EM waves. **S. Kumari** *et al.* [82] said that the performance of FFT OFDM in the presence of CFO is poor than the FrFT based OFDM system under similar conditions for different values of ' $\alpha$ '. **A. C. McBride** [151] discussed the fractional powers for FT. They found this theory ambiguous, so to make it unambiguous, author modified the Namias's fractional operators. As a result, some theorems are then proved for the modified Namias's fractional operators and developed an operational calculus on it. **S. C. Pei** [152] gave the generalization of dimensional data can be generated from the extension procedure as the 1-D Fourier transform has also been extended to form FrFT. The generalization of the 2D FT is to have the 2D separable FrFT with 4 parameters. **S. C. Pei** [79] presented FT in a generalized way. Author has described many fractional operations. Author proposed linear canonical transform (LCT) as the generalized form of FrFT. Authors also presented the relations between the operations such as fractional convolution, correlation, the Hilbert transform and some important time-frequency distributions (TFDs), such as the Wigner Distribution Function (WDF), the ambiguity function (AF), the signal correlation function, and the spectrum correlation function. **S.C. Pei** *et al.* [153] made two schemes of fractional Fourier analysis methods. Conventional Fourier has many signal processing types for different signals like FT, Fourier series DFT and Fourier transform. The proposed schemes are fractional Fourier series and discrete-time fractional Fourier transform, and they are the generalized forms of Fourier series and discrete-time Fourier transform, respectively.

**R. Saxena** *et al.* [83] presented the review of FrFT. It depends on a parameter ' $\alpha$ ' and can be given as a rotation by an angle in the time-frequency plane or disintegration of the signal in terms of chips. It is further based on simulation results of discrete FrFT, also called DFrT,

time-frequency distributions related to FrFT, optimal filter and beam former in FrFT domain and other fractional transforms along with the simulated results. **R. Saxena** [84] told that communication is normally intended to establish between the transmitter and receiver under the scenario where, the transmitter / receiver or both having their respective movements, and due to this relative motion of the receiver, a Doppler shift is introduced in the received frequency, which makes the received frequency component a time-variant. The analysis of the signal to be performed in a time-frequency plane was enforced by the non-stationary behaviour of the signal. To tackle this state of affair of the signal using a better mathematical tool, the FrFT has been established. The efficiency of the FrFT, as a transforming tool, is also investigated in 2-dimensional signal processing applications viz., encryption and watermarking. Two more security options per FrFT block are provided by the FrFT, in both encryption and watermarking, which can be used as decryption keys. Actually, these keys are generated in terms of the column wise and row wise transformation and this beneficial feature can be originated only with the FrFT. Thus, in comparison with the FT, the FrFT proved to be a better technique, in terms of the greater number of keys offered by this method. This study succeeded in pushing the FrFT towards a complete and perfect Integral Transform. **A. K. Singh et al.** [154] presented the emergence of the FrFT. It helped a lot in the signal processing by acting as tool for signals, which changes their frequency with time. The main reason for non acceptance of convolution theorem of FrFT given by many authors is due to its generalized form; as does not map with classical FT. However, author proposed a modified convolution theorem for FrFT and is compared with the existing ones for better and befitting proposition. **A. K. Singh et al.** [148] reviewed all the conventional methods for computing the discrete fractional Fourier transform (DFrFT). DFrFT is further divided into four categories. The best DFrFT is found to have minimum computational complexity and errors. The effect of Doppler shift caused due to motion of transmitters and receivers in OFDM had been mitigated upto large extent by this new modified convolution theorem of FrFT. **K. Singh** [80] had presented study and comparison of various classes of DFrFT algorithms has been done. FrFT has led to the generalization of the concept of frequency and space domain. There are several applications of FrFT in signal processing and optics. Various applications of DFrFT are in 1-D and 2-D such as filtering using window functions, optical beam forming, beam forming for mobile antenna, optimal filtering, etc. 2-D applications include image processing and encryption. The role of windows is quite economical from the aspect of computational complexity. The randomness of signals, Doppler spread, and multipath environment has been studied. **K. Singh et al.** [155] presented a novel closed form

analytical expression of fractional derivative of a signal in FT. This generalization of differentiation property has been based on Caputo's definition of fractional differ integral causing the flexibility of rotation angles in time. Thus, the confluent hyper geometric function is used to derive the closed form analytical expression in terms of famous higher transcendental function. These design examples demonstrate the comparative analysis between the proposed and established method for casual signals which have been damaged by high frequency chirp noise. **D. Xie** *et al.* [156] said that the most prominent and promising candidate for UWB systems is Multi Band-OFDM (MB-OFDM). It has higher spectral efficiencies and superior system performance. When the channel is doubly selective, the classical FT scheme may fail. Despite using exponential functions, chirp-like basis (FrFT based) can be utilized to overcome this complication. However, both FFT based OFDM and FrFT based OFDM suffers from the problem of PAPR. The problem of PAPR can be solved by implementing any of the PAPR reduction techniques like; SLM or PTS. **E. Chen** *et al.* [90] reduced the ICI by proposing an OFDM system based on the FrFT. In this paper, author implemented the FrFT for symbol modulation and demodulation by replacing it with FFT used in traditional OFDM system. This FrFT based OFDM system is considerable removing the effect of ICI under wireless channel. Simulation results presented in the paper show that FrFT based equalizer in FrFT domain is able to provide improved system performance as compared to FFT based equalizer. **Z. Jing** *et al.* [157] had focused on the effect of CFO on the performance of FrFT- OFDM system under time-frequency selective fading channels. By the deployment of FrFT, OFDM systems are generalized by FrFT based OFDM systems. The formulation of SIR as a result of ICI is marked by different fading channels. Functionality of both the systems is same under flat channel. The former channels are cavalier in SIR performance as they choose the optimal fractional factor.

## 2.8 MOTIVATION

The literature available mainly focused on work done on OFDM, FrFT and a small work on FrFT based OFDM systems. Still, a lot of work has to be carried out by the analysis of FrFT based OFDM system for wireless communication to get maximum throughput of the wireless systems. By analyzing the advanced techniques, developed with the FFT based OFDM system on the FrFT based OFDM system; better performance for large value of sub carriers can be achieved. There is a scope of improvement in the performance for the FrFT based OFDM system by optimizing Doppler spread. Further, optimization of fractional variable ' $\alpha$ '

can be done. The existing systems are working at the data rate between 6 Mbps to 48 Mbps. It can be taken upto 64 Mbps to further increase the system throughput and bandwidth utilization.

## 2.9 GAPS IN STUDY

The literature survey provided above has proved that multicarrier systems have many advantages like spectral efficiency and higher data transmission over single carrier systems in wireless domain, and OFDM is the one of multicarrier techniques. The conclusion of literature review presented in this chapter relived that besides many advantages of OFDM, there are some problems with OFDM systems which degrade their performance. Various problems of OFDM system have been reviewed in this chapter. Many authors have provided solutions for the said problems, but there is still scope to further improve the system performance. Following gaps have been found in the literature;

- a) The data transmitted in wireless domain could be easily accessed by unauthorized users because of plain text transmission in OFDM. It is very important to securely transmit the data in wireless domain. Hence a work could be carried out to enhance the security to OFDM data by appending FrFT with traditional OFDM system.
- b) It is very critical to find out the exact start of OFDM symbol at the receiver. Any mismatch in the estimation of timing of OFDM symbol, will cause de-synchronization of receiver and degrade the system performance. Further, the system performance degrades due to frequency selective time varying fading channels. The literature review has shown FrFT as the best solution for analysing time varying frequency selective wireless channels. Hence, work could be done by replacing traditional FFT based OFDM system with FrFT based OFDM system.
- c) Another major problem faced by traditional FFT based OFDM system is Inter carrier interference caused due to CFO. The literature has shown that FrFT could estimate the CFO. In addition, the modulation techniques like GMSK and  $\pi/4$  DQPSK are also helpful in answering the problem of CFO. Hence, work could be done by combining FrFT based OFDM with GMSK and  $\pi/4$  DQPSK modulation techniques to calculate the exact BER of proposed OFDM system.
- d) FFT based OFDM systems are suffering from high PAPR. The performance of OFDM system degrades largely due to the loss of orthogonality between subcarriers of OFDM system. A work could be carried out to apply any clipping technique on

proposed FrFT based OFDM system for improving the system performance with GMSK and  $\pi/4$  DQPSK modulation techniques.

- e) OFDM cannot be considered for every communication system because of its increased complexity and higher transmitter and receiver demands. However, by implementing modern digital signal processing techniques, it is possible to use this modulation system to improve the reliability of the communications link up to great extent.
- f) The work has been done on the use of chirp basis to replace exponential basis and equalizing the received signals in FrFT domain which is more suitable for multicarrier transmission over rapidly time-varying channels.
- g) The sub carrier modulation and demodulation are implemented by means of the Inverse discrete fractional Fourier transform (IDFrFT) and discrete fractional Fourier transforms (DFrFT). Simulation results show that this scheme is more suitable for the fast-fading channel than the classic OFDM scheme and can reduce the ICI significantly. But a further study has to be carried out on chirping of signal and getting the results closer to practical values.

## **2.10 OBJECTIVES**

Based on the initial studies, literature survey (as reported) and the understanding established the following objectives are proposed:

1. Study of OFDM systems and its performance evaluation with various existing modulation techniques.
2. Study of the OFDM based wireless communication system in FrFT domain and its performance determination.
3. Throughput analysis of proposed OFDM based wireless system in (2).

## **2.11 RESEARCH METHODOLOGY**

In this research work, the wireless communication systems are considered based on OFDM system. Firstly, the study of various existing wireless systems like; WLANs, WiMAX networks along with the various Spread Spectrum Techniques had been carried out. Then the areas of FrFT, OFDM and wireless systems had been reviewed and a suitable experimental setup by way of simulation had been established. Based on simulation and experimental set up, FrFT based OFDM system had been implemented by appending FrFT with existing FFT

based OFDM system. The security provided to the existing OFDM system by appending FrFT is studied in terms of BER. The security of OFDM modulated signal in wireless domain had been enhanced by encrypting the signal before transmission using FrFT.

Secondly, by combining the concept of FrFT and OFDM, determination of performance measures had been done by developing the source code. Based on the simulation results the performance analysis of the said system had been done. Also a comparative study had been carried out for different modulation techniques in OFDM environment like 1024-PSK, 1024-QAM,  $\pi/4$  DQPSK and GMSK. Additionally, the throughput analysis of FrFT based OFDM system is done on the basis of various performance metrics namely; BER, SNR, CFO, ICI and PAPR.

# CHAPTER 3

## FFT BASED OFDM SYSTEM

### APPENDED WITH FrFT LINK

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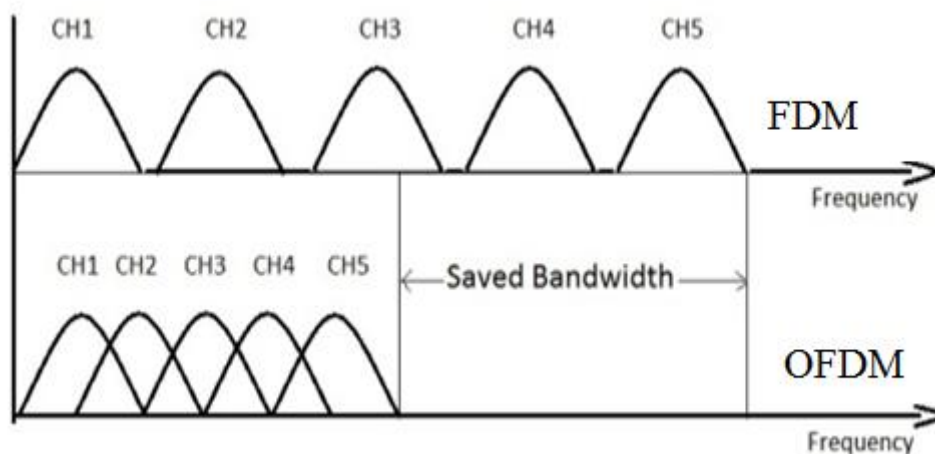
The existing FFT based OFDM has no doubt given tremendous growth in the evolution of wireless communication systems [1, 101, 104]. Nevertheless, the information transmitted in wireless domain was not safe, as the OFDM system transmits the plain or encrypted data on the wireless channel [104]. This makes the system insecure and prone to information breach in the wireless field by cracking the encrypting key. In this chapter, the security issue of the existing OFDM system has been resolved by appending the FrFT link with the FFT based OFDM system. Further, the performance evaluation of FrFT appended OFDM has been done by comparing it with the existing FFT based OFDM system for different modulation techniques under various wireless fading channels.

### 3.1 INTRODUCTION

The FFT based OFDM system has used the bandwidth very efficiently and solved the problem of scarcity of spectrum [5, 30]. The major benefit has been established due to overlapping of sub carriers used for modulating the data symbols. Computational complexity of bank of subcarriers oscillators at transmitter and receiver used for generating orthogonal subcarriers was reduced by using FFT [30, 121]. These OFDM symbols are then transported in a wireless channel after adding cyclic prefix with each symbol to avoid inter symbol interference (ISI). The orthogonality between the subcarriers helps in recovering the information at the receiver [22, 57]. Traditional FFT based OFDM system does not have hold of any measures to fix the wireless link where, the raw information is sent. In this research work, a secured OFDM system has been implemented by appending an additional FrFT block with the existing system immediately before and after the channel. The FrFT appended OFDM system is compared with existing FFT based OFDM system.

### 3.2 FFT BASED OFDM

The basic principal of OFDM system is to send large data flow into smaller data streams using various subcarriers and transmit all modulated subcarriers in parallel [135]. These subcarriers are having smaller bandwidth, because of parallel transmission. This parallel transmission also helps in reducing ISI. The OFDM system can be viewed as both modulation techniques in terms of relationship between input and output signal as well as multiplexing technique, as the output signal is compounding of various modulated signals [158]. OFDM is a lot better than FDM as it allowed to use the overlapping of subcarriers whereas in FDM the subcarriers are supposed to be sorted by a guard band to avoid inter channel interference [19]. This overlapping of subcarriers improved the spectral efficiency of OFDM systems as compared to FDM systems as shown in Figure 3.1:



**Figure 3.1: Spectrum efficiency of OFDM over FDM [159]**

The OFDM signals are generated by digital signal processing rather than frequency synthesizers. Let  $[S_0, S_1, S_2, \dots, S_{N-1}]$  are the input data words and  $[s_0, s_1, s_2, \dots, s_{N-1}]$  are the OFDM symbols, which can be mapped on to input symbols using FFT to generate OFDM modulated signal as given in [114]:

$$s_k = \sum_{n=0}^{N-1} S_n e^{j2\pi n \frac{k}{N}} \quad (3.2.1)$$

where,  $e^{j\frac{2\pi n}{N}}$  is the symmetric and orthogonal matrix, after FFT cyclic prefix is added to each block of length  $k_1$  as pre cyclic prefix and of length  $k_2$  as the post cyclic prefix. Then this

signal is passed through D/A converter at a rate of  $f_s$  and low pass filter. The final OFDM modulated base band transmitted signal is given by  $x(t)$ ,

$$x(t) = \sum_{n=0}^{N-1} \left[ S_n e^{j2\pi \frac{n}{N} f_s t} \right] \quad (3.2.2)$$

$$\text{for } -\frac{k_1}{f_s} < t < \frac{N + k_2}{f_s}$$

The received signal for a time varying random channel is given by  $y(t)$  as given in [114]

$$y(t) = \int_0^{\infty} x(t - \tau) h(t, \tau) d\tau + w(t) \quad (3.2.3)$$

where,  $w(t)$  is the White Gaussian noise.

The received signal is sampled at  $t = kl f_s$  for  $k = \{-k_1, \dots, N + k_2 - 1\}$ . The output of FFT block at receiver is given by [28]

$$S_m = \frac{1}{N} \sum_{k=0}^{N-1} y_k e^{-2\pi m \frac{k}{2N}} \quad (3.2.4)$$

$$\text{where, } y_k = \sum_{n=0}^{N-1} G_n S_n e^{j2\pi \frac{n}{2N} k} + w(k)$$

$G_n$  is the frequency response of channel  $h(t, \tau)$  at frequency  $\frac{n}{T}$ . The final demodulated signal at receiver is given by

$$S_m = \begin{cases} G_n S_n + W(n), & n = m \\ W(n), & n \neq m \end{cases} \quad (3.2.5)$$

OFDM uses the spectrum very efficiently by overlapping the sub carriers. The  $N$  equally spaced subcarriers in OFDM will be orthogonal [21, 36] if the consecutive subcarriers are separated by  $\Delta f = \frac{1}{N.T_s} = \frac{1}{T}$  where,  $N.T_s$  is the symbol duration.

Mathematically, the orthogonality between two signals  $y_k(t)$  and  $y_i(t)$  over time period  $N.T_s$  is given by [36]

$$\int_0^{NT_s} y_k(t) \cdot y_l^*(t) dt = \begin{cases} 0, & k \neq l \\ U, & k = l \end{cases} \quad (3.2.6)$$

where, U is a constant [145]. The OFDM system would render the desired effects if this condition of orthogonality is fulfilled else, its performance would degrade due to ICI.

The existing OFDM system transmits data either as plain text or encrypted with certain keys, which may be vulnerable to intruders. So it generated a need for development of a more robust and secured OFDM system.

### 3.3 FrFT APPENDED OFDM SYSTEM

In this research work, the security of OFDM modulated data has enhanced by appending FrFT link immediately before and after the wireless channel. The block diagram of FrFT appended OFDM is given in Figure 3.2.

In this model, the security of the OFDM modulated signal had enhanced by appending FrFT block. As depicted in Figure 3.2 the FrFT block is appended after cyclic prefix block in the transmitter and at the receiver, the signal first goes through the IFrFT block. Here, the OFDM modulated signal is encrypted with the fractional variable ' $\alpha$ ' by varying its value in the range of 0.0 to 1.0. This encrypted signal is transmitted along the wireless channel. On the receiver side, it can be de-encrypted by the same value of ' $\alpha$ ' which was used at transmitter, for all other values of ' $\alpha$ ' the signal would appear as noise. This addition of FrFT had made the OFDM system very secure and more efficient.

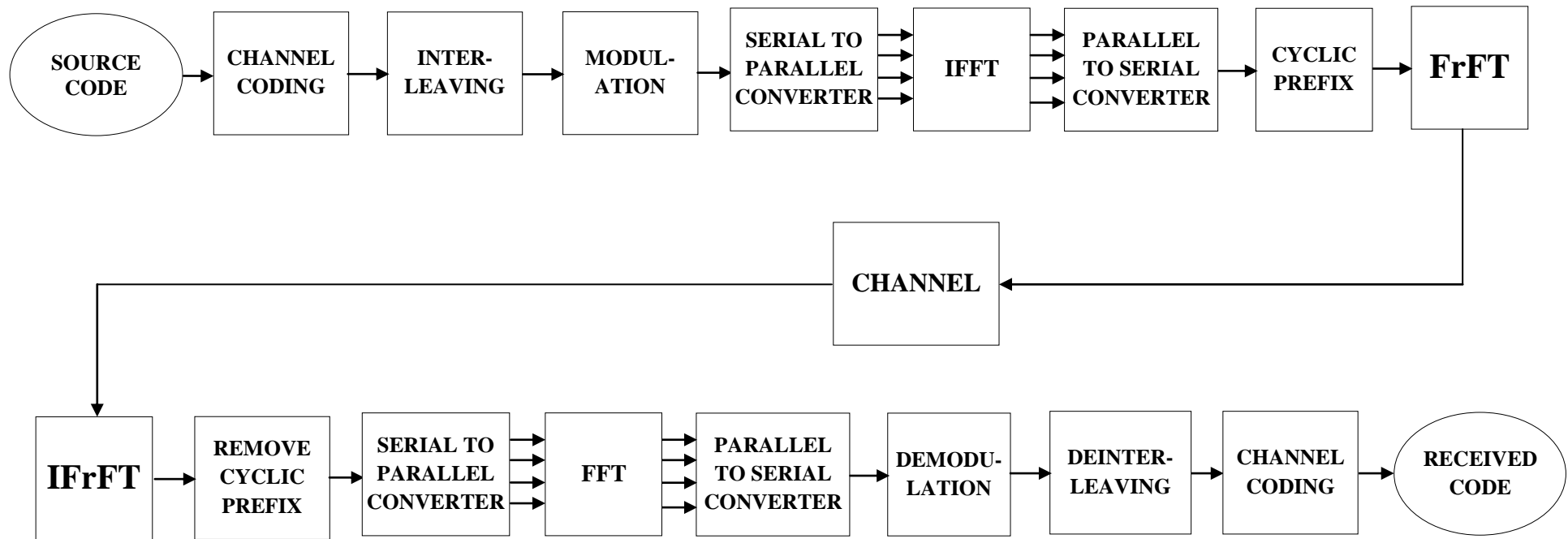


Figure 3-2: Block diagram of FrFT appended OFDM system

### 3.4 SYSTEM MODEL

In this appended OFDM model FrFT had been added at both transmitter and receiver. In this system, FrFT had been applied to observe and estimate the interference factor.

The original OFDM modulated signal is given by [160]

$$x(t) = \sum_{n=1}^N s_n(t) \sin(2\pi nt) \quad (3.4.1)$$

This signal was passed through FrFT represented by  $F^{+\alpha}$  for the unified time-frequency analysis of OFDM signal in the wireless channels namely; AWGN, Rayleigh, Rician, or Nakagami.

After passing through FrFT the OFDM signal given in (3.4.1) becomes [148]

$$\{F^{+\alpha}\{x(t)\}\} = \sqrt{\frac{1-icot\phi}{2\pi}} \int_{-T/2}^{+T/2} x(t) e^{\frac{j}{2}(u^2+t^2)\cot\phi - iut\csc\phi} dt \quad (3.4.2)$$

By putting the value of  $x(t)$  from (3.4.1) and (3.4.2) becomes

$$\{F^{+\alpha}\{x(t)\}\} = \sqrt{\frac{1-icot\phi}{2\pi}} XA \quad (3.4.3)$$

where,  $A$  is given by

$$A = \int_{-T/2}^{+T/2} \sum_{n=1}^N s_n(t) \sin(2\pi nt) e^{\frac{j}{2}(u^2+t^2)\cot\phi - iut\csc\phi} dt$$

The final transmitted signal of FrFT appended OFDM system is given by  $\{F^{+\alpha}\{x(t)\}\}$  and had passed through the wireless channels namely; AWGN, Rayleigh, Rician, and Nakagami.

After channel the signal  $X_\alpha$  was passed through Inverse Fractional Fourier Transform (IFrFT), given by [148];

$$\{F^{-\alpha}\{F^{+\alpha}\{x(t)\}\}\} = F^{-\alpha} \left\{ \sqrt{\frac{1-icot\phi}{2\pi}} XA \right\} \quad (3.4.4)$$

$$\text{or } \{F^{-\alpha}\{F^{+\alpha}\{x(t)\}\}\} = x(t) \quad (3.4.5)$$

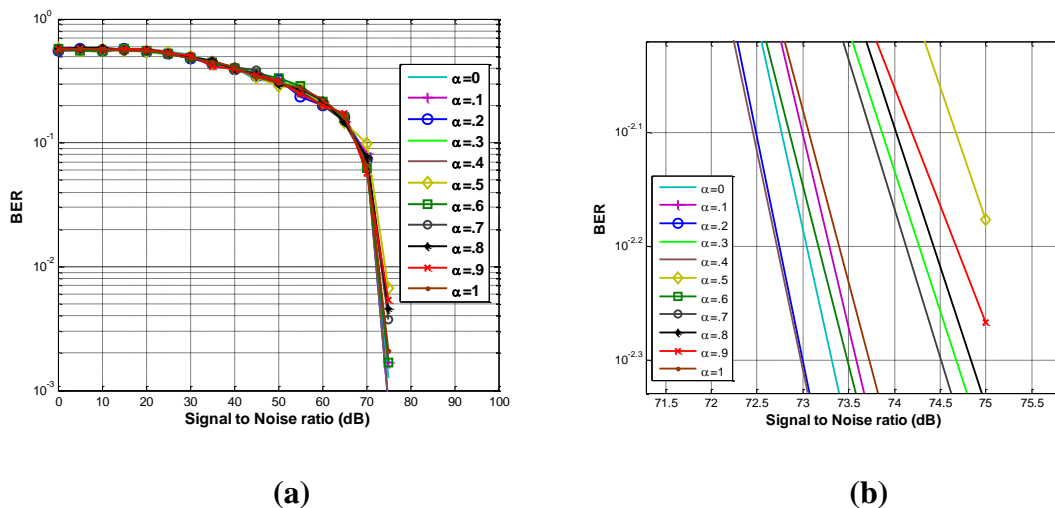
Hence in (3.4.5), the originally transmitted signal had been recovered after passing through IFFT at the receiver side.

### 3.5 PERFORMANCE EVALUATION

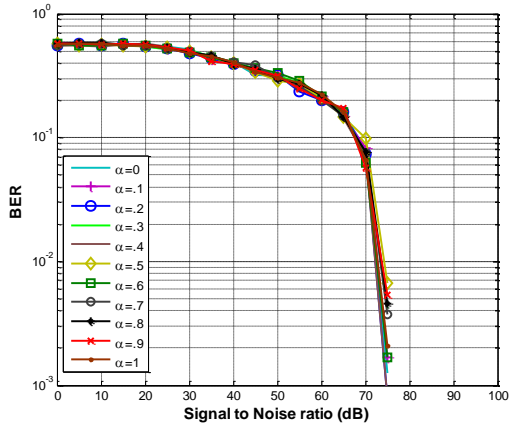
In this section, the performance of proposed FrFT appended OFDM system has been evaluated under various wireless channels. It is compared with traditional FFT based OFDM system using same modulation technique. Here, the performance is measured in two parts. First part compares the performance of FrFT appended system with traditional FFT based OFDM system in terms of BER vs. SNR. Second part explains the security added by FrFT in wireless domain by encrypting the data with fractional variable ' $\alpha$ '.

#### 3.5.1 Comparison between FrFT appended OFDM with FFT based OFDM

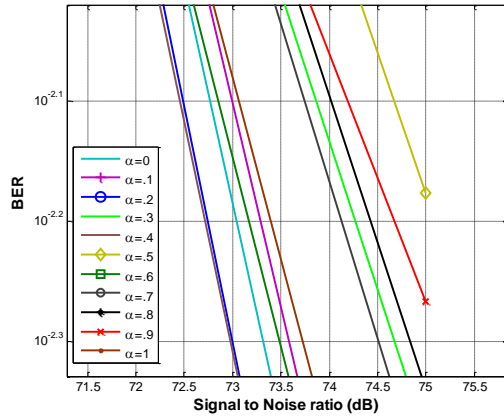
The analysis of the BER vs. SNR of different wireless fading channels on the proposed model for 1024-PSK modulation of different values of ' $\alpha$ ' in the range of 0.0 to 1.0 had been done. Figure 3.3 (a) to 3.6 (b) show the plots created from the appended model for BER vs. SNR for different wireless fading channels.



**Figure 3-3: (a) BER Vs SNR Pattern for 1024-PSK in AWGN Channel (b) Sectional view of Figure 3.3(a)**

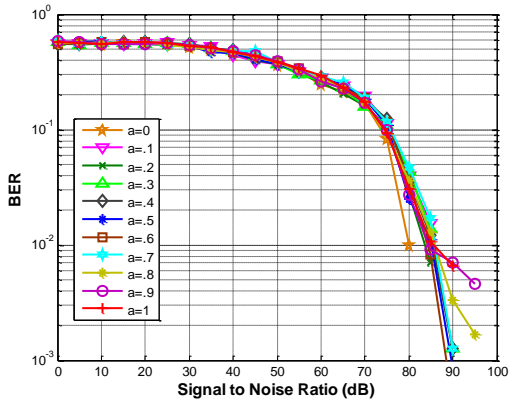


(a)

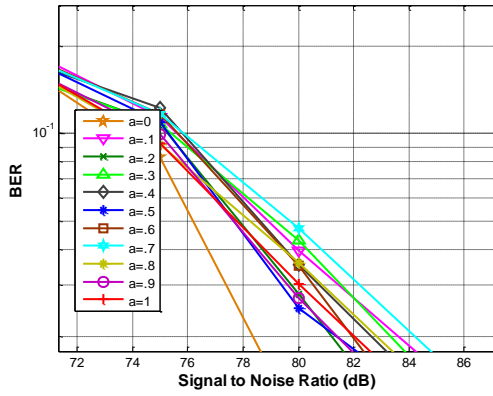


(b)

**Figure 3-4: (a) BER Vs SNR Pattern for 1024-PSK in Rayleigh Channel (b) Sectional view of Figure 3.4(a)**

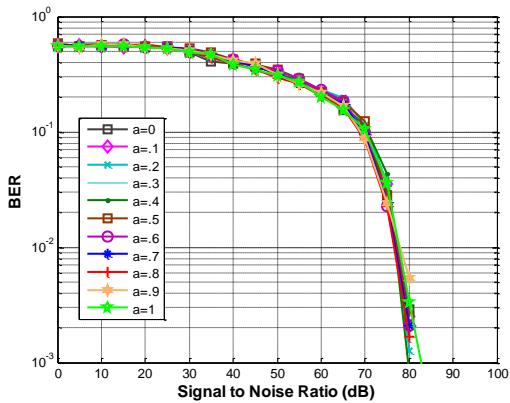


(a)

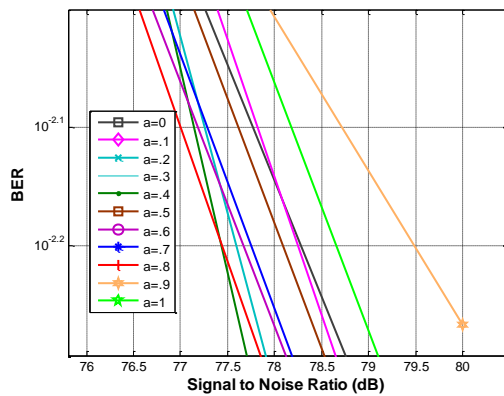


(b)

**Figure 3-5: (a) BER Vs SNR Pattern for 1024-PSK in Rician Channel (b) Sectional view of Figure 3.5(a)**



(a)



(b)

**Figure 3-6: (a) BER Vs SNR Pattern for 1024-PSK in Nakagami Channel (b) Sectional view of Figure 3.6(a)**

In Figures 3.4 to 3.6 the BER performance of proposed FrFT appended OFDM system has been analysed for different values of ' $\alpha$ ' with 1024-PSK modulation technique under various wireless fading channels. Along with the results the sectional view has also been shown for easy interpretation of BER of FrFT appended system at different values of ' $\alpha$ '. From results shown in Figures 3.4 to 3.6, it could be depicted that the said system gives minimum SNR for Nakagami channel and able to get a gain of 1.6 dB as compared to traditional FFT based OFDM system.

Table 3.1 shows the improvement in BER achieved for the best value of ' $\alpha$ '<sub>opt</sub> for wireless fading channels at 1024-PSK calculated from the above shown plots. Further, the improvement here had been calculated by comparing the results of ' $\alpha$ '<sub>opt</sub> with respect to the results of existing system i.e. for  $\alpha = 1$  which is the case for FFT at particular BER.

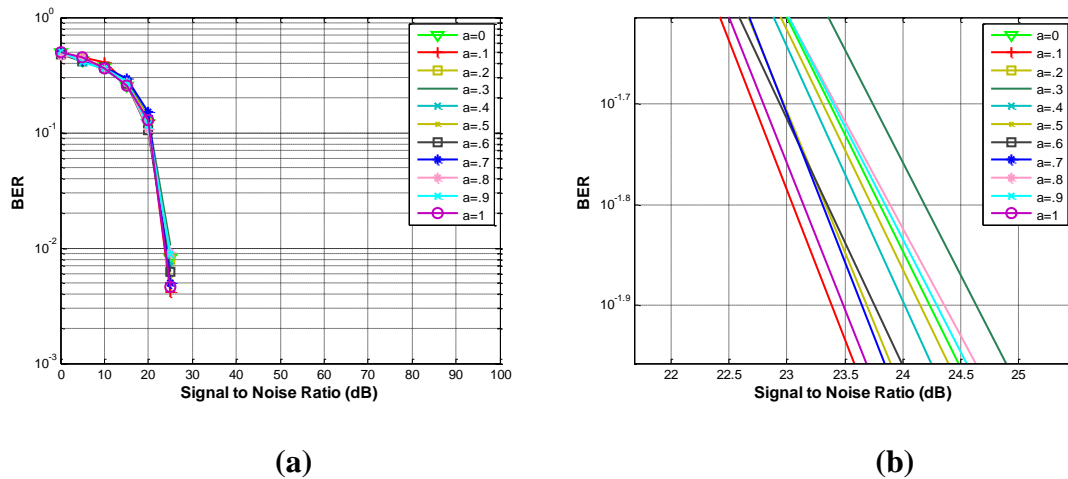
**Table 3-1: Improvement in SNR for M-PSK by keeping best BER for different channels.**

1024-PSK						
S. No.	Channels	BER	Original System	Proposed System		Improvement in SNR (in dB)
			SNR at $\alpha = 1$ (in dB)	' $\alpha$ ' <sub>opt</sub>	SNR (in dB)	
1	AWGN	$10^{-2.3}$	73.7	0.4	72.8	0.9
2	Rayleigh	$10^{-2.1}$	83.7	0.1	81.8	1.9
3	Rician	$10^{-1.7}$	82.0	0.5	81.2	0.8
4	Nakagami	$10^{-2.3}$	79.2	0.4	77.6	1.6

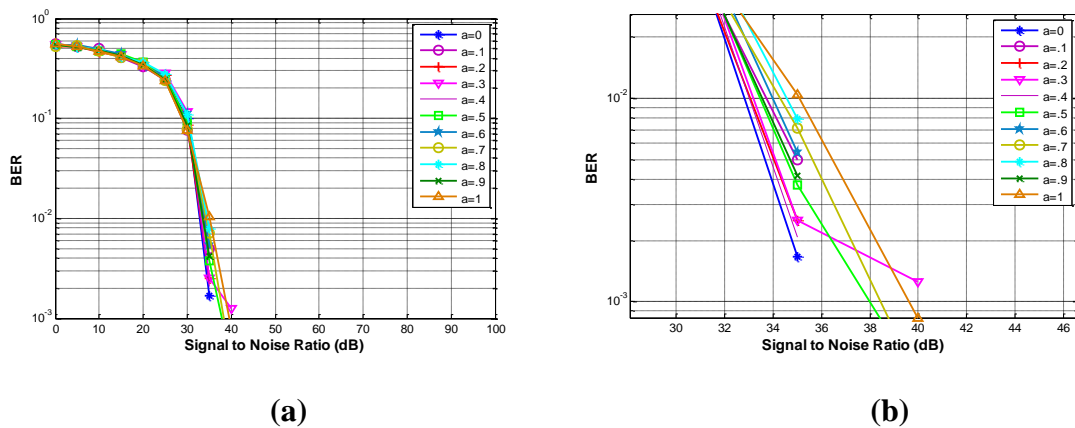
In AWGN, Rayleigh and Rician channels proposed system had given improvement of 0.9 dB at  $10^{-2.3}$  BER, 1.9 dB at  $10^{-2.1}$  BER and 0.8 dB at  $10^{-1.7}$  BER respectively for 1024-PSK modulation. However, Nakagami channel had given highest improvement of 1.6 dB for same modulation at  $10^{-2.3}$  BER for same modulation technique.

### 3.5.2 Analysis for 1024-QAM modulation for wireless fading channels

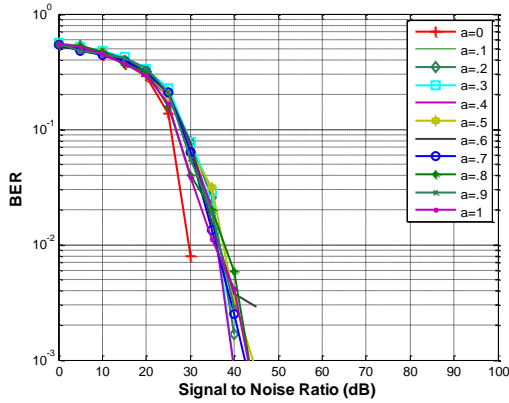
The analysis of BER vs. SNR of various wireless fading channels on said model had been done for 1024-QAM modulation by using different values of ' $\alpha$ ' in the range of 0.0 to 1.0. Figure 3.7 (a) to 3.10 (b) show the plots from the said model for BER vs. SNR for 1024-QAM modulation technique under different wireless fading channels.



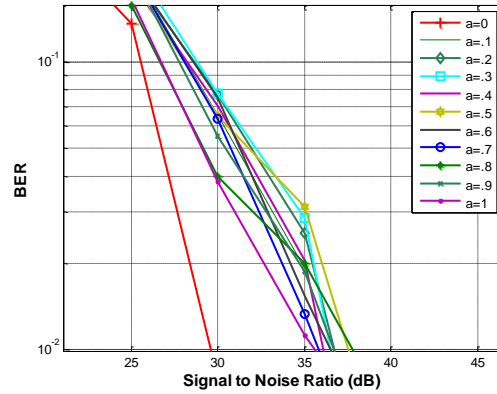
**Figure 3-7: (a) BER Vs SNR Pattern for 1024 QAM in AWGN Channel (b) Sectional view of Figure 3.7(a)**



**Figure 3-8: (a) BER Vs SNR Pattern for 1024 QAM in Rayleigh Channel (b) Sectional view of Figure 3.8 (a)**

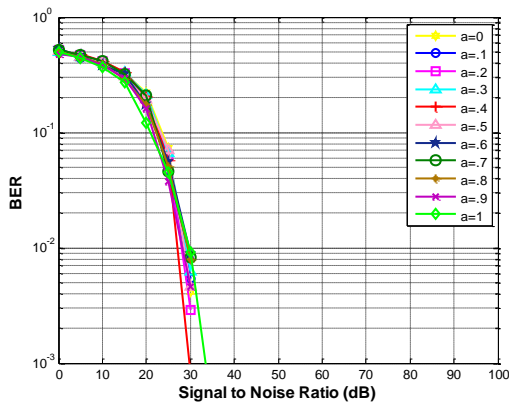


(a)

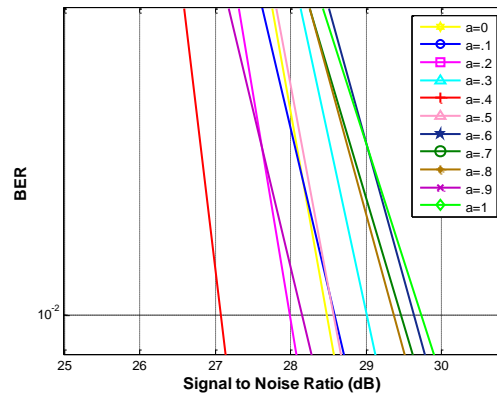


(b)

**Figure 3-9: (a) BER Vs SNR Pattern for 1024 QAM in Rician Channel (b) Sectional view of Figure 3.9 (a)**



(a)



(b)

**Figure 3-10: (a) BER Vs SNR Pattern for 1024 QAM in Nakagami Channel (b) Sectional view of Figure 3.10(a)**

The results shown in Figures 3.7 to 3.10 for the performance of said system under various fading channels. if could be shown that the FrFT appended OFDM system outperforms for Nakagami channel again for 1024-QAM modulation technique. It has able or achieve gain of 3.5 dB as compared to older system. However, as shown in Figure 3.9, the performance of said model degrades in Rician channel as compare to FFT base OFDM system and has a loss of 0.5 dB gain.

Table 3.2 shows the improvement achieved in BER for the best value of ' $\alpha_{opt}$ ' for various wireless fading channels for 1024-QAM calculated from the above shown plots. The improvement here has been calculated by comparing the results of ' $\alpha_{opt}$ ' with respect to the results of  $\alpha = 1$  i.e. existing FFT based OFDM system at given BER.

**Table 3-2: Improvement in SNR for M-QAM by keeping best BER for different channels.**

1024-QAM						
S. No.	Channels	BER	Original System	Proposed System		Improvement in SNR (in dB)
			SNR at $\alpha = 1$ (in dB)	' $\alpha_{opt}$ '	SNR (in dB)	
1	AWGN	$10^{-1.8}$	25.0	0.1	23.5	1.5
2	Rayleigh	$10^{-1.3}$	30.9	0.2	31.3	0.4
3	Rician	$10^{-2.0}$	35.0	0.7	35.5	-0.5
4	Nakagami	$10^{-2.5}$	31.5	0.4	28.0	3.5

In the case of 1024 M-QAM the improvement in SNR was 1.5 dB at  $10^{-1.8}$  BER and 0.4 dB at  $10^{-1.3}$  BER for AWGN and Rayleigh channel respectively. For Rician channel the proposed model had not achieved any improvement, here the FFT based system achieved 0.5 dB of improvement as compared to FrFT appended system. The improvement was 3.5 dB in the case of Nakagami channel from the appended OFDM system at  $10^{-2.5}$  BER for said modulation technique.

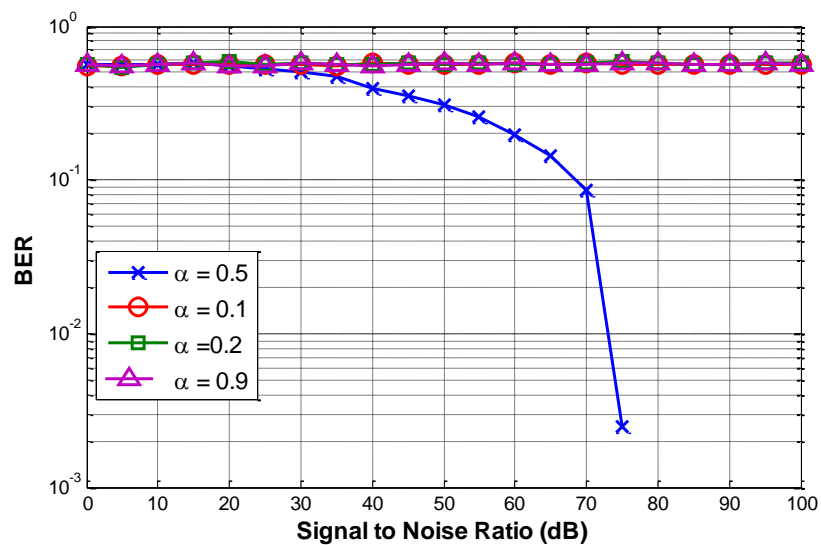
Henceforth, it could be concluded that the appending of FrFT with existing FFT based OFDM will slightly improve the BER and the improvement is maximum under Nakagami channel for both the modulation techniques discussed above. However, the major advantage of appending FrFT is in terms of security provided to existing FFT based OFDM discussed in next section.

### 3.6 SECURITY PROVISIONS

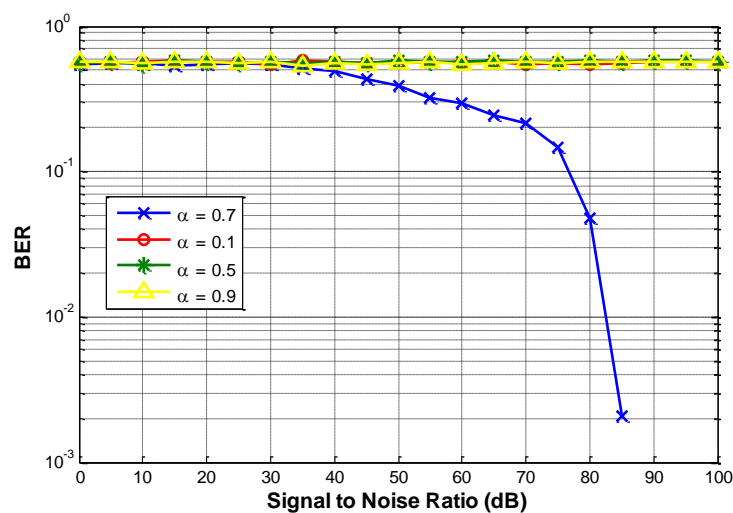
In this section, the security added by encrypting OFDM signal using fractional variable ' $\alpha$ ' in traditional FFT based OFDM is presented. The encrypted data could only be decoded with

the same value of ' $\alpha$ ' at receiver with which it was encrypted at transmitter. For all other values of ' $\alpha$ ', the receiver will not be able to decrypt the data and consider it as noise. The same has been shown in Figures 3.11 (a) to (d) and 3.12 (a) to (d) for both 1024-PSK and 1024-QAM modulation under various wireless fading channels.

The Figure 3.11(a) to 3.11 (d) shows the BER vs. SNR of FrFT appended OFDM system for 1024-PSK modulated signal under various fading channels namely AWGN, Rayleigh, Rician and Nakagami.

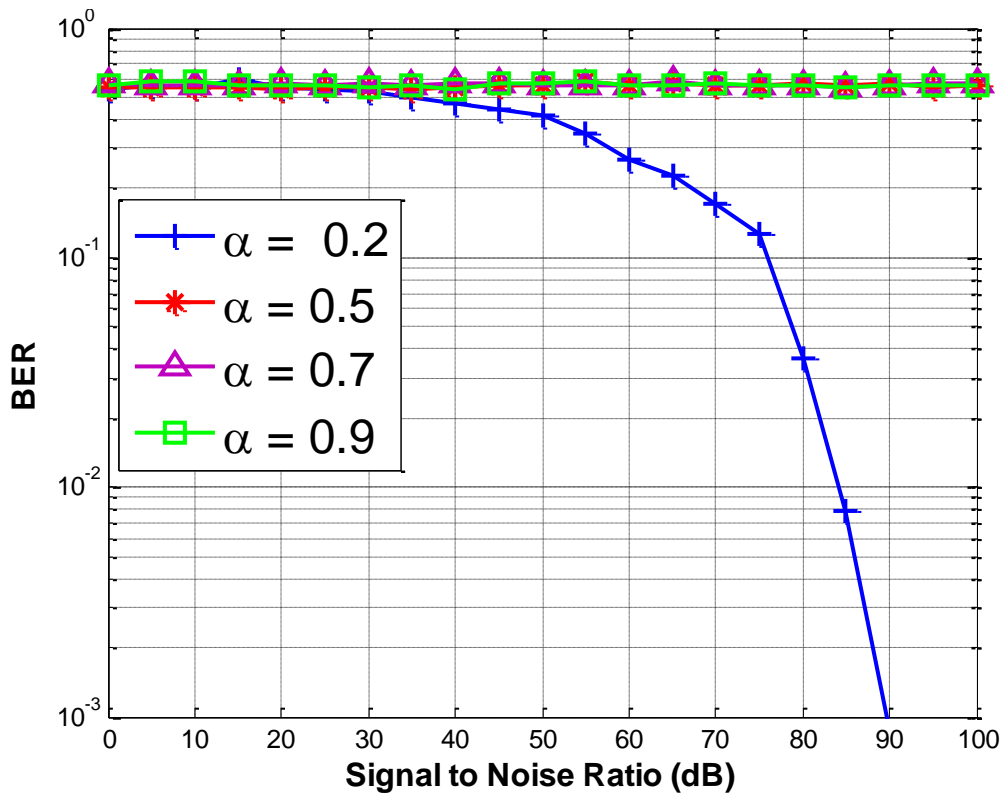


(a)

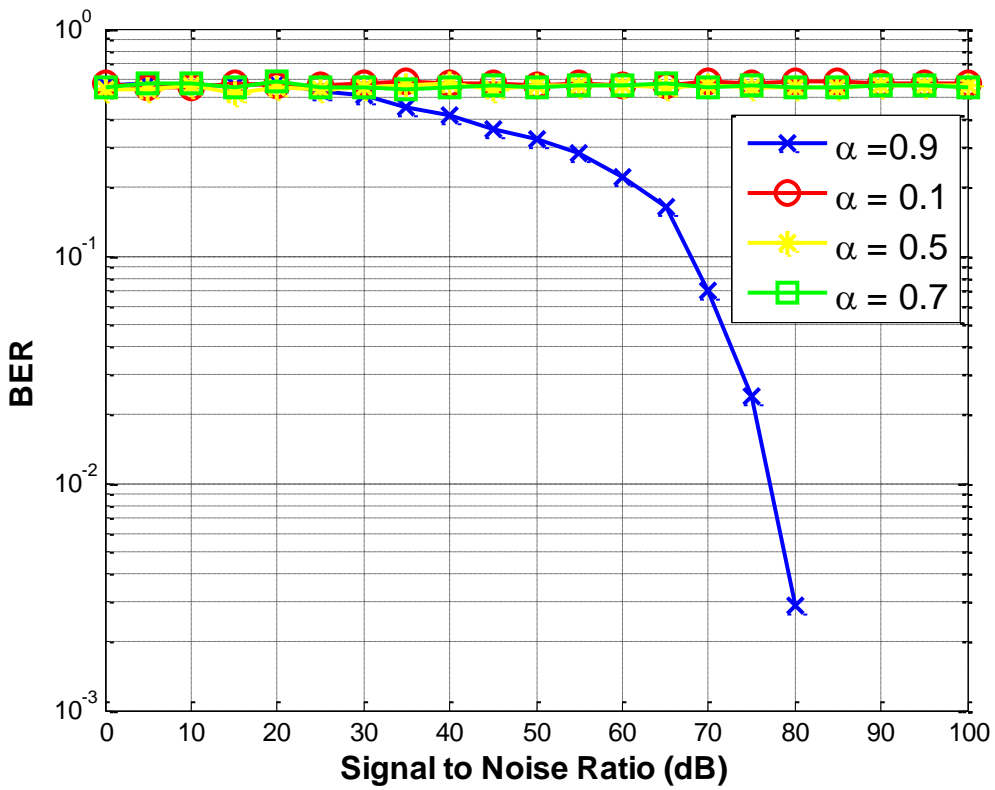


(b)

**Figure 3-11: BER vs. SNR for 1024-PSK under (a) AWGN (b) Rayleigh (c) Rician and (d) Nakagami Channel**



(c)

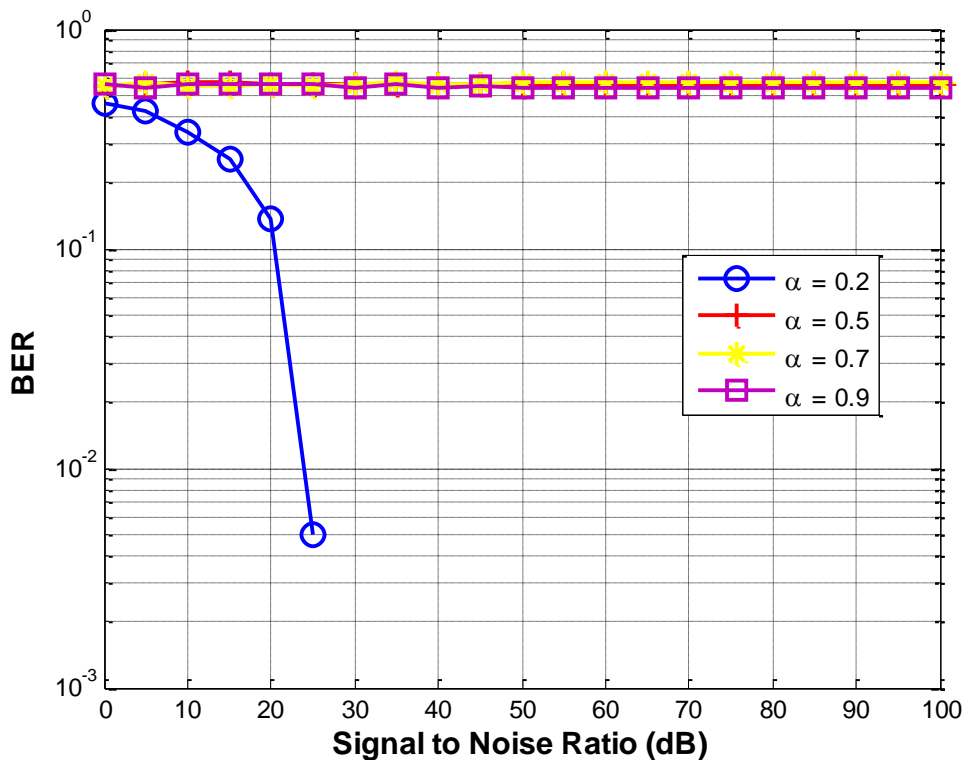


(d)

Figure 3-11 (Continued)

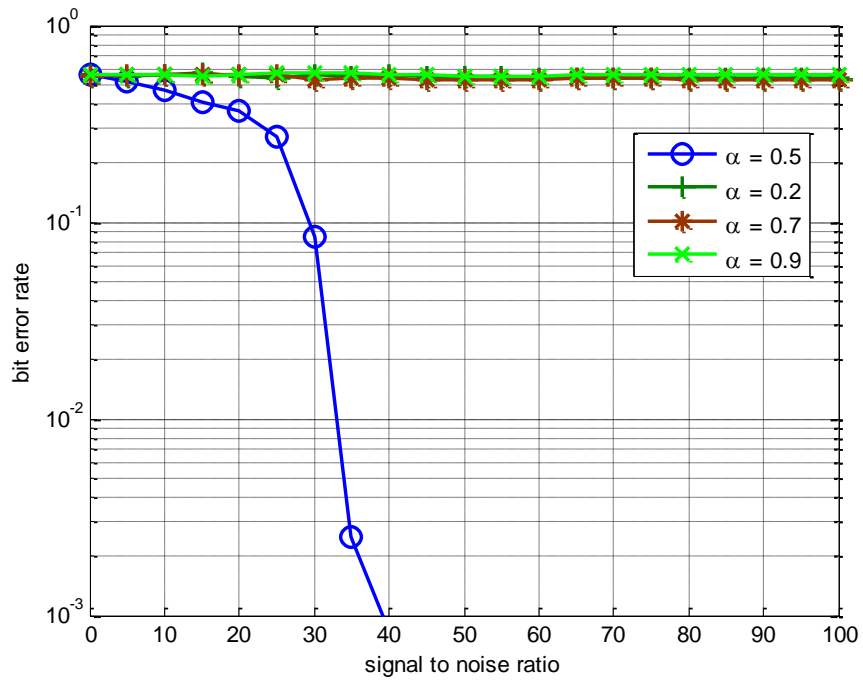
In Figure 3.11 (a) the BER vs SNR of proposed FrFT appended model with 1024-PSK modulation is shown. In this the OFDM modulated signal was encrypted with  $\alpha = 0.5$ . On the receiver side when the said signal was decrypted with  $\alpha = 0.5$ , the system was able to decrypt the signal and SNR of 73 dB at  $10^{-2.8}$  BER was achieved. For all other values of ' $\alpha$ ' like 0.2, 0.7 and 0.9 as shown in Figure 3.11(a), the system decrypted data as noise only. Similarly for Rayleigh, Rician, and Nakagami channels the said model with 1024-PSK modulation have shown very encouraging results for using FrFT as a security tool. In case of Rayleigh, Rician, and Nakagami channels as shown in Figure 3.11 (b), 3.11 (c) and 3.11(d), the proposed FrFT appended system has been used to encrypt the data using  $\alpha = 0.2$ ,  $\alpha = 0.7$ , and  $\alpha = 0.9$  respectively. Hence, it could be concluded that the said system demodulates transmitted data only at the matched value of ' $\alpha$ ' with transmitter, for all other values of ' $\alpha$ ' the system shows received signal as noise and transmitted data could not be recovered.

In Figures 3.12 (a) to 3.12 (d), the security of the 1024-QAM modulated OFDM signal under various wireless fading channels for the FrFT appended OFDM system have been analysed.

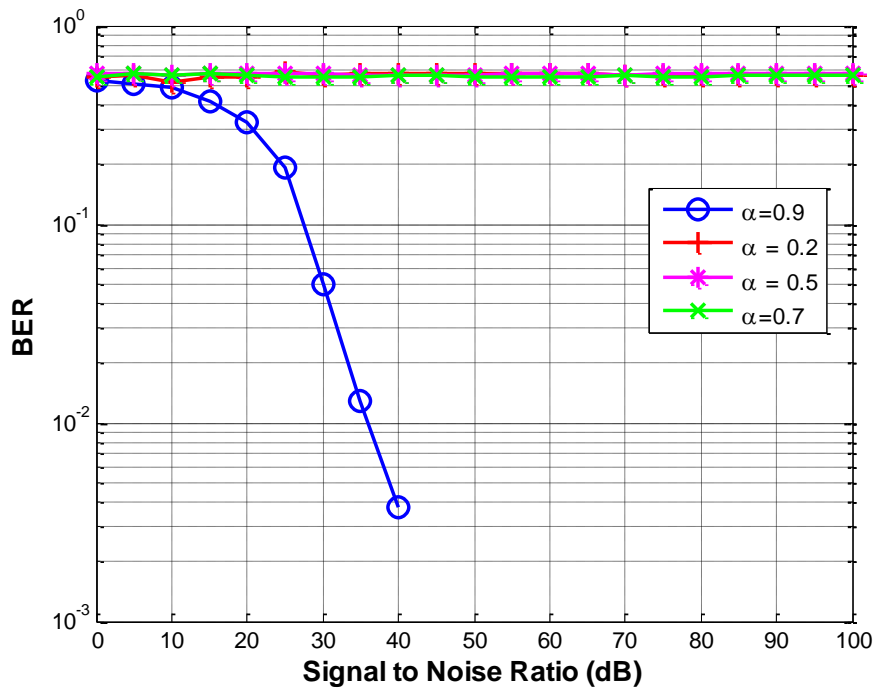


(a)

**Figure 3-12: BER vs. SNR for 1024-QAM under (a) AWGN (b) Rayleigh (c) Rician and (d) Nakagami Channel**

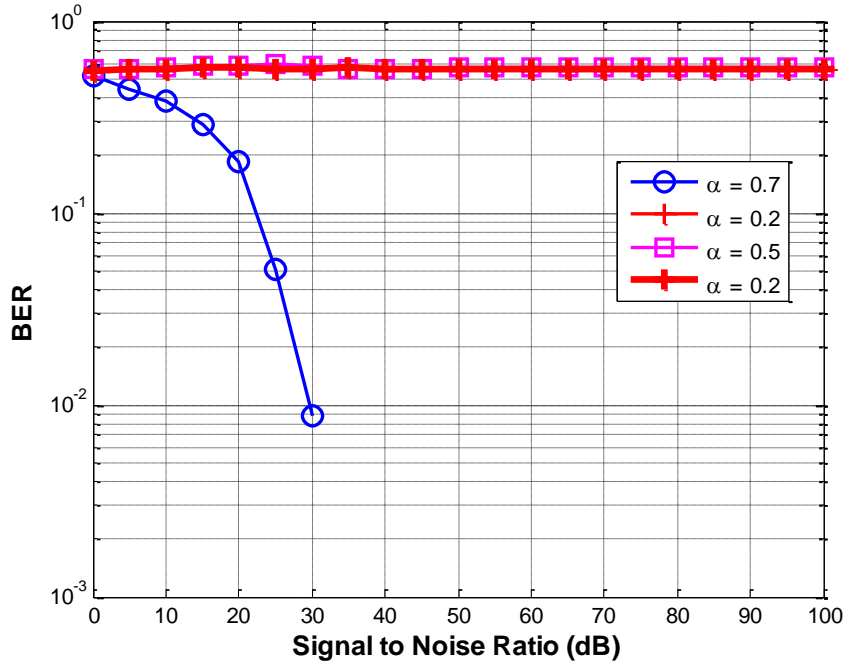


(b)



(c)

Figure 3-12: (Continued)



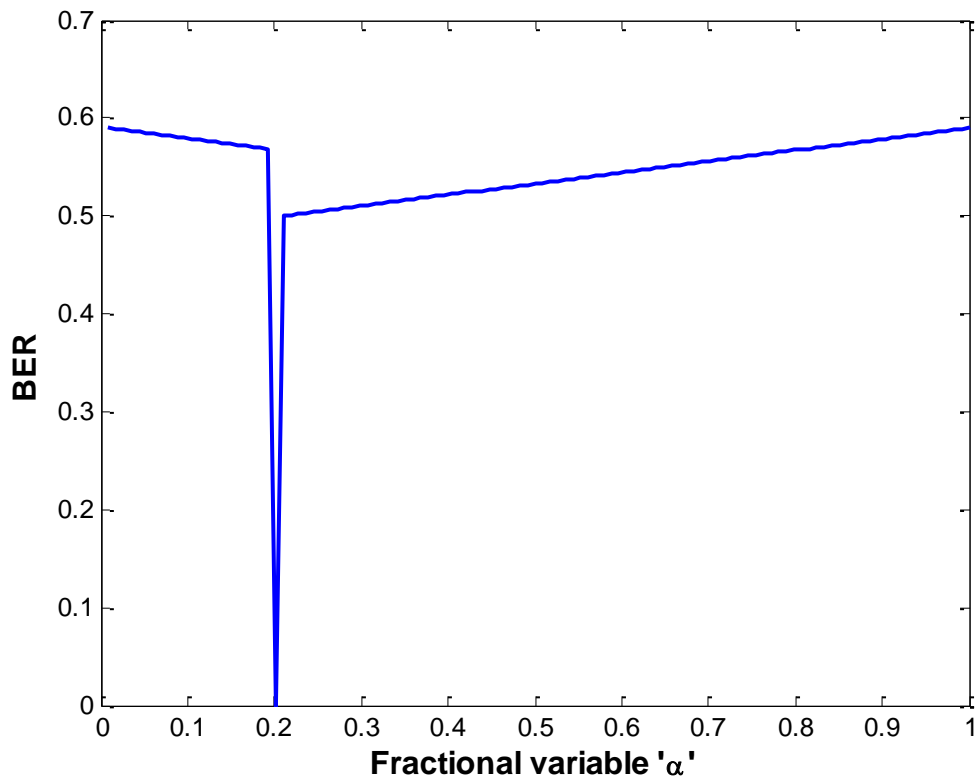
(d)

**Figure 3-12: (Continued)**

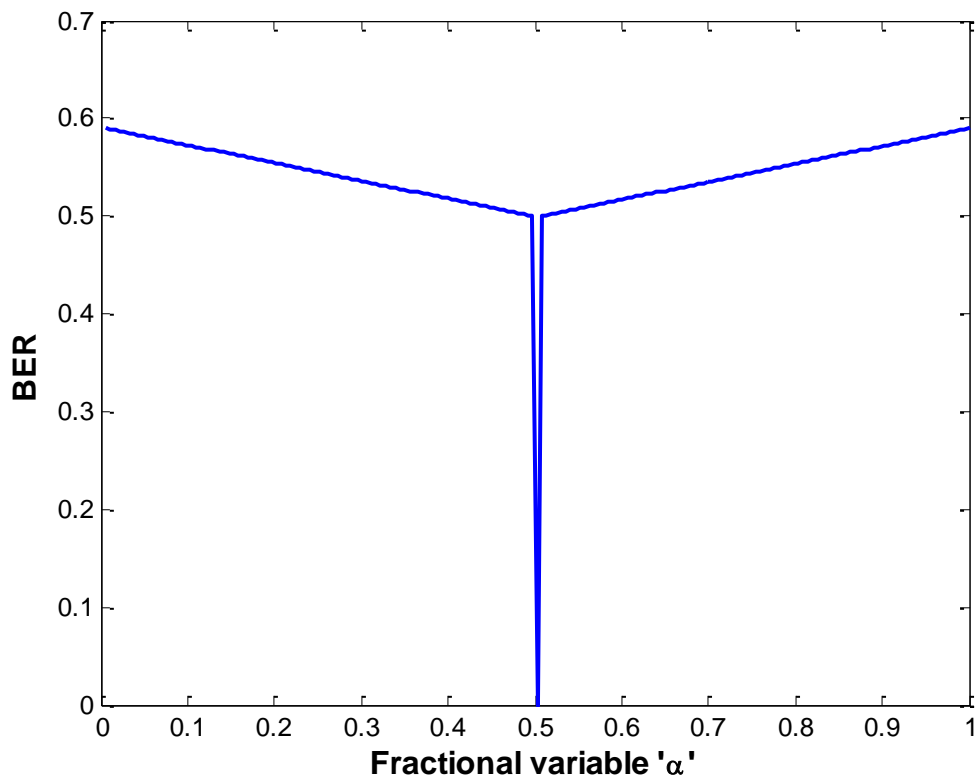
In Figure 3.12 (a), the BER vs. SNR for FrFT appended OFDM system is shown for 1024-QAM modulation under the AWGN channel. In this Figure, the receiver could only decrypt the data at  $\alpha = 0.2$  which was used at transmitter for encryption; rest all other values of ' $\alpha$ ' could not decrypt the data at the receiver. Likewise, the results presented in Figure 3.12 (b) to 3.12 (d) for Rayleigh, Rician, and Nakagami channels depicts that, the proposed arrangement could decrypt only for the exact value of ' $\alpha$ ' at transmitter. Henceforth, it could be stated that the FrFT domain can be used as real beneficial tool for enhancing the security to OFDM signals in wireless domain.

### 3.7 SENSITIVITY OF FRACTIONAL ORDER

The important aspect of FrFT link appended OFDM system is its capability to specify a key based on fractional variable ' $\alpha$ ' which encrypts the transmitted signal differently for different values of ' $\alpha$ ', which requires the unique fractional variable ' $\alpha$ ' to decrypt. This encryption would enhance the security of OFDM modulated signal in wireless domain. The sensitivity of decryption key i.e. fractional variable ' $\alpha$ ' can be measured with the effect on BER.

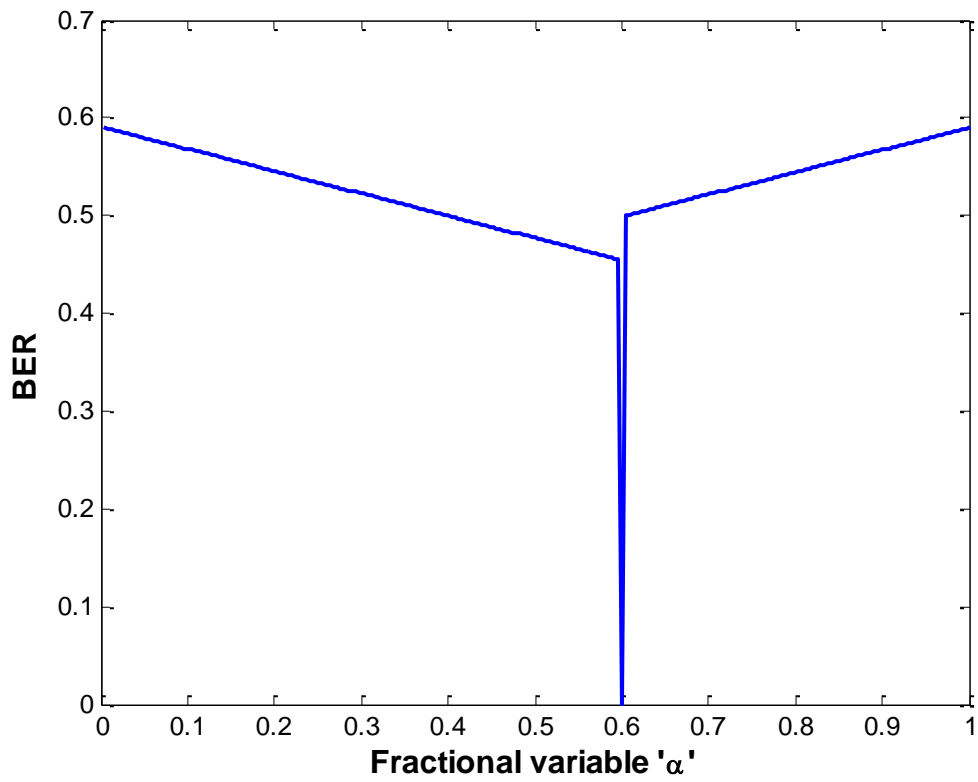


(a) Change in BER vs. First fractional order

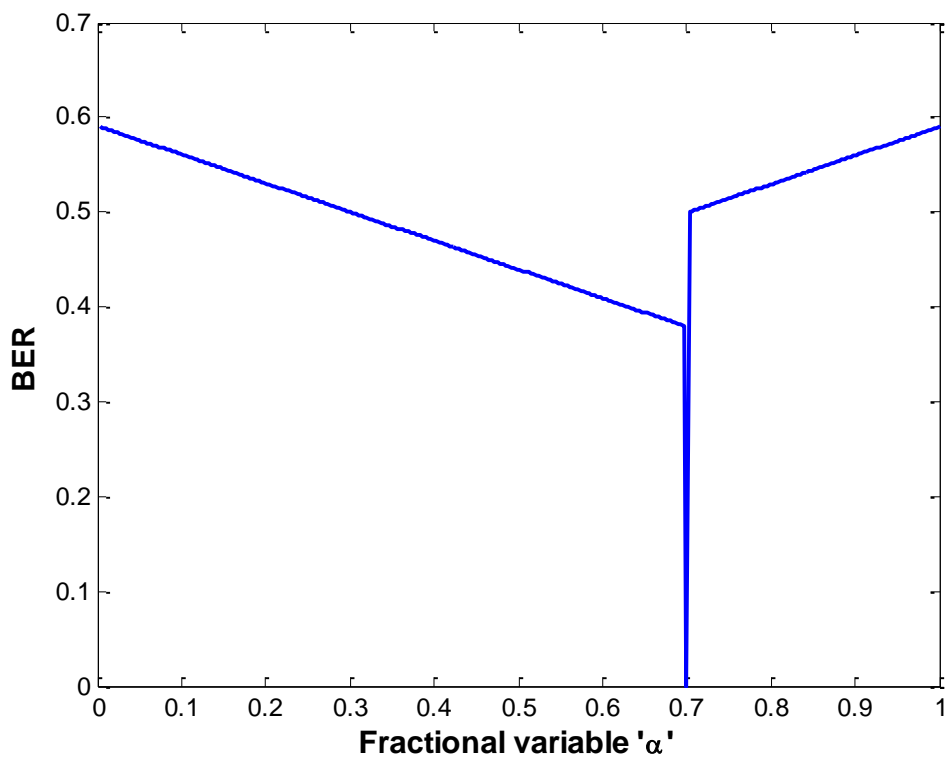


(b) Change in BER vs. Second fractional order

Figure 3-13: Change in BER vs. the deviation in Fractional variable using FrFT



(c) Change in BER vs. Third fractional order



(d) Change in BER vs. Fourth fractional order

Figure 3-12: (Continued)

It has been observed from Figure 3.13 that the BER is minimized at appropriate fractional variable ' $\alpha$ ' and is maximized for all other values of fractional variable ' $\alpha$ '.

### **3.8 SUMMARY**

A new FrFT appended OFDM system has been proposed which is not available in literature. The addition of FrFT along with OFDM system added a new level of security in wireless communication. Here, fractional variable ' $\alpha$ ' has been used for encrypting the transmitted signal. Further, this FrFT appended system also improved the BER vs. SNR of traditional FFT based OFDM system. An improvement of as high as 5.7 dB in SNR has achieved for 1024-PSK modulated OFDM system under Nakagami channel and of 4.6 dB improvement in SNR for 1024-QAM modulated signal has been achieved under Rician channel.

#### ***Contribution of Chapter***

*The encryption of OFDM signal before transmission using fractional variable ' $\alpha$ ' is a novel way of encrypting the signal transmission. This addition of FrFT block with traditional OFDM system results in more secure OFDM transmission in wireless networks.*

# CHAPTER 4

## OFDM SYSTEM WITH FrFT

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In this chapter, an OFDM system has been proposed based on 1024-PSK and 1024-QAM modulation techniques. In this system, the traditional FFT based OFDM system has been modified by replacing IFFT and FFT with IFrFT and FrFT at transmitter and receiver respectively. The FrFT based OFDM model provided much better results in terms of BER compared to the traditional OFDM system in wireless domain for said modulation techniques. The performance of the proposed system is assessed for higher order modulation techniques like 1024-PSK and 1024-QAM under various wireless fading channels like AWGN, Rayleigh, Rician, and Nakagami. Further, PAPR analysis of the said system for 1024-PSK and 1024-QAM modulation technique has been done using SLM clipping technique.

### 4.1 BENEFIT OF REPLACING FrFT WITH FFT

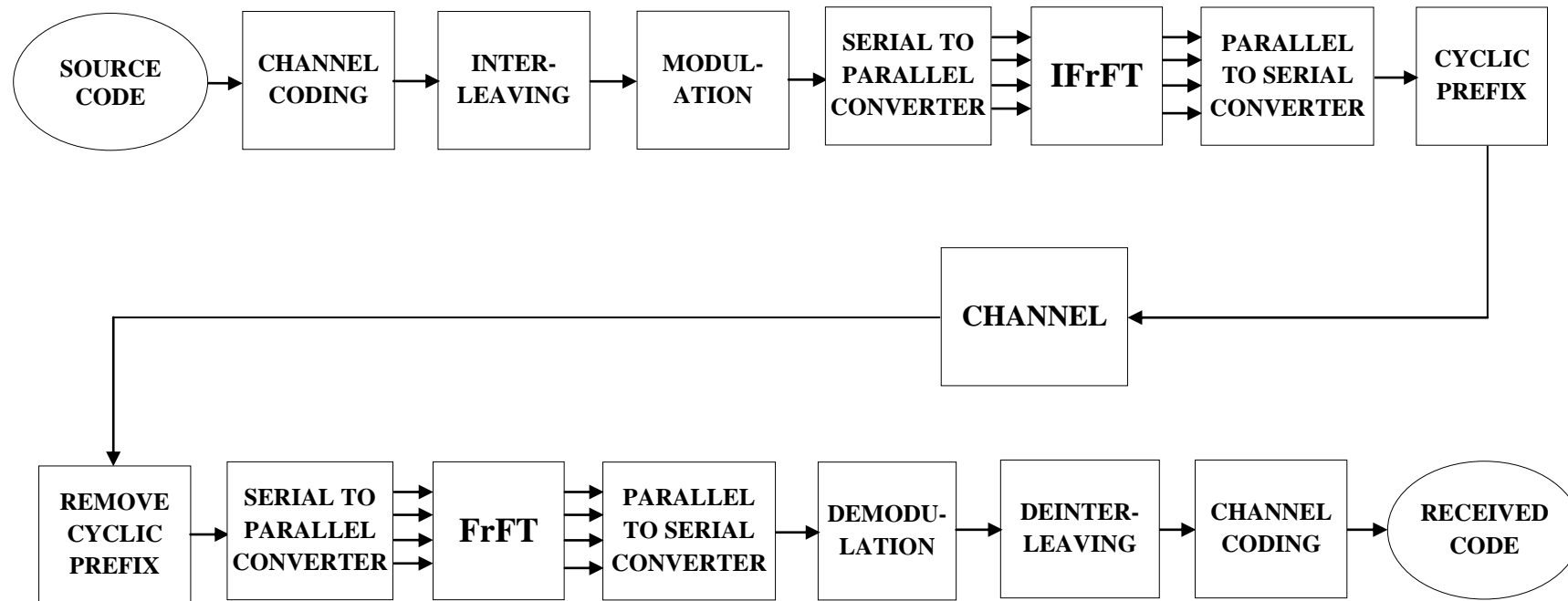
Any signal can be defined as the function of time. It will exclusively provide the change in amplitude of signal with time. Nevertheless, it will be silent about the change in frequency of the signal at any period of time [147]. Also if a signal is rendered in the frequency domain by its FT, it will supply the frequency components available in the signal but will be silent about the time of arrival of these frequencies in a signal. Hence, a technique has to be evolved, which will define the signal based on two variables namely; time and frequency instead of signal variable time or frequency individually [78]. FT is used to draw out information contained in the signal. Initially in the time domain the modulated signal gives change in amplitude of signal in the time domain but is silent about frequency component. After applying FT to the said signal, in frequency domain signal gives exact information about the component of frequency along with amplitude associated with every frequency [154]. FT is most widely used in signal processing and communication. However, FT fails to give analysis of non-stationary signals. FrFT is the answer for this problem. It is a mathematical tool which maps a signal from one domain to another in time-frequency plan [80].

FrFT was defined as transformation method by defining the fractional power of Eigen functions for ordinary FT proposed by V. Namias [74]. The major benefit of FrFT is that any transformed signal can be retrieved to its original value by applying the inverse FrFT to already transformed signal [83]. The FrFT on any signal can be implied using the fractional variable ' $\alpha$ ' and it's inverse by ' $-\alpha$ '. Thus, any signal in frequency domain that is processed in FrFT domain can be transformed into time domain by ' $-\alpha$ '.

## 4.2 FrFT BASED OFDM

Here, the PSK modulation is used with 1024 bits as the symbol size for the OFDM system. The higher symbol was chosen to facilitate large data transmission in wireless domain [71]. The basic block diagram of proposed FrFT based OFDM system is shown in Figure 4.1. The fundamental difference of this proposed model as shown in Figure 4.1 from the traditional OFDM system is that, here IFFT and FFT blocks had replaced with IFrFT and FrFT blocks respectively. The basic block diagram of proposed system is given in Figure 4.1.

The input data symbols are passed through channel coder and interleaver to minimise the BER. After converting to parallel this input data streams are passed through inverse FrFT and again reconverted to serial bits. Cyclic prefix is added in each of these data envelopes and then transmitted. Here, data symbols of 1024-PSK and 1024-QAM is used for transmission with OFDM sub-carriers. The behaviour of various wireless fading channels for the said transmitted signals is analysed here. The channels considered are AWGN, Rayleigh, Rician, and Nakagami. At the receiver side, again the received bits are first converted to parallel from serial after removing the cyclic prefix. FrFT transformation is then applied on these data bits. These bits are again converted to serial through parallel to serial converter. After demodulation, deinterleaving and channel decoding is carried out and original data has been recovered. In the next sections the performance analysis of FrFT based OFDM system is presented.



**Figure 4-1: Block diagram of FrFT based OFDM system**

### 4.3 MATHEMATICAL ANALYSIS

The input data stream of binary data was grouped and mapped into multiphase signals, with values from a finite alphabet set given by  $\mathcal{A} = \{a_1, a_2, \dots, a_A\}$ . Here 1024-PSK modulation had employed. Let the number of subcarriers be  $N$ . An OFDM symbol constructed by stacking a serial information sequence of the mapped signals  $\{s_0, s_1, s_2, s_3, \dots, s_{N-1}\}$  of length  $N$  by serial-to-parallel (S/P) conversion where,  $s_n \in \mathcal{A}$ . Subsequently, an  $N$ -points IDFrFT is applied to produce the  $N$  dimensional time-domain data, transmitted by converting parallel to serial. Then a cyclic prefix (CP) of length  $N_{cp}$  was inserted at the beginning of the symbol in order to mitigate the multipath effects (ISI). The transmitted symbol  $\{s(m)\}$  is expressed as [78]

$$s(m) = \sqrt{\frac{N}{N + N_{CP}}} \sum_{k=0}^{N-1} s(k) F_{-\alpha}(m, k) \quad -N_{CP} \leq m < N \quad (4.3.1)$$

where,  $k = (0, \dots, N-1)$

$N$  = Number of Subcarriers,

$N_{CP}$  = Cyclic Prefix length,

$k = k^{th}$  subcarrier for  $m^{th}$  symbol,

$s(m) = m^{th}$  sample of  $i^{th}$  frame,

$s_i(k) =$  Symbol to be transmitted

The inverse FrFT kernel as expressed in [79, 148]

$$F_{-\alpha}(m, k) = \sqrt{\frac{\sin \alpha + j \cos \alpha}{N}} e^{\left[ \frac{-j}{2} m^2 (T_s)^2 \cot \alpha \right]} e^{\left[ \frac{-j}{2} k^2 u^2 \cot \alpha \right]} e^{\left[ j \frac{2\pi mk}{N} \right]} \quad (4.3.2)$$

$$\text{and } uT_s = \frac{2\pi(\sin \alpha)}{N}$$

where,  $T_s$  and  $u$  were the sampling intervals in the time and FrFT domain respectively. The

FrFT domain makes angle  $a = \frac{\alpha\pi}{2}$  with the time domain. For  $\alpha = \pi/2$  or  $\alpha = 1$ , IFrFT converges to IFFT.

The discrete expression of the channel impulse response (CIR) is represented by  $h(n, l)$  and the cross-correlation function of the CIR is given by [157]

$$E[h(p, l)h^*(q, k)] = \sigma_i^2 J_o(2\pi \Delta t f_d) \delta(l - k) \quad (4.3.3)$$

where,  $\Delta t = |p - q|T_s$  and  $\sigma_l^2$  was total power of the  $l^{th}$  path,  $J_0$  was  $0^{th}$  order Bessel function,  $f_d$  is the maximum Doppler frequency shift and  $\delta(l)$  is Kronecker delta function. By assuming the frame is synchronized, the  $n^{th}$  sample of the received frame had given by [157]

$$r(n) = \sum_{i=-\infty}^{\infty} \sum_{m=-N_g}^{N-1} h_{i,j}(n, n-m) s_i(m) e^{j\frac{2\pi n \epsilon}{N}} + w(n) \quad (4.3.4)$$

where,  $w(n)$  is the AWGN noise and  $\epsilon = \Delta f N T_s$  is the frequency offset and  $h_{i,j}(nl) = h(j(N + N_g) + n, l + (j-1)(N + N_g))$  for the  $j^{th}$  received frame [43].

At the receiver, after removing the cyclic prefix and applying FrFT, the final received signal is given by

$$\hat{s}(\hat{k}) = \sum_{n=0}^{N-1} F_{\alpha}(\hat{k}, n) r(n), \quad 0 \leq \hat{k} < N \quad (4.3.5)$$

$$\text{where, } F_{\alpha}(m, n) = \frac{\sqrt{\sin \alpha - j \cos \alpha}}{N} e^{j\frac{j}{2}n^2(T_s)^2 \cot \alpha} e^{j\frac{j}{2}m^2 u^2 \cot \alpha} e^{-j\frac{2\pi m n}{N}} \quad (4.3.6)$$

Combining the (4.3.5) and (4.3.6), the signal at the receiver is expressed as

$$\hat{s}(\hat{k}) = \sqrt{\frac{N}{N + N_{cp}}} \sum_{i=-\infty}^{\infty} \sum_{k=0}^{N-1} s(k) \sum_{n=0}^{N-1} \sum_{m=-N_g}^{N-1} F_{\alpha}(\hat{k}, n) \cdot F_{-\alpha}(m, k) h_{i,j}(n, n-m) e^{j\frac{2\pi n \epsilon}{N}} + w(\hat{k}) \quad (4.3.7)$$

By putting,  $IS_{ij}(\hat{k}, k) = \sum_{n=0}^{N-1} \sum_{m=-N_g}^{N-1} F_{\alpha}(\hat{k}, n) F_{-\alpha}(m, k) h_{i,j}(n, n-m) e^{j\frac{2\pi n \epsilon}{N}}$  in (4.3.7), the final received signal is given as

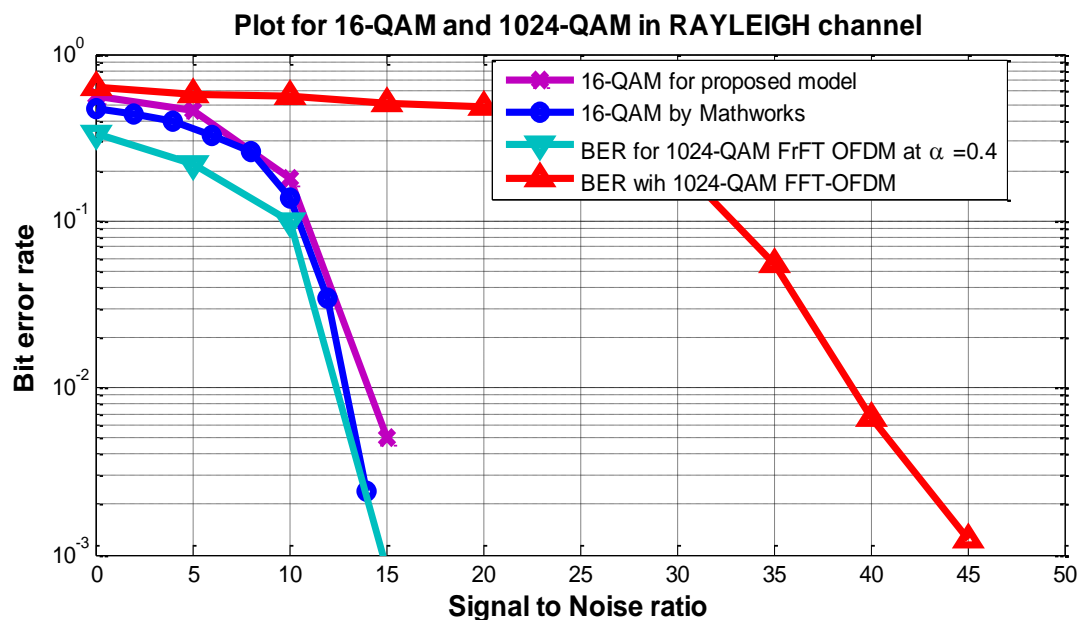
$$\hat{s}(\hat{k}) = \sqrt{\frac{N}{N + N_{cp}}} \sum_{i=-\infty}^{\infty} \sum_{k=0}^{N-1} IS_{ij}(\hat{k}, k) s(k) + w(\hat{k}) \quad (4.3.8)$$

Hence, the final received signal  $\hat{s}(\hat{k})$  is obtained for the originally transmitted signal  $u(m)$  after passing through FrFT based OFDM system. Further, its BER analysis is done under various wireless fading channels for different values of ' $\alpha$ ' in the range of 0.0 to 1.0.

#### 4.4 RESULTS AND DISCUSSION

BER analysis of FrFT based OFDM system had been done for 1024-PSK and 1024-QAM modulations under various wireless fading channels. The response of proposed system with different values of ' $\alpha$ ' in the range of 0.0 to 1.0 had been evaluated and reported. Here, 1024-PSK symbols was used for one symbol of OFDM along with  $10^3$  frames. This large symbol size would help in achieving the higher data rates. However, with increase in symbol size along with large number of frames, the BER of traditional FFT based OFDM system increased to approximately 74 dB.

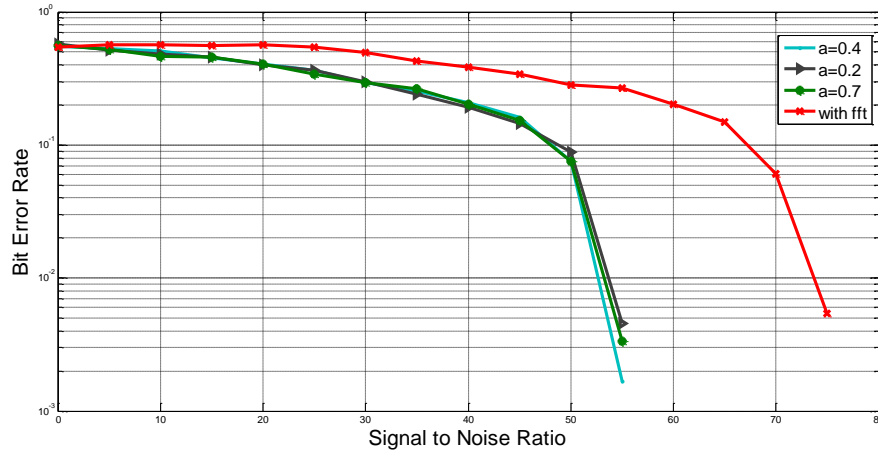
The proposed FrFT based OFDM system is converged to existing FFT based OFDM system at  $\alpha=1$ . The proposed FrFT based OFDM system for 16-QAM modulation technique is compared with the results presented by **Qi Zhang et al.** [161] and **M. Toabi et al.** [162].



**Figure 4-2: Plots of BER vs. SNR for 16-QAM FFT based OFDM, 16-QAM FrFT based OFDM, 1024-QAM FFT and FrFT based OFDM system**

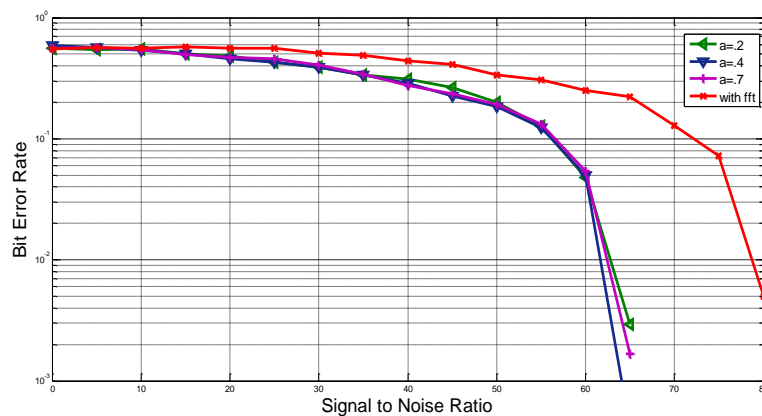
From the results achieved, it could be depicted that the proposed model had achieved almost same BER as was proposed in [161, 162] for 16-QAM modulation technique. In addition, the proposed model has been implemented for higher order modulation techniques such as 1024-PSK and 1024-QAM. In Figure 4.2, the simulation results for higher order modulation have also been given and it can be concluded that the proposed system outperforms the FFT based OFDM system even for 1024-QAM modulation technique.

Here, by proposing FrFT based OFDM system, this BER for same set of data improved to a great extent. In Figure 4.3, the BER vs. SNR for said model had been represented under AWGN channel for different values of ' $\alpha$ '.



**Figure 4-3: BER Vs SNR for FrFT based OFDM system with 1024-PSK modulation under AWGN Channel**

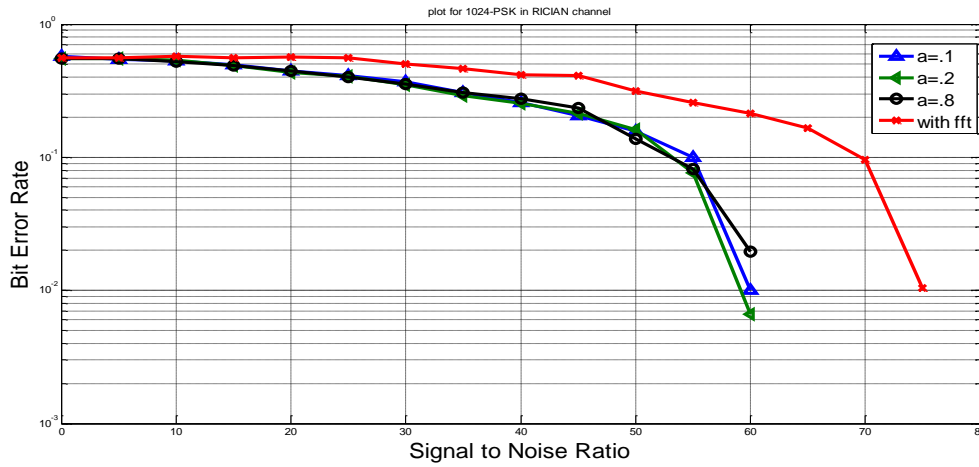
From Figure 4.3, it can be depicted that at  $\alpha = 0.4$ , the proposed system gives best results as compared to the system performance at other values of ' $\alpha$ ' in range 0.0 to 1.0. Further, FrFT based OFDM system was able to achieve  $10^{-1.8}$  BER at 53 dB SNR, where, as FFT based OFDM system got only  $10^{-0.4}$  BER at the same SNR. The proposed model was analysed for Rayleigh channel with same modulation. Figure 4.4 shown the BER vs. SNR of said model for Rayleigh channel with different values of ' $\alpha$ '.



**Figure 4-4: BER Vs SNR for FrFT based OFDM system with 1024-PSK modulation under Rayleigh Channel**

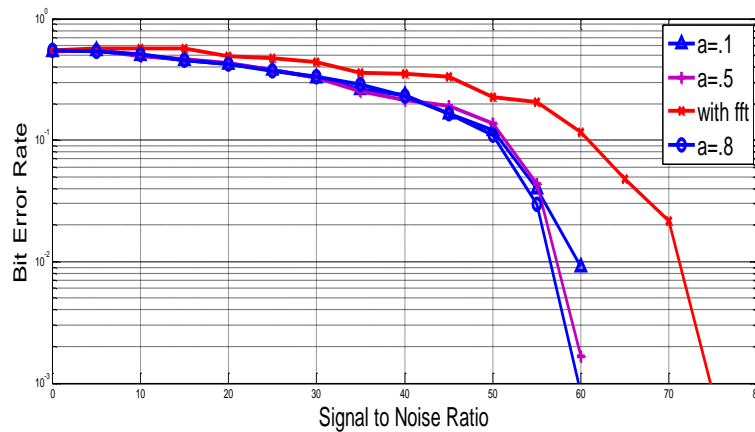
As observed from Figure 4.4, the system performance is optimal at  $\alpha = 0.4$  for Rayleigh channel. Moreover, at an SNR of 60 dB, the FrFT based OFDM system achieved far better

BER that is  $10^{-2.5}$  than the traditional FFT based OFDM system which is  $10^{-0.9}$ . The proposed system is then studied under Rician channel and results are presented in Figure 4.5.



**Figure 4-5: BER Vs SNR for FrFT based OFDM system with 1024-PSK modulation under Rician Channel**

Under Rician channel as shown in Figure 4.5, the proposed system achieved the best results at  $\alpha = 0.4$  as compared to rest of the values of ' $\alpha$ '. Here, at SNR of 60 dB the proposed system achieved BER of  $10^{-2.4}$  whereas the FFT based OFDM system achieved  $10^{-0.9}$  BER at same SNR. Finally, in Figure 4.6 the results of proposed model under Nakagami channel has been shown.



**Figure 4-6: BER Vs SNR for FrFT based OFDM system with 1024-PSK modulation under Nakagami Channel**

From Figure 4.6 it has been observed that, under Nakagami channel the value of ' $\alpha$ ' is 0.8 for which the proposed system gives best results. At SNR of 60 dB, under Nakagami channel, the proposed system achieved an BER of  $10^{-0.3}$  for FrFT based OFDM system.

The performance of FrFT based OFDM system by using proposed 1024-PSK modulation technique under various wireless fading channels is tabulated in Table: 4.1. The improvement

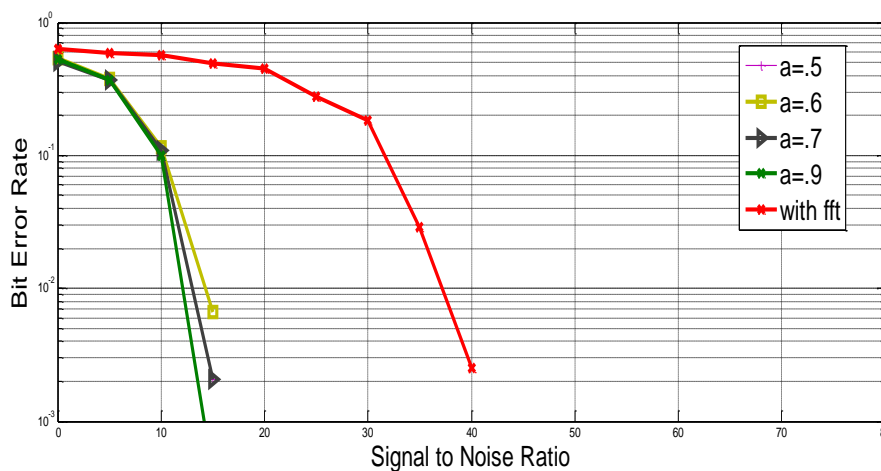
is calculated by comparing the results of ' $\alpha_{opt}$ ' with respect to the results of  $\alpha=1$  i.e. existing FFT based OFDM system at given BER.

**Table 4-1: Improvement in SNR for M-PSK by keeping best BER for different channels**

1024-PSK						
S. No.	Channels	BER	Original System SNR at $\alpha = 1$ (in dB)	Proposed System		Improvement in SNR (in dB)
				' $\alpha_{opt}$ '	SNR (in dB)	
1	AWGN	$10^{-2.5}$	54.0	0.4	75.0	21.0
2	Rayleigh	$10^{-2.9}$	89.4	0.8	64.3	25.1
3	Rician	$10^{-2.0}$	75.0	0.2	60.0	15.0
4	Nakagami	$10^{-3.0}$	75.0	0.8	59.8	15.2

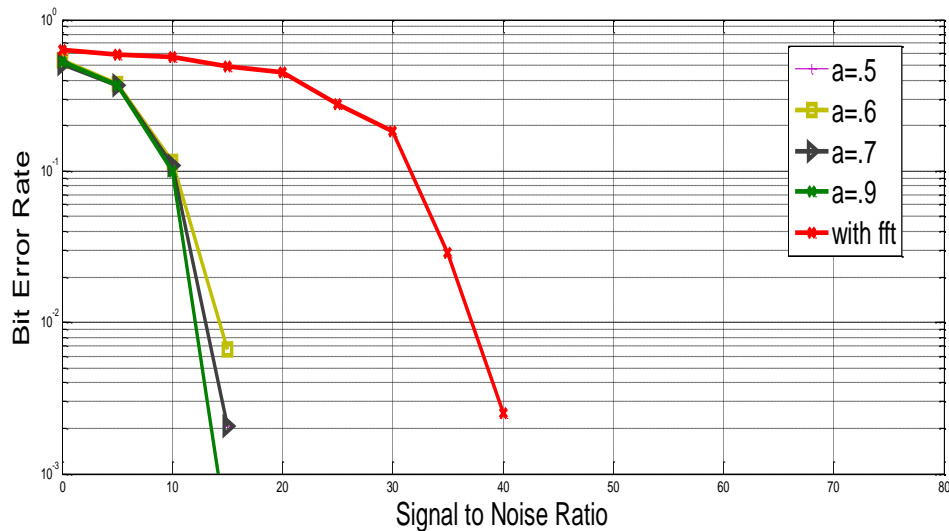
In AWGN, Rayleigh, and Rician channels, proposed system had shown improvement of 21.0 dB at  $10^{-2.5}$  BER, 25.1 dB at  $10^{-2.9}$  BER and 15.0 dB at  $10^{-2.0}$  BER respectively for 1024-PSK modulation. However, Nakagami channel had given highest improvement of 15.2 dB for same modulation at  $10^{-3.0}$  BER for same modulation technique.

Further, the same model was implemented for 1024-QAM modulation technique and the results achieved had been presented. Figure 4.7 shows the BER vs SNR for AWGN channel for different values of ' $\alpha$ '.



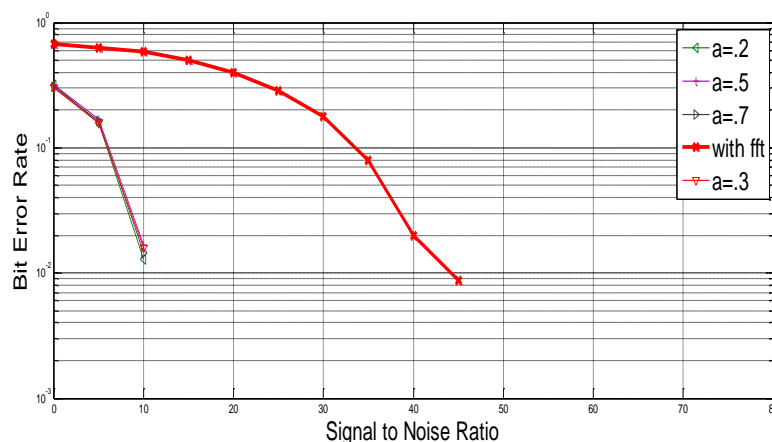
**Figure 4-7: BER Vs SNR for FrFT based OFDM system with 1024-QAM modulation under AWGN Channel**

From Figure 4.7, it could be depicted that with  $\alpha = 0.9$  the proposed system gives best results as compared to other values of ' $\alpha$ '. Further, FrFT based OFDM system was able to achieve  $10^{-2.8}$  BER at 15 dB SNR where, as FFT based OFDM system got  $10^{-0.8}$  BER at the same SNR. Then the proposed model was analysed for Rayleigh channel with same modulation. Figure 4.8 shown the BER vs SNR of proposed model for Rayleigh channel with different values of ' $\alpha$ '.



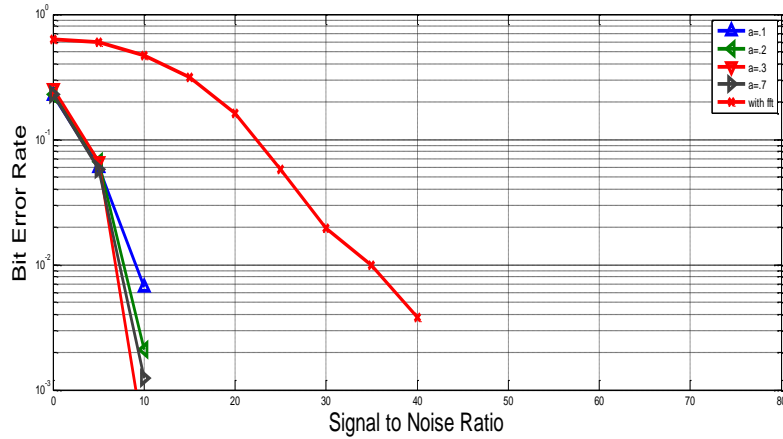
**Figure 4-8: BER Vs SNR for FrFT based OFDM system with 1024-QAM modulation under Rayleigh Channel**

The results shown in Figure 4.8, shows that  $\alpha = 0.9$  is the optimal value of fractional order for which the proposed system is producing best results. FrFT based OFDM system achieved  $10^{-2.9}$  BER at an SNR of 14 dB whereas in FFT based OFDM system the BER is  $10^{-0.5}$  at same SNR. In Figure 4.9 the analysis of same model under Rician channel is shown for different values of ' $\alpha$ '.



**Figure 4-9: BER Vs SNR for FrFT based OFDM system with 1024-QAM modulation under Rician Channel**

In Rician channel the FrFT based OFDM system was able to achieve  $10^{-1.9}$  BER at an SNR of 10 dB. From Figure 4.9, it could be depicted that the optimal value of ' $\alpha$ ' is 0.7 at which the proposed system gives best results as compared to  $10^{-0.4}$  BER of FFT based OFDM system for same SNR.



**Figure 4-10: BER Vs SNR for FrFT based OFDM system with 1024-QAM modulation under Nakagami Channel**

From Figure 4.10, it is observed that the best value of fractional order parameter ' $\alpha$ ' is 0.3. Further FrFT based OFDM system had been able to achieve  $10^{-3.0}$  BER at SNR of 9 dB whereas FFT based OFDM system got  $10^{-0.4}$  BER at the same SNR. Behaviour of all the wireless fading channels for proposed model with 1024-QAM shows that with 1024-QAM modulation, the proposed models achieved best results under Nakagami channel.

The performance of FrFT based OFDM system by using proposed 1024-QAM modulation technique under various wireless fading channels is tabulated in Table 4.2. It shows the improvement achieved in BER for the best value of ' $\alpha_{opt}$ ' for various wireless fading channel for 1024-QAM calculated from the above shown plots. The improvement here is calculated by comparing the results of ' $\alpha_{opt}$ ' with respect to the results of  $\alpha=1$  i.e. existing FFT based OFDM system at given BER.

**Table 4-2: Improvement in SNR for M-QAM by keeping best BER for different channels**

1024-QAM						
S. No.	Channels	BER	Original System	Proposed System		Improvement in SNR (in dB)
			SNR at $\alpha = 1$ (in dB)	' $\alpha_{opt}$ '	SNR (in dB)	
1	AWGN	$10^{-2.9}$	35.0	0.5	5.0	30.0
2	Rayleigh	$10^{-2.8}$	45.0	0.4	14.4	30.6
3	Rician	$10^{-1.8}$	40.0	0.9	9.5	30.5
4	Nakagami	$10^{-2.7}$	40.0	0.3	8.5	31.5

In the case of 1024-QAM, the improvement in SNR was 30.0 dB at  $10^{-2.9}$  BER and 30.6dB at  $10^{-2.8}$  BER for AWGN and Rayleigh channel respectively. For Rician channel the proposed model achieved an improvement of 30.5 dB at  $10^{-1.8}$  BER. The improvement was 31.5 dB in the case of Nakagami channel by the appended OFDM system at  $10^{-2.7}$  BER for the said modulation technique.

#### 4.5 PAPR ANALYSIS OF FrFT BASED OFDM SYTEM

The OFDM system is no doubt much beneficial for transmitting data in wireless domain. It is using the spectrum very efficiently as compared to single carrier communication systems. However, OFDM also suffers from certain limitations like; its dependence on carrier frequency deviation in wireless domain, to maintain orthogonality between sub-carriers, PAPR and system complexity etc. PAPR is one of the major limitations of OFDM and need to be addressed for overall good performance of system [71]. As the frames of OFDM signal modulated on different subcarriers, all frames have different peak powers. This large variation in peak amplitudes of OFDM envelopes is the major drawback of OFDM, because

the practical communication amplifiers are peak-power limited [69]. These amplifiers are not able to handle the change in instantaneous signal power, which is much larger than signal power. In order to compensate this problem, the amplifiers are required to have large linear operating range [29]. This problem is defined as PAPR problem. In this section, the problem of PAPR is dealt with by proposing FrFT based OFDM system using 1024-PSK and 1024 QAM modulation techniques.

The FrFT based OFDM signal is as discussed in section 4.3 and is given by (4.3.1) and (4.3.2).

The definition of PAPR as given in [69]:

$$PAPR = \frac{P_{peak}}{P_{average}} = \frac{\max \left\{ |s(t)|^2 \right\}}{E \left\{ |s(t)|^2 \right\}} \quad (4.5.1)$$

PAPR is given as the ratio of the peak value of signal to the mean square value of signal. A CCDF curve shows a plot between the relative power levels of the signal versus probability of a signal to have power higher than the threshold level ' $\lambda$ '. So CCDF curves measures the probability of a signal's instantaneous power higher than a specific level over its average power [156]. That is,

$$P_r \{PAPR > \lambda\} = 1 - P_r \{PAPR \leq \lambda\} = 1 - (1 - e^{-\lambda})^N \quad (4.5.2)$$

If  $U$ , the statistically independent FrFT based OFDM frame and represent the same information, then the probability of PAPR is given by [16]

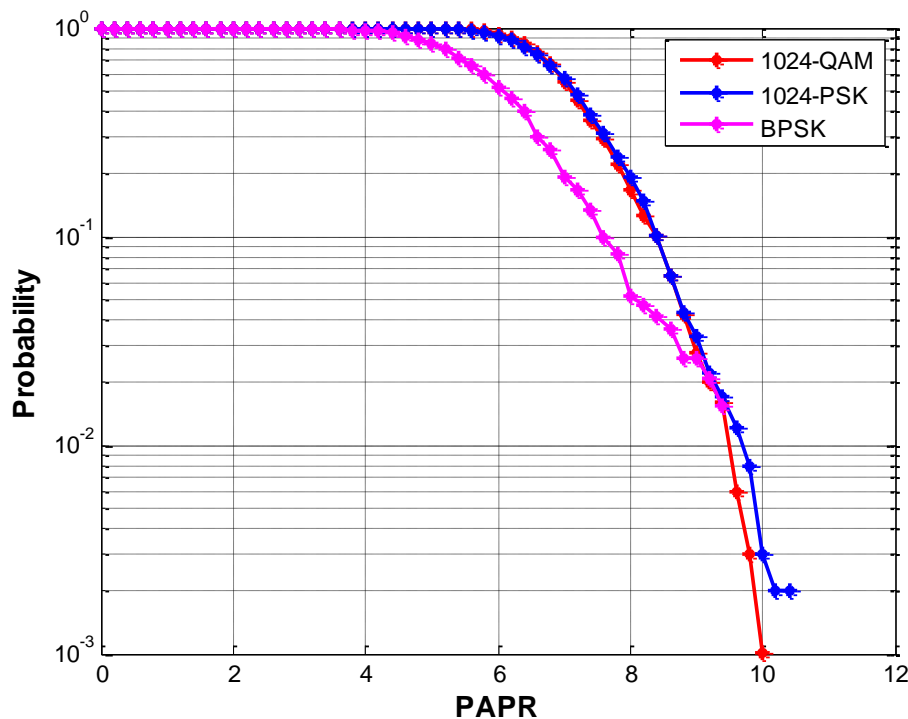
$$P_r = \{PAPR > \lambda\} = 1 - (P_r \{PAPR \leq \lambda\})^U = 1 - ((1 - e^{-\lambda})^N)^U \quad (4.5.3)$$

## 4.6 SIMULATION RESULTS

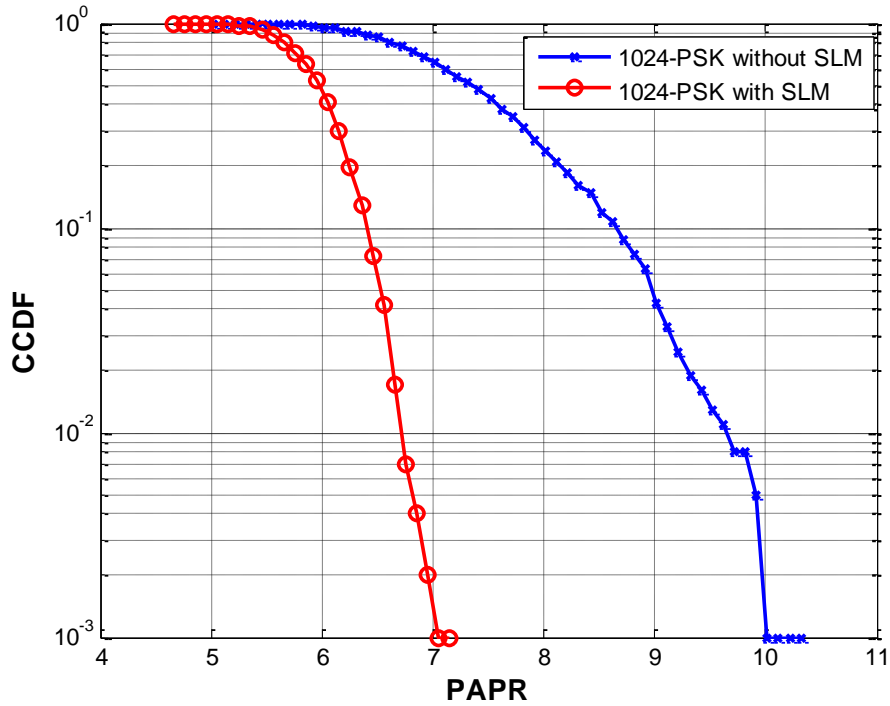
The PAPR analysis of FrFT based OFDM system with 1024-PSK and 1024-QAM modulation techniques and the results obtained were compared with FFT based OFDM system. For simulation, 64 subcarriers of OFDM is considered with 1000 frames. Further, the results were obtained on 10,000 symbols of OFDM instead of 1,00,000 symbols. The PAPR results for comparison between FFT based OFDM and FrFT based OFDM are shown in Figures 4.11 for different modulation techniques, for example; BPSK, 1024-PSK and 1024-QAM. It is observed from the simulation that there is not much change in the PAPR when

traditional FFT based OFDM system is replaced with FrFT based OFDM system for given modulation techniques.

In Figure 4.11, the PAPR of FFT based OFDM with BPSK modulation technique is marginally less than the PAPR of FrFT based OFDM with different modulation techniques. Moreover, it could be depicted from the results shown in Figure 4.11 that the PAPR of FrFT based OFDM for all the higher order modulations like; 1024-PSK and 1024-QAM is almost exactly same and overlapping. However, when select mapping clipping technique (SLM) is applied on the proposed system; extreme improvement in PAPR is achieved for all the modulation techniques under observation with FrFT based OFDM as compared to FFT based OFDM system.

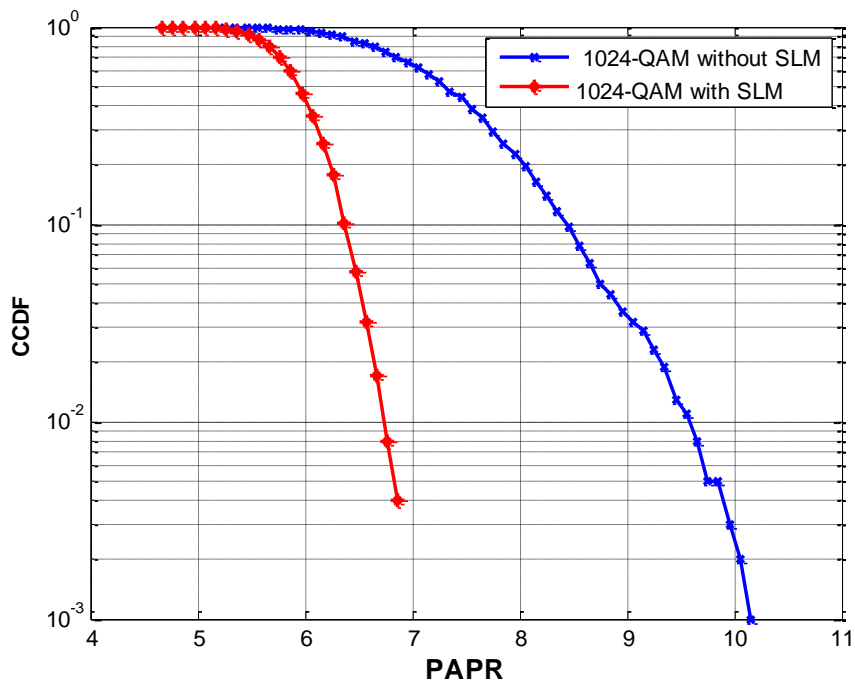


**Figure 4-11: Comparison of CCDF of PAPR for FrFT based OFDM with 1024-PSK and 1024-QAM modulation techniques along with FFT based OFDM with BPSK modulation technique**



**Figure 4-12: CCDF of PAPR for 1024-PSK modulation based FrFT based OFDM with and without SLM clipping technique**

Figures 4.12 and 4.13 show the CCDF of PAPR for 1024-PSK and 1024-QAM modulation technique based on FrFT based OFDM with and without SLM technique respectively.



**Figure 4-13: CCDF of PAPR for 1024-QAM modulation based FrFT based OFDM with and without SLM clipping technique**

Figure 4.13 shows the PAPR of 1024-QAM based OFDM system has been compared with and without SLM clipping technique. The SLM clipping overcomes the problem of PAPR in OFDM system a great extent. From Figure 4.12, it can be depicted that the FrFT based OFDM system using 1024-PSK modulation is able to save approximately 3.0 dB of PAPR with SLM clipping technique as compared to the one without SLM technique for same modulation technique at CCDF of  $10^{-3.0}$ . In 1024-QAM based FrFT based OFDM, the PAPR is improved with SLM. From Figure 4.13, it can be observed that the FrFT based OFDM system using 1024-QAM modulation is able to save approximately 3.5 dB of PAPR with SLM clipping technique as compared to the one without SLM technique with same modulation technique at CCDF of  $10^{-2.6}$ .

#### 4.7 SUMMARY

In this chapter, performance analysis of FrFT based OFDM system is carried out under various wireless fading channels, namely AWGN, Rayleigh, Rician, and Nakagami along with PAPR analysis with different modulation techniques. The BER of proposed model is discussed in this thesis work. Here, the 1024-PSK and 1024-QAM modulation technique is used with different values of ' $\alpha$ ' in the range of 0.0 to 1.0 for analysing the BER performance of proposed system. It had been observed that the FrFT based OFDM system outperforms the FFT based system under all wireless fading channels with both 1024-PSK and 1024-QAM modulation techniques. From the results achieved, it could be depicted that proposed system outperforms FFT based OFDM system and achieves best performance under Nakagami channel for both 1024-PSK and 1024-QAM modulation techniques.

The major problem of PAPR in OFDM system is dealt with in this chapter using SLM techniques. The best improvement in PAPR is achieved by 1024-PSK based FrFT based OFDM system, it gives improvement of 4.3 dB at CCDF of  $10^{-3.0}$ . In addition, the 1024-QAM modulation technique is able to achieve the improvement of 3.5 dB at  $10^{-2.6}$  of CCDF.

The shift in carrier frequency of OFDM modulated signal due to CFO causes ICI, which eventually destroys the orthogonality between sub carriers. This will cause the increase in BER for the proposed system. The impact of ICI on system performance for  $\pi/4$  DQPSK and GMSK modulation techniques is analysed and resolved in the next chapters.

#### ***Contribution of Chapter***

*In this chapter a novel way of BER analysis of FrFT based OFDM system has been carried out for higher order modulations like 1024-PSK and 1024-QAM under various wireless*

*fading channels which is an addition to the available literature. The proposed system is optimized for a value of fractional order parameter ' $\alpha$ ' in the range from 0.0 to 1.0. Further, the problem of PAPR in OFDM systems has also been dealt for the FrFT based OFDM system, which helped to reduce error in the proposed system.*

# CHAPTER 5

## ICI ANALYSIS OF FrFT BASED OFDM SYSTEM FOR $\pi/4$ DQPSK

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The change in carrier frequencies of transmitting an OFDM signal in a wireless channel causes loss of orthogonality between subcarriers. This change in carrier frequency may be due to channel or due to movement of source and destination i.e. Doppler effect. This frequency offset of subcarriers introduces ICI [22]. ICI affects both channel estimation and OFDM symbol recovery at the receiver [115] and degrades the overall OFDM system performance. In this chapter, the effect of ICI has been mitigated by proposing FrFT based OFDM system with  $\pi/4$  DQPSK modulation technique. Unlike the traditional systems where, ICI was treated as noise, here the proposed system considers the effect of CFO to estimate the BER vs. SNR of the overall OFDM system with said modulation technique.

### 5.1 INTRODUCTION

The need for large data transmission on wireless domain had evolved the necessity for using multicarrier communication techniques for transmission in wireless domain. Further, the data transmission capacity of multicarrier systems like OFDM has enhanced by replacing modulation techniques like BPSK, QPSK, etc. with modulation techniques that can carry large data with less bandwidth occupancy as compared to other binary modulation techniques as well as are also capable of demodulating signal more efficiently [1].  $\pi/4$  Differential QPSK (DQPSK) is a modulation technique of such a kind [131]. The major benefit of  $\pi/4$  DQPSK modulation technique is its capability to provide better spectral efficiency as compared to binary modulation techniques. Also in  $\pi/4$  DQPSK signal constellation does not pass through origin, hence gives better output spectrum characteristics as compared to other modulation techniques [131].

In OFDM, data is transmitted using narrowband subcarriers in parallel. This gives large symbol period to each subcarrier and reduces the chance of inter symbol interference (ISI).

Addition of cyclic prefix completely removes the chance of ISI in OFDM. However, OFDM symbols suffer from ICI. It occurs mainly due to Doppler shift and multipath fading [15]. In wireless domain, due to channel variation and mobility between source and destination, the probability of both Doppler shift and multipath fading is highest and hence the orthogonality between subcarrier gets lost [22]. This CFO will cause ICI and degrades the performance of overall OFDM system. In this chapter, the effect of CFO has been dealt with by proposing FrFT based OFDM system using  $\pi/4$  DQPSK modulation technique.

## 5.2 EFFECT OF ICI ON OFDM SYSTEM

Channel estimation is most important in wireless communication for error free reception of the signal. OFDM has emerged as a technique, which can combat the effect of frequency selective fading caused due to multipath fading. At the same time, ICI degrades the performance of OFDM system due to introduction of CFO. Orthogonality between the subcarriers will lose due to ICI and the system performance degrades. The effects like Doppler spread and multipath fading can only be mitigated but cannot be eliminated. Several techniques have been proposed in the literature to compensate the effect of ICI.

The effect of ICI in OFDM system can be reduced by offering a combined transmission scheme using M-array frequency shift keying and differential shift keying [67]. In [40], addition of time with each symbol was suggested along with reshaping of pulses at the receiver position to combat the effect of Doppler shift. A novel method for covering the fading distortion in OFDM signal was proposed by using equalization at receivers discussed in [163]. ICI self cancellation scheme was proposed in [18, 134], where, the symbol is modulated on adjacent subcarriers with weighted coefficients at transmitter side. At the receiver side the symbols were combined linearly with proposed coefficients which help in self cancellation of ICI. An all phase OFDM (AP-OFDM) was proposed by [164] to overcome the ICI. In this scheme, all phase FFT was used in time domain and zero insertion in frequency domain to eliminate or reduce the effect of ICI due to CFO. A channel estimation algorithm using comb-type double pilots with ICI self-cancellation scheme was proposed by [165-167]. The algorithm estimates the channel state information (CSI) with minimum ICI and makes a time varying CIR matrix with two OFDM symbols using linear interpolation. From this matrix ICI, coefficient matrix is obtained by transformation of CSI matrix. Finally, by combining the ICI matrix and received signal, effect of ICI can be mitigated. Various modulation techniques like Magnitude keyed modulation, PSK and QAM

etc. were used to analyse the effect of ICI on SC-OFDM system [36]. A ML estimation algorithm had been proposed in [140] for estimating symbol timing and CFO over wireless channel. The effect of ICI has been mitigated by reducing the time of channel variation with the help of Frank's window in [117, 136]. Here, time domain ICI self-cancellation method was used with window to remove ICI. Another algorithm was proposed in [137] to improve the detection error by reducing ICI. It optimized the phase detection of OFDM symbols and used long cyclic prefix, to tackle problem of ICI in OFDM [168].

### 5.3 $\pi/4$ DQPSK MODULATION TECHNIQUE

The bits 0 and 1 are represented by changing the phase of the carrier in PSK modulation technique. For transmission of 0 and 1, there is a phase difference of  $\pi$  radians in the carrier signal. The PSK modulated signal can be represented as

$$x(t) = A \cos(2\pi f_c t) \quad \text{for 0} \quad (5.3.1)$$

$$x(t) = A \cos(2\pi f_c t + \pi) \quad \text{for 1} \quad (5.3.2)$$

For quadrature shift keying modulation technique, the bits are transmitted with four different phases between successive bits with a phase difference of  $\pi/4$  radians [169]. The QPSK modulated signal is given by [169]

$$x(t) = A \cos(2\pi f_c t + \frac{\pi}{4}) \quad \text{for 10} \quad (5.3.3)$$

$$x(t) = A \cos(2\pi f_c t + \frac{3\pi}{4}) \quad \text{for 11} \quad (5.3.4)$$

$$x(t) = A \cos(2\pi f_c t - \frac{\pi}{4}) \quad \text{for 01} \quad (5.3.5)$$

$$x(t) = A \cos(2\pi f_c t - \frac{3\pi}{4}) \quad \text{for 00} \quad (5.3.6)$$

Due to the presence of phase difference in carrier signal, the receiver need not be phase locked with the transmitted signal [170]. This makes the designing of receiver much simpler in QPSK modulation as compared to other modulation techniques. This also helps in efficient use of bandwidth and provides good spectral efficiency. In differential BPSK, the binary 1 is transmitted when carrier signal changes its phase as compared to previous signal and if carrier does not change its phase with respect to previous signal then binary 0 is transmitted. But if four phase differences are used for representing 00, 01, 10 and 11, then it is called as

DQPSK. However, DQPSK modulation technique becomes difficult to be synchronised at receiver if a long run of zeros occur in the data sequence. The answer to this problem is addressed by  $\pi/4$  DQPSK modulation technique [171]. In this modulation, another phase difference of  $\pi/4$  is added between symbols [171]. This  $\pi/4$  phase between successive symbols enables the receiver to perform synchronization even in the case of long sequence of zeros [131].

The  $\pi/4$  DQPSK is most commonly used modulation technique for mobile communication [67]. The performance of  $\pi/4$  DQPSK modulation in terms of adjacent channel interference and co-channel interference along with Doppler shift is evaluated by many users for digital cellular systems and concluded to be better than other binary modulated modulation techniques [172]. In  $\pi/4$  DQPSK, modulation data is differentially generated by encoding the difference of two successive symbols. The benefit of  $\pi/4$  DQPSK is its constant envelop and high frequency efficiency [173]. In addition, one does not need exact phase of carrier to recover the phases i.e. non-coherent detection can be done using  $\pi/4$  DQPSK modulation technique [174].  $\pi/4$  DQPSK signal is generated by differentially encoding two QPSK constellations, which are separated by  $45^\circ$  with respect to each other. The  $\pi/4$  DQPSK signal can be considered as superposition of two QPSK signal constellations separated by  $\pi/4$  radians or  $45^\circ$  and generate eight phases [175]. Each of these phases has a phase difference of  $\pm\pi/4$  and  $\pm3\pi/4$  between successive symbols. Another advantage of it is that, the envelop produced by  $\pi/4$  DQPSK modulation technique is more linear as compared to envelops produced by other binary modulation techniques as it does not pass through origin and hence possesses better spectral efficiency [173].

#### 5.4 MATHEMATICAL ANALYSIS OF $\pi/4$ DQPSK

In  $\pi/4$  DQPSK, the data is modulated using change in phase of the carrier signal. Let  $X_{n-1}$  be the last transmitted symbol and  $\theta$  is the phase of transmitted carrier. Then, the last symbol can be given as [176]

$$X_{n-1} = A \cos(\omega_c t - \theta) \quad (5.4.1)$$

The new symbol is given by;

$$X_n = A \cos(\omega_c t - (\theta + \Delta\theta)) \quad (5.4.1)$$

where,  $\Delta\theta$  is phase change between last and new symbol.

Equation (5.4.2), can be written as

$$X_n = A \cos(\theta + \Delta\theta) \cos \omega_c t + A \sin(\theta + \Delta\theta) \sin \omega_c t \quad (5.4.2)$$

$$X_n = X^I \cos \omega_c t + X^Q \sin \omega_c t \quad (5.4.3)$$

$$X^I = A \cos(\theta + \Delta\theta) \quad (5.4.5)$$

$$X^I = A \cos \theta \cos \Delta\theta - A \sin \theta \sin \Delta\theta \quad (5.4.4)$$

$$X^I = X_{n-1}^I \cos \Delta\theta - X_{n-1}^Q \sin \Delta\theta \quad (5.4.5)$$

$$\text{and } X^Q = A \sin(\theta + \Delta\theta) \quad (5.4.8)$$

$$X^Q = A \sin \theta \cos \Delta\theta + A \cos \theta \sin \Delta\theta \quad (5.4.9)$$

$$X^Q = X_{n-1}^Q \cos \Delta\theta + X_{n-1}^I \sin \Delta\theta \quad (5.4.10)$$

## 5.5 OFDM WITH $\pi/4$ DQPSK

Let us consider the traditional OFDM system where, IFFT and FFT are used at transmitter and receiver respectively. It is using  $\pi/4$  DQPSK modulation for modulating sub-carriers. Here the OFDM signal is given by [131];

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=-\infty}^{+\infty} \sum_{l=0}^{N-1} X_{k,l} e^{\frac{j2\pi l(t-T_{cp}-kT_t)}{T_d}} g(t-kT_t) \quad (5.5.1)$$

where,  $N$  is number of OFDM samples and  $X_{k,l}$  is the input data symbol modulated on  $l^{\text{th}}$  subcarrier in  $k^{\text{th}}$  OFDM symbol. Here,  $T_t = T_d + T_{cp}$  where,  $T_d$  is data duration of OFDM symbol and  $T_{cp}$  is the guard time of cyclic prefix and  $g(t)$  is given by [131];

$$g(t) = \begin{cases} 1 & 0 < t < T_t \\ 0 & \text{otherwise} \end{cases} \quad (5.5.2)$$

The  $\pi/4$  DQPSK modulation symbol under the effect of Rayleigh fading channel with CFO [67]  $\Delta f$  is given by;

$$X_{k,l} = X_{k,l-1} e^{j\Delta\gamma_l[k]}$$

$$X_{k,l} = \sqrt{2E_b} e^{j(\gamma_{l-1}[k] + \Delta\gamma_l[k])} \quad (5.5.3)$$

where,  $E_b$  is the bit energy,  $\gamma_{l-1}[k]$  is the phase of symbol modulated on  $(l-1)^{th}$  sub-carrier of  $k^{th}$  symbol and  $\gamma_l[k] \in (\pm \frac{\pi}{4}, \pm \frac{3\pi}{4})$  is the phase shift between successive carriers in  $\pi/4$  DQPSK modulation [177].

The data modulated on the  $k^{th}$  symbol is given by [177]

$$x[k] = [X_{k,0}, X_{k,1}, \dots, X_{k,N-1}] \quad (5.5.4)$$

$$x[k] = \begin{bmatrix} \sqrt{2E_b} \\ \sqrt{2E_b} e^{j\Delta\gamma_1[k]} \\ \sqrt{2E_b} e^{j(\Delta\gamma_1[k] + \Delta\gamma_2[k])} \\ \vdots \\ \vdots \\ \vdots \\ \sqrt{2E_b} e^{j(\Delta\gamma_1[k] + \dots + \Delta\gamma_{N-1}[k])} \end{bmatrix}^T \quad (5.5.5)$$

where,  $X_{k,0}$  is the OFDM symbol and has assumed value of  $\sqrt{2E_b}$  for detection at the receiver. As far as there is no phase shift between two successive sub-carriers, the proposed system is able to provide the detection of OFDM symbols [178].

The channel impulse response of time varying  $M$  tap Rayleigh fading channel is given by [179];

$$h(\psi, t) = \sum_{q=0}^{M-1} h_q(t) \delta(\psi - \psi_q) \quad (5.5.6)$$

where,  $h_q(t)$  and  $\psi_q$  are complex amplitude and propagation delay of  $M^{th}$  tap in Rayleigh adding channel and  $h_q(t)$  is the Gaussian distribution.

The transfer function of channel at any time  $t$  and frequency  $f$  is given by [179];

$$H(t, f) = \sum_{q=0}^{M-1} h_q(t) e^{-j2\pi f \psi_q} \quad (5.5.7)$$

The received signal with CFO of  $\Delta f$  is given by [67];

$$y(t) = e^{j2\pi\Delta ft} \sum_{q=0}^{M-1} h_q(t) \cdot s(t - \psi_q) + w(t) \quad (5.5.8)$$

$$y(t) = \frac{1}{\sqrt{N}} e^{j2\pi\Delta f t} \sum_{q=0}^{M-1} h_q(t) \sum_{k=p-1}^p \sum_{l=0}^{N-1} X_{k,l} e^{\frac{j2\pi l(t-T_{cp}-kT_t-\psi_q)}{T_d}} g(t-kT_t-\psi_q) + w(t) \quad (5.5.9)$$

where,  $w(t)$  is Gaussian noise with variance  $\sigma^2$  per dimension. Let us assume that the receiver is synchronized to  $0^{th}$  tap with delay  $\psi = 0$  and is sampled at [179]

$$t_{p,r} = pT_t + T_{cp} + \frac{rT_d}{N}, \quad r = 0, 1, \dots, N-1 \quad (5.5.10)$$

and the samples within the cyclic prefix time  $T_{cp}$  are ignored because of repetition.

Thus the received  $N$  samples in  $p^{th}$  symbol are given by

$$y_{p,r} = \frac{1}{\sqrt{N}} e^{j2\pi\Delta f(pT_t+T_{cp})} \sum_{l=0}^{N-1} X_{p,l} H(t_{p,r}, f_l) e^{\frac{j2\pi(l+\xi)r}{N}} + w_r \quad (5.5.11)$$

where,  $\xi = \Delta f T_d$  is the normalized CFO.

$H(t_{p,r}, f_l)$  is the channel response at sampling time  $t_{p,r}$  and sub-carriers frequency  $f_l = \frac{l}{T_d}$

$$\text{Therefore } H(t_{p,r}, f_l) = \sum_{q=0}^{M-1} h_q(t_{p,r}) e^{\frac{-j2\pi l \psi_q}{T_d}} \quad (5.5.12)$$

The channel response of  $H(t_{p,r}, f_l)$  at different time and frequency are zero-mean jointly complex Gaussian random variables and its correlation is given by [177]

$$E[H(t_{p_1, r_1}, f_{l_1}) H^*(t_{p_2, r_2}, f_{l_2})] = \frac{2\sigma_f^2 J_0(2\pi\partial|(p_1 - p_2)(1 + \beta) + (r_1 - r_2) / N|)}{1 - [2\pi(l_2 - l_1)\lambda]^2} \quad (5.5.13)$$

where,  $E[X]$  is the expectation of the random variable  $X$ ,  $J_0[.]$  is the Bessel function of  $0^{th}$  order,  $\beta = \frac{T_{cp}}{T_d}$  and  $\partial = f_D T_d$  is the maximum Doppler spread, whereas the mean delay spread

is given by [176],  $\lambda = \frac{\bar{\psi}}{T_d}$

At the receiver side, the FFT is performed on the received symbols  $\{y_{p,r}\}_{r=0}^{N-1}$  in the  $p^{th}$  OFDM symbol to get data sequence  $\{u_{e,z}[p]\}_{z=0}^{N-1}$  as

$$u_{e,z}[p] = \frac{1}{N} e^{j2\pi\Delta f(pT_t+T_{cp})} \left( R_{z,z}[p] X_{p,z} + \sum_{\substack{l \neq k \\ l=0}}^{N-1} R_{l,z}[p] X_{p,l} \right) + l_{p,z} \quad z = 0, 1, \dots, N-1 \quad (5.5.14)$$

where,  $R_{l,z}[p]$  is given by

$$R_{l,z}[p] = \sum_{r=0}^{N-1} H(t_{p,r}, f_l) e^{\frac{j2\pi(l-z+\xi)r}{N}} \quad (5.5.15)$$

and  $l_{p,z}$  is the Gaussian noise with variance  $\sigma^2$

$d_z[p]$  can be defined as  $1 \times N$  vector and is given by

$$d_z[p] = [R_{0,z}^*[p] \ R_{1,z}^*[p] \ \dots \ R_{N-1,z}^*[p]] \quad (5.5.16)$$

$$\text{or } u_{e,z}[p] = \frac{1}{N} e^{j2\pi\Delta f(pT_i + T_{cp})} x[k] d_k[p]^H + l_{p,z} \quad z = 0, 1, \dots, N-1 \quad (5.5.17)$$

where,  $d_k[p]^H$  is the conjugate transpose of the vector  $d_k[p]$  [177].

## 5.6 FrFT BASED OFDM WITH $\pi/4$ DQPSK

Consider the FrFT based OFDM system with  $\pi/4$  DQPSK modulation technique. The effect of Rayleigh fading channel and CFO on the transmitted OFDM signal is analysed. At the transmitter, the input data stream  $(X_0, X_1, X_2, \dots, X_{N-1})$  is modulated with  $\pi/4$  DQPSK modulation, afterwards these symbols are transformed using IDFrFT. The  $l^{\text{th}}$  symbol of OFDM modulated signal obtained finally at transmitter is given by [147]

$$x(l) = \sqrt{\frac{N}{N + N_{cp}}} \sum_{v=0}^{N-1} X_{k,l} F_{-\alpha}(l, v) \quad N_{cp} < l < N \quad (5.6.1)$$

where,  $N_{cp}$  is the length of cyclic prefix and  $X_{k,l}$  is the  $l^{\text{th}}$  symbol transmitted on the  $k^{\text{th}}$  frame.

The kernel of IDFrFT  $F_{-\alpha}(l, v)$  is defined by [147];

$$F_{-\alpha}(l, v) = \sqrt{\frac{\sin\alpha + j\cos\alpha}{N}} e^{\frac{-jl^2T_i^2 \cot\alpha}{2}} e^{\frac{-jv^2u^2 \cot\alpha}{2}} e^{\frac{j2\pi lv}{N}} \quad (5.6.2)$$

In case of  $\pi/4$  DQPSK modulation  $X_{k,l}$  is given by [179];

$$X_{k,l} = X_{k,n-1} e^{j\Delta\theta_l[k]} \quad (5.6.3)$$

$$X_{k,l} = \sqrt{2E_b} e^{j(\theta_{n-1}[k] + \Delta\theta_l[k])} \quad (5.6.4)$$

where,  $\theta_{l-1}[k]$  is the phase of symbol modulated on  $(l-1)^{th}$  subcarrier of  $k^{th}$  OFDM symbol and  $\Delta\theta_l[k]$  is the differential phase between the consecutive carrier signals.

The received signal  $y_j(l)$  after passing through Rayleigh fading channel and affected with CFO is given by [147];

$$y_j(l) = \sqrt{\frac{N}{N+N_{cp}}} \sum_{k=-\infty}^{+\infty} \sum_{m=0}^{N-1} h_{k,j} x_k(r) e^{\frac{j2\pi\xi r}{N}} + w(r) \quad r = 0, 1, \dots, N-1 \quad (5.6.5)$$

where,  $\xi = \Delta f T_d$  is CFO and  $h_{k,j}$  is the channel impulse response. After removing cyclic prefix and taking DFrFT of received signal  $y_j(l)$ , the received data signal in  $v^{th}$  OFDM symbol is given by [147];

$$r_j(v) = \sqrt{\frac{N}{N+N_{cp}}} \sum_{q=0}^{N-1} F_\alpha(v, q) y_j(q) \quad q = 0, 1, \dots, N-1 \quad (5.6.6)$$

where,

$$F_\alpha(v, q) = \sqrt{\frac{\sin \alpha - j \cos \alpha}{N}} e^{\frac{jq^2 T_d^2 \cot \alpha}{2}} e^{\frac{qv^2 \cot \alpha}{2}} e^{-\frac{j2\pi q l}{N}} \quad (5.6.7)$$

on substituting (5.6.7) in (5.6.6), we get

$$y_j(l) = \sqrt{\frac{N}{N+N_{cp}}} \sum_{q=0}^{N-1} X_{k,q} \sum_{l=0}^{N-1} \sum_{r=-N_{cp}}^{N-1} F_\alpha(v, r) F_{-\alpha}(r, q) h_{k,q}(l, l-r) e^{\frac{j2\pi\xi l}{N}} + w(v) \quad (5.6.8)$$

or the received signal is given by

$$y_j(l) = \sqrt{\frac{N}{N+N_{cp}}} \left( \sum_{k=-\infty}^{+\infty} IS_{k,j}(q, q) X_{z,q} + \sum_{k=-\infty}^{\infty} \sum_{\substack{q=0 \\ q \neq v}}^{N-1} IS_{k,j}(v, q) X_{k,q} \right) + w(v) \quad (5.6.9)$$

where,  $IS_{k,j}(v, q)$  is the ICI coefficient and is given by

$$IS_{k,j}(v, q) = \sum_{l=0}^{N-1} \sum_{r=-N_{cp}}^{N-1} F_\alpha(v, r) F_{-\alpha}(r, q) h_{k,q}(l, l-r) e^{\frac{j2\pi\xi l}{N}} \quad (5.6.10)$$

Further,  $v^{th}$  symbol on  $z^{th}$  symbol can be rewritten as;

$$y_z(v) = \sqrt{\frac{N}{N + N_{cp}}} \sum_{k=-\infty}^{+\infty} IS_{k,j}(q, q) X_{z,q} + \sum_{k=-\infty}^{+\infty} \sum_{\substack{q=0 \\ q \neq v}}^{N-1} IS_{k,j}(v, q) X_{k,q} + w(v) \quad (5.6.11)$$

$$\text{Let } X[v] = [X_{k,0}, X_{k,1}, \dots, X_{k,N-1}] \quad (5.6.12)$$

and

$$d_z[v] = [IS_{k,j}(v, 0), IS_{k,j}(v, 1), \dots, IS_{k,j}(v, N-1)] \quad (5.6.13)$$

Hence, final received signal is given by;

$$y_z(v) = \sqrt{\frac{N}{N + N_{cp}}} X[v] d_z[v]^H + w(v) \quad (5.6.14)$$

## 5.7 BER ANALYSIS OF FrFT BASED OFDM SYSTEM WITH $\pi/4$ DQPSK MODULATION

In this section, BER analysis of proposed system is carried out. The BER analysis of FrFT based OFDM system has been done here for  $\pi/4$  DQPSK modulation technique under Rayleigh fading channel with CFO. The receiver implements differential detection of  $\pi/4$  DQPSK modulated signal in the frequency domain. By using maximum ratio combining technique [29], the received signal is given by

$$X_{v,z} = \sum_{e=1}^E u_{e,z}[v] u_{e,z-1}^*[v] \quad (5.7.1)$$

where,  $u_{e,z}[v]$  is the received signal from the  $e^{th}$  diversity channel and  $u_{e,z-1}^*[v]$  is the complex conjugate of  $u_{e,z-1}[v]$ . The received bits of  $\pi/4$  DQPSK modulated signal are given by real and imaginary part of  $X_{v,z}$  and is given by [175];

$$X_{v,z}^I = \sum_{e=1}^E \text{Re}\{u_{e,z} u_{e,z-1}^*\} \text{ where, } X_{v,z}^I \text{ represents the real part of } X_{v,z} \text{ and}$$

$$X_{v,z}^Q = \sum_{e=1}^E \text{Im}\{u_{e,z} u_{e,z-1}^*\} \text{ where, } X_{v,z}^Q \text{ represents the imaginary part of } X_{v,z}$$

$$u_{e,z}[v] = \frac{1}{N} e^{j2\pi\Delta f(vT_I + T_{cp})} x[p] d_k[p]^H + l_{p,z} \quad z = 0, 1, \dots, N-1 \quad (5.7.2)$$

where,  $l$  is the complex Gaussian noise with variance  $\sigma^2$  per dimension and is given by

$$l_{p,z} = l_{R(p,z)} + l_{I(p,z)} \quad (5.7.3)$$

For a given data sequence or a differential phase sequence,  $u_{e,z}$  the sum of several jointly complex Gaussian random variables is given by  $u$ . It is, therefore a complex Gaussian random variable [30] with zero mean and variance  $\sigma^2$  is given by

$$\sigma^2 = E[u_{e,z}[v]u^H[v]] \quad (5.7.4)$$

$$\sigma^2 = E\left[\left(\frac{1}{N} e^{j2\pi\Delta f(vT_i+T_{cp})} x[p]d_k^H[p] + (l_{R(p,z)} + l_{I(p,z)})\right) X\left(\frac{1}{N} e^{-j2\pi\Delta f(vT_i+T_{cp})} x^H[p]d_k[p] + (l_{R(p,z)}^H + l_{I(p,z)}^H)\right)\right] \quad (5.7.5)$$

$$\sigma^2 = E\left[\frac{1}{N^2} x[p]d_k^H[p]x^H[p]\right] + E\left[(l_{R(p,z)} + l_{I(p,z)})(l_{R(p,z)}^H + l_{I(p,z)}^H)\right] \quad (5.7.6)$$

Rest all the terms are mutually uncorrelated and hence their value is zero.

$$\text{Let } A = E\left[\frac{1}{N^2} x[p]d_k^H[p]d_k[p]x^H[p]\right]$$

$$\text{or } A = \frac{1}{N^2} x[p]E\left[d_k^H[p]d_k[p]\right]x^H[p]$$

$$\text{Let } \chi_{z,z} = E\left[d_k^H[p]d_k[p]\right]$$

$$\text{Then, } A = \frac{1}{N^2} x[p].\chi_{z,z}x^H[p] \quad (5.7.7)$$

$$B = E\left[(l_{R(p,z)} + l_{I(p,z)}) + (l_{R(p,z)}^H + l_{I(p,z)}^H)\right]$$

$$B = E\left[l_{R(p,z)}l_{R(p,z)}^H + l_{R(p,z)}l_{I(p,z)}^H + l_{I(p,z)}l_{R(p,z)}^H + l_{I(p,z)}l_{I(p,z)}^H\right] \quad (5.7.8)$$

As  $(l_{I(p,z)}, l_{R(p,z)}^H)$  and  $(l_{R(p,z)}, l_{I(p,z)}^H)$  pairs are uncorrelated, their product is zero, so (5.7.8)

reduces to;

$$B = E\left[l_{R(p,z)}l_{R(p,z)}^H\right] + E\left[l_{I(p,z)}l_{I(p,z)}^H\right] \quad (5.7.9)$$

$$B = \sigma^2 + \sigma^2 = 2\sigma^2 \quad (5.7.10)$$

Hence, variance  $\sigma^2$  is given by

$$\sigma^2 = A + B$$

$$\text{or } \sigma_q^2 = \frac{1}{N^2} x[p] \chi_{z,z} x^H[p] + 2\sigma^2 \quad (5.7.11)$$

$$\text{Let } \mu_{l_1, l_2} = E \left[ d_{l_1, z_1} d_{l_2, z_2}^* \right]$$

where,  $\mu_{l_1, l_2}$  is the element at the  $l_1^{\text{th}}$  row and the  $l_2^{\text{th}}$  column with  $0 \leq l_1, l_2 \leq N-1$  for matrix  $\chi_{z,z}$

$$d_{l,z}[v] = \sum_{r=0}^{N-1} H(t_{v,r}, f_l) e^{\frac{j2\pi(l-z+\xi)r}{N}} \quad (5.7.12)$$

$$\text{or } H(t_{v,r}, f_l) = \sum_0^{M-1} h_q(t_{v,r}) e^{\frac{-j2\pi l \tau_q}{T_d}} \quad (5.7.13)$$

$H$  is the channel response at the sampling time instant  $t_{v,r}$ , and the subcarrier frequency  $f_l = \frac{l}{T_d}$ . The channel response  $H(t_{v,r}, f_l)$  at different times and frequencies are zero mean jointly complex Gaussian random variables and the correlations of these complex Gaussian random variables are given by [33, 177].

$$E \left[ H_{(t_{v_1, r_1}, f_{l_1})} H_{(t_{v_2, r_2}, f_{l_2})}^* \right] = E \left[ \left( \sum_{q=0}^{M-1} (h_q(t_{v_1, r_1}) e^{\frac{-j2\pi l_1 \tau_q}{T_d}}) \right) \left( \sum_{q=0}^{M-1} h_q^*(t_{v_2, r_2}) e^{\frac{j2\pi l_2 \tau_q}{T_d}} \right) \right] \quad (5.7.14)$$

$$E \left[ H_{(t_{v_1, r_1}, f_{l_1})} H_{(t_{v_2, r_2}, f_{l_2})}^* \right] = \frac{2\sigma_f^2 J_0 \left( 2\pi \partial \left| (v_1 - v_2)(1 + \beta) + \frac{(r_1 - r_2)}{N} \right| \right)}{1 - [2\pi(l_2 - l_1)\eta]^2} \quad (5.7.15)$$

where,  $J_0(\cdot)$  is the Bessel function of the first kind of  $0^{\text{th}}$  order and the normalized maximum Doppler spread is given by  $\partial = f_d T_d$  and normalized mean delay spread is given by  $\eta = \frac{\bar{T}}{T_d}$

$$\mu_{l_1, l_2} = E \left[ d_{l_1, z_1} d_{l_2, z_2}^* \right] \quad (5.7.16)$$

$$\mu_{l_1, l_2} = \sum_{r_1=0}^{N-1} \sum_{r_2=0}^{N-1} E \left[ H(t_{r_1}, f_{l_1}) H^*(t_{r_2}, f_{l_2}) \right] \times e^{\frac{j2\pi(l_1 - z_1 + \xi)r_1}{N}} e^{\frac{-j2\pi(l_2 - z_2 + \xi)r_2}{N}} \quad (5.7.17)$$

As  $v_1 = v_2 = v$ , (5.7.17) can be written as

$$\mu_{l_1, l_2} = \frac{2\sigma_s^2 J_0\left(\frac{2\pi(r_1 - r_2)\partial}{N}\right)}{1 - j2\pi(l_2 - l_1)\eta} \cdot e^{\frac{j2\pi(l_1 - z_1)r_1}{N}} \cdot e^{\frac{-j2\pi(l_2 - z_2)r_2}{N}} \cdot e^{\frac{j2\pi\partial(r_2 - r_1)}{N}} \quad (5.7.18)$$

The unconditional pdf of the received signal  $u_{e,z}$  can be written as the sum of several conditional pdfs given by  $f_s$  [177].

According to total probability theorem [177]

$$f(s) = \sum_{q=1}^v f(s | x_q) \text{prob}(x_q) \quad (5.7.19)$$

where,  $s$  is a complex variable and  $v$  represents the number of all possible data sequences or phase sequences given by  $\Delta\phi_1, \Delta\phi_2, \dots, \Delta\phi_{N-1}$ . Further, the probability of a specific data sequence  $x_q$  is given as  $\text{prob}(x_q)$

Gaussian pdf is given as [177]

$$f(s | x_q) = \frac{1}{\pi\sigma_q^2} e^{\frac{-s^H s}{\sigma_q^2}} \quad (5.7.20)$$

$$\text{Hence, } f(s) = \sum_{q=1}^v \frac{1}{\pi\sigma_q^2} e^{\frac{-s^H s}{\sigma_q^2}} \text{prob}(x_q) \quad (5.7.21)$$

Here, pdf is not necessarily a Gaussian pdf except when  $d_{0,z}, d_{1,z}, \dots, d_{N-1,z}$  are independent, but not in the case of OFDM system. The pdf was called as a mixture of complex Gaussian distribution in [177].  $u_{x,z}$  and  $u_{x,z-1}$  are conditional proper complex Gaussian random variables. Circular symmetry property states that if the joint density of the two random variables  $x$  and  $y$  is circular symmetrical and independent, then they are normal and independent, they are normal with zero mean and equal variance [177].

$$\text{Hence, Mean} = E[u_{x,z} u_{x,z-1} | \Delta\phi_1, \Delta\phi_2, \dots, \Delta\phi_{N-1}] = 0 \quad (5.7.22)$$

Let  $A$  is Hermitian and  $(tA)$  is skew Hermitian [177]. The skew Hermitian matrix has property that

$$a_{ij} = -\bar{a}_{ij}$$

The eigenvalues of a skew-Hermitian matrix are all purely imaginary or zero. All entries on the main diagonal of a skew-Hermitian matrix have to be pure imaginary, i.e., on the imaginary axis.

Thus due to the properties stated above  $Q_r$  is the Hermitian if  $Q_i = {}^t Q_r$ . Hence substituting  $Q_r$  and property  $a_{ij} = -\bar{a}_{ij}$ ,

$$\text{we get } Q_i = \begin{pmatrix} 0 & -\frac{1}{2j} \\ \frac{1}{2j} & 0 \end{pmatrix} \quad (5.7.23)$$

An expression of form  $Q = s^H A s$ , is called a quadratic form in  $l$  variables [177].

$$Q = s^H A s = \sum_i^l \sum_j^l a_{ij} s_i s_j \quad (5.7.24)$$

If the constants  $a_{i,j}$  are real numbers, then it is called a quadratic form

$$A s^2 + B s y + C y^2 = [x^H \ y^H] \begin{pmatrix} A & \frac{B}{2} \\ \frac{B}{2} & C \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = [x^H \ y^H] \begin{pmatrix} A & \frac{B}{2} \\ \frac{B}{2} & C \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \quad (5.7.25)$$

Now in (5.7.2),  $\text{Re}\{u_{x,z}, u_{x,z-1}^*\}$ , where,  $\text{Re}$  denotes the real part. Also  $A$  and  $C$ , the coefficients of  $u_{x,z}^2$  and  $u_{x,z-1}$  are zero and  $B = 1$ , then

$$R = \frac{u_{x,z}}{u_{x,z-1}} \text{ and } R^H = [u_{x,z}^*, u_{x,z-1}]$$

$$\text{or } Q_r = \begin{pmatrix} 0 & \frac{1}{2} \\ \frac{1}{2} & 0 \end{pmatrix} \quad (5.7.26)$$

Hence,  $R\{u_{x,z}, u_{x,z-1}^*\} = R^H Q_r R$ .

Similarly, imaginary part of  $I\{u_{x,z} u_{x,z-1}^*\}$  can be obtained with  $Q_i = \begin{pmatrix} 0 & -\frac{1}{2j} \\ \frac{1}{2j} & 0 \end{pmatrix}$  and is given

by

$$I\{u_{x,z} u_{x,z-1}^*\} = R^H Q_i R \quad (5.7.27)$$

#### Derivation of the Characteristic Function

Let  $v_n$  be a set of complex random variables where,  $(n = 1, 2, \dots, N)$ .

$v_n = x_n + iy_n$  where,  $x_n$  is real part of  $v_n$  and  $y_n$  is the imaginary part of  $v_n$ . Further,  $x_n$  and  $y_n$  are normally distributed and satisfy the relationships [22]:

$$C_{xx} = E[(x_m - \bar{x}_m)(x_n - \bar{x}_n)] \quad (5.7.28)$$

$$C_{yy} = E[(y_m - \bar{y}_m)(y_n - \bar{y}_n)] \quad (5.7.29)$$

$$C_{xx} = C_{yy}; C_{xy} = -C_{yx}$$

Let  $\bar{v} = E(v)$

$L = E[(v - \bar{v})(v - \bar{v})^H]$ ; where,  $L$  is the non-singular covariance matrix.  $Q$  is a hermitian matrix.

Characteristic function of the (real) quadratic form is given by [22];

$$f = v^H Q v$$

$$\phi(t) = |I - jtLQ|^{-1} \exp\left(-\bar{v}^H L^{-1} \left[ I - (I - jtLQ)^{-1} \right] \bar{v}\right) \quad (5.7.30)$$

where,  $I$  is unity matrix. Characteristic function of the random variable  $f$  is defined as:

$$\phi(t) = E[e^{itf}] = \int_{\nu} p(\nu) e^{in^H Q \nu} d\nu \quad (5.7.31)$$

$$d\nu = \prod_{n=1}^N dx_n dy_n \quad (5.7.32)$$

where,  $p(\nu)$  is the multivariate density function of  $N$  and is given by ;

$$p(v) = \frac{1}{(\pi)^N} \frac{1}{L} e^{[-(v-\bar{v})^H L(v-\bar{v})]} \quad (5.7.33)$$

Further,  $(v-\bar{v})^H L^{-1}((v-\bar{v})) = -\bar{v}^H L^{-1}\bar{v} - v^H L^{-1}v + \bar{v}^H L^{-1}v + v^H L^{-1}\bar{v}$

Also,  $(L^{-1})' = (L^{-1})^*$

Hence,  $\bar{v}^H L^{-1}v = [\bar{v}'(L)^* v^*]^* = [\bar{v}'(L)' v^*]^*$

$$\bar{v}^H L^{-1}v = [\bar{v}^H (L)^* v]^* - v^H L^{-1}v - v^H L^{-1}v + 2\text{Re}([\bar{v}^H L^{-1}v])$$

$$\text{or } \varphi(t) = \frac{1}{\pi^N} |L|^{-1} \exp(-v^H L^{-1}\bar{v}) \int_v [2\text{Re}(\bar{v}^H L^{-1}v) - v^H (L^{-1} - tq)v] dv \quad (5.7.34)$$

$$\int e^{(\text{Re}(A^H v) - v^H (B+iC)v)} dv = \pi^N (B+iC)^{-1} e^{\frac{1}{2}A^H (B+iC)^{-1}A}$$

Substitute  $B = L^{-1}$ ,  $C = -tq$  and  $A = -L^{-1}\bar{v}$ , we get

$$\int e^{(\text{Re}(A^H v) - v^H (B+iC)v)} dv = \pi^N (L^{-1} - itq)^{-1} e^{\frac{1}{2}v^H L^{-1} (L^{-1} - itq)^{-1} L^{-1}v}$$

Density function given by  $p(f) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \varphi(t) e^{-ift} dt$  is generally difficult to obtain. However,

we have variables  $v_n$  having zero means, thus by putting  $\bar{v} = 0$  in the following equation

$$\varphi(t) = \frac{e^{(-v^H L^{-1}\bar{v})} \pi^N (L^{-1} - itQ)^{-1} e^{[(-\bar{v}^H L^{-1})((L^{-1} - itQ)^{-1} L^{-1}v)]}}{\pi^N |L|^{-1}} \quad (5.7.35)$$

we get,  $\varphi(t) = \frac{1}{\pi^N} |L|^{-1} [\pi^N (\frac{1}{L} - itQ)^{-1}]$

$$\varphi(t) = \frac{1}{\pi^N} |L|^{-1} [\pi^N (1 - itQL)^{-1} \frac{1}{L^{-1}}] = (I - LQ)^{-1} \quad (5.7.36)$$

Now, the CHF of  $\text{Re}\{u_{x,z} u_{x,z-1}^*\}$  conditioned on  $g = [\Delta\phi_1 \dots \Delta\phi_{z-1} \Delta\phi_{z+1} \dots \Delta\phi_{N-1}]$  and

$\Delta\phi_z$  can be written as

$$\phi^I(w | g, \Delta\phi_z) = I_2 - jwMQ_u |^{-1}$$

where, M is covariance matrix and is given by

$$M = E[RR^H | g, \Delta\phi_2]$$

$$R = \begin{pmatrix} u_{x,z} \\ u_{x,z-1} \end{pmatrix} \text{ and } R^H = [u_{x,z}^* \ u_{x,z-1}^*]$$

$$E[RR^H | g, \Delta\phi_p] = \begin{pmatrix} u_{x,z} \\ u_{x,z-1} \end{pmatrix} [u_{x,z}^* \ u_{x,z-1}^*]$$

$$E[RR^H | g, \Delta\phi_p] = \begin{pmatrix} E[u_{x,z} u_{x,z}^* | g, \Delta\phi_z] & E[u_{x,z} u_{x,z-1}^* | g, \Delta\phi_z] \\ E[u_{x,z-1} u_{x,z}^* | g, \Delta\phi_z] & E[u_{x,z-1} u_{x,z-1}^* | g, \Delta\phi_z] \end{pmatrix} \quad (5.7.37)$$

$$\text{Let } \theta = E[u_{x,z} u_{x,z}^* | g, \Delta\phi_z] = \frac{1}{N^2} x \chi_{(z,z)} x^H + 2\sigma^2$$

$$\rho = E[u_{x,z} u_{x,z-1}^* | g, \Delta\phi_z] = \frac{1}{N^2} x \chi_{(z-1,z-1)} x^H + 2\sigma^2 \quad (5.7.38)$$

$$\alpha + j\beta = E[u_{x,z-1} u_{x,z}^* | g, \Delta\phi_z] = \frac{1}{N^2} x \chi_{(z,z-1)} x^H$$

$$\alpha - j\beta = E[u_{x,z-1} u_{x,z-1}^* | g, \Delta\phi_z]$$

$$E[u_{x,z-1} u_{x,z-1}^* | g, \Delta\phi_z] = E\left[ \left( \frac{1}{N} e^{j2\pi f(vT_i + T_{cp})} x[v] d_{z-1}^H[v] + l_{v,z-1} \right) X \left( \frac{1}{N} e^{-j2\pi f(vT_i + T_{cp})} x^H[v] d_z[v] + l_{v,z}^H \right) \right]$$

$$\alpha - j\beta = \frac{1}{N^2} x[v] E[d_{z-1}^H[v] d_z[v]] x^H[v] = \frac{1}{N^2} x \chi_{z-1,z} x^H$$

$$\text{or } E[l_{v,z-1} l_{v,z}^*] = 0$$

$$E[n_{k,p-1} n_{k,p}^*] = 0$$

$$\text{Thus } M = \begin{pmatrix} \theta & \alpha + j\beta \\ \alpha - j\beta & \rho \end{pmatrix}$$

Similarly, the CHF of  $I\{u_{x,z} \ u_{x,z-1}^*\}$  conditioned on  $g$  and  $\Delta\phi_p$  can be derived as

$$\phi^Q(w|g, \Delta\phi_z) = \frac{1}{1 - jw\beta - \frac{1}{4}w^2(\alpha^2 + \beta^2 - \rho\theta)} \quad (5.7.39)$$

where,  $\theta, \rho, \alpha$  and  $\beta$  are variables dependent on differential phase sequence  $g$  and  $\Delta\phi$ .

I-bit error probability of  $P_{P,I}^1(g_q)$  for  $z^{th}$  subcarrier conditioned on specific phase sequence  $g_q = [\Delta\phi_{1,q}, \Delta\phi_{2,q}, \dots, \Delta\phi_{N-1,q}]$  is given by [143];

$$P_{P,I}^1(g_q) = \frac{1}{4}P_{P,I}^1\left(g_q, \Delta\phi_P = \frac{\pi}{4}\right) + \frac{1}{4}P_{P,I}^1\left(g_q, \Delta\phi_P = \frac{3\pi}{4}\right) \\ + \frac{1}{4}P_{P,I}^1\left(g_q, \Delta\phi_P = -\frac{\pi}{4}\right) + \frac{1}{4}P_{P,I}^1\left(g_q, \Delta\phi_P = -\frac{3\pi}{4}\right)$$

$$P_{P,I}^1(g_q) = \frac{1}{4}prob\left\{X_{v,z}^I < 0 \mid g_q, \Delta\phi_z = \frac{\pi}{4}\right\} + \frac{1}{4}prob\left\{X_{v,z}^I \geq 0 \mid g_q, \Delta\phi_z = \frac{3\pi}{4}\right\} \\ + \frac{1}{4}prob\left\{X_{v,z}^I < 0 \mid g_q, \Delta\phi_z = -\frac{\pi}{4}\right\} + \frac{1}{4}prob\left\{X_{v,z}^I \geq 0 \mid g_q, \Delta\phi_z = -\frac{3\pi}{4}\right\}$$

$$\text{or } P_{P,I}^1\left(g_q, \Delta\phi_P = \frac{\pi}{4}\right) = \frac{1}{2} - \int_0^\infty \frac{I\{\phi^I(\omega|g_q, \Delta\phi_P)\}}{\pi\omega} d\omega$$

$$P_{P,I}^1\left(g_q, \Delta\phi_P = \frac{\pi}{4}\right) = \frac{1}{2} - \frac{x_{1,q}}{2\sqrt{\theta_{1,q\rho_{1,q}} - \beta_{1,q}^2}} \quad (5.7.40)$$

Similarly other three probabilities can be calculated and on substituting their values, we get

$$P_{P,I}^1(g_q) = \frac{1}{2} - \sum_{o=1}^4 \frac{\sqrt{2\cos(\Delta\phi_{P,o})}\alpha_{o,q}}{8\sqrt{\theta_{o,q\rho_{1,q}} - \beta_{o,q}^2}} \quad (5.7.41)$$

Similarly,

$$P_{P,Q}^1(g_q) = \frac{1}{2} - \sum_{o=1}^4 \frac{\sqrt{2\sin(\Delta\phi_{P,o})}\beta_{o,q}}{8\sqrt{\theta_{o,q\rho_{1,q}} - \alpha_{o,q}^2}} \quad (5.7.42)$$

$$P_b^1(g_q) = \frac{1}{2(N-1)} \sum_{P=1}^{N-1} [P_{P,I}^1(g_q) + P_{P,Q}^1(g_q)] \quad (5.7.43)$$

For  $\pi/4$  DQPSK modulation, total number of possible phase sequence  $g$ , can be given by  $4^{N-2}$ . Hence average bit error rate is given by

$$P_b^1 = \frac{1}{4^{N-2}} \sum_{q=1}^{4^{N-2}} P_b^1(g_q) \quad (5.7.44)$$

The formula given in (5.7.44) is good to calculate the BER of small number of symbols. But for large symbols Monte Carlo method is the better option to estimate BER over  $Z$  phase sequence and is given by;

$$P_e = \frac{1}{Z} \sum_{q=1}^Z P_b^1(g_q) \quad (5.7.45)$$

and its variance is given by

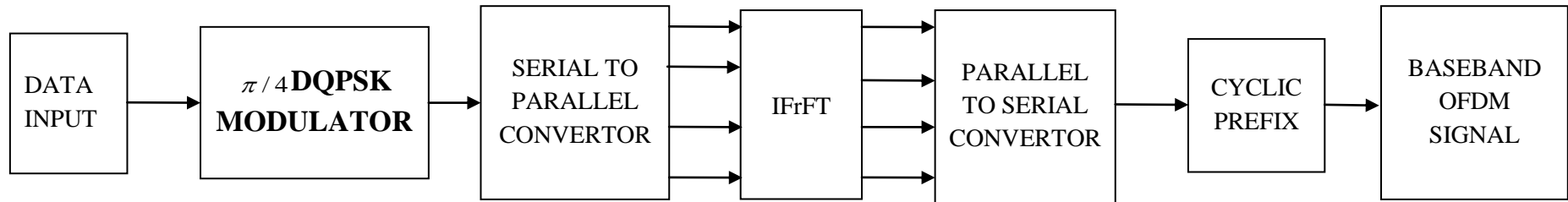
$$\sigma_e^2 = \frac{\psi^2 - (\psi)^2}{Z} \quad (5.7.46)$$

where,  $\psi^2 = \frac{1}{Z} \sum_{q=1}^Z [P_b^1(g_q)]^2$  and  $\psi = \frac{1}{2} \sum_{q=1}^Z P_b^1(g_q)$

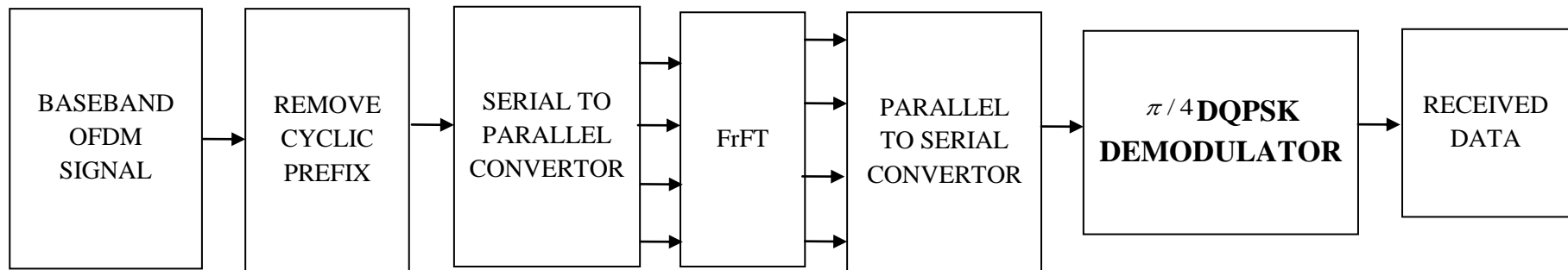
## 5.8 SYSTEM MODEL

The block diagram of transmitter for proposed system is shown in Figure 5.1. Here, to compensate the effect of change in frequency with time FFT used in traditional OFDM system had replaced by FrFT.  $N$  point IFrFT had used for generating OFDM modulated sub-carriers at transmitter.

In this FrFT based OFDM system the stream of data is divided into  $N$  symbols and these  $N$  symbols are transmitted in parallel on  $N$  orthogonally separated sub-carriers. This use of different sub-carriers provides large symbol duration to each symbol and hence reduces the ISI upto large extent. In addition, the ISI effect is mitigated by adding cyclic prefix to each sample. The length of cyclic prefix is made equal to channel length. This process converts the linear convolution of transmitted sequence to circular convolution. Hence, the effect of ISI from the proposed FrFT based OFDM system had removed completely. However, presence of Doppler shift due to mobility of users (transmitter and receiver) and carrier frequency offset due to frequency dispersion in wireless channel will generate inter carrier interference (ICI) in the signal and degrades the overall performance of proposed FrFT based OFDM system.



**Figure 5-1: Block diagram of  $\pi/4$ DQPSK transmitter**



**Figure 5-2: Block diagram of  $\pi/4$ DQPSK receiver**

In the transmitter shown in Figure 5.1, the data is first of all passed through 1/2 convolution encoder for reliable transmission of data. Then these encoded bits are passed through bit inter-leaver for spreading the burst error into various symbols for more accurate recovery of bits at receiver. These bit-interleaved bits are then modulated using  $\pi/4$  DQPSK modulation technique. After modulation, each symbol is transformed from serial to parallel. These symbols are then transformed with IFFT. These modulated symbols are again converted from parallel to serial for generating a stream of data for transmission. Before transmitting, cyclic prefix is added with each symbol. These symbols are then converted to analog signal using D to A converters for transmission using RF transmitters in wireless domain.

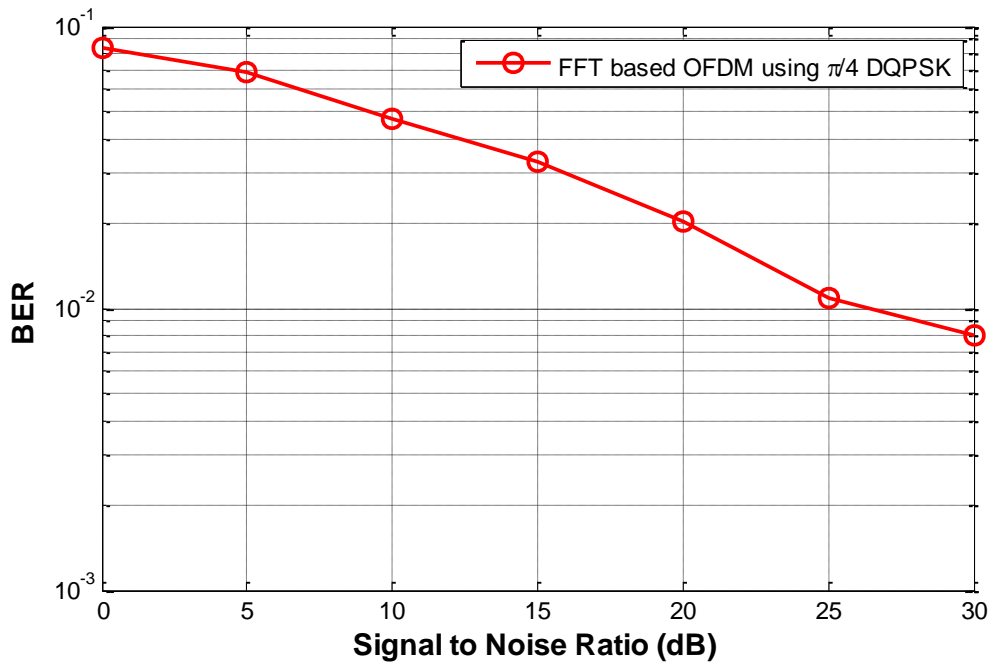
At receiver side the reverse of transmitter is done for data recovery. The block diagram of receiver is shown in Figure 5.2. After receiving the base band RF signal is converted to digital signal using A to D converter.

At receiver, the cyclic prefix is removed from each symbol which was added to mitigate ISI. Then each symbol is converted from serial to parallel. These parallel symbols are then passed through FFT and again converted back to serial using parallel to serial converter. Then these symbols are demodulated using  $\pi/4$  DQPSK demodulator and original transmitted data is recovered.

## 5.9 SIMULATION AND RESULTS

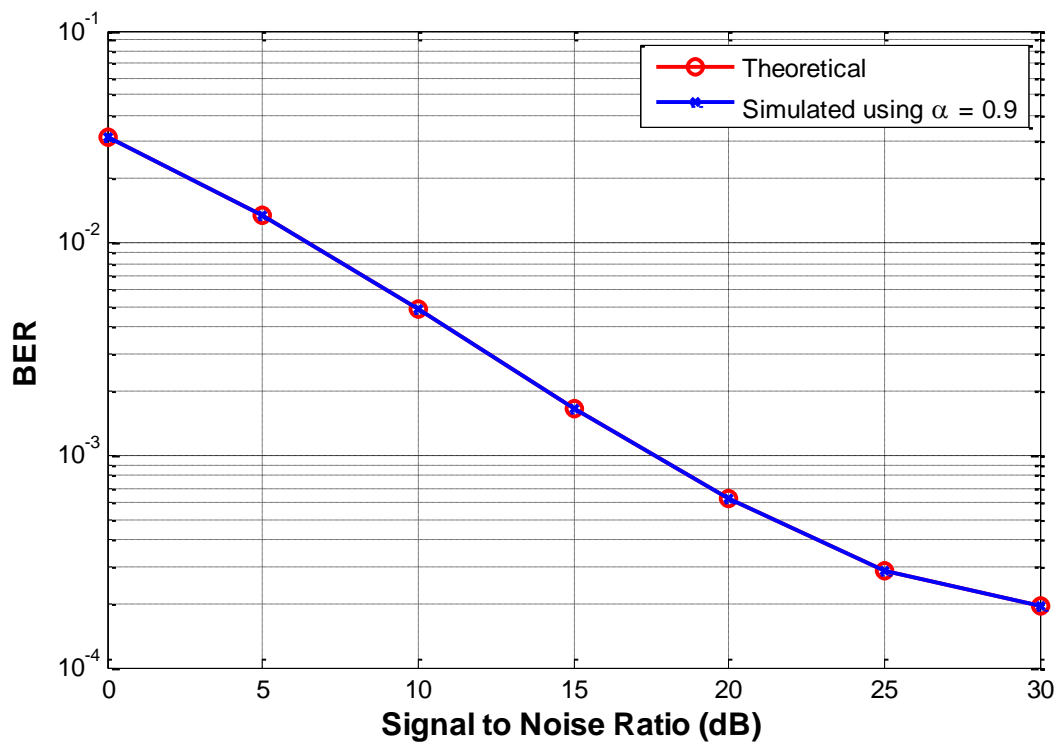
In this section, the BER performance of the  $\pi/4$  DQPSK FFT based OFDM system under frequency selective Rayleigh fading channel had been evaluated with CFO. The results achieved had been compared with the BER performance of FFT based OFDM system with same modulation technique under similar conditions. For simulations in this model we have used 8 sub carriers and CFO of 0.1. Besides the theoretical results have been calculated with 100 randomly chosen differential phase sequences for giving FFT based OFDM system.

The BER vs. SNR of  $\pi/4$  DQPSK modulated FFT based OFDM system has been shown in Figure 5.3. From Figure 5.3 it can be depicted that the FFT based OFDM system can give SNR of 30 dB at  $10^{-2.2}$  BER.



**Figure 5-3: BER Vs. SNR of  $\pi/4$  DQPSK modulated FFT based OFDM**

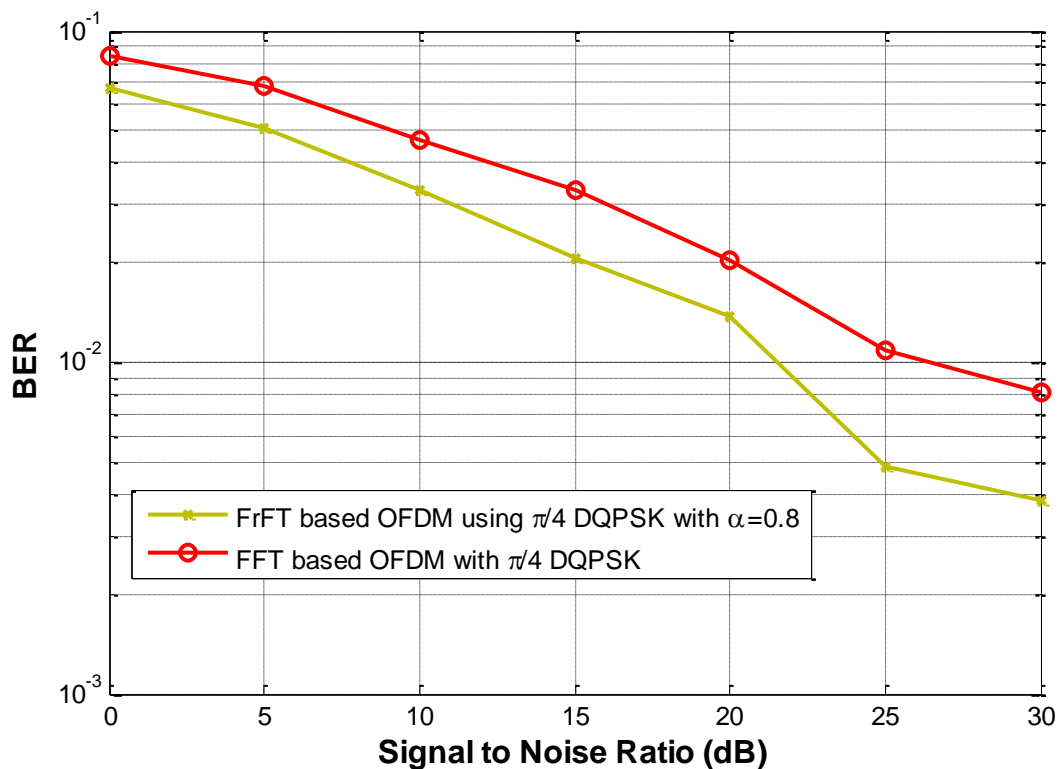
The BER vs. SNR plot for theoretical and simulated FrFT based OFDM system with  $\pi/4$  DQPSK modulation technique is presented in Figure 5.4.



**Figure 5-4: Theoretical and Simulated BER Vs. SNR of  $\pi/4$  DQPSK modulated FrFT based OFDM**

The results depicted in Figure 5.4 show that the theoretical and simulated results for the proposed model i.e. FrFT based OFDM system using  $\pi/4$  DQPSK modulation technique is just like. The simulation results demonstrated in Figure 5.4 are achieved by using the fractional variable to be 0.9. It has been shown that the proposed model has achieved a SNR of 30 dB at  $10^{-3.9}$  BER for  $\alpha = 0.9$ .

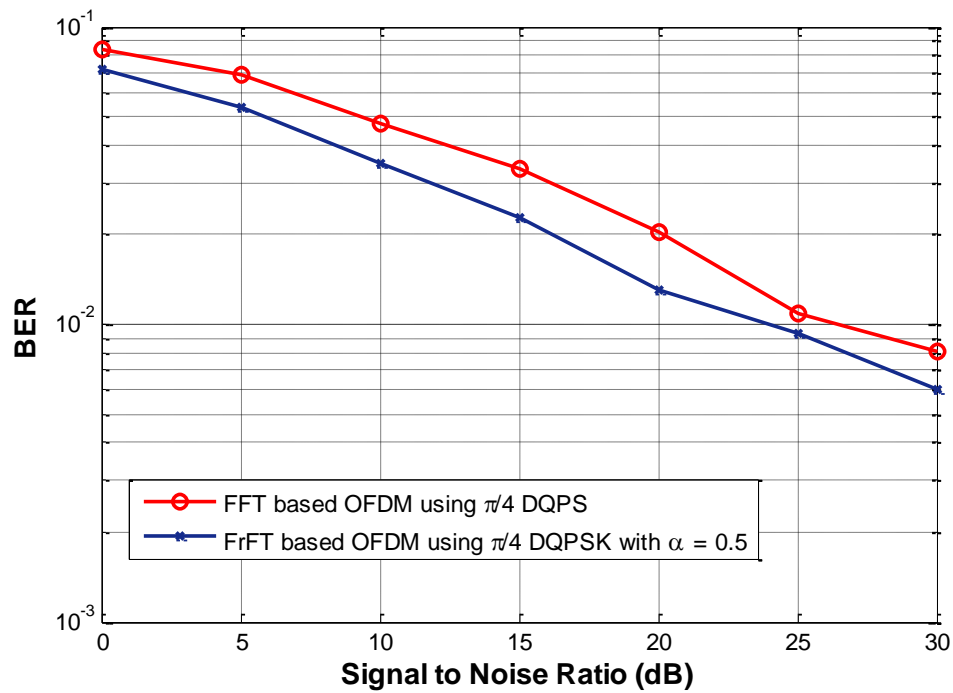
Further, the proposed models performance has been evaluated for various other values of fractional variable ' $\alpha$ ' for CFO 0.1. The results of it have been shown in Figures 5.5 to 5.8.



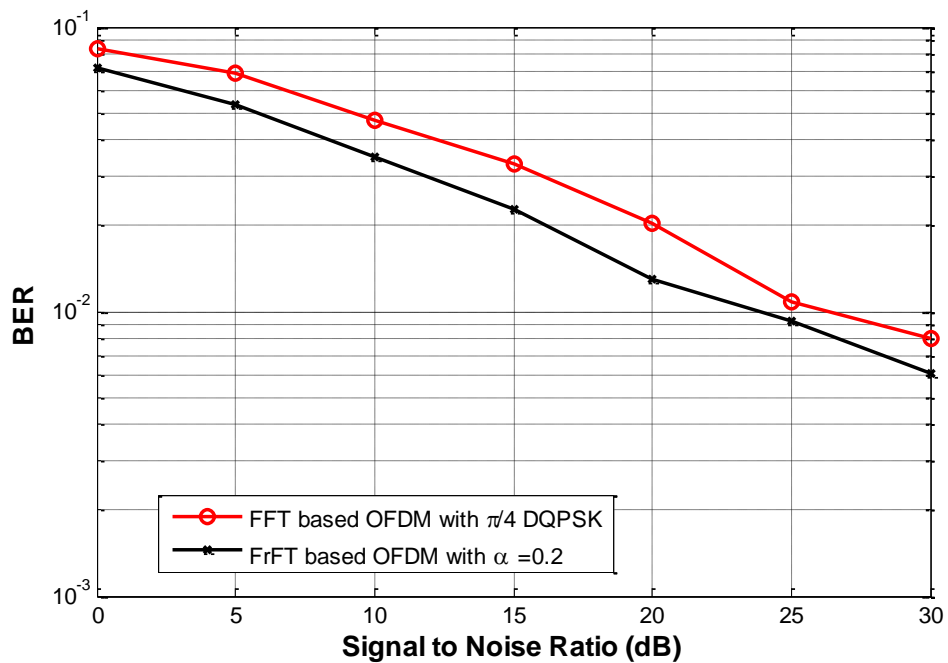
**Figure 5-5: BER Vs. SNR of  $\pi/4$  DQPSK modulated FFT based OFDM and FrFT based OFDM with  $\alpha = 0.8$ .**

In Figure 5.5, the BER vs SNR plot for proposed FrFT based OFDM system using  $\pi/4$  DQPSK modulation for  $\alpha = 0.8$  has been compared with FFT based OFDM system using same modulation technique. It can be seen that the proposed model performs better than FFT based OFDM system under similar conditions. The FFT based OFDM system achieved 30 dB SNR at  $10^{-2.2}$  BER whereas proposed system achieved same SNR at  $10^{-2.7}$  BER. In Figure 5.6, the BER vs. SNR plot for proposed FrFT based OFDM system using  $\pi/4$  DQPSK modulation for  $\alpha = 0.5$  has been compared with FFT based OFDM system using same modulation technique. It can be seen that the proposed model performs better than FFT based OFDM system under similar conditions but approaches the FFT based system. The FFT based

OFDM system achieved 30 dB SNR at  $10^{-2.2}$  BER whereas proposed system achieved same SNR at  $10^{-2.4}$  BER.

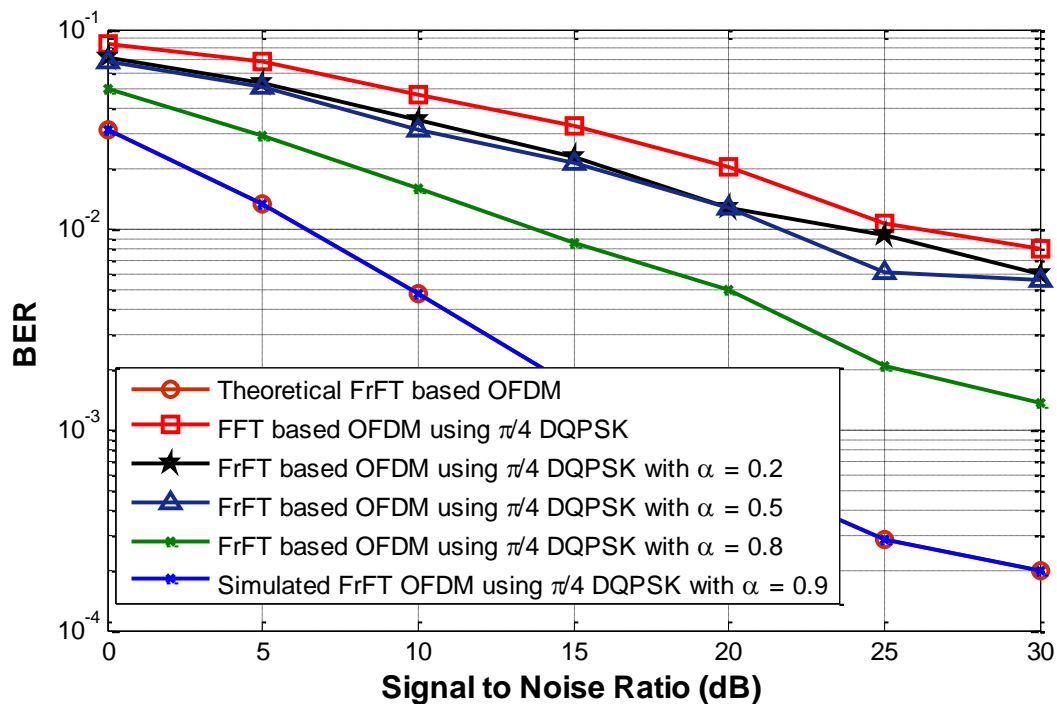


**Figure 5-6: BER Vs. SNR of  $\pi/4$  DQPSK modulated FFT based OFDM and FrFT based OFDM with  $\alpha = 0.5$**



**Figure 5-7: BER Vs. SNR of  $\pi/4$  DQPSK modulated FFT based OFDM and FrFT based OFDM with  $\alpha = 0.2$ .**

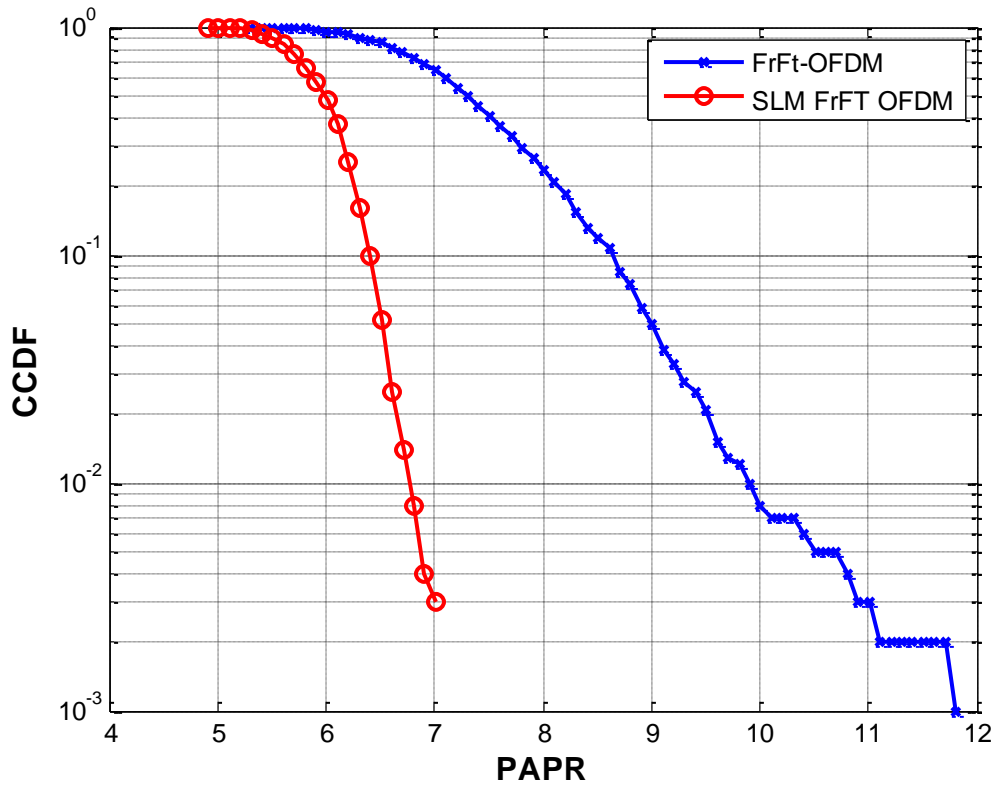
In Figure 5.7, the BER vs. SNR plot for proposed FrFT based OFDM system using  $\pi/4$  DQPSK modulation for  $\alpha=0.2$  is compared with FFT based OFDM system using same modulation technique. It can be seen that the proposed model performs better than FFT based OFDM system under similar conditions but approaches to FFT based system and is almost similar to the performance given by proposed model at  $\alpha=0.5$ . The FFT based OFDM system achieved 30 dB SNR at  $10^{-2.2}$  BER, whereas, proposed system achieved same SNR at  $10^{-2.4}$  BER.



**Figure 5-8: BER Vs. SNR of  $\pi/4$  DQPSK modulated FFT based OFDM and FrFT based OFDM with  $\alpha = 0.2, 0.5, 0.8, 0.9$  along with theoretical results.**

Figure 5.8 shows the combined result of proposed model for different values of ' $\alpha$ '. It is concluded from the plots that the FrFT based OFDM system outperforms the FFT based system for said modulation technique. Moreover, the performance of proposed system varies with change in the ' $\alpha$ '. The proposed system has been able to achieve the BER of as low as upto  $10^{-2.9}$  at SNR of 30 dB which is not only far better than FFT based system which gives same SNR at BER of  $10^{-2.2}$  but at the same time, it is also better than the response given by same model for other values of ' $\alpha$ '.

The PAPR analysis of FrFT based OFDM system was also done on  $\pi/4$  DQPSK modulation technique. Figure 5.9 shows the PAPR analysis of  $\pi/4$  DQPSK based FrFT based OFDM with and without SLM clipping technique. The results shown in Figure 5.9 shows that SLM clipping technique has improved the PAPR of proposed system upto great extent.



**Figure 5.9: CCDF of PAPR for  $\pi/4$  DQPSK modulation based FrFT based OFDM with and without SLM clipping technique**

In Figure 5.9, the improvement of approximately 3.8 dB has been observed in the case of  $\pi/4$  DQPSK with SLM clipping as compared to PAPR achieved without SLM clipping at  $10^{-3.0}$  CCDF.

## 5.10 SUMMARY

In this chapter the FrFT based OFDM system is proposed using  $\pi/4$  DQPSK modulation technique. The mathematical analysis of FFT based OFDM system and FrFT based OFDM system has been presented for said modulation technique. Afterwards, the exact BER of proposed model has been derived with said modulation technique under Rayleigh fading channel with CFO. The theoretically calculated BER is then compared with simulated results. It has been shown that the proposed model have produced exactly same simulated results for a 100 samples of data as was expected theoretically for  $\alpha = 0.9$ . Further, the proposed

models response was analysed for other values of ' $\alpha$ ' like 0.2, 0.5 and 0.8. The simulated results for different values of ' $\alpha$ ' have been presented and compared with FFT based OFDM system under similar conditions. The combined plot of all proves that the FrFT based OFDM system with  $\pi/4$  DQPSK modulation technique outperforms FFT based OFDM system and gives best result at  $\alpha=0.9$ .  $\pi/4$  DQPSK modulation techniques had able to achieve improvement of 3.2 dB at CCDF of  $10^{-3.0}$  in FrFT based OFDM system as compared to without SLM clipping technique for same system under consideration.

### ***Contribution of Chapter***

*In this chapter the analysis of  $\pi/4$  DQPSK modulation technique for FrFT based OFDM system is a totally new approach for multicarrier communication and has opened new avenue for using the proposed model for upcoming 4G systems. The mathematical analysis carried out for the said modulation technique, which is currently not available in literature is a major contribution to literature and the **equations 5.6.11, 5.6.14 and 5.7.40 to 5.7.46** are the new analytical results which has been derived for the proposed model. These theoretical results are then simulated and comparison is drawn between them which act as a benchmark. In addition to this the PAPR analysis of FrFT based OFDM system with  $\pi/4$  DQPSK modulation technique has also been carried out and the effect of PAPR have been reduced by using SLM technique.*

# CHAPTER 6

## PERFORMANCE ANALYSIS OF GMSK BASED FrFT BASED OFDM SYSTEM

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### 6.1 INTRODUCTION

The requirement for higher data rate under wireless communication had increased tremendously in recent past due to increasing demand of multimedia applications on wireless networks. This leads to development of advanced system, which can work with high reliability and uses bandwidth very efficiently. The OFDM had proven boom for these demands of higher data rate [40]. It is a multicarrier communication technique. Many symbols can be transmitted simultaneously by OFDM over wireless channel by using orthogonally separated sub carriers. It is based on IEEE 802.11 a/g/n protocol. In this large data stream had split into small data streams and each of this stream had transmitted on orthogonally separated sub carriers [40]. Hence, OFDM is able to eliminate ISI caused due to channel fading, very effectively as compared to single carrier communication [34]. OFDM is considered as FDM, which also transmits multiple messages on single channel, but the OFDM based system implements FDM in a very controlled manner with the help of spectrum overlapping which helps in improving spectral efficiency of OFDM as compare to single carrier communication [1]. Gaussian Minimum shift keying (GMSK) is a type of modulation technique. In GMSK, the modulating signal varies the phase of carrier signal instantaneously [68]. The fundamental difference of GMSK from MSK is that GMSK has a Gaussian filter with suitable bandwidth before modulating stage [158].

In this chapter the performance analysis of FrFT based OFDM system is done using GMSK modulation technique. The performance of proposed model is measured for various wireless fading channels like AWGN, Rayleigh and Rician channels. The effect of CFO has been taken in account to measure the BER of proposed system for different values of fractional

variable ' $\alpha$ '. Further the results have also been shown for the traditional FFT based OFDM system for said modulation technique. Finally, the results of both FFT based OFDM and FrFT based OFDM system are presented and compared. It has been shown that, at different values of fractional variable ' $\alpha$ ', the proposed FrFT based OFDM system outperforms then traditional FFT based OFDM system.

## **6.2 GMSK MODULATION TECHNIQUE**

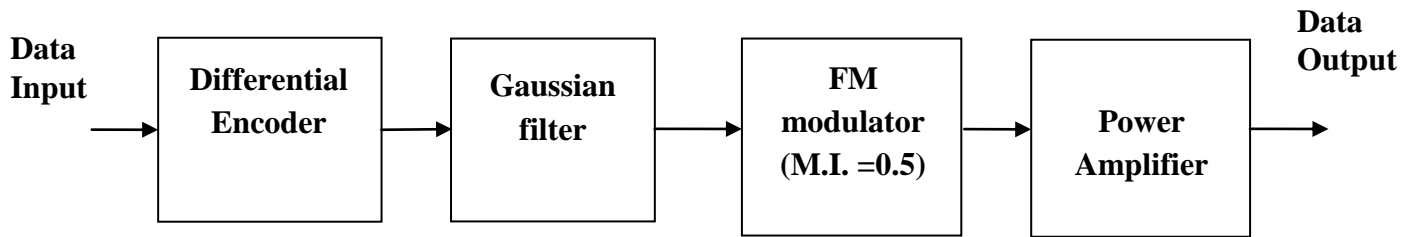
GMSK is a modulation technique, which is used widely by many digital radio communication systems worldwide. Its major advantage is efficient use of spectrum while modulating digital systems [126]. The biggest problem of PSK modulations is its sidebands, which extends much away from main carrier and interfere with adjacent channels [180]. GMSK solved this problem by using Gaussian filter to eliminate the interference caused due to side bands by suppressing. Hence, it is also called as Gaussian filtered minimum shift keying [126]. GSM (2G and 2.5 G) technology is the based on GMSK modulation. GMSK can also be seen as modified form of Minimum Shift Keying (MSK). In GMSK, the phase used for modulation is further filtered through Gaussian filter for eliminating the extended side bands [68]. GMSK is derived from MSK modulation, whereas MSK is the form of continuous phase frequency shift keying. In MSK, there are no phase discontinuities as phase transition always take place at zero crossing of carriers. It is because of 0.5 modulation index of MSK modulation [130].

The results have shown that MSK signal's sidebands always extends beyond the defined bandwidth, this problem can be solved by passing the signal through a low pass filter before modulation. The filter used here must have very sharp cut off, very narrow bandwidth and most importantly, its impulse response should not produce overshoots. Gaussian filter is the best choice for these conditions; an ideal Gaussian filter fulfils all of these conditions [130]. This modulator of MSK with Gaussian filter is called as Gaussian MSK modulator and hence names Gaussian Minimum shift Keying Modulation (GMSK) [127].

## **6.3 MODULATION AND DEMODULATION OF GMSK**

The GMSK modulation can be generated by passing the modulating signal through Gaussian filter and then frequency modulate the signal by keeping modulation index 0.5 [130]. In this

process, it is very important to keep modulation index as 0.5. The simple block diagram for generation of GMSK is shown in Figure 6.1:



**Figure 6-1: Generation of GMSK modulated signal**

As shown in Figure 6.1, the GMSK transmitter consists of a differential encoder, a Gaussian filter, and a FM modulator with modulation index of 0.5 and a power amplifier. The transfer function of Gaussian filter is given by [124];

$$H(f) = \exp(-\delta^2 f^2) \quad (6.3.1)$$

where,  $\delta$  is based on 3 dB bandwidth symbol time product ( $BT_b$ ) given by [124];

$$\delta = \frac{\sqrt{\ln_2} T_b}{\sqrt{2} BT_b} \quad (6.3.2)$$

as  $\delta$  rises, the ISI at receiver increases due to decrease in spectral occupancy of Gaussian filter and hence the impulse response of symbol under consideration is spread into adjacent symbols. GMSK modulation technique is widely used in cellular and DECT technologies. Further, due to constant envelope modulation, GMSK is widely used in mobile communication [181]. Another major advantage of GMSK is its immunity to power amplifiers non linearity and its capability to combat wireless channel fading. However, GMSK gives less spectral efficiency. 2G Cellular systems uses GMSK modulation technique with modulation index 0.5 filter bandwidth times bit period 0.3 and a modulation rate of 271 kbauds [158]. The normalized value of bandwidth symbol time product  $BT_b$  is -3dB. If one increases the value of bandwidth symbol time product above 0.3, it will increase the power level in side lobes, which further increases interference with adjacent symbols. Henceforth, 0.3 is the most optimized value of bandwidth symbol time product that gives good spectral efficiency as well as avoids ISI considerably [158].

The diametrically opposite input data given to differential encoder in GMSK modulator is given by  $d_i$  and its output is given by  $g_i$ . For single bit differential encoder, the output of

differential encoder is same as that of input i.e.  $g_i = d_i$ . Whereas for two bit differential encoder, the output is given by [127]

$$g_i = -d_i g_{i-1} \quad (6.3.3)$$

For a NRZ input to Gaussian filter, the output of Gaussian filter is given by [127]

$$x(t) = \sum_{l=-\infty}^{+\infty} g_l m(t - lT_b) \quad (6.3.4)$$

where,  $m(t)$  is the transfer function of Gaussian filter for a rectangular pulse of duration  $T$  and amplitude as unity.  $m(t)$  is given as [182]

$$m(t) = \frac{1}{2T_b} \left[ Q \left( i_1 B T_b \left( -\frac{t}{T_b} \right) \right) - Q \left( i_1 B T_b \left( 1 - \frac{t}{T_b} \right) \right) \right] \quad (6.3.5)$$

In eq. (6.3.5)  $B$  is 3 dB bandwidth of Gaussian filter,  $T_b$  is bit duration,  $B T_b$  is the bandwidth time product of transmitter and  $i_1 = 7.546$  [126].  $Q$  is given by [126]

$$Q(r) = \frac{1}{\sqrt{2\pi}} \int_r^{\infty} e^{-\frac{s^2}{2}} ds \quad (6.3.6)$$

The output of FM modulator is given by

$$r(t) = A_0 \cos(\omega_c t + \theta(t) + \psi) \quad (6.3.7)$$

where,  $A_0$  is amplitude of signal,  $\omega_c$  is the carrier frequency,  $\psi$  is the initial phase and  $\theta(t)$  is the excess phase and is defined as [129]

$$\theta(t) = i_n \int_{-\infty}^t x(\tau) d\tau = i_n \sum_{q=-\infty}^{+\infty} b_q \int_{-\infty}^t m(\tau - qT_b) d\tau \quad (6.3.8)$$

The phase change over one symbol interval is given by [128]

$$\Delta\theta_l = \theta(lT_b) - \theta(lT_b - T_b)$$

$$\text{or } \Delta\theta_l = i_m \sum_{q=-\infty}^{+\infty} b_q \int_{lT_b - \tau}^{lT_b} m(\tau - qT_b) d\tau \quad (6.3.9)$$

The maximum value of area covered by  $m(t)$  is  $T_b$ . For FM modulator the modulation index must be 0.5 and binary input data  $(\Delta\theta_l)_{\max} = \frac{\pi}{2}$  [68].

Therefore,  $i = \frac{\pi}{2T_b}$

At receiver side, the GMSK signal can be received by using differential detector. For one-bit differential detector, let the received signal is affected by AWGN noise only and with one side spectral density  $N_0$ . Hence, the output is given by [126]

$$s(t) = p(t) \cos(\omega_c t + \theta'(t)) + w_c(t) \cos(\omega_c t) - w_s(t) \sin(\omega_c t) \quad (6.3.10)$$

where,  $p(t)$  is time varying envelop of the signal,  $\theta'(t)$  is the distorted signal phase.  $w_c(t)$  and  $w_s(t)$  are in phase and quadrature components of noise.

The output of one bit phase detector is given by [10]

$$y_1(t) = p(t) \cdot p(t - T_b) \cdot \sin \left( i_n \sum_{q=-\infty}^{+\infty} g_i \int_{t-T_b}^t m(\tau - qT_b) d\tau \right) + w_1(t) \quad (6.3.11)$$

where,  $w_1(t)$  is overall noise. The output of two-bit differential detector is given by [10]

$$y_2(t) = p(t) \cdot p(t - 2T_b) \cdot \cos \left( i_n \sum_{q=-\infty}^{+\infty} g_i \int_{t-2T_b}^t m(\tau - qT_b) d\tau \right) + w_2(t) \quad (6.3.12)$$

Henceforth, by using one-bit differential detector or two-bit differential detector at receiver one can easily demodulate the GMSK signal. At receiver side, the decision of whether 1 or 0 was transmitted is taken on the basis of following:

For one-bit differential detector [126]

$$\begin{cases} 1 & \text{if } y_1(t) = A \sin(\Delta\theta(T_b) - \theta) \geq 0 \\ 0 & \text{if } y_1(t) = A \sin(\Delta\theta(T_b) - \theta) < 0 \end{cases} \quad (6.3.13)$$

For two-bit differential detector [126]

$$\begin{cases} 1 & \text{if } y_2(t) = A \cos(\Delta\theta(2T_b) - \psi) \geq 0 \\ 0 & \text{if } y_2(t) = A \cos(\Delta\theta(2T_b) - \psi) < 0 \end{cases} \quad (6.3.14)$$

The average bit error probability for one-bit detector is given by [126]

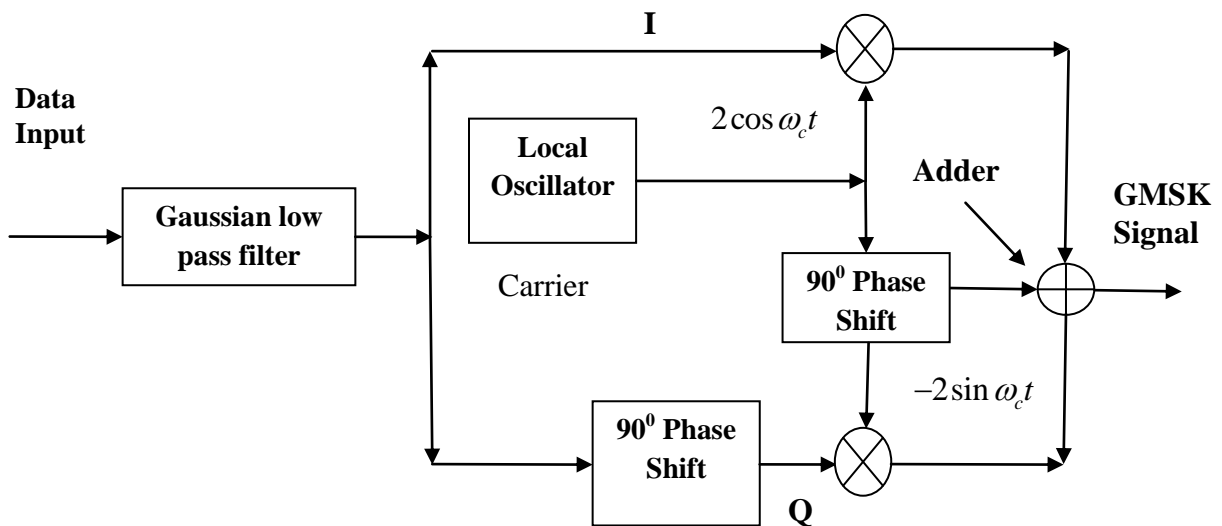
$$P_b = \frac{1}{2} \overline{P_r \{ \sin \Delta\theta(T_b) < 0 \mid y(t) \}} + \frac{1}{2} \overline{P_r \{ \sin \Delta\theta(T_b) > 0 \mid y(t) \}} \quad (6.3.15)$$

whereas for two-bit detector the probability of average bit error rate is given by [124]

$$P_b = \frac{1}{2} \overline{P_r \{ \cos \Delta\theta(2T_b) < 2\psi \mid y(t) \}} + \frac{1}{2} \overline{P_r \{ \sin \Delta\theta(T_b) > 2\psi \mid y(t) \}} \quad (6.3.16)$$

In (6.3.15) and (6.3.16), the probabilities are calculated by averaging all the equal likely input data sequences.

However, it is very difficult to maintain the exact modulation index of 0.5 because of analog circuit tolerance variations. The other easy way to generate the 0.5 modulation index is by using a quadrature modulator. The quadrature modulator is shown in Figure 6.2:



**Figure 6-2: Block diagram of GMSK modulator**

The quadrature modulator can generate in phase and quadrature phase signal. It is also called as I Q modulator [127]. This quadrature modulator helps to generate modulation index of 0.5 and it generates the desired modulation index without any additional settings requirement to set the modulation index to be exactly 0.5. At receiver side, the GMSK signal can be demodulated by simply doing the reverse of operations implemented in modulator [127].

## 6.4 APPLICATIONS OF GMSK MODULATION

The major applications of GMSK modulation technique are given as:

- a) GMSK modulation provides very good spectral efficiency as compared to any other phase shift keying modulation technique [68].
- b) It can be amplified by non-linear filters. Hence, it can be used with portable receivers like mobiles without any compromise on signal quality [2].
- c) Low power consumption.
- d) Its performance does not degrade due to variation in signal amplitude.
- e) It provides constant envelope and good power efficiency too [68].

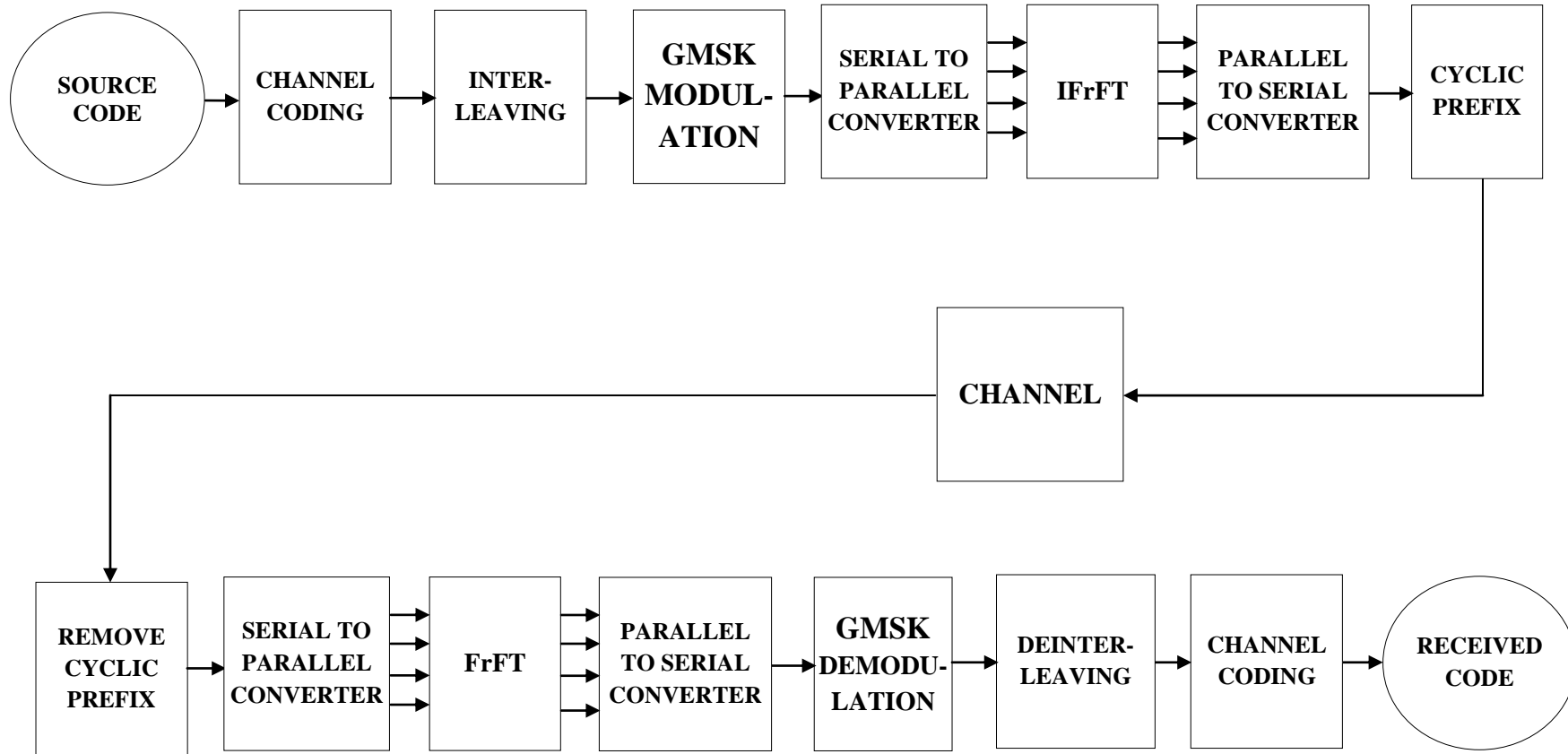
In GMSK the degradation of signal due to ISI does not degrades its performance [128] i.e. GMSK can compensate the effect of ISI and hence it is highly useful in wireless applications.

## **6.5 FrFT BASED OFDM SYSTEM USING GMSK MODULATION**

The requirement for higher data rate under wireless communication had increased tremendously in recent past due to increasing demand of multimedia applications on wireless networks. This leads to development of advanced system, which can work with high reliability and uses bandwidth very efficiently. OFDM had proven boom for these demands of higher data rate.

The major benefit of implementing the GMSK modulation with FrFT can be seen in the future 4G communications. As currently 2G and 2.5G, technology in GSM had totally deployed on GMSK modulation [2]. In this thesis work, an idea had proposed where, the same modulation technique can be deployed in next generation communication systems like 4G. Here the benefits of multicarrier communication have further enhanced the efficiency of GMSK modulation. The implementation of FrFT has made the proposed system more efficient by considering the signal response in time-frequency domain using FrFT along with CFO.

In this proposed system GMSK, modulation had used to modulate the carrier signal. The block diagram of proposed system had shown in Figure 6.3:



**Figure 6-3: Block diagram of GSM modulation based FrFT based OFDM system's Transmitter and Receiver**

In this proposed system, a NRZ sequence between -1 to +1 was created from binary input data stream of 0 and 1 from source code. Then  $N$  samples per symbol are created. These samples had further integrated and convolved with Gaussian function. After convolution quadrature components of baseband, GMSK signal had been computed i.e.  $I$  and  $Q$  component. Finally these two components  $I$  and  $Q$  were multiplied with  $\cos(n\omega_0)$  and  $-\sin(n\omega_0)$  respectively and added to achieve GMSK modulated signal. This signal had further converted from serial to parallel to take the IFFT of each symbol. After IFFT, again the signal had converted from parallel to serial. To avoid ISI cyclic prefix had added with each symbol and transmitted through wireless channel. At receiver side, reverse of all the above stated steps had done and after GMSK, demodulation original transmitted code had reproduced.

## 6.6 BER ANALYSIS OF FRFT BASED OFDM SYSTEM FOR GMSK MODULATION

The response of GMSK in frequency domain with  $L=3$  (meaning that all ISI came only from the two adjacent symbols), was given by [68]:

$$g(t) = Q\left(\frac{2\pi BT_b}{\sqrt{\ln \ln 2}}\left(\frac{t}{T_b} - 1\right)\right) - Q\left(\frac{2\pi BT_b}{\sqrt{\ln \ln 2}}\left(\frac{t}{T_b}\right)\right) \quad (6.6.1)$$

where,  $T_b$  is the symbol interval and  $BT_b$  is the normalized bandwidth and [126]

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{x^2}{2}} dx \quad (6.6.2)$$

The phase trajectory of  $\mu_m$  therefore was affected solely by  $\mu_{m-1}$  and  $\mu_{m+1}$  and was independent of all other future and past symbols. This assumption was valid as long as  $T_b \geq 0.3$ , so that [127]

$$Q\left(-\frac{2\pi BT_b}{\sqrt{\ln 2}}\right) \approx 1 \quad (6.6.3)$$

Upon rewriting, the Gaussian Q-function could be written in terms of the error function as [127]

$$Q(x) = \frac{1}{2} \left[ 1 + \operatorname{erf} \left( \frac{x}{\sqrt{2}} \right) \right] \quad (6.6.4)$$

The frequency trajectory during the  $m^{\text{th}}$  symbol interval had expressed as follows [127]:

$$g(t) \approx \mu_{m-1} \left[ 1 - \operatorname{erf}(\beta(t - mT_b)) \right] + \mu_m \left[ \begin{array}{l} \operatorname{erf}(\beta(t - mT_b)) \\ -\operatorname{erf}(\beta(t - (m+1)T_b)) \end{array} \right] - \mu_{m+1} \left[ 1 + \operatorname{erf}(\beta(t - (m+1)T_b)) \right] \quad (6.6.5)$$

where,  $\beta = \pi B \sqrt{\frac{2}{\ln 2}}$

The phase response had obtained from  $g(t)$  using  $q(t) = \int_t^{-\infty} g(\tau) d\tau$ .

$I$  and  $Q$  components, were given by [125]:

$$I(t) = \operatorname{Re}\{q(t)\} \text{ and } Q(t) = \operatorname{Im}\{q(t)\} \quad (6.6.6)$$

The phase trajectories of all the eight data sequence  $\{\mu_{m-1}, \mu_m, \mu_{m+1}\}$  combinations is given by the Table 6.1 [127]:

**Table 6-1: Phase trajectories corresponding to each possible combination of the data sequence**

$\{\mu_{m-1}, \mu_m, \mu_{m+1}\}$	$q(t)$
000	$-t$
001	$I_1(\beta, t - T_b) - T_b$
010	$[I_1(\beta, t) - I_1(\beta, 0) - I_1(\beta, t - T_b) + T_b - t]$
011	$I_1(\beta, t) - I_1(\beta, 0)$
100	$[I_1(\beta, 0) - I_1(\beta, t)]$
101	$-I_1(\beta, t) + I_1(\beta, 0) + I_1(\beta, t - T_b) - T_b + t$
110	$-I_1(\beta, t - T_b) + T_b$
111	$t$

where,

$$I_1(\beta, x) = \int \operatorname{erf}(\beta x) dx = x \operatorname{erf}(\beta x) + \frac{e^{-\beta^2 x^2}}{\beta \sqrt{\pi}} \quad (6.6.7)$$

GMSK generated a 16 state phase Trellis from the set of different trajectories for the even and odd symbol periods. The phase values at the symbol interval boundaries with modulo  $2\pi$  were members of a discrete finite set. There was one set for odd intervals and another for even intervals.

The possible phase values at the boundaries for even intervals were always in the set, given by [127]

$$S_e = \{-\pi, -\pi + 2\Delta, -2\Delta, 0, 2\Delta, \pi - 2\Delta, \pi\} \quad (6.6.8)$$

and for the odd intervals in the set, given by [127]

$$S_o = \left\{ \begin{array}{l} -\frac{\pi}{2} - 2\Delta, -\frac{\pi}{2}, -\frac{\pi}{2} + 2\Delta, \\ \frac{\pi}{2} - 2\Delta, \frac{\pi}{2}, \frac{\pi}{2} + 2\Delta \end{array} \right\} \quad (6.6.9)$$

where,

$$\Delta = \sqrt{\frac{\ln 2}{2\pi}} \frac{1}{4(BT_b)} \quad (6.6.10)$$

For GMSK based FrFT based OFDM; sample the GMSK modulated signal at the symbol boundaries to obtain symbols from the discrete set  $S_e$  and  $S_o$ . Let this sequence be represented by  $S_k$ . Then the  $m^{\text{th}}$  sample of the  $i^{\text{th}}$  transmitted frame was given by

$$s_i(m) = \sqrt{\frac{N}{N+N_g}} \sum_{k=0}^{N-1} S_i(k) \cdot F_{-d}(m, k) \quad -N_g \leq m < N \quad (6.6.11)$$

where,  $N_g$  the cyclic prefix length,  $N$  is the number of subcarriers and  $S_i(k)$  is the symbol to be sent. The IFrFT kernel had expressed as [147]

$$F_{-d}(m, k) = \sqrt{\frac{\sin \alpha + j \cos \alpha}{N}} e^{\left[ -\frac{j}{2} m^2 (T_s)^2 \cot \alpha \right]} \cdot e^{\left[ -\frac{j}{2} k^2 u^2 \cot \alpha \right]} e^{\left[ j \frac{2\pi mk}{N} \right]} \quad (6.6.12)$$

and

$$uT_s = \frac{2\pi(\sin \alpha)}{N} \quad (6.6.13)$$

where,  $T_s$  and  $u$  were the sampling intervals in the time and fractional Fourier domain. The fractional Fourier domain makes angle  $a = \frac{\alpha\pi}{2}$  with the time domain. For  $a = \frac{\pi}{2}$  or  $\alpha = 1$ , IFRFT converts to IFFT.

In case of Rayleigh channel, the discrete expression of the channel impulse response (CIR) is represented by  $h(n, l)$  and the cross-correlation function of the CIR is given by [114]:

$$E[h(p, l).h^*(q, k)] = \sigma_l^2 J_0(2\pi\Delta t f_d) \delta(l - k) \quad (6.6.14)$$

where,  $\Delta t = |p - q|T_s$ ,  $\sigma_l^2$  is total power of the  $l^{th}$  path,  $J_0$  is 0<sup>th</sup> order Bessel function,  $f_d$  is the maximum Doppler frequency shift and  $\delta(l)$  is Kronecker delta function [57].

In case of Rician channel along with multipath scattered components, Line of sight (LOS) component is also present [125]. It is given by;

$$h(p, l) = m_{LOS} + h^{sca}(p, l) \quad (6.6.15)$$

where,  $m_{LOS}$  is line of sight component and  $h^{sca}(p, l)$  is the scattered multipath components and is given by;

$$h^{sca}(p, l) = \sigma_l^2 J_0(2\pi\Delta t f_d) \delta(l - k) \quad (6.6.16)$$

By putting (6.7.16) in (6.7.15), (6.7.14) can be written as

$$E[h(p, l).h^*(q, k)] = |m_{LOS}|^2 + \sigma_l^2 J_0(2\pi\Delta t f_d) \delta(l - k) \quad (6.6.17)$$

Equation (6.7.17) can further, be written as;

$$E[h(p, l).h^*(q, k)] = \frac{P_t}{K+1} \{K + J_0(2\pi\Delta t f_d) \delta(l - k)\} \quad (6.6.18)$$

where,  $P_t = |m_{LOS}|^2 + \sigma_l^2$  and Rician parameter  $K$  is defined as;

$K = \frac{|m_{LOS}|^2}{\sigma_i^2}$ . When  $K = 0$ , Rician fading channel becomes Rayleigh fading channel.

For Rayleigh channel, the discrete expression of the channel impulse response (CIR) had represented by  $h(n, l)$  and the cross-correlation function of the CIR had given by:

$$E[h(p, l) \cdot h^*(q, k)] = \sigma_i^2 J_0(2\pi \Delta t f_d) \delta(l - k) \quad (6.6.19)$$

where,  $\Delta t = |p - q|T_s$ .

Whereas for Rician channel  $\sigma_i^2$  was total power of the  $l^{th}$  path,  $J_0$  was  $0^{th}$  order Bessel function,  $f_d$  was the maximum Doppler frequency shift and  $\delta(l)$  is Kronecker delta function. Assuming the frame had synchronized, the  $n^{th}$  sample of the  $j^{th}$  received frame was:

$$r_j(n) = \sum_{m=-\infty}^{+\infty} \sum_{N-1}^{m=-N_g} h_{i,j}(n, n-m) \cdot S_i(m) e^{j \frac{2\pi n \epsilon}{N}} + w(n) \quad (6.6.20)$$

where,  $w(n)$  was the AWGN noise and  $\epsilon = \Delta f N T_s$  was the frequency offset.

$$h_{i,j}(n, l) = h(j(N + N_g) + n, l + (j-1)(N + N_g)) \quad (6.6.21)$$

After removing the cyclic prefix and applying DFrFT, the signal obtained had given by

$$\hat{S}_j(\hat{k}) = \sum_{N-1}^{n=0} F_d(\hat{k}, n) \cdot r_j(n), \quad 0 \leq \hat{k} < N \quad (6.6.22)$$

$$\text{where, } F_d(m, n) = \sqrt{\frac{\sin \alpha - j \cos \alpha}{N}} e^{j \frac{1}{2} n^2 (T_s)^2 \cot \alpha} e^{j \frac{1}{2} m^2 u^2 \cot \alpha} e^{-j \frac{2\pi m n}{N}} \quad (6.6.23)$$

Combining the (6.7.22) and (6.7.23), the received signal had expressed as:

$$\hat{S}_j(\hat{k}) = \sum_{+\infty}^{i=-\infty} \sum_{N-1}^{k=0} S_i(k) \sum_{N-1}^{n=0} \sum_{N-1}^{m=-N_g} F_d(\hat{k}, n) \cdot F_{-d}(m, k) h_{i,j}(n, n-m) \cdot e^{j \frac{2\pi n \epsilon}{N}} \sqrt{\frac{N}{N + N_g}} + w(\hat{k}) \quad (6.6.24)$$

Let

$$IS_{ij}(\hat{k}, k) = \sum_{N-1}^{n=0} \sum_{N-1}^{m=-N_g} F_d(\hat{k}, n) \cdot F_{-d}(m, k) h_{i,j}(n, n-m) e^{j \frac{2\pi n \epsilon}{N}} \quad (6.6.25)$$

The transposed signal in (6.7.25) can be written as:

$$\hat{S}_j(\hat{k}) = \sqrt{\frac{N}{N+N_g}} \sum_{+\infty}^{i=-\infty} \sum_{N-1}^{k=0} IS_{ij}(\hat{k}, k) \cdot S_i(k) + w(\hat{k}) \quad (6.6.26)$$

As it is assumed the cyclic prefix is longer than the channel response, there is no ISI between different OFDM symbols and the received signal  $\hat{S}(q)$  for the  $q^{th}$  sub-carrier can be expressed as

$$\hat{S}(q) = \beta(q) S(q) IS(q, q) + \sum_{k=0, k \neq q}^{N-1} \beta(k) S(k) IS(q, k) + W(q) \quad (6.6.27)$$

where,

$$IS(q, k) = \frac{1}{N} \sum_{n=0}^{N-1} e^{j2\pi \epsilon n / N} \times \sum_{m=-N_g}^{N-1} e^{-j(m^2 - n^2) \Gamma_s^2 \cot \alpha / 2} \cdot e^{j(q^2 - k^2) u^2 \cot \alpha / 2} \cdot e^{j2\pi(mk - nq) / N} \quad (6.6.28)$$

$\beta(k)$  is the channel response in frequency domain for  $k^{th}$  sub carrier where,  $\{\beta(0), \beta(1), \dots, \beta(N-1)\} = F_L h$ ,  $F_L$  representing the first  $L$  columns of DFrFT matrix and  $h = (h(0), h(1), h(2), \dots, h(L-1))^T$  representing the channel response in time domain at that instant.  $IS(q, k)$  is the ICI coefficient.

After multiplying (6.7.28) by the conjugate of  $\beta(0)$ , represented as  $\bar{\beta}(0)$  and taking the imaginary part ( $\Im[\cdot]$ ) only, we get

$$\Im[\bar{\beta}(0) Y(0)] = |\beta(0)|^2 \Im[IS(0, 0)] + \sum_{K=1}^{N-1} \Im[\bar{\beta}(0) \beta(k) S(k) IS(0, k)] + \Im[W(0) \bar{\beta}(0)] \quad (6.6.29)$$

CHF of  $\Im[\bar{\beta}(0) Y(0) / \beta(0), \beta]$  can be written as

$$\Psi_{\Im\left[\frac{\bar{\beta}(0) Y(0)}{\beta(0)}, \beta\right]}(j\omega) = \frac{1}{2^{N-1}} e^{j\omega |\beta(0)|^2 \Im[IS(0, 0)]} e^{(-\omega^2 \sigma_\beta^2) / 2} \sum_{k=0}^{2^{N-2}-1} (e^{j\omega \Im[\bar{\beta}(0) (S_k)^T \beta]} + e^{-j\omega \Im[\bar{\beta}(0) (S_k)^T \beta]}) \quad (6.6.30)$$

The GMSK signal could demodulated by considering  $\varphi(k)$  as the phase at the  $k^{\text{th}}$  subcarrier  $0 \leq k < N$  and  $\varphi(0)=0$  then the binary data transmitted had given by:

$$d(k) = \begin{cases} 1 & \text{if } \sin(\varphi(k) - \varphi(k-1)) \leq 0 \\ 0 & \text{if } \sin(\varphi(k) - \varphi(k-1)) > 0 \end{cases} \quad (6.6.31)$$

or let  $\Delta\varphi = \varphi(k) - \varphi(k-1)$ , then

$$d(k) = \begin{cases} 1 & \text{if } \sin(\Delta\varphi) \leq 0 \\ 0 & \text{if } \sin(\Delta\varphi) > 0 \end{cases} \quad (6.6.32)$$

Assuming the first bit transmitted as  $S_0 = 1$  and the initial phase to be  $\varphi(-1) = 0$ , then an error would occur if

$$\sin(\varphi(0) - \varphi(-1)) > 0 \quad (6.6.33)$$

$$\text{or } \sin(\varphi(0)) > 0$$

$$\text{or } 0 \leq \varphi(0) \leq \pi$$

Hence,

$$\Im \left[ \frac{\bar{\beta}(0) \hat{S}(0)}{\beta(0)}, \beta \right] > 0 \quad (6.6.34)$$

Using CHF defined in (6.7.28), the conditional bit error probability can be written as

$$P_b\left(\frac{\xi}{\beta(0), \beta}\right) = \frac{1}{2^{N-1}} \sum_{k=0}^{2^{N-2}-1} \left\{ Q\left(\frac{|\beta(0)|^2 \Im[IS(0,0)] - \Im[\bar{\beta}(0)(S_k)^T \beta]}{\sigma_\beta}\right) + Q\left(\frac{|\beta(0)|^2 \Im[IS(0,0)] + \Im[\bar{\beta}(0)(S_k)^T \beta]}{\sigma_\beta}\right) \right\} \quad (6.6.35)$$

With the help of (6.7.35), the unconditional  $BER(P_b)$  can be determined as

$$P_b = \int \int P_b(\xi / \beta(0), \beta) p_{\beta/\beta(0)}(\beta / \beta(0)) d\beta p_{\beta(0)}(\beta(0)) d\beta(0) \quad (6.6.36)$$

Replacing the multidimensional integration into many-single dimensional integration by averaging  $P_b(\xi / \beta(0), \beta)$  over  $p_{\beta/\beta(0)}(\beta / \beta(0))$  in equation (6.7.36), we get

$$P_b = \int P(\xi / \beta(0)) p_{\beta(0)}(\beta(0)) d\beta(0) \quad (6.6.37)$$

where,

$P(\xi / \beta(0))$  is defined as

$$P(\xi / \beta(0)) = \frac{1}{2^{N-1}} \sum_{k=0}^{2^{N-2}-1} \left\{ Q \left( \frac{|\beta(0)|(\Im[\text{IS}(0,0)] - z_k)}{\sigma \sqrt{1 + (a_k / 2\sigma^2)}} \right) + Q \left( \frac{|\beta(0)|(\Im[\text{IS}(0,0)] + z_k)}{\sigma \sqrt{1 + (a_k / 2\sigma^2)}} \right) \right\} \quad (6.6.38)$$

Rearranging (6.7.38) by using the the polar form of the Q-function and changing the variable as  $\{|\beta(0)|^2 / 2\sigma^2\} \rightarrow \gamma / \bar{\gamma}$  and using the PDF of Rayleigh fading distribution in terms of  $\gamma$ ,

$P_b$  can written as

$$P_b = \frac{1}{\pi 2^{N-1}} \sum_{k=0}^{2^{N-2}-1} \int_0^{2\pi} \left\{ \int_0^\infty \exp \left( -\frac{\gamma (\Im[\text{IS}(0,0)] - z_k)^2}{\bar{\gamma} (1 + (a_k / 2\sigma^2)) \sin^2 \theta} \right) p_\gamma(\gamma) d\gamma \right. \\ \left. + \int_0^\infty \exp \left( -\frac{\gamma (\Im[\text{IS}(0,0)] + z_k)^2}{\bar{\gamma} (1 + (a_k / 2\sigma^2)) \sin^2 \theta} \right) p_\gamma(\gamma) d\gamma \right\} d\theta \quad (6.6.39)$$

Solving equation (6.7.39) by the moment generating function for the Rayleigh fading channel and multiplying  $\gamma$  in the numerator and denominator,  $P_b$  can be obtained as

$$P_b = \frac{1}{2} - \frac{1}{2^N} \sum_{k=1}^{2^{N-2}} \left( \sqrt{\frac{\gamma 2\sigma^2 (\Im[\text{IS}(0,0)] - z_k)^2}{1 + \gamma \{2\sigma^2 (\Im[\text{IS}(0,0)] - z_k)^2 + a_k\}}} \right. \\ \left. + \sqrt{\frac{\gamma 2\sigma^2 (\Im[\text{IS}(0,0)] + z_k)^2}{1 + \gamma \{2\sigma^2 (\Im[\text{IS}(0,0)] + z_k)^2 + a_k\}}} \right) \quad (6.6.40)$$

Since

$$\text{IS}(0,0) = \frac{1}{N} \sum_{n=0}^{N-1} e^{j2\pi \epsilon n / N} \times \sum_{m=-Ng}^{N-1} e^{-j(m^2 - n^2) T_s^2 \cot \alpha / 2} \quad (6.6.41)$$

By putting (6.7.41) in (6.7.40);

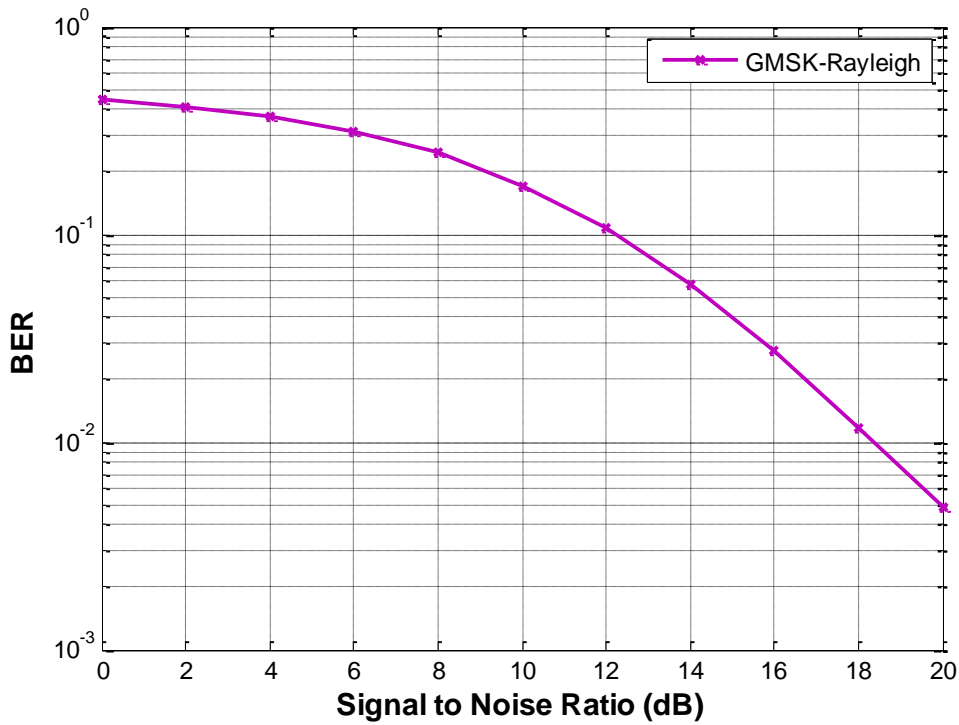
$$P_b = \frac{1}{2} - \frac{1}{2^N} \sum_{k=1}^{2^{N-2}} \left( \sqrt{\frac{\gamma 2\sigma^2 \left( \Im \left[ \frac{1}{N} \sum_{n=0}^{N-1} e^{j2\pi cn/N} \times \sum_{m=-Ng}^{N-1} e^{-j(m^2-n^2)T_s^2 \cot\alpha/2} \right] - z_k \right)^2}{1 + \gamma \left\{ 2\sigma^2 \left( \Im \left[ \frac{1}{N} \sum_{n=0}^{N-1} e^{j2\pi cn/N} \times \sum_{m=-Ng}^{N-1} e^{-j(m^2-n^2)T_s^2 \cot\alpha/2} \right] - z_k \right)^2 + a_k \right\}}} + \sqrt{\frac{\gamma 2\sigma^2 \left( \Im \left[ \frac{1}{N} \sum_{n=0}^{N-1} e^{j2\pi cn/N} \times \sum_{m=-Ng}^{N-1} e^{-j(m^2-n^2)T_s^2 \cot\alpha/2} \right] + z_k \right)^2}{1 + \gamma \left\{ 2\sigma^2 \left( \Im \left[ \frac{1}{N} \sum_{n=0}^{N-1} e^{j2\pi cn/N} \times \sum_{m=-Ng}^{N-1} e^{-j(m^2-n^2)T_s^2 \cot\alpha/2} \right] + z_k \right)^2 + a_k \right\}}} \right) \quad (6.6.42)$$

$P_b$  given in equation (6.7.42) is the final probability of bit error rate given by proposed OFDM system with GMSK modulation technique under wireless fading channels with carrier frequency offset.

## 6.7 THEORETICAL AND SIMULATION RESULTS

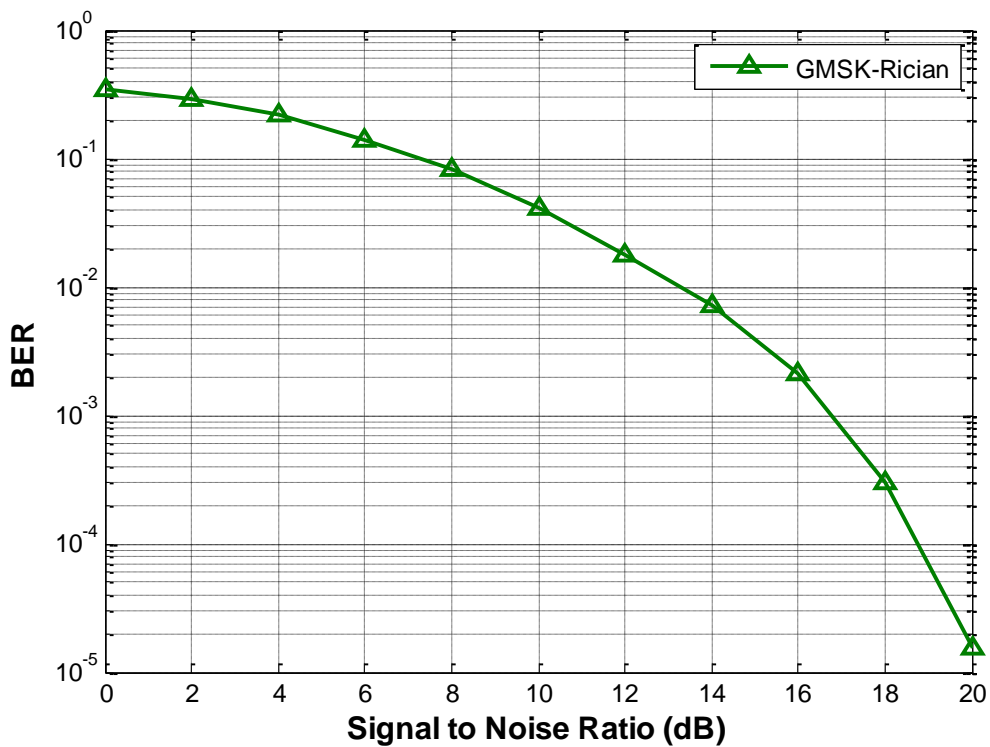
In this section BER performance of GMSK modulation based FrFT- OFDM system had evaluated under Rayleigh and Rician fading channel with CFO. For simulation, the number of sub carriers used is 8 with CFO of 0.1 under Rayleigh and Rician fading channel. In addition, the theoretical results had been obtained with 100 randomly chosen GMSK modulated signals for given FrFT and FFT based OFDM system.

In Figure 6.4 the BER vs. SNR of GMSK modulation technique is shown under Rayleigh channel.



**Figure 6-4: BER vs. SNR of only GMSK modulation under Rayleigh channel.**

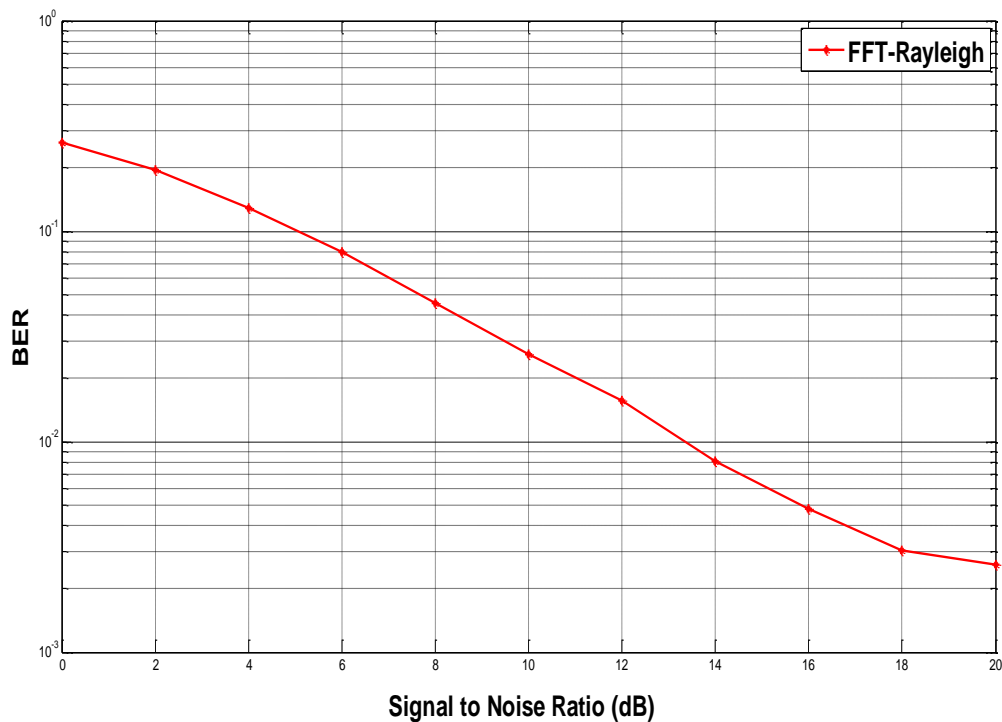
In Figure 6.4, the GMSK modulator is able to achieve SNR of 20 dB at  $10^{-2.65}$ . The performance of GMSK modulator is measured under Rician fading channel. Figure 6.5 shown gives the BER vs. SNR of GMSK modulator under Rician channel



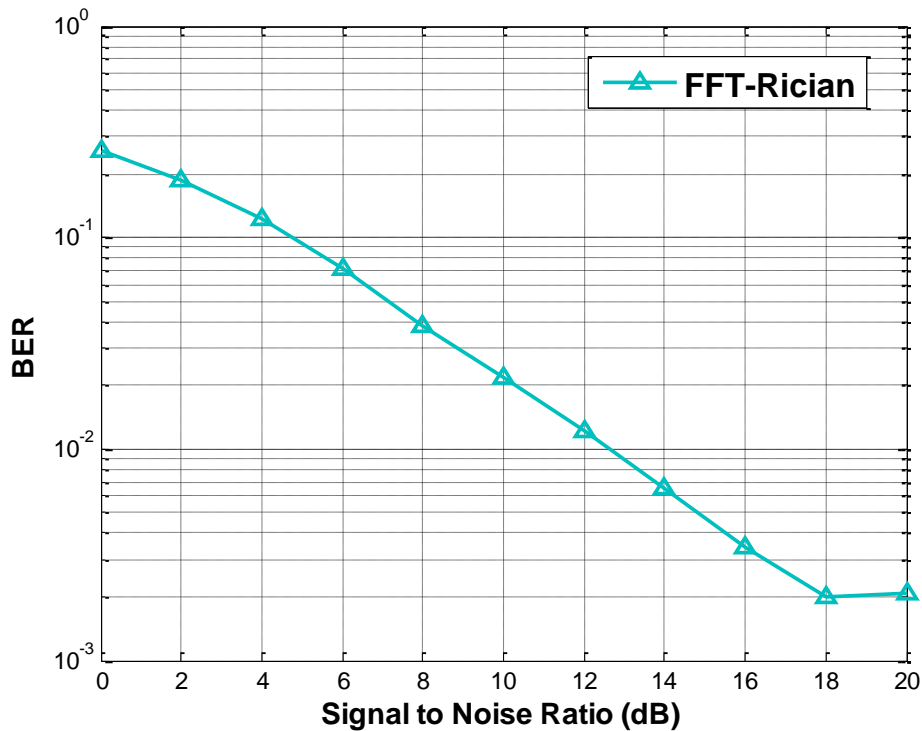
**Figure 6-5: BER vs. SNR of only GMSK modulation under Rician channel**

The BER vs. SNR of GMSK modulator under Rician channel has been shown in Figure 6.5. The said system under Rician channel is able to achieve the SNR of 20 dB at BER of  $10^{-4.95}$ . The results shown in Figure 6.4 and 6.5 shows that due to presence of line of sight component in Rician channel, the GMSK modulator performed much better as compared to Rayleigh channel.

Further, the performance of original FFT based OFDM system is analyzed with GMSK modulation under Rayleigh and Rician fading channel with carrier frequency offset of 0.1. The results of said system are shown in Figure 6.6 and 6.7 for Rayleigh and Rician fading channel respectively.



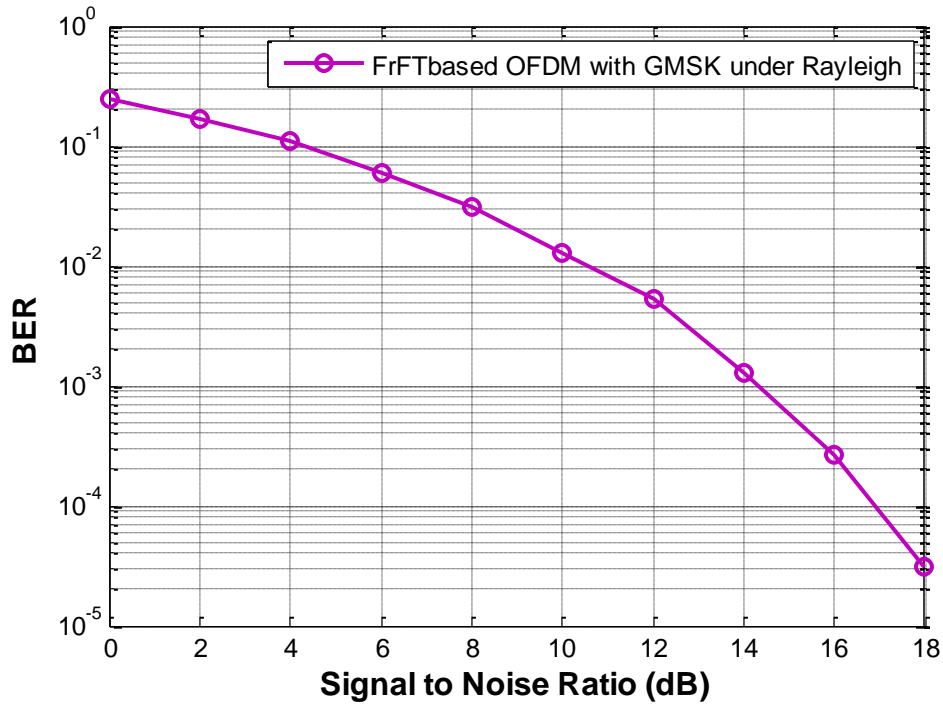
**Figure 6-6: BER vs. SNR of FFT based OFDM with GMSK modulation under Rayleigh Channel.**



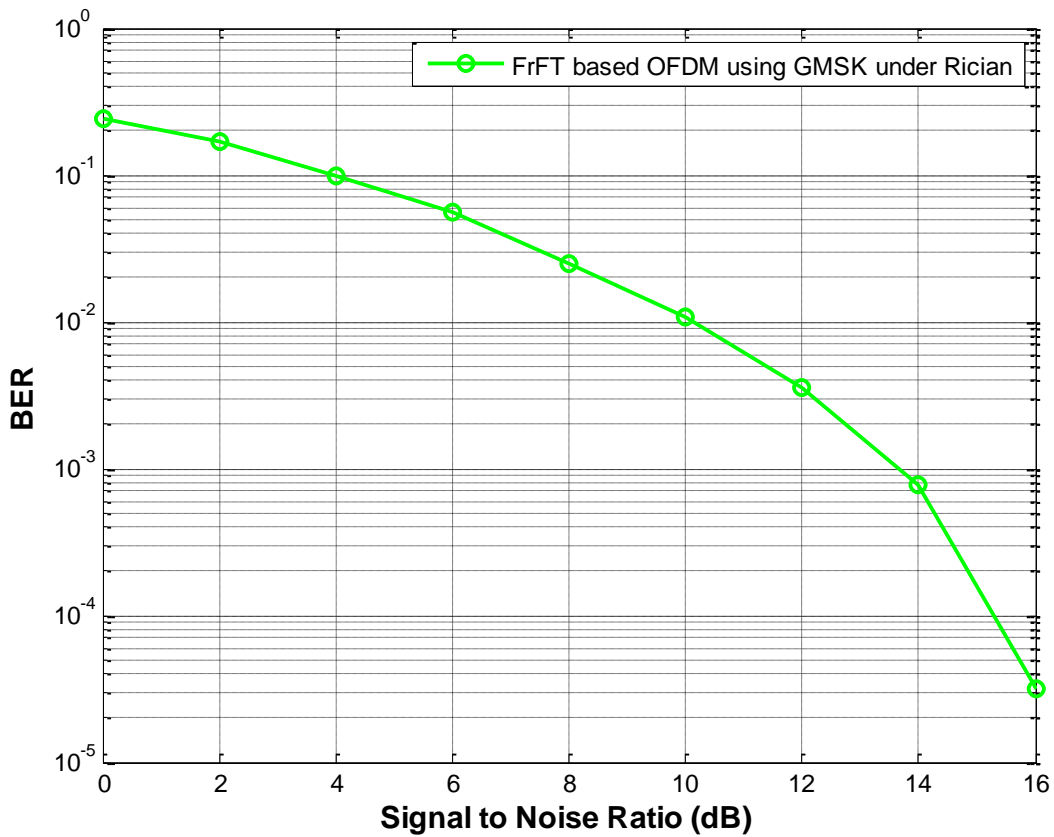
**Figure 6-7: BER vs. SNR of FFT based OFDM with GMSK modulation under Rician Channel.**

Figures 6.6 and 6.7 show the performance of traditional FFT based OFDM system with GMSK modulation systems outperforms as compared to GMSK modulator for both Rayleigh and Rician channel. However, there is not much change in the performance of FFT based OFDM system with GMSK modulation under Rayleigh and Rician channel as was the case for only GMSK modulator. Only marginal improvement is observed in the case of Rician channel as compared to Rayleigh channel.

Now the performance of FrFT based OFDM system with GMSK modulation is analysed for optimum value of fractional variable  $\alpha = 0.9$ . Figures 6.8 and 6.9 give the results achieved for proposed system under Rayleigh and Rician channel respectively.



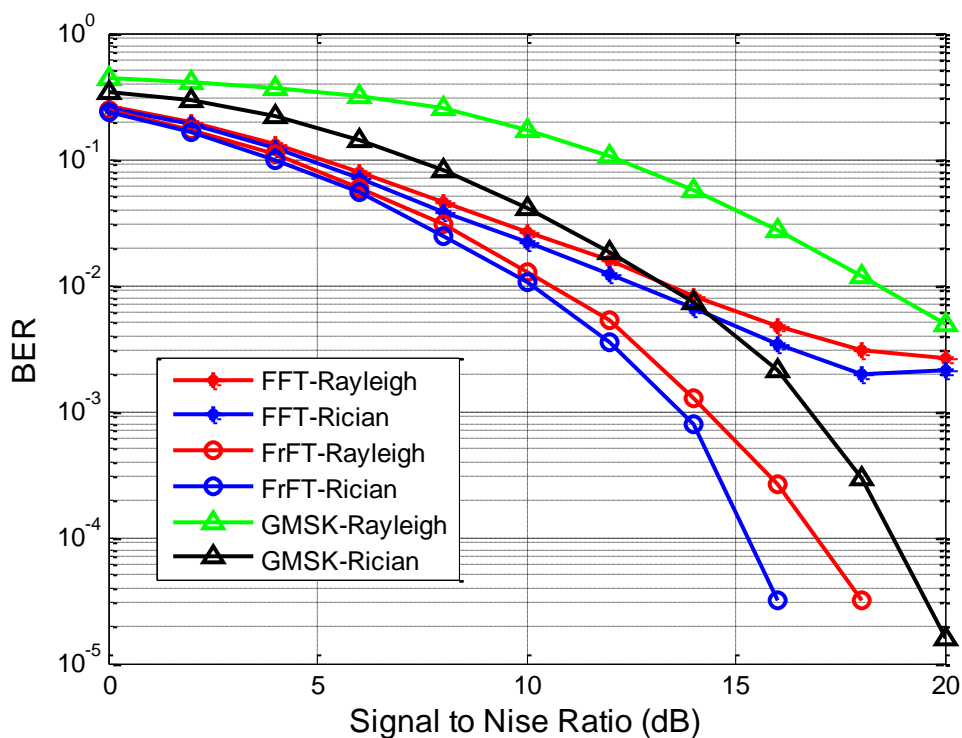
**Figure 6-8: BER vs. SNR of FrFT based OFDM with GMSK modulation under Rayleigh Channel.**



**Figure 6-9: BER vs. SNR of FrFT based OFDM with GMSK modulation under Rician Channel.**

The results achieved for FrFT based OFDM under both channels for GMSK modulation presented in Figures 6.8 and 6.9 have shown that the proposed system outperforms traditional FFT based OFDM system under similar conditions. The FrFT based OFDM with GMSK modulation under Rayleigh channel is able to achieve the SNR of 18 dB at BER of  $10^{-2.8}$  whereas, same model under Rician channel is able to achieve the SNR of 16 dB at same BER. Hence, the FrFT based OFDM system under Rician channel performs even better than under Rayleigh channel for similar conditions.

Figure 6.10 shown gives the combined results of proposed system under all the conditioned for easy comparison.

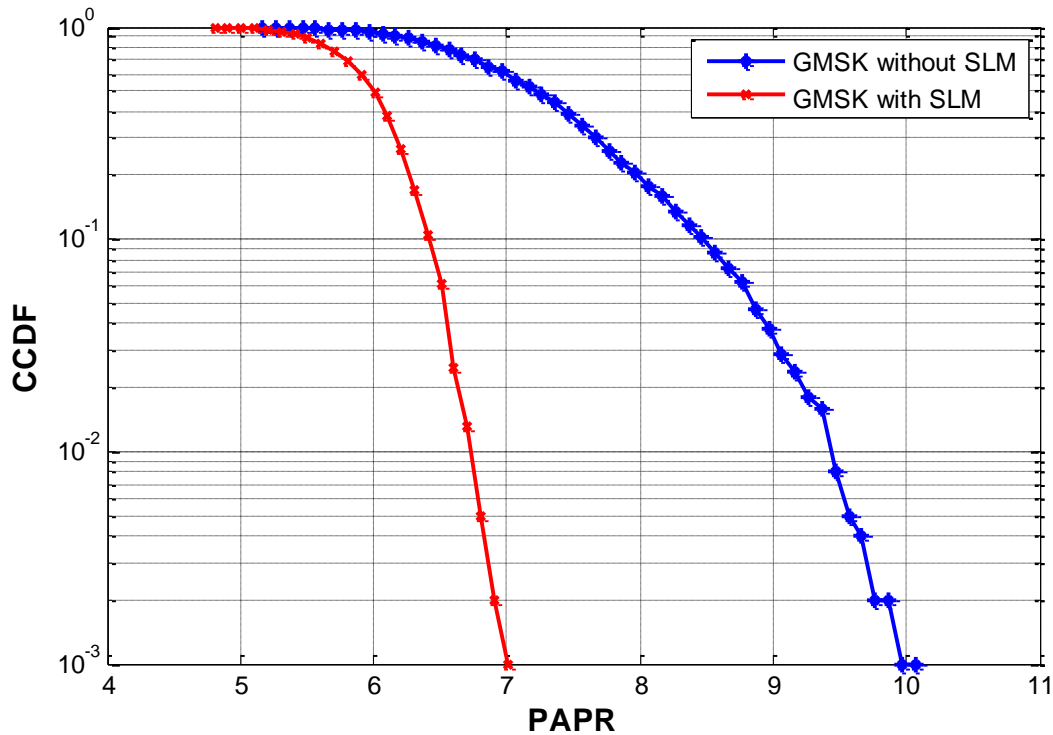


**Figure 6-10: Combined BER vs. SNR of GMSK modulator, FFT based OFDM and FrFT based OFDM with GMSK modulation under Rayleigh and Rician Channel.**

Figure 6.10 shows the combined results of BER vs. SNR of OFDM system using FFT and FrFT under Rayleigh and Rician channels. It could be deduced from results shown in Figure 6.10 that FrFT based OFDM system using GMSK modulation under Rician channel outperforms and gives minimum BER for given SNR as compared to FrFT based OFDM under Rayleigh channel as well as FFT based OFDM system under both channels. The proposed FrFT based OFDM system had achieved a BER of  $10^{-4.8}$  at 16 dB SNR under Rician channel, as compared to  $10^{-2.8}$  BER at same SNR for FFT based OFDM system with optimum value of ' $\alpha$ ' under Rician channel with CFO = 0.1. Further, under Rayleigh

channel, the proposed system achieved the  $10^{-4.8}$  BER at 18 dB SNR whereas, FFT based OFDM system achieved the same SNR at  $10^{-2.8}$  BER. Hence, it is concluded that the proposed FrFT based OFDM system behaves better than the FFT based OFDM system for GMSK modulation.

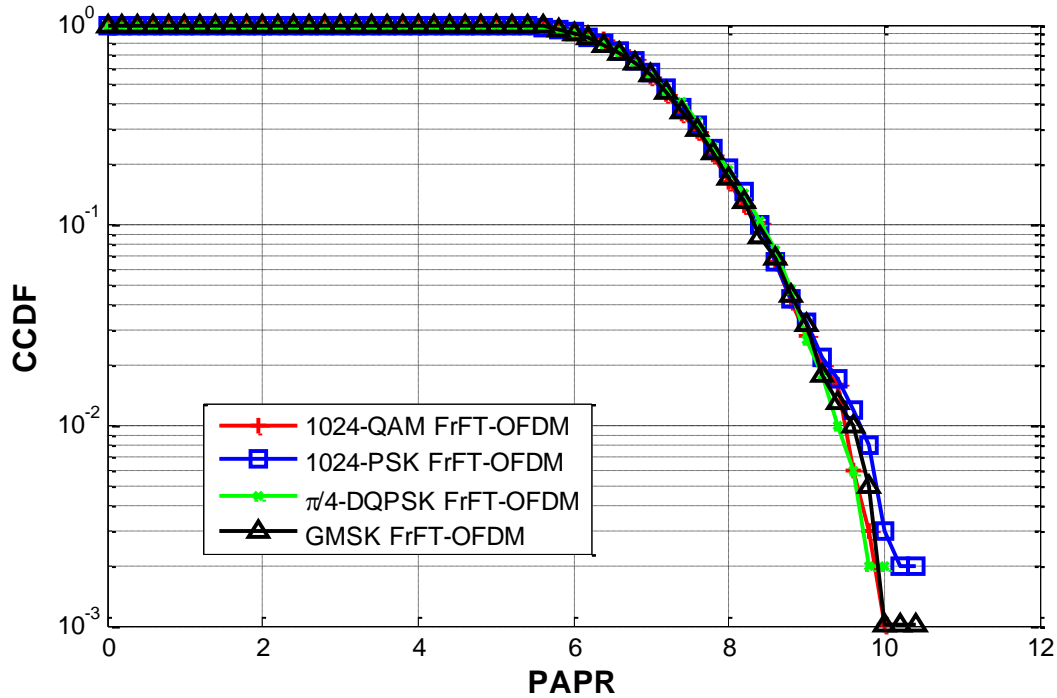
In Figure 6.11, the PAPR analysis of GMSK based FrFT based OFDM is done with and without SLM clipping technique.



**Figure 6.11: CCDF of PAPR for GMSK modulation based FrFT based OFDM with and without SLM clipping technique**

In GMSK based FrFT based OFDM the PAPR has shown improvement with SLM as compared to when PAPR is measured without clipping technique. From Figure 4.13, it can be observed that the FrFT based OFDM system using GMSK modulation had been able to save approximately 3.2 dB of PAPR with SLM clipping technique as compared to without SLM technique for same modulation technique at CCDF of  $10^{-3.0}$ .

Finally, the combined CCDF vs. PAPR graph for proposed FrFT based OFDM with different types of modulation techniques discussed above with SLM clipping technique has been shown in Figure 6.12.



**Figure 6.12: Combined CCDF vs. PAPR for FrFT based OFDM with 1024-PSK, 1024-QAM, GMSK and  $\pi/4$  DQPSK modulation techniques**

From Figure 6.12 it could be depicted that the PAPR of FrFT based OFDM improved significantly with the use of SLM clipping technique and reduced from 11 dB to 6.8 dB approximately. But the PAPR of proposed FrFT based OFDM system remains almost same for all the types of modulation techniques used here for analysis.

Hence, it can be said that the proposed model of FrFT based OFDM system has been able to give improvement in BER as well as PAPR that too under the influence of carrier frequency offset of 0.1 for wireless fading channels.

## 6.8 SUMMARY

In this chapter, a novel GMSK based FrFT- OFDM system is proposed for 4G. Its performance is compared with FFT based OFDM system. The GMSK modulation technique is selected because already 2G and 2.5G systems are using the same modulation. The problem of ISI and moderate spectral efficiency of GMSK have been dealt with considerably in this chapter by proposing the same modulation technique with FrFT based OFDM system. The results show an improvement of approximately 5.4 dB in SNR at  $10^{-2.8}$  in FrFT based OFDM system as compared to FFT based OFDM system at the optimum value of  $\alpha=0.9$  with carrier offset of 0.1 under Rayleigh fading channel. Under Rician channel the results

achieved had shown an improvement of approximately 5.8 dB in SNR at  $10^{-2.8}$  in FrFT based OFDM system as compared with FFT based OFDM system at the optimum value of  $\alpha=0.9$  with carrier offset of 0.1.

GMSK modulation techniques is able to achieve improvement of 3.8 dB at CCDF of  $10^{-3.0}$  in FrFT based OFDM system as compared to without SLM clipping technique for same system under consideration.

### ***Contribution of Chapter***

*The use of GMSK modulation technique with FrFT based OFDM system is novelty of this chapter. As the GMSK modulation has shown tremendous benefits in the case of 2G and 2.5G systems, but existing literature does not shown the use of said modulation technique in the multicarrier communication system. This work has explored the use of GMSK modulation in the upcoming 4G systems. The final probability of BER  $P_b$  presented in **equation 6.7.42** is an addition to literature and simulated the proposed FrFT based OFDM system with GMSK modulation. The PAPR analysis of GMSK modulation with proposed system is also a new area explored which has not earlier been taken care of in the existing literature.*

# CHAPTER 7

## CONCLUSIONS

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*There are two modes of acquiring knowledge, namely, by reasoning and experience. Reasoning draws a conclusion and makes us grant the conclusion, but does not make the conclusion certain, nor does it remove doubt so that the mind may rest on the intuition of truth unless the mind discovers it by the path of experience.*

*Opus Majus*

The analytical and simulation studies reported in this thesis are utilized to draw a set of conclusions. In this chapter, conclusion and future scope of work is presented in the following sections.

### 7.1 CONCLUSION

This thesis work has mainly focused on the Improvement of FrFT appended OFDM system and FrFT based OFDM system in terms of enhanced security and BER using benefits of FrFT in the field of wireless communication. A new FrFT appended OFDM system is proposed in this research work. The addition of FrFT along with OFDM system enhanced the security in wireless communication. The rotation of time-frequency plain by the fractional variable ' $\alpha$ ' has encrypted the OFDM modulated signal before transmission. Now the signal can only be decrypted with the particular value of ' $\alpha$ ', which was used at transmitter. For all other values of ' $\alpha$ ', the proposed system gives output as noise. It is a new contribution towards already reported work. This FrFT appended system has not only added security, but also improved the BER of existing FFT based OFDM system. An improvement of as high as 1.9 dB in SNR had achieved with the 1024-PSK modulated OFDM system under Rayleigh channel and of 3.5 dB improvement in SNR for 1024-QAM modulated signal has been achieved under Nakagami channel for FrFT appended OFDM system as compared to the existing OFDM system.

Further, the performance analysis of FrFT based OFDM system under various wireless fading channels, namely AWGN, Rayleigh, Rician and Nakagami along with PAPR analysis with different modulation techniques was carried out. In this proposed model, the FFT and IFFT blocks were replaced by FrFT and IFrFT blocks respectively. Here, the 1024-PSK and 1024-QAM modulation techniques had considered with different values of ' $\alpha$ ' in the range of 0.0 to 1.0 for analyzing the BER performance of the proposed system. It is proved that the FrFT based OFDM system outperforms FFT based system under all wireless fading channels with both 1024-PSK and 1024-QAM modulation techniques. Simulation results proved that the FrFT based OFDM system behaves much better under Nakagami channel as compared to other wireless fading channels for both modulation techniques and achieved a lowest BER of  $10^{-3.0}$  as compared to other wireless fading channels.

Afterwards, the FrFT based OFDM system is proposed using  $\pi/4$  DQPSK modulation technique. The mathematical analysis of FFT based OFDM system and FrFT based OFDM system has been presented for said modulation technique, which is addition in literature. The exact BER of proposed model is derived with said modulation technique under Rayleigh fading channel with CFO. The theoretically calculated BER was then compared with simulated results. The simulated results for different values of ' $\alpha$ ' are presented and are compared with existing FFT based OFDM system under similar conditions. The combined results of all modulation techniques proved that the FrFT based OFDM system with  $\pi/4$  DQPSK modulation technique outperforms FFT based OFDM system and gives best result at optimum ' $\alpha$ '.

Next, a novel GMSK modulated FrFT based OFDM system is proposed for 4G. Its performance is compared with FFT based OFDM system. The problem of ISI and moderate spectral efficiency of GMSK have been dealt with considerably in this research work by proposing it with FrFT based OFDM system. The results achieved had shown an improvement of approximately 5.4 dB in SNR at  $10^{-2.8}$  in FrFT based OFDM system as compared with FFT based OFDM system at the optimum value of ' $\alpha$ ' with carrier offset of 0.1 under the Rayleigh fading channel.

Finally, the major problem of PAPR in OFDM system is discussed in this chapter using the SLM clipping technique for different modulation techniques namely 1024-PSK, 1024-QAM, GMSK and  $\pi/4$  DQPSK. GMSK and  $\pi/4$  DQPSK modulation techniques has able to achieve improvement of 3.2 dB and 3.8 dB respectively at CCDF of  $10^{-3.0}$  in FrFT based

OFDM system as compared to without SLM clipping technique for the same system under consideration. The best improvement of 4.3 dB at CCDF of  $10^{-3.0}$  in PAPR is achieved by 1024-PSK based FrFT based OFDM system.

*“The OFDM modulated signal can be demodulated more precisely by using FrFT. Also FrFT helped in encrypting the signal and enhanced the security of signal in the wireless domain. Improvement in BER vs. SNR, ICI cancellation and PAPR are the major advantages of FrFT based OFDM”.*

## **7.2 FUTURE SCOPE OF WORK**

In this thesis, the deficits of traditional OFDM systems have been dealt efficiently by proposing FrFT based OFDM system. The system performance could further be enhanced by exploring the other fields of the proposed area. Henceforth, following are the ideas which can be explored in future:

- i. The behaviour of the channel is very random in nature. In this thesis, although the performance of the system is evaluated by considering the CFO introduced by the channel, other channel estimation techniques may be implemented along with proposed system to further enhance the system performance.
- ii. The current study totally concentrates on OFDM system. The efficiency of the system degrades under highly noisy channel. On the other hand, the performance of MIMO systems improves under noisy channel. Hence, the area of MIMO-OFDM system using FrFT can be explored in future.
- iii. The mechanism of ICI self cancellation techniques may be adapted for efficient recovery of transmitting signal along with CFO estimation.

Finally, the research could be preceded in the development of more efficient fractional transform for time-frequency components of wireless signal more accurately and precisely.

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