BER ANALYSIS FOR OFDM USING WINDOWING AND EQUALIZATION TECHNIQUES

A Dissertation submitted in the partial fulfilment of requirement for the award of degree of

Master of Engineering

In

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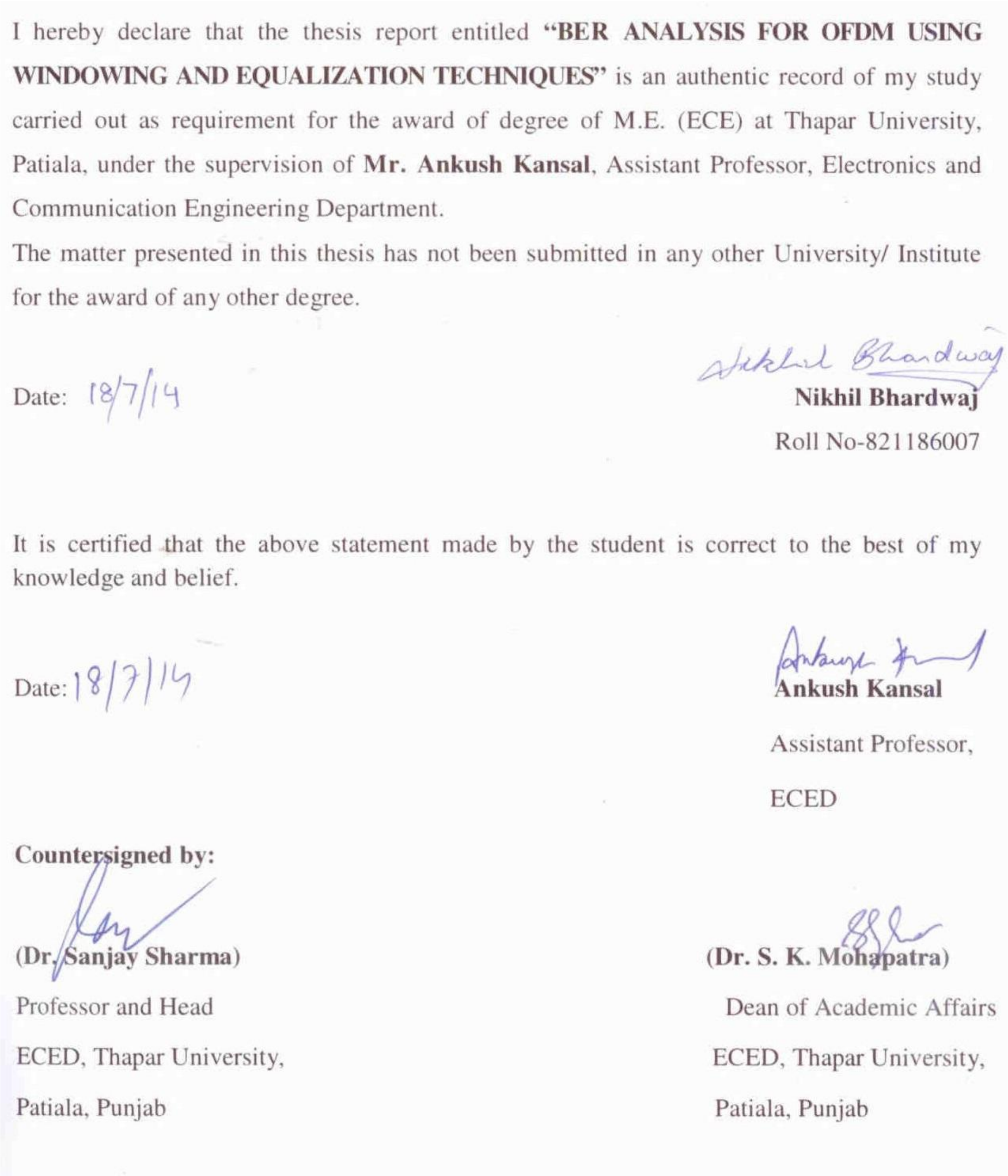
DEDICATION

This work is dedicated to my mentor **Dr. BHIMINDER SINGH**. Sir, your teachings are a treasure trove which would be a guiding force for me throughout my life.

CERTIFICATE



I hereby declare that the thesis report entitled **“BER ANALYSIS FOR OFDM USING WINDOWING AND EQUALIZATION TECHNIQUES”** is an authentic record of my study carried out as requirement for the award of degree of M.E. (ECE) at Thapar University, Patiala, under the supervision of **Mr. Ankush Kansal**, Assistant Professor, Electronics and Communication Engineering Department.

The matter presented in this thesis has not been submitted in any other University/ Institute for the award of any other degree.

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

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ABSTRACT

Wireless communications is emerging as the largest sectors of the telecommunications industry. Wireless communications system design is a very comprehensive field of study for the future. Its major challenges include increased spectral efficiency and improved link reliability. The radio channel which constitutes the propagation medium suffers from fading and interference from other users. A frequency selective fast time varying fading channel only can model such a hostile environment. It had established with studies that the multicarrier data transmission techniques such as the Orthogonal Frequency Division Multiplexing (OFDM) is best suited for such channels. The demand for high speed data services have been increasing, which is impossible to achieve by the conventional serial data transmission system without a trade-off between the data services and without the bandwidth of the system getting increased. OFDM can also be defined as a combination of modulation and multiplexing. In OFDM, ultimately the spectrum has to be shared with different sub-carriers. The multiplexing, in OFDM is applied to independent signals but they are the subset of the one main signal. Multipath generates two types of interferences at the receiver. Frequency selective fading and Inter symbol interference (ISI). The attraction of OFDM is mainly due to how the system handles these effects. The flatness perceived by a narrow band channel overcomes frequency selective fading and modulating at a very low symbol rate, makes the symbols much longer than the channel impulse response, and diminishes the ISI. Insertion of an extra guard interval between consecutive OFDM symbols reduces the ISI even more. While, using powerful error correcting codes and time or frequency interleaving yields even more robustness against frequency selective fading. The SNR vs. BER performance of the OFDM improves significantly using windowing and equalization techniques. Windowing technique had used for reducing the spectral side-lobes of OFDM. A popular window usually used for this purpose is the Raised-Cosine Window, due to its tapered and smooth edges. When the window function is applied to an OFDM signal, the spectrum reduces at the edges. Some reduction effect also takes place at the middle of the band as well. Whereas the equalization nullified the effect of channel during transmission of OFDM signal. Equalization can be performed by several equalizers composed by a single-tap at each frequency of the received signal. In this thesis, by adding Raised Cosine (RC) Window along with Equalization function in OFDM system with 16-QAM modulation technique, at $10^{-2.9}$ Bit Error Rate (BER) an improvement of 5 dB had achieved in the SNR value for AWGN Channel as compared to traditional OFDM system had achieved. An improvement of 15dB

had achieved in the SNR value for Rayleigh Channel and an improvement of 24 dB had achieved in the SNR value for Rician Channel in the proposed OFDM system as compared to traditional OFDM system at $10^{-2.9}$ BER.

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INTRODUCTION

The information exchange between different destinations which are not otherwise not joined with the help of any electrical connection may be termed as wireless communication. The most common technology used to achieve this feat is the radio. It facilitates communication between a myriad of devices including cellular phones, two-way radios, PDAs etc. Radio communication is also utilized in computer peripherals, electronic devices, satellite television sets, cordless phones etc. Wireless operations allow us the luxury of long-range communications, which are down-right impossible to achieve with the use of wired conductors. Thus, information is transferred over both short and long distances using electromagnetic energy or radio waves. The common use of word wireless communications was used to refer to the radio, but now the term is used in a more liberal fashion to describe wireless communication devices and networks. Any operation that involves a transfer of data from one source to a destination without the use of and wired conductor may refer to as wireless communications. Wireless communication is the industry which is often attributed with being able to grow very fast and thus capture the awe of humans, which explains an explosion in research and development in this field which has been the driver for new communication products and services which are being launched into the market with great rapidity. Exponential growth has been experienced by the followers of this field. Wireless communications industry has become a true driver of growth in businesses and by extension it has become an indispensable part of our lives. Also, wireless LANs have started to supplement or completely replace wired networks in many homes, businesses and campuses. New wireless applications are constantly emerging from research ideas to practical applications with an impressive rapidity [1].

The third generation (3G), a series of specifications of cell phone data standards, had promised broadband internet speeds delivered straight to our mobile internet communications devices. It is substantially faster than the 2G and 2.5G systems that it replaced (GPRS and EDGE). But it also carries with it a number of disadvantages for the average consumer. The cost of setting up cellular infrastructure, i.e. upgrading the base stations is high, together with the need for common user to purchase a different handset. It has high power consumption requirements. Also, 3G also poses connection problems in certain areas thus forcing the companies to install BTS towers in close proximity to each other, further pushing the cost of setting up a 3G communication system. But most importantly, its services are unable to provide a very big dynamic range of data rates, nor can it meet the expectations and requirements of a variety of industry uses with its voice transportation still relying on the same method as is used in second-generation (2G) communication systems, i.e. circuit-switching. Therefore, based on the above mentioned considerations there was a need to extend the feature characteristics of 3G standard. Thus we came up with the fourth generation (4G) mobile telecommunications technology. Moreover the 4G technology is also a benefactor of mobile broadband internet services. This is of great utility for mobile communication devices including laptops, phones etc [2].

The fourth generation (4G) communication standard depends upon a network which is packet switched and belongs to an all IP category. It has very high rates of data transfer which further facilitate high mobility. It dynamically shares and implements the resources of the provided networks for supporting many more connections. It has high system spectral efficiency and it incorporates handovers that are seamless across different types of networks and offers very high quality of service for different types of data that are to be transferred.

IMT Advances, the standard for 4G uses OFDM as one of the strongest way to achieve data rates upto 1Gbps for low mobile applications and 100Mbps for highly mobile applications. OFDM has been considered as the standard multiplexing technique for the present day 4G technologies. OFDM is a digital multicarrier FDM or modulation scheme for high speed communication. Due to its superior performance, OFDM has therefore been adopted. It promises to become a much significant high speed wireless communication technology.

1.1 Wireless Communications

Wireless communications may be defined as the transfer of data between two locations which are not connected with the help of any wired media. The communication process may take place over a very long distance. Wireless form of communication encompasses both fixed and mobile devices which have many applications in the real world. These applications may include being able to communicate with someone present at a certain distance or to be able to communicate with an electronic device to achieve certain function. Our daily lives have become a lot better with the advent of communication technology and the high level of penetration of communication equipment in our lives, be it in our offices or our homes. Wireless communication has made our lives simple to lead. The present day technology of Global Positioning System is also another example of the usefulness of the technology. Now, the impracticality of setting up wires between so many different locations on earth, many of which have very hostile terrain has led to an explosion in the research and development activities of the wireless field and the implementation of Wireless operations thus permit us to set up communication between different points where otherwise communication would have been impossible [3].

1.2 Principles of Wireless Communication

Wireless communications begins with some data which is either an analog signal that is produced by humans i.e. a voice signal or heart beats which is also a form of a signal etc. This signal is converted from its physical form to an electronic form. This is achieved with the help of a device called a transducer. The transducer thereafter feeds this electrical analog of the signal to the communication equipment for further processing and transmission processes. The result is either an analog signal that is modulated over a high frequency or a high amplitude signal or a digital signal which after being encoded for encryption and security is digitally modulated for further transfer.

At the receiving end there are receivers which perform the reverse function as was done at the transmitter stage. The demodulation process along with decoding etc. which results in the original signal being detected once again. Wireless communication takes place through a channel. the channel is a part of the communication system that affects the signal most.

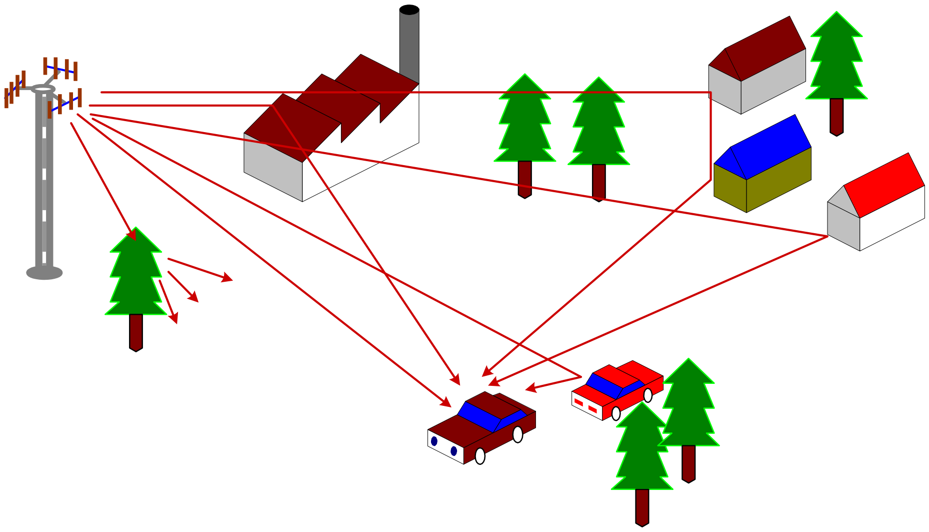

Figure 1.1: Multipath Wireless Channel

In the analysis of communication systems, we model our channels and incorporate the results of these channel models in our communication equipment so as to counter the effect of the fading which occurs in that stage of the communication system. Figure 1.1 shows a pictorial representation of Multipath channel that is encountered in general by all wireless communication equipments.

1.3 Motivation

In today's connected world multimedia has origins in computing, communications, entertainment; journalism etc. new applications are emerging daily. The days of low bit-rate data services are almost nearing their end. And high speed data transfer is the latest fad in the communications industry. To achieve wireless communications, the designers have to design equipment that counters the harsh radio environment. Reflections and refractions form a few of the pitfalls that a designer must keep in mind while designing communication equipment for use by the general public. The power requirement of the product and the environment at large in which the communication device is to be operating has to be kept in mind by the designers.

Complex equalizers can counter the effects of fading channels but at great cost to the consumer. Instead, a multi-carrier modulation technique called the Orthogonal Frequency Division Multiplexing (OFDM) which is a robust technique providing high spectral efficiency, robustness against multi-path channel and fading that occurs. Many modifications to the OFDM technique have been implemented for adjusting delay spreads of the carriers. The cyclic prefix length can also be varied so as to counter this effect. It provides a way for different users to utilize the same channel simultaneously thus allowing simultaneous communication by different users and hence the efficient utilization of the channel.

The problems that are encountered while utilizing this technique for communication are:

- Dispersion of tie leading to ISI.
- High power requirement.
- Multi-path fading effect.
- Spectral efficiency issues.

Now, in a typical environment, the signal that is transmitted arrives at the receiver travelling through different paths of various lengths. These versions of signal might interfere thus making it a nightmare for the designer of the receiving systems to extract the information that was originally transmitted. The use of Orthogonal Frequency Division Multiplexing provides an answer for addressing such communication issues.

1.4 Single Carrier vs. Multicarrier Communication

The technique for communication called the Single-carrier communication technique uses one sine wave. But the multi-carrier communication technique uses several sine waves. The single carrier communication techniques modify any one parameter i.e. phase, frequency or amplitude – of the sine wave according to the information that is to be transmitted. Accordingly, they are called shift-keying of phase, frequency or amplitude. The basic single carrier communication takes a beating when it comes to the fading channel which selectively fades different frequency components of the signal [4]. Thus, multicarrier communication comes in the picture. Now, equalizers can counter the fading effect of the channel, but in a deep-fade scenario, the best equalizers can fail as they enhance the noise that is affecting the signal as well.

Then came the proposal to counter this weakness through the use of parallel data modulation transmitters. Thus only the sub-channels that fell within the deep fade band of frequency used carriers. The FEC codes added an extra advantage in extracting the information successfully at the receiver. Figure 1.2 shows the sub channels using different carriers according to the fading encountered in the channels.

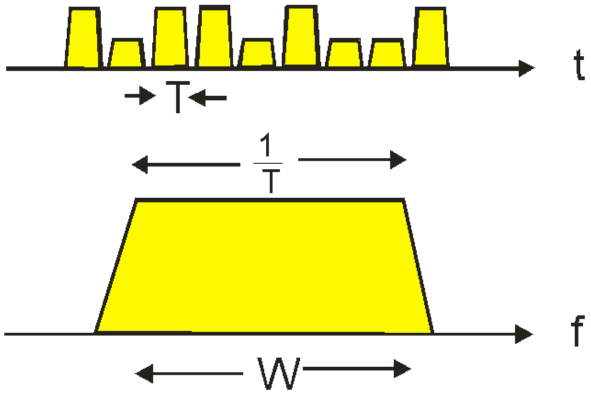

Figure 1.2: Single Carrier Communication System

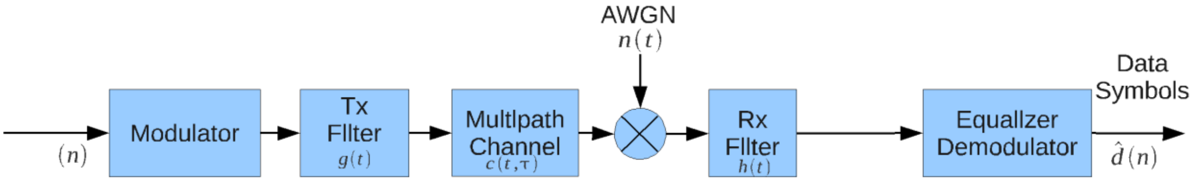

Figure 1.3: Block Diagram of Single Carrier Communication System

Figure 1.3 shows the block diagram of a single carrier communication system. Now, the multi-carrier communication splits the data in different components and sends them over their own separate carriers. The result is that the bandwidth of each carrier is now narrow thus creating equality between the frequency response of the sub-channels. This lower rate nearly helps to eliminate ISI due to longer symbol duration.

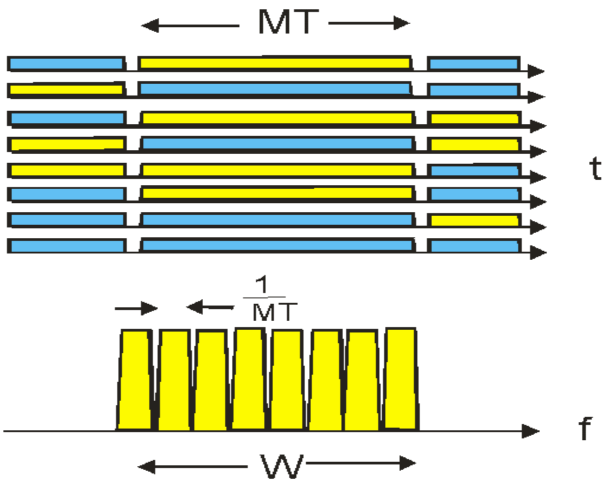

Figure 1.4: Multicarrier Communication System

Figure 1.4 shows that if the sub-channels are narrow enough, the channel frequency response is approximately constant with respect to each sub-channel. This makes equalization much less complicated than in the single carrier system. While the sub-channels can be chosen in any manner with respect to bandwidth, centre frequency, and guard interval, we next consider a special case in which sub-channel parameters allow for increased bandwidth efficiency (near Nyquist efficiency) and computationally efficient modulator and demodulator design.

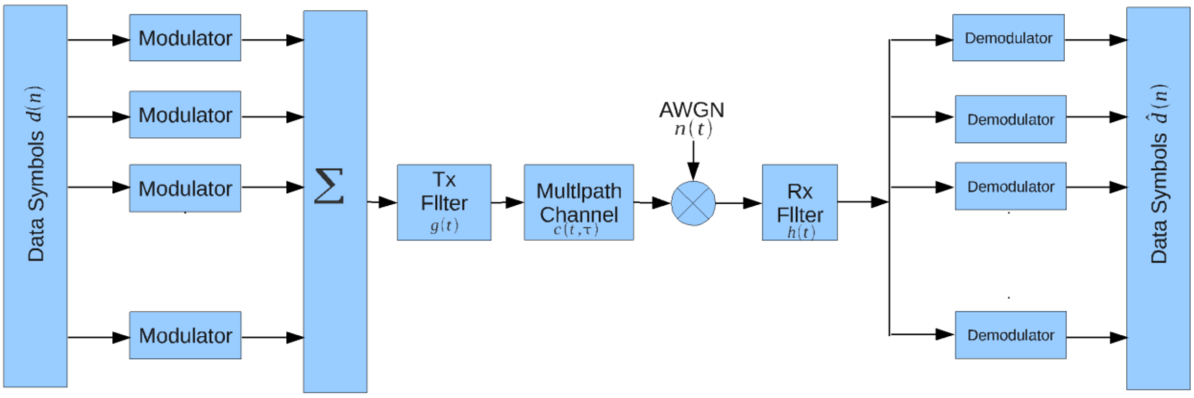

Figure 1.5: Block Diagram Of Multicarrier Communication System

The only limitation that merits consideration are the requirement for synchronization and a need for linear amplification.

1.5 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a technique to modulate and multiplex together. The signals used are those that are produced by different sources. Here we multiplex different signals which are in fact a sub-set of the one main signal. Modulation follows splitting of the signal into different channels and that is followed by multiplexing to create OFDM carrier. The users are separated in the frequency domain. The carriers, in order to maintain exclusivity are placed sufficiently apart [5]. Moreover, guard bands are to be provided between carriers thereby depleting spectral efficiency. Thus, we utilize the concept of orthogonality to increase the spectral efficiency of OFDM. The carriers or channels are orthogonal to each other. Thus even in a frequency selective channel the issue of ISI (Inter Symbol Interference) is thoroughly mitigated.

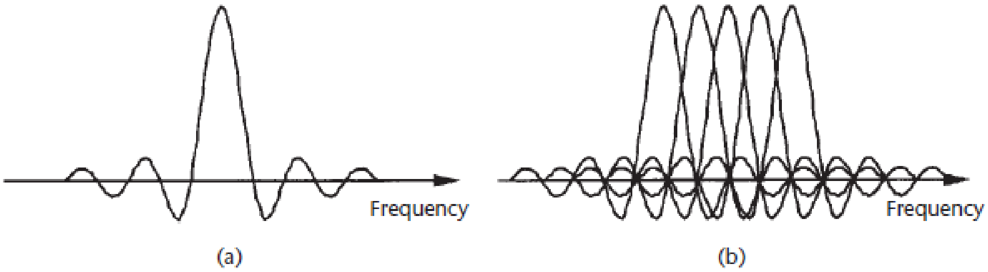

Figure 1.6: OFDM Spectrum Showing Orthogonal Sub-Carriers

Thus even with the overlapped sub-channels the spectral requirements are minimal thus the transmission rate is increased. We can also use various coding techniques to further enhance the robustness of the system.

Inter Carrier Interference is another problem that is encountered by the OFDM mainly due to its sensitivity to carrier frequency offset. Orthogonality is one remedy that mitigates the problem of ICI.

1.5.1 Block Diagram

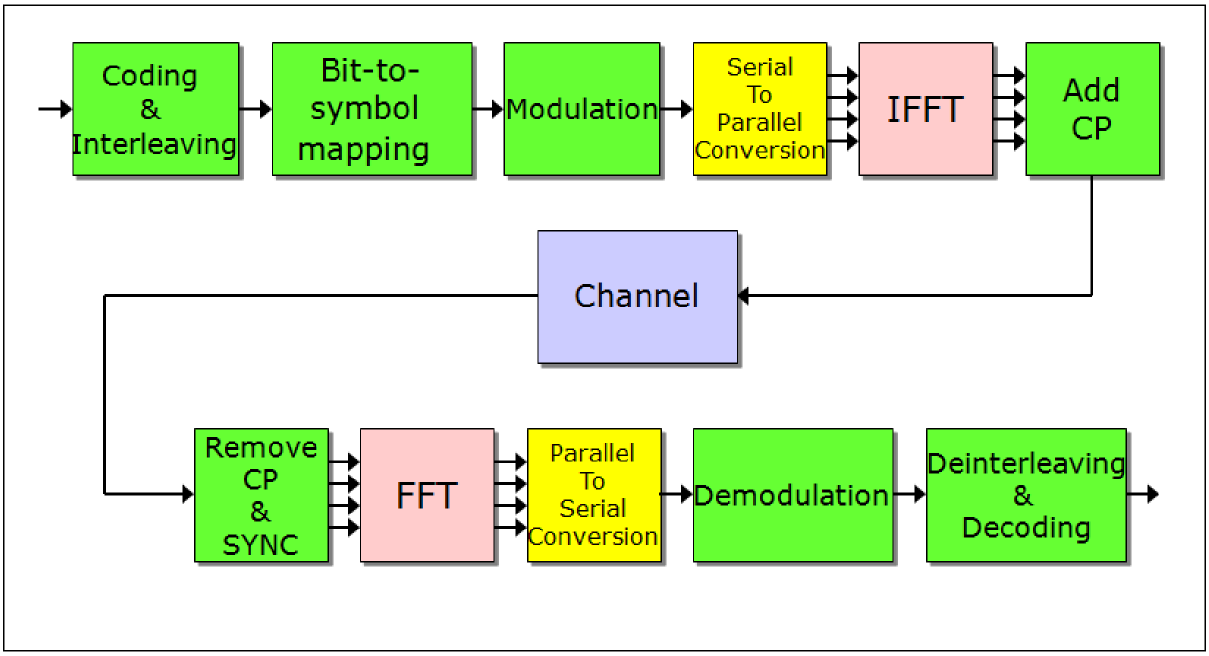

Figure 1.7: OFDM System Block Diagram

Source Encoder/Decoder

The information which is generally analog, is converted to binary. Padding occurs at this stage to create symbols to go with the scheme of modulation used. Receiver does the reverse operation to recover the information.

Channel Encoder/Decoder

Encoding is done for the channel which is based on its rate. Decoding does the reverse operation as is done at the transmitter.

Interleaving

Digital data transmission employs this to eliminate the burst error effects which effects decoding of the information. Thus interleaving is done before transmission thus decoding is done properly.

Mapping / Recovering Symbols

Based on the method of modulation grouping of bits is done to form symbols.

Modulation/Demodulation

Differential encoding of the data is done using PSK, QAM format etc.

Serial to Parallel Conversion

Each channel is then broken into sub-carriers, thus making optimal use of the frequency spectrum. The receiver performs the reverse operation to that of the transmitter.

IFFT/ FFT

After insertion of the pilots into the data symbols, the data is put through IFFT block, which maps the frequency domain data to time domain OFDM. The Fast Fourier Transformation (FFT) is used to convert data in time domain to the frequency domain at the receiver

Cyclic Prefix

It prefixes the symbol with a repetition of the end. It acts as a guard interval thus eliminating ISI.

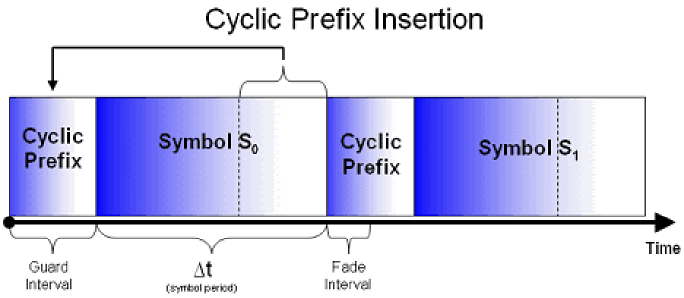

Figure 1.8: Cyclic Prefix

The length of the cyclic prefix should be equal to the length of the multipath channel for cyclic prefix to be effective.

Channel

A channel model is then applied to the transmitted signal. The model allows for the signal to noise ratio, multipath, and peak power clipping to be controlled.

1.5.2 Inter Symbol Interference (ISI)

Inter symbol interference (ISI) is a distortion of a signal in which the symbols interfere with each other. It is unwanted as the noise of the previous symbols makes the communication process less reliable. It usually occurs because of Multipath effects of the channel or its non-linearity. Adaptive equalization and FEC codes are few of the ways to fight ISI. In the present work use of pulse shaping or windowing is explored [6].

1.5.3 Inter Carrier Interference (ICI)

An impairment which arises generally from Carrier Frequency Offsets (CFO) or the Doppler spreads etc due to the sensitivity of the OFDM to the frequency between the sent or the received signal [7]. The CFO is the main cause of loss of orthogonality which thereby causes ICI. Many approaches have been suggested to counter this. Many new researches are being carried out in this field.

1.5.4 Peak to Average Power Ratio (PAPR)

PAPR is quite a serious problem which afflicts the multicarrier communication or OFDM. Due to this there are amplitude excursions which cause loss from the transmitted signal. Now OFDM system is just a complex sum of modulated sub-carriers. But sometimes vector addition takes place and they may cancel each other thus producing zero output or they may add in phase and the output produced might be very large. Thus linearity is maintained at the front end of the amplifier [8]. It is highly researched fields today to mitigate PAPR.

An OFDM Signal can be expressed as,

$$s(t)=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} S_k e^{j2\pi kt/NT}, \quad t\in\left[0,NT\right] \qquad \begin{cases} S_k \,□\, \text{Complex baseband modulated symbol} \\ N \,□\, \text{Number of subcarriers} \end{cases} \tag{1.1}$$

If the OFDM signal is sampled at $t=nT$, the complex samples can be described as,

$$s_n=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} S_k e^{j2\pi kn/N}, \quad n\in\left[0,N-1\right] \tag{1.2}$$

Let $\mathbf{s}^{(m)}$, be the m^{th} OFDM symbol, then its PAPR is defined as,

$$\mathrm{PAPR}_m = \frac{\left\|\mathbf{s}^{(m)}\right\|_{\infty}^{2}}{E\left[\left\|\mathbf{s}^{(m)}\right\|^{2}\right]\Big/N} \tag{1.3}$$

The CCDF of the PAPR of a non-oversampled OFDM signal is,

$$\Pr\left(\gamma > \gamma_0\right) = 1 - \left(1 - e^{-\gamma_0}\right)^{N} \tag{1.4}$$

CCDF of PAPR increases with the number of subcarriers in the OFDM system, i.e. the more subcarriers are used in an OFDM system worse will be the distortion caused by the nonlinearity.

1.6 Modulation Techniques for OFDM

We vary one or more properties of a signal to modulate it with a baseband signal. The baseband signal or the modulating signal is the one that contains the information or data that is intended to be sent. This is achieved with the help of a modulator. A demodulator does the reverse operation at the receiver location. The device that can perform both operations is a modem (modulator-demodulator).

In order to achieve good efficiency of the spectrum efficient techniques of modulation are put to use:

- Compact Power Density Spectrum
- Robust Communication.
- Desirable Envelope Properties.

Fundamental modulation techniques:

- PSK (phase-shift keying)
- FSK (frequency-shift keying)
- ASK (amplitude-shift keying)
- QAM (quadrature amplitude modulation)

In QAM modulation technique one in-phase signal (or I e.g. cosine wave) and a quadrature phase signal (or Q e.g. sine wave) are amplitude modulated with a finite number of amplitudes, and then summed. The system that results is a combination of the techniques ASK and PSK.

1.6.1 QAM Modulation Technique

The modulation scheme is both analog and digital. It has two carrier waves, out of phase with each other by 90° and are thus called quadrature components — hence the name of the scheme. The modulated waves are summed and the result is a sum of ASK and PSK. And for analog modulation a sum of PM and AM. For digital, a finite number of at least two phases and at least two amplitudes are used. PSK modulators are often designed using the QAM principle, but are not considered as QAM since the amplitude of the modulated carrier signal is constant. QAM is used extensively in the digital domain

QAM also conveys data by changing some aspect of a carrier signal, or the carrier wave, in response to a data signal. The amplitude of two waves, 90° out-of-phase with each other (in quadrature) are changed (modulated or keyed) to represent the data signal. The merit of QAM is that it is able to carry more information per symbol. By selecting still higher order format of QAM, there is an increase of the data rate. But they are not that resilient to noise and interference.

Constellation Diagrams for QAM

Different positions for the states are shown within different forms of QAM. With the increase in the order, the number of points on the QAM constellation diagram increases.

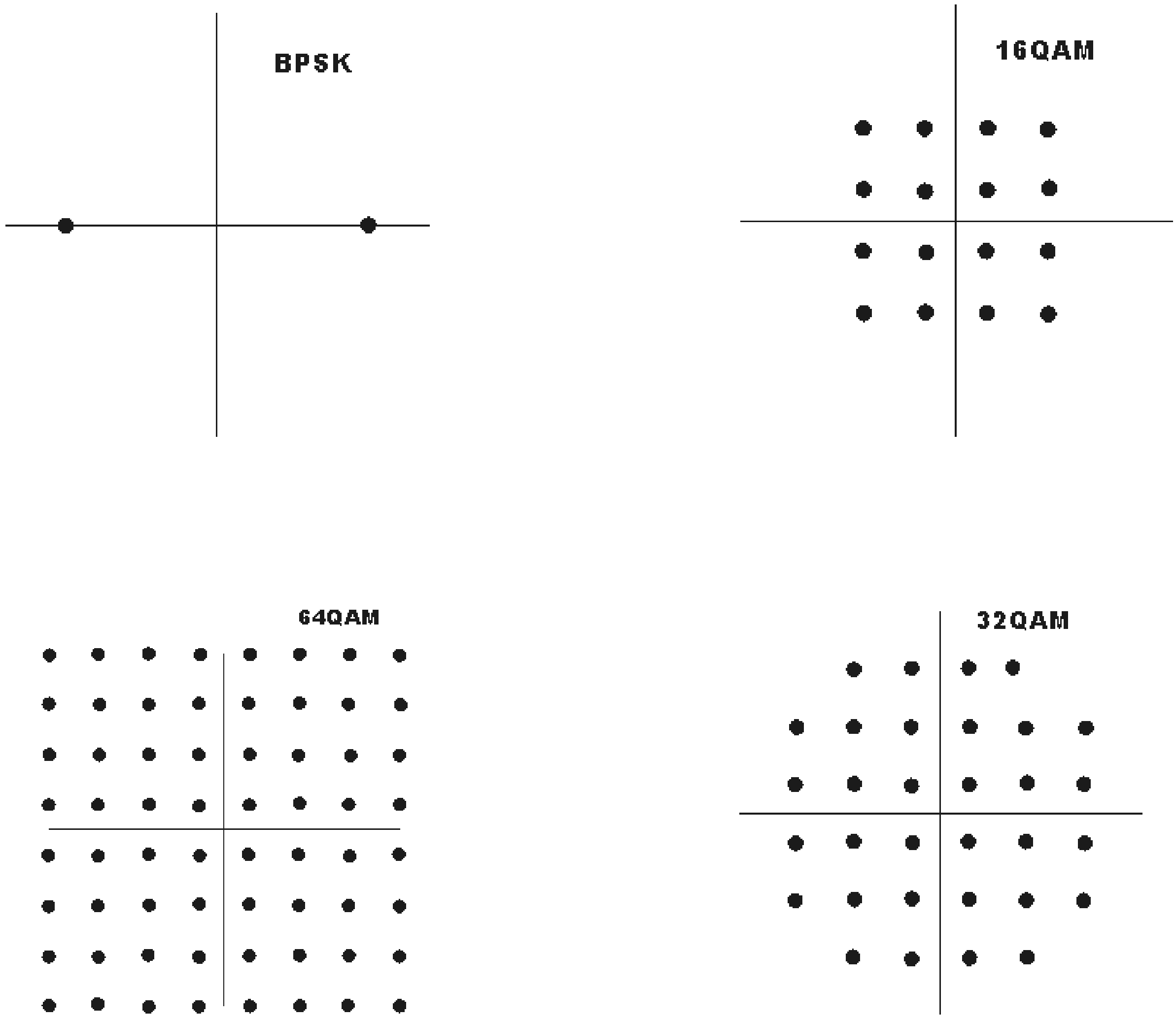

Figure 1.9: QAM Constellation Diagrams

1.6.2 Mathematical Analysis of QAM

When transmitting two signals by modulating them with QAM, the transmitted signal will be of the form:

$$s(t) = R\{[I(t) + iQ(t)]e^{i2\pi f_0 t} \qquad (1.5)$$

$$= I(t)\cos(2\pi f_0 t) - Q(t)\sin(2\pi f_0 t) \qquad (1.6)$$

where $i^2 = -1$, I(t), and Q(t) are the modulating signals, f_0 is the carrier frequency and R(0) is the real part.

At the receiver,

$$r(t) = s(t)\cos(2\pi f_0 t) \tag{1.7}$$

$$= I(t)\cos(2\pi f_0 t)\cos(2\pi f_0 t) - Q(t)\sin(2\pi f_0 t)\cos(2\pi f_0 t) \tag{1.8}$$

Rewriting:

$$r(t) = \frac{1}{2}I(t)[1 + \cos(4\pi f_0 t)] - \frac{1}{2}Q(t)\sin(4\pi f_0 t) \tag{1.9}$$

$$= \frac{1}{2}I(t)\ \frac{1}{2}I(t)\cos(4\pi f_0 t)] - Q(t)\sin(4\pi f_0 t) \tag{1.10}$$

In the frequency domain, QAM has a similar spectral pattern to DSB-SC modulation. Using the properties of the Fourier transform, we find that:

$$S(f) = \frac{1}{2}\ [M_I(f - f_0) + M_I(f - f_0) + \frac{1}{2}\ [M_Q(f - f_0) - M_Q(f + f_0)] \tag{1.11}$$

Where S(f), M_I(f) and M_Q(f) are the Fourier transforms (frequency-domain representations) of s(t), I(t) and Q(t), respectively.

The mapping of the bit blocks to the M-QAM symbols can have an effect on the bit-error rate. To minimize the bit-errors when a symbol error is present, Gray coding is employed. Gray coding is a means by which neighbouring symbols differ by only one bit, as seen in

Received signal,

$$r(t) = -x(t)\sin(2\pi fc\ t)$$

$$= -2\mathrm{Re}\{u(t)\}\sin(2\pi fct)\cos(2\pi fc\ t) + 2\mathrm{Im}\{u(t)\}\sin(2\pi fc\ t)\sin(2\pi fc\ t)$$

$$= -\mathrm{Re}\{u(t)\}\sin(4\pi fc\ t) - \mathrm{Im}\{u(t)\}[1 - \cos(4\pi fc\ t)]$$

$$= \mathrm{Im}\{u(t)\} - [\mathrm{Re}\{u(t)\}\sin(4\pi fc\ t) + \mathrm{Im}\{u(t)\}\cos(4\pi fc\ t)]\ . \tag{1.12}$$

1.7 General Channel Models

The path that separates the source from the destination be it wire line or wireless. These are the mathematical models or equations that elucidate the behaviour of the channel between the source and the destination [9]. If both the source and destination of the information are static, the channel is referred to as time-invariant. If both or any one of them are in motion then the channel is called time-variant e.g. cellular communication system.

The basic channel models may be classified as:

- AWGN
- Rayleigh
- Rician

The design engineer uses these models to validate the source and the destination or the transmitter or the receiver communication equipment. The design engineer considers various parameters such as delay, number of paths, terrain, Doppler frequency or speed while designing the channel models.

1.7.1 AWGN channel

A universal channel known as the Additive white Gaussian noise (AWGN) channel is used to analyse new schemes [10]. The channel in this model just adds a white Gaussian noise to the signal passing through it. In this channel no fading component exists. Being a theoretical channel it is only used for analytical purposes.

So, if $s(t)$ is transmitted symbol then the received symbol is given as:-

$$R(t) = s(t) + \eta(t) \tag{1.13}$$

Where $\eta(t)$ is the additive white Gaussian noise.

1.7.2 Rayleigh Channel

A statistical model, the Rayleigh fading channel is primarily used to represent the multi-path environment effect on the signal that is being transmitted. It occurs when a direct line of sight does not exist between the source and the receiver

So, if $s(t)$ is transmitted symbol then the received symbol is given as:-

$$R(t) = s(t) * h(t) + \eta(t) \tag{1.14}$$

Here $R(t)$ is distributed by using Rayleigh distribution function.

Where $\eta(t)$ is the Additive White Gaussian Noise (AWGN).

The fading of the signal when the signal passes through this channel occurs randomly or according to the Rayleigh fading. It reasonably simulates space wave communication or communication through urban environments.

1.7.3 Rician Channel

Again, statistical models just like the Rayleigh fading channel. It also models propagation that is multipath. It generally occurs when one of the signals received due to multipath is stronger or dominant as compared to the others. Rician distribution thus characterises the gain.

So, if $s(t)$ is transmitted symbol then the received symbol is given as:-

$$R(t) = s(t) * h(t) + \eta(t) \tag{1.15}$$

Here, received signal is distributed by Rician probability distribution function.

CHAPTER 2

LITERATURE REVIEW

Tareq Y. Al-Naffouri *et al.* [11] proposed an algorithm for estimating the channel and coefficients of interference for Multicarrier systems for mobile scenario. The main thoughts utilized by the authors for the development of this algorithm explore the correlation between the frequency and time. The matrices of circulant and Toeplitz are considered and discussed. More performance gains have been observed by authors while optimism of the sub-carrier group which is the pilot thus the performance being bought very close to perfection of CSI at overhead ratio training.

A structure for OFDM which is quite flexible is proposed with code for communication systems has been proposed by Yafei Hou *et al.*[12]. OFDM structure is introduced based on a IFFT property. Parallel combinatory code is combined along with the proposed flexible OFDM, the authors have designed such an arrangement with the transmission rate that is moderate. Better PAPR characteristics that have been so achieved promise good BER performance.

Ebrahim Saberinia *et al.* [13], used the model that is digital thence showing a multicarrier modulation signal that is pulsating. With upsampling after IFFT, the subcarriers reduce thus power is saved and complexity is also reduced. A different receiver structure was also proposed which had lower complexity.

Kitaek Bae *et al.* [14] studied selected mapping on multicarrier systems with nonlinear conditions over Gaussian channel. the distribution for the power was derived BER and TD were studied as functions. The accuracy of the proposed result was verified.

A time slicing technique for mobile multimedia communications was proposed by Xianbin Wang *et al.* [15] in which cyclic prefix was bettered with pn sequences that were pre-coded. Multiple data streams were able to be multiplexed, thus allowing the mobile units to conserve power. Thereby extending their operating life.

Akhilesh Chandra Yadav *et al.* [16] proposed a technique to compensate PAPR without affecting efficiency. Complexity is quite insignificant. Arbitrary number of sub-carriers are used. The OFDM symbols being independent, identically distributed Gaussian random variables. By applying the weighting coefficients, successive peaks were limited to the given threshold level. Through the window length vs. BER, it was found out that it is prohibited to increase the length of the window to a certain value due to degradation of performance.

Daniel Castanheira *et al.* [17] considered some designs involving windowed OFDM technique. Simple modification through a different windowing allows to limit out of band roll-off of the pulse. The combination of OFDM and windowing ensures no spill over of energy

An exact BER expression was discussed for windowing reception OFDM systems for Rayleigh fading channels in the presence of CFO by Norman C. Beaulieu *et al.* [18]. The effects of several Nyquist windows including the BTRC window, the raised-cosine window, the SOCW window, the Franks window was examined. Window designs founded on lowering ICI or maximizing SIR may not result in the pulse designs with the best BER performance in the fading channels.

Sungkeun Cha *et al.* [19] proposed an advanced peak windowing method as a PAPR reduction technique in OFDM systems. The proposed peak windowing method called APW, suppress peak values to desired threshold levels. New weighting coefficients were applied by the authors and the successive peaks were limited. Matrix inversion was introduced. In addition, through the simulation of window length vs. BER, it was shown that by increasing the window length the BER performance eventually degrades.

Alphan Sahin *et al.* [20] proposed a new windowing method for efficient spectral shaping in OFDM based systems. Raised-cosine windowing function was considered. In the proposed approach, windowing is heavily applied to the sub-carriers located at the edges of the band; shorter windowing sizes were applied for inner subcarriers. Instead of introducing additional windowing interval, in the proposed scheme, the windowing time is taken up from the cyclic extension size. Thus side-lobe suppression is achieved with spectral efficiency.

Smita Jolania *et al.* [21] showed that the PAPR is reduced in a big way with no change in the value of out-of-band power. The effect of different windows on the SER also came under the perview. The results signify that due to fading noise will not matter as far as the system's SER is concerned. Further system can be optimized according to the achieved results.

Md. Al-Mahadi Hasan *et al.* [22] used five different widely used window functions as the envelope of OFDM symbols and their relative performance in context of power of desired signal, power of ICI and SIR are discussed. As suggested by the authors that there is scope of incorporation of 'Raised Cosine Pulse' for the same analysis to observe whether its performance is better than or not as compared to the existing window functions. The authors only considered frequency offset and phase error as the impact of wireless channel but the entire work could be extended for Rayleigh and Rician fading channels including AWGN.

R. Zhang *et al.* [23] described a way to decrease the effect of CFO on the performance of the system using a DFT which is weighted to OFDM. The window function was applied on the samples that were received before the demodulation of DFT.

A minimum BER block based pre-coder and a cascaded ZF equalizer for block transmission systems with sufficient or insufficient redundancy was designed by Chun-Hsien Wu *et al.* [24]. For a pre-coder that is block based the two redundancy schemes were taken into consideration. Oblique projection property was explored and IBI was completely obliterated or removed. Cascaded for of the equalizers were also studied and insufficient redundancy cases were extended to.

WL approach that is iterative to equalization for frequency-selective channels was proposed by Pei Xiao *et al.* [25]. The algorithm is applicable to complex and real signalling formats. BPSK and QPSK modulations were used. The algorithm leads to good performance.

Koon-Lun Jackie Wong *et al.* [26] have proposed an edge equalization for the reduction of ISI. A wider eye opening is observed. Edge equalizers are proposed thus compensating for data and transition samples.

S. H. Song *et al.* [27] investigated the diversity gain of equalizers that are linear over fading channels. With cyclic prefix ZF equalizers could only obtain order I gain diversity.

Anuj Kanchan *et al.* [28] compared the BER performance for equalizers. The equalizer tap was increased and performance improvement was achieved. In a noisy channel, the noise is also amplified. Thus the observation is that MMSE is more balanced equalizer, for which the ISI is not completely eliminated.

The probability for capturing the signals transmitted through Rician fading channels has been analysed by Jaime Sanchez Garcia *et al.* [29]. The authors showed a procedure to derive an equation for the pdf. An equation for the capture. There was still an increase in the throughput due to the fact that the capture probability is greater than zero.

Li-Chun Wang *et al.* [30] proposed an exact analytical method of calculating the CCI probability on a shadowed-Nakagami (desired)/ shadowed-Rician (interfering) channel. This model allows for the LoS components and Rice-factors, different shadowing spreads, and different transmitted powers (i.e. irregular cell sizes). The proposed analytical technique by the authors allows us the study of more complicated situations.

BER evaluation for different channels under various modulation schemes is done by A. Sudhir Babu *et al.* [31]. The performance of the various channels was analysed considering the data modulation and data rate for the analysis of modes of performance for different models of channels and antenna arrangements.

Nuzhat Tasneem Awon *et al.* [32] studied OFDM depended WIMAX with different coding schemes and digital modulation scheme; M-ary QAM. AWGN and fading (Rayleigh & Rician) channels under QAM, 16-QAM & 64-QAM modulation techniques. From this work conclusions can be drawn regarding the BER performance evaluation of WIMAX Communication system over the AWGN and fading (Rayleigh and Rician) channels. The performance of AWGN channel is the best of all as it has the lowest BER under QAM, 16QAM and 64QAM modulation schemes. The amount of noise occurs in the BER of this channel is quite slighter than fading channels.

K. Vidhya *et al.* [33] implemented different channel models using various algorithms. The system is simulated in MATLAB and analyzed in terms of BER vs. SNR.

An algorithm for SNR estimation in Rician channel in wireless OFDM systems is proposed by D. Sreenivasa Rao *et al.* [34]. In this novel algorithm, synchronization training symbols are reused for the estimation of SNR. The considered preamble structure uses time-domain for reduction for frame overhead. This also increases the estimator sensitivity to frequency selectivity. The proposed estimator favours the OFDM systems in complexity, bandwidth efficiency compared to the previous SNR estimator using preambles in the given research by the authors.

Suchitra Varade *et al.* [35] compared the performance of MIMO-OFDM communication with and without using adaptive beamforming. The proposed scheme was verified in the various channel models. A lot of future scope of the present work was noted.

M. F. Huang *et al.* [36] experimentally demonstrated transmission of 68.3Gbps WDM polarization division multiplexing- orthogonal frequency division multiplexing. Both the signals passed the 20% threshold for error correction. The authors claim that the results showed similarity for a long distance transmission of signals.

Yufeng Shao *et al.* [37] designed and experimentally demonstrated a novel 60 Ghz RoF system with 16 QAM-OFDM signals that were generated by partial transmit sequence (PTS) segmentation methods. The results show that segmentation that is interleaved provides a trade-off between the PAPR and computational complexity.

CHAPTER 3

OFDM WITH WINDOWING AND EQUALIZATION

3.1 OFDM

The definition of OFDM could be simply stated as the form of multicarrier communication where the spacing of the carrier is so selected with care that the orthogonality of the sub-carriers is maintained with respect to the other sub-carriers. Now the dot product between two signals defines the orthogonality between the two signals. Its value being zero for the same. The achievement of this condition is done with the selection of spacing between the carriers with care. So as to make equal the useful carrier symbol period and the reciprocal of carrier spacing. Therefore a null is achieved at the central frequency of each carrier for all the other carriers [38]. Therefore the interference between carriers is zero making it possible for the designers to keep them as close as is possible in the spectrum thus giving rise to great spectral efficiency. Orthogonality is an important property whereby the carrier spacing frequencies are chosen with care.

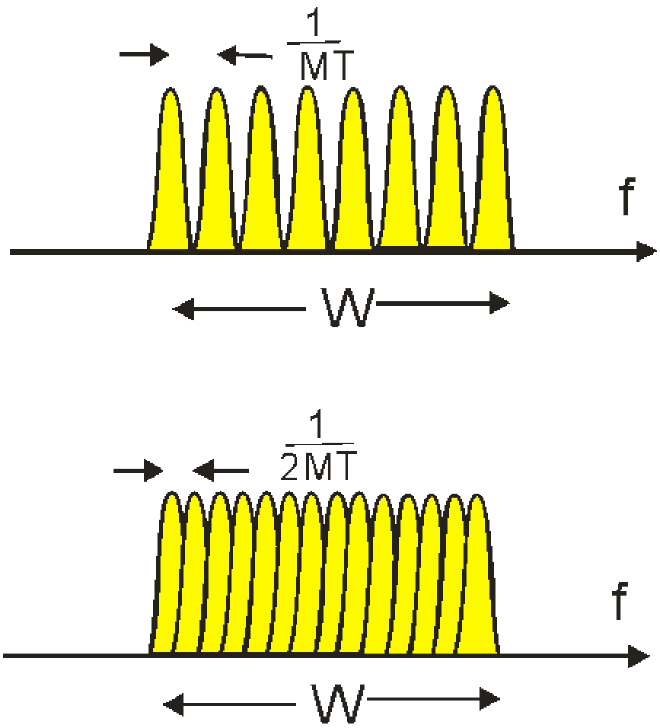

Figure 3.1: CONVENTIONAL V/S MULTICARRIER SYSTEM

Thus at the null frequency values, the inter carrier interference is eliminated, though the overlap between spectra might exist. Many correlation techniques exist which allow the separation of these signals at the destination where the group of demodulators forming part of the receiver converts each carrier value to it's baseband value thus leading to the recovery of the data.

Mathematically, orthogonality could be defined by the following equation. Due to this property, the sub-carrier of interest is extracted,

$$\int_a^b \Psi_p(t)\Psi_q(t)dt = k; for\ p = q \tag{3.1}$$

Communication Standards e.g. 802.11a, allow for the pulses to be modified at the rising and falling edges to be soft i.e. (Raised cosine) at the edge of their assigned spectrum, helping the spectrum to be contained. Thus the equalization is made easy. The use of the available bandwidth is made very efficient.

Now, the latest advancement in DSP techniques and the VLSI technology has made the modulation and demodulation process to be easily achieved. Thus, helps in implementation of OFDM.

3.2 Mathematical Analysis of OFDM

The sequence of OFDM symbols could be written as,

$$s(t) = \sum_{k=-\infty}^{\infty} g_k(t - kT) \tag{3.2}$$

The *k*th OFDM symbol (in complex LPE form) is,

$$g_k(t) = \sum_{\substack{n=-N/2 \\ n\neq 0}}^{N/2} a_{n,k} \exp\left(j2\pi \frac{n}{T_{FFT}} t \right) \quad \text{, for} \quad (k-1)T < t < kT \tag{3.3}$$

where n = subcarriers,
$T = T_G + T_{FFT}$ = period of symbols
$a_{n,k}$ is the complex data symbol that modulates the nth subcarrier.

$$N_{carriers} \leq \frac{IFFTsize}{2} - 2 \quad \text{(real - valuedtimesignal)} \tag{3.4}$$

$$N_{carriers} \leq IFFTsize - 1 \quad \text{(complex- valuedtimesignal)} \tag{3.5}$$

ContinuousTime:

$$\int_0^T \cos(2\pi n f_0 t) \times \cos(2\pi m f_0 t) dt = 0 \quad (\mathrm{n} \neq \mathrm{m}) \tag{3.6}$$

Discrete Time:

$$\sum_{\mathrm{k}=0}^{\mathrm{N-1}} \cos\left(\frac{2\pi \mathrm{kn}}{\mathrm{N}}\right) \times \cos\left(\frac{2\pi \mathrm{km}}{\mathrm{N}}\right) = 0 \quad (\mathrm{n} \neq \mathrm{m}) \tag{3.7}$$

Single (Real) OFDM modulated carriers,

$$S(k) = e^{j\theta_m} \delta\left(k - m - \frac{N}{2}\right) + e^{-j\theta_m} \delta\left(k + m - \frac{N}{2}\right) \tag{3.8}$$

k = frequency (0 to N - 1)
m = OFDM carrier frequency
N = IFFT bin size

Composite (Real) OFDM modulated carriers,

$$S(k)_{ofdm} = \sum_{m=c_{first}}^{c_{last}} \left[e^{j\theta_m} \delta\left(k - m - \frac{N}{2}\right) + e^{-j\theta_m} \delta\left(k + m - \frac{N}{2}\right) \right] \tag{3.9}$$

c = OFDM carrier (first through last)

$$s(n) = \sum_{m=c_{first}}^{c_{last}} \sum_{n=0}^{N-1} \cos\left(\frac{2\pi mn}{N} + \theta_m\right) \tag{3.10}$$

n = time sample
m = OFDM carrier
N = IFFT bin size
θ_m = phase modulation for OFDM carrier (m)
$\mathrm{c}_{\mathrm{first}}, \mathrm{c}_{\mathrm{last}}$ = OFDM carriers (first and last)

$$\int_0^T \cos(2\pi m f_0 t)\cdot\cos(2\pi n f_0 t)dt = \begin{cases} \frac{T}{2} @(m=n) \\ 0@(m\neq n) \end{cases} \tag{3.11}$$

$$\int_0^T \sin(2\pi m f_0 t)\cdot\sin(2\pi n f_0 t)dt = \begin{cases} \frac{T}{2} @(m=n) \\ 0@(m\neq n) \end{cases} \tag{3.12}$$

$$\int_0^T \cos(2\pi m f_0 t)\cdot\sin(2\pi n f_0 t)dt = 0 \tag{3.13}$$

Where; m, n – integers and T=1/f_0.

A sub-carrier of n = n_0 is,

$$a_n\cdot\cos(2\pi n f_0 t)-b_n\cdot\sin(2\pi n f_0 t)=\sqrt{{a_n}^2+{b_n}^2}\cos(2\pi n f_0 t+\phi_n),@\phi_n=\tan^{-1}\frac{b_n}{a_n} \tag{3.14}$$

Base-band OFDM Signal,

$$s_B(t)=\sum_{n=0}^{N-1}\{a_n\cos(2\pi n f_0 t)-b_n\sin(2\pi n f_0 t)\} \tag{3.15}$$

Pass-band OFDM Signal,

$$s(t)=\sum_{n=0}^{N-1}\left[a_n\cos\{2\pi(f_c+nf_0)t\}-b_n\sin\{2\pi(f_c+nf_0)t\}\right] \tag{3.16}$$

At the OFDM Transmitter, the time-domain waveform generated by IFFT;

$$d[n,i]=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}s[n,k]e^{j2\pi i\frac{k}{N}} \tag{3.17}$$

At the OFDM Receiver, the frequency-domain waveform generated by FFT;

$$r[n,k]=\frac{1}{\sqrt{N}}\sum_{i=0}^{N-1}d'[n,i]e^{-j2\pi k\frac{i}{N}} \tag{3.18}$$

Input to time-domain;

$$x(n)=IFFT\{X(k)\}\ldots where, n=0,1,2,...,N-1 \tag{3.19}$$

$$
\begin{aligned}
x[n+L] &= \frac{1}{N}\sum_{k=-\frac{N_F}{2}}^{\frac{N_F}{2}} c_k e^{jk\frac{2\pi}{N}n} \\
&= \frac{1}{N}\sum_{k=1}^{\frac{N_F}{2}} c_k e^{jk\frac{2\pi}{N}n} + \frac{1}{N}\sum_{k=-\frac{N_F}{2}}^{-1} c_k e^{j(N+k)\frac{2\pi}{N}n} \qquad
\begin{matrix}
X[k]=c_k, & k=1,\ldots,N_F/2 \\
X[N+k]=c_k, & k=-1,\ldots,-N_F/2 \\
X[k]=0, & \text{otherwise}
\end{matrix} \\
&= \frac{1}{N}\sum_{k=0}^{N-1} X[k]e^{jk\frac{2\pi}{N}n} = IFFT\left\{X[k]\right\}
\end{aligned}
\tag{3.20}
$$

$$
\frac{1}{T_b}\int_{t_0}^{t_0+T_b} e^{j2\pi F_k t} e^{-j2\pi F_\ell t}\,dt = \frac{1}{T_b}\int_{t_0}^{t_0+T_b} e^{j2\pi(k-\ell)\Delta F t}\,dt = \begin{cases} 1 & \text{if } k=\ell \\ 0 & \text{if } k\neq\ell \end{cases}
\tag{3.21}
$$

$$
x_f(n) = \begin{cases} x(N+n), & n=-N_g,-N_g+1,\ldots,-1 \\ x(n), & n=0,1,\ldots,N-1 \end{cases}
\tag{3.22}
$$

$$
y_f = x_f(n)\otimes h(n) + w(n)
\tag{3.23}
$$

$$
\begin{aligned}
&H[k]X[k] = FFT\left\{y[L],\ldots,y[L+N-1]\right\} \\
&H[k] = FFT\left\{h[0],\ldots,h[L-1],0,\ldots,0\right\} \qquad \text{With,} \quad k=0,\ldots,N-1
\end{aligned}
\tag{3.24}
$$

$$
\begin{aligned}
y[n+L] &= h[n]*x[n+L] \\
&= h[n]*\frac{1}{N}\sum_{k=0}^{N-1} X[k]e^{j\frac{2\pi}{N}kn} \\
&= \frac{1}{N}\sum_{k=0}^{N-1} H[k]X[k]e^{j\frac{2\pi}{N}kn} = IFFT\left\{H[k]X[k]\right\}
\end{aligned}
\tag{3.25}
$$

$$
y(n) = y_f(n) \quad n=0,1,\ldots,N-1
\tag{3.26}
$$

$$
Y(k) = FFT\left\{y(n)\right\}\ldots\ldots\ldots\ldots k=0,1,2,\ldots,N-1
\tag{3.27}
$$

$$
Y(k) = X(k)H(k) + I(k) + W(k)\ldots\ldots\ldots\ldots k=0,1,\ldots,N-1
\tag{3.28}
$$

$$
X_e(k) = \frac{Y(k)}{H_e(k)} \quad k=0,1,\ldots,N-1
\tag{3.29}
$$

$$
\begin{aligned}
&X = diag\{X_0, X_1, ..., X_{N-1}\}\\
&Y = [Y_0, Y_1, ..., Y_{N-1}]^T\\
&H = [H_0, H_1, ..., H_{N-1}]^T = DFT_N(h)\\
&W = [W_0, W_1, ..., W_{N-1}]^T, iid, zero\ mean, Gaussian
\end{aligned}
$$

$$
Y = XFh + W = XH + W \qquad F = \begin{bmatrix} W_N^{00} & \cdots & W_N^{0(N-1)} \\ . & . & . \\ . & . & . \\ . & . & . \\ W_N^{(N-1)0} & \cdots & W_N^{(N-1)(N-1)} \end{bmatrix} \qquad W_N^{nk} = \frac{1}{N} e^{-j2\pi \frac{n}{N} k} \tag{3.30}
$$

$$
H_{MMSE} = FR_{MMSE} = FR_{hY}R_{YY}^{-1}Y \qquad \begin{aligned} &R_{hY} = E[hY] = R_{hh}F^H X^H \\ &R_{yy} = E[YY] = XFR_{hh}F^H X^H + \sigma^2 I_N \end{aligned} \tag{3.31}
$$

$$
H_{LS} = X^{-1}Y \qquad \begin{aligned} &X = diag\{x_0, x_1, ..., x_{N-1}\} \\ &y = \begin{bmatrix} y_0 \\ . \\ . \\ . \\ y_{N-1} \end{bmatrix} \end{aligned} \tag{3.32}
$$

$$
X_e(k) = \frac{Y(k)}{H_e(k)} \qquad k = 0,1,...,N-1 \tag{3.33}
$$

$$
X_e(k) \rightarrow \text{signal demapper} \rightarrow \text{signal mapper} \rightarrow X_{pure}(k)
$$

$$
H_e(k) = \frac{Y(k)}{X_{pure}(k)} \qquad k = 0,1,...,N-1 \tag{3.34}
$$

3.3 Windowing Methods

A technique for shaping the time portion of our measured data so as to minimize the effects of the edges thus reducing the leakage that arises out of the spectrum in the spectrum of FFT is called windowing [39]. The enhancement of the resolution of the domain of frequency is achieved with the correct use of this function. When a new function being multiplied with a window function gives a zero valued product outside the interval, the portion being overlapped remains, which is the view for the given window. The main aim of windowing in spectral analysis is the ability of zooming into the finer details of the signal rather than looking the whole signal as such. Short Time Fourier Transforms(STFT) are of prime importance in case of speech signal processing where the information like pitch or the formant frequencies are extracted by analyzing the signals through a window of specific duration.

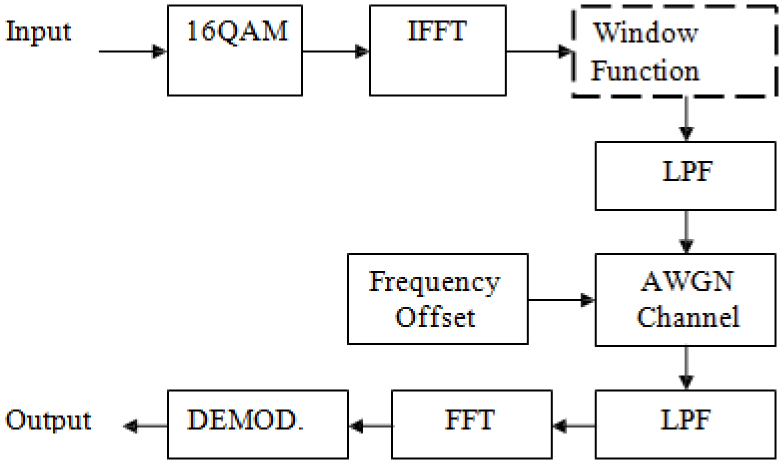

Figure 3.2: Block Diagram of Time Domain Windowing Scheme

3.3.1 Important Window Functions

- **Rectangular Window**

  The rectangular window is the simplest of all. This replaces all but N values of data by zero sequences. Thus giving the waveform an on and off appearance. The Rectangular Window could be defined by the mathematical expression:

  $$w(n) = 1. \tag{3.35}$$

- **Hanning Window (Raised Cosine Window)**

  The Hanning window is a period of raised value of cosine function so the negative peaks of the window just touch the nil mark, hence giving its name [40]. The hanning window could be represented by the mathematical representation,

$$w(n) = 0.5(1 - \cos(\frac{2\pi n}{N-1})) \tag{3.36}$$

- **Hamming Window**

  Proposed by Richard W. Hamming, it is optimized to reduce the nearest lode which is present to the side [41]. The formula with which this window might be represented is,

$$w(n) = 0.54 - 0.46\cos(\frac{2\pi n}{N-1}) \tag{3.37}$$

- **Gaussian Window**

  The log of a Gaussian produces a parabole figure which facilitates estimation of the frequency components.

  Mathematically, Gaussian window may be defined by the expression:

$$w(n) = e^{-\frac{1}{2}(\frac{n-\frac{(N-1)}{2}}{\frac{\sigma(N-1)}{2}})^2} \tag{3.38}$$

- **Flat Top Window**

  It is a partially negative-valued window having a flat top in the frequency domain. They facilitate measurements of amplitudes of the sine components of the frequency. The flat-top window may be mathematically represented by:

$$w(n) = a_0 - a_1\cos\left(\frac{2\pi n}{N-1}\right) + a_2\cos\left(\frac{4\pi n}{N-1}\right) - a_3\cos\left(\frac{6\pi n}{N-1}\right) + a_4\cos(\frac{8\pi n}{N-1}) \tag{3.39}$$

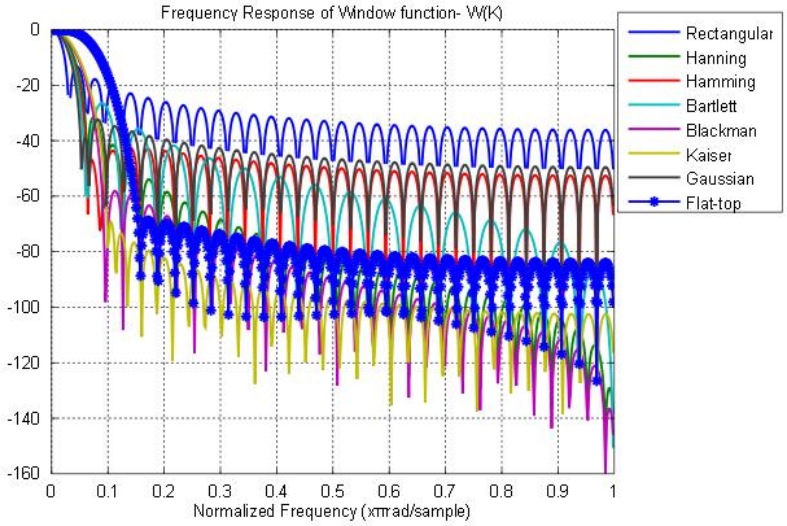

Figure 3.3: Frequency-Domain Plot of Common Window Functions [42]

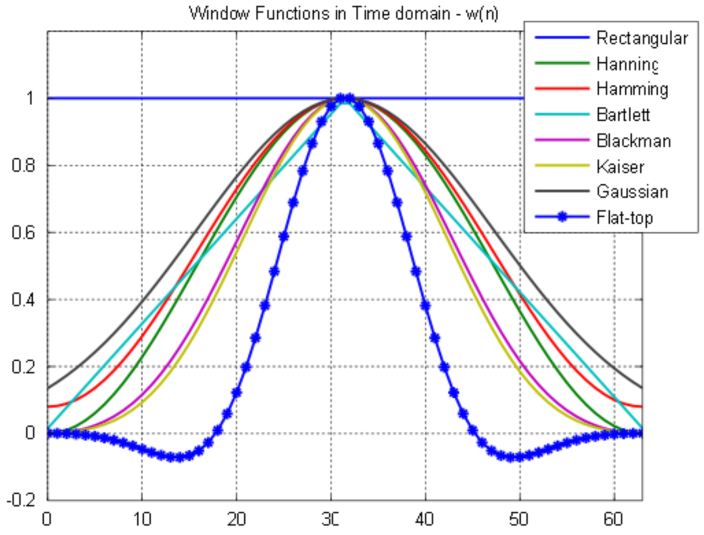

Figure 3.4: Time-Domain Plot of Common Window Functions [43]

The above plots show some common window functions in both frequency domain and time domain. Most windows begin and end at zero and rise to unity in the middle. The narrowest windows in the time domain have the widest main lobes in the frequency domain, and vice-versa.

3.3.2 Raised Cosine Window

A series of IFFTs are concatenated to form the multicarrier OFDM signal. However a discontinuity occurs at each signal period boundary due to the differences between the start and finish points [44]. Thus leading to a high noise factor. Therefore a function called the window function is applied to each symbol which attenuates the signal at precisely these points so as to reduce the discontinuities and the high distortion. But the drawback being that the signal is distorted as well thereby losing some content as well.

OFDM symbol may be represented as,

$t = t_s = kT_s$ is

$$s(t) = \mathrm{Re}\{w(t - t_s)\sum_{i=0}^{N_s-1} d_i \exp(j2\pi f_i (t - t_s - T_{prefix}))\}; \qquad (3.40)$$

$$t_s \le t \le t_s + T_s(1+\beta),$$
$$s_k(t) = 0, t < t_s \wedge t > t_s + T_s(1+\beta)$$

Where, ‘ β ’ is the roll-off factor of the raised cosine

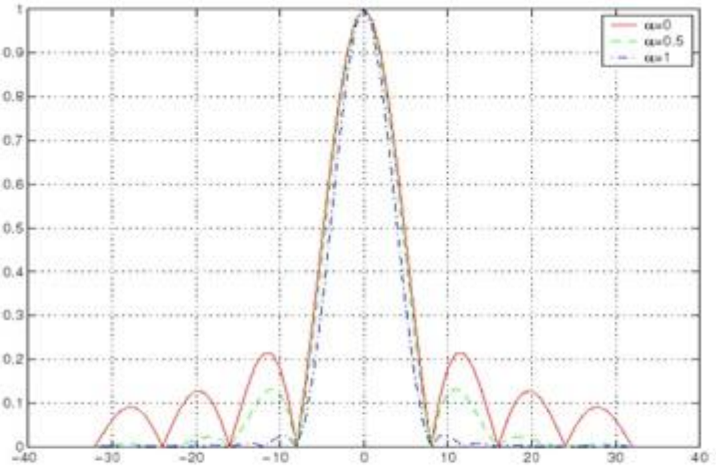

Figure 3.5: RC Window Response

Applications of RC window

- Noise measurements.
- In DSP applications.
- For application of smoothing window when the nature of the signal is unknown.

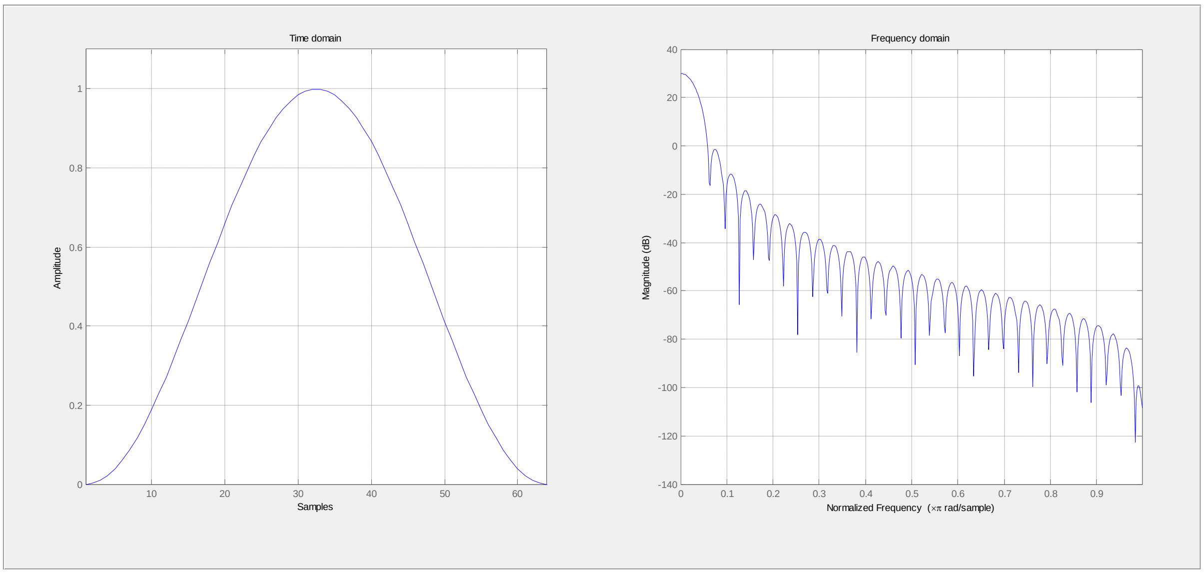

Figure 3.6: Time Domain and Frequency Domain Representation of 64-Point Raised Cosine Window

3.3.4 Mathematical Analysis of Raised Cosine Window

This spectral shaping technique is applied in time domain, after adding the guard interval (GI). But I find it easier to add GI and the cyclic extension for windowing in one step. Let x(n) be an N subcarriers OFDM symbol without guard interval. Then W+G samples are copied to the beginning accounting for guard interval and windowing samples. Additionally, W samples are copied to the end, also for windowing

$$
\begin{aligned}
y(n) = {} & x(n+N) \; for \; -G-W \leq n \leq -1 \\
& = x(n) \; for \; 0 \leq n \leq N-1 \\
& = x(n-N) \; for \; N \leq n \leq N+W-1
\end{aligned}
\qquad (3.41)
$$

In the next step, the raised cosine function is applied to the first and last W samples of y(n), respectively. The windowing function w(n) is given by:

$$
\begin{aligned}
w(n) = {} & cos^2\left(\frac{n+G+1}{w-1} . \frac{\pi}{2}\right) \; for \; -G-W \leq n \leq -G-1 \\
& = 1 \; for \; -G \leq n \leq N-1 \\
& = cos^2\left(\frac{n-N}{w-1} . \frac{\pi}{2}\right) \; for \; N \leq n \leq N+W-1 \\
& = 0 \; otherwise
\end{aligned}
\qquad (3.42)
$$

w(n) is similar but not equal to the transfer function of a raised cosine filter often used as impulse shaper in single carrier transmission systems. The two differences are: (1) the raised cosine function is applied in time domain for OFDM systems and in frequency domain for single carrier systems and (2) the "flat top" is usually much longer for OFDM systems, whereas its length is in a fixed relation with the flanks' length, given by the roll-off factor, for single carrier systems.

Finally, the OFDM symbol including GI and spectral shaping is calculated by

$$z(n) = w(n)y(n) \qquad (3.43)$$

When transmitting several OFDM symbols zi(n), two consecutive symbols overlap at W samples. The discrete transmit signal u(n) is therefore given by:

$$u(n) = \sum_{i=-\infty}^{\infty} z_i(n - i(N+G+W)) \qquad (3.44)$$

Note: Raised Cosine Window in frequency domain;

$$P(f) = \left[\frac{\sin(\pi f T)}{\pi f T}\left(\frac{\cos(\pi \alpha f T}{1-(2\alpha f T)^2}\right)\right], \quad 0 \le \alpha \le 1 \tag{3.45}$$

Where, $\alpha = 0$, is a Rectangular Window (i.e. no shaping).

Raised Cosine Window in time Domain;

$$\begin{aligned} w(t) &= 1, \ 0 \le |t| < \frac{T - T_W}{2} \\ &= \frac{1}{2}\left\{1 + cos\left[\frac{\pi}{T_W}\left(|t| - \frac{T - T_W}{2}\right)\right]\right\}, \left(\frac{T - T_W}{2}\right) \le |t| < \frac{T - T_W}{2} \\ &= 0\,, otherwise \end{aligned} \tag{3.46}$$

Where,

T - represents the OFDM symbol duration including the guard interval.

T_W - represents the duration of the window.

3.4 Equalization

Over a sub-channel of the OFDM modulation scheme, the effect of the fading that is the result of multipath propagation could be considered stationary or constant or flat. Thus the equalization in the frequency domain is made possible at the destination stage. This process is far easier to implement and stable in operation as compared to the single carrier communication scheme. The equalizer's function at the receiving end of the communication process is to find the product of each sub-carrier that is detected in the symbols of OFDM with a complex constant value. However differential modulation that is applied to the subcarriers omits this need too. The sub channels may carry some pilot signals to measure the channel conditions or for synchronization [45].

The ICI that is caused in the OFDM system of communication destroys the impact of orthogonality thus it becomes cardinal that equalization be applied to the communication system. Replicas of the signals are created at the destination location with difference in their properties of amplitude, phase and frequency, thus making it necessary for the destination to have equalizing functions to compensate for the losses that accompany the signal reception in such a fading channel environment. At the destination stage Equalization is nothing but a set of multipliers. One is provided for each subcarrier. Amplitude equalization and channel equalization are few of the techniques available to the design engineers for countering the effects caused by multipath propagation.

CHAPTER 4

RESULTS AND DISCUSSIONS

In OFDM, the available spectrum had divided into many closely spaced parallel subcarriers, each one modulated by a low rate data stream. By reducing the bit error rate per subcarrier, the influence of ISI had significantly reduced. As the frequency response over each subcarrier is relatively flat, equalization is potentially simpler than in a serial data system. Here, Raised Cosine (RC) window function had applied along with equalization to the OFDM signal using 16-QAM modulation scheme. The analysis had done over various wireless fading channels namely: AWGN, Rayleigh and Rician channel. It had observed that BER vs. SNR for AWGN channel shows a significant improvement after the application of Raised Cosine window and equalization as compared to traditional OFDM.

4.1 Original OFDM system

In the initial work, Orthogonal Frequency Division Multiplexing (OFDM) had implemented using 16-QAM modulation technique. This system had implemented in three channels, namely Additive White Gaussian Noise (AWGN) Channel, Rayleigh Fading Channel and Rician Fading Channel. The results of implementation of the said modulation scheme in all these three channels had shown in figure 4.1 below.

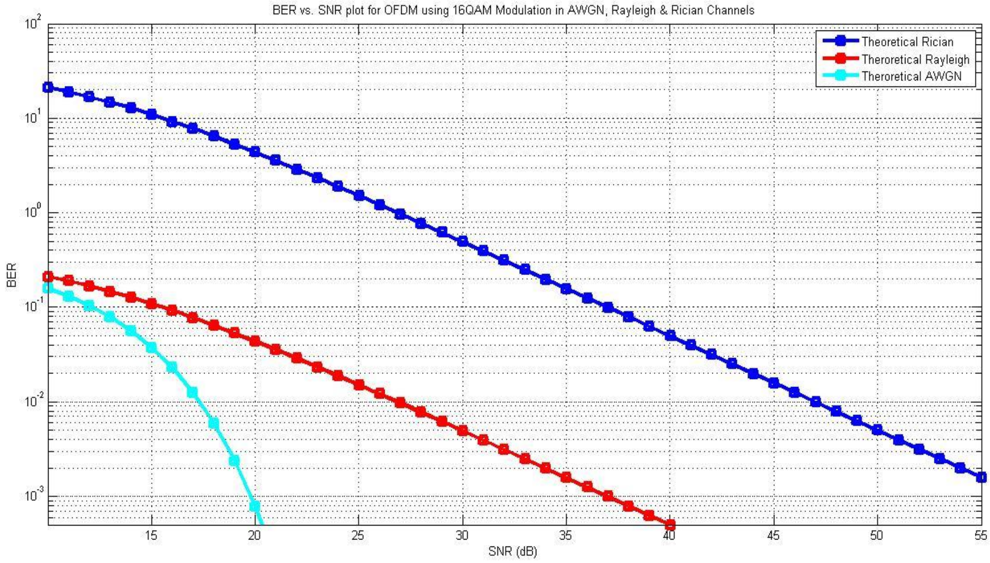

Figure 4.1: BER vs. SNR OFDM using 16-QAM for AWGN, Rayleigh and Rician channels

These results represent BER of OFDM using 16-QAM modulation technique; without the use of any window function or equalization. In the above figure 4.1, at $10^{-2.9}$ BER the SNR value of 19 dB had achieved for AWGN Channel. The SNR of 35 dB had achieved for Rayleigh Channel and the SNR of 55dB had achieved for Rician Channel at $10^{-2.9}$ BER.

4.2 Proposed OFDM using windowing and Equalization under different wireless fading channels

In the figure 4.2, the result for BER vs. SNR for OFDM using 16-QAM modulation technique with raised cosine window and equalization had plotted under the AWGN wireless channel and compared with traditional OFDM system.

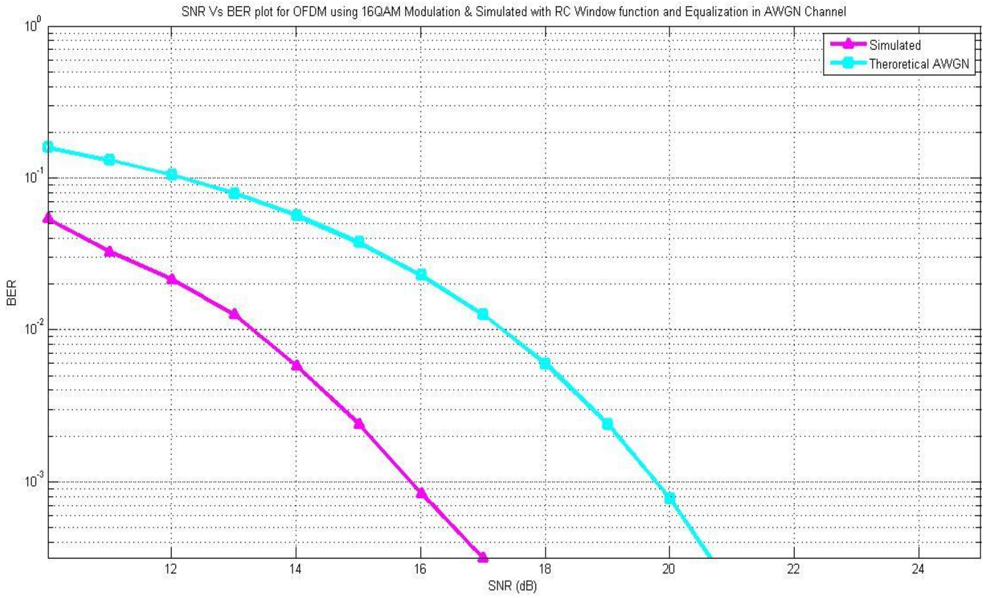

Figure 4.2: BER vs. SNR OFDM using 16-QAM with RC windowing and equalization along with traditional OFDM system under AWGN channel

It has been observed from figure 4.2, that OFDM using 16-QAM modulation along with Raised Cosine windowing technique and equalization technique had achieved SNR of 16 dB as compared to 21 dB for $10^{-2.9}$ BER under AWGN channel. So, an improvement of 5 dB had achieved with proposed OFDM system as compared to traditional OFDM system.

In the figure 4.3, the result for BER vs. SNR for OFDM using 16-QAM modulation technique with raised cosine window and equalization had plotted under the Rayleigh wireless channel and compared with traditional OFDM system.

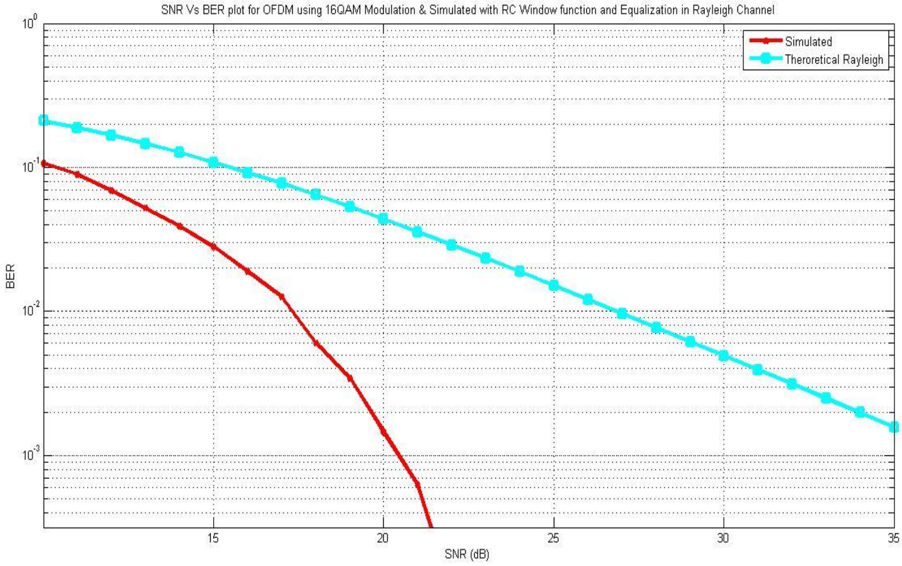

Figure 4.3: BER vs. SNR OFDM using 16-QAM with RC windowing and equalization along with traditional OFDM system under Rayleigh channel

It has been observed from figure 4.3, that OFDM using 16-QAM modulation along with Raised Cosine windowing technique and equalization technique had achieved SNR of 34 dB as compared to 19 dB for $10^{-2.9}$ BER under Rayleigh channel. So, an improvement of 15 dB had achieved with proposed OFDM system as compared to traditional OFDM system.

In the figure 4.4, the result for BER vs. SNR for OFDM using 16-QAM modulation technique with raised cosine window and equalization had plotted under the Rician wireless channel and compared with traditional OFDM system.

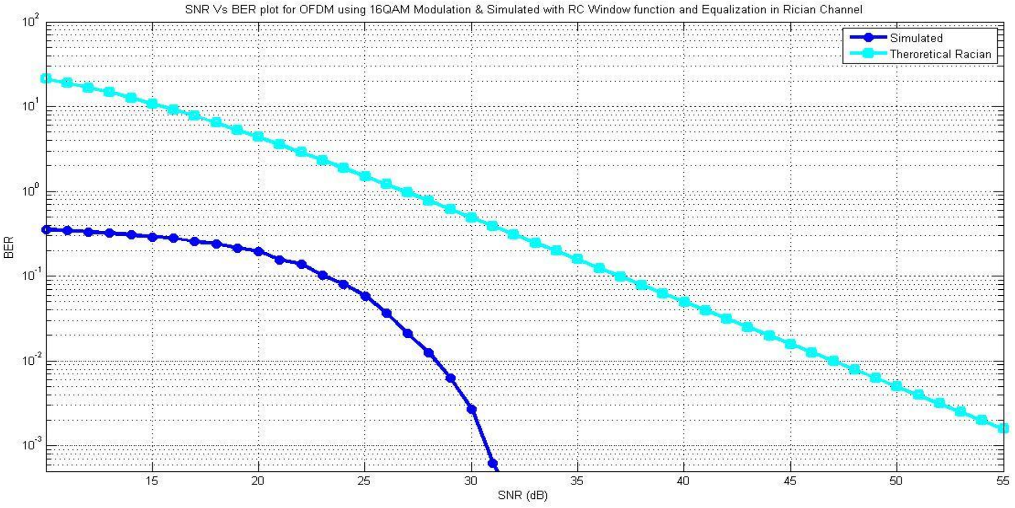

Figure 4.4: BER vs. SNR OFDM using 16-QAM with RC windowing and equalization along with traditional OFDM system under Rician channel

It has been observed from figure 4.4, that OFDM using 16-QAM modulation along with Raised Cosine windowing technique and equalization technique had achieved SNR of 55 dB as compared to 31 dB for $10^{-2.9}$ BER under Rician channel. So, an improvement of 24 dB had achieved with proposed OFDM system as compared to traditional OFDM system.

Finally, all the results achieved for proposed OFDM system with raised cosine window and equalization under various wireless fading channels had presented in figure 4.5 below.

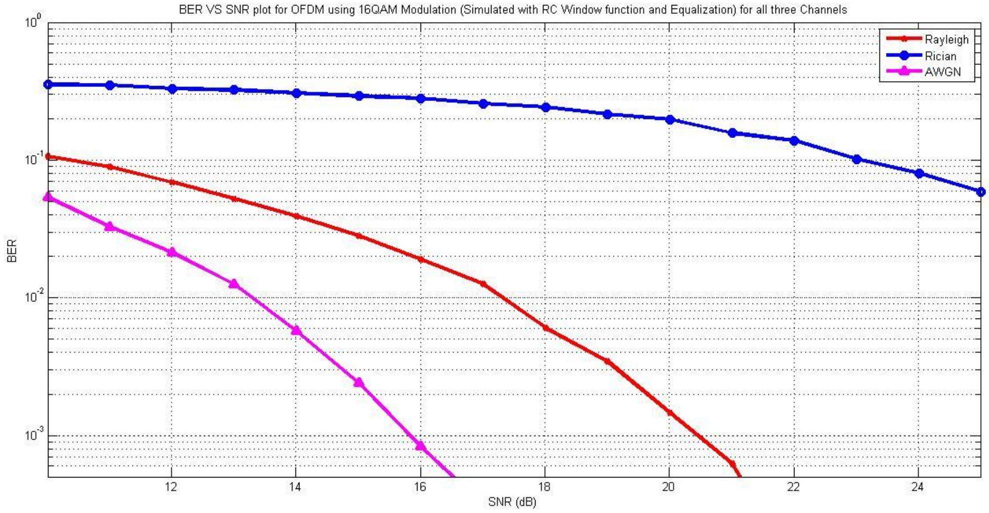

Figure 4.5: BER vs. SNR OFDM using 16-QAM with RC windowing and equalization under AWGN, Rayleigh and Rician channel

In the figure 4.5, the BER vs. SNR results for OFDM using 16-QAM modulation technique using raised cosine windowing function and equalization under AWGN, Rayleigh and Rician fading channel had plotted together. It had observed that the least BER is for AWGN channel. The value of BER increases for Rayleigh Fading channel; and it is the highest for Rician Fading channel. However, when the BER vs. SNR performance of proposed system had compared with the traditional OFDM system, it had observed that the maximum improvement of 24 dB had achieved under Rician fading channel for the proposed system as compared to other fading channels.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation technique where multiple low data rate carriers had combined to form a composite high data rate transmission. It makes efficient use of the spectrum by allowing overlap. It is also resistant to frequency selective fading as it is a multi-carrier transmission scheme, i.e. it divides the channel into narrowband flat-fading sub-channels. The BER analysis of OFDM system for 16-QAM modulation technique using AWGN, Rayleigh and Rician had presented in this thesis by adding windowing and equalization technique. The different channel configurations had coupled with Equalization and Raised Cosine Windowing technique for analysing bit error rate. The channel equalization is simple to implement than by using adaptive equalization techniques for single-carrier systems. In this thesis, by adding Raised Cosine (RC) Window along with Equalization function in OFDM system with 16-QAM modulation technique, at $10^{-2.9}$ Bit Error Rate (BER) an improvement of 5 dB had achieved in the SNR value for AWGN Channel as compared to traditional OFDM system had achieved. An improvement of 15dB had achieved in the SNR value for Rayleigh Channel and an improvement of 24 dB had achieved in the SNR value for Rician Channel in the proposed OFDM system as compared to traditional OFDM system at $10^{-2.9}$ BER.

5.2 Future Work

In the present work, performance of OFDM system is analyzed under different fading channels. OFDM systems can be implemented using higher order modulations to achieve large data capacity. A lot of work had pursued in the field of OFDM and a combination of MIMO (Multiple Input Multiple Output) and OFDM. The present work by adding windowing and equalization could extend to MIMO-OFDM. Further, we can utilize combinations of different coding schemes and other channel models for further improvement in SNR and BER. In addition, there is an opportunity to implement OFDM system by using different modulation schemes. A more comprehensive study in which performance comparison of different types of equalizers along with the different window functions could carry out over

MIMO-OFDM. The type of window could carefully choose to match the modulation scheme used to improve the BER performance of the system.

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