SUPPRESSION OF IMPULSIVE NOISE IN OFDM SYSTEM USING IMPERFECT CHANNEL STATE INFORMATION

Thesis submitted towards the partial fulfilment of requirement for the award of degree of

MASTER OF ENGINEERING

IN

WIRELESS COMMUNICATION

Submitted By

Abhishek Bansal

Roll No. 801363001

Under the guidance of

Dr. Amit Kumar Kohli

Associate Professor, ECED

Thapar University, Patiala

ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

(Established under the section 3 of UGC Act, 1956)

PATIALA – 147004, PUNJAB, INDIA

JUNE 2015

DECLARATION

I, **Abhishek Bansal,** hereby declare that the thesis entitled **"Suppression of Impulsive Noise in OFDM System using Imperfect Channel State Information"** is an authentic record of my own work carried out towards the partial fulfilment for the award of the degree of Master of Engineering in Wireless Communication at Thapar University, Patiala, under the supervision of **Dr. Amit Kumar Kohli**, Associate 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.

Date: 30/6/2015

Abhishek Bansal

Roll No. 801363001

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

Date: 30/6/15

Dr. Amit Kumar Kohli

Associate Professor

ECED, TU, Patiala

Countersigned by:

(Dr. Sanjay Sharma)

Professor and Head ECED

Thapar University, Patiala

(Dr. S.S. Bhatia)

Dean of Academic Affairs

Thapar University, Patiala

ACKNOWLEDGEMENT

Foremost, I would like to express my sincere gratitude to my guide **Dr. Amit Kumar Kohli**, Associate Professor and P. G. Coordinator, ECED, Thapar University, Patiala, for his patience, motivation, enthusiasm, immense knowledge and continuous support for my thesis. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better guide for my M.E. thesis.

Besides my guide, I am thankful to **Dr. Sanjay Sharma**, Prof. and Head, Electronics and Communication Engineering Department and **Mr. Hemdutt Joshi**, Assistant Professor, Program Coordinator of Wireless Communication, who have been a constant source of inspiration for me throughout this work, and for providing us with adequate infrastructure in carrying the work.

I would like to thank all the faculty members of ECED for the full support of my work. I am also thankful to my friends **Divneet Singh Kapoor**, **Bhupinder Singh** and **Sandipta Dutta Gupta**, for encouraging the use of correct grammar and consistent notation in my writings and for carefully reading and commenting on countless revisions of this manuscript. I am also thankful to the authors whose work have been consulted and quoted in this work.

At last but not the least, I would also like to thank my parents for supporting me spiritually throughout my life.

Place: TU, Patiala **Abhishek Bansal**

Date: **Roll No. 801363001**

ABSTRACT

Multi-carrier modulation is a scheme that transmits the data by dividing the serial high data-rate streams into a number of parallel low data rate streams. Orthogonal frequency division multiplexing (OFDM) is a form of multi-carrier modulation, which divides the available spectrum into a number of parallel subcarriers and each subcarrier is modulated by a low data-rate stream at different carrier frequency. OFDM is the division of the frequency selective transmission channel into several subchannels, which can be characterized as flat fading channels. Impulsive noise severely affects the performance of OFDM system, if the amplitude of impulsive noise is very high. It is generated by power lines, heavy current switches, and other sources.

A simple method to improve the performance of OFDM system in an impulsive noise environment is the blanking nonlinearity. It is implemented in the time-domain. Whereas another method for the impulsive noise suppression is implemented in the frequency-domain after OFDM demodulation and channel equalization. This method is called impulsive noise compensation method.

This thesis propounds the OFDM system working under the Nakagami-m multipath fading channels, which utilizes the impulsive noise excision technique. Its performance is also evaluated under the imperfect channel state information (CSI) constraint. Although the impact of noise reduces due to the noise bucket effect appearing in the OFDM systems with longer symbol duration, yet the impulsive noise energy spreads over OFDM subcarriers, which appears as a hazard in the demodulation and detection, when the energy of impulsive noise exceeds a certain threshold level. Under realistic conditions, the channel estimators can't provide perfect/ideal channel state information. In this work, we use the impulsive noise compensation method as a technique for the suppression of impulsive noise in the frequency-domain. Under the aforementioned scenario, the simulation results are demonstrated for the performance evaluation of underlying OFDM communication system, under the Nakagami-m multipath fading channel, which also focuses on the adverse effects of imperfect CSI at the receiver, in terms of bit error rate. It is also apparent from that approximately 3 dB improvement is observed $m = 2$ relative to $m = 1$ and 3 dB performance degradation is observed $m = 0.5$ relative to $m = 1$ at BER 0.04 under perfect CSI at the receiver.

Keywords - OFDM, impulsive noise, channel state information, noise bucket effect.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

ADSL	Asymmetric Digital Subscriber Line
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BW	Bandwidth
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
CSI	Channel State Information
DAB	Digital Audio Broadcasting
dB	decibel
DFT	Discrete Fourier Transform
DVB	Digital Video Broadcasting
FDM	Frequency Division Multiplexing
FER	Forward Error Correction
FFT	Fast Fourier Transform
GI	Guard Interval
GRP	Gaussian Random Process
GSM	Global System for Mobile Communication
ICI	Inter-Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
ISI	Inter-Symbol Interference
LAN	Local Area Network
LOS	Line of Sight
MATLAB	Matrix Laboratory
MCM	Multi-carrier Modulation
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak to Average Power Ratio
PDF	Probability Density Function
QAM	Quadrature Amplitude Modulation

RF	Radio Frequency
RMS	Root Mean Square
Rx	Receiver
SCs	Subcarriers
SC	Single-Carrier
SER	Symbol Error Rate
SNR	Signal-to-Noise Ratio
Tx	Transmitter
Wi-MAX	Worldwide Interoperability for Microwave Access

LIST OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

This chapter gives a brief introduction of the thesis. It also includes the concept of OFDM (Orthogonal frequency division multiplexing), different types of fading, impulsive noise, and at the end it gives details about the organization of the thesis.

1.1. Introduction

The demand for high data-rate communication system is growing with an extremely rapid tread. OFDM is the widely used for achieving high data-rates as well as coping with a high degree of multipath distortions [1]. It is a special case of the multi-carrier transmission where a single wideband carrier is divided into a smaller or narrowband parallel subcarriers (SCs). It is the 4^{th} generation wireless communication system and used to send multiple signals in the parallel form on orthogonal subcarriers. These SCs are partially overlapping with frequency bands. OFDM symbols have a longer symbol duration as compared to the single-carrier system so it will convert the frequency selective fading channel into the flat fading channel [2]. The main advantages of the OFDM system are efficient use of the bandwidth and robustness to multipath distortions. To ensure about the accurate measurements in the lab, channel model must accounts all the aspects of practical radio environment [3-5].

Multipath fading occurs in any environment. When we have sent the signal from transmitter side, it can take different paths to reach at the receiver side [6-7]. The path might be taken straight line or including reflections from the atmosphere or earth surface. It is also due to motion between the sender and receiver in the radio communication system. The strength of the signal value will depend upon the reflected signal level. Fading through multipath channel can often be relatively deep, i.e., the signal gets completely fade away [8-9]. It means the strength of signal level below the usable limit. Small-scale fading has mostly affected the strength of the signal. The classification of fading can be represented through the following Fig. 1.1. Due to fading, the signal strength changes rapidly over small travel distance [10-11].

The Rayleigh distribution is generally utilized to model of fading channel, It is the special case of Nakagami-m distribution channel. Nakagami-m distribution is utilized to model of signal fading conditions that range from severe to moderate, to light or no fading.

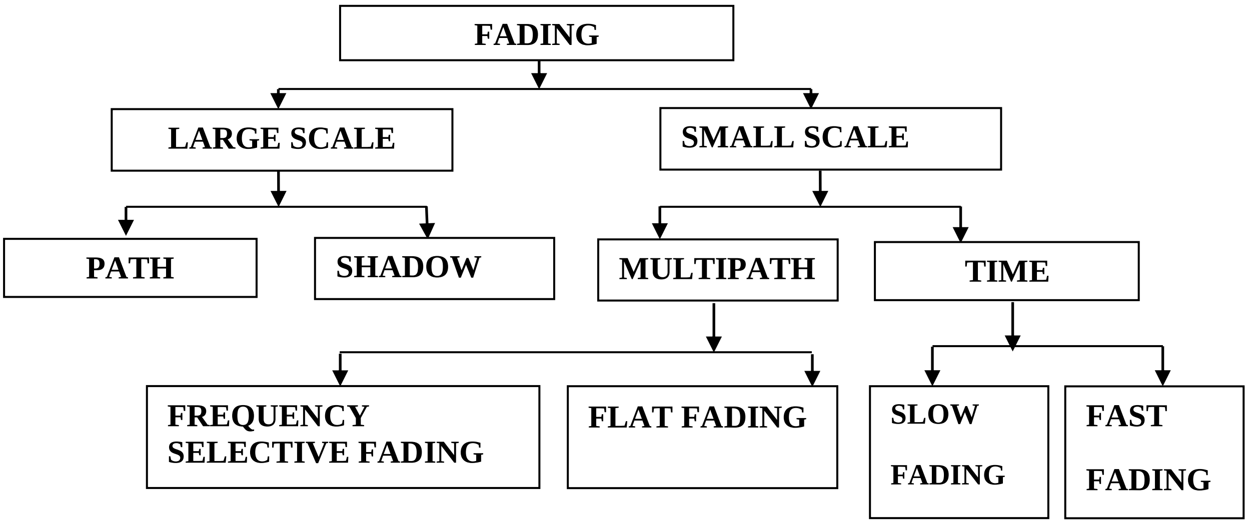


Fig. 1.1. Classification of fading signal

In practical wireless system, OFDM signal is not only affected through the fading channel, it also affects through the additive white Gaussian noise (AWGN) or thermal noise and impulsive noise. Impulsive noise is described as one or more repetitive or non-repetitive pulses with the random duration and the occurrence. It's mainly composed of relatively short duration on/off pulses, caused by a number of sources, like as switching noise, adverse channel conditions in a communication system, clicks from the computer keyboard, vehicle ignition system, sharp sounds, and machines also. Impulsive noise can be modeled through different type of models, for example, Bernoulli-Gaussian Model and Poisson-Gaussian Model.

1.2. Motivation

In the today scenario, requirements of communication engineering have become more stringent, it doesn't take only more detailed information about signal intensity, but also want to know the effect of impulsive noise and fading characteristics of the radio signal. In many communication applications such as OFDM, the modulated signal is often corrupted by impulsive noise and additive white Gaussian noise. This in turn deteriorates the amplitude of the received signal and consequently deteriorates the overall performance of the system. When the strength of the impulsive noise is high, then the desired signal is highly corrupted. In such scenarios, therefore, the impulsive noise compensation method is used for the suppression of impulsive noise.

Such method is required a plenty of experiments and theoretical investigations to be performed. Field test is an option to perform the experiments in a mobile environment but it is quite expensive and also requires the permission of Telecom Regulatory Authority of India (TRAI). These experiments in the mobile environment are very difficult because atmospheric conditions are also playing a major role in the environment. Limitations of the Field test experiments can be overcome through the simulations.

A simulation is like an impersonation of the real phenomenon or process. The act of simulating generally implies and representing the certain behavior or characteristics of the original physical system. Simulations are used in many contexts for modeling the natural system in order to gain their perception into their functioning. Simulation of the physical system is also used for the performance optimization. It can be used to show the real effects of different type of conditions and actions. It is the most useful technique for the researchers and it deals with the reality.

Simulators can also be used for the performance evaluation of the different modulation schemes. Random binary sequences are generated and modulated with different modulation schemes (e.g. 64 QAM) through the simulator. After that modulated sequence added with different types of noise like the additive white Gaussian noise (AWGN), Impulsive noise, and fading. Impulsive noise is typically generated through different kind of processes, for example, Bernoulli-Gaussian Process and fading can be modeled through typically have the Nakagami-m distribution or Rayleigh Distribution. Both are generated with the help of a simulator. After demodulation of binary sequence, plot the graph for bit error rate (BER) versus signal-to-noise ratio (SNR). This graph is exploited to demonstrate the consequences of the system.

1.3. Thesis Objective

In this work, an attempt has been made to implement a method for the excision of impulsive noise in the OFDM system under the effect of the Nakagami-m fading distribution with the perfect as well as imperfect channel state information. For suppression of impulsive noise, we used existing methods like the impulsive noise compensation method and the blanking nonlinearity method. OFDM system with effect of fading, impulsive noise, and AWGN can be expressed as

$$r_k = h_k s_k + n_k + u_k \tag{1.1}$$

where, u_k is the impulsive noise. It can be suppressed with the impulsive noise compensation method under the effect of the Nakagami-m fading distribution.

Generally, the channel estimators can't provide perfect channel state information (CSI) at the receiver. So it will also focus on the adverse effects of the CSI at the receiver side.

1.4. Thesis Organization

The remaining chapters represent the following research work

- **Chapter 2: Literature Survey:** This chapter includes the literature survey for suppression of impulsive noise in the OFDM system.
- **Chapter 3: Basics of Orthogonal Frequency Division Multiplexing:** This chapter gives a detailed study of the OFDM system, block diagram of the OFDM system, mathematical model, and implementation of the OFDM system with the help of MATLAB.
- **Chapter 4: Fading Channels and Impulsive Noise:** This chapter gives the detailed study of different types of fading and models of the fading channel. It also includes the concept of the impulsive noise and modeling of the impulsive noise.
- **Chapter 5: Impulsive Noise Compensation with Imperfect CSI:** In this chapter, the impulsive noise compensation method used for suppression of impulsive noise in the OFDM system under the Nakagami-m multipath fading channel. Here, we evaluated the performance under two conditions. First is the perfect channel state information and other is the imperfect channel state information.
- **Chapter 6: Concluding Remarks and Future Scope:** At last in this chapter, we conclude the work by equating the performance under the different values of the Nakagami fading parameter m and it also gives suggestion for future research.

Chapter 2

LITERATURE SURVEY

This chapter gives the brief introduction about adverse effects of impulsive noise in the OFDM system and methods available in the literature for suppression of impulsive noise.

Impulsive Noise in the OFDM System

Impulsive noise consists of non-repetitive pulses of a short and random duration with the high amplitude. It is caused by the number of sources such as keyboard switches, heating systems and ignition devices. These noises are degrading the performance of the OFDM system, but when the duration of the OFDM symbol period is very large, then the effect of the impulsive noise is very less. Now we are going to discuss some techniques present in literature for mitigation of the impulsive noise.

In [12], Ghosh has analyzed the consequences of impulsive noise on the multi-carrier as well as the single-carrier system. The performance of both system depends upon the probability of the impulsive noise. This is modeled through the Bernoulli Gaussian impulse noise model. It can be defined as the product of a real Bernoulli process and complex Gaussian process. It could be thought as each transmitted symbol hit by an impulsive noise independently according to the probability (P). In which, it also compares the performance of Bernoulli-Gaussian model under QAM. If the probability of the impulsive noise is high, then the single-carrier system is better performed as compared to multi-carrier system. From the simulation results observed that the single-carrier system is better performed than the multi-carrier system. If the probability of impulsive noise is very low, then multi-carrier system better performs.

In the next papers, we see that impulsive noise is more immune to multi-carrier system as compared to the single-carrier system and what are the problems arises through the impulsive noise in digital applications.

In [13], Suraweera *et al*. have presented new techniques for mitigation of the impulsive noise in the Digital TV systems. Impulsive noise can cause severe problems in digital TV reception. OFDM is more immune to the effects of impulsive noise than the single-carrier systems. Coding, interleaving, and clipping techniques are used for the mitigation of the impulsive noise. It is used for nonlinear processing techniques on the digital input signals to limit the size of impulses to reaching the demodulator. The most effective technique of nonlinear processing is clipping the input signals with larger amplitudes. At the receiver, check the received signal level and set the threshold measure, if the level of receiving signal is below the threshold then it will go for demodulation otherwise if the corresponding level of the received signal is above the threshold then the output for that particular signal is null. It means high peak of the impulsive noise is ignored. Nonlinear processing techniques are analyzed by Bussgang's theorem.

In the previous paper, if the impulsive noise is more than the threshold, it will be clipped. In the next, we will see a new technique for suppression of impulsive noise in the frequency-domain. It has utilized after channel equalization. Next technique is mainly used throughout in my thesis work.

In [14], Zhidkov has proposed an algorithm for suppression of the impulsive noise in the frequency-domain. If the amplitude of impulsive noise has low, then long duration of OFDM symbol gives an advantage. It means energy of the impulsive noise is spread along the OFDM symbol and if the energy of impulsive noise is very high, then the performance will be very low. Here, the method used for suppression of impulsive noise is called the impulsive noise compensation method, it has utilized after OFDM demodulation and channel equalization. All other methods for suppression of impulsive noise are mostly used in the time-domain and before OFDM demodulation. Many applications of the OFDM system like digital terrestrial video broadcasting (DVB-T) system uses 64-QAM as a modulation technique, it also could be seriously affected by impulsive interference. Here, the impulsive noise is modeled through Bernoulli-Gaussian model.

Armstrong and Suraweera [15] have presented a new technique for suppression of the impulsive noise in the OFDM system for the estimation of impulsive noise component. This technique will not use the pilot tones. It's only estimated the impulsive noise component for each input sample received, when the value of this component is large, then subtracted the actual input sample from the estimated noise component. Estimation can be done from preliminary based decision of noisy signals. When the impulsive noise occurs, this technique reduced the noise power up to a great extent. This technique using the Bussgang's theorem for the decision process and this process considered as nonlinear process. This technique is used to reduce the bit error rate by two to three orders of magnitude.

Suraweera and Armstrong [16] have explained the noise bucket effect. Impulsive noise is the main problem with many OFDM applications. It tells about the performance degradation of OFDM system induced by impulsive noise, it depends only on the total amount of energy of the impulsive noise during the each OFDM symbol. It shows that when a small number of impulses per symbol is occurring, then noise distribution of the input of the receiver will be approximately Gaussian. Here, it doesn't focus on the descriptive structure of the impulsive noise, in which case BER is observed is same as the BER in the case of Gaussian noise for total energy per symbol. Noise bucket effect means spreading the noise after the fast Fourier transform of received signal so the degradation of performance mainly depends mainly upon energy of the impulsive noise in the OFDM symbol.

Till now, we discussed the techniques for mitigation of impulsive noise like clipping, thresholding, and spreading the noise after the discrete Fourier transform (DFT). Further, we proceed new techniques for mitigation of impulsive noise by using syndromes or pilot tones.

Abdelkefi *et al*. [17] have used the procedure for the impulsive noise compensation, when syndromes are scattered among the transmitted symbols. The signal will be a mixture of different types of noise like as Gaussian noise and impulsive noise, when it sent over the channel. The impulsive noise will be removed by the channel decoding like procedure. It is used 'syndrome' for carrying the information. Pilot symbols are transmitted for symbol synchronizations or estimation wise. These symbols are usually sent with the information symbols to detect or correct the impulsive noise. Here, they used powerful encoder for mitigation of impulsive noise. It is called Reed-Solomon encoder (RS). This encoder can be used as the impulsive noise canceller. It is used to remove the impulsive noise in the presence of receiving vector at each component. In which singular value decomposition is also used to find out the location and total number of the impulsive noise vectors.

Zhidkov [18] has implemented an elementary method for the excision of impulsive noise. It is called a blanking nonlinearity method. This method is used before OFDM demodulation in the time-domain. Here, closed expressions of signal-to-noise ratio will be given for optimal blanking threshold. The better performance of this method is achieved with the help of a large number of the OFDM subcarrriers. The blanking nonlinearity is one of the uncomplicated methods utilizing the nonlinear preprocessing techniques. The main objective is to find optimal threshold under different impulsive noise premises and find out the worst case scenario. This is a conventional method for suppression of impulsive noise.

In [19], Caire *et al*. have introduced the scheme for the effect of impulse has been cancelled through to reconstruction sparse signals observed through projections, it has also used convex programming techniques. It is also cognized as compressed sampling. This method is much robustness to background noise. In the OFDM system not used some frequencies, at those frequencies attenuation will be very high and also some frequencies allocated for pilot symbols. These frequencies are used for the synchronization and the estimation of channel. In which it will reconstruct the projection matrices and also compare the bit error rate using a method with the some lower or upper bounds and with a capacity of a Gaussian erasure channel. It will not detect the exact location of an impulse.

Chen *et al*. [20] have proposed an expense and low complexity technique for estimation as well as compensation of noise in the OFDMA systems. Conventionally estimation schemes for clipping noise have needed all demodulated data symbols. It might not be used in the OFDMA systems, where a particular exploiter known his scheme for modulation the symbols. The proposed method in this paper uses equalized output to identify the no of clips and then uses the information on known subcarriers to reconstruction of the clipping signal. This scheme is only applicable where each user has limited knowledge of the entire signal. OFDMA uses the clipping noise recovery technique. It exploits the knowledge of Known Subcarriers instead of decision directed approach. For example, in the Wi-MAX system only 10% of the subcarriers are already known to the receiver. In which the proposed scheme is used to find out the location of clipped samples from the equalized samples and then uses the equation to determine the clipping noise. Simulation results show that the given scheme could be significantly improved system performance.

Kitamura *et al*. [21] have proposed an iterative scheme for the suppression of impulsive noise. It has a very short duration and wide band property. Impulsive noise affects the mostly all subcarriers after the DFT Operation and performance will be degraded. If the impulsive noise is very high, it mainly effects on the subcarriers of the OFDM system. In which reduce the effect of impulsive noise by yielding the replicated signal of the impulsive noise and reduce it from the received signal, each ideal impulse is estimated iteratively and subtracted from the received signal in the time-domain. First all the received data symbols passed to the DFT and demodulate each subcarrier, symbols also contained an impulsive noise and then performed equalization and noisy estimation. After that channel multiplied to the symbols and preformed IDFT and then subtract the original symbols from the estimated symbols. This scheme achieves a better bit error rate as compared to conventional schemes.

Lampe [22] has proposed scheme when impulsive noise occurs in bursts. If those bursts are short as compared to coding frame, then it is hope to successfully mitigate the impulsive noise. It is based on the block compresses sensing. It is used of null-subcarriers in power line Communication (PLC) for OFDM transmission system and the burst structure of impulsive noise used to detect the location and the values of noise samples of signal at the receiver side. This scheme is only applicable if the length of OFDM symbol is more than the impulsive noise burst otherwise the entire OFDM symbol will be destroyed, when the length of impulse noise burst signal is more. The bursty nature of the impulsive noise is based on the application of compressed sensing for block-sparse signals. A compressed sensing technique successfully mitigates the impulsive noise and improves transmission reliability. Numerical results shown that block based compressed sensing technique is easily found out the impulsive noise bursts and provide better estimates.

Al-Naffouri *et al*. [23] have used guard band null subcarriers for estimation and cancellation of impulsive noise. It is a bottleneck problem in the digital subscriber line (DSL) communication. Here, impulsive noise is considered as a sparse vector and developed sparse reconstruction algorithm would be used to combat the impulsive noise. It is used a priori information for sparse signal recovery. Complexity of sparse reconstruction algorithm is very low as compared to minimization techniques. Here, they used free guard band subcarriers to estimation and cancellation of impulsive noise and compressed sensing is done by using Bayesian method. It will give a priori information to optimal estimation with lower complexity. The performance of this method is better as compared to other techniques like minimization techniques and other sparse recovery techniques. This method achieves high date rate in DSL lines with impulsive noise estimation and cancellation.

Yih [24] has proposed an iterative cancellation technique for impulsive noise in the OFDM system. Basically, it is used the blanking nonlinearity [18] scheme iteratively, when the blanking nonlinearity is used for suppression of impulsive noise as a single iteration then sacrificed the signal power and inter-carrier interference. These problems will be alleviated, when the blanking nonlinearity used iteratively, it will effectively reduce inter-carrier interference. It is very simple and practically applicable method. This method is nonlinear operation, after the implication signal will not be orthogonal and generates inter-carrier interference. It will degrade the performance of OFDM system drastically. If a blanking nonlinearity method uses an adaptive threshold for each method, then it will give better performance after three iterations. It has fast convergence and less complexity.

Tseng *et al*. [25] have provided an efficient approach is clipping for suppression the impulsive noise in the OFDM system. It is derived the threshold value without using a priori knowledge of the probability density function (PDF) of noise. In most practical scenarios, the PDF of impulsive noise is rapidly changing over time. A decoding metric is used with clipping technique. Channel coding is approximate the performance of capacity limit. It is ineffective, when the probability of impulsive noise is very high. Clipping threshold enhances the bit error rate drastically, whenever it can placed in front of the DFT demodulator.

In [26], Ren *et al*. have proposed scheme to make less severe the periodic impulsive noise with the help of IIR notch filters. When the signal is received at the receiver, it will interfere by the periodic impulses that is equivalent to damping sinusoids add into the received signal. Whenever the impulsive noise will be occurring, then the synchronization between OFDM and power line communication system may not work properly and the performance will be degraded. So noise should be extenuated before the synchronization of the OFDM system to assure that the system will work properly. It will also shorten the adverse effects of impulsive noise. Here, it will suppress the impulsive noise by using three steps: first it will detect the impulsive noise or estimate the location of impulsive noise and in the second step it will find out the frequency of the impulsive noise and in the last step, it will crush the impulsive noise by using an adaptive IIR filter. At last get the output from the IIR filter. It is suitable for narrowband applications.

Mathew and Jeevitha [27] have propounded the two different algorithms for canceling the effect of impulsive noise in the OFDM system. Impulsive noise is very short duration as compared to the long OFDM symbol duration. It provides the immunity to noise, when the strength of impulses is less. After fast Fourier transform, it affects all subcarriers in the OFDM system. The approach is used here for cancellation of impulsive noise with two algorithms impulsive noise location and value search algorithms. After performing the cancellation techniques iteratively, it will compact the impulsive noise error and improves the performance significantly.

Al-Naffouri *et al*. [28] have proposed an algorithm that uses the guard band null subcarriers for the cancellation and estimation of impulsive noise. When the strength of noise is strong in the time-domain, it will erase whole OFDM symbol. This algorithm is used in the smart receivers to estimate and mitigate the impulsive noise. These receivers have a significant advantage with respect to spectral efficiency, speed, and simplicity. Here, the impulsive noise is assumed to be sparse and thus any sparse reconstruction algorithm can be used at the receiver. This collectively uses a partial DFT matrix in the OFDM system and a priori information of the impulsive noise distribution. It is an efficient and fast algorithm.

Chapter 3

BASICS OF ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

This chapter provides the brief introduction about the OFDM system. It discusses the block diagram and mathematical model of the OFDM system. In which we also discussed the implementation and simulation of OFDM system using MATLAB, in order to know the performance of OFDM system under different modulation techniques and different channel conditions.

3.1. Introduction

Technologies of wireless engineering, such as cellular telephones and wireless networking are now commercially driven by ever more demanding consumers, who are ready for seamless integration of communication networks from home to car, and into the office. There is a need to enhance the data-rates so information transmits accurately and quickly. Engineers have a suitable technique Orthogonal frequency division multiplexing (OFDM) is utilized for high data-rate wireless applications.

3.2. Fundamental Concepts of OFDM

3.2.1. What is Orthogonal Frequency Division Multiplexing?

Orthogonal frequency division multiplexing (OFDM) is based on worldwide interoperability for microwave access [1, 29]. It is a key broadband wireless technology, which supports the data-rates in excess of 100 Mbps. It is an effective solution to the alleviate the effect of inter-symbol interference (ISI) caused by dispersive channel and also widely exploited for combating the multipath fading in the communication system.

OFDM is the special case of the multi-carrier modulation [30]. In this modulation scheme, data are transmitted by dividing the bandwidth into N number of subcarriers. Each subcarrier is represented as smaller subband, it has a smaller bandwidth as compared to the single-carrier system. One of the main advantages of the OFDM system is to increase robustness against frequency selective fading. In a single-carrier system, if the deep fade occur, it could affected the whole link, but in the multi-carrier system, only little number of subcarriers will be affected.

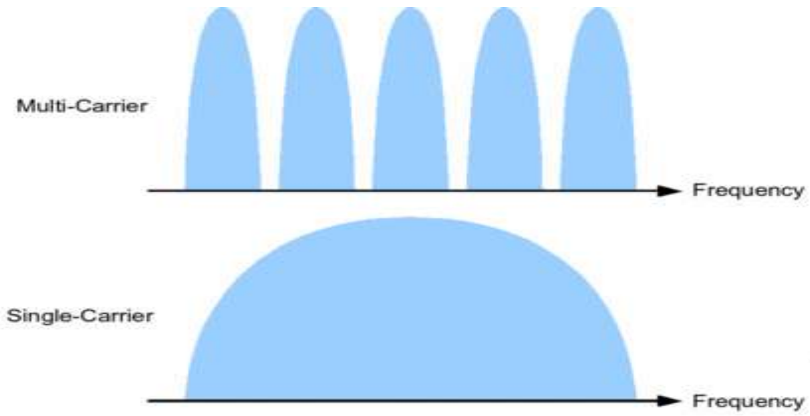


Fig. 3.1. Multi-carrier and single-carrier system [29]

Here, data bits are transmitted parallel on the different number of frequencies and as a consequence, the length of symbol period is much longer as compared to a single-carrier system. In the both system data-rate will be same. Consider a bandwidth (B) available for communication, in the single-carrier system symbol time is

$$T = \frac{1}{B} \tag{3.1}$$

For multi-carrier system symbol time is

$$T = \frac{N}{B} \tag{3.2}$$

But the overall symbol rate in single-carrier and multi-carrier systems is unchanged. In both cases symbol rate is B. In the parallel or frequency division multiplexing (FDM) system, the total spectrum is divided into N non-overlapping frequencies, and it provides guard bands between those frequencies. This leads to not an efficient use of the available spectrum. But in the OFDM system, the total spectrum is divided into N overlapping frequency subbands, which are orthogonal to each other. In Fig. 3.2 shows almost 50% of the bandwidth is saved.

3.2.2. OFDM Message

The OFDM message is generated through the complex baseband symbols. Each symbol is modulated onto the corresponding subcarrier by using different modulation schemes like phase shift keying (PSK) and quadrature amplitude modulation (QAM). Before transmission data symbols are converted serial to parallel format. The frequency spacing between the adjacent subcarriers are same, where N is the number of subcarriers. This can be accomplished by using the inverse discrete Fourier transform (IDFT) at the transmitter side and discrete Fourier transform at the receiver side. In practice, the baseband OFDM transmitter and receiver perform the inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) respectively.

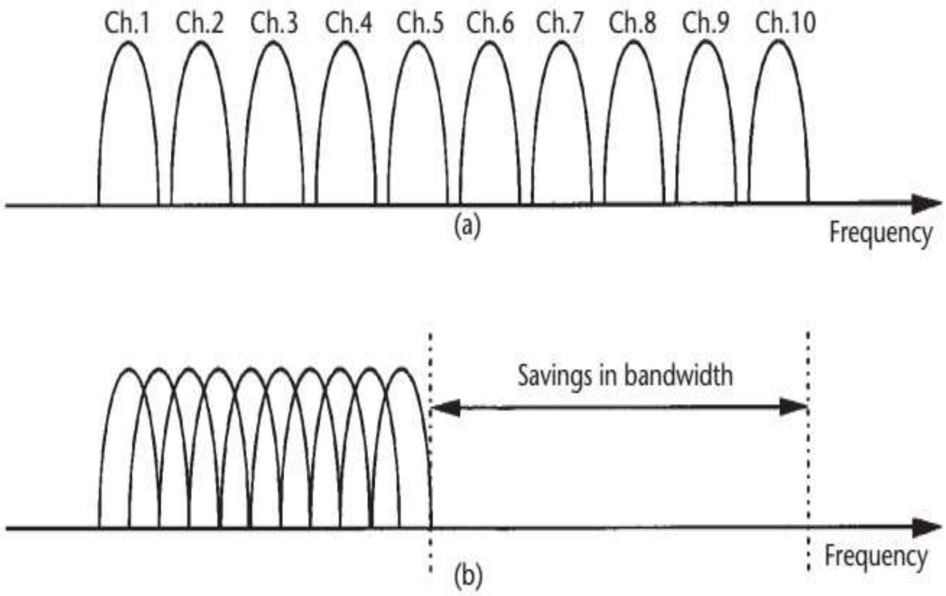


Fig. 3.2. (a) Conventional multi-carrier technique and (b) Orthogonal multi-carrier modulation technique [29]

3.3. Mathematical Model of OFDM

In the OFDM system, the main component on the transmitter side is a block of IFFT and at the receiver side is FFT . These blocks are distinguishing the function of OFDM system from the single-carrier system. Fig. 3.3 shows the block diagram of an OFDM communication system [1]. Now, let us discuss all the blocks one by one.

Input applied to the block of IFFT in the form of a complex vector. This vector has modulated through the PSK or QAM. Complex vector is $X = \left[X_0 \; X_1 \; X_2 \ldots X_{N-1} \right]^T$, the length of vector is N, now the length of IFFT is also N [31]. All elements of the X vector represent data to be channeled on the accompanying subcarrier. Throughout this work we used upper case to represent the frequency-domain and lower case to represent time-domain. Now the mathematical expression of inverse discrete Fourier transform is given as

$$x_m = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n \exp\left(\frac{j2\pi nm}{N} \right) \quad for\ 0 \le m \le N-1 \tag{3.3}$$

Most QAM, and PSK modulation are used in OFDM systems so each element of X is represented as a QAM and PSK constellation point.

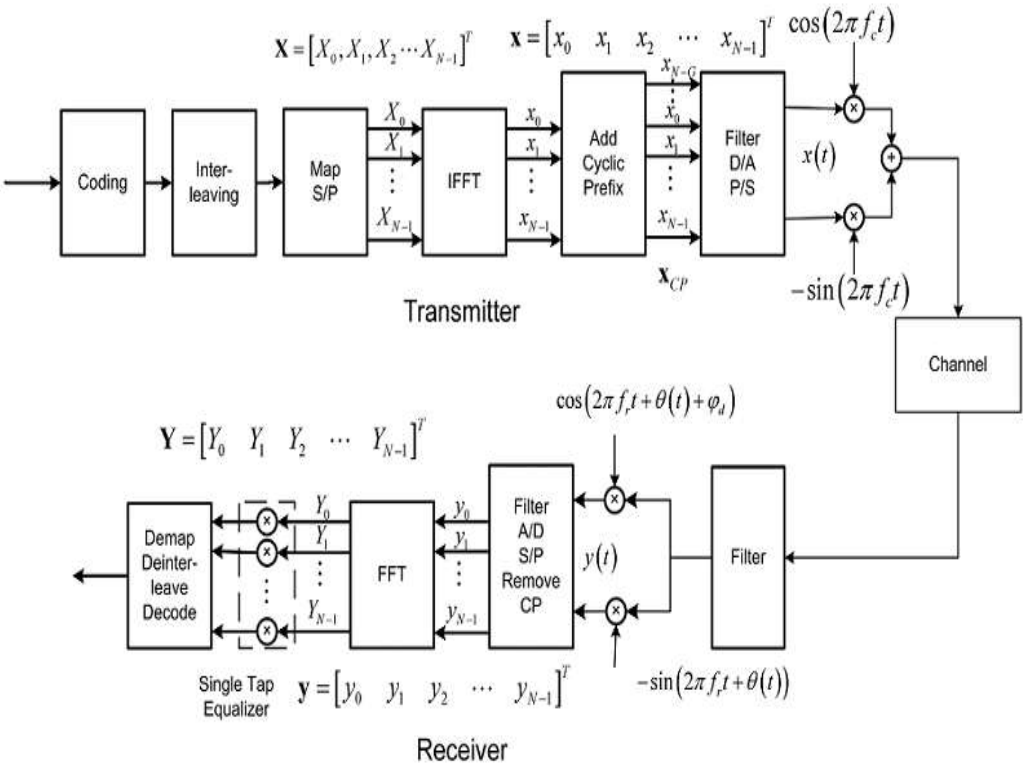


Fig. 3.3. Block diagram of an OFDM communication system [1]

The output of IFFT is also a complex vector in the discrete time-domain, it is represented by; $x = [x_0 \; x_1 \; ....x_{N-1}]^T$, then apply as input to the FFT block. The mathematical expression of discrete Fourier transform is given as

$$X_n = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} x_m \exp\left(\frac{-j2\pi nm}{N}\right) \quad \textit{for } 0 \le n \le N-1 \qquad (3.4)$$

Now, we get the discretized signals in the time-domain at the input of FFT and the output of IFFT, after transforming both will have the same amount of energy and average power. In Fig. 3.4 shows an example of IFFT and FFT for 4-QAM and $N = 16$. The input is given to the IFFT in the form of 4 complex symbols and gets the same output of complex symbols after the FFT Operation. Apply X vector as input in the form of random values for 4-QAM Constellation points $\{1+j, 1-j, -1-j, -1+j\}$ to the IFFT, now the output is in the time-domain and apply as input to the FFT block, we get the same X complex vector. For $N \ge 64$, the real as well as imaginary components of the IFFT in the time-domain are roughly as a Gaussian. For wireless OFDM system the value of N subcarriers ranging from 64 in the wireless local area network system to 8096 in the digital television system.

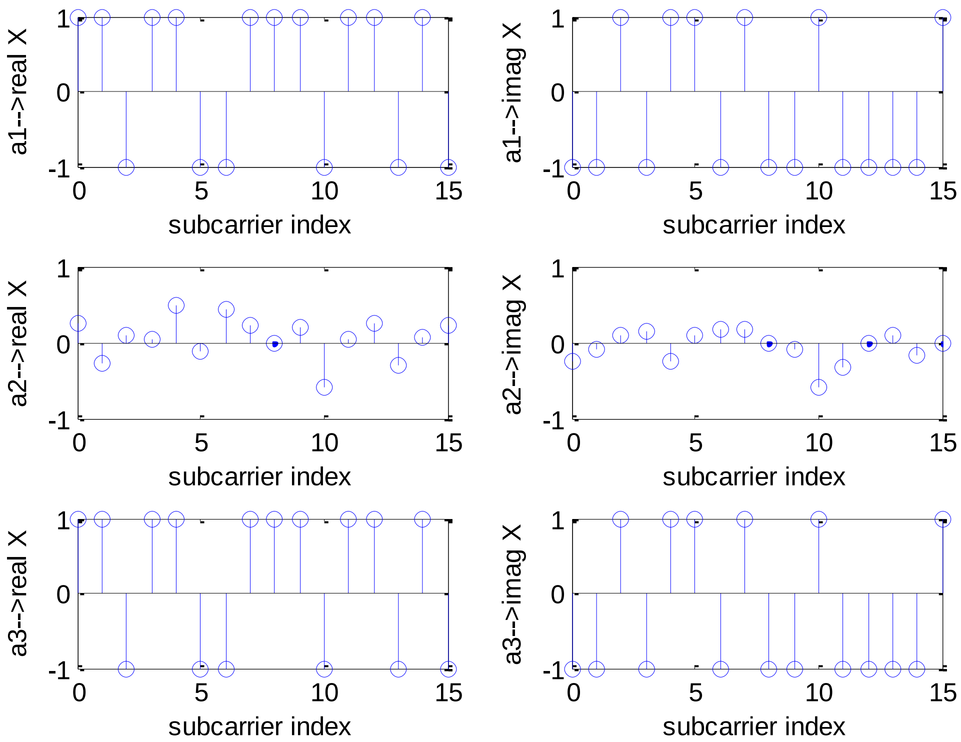


Fig. 3.4. a_1) Input to the IFFT, a_2) Output of the IFFT, and a_3) Output of the FFT

The next block gives the introduction of a cyclic prefix (CP) as a guard interval (GI) [32], length of the guard interval should be more as compared maximum to excess delay of the multipath propagation channel. When we considered a sequence of symbols $\mathrm{x}(i) = [\mathrm{x}_0(i)\ x_1(i)\ x_2(i) \ldots x_{N-1}(i)]^T$ being the output in the i^{th} symbol period of IFFT. In the OFDM system cyclic prefix is appended to the beginning of each time-domain signal before transmission. It can also be described as a number of samples taken from the end of symbol is added to the beginning of the symbol. The sequence after adding cyclic prefix is

$$\mathrm{x}_{CP}(i) = [x_{N-G}(i) \ldots x_{N-1}(i), x_0(i) \ldots x_{N-1}(i)]^T \tag{3.5}$$

where G is the length of the CP, it also introduces the some redundancy and reduces the overall data-rate. It removes the effect of both inter-symbol interference (ISI) and inter-carrier interference (ICI) [33-34].

To understand, consider a simple case where the received baseband signal is the addition of different gains (g_1, g_2) and delays (τ_1, τ_2) of the transmitted signal.

$$y(t) = g_1 x(t+\tau_1) + g_2 x(t+\tau_2) \tag{3.6}$$

Here, the signals will be complex. Fig. 3.5 shows the two delayed versions of OFDM symbol and time window for the receiver FFT. The output of the FFT at the receiver side for each OFDM symbol within the time period is shown. In this case, if the delay spread $(\tau_2 - \tau_1)$ is less than the length of the cyclic prefix, there are no ISI, and the receiver FFT

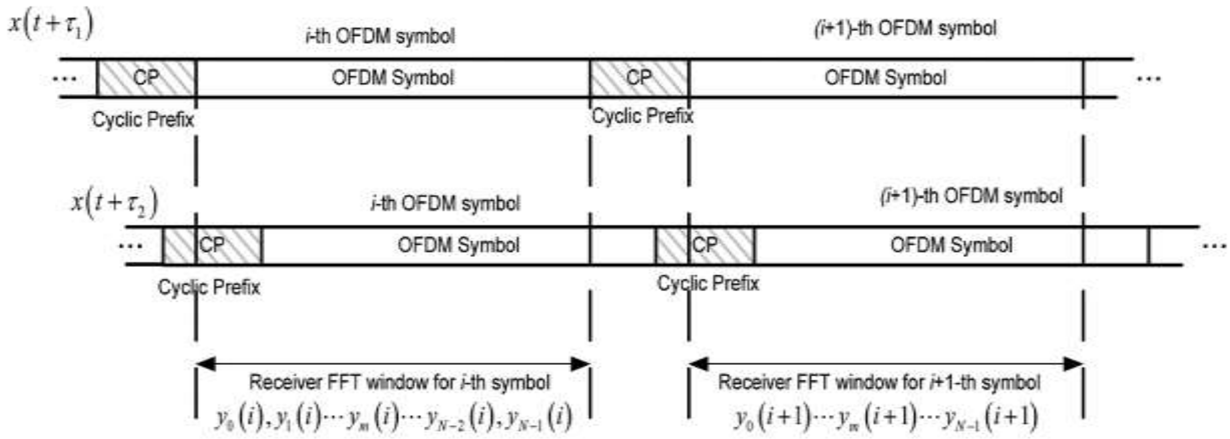


Fig. 3.5. OFDM symbols in multipath channel [1]

windows is synchronized with the beginning of the main symbol period of the arriving signal, then no ISI or ICI occurs [35].

When AWGN is imparted to the received signal, then signal before FFT is represented as

$$y_m = x_m + w_m \tag{3.7}$$

where w_m is a sample of white noise, now the RX vector in the time-domain is applied to the FFT operation $y = [y_0\ y_1\ y_2....y_{N-1}]^T$ and the output of the FFT is $Y = [Y_0\ Y_1\ Y_2....Y_{N-1}]^T$, samples are required per symbol (excluding CP)

$$Y_n = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} y_m \exp\left(\frac{-j2\pi mn}{N}\right) = X_n + W_n \tag{3.8}$$

where

$$W_n = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} w_m \exp\left(\frac{-j2\pi nm}{N}\right) \qquad \text{For } 0 \le n \le N-1 \tag{3.9}$$

W_n is the white noise component after the FFT operation. So after demodulation of the OFDM symbol is recovered and admitting the effect of noise [36-37]. The transmitted symbols can be recovered from the faded received symbols by using a technique called equalization.

$$\hat{X}_n = \frac{Y_n}{H_n} = X_n + \frac{W_n}{H_n} \tag{3.10}$$

3.3.1. Orthogonality in OFDM

One of the most important advantages of OFDM is the efficient use of the frequency spectrum, when the number of subcarriers overlaps with each other in the frequency-domain. These subcarriers will be orthogonal to each other otherwise interference will occur. The frequency separation between the adjacent subcarriers is $\Delta f = \frac{1}{N.T_s} = \frac{1}{T}$, where $N.T_s$ the symbol duration. It will have a sinc waveform frequency response, Fig. 3.6 shows the frequency response. This frequency response shows for only 5 subcarriers which are orthogonal to each other.

Mathematically, Orthogonality of the two signals can be described as, $\xi_k(t)$ and $\xi_l(t)$ over time period $N.T_s$.

$$\int_o^{NT_s} \xi_k(t)\, \xi_l^*(t)dt = \begin{cases} 0, k \neq l \\ 1, k = l \end{cases} \tag{3.11}$$

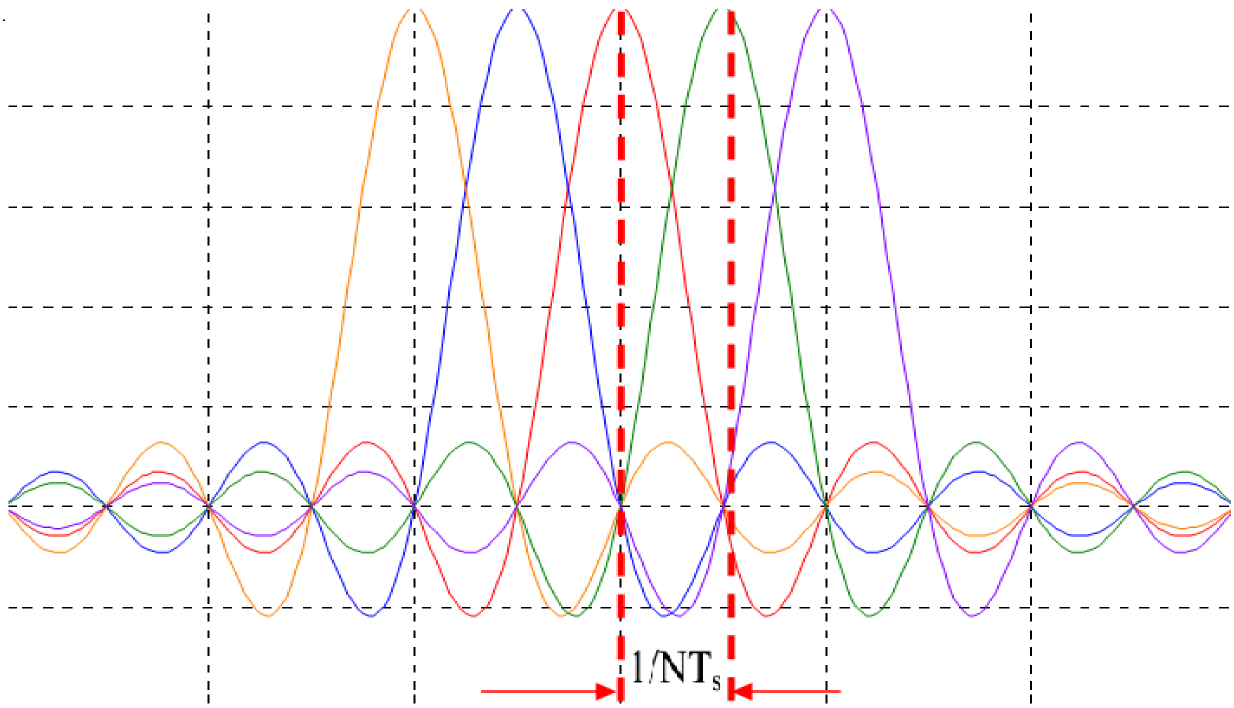


Fig. 3.6. Orthogonality of the subcarriers [29]

3.4. Implementation of OFDM

In this section, we discussed the implementation of the OFDM system, in order to know about the performance of the OFDM system under AWGN or thermal noise and different fading conditions. We analyze the performance of the OFDM system, under the different modulation schemes, for example, BPSK, 4-QAM, 64-QAM and plot the BER versus SNR.

3.4.1. OFDM Model for Simulation

It is simulated through the MATLAB and to analyze the performance of the OFDM system under the different modulation techniques and different channel conditions. OFDM system is used to convert the frequency selective fading channel into the flat fading channel, by transmitting the symbols onto an N number of subcarriers as compared to single-carrier. This is the main advantage of the OFDM system. There are mainly four terms are used for assessing the performance of the OFDM system. They are peak power clipping, multipath delay spread, channel noise, and time synchronization errors. Fig. 3.7 shows model of the OFDM system. In which we will discuss each main block of the OFDM system separately. It also provides simulation results of the OFDM system under AWGN and fading channels [38-39].

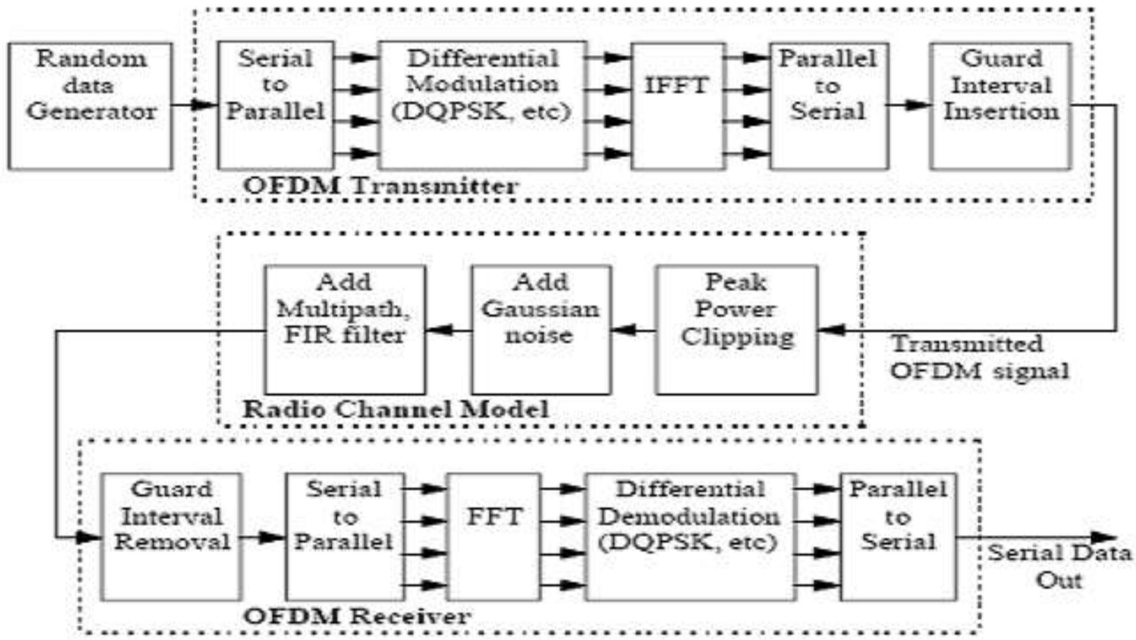


Fig. 3.7. OFDM model for simulation [38]

3.4.2. Data Stream Modulation

The data to be transmitted on a different number of subcarriers by using different schemes of modulation like phase shift keying and quadrature amplitude modulation. BPSK is the simplest technique is used for the modulation in the OFDM system. BPSK produces a constant amplitude signal with the varying phase. So it will reduce the amplitude fluctuations during the fading conditions.

3.4.3. Serial to Parallel Converter

In which we convert the serial data into the parallel data by using serial to parallel converter block. First modulate the input data stream by using different type of modulation schemes like 64-QAM, 4-QAM, and BPSK then, it will pass through the serial to parallel converter and apply to the IFFT block.

3.4.4. Inverse Fast Fourier Transform (IFFT)

IFFT is used to convert the symbols from frequency-domain to time-domain. After the IFFT operation, the guard period or cyclic prefix is added to input data modulated streams.

3.4.5. Cyclic Prefix

Cyclic prefix is used to eliminate the adverse effect of ISI. Length of CP depends on the channel delay spread, If the delay spread of two OFDM symbols is more than the length of cyclic prefix is more or vice versa.

3.4.6. Channel

Overall channel in the OFDM system is the frequency selective channel, but the channel experienced by each subcarrier is the flat fading channel, in which each subcarrier experience independent fading. FIR filter is used for simulation purpose. The length of FIR filter depends upon the number of taps used.

3.4.7. Receiver of the OFDM System

The receiver performs the reverse operation of the transmitter. In which, first CP is removed, after that it will convert serial data into parallel data. After conversion, performs the fast Fourier transform operation (FFT). The output of the FFT will convert back to the input symbols through demodulation.

3.4.8. OFDM Simulation Results

The modulation method is used for the simulation of the OFDM system is BPSK, 4-QAM, 64-QAM [40]. Correspondingly, each modulation has a different bit error rate versus signal-to-noise ratio. Table 3.1 shows all the configuration used for simulation of the OFDM system.

Table 3.1. OFDM system parameters used for simulation

Parameter	**Value**
Modulation Used	4-QAM, 64-QAM,BPSK
Number of Subcarriers	2048
Cyclic Prefix	512
Number of L Tap	5
SNR (dB)	0 to 20

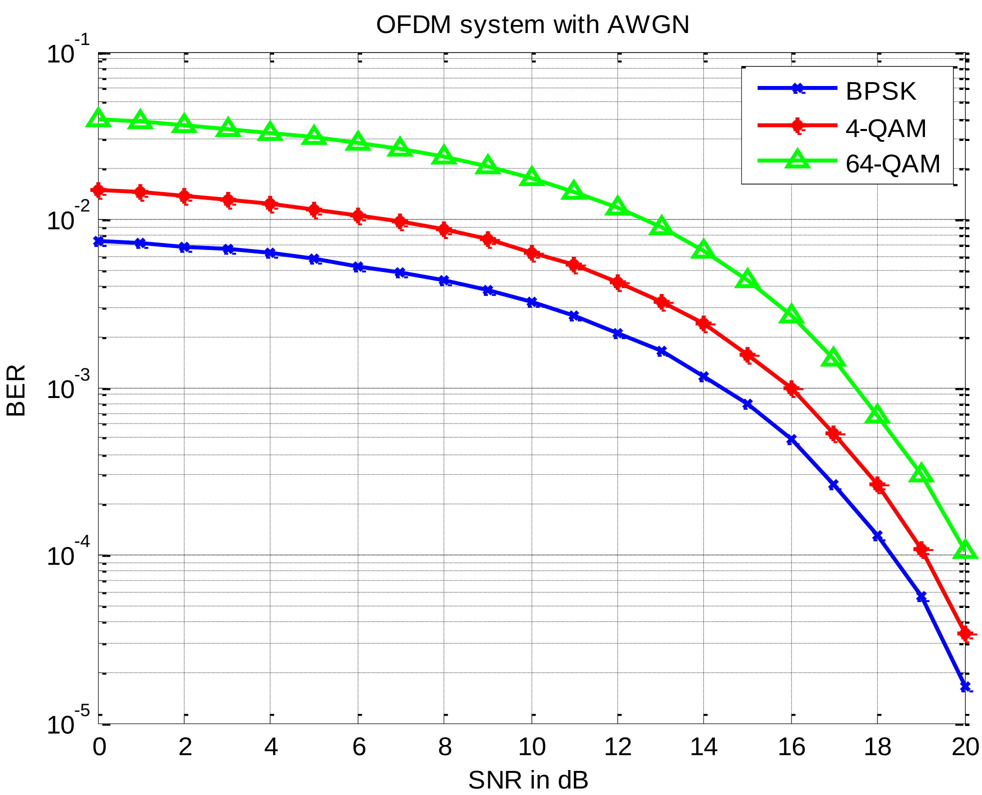


Fig. 3.8. BER performance of OFDM system in an AWGN channel

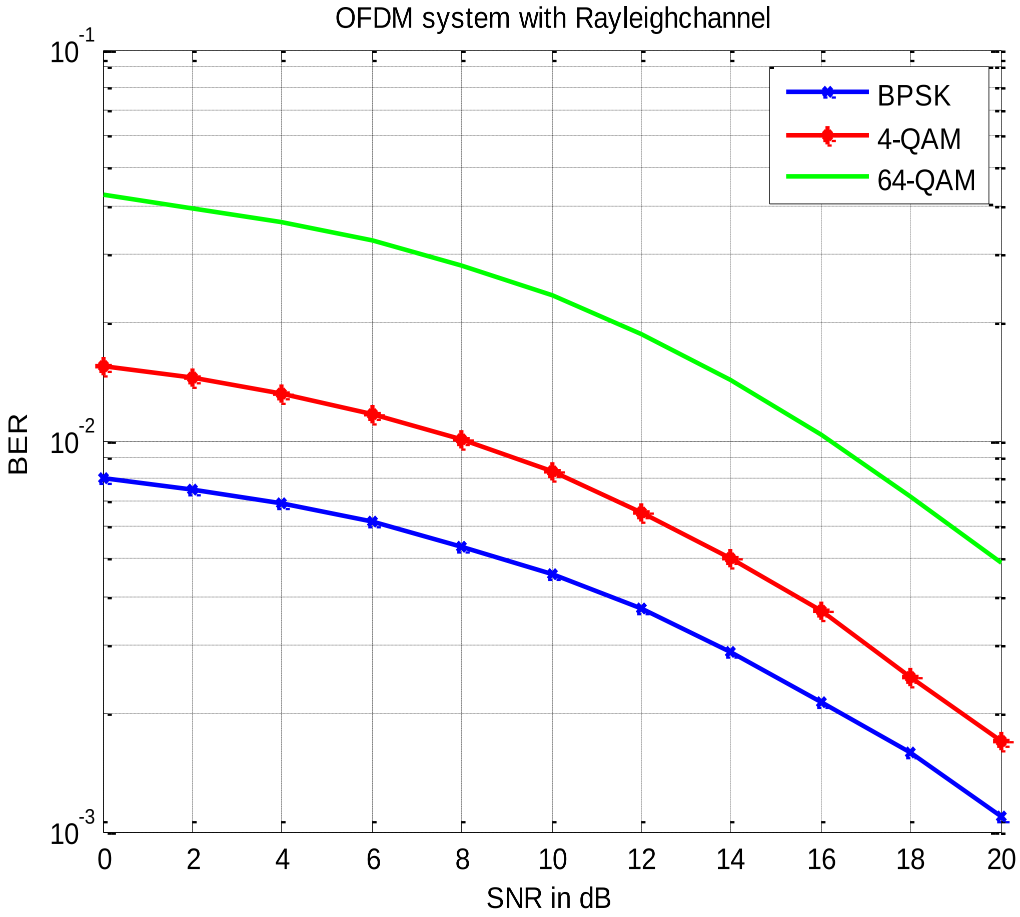


Fig. 3.9. BER performance of OFDM system in a Rayleigh fading channel

From Fig. 3.8 observed the performance of OFDM system in an AWGN channel by using different modulation schemes like QAM and PSK. For 64-QAM modulation scheme probability of bit error rate is high as compared to the 4-QAM. For SNR 10 dB, P_e is $10^{-1.5}$ in 64-QAM for AWGN channel and in the 4-QAM P_e is $10^{-2.2}$. Fig. 3.9 shows the BER performance of OFDM system for Rayleigh fading channels, in which performance is more degraded as compared to AWGN channel due to the effect of multipath fading [41-42].

3.5. Advantages of OFDM System

The main advantages of OFDM system are

1. The OFDM system efficiently uses the spectrum overlapping in the orthogonal subcarriers.
2. It is more immune to the frequency selective fading by converting the wide band into narrow band subcarriers.

3. It eliminates inter-symbol interference and inter-carrier interference.
4. It provides protection against the co-channel interference and the impulsive noise or low amplitude of impulses.
5. OFDM is the mathematically and practically efficient by using FFT and IFFT implementation techniques.

3.6. Limitations of OFDM System

The main limitations of OFDM are nonlinearities and frequency synchronization problem.

1. In the process of timing synchronization is finding the commencement of a symbol in the receiver, if the timing mismatch is within the CP the demodulation produces a linear phase, which is corrected at the output of FFT by the channel estimator, If it is not corrected, then interference will occur.
2. Due to the mismatch of the RF oscillator at the transmitter and receiver side, carrier phase noise will occur.
3. Frequency offset errors are induced by mismatch between the RF oscillators and the Doppler shifts.
4. In the OFDM modulation is the highest instantaneous signal peak relative to the average signal power.

Chapter 4

FADING CHANNELS AND IMPULSIVE NOISE

This chapter gives a brief introduction to the fading and distinct types of multipath fading. The important processes used to model the fading channel are introduced. It also includes the basic concept of impulsive noise and modeling of impulsive noise.

4.1. Introduction of Fading

The most severe problem in the radio signals is a variation of the signal strength in terms of amplitude, phases, or multipath delay over a short duration of time is called fading. Fading is induced by the interference between two or more versions of transmitting signal arrives at the receiver slightly at distinct times.

There are many factors that can produce fading Reflection, Diffraction and Scattering. Reflection occurs when the electromagnetic waves impinge on an object which has very large dimensions as compared to the wavelength. For example, when the radio waves are reflected from the earth's surface, random variations in the polarization of the wave may occur.

Due to the change of polarization, length of the signal level is reduced because of an antenna has inability to change of the polarization. Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities. Due to the absorption of RF energy in the ionosphere fading occurs. Absorption fading occurs for a longer period than the other types of fading. Multipath will occur due to the reflections from the ground and surrounding structures [43].

4.1.1. Path Loss

With the increasing distance between transmitter and receiver, the average power will be decreased. It may also be defined as the difference between the effective, transmitted power and received power. It represents the signal attenuation as a positive quantity measured in dB. In free space, when there is the direct line of sight between transmitter and receiver and there are no secondary waves from the medium objects, the received power is inversely proportional to the square of the carrier frequency and the square of the distance given as

$$P_R \propto \frac{GP_T}{f^2 d^a} \tag{4.1}$$

where P_R and P_T are the received and transmitted powers, f is the carrier frequency, d is the distance between transmitter and receiver, G is the power gain, and a is the path loss component. The free space path loss model can be defined as

$$PL(dB) = 10\log\frac{P_T}{P_R} = -10\log\left[\frac{G_T G_R \lambda^2}{(4\pi)^2 d^2}\right] \tag{4.2}$$

where PL is path loss in dB.

4.1.2. Shadowing Effect

In which the received power fluctuates randomly due to objects obstructing in the medium. When the locations of the transmitter and receiver have different surroundings or conditions, the variation in the strength of the signal should be different. If the large variations in the shadowing process, then the performance of the wireless cellular communication is worst.

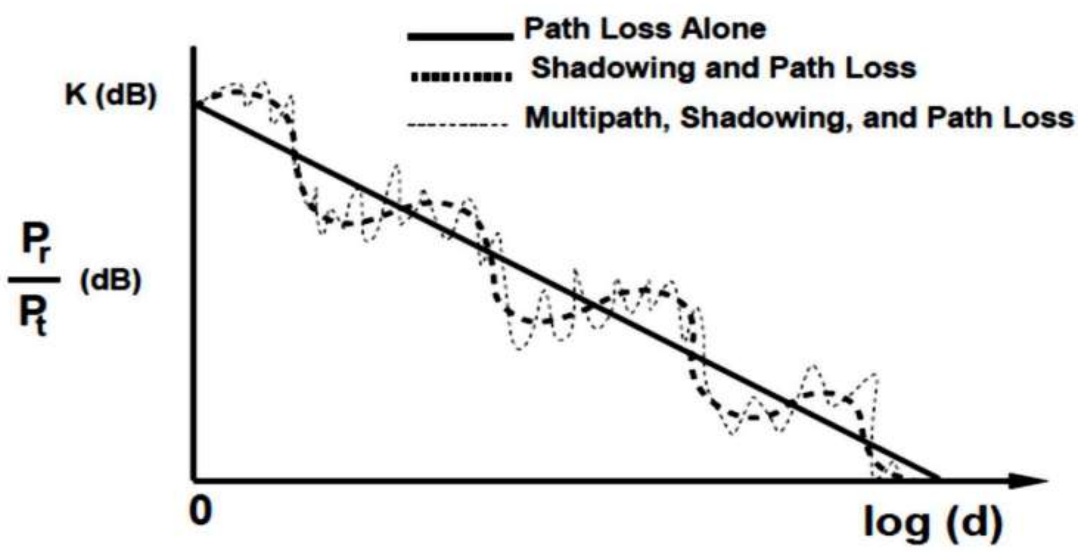


Fig. 4.1. Received to transmitted power ratio versus distance [7]

The path loss is measured in dB. It means path loss randomly and log-normally distributed. In the path loss equation does not consider the environmental conditions because they will be varied highly at two different locations having the same transmitter and receiver distance. Log-normal shadowing describes the shadowing effects which occur over a large number of measurement locations having the same transmitter and receiver distance.

$$PL(dB) = PL(d) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \tag{4.3}$$

where X_σ is a zero-mean Gaussian distributed random variable with a standard deviation σ. In Table 4.1 discus about the attenuation due to shadowing effect in heavy built urban areas, sub-urban areas, and rural areas.

Table 4.1. Attenuation in the radio channel

Description	**Typical Attenuation due to shadowing**
Urban areas	20 dB variation from street to street
Suburban areas	10 dB greater signal power than urban areas
Open rural areas	20 dB greater signal power than urban areas
Terrain irregularities	3-12 dB signal power variation

4.2. Mobile Multipath Fading Parameters

When multipath components are present, fading is always present. Multipath components arrived at the receiver at the slightly different times. If both transmitter and receiver components are moving then there is a phase difference between the received components which leads to shift in the frequency. We can define these parameters with the help of power delay profile of the channel. The power delay profile represents the plot of receiving power as a function of excess delay with respect to the fixed delay interval [7, 43].

Parameters are divided into two types of categories

1. Time Dispersion Parameters
2. Frequency Dispersion Parameters

4.2.1. Time Dispersion Parameters

- Mean Excess Delay
- RMS Delay Spread
- Maximum Excess Delay
- Coherence Bandwidth

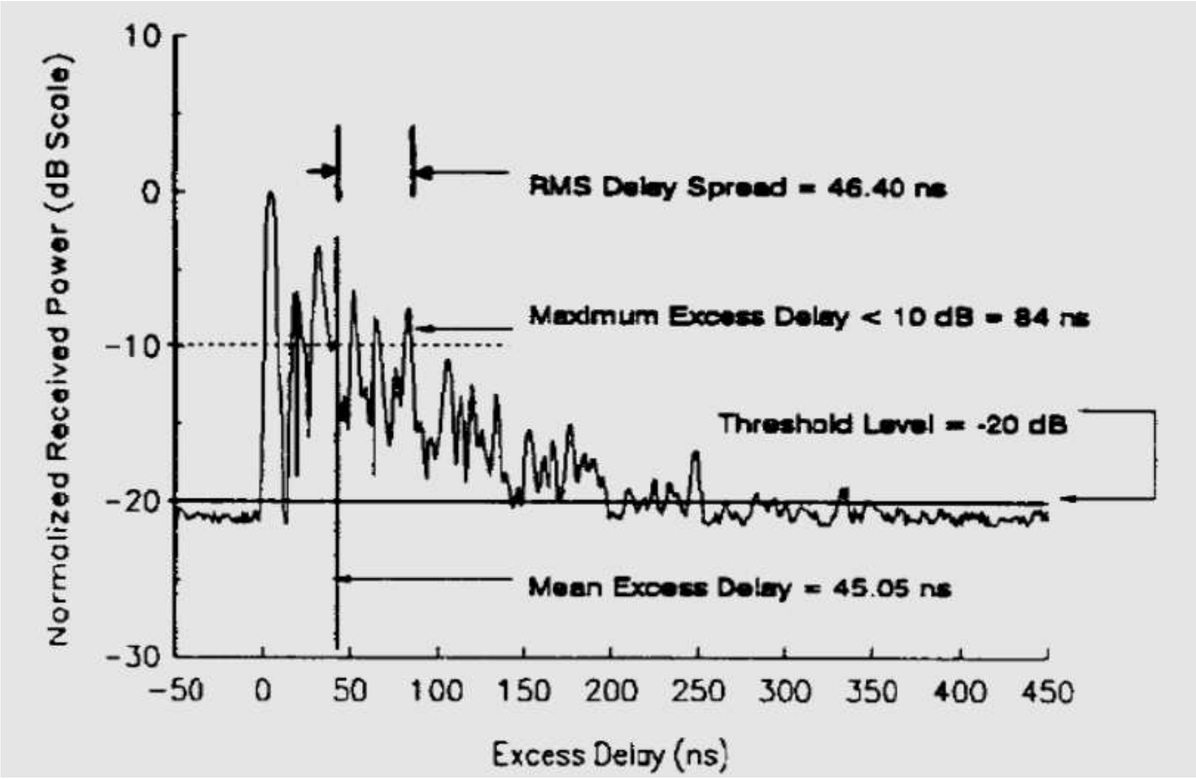


Fig. 4.2. Power delay profile parameters [7]

4.2.1.1. Mean Excess Delay $(\bar{\tau})$

The mean excess delay can be determined from the power delay profile. The mean excess delay is the first moment of the power delay profile. It can be defined as

$$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)} \tag{4.4}$$

4.2.1.2. RMS Delay Spread (σ_τ)

The RMS delay spread is the square root of second central moment of the power delay profile. It can be defined as

$$\sigma_\tau = \sqrt{\bar{\tau}^2 - (\bar{\tau})^2} \tag{4.5}$$

where σ_τ is RMS delay spread of the wireless channel

$$\bar{\tau}^2 = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)} \tag{4.6}$$

where a_k is arriving path gain or receiver power and τ_k is the delay path.

4.2.1.3. Maximum Delay Spread $(\tau_{\max})$

It can calculate when first arriving component at τ_0 and last arriving component at τ_{L-1}. L is the total length of delay spread in power delay profile.

$$\tau_{\max} = \tau_0 - \tau_{L-1} \tag{4.7}$$

4.2.1.4. Coherence Bandwidth (B_c)

It is the statistical measure of the range of frequencies over which the channel can be considered flat. It means channel which passes all the spectral components with equal gain and linear phase. It can also be said that coherence bandwidth is over which frequency component strong potential for amplitude correlation has. Coherence bandwidth is denoted by B_c. If the coherence bandwidth is defined as the bandwidth over which the frequency correlation function above 0.9 then coherence bandwidth is

$$B_c = \frac{1}{50\sigma_\tau} \tag{4.8}$$

where σ_τ is RMS delay spread, if the correlation function above 0.5

$$B_c = \frac{1}{5\sigma_\tau} \tag{4.9}$$

4.2.2. Frequency Dispersion Parameters

- Doppler Spread
- Coherence Time

4.2.2.1. Doppler Spread (B_D)

A channel shows time varying nature when there is movement between transmitter and receiver or even movement of objects between transmitter and receiver. Doppler spread B_D is a measure of spectral broadening caused by a time rate change of the mobile radio channel. When a pure sinusoidal tone of frequency f_c is transmitted, the received signal spectrum is called the Doppler spectrum. This spectrum will have components In the range $f_c - f_d$ to $f_c + f_d$, where f_d is the Doppler shift. If the bandwidth of baseband signal (B_s) is more than (B_D) then the effects of Doppler spread on the receiver is negligible. This is slow fading. If (B_s) is less than (B_D) then the effects of Doppler spread on the receiver is high. This is fast fading.

4.2.2.2. Coherence Time (T_c)

Coherence time is the statistical time duration over which the channel impulse response is invariant. It is defined as time duration over which received signals have a stronger potential for amplitude correlation. If the reciprocal bandwidth of baseband signal is more than coherence time, thus causing distortion at the receiver.

$$T_c \approx \frac{1}{f_m} \tag{4.10}$$

where f_m is maximum Doppler shift.

4.3. Multipath Fading

The presence of reflecting objects and scatters in the channel creates a constantly changing environment that dissipates the signal energy in amplitude, phase and time. These effects result in multiple versions of the transmitted signal that arrive at the receiving antenna.The multipath fading feature is used to design a radio communication system. In any terrestrial radio communication system, the signal will reach the receiver through multiple paths. It's due to the reflection from the hill, surface, buildings, moving objects, and ground etc. In Fig. 4.3 shows the signal through multipath reached for the receiver.

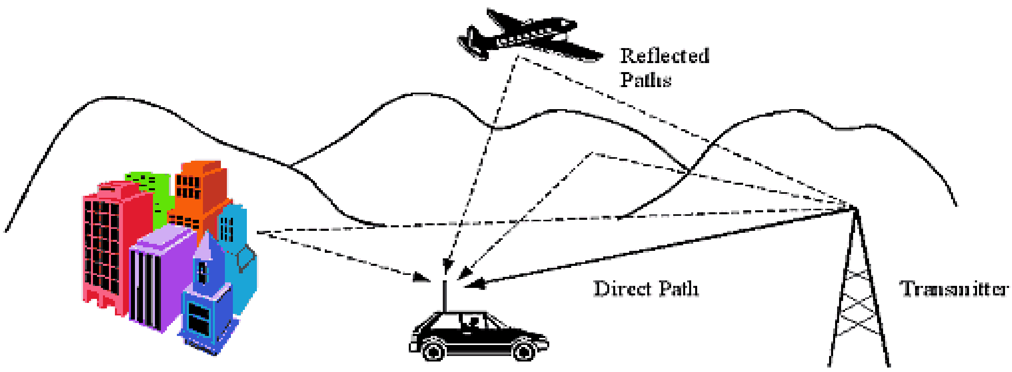


Fig. 4.3. Multipath fading channel [7]

At the receiver side output signal is a sum of all the signals from the independent paths, all they have different path lengths, the signals will add or subtract depends upon the relative phases.

Most of the time relative path length of signal will be changed. Because of motion between the radio transmitter, or receiver or any of the objects that provides a reflective surface moving. This will result in the change of phase shift of the signal arriving at the receiver, in turn strength of signal level is varying as the result of the different way in which signals will sum together. It is the main reason of the fading present in the signals. These cause problems like phase distortion and ISI, so it is necessary to incorporate some features that minimize the effects of these problems. Now, we will discuss about the different types of multipath fading.

4.3.1. Types of Multipath Fading

Propagation models have traditionally focused on predicting the average received signal strength at a given distance from the transmitter, as well as the variability of the signal strength in close spatial proximity to a particular location. In Fig. 4.4 shows the different types of multipath fading. Multipath fading is mainly classified into two types

- Large-Scale Fading
- Small-Scale Fading

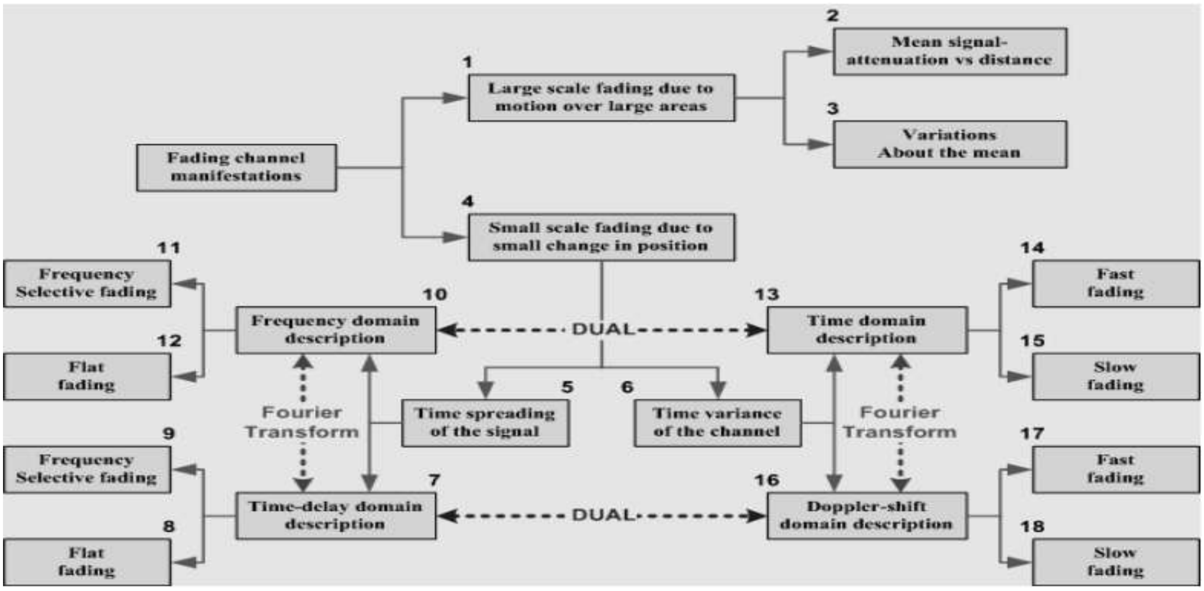


Fig. 4.4. Different types of multipath fading [7]

4.3.1.1. Large-Scale Fading

Propagation models that predict the mean signal strength from an arbitrary transmitter-receiver separation distance is very useful for estimating the radio coverage area of a transmitter. In a large-scale propagation model characterized the signal strength over large transmitter-receiver separation distances (several hundreds or thousands of meters) when the mobile moves away from the transmitter over much larger distances, the local average received signal will gradually decrease, it is mainly due to absorption of RF energy in the ionosphere. Absorption mainly occurs due to three types, they are Reflection, Diffraction and Scattering.

Different fading models are developed to estimate this large-scale fading such as Longley-Rice model, Durkin's model, Okumura model, Hata model etc.

4.3.1.2. Small-Scale Fading

A small-scale propagation model characterized the signal strength over very small transmitter-receiver separation distances. When the mobile moves away, the instantaneous received signal strength may fluctuate rapidly giving rise to small-scale fading. In small-scale fading, the received signal power may vary by as much as three or four orders of magnitude (30 or 40 dB) when the receiver is moved by only a fraction of a wavelength. Fig. 4.5 shows the relation between small-scale fading and large-scale fading.

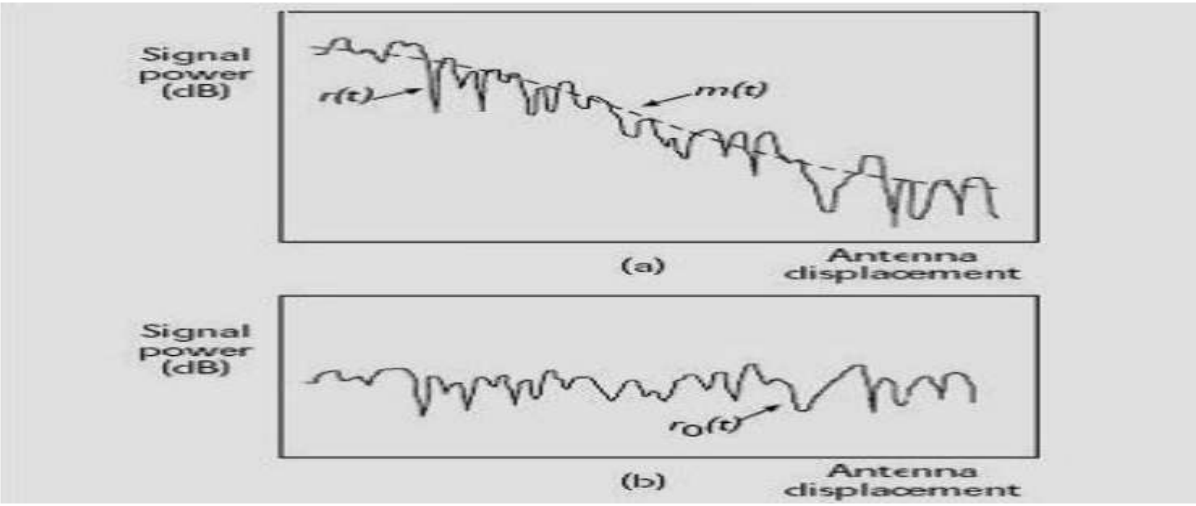


Fig. 4.5. Large-scale and small-scale fading [7]

Fig. 4.5(a) shows large-scale fading $m(t)$ is superimposed on the small-scale fading $r(t)$ can be easily identified. In Fig. 4.5(b) shows only small-scale fading.

Depending on the impulse response of the fading channel, small-scale fading is based on multipath time delay spread and Doppler spread. Further, small-scale fading divided into four types named as flat fading, frequency selective fading, fast fading, and slow fading.

4.4. Types of Small-Scale Fading

The type of fading experienced by a signal propagating through a mobile radio channel depends on the transmitted signal and characteristics of the channel. It will depend on signal parameters like bandwidth and symbol period, it will also depend on channel parameters like RMS delay spread and Doppler shift. Fig. 4.6 shows different types of small-scale fading. Here, we mainly discuss four different types of fading.

- Flat Fading
- Frequency Selective Fading
- Fast Fading
- Slow Fading

4.4.1. Flat Fading

If the channel has a constant gain and linear phase response over a bandwidth which is greater than the bandwidth of the transmitted signal, then the received signal will experience flat fading. In which characteristics of the transmitted signal preserved at the receiver. The amplitude of the received signal is varied due to fluctuation in the gain of the channel caused by multipath. Transmitted signal experienced flat fading if

$$B_S \ll B_C \tag{4.11}$$

and

$$T_S \gg \sigma_\tau \tag{4.12}$$

where T_s is the reciprocal of bandwidth and B_s is the bandwidth of the transmitted signal, σ_τ is the RMS delay spread and B_c is the coherence bandwidth.

4.4.2. Frequency Selective Fading

If the channel has a constant gain and linear phase response over a bandwidth which is smaller than the bandwidth of the transmitted signal, then the received signal will experienced frequency selective fading. In which characteristics of the transmitted signal didn't preserve at the receiver. Thus channel induces inter-symbol interference. The amplitude of the received signal is varied due to fluctuation in the gain of the channel caused by multipath. Transmitted signal experienced frequency selective fading if

$$B_S \gg B_C \tag{4.13}$$

and

$$T_S \ll \sigma_\tau \tag{4.14}$$

where T_s is the reciprocal of bandwidth and B_s is the bandwidth of the transmitted signal, σ_τ is the RMS delay spread and B_c is the coherence bandwidth.

Frequency selective fading channel is much more difficult to model than flat fading channels since each multipath signal must be modeled and channel must be considered to a linear filter.

4.4.3. Fast Fading

It depends on how the transmitted signal changes as compared to the rate of change of the channel. In the fast fading, channel impulse response will be rapidly varied within the symbol period duration. It causes frequency dispersion due to Doppler spreading, which leads to high distortion in the signal. When the increase in the Doppler spread, signal distortion will be increased. Transmitted signal experienced fast fading if

$$T_S \gg T_C \tag{4.15}$$

and

$$B_S \ll B_D \tag{4.16}$$

where T_s is the reciprocal of bandwidth and T_c is the reciprocal of coherence bandwidth, B_D is the Doppler spread and B_s is the baseband signal bandwidth.

4.4.4. Slow Fading

In the slow fading, channel impulse response changes at a much slower rate than the baseband transmitted signal. In which Doppler spread of the channel is much less than the bandwidth of the baseband signal. Transmitted signal experienced slow fading if

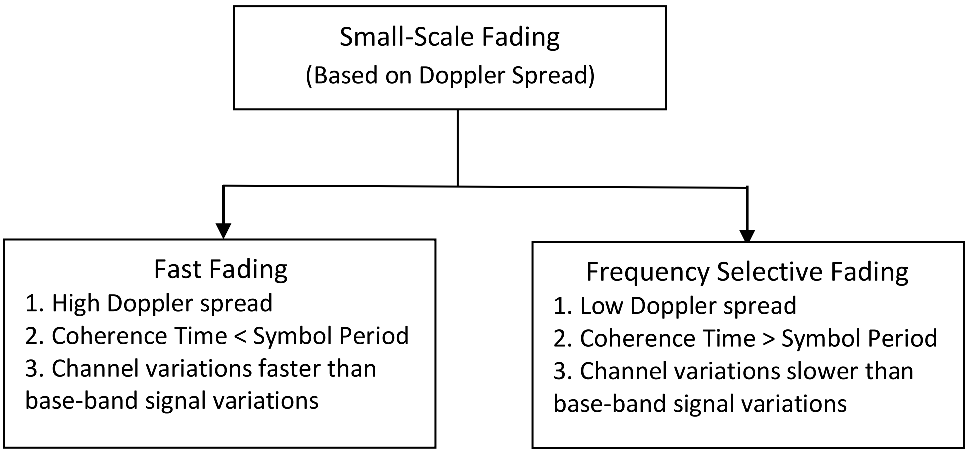
$$T_S \ll T_C \tag{4.17}$$

and

$$B_S \gg B_D \tag{4.18}$$

where T_s is the reciprocal of bandwidth and T_c is the reciprocal of coherence bandwidth, B_D is the Doppler spread and B_s is the baseband signal bandwidth.

The small-scale fading occurring in the multipath channel statistically obeys the different characteristics of different random process such as Rayleigh, Nakagami- m .



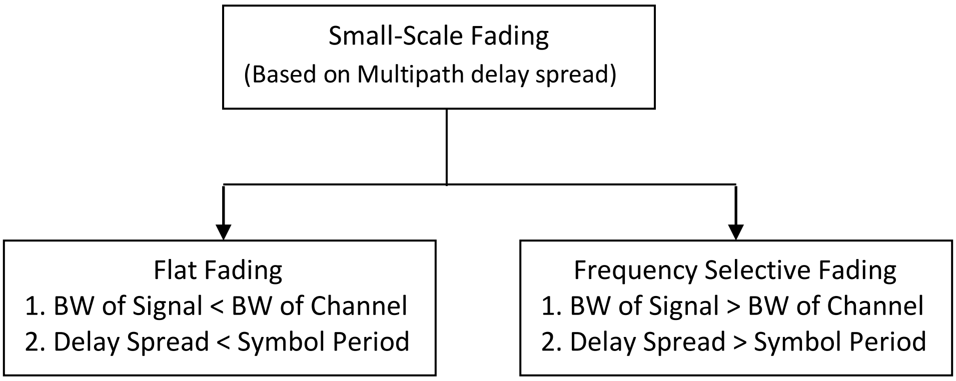


Fig. 4.6. Types of small-scale fading

4.5. Different Types of Random Processes

There are many different types of random processes, which can be useful to design different systems much have importance in the wireless applications. These are used to design a reliable communication link between the transmitter and receiver depends on the time varying statistical behavior of the existing channel. Mostly used random processes are

- Gaussian Random Process
- Rayleigh Random Process
- Nakagami- m Random Process

4.5.1. Gaussian Random Process

Gaussian process is a stochastic process. Its probability density function (PDF) can be written as

$$f_X(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-m)^2}{2\sigma^2}} \quad , -\infty < x < +\infty \tag{4.19}$$

The PDF of the Gaussian variables has mainly two parameters m and σ, which can be described as mean and standard deviation. The parameter σ^2 is referred to as the variance. The Gaussian PDF width has proportional to σ and centered about the point $x = m$.

The cumulative distribution function (CDF) is used to find the probability that a Gaussian random variable lies above or below some threshold level. The CDF of Gaussian

$$F_X(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(y-m)^2}{2\sigma^2}} dy \tag{4.20}$$

In Fig. 4.7 shows the PDF and CDF of Gaussian Function. It is standard practice to introduce a shorthand notation to describe a Gaussian random variable, $X \sim N(m, \sigma^2)$. It can be defined as X is distributed normally with mean m and variance σ^2.

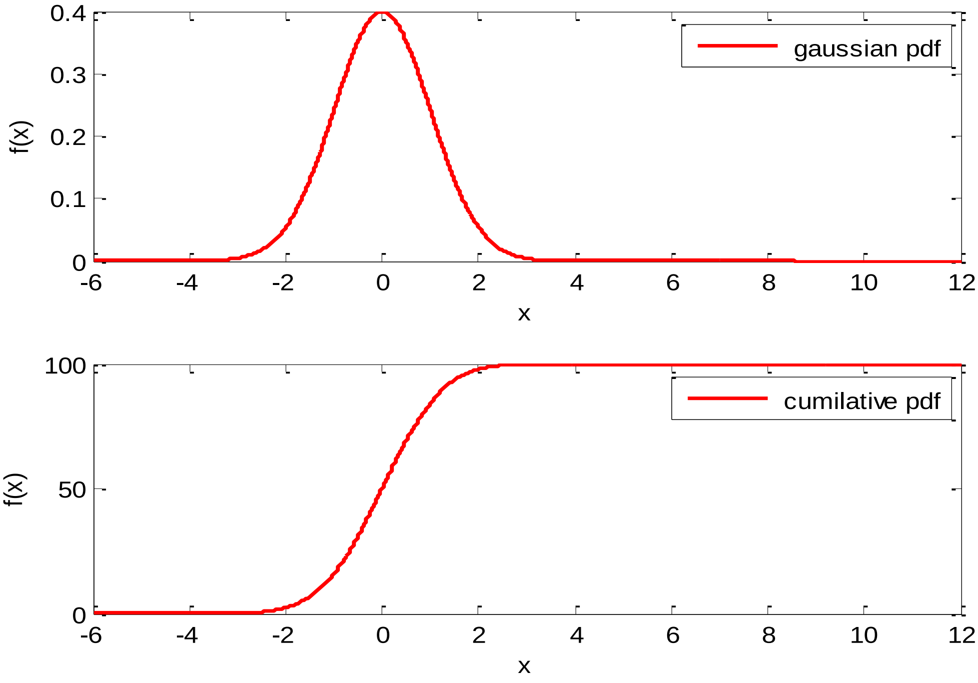


Fig. 4.7. PDF and CDF of a Gaussian random variable with $m = 0, \sigma = 1$

4.5.2. Rayleigh Random Process

Rayleigh distribution is well known as the envelope of the sum of two quadrature Gaussian noise signals. It is commonly used to describe the statistical time varying nature of the received envelope of the flat fading channel or the envelope of an individual multipath component [49]. When LOS (Line of Sight) component is not present between the transmitter and receiver then Rayleigh fading occurs. Fig. 4.8 shows the PDF and CDF of a Rayleigh random variable X . The Rayleigh distribution has a probability density function and cumulative distribution function is given below

$$f_X(x) = \left(\frac{x}{\sigma^2}\right) e^{-\frac{x^2}{2\sigma^2}} u(x) \tag{4.21}$$

$$F_X(x) = \left(1 - e^{-\frac{x^2}{2\sigma^2}}\right) u(x) \tag{4.22}$$

The Rayleigh distribution is mostly used to determine the time varying nature of the channel. It describes the probability of the signal level being received due to fading. Table 4.2 shows the probability of signal level in the Rayleigh distribution.

Table 4.2. Probability of signal level in the Rayleigh distribution

Signal level (dB)	**% Probability of Signal Level**
10	99
0	50
-10	5
-20	0.5
-30	0.05

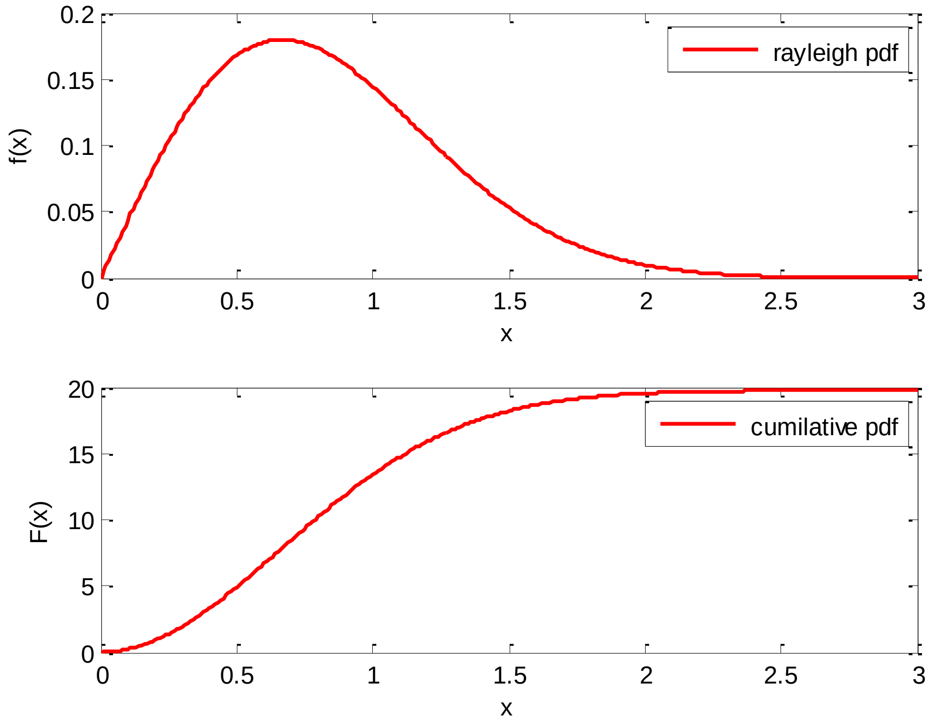


Fig. 4.8. PDF and CDF of a Rayleigh random variable with $\sigma = 0.707$

4.5.3. Nakagami- m Random Process

Nakagami- m distribution is the probability distribution and it is related to gamma distribution [44]. It has mainly two parameters: a shape parameter m and controlling spread is Ω. By using parameter m, the distribution can model signal fading conditions from severe to moderate, to light or no fading. It is used as the square root of a sum of squares of n zero mean identically distributed Gaussian Random variables has Nakagami-m distribution with $m = n/2$. This is called brute force method [45]. The Nakagami-m distribution probability density function (PDF) is given as

$$f_X(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} e^{-(m/\Omega)r^2} \tag{4.23}$$

where m is a parameter that controls the severity and depth of amplitude fading. When $m = 1$ then Nakagami-m fading is equal to Rayleigh fading, Nakagami is the special case of Rayleigh fading. When $m < 1$ corresponds to fading severe than Rayleigh fading and $m > 1$ corresponds to fading less severe than Rayleigh fading. In Fig. 4.9 shows a PDF plot of Nakagami-m distribution function with different values.

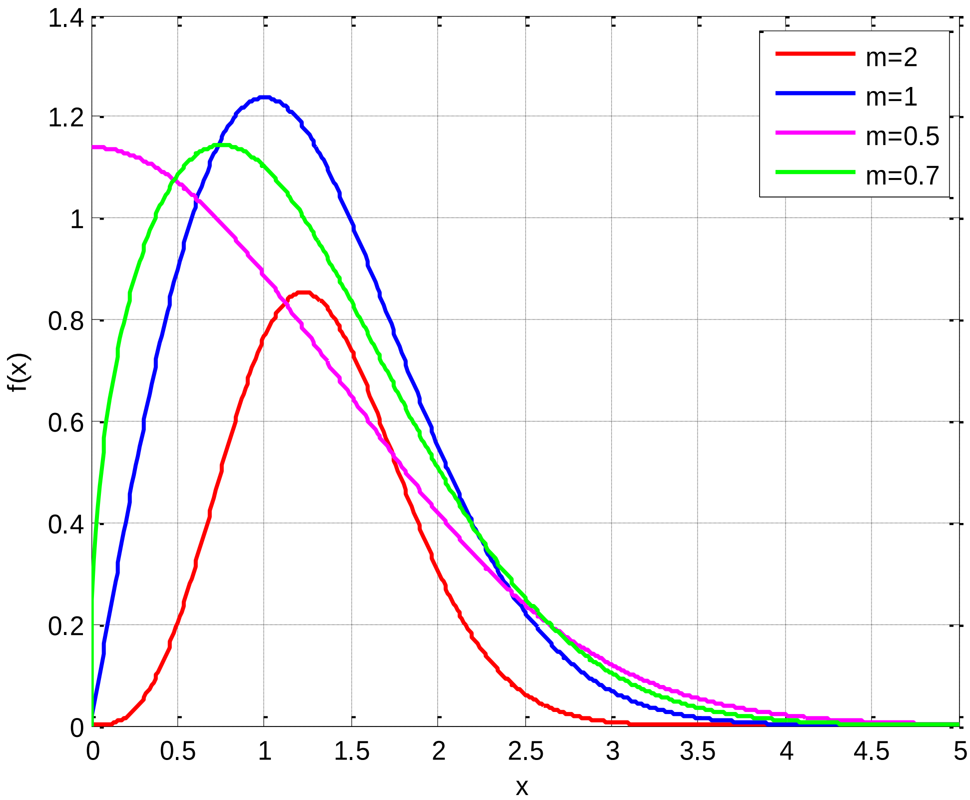


Fig. 4.9. Nakagami-m distribution with different values of m

4.6. Impulsive Noise

Impulsive noise can be described as one or more repetitive pulses with a random intensity, duration and occurrence. Impulsive noise mainly consists of relatively short and random duration on/off noise pulses, induced by a number of sources, like as switching noise, adverse channel conditions in the communication system, clicks from the computer keyboard, vehicle ignition system, sharp sounds, and machines also [46].

For favorable performance, we must remove an impulsive noise. It should exploit the different features of the noise and signal in the time-domain as well as the frequency-domain, and the statistics of noise process.

4.6.1. Mathematical Model of Impulsive Noise

Consider the pulse $p(t)$, it has unit-area presented in the Fig. 4.10 (a) as the width of pulse Δ tends to zero, the pulse tends to an impulse. The impulse shown in Fig. 4.10 (b) is defined as a pulse with an infinitesimal time width as

$$\delta(t) = \underset{\Delta \to 0}{\mathrm{limit}}\ p(t) = \begin{cases} 1/\Delta, & |t| \le \Delta/2 \\ 0, & |t| \ge \Delta/2 \end{cases} \tag{4.24}$$

The Integral value of the impulse function is represented as

$$\int_{-\infty}^{\infty} \delta(t)dt = \Delta \times \frac{1}{\Delta} = 1 \tag{4.25}$$

The transformation of the impulse function is represented as

$$\Delta(f) = \int_{-\infty}^{\infty} \delta(t) e^{-j2\pi ft} dt = e^{0} = 1 \tag{4.26}$$

After Fourier transform, an impulse signal contains all the frequencies in the equal amount. It is a spectrally rich signal.

A digital impulse signal $\delta(n)$, is described as a signal with an “on” duration of one unit sample, it's expressed as

$$\delta(n) = \begin{cases} 1, & n = 0 \\ 0, & n \ne 0 \end{cases} \tag{4.27}$$

where the discrete variable n assigned as the discrete-time index.

In the communication systems, normally real type impulsive noise has more than one pulses. For example, short and random duration, sharp pulses, up to 5 milliseconds. It contains 50 samples at a 10 KHz sampling rate. A real impulsive pulse originates at some point in time and space randomly, and then propagates through the channel to the receiver. General characteristics of the communication channel might be linear or nonlinear, stationary or time-varying.

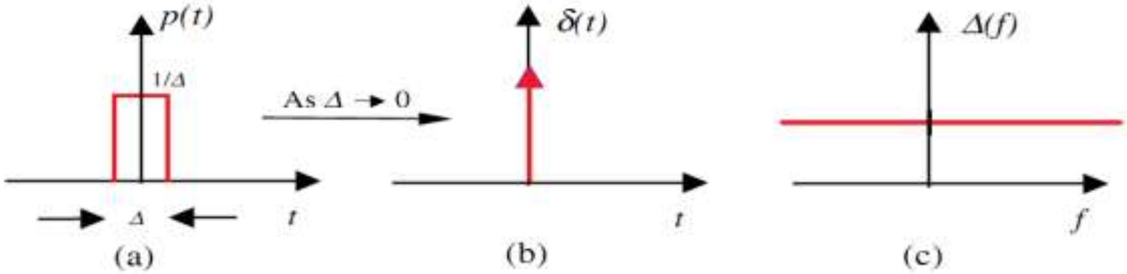


Fig. 4.10. (a) A unit-area pulse (b) The pulse becomes an impulse as $\Delta \rightarrow 0$ (c) The spectrum of the impulse function.

Impulsive noise can be broadly divided into two types first is aperiodic impulsive noise and other is periodic impulsive noise. Aperiodic impulsive noise is defined by impulses occurring at a random time, with short duration and high power. Periodic impulsive noise is characterized by impulses occurring at periodically in time and with long duration. Impulsive noise is usually more difficult to detect in the frequency-domain rather than the time-domain. Normally, we reduce the average effect of noise over a number of samples. In the Fig. 4.11 shows the time-domain and the frequency-domain representation of an impulse signal.

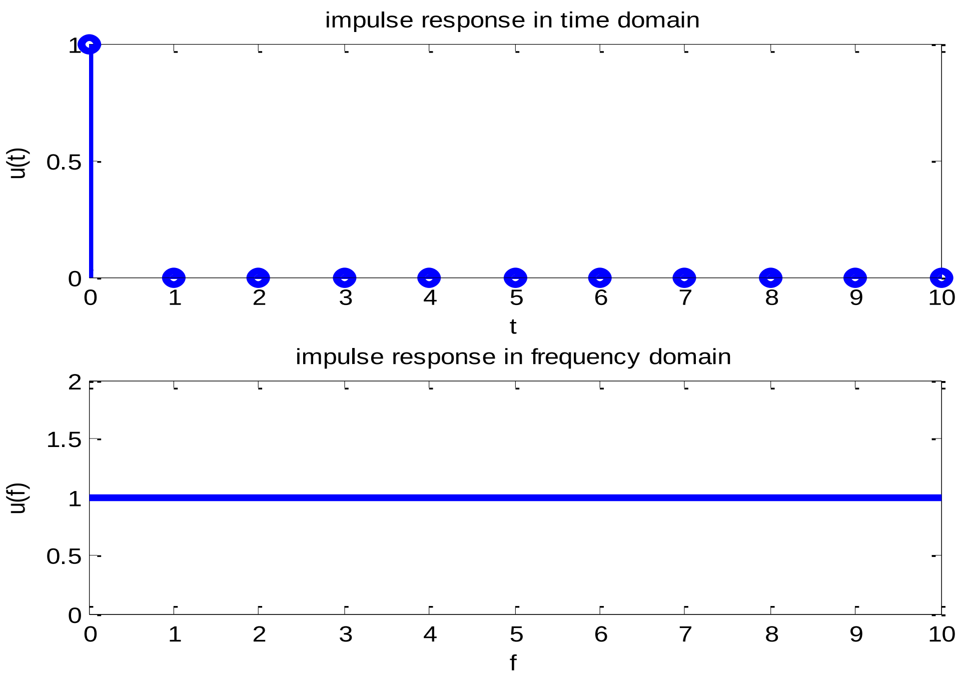


Fig 4.11. Time and frequency response of an Impulse signal

4.6.2. Statistical Models for Impulsive Noise

We have analyzed the number of models for the characterization of impulsive noise. The output of the filter is excited by the amplitude modulated random binary sequence as

$$z_i(n) = \sum_{k=0}^{P-1} h_k l(n-k) b(n-k) \tag{4.28}$$

where $b(n)$ is binary random sequence model of the time of occurrence of impulsive noise, $l(n)$ is a continuous valued random process model of the pulse amplitude, and $h(n)$ is the impulse response of the filter.

Mainly, we have important statistical processes for modeling impulsive noise process as an amplitude modulated random binary sequence is the Bernoulli-Gaussian Process.

4.6.3. Bernoulli-Gaussian Model of Impulsive Noise

In this process, the random duration of occurrence of the impulses is generated by a binary Bernoulli process $b(n)$ and the strength of the impulses is modeled through the Gaussian process $l(n)$. A Bernoulli process $b(n)$ is a binary process that takes a value of "1" with a probability of χ and a value of "0" with a probability of $1-\chi$. The probability mass function of a Bernoulli process is represented by

$$P_B(b(n)) = \begin{Bmatrix} \chi & for\ b(n) = 1 \\ 1-\chi & for\ b(n) = 0 \end{Bmatrix} \tag{4.29}$$

A Bernoulli Process has mean

$$\mu_b = E\left[\left(b(n)\right)\right] = \alpha \tag{4.30}$$

and variance

$$\sigma_b{}^2 = E\left[\left(b(n) - \mu_b\right)^2\right] = \chi(1-\chi) \tag{4.31}$$

A zero-mean Gaussian probability density function model of the random amplitudes of impulsive noise is given by

$$f_l(l(n)) = \frac{1}{\sqrt{2\pi}\sigma_n} e^{\frac{-l^2(n)}{2\sigma_l^2}} \tag{4.32}$$

$\sigma^2{}_n$ is the variance of the noise amplitude. In a Bernoulli-Gaussian model the PDF of an impulsive noise $\mathrm{n}_i(m)$ is given by

$$f_N^{BG}\left(l_i(n)\right)=\left(1-\chi\right)\delta\left(l_i(n)\right)+\chi f_N\left(l_i(n)\right) \tag{4.33}$$

$\delta(l_i(n))$ is the Kronecker delta function. Note that the function $\mathrm{f}_N^{BG}(l_i(n))$ is a mixture of a discrete probability mass function and a continuous probability density function $\mathrm{f}_N(n(m))$. Fig. 4.12 shows the impulsive noise model as the output of filter excited by an amplitude-modulated binary sequence.

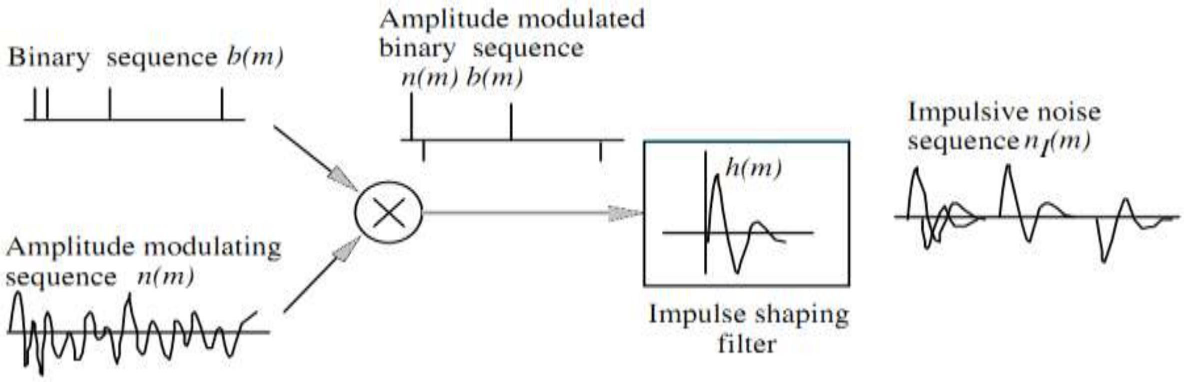


Fig 4.12. Illustration of the impulsive noise model with the filter output excited by an amplitude modulated binary sequence [46]

Chapter 5

IMPULSIVE NOISE COMPENSATION WITH IMPERFECT CSI

This chapter discusses about the suppression of impulsive in the OFDM system under Nakagami-m multipath fading channel. In which we are evaluating the performance of the impulsive noise compensation method under the perfect and the imperfect Channel state information CSI. This method is used as a technique for the excision of impulsive noise in the frequency-domain and it has implemented after OFDM demodulation and channel equalization.

5.1. Introduction

In the field of wireless communication, orthogonal frequency division multiplexing is widely utilized for the high data-rate applications [1]. It is used in terrestrial digital video broadcasting (DVB-T) and many modern applications. The main advantage of OFDM system is robustness to multipath distortions. Mostly OFDM communication systems are affected by the man-made noise, usually in the urban environment. Here man-made noise is considered as impulsive noise [47]. These noises occur due to several reasons for e.g. power lines, heavy current switches, etc. The longer duration of an OFDM symbol, gives an advantage in a presence of the weak impulsive noise, because after the FFT operation the energy of impulsive noise is spread among simultaneously transmitted OFDM subcarriers. If the strength of impulsive noise is very high this advantage turns into the disadvantage. In OFDM communication system, the nature, origin and prediction of noise sources are essential to develop effective techniques to alleviate bit error rate (BER) [8, 48].

The OFDM system, being the multi-carrier modulation system, is more resistant to the effects of impulsive noise because this system has an efficient implementation of the FFT as compared to the single-carrier system. A simple procedure is used to remove the deleterious effect of impulsive noise which is known as a blanking nonlinearity method. This method is efficient and simple to implement. It is incorporated in the time-domain before OFDM demodulation [18]. There is another method proposed by Zhidkov in [14], which is interpreted as the impulsive noise compensation method. This method is implemented in the frequency-domain after OFDM demodulation and channel equalization. In this paper, we mainly focus on impulsive noise compensation method.

The aim of our study is to analyze the performance of the impulsive noise compensation method with channel state information (CSI) imperfections for the suppression of impulsive noise. First, we evaluate the performance of the impulsive noise compensation method under the Nakagami-m multipath fading channels. The signal received at receiver is represented as

$$y_i = a_i u_i + n_i \tag{5.1}$$

where a_i is the input from the OFDM system, u_i is the fading channel response, n_i is the noise component. In the Nakagami-m fading channel, we use the square root of the squares of n zero-mean identically distributed Gaussian random variables (RVs) with fading parameter $m = n/2$, when m is an integer. This method is also known as "brute force method" [45]. The improvement in BER mainly depends on the value of m, i.e., when $m = 0.5 < 1$, the diversity gain deteriorates by 3 dB as compared to the Rayleigh, but when $m = 2 > 1$, the diversity gain improves by 2 dB. We also deal the problem of CSI imperfection and evaluate the performance of an OFDM receiver that uses an impulsive noise compensation method [14] for the suppression of impulsive noise.

5.2. Model of OFDM System and Channel with Impulsive Noise

In which we present the model of OFDM system for transmission as well as reception. In Fig. 5.1 shows the block scheme of the transmission system. In the OFDM system, first the information bits are mapped into the baseband modulated symbols $\{X_k\}$ by using quadrature amplitude modulation or phase shift keying. Mostly QAM modulation is utilized in the OFDM communication system, so each element in the OFDM symbol is a complex number representing the each QAM constellation point. In every OFDM symbol, each element $\{X_k\}$ is transformed by means of inverse fast Fourier transform (IFFT). Throughout this paper, we use upper case to represent the frequency-domain and lower case for the time-domain symbols. Digital to analog conversion of complex baseband OFDM symbol can be expressed as

$$x(n) = \sum_{k=0}^{N-1} X_k e^{j2\pi \frac{B}{N} n}, \quad 0 < n < T_m \tag{5.2}$$

where B is the total bandwidth allocated to the OFDM symbol, N is the total number of subcarriers in the OFDM symbol, and T_m is the OFDM symbol interval.

$$\frac{B}{N} = \Delta f \tag{5.3}$$

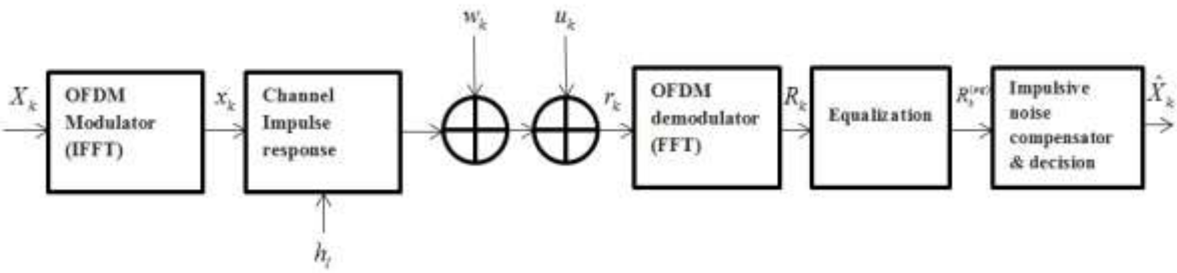


Fig. 5.1. Block scheme of transmission system

where Δf represents the frequency separation between two adjacent subcarriers. Now the output of OFDM symbol from the IFFT block can be expressed as

$$x(n) = \sum_{k=0}^{N-1} X_k e^{j2\pi\Delta fn}, \quad 0 < n < T_m \tag{5.4}$$

The received time-domain OFDM signal after analog-to-digital conversion can be represented as

$$r_k = z_k + w_k + u_k, \quad k = 0,1,......, N-1 \tag{5.5}$$

where, z_k, w_k, u_k are assumed to be mutually independent and z_k is given as

$$z_k = \sum_{l=1}^{L} h_l x_{k-l} \tag{5.6}$$

where $x_k = x(kT_m / N)$, h_l is the channel impulse response, L is the length of the channel impulse response. Now the (5.5) can be represented as

$$r_k = \sum_{l=1}^{L} h_l x_{k-l} + w_k + u_k, \quad k = 0,1,......, N-1 \tag{5.7}$$

where w_k is the additive white Gaussian noise (AWGN) with zero mean, and u_k is the impulsive noise. All these quantities are assumed to be complex. The characterization of impulsive noise is quite difficult. Let us assume that impulsive noise can be modeled as a Bernoulli-Gaussian random process and is expressed as

$$u_k = b_k g_k, \quad k = 0,1...., N-1 \tag{5.8}$$

It is a product of the real Bernoulli process (b_k) and a complex Gaussian process (g_k) with zero mean. We also assume impulsive noise energy is much higher than that of thermal noise. Moreover, the duration of impulsive noise is much shorter than the OFDM symbol duration T_m. After fast Fourier transform of the received signal, it can be expressed as

$$R_k = H_k X_k + W_k + U_k \tag{5.9}$$

where $\vec{H} = [H_{0,} H_1, ..., H_{N-1}]$ is the fast Fourier transform (FFT) of the channel impulse response, $\vec{X} = [X_0, X_1, ...X_{N-1}]$ is the FFT of the transmitted signal, $\vec{W} = [W_0, W_1, ..., W_{N-1}]$ is the FFT of additive white Gaussian noise, and $\vec{U} = [U_0, U_1, ..., U_{N-1}]$ is the FFT of impulsive noise.

5.3. Mathematical Model for Impulsive Noise Compensation with Imperfect CSI

Previous method [14] for the suppression of impulsive noise is implemented in the time-domain before OFDM demodulation, but impulsive noise compensation method [18] is implemented in the frequency-domain after OFDM demodulation with the estimated channel state information.

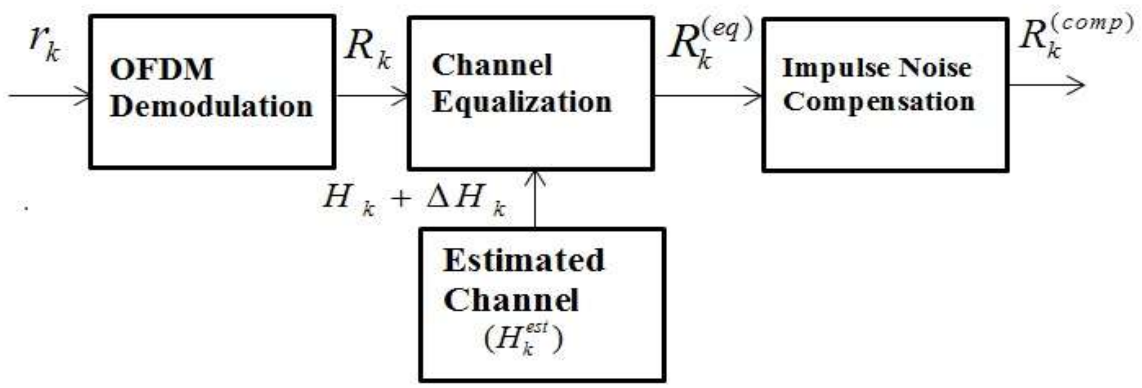


Fig. 5.2. Block scheme of reception with imperfect CSI

However, in practice, the channel is never perfectly known at the receiver. The channel imperfection is caused either by errors in the estimation of the channel or by variations in the channel due to the motion of the transmitter and/or the receiver [50]. At the receiver, we assume the estimated channel (i.e., $H_k^{est} = H_k + \Delta H_k$). Now, after the channel equalization by using estimated CSI, an equalized signal can be expressed as

$$R_k^{(eq)} = R_k (H_k^{(est)})^{-1} = H_k X_k (H_k^{(est)})^{-1} + W_k (H_k^{(est)})^{-1} + U_k (H_k^{(est)})^{-1}, \quad k = 0,1,...,N-1 \quad (5.10)$$

where, ΔH_k is an error in the channel estimation. It can be represented by a complex number in the form of $\Delta H_k = a_k + jb_k$; here a_k and b_k are independent identically Gaussian distributed random variables with zero mean and variance $\sigma_k^2/2$.

$$R_k (H_k + \Delta H_k)^{-1} = H_k X_k (H_k + \Delta H_k)^{-1} + W_k (H_k + \Delta H_k)^{-1} + U_k (H_k + \Delta H_k)^{-1} \quad (5.11)$$

Taking H_k^{-1} common on both sides of the equation (10), which leads to

$$R_k H_k^{-1} \left(1 + \frac{\Delta H_k}{H_k}\right)^{-1} = X_k \left(1 + \frac{\Delta H_k}{H_k}\right)^{-1} + W_k H_k^{-1} \left(1 + \frac{\Delta H_k}{H_k}\right)^{-1} + U_k H_k^{-1} \left(1 + \frac{\Delta H_k}{H_k}\right)^{-1} \quad (5.12)$$

By using Taylor series expansion, i.e., $(1+x)^{-1} \approx (1-x)$ for, it can be shown that

$$R_k H_k^{-1} \left(1 - \frac{\Delta H_k}{H_k}\right) = X_k \left(1 - \frac{\Delta H_k}{H_k}\right) + W_k H_k^{-1} \left(1 - \frac{\Delta H_k}{H_k}\right) + U_k H_k^{-1} \left(1 - \frac{\Delta H_k}{H_k}\right) \quad (5.13)$$

$$R_k^{(eq)} = X_k \left(1 - \frac{\Delta H_k}{H_k}\right) + \left(W_k + U_k\right) H_k^{-1} \left(1 - \frac{\Delta H_k}{H_k}\right) \quad (5.14)$$

Let the estimated transmitted baseband symbol be $\hat{X}_k$ [14] and the estimated noise term be $A_k = W_k + U_k$, where $k = 0,1,...,N-1$, the following expression can be expressed as

$$A_k^{(est)} = \left(R_k^{(eq)} - \hat{X}_k \left(1 - \frac{\Delta H_k}{H_k}\right)\right) H_k \left(1 - \frac{\Delta H_k}{H_k}\right)^{-1} \quad (5.15)$$

$$A_k^{(est)} = \left((R_k H_k^{-1} - \hat{X}_k) H_k \left(1 - \frac{\Delta H_k}{H_k}\right)\right) \left(1 - \frac{\Delta H_k}{H_k}\right)^{-1} \quad (5.16)$$

$$A_k^{(est)} = \left(R_k H_k^{-1} - \hat{X}_k\right) H_k \left(1 - \left(\frac{\Delta H_k}{H_k}\right)^2\right) \quad (5.17)$$

But, it is already known that $\left(R_k H_k^{-1} - \hat{X}_k\right) H_k = W_k + U_k$

$$A_k^{(est)} = \left(W_k + U_k\right) \left(1 - \left(\frac{\Delta H_k}{H_k}\right)^2\right) \quad (5.18)$$

$$A_k^{(est)} = A_k + \varepsilon \quad (5.19)$$

Here, $\vec{A} = [A_0, A_1, ..., A_{N-1}]$ represents the total noise term, and this term is the frequency-domain representation of the impulsive noise and additive white Gaussian noise. However, ε represents the error in the total noise term. It is due to imperfect CSI at the receiver. In the frequency-domain, the impulsive noise could be represented as the sum of complex sinusoids

$$U_k = S_1 e^{j2\pi k l_1/N} + S_2 e^{j2\pi k l_2/N} + ... + S_M e^{j2\pi k l_M/N} \tag{5.20}$$

where, M number of samples are affected by impulsive noise, $l_1, l_2 ...., l_m$ are the locations of these samples and $S_1, S_2 ...., S_M$ are the amplitudes of impulsive interference. The purpose of the impulsive noise compensation method is to find out the locations $l_1, l_2, ..., l_3$ and the amplitudes $S_1, S_2, ..., S_3$ of impulsive interference and reconstruct the impulsive noise vector.

$$\hat{U} = [\hat{U}_0, \hat{U}_1, ..., \hat{U}_{N-1}] \tag{5.21}$$

For reconstruction of vector, first transform the total noise term in the time-domain by means of IFFT. Now apply the output vector of IFFT to peak detector [14] and estimate the impulsive noise vector in time-domain $\hat{u} = [\hat{u}_0, \hat{u}_1, ..., \hat{u}_{N-1}]$. Transform the impulsive noise vector into the frequency-domain $\hat{U} = [\hat{U}_0, \hat{U}_1, ..., \hat{U}_{N-1}]$, and then subtract it from the equalizer output. Subsequently, using impulsive noise compensation [14] method, $R_k^{(comp)}$ in Fig. 5.2 can be written as

$$R_k^{(comp)} = R_k^{(eq)} - \hat{U}_k (H_k^{(est)})^{-1} \tag{5.22}$$

$$R_k^{(comp)} = R_k^{(eq)} - \hat{U}_k (H_k + \Delta H_k)^{-1} \tag{5.23}$$

$$R_k^{(comp)} = R_k^{(eq)} - \hat{U}_k H_k^{-1} \left(1 + \frac{\Delta H_k}{H_k}\right)^{-1} \tag{5.24}$$

For the performance improvement, the compensated signal can be recursively applied to the impulsive noise compensation algorithm. If the amplitude of the impulsive noise is very high, then the impulsive noise compensation method becomes less reliable. In this case, it is advantageous to use the time-domain method (blanking non-linearity [18]) before OFDM demodulation. In the next section, we discussed about the simulation results for the impulsive noise compensation method under Nakagami-m multipath fading channel for perfect and imperfect channel state information in the OFDM system

5.4. Simulation Results

We will try to understand the behavior of the impulsive noise compensation method with Nakagami-m fading channels in the OFDM system to analyze the effects of impulsive noise on its performance. We will also compare the performance of the underlying OFDM system at different values of Nakagami fading parameter m (i.e., $m = 0.5, 1$ or 2) under perfect and imperfect channel state information at the receiver. The performance of the impulsive noise compensation method has been studied by computer simulations.

5.4.1. Performance Evaluation of OFDM System with Perfect CSI

The simulation results for the impulsive noise compensation method in the OFDM system with the perfect channel estimation information are presented in the Fig. (5.3) to Fig. (5.6). These results are obtained from the 64-QAM OFDM system with 2048 subcarriers. Here, Bernoulli-Gaussian model is used for the generation of impulsive noise [8, 12]. The probability of the occurrence of the impulses in single OFDM symbol is set to be 0.01. Bernoulli model is represented as $u_k = b_k g_k$.

where b_k is independent and identically distributed random sequence of the zeros and ones with probability $P(b_k = 1) = 0.01$, and g_k is complex Gaussian noise with zero mean. The standard deviation of g_k is kept $10\sigma_w$, where σ_w is the standard deviation of background noise. For reduction of high amplitude impulses, blanking nonlinearity is applied in time-domain signal before OFDM demodulation. Now, we show the simulation results for suppression of impulsive noise under Nakagami-m fading channel with different values of m in the OFDM system.

The simulation results presented in Fig. (5.3) to (5.5) under the perfect CSI, it can be observed that the BER reduces as the value of m increases. The results obtained for a Nakagami fading parameter at $m = 1$ are approximately equivalent to Rayleigh channel. Results presented in Fig. 5.4 and Fig. 5.5 depict that when a parameter $m = 2$, it gives approximately 2 dB performance advantage over Nakagami fading parameter $m = 1$. The performance of the impulsive noise compensation method is better, when the number of iterations is increased and the Nakagami fading parameter is greater than 1 $(m > 1)$ under the perfect CSI.

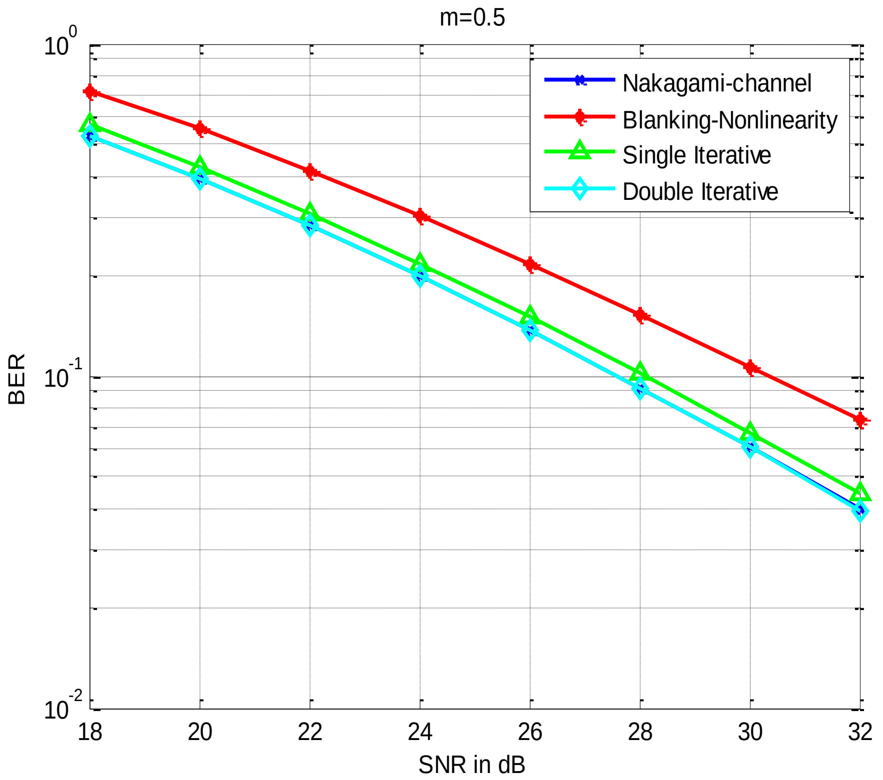


Fig. 5.3. Simulated performance in the Bernoulli-Gaussian noise and Nakagami- m channel with fading parameter $m = 0.5$

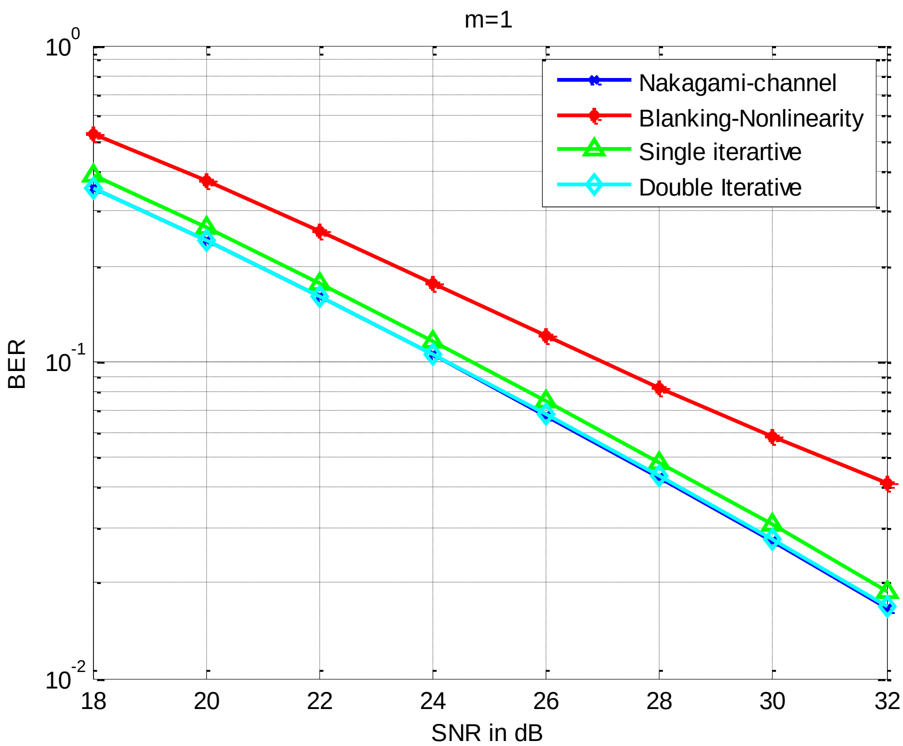


Fig. 5.4. Simulated performance in the Bernoulli-Gaussian noise and Nakagami- m channel with fading parameter $m = 1$

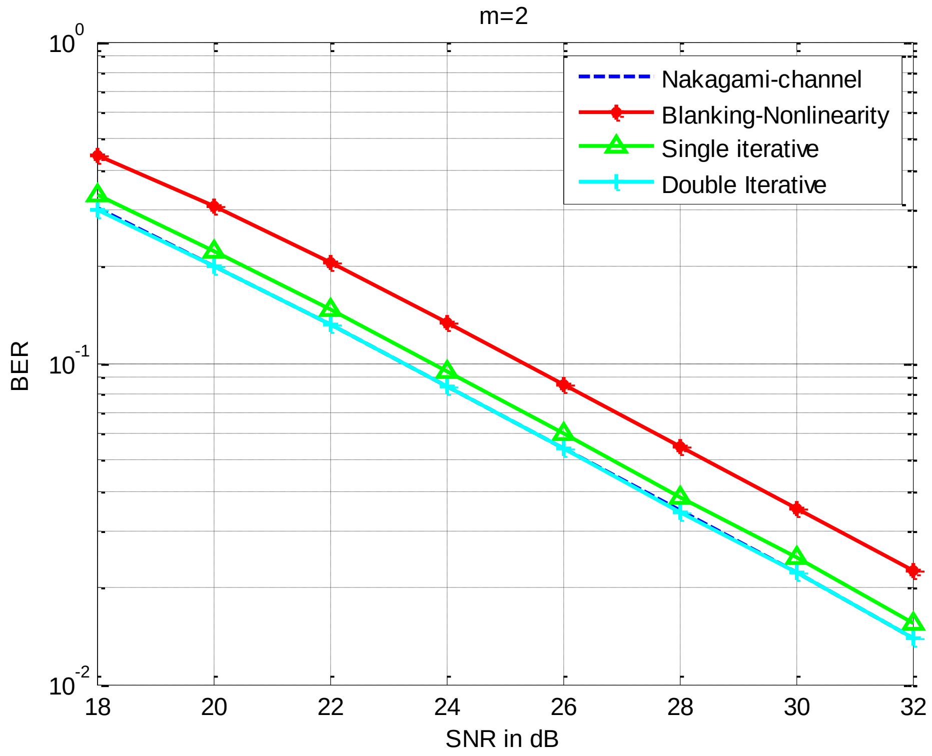


Fig. 5.5. Simulated performance in the Bernoulli-Gaussian noise and Nakagami-m channel with fading parameter $m = 2$

In Fig. 5.6, we have presented the simulation results for the impulsive noise compensation method with different values of Nakagami fading parameter m on a single graph. It is clear that the impulsive noise compensation method shows significant performance improvements with single as well as double iterative method.

5.4.2. Performance Evaluation of OFDM System with Imperfect CSI

In this section, we present the simulation results obtained with the imperfect knowledge of the transmission channel. The channel state estimator provides imperfect CSI at the receiver, in which the estimation error is ΔH_k . In Fig. (5.7) to Fig. (5.9), all the results are demonstrated for imperfect CSI at the particular value of signal-to-noise (SNR) ratio i.e., 30 dB. It is apparent that the degradation in BER performance begins to occur when the channel estimation error is greater than -40 dB.

In case, if the channel estimation error is -15 dB, then the BER is 10^{-1} at SNR 30 dB for Nakagami fading parameter $m = 2$ in the OFDM system. However, at -40 dB channel estimation error,

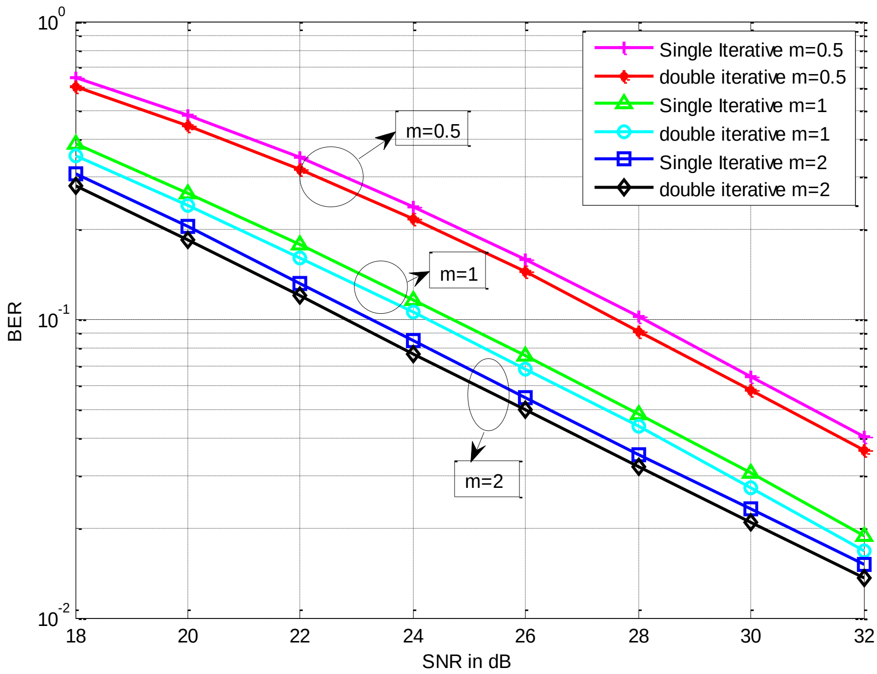


Fig 5.6. Performance of impulsive noise compensation method for different values m

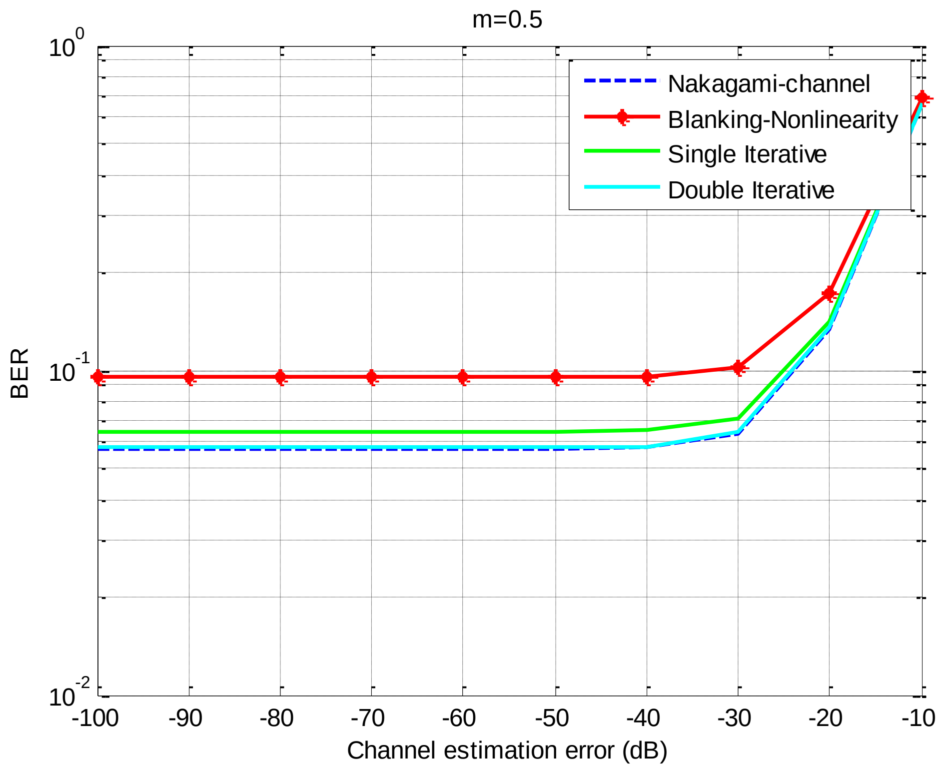


Fig. 5.7. Simulated performance of impulsive noise compensation method with imperfect CSI Channel (m = 0.5)

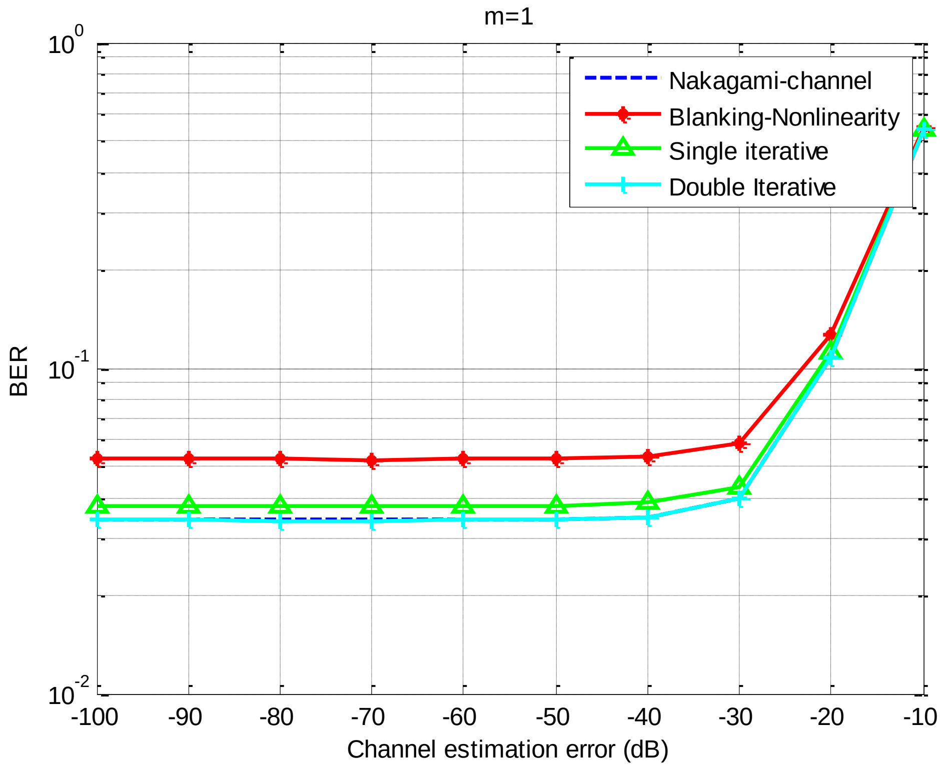


Fig. 5.8. Simulated performance of impulsive noise compensation method with imperfect CSI channel (m =1)

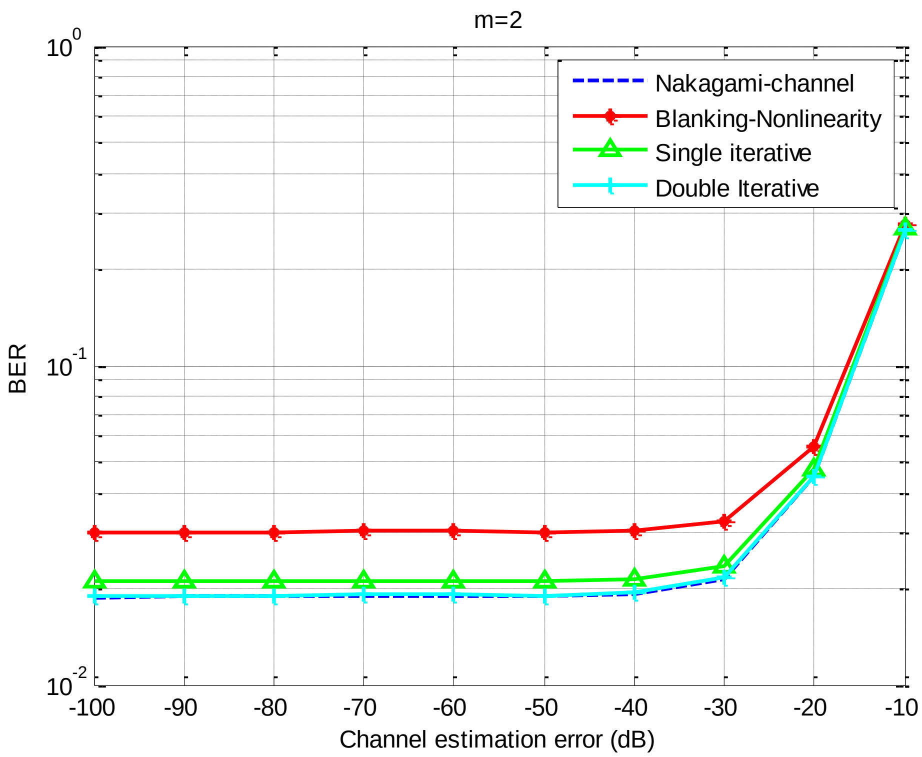


Fig. 5.9. Simulated performance of impulsive noise compensation method with imperfect CSI channel (m =2)

the adverse effects of the CSI imperfections are too low to influence the BER performance.

Therefore, the efficiency of the proposed scheme is dependent on the performance of channel estimator. However, it is noteworthy that the blanking nonlinearity method is found to be useful to reduce the amplitude of large-scale impulses.

Chapter 6

CONCLUDING REMARKS AND FUTURE SCOPE

6.1. Concluding Remarks

In this research work, the impulsive noise compensation method is used for the suppression of impulsive noise working under the Nakagami-m multipath fading channel. Many applications of OFDM system could be seriously affected by the impulsive interference. The objective of this thesis is to analyze the performance of the impulsive noise compensation method with perfect and imperfect channel state information (CSI) for the excision of impulsive noise. There are numerous methods that can be seen in literature and every method exhibits its own properties, but the motive of every method is to reduce or minimize the impulsive noise. Among various impulsive noise suppression methods, the impulsive noise compensation method shows large performance improvement within a few iterations under high signal-to-noise (SNR) ratio conditions. The performance of the impulsive noise compensation method in an impulsive noise environment is approximately same as under non impulsive environment (under high SNR). The presented method supersedes the blanking nonlinearity method under similar conditions.

The simulation results are presented in Fig. 5.6 under the perfect CSI, and it compares the performance of the impulsive noise compensation method at the different values of m. It shows that BER reduces when the value of m increases. The impulsive noise compensation method provides significant improvement in the performance when Nakagami fading parameter m is greater than unity. The simulation results of this method depict that when Nakagami fading parameter $m = 2$, it gives approximately 2 dB advantage over the results with Nakagami fading parameter $m = 1$.

However, the simulation results presented in Fig. (5.7) to Fig. (5.9) under the imperfect CSI evidenced that the channel estimator is the backbone of the impulsive noise compensation method. It is observed that the degradation in BER performance begins to occur when the channel estimation error is greater than -40 dB. In case, when a channel estimator error is -15 dB, then the BER is 10^{-1} at the particular value of SNR 30 dB for the Nakagami fading parameter $m = 2$. However, the impulsive noise compensation method with double iterations outperforms the single iterative scheme and blanking nonlinearity method under the low channel estimation error conditions.

6.2. Future Scope

- The combination of impulsive noise compensation method with the different error correction decoding techniques can further improve the performance. It can also be implemented with or without perfect CSI.
- The impulsive noise compensation method is computationally intensive. It would require a significant silicon area. Future work includes the complexity reduction schemes.

REFERENCES

[1] J. Armstrong, "OFDM for optical communications," *J. of Lightw. Technol.*, vol. 27, no. 3, pp. 189-204, Feb. 2009.

[2] Y. Li, L. J. Cimni, and N. R. Sollenberger, "Robust channel estimation for OFDM systems with rapid dispersive fading channels," *IEEE Trans. on Commun.*, vol. 46, no. 7, pp. 902-915, Jul. 1998.

[3] H. Liu and G. Li, *OFDM based Broadband Wireless Networks: Design and Optimization*, 1st ed. Hoboken, NJ: John Willey & Sons, 2005.

[4] Y. Mostofi and D. C. Cox, "Mathematical analysis of the impact of timing synchronization errors on the performance of an OFDM system," *IEEE Trans. on Commun.*, vol. 54, no. 2, pp. 226-230, Feb. 2006.

[5] L. Wan and V. K. Dubey, "Bit error probability of OFDM system over frequency nonselective fast Rayleigh fading channels," *IEEE Electron. Lett.*, vol. 36, no. 15, pp. 1306-1307, Jul. 2000.

[6] B. Sklar, *Digital Communications: Fundamentals and Applications*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2002.

[7] T. S. Rappaport, *Wireless Communications*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, 1996.

[8] K. L. Blackard, T. S. Rappaport, and C. W. Bostian, "Measurment and models of radio frequency impulsive noise for indoor wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 11, no. 7, pp. 991-1001, Sept. 1993.

[9] J. G. Prokias, *Digital Communications*, 5th ed. Avenue of the America, NY: McGraw-Hill, 2008.

[10] T. Kitamura, K. Ohno, and M. Itami, "A study on schemes of reducing influence of impulsive noise in OFDM under multipath channel," *IEEE Int. Conf. on Consum. Electron.*, pp. 119-120, Jan. 2010.

[11] L. J. Cimini, "Analysis and simulation of digital mobile channel using orthogonal frequency divison multiplexing," *IEEE Trans. on Commun.*, vol. 33, no. 7, pp. 665-

675, Jul. 1985.

[12] M. Ghosh, "Analysis of the effect of impulsive noise on multi-carrier and single-carrier QAM systems," *IEEE Trans. on Commun.*, vol. 44, no. 2, pp. 145-147, Feb. 1996.

[13] H. A. Suraweera, C. Chai, J. Shentu, and J. Armstrong, "Analysis of impulse noise mitigation techniques for digital television systems," *Proc. 8th Int. OFDM Workshop*, pp. 172-176, Sept. 2003.

[14] S. V. Zhidkov, "Impulsive noise suppression in OFDM based communication system," *IEEE Trans. on Consum. Electron.*, vol. 49, no. 4, pp. 944-948, Nov. 2003.

[15] J. Armstrong and H. A. Suraweera, "Impulsive noise mitigation for OFDM using decision directed noise estimation," *IEEE Int. Symp. on Spread Spectrum Techniques and Applicat.*, pp. 174-178, Sept. 2004.

[16] H. A. Suraweera and J. Armstrong, "Noise bucket effect for impulsive noise in OFDM," *IET Electron. Lett.*, vol. 40, no. 8, pp. 1156-1157, Sept. 2004.

[17] F. Abdelkefi, P. Duhamel, and F. Alberge, "Impulsive noise cancellation in multi-carrier transmission," *IEEE Trans. on Commun.*, vol. 53, no. 1, pp. 94-106, Jan. 2005.

[18] S. V. Zhidkov, "Performance analysis and optimization of OFDM receiver with blanking nonlinearity in impulsive noise environment," *IEEE Trans. on Veh. Technol.*, vol. 55, no. 1, pp. 234-242, Jan. 2006.

[19] T. Y. Al-Naffouri, A. K. Narayanan, and G. Caire, "Impulse noise cancellation in OFDM: an application of compressed sensing," *IEEE Int. Symp. on Inf. Theory*, pp. 1293-1297, Jul. 2008.

[20] Y. Chen, J. Zhang, and A. D. S. Jayalath "Estimation and compensation of clipping noise in OFDMA systems," *IEEE Trans. on Wireless Commun.*, vol. 9, no. 2, pp. 523-527, Jul. 2010.

[21] T. Kitamura, K. Ohno, and M. Itami, "Iterative impulsive noise reduction by

generating its replica signal in OFDM reception," *IEEE Int. Conf. on Consum. Electron.*, pp. 389-390, Jan. 2011.

[22] L. Lampe, "Bursty impulse noise detection by compressed sensing," *IEEE Int. Symp. on Power Line Commun.*, pp. 30-34, Apr. 2011.

[23] T. Y. Al-Naffouri, A. A. Quadeer, and G. Caire, "Impulsive noise estimation and cancellation in DSL using orthogonal Clustering," *IEEE Int. Symp. on Inf. Theory*, pp. 2841-2845, Aug. 2011.

[24] C. H. Yih, "Iterative interference cancellation for OFDM signals with blanking nonlinearity in impulsive noise channels," *IEEE Signal Process. Lett.*, vol. 19, no. 3, pp. 147-150, Mar. 2012.

[25] D. Tseng, Y. S. Han, W. H. Mow, L. Chang, and A.J. Han Vinck, "Robust clipping for OFDM transmissions over memory-less impulsive noise channels," *IEEE Commun. Lett.*, vol. 16, no. 7, pp. 1110-1113, Jul. 2012.

[26] G. Ren, S. Qiao, H. Zhao, C. Li, and Y. Hei, "Mitigation of periodic impulsive noise in OFDM-based power-line communications," *IEEE Trans. on Power Del.*, vol. 28, no. 2, pp. 825-834, Apr. 2013.

[27] M. E. Mathew and J. Jeevitha, "An impulsive noise cancellation using iterative algorithms," *IEEE Int. Conf. on Electron. and Commun*. Syst., pp. 1-6, Feb. 2014.

[28] T. Y. Al-Naffouri, A. A. Quadeer, and G. Caire, "Impulsive noise estimation and removal for OFDM systems," *IEEE Trans. on Commun.*, vol. 62, no. 3, pp. 976-989, Mar. 2014.

[29] R. Prasad, *OFDM for Wireless Communication*, 2^{nd} ed. Artech House, UK: Universal Personal Communications, 2004.

[30] Y. Wu and W. Y. Zou, "Orthogonal frequency division multiplexing: A multi-carrier modulation scheme," *IEEE Trans. on Consum. Electron.*, vol. 41, no. 3, pp. 392-399, Aug. 1995.

[31] S. B. Wienstein and P. M. Ebert, "Data transmission by frequency-division multiplexing using discrete Fourier transform," *IEEE Trans. on Commun. Tech.*,

vol. 19, no. 5, pp. 628-634, Oct. 1971.

[32] Y. Zhao and S. Haggman, "Inter-carrier interference self-cancellation scheme for OFDM mobile communication systems," *IEEE Trans. on Commun.*, vol. 49, no. 7, pp. 1185-1191, Jul. 2001.

[33] Y. Li, "Pilot-symbol-aided channel estimation for OFDM in wireless systems," *IEEE Trans. veh. Technol.*, vol. 49, no. 4, pp. 1207-1215, Jul. 2000.

[34] O. Gonzalez, R. Perez-Jimenez, S. Rodriguez, J. Rabadan, and A. Ayala, "OFDM over indoor wireless optical channel," *IEEE Proc. Optoelectron.*, vol. 152, no. 4, pp. 199-204, Mar. 2006.

[35] T. M. Schmidl and D. C. Cox, "Robust frequency and timing synchronization for OFDM," *IEEE Trans. on Commun.*, vol. 45, no. 12, pp. 1613-1621, Dec. 1997.

[36] S.B. Bulumulla, S. A. Kassam, and S. S. Venkatesh, "A systematic approach to detecting OFDM signals in a fading channel," *IEEE Trans. on Commun.*, vol. 48, no. 5, pp. 725-728, May 2000.

[37] Y. H. Ma and E. Gunawan, "Performance analysis of the OFDM system for broadband power line communications under impulsive noise and multipath effects," *IEEE Trans. on Power Del.*, vol. 20, no. 2, pp. 674-682, Apr. 2005.

[38] N. A. Gugudu, "Evaluation of channel coding in OFDM systems," M. Tech thesis, Dept. Electron. and Commun. Eng., National Institute of Technology, Rourkela, 2006.

[39] A. Pavani, E. V. K. Rao, and B. P. Rao, "A new OFDM standard for high rate wireless LAN in the 5 GHZ band," *Int. J. of Future Gen. Commun. and Netw.*, vol. 4, no. 4, pp. 57-64, Dec. 2011.

[40] K. Fazel, "Performance of OFDM for mobile communication system," *IEEE Pers. Commun.*, vol. 2, pp. 975-979, Oct. 1993.

[41] S. A. Fechtel, "OFDM carrier sampling frequency synchronization and its performance on stationary and mobile channels," *IEEE Trans. on Consumer Electron.*, vol. 46, no. 3, pp. 438-441, Aug. 2000.

[42] J. Armstrong and A.J. Lowery, "Power efficient optical OFDM," *IET Electron. Lett.*, vol. 42, no. 6, pp. 370-372, Mar. 2006.

[43] A. Goldsmith, *Wireless Communication,* 2nd ed. West 20th Street, NY: Cambridge University Press, 2005.

[44] M. R. Rao, "Simulation modeling of statistical Nakagmi- m fading channels," M.E. thesis, Dept. Electron. and Commun. Eng., Thapar University, Patiala.

[45] N. C. Beaulieu and C. Cheng, "Efficient Nakagami-m fading channel simulation," *IEEE Trans. on Veh. Technol.*, vol. 54, no. 2, pp. 413-424, Mar. 2005.

[46] S. V. Vaseghi, *Advance Digtial Signal Processing and Noise Reduction*, 2nd ed. West Sussex, UK: John Wiley & Sons, 2008.

[47] M. G. Sanchez et al., "Impulsive noise measurements and characterization in a UHF digital TV channel," *IEEE Trans. Electromagn. Compat.*, vol. 41, no. 2, pp. 124-136, May 1999.

[48] D. Middleton, "Statistical-physical models of electromagnetic interference," *IEEE Trans. Electromagn. Compat.*, vol. 19, no. 3, pp. 106-127, Aug. 1977.

[49] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, 4th ed. West Patel Nagar, ND: Tata McGraw-Hill, 1995.

[50] A. Leke and John M. Cioffi, "Impact of imperfect channel knowledge on the performance of multi-carrier systems," *IEEE Conf. on Global Telecommun.*, vol. 2, pp. 951-955, Nov. 1998.