BER Performance Analysis of Optical NOMA-OFDM System and Its Application in Hybrid LIFI

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Shraban Roy

Class Roll No: 002210702003

Registration No: 163530 of 2022-23

Examination Roll No: M4ETC24002

Under the guidance of

Dr. Jaydeb Bhaumik

Professor

Department of Electronics and Tele-Communication Engineering

Jadavpur University

Kolkata - 700032

West Bengal, India

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FACULTY OF ENGINEERING AND TECHNOLOGY
JADAVPUR UNIVERSITY

CERTIFICATE OF RECOMMENDATION

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_____

Prof. Jaydeb Bhaumik

Supervisor
Department of Electronics and Tele-Communication Engineering
Jadavpur University
Kolkata – 700032

_____

Prof. Sudhabindu Ray

Head of the Department
Department of Electronics and
Tele-Communication Engineering
Jadavpur University
Kolkata – 700032

_____

Prof. Dipak Laha

Dean
Faculty Council of Engineering &
Technology
Jadavpur University
Kolkata – 700032

FACULTY OF ENGINEERING AND TECHNOLOGY
JADAVPUR UNIVERSITY

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Committee on Final Examination
for Evaluation of the Thesis

_____
Signature of External Examiner

_____
Signature of Supervisor

Prof. Jaydeb Bhaumik
Supervisor
Department of Electronics and Tele-Communication Engineering
Jadavpur University
Kolkata – 700032

*Only in the case the thesis is approved.

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JADAVPUR UNIVERSITY

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I hereby declare that this thesis entitled **"BER Performance Analysis of Optical NOMA-OFDM System and Its Application in Hybrid LIFI"** contains a literature survey and original research work by the undersigned, as part of my degree of **Master of Engineering in Electronics and Tele-Communication Engineering**, with specialization in **Communication Engineering**.

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Name: **Shraban Roy**

Class Roll No.: **002210702003**

Registration No.: **163530 of 2022-23**

Examination Roll No.: **M4ETC24002**

Thesis Title: **BER Performance Analysis of Optical NOMA-OFDM System and Its Application in Hybrid LIFI**

_____

Signature of Candidate

Dedicated to

My father

Mr. Shibnath Roy

And

My mother

Mrs. Aparna Roy

And

My teacher

Dr. Jaydeb Bhaumik

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Shraban Roy
Jadavpur University
Kolkata – 700032
West Bengal
India

ABSTRACT

In optical wireless communication, data transfer between transmitter and receiver occurs wirelessly using visible light wave as carrier. Bit Error Rate (BER) is one of the most important performance measure of any communication system. In this thesis, performance of different optical Orthogonal Frequency Division Multiplexing (OFDM) modulation schemes such as Asymmetrically Clipped Optical OFDM (ACO-OFDM), DC Biased Optical OFDM (DCO-OFDM) and Asymmetrically Clipped DC Biased Optical OFDM (ADO-OFDM) is evaluated by measuring BER. Multiuser system has been evaluated considering Non Orthogonal Multiple Access (NOMA) scheme based on static and dynamic power allocation strategies. Static power allocation strategy such as Fixed Power Allocation (FPA) and dynamic power allocation strategies such as Gain Ratio Power Allocation (GRPA) and Normalized Gain Difference Power Allocation (NGDPA) have been considered for allocating power to users. The BER performances have been evaluated for both 2-user and 3-user systems. The ACO-OFDM shows the best BER performance among the three followed by DCO-OFDM and then ADO-OFDM modulation scheme. Fixed Power Allocation performs well in predefined user locations and controlled indoor environments. Dynamic power allocation strategy GRPA works well where users are largely separated from each other. On the other hand, NGDPA works well where users are distributed in a very closely packed manner. Also a hybrid Lifi – Wifi system has been simulated and its SNR profile has been evaluated in the indoor environment. Hybrid TDMA – NOMA has been used for resource allocation to users of this system and 16-QAM based DCO-OFDM has been used as optical modulation scheme. A priority based resource allocation technique has been introduced in Hybrid TDMA-NOMA multiple access scheme. Resources are allocated to users based on their prioritization set at the Access point (AP). The sharing of resources among users has been determined by grouping them into two clusters: priority and non-priority. The BER and sum rate performance of the proposed system have been evaluated considering 4-user which includes one priority user and three non priority users.

Keywords**:** Bit Error Rate, ACO-OFDM, DCO-OFDM, ADO-OFDM, Non Orthogonal Multiple Access, Fixed Power Allocation, Gain Ratio Power Allocation, Normalized Gain Difference Power Allocation, Hybrid Time Division Multiple Access – Non Orthogonal Multiple Access, Hybrid Lifi – Wifi, User Prioritization.

Contents

1 Introduction **1**

1.1 Aim of Thesis 2

1.2 Thesis Layout 2

2 Background and Literature Survey **4**

2.1 Optical OFDM Schemes 4

2.1.1 DC Biased Optical Orthogonal Frequency Division Multiplexing (DCO-OFDM) 5

2.1.2 Asymmetrically Clipped Optical Orthogonal Frequency Division Multiplexing (ACO-OFDM). 7

2.1.3 Asymmetrically Clipped DC biased Optical Orthogonal Frequency Division Multiplexing (ADO-OFDM) 8

2.2 Multiple Access Schemes 12

2.2.1 Orthogonal Multiple Access (OMA) 12

2.2.2 Code Division Multiple Access (CDMA) 13

2.2.3 Space Division Multiple Access (SDMA) 13

2.2.4 Non Orthogonal Multiple Access (NOMA) 13

2.2.4.1 Code Domain NOMA (CD NOMA) 14

2.2.4.2 Power Domain NOMA (PD NOMA) 14

2.2.5 Power Allocation Strategies in NOMA 17

2.2.5.1 Fixed Power Allocation (FPA) 17

2.2.5.2 Gain Ratio Power Allocation (GRPA) 17

2.2.5.3 Normalized Gain Difference Power Allocation (NGDPA) 18

2.3 Optical Wireless Communication Channel 19

2.4 Noise in Optical Wireless Communication 21

2.4.1 Additive White Gaussian Noise (AWGN) 21

2.4.2 Shot Noise 22

2.5 Performance Metrics 23

2.5.1 Bit Error Rate (BER) 23

2.5.2 Channel Capacity 23

2.6 Literature Survey 25
2.7 Conclusions 29

3 BER Performance of DCO-OFDM Modulation under Different Conditions 30
3.1 BER Performance of DCO-OFDM 31
3.2 BER Performance of DCO-OFDM for Two Users NOMA 34
3.2.1 BER Performance for Two Users NOMA with Fixed Power Allocation (DCO-OFDM) 34
3.2.2 BER Performance for Two Users NOMA with Gain Ratio Power Allocation (DCO-OFDM) 38
3.2.3 BER Performance for Two Users NOMA with Normalized Gain Difference Power Allocation (DCO-OFDM) 41
3.3 BER Performance of DCO-OFDM for Three Users NOMA 44
3.3.1 BER Performance for Three Users NOMA with Fixed Power Allocation (DCO-OFDM) 44
3.3.2 BER Performance for Three Users NOMA with Gain Ratio Power Allocation (DCO-OFDM) 47
3.3.3 BER Performance for Three Users NOMA with Normalized Gain Difference Power Allocation (DCO-OFDM) 50
3.4 Conclusions 53

4 BER Performance of ACO-OFDM Modulation under Different Conditions 54
4.1 BER Performance of ACO-OFDM 55
4.2 BER Performance of ACO-OFDM for Two Users NOMA 58
4.2.1 BER Performance for Two Users NOMA with Fixed Power Allocation (ACO-OFDM) 58
4.2.2 BER Performance for Two Users NOMA with Gain Ratio Power Allocation (ACO-OFDM) 62
4.2.3 BER Performance for Two Users NOMA with Normalized Gain Difference Power Allocation (ACO-OFDM) 65
4.3 BER Performance of ACO-OFDM for Three Users NOMA 68
4.3.1 BER Performance for Three Users NOMA with Fixed Power Allocation (ACO-OFDM) 68
4.3.2 BER Performance for Three Users NOMA with Gain Ratio Power

Allocation (ACO-OFDM) 71
4.3.3 BER Performance for Three Users NOMA with Normalized Gain Difference Power Allocation (ACO-OFDM) 74
4.4 Conclusions 77

5 BER Performance of ADO-OFDM Modulation under Different Conditions 78
5.1 BER Performance of ADO-OFDM 79
5.2 BER Performance of ADO-OFDM for Two Users NOMA 82
5.2.1 BER Performance for Two Users NOMA with Fixed Power Allocation (ADO-OFDM) 82
5.2.2 BER Performance for Two Users NOMA with Gain Ratio Power Allocation (ADO-OFDM) 86
5.2.3 BER Performance for Two Users NOMA with Normalized Gain Difference Power Allocation (ADO-OFDM) 89
5.3 BER Performance of ADO-OFDM for Three Users NOMA 92
5.3.1 BER Performance for Three Users NOMA with Fixed Power Allocation (ADO-OFDM) 92
5.3.2 BER Performance for Three Users NOMA with Gain Ratio Power Allocation (ADO-OFDM) 95
5.3.3 BER Performance for Three Users NOMA with Normalized Gain Difference Power Allocation (ADO-OFDM) 98
5.4 Conclusions 101

6 Application in Downlink of Hybrid Lifi - Wifi Networks 102
6.1 Hybrid TDMA-NOMA Multiple Access 102
6.2 Resource Allocation in Hybrid TDMA-NOMA 103
6.3 Performance Evaluation of Hybrid TDMA – NOMA 104
6.4 Conclusions 110

7 Summary and Future Work 111

Bibliography 114

List of Figures

2.1 Block Diagram of DCO-OFDM Systems 5

2.2 Block Diagram of ACO-OFDM System 7

2.3 Block Diagram of ADO-OFDM Transmitter System 8

2.4 Block Diagram of ADO-OFDM Receiver System 10

2.5 Resource Utilization in (a) OMA and (b) NOMA 14

2.6 Block Diagram of NOMA Multiple Access Methodology 15

2.7 Block Diagram of NOMA Multiple Access Algorithm 16

2.8 Indoor Visible Light Communication (VLC) Channel Model 19

3.1 BER vs E_b/N_0 graph for DCO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM 33

3.2 BER vs E_b/N_0 graph for DCO-OFDM modulation under two users NOMA multiple access scheme based on FPA 36

3.3 BER vs Power Allocation Factor graph for DCO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy 37

3.4 BER vs E_b/N_0 graph for DCO-OFDM modulation under two users NOMA multiple access scheme based on GRPA strategy 40

3.5 BER vs E_b/N_0 graph for DCO-OFDM modulation under two users NOMA multiple access scheme based on NGDPA strategy 43

3.6 BER vs E_b/N_0 graph for DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy 46

3.7 BER vs E_b/N_0 graph for DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy 49

3.8 BER vs E_b/N_0 graph for DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy 52

4.1 BER vs E_b/N_0 graph for ACO-OFDM and DCO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM 57

4.2 BER vs E_b/N_0 graph for ACO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy 60

4.3 BER vs Power Allocation Factor graph for ACO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy 61

4.4 BER vs E_b/N_0 graph for ACO-OFDM modulation under two users NOMA multiple access scheme based on GRPA strategy 64

4.5 BER vs E_b/N_0 graph for ACO-OFDM modulation under two users NOMA multiple access scheme based on NGDPA strategy 67

4.6 BER vs E_b/N_0 graph for ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy 70

4.7 BER vs E_b/N_0 graph for ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy 73

4.8 BER vs E_b/N_0 graph for ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy 76

5.1 BER vs E_b/N_0 graph for ADO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM 81

5.2 BER vs E_b/N_0 graph for ADO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy 84

5.3 BER vs Power Allocation Factor graph for ADO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy 85

5.4 BER vs E_b/N_0 graph for ADO-OFDM modulation under two users NOMA multiple access scheme based on GRPA strategy 88

5.5 BER vs E_b/N_0 graph for ADO-OFDM modulation under two users NOMA multiple access scheme based on NGDPA strategy 91

5.6 BER vs E_b/N_0 graph for ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy 94

5.7 BER vs E_b/N_0 graph for ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy 97

5.8 BER vs E_b/N_0 graph for ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy 100

6.1 Hybrid TDMA-NOMA User Clustering 103

6.2 SNR Profile of Simulated Hybrid Lifi Wifi System 106

6.3 BER vs E_b/N_0 graph of Hybrid Lifi – Wifi system for four users Hybrid NOMA multiple access scheme based on Fixed Power Allocation strategy 108

List of Tables

3.1 Simulation Parameters for DCO-OFDM 31

3.2 BER measurement of DCO-OFDM modulation with AWGN communication channel based on 4 QAM, 16 QAM and 64 QAM 32

3.3 BER measurement of DCO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on FPA strategy 35

3.4 BER measurement of DCO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on GRPA strategy 39

3.5 BER measurement of DCO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on NGDPA strategy 42

3.6 BER measurement of DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy 45

3.7 BER measurement of DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy 48

3.8 BER measurement of DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy 51

4.1 Simulation Parameters of ACO-OFDM 55

4.2 BER measurement of ACO-OFDM and DCO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM 56

4.3 BER measurement of ACO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on FPA strategy 59

4.4 BER measurement of ACO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on GRPA strategy 63

4.5 BER measurement of ACO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on NGDPA strategy 66

4.6 BER measurement of ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy 69

4.7 BER measurement of ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy 72

4.8 BER measurement of ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy 75

5.1 Simulation Parameters of ADO-OFDM 79

5.2 BER measurement of ADO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM 80

5.3 BER measurement of ADO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on FPA strategy 83

5.4 BER measurement of ADO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on GRPA strategy 87

5.5 BER measurement of ADO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on NGDPA strategy 90

5.6 BER measurement of ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy 93

5.7 BER measurement of ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy 96

5.8 BER measurement of ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy 99

6.1 Simulation Parameters for Hybrid Lifi – Wifi 105

6.2 BER measurement of Hybrid Lifi – Wifi system under four users Hybrid NOMA multiple access scheme based on Fixed Power Allocation strategy 107

6.3 Sum Rate and Individual user Data Rate in Hybrid Lifi Wifi System 109

Chapter 1

Introduction

Optical wireless communication can be described as the transfer of information between multiple sources and destinations wirelessly where instead of using radio frequency waves (RF signal), we use visible light waves. There are multiple advantages of using optical wireless communication over traditional RF wireless communication. Some of the advantages are as follows:

- Visible light spectrum (400THz – 780THz) has approximately 1000 times more bandwidth than RF wave spectrum (30KHz – 300GHz).
- Visible light spectrum is a better choice compare to RF spectrum. Visible light spectrum is generally considered safe for human exposure in the power levels used for communication. There are no known health risks associated with VLC. There are ongoing concerns and debates about the long-term health effects of exposure to RF radiation.
- VLC does not cause electromagnetic interference (EMI). It can be used in environments where EMI can disrupt sensitive equipments e.g. in hospitals or aircrafts.
- It is very cost effective and can be installed in indoor premises very easily.

However, for proper implementation of optical wireless communication in indoor environments major research and exploration is required to maximize resource utilization. Many popular modulation schemes are available for use in indoor optical wireless communication like OOK (On-Off Keying), CSK (Colour Shift Keying), PAM (Pulse Amplitude Modulation), PWM (Pulse Width Modulation) and VPPM (Variable Pulse Position Modulation) etc. But this modulation schemes are not capacity achieving and making them spectrally inefficient. However, they have good error performance in terms of bit error rate. For this reason some higher order modulation schemes are introduced in indoor optical wireless channel like DCO-OFDM (Direct Current biased Optical Orthogonal Frequency Division Multiplexing), ACO-OFDM (Asymmetrically Clipped Optical Orthogonal Frequency Division Multiplexing) and ADO-OFDM (Asymmetrically Clipped DC-biased Optical Orthogonal Frequency Division Multiplexing). Apart from this, we need suitable multiple access scheme to accommodate multiple users in the indoor optical wireless communication network. Multiple

access scheme is necessary in wireless communication system for seamless simultaneous connectivity for different users within the network. We have considered for our study Additive White Gaussian Noise (AWGN) dominated channel and evaluated the BER (Bit Error Rate) performance under different simulation conditions.

Now, to understand the effect of different modulation scheme with multiple access conditions, at first we have studied single user performance. Then we have extended our study to multiple users. We have considered Non Orthogonal Multiple Access (NOMA) scheme for this as it is a promising capacity achieving technique predominantly used in 5G and beyond wireless communication systems. We have also extended our study by considering different dynamic power allocation strategies of NOMA.

After evaluating BER performance of these modulation schemes under different conditions, we have tried to simulate a Light Fidelity (LIFI) system from application point of view. Different modulation schemes are used in LIFI along with hybrid TDMA-NOMA based multiple access scheme. This system performance has been evaluated using metrics like BER, sum rate etc. All the studies and experiments are performed in MATLAB simulation environment.

1.1 Aim of Thesis

Measurement of bit error rate (BER) of different orthogonal frequency division multiplexing (OFDM) based optical modulation schemes with non orthogonal multiple access (NOMA) scheme with different power allocation strategies, its application to a LIFI system and performance evaluation.

1.2 Thesis Layout

The remaining parts of this thesis are constituted as follows

Chapter 2: In this chapter, theoretical foundations and concepts are explained. Later, literature survey is also included in this chapter.

Chapter 3: In this chapter, BER performance of DCO-OFDM modulation scheme is described. All the experimental results and plots for different conditions are included in this chapter.

Chapter 4: In this chapter, we have shown BER performance of ACO-OFDM modulation scheme for different scenarios. Simulation results and graph for BER vs SNR are provided in this chapter.

Chapter 5: In this chapter, BER performance of ADO-OFDM modulation scheme are highlighted along with the simulation results and necessary plots considering all the conditions and scenarios.

Chapter 6: In this chapter, we have simulated a LIFI system considering the above mentioned modulation schemes and hybrid TDMA-NOMA based multiple access scheme. Simulation results and all the plots are provided here.

Chapter 7: Finally, the thesis is concluded by providing a summary and discussing future prospects of the work.

Chapter 2

Background and Literature Survey

This chapter thoroughly covers all the fundamental aspects of the related topics. Three popular OFDM based optical modulation schemes known as DCO-OFDM (Direct Current biased Optical Orthogonal Frequency Division Multiplexing), ACO-OFDM (Asymmetrically Clipped Optical Orthogonal Frequency Division Multiplexing) and ADO-OFDM (Asymmetrically Clipped DC-biased Optical Orthogonal Frequency Division Multiplexing) are used for the experiments. Non Orthogonal Multiple Access (NOMA) technique along with suitable different power allocation methods like Fixed power allocation (FPA), Gain ratio power allocation (GRPA) and Nominal gain difference power allocation (NGDPA) has been considered in this thesis. Additive white Gaussian noise (AWGN) has been used for modelling the channel noise. Optical wireless channel is a deterministic channel unlike Radio Frequency (RF) channel which is probabilistic in nature. We have considered Lambertian channel model for our experiments.

2.1 Optical OFDM Schemes

By definition, modulation is the process of varying carrier wave properties like amplitude, frequency or phase according to the modulating signal. Some of the popular modulation schemes in optical domain are Pulse amplitude Modulation (PAM), Pulse Position Modulation (PPM), DCO-OFDM (Direct Current biased Optical Orthogonal Frequency Division Multiplexing), ACO-OFDM (Asymmetrically Clipped Optical Orthogonal Frequency Division Multiplexing and ADO-OFDM (Asymmetrically Clipped DC-biased Optical Orthogonal Frequency Division Multiplexing). In the next subsections basics of these 3 used modulation schemes DCO-OFDM, ACO-OFDM and ADO-OFDM have been discussed.

2.1.1 Direct Current biased Optical Orthogonal Frequency Division Multiplexing (DCO-OFDM)

DCO-OFDM is an optical modulation technique which is based on orthogonal frequency division multiplexing (OFDM). In case of traditional OFDM modulation at RF systems, transmitted and received signals can be complex and bipolar in nature. But in case of optical domain, all the optical signals must be real and unipolar. These imposed restrictions helps in the implementation of IM/DD (Intensity Modulation and Direct Detection) at the transmitter and receiver side.

DCO-OFDM maintains these constraints by using two features – one is ensuring Hermitian symmetry all the time to make it real and another is applying a DC bias shift to make it unipolar.

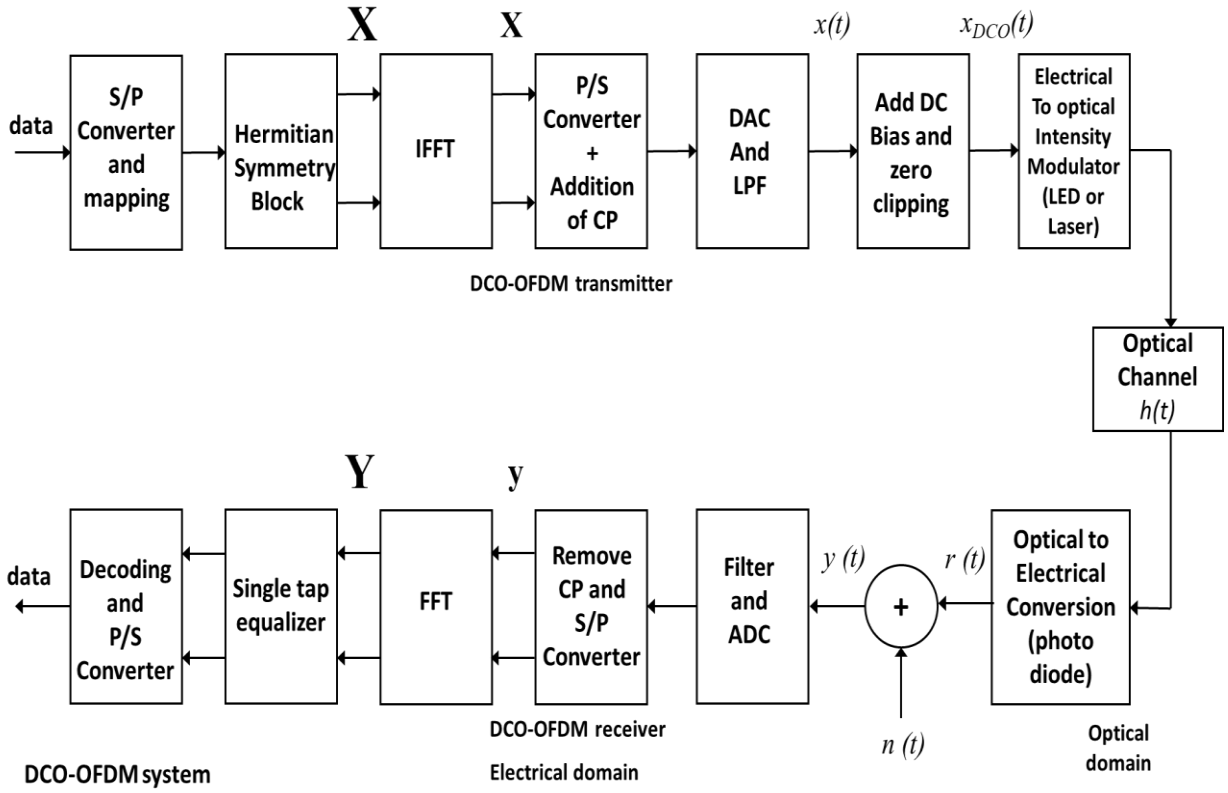


Figure 2.1: Block Diagram of DCO-OFDM System

Here a DCO-OFDM transceiver system is shown in Figure 2.1. Input data streams are first mapped to complex signal $\boldsymbol{X}$ usually by an M – QAM (M-ary Quadrature Amplitude Modulation) modulator. The complex data signal, $\boldsymbol{X} = [X_0, X_1, X_2, \ldots, X_{N-1}]$ is fed into the

inverse fast Fourier transform (IFFT), where $\boldsymbol{X}$ is required to exhibit Hermitian symmetry, as described subsequently,

$$\boldsymbol{X_i = X^*_{N-i}} \quad , \ \forall\, i \ \epsilon \ \ 0 < i < \frac{N}{2} \tag{2.1}$$

and the remaining two components must be zero i.e. $\boldsymbol{X_0} = \boldsymbol{X_{N/2}} = 0$. Lowercase symbols will be used for discrete time domain signals and upper case symbols will be used for discrete frequency domain signals throughout our discussion. The kth time domain sample for **x** denoted by $\boldsymbol{x_k}$ is defined by,

$$\boldsymbol{x_k = \frac{1}{N}\sum_{i=0}^{N-1} X_i e^{\frac{j\,2\pi k i}{N}}} \tag{2.2}$$

Where N denotes the points on IFFT operation and X_i is the ith subcarrier component of signal $\boldsymbol{X}$. Due to imposing of Hermitian Symmetry, the number of distinct data carrying subcarriers limits to (N/2) – 1. Thus orthogonal subcarriers are generated for OFDM and QAM modulated signals are imposed on this. Then generated parallel input x is converted to serial output x (t) using a parallel to serial converter (P/S) block. This signal is real and bipolar in nature. To transmit a signal through LED, the signal must be real and unipolar. A suitable DC bias is added to this signal and after that remaining negative peaks are clipped to zero. In general OFDM signals have very high peak to average power ratio (PAPR). Consequently, very high bias is required to eliminate all peaks. Hence moderate bias is used followed by clipping operation [1].The DC bias level in DCO – OFDM systems is given by [2],

$$\boldsymbol{\beta = \mu \sqrt{E\{x(t)^2\}}} \tag{2.3}$$

Where μ is a constant of proportionality. β is defined as a bias which is equal to $10\log_{10}(\mu^2+1)$ dB. As discussed earlier after addition of β, all the remaining negative peaks of x (t) are clipped to zero. After that cyclic prefix is added to it to combat Inter Symbol Interference (ISI) and the desired $\mathbf{x_{DCO}(t)}$ is obtained. This electrical signal is then converted to optical signal using an LED based optical converter and transmitted via optical wireless communication (OWC) channel [3].

At the receiver end, first the optical signal is converted into an electrical signal using a Photodetector (PD). After that DC bias is removed and signal is passed through an equalizer. The remaining steps in the receiver are same as RF based OFDM modulation [4].

2.1.2 Asymmetrically Clipped Optical Orthogonal Frequency Division Multiplexing (ACO-OFDM)

ACO–OFDM is also an Optical Orthogonal Frequency Division Multiplexing based modulation scheme where only odd subcarriers are used for data transmission. This imposed restriction on even subcarriers supplies a bias to the OFDM symbol. As a result, non negativity condition is met [1].

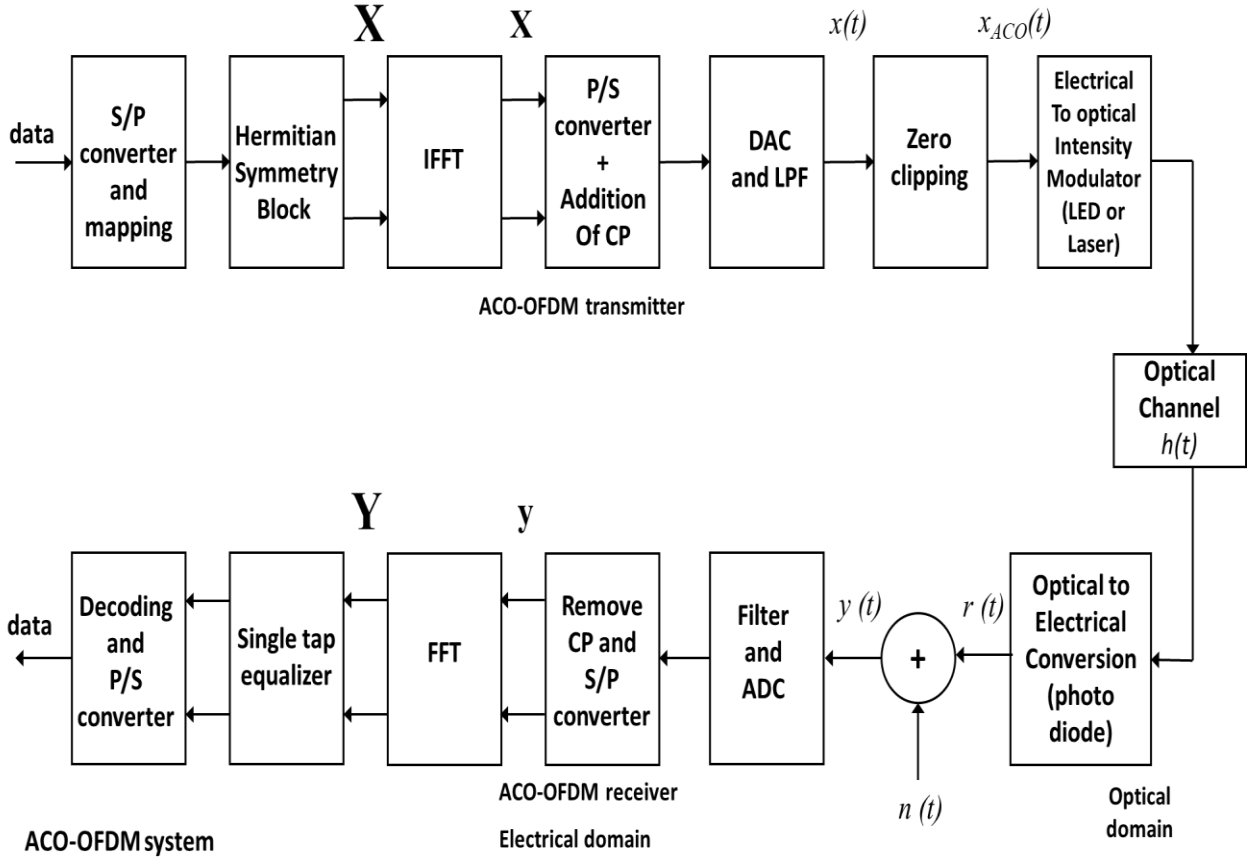


Figure 2.2: Block Diagram of ACO-OFDM System

The above figure 2.2 depicts an ACO-OFDM transceiver system. Input data streams are first QAM modulated. The input signal of the IFFT block **X** will essentially have odd components like $\boldsymbol{X} = [0, X_1, 0, X_3, \ldots, 0, X_{N-1}]$. The Hermitian symmetry block ensures that the elements of the input signal **X** after IFFT operation will give real signal suitable for optical transmission. The symmetry condition is same as defined in (1). This imposed condition on odd subcarriers of ACO-OFDM systems introduces anti-symmetry property in the time domain real signal x as defined by [5],

$$x_i = -x_{i+\frac{N}{2}}\ ,\ \forall\ i\ \epsilon\ \ 0 < i\ < \frac{N}{2} \tag{2.4}$$

Similar like DCO-OFDM systems, x is first converted into a serial signal. All the remaining negative peaks of the resultant signal x (t) are clipped to zero as negative signals are not suitable for transmission through IM/DD systems. After that a cyclic prefix of suitable length is added to x (t), which gives the desired ACO-OFDM signal $\mathbf{x_{ACO}(t)}$.

The anti-symmetry property of signal **x** ensures no loss of information due to clipping operation [5]. The clipping operation in signal $\mathbf{x_{ACO}(t)}$ results in odd elements becoming as $\mathbf{X_i/2}$ where $\mathbf{X_i}$ is the i^{th} subcarrier of the discrete frequency transform vector of $\mathbf{x_{ACO}(t)}$ and a clipping noise interference is introduced in the even subcarriers only [6]. The signal $\mathbf{x_{ACO}(t)}$ is fed into an optical modulator for intensity modulation purpose.

The demodulation process for ACO-OFDM signal is same as DCO-OFDM modulated signals. But here demodulation is done only for odd subcarriers. The reason behind this is the odd subcarriers are data carrying subcarriers and even subcarriers are carrying clipping noise.

2.1.3 Asymmetrically Clipped DC Biased Optical Orthogonal Frequency Division Multiplexing (ADO-OFDM)

In ADO-OFDM system both DCO-OFDM and ACO-OFDM signals are transmitted simultaneously. Here odd data carriers are ACO-OFDM modulated and even data carriers are DCO-OFDM modulated.

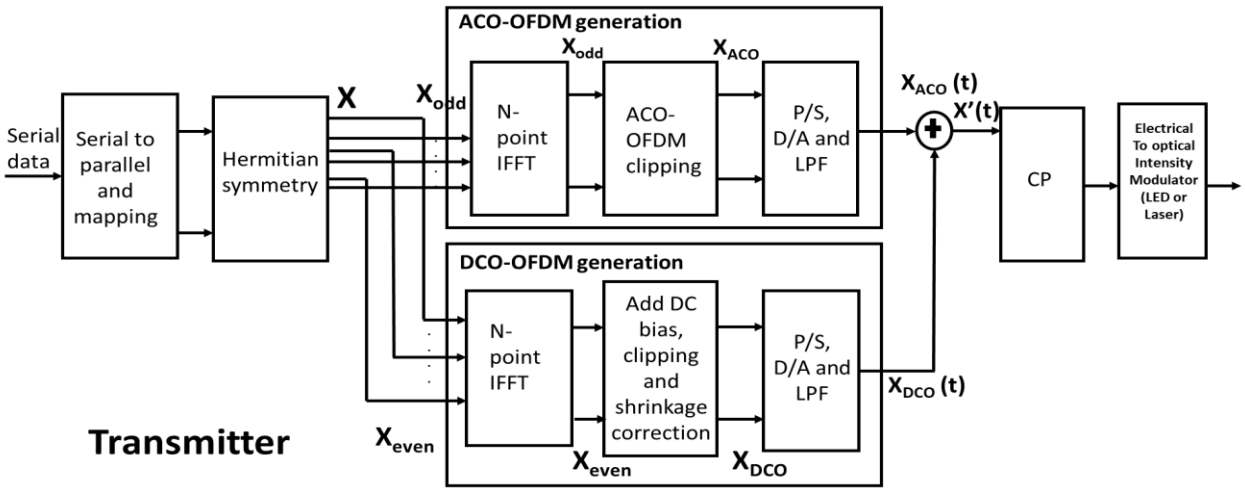


Figure 2.3: Block Diagram of ADO-OFDM Transmitter System

Figure 2.3 shows an ADO-OFDM transmitter block diagram. The upper path in the transmitter generates the ACO-OFDM signals and the lower path generates the DCO-OFDM signals. The ACO-OFDM path's signal processing is extremely similar to that of a traditional ACO-OFDM transmitter [7]. The input data vector X is split into odd and even components i.e. $\mathbf{X_{odd}}$ and $\mathbf{X_{even}}$ with Hermitian symmetry being a constraint where $\mathbf{X_{odd}}$ = [0, X_1, 0, X_3, 0, . . . , 0, X_{N-1}] and $\mathbf{X_{even}}$ = [X_0, 0, X_2, 0, …, X_{N-2}, 0]. The elements of $\mathbf{X_{odd}}$ and $\mathbf{X_{even}}$ will have Hermitian symmetry since the elements of **X** have Hermitian symmetry. After that, $\mathbf{X_{odd}}$ and $\mathbf{X_{even}}$ are fed into two different IFFT blocks to yield $\mathbf{x_{odd}}$ and $\mathbf{x_{even}}$ respectively where $\mathbf{x_{odd}}$ = [$x_{odd,0}$, $x_{odd,1}$, …, $x_{odd,N-1}$] and $\mathbf{x_{even}}$ = [$x_{even,0}$, $x_{even,1}$, …, $x_{even,N-1}$]. Both the signals generated $\mathbf{x_{odd}}$ and $\mathbf{x_{even}}$ are real and bipolar in nature. After that ACO-OFDM signal $\mathbf{x}_{ACO}$ is generated by clipping the negative peaks of $\mathbf{x_{odd}}$ and is given by,

$$\boldsymbol{x}_{ACO} = \frac{1}{2}\boldsymbol{x}_{odd} + \boldsymbol{n}_{ACO} \tag{2.5}$$

where n_{ACO} is the noise arises due to clipping operation [6].

The discrete time domain signal, $\mathbf{x_{even}}$, is subjected to a DC-bias in order to generate the $\mathbf{x_{DCO}}$ signal in the DCO-OFDM. Any residual negative peaks are then clipped. $\mathbf{x_{even}}$ has even symmetry since it is formed from solely the even index subcarriers. Consequently,

$$\boldsymbol{x}_{even,i} = \boldsymbol{x}_{even,i+N/2} \qquad 0 \le i < \frac{N}{2} \tag{2.6}$$

If B_{DC} is the DC bias added to the signal and n_{DCO} is the clipping noise then resulting DCO-OFDM bias signal is given by,

$$\boldsymbol{x}_{DCO} = \boldsymbol{x}_{even} + \boldsymbol{n}_{DCO} + \boldsymbol{B}_{DC} \tag{2.7}$$

Where

$$\boldsymbol{x}_{DCO,i} = \boldsymbol{x}_{DCO,i+N/2} \ \ and \ \boldsymbol{n}_{DCO,i} = \boldsymbol{n}_{DCO,i+N/2} \ \ 0 \le i < \frac{N}{2} \tag{2.8}$$

Consequently, only the even index subcarriers will be impacted by nDCO when the original DCO-OFDM signal only contains even subcarriers. This is significant since it indicates that the DCO-OFDM clipping noise does not impair the ACO-OFDM's performance. After that two signals $\mathbf{X_{ACO}}$ and $\mathbf{X_{DCO}}$ are serialized and converted into analog signals using P/S converter. These results into time domain signal $\mathbf{x_{ACO}(t)}$ and $\mathbf{x_{DCO}(t)}$. Then these signals $\mathbf{x_{ACO}(t)}$ and $\mathbf{x_{DCO}(t)}$ are added together to generate resultant signal $\mathbf{x_{ADO}(t)}$.

$$\boldsymbol{x_{ADO}(t) = x_{ADO}(t) + x_{DCO}(t)} \tag{2.9}$$

After that cyclic prefix is appended with it and the resultant signal is transmitted through an optical modulator preferably LED.

On the receiver side, reverse operations are performed to demodulate the ADO-OFDM signal. A receiver structure is shown in the below figure 2.4.

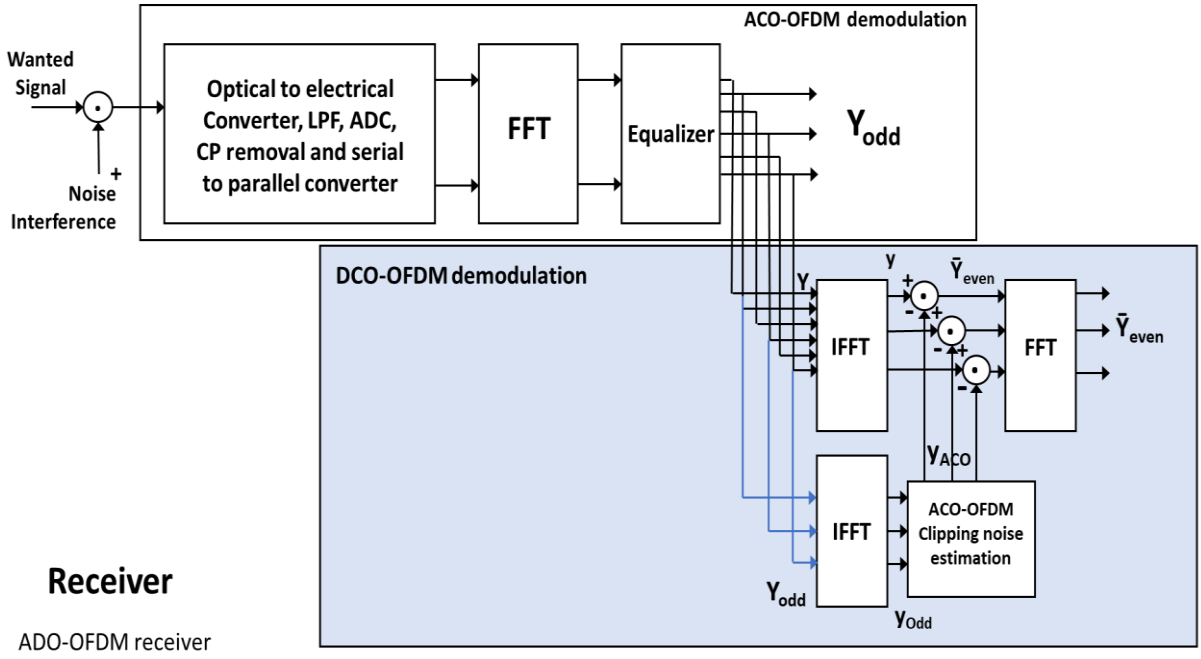


Figure 2.4: Block Diagram of ADO-OFDM Receiver System

Figure 2.4 shows an ADO-OFDM receiver which has two separate paths of demodulation, one for ACO-OFDM symbols and another for DCO-OFDM symbols. If we consider a flat AWGN channel for further analysis, the affecting noise can be modelled separately as odd component $\mathbf{n}_{\text{odd}}$ and even component $\mathbf{n}_{\text{even}}$. Hence the received signal is given by,

$$y = \frac{1}{2}x_{odd} + n_{ACO} + x_{even} + n_{DCO} + B'_{DC} + n_{odd} + n_{even} \tag{2.10}$$

After receiving the signal through an optical photodiode, it is converted into digital signal using A/D converter. The serialized discrete time domain signal is converted to parallel frequency domain signal by using an S/P converter block followed by a FFT operation block.

Among the components of the equation (2.10), only $\mathbf{x}_{odd}/2$ and $\mathbf{n}_{odd}$ contributes to the odd frequency subcarriers. Hence the odd component of Y is given by,

$$Y_{odd} = \frac{1}{2}X_{odd} + N_{odd} \tag{2.11}$$

Hence, the odd subcarriers at the receiver will allow for the recovery of data that was transmitted through ACO-OFDM on the same subcarriers at the transmitter side.

On the other hand, we need to subtract out ACO-OFDM signal from the total received signal to demodulate the DCO-OFDM signal. A local estimate of the ACO-OFDM signal is generated for this reason and subtracted out from the received signal. Y_{odd} is sent to input of an IFFT to generate y_{odd}. Then it is doubled to generate an estimate of x_{odd}. Then y_{aco} is obtained from it by clipping it to zero.

$$y_{ACO} = x_{ACO} + n_{ACO\ even} + n_{ACO\ odd} \tag{2.12}$$

A noise power component, $n_{ACO\ even}$, is produced in the even subcarriers by this estimate procedure, and $n_{ACO\ odd}$, in the odd subcarriers. Because of equal overall power in odd and even subcarriers using ACO clipping [6], the odd and even components i.e. $n_{ACO\ odd}$ and $n_{ACO\ even}$ will have equal average noise power. The locally estimated ACO-OFDM signal y_{ACO} is subtracted out from the received signal y and $\bar{y}_{even}$ is obtained. This $\bar{y}_{even}$ is fed to the input of an FFT block to obtain $\bar{Y}_{even}$. This $\bar{Y}_{even}$ gives a noisy estimate of the transmitted DCO-OFDM signal. The expression for $\bar{Y}_{even}$ can be obtained from eqn. 10, eqn. 11 and eqn. 12 as follows–

$$\bar{Y}_{even} = X_{even} + N_{DCO} + B'_{DC} + N_{ACO\ even} + N_{even} \tag{2.13}$$

$\bar{Y}_{even}$ contains three noise sources, the AWGN channel noise, DCO-OFDM clipping noise and another noise component due to noisy estimation of the ACO-OFDM signal during successive interference cancellation process. After QAM demodulation of this $\bar{Y}_{even}$ the original data is retrieved.

2.2 Multiple Access Schemes

VLC has a significant downside. It is limited in its ability to provide high data rate due to the small modulation bandwidth (measured in MHz) of LED light sources [8]. Taking care of this drawback is necessary in order to fully utilize VLC's benefits. This is addressed in this section along with multiplexing techniques that are employed to get around it. The majority of multiplexing methods created for radio frequency (RF) applications cannot be directly utilized in indoor VLC based communication systems without the necessary adjustments. It is necessary to do processing at the transmitter to transform complicated data into real and non-negative since VLC uses IM/DD modulation, which requires real and non-negative data [9]. 2G cellular networks employed traditional schemes like frequency division multiple access (FDMA), which assigns different frequencies to different users, and time division multiple access (TDMA), which assigns different time slots to each user while operating in the same frequency channel. These schemes cannot be applied to VLC directly. However, with necessary readjustments, this multiple access schemes can be used in VLC systems. At present time, VLC system employs the following popular multiplexing schemes –

2.2.1 Orthogonal Multiple Access (OMA)

OMA is generally implemented by Orthogonal Frequency Division Multiple Access (OFDMA). OFDMA was introduced for high data rate communication. Different users are assigned different resource blocks, which are different sub-carriers, in this multiple access scheme. In VLC, inter-symbol interference (ISI) occurs due to LED bandwidth limitation as data rate increases. Equalization techniques can be used to minimize this effect. OFDM is efficient in terms of ISI because it uses a large number of low rate orthogonal subcarriers. However, due to some limitations, OFDM is not that popular in VLC. First, it generates complex and bipolar waveforms that are incompatible with VLC. This can be resolved by using Hermitian Symmetry on subcarriers to produce real signals. Certain methods were used to make this real signal bipolar. These methods are:

- DC Biased OFDMA,
- Asymmetrically Clipped OFDMA,
- Asymmetrically Clipped DC Biased OFDMA, etc.

2.2.2 Code Division Multiple Access (CDMA)

In Code Division Multiple Access (CDMA), every individual is allocated a distinct code referred to as a pseudorandom code, facilitating each user to utilize the complete frequency spectrum concurrently. Within the realm of optics, CDMA makes use of optical orthogonal codes. To ensure optimal retrieval at the recipient terminal, these codes must adhere to specific criteria [10]. This complexity contributes to the challenge in generating such codes. Consequently, due to its intricate nature, CDMA is not commonly implemented in Visible Light Communication (VLC).

2.2.3 Space Division Multiple Access (SDMA)

Spatial diversity is utilized in order to allocate common time and frequency resources to multiple users. Spatial Division Multiple Access (SDMA) utilizes directionality features to access the communication channel with the aim of enhancing spectrum efficiency. Due to the directional nature of transmitters in Visible Light Communication (VLC), SDMA proves to be beneficial in this context.

2.2.4 Non Orthogonal Multiple Access (NOMA)

NOMA, a recently introduced multiple access scheme, has the potential to support widespread connectivity within Visible Light Communication (VLC) systems. The concept of NOMA was initially presented within the realm of 5G networks [11]. Within NOMA, individual users are assigned varying power levels depending on their specific channel conditions, enabling each user to fully utilize the available bandwidth. Contrary to traditional Orthogonal Multiple Access (OMA) methods, NOMA stands out by permitting the utilization of the complete spectrum of frequency and time resources [12].

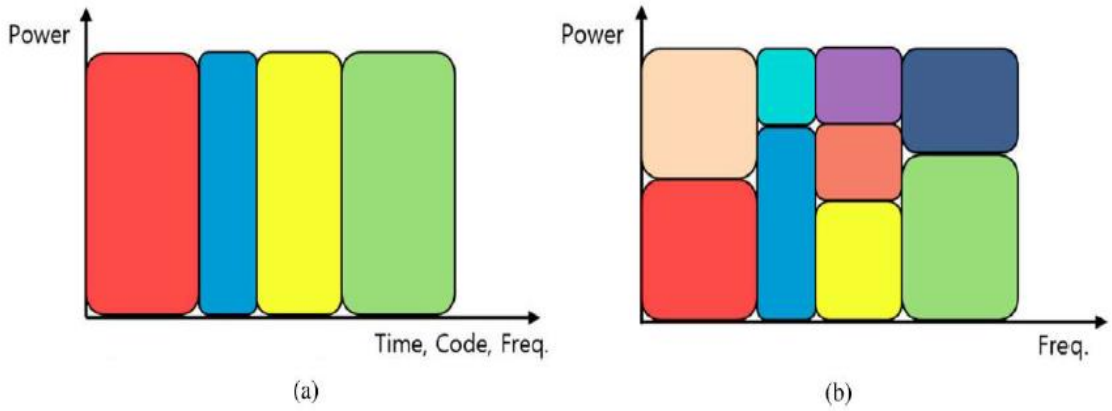


Figure 2.5: Resource Utilization in (a) OMA and (b) NOMA

NOMA is a very efficient multiple access scheme. It improves overall spectral efficiency, latency, fairness and sum rate or capacity of the system. NOMA can be implemented in two ways -

- Code-domain NOMA (CD-NOMA)
- Power-domain NOMA (PD-NOMA)

2.2.4.1 Code-domain NOMA (CD-NOMA)

Every user in CD-NOMA is assigned a spreading sequence that is unique to them. The frequency-time resources are shared by the users. Through coding or spreading, the CD-NOMA adds redundancy, increasing user separation at the receiver. In general, PD-NOMA is preferred over CD-NOMA as it has the same problems related to orthogonal codes in CDMA schemes.

2.2.4.2 Power-domain NOMA (PD-NOMA)

Our primary focus in VLC systems is PD-NOMA. A distinct power level is assigned to each user based on their channel conditions in this multiple access scheme. The fundamental concept of NOMA is to allocate less power to near users i.e. users having good channel conditions and more power to far users i.e. users having worse channel conditions. These users utilize successive interference cancellation (SIC) to eliminate signals intended for other users before

decoding their own messages [12]. Since PD-NOMA is a major topic of this thesis, NOMA throughout the subsequent discussion will refer to PD-NOMA. Foundation of NOMA scheme is set up on two concepts:

- **Superposition Coding**

  This is utilized at the transmitter to provide data simultaneously to every customer being served. Following the allocation strategy of the required power to each message signal, a single signal is generated by summing the intensities of all the individual signals and the resultant one is broadcast by the LED transmitter. The signal received after superposition coding is represented by the symbol x in the illustration.

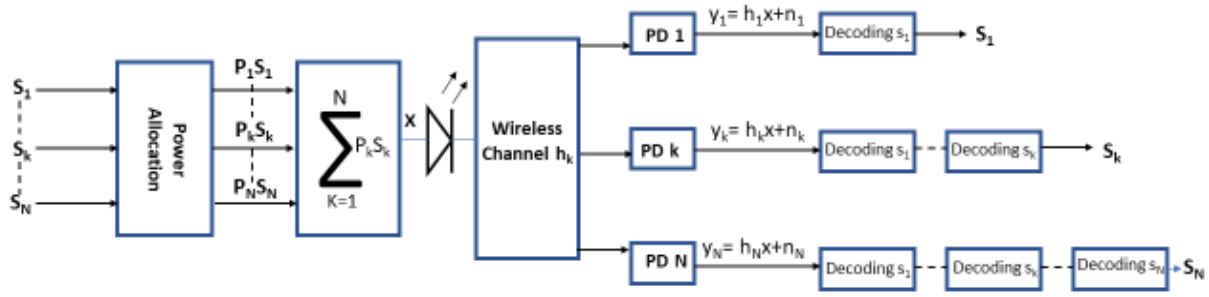


Fig 2.6: Block Diagram of NOMA Multiple Access Methodology

- **Successive Interference Cancellation (SIC)**

  Before identifying the signal meant for each user, SIC is applied at the receiver to the received signal (y_i). In SIC, the highest strength signal is decoded by the receiver and then subtracted from the whole signal. This procedure keeps on until the receiver receives the signal that is meant for it. All signals that are weaker or have a strength lower than the receiver's intended signal power are regarded as noise. For successful decoding of the signal at each receiver, sent through NOMA scheme, there should be perfect channel state information (CSI) maintained between transmitter and all the receivers. Figure 2.7 provides a step by step procedure of NOMA algorithm.

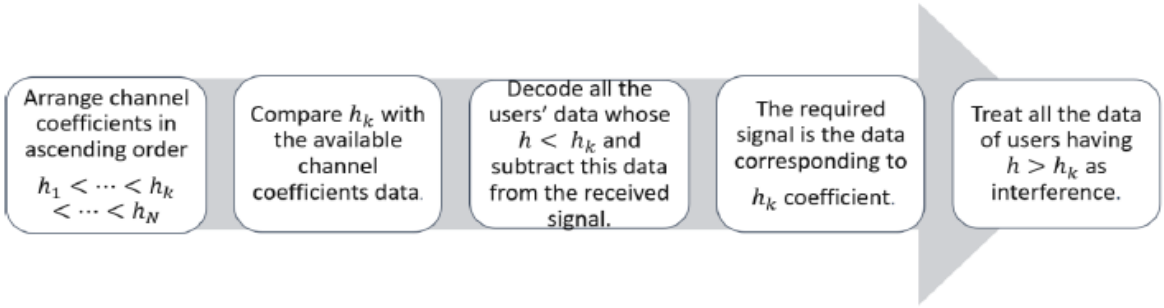


Figure 2.7: Block Diagram of NOMA Multiple Access Algorithm

Suppose there are N number of users. They are communicated with an access point (AP) through NOMA scheme in the downlink. The data signal sent for i[th] user is denoted by S_i. Depending on the channel conditions i.e. channel coefficients these users are assigned different power levels. The associated power assigned to the i[th] user is depicted by P_i. Then after superimposing all these signals, signal x transmitted by the transmitter LED is given by,

$$x = \sum_{i=1}^{N} P_i S_i \tag{2.14}$$

$$= P_1 S_1 + P_2 S_2 + \cdots + P_i S_i + \cdots + P_N S_N$$

This signal is propagated through VLC channel having channel gain h_i for i[th] user. Then signal received at the i[th] user receiver is given by,

$$y_i = h_i x + n$$

$$= h_i \left[\sum_{j=1}^{i-1} P_j S_j + P_i S_i + \sum_{j=i+1}^{N} P_j S_j\right] + n \tag{2.15}$$

Where n refers to the Additive White Gaussian Noise (AWGN) with zero mean. The first term in the bracket refers to the signals which will be removed in the i[th] receiver through SIC operation, the second term refers the actual desired signal of the i[th] receiver and the third term refers the undesired interference in the received signal, basically signals with poor powers sent to users with good channel conditions.

2.2.5 Power Allocation Strategies in NOMA

The most vital resource in NOMA is power. Hence it should be efficiently allocated and managed. In the NOMA system, users experiencing degraded channel conditions receive higher power levels, leading to the relationship $P_1 \geq \cdots \geq P_i \geq \cdots \geq P_N$. When it comes to the i^{th} user, successive interference cancellation (SIC) is executed on the signal y_i that is received. Prioritized allocation of power is given to users preceding the i^{th} user due to their inferior channel conditions. The transmission intended for these specific users is decoded and removed from the incoming signal. Conversely, users ranging from $(k+1)$ to N exhibit superior channel conditions and are subjected to lower power levels compared to the i^{th} user, being regarded as sources of interference. Here we will discuss some popular power allocation strategies of NOMA.

2.2.5.1 Fixed Power Allocation

This is the most basic and simple power allocation strategy available in NOMA. This is also known as static power allocation strategy of NOMA. In this strategy each user is given a fixed amount of power based on channel conditions such that power allocated to i^{th} user is given by [13],

$$P_i = \alpha P_{i-1} \tag{2.16}$$

Where α is called as the power allocation factor of the strategy. This allocation factor is chosen randomly without considering any channel parameters and users desired QoS such that sum of all individual power levels is equal to the total transmitted power by the LED transmitter.

2.2.5.2 Gain Ratio Power Allocation (GRPA)

It is a dynamic power allocation strategy of NOMA. In this strategy during power allocation, every user's channel parameters are considered. Power allocated to i^{th} user depends on the channel parameters of the first user and the i^{th} user itself. Power assigned to the user i, P_i is given by [9],

$$P_i = \left(\frac{h_1}{h_i}\right)^i P_{i-1} \quad (2.17)$$

Where h_i and h_1 are channel coefficients corresponding to ith and 1st user and P_{i-1} is the allocated power of (i-1)th user.

2.2.5.3 Normalized Gain Difference Power Allocation (NGDPA)

It is also a dynamic power allocation strategy of NOMA. In this strategy power is allocated based on channel gain difference among different users. In general, power allocated to ith user depends on the channel parameters of 1st user and channel gain difference between 1st user and ith user. Power allocated to ith user is given by [13],

$$P_i = \left(\frac{h_1}{h_1 - h_i}\right)^{i-1} P_{i-1} \quad (2.18)$$

NGDPA strategy uses channel gain difference for power allocation purpose. As a result, it increases the sum rate of NOMA systems.

2.3 Optical Wireless Communication Channel

Optical Wireless Communication Channel also known as OWC channel is a type of deterministic channel unlike the Radio Frequency (RF) channel which is probabilistic in nature. Optical wireless channel is of two types: i) Indoor Visible Light Communication (VLC) channel and ii) Free Space Optical (FSO) channel. Light Fidelity (LIFI) works in VLC channel model as it is an indoor short range system. Here we will discuss mainly on indoor VLC channel model and FSO channel is beyond our discussion.

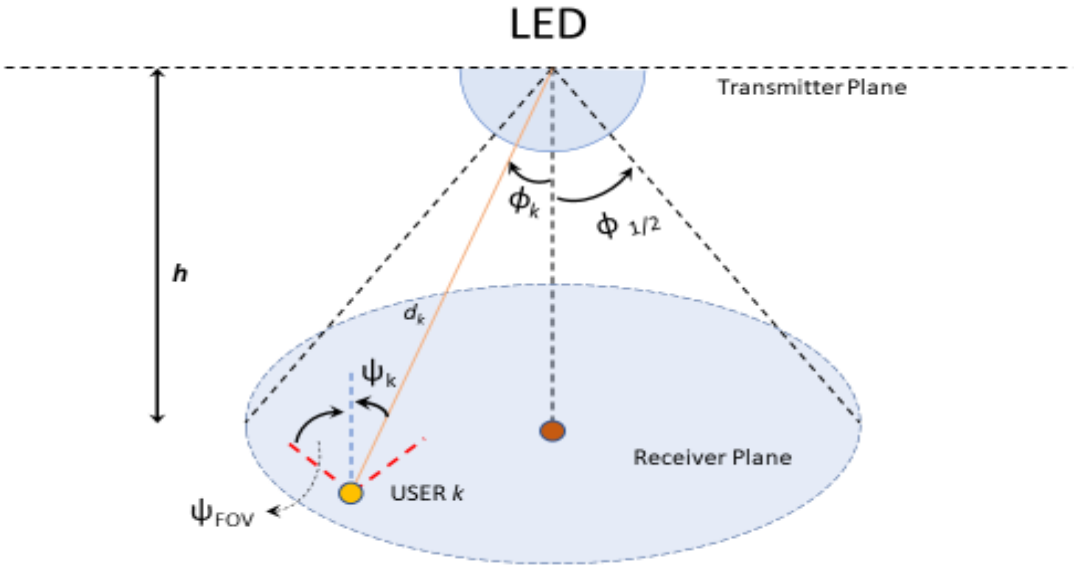


Figure 2.8: Indoor Visible Light Communication (VLC) Channel Model

Indoor VLC channel response can be represented as sum of Line of Sight (LOS) response from LED source to k^{th} receiver and Non Line of Sight (NLOS) response from LED source to k^{th} receiver through multiple reflection paths. L. Zeng *et al*. in [14] has shown that there are many NLOS components out of which the strongest NLOS component is 7dB lower than the weakest LOS component. Hence only the LOS component is responsible for channel response. LOS channel response is given in [15],

$$H_K^{LOS} = \begin{cases} \frac{A_k}{d_k^2} R_0(\varphi_k) T_s(\phi_k) g(\phi_k) \cos\phi_k & for \quad 0 \le \phi_k \le \phi_c \\ 0 & for \quad \phi_k > \phi_c \end{cases} \tag{2.19}$$

where A_k is the effective area of receiver photodetector, d_k is the distance between LED transmitter and k^{th} user receiver, φ_k is the emergence angle with respect to vertical axis of the

transmitter LED, ϕ_k is the incidence angle with respect to receiver photodetector vertical axis, ϕ_c is called the critical angle or field of view (FOV) of the receiver photodetector, $T_s(\phi_k)$ is the gain of optical filter and $g(\phi_k)$ is the gain of the optical concentrator. This optical concentrator gain is provided in [15],

$$g(\phi_k) = \begin{cases} \frac{\mu^2}{\sin^2(\phi_c)} & for \quad 0 \le \phi_k \le \phi_c \\ 0 & for \quad \phi_k \ge \phi_c \end{cases} \tag{2.20}$$

where μ denotes the refractive index corresponding to optical wireless channel medium. In the equation (2.19), $R_0(\varphi_k)$ denotes the angular dispersion of the radiation intensity pattern of the transmitter LED. This radiation intensity pattern is modelled using Lambertian radiant intensity with given distribution [15],

$$R_0(\varphi_k) = \begin{cases} \frac{(m+1)}{2\pi}\cos^m(\varphi_k) & for \quad -\frac{\pi}{2} \le \varphi_k \le \frac{\pi}{2} \\ 0 & otherwise \end{cases} \tag{2.21}$$

where m is called Lambert's mode number expressing directivity of source beam or simply the order of Lambertian emission, and it is expressed as.

$$m = \frac{-\ln(2)}{\ln(\cos(\varphi_{1/2})} \tag{2.22}$$

where $\varphi_{1/2}$ is called the semi – angle of LED at half power. If we assume a fixed Field of View (FOV) of LED, then the LOS channel gain mentioned in eqn. (19) can also be expressed as a distance dependent function between the LED transmitter and user photodetector receiver only. As the emergence angle φ_k and receiver's incidence angle ϕ_k are same for perpendicular alignment, this LOS gain expression can also be written [16]

$$H_k^{LOS} = \frac{A_k}{d_k^2}\frac{(m+1)}{2\pi}\cos^{m+1}(\phi_k)\, T_s(\phi_k) g(\phi_k) \tag{2.23}$$

$$= \frac{A_k(m+1)}{2\pi\, d_k^2} T_s(\phi_k) g(\phi_k) \frac{z^{m+1}}{d_k^{m+1}}$$

$$= \xi\, \frac{1}{d_k^{m+3}}$$

where z is the vertical distance between photodetector receiver and transmitter LED that is fixed for a particular access point and its users and $\xi = \frac{A_k(m+1)}{2\pi} T_s(\phi_k) g(\phi_k) z^{m+1}$ is a constant for a particular user within an indoor environment.

Now, we consider the location coordinate of k^{th} user receiver in polar coordinate system is (r_k, θ_k). Thus the LOS distance becomes $d_k = \sqrt{r_k^2 + z_k^2}$. The final expression for LOS channel gain is given by,

$$H_k^{LOS} = \xi \frac{1}{(r_k^2 + z^2)^{\frac{m+3}{2}}} \tag{2.24}$$

Here, throughout the thesis channel gain will refer to LOS channel gain only and neglect the insignificant NLOS channel gain. As a result, we can see from above eq. (24) that optical wireless channel is deterministic in nature and channel gain is inversely proportional with exponent of distance between transmitter LED or Access Point of LIFI and photodetector receiver.

2.4 Noise in Optical Wireless Communication

Noise is a very part in any communication system. Any undesired signal added to the original signal during transmission process which corrupts different parameters of original signal are termed as Noise. Two major types of noise in optical wireless communication are discussed below as follows.

2.4.1 Additive White Gaussian Noise (AWGN)

Additive White Gaussian Noise (AWGN) [17] is a simple noise model used in different wireless and wired communication channel. The received signal can be described as

$$r(t) = x(t) + n(t) \tag{2.25}$$

Where x(t) is transmitted signal and n(t) is AWGN noise.

The power spectral density of AWGN noise is equally distributed over all the frequencies. The AWGN noise follows the normal distribution or Gaussian distribution. The probability density function (pdf) of AWGN noise has Gaussian pdf and it is as follows.

$$f_n(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{2.26}$$

Where μ is the mean value and σ is the standard deviation of the Gaussian process.

The autocorrelation function of AWGN is defined by,

$$R_n(\tau) = \frac{N_0}{2}\delta(\tau) \tag{2.27}$$

The power spectral density of AWGN is defined by,

$$S_n(f) = \frac{N_0}{2} \tag{2.28}$$

2.4.2 Shot Noise

Shot noise arises in communication system because of the quantization nature of charge and photons. So, it is also known as quantum noise. Electrons and photons leave sources and arrive at detectors as quanta. While the average flow rate may be constant, at a given instant there are more quanta arriving than at other instant. There is a slight fluctuation due to quantum nature of things. Optical photodetectors are the source of shot noise in optical communication systems. Shot noise arises in photodetectors due to dark current. When there is no optical power incident on the photodetectors, a small reverse leakage current still flows from the device terminals. This is called dark current. This dark current contributes to the total system noise. The shot noise due to dark current can be expresses as [17] –

$$I_{s,rms} = \sqrt{2qBI_d} \tag{2.29}$$

Where q is the charge of electron, I_d is the dark current in photodetector and B is the effective noise bandwidth in Hz.

When the photocurrent arises in the picture, total shot noise expression is slightly modified as shown below –

$$I_{s,rms} = \sqrt{2qB(I_p + I_d)} \tag{2.30}$$

Where I_p is the photocurrent generated into the photodetector receiver.

Shot noise is independent of temperature of the system. Shot noise has a uniform power spectral density similar to white noise. Here throughout the thesis we have considered noise as total sum effect of both AWGN and shot noise.

2.5 Performance Metrics

For performance evaluation of digital communication systems some parameters are defined. Measurement of these parameters helps us to evaluate the performance as well as compare it with other standard system's performance. Here we will discuss about two important performance parameters that are used in this thesis work.

2.5.1 Bit Error Rate (BER)

Bit error rate or BER is a very important parameter in digital communication systems. When data is transmitted through a communication network, errors may occur within the data due to presence of noise, interference and other channel impairments. This impacts the overall performance of the system. Thus, assessing the system's operation becomes crucial. Here, Bit Error Rate (BER) emerges as a valuable tool for scrutinizing system efficiency. Serving as a foundational metric, BER is employed in the evaluation of communication networks. BER is defined as the ratio of erroneous bits to the total bits transmitted within a specific timeframe.

$$BER = \frac{Number\ of\ Erroneous\ Bits\ Received}{Total\ number\ of\ Bits\ Received} \tag{2.31}$$

For M-QAM modulation scheme expression for BER is given by [17],

$$BER = \frac{4}{\log_2 M}\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3\ \log_2(M) E_b}{(M-1)N_0}}\right) \tag{2.32}$$

BER expression for M-QAM optical OFDM in AWGN channel is given by [18],

$$BER = \frac{2(M-1)}{M\ \log_2 M}\ Q\left(\sqrt{6\frac{E_b}{N_0}\ \frac{\log_2 M}{M^2-1}}\right) \tag{2.33}$$

Where E_b is the energy per information bit and N_0 is the noise power spectral density.

2.5.2 Channel Capacity

The notion of channel capacity is a fundamental principle within information theory, denoting the maximum rate at which data can be transmitted through a communication channel of specified bandwidth in the presence of noise. This rate is quantified in bits per second (bps)

and is influenced by the inherent characteristics of the channel as well as the interference from noise impacting the signal. Claude Shannon originally presented this concept in his pioneering research on information theory. For a continuous communication channel with bandwidth B and subject to Gaussian noise, the channel capacity C is given by [19],

$$C = B \log_2 \left(1 + \frac{S}{N}\right) \tag{2.34}$$

In case of NOMA the above formula becomes [16],

$$Sum\ Rate = \sum_{i=1}^{K} B \log_2 \left(1 + \frac{P_i h_i^2}{N_0 B + \sum_{j=i+1}^{K} P_j h_i^2}\right) \tag{2.35}$$

Where C is channel capacity in bits per second, B is channel bandwidth in Hz, S is average signal power, N_0 is average noise power spectral density, N is the average noise power and the ratio of S to N gives the Signal to Noise power Ratio (SNR), K is total number of users, P_i is power allocated to i^{th} user and h_i is channel gain coefficient for i^{th} user.

Channel capacity is the theoretical maximum limit of data rate. For multiple users associated communication systems sum rate is used instead of data rate. It is the sum of data rates of all individual user's communication link.

2.6 Literature Survey

Svilen Dimitrov et al. [20] proposed a piecewise polynomial function as a generalized model for the nonlinear transfer characteristic of the transmitter for optical wireless communications (OWC). He showed the BER performance of the two general multicarrier modulation formats for OWC based on orthogonal frequency-division multiplexing (OFDM), direct-current-biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM) for different MQAM modulation. He achieved Shannon capacity in DCO-OFDM with non-linear optimization techniques and showed a 3-dB gap at higher information rates for ACO-OFDM.

S. M. Hammed et al. [21] proposed framework to use the convolutional encoder with a rate of 2/3 and seven memory cells in the transmitter using O-OFDM to improve Bit Error Rate (BER). In the receiver, the Viterbi algorithm is utilized for decoding with either hard or soft-decision approaches. The effectiveness of the scheme is assessed in both Line-of-Sight and Non-Line-of-Sight (NLOS) scenarios. Within the NLOS configuration, a Zero Forcing Equalizer (ZFE) is integrated into the receiver path along with channel estimation to mitigate the impacts of multipath diffused components. This research demonstrates the efficacy of the proposed system in addressing LED non-linearity issues and decreasing BER.

S. C. Pall et al. [22] studied BER performance of different Optical OFDM based modulation techniques including ACO-OFDM, DCO-OFDM, HACO-OFDM (Hybrid Asymmetrically Clipped Optical OFDM) and ADO-OFDM under indoor VLC channel environment in presence of AWGN. He found that HACO-OFDM gave best BER among all techniques. But its implementation is very much difficult due to huge computational complexity. R. Bai et al. [23] proposed ADO-OFDM, that combines absolute value DCO-OFDM and ACO-OFDM for efficient IM/DD optical systems. It offers improved energy efficiency and performance over conventional methods due to reduced DC bias and absence of clipping distortion.

H. Abumarshoud et al. [24] introduced a novel cross-layer design framework for dynamic multiple access selections (DMAS) in intelligent Lifi APs. They developed it and showed that DMAS introduces an effective solution for multiuser resource allocation by achieving better satisfaction of the system requirements compared to the static configuration of a single MA scheme.

J. Shi et al. [25] suggested a roadmap for developing machine learning-based intelligent visible light communication in 6G. They laid out a detailed overview of advances in intelligent physical layers, including optimal coding, channel emulator, MIMO, channel equalization, and optimal decision presented.

H. Hesham et al. [26] proposed an indoor VLC transmission system consisting of a combination of non-orthogonal multiple access (NOMA), asymmetrically-clipped optical (ACO), and filter bank multicarrier (FBMC) techniques combined with offset quadrature amplitude modulation (OQAM). They achieved throughput increased by 1.8 compared to FBMC, OFDM, and OFDM-NOMA. They also reduced unserved users to below 10% with their proposed scheme. A. K. Hussein et al. [27] evaluated the performance of OFDM based NOMA VLC system. He found out that NOMA/ACO-OFDM outperforms NOMA/DCO-OFDM in VLC environment. He also showed that BER of users converges with increasing SNR for both models. S. A. H. Mohsan et al. [28] showed that the potentials of NOMA-based VLC systems are to increase the number of users, system's capacity, massive connectivity, and enhance the spectrum and energy efficiency for future communication scenarios.

R. Yang et al. in [29] derived the exact achievable rate of the DCO-OFDM system with finite-alphabet inputs for the first time and proposed a multi-level mercury-water-filling power allocation scheme to achieve the maximum spectral efficiency. S. Feng et al. in [30] proposed a spectrum enhanced ACO-OFDM scheme with a novel symbol mapping strategy, in which an efficient positivity-forcing signal is elaborately conceived for maintaining the non-negative of the transmitted signal. Spectrally efficient ACO-OFDM outperforms conventional O-OFDM in Peak to Average Power Ratio (PAPR) and BER with lower receiver complexity.

J. Pradhan et al. in [31] simulated ACO-OFDM based VLC NOMA model. He showed energy efficiency in their proposed model and evaluated performance based on both LOS and Non LOS link. A. Rigonen et al. in [32] compared performance of DCO-OFDM, ACO-OFDM, and ADO-OFDM in IM/DD systems. They evaluated noise immunity and optimal parameters for minimizing BER under Relative Intensity Noise and Chromatic Dispersion conditions in fiber-optic communication. S. F. Nawaf et al. in [33] investigated the performance of DCO-OFDM and ACO-OFDM in visible light communication. The DCO-OFDM and ACO-OFDM are compared in terms of performance and DCO outperformed ACO in terms of power efficiency at larger modulation orders. But ACO outperformed DCO in terms of bit error rate. M. Rubaiyat et al. in [34] compared the performance of DCO-OFDM, ADO-OFDM and HNC-

OFDM for Optical Wireless Communication. HNC-OFDM combines noise cancellation and DCO-OFDM benefits with less complexity. Optimal bias levels vary based on factors like BER, constellation size, and link type. Simulations results show that with an optimum bias, HNC-OFDM can outperform others in an average power limited channel, while DCO-OFDM is a better choice for a peak power limited channel.

M. Bindhu et al. in [35] evaluates the effectiveness of NOMA in downlink visible light communication systems. They showed improved throughput compared to previous strategies, with optimal power allocation coefficients for QoS provisioning.

S. Hesham et al. in [36] explores Power Allocation Techniques for Non-Orthogonal Multiple Access in MIMO Visible Light Communication systems, enhancing rates through efficient schemes like Fixed Power Allocation (FPA), Gain Ratio Power Allocation (GRPA), and Normalized Gain Difference Power Allocation (NGDPA). A NOMA scheme is applied with a multiple-input multiple-output (MIMO) technique for enhancing the achievable rate of VLC systems and the superiority of FPA over NGDPA and GRPA are clearly highlighted. FPA achieved best rate with 0.9 power allocation factor. Z. Liu et al. in [37] NOMA is compared with OMA for VLC systems. They showed a different relationship than in RF systems. They introduced a hybrid NOMA-OMA scheme with genetic algorithm optimization in user pairing method. It enhances sum rate performance of the overall system significantly.

G. Tran et al. in [38] investigated the short packet communication (SPC) in non-orthogonal multiple access (NOMA) for a downlink visible light communication (VLC) system with the imperfect channel state information (CSI). They found out that SPC based NOMA VLC system outperformed SPC based OMA VLC system in terms of throughput. They also derived optimal transmission rates and power allocation coefficients.

A. H. Alqahtani et al. in [39] proposes a decoding-order-based power allocation (DOPA) scheme for NOMA VLC systems. DOPA method effectively reduces multi-user interference. This method also provides more sum rate compared to benchmarking schemes.

A. A. hammadi et al. in [40] proposes a deep Q-learning framework to optimize the performance of an indoor NOMA-VLC downlink network. In this method, a joint power allocation and LED transmission angle tuning optimization problem was formulated to maximize the average sum rate and the average energy efficiency. The algorithm outperforms genetic algorithm and differential evolution algorithm in terms of average sum rate. P. Q. Thai

et al. in [41] proposed for the first time, a de-multiplexing process using a probabilistic neural network (PNN). Their experimental results indicated that the PNN method was more robust against interference than the SIC method for demodulation of multi-user NOMA signals.

Therefore, most of the works in this field is largely comparison among two OFDM modulation schemes either ACO-OFDM and DCO-OFDM or DCO-OFDM and ADO-OFDM. Many researchers have studied performance of NOMA based wireless VLC systems. But most of them have studied NOMA performance based on single modulation scheme only like on - off Keying (OOK) or pulse width modulation (PWM) or single OFDM like DCO-OFDM or ACO-OFDM. Many researchers have introduced some improvements on the basic optical OFDM modulations. Some introduced error correcting codes in this modulation schemes too. They derived Hybrid ACO-OFDM (HACO-OFDM), Enhanced ADO-OFDM (EADO-OFDM), Hybrid Diversity Combined OFDM (HDC-OFDM) and Hybrid noise cancelled OFDM (HNC-OFDM) etc. But the fundamental optical OFDM modulations are kept same ACO-OFDM, DCO-OFDM and ADO-OFDM. So, a performance comparison among these three fundamental OFDM modulations are required by considering all the necessity aspects.

NOMA is becoming the next generation multiple access scheme. NOMA has superiority over traditional multiple access scheme. It has unique resource allocation scheme over frequency and time. So, in the field of optical wireless communication, application of NOMA is increasing day by day. Consequently, performance analysis among different power allocation strategy of NOMA scheme along with compatible optical OFDM modulations are required.

In this thesis, we have studied three fundamental optical OFDM modulations and three different power allocation strategies of NOMA. We have simulated their performance by considering all the necessary parameters and simulation environment as real as possible.

2.7 Conclusions

Theoretical background of all the required concepts have been discussed and literature survey has been provided in this chapter. Different optical OFDM based modulation and their demodulation processes, NOMA and its different power allocation strategies, AWGN noise and OWC channel etc. have been discussed in this chapter. In the next three chapters, BER performance of different optical OFDM modulations and also its performance under different power allocation strategies of NOMA are presented.

Chapter 3

BER Performance of DCO-OFDM Modulation under Different Conditions

In this chapter, we have analyzed BER performance of DC biased Optical OFDM (DCO-OFDM) modulation scheme under different conditions. The simulation environment and the simulation parameters used for the experiment have also been discussed in this chapter. The channel which has been considered is Optical Wireless Channel (OWC). The channel is considered to be predominantly affected by AWGN noise only. BER performance has been evaluated for DCO-OFDM based on different MQAM modulation. Then BER performance has been evaluated for DCO-OFDM under Non Orthogonal Multiple Access of different power allocation strategies like Fixed Power Allocation (FPA), Gain Ratio Power Allocation (GRPA) and Nominal Gain Difference Power Allocation (NGDPA) for 2 users and 3 users respectively.

Simulation Environment

For the simulation purpose, we have considered the following parameters in our MATLAB environment.

Table 3.1: Simulation Parameters for DCO-OFDM

Sl No.	Description	Notation	Value
1	Responsivity of PD	η_{PD}	0.5 A/W
2	Transmitter Semi- Angle	φ_k	60 deg
3	FOV of the PDs	ϕ_c	60 deg
4	Vertical Distance	z	2.15 m
5	Physical Area of PD	A_k	1.0 cm^2
6	Refractive Index of PD lens	n	1.5
7	Gain of Optical Filter	$T_s(\phi_k)$	1.0
8	Total Number of Subcarriers	N_{FFT}	128
9	QAM Modulation Order	M	4/16/64
10	DC Bias	B_{DC}	5 dB
11	Horizontal Distance From Source	r	0.5-2.4 m

3.1 BER Performance of DCO-OFDM

With the given setup, we have performed DCO-OFDM modulation for a particular user at a fixed distance in presence of AWGN channel. The measured BER values have been recorded in the Table 3.2.

Table 3.2: BER measurement of DCO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM

E_b/N_0	BER(4-QAM)	BER (16-QAM)	BER (64-QAM)
0	0.21086746	0.260324008	0.307718757
2	0.156097619	0.209999802	0.265667593
4	0.101578571	0.162261905	0.220604841
6	0.054546032	0.117639286	0.176272937
8	0.021804762	0.076179365	0.135820582
10	0.005609127	0.041030754	0.09945246
12	0.000680952	0.016493452	0.066461005
14	2.50E-05	0.004164683	0.037503069
16	7.94E-07	0.000516865	0.016297963
18	0	2.14E-05	0.004666481
20	0	1.98E-07	0.000710926
22	0	0	3.80E-05
24	0	0	5.03E-07
26	0	0	0
28	0	0	0
30	0	0	0

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 3.1 for DCO-OFDM modulation based on all the three different MQAM modulation schemes.

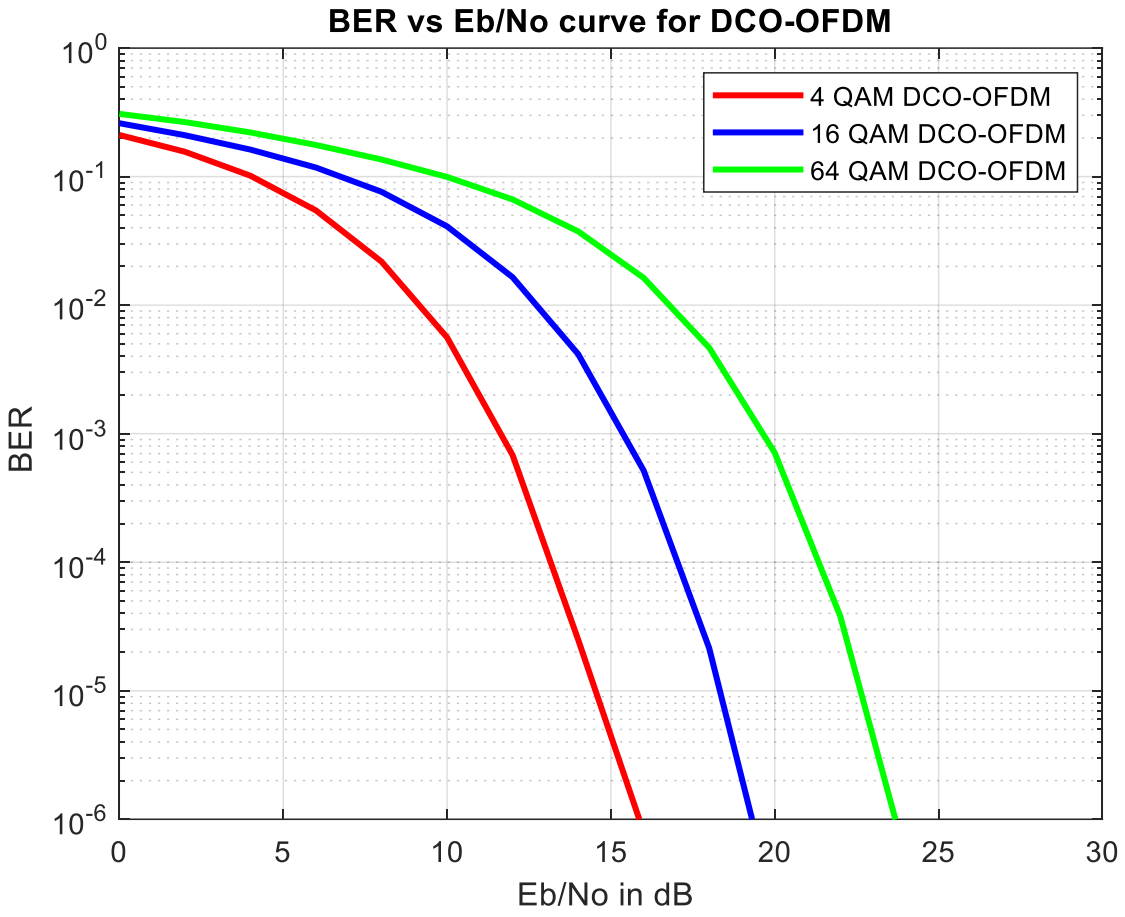


Figure 3.1: BER vs E_b/N_0 graph for DCO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM

Figure 3.1 shows the BER performance of DCO-OFDM modulation under AWGN communication channel. Here performance has been evaluated considering three different MQAM modulations based DCO-OFDM i.e. 4-QAM, 16-QAM and 64-QAM. It is found that BER decreases with the increase of E_b/N_0 level as it is expected. For a fixed value of E_b/N_0, 4-QAM has the best possible BER, 64-QAM has the worst possible BER and 16-QAM gives an intermediate value between the level of 4-QAM and 64-QAM.

3.2 BER Performance of DCO-OFDM for Two Users NOMA

In this section, BER performance has been evaluated for two users NOMA. While doing so, different power allocation strategies have been considered. We have considered same simulation parameters as mentioned in Table 3.1.

3.2.1 BER Performance for Two Users NOMA with Fixed Power Allocation

For this experimental setup 16-QAM has been considered. With the given setup we have performed DCO-OFDM modulation with Non Orthogonal multiple Access for two users at two fixed distances in presence of AWGN channel. User with least distance from optical source has been considered as near user. The other user with larger distance has been considered as far user. Also users are allocated power here according to their distances from transmission source. The measured BER values for two different users have been recorded in the Table 3.3.

Table 3.3: BER measurement of DCO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on FPA strategy.

E_b/N_0	BER(Near User)	BER(Far User)
0	0.491540873	0.527325
2	0.491090476	0.428387698
4	0.48990873	0.335142857
6	0.487201984	0.249516667
8	0.477432738	0.17098373
10	0.455715079	0.10393254
12	0.422809325	0.05441746
14	3.83E-01	0.022957143
16	3.38E-01	0.007355159
18	0.289342857	1.51E-03
20	0.238784127	1.42E-04
22	0.188861111	2.78E-06
24	0.142927381	0
26	0.099303373	0
28	0.059832738	0
30	0.028775992	0
32	0.009749206	0
34	0.001888889	0
36	0.000158532	0
38	3.17E-06	0
40	0	0

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 3.2 for DCO-OFDM modulation under two users NOMA multiple access scheme based on fixed power allocation strategy.

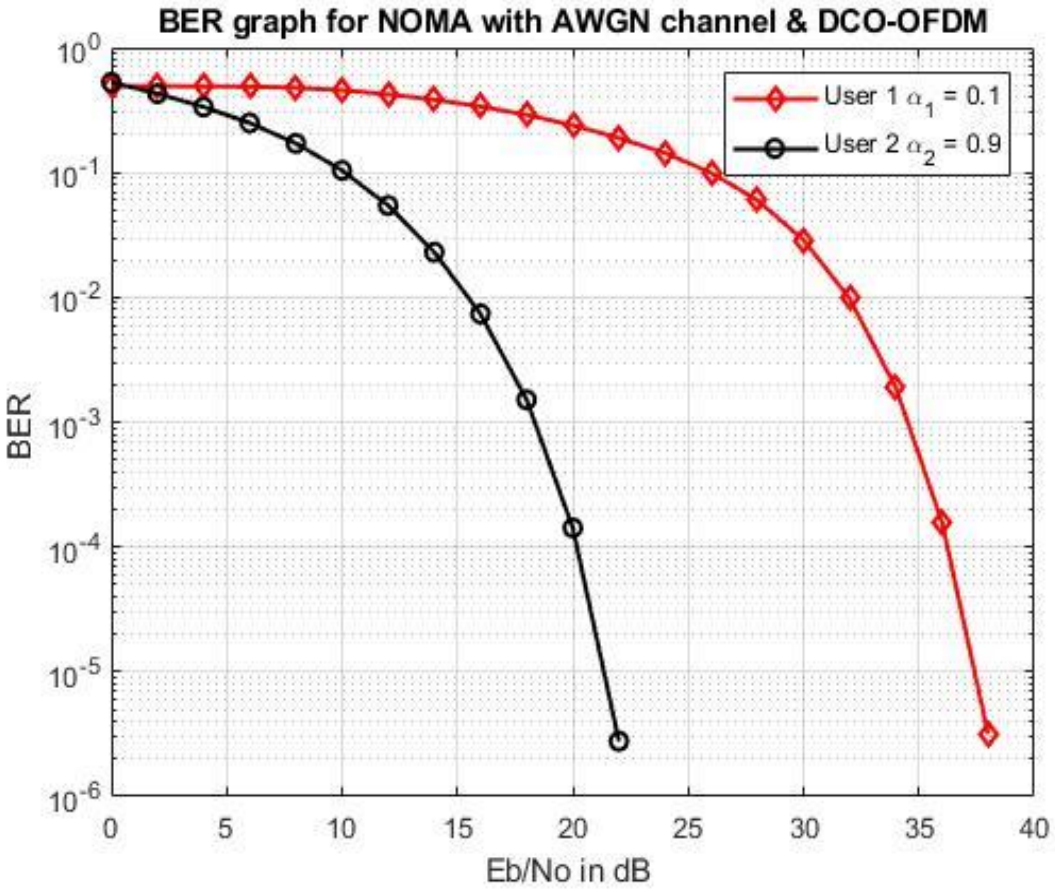


Figure 3.2: BER vs E_b/N_0 graph for DCO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy

Figure 3.2 shows the BER performance of DCO-OFDM modulation under two users NOMA with fixed power allocation in AWGN communication channel. Here performance has been studied for two users – near user at 1.2 m distance from optical source and far user at 2.4 m distance from optical source. Power loss increases with the increasing distance of receiver from optical source. As a result, SNR level degrades in receivers with the increasing distance from source. To maintain ample SNR level in each user receiver, generally far user is allocated

more power and near user is allocated less power. In our fixed power allocation strategy we have allocated 90% power to far user and 10% power to near user. As a result, far user has better BER performance than near user. For fixed power allocation strategy BER performance depends on the allocated power. User receivers' distances from source is fixed. So, optimal power allocation coefficient need to find out in this case for better BER performance among all users. We have varied the power allocation coefficient from 0 to 0.5 and measured the corresponding BER values for both users at a fixed value of SNR 30 dB. Obtained data is shown in Fig 3.3.

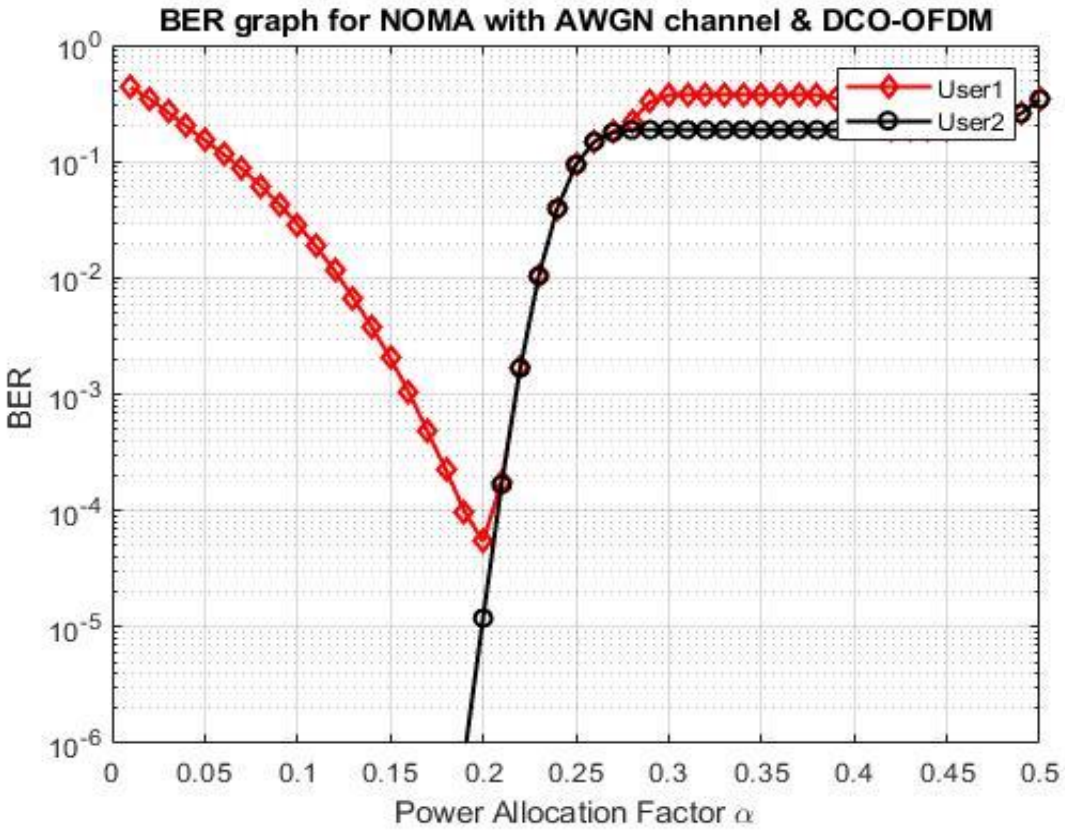


Figure 3.3: BER vs Power Allocation Factor graph for DCO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy

Figure 3.3 shows BER performance of DCO-OFDM modulation under two users NOMA with fixed power allocation in AWGN communication channel for different values of

Power Allocation Factor. It is seen that least possible BER values for both users are obtained in case of 20% allocated power to near user. In this scenario, far user is allocated rest of the power i.e. 80%.

3.2.2 BER Performance for Two Users NOMA with Gain Ratio Power Allocation

Gain Ratio Power Allocation (GRPA) is a dynamic power allocation strategy of NOMA multiple access scheme. It is used to model situations where users' distribution is not isotropic with respect to the transmission source. For this experimental set up we have considered 16-QAM based DCO-OFDM modulation too. With the given setup we have performed DCO-OFDM modulation with Non Orthogonal multiple Access using GRPA power allocation strategy for two users at two fixed distances in presence of AWGN channel. Power is allocated to users according to this strategy as discussed in chapter 2 of this thesis. The measured BER values for two different users have been recorded in the Table 3.4.

Table 3.4: BER measurement of DCO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on GRPA strategy.

E_b/N_0	BER(Near User)	BER(Far User)
0	0.483470238	0.539639683
2	0.482612103	0.445803571
4	0.480827381	0.357348413
6	0.475529563	0.278722222
8	0.458526389	0.210046825
10	0.420764087	0.152187698
12	0.364218651	0.106075
14	2.98E-01	0.069805952
16	2.34E-01	0.042188889
18	0.175778175	2.21E-02
20	0.124510119	9.03E-03
22	0.079535119	2.40E-03
24	0.042691468	0.000315476
26	0.017361111	1.51E-05
28	0.004582341	3.97E-07
30	0.000589683	0
32	3.04E-05	0
34	1.98E-07	0
36	0	0
38	0	0
40	0	0

From the simulation results, BER vs E_b/N_0 graph has been shown in Figure 3.4 for DCO-OFDM modulation under two users NOMA multiple access scheme based on Gain Ratio Power Allocation strategy.

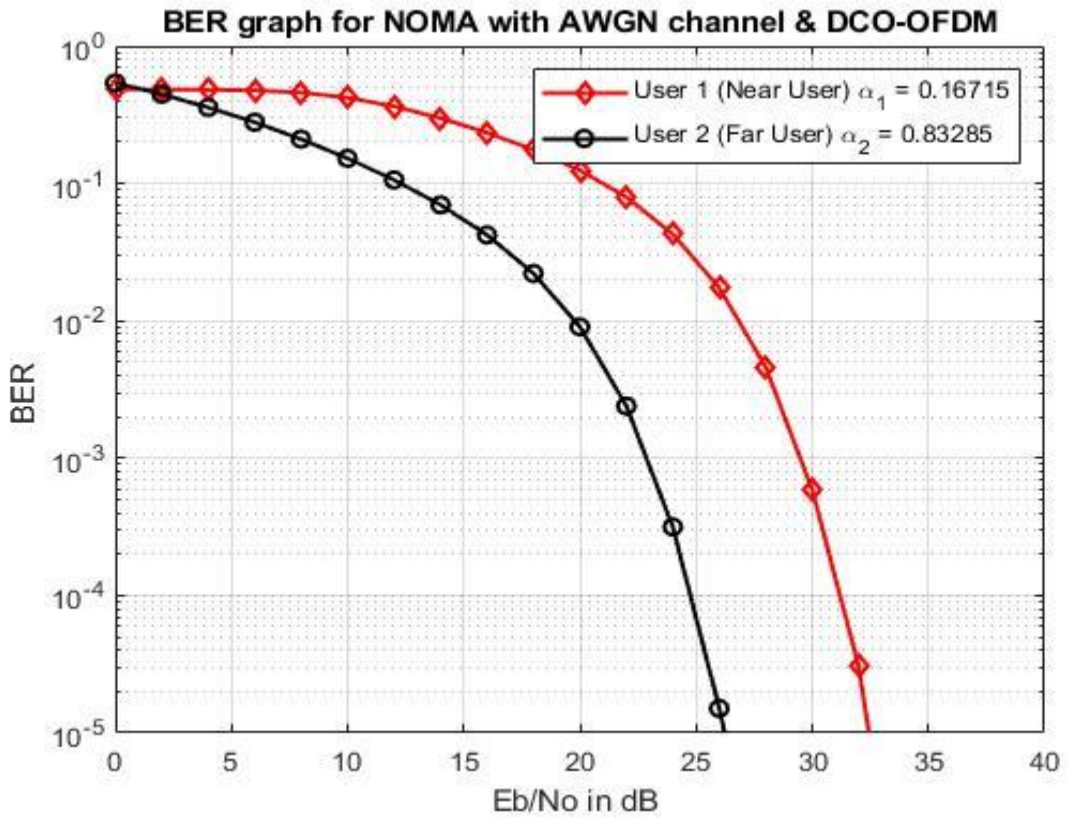


Figure 3.4: BER vs E_b/N_0 graph for DCO-OFDM modulation under two users NOMA multiple access scheme based on GRPA strategy

Figure 3.4 shows BER performance of DCO-OFDM modulation under two users NOMA with Gain Ratio Power Allocation in AWGN communication channel. Here performance has been studied for two users – near user at 0.8 m distance from optical source and far user at 1.8 m distance from optical source. In this power allocation strategy, power is allocated dynamically according to their channel conditions. OWC channel is a deterministic channel. As a result, channel conditions depend on user location with respect to the source. Here in this case, it is the distance between the optical source and user receiver. According to

the values of channel coefficients, 16.71% power is allocated to near user and far user is allocated to rest of the power i.e. 83.29%.

BER performance of this strategy for DCO-OFDM NOMA has been shown for two users' case. It is observed that this strategy allocates power well in conditions where users are very far among themselves. It means user separation should be fair enough to apply this strategy to get good result. It will give better result when near user is present very close to transmission source and far user is present at maximum possible distance from the source. Then this strategy will give fair power allocation to users and give minimum possible BER for two users NOMA system. In practical scenario, users can be anywhere in the OWC channel environment. So, it will be used in scenarios where users have large separation among themselves.

3.2.3 BER Performance for Two Users NOMA with Normalized Gain Difference Power Allocation

Normalized Gain Difference Power Allocation (NGDPA) is also a dynamic power allocation strategy of NOMA. This strategy is also used to model situations where users' distribution is not isotropic with respect to the transmission source. It is used specially where users are congested in a very little space. For this experimental set up we have considered 16-QAM based DCO-OFDM modulation too. With the given setup we have performed DCO-OFDM modulation with Non Orthogonal multiple Access using NGDPA power allocation strategy for two users at two fixed distances in presence of AWGN channel. Power is allocated to users according to this strategy as mathematical expressions discussed in chapter 2 of this thesis. The measured BER values for two different users have been recorded in the Table 3.5.

Table 3.5: BER measurement of DCO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on NGDPA strategy.

E_b/N_0	BER(Near User)	BER(Far User)
0	0.488718849	0.530380952
2	0.487905357	0.432735714
4	0.486482937	0.340190476
6	0.48297996	0.256478175
8	0.470935516	0.181387302
10	0.443193849	0.116817063
12	0.400792262	0.067447619
14	3.50E-01	0.033723016
16	2.95E-01	0.013656746
18	0.240563095	3.98E-03
20	0.189456548	6.98E-04
22	0.142799802	4.68E-05
24	0.099472619	3.97E-07
26	0.060096627	0
28	0.028910913	0
30	0.009806548	0
32	1.88E-03	0
34	1.63E-04	0
36	1.98E-06	0
38	0	0
40	0	0

Based on simulation result, BER vs E_b/N_0 graph has been shown in Figure 3.5 for DCO-OFDM modulation under two users NOMA multiple access scheme based on Normalized Gain Difference Power Allocation strategy.

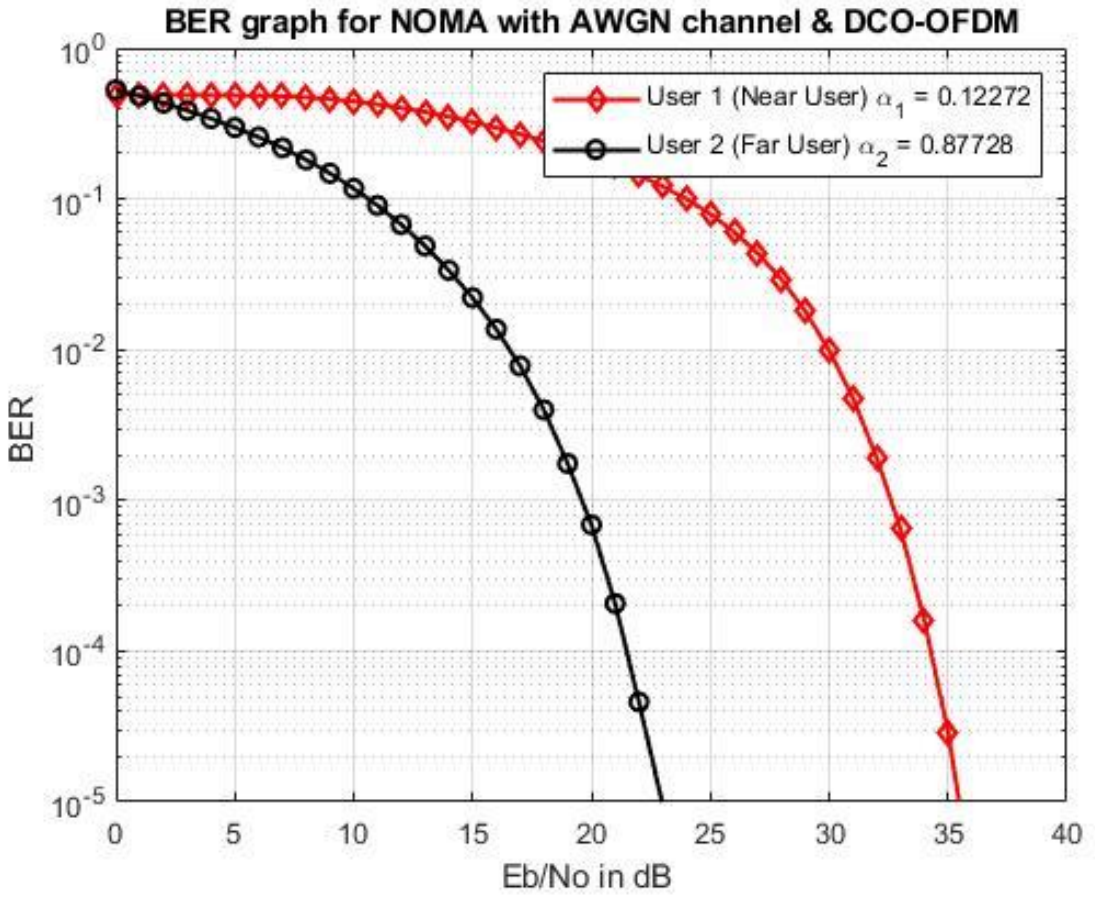


Figure 3.5: BER vs E_b/N_0 graph for DCO-OFDM modulation under two users NOMA multiple access scheme based on NGDPA strategy

Figure 3.5 shows BER performance of DCO-OFDM modulation under two users NOMA with Normalized Gain Difference Power Allocation in AWGN communication channel. Here performance has been studied for two users – near user at 1 m distance from optical source and far user at 1.2 m distance from optical source. In this power allocation strategy, power is also allocated dynamically according to their channel conditions. According

to the values of channel coefficients, 12.27% power is allocated to near user and far user is allocated to rest of the power i.e. 87.73%.

BER performance of this strategy for DCO-OFDM NOMA has been shown for two users' case. It is observed that this strategy allocates power well in conditions where users are in very close vicinity. It means users should be concentrated in a very little field area to apply this strategy to get good result. It will give better result when both near user and far user are present at a very close distance. Then this strategy will give fair power allocation to those congested users and give minimum possible BER for two users NOMA system. In practical scenario, users can be anywhere in the OWC channel environment. So, it will be used in scenarios where users have very little separation among themselves.

3.3 BER Performance of DCO-OFDM for Three Users NOMA

In this section, BER performance has been evaluated for three users NOMA multiple access scheme modulated by DCO-OFDM. For this evaluation, different power allocation strategies of NOMA have been considered. We have considered same simulation parameters as mentioned in Table 3.1.

3.3.1 BER Performance for Three Users NOMA with Fixed Power Allocation

For this experimental setup, 16-QAM has been considered. With the given setup we have performed DCO-OFDM modulation with Non Orthogonal multiple Access for three users at three fixed distances in presence of AWGN channel. User with least distance from optical source has been considered as near user. The other user with larger distance has been considered as far user. Remaining user is considered as mid user. The measured BER values for three different users have been recorded in the Table 3.6.

Table 3.6: BER measurement of DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy.

E_b/N_0	BER(Near User)	BER(Mid User)	BER(Far User)
0	0.497562469	0.488009983	0.312801688
3	0.497167194	0.487099106	0.241360328
6	0.497240048	0.485779584	0.170876349
9	0.49642644	0.478496055	0.110101997
12	0.494318693	0.448865521	0.059976438
15	0.491134789	0.389973183	0.025994582
18	0.487655397	0.314849175	0.008026995
21	4.84E-01	2.37E-01	0.001433454
24	4.77E-01	1.71E-01	8.78E-05
27	0.450746954	0.119490947	1.94E-07
30	0.377388703	0.082232569	0
33	0.274032157	0.055598958	0
36	0.179215301	0.035790241	0
39	0.098555308	0.019717068	0
42	0.035866002	0.007159714	0
45	0.005825079	0.0011711	0
48	1.87E-04	4.15E-05	0
51	3.88E-07	0	0
54	0	0	0
57	0	0	0
60	0	0	0

From simulation results, BER vs E_b/N_0 graph has been plotted in Figure 3.6 for DCO-OFDM modulation under three users NOMA multiple access scheme based on FPA strategy.

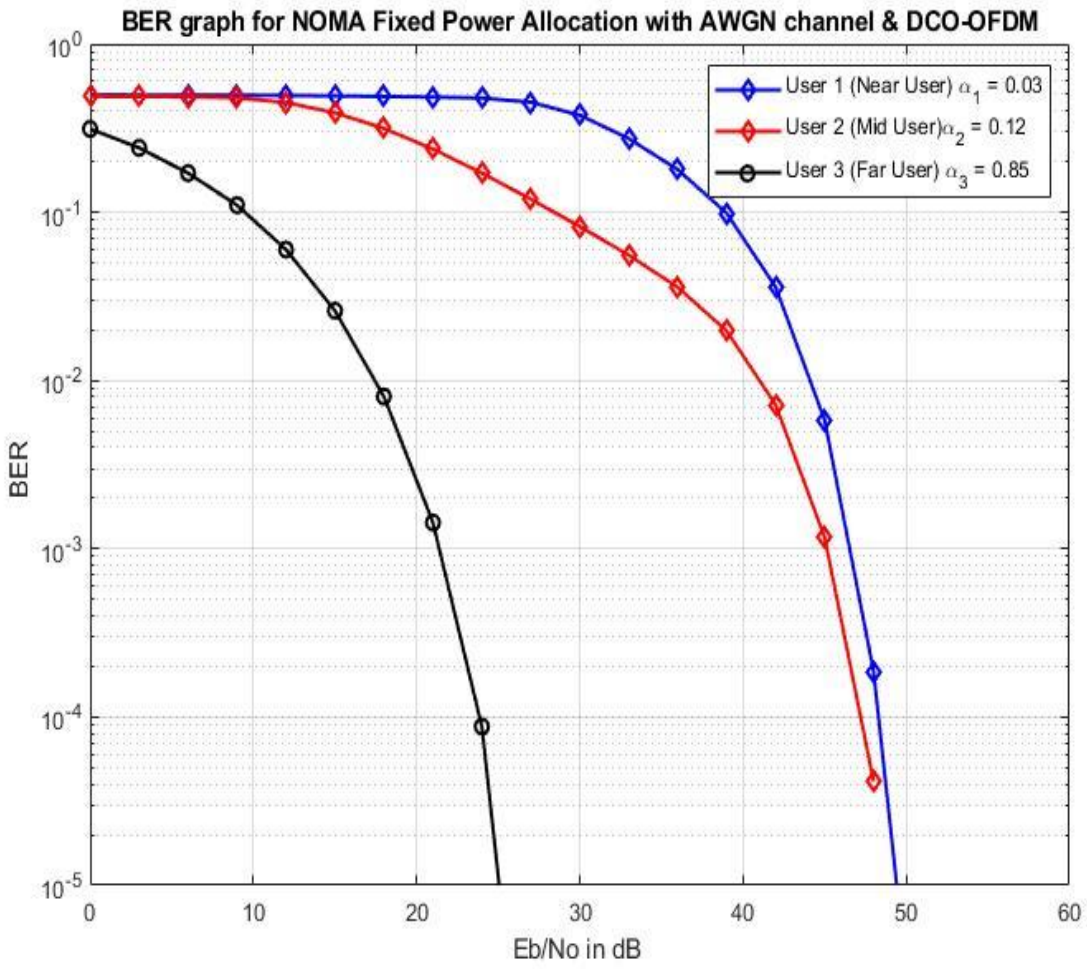


Figure 3.6: BER vs E_b/N_0 graph for DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy.

Figure 3.6 shows BER performance of DCO-OFDM modulation under three users NOMA with fixed power allocation in AWGN communication channel. Here performance has been studied for three users – near user at 1 m distance from optical source and far user at 1.8 m distance from optical source. Mid user is at 1.4 m distance from optical source. Power loss increases with the increasing distance of receiver from optical source. As a result, SNR level degrades in receivers with the increasing distance from source. To maintain ample SNR level

in each user receiver, generally far user is allocated more power, near user is allocated less power and mid user is allocated to medium level of power. In our fixed power allocation strategy we have allocated 85% power to far user, 12% power to mid user and 3% power to near user. As a result, far user has best BER performance than near user and mid user. Due to higher power allocation, mid user has better BER performance than near user. For fixed power allocation strategy BER performance depends on the allocated power. User receivers' distances from source is fixed. So, optimal power allocation coefficient need to find out in this case for better BER performance among all users.

3.3.2 BER Performance for Three Users NOMA with Gain Ratio Power Allocation

Gain Ratio Power Allocation (GRPA) is applied here to dynamically allocate power to three users sharing resources through NOMA multiple access scheme. For this experimental set up, we have considered 16-QAM based DCO-OFDM modulation too. With the given setup we have performed DCO-OFDM modulation with Non Orthogonal multiple Access using GRPA power allocation strategy for three users at three fixed distances in presence of AWGN channel. Power is allocated to users according to the strategy as discussed in chapter 2 of this thesis. The measured BER values for three different users have been recorded in the Table 3.7.

Table 3.7: BER measurement of DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy.

E_b/N_0	BER(Near User)	BER(Mid User)	BER(Far User)
0	0.499343727	0.494583953	0.309769888
3	0.499301099	0.494245838	0.236188616
6	0.498714968	0.493090627	0.164470176
9	0.49840301	0.489517842	0.1003914
12	0.493662613	0.471877713	0.046508402
15	0.487720695	0.439257619	0.013562787
18	0.481268214	0.397663225	0.001834542
21	4.77E-01	3.46E-01	7.15E-05
24	4.75E-01	2.83E-01	6.23E-06
27	0.471032909	0.218222773	5.38E-07
30	0.462238808	0.164646306	0
33	0.429830109	0.126080225	0
36	0.353129069	0.100102694	0
39	0.257334488	0.082600718	0
42	0.169052076	0.071160211	0
45	0.099507262	0.061523825	0
48	5.73E-02	4.99E-02	0
51	3.59E-02	0.035424998	0
54	0.020197211	0.020235189	0
57	0.00749318	0.007506743	0
60	0.001295495	0.001268175	0

From the simulation results, BER vs E_b/N_0 graph has been shown in Figure 3.7 for DCO-OFDM modulation under three users NOMA multiple access scheme based on Gain Ratio Power Allocation strategy.

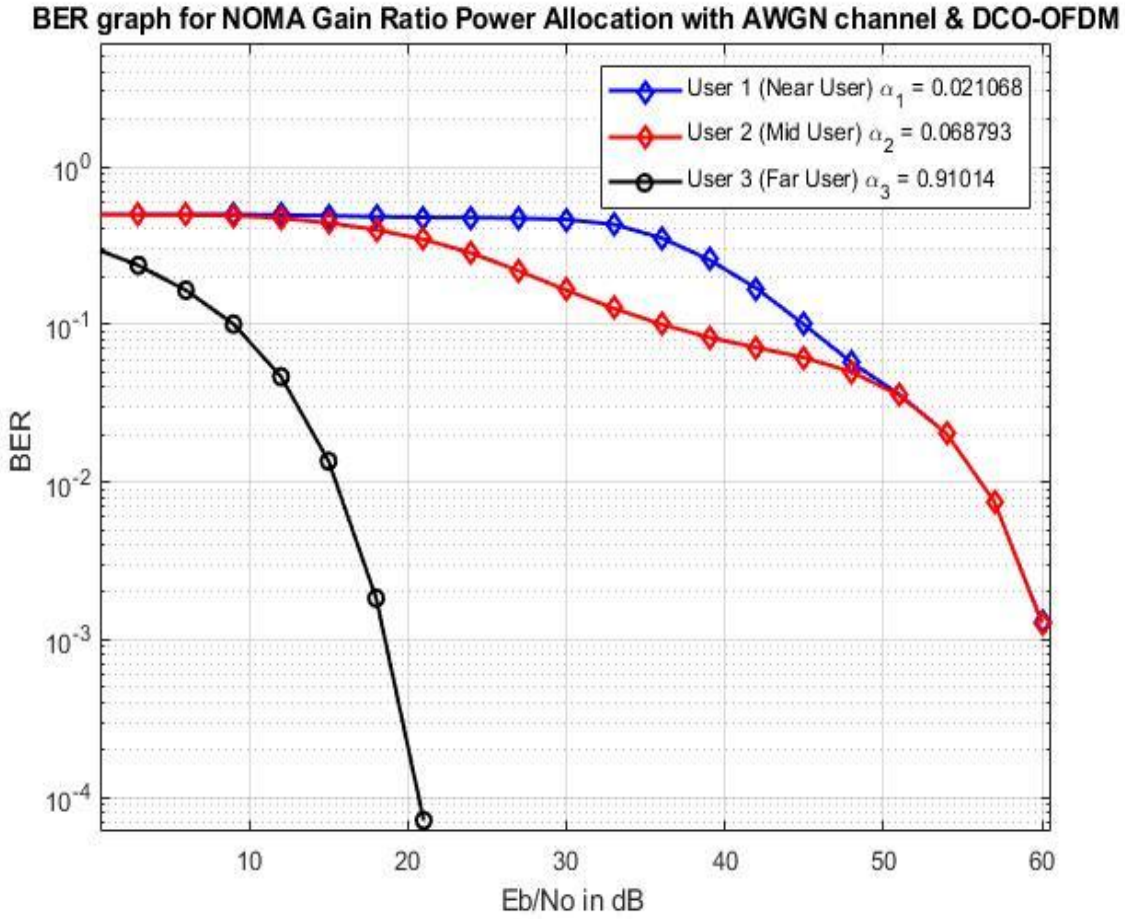


Figure 3.7: BER vs E_b/N_0 graph for DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy.

Figure 3.7 shows BER performance of DCO-OFDM modulation under three users NOMA with Gain Ratio Power Allocation in AWGN communication channel. Here performance has been studied for three users – near user at 0.7 m distance from optical source and far user at 1.8 m distance from optical source. Mid user is at a distance of 1.5m from optical source. In this power allocation strategy, power is allocated dynamically according to their channel conditions. OWC channel is a deterministic channel. As a result, channel conditions depend on user location with respect to the source. In GRPA strategy, power allocation depends on user distribution from optical sources. Minimum BER for all resource shared users will be

possible by this algorithm only when user separation distance is large i.e. well isolated from each other. According to the values of channel coefficients (based on the positions of the users), here in this case, 2.1% power is allocated to near user, 6.9% power is allocated to mid user and far user is allocated to remaining amount of the power i.e. 91%. Far user shows best BER performance among the three users and near and mid user shows almost same BER performance. This implies that GRPA is not able to properly allocate power to users for achievement of minimum BER in this case. User distribution is not fair enough to achieve minimum BER through this dynamic power allocation algorithm.

3.3.3 BER Performance for Three Users NOMA with Normalized Gain Difference Power Allocation

For this experimental set up, we have considered 16-QAM based DCO-OFDM modulation too. With the given setup we have performed DCO-OFDM modulation with Non Orthogonal multiple Access using NGDPA power allocation strategy for three users at two fixed distances in presence of AWGN channel. Power is allocated to users according to this strategy as mathematical expressions discussed in Chapter 2 of this thesis. The measured BER values for three different users have been recorded in the Table 3.8.

Table 3.8: BER measurement of DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy.

E_b/N_0	BER(Near User)	BER(Mid User)	BER(Far User)
0	0.497328985	0.491126263	0.310873171
3	0.497083876	0.490642826	0.238274856
6	0.497476632	0.489358956	0.166735452
9	0.497042604	0.483918108	0.104091874
12	0.495117769	0.459747993	0.051192414
15	0.491785443	0.412963867	0.017470199
18	0.489353144	0.351835317	0.00335209
21	4.88E-01	2.79E-01	2.35E-04
24	4.86E-01	2.06E-01	1.74E-06
27	0.482328869	0.139872233	0
30	0.461442251	0.08431319	0
33	0.404479012	0.042491513	0
36	0.323718262	0.016174704	0
39	0.237622845	0.003908575	0
42	0.161338394	0.000358267	0
45	0.095536296	3.10E-06	0
48	4.02E-02	0	0
51	8.77E-03	0	0
54	0.000497388	0	0
57	2.33E-06	0	0
60	0	0	0

Based on simulation result, BER vs E_b/N_0 graph has been shown in Figure 3.8 for DCO-OFDM modulation under three users NOMA multiple access scheme based on Normalized Gain Difference Power Allocation strategy.

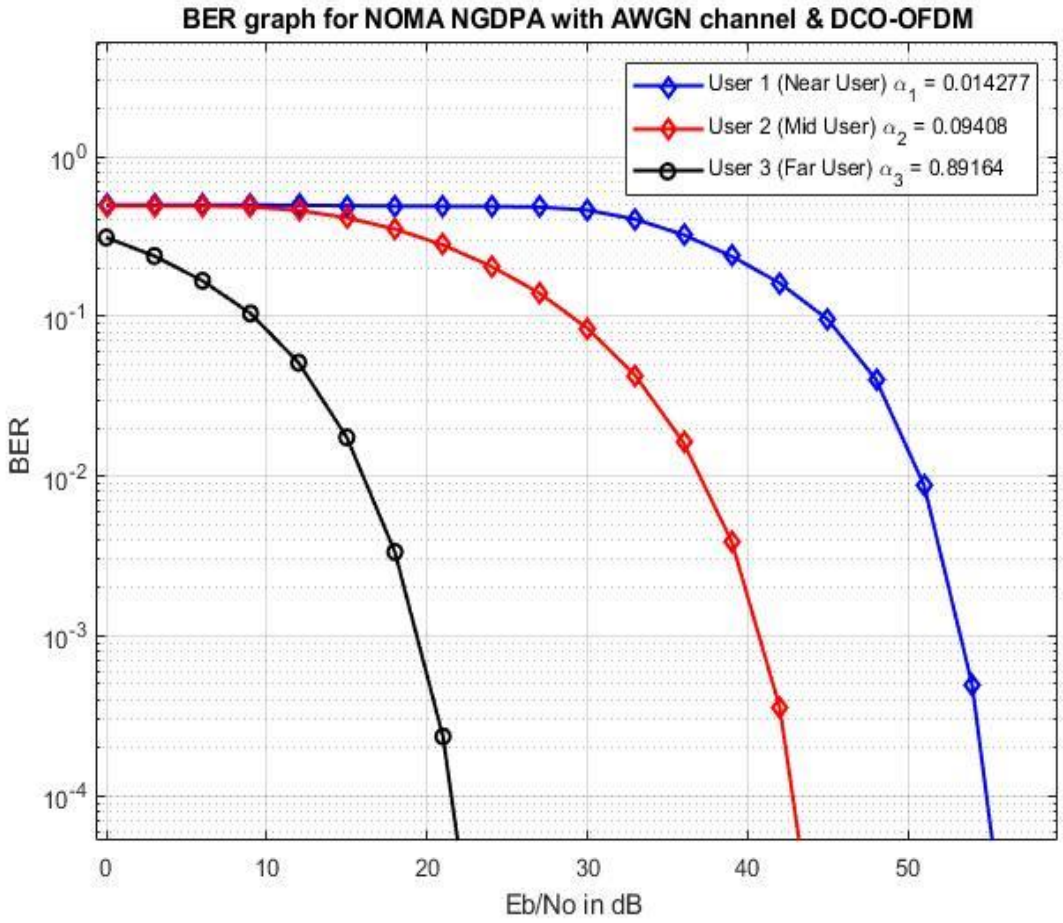


Figure 3.8: BER vs E_b/N_0 graph for DCO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy.

Figure 3.8 shows BER performance of DCO-OFDM modulation under three users NOMA with Normalized Gain Difference Power Allocation in AWGN communication channel. Here performance has been studied for three users – near user at 1.2 m distance from optical source and far user at 1.66 m distance from optical source. Mid user is located at 1.4m distance from optical source. In this power allocation strategy, power is also allocated dynamically according to their channel conditions. According to the values of channel

coefficients, 1.43% power is allocated to near user, 9.4% power is allocated to mid user and far user is allocated to rest of the power i.e. 89.17%.

BER performance of this strategy for DCO-OFDM NOMA has been shown for three users' case. It is observed that this strategy allocates power well in conditions where users are in very close vicinity. It means users should be concentrated in a very little field area to apply this strategy to get good result. Here the algorithm has done a good job in optimized power allocation. As a result, minimum BER performance has been achieved. It has been possible due to user's distribution at a very close vicinity.

3.4 Conclusions

In this chapter, we have evaluated the BER performance for DCO-OFDM modulation with NOMA multiple access scheme through FPA, GRPA, and NGDPA power allocation strategies for both 2 users and 3 users' scenario. It is seen that FPA is used for arbitrarily power allocation. Optimization cannot be done due to static allocation method. GRPA and NGDPA both are dynamic power allocation strategy. GRPA can be used where users are separated from each other. This algorithm allocates power with more optimization in this situations. NGDPA can be used where users are located with close vicinity. This algorithm allocates power with more optimization in huge user density area. DCO-OFDM has a good BER performance of the order of 10^{-4} for throughout all the power allocation strategies at best 25 dB E_b/N_0 and worst at 55 dB E_b/N_0. But it requires very high Peak to Average Power ratio. This limits the application of DCO-OFDM only in predefined situations.

Chapter 4

BER Performance of ACO-OFDM Modulation under Different Conditions

In this chapter, we have analyzed BER performance of Asymmetrically Clipped Optical OFDM (ACO-OFDM) modulation scheme under different conditions. The simulation environment and the simulation parameters used for the experiment have also been discussed in this chapter. The channel which has been considered here is indoor Visible Light Communication Channel (VLC). The channel is considered to be predominantly affected by AWGN noise only. BER performance has been evaluated for ACO-OFDM, based on different MQAM modulation. Then BER performance has been evaluated for ACO-OFDM under Non Orthogonal Multiple Access of different power allocation strategies like Fixed Power Allocation (FPA), Gain Ratio Power Allocation (GRPA) and Normalized Gain Difference Power Allocation (NGDPA) for 2 users and 3 users respectively.

Simulation Environment

For the simulation purpose we have chosen the following parameters in our MATLAB environment.

Table 4.1: Simulation Parameters of ACO-OFDM

Sl No.	Description	Notation	Value
1.	Responsivity of PD	η_{PD}	0.6 A/W
2.	Transmitter Semi- Angle	φ_k	60 deg
3.	FOV of the PDs	ϕ_c	60 deg
4.	Vertical Distance	z	2.15 m
5.	Physical Area of PD	A_k	1.0 cm^2
6.	Refractive Index of PD lens	n	1.5
7.	Gain of Optical Filter	$T_s(\phi_k)$	1.0
8.	Total Number of Subcarriers	N_{FFT}	128
9.	QAM modulation Order	M	4/16/64
10.	Horizontal Distance From Source	r	0.5-2.4 m

4.1 BER Performance of ACO-OFDM

With the given setup, we have performed ACO-OFDM modulation for a particular user at a fixed distance in presence of AWGN channel. The measured BER values have been recorded in below Table 4.2.

Table 4.2: BER measurement of ACO-OFDM and DCO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM.

E_b/N_0	**4-QAM BER ACO**	**4-QAM BER DCO**	**16-QAM BER ACO**	**16-QAM BER DCO**	**64-QAM BER ACO**	**64-QAM BER DCO**
0	0.0789274	0.21190456	0.14094906	0.26026281	0.19980471	0.3078855
2	0.0377100	0.15686261	0.09768503	0.20995507	0.15705221	0.2657975
4	0.0126082	0.10241345	0.05875375	0.16216549	0.11854684	0.2209201
6	0.0024052	0.05516039	0.02786218	0.11746313	0.08389846	0.1765472
8	0.0002035	0.02218611	0.00922980	0.07606664	0.05239145	0.1359749
10	4.30E-06	0.005724762	0.001746836	0.040864464	0.026579427	0.0997035
12	0	0.00072504	0.00014273	0.01627371	0.00972765	0.0666041
14	0	3.02E-05	2.70E-06	0.00412283	0.00214963	0.0377303
16	0	1.98E-07	0	0.00051716	0.00021799	0.0164028
18	0	0	0	2.12E-05	5.83E-06	0.0047326
20	0	0	0	2.78E-07	0	0.0007186
22	0	0	0	0	0	4.08E-05
24	0	0	0	0	0	5.16E-07
26	0	0	0	0	0	1.32E-08
28	0	0	0	0	0	0
30	0	0	0	0	0	0

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 4.1 for ACO-OFDM modulation based on all the three different MQAM modulation.

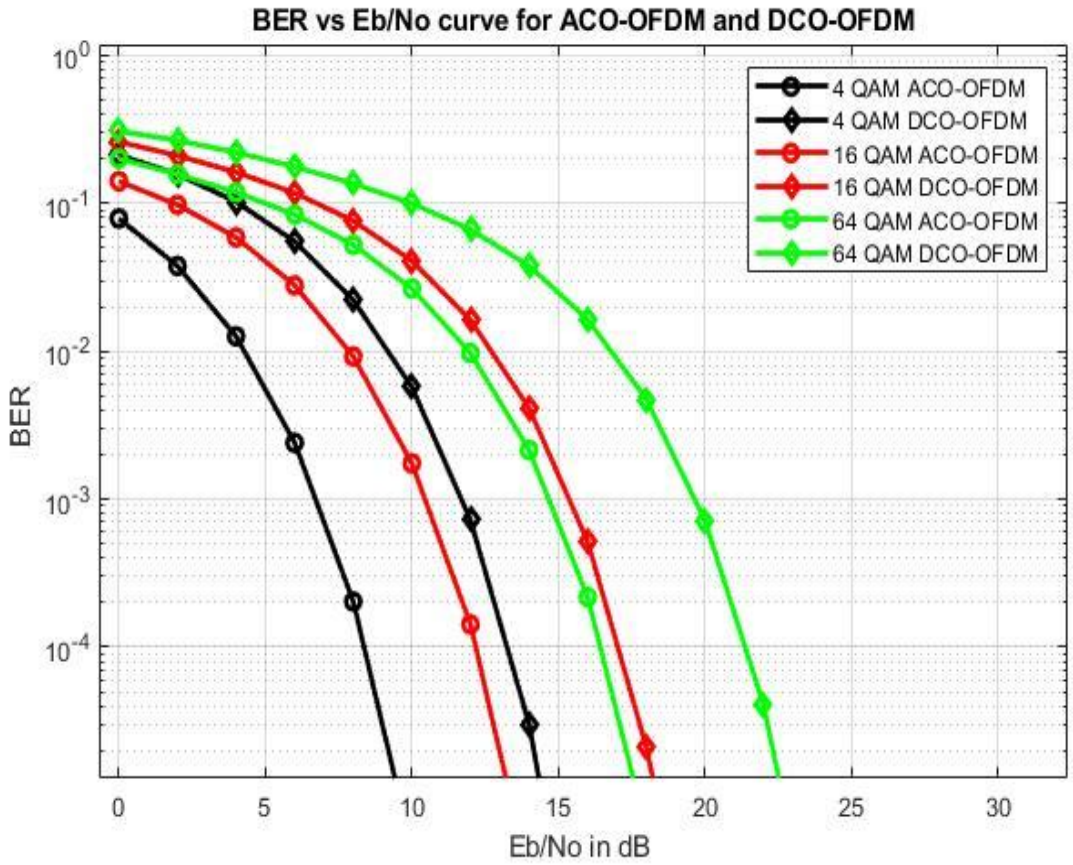


Figure 4.1: BER vs E_b/N_0 graph for ACO-OFDM and DCO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM.

Figure 4.1 shows BER performance of ACO-OFDM modulation under AWGN communication channel. Here performance has been studied for three different MQAM modulations based DCO-OFDM i.e. 4-QAM, 16-QAM and 64-QAM. It is found that BER decreases with the increase of E_b/N_0 level as it is expected. For a fixed value of E_b/N_0, 4-QAM has the best possible BER, 64-QAM has the worst possible BER and 16-QAM gives an intermediate value between the level of 4-QAM and 64-QAM. Each MQAM based ACO-OFDM modulation has better BER performance than each MQAM based DCO-OFDM modulation.

4.2 BER Performance of ACO-OFDM for Two Users NOMA

In this section, BER performance has been evaluated for two users NOMA. While doing so, different power allocation strategies have been considered. We have considered same simulation parameters as mentioned in Table 4.1.

4.2.1 BER Performance for Two Users NOMA with Fixed Power Allocation

For this experimental setup, 16-QAM has been considered. With the given setup we have performed ACO-OFDM modulation with Non Orthogonal multiple Access for two users at two fixed distances in presence of AWGN channel. User with least distance from optical source has been considered as near user. The other user with larger distance has been considered as far user. The measured BER values for two different users have been recorded in below Table 4.3.

Table 4.3: BER measurement of ACO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on FPA strategy.

E_b/N_0	BER(Near User)	BER(Far User)
0	0.491425992	0.525854365
2	0.490930952	0.427898016
4	0.489988889	0.333695635
6	0.487115675	0.248530952
8	0.476829167	0.170636905
10	0.455042063	0.10398254
12	0.422425	0.054195238
14	3.82E-01	2.30E-02
16	3.37E-01	7.38E-03
18	0.288571429	0.001464286
20	0.237686508	0.000136508
22	0.188583333	5.95E-06
24	0.142094841	0
26	0.098651587	0
28	0.059500198	0
30	0.028640476	0
32	9.54E-03	0
34	1.86E-03	0
36	0.00015496	0
38	2.78E-06	0
40	0	0

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 4.2 for ACO-OFDM modulation under two users NOMA multiple access scheme based on fixed power allocation strategy.

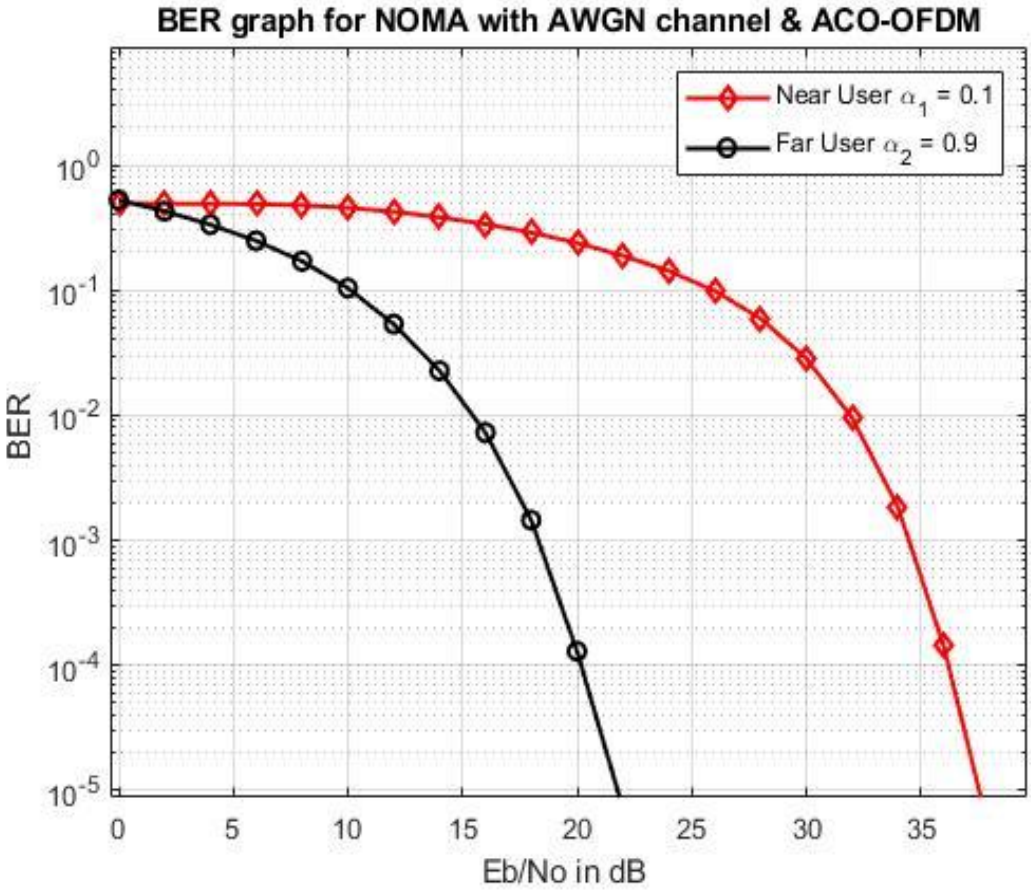


Figure 4.2: BER vs E_b/N_0 graph for ACO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy

Figure 4.2 shows BER performance of ACO-OFDM modulation under two users NOMA with fixed power allocation in AWGN communication channel. Here performance has been studied for two users – near user at 1.2 m distance from optical source and far user at 2.4 m distance from optical source. Power loss increases with the increasing distance of receiver from optical source. As a result, SNR level degrades in receivers with the increasing distance from source. To maintain ample SNR level in each user receiver, generally far user is allocated

more power and near user is allocated less power. In our fixed power allocation strategy we have allocated 90% power to far user and 10% power to near user. As a result, far user has better BER performance than near user. For fixed power allocation strategy BER performance depends on the allocated power. User receivers' distances from source is fixed. So, optimal power allocation coefficient need to find out in this case for better BER performance among all users. We have varied the power allocation coefficient from 0 to 0.5 and measured the corresponding BER values for both users at a fixed value of SNR 30 dB. Obtained data is shown in Fig 4.3.

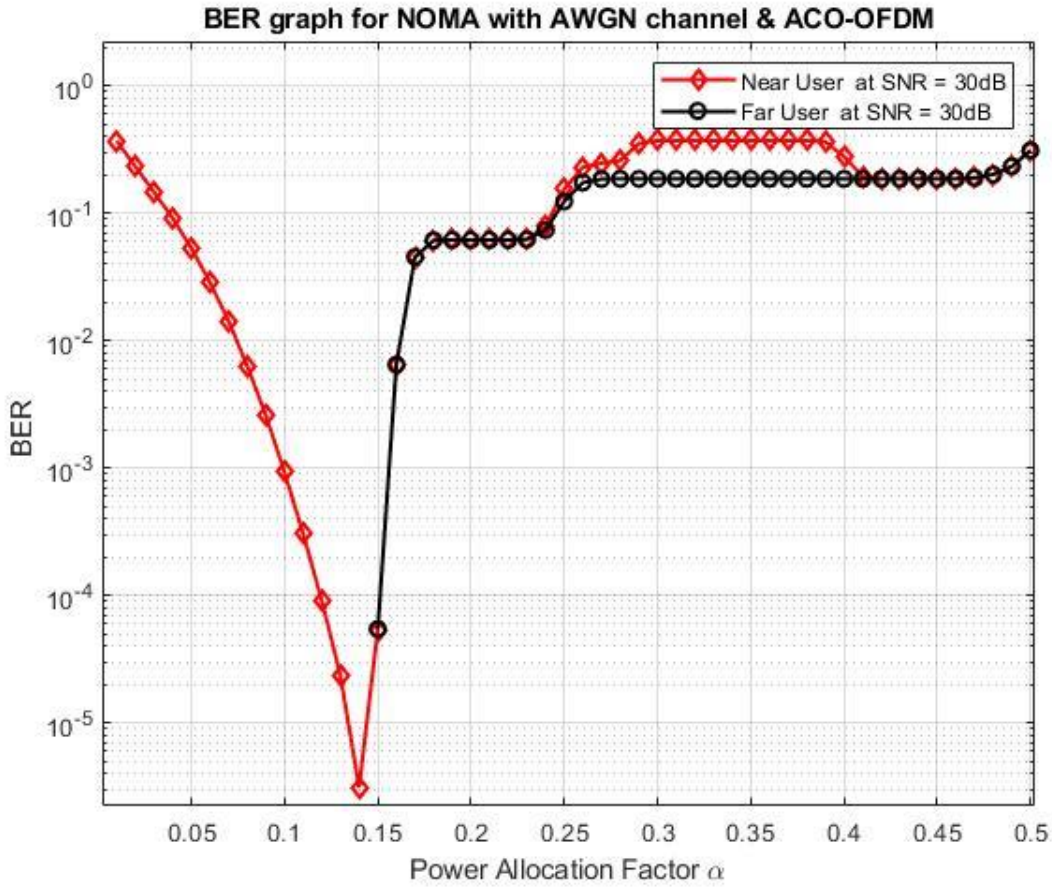


Fig 4.3: BER vs Power Allocation Factor graph for ACO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy

Figure 4.3 shows BER performance of ACO-OFDM modulation under two users NOMA with fixed power allocation in AWGN communication channel for different values of

Power Allocation Factor. It is seen that least possible BER values for both users are obtained in case of 14% allocated power to near user. In this scenario, far user is allocated rest of the power i.e. 86%. ACO-OFDM has overall better BER performance than DCO-OFDM. In this case, ACO-OFDM requires less power allocation to near user than DCO-OFDM to achieve minimum BER performance possible for two users system.

4.2.2 BER Performance for Two Users NOMA with Gain Ratio Power Allocation

For this experimental set up we have considered 16-QAM based ACO-OFDM modulation too. With the given setup we have performed ACO-OFDM modulation with Non Orthogonal multiple Access using GRPA power allocation strategy for two users at two fixed distances in presence of AWGN channel. Power is allocated to users according to this strategy as discussed in chapter 2 of this thesis. The measured BER values for two different users have been recorded in below Table 4.4.

Table 4.4: BER measurement of ACO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on GRPA strategy.

E_b/N_0	BER(Near User)	BER(Far User)
0	0.482563672	0.165425391
2	0.47780625	0.128978516
4	0.461192578	0.096884766
6	0.426681641	0.070271484
8	0.378517578	0.049578125
10	0.322343359	0.034847656
12	0.262934766	0.024350391
14	2.07E-01	1.73E-02
16	1.55E-01	1.23E-02
18	0.108169922	0.008405078
20	0.065170703	0.005085547
22	0.031436719	2.49E-03
24	0.010558984	0.00089375
26	0.002054688	0.000167969
28	0.000174219	1.13E-05
30	3.52E-06	3.91E-07
32	0	0
34	0	0
36	0	0
38	0	0
40	0	0

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 4.4 for ACO-OFDM modulation under two users NOMA multiple access scheme based on Gain Ratio Power Allocation strategy.

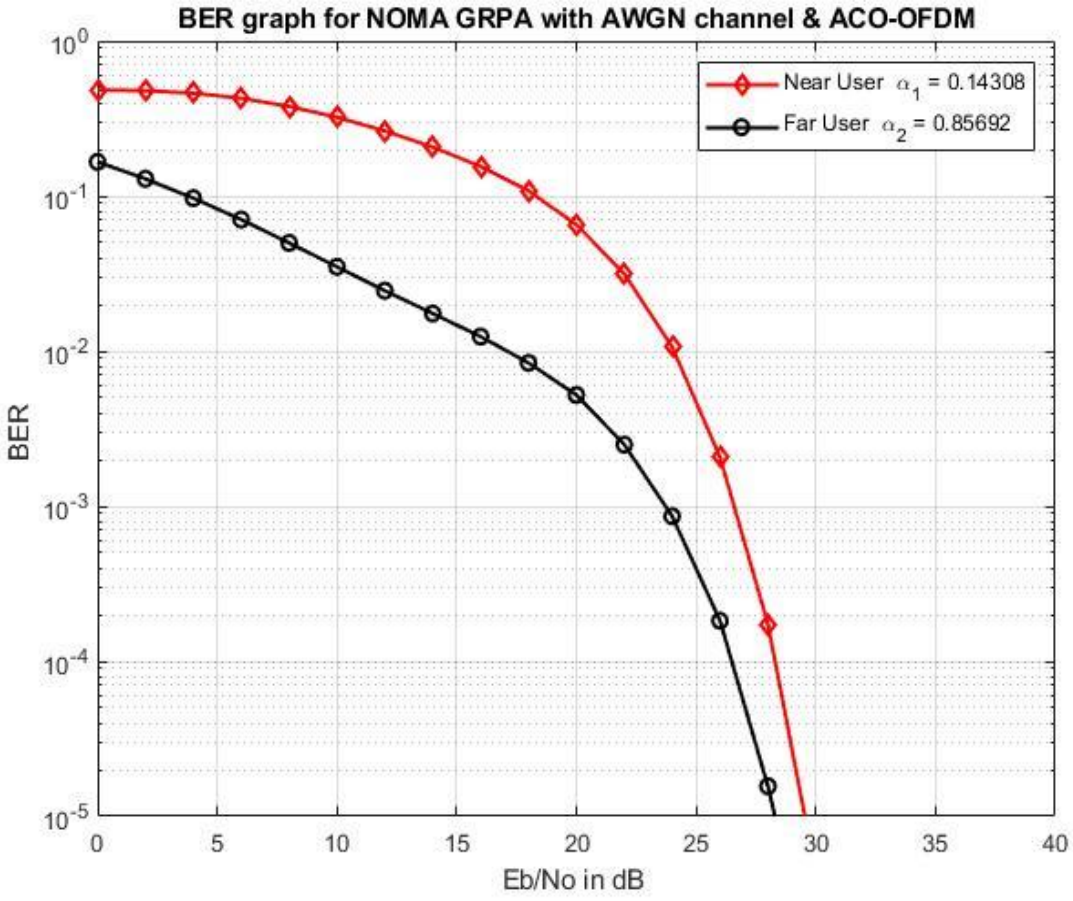


Figure 4.4: BER vs E_b/N_0 graph for ACO-OFDM modulation under two users NOMA multiple access scheme based on GRPA strategy

Figure 4.4 shows BER performance of ACO-OFDM modulation under two users NOMA with Gain Ratio Power Allocation in AWGN communication channel. Here performance has been studied for two users – near user at 0.8 m distance from optical source and far user at 1.9 m distance from optical source. In this power allocation strategy, power is allocated dynamically according to their channel conditions. OWC channel is a deterministic

channel. As a result, channel conditions depend on user location with respect to the source. Here in this case, it is the distance between the optical source and user receiver. According to the values of channel coefficients, 14.3% power is allocated to near user and far user is allocated to rest of the power i.e. 85.7%.

BER performance of this strategy for ACO-OFDM NOMA has been shown for two users' case. It is observed that this strategy allocates power well in conditions where users are very far among themselves. It means user separation should be large enough to apply this strategy to get good result. It will give better result when near user is present very close to transmission source and far user is present at maximum possible distance from the source. Then this strategy will give fair power allocation to users and give minimum possible BER for two users NOMA system. In practical scenario, users can be anywhere in the OWC channel environment. So, it will be used in scenarios where users have large separation among themselves. ACO-OFDM also in this strategy performs well compared to DCO-OFDM, analyzed in previous chapter.

4.2.3 BER Performance for Two Users NOMA with Normalized Gain Difference Power Allocation

For this experimental set up we have considered 16-QAM based ACO-OFDM modulation too. With the given setup we have performed ACO-OFDM modulation with Non Orthogonal multiple Access using NGDPA power allocation strategy for two users at two fixed distances in presence of AWGN channel. Power is allocated to users according to this strategy as mathematical expressions discussed in chapter 2 of this thesis. The measured BER values for two different users have been recorded in below Table 4.5.

Table 4.5: BER measurement of ACO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on NGDPA strategy.

Eb/N0	**BER(Near User)**	**BER(Far User)**
0	0.486862891	0.16004375
2	0.481868359	0.121672656
4	0.466727344	0.087905859
6	0.437075391	0.058983984
8	0.394248438	0.037566797
10	0.343562109	0.022535938
12	0.287314063	0.013008594
14	2.32E-01	7.06E-03
16	1.79E-01	3.45E-03
18	0.131958594	0.001334766
20	0.087795313	0.000325391
22	0.050610547	3.05E-05
24	0.022177734	2.73E-06
26	0.006633984	0
28	0.001019922	0
30	5.55E-05	0
32	3.91E-07	0
34	0	0
36	0	0
38	0	0
40	0	0

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 4.5 for ACO-OFDM modulation under two users NOMA multiple access scheme based on Normalized Gain Difference Power Allocation strategy.

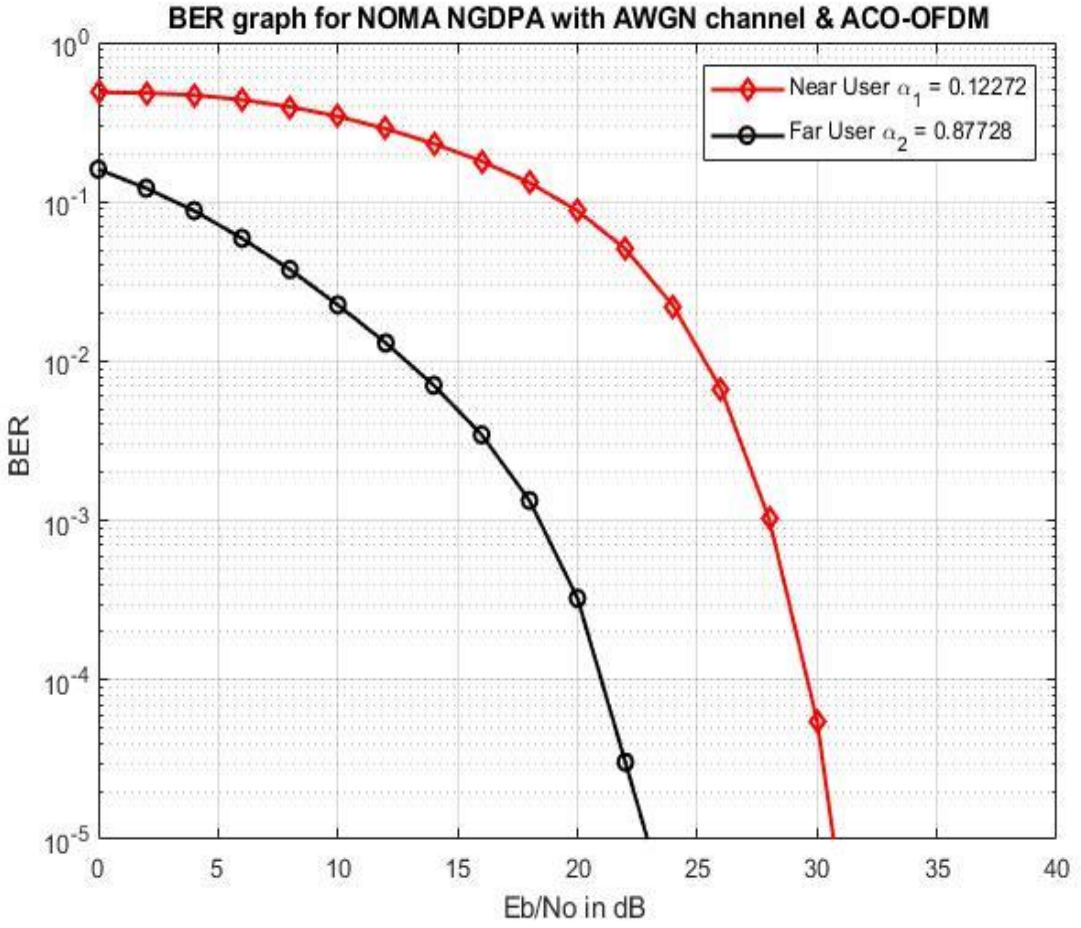


Figure 4.5: BER vs E_b/N_0 graph for ACO-OFDM modulation under two users NOMA multiple access scheme based on NGDPA strategy

Figure 4.5 shows BER performance of ACO-OFDM modulation under two users NOMA with Normalized Gain Difference Power Allocation in AWGN communication channel. Here performance has been studied for two users – near user at 1 m distance from optical source and far user at 1.2 m distance from optical source. In this power allocation strategy, power is also allocated dynamically according to their channel conditions. According

to the values of channel coefficients, 12.27% power is allocated to near user and far user is allocated to rest of the power i.e. 87.73%.

BER performance of this strategy for ACO-OFDM NOMA has been shown for two users' case. It is observed that this strategy allocates power well in conditions where users are in very close vicinity. It means users should be concentrated in a very little field area to apply this strategy to get good result. It will give better result when both near user and far user are present at a very close distance. Then this strategy will give fair power allocation to those congested users and give minimum possible BER for two users NOMA system. In practical scenario, users can be anywhere in the OWC channel environment. So, it will be used in scenarios where users have very little separation among themselves. By observing far user's performance it is seen that ACO-OFDM also in this strategy performs well compared to DCO-OFDM, analyzed in previous chapter.

4.3 BER Performance of ACO-OFDM for Three Users NOMA

Here BER performance has been evaluated for three users NOMA multiple access scheme modulated by ACO-OFDM. For this evaluation, different power allocation strategies of NOMA have been considered. We have considered same simulation parameters as mentioned in Table 4.1.

4.3.1 BER Performance for Three Users NOMA with Fixed Power Allocation

For this experimental setup 16-QAM has been considered. With the given setup we have performed ACO-OFDM modulation with Non Orthogonal multiple Access for three users at three fixed distances in presence of AWGN channel. User with least distance from optical source has been considered as near user. The other user with larger distance has been considered as far user. Remaining user is considered as mid user. The measured BER values for three different users have been recorded in below Table 4.6.

Table 4.6: BER measurement of ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy.

Eb/N0	BER(Near User)	BER(Mid User)	BER (Far User)
0	0.486862891	0.484469986	0.164209747
2	0.481868359	0.476067734	0.109983444
4	0.466727344	0.440494919	0.066551971
6	0.437075391	0.377777863	0.037606812
8	0.394248438	0.30151329	0.020619583
10	0.343562109	0.225137329	0.011327362
12	0.287314063	0.161112595	0.006017303
14	2.32E-01	1.12E-01	0.002835464
16	1.79E-01	7.66E-02	0.001021957
18	0.131958594	0.051478577	0.000230408
20	0.087795313	0.032788467	1.34E-05
22	0.050610547	1.71E-02	0
24	0.022177734	5.66E-03	0
26	0.006633984	0.000747299	0
28	0.001019922	1.53E-05	0
30	5.55E-05	0	0
32	3.91E-07	0	0
34	0	0	0
36	0	0	0
38	0	0	0
40	0	0	0

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 4.6 for ACO-OFDM modulation under three users NOMA multiple access scheme based on fixed power allocation strategy.

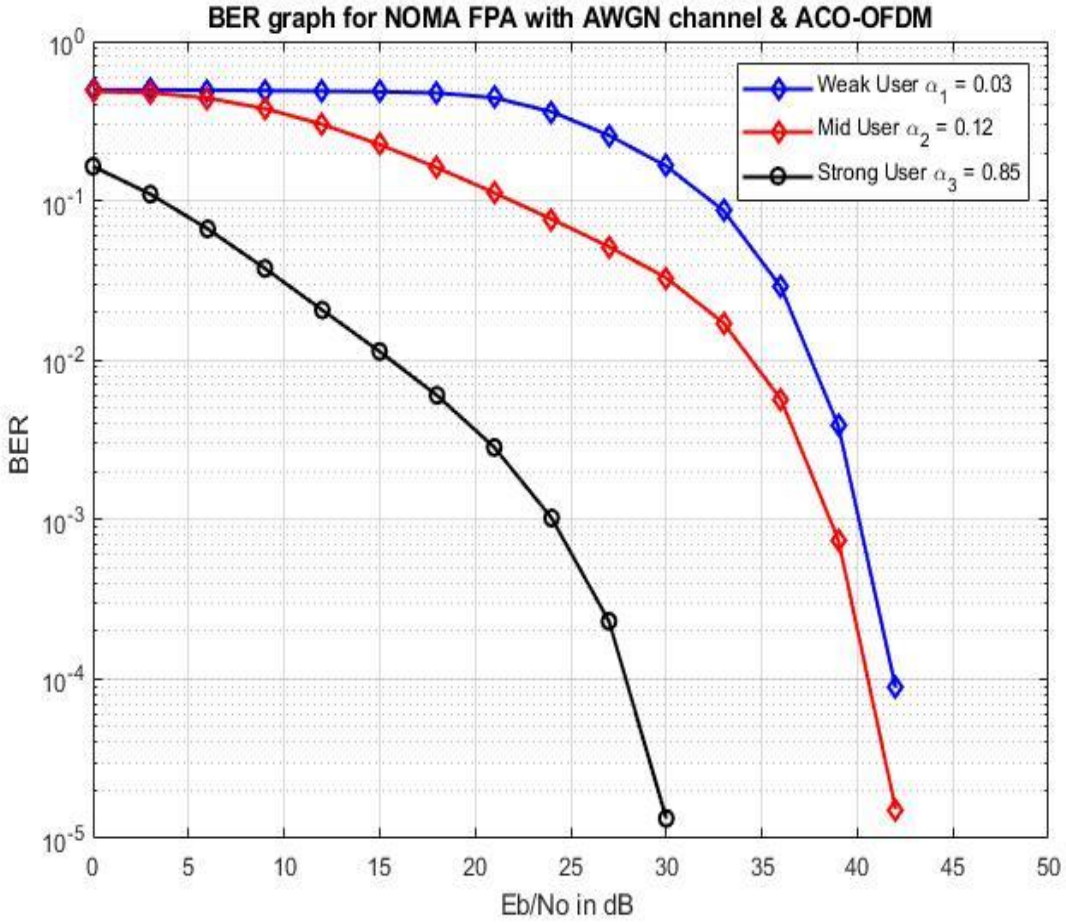


Figure 4.6: BER vs E_b/N_0 graph for ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy

Figure 4.6 shows BER performance of ACO-OFDM modulation under three users NOMA with fixed power allocation in AWGN communication channel. Here performance has been studied for three users – near user at 1 m distance from optical source and far user at 1.8 m distance from optical source. Mid user is at 1.4 m distance from optical source. Power loss increases with the increasing distance of receiver from optical source. As a result, SNR level degrades in receivers with the increasing distance from source. To maintain ample SNR level in each user receiver, generally far user is allocated more power, near user is allocated less power and mid user is allocated to medium level of power. In our fixed power allocation

strategy we have allocated 85% power to far user, 12% power to mid user and 3% power to near user. As a result, far user has best BER performance than near user and mid user. Due to higher power allocation, mid user has better BER performance than near user. For fixed power allocation strategy BER performance depends on the allocated power. User receivers' distances from source is fixed. So, optimal power allocation coefficient need to find out in this case for better BER performance among all users. Fixed power allocation strategy has a better BER performance in case of ACO-OFDM compared to DCO-OFDM as analyzed in chapter 3 of this thesis.

4.3.2 BER Performance for Three Users NOMA with Gain Ratio Power Allocation

Gain Ratio Power Allocation (GRPA) is applied here to dynamically allocate power to three users sharing resources through NOMA multiple access scheme. For this experimental set up we have considered 16-QAM based ACO-OFDM modulation too. With the given setup we have performed ACO-OFDM modulation with Non Orthogonal multiple Access using GRPA power allocation strategy for three users at three fixed distances in presence of AWGN channel. Power is allocated to users according to the strategy as discussed in chapter 2 of this thesis. The measured BER values for three different users have been recorded in below Table 4.7.

Table 4.7: BER measurement of ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy.

Eb/N0	BER(Near User)	BER(Mid User)	BER (Far User)
0	0.495721054	0.486754227	0.162759781
2	0.494983292	0.47779007	0.107486343
4	0.49177475	0.444483185	0.063229752
6	0.48760376	0.386359406	0.033677292
8	0.483806992	0.313644791	0.017095184
10	0.479383087	0.239720535	0.008458328
12	0.471777344	0.177167511	0.003868866
14	4.46E-01	1.31E-01	0.001462936
16	3.76E-01	9.86E-02	0.000349426
18	0.276413727	0.076579285	3.78E-05
20	0.18313942	0.061205673	1.14E-06
22	0.105218887	4.75E-02	0
24	0.048386383	3.23E-02	0
26	0.018516922	0.017032623	0
28	0.005503464	5.43E-03	0
30	7.09E-04	0.000716019	0
32	1.37E-05	1.30E-05	0
34	0	0	0
36	0	0	0
38	0	0	0
40	0	0	0

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 4.7 for ACO-OFDM modulation under three users NOMA multiple access scheme based on GRPA strategy.

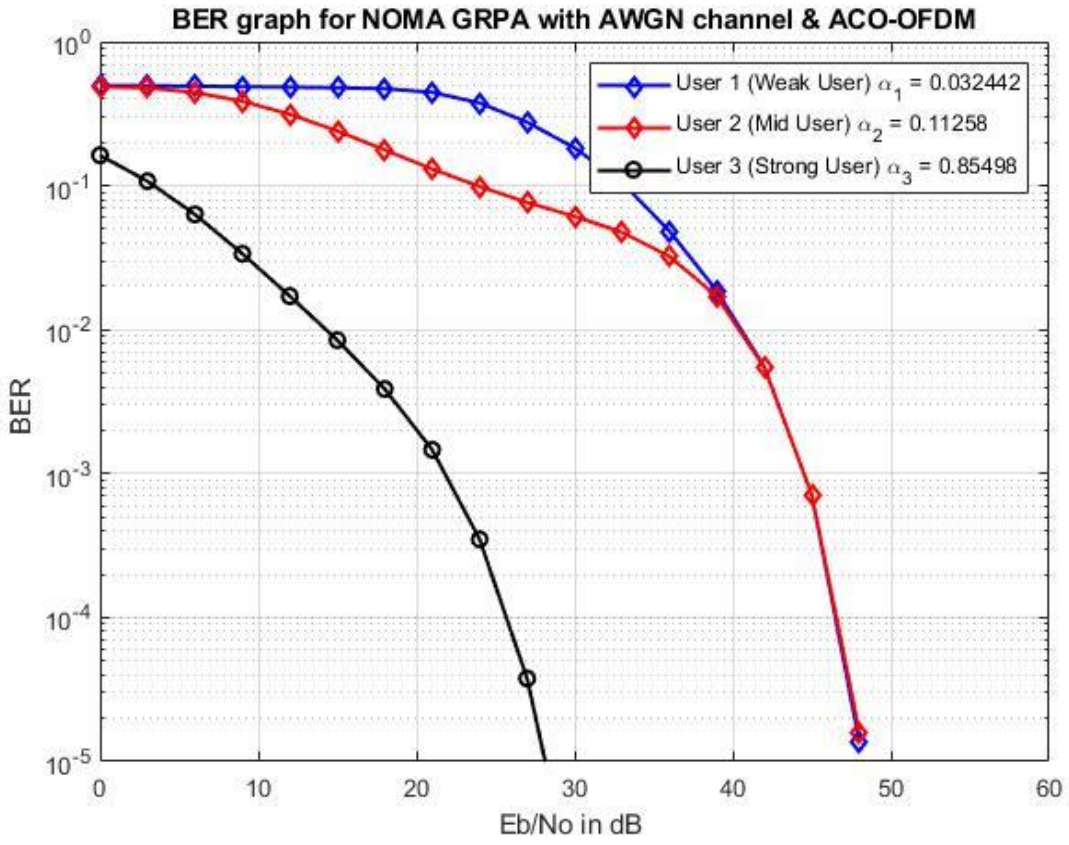


Figure 4.7: BER vs E_b/N_0 graph for ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy.

Figure 4.7 shows BER performance of ACO-OFDM modulation under three users NOMA with Gain Ratio Power Allocation in AWGN communication channel. Here performance has been studied for three users – near user at 0.7 m distance from optical source and far user at 1.8 m distance from optical source. Mid user is at a distance of 1.5m from optical source. In this power allocation strategy, power is allocated dynamically according to their channel conditions. OWC channel is a deterministic channel. As a result, channel conditions depend on user location with respect to the source. In GRPA strategy, power allocation depends on user distribution from optical sources. Minimum BER for all resource shared users will be possible by this algorithm only when user separation distance is large i.e. well isolated from

each other. According to the values of channel coefficients (based on the positions of the users), here in this case, 2.1% power is allocated to near user, 6.9% power is allocated to mid user and far user is allocated to remaining amount of the power i.e. 91%. Far user shows best BER performance among the three users and near and mid user shows almost same BER performance. This implies that GRPA is not able to properly allocate power to users for achievement of minimum BER in this case. User distribution is not fair enough to achieve minimum BER through this dynamic power allocation algorithm. Gain Ratio Power allocation strategy has a better BER performance in case of ACO-OFDM compared to DCO-OFDM as analyzed in chapter 3 of this thesis.

4.3.3 BER Performance for Three Users NOMA with Normalized Gain Difference Power Allocation

For this experimental set up we have considered 16-QAM based ACO-OFDM modulation too. With the given setup we have performed ACO-OFDM modulation with Non Orthogonal multiple Access using NGDPA power allocation strategy for three users at three fixed distances in presence of AWGN channel. Power is allocated to users according to this strategy as mathematical expressions discussed in chapter 2 of this thesis. The measured BER values for three different users have been recorded in below Table 4.8.

Table 4.8: BER measurement of ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy.

E_b/N_0	BER(Near User)	BER(Mid User)	BER (Far User)
0	0.497578049	0.489930725	0.15544281
2	0.496460724	0.481977463	0.09690361
4	0.494821167	0.452745819	0.049279404
6	0.492044449	0.401769257	0.019718552
8	0.489343262	0.338132858	0.0061203
10	0.487225342	0.264318466	0.001221085
12	0.486276627	0.191449356	0.000113678
14	4.81E-01	1.28E-01	1.53E-06
16	4.53E-01	7.47E-02	0
18	0.389458466	0.035752106	0
20	0.30647049	0.012710571	0
22	0.221457672	2.70E-03	0
24	0.14721489	1.77E-04	0
26	0.083166122	1.53E-06	0
28	0.031518936	0	0
30	5.51E-03	0	0
32	2.19E-04	0	0
34	3.81E-07	0	0
36	0	0	0
38	0	0	0
40	0	0	0

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 4.8 for ACO-OFDM modulation under three users NOMA multiple access scheme based on Normalized Gain Difference Power Allocation strategy.

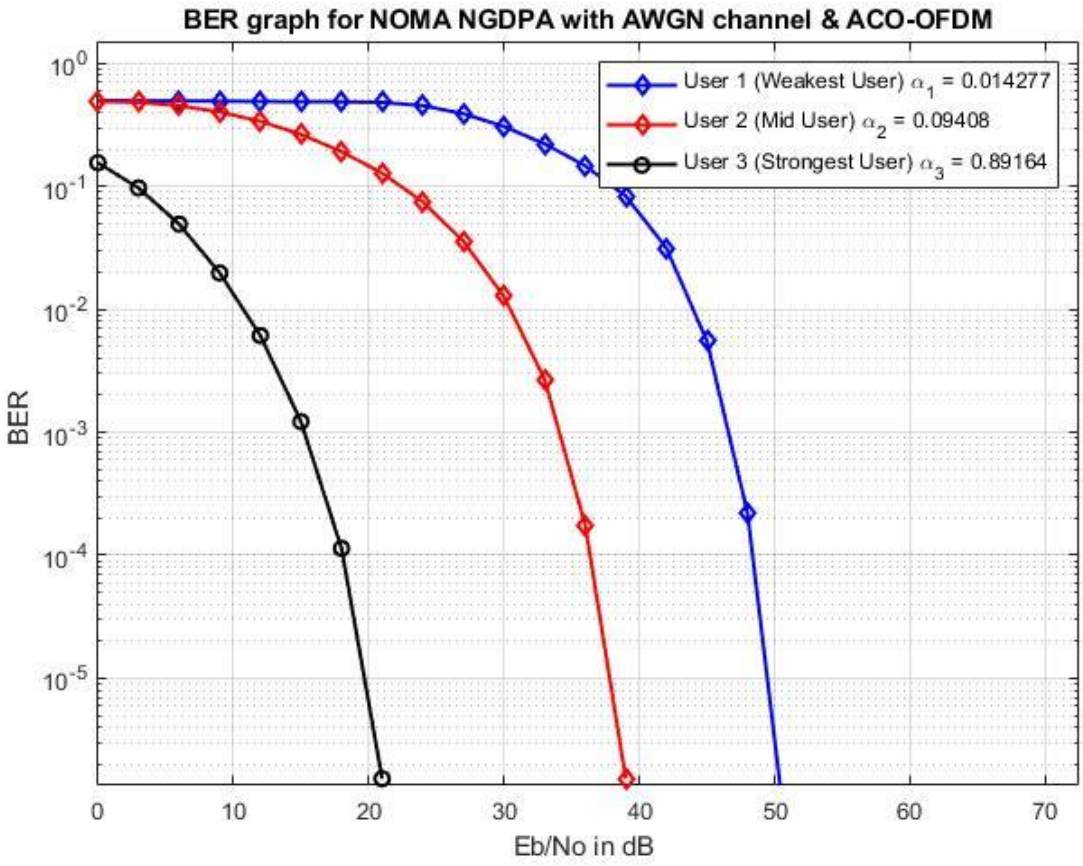


Figure 4.8: BER vs E_b/N_0 graph for ACO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy.

Figure 4.8 shows BER performance of ACO-OFDM modulation under three users NOMA with Normalized Gain Difference Power Allocation in AWGN communication channel. Here performance has been studied for three users – near user at 1.2 m distance from optical source and far user at 1.66 m distance from optical source. Mid user is located at 1.4m distance from optical source. In this power allocation strategy, power is also allocated dynamically according to their channel conditions. According to the values of channel coefficients, 1.43% power is allocated to near user, 9.4% power is allocated to mid user and far user is allocated to rest of the power i.e. 89.17%.

BER performance of this strategy for ACO-OFDM NOMA has been shown for three users' case. It has a better BER performance in case of ACO-OFDM compared to DCO-OFDM. It is observed that this strategy allocates power well in conditions where users are in very close vicinity. It means users should be concentrated in a very little field area to apply this strategy to get good result. Here the algorithm has done a good job in optimized power allocation problem. As a result, minimum BER performance has been achieved. It has been possible due to user's distribution at a very close vicinity.

4.4 Conclusions

In this Chapter, we have studied BER performance for ACO-OFDM modulation with NOMA multiple access scheme through FPA, GRPA, and NGDPA power allocation strategies for both 2-users and 3-users scenario. It is found that FPA is used for arbitrarily power allocation. The GRPA can be used where users are separated from each other. This algorithm allocates power with more optimization in this situations. NGDPA can be used where users are located with close vicinity. This algorithm allocates power with more optimization in huge user density area. In every cases, ACO-OFDM has a far better BER performance under NOMA multiple access with both static and dynamic power allocation strategy than DCO-OFDM for OWC channel. For ACO-OFDM, BER performance of 10^{-5} order has been obtained for lowest E_b/N_0 of 30 dB and worst E_b/N_0 of 50 dB.

Chapter 5

BER Performance of ADO-OFDM Modulation under Different Conditions

In this chapter, we have analyzed BER performance of Asymmetrically Clipped DC Biased Optical OFDM (ADO-OFDM) modulation scheme under different conditions. The simulation environment and the simulation parameters used for the experiment have also been discussed in this chapter. The channel which has been considered here is indoor Visible Light Communication Channel (VLC). The channel is considered to be predominantly affected by AWGN noise only. BER performance has been evaluated for ADO-OFDM, based on different MQAM modulation. Then BER performance has been evaluated for ADO-OFDM under Non Orthogonal Multiple Access of different power allocation strategies like Fixed Power Allocation (FPA), Gain Ratio Power Allocation (GRPA) and Normalized Gain Difference Power Allocation (NGDPA) for 2 users and 3 users respectively.

Simulation Environment

For the simulation purpose, we have considered the following parameters in our MATLAB environment.

Table 5.1: Simulation Parameters of ADO-OFDM

Sl No.	Description	Notation	Value
11.	Responsivity of PD	η_{PD}	0.7 A/W
12.	Transmitter Semi- Angle	φ_k	60 deg
13.	FOV of the PDs	ϕ_c	60 deg
14.	Vertical Distance	z	2.15 m
15.	Physical Area of PD	A_k	1.0 cm^2
16.	Refractive Index of PD lens	n	1.5
17.	Gain of Optical Filter	$T_s(\phi_k)$	1.0
18.	Total Number of Subcarriers	N_{FFT}	128
19.	QAM modulation Order	M	4/16/64
20.	Horizontal Distance From Source	r	0.5-2.4 m
21.	DC Bias	B_{dc}	3 dB

5.1 BER Performance of ADO-OFDM

With the given setup, we have performed ADO-OFDM modulation for a particular user at a fixed distance in presence of AWGN channel. The measured BER values have been recorded in Table 5.2.

Table 5.2: BER measurement of ADO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM

E_b/N_0	BER(4-QAM)	BER(16-QAM)	BER (64-QAM)
0	0.313791406	0.359138477	0.386707682
2	0.273860547	0.322629102	0.358749219
4	0.228114063	0.280522461	0.326769792
6	0.178924219	0.235339648	0.290978255
8	0.128295703	0.190295117	0.251863411
10	0.081710547	0.148264453	0.211873177
12	0.043285938	0.109303711	0.172846094
14	1.77E-02	7.35E-02	1.37E-01
16	5.20E-03	4.33E-02	0.105344792
18	0.001008984	0.021975586	0.076283984
20	0.000183203	0.009739063	0.051037891
22	4.02E-05	4.35E-03	0.031340365
24	1.02E-05	2.21E-03	0.018775391
26	3.13E-06	1.22E-03	0.012111719
28	3.91E-07	6.95E-04	0.008639583
30	3.91E-07	0.000438281	0.006364323
32	3.91E-07	2.90E-04	0.00474974
34	3.91E-07	0.000213086	0.00389974
36	0	9.57E-05	0.003009375
38	0	7.95E-05	0.002491406
40	0	7.25E-05	0.002052865

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 5.1 for ADO-OFDM modulation based on all the three different MQAM modulation.

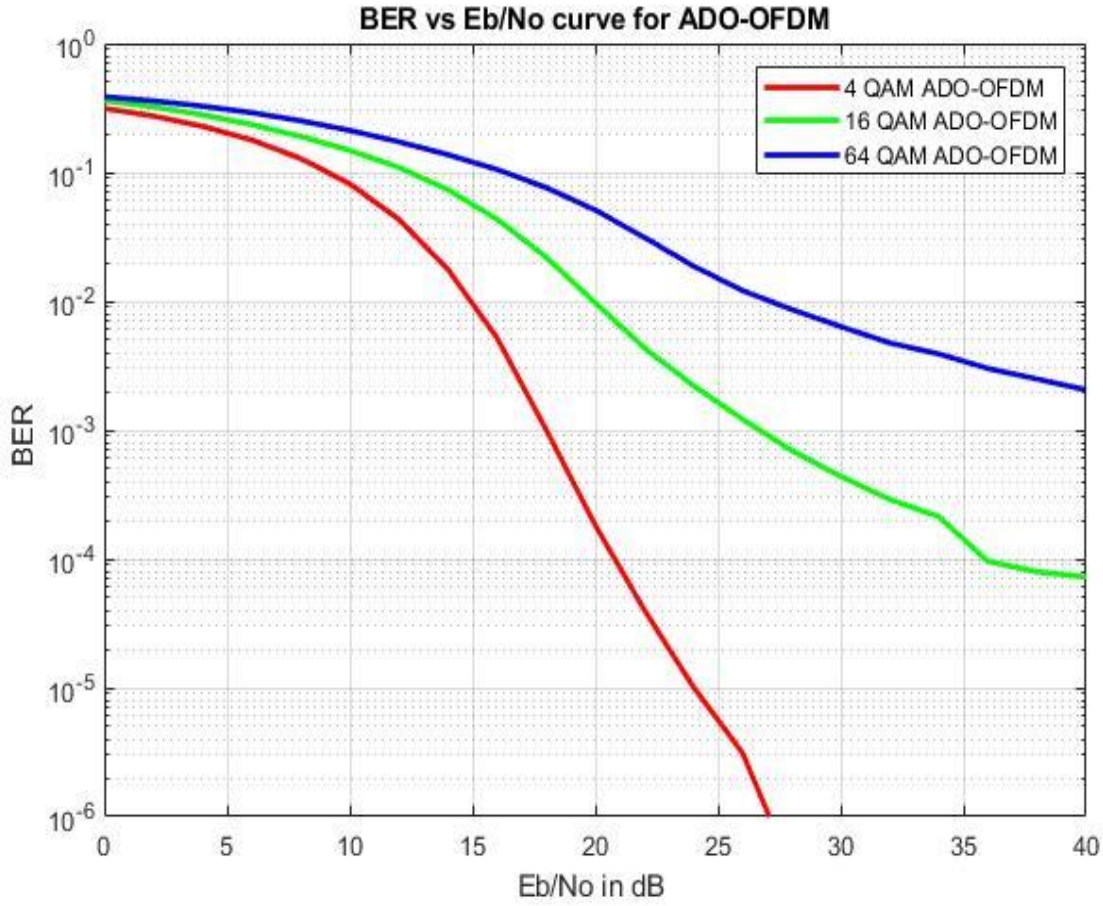


Figure 5.1: BER vs E_b/N_0 graph for ADO-OFDM modulation with AWGN communication channel based on 4-QAM, 16-QAM and 64-QAM

Figure 5.1 shows BER performance of ADO-OFDM modulation under AWGN communication channel. Here performance has been studied for three different MQAM modulations based ADO-OFDM i.e. 4-QAM, 16-QAM and 64-QAM. It is found that BER decreases with the increase of E_b/N_0 level as it is expected. For a fixed value of E_b/N_0, 4-QAM has the best possible BER, 64-QAM has the worst possible BER and 16-QAM gives an intermediate value between the level of 4-QAM and 64-QAM. ADO-OFDM has worst BER performance compared to DCO-OFDM and ACO-OFDM. But ADO-OFDM is optically more power efficient compared to DCO-OFDM.

5.2 BER Performance of ADO-OFDM for Two Users NOMA

In this section, BER performance has been evaluated for two users NOMA. While doing so, different power allocation strategies have been considered. We have considered same simulation parameters as mentioned in Table 5.1.

5.2.1 BER Performance for Two Users NOMA with Fixed Power Allocation

For this experimental setup, 16-QAM has been considered. With the given setup, we have performed ADO-OFDM modulation with Non Orthogonal multiple Access for two users at two fixed distances in presence of AWGN channel. User with least distance from optical source has been considered as near user. The other user with larger distance has been considered as far user. The measured BER values for two different users have been recorded in Table 5.3.

Table 5.3: BER measurement of ADO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on FPA strategy.

E_b/N_0	BER(Near User)	BER(Far User)
0	0.494873438	0.361151172
2	0.494285938	0.283343164
4	0.49305957	0.194479102
6	0.488856641	0.115172461
8	0.467804102	0.05267168
10	0.420197852	0.017176172
12	0.343944727	0.006081445
14	2.55E-01	3.42E-03
16	1.71E-01	2.53E-03
18	0.101222852	0.002261523
20	0.058029688	0.002100977
22	4.50E-02	2.05E-03
24	4.24E-02	2.02E-03
26	4.12E-02	1.99E-03
28	4.11E-02	1.98E-03
30	4.08E-02	0.001967578
32	4.05E-02	1.96E-03
34	4.05E-02	0.001961328
36	0.040491016	1.96E-03
38	0.040508008	1.96E-03
40	0.040558008	1.96E-03

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 5.2 for ADO-OFDM modulation under two users NOMA multiple access scheme based on fixed power allocation strategy.

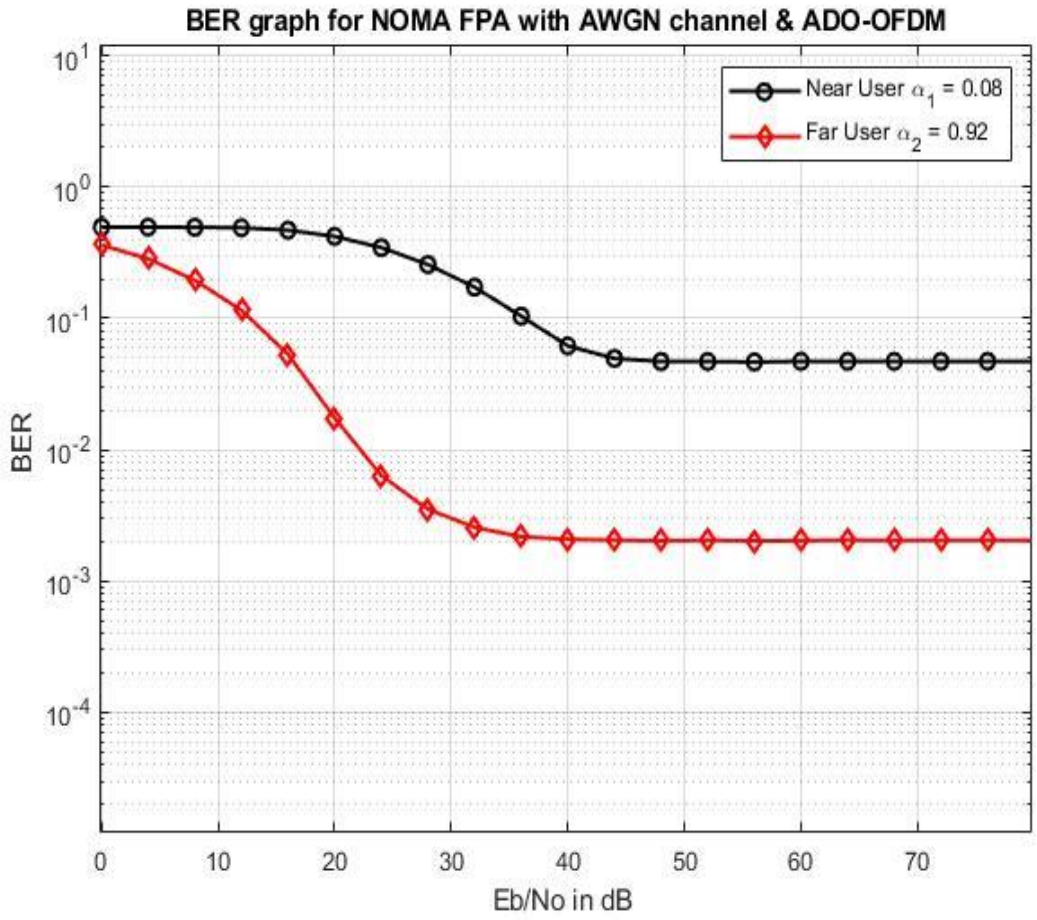


Figure 5.2: BER vs E_b/N_0 graph for ADO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy

Figure 5.2 shows BER performance of ADO-OFDM modulation under two users NOMA with fixed power allocation in AWGN communication channel. Here performance has been studied for two users – near user at 1.2 m distance from optical source and far user at 2.4 m distance from optical source. Power loss increases with the increasing distance of receiver from optical source. As a result, SNR level degrades in receivers with the increasing distance from source. To maintain ample SNR level in each user receiver, generally far user is allocated more power and near user is allocated less power. In our fixed power allocation strategy we have allocated 92% power to far user and 8% power to near user. As a result, far user has better

BER performance than near user. For fixed power allocation strategy BER performance depends on the allocated power. User receivers' distances from source is fixed. So, optimal power allocation coefficient need to find out in this case for better BER performance among all users. We have varied the power allocation coefficient from 0 to 0.5 and measured the corresponding BER values for both users at a fixed value of SNR 30 dB. Obtained data is shown in Figure 5.3.

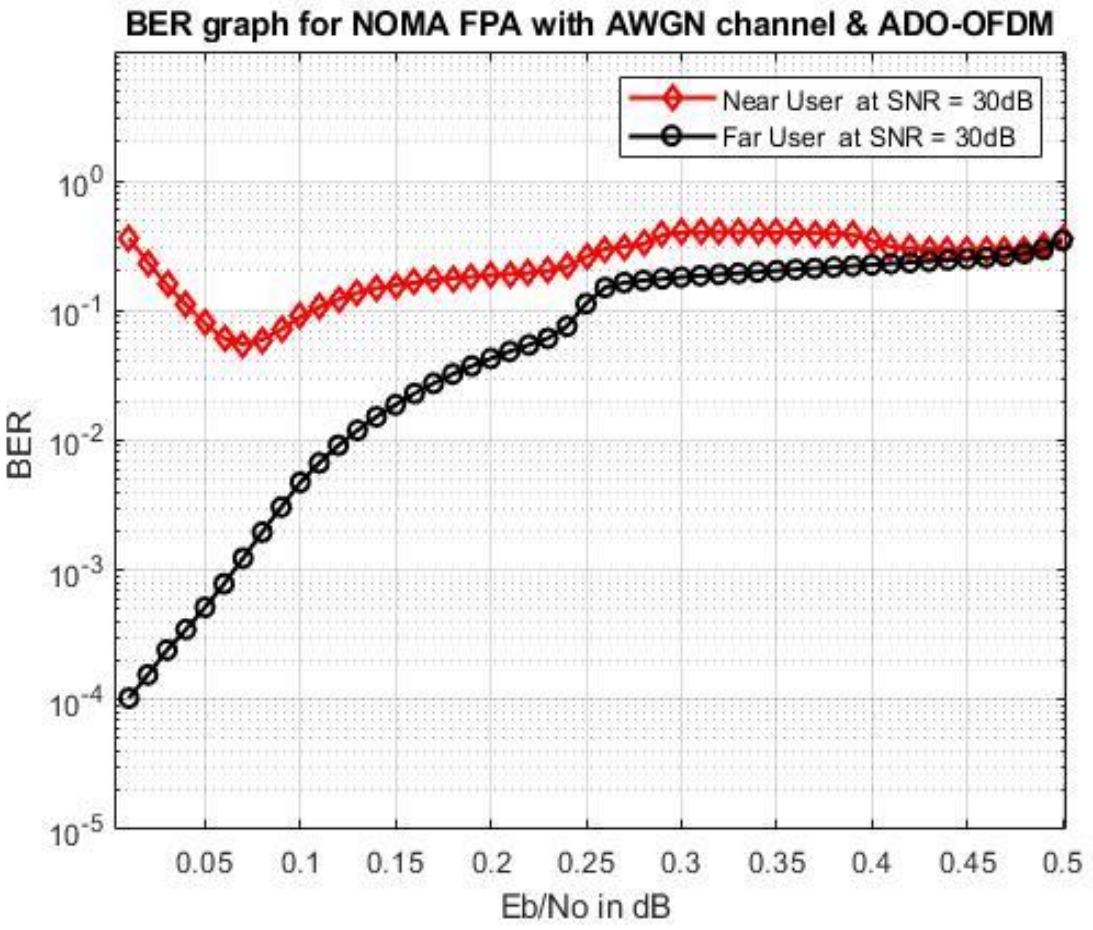


Figure 5.3: BER vs Power Allocation Factor graph for ADO-OFDM modulation under two users NOMA multiple access scheme based on FPA strategy

Figure 5.3 shows BER performance of ADO-OFDM modulation under two users NOMA with fixed power allocation in AWGN communication channel for different values of Power Allocation Factor. It is seen that least possible BER values for both users are obtained in case of 7% allocated power to near user. In this scenario, far user is allocated rest of the power i.e. 93%.

5.2.2 BER Performance for Two Users NOMA with Gain Ratio Power Allocation

Gain Ratio Power Allocation (GRPA) is a dynamic power allocation strategy of NOMA multiple access scheme. It is used to model situations where users' distribution is not isotropic with respect to the transmission source. For this experimental set up we have considered 16-QAM based ADO-OFDM modulation too. With the given setup we have performed ADO-OFDM modulation with Non Orthogonal multiple Access using GRPA power allocation strategy for two users at two fixed distances in presence of AWGN channel. Power is allocated to users according to this strategy as discussed in chapter 2 of this thesis. The measured BER values for two different users have been recorded in Table 5.4.

Table 5.4: BER measurement of ADO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on GRPA strategy.

E_b/N_0	BER(Near User)	BER(Far User)
0	0.491761328	0.361904492
2	0.491294922	0.283723633
4	0.489668945	0.194719531
6	0.485076172	0.116915234
8	0.461002344	0.05544707
10	0.405771875	0.020213672
12	0.324823242	0.008083789
14	2.38E-01	5.17E-03
16	1.64E-01	4.12E-03
18	0.105388477	0.003705859
20	0.07657793	0.003553516
22	7.04E-02	3.47E-03
24	6.81E-02	3.48E-03
26	6.79E-02	3.45E-03
28	6.74E-02	3.45E-03
30	6.74E-02	0.003427148
32	6.76E-02	3.43E-03
34	6.76E-02	0.003430078
36	0.067671484	3.44E-03
38	0.067556641	3.44E-03
40	0.06756543	3.44E-03

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 5.4 for ADO-OFDM modulation under two users NOMA multiple access scheme based on Gain Ratio Power Allocation strategy.

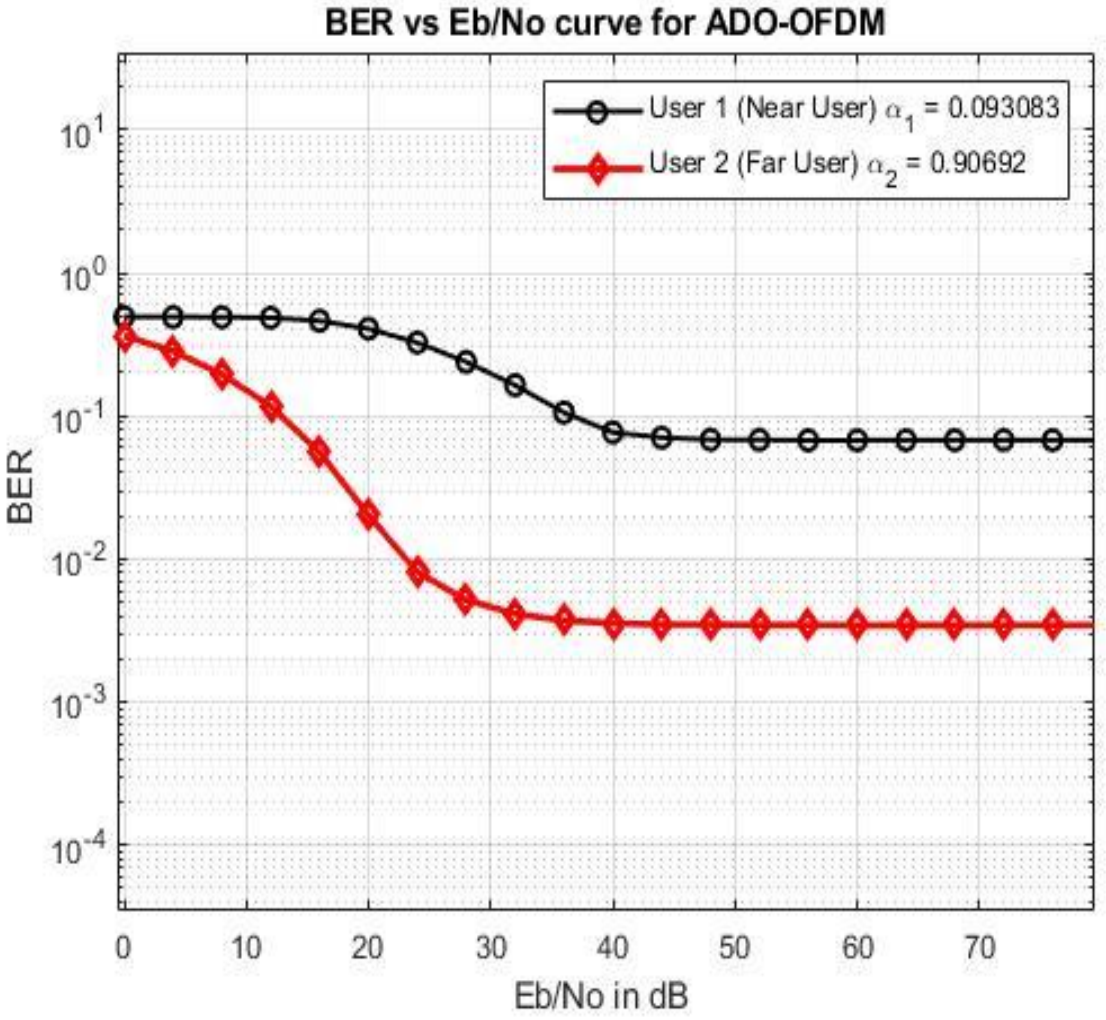


Figure 5.4: BER vs E_b/N_0 graph for ADO-OFDM modulation under two users NOMA multiple access scheme based on GRPA strategy

Figure 5.4 shows BER performance of ADO-OFDM modulation under two users NOMA with Gain Ratio Power Allocation in AWGN communication channel. Here performance has been studied for two users – near user at 0.7 m distance from optical source and far user at 2.1 m distance from optical source. In this power allocation strategy, power is allocated dynamically according to their channel conditions. OWC channel is a deterministic channel. As a result, channel conditions depend on user location with respect to the source.

Here in this case, it is the distance between the optical source and user receiver. According to the values of channel coefficients, 9.3% power is allocated to near user and far user is allocated to rest of the power i.e. 90.7%.

BER performance of this strategy for ADO-OFDM NOMA has been shown for two users' case. It is observed that this strategy allocates power well in conditions where users are very far among themselves. It means user separation should be large enough to apply this strategy to get good result. It will give better result when near user is present very close to transmission source and far user is present at maximum possible distance from the source. Then this strategy will give fair power allocation to users and give minimum possible BER for two users NOMA system. In practical scenario, users can be anywhere in the OWC channel environment. So, it will be used in scenarios where users have large separation among themselves. ADO-OFDM also in this strategy performs worse compared to ACO-OFDM and DCO-OFDM, analyzed in previous chapter.

5.2.3 BER Performance for Two Users NOMA with Normalized Gain Difference Power Allocation

For this experimental set up, we have considered 16-QAM based ADO-OFDM modulation too. With the given setup we have performed ADO-OFDM modulation with Non Orthogonal multiple Access using NGDPA power allocation strategy for two users at two fixed distances in presence of AWGN channel. Power is allocated to users according to this strategy as mathematical expressions discussed in chapter 2 of this thesis. The measured BER values for two different users have been recorded in Table 5.5.

Table 5.5: BER measurement of ADO-OFDM modulation with AWGN communication channel under two users NOMA multiple access scheme based on NGDPA strategy.

E_b/N_0	BER(Near User)	BER(Far User)
0	0.495198438	0.361902734
2	0.494494727	0.283248047
4	0.493367188	0.193790625
6	0.489167578	0.114516797
8	0.468833789	0.051066602
10	0.420833398	0.015875195
12	0.345451367	0.005078711
14	2.54E-01	2.62E-03
16	1.69E-01	1.83E-03
18	0.095910352	0.001533984
20	0.048359766	0.001382031
22	3.32E-02	1.34E-03
24	3.04E-02	1.34E-03
26	2.98E-02	1.33E-03
28	2.89E-02	1.33E-03
30	2.88E-02	0.001338281
32	2.88E-02	1.34E-03
34	2.87E-02	0.001339258
36	0.028738477	1.34E-03
38	0.028703906	1.34E-03
40	0.028766992	1.34E-03

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 5.5 for ADO-OFDM modulation under two users NOMA multiple access scheme based on Normalized Gain Difference Power Allocation strategy.

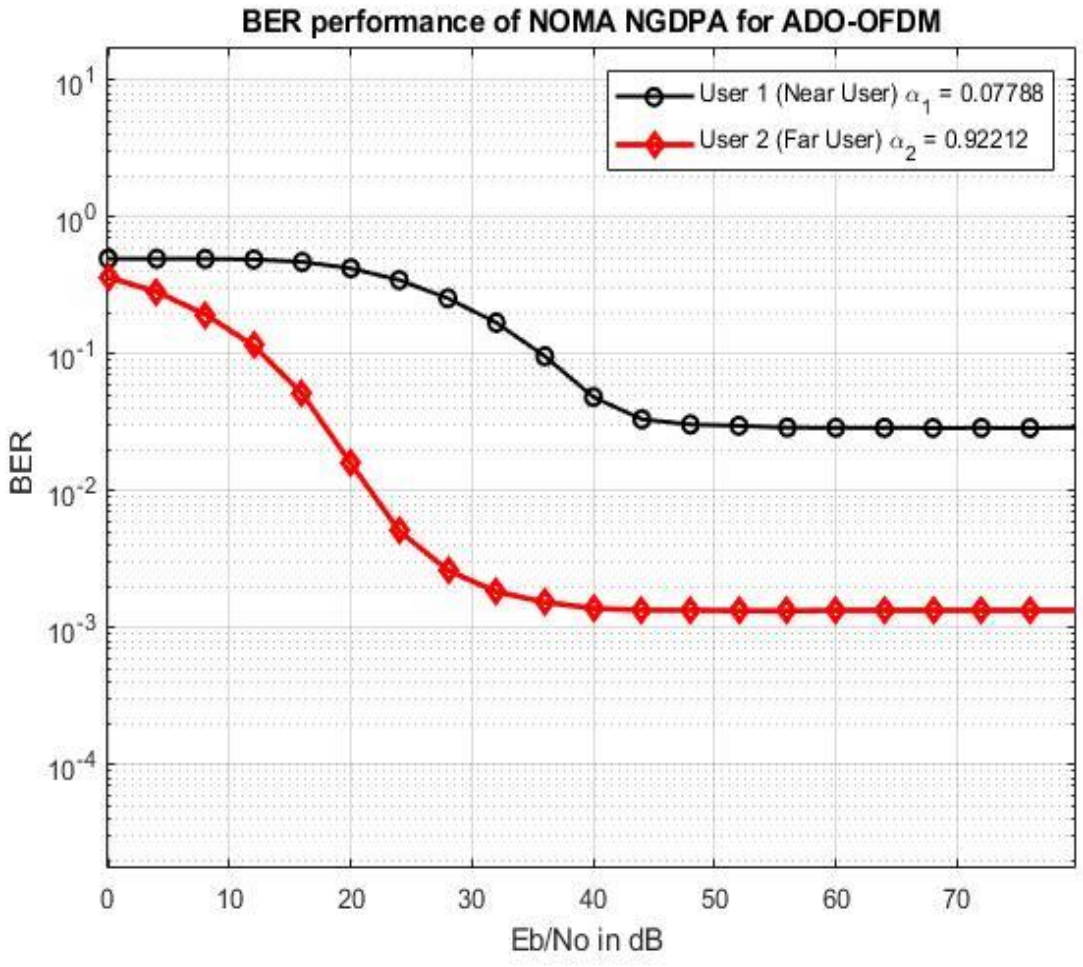


Figure 5.5: BER vs E_b/N_0 graph for ADO-OFDM modulation under two users NOMA multiple access scheme based on NGDPA strategy

Figure 5.5 shows BER performance of ADO-OFDM modulation under two users NOMA with Normalized Gain Difference Power Allocation in AWGN communication channel. Here performance has been studied for two users – near user at 1.5 m distance from optical source and far user at 1.6 m distance from optical source. In this power allocation strategy, power is also allocated dynamically according to their channel conditions. According to the values of channel coefficients, 7.8% power is allocated to near user and far user is allocated to rest of the power i.e. 92.2%.

BER performance of this strategy for ADO-OFDM NOMA has been shown for two users' case. It is observed that this strategy allocates power well in conditions where users are in very close vicinity. It means users should be concentrated in a very little field area to apply this strategy to get good result. It will give better result when both near user and far user are present at a very close distance. Then this strategy will give fair power allocation to those congested users and give minimum possible BER for two users NOMA system. In practical scenario, users can be anywhere in the OWC channel environment. So, it will be used in scenarios where users have very little separation among themselves. By observing far user's performance it is seen that ADO-OFDM also in this strategy performs worse compared to DCO-OFDM and ACO-OFDM, analyzed in previous chapter.

5.3 BER Performance of ADO-OFDM for Three Users NOMA

In this section, BER performance has been evaluated for three users NOMA multiple access scheme modulated by ADO-OFDM. For this evaluation, different power allocation strategies of NOMA have been considered. We have considered same simulation parameters as mentioned in Table 5.1.

5.3.1 BER Performance for Three Users NOMA with Fixed Power Allocation

For this experimental setup, 16-QAM has been considered. With the given setup, we have performed ADO-OFDM modulation with Non Orthogonal multiple Access for three users at three fixed distances in presence of AWGN channel. User with least distance from optical source has been considered as near user. The other user with larger distance has been considered as far user. Remaining user is considered as mid user. The measured BER values for three different users have been recorded in Table 5.6.

Table 5.6: BER measurement of ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy.

E_b/N_0	BER(Near User)	BER(Mid User)	BER (Far User)
0	0.500995156	0.496413906	0.361705859
2	0.500820547	0.495992109	0.260772891
4	0.50095625	0.494914219	0.151081797
6	0.500070156	0.486436406	0.061186172
8	0.497272578	0.454890313	0.012112266
10	0.494889688	0.395492656	0.002503516
12	0.493351875	0.303429766	0.000911484
14	4.91E-01	1.92E-01	4.70E-04
16	4.80E-01	1.00E-01	0.0003525
18	0.427912109	0.039637422	0.000305469
20	0.332558125	0.018286172	0.000281016
22	2.31E-01	1.40E-02	0.000274453
24	1.52E-01	1.25E-02	0.000264063
26	1.07E-01	1.21E-02	0.000265781
28	9.80E-02	1.20E-02	0.0002675
30	9.68E-02	0.011892578	0.000267969
32	9.65E-02	1.19E-02	0.000267344
34	9.65E-02	0.011847344	0.000267266
36	0.096406641	1.19E-02	0.000265469
38	0.096301484	1.18E-02	0.000264922
40	0.096275625	1.17E-02	0.000263047

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 5.6 for ADO-OFDM modulation under three users NOMA multiple access scheme based on fixed power allocation strategy.

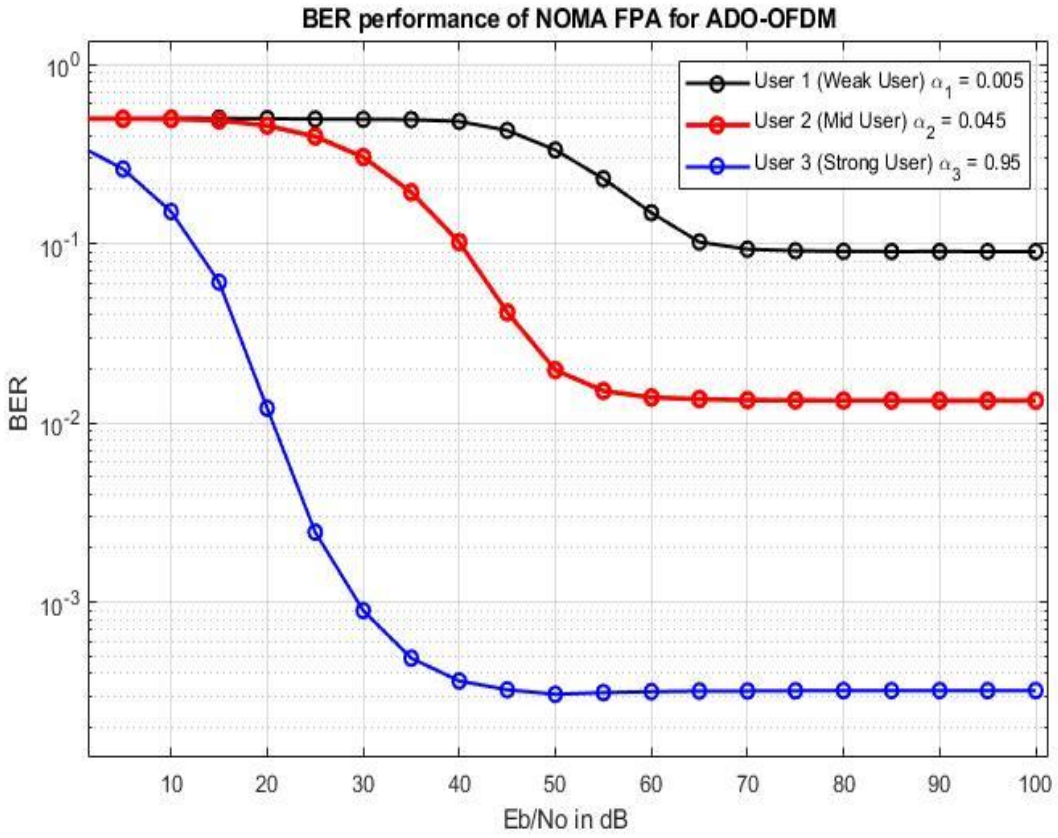


Figure 5.6: BER vs E_b/N_0 graph for ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on FPA strategy

Figure 5.6 shows BER performance of ADO-OFDM modulation under three users NOMA with fixed power allocation in AWGN communication channel. Here performance has been studied for three users – near user at 1 m distance from optical source and far user at 1.8 m distance from optical source. Mid user is at 1.4 m distance from optical source. Power loss increases with the increasing distance of receiver from optical source. As a result, SNR level degrades in receivers with the increasing distance from source. To maintain ample SNR level in each user receiver, generally far user is allocated more power, near user is allocated less power and mid user is allocated to medium level of power. In our fixed power allocation strategy we have allocated 95% power to far user, 4.5% power to mid user and 0.5% power to near user. As a result, far user has best BER performance than near user and mid user. Due to

higher power allocation, mid user has better BER performance than near user. For fixed power allocation strategy BER performance depends on the allocated power. User receivers' distances from source is fixed. So, optimal power allocation coefficient need to find out in this case for better BER performance among all users. Fixed power allocation strategy has a better BER performance in case of ACO-OFDM compared to DCO-OFDM and ADO-OFDM as analyzed in chapter 4 of this thesis. As a result, ADO-OFDM requires more power separation in power domain among users to properly demodulate data of respective users.

5.3.2 BER Performance for Three Users NOMA with Gain Ratio Power Allocation

Gain Ratio Power Allocation (GRPA) is applied here to dynamically allocate power to three users sharing resources through NOMA multiple access scheme. For this experimental set up we have considered 16-QAM based ADO-OFDM modulation too. With the given setup we have performed ADO-OFDM modulation with Non Orthogonal multiple Access using GRPA power allocation strategy for three users at three fixed distances in presence of AWGN channel. Power is allocated to users according to the strategy as discussed in chapter 2 of this thesis. The measured BER values for three different users have been recorded in Table 5.7.

Table 5.7: BER measurement of ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy.

E_b/N_0	BER(Near User)	BER(Mid User)	BER (Far User)
0	0.499051172	0.494839648	0.361221289
2	0.498605469	0.494316797	0.259965039
4	0.498660156	0.492396289	0.150755273
6	0.496354883	0.481168164	0.062429297
8	0.490210352	0.438347461	0.013841992
10	0.485453906	0.361230078	0.003263672
12	0.481701172	0.258172656	0.001442969
14	4.73E-01	1.68E-01	9.63E-04
16	4.26E-01	1.09E-01	0.000832813
18	0.327310938	0.076087891	0.000794922
20	0.246342773	0.058611328	0.000803516
22	1.99E-01	5.23E-02	0.000801367
24	1.89E-01	5.13E-02	0.000792383
26	1.88E-01	5.10E-02	0.000784766
28	1.87E-01	5.11E-02	0.00078418
30	1.87E-01	0.051041797	0.00078457
32	1.87E-01	5.11E-02	0.000780273
34	1.87E-01	0.051151563	0.00077832
36	0.186917188	5.11E-02	0.000777734
38	0.186873438	5.11E-02	0.000777344
40	0.186888086	5.11E-02	0.000777344

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 5.7 for ADO-OFDM modulation under three users NOMA multiple access scheme based on Gain Ratio Power Allocation strategy.

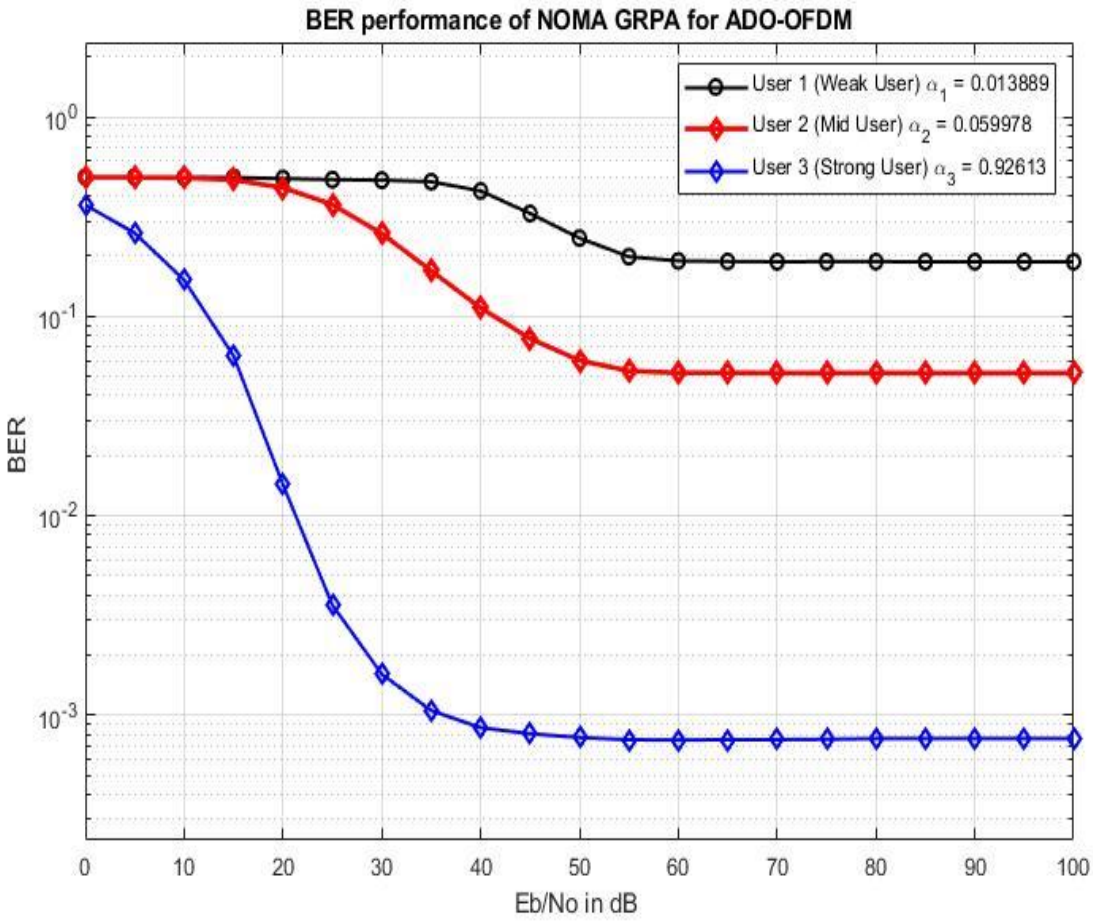


Figure 5.7: BER vs E_b/N_0 graph for ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on GRPA strategy.

Figure 5.7 shows BER performance of ADO-OFDM modulation under three users NOMA with Gain Ratio Power Allocation in AWGN communication channel. Here performance has been studied for three users – near user at 0.6 m distance from optical source and far user at 1.8 m distance from optical source. Mid user is at a distance of 1.6m from optical source. In this power allocation strategy, power is allocated dynamically according to their channel conditions. OWC channel is a deterministic channel. As a result, channel conditions depend on user location with respect to the source. In GRPA strategy, power allocation depends

on user distribution from optical sources. Minimum BER for all resource shared users will be possible by this algorithm only when user separation distance is large i.e. well isolated from each other. According to the values of channel coefficients (based on the positions of the users), here in this case, 1.4% power is allocated to near user, 6% power is allocated to mid user and far user is allocated to remaining amount of the power i.e. 92.6%. Far user shows best BER performance among the three users and near and mid user shows almost same BER performance. This implies that GRPA is not able to properly allocate power to users for achievement of minimum BER in this case. User distribution is not fair enough to achieve minimum BER through this dynamic power allocation algorithm. Gain Ratio Power allocation strategy has a better BER performance in case of ACO-OFDM compared to DCO-OFDM and ADO-OFDM as analyzed in chapter 4 of this thesis. Consequently, ADO-OFDM requires more power separation in power domain among users to properly demodulate data of respective users.

5.3.3 BER Performance for Three Users NOMA with Normalized Gain Difference Power Allocation

For this experimental set up, we have considered 16-QAM based ADO-OFDM modulation too. With the given setup we have performed ADO-OFDM modulation with Non Orthogonal multiple Access using NGDPA power allocation strategy for three users at three fixed distances in presence of AWGN channel. Power is allocated to users according to this strategy as mathematical expressions discussed in chapter 2 of this thesis. The measured BER values for three different users have been recorded in Table 5.8.

Table 5.8: BER measurement of ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy.

E_b/N_0	BER(Near User)	BER(Mid User)	BER (Far User)
0	0.499766992	0.498578711	0.360325781
2	0.499352539	0.498606836	0.258803906
4	0.499461328	0.498096094	0.149074023
6	0.49911875	0.495477539	0.058038672
8	0.498493359	0.485527344	0.010141211
10	0.497345117	0.468007422	0.001825781
12	0.495974609	0.439087695	0.00049082
14	4.95E-01	3.86E-01	1.95E-04
16	4.94E-01	2.95E-01	8.98E-05
18	0.492188672	0.184153516	6.91E-05
20	0.48400293	0.089965039	5.53E-05
22	4.43E-01	2.76E-02	4.61E-05
24	3.59E-01	8.01E-03	5.16E-05
26	2.48E-01	4.66E-03	5.21E-05
28	1.46E-01	3.86E-03	5.02E-05
30	6.95E-02	0.003523828	5.02E-05
32	4.09E-02	3.47E-03	5.04E-05
34	3.69E-02	0.003454492	5.08E-05
36	0.035080078	3.43E-03	5.08E-05
38	0.034501172	3.42E-03	5.08E-05
40	0.034342773	3.42E-03	5.08E-05

From the simulation results, BER vs E_b/N_0 graph has been plotted in Figure 5.8 for ADO-OFDM modulation under three users NOMA multiple access scheme based on Normalized Gain Difference Power Allocation strategy.

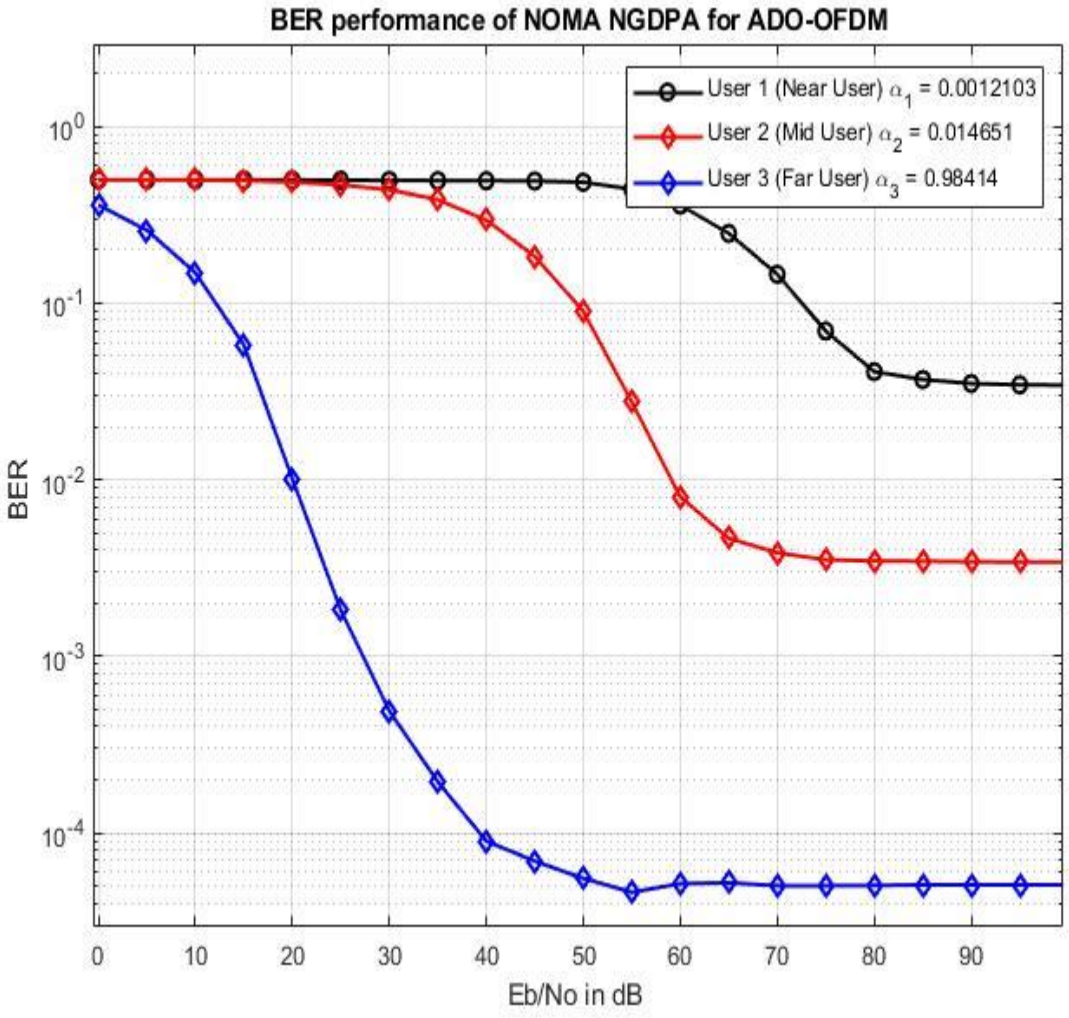


Figure 5.8: BER vs E_b/N_0 graph for ADO-OFDM modulation with AWGN communication channel under three users NOMA multiple access scheme based on NGDPA strategy.

Figure 5.8 shows BER performance of ADO-OFDM modulation under three users NOMA with Normalized Gain Difference Power Allocation in AWGN communication channel. Here performance has been studied for three users – near user at 1.4 m distance from optical source and far user at 1.55 m distance from optical source. Mid user is located at 1.5 m distance from optical source. In this power allocation strategy, power is also allocated dynamically according to their channel conditions. According to the values of channel

coefficients, 0.12% power is allocated to near user, 1.46% power is allocated to mid user and far user is allocated to rest of the power i.e. 98.42%.

BER performance of this strategy for ADO-OFDM NOMA has been shown for three users' case. It has a better BER performance in case of ACO-OFDM compared to DCO-OFDM and ADO-OFDM. It is observed that this strategy allocates power well in conditions where users are in very close vicinity. It means users should be concentrated in a very little field area to apply this strategy to get good result. Here the algorithm has done a good job in optimized power allocation problem. As a result, minimum BER performance has been achieved. It has been possible due to user's distribution at a very close vicinity.

5.4 Conclusions

In this Chapter, we have evaluated BER performance for ADO-OFDM modulation with NOMA multiple access scheme through FPA, GRPA, and NGDPA power allocation strategies for both 2 users' and 3 users' scenario. It is seen that FPA is used for arbitrarily power allocation. Optimization cannot be done due to static allocation method. GRPA and NGDPA both are dynamic power allocation strategy. GRPA can be used where users are separated from each other. This algorithm allocates power with more optimization in this situations. NGDPA can be used where users are located with close vicinity. This algorithm allocates power with more optimization in huge user density area. In every cases, ACO-OFDM has a far better BER performance under NOMA multiple access with both static and dynamic power allocation strategy than DCO-OFDM and ADO-OFDM for OWC channel. ADO-OFDM is more power efficient compared to other two modulation schemes. Its efficiency varies by allocation of data among odd and even subcarriers. But it has poor BER performance compared to other two modulation schemes. ADO-OFDM has a BER performance of 10^{-3} order best at 40 dB E_b/N_0 value and worst at 80 dB E_b/N_0 value. Further, it is observed that its BER performance cannot be reduced after a certain value even if increasing the SNR level at the receiver. The reason for this is the presence of clipping noise and noisy estimation of ACO-OFDM signal of the odd subcarriers at the receiver, as discussed in Chapter 2 of this thesis.

Chapter 6

Application in Downlink of Hybrid Lifi - Wifi Networks

In previous chapters of this thesis, we have analysed BER performance of different optical OFDM modulation schemes with Non Orthogonal Multiple Access scheme based on different power allocation strategies. Here we have tried to simulate a hybrid Lifi-Wifi system and tried to evaluate its BER performance and sum capacity. The simulated system is considered as hybrid system. Its downlink works in visible light communication and its uplink works in Radio frequency (RF) range. It is done to avoid any interference between the uplink and downlink. We have assumed perfect Channel State Information (CSI) between the user receivers and access point (AP). The users have shared resources through TDMA – NOMA hybrid multiple access scheme for further optimization in performance.

6.1 Hybrid TDMA-NOMA Multiple Access

NOMA is discussed in detail in chapter 2 of this thesis. Here we shall include only the further modification in NOMA due to hybridisation with TDMA multiple access scheme. It helps in resource sharing thorough both time and power domains. As a result, users can be set based on priority. Non Priority users will share through common time division while priority users can send data simultaneously. All the priority group users will use different power levels in PD-NOMA and non priority users will use only two or four reserved power levels in PD-NOMA.

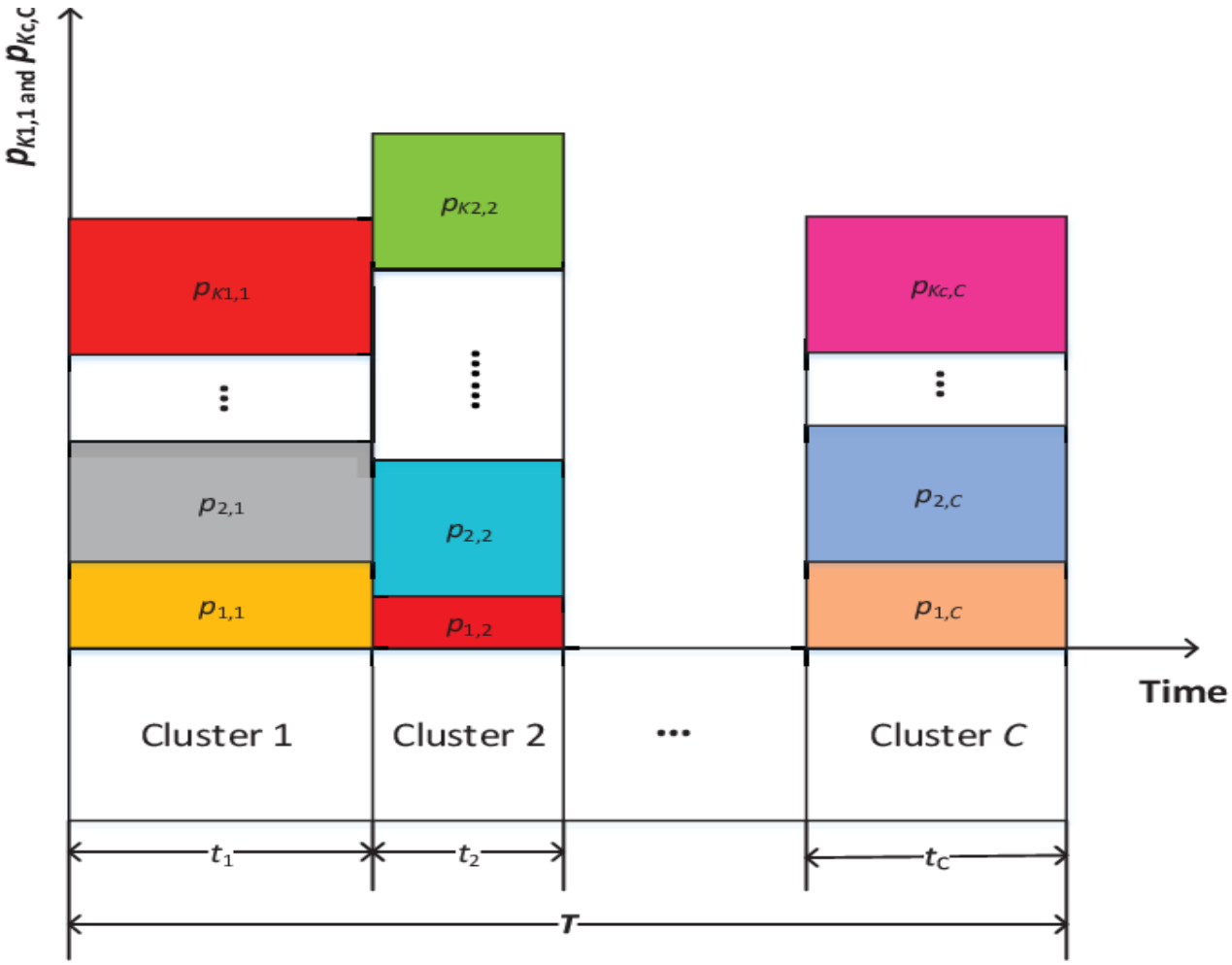


Figure 6.1: Hybrid TDMA-NOMA User Clustering

For our experiment, we have grouped users based on priority users and non priority users. We have assumed each user's message is of same bit duration for the simplicity of our experiment.

6.2 Resource Allocation in Hybrid TDMA-NOMA

Here, resource allocation is discussed of hybrid TDMA-NOMA multiple access scheme. Resources are allocated here based on user priority. Priority based resource allocation has been discussed here in below section.

6.2.1 Resource Allocation for Non Priority Users

For power allocation purpose each user message is splitted up into two parts – part A and part B. Part A of all user's message are combined into a cluster and part B are combined into another cluster. Suppose N non priority users are there and communicating with hybrid

Lifi Wifi AP in the downlink. Then each user message streams will be divided equally. Let's say, for kth user it is A_k and B_k. For all users same operation is done. Messages from same cluster will be transmitted through Time Division Multiple Access (TDMA). Messages from different clusters will be shared resources through Non Orthogonal Multiple Access. It means that messages will be transmitted at different power levels and will be separated from each other in power domain.

6.2.2 Resource Allocation for Priority Users

Priority users will be assigned separate cluster. Priority user clusters are different from non priority user's clusters. As a result, priority user can use total time resources simultaneously. They will transmit with a separate power level. They will only share power with non priority users. In power domain they will be placed at a more significant hierarchy separated from other non-priority users.

6.3 Performance Evaluation of Hybrid TDMA – NOMA

We have evaluated the performance of Hybrid TDMA – NOMA multiple access scheme by simulating a hybrid Lifi – Wifi system in MATLAB based on following simulation parameters.

Simulation Environment

For the simulation purpose we have chosen the following parameters in our MATLAB environment.

Table 6.1: Simulation Parameters for Hybrid Lifi – Wifi

Sl. No.	Description	Notation	Value
1	Responsivity of PD	η_{PD}	0.8 A/W
2	Transmitter Semi- Angle	φ_k	60 deg
3	FOV of the PDs	ϕ_c	60 deg
4	Vertical Distance of AP	z	3 m
5	Physical Area of PD	A_k	1.0 cm^2
6	Refractive Index of PD lens	n	1.5
7	Gain of Optical Filter	$T_s(\phi_k)$	1.0
8	Total Number of Subcarriers	N_{FFT}	128
9	QAM modulation Order	M	16
10	Number of Users	K	4
11	Number of Non Priority Users	-	3
12	Distance of Non Priority Users from AP	r_1 , r_2 , r_3	1.0 m , 1.5 m , 1.8m
13	Number of Priority Users	-	1
14	Distance of Priority User from AP	r_4	0.6 m
15	Room Dimension	L x b x h	5 x 5 x 5 m
16	Receiver Noise PSD	N_0	10^{-20} A^2/Hz
17	System Bandwidth	B	20 MHz
18	LED Power	P	1 W (normalized)

Based on the above values in simulation environment, we have simulated hybrid Lifi – Wifi system in the room and have obtained the graph of SNR dB profile for the system.

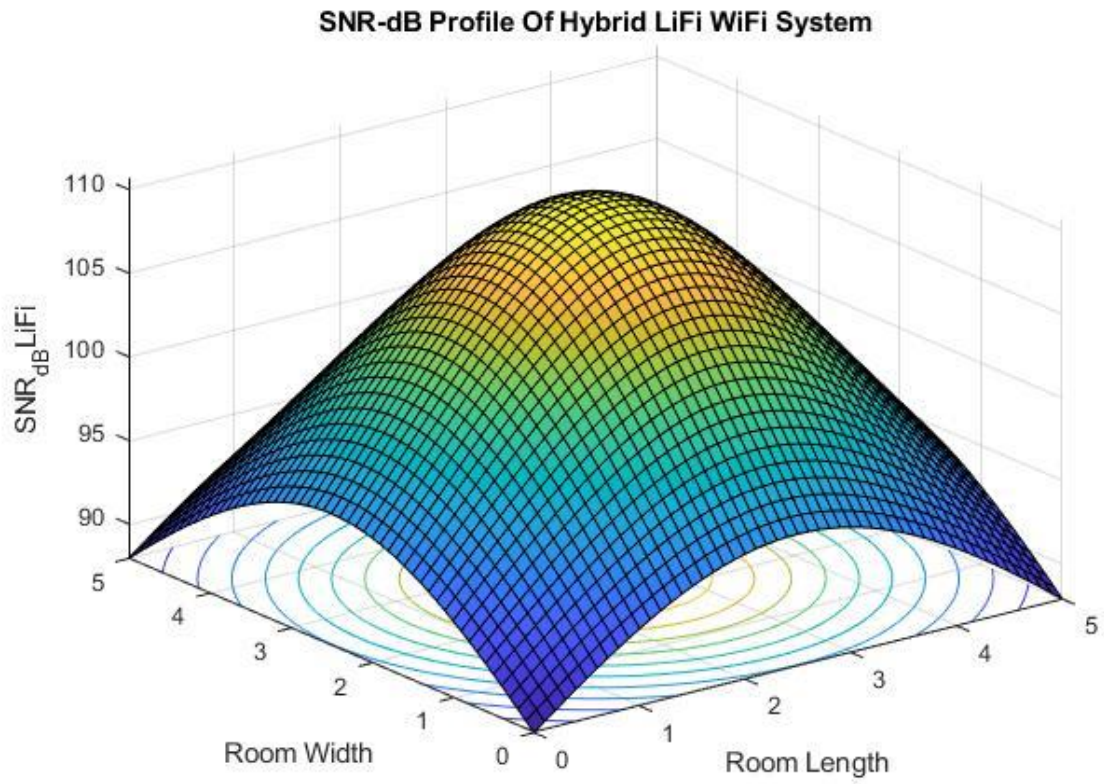


Figure 6.2: SNR Profile of Simulated Hybrid Lifi Wifi System

Here, we can see the SNR profile of the received signal based on different locations of the user receiver in the room. We have considered here receiver PD's noise along with AWGN channel background noise for performance evaluation. More than 100 dB SNR available for an average user in the room as VLC channel is a deterministic, controlled environment and line of sight channel. SNR strength of the signal is maximum at the centre of the room. Then it gradually decreases towards the corner of the room.

6.3.1 BER Performance

BER performance for this Lifi – Wifi system has been evaluated for downlink here. It uses Hybrid TDMA-NOMA based multiple access scheme based on fixed power allocation strategy. For modulation purpose, we have considered 16 QAM based DCO-OFDM modulation for this hybrid system. We have considered 4-user receivers based system. Among 4 users, 3 users belong to Non priority group and one user belong to priority group. The measured BER values for four different users have been recorded in Table 6.2.

Table 6.2: BER measurement of Hybrid Lifi – Wifi system under four users Hybrid NOMA multiple access scheme based on Fixed Power Allocation strategy.

E_b/N_0	BER(Non Priority User 1)	BER(Non Priority User2)	BER (Non Priority User3)	BER (Priority User)
0	0.492809524	0.493241667	0.493222421	0.44760754
2	0.491348016	0.491678175	0.492065079	0.311359127
4	0.484716667	0.48534246	0.485264286	0.193726587
6	0.461535317	0.462294444	0.462203175	0.10016627
8	0.424309524	0.424905357	0.425065079	0.040495238
10	0.382948611	0.382931746	0.383055556	0.011367857
12	0.343979762	0.344529167	0.34445	0.001655159
14	3.11E-01	3.11E-01	3.11E-01	6.94E-05
16	2.72E-01	2.72E-01	2.72E-01	3.97E-07
18	0.213724802	0.21347877	2.14E-01	0
20	0.150319841	0.150081746	1.50E-01	0
22	9.54E-02	9.52E-02	9.53E-02	0
24	4.89E-02	4.87E-02	4.88E-02	0
26	1.54E-02	1.54E-02	1.53E-02	0
28	1.85E-03	1.87E-03	1.84E-03	0
30	3.39E-05	2.94E-05	4.03E-05	0
32	0	0	0	0
34	0	0	0	0
36	0	0	0	0
38	0	0	0	0
40	0	0	0	0

Based on simulation result, BER vs E_b/N_0 graph has been shown in Figure 6.3 for Hybrid Lifi – Wifi system under four users Hybrid NOMA multiple access scheme based on Fixed Power Allocation strategy.

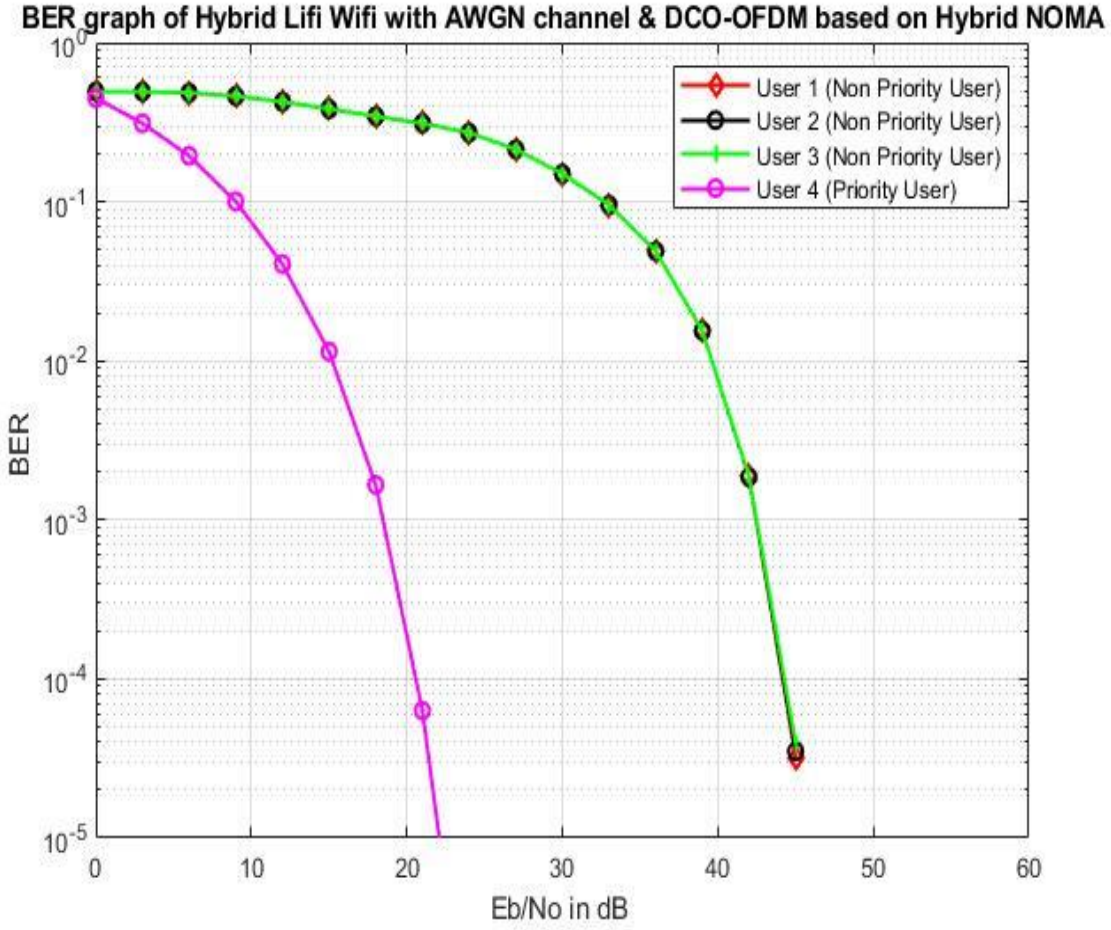


Figure 6.3: BER vs E_b/N_0 graph of Hybrid Lifi – Wifi system for four users Hybrid NOMA multiple access scheme based on Fixed Power Allocation strategy.

The Figure 6.3 shows that BER performance of Hybrid Lifi – Wifi system under four users Hybrid NOMA multiple access scheme based on Fixed Power Allocation strategy in optical wireless communication channel. Here performance has been studied considering four users located at distances 0.6 m, 1.0 m, 1.5 m and 1.8 m from optical source i.e. the Lifi – Wifi access point (AP). Among the four users, the user located at 0.6m belong to priority group and the other three users belong to non priority group as mentioned in Table 6.1.

Here fixed power allocation strategy is used to allocate power to four users. Three users here belong to non priority groups. Hence, their messages are transmitted using two power levels in NOMA by separating them into two separate clusters. Fourth user being a priority user is placed into a separate cluster. Messages of this cluster are transmitted through different power level in NOMA. For priority user 85% power is allocated and non-priority users' two power levels 12% and 3% are allocated. As a result, all the non priority users have shown same BER performance and priority user has shown better BER performance compared to non priority users.

6.3.2 Sum Rate Performance

Sum rate performance for this hybrid Lifi – Wifi system has been evaluated here. For this purpose same 4 users are considered here. 100 dB SNR available for average user in the room.

$$Sum\ Rate = \sum_{i=1}^{k} B \log_2(1 + SNR_i) \tag{6.1}$$

As mentioned in chapter 2, equation (2.35) of this thesis the formula becomes different for NOMA –

$$Sum\ Rate = \sum_{i=1}^{K} B \log_2\left(1 + \frac{P_i\, h_i^2}{N_0 B + \sum_{j=i+1}^{K} P_j h_i^2}\right) \tag{6.2}$$

Using this formula data rate for each individual users and sum rate of the total system is calculated and recorded in table 6.3.

Table 6.3: Sum Rate and Individual user Data Rate in Hybrid Lifi Wifi System

Data Rate (Non Priority User 1)	**Data Rate (Non Priority User2)**	**Data rate (Non Priority User3)**	**Data Rate (Priority User)**	**Sum Rate**
35.19 Mbps	35.19 Mbps	35.19 Mbps	54.40 Mbps	159.97 Mbps

6.4 Conclusion

Here we have simulated the Hybrid Lifi - Wifi System using hybrid TDMA - NOMA multiple access scheme. We have obtained at least 90 dB SNR profiling in the corner of the room and 100 dB on average in the middle of the room. The BER performance has been evaluated for the system by varying SNR level. Sum rate and data rate have been evaluated for the system and individual users. We have achieved sum rate of 159.97 Mbps, 35.19 Mbps data rate for each non priority user and 54.40 Mbps for the priority user. All this has been performed by considering 3 non priority users and 1 priority user.

Chapter 7

Summary and Future Work

All the system has been simulated in MATLAB. The Channel considered in experiments is optical wireless communication (OWC) channel. First DCO-OFDM has been considered as optical modulation. The BER performance has been evaluated based on MQAM modulation namely 4-QAM, 16-QAM and 64-QAM based DCO-OFDM modulation has been considered. Then BER performance has been evaluated for Non Orthogonal Multiple Access (NOMA) Scheme based on same optical modulation. While doing so, different power allocation strategies have been considered namely Fixed Power Allocation (FPA), Gain Ratio Power Allocation (GRPA) and Normalized Gain Difference Power Allocation (NGDPA) to allocate power to users based on static and dynamic channel conditions. The BER performance has been evaluated for both 2-user and 3-user systems. The AWGN has been considered as channel and Photodetector receiver's noise.

Another optical OFDM modulation, ACO-OFDM has been considered. The BER performance has been evaluated for the same based on 4-QAM, 16-QAM and 64-QAM. The AWGN channel has been considered for performance evaluation. Then BER performance has been evaluated based on multiple user system shared resource through NOMA multiple access scheme. For this evaluation, 16-QAM based ACO-OFDM has been considered. BER performance has been evaluated for both 2-user and 3-user systems. For NOMA power allocation, three different allocation strategies FPA, GRPA and NGDPA have been considered to allocate power to users based on static and dynamic channel conditions. The BER performance has been evaluated for all these cases.

Also optical OFDM modulation ADO-OFDM has been considered for BER performance evaluation. In this thesis, 4-QAM, 16-QAM and 64-QAM based ADO-OFDM modulation schemes are considered. Their BER performances have been evaluated and compared. Also BER performances have been evaluated for multiuser system. In multiuser system, 16-QAM ADO-OFDM has been considered for BER performance evaluation. The NOMA multiple access scheme has been considered for resource sharing among users in multiuser system. For allocating power to users both static or fixed power allocation and two

dynamic power allocation strategies i.e. GRPA and NGDPA have been considered. The BER performances have been evaluated for both 2-user and 3-user systems. The AWGN noise has been considered to model channel noise and photodetector receiver's noise.

For all these BER performance evaluation cases, ACO-OFDM stands out among the three optical OFDM modulation. But it is spectrally least efficient as only 1/4 of the total subcarriers has been used for transmission. On the other hand, DCO-OFDM has an intermediate class BER performance. But it is spectrally more efficient than ACO-OFDM and ADO-OFDM. But its power efficiency is very poor due to high peak to average power ratio (PAPR). Whereas, ADO-OFDM has worst BER performance among the three optical modulation schemes because of the presence of clipping noise and noise due to data estimation. But it has better power efficiency compared to DCO-OFDM and lesser compared to ACO-OFDM modulation scheme. Its power efficiency lies in tuning the power allocation among the odd and even subcarriers as required. ADO-OFDM has spectral efficiency better compared to ACO-OFDM and lesser compared to DCO-OFDM modulation scheme. Among the different power allocation strategies of NOMA static power allocation works good in predetermined controlled environment conditions. Gain Ratio Power Allocation works well where user distribution is loosely packed and stretched over a large base area. Normalized Gain Difference Power allocation works well where user distribution is closely packed and large number of users are located in a small base area.

Then a hybrid Lifi – Wifi system has been simulated and its performance has been evaluated. The system considered here is a hybrid system and its downlink uses visible light communication. So downlink performance has been evaluated. Hybrid TDMA-NOMA based multiple access scheme has been considered here where users are grouped based on priority assignment. In this scheme, DCO-OFDM modulation has been considered. To allocate power to users, fixed power allocation has been considered. The SNR profiling has been evaluated for the hybrid Lifi – Wifi system. Here, 4 users has been considered for performance evaluation. Among which 1 user belong to priority group and other 3 users belong to non priority group. Also, BER performance has been evaluated for the system by varying SNR level. Finally, data rate has been evaluated for individual users and then overall sum rate has been evaluated for the whole system.

There are other hybrid optical modulation schemes available. Some are OFDM based and some are non OFDM based. In future, BER performance of the OWC channel can be

evaluated for other optical modulation schemes and can be compared with the used optical OFDM modulations. In this thesis, static and dynamic power allocation strategies of NOMA have been considered. Other novel power allocation strategies can be considered and BER performance analysis can be done in future. A hybrid Lifi – Wifi system has been simulated and sum rate and BER performance have been evaluated considering DCO-OFDM and priority based power allocation strategies. The BER and sum rate performance can be evaluated using different optical OFDM modulations and different power allocation strategies of NOMA and can be compared with the obtained results. In this thesis, hybrid TDMA – NOMA has been considered for performance evaluation based on priority grading of users which includes 1 priority and 3 non priority users. System performance can further be evaluated for more number of priority and non priority users. This priority grouping of users can be replaced with NOMA clustering based techniques and system performance can further be enhanced.

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