T.C.

ALTINBAS UNIVERSITY
Electrical and Computer Engineering

COMPARISON THE RELIABILITY OF VISIBLE LIGHT COMMUNICATION USIN WHIT LEDs BASED MIMO WITH RGBY LEDs BASED WDM

Hussein Abbas Jasim

Master Thesis

Supervisor

Oguz Bayat

Istanbul, (2019)

COMPARISON THE RELIABILITY OF VISIBLE LIGHT COMMUNICATION USIN WHIT LEDs BASED MIMO WITH RGBY LEDs BASED WDM

by

Hussein Abbas Jasim

Electrical and Computer Engineering

Submitted to the Graduate School of Science and Engineering

in partial fulfillment of the requirements for the degree of

Master of Science

ALTINBAŞ UNIVERSITY

2019

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

____

Prof. Dr. Oguz BAYAT
Supervisor

Examining Committee Members (first name belongs to the chairperson of the jury and the second name belongs to supervisor)

Prof.Dr. Oguz BAYAT	School of Engineering and Natural Sciences, Altinbas University	_________________
Prof.Dr.Osman Nuri UCAN	School of Engineering and Natural Sciences, Altinbas University	_________________
Prof.Dr. Hasan Huseyin BALIK	Air Force Academy, National Defense University	_________________

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

____
Asst. Prof.Dr. Cagatay AYDIN
Head of Department

Approval Date of Graduate School of
Science and Engineering: ____/____/____

____
Prof.Dr. Oguz BAYAT
Director

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Hussein Abbas Jasim

DEDICATION

I dedicate this thesis to my family, classmates and all my friends for the support and encouragement throughout my education and life. Special dedication goes to my supervisor Prof. Dr. Oguz Bayat anyone who help me in my research work.

ACKNOWLEDGEMENTS

I offer my thanks and gratitude to anyone who helped me in my studies or wished me good. Greetings to the supervisors who guided me in my research.

Greetings to our esteemed university.

ABSTRACT

COMPARISON THE RELIABILITY OF VISIBLE LIGHT COMMUNICATION USING WHIT LEDs BASED MIMO WITH RGBY LEDs BASED WDM

jasim, Hussein Abaas

M.Sc., Electrical and Computer Engineering, Altınbaş University,

Supervisor: Oguz Bayat

Co-Supervisor: Saad Hardan

Date: October 2019

Pages: 43

Visible light communications VLC for indoor application nowadays rapidly increased especially when LEDs be used for illumination, that give the lighting system another task which is high data rate communication, and some time positioning task. In this thesis two typed of VLC systems simulated depending on transmitters type (white LEDs and RGBY LEDs). Modulation techniques effect also studied. CMO, DCO and GLID modulation schemes simulated. Rotating angle of effect studied, results recorded and discussed. Conclusions illustrated and future works also suggested.

Keywords:VLC, LEDs, RGBY, CMO, DCO, GLID.

TABLE OF CONTENTS

Pages

LIST OF TABLE

pages

LIST OF FIGURES

pages

LIST OF ABBREVIATIONS

MIMO : Multiple input multiple output

LED : Light emitting diode

OFDM : Orthogonal frequency division multiplexing

BER : Bit error rate

RGB : Red blue green

RGBY : Red blue green yellow

LOS : Line of sight

VLC : Visible light communication

WDM : Wavelength division multiplexing

CASCC : Channel adaptive space collaborated constellation

ML : Maximum likelihood

TDC : Time domain cooperation

DC : Direct current

CMO : Codded modulated optical

GLIM : Generalized LED index modulation

DCO : DC-bias coding

RF : Radio frequency

OCDM : Optical code division multiplexing

SNR : Signal to noise ratio

IEEE : Institute of electrical and electronics engineering

OOK : On-off keying

PD : Photo detector

AWGN : Additive white Gaussian noise

OWC : Optical wireless communications

RZ : Return to zero

NRZ : None return to zero

PAM : Pulse amplitude modulation

PPM : Pulse position modulation

IFFT : Inverse fast Fourier transform

QPSK : Quadrature phase shift keying

QAM : Quadrature amplitude modulation

FDM : Frequency division multiplexing

SISO : Single input single output

C.A. : Coverage area

FDM : Frequency division multiplexing

INTRODUCATION

1.1 LITERATURE REVIEW

In 2009 Lubin Zeng and others studied imaging and non-imaging high data rate multiple-input multiple-output (MIMO) optical visible light wireless communication system using white LEDs. They also, investigated that non-imaging MIMO system does not implemented at all receivers because of the system entry , while imaging MIMO system can operate at all expected conditions. The proposed system simulated and the simulation results show that the system can operate in the range of hundreds Mbits/S up to Gbits/S[1].

In 2010 Ahmed HilmiAzhar and Tuan-Anh Tran attested MIMO high speed data transmission system using orthogonal frequency division multiplexing (OFDM). The studied system implemented using two white LEDs transmitters and 9 photo detectors placed as 3×3 matrix. In the study the specification of design explained, optical designed and experimental results were explained. Data transmission rate was about 220 Mbits/S with bit error rate (BER) of 10^{-3} over distance of 1 meter. They concluded that the data transmission rate by the low LED bandwidth (≤ 2 MHz), so that an improvement can be made by using wide bandwidth LEDs[2].

White light in such way the Stanislav Hejduk and others in 2014 presented basic information about red green blue yellow (RGBY) LEDs for mobile visible light mobile communications. And also, they presented the differences between traditional RGB and RGBY LEDs in the coverage area and white light generation since the first used four color light, hence yellow light addition effect in generating eyes could not recognize it, since human eyes reorganization depend on meat vale controlling. Proposed system coverage area calculations for three possible cases for base station and mobile: line of site (LOS) direct, LOS non-direct and non-line of site (diffusive)[3].

In the same year Wang Yanquan and Chi Nan proposed and experimentally implemented a bi-directional visible light communication system VLC depends on RGB LEDs. Severe frequency response for indoor channel compensated in both before and after equalization by advanced digital signal processing operation. The proposed system for each color the low frequency used for download link while the high frequency used for upload link. For both links upload and download data rate was about 1.15 Gbits/S and 300 Mbits/S respectively. Bit error rate BER for the system was less than 3×10^{-3} in distance about 0.7 meter for indoor communication. The researchers considered that the proposed system is the heights data rate bi-directional system until that time[4]. In 2016 Lu Cui and others studied analyzing multi-channel wavelength division multiplexing (WDM) visible light communication system VLC. By using WDM the highest data rate achieved. In this study a formula for channel crosstalk from filter transmittance and detector spectral response. An experimental model used to proof channel crosstalk equation. The experimental results showed that for indoor communication system with on-off keying modulation and 33 nm channel spacing the bit error rate BER about 10^{-3}, maximum channel number is 12 channels while the optimum number is 10 channels. Data rate achieved was about 5.1 Gbits/S which is a three times data rate of single channel[5].

In 2017 Ke Xu and others introduced a new criterion for MIMO visible light communication system VLC and called it **"channel – adaptive space - collaborated constellation "(**CASCC). A relationship among LEDs to utilize special resources instead of wasting spatial resources. Proposed system implemented for 2×2 multiple-input multiple output MIMO VLC system by means of four-point and high-order constellation. Also, they proposed an algorithm for fast maximum likelihood (ML) detection. Simulation results showed that proposed system performed best error performance and widely application range compared with traditional MIMO-VLC systems. The proposed algorithm reduced the complexity of computations and without any losses in performance[6]

In the same year Peixuan He and others proposed smart VLC system based on Trible-Domain-Cooperation scheme (TDC) for both positioning and communications. Proposed system experimental results showed that communication bit error rate BER of 10^{-5} achieved in a 0.6m×0.6m×0.65m space and positioning average error of about 0.04m, positioning and communication made in same time. The proposed system realized combination of communication and positioning in real time. Cells dividing based on four color theorem while correctional method used to positioning accuracy[7].

In 2018 Saad MushhainHardan and others proposed precoding/decoding algorithm for efficiently spectral orthogonal frequency division multiplexing OFDM communication system. Coded modulated optical system can be applied for both MIMO and SISO communication systems. Time domain signals for OFDM can be obtained by invoking precoding /decoding system without Hermitian symmetry.Special multiplexing technique or DC-bias adding can be used to obtain positive signals. The researchers made a comparison between their system performance improvements and OFDM approaches. Simulation results showed that the proposed system enhances both bit error rate BER and spectral efficiency for OFDM based VLC [8].

PROBLEMSTATEMENT

Many studies and proposals introduced in VLC MIMO communication systems, but the need to a universal study to make a comparison between two white LEDs based OFDM and RGBY LEDs based systems.

Deciding which suitable MIMO VLC system to be used efficiently for indoor application. Make all required simulation, systems to be compared design, environments that may be faced to VLC system during application.

THESIS OUTLINES

This thesis contains five chapters, chapter two covers visible light communications VLC, VLC system components such as (light emitting diodes LEDs, RGB LEDs and photo detectors PDs). VLC modulation techniques also discussed in this chapter. Chapter three includes proposed system simulation for multi cases. White LEDs based MIMIO-VLC systems, RGBY LEDs based MIMO-VLC systems. Simulation results for CMO, DCO, and GLIM MIMO-VLC systems. And CMO modulation case results for different rotation angles. Chapter four contains simulation results discussion. Conclusion and future works illustrated in chapter five.

2. VISIBLE LIGHT COMMUNICATIONS

2.1 INTRODUCTION

Visible light communications recently introduced as a future wireless communication system especially in indoor communication, also VLC has an advantage compared with RF traditional communication systems since those system have wide bandwidth, electromagnetic interference protection, low cost[9].Light emitting diodes LEDs arrays nowadays widely used for lighting systems, also those devices are used for communications in visible light communication VLC systems [10]. unregulated visible light (380-780)nm uses as a carrier in VLC , which gives this type of communication systems very wide bandwidth especially when multiple input multiple output MIMO technique used with special modulation processes [8]. To avoid interference when using single channel VLC communication system optical code division multiplexing access OCDM scheme may be used, in this scheme individual signals transmitted in with different codes in the same medium but the users' number still limited. Orthogonal frequency division multiplexing (OFDM) scheme also introduced to increase bandwidth, this scheme has other advantage that it has high signal to noise ratio SNR [5]. To use multiple wavelength communication, it is necessary to use white light consists of individual lights. That leads to RGB LEDs which have the ability to create white light from three colors red, green and blue. To achieve missing wave length in RGB LEDs output light and need to supplement by combination of the three colors that leads to propose RGBY LEDs which can produce white light from four individual colors red, green, blue and yellow [3].

2.2 LIGHT EMITTING DIODES LEDs

Two types of LEDs are widely used in optical communications RGB LEDs and white phosphor LEDs, the first emits white light by combining thee colors (red-625nm, blue-525nm and green-470nm). RGB LEDs contain three individual chips, that makes it suitable for wavelength division multiplexing WDM communication scheme. While white phosphor LED contains blue chip covered by yellow phosphor layer which cause shift to longer wavelength [11][12]. Figure (2.1) shows LEDs types.LEDs originally introduced for illumination for indoor environments, it's very important to take in care when designing VLC system, the illumination level must be in the limit (400 – 1000) lx for typical applications. LEDs in VLC system must perform two tasks: illumination and communication. VLC system must have working continuity even when illumination is visually off. Due to human wants, illumination level varies from maximum to minimum level, that add more difficulties to VLC system design, because the VLC system must have its functionality in case of user changes illumination level. In IEEE 802.15.7 standard several methods illustrated to ensure VLC system functionality keeping such as changing the pulse width and pulse amplitude in on-off keying OOK modulation scheme [13].

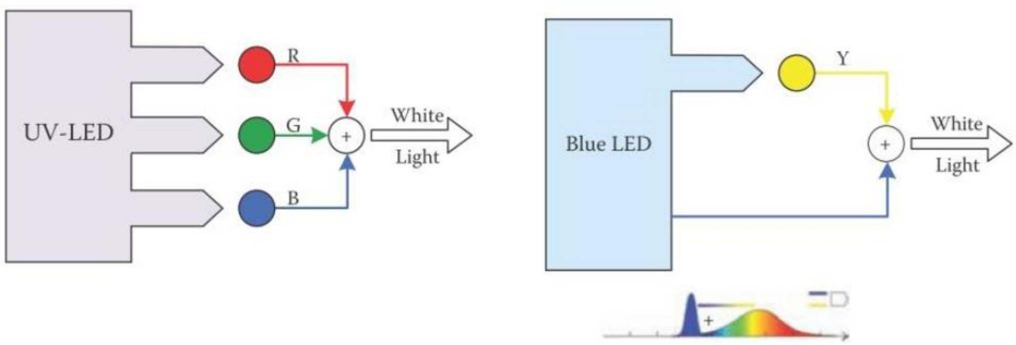


Figure2.1: LEDs Types

2.3 PHOTO DETECTORS

Photodetector (PD) is an optoelectronic device which convert optical power into electrical current depends on the square of the optical power that incident on its surface. PD responsivity R is an expression to explain the relationship between generated electrical current and incident optical power, responsivity units is A/W. figure (2-2) shows semiconductor PD responsivity.

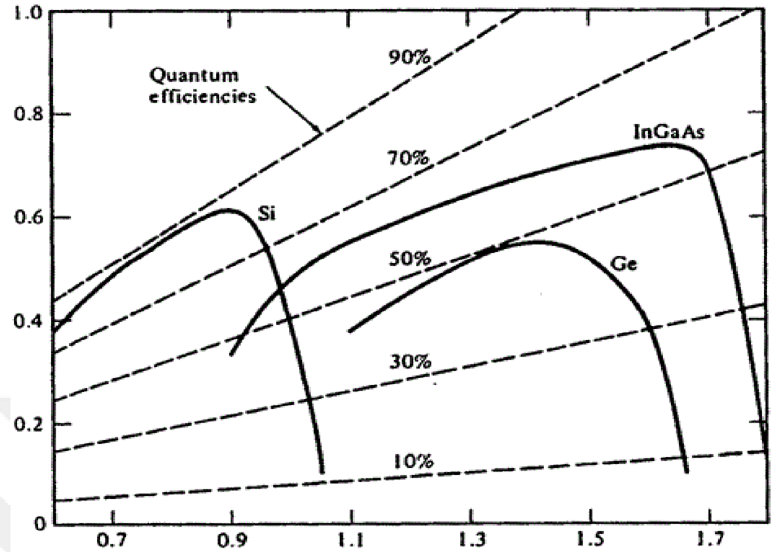


Figure 2.2: Semiconductor PD responsivity

PIN photodiodes and avalanche PD are widely used in VLC systems receivers. Other PD like metal semiconductors and photodetectors have higher sensitivity than the first two types but also have a disadvantage in the other hand which is the high noise [10].

2.4 MULTIPLE – INPUT MULTIPLE – OUTPUTCOMMUNICATIONSYSTEMS

Communication systems contain N_t number of transmitter antennas and N_r number of receiver antennas called multiple input multiple output MIMO communication systems. If $N_t = N_r = 1$ the system in this case called single input single output SISO system which is a special case of MIMO systems. MIMO communication system channel matrix can be denoted as in equation (2-1):

$$H = \begin{pmatrix} h_{11} & h_{12} & \dots & h_{1N_t} \\ h_{21} & h_{22} & \dots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \dots & h_{N_rN_t} \end{pmatrix} \tag{2.1}$$

Where h_{Nt}denotes the channel gain of the optical wireless link between the transmitter N_t and receiver N_r. The received signal y can be expressed in the form of ($N_r \times 1$) vector:

$$y = Hx + N_{AWGN},\ y \in R^{Nr} \tag{2.2}$$

Where x is a (N_t×1) vector representing the transmitted signals while, N_{AWGN} is the noise vector with N_r elements, assumed to be real valued additive white Gaussian noise (AWGN) with zero mean, double-sided power spectral density [8]. In fact, N_{AWGN} represents the sum of ambient shot light noise and thermal noise [9]. Figure (2.3) shows MIMO VLC system block diagram.

2.5 MODULATION TECHNIQUES IN VLC SYSTEMS

Some of RF wireless communications have been adaptive for optical wireless communications OWC like On-Off keying, pulse amplitude modulation, pulse position modulation and optical orthogonal frequency division multiplexing OFODM.

2.5.1 On-Off Keying

This modulation technique as mention in its name on and off switching stream according to data level. The desired illumination level can be achieved by setting on and off intensity levels. OOK modulation implemented typically under none return to zero model (NRZ) or return to zero (RZ)

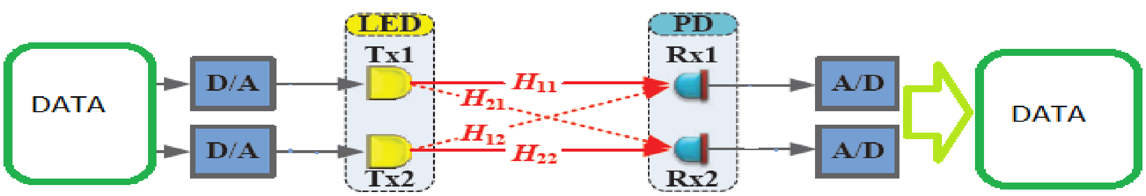


Figure 2.3: MIMO VLC system

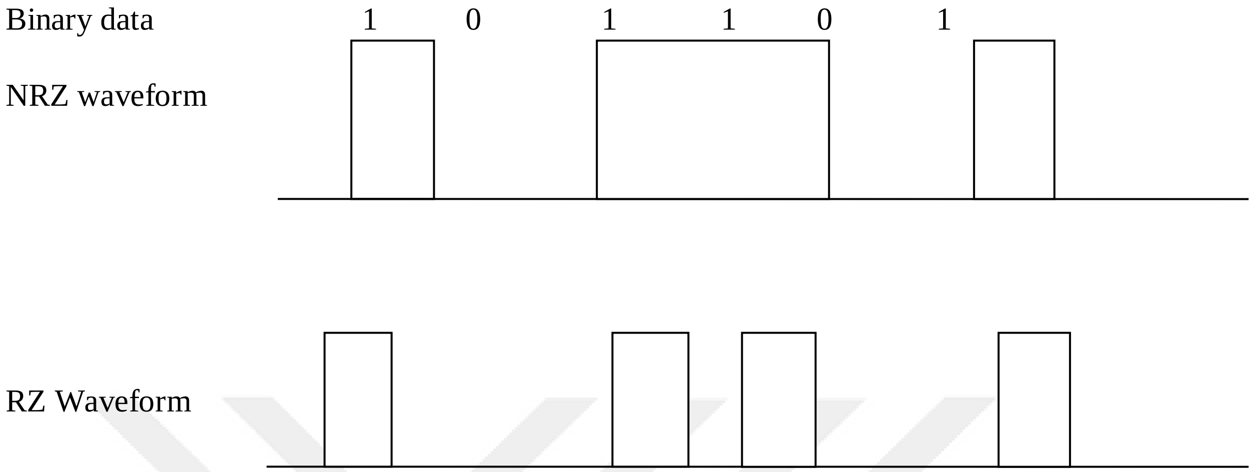


Figure 2.4: OOK NRZ and RZ

2.5.2 Pulse Amplitude Modulation

Pulse amplitude modulation (PAM) means varying pulses amplitude according to signal amplitude, N pulses amplitudes can be calculated depends on bit numbers which can be calculated as: $\log_2(N)$. N different amplitude levels can be calculated depends on highest and lowest pulse amplitude i.e. if A_{hi} is the highest pulse amplitude and A_{lo} is the lowest pulse amplitude.

$$A_i = A_{lo} + i \times (Ah_i - A_{lo})\ (N-1);\ 0 \leq i < M. \tag{2.3}$$

Figure (2-5) shows optical 4-PAM signals [14].

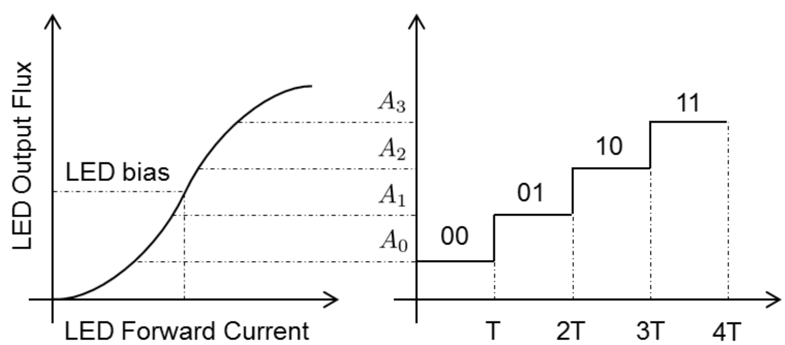


Figure 2.5: Optical 4-PAM signals

2.5.3 Pulse position modulation

In pulse position modulation PPM information transferring done by varying the position for low-to-high edge of transmitted pulse. Pulse duty cycle and amplitude not changed during modulation. Figure (2-6) shows PPM signals with 50% duty cycle.

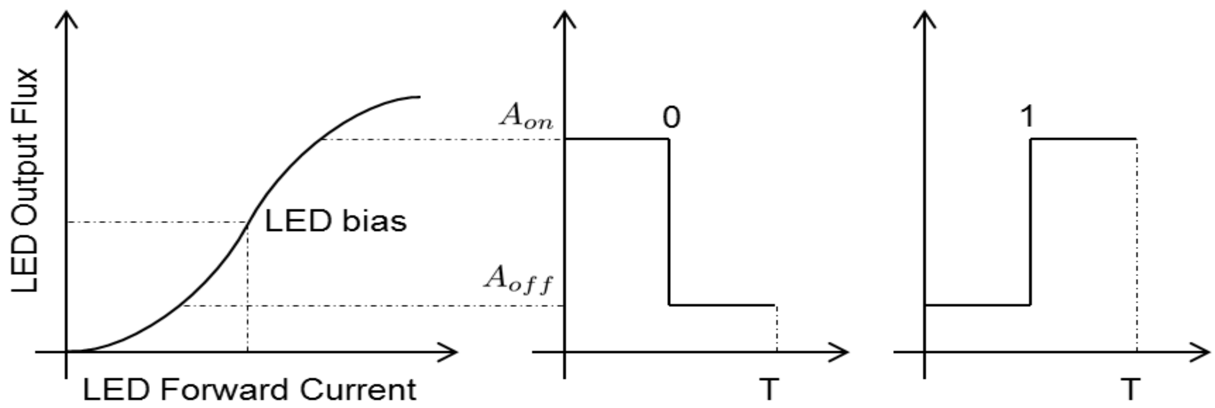


Figure 2.6: Pulse position modulation PPM

2.5.4 Orthogonal frequency division multiplexing OFDM

In 1966 Chang firstly proposed OFDM as a special multi carrier modulation scheme that more than one carrier in the same single channel, in which the coherence bandwidth of the channel is more than each carrier bandwidth. That means instead of transmitting high data rate in single carrier, OFDM generates closely orthogonal subcarriers parallelly transmitted using IFFT algorithm. QPSK, 16QAM and other traditional digital modulation techniques are used to transmit subcarriers [15]. In OFDM the same principles that used in FDM, but in OFDM all subcarriers orthogonal to each other. When a subcarrier is in peak the other subcarriers should be at zero. That leads to make OFDM bandwidth more efficient than FDM. Frequency domain spectrum for both FDM and OFDM shown in figure (2-7). Between each adjusted two channels a safety band inserted to avoid inter channel interface ICI[16]. Among subcarriers different symbols transmitted independently in frequency domain. To obtain OFDM symbols in time domain IFFT performed in frequency domain. In the receiver radio channel, the ISI caused by using guard intervals occurred due to multi path delay in radio frequency channels can be overcome. Original data construction can be done by applying FFT on the OFDM symbols at receiver[17].

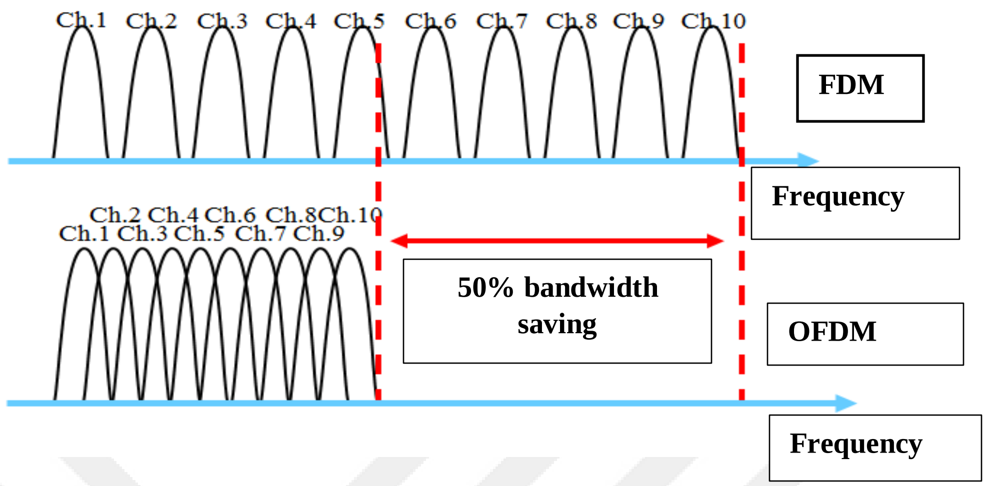


Figure 2.7: Spectrum of FDM and OFDM systems

Signals assumed to be orthogonal if they are uncorrelated to each other. In OFDM to have orthogonal signals, each successive subcarrier must be adjusted by spacing them with interval Δf equal to inverse sample duration T_S, that can be done by implementing IFFT in the transmitter. That ensure that all subcarriers in OFDM are at zero if one on the peak. This advantage makes it easy to detect subcarrier in receiver[18]. Figure (2-8) shows five subcarriers in OFDM frequency spectrum.

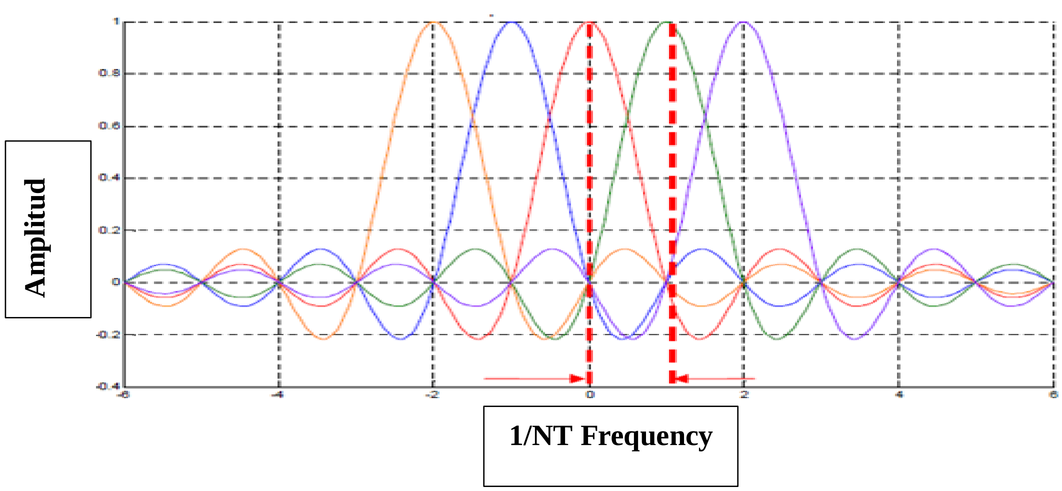


Figure 2.8: Five subcarrier OFDM frequency spectrum

2.6 OFDM IN VLC

Modulation scheme selection is the key step in VLC system design. Some required performances should be offered by the selected modulation scheme in VLC system such as:

1. Power efficiency.
2. Bandwidth improvement.
3. Transmission reliability.
4. Ambient light robustness.
5. Cost reduction.

Three optical modulation schemes will be illustrated in this chapter which are the used schemes in our system simulation.

2.6.1 Coded Modulated Optical CMO-OFDM

CMO-OFDM is a precoding/decoding algorithm. It can be applied in both SISO and MIMO OFDM communication system. Time domain signals of OFDM communication system can be obtained by invoking precoding/decoding algorithm without the Hermitian symmetry. By adding a special multiplexing or DC-bias positive signal can be achieved. CMO-OFDM algorithm proposed by SaadMshhianHardan and others for improving spectral efficiency in VLC systems without requiring Hermitian symmetry to obtain real signal [8]. Figure (2-9) shows CMO-OFDM block diagrams for both SISO and MIMO VLC communication systems.

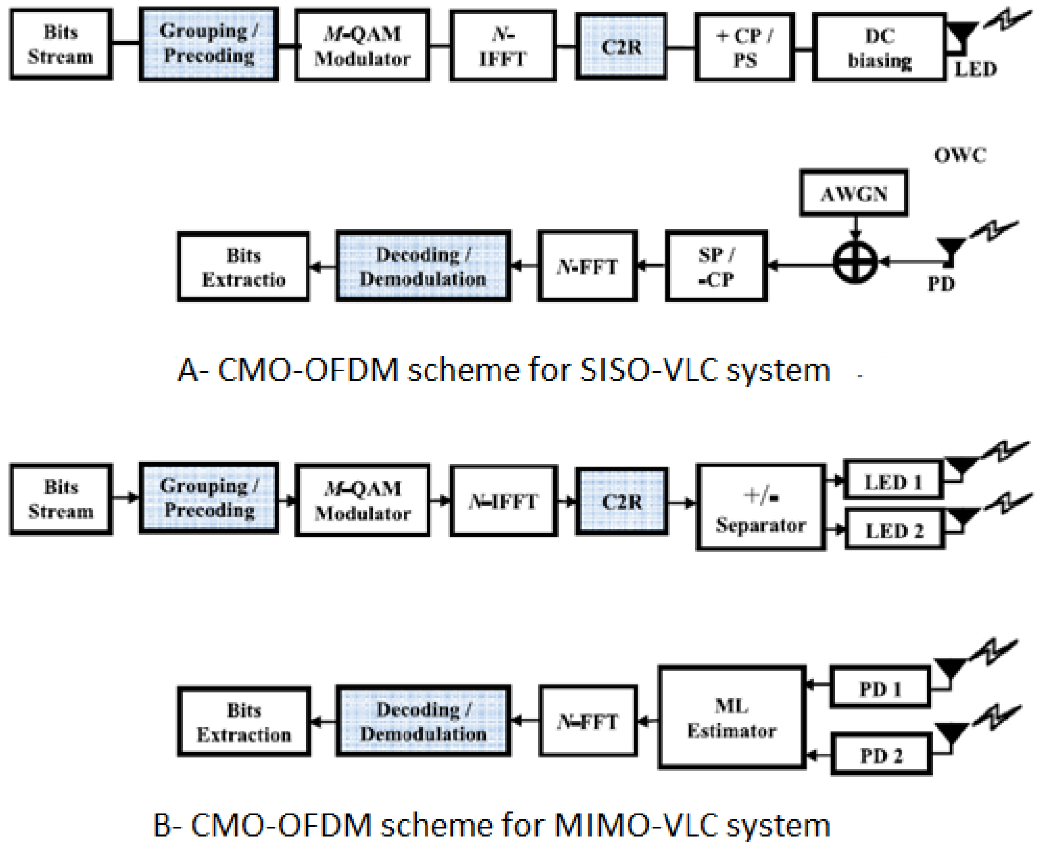
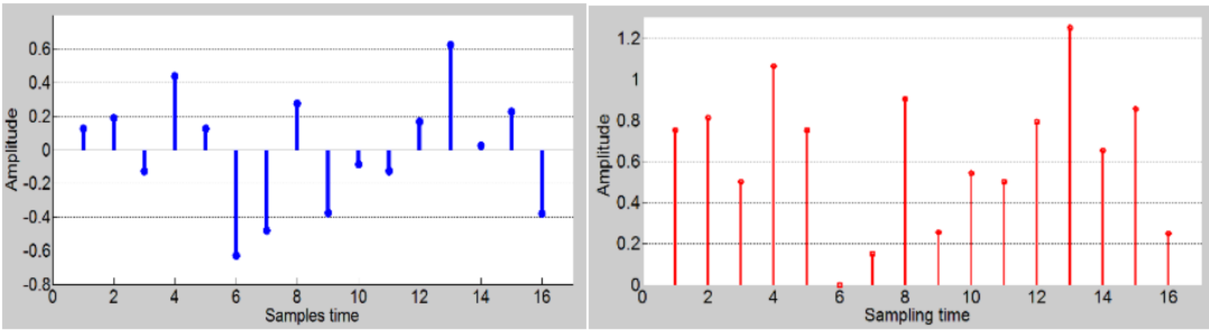


Figure 2.9: CMO-OFDM block diagram for (A-SISO and B-MIMO) VLC communication systems

2.6.2 DC-biased optical algorithm DCO-OFDM

DC-biased optical algorithm implemented by adding DC voltage before optical to electronic conversion. OFDM signals become positive by adding DC-bias voltage which level must be equal to highest negative OFDM amplitude. High DC voltage level is the main disadvantage of this technique especially with those systems which include dimming controllers that cause clipping noise [19][20]. Figure (2.10) shows DCO-OFDM time domain signal before and after adding DC-bias.



a- before adding DC bias b- after DC bias adding

Figure 2.10: DCO-OFDM time domain signal before and after DC

2.6.3 Generalized LED Index Modulation GLIM-OFDM

Light emitting diodes LEDs widely used for indoor illumination, for high illumination more than one diode may be used. Also, LEDs can be used for VLC systems, while there are more than one LED that leads to use those LEDs in MIMO VLC communication system [21][22]. block diagram for GLIM-OFDM shown in figure (2.11).

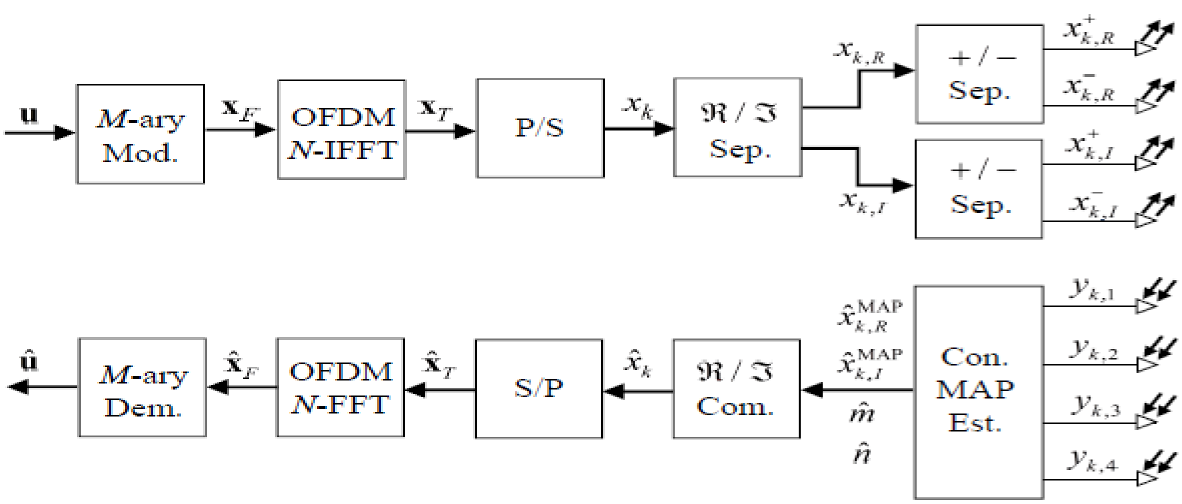


Figure 2.11: GLIM-OFDM block diagram

3. PROPOSED SYSTEM SIMULATION

3.1 WHITE LEDs BASED MIMO-VLC CHANNELMODEL:

In this study, a 4 × 4 MIMO-VLC system that is operating in a 4 m × 4 m × 3 m typical room. In general, the $N_R \times N_T$optical channel matrix H is formed by the DC gains between transmitter (LEDs) and receiver (PDs)[3].

$$H = \begin{pmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN_t} \end{pmatrix} \quad (3.1)$$

Where $h_{n_R n_T}$ denotes the channel gain of the optical wireless link between the transmitter N_T and receiverN_R. Thereceived signal y can be expressed in the form of $(N_R \times 1)$ vector:

$$y = Hx + \mathcal{N}_{AWGN}\ , y \in \mathbb{R}^{N_r} \quad (3.2)$$

Where $\boldsymbol{x}$ is a $(N_T \times 1)$ vector representing the transmitted signals while, $\mathcal{N}_{AWGN}$ is the noise vector with n_R elements, assumed to be real valued additive white Gaussian noise(AWGN) with zero mean, double-sided power spectral density[8].In fact,$\mathcal{N}_{AWGN}$represents the sum of ambient shot light noise and thermal noise[9].In this paper, optical wireless links with LOS characteristics is assumed. Figure (3-1) illustrates the geometric scenario used for calculating the channel coefficients, where, d denotes the distance between the corresponding LED and PD pair, $\phi$is the angle of emergence with respect to the transmitter (TX) axis and $\theta$is the angle of incidence with respect to the receiver (RX) axis. The channel gain has been calculated as follows[8].

$$h = \begin{cases} \frac{(\mathcal{K}+1)A\,\zeta}{2\pi d^2} cos^{\mathcal{K}}(\phi)\cos(\theta) & 0 \le \theta \le \theta_{\frac{1}{2}} \\ 0 & \theta > \theta_{\frac{1}{2}} \end{cases} \quad (3.3)$$

With the order of Lambertian emission $\mathcal{K} = \frac{\ln(2)}{\ln(\cos(\Phi_{\frac{1}{2}}))}$, where $\Phi_{\frac{1}{2}}$denotes the semi-angle of the LED. $\theta_{\frac{1}{2}}$is the field-of view (FOV) semi angle of the PD. A denotes the PD area. Moreover, ζ denotes the optical-to-electrical conversion coefficient. Without loss of generality, ζ is assumedto be unity.

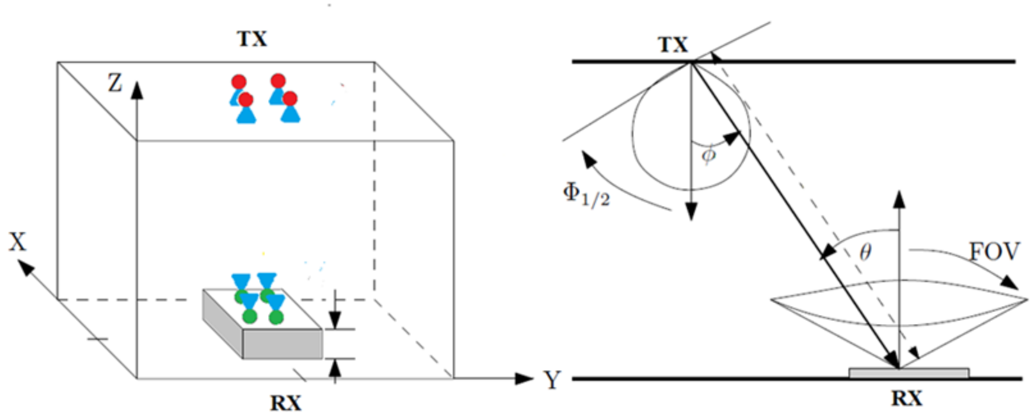


Figure 3.1: Geometric scenario used for calculation of channel coefficients

3.2 RGBY LEDs BASED WDM:

For RGBY LEDs based WDM, we have considered the same scenario for White LEDs based MIMO-VLC system except that the four white LEDs in transmitter are replaced by for colored LEDs such that LED1, LED2, LED3, LED4, is replaced by Red LED, Green LED, Blue LED and Yellow respectively while at the receiver side the four Photo Diodes are provided by Red, Greed, Blue and Yellow filter. The optical channel matrix H is formed by the DC gains between transmitter (RGBY LEDs) and receiver (PDs) can be expressed as [10]:

$$H_{RGBY} = \begin{pmatrix} h_{Red} & 0 & 0 & 0 \\ 0 & h_{Green} & 0 & 0 \\ 0 & 0 & h_{Blue} & 0 \\ 0 & 0 & 0 & h_{Yellow} \end{pmatrix} \tag{3.4}$$

It is clear from the above equation that RGBY is a diagonal matrix and can be considered an uncorrelated channel, applying equation (2) on RGBY LEDs leads to obtain equation (3.5):

$$\begin{pmatrix} y_R \\ y_G \\ y_B \\ y_Y \end{pmatrix} = \begin{pmatrix} h_{Red} & 0 & 0 & 0 \\ 0 & h_{Green} & 0 & 0 \\ 0 & 0 & h_{Blue} & 0 \\ 0 & 0 & 0 & h_{Yellow} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} + \begin{pmatrix} N_R \\ N_G \\ N_B \\ N_Y \end{pmatrix} \tag{3.5}$$

For each photo diode (receiver) the received signal can be expressed as:

$$y_R = h_{Red} \times x_1 + N_R \tag{3.6}$$

$$y_G = h_{Green} \times x_2 + N_G \tag{3.7}$$

$$y_B = h_{Blue} \times x_3 + N_B \tag{3.8}$$

$$y_Y = h_{Yello} \times x_4 + N_Y \tag{3.9}$$

3.3 SYSTEM SIMULATION:

The effective coverage area (C.A.) of RGBY spaced 4 by 4 meters is shown in figure (3.2). by inspection the C. A. can be divided into 13 zone depends on each LED coverage area, each zone can be covered by three LEDs only, while zone 1 which is the aim of the study is covered by the four LEDs. The mobile photo diode array in zone 1 can detect RGBY lights.

For White LEDs based MIMO-VLC system, we have considered a 4 × 4 MIMO-OFDM scenario (N_r = 4 and N_t = 4) which is located within a 4.0m × 4.0m× 3.0m room. In this scenario, the LEDs are placed at a height of z = 2.50 m and are oriented downwards to point straight down from the ceiling. The PDs are located at a height of z = 0.75 m and are oriented upwards to point straight up at the ceiling. Transmitters LEDs are aligned in a symmetric position about the center of the room.

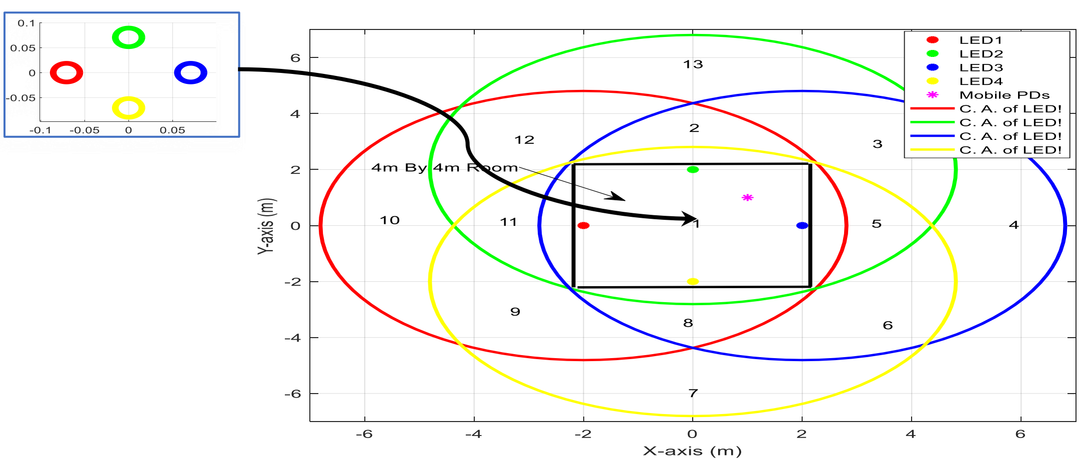


Figure 3.2: Effective coverage area (C. A.) of RGBY spaced 4 by 4 meters

on the x- and y-axis. Seven setups A, B, C, D, E, F and G have been considered according to this scenario moving the receiver on the x- and y-axis, which is depicted by d_{TX}. By considering the parameters illustrated in the Table 1, the analytical gains of the optical wireless channel for Configurations A, B,C,D,E,F and G are calculated according to equation 3 respectively as follows:

For configuration A:

$$H_A = \begin{pmatrix} 0.2006 & 0.1862 & 0.1862 & 0.1734 \\ 0.1862 & 0.2006 & 0.1734 & 0.1862 \\ 0.1862 & 0.1734 & 0.2006 & 0.1862 \\ 0.1734 & 0.1862 & 0.1862 & 0.2006 \end{pmatrix} \times 10^{-5} \tag{3.10}$$

For configuration B:

$$H_B = \begin{pmatrix} 0.1562 & 0.1418 & 0.1511 & 0.1374 \\ 0.5099 & 0.5439 & 0.4791 & 0.5099 \\ 0.0702 & 0.0659 & 0.0750 & 0.0702 \\ 0.1374 & 0.1418 & 0.1511 & 0.1562 \end{pmatrix} \times 10^{-5} \tag{3.11}$$

For configuration C:

$$H_C = \begin{pmatrix} 0.0862 & 0.0785 & 0.0862 & 0.0785 \\ 0.8529 & 0.8529 & 0.8529 & 0.8529 \\ 0.0305 & 0.0289 & 0.0322 & 0.0305 \\ 0.0785 & 0.0785 & 0.0862 & 0.0862 \end{pmatrix} \times 10^{-5} \tag{3.12}$$

For configuration D:

$$H_D = \begin{pmatrix} 0.0750 & 0.0702 & 0.0702 & 0.0659 \\ 0.1511 & 0.1562 & 0.1374 & 0.1418 \\ 0.1511 & 0.1374 & 0.1562 & 0.1418 \\ 0.4791 & 0.5099 & 0.5099 & 0.5439 \end{pmatrix} \times 10^{-5} \tag{3.13}$$

For configuration E:

$$H_E = \begin{pmatrix} 0.0645 & 0.0596 & 0.0620 & 0.0573 \\ 0.3596 & 0.3596 & 0.3248 & 0.3248 \\ 0.0620 & 0.0573 & 0.0645 & 0.0596 \\ 0.3248 & 0.3248 & 0.3596 & 0.3596 \end{pmatrix} \times 10^{-5} \tag{3.14}$$

For configuration F:

$$H_F = \begin{pmatrix} 0.0226 & 0.0211 & 0.0220 & 0.0206 \\ 0.2006 & 0.1862 & 0.1862 & 0.1734 \\ 0.0220 & 0.0206 & 0.0226 & 0.0221 \\ 0.1862 & 0.1734 & 0.2006 & 0.1862 \end{pmatrix} \times 10^{-5} \tag{3.15}$$

For configuration G:

$$H_G = \begin{pmatrix} 0.0803 & 0.0734 & 0.0785 & 0.0718 \\ 0.6717 & 0.6717 & 0.6249 & 0.6249 \\ 0.0445 & 0.0417 & 0.0468 & 0.0438 \\ 0.1563 & 0.1563 & 0.1732 & 0.1732 \end{pmatrix} \times 10^{-5} \quad (3.16)$$

Physical parameters for the simulation environments illustrated in table (3.1). Photo detectors placed in seven variable places within an area of 4*4 meters as shown in figure (3.4).

Parameters	**Values**	
Room Dimensions (W× L × H)	4.0**m** × 4.0**m**× 3.0**m**	
Number of Luminaries	4	
4 PDs are symmetrized about Positions (x; y; z) (m)	Position A	0,0
	Position B	**0,1,0.75**
	Position C	**0,2,0.75**
	Position D	**1,1,0.75**
	Position E	**2,2,0.75**
	Position F	**0.5, 1.5, 0.75**
	Position G	**1,2, 0.75**
LEDss Positions (x; y; z) (m)	**LED1**: (-2, 0, 2.5), **LED2**: 0, 2, 2.5) **LED3**: (2, 0, 2.5) ,**LED4**: 0, -2, 2.5)	
Viewing angle of Luminary(degrees)	70°	
FOV semiangle of Receiver (degrees)	70°	
Area of PD (cm^2)	1	

Table 3.1: The physical parameters of simulation environment for White LEDs based MIMO-VLC system

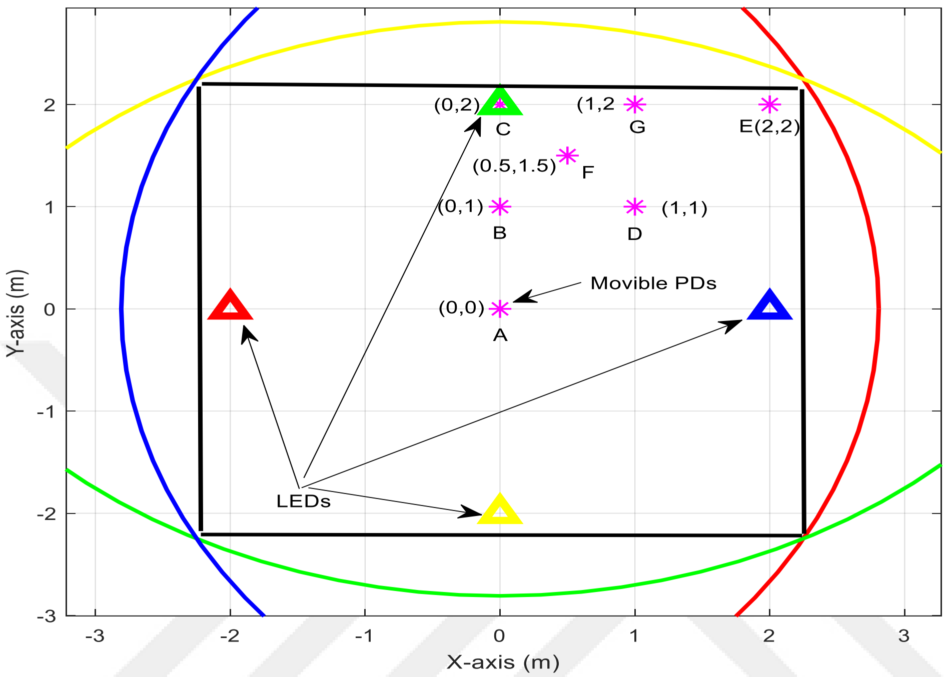


Figure 3.3: The PD seven movement positions

Bit error rate BER vs signal to noise ratio SNR for both white LED and RGBY in in case of multi position photo detector in three modulation schemes, deferent angle of rotation effect on BER/SNR for white LED in CMO MIMO-OFDM scheme and the three modulation schemes effect on RGBY BER/SNR performance are studied in the simulation part.

3.3.1 CMO MIMO-OFDM scheme

In this case BER/SNR performance shown in figure (3.4). It is clear in figure (3.4) that RGBY performance is efficient than white LEDs, RGBY BER is about 10^{-3} when SNR is about 36 dB, while in white LED case the best BER achieved when SNR about 76 Db.

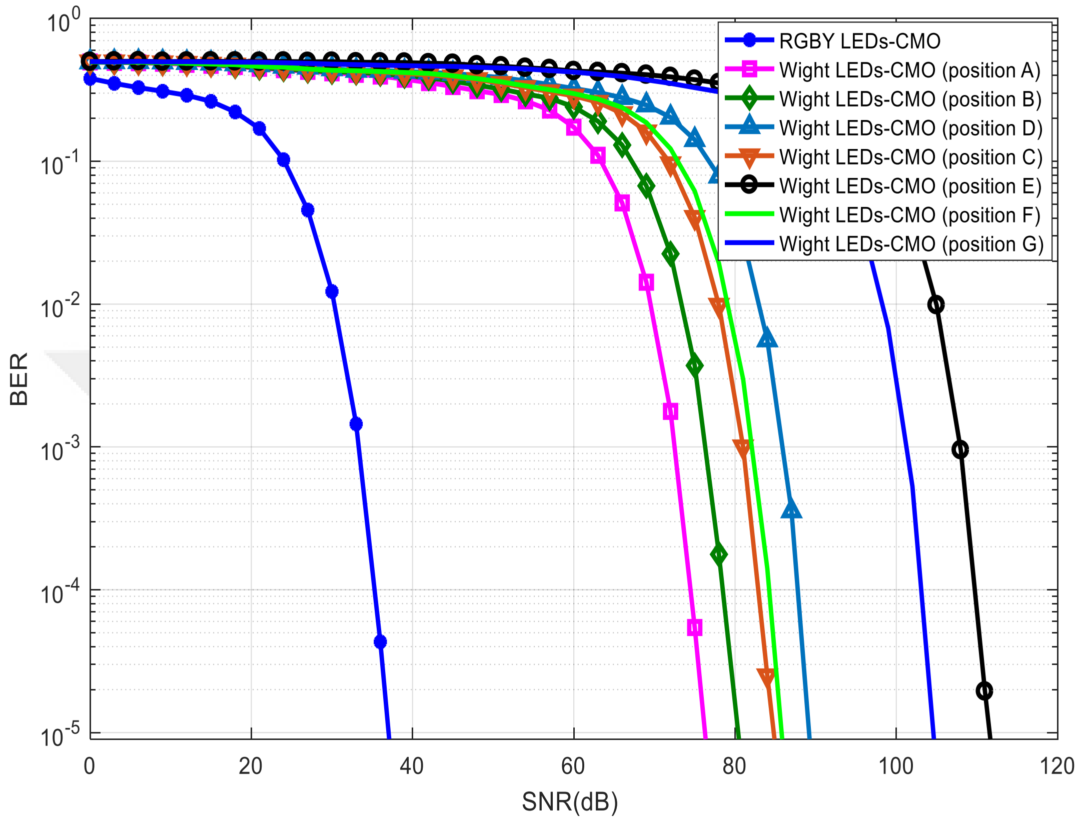


Figure 3.4: BER performance of a 6 bits/s/Hz white LED based CMO MIMO-OFDM schemes for different movement positions as compared with a 6 bits/s/Hz RGBY LED based CMO MIMO-OFDM schemes

3.3.2 DCO MIMO-OFDM scheme

DCO MIMO-OFDM modulation scheme BER/SNR performances for both RGBY and white LEDs shown in figure (3.5). In this case BER/SNR performances is less than the performance in case of CMO MIMO-OFDM modulation scheme, in spite of that RGBY BER/SNR is better than that of white LEDs.

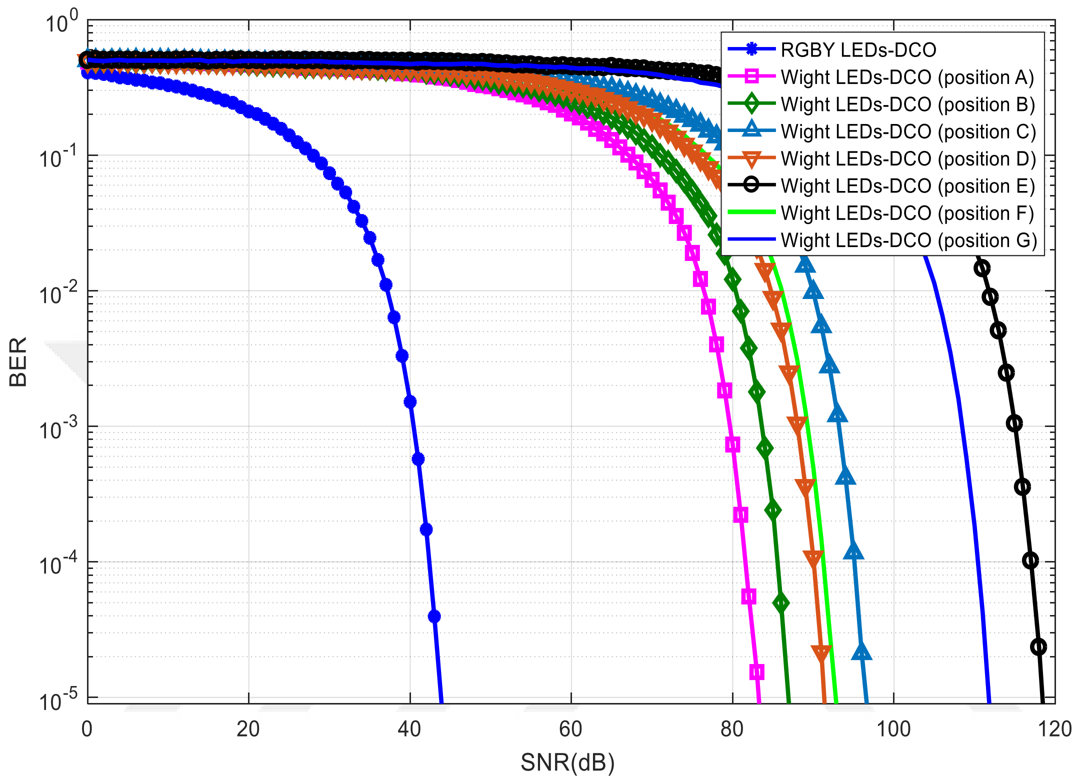


Figure 3.5: BER performance of 6 bits/s/Hz white LED based DCO MIMO-OFDM schemes for different movement positions as compared with a 6 bits/s/Hz RGBY LED based DCO MIMO-OFDM schemes

3.3.3 GLIM MIMO-OFDM scheme

Figure (3.6) shows BER/SNR performance for both RGBY and white LEDs. BER/SNR performances is less than the two previous cases, where BER for RGBY LED achieved 10^{-3} when SNR when SNR is about 45 Db.

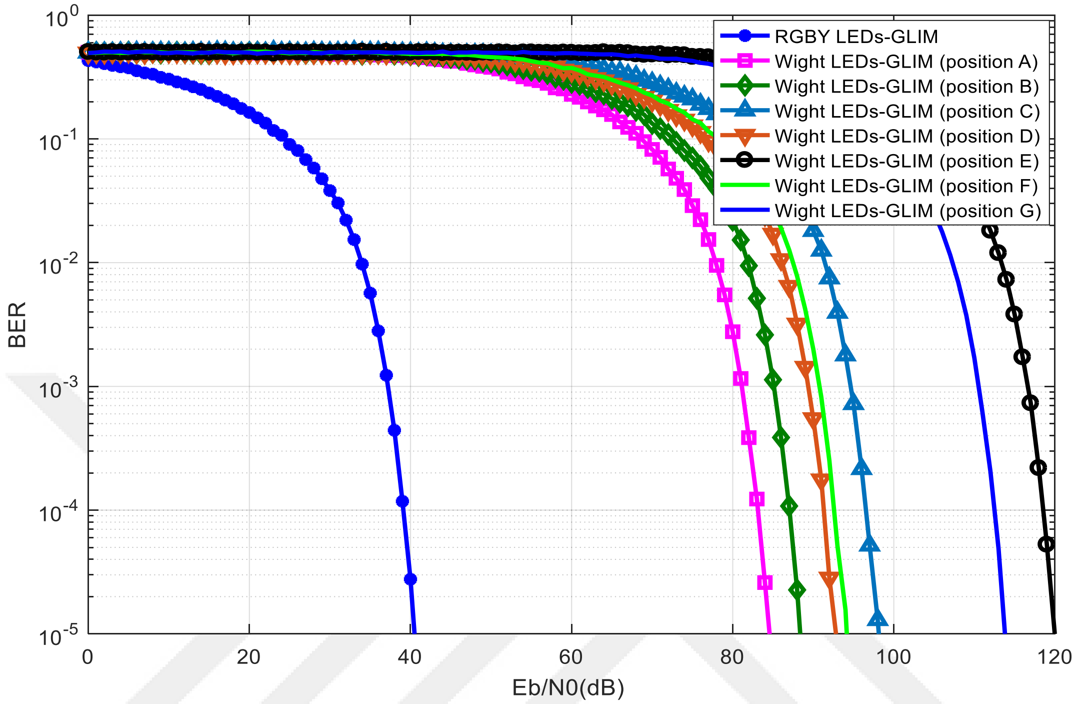


Figure 3.6: BER performance of 6 bits/s/Hz white LED based DCO MIMO-OFDM schemes for different movement positions as compared with a 6 bits/s/Hz RGBY LED based DCO MIMO-OFDM schemes

3.3.4 CMO MIMO-OFDM schemes for different angle of rotation about position

In this case the effect of rotation angle on BER/SNR performance for white LEDs in case of CMO MIMO-OFDM modulation scheme. Simulation results shown in figure (3.7). It's clear that the best BER/SNR performance occurs in position A with zero rotation. And in decreases with angle increasing. When the rotation angle is 45-degree BER is very high as explained in red curve, BER minimum value is about 10^{-1} while SNR was more than 120 db. In the other hand when rotation angle increased until reaches 90-degree BER perform more efficient performance than in case of 45-degree i.e. in this case BER reaches 10^{-5} limit when SNR about 82 db. As shown in black curve.

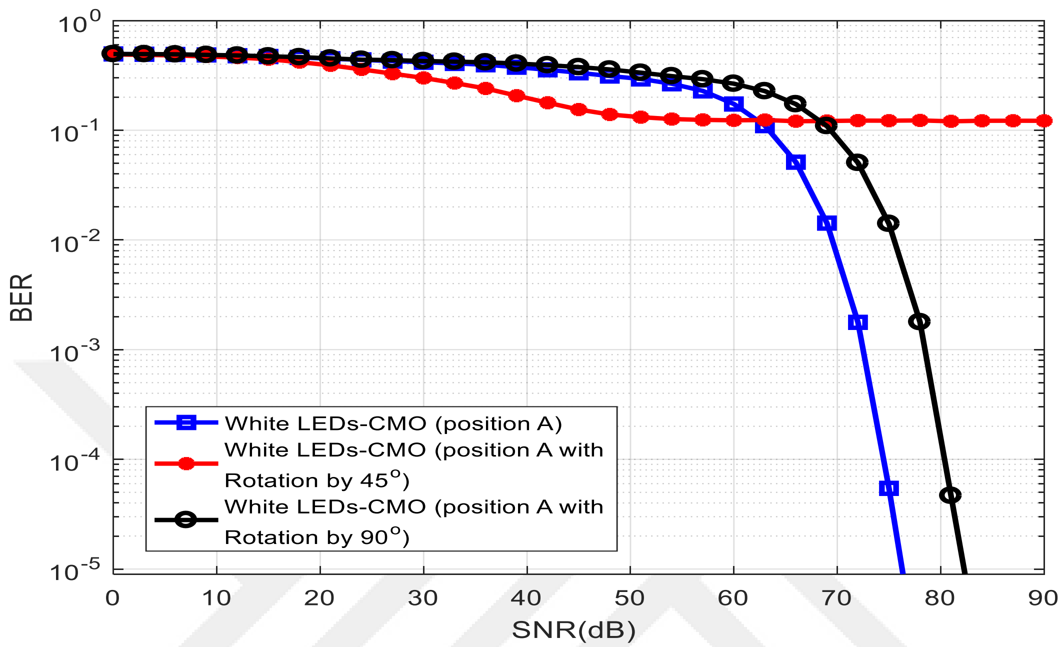


Figure 3.7: performance comparison of 6 bits/s/Hz optical CMO MIMO-OFDM schemes for different angle of rotation about position

3.3.5 Effect of modulation schemes on BER/SNR for RGBY LEDs.

Figure (3.8) shows BER/SNR for RGBY LEDs in all three case of modulation mentioned above. Her three cases of modulation schemes implemented on RGBY LEDs to illustrate the effect of modulation on the BER performance of RGBY LEDs based system. In figure (3.8) red curve represents RGBY 4x4 MIMO CMO modulation scheme in which the best BER performance occurred where BER reaches 10^{-5} limit when SNR about 37 db. While in RGBY 4X4 MIMO GLIM which is illustrated in black curve BER reaches 10^{-5} limit when SNR about 41 db. Blue curve represents RGBY 4X4 MIMO DCO system performance in this curve BER reaches 10^{-5} limit when SNR reaches 44 db. From this comparison results the modulation technique is not very high affected parameter in BER performance in case of RGBY LEDs based VLC system.

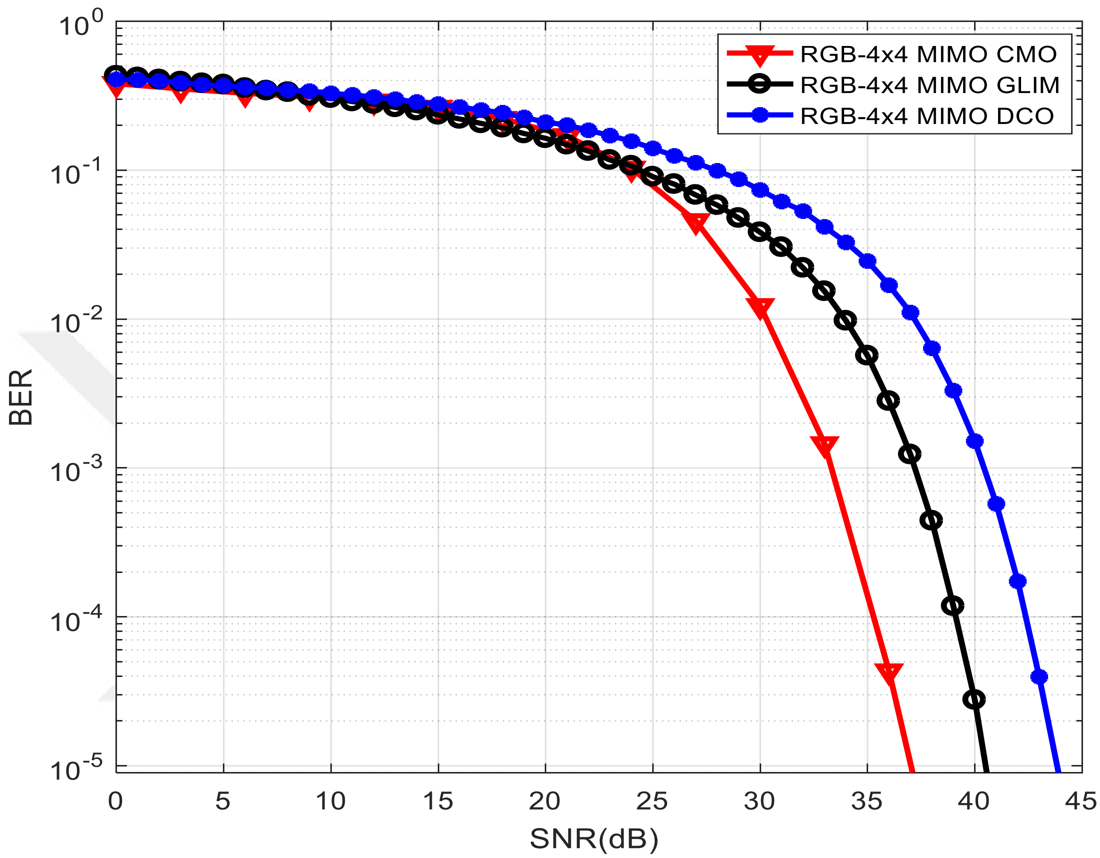


Figure 3.8: BER VS SNR for RGBY LEDs in all three case of modulation

4. SIMULATION RESULTS DISCUSSION

PD positions shown in figure (3.4) as following: A (0,0) m, B (0,1) m, C (0,2) m, D (1,1) m, E (2,2) m, F (0.5,1.5) m, and G (1,2) m. studied room dimensions is 4x4x3 meters.

4.1 CMO-OFDM MIMO

As shown in figure (3.4) BER performance for RGBY achieved 10^{-5} with SNR about 37 dB unaffected by PD position (blue curve) while, white LEDs BER response showed high effectiveness for PD position. In position A (pink curve) the high BER performance which is about 10^{-5} when SNR about 76 dB, the worst case occurred in position E (black curve) it not achieves 10^{-5} limit until SNR reached 113 dB.

4.2 DCO-OFDM MIMO

BER performance shown in figure (3.5) for RGBY the PD position not effected in BER performance (blue curve) which reaches 10^{-5} limit when SNR about 47 dB. In white LEDs case PD position is more effected parameter hence in position A (pink curve) which is the best performance in this scheme BER curve reaches 10^{-5} limit when SNR about 82 dB, while the worst case occurs in position E (black curve) here BER curve reaches 10^{-5} limit when SNR reaches 120 Db.

4.3 GLIM-OFDM MIMO

BER performance shown in figure (3.6), for RGBY LEDs the position of PD not effected BER performance as shown in blue curve, but it is very effect parameter in case of white LEDs. In position A (pink curve) BER reaches 10^{-5} limit when SNR reaches 83 Db, while in position E (black curve) the worst case occurs, BER curve reaches 10^{-5} limit when SNR about 120 dB.

4.4 ROTATION ANGLE EFFECT

Rotation angle effect shown in figure (3.7) for white LEDs in position A in case of zero rotation angle BER curve reaches 10^{-5} limit when SNR about 76 db (blue curve), when the rotation angle becomes 45-degree BER curve will not be less than 10^{-1} even when SNR more than 120 db (red curve). When rotation angle reaches 90-degree BER curve reaches 10^{-5} limit but when SNR about 83 db (black curve).

4.5 MODULATION TECHNIQUE EFFECT ON RGBY BER PERFORMANCE

For RGBY LEDs the main effective parameter is the modulation technique. As shown in figure (3.8) CMO-OFDM has the highest BER performance which is about 10^{-5} when SNR is about 37 db (red curve), while in GLIM-OFDM has the second BER performance (black curve) which is about 10^{-5} when SNR about 41 db. The minimum BER performance in DCO-OFDM modulation case which is about 10^{-5} when SNR is about 44 db.

4.6 ADVANTAGE of RGBY VSWHITE LEDs

Three modulation techniques, seven positions and three rotation angles had been used in simulated system. In all studied cases RGBY LEDs performs the best performance (minimum BER) even with low SNR. White LEDs in case of 45-degree rotation angle BER is more than 10^{-1} while SNR is more than 120 db.

5. CONCLUSIONAND FUTURE WORKS

5.1 CONCLUSION

In this study three types of modulation (DCO, CMO, and GLIM) had been simulated using MATLAB for two types of LEDs (RGBY and white LED). Simulation results recorded and discussed. Rotation angle effect also studied for both types of LED and for CMO modulation scheme. For all studied modulation cases RGBY LEDs perform the best BER performance and the better case was in CMO modulation technique in which case BER reaches 10^{-3} limit when SNR reaches 37 db. Rotation angle more effected on white LEDs than RGBY LEDs. The best-case angle is in zero degree, while the worst case was in case of 45 degree.

5.2 FUTURE WORKS

Proposed system may be implemented by using another type of LEDs, also diming control effect may be studied for using the proposed system for illumination as well as for communication. Positioning system may be added for the tasks performed by the proposed system. All that above may be future works for other researchers.

REFERENCE

[1] L. Zeng *et al.*, “High data rate multiple input multiple output (MIMO) optical wireless communications using white LED lighting,” *IEEE J. Sel. Areas Commun.*, vol. 27, no. 9, pp. 1654–1662, 2009.

[2] A. H. Azhar, T.-A. Tran, and D. O’Brien, “Demonstration of high-speed data transmission using MIMO-OFDM visible light communications,” in *2010 IEEE Globecom Workshops*, 2010, pp. 1052–1056.

[3] S. Hejduk, K. Witas, J. Latal, J. Vitasek, and J. Bocheza, “Use of the RGBY model for indoor mobile visible light communication,” in *2014 16th International Conference on Transparent Optical Networks (ICTON)*, 2014, pp. 1–4.

[4] W. Yuanquan and C. Nan, “A high-speed bi-directional visible light communication system based on RGB-LED,” *China Commun.*, vol. 11, no. 3, pp. 40–44, 2014.

[5] L. Cui, Y. Tang, H. Jia, J. Luo, and B. Gnade, “Analysis of the multichannel WDM-VLC communication system,” *J. Light. Technol.*, vol. 34, no. 24, pp. 5627–5634, 2016.

[6] K. Xu, H.-Y. Yu, Y.-J. Zhu, and H.-B. Cai, “Channel-adaptive space-collaborative constellation design for MIMO VLC with fast maximum likelihood detection,” *IEEE Access*, vol. 5, pp. 842–852, 2017.

[7] P. He, Z. Huang, M. Huang, W. Li, M. Liu, and Y. Ji, “Indoor intelligent visible light system based on Triple-Domain-Cooperation scheme,” in *2017 16th International Conference on Optical Communications and Networks (ICOCN)*, 2017, pp. 1–3.

[8] S. M. Hardan, O. Bayat, and A. A. Abdulkafi, “A new precoding scheme for spectral efficient optical OFDM systems,” *Opt. Commun.*, vol. 419, pp. 125–133, 2018.

[9] T. Komine and M. Nakagawa, “Fundamental analysis for visible-light communication system using LED lights,” *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 100–107, 2004.

[10] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical wireless communications: system and channel modelling with Matlab®*. CRC press, 2019.

[11] J. Vučić, C. Kottke, K. Habel, and K.-D. Langer, “803 Mbit/s visible light WDM link based on DMT modulation of a single RGB LED luminary,” in *2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference*, 2011, pp. 1–3.

[12] S. Rajbhandari, “Spatial and wavelength division multiplexing for high-speed VLC systems: An overview,” in *2016 10th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, 2016, pp. 1–6.

[13] A. Tsiatmas, C. P. M. J. Baggen, F. M. J. Willems, J.-P. M. G. Linnartz, and J. W. M. Bergmans, “An illumination perspective on visible light communications,” *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 64–71, 2014.

[14] J. Grubor, S. Randel, K.-D. Langer, and J. W. Walewski, “Broadband information broadcasting using LED-based interior lighting,” *J. Light. Technol.*, vol. 26, no. 24, pp. 3883–3892, 2008.

[15] R. Prasad, *OFDM for wireless communications systems*. Artech House, 2004.

[16] Y. S. Cho, J. Kim, W. Y. Yang, and C. G. Kang, *MIMO-OFDM wireless communications with MATLAB*. John Wiley & Sons, 2010.

[17] A. R. S. Bahai, B. R. Saltzberg, and M. Ergen, *Multi-carrier digital communications: theory and applications of OFDM*. Springer Science & Business Media, 2004.

[18] G. Hill, “Peak power reduction in orthogonal frequency division multiplexing transmitters.” Victoria University, 2011.

[19] S. Dimitrov and H. Haas, *Principles of LED light communications: towards networked Li-Fi*. Cambridge University Press, 2015.

[20] S. D. Dissanayake and J. Armstrong, “Comparison of aco-ofdm, dco-ofdm and ado-ofdm in im/dd systems,” *J. Light. Technol.*, vol. 31, no. 7, pp. 1063–1072, 2013.

[21] T. Fath and H. Haas, “Performance comparison of MIMO techniques for optical wireless communications in indoor environments,” *IEEE Trans. Commun.*, vol. 61, no. 2, pp. 733–742, 2012.

[22] E. Başar, E. Panayirci, M. Uysal, and H. Haas, “Generalized LED index modulation optical OFDM for MIMO visible light communications systems,” in *2016 IEEE International Conference on Communications (ICC)*, 2016, pp. 1–5.