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Avalanche photo detection based indoor VLC behaviour using simulation.

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The authors declare that they are the sole authors of this thesis and that they have not used any sources other than those listed in the bibliography and identified as references. They further declare that they have not submitted this thesis at any other institution to obtain a degree.

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Abstract

In recent years visible light communication (VLC) has been one of the technologies overgrowing in this competitive world and breaking through the wireless transmission of future mobile communications. This VLC replaces radio frequency (RF), which has several important features like large bandwidth, low cost, unlicensed spectrum. In telecommunications, there is a need for high bandwidth and secure transmission of data through a network. Communication can be done through wired and wireless. Wired communication such as coaxial cable, twisted wire, fiber optics, and wireless are RF, light fidelity (Li-Fi), optical wireless communication(OWC). In our daily lives, we are transferring data from one place to another through a network connection. The network is connected to multiple devices as the network bandwidth provided by VLC is higher than the RF communications. When multiple devices are connected to RF, the latency is high. In the case of VLC, the latency is low. In this research, the light emitting diode (LED) bulbs act as the transmitter(Tx), and the avalanche photodiode (APD) acts as a receiver(Rx).

This research mainly focuses on creating a MATLAB simulation environment for a two-room VLC system with given spectral power distributions. We have simulated two rooms with the exact dimensions. The LEDs are placed in opposite positions in each room. LED is placed at the middle top of the ceiling in one room, and a photodiode (PD) is placed on top of the table under the light in the same room. Moreover, in another room, the light is placed on top of the table at the bottom, and PD is placed at the middle top of the ceiling. Moreover, these two rooms are connected to the same network. The input parameters are taken from the previous studies, but the transmitting power is calculated from the Red-Green-Blue(RGB or White) light spectrum distribution using the OOK modulation technique. We obtained responsivity of APD at a single point and bit error rates(BER) of APD at multi-points inside both the rooms.

Keywords: VLC two rooms, OOK, APD, MATLAB-simulation.

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Contents

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List of Abbreviations

VLC	Visible Light Communication
OWC	Optical Wireless Communication
LED	Light Emitting Diode
RGB	Red-Green-Blue
RF	Radio Frequency
LOS	Line-Of-Sight
NON-LOS	Non-Line Of sight
DC	Direct Current
FOV	Field of View
BER	Bit Error Rate
SNR	Signal to Noise Ratio
PD	Photo Diode
OOK	On-Off keying
Tx	Transmitter
Rx	Receiver
IM	Intensity Modulation
DD	Direct Detection
LI-FI	Light Fidelity
WI-FI	Wireless Fidelity
OOK	On-Off keying
PPM	Pulse position modulation
APD	Avalanche photo diode
RMS	Root mean square
AWGN	Additive White Gaussian noise
AGC-OOK	Aided Gain Channel-OOK

Chapter 1

Introduction

Wireless communication has spread at an unprecedented rate in the last two decades. This transfer of information between two or more points does not consider any object that allows a flow of charge as a medium. In this scenario, RF communication and OWC are widely [28]. Both these communications use electromagnetic radiation, but the RF communication type is frequently disrupted after initial transmission. In order to avoid these instabilities, OWC is used to have stable, reliable, and robust transmissions [22].

Visible light communication

VLC is a developing modern technology in the communications industry that competes with traditional RF technologies [22]. Due to avoidance of light propagation through the walls, VLC exhibits secure communication, which keeps its users safe from hacking compared with RF communication systems[28]. The VLC is gaining popularity among researchers and users due to several characteristics such as large bandwidth, low cost, low power consumption [28], and the lack of spectrum regulations [11]. Figure 1.1 depicts the spectrum range of VLC systems, which ranges from 360nm to 750nm, and their corresponding frequency spectrum range, which ranges from 430THz to 790THz [11].

VLC technology applications can be divided into two categories indoor VLC and outdoor VLC. The use of smartphones, tablets, and computers has dramatically improved. If this trend continues, there will be a mobile data transmission crisis, resulting in high latency. The RF spectrum is limited, and overcoming it is costly. New technologies are currently being developed to reduce spectrum utilization. Another method for replacing RF communication is OWC, which has more advanced features than RF transmitter[7][9].

- This can be used in homes, offices, industrial settings, military bases, hospitals, and financial messaging. VLC can be especially useful for highly confidential purposes. Because the light illuminating will be contained within the room environment, it will not be likely to transmit through the walls; thus, there will be less chance of eavesdropping, and data transmission will be secure[29] [15].

- With the increase of solid-state lighting, longevity, low power consumption, high bandwidth, and data security, LED lights can be used for data transmission and illumination [29].

- The implementation of OW will result in a reduction of health risks [29].

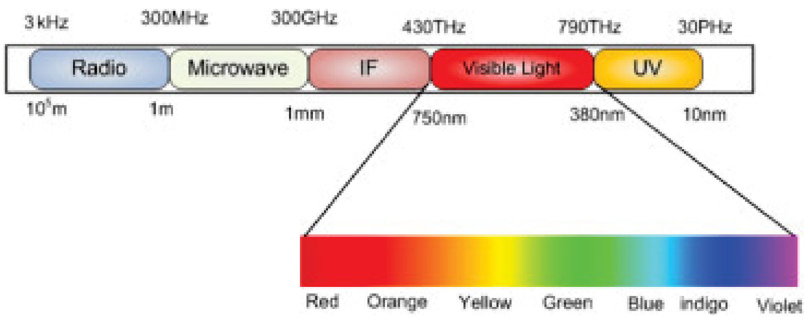

Figure 1.1: Visible Light Spectrum [11]

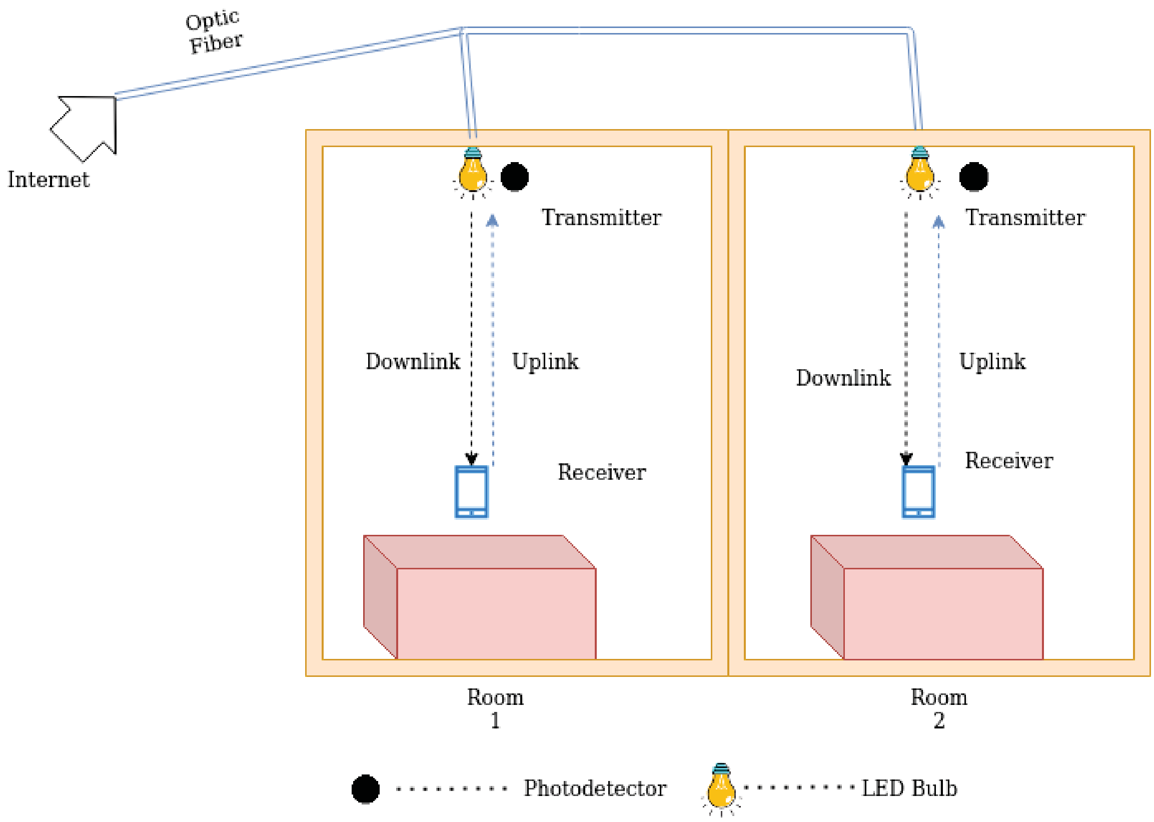

Figure 1.2: VLC system Architecture

1.1 Motivation

RF transmissions have quite few instabilities after its initial transmission. It has limited capabilities due to this advent behaviour and also due to its multi path fading, RF communication generates high BERs (performance metrics) during its transmission in single place as well as in multiple places. The main focus is to observe the complexity and behaviour of VLC in between two rooms (See Figure 1.2) which acts as a replacement for RF communication. Performance metrics like responsivity and bit errors rates are obtained in order to obtain this behaviour by simulating this environment.This thesis explores visible light communication via simulation in MATLAB by sending a sample message from one room to another room and checking whether a message is delivered as per the given input data.

1.2 Aims and Objectives

In this thesis work, we aim to implement a visible light communication system in two rooms for communicating the electronic devices. The main objective of the thesis is

- To find out the background features and factors that affect the VLC when compared to that of radio frequency communication (RF).
- To conduct an experiment that mainly focuses on simulation environment buildup on OOK modulation techniques to obtain the desired VLC system.
- To analyze the BERs, output PD responsivity for given input light in the VLC system.

The main objectives of the project are discussed below:

- Implementing a simulation environment consists of two rooms having typical dimensions.
- Light source is placed at a fixed point. A Rx is placed at rapid points in the room.
- Establishing communication using OOK modulation scheme.

1.3 Research Questions

Research Questions are as follows:

- RQ[1]What are the optical photo diodes responsivities inside the two rooms?

  Method used: Simulation .

- RQ[2]What are the BERs variations from room to room for given LED power sources?

  Method used: Simulation.

1.4 Scope of thesis

However, the previous works show a single-room home application using unidirectional and bidirectional communications. The sources as white light LEDs and colored LEDs. The connections using point to point and multi-point links for transmitting and receiving signals. The main modulation schemes available are (IM/DD), on-off keying (OOK), pulse position modulation (PPM), and optical frequency division modulation (OFDM). We have proposed a bidirectional OOK two rooms visible light communication system for indoor applications. We are also calculating multi point BERs and APD responsivity of the OOK technique in transmitting data between two rooms.

1.5 Outline

The total documentation is described according to session wise described below:

- 1st section describes the total fundamental part of a document including the index.
- 2nd section describes the introduction part of thesis work.
- 3rd section describes the total background part of visible light communication and modulation techniques.
- 4th section contains the methodology part and input part, which describes the setup of the experiment part.
- 5th and 6th section show analysis of output results, conclusion and future work.

Chapter 2

Conceptual Background

2.1 Basic concept of VLC

VLC is wireless communication that transfers data at high speed through light. There are different types of lights available for OWC but LED shows a significant response compared to other lights, and this technology is called LI-FI[14]. Both Wireless fidelity (WI-FI) and LI-FI are similar[18]. The difference is WI-FI sends information through RF, and LI-FI sends information through transceiver fitted LED lamps, which works in two ways like illuminating light and data transfer in the indoor with an extra high speed compared to RF[18]. The LED light boosts the speed of bandwidth up to 244 gigabits per second[28]. The multiple devices are working nowadays, more updated appliances may come up in the future, which leads to heavy traffic in a communication system. When there is more traffic in communication, there is a chance of signal clogging that leads to transmission errors, and this can be prevented by using LI-FI technology.

2.2 Model of VLC

The VLC consist of LEDs as photon emitting diodes, PDs as photon detecting diodes. The Amplification and processing the received data is the two important tasks of APD. The factors we must also consider are

- Presence of light must be LOS.
- Lamp driver where internet connection, switch and LED lamp connected.
- For better performance use LED bulbs.
- APD received data.

As shown in Figure 2.1, the streaming content is connected to the input lamp driver, the internet and server are also connected to the streaming content via an optical fiber for operating the power switch, and the LED light is connected to the lamp driver. A PD is connected to amplification and processing at the Rx dongle. The devices, smartphones, laptops, and PC, are linked via LAN or free space. The Tx transmits the input signal light with encoding via frequency, and the PD is perpendicular to the Tx's line of sight. When data is transmitted, the light will flicker, and the data will be transmitted to an Rx. The PD will take the input signal,

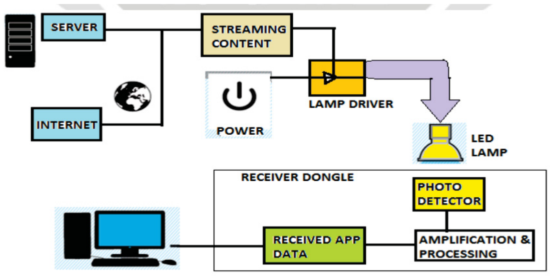

Figure 2.1: Architecture of LI-FI[30]

decode it, and convert it into an electrical signal before passing it to a destination, where the data will be stored in streaming content through a microchip whenever the switch is turned on [31].

2.3 Working mechanism

The light works as a Tx, while the PD acts as an Rx. The device communicates with the other device. The input is sent from the Tx to the Rx via light in free space, and the Rx converts the input light into an electrical signal. The data modulation on light is transferred through switching on and off mechanism within a second, which a human eye cannot catch while it is transferring [6].

2.3.1 Working of LED and Benefits

The transmission of an electron from an excited state to a lower state produces light. Changes in light are caused by changes in energy in the transition from non-radiative to radiative. This radiation is the primary source of light generation, while non-radiation results in the generation of heat. The photon transfers its energy from an electron's filled valence band to its empty conduction band. When the valance band emits a photon, an electron enters an empty state, a process known as spontaneous recombination of radiation. [29].

When compared to other lights, LEDs are the most efficient. LED saves up to 85 more energy than incandescent bulbs and has a longer lifespan. LEDs are made of various inorganic semiconductor materials that are doped with impurities to form a p-n junction[25][13]. There are two kinds of flashes of lightning. One is used solely for light illumination, while the other is used for both illumination and data transfer. The light used in VLC communication is a mixture of red, green, and blue rays[25][13]. Data is transferred between these rays [6].

2.3.2 Photo Detector

In OWC, PDs serve as Rxs. They have a high attracting sensing power to optical signals illuminated by an LED light. Because the optical signal received from the Tx is encoded, it must first decode it and convert it to electrical signals. These signals are utterly proportional to light from the sensor's surface area, and the PD should handle fast response time to light as well as light fluctuations in any case of low power efficiency[18] [9]. There are three types of PDs available. The silicon photodiodes, PIN photodiodes, and Avalanche photodiode (APD).

2.3.3 Avalanche photo diode:

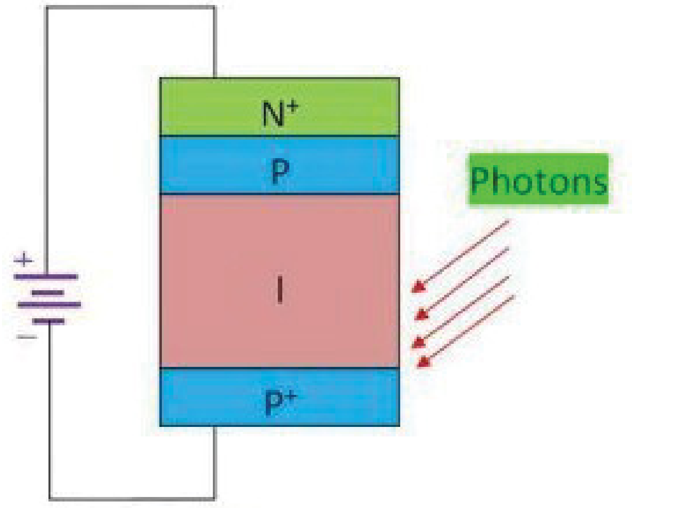

Figure 2.2: Avalanche photo diode reverse bias diagram[1]

An APD is made up of 4 layers, as shown in Figure 2.2. The p^+ and n^+ layers are heavily doped regions[26]. So, the resistivity of these regions is very low. The 'i' and 'p' layers are lowly doped regions[26]. When APD is used in the reverse bias, it works like a PD. It produces electric power concerning input optical power. Due to reverse bias, a large depletion region is created. The light rays that enter into the depletion region generate electron-hole pairs[26]. The reverse bias makes the experience of a high electric field in the PD. The drifting may be occurring in the depletion region, which causes electron of pn^+ gain of the more electric field. The acceleration of these electrons will produce secondary electrons in its path and so on[26]. The generated secondary electrons have sufficient kinetic energy (KE) to generate pairs of 'M' number of electron-hole, an impact ionization process. Only electrons are responsible for this whole process[26]. The responsivity and sensitivity of PD increase concerning electron-hole pairs for the APD[26]. The equation calculates the generated photocurrent.

$$I_p = qN_e^M \tag{2.1}$$

where q = charge of electron, 1.6 x 10-19C
N_e = number of electrons generated
M = multiplication factor

The electric field concerning the length of APD is as shown in figure 2.3[26]. In the i and p+, there is minimum electric field observed, but in the p_+ and n layers, the electric field increases because of ionization, which causes internal amplification in APD[26]. The maximum electric field appears in the avalanche region[26].

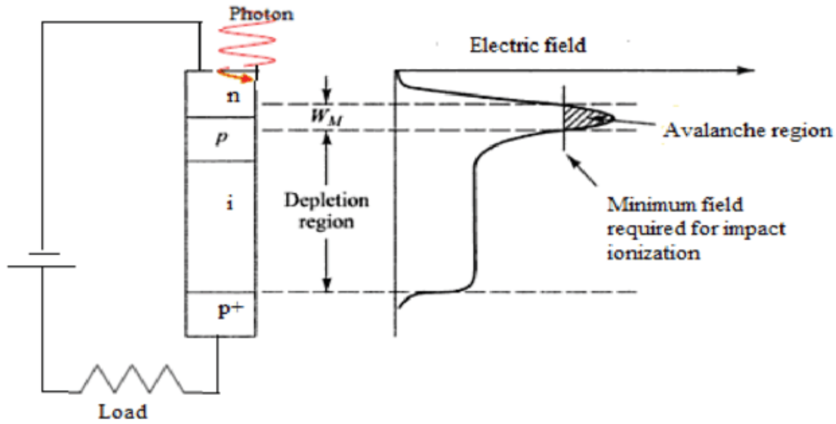

Figure 2.3: Electric field vs length of Avalanche photo diode curve[17]

2.3.4 Dark Current

If no light falls on the PD in reverse bias, we will get some current known as dark current. The dark current should be minimized as much as possible for any PD because it acts as noise for the generated photocurrent [18] [6].

2.3.5 Channel modelling to communication

There are various types of link configurations in OWC, and the links are differentiated based on various background locations. The light illuminates and travels in various directions in visible light touch, and these directions, reflections, and any obstacles should be considered in visible light communication[5]. There are various types of indoor link configurations that are designed to accommodate various lighting capacities[5]. They are listed below.

- "Direct line-of-sight(LOS)
- Non-directed line-of-sight (NON-LOS)
- Diffused
- Tracked " [6]

In an indoor communication system, light travels around between the walls, but it cannot pass through the walls and obstacles, so the reflection of the walls, ceilings, and floor must be considered[5]. Outdoors, the light is scattered, and it is a little more complicated because there will be noise, air, illumination deflection, and high sunlight levels, all of which can interfere with data transmission [6].

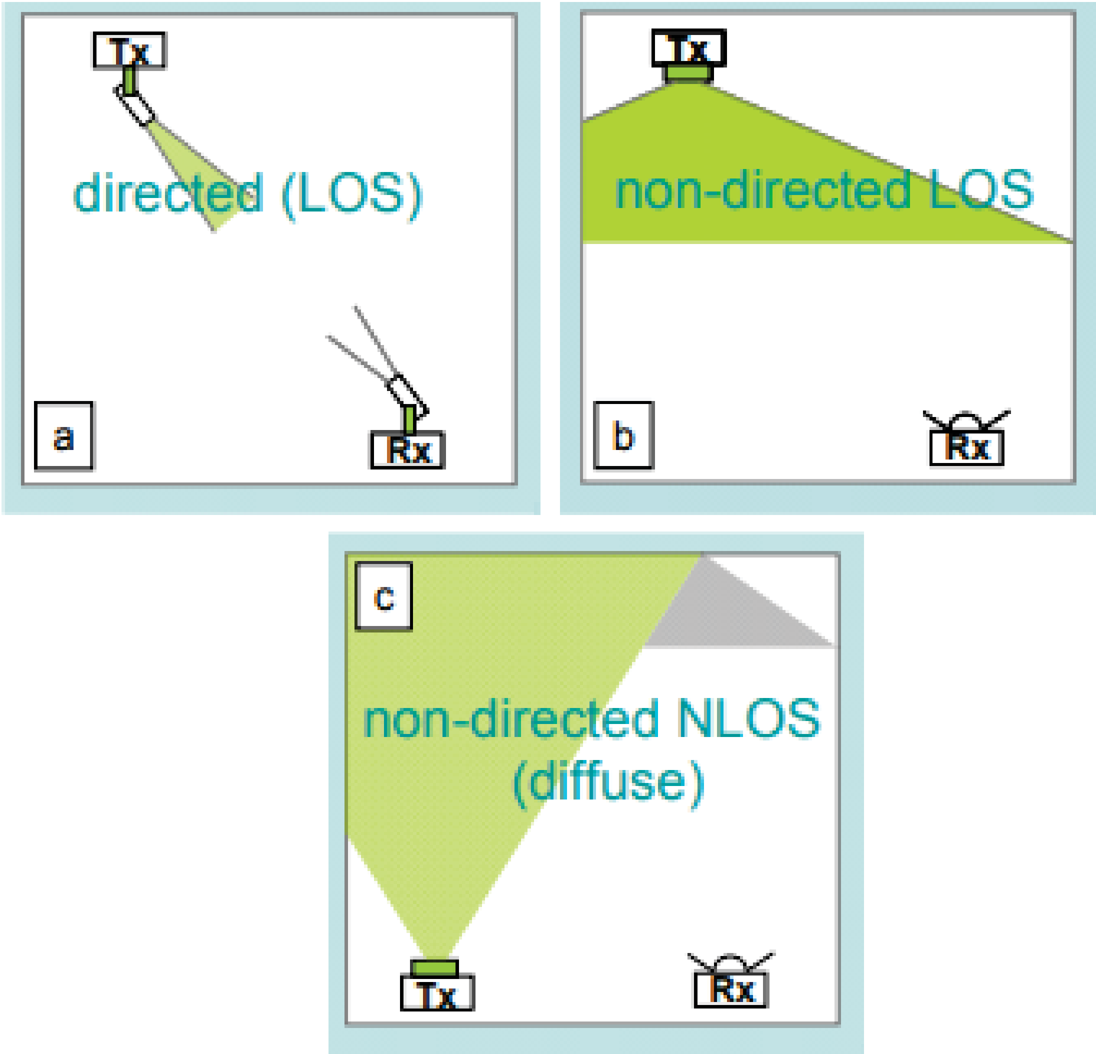

Figure 2.4: a) Directed LOS b) Non Directed LOS c) Non directed NON-LOS [14]

2.3.6 Directed LOS

The direct LOS in OWC can be implemented depending on the location-based Tx and Rx, led as a Tx illuminates a light in a sharp narrowband line, and the PD uses a direct detection scheme to intake the Tx's illumination[5]. The Rx should be positioned precisely where the illumination point from the Tx. Because there is no scattering, the power efficiency is whole directed to a narrow line of sight, so there will be less noise from surrounding[5] and is primarily used in outdoor applications, but an indoor light should illuminate broad wide around the surface area for connecting more devices and for more flexibility non directed LOS is more applicable [14] [7][5].

2.3.7 Non directed LOS

Non-directed LOS is one of the most prominent techniques in indoor VLC, and it applies to almost every indoor communication due to its broad illumination scattering throughout the room[5]. The light transmits in various directions from the Tx.

Because of the high path loss caused by light scattering, the Rx can be placed in multiple locations[5]. As a result, every reflection should be considered from surface to surface based on parameters such as room size, the incidence angle of a Tx and Rx, and Rayleigh criteria. [14] [6][5].

2.4 Modulation techniques

In OWC, the modulation technique is an essential technique to be selected; there are different modulation techniques in VLC. There are a single carrier modulation technique, multi-signal carrier modulation technique, and many other pulse modulation techniques. We chose the OOK modulation technique because of its features and having a multi-signal carrier. In this OOK modulation technique, the signal is more straightforward and suitable to receive. The standard radiofrequency OOK technique should be modified to become suitable for IM/DD system by using a line of sight, and NON-LOS communication [20].

2.4.1 Optical carrier modulation

Optical carrier modulation is the Rxs that employ heterodyne or homodyne down counters compressed by local oscillators and mixers. The efficient operation of this mixer relies upon the frequency stability of the carrier and on local oscillators. At the same time, the coherent optical Rx detects the optical carrier phase, which requires a local oscillator and local filter. So whatever LEDs we are using emits incoherent light; therefore, it is not easy to collect appreciable signal power in the electromagnetic signal link[20]. So, in OWC, the most flexible modulation technique is Intensity modulation/Direct detection (IM/DD). Here IM acts as an up-link and DD as a downlink. The most desirable waveform is modulated into instantaneous power of optical carrier, and here DD will use PD to receive the data, compared to coherent DD is very simple to detect the Intensity of optical wave that has no frequency in-phase information. In general, indoor optical applications use intensity modulation with DD for transmission to achieve low-cost and straightforward optical modulation and demodulation[20] [6].

2.4.2 OOK Modulation technique

The modulation technique used in this thesis is the OOK modulation technique due to its simplest form that represents digital data as the presence or absence of a carrier wave[8][18]. The presence of a carrier for a specific duration represents a binary 1, and the absence of the same duration represents a binary 0. The OOK modulator is used in the Tx side and Rx side in the VLC to transfer data from source to photo destination[8][18]. The bit errors are low compared to other modulation techniques[8][18]. The data rates are also less[8][18].

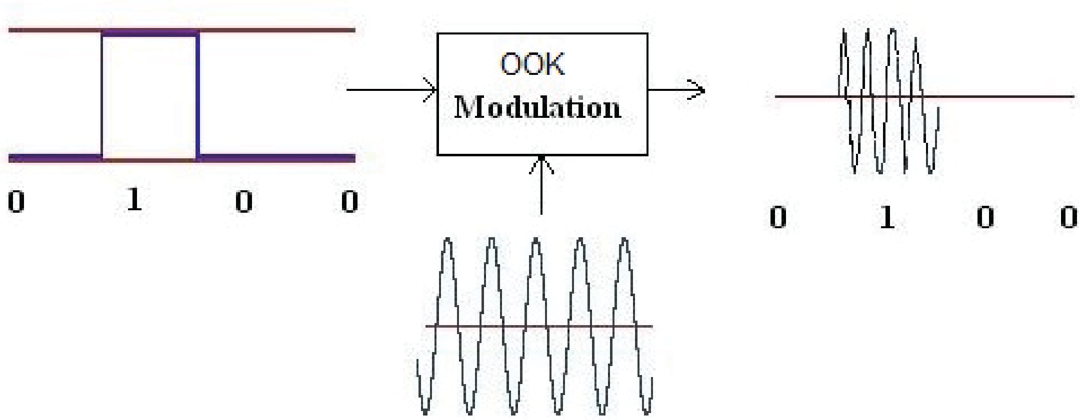

Figure 2.5: On-off keying modulation[2]

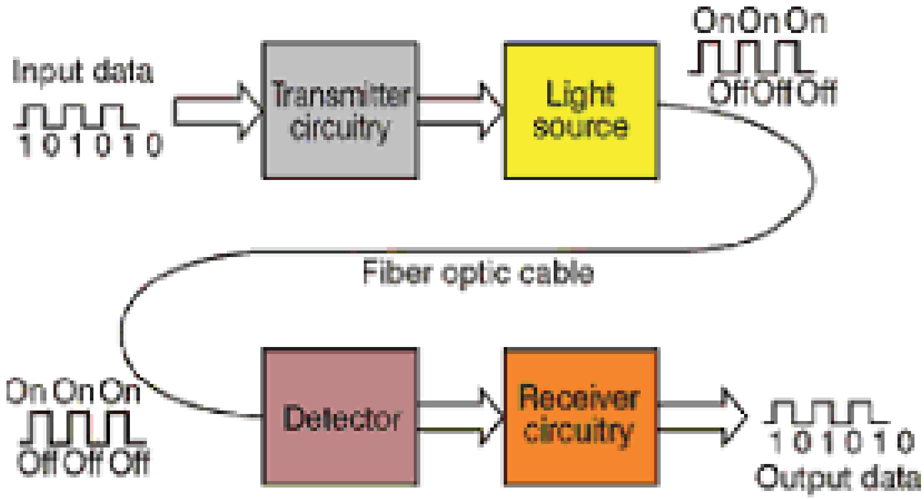

Figure 2.6: Basic fiber optic communication system[24]

2.5 Optical Fiber

A cylindrical dielectric wave-guide medium is made up of low-loss materials such as glass (or) fiber[3]. The fiber consists of three central components core, cladding, and guard. The light is transmitted along with the fiber by following the total internal reflection principle. The refractive index of light inside the core is slightly higher than the cladding. Optical systems are simple to far complex systems. As depicted in the diagram below 2.6, a primary and cost-effective fiber optic communication system using an LED, plastic fiber, silicon PD, and simple electronic circuitry. Fiber-optic communication can be divided into two kinds [3]as shown in fig 2.7.

1. Step Index fibers
   (a) Single mode
   (b) Multi mode

2. Graded Index fibers

1. Step Index fibers: The core and cladding of these fibers have distinct boundaries, and the indices of refraction are well defined[3]. A single index of refraction is used throughout the core.

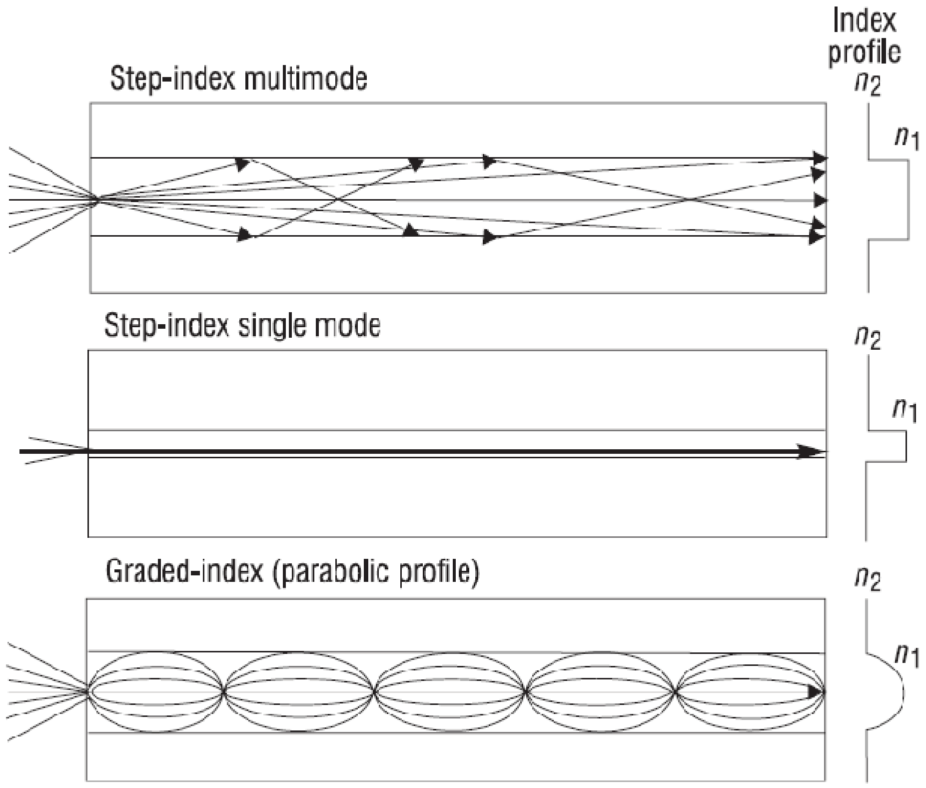

Figure 2.7: a)Step-index multimode b) Step-index single mode c) Graded-index fibers[23]

(a) Single mode-Step Index fiber: Single-mode means light follows a single path throughout the core[4][21][3]. Step index of these fibers refraction between core and cladding interface are sharp as well. The core diameter is 8 to 9 microns range.

(b) Multi mode-Step Index fiber: Multimode means light follow multi-path throughout the core. Step index of these fibers refraction between core and cladding interface are smooth. The core diameter is 50 or 62.5 microns.

2. Multi mode-Graded Index fiber: Graded index argues that the core refractive index gradually decreases as light moves away from the center of the core[3]. The increase of refractive index slows the speed of some light rays at the center. This allows all the light waves to reach the fiber endpoint at the same time causes dispersion. We use a single-mode step-index fiber to model the optical channel between the two rooms in the system model.

2.6 MATLAB

In this thesis, by using MATLAB, the simulation of indoor VLC is established. MATLAB is mainly used for mathematical calculations and programming purposes. It is user-friendly for giving the inputs and taking exact output values according to theoretical and practical values. MATLAB is mainly used by researchers, students, artificial intelligence, neural networks, signal processing, circuit designing, and simulation purpose because multiple inputs and multiple outputs can be taken at a time. It can also help convert algorithms into C/C++ languages also. In this thesis, MATLAB is used for the simulation purpose to build the system, recreate inputs. By using the inputs, find out outputs like BERs, responsivity, graphs, and tables. The latest version of MATLAB 2020b is used.

Chapter 3

Related Work

The relief of VLC is due to drastic changes and effects of WI-FI, which causes damage to the environment and human health hazards. In visible light communication, light acts as a transmitter, and PD acts as a receiver. For transmission of light, led is taken for illumination and data transfer. There are many other sources for transmitter purposes, but LEDs give the best result compared to other lights, leading to having the best light-emitting diodes, long lifetime, and the bandwidth can be increased or decreased by using blue filter elimination.[15][10].

Following are the related publications that were helpful to obtain the performance metrics of VLC within a single occupied space. When compared with our research, the ultimate difference is multi-dimensional space with different inputs and having other resources.

In this research paper[32] a technique employing the parameters Q to identify the best architecture of channel quality is suggested[32]. It is help full for taking the consideration as first reflected light from the background. Moreover, a brief description of the luminous intensity helps us to find out the direction of the light in LOS and NLOS[32]. The diagram for this experiment is as below Fig.3.1.

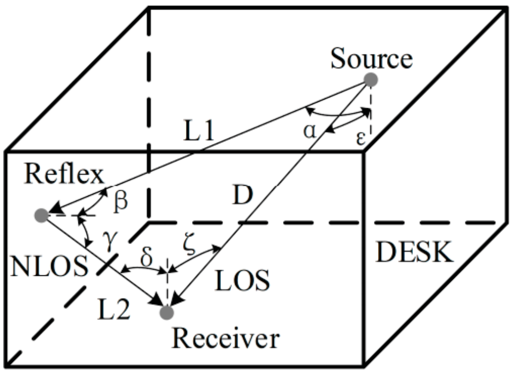

Figure 3.1: Indoor visible light communication (VLC) communication diagram. [32]

From the reference of optical wireless communication book, [6] and [18] , and from previous thesis the related codes on MATLAB have been considered and modification has been made and implemented on VLC according to the research questions. The previous work is done based on the single room communication with multiple LEDs[25] [18]and the OOK[8] modulation technique. In our thesis, the study is based on two-room communication with a single LED[25] on the OOK modulation technique in order to observe the behaviour of performance metrics with more dimensional space and transmitting the data between them. Below is the simulation setup (Fig.3.2) establiished in order to study wavelength dependency of Si PD and in our study as mentioned the required simulation setup has been established for large dimensional space The OOK modulation technique codes are taken from optical wireless communication, and the implementation of VLC room-based code has been taken from our professor[8]. The BER's inside two rooms, PD responsivity, and output messages are plotted.

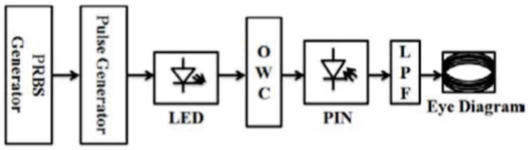

Figure 3.2: Simulation Setup to study wavelength dependency of Si PD [25]

This paper discusses the communication and illumination of led light performance on RGB. From the results of the experiment, finally, they observed that visible light communication from OWC can be implemented indoor for high-speed data communications[25]. As usual, they have tested that red light has a high wavelength compared to other green and blue light in a short-range[25]. By procrastinating results based on the BER, the red has a nominal bit error rate. These rates have been calculated by using the OOK modulation technique in the range of 100Mbps for 5m and 10m optical wireless communication channels[25].

A study of new visible light for future discussion on implementing the standard light. This new concept describes adding white light with RGB colors[27]. This paper is also taken into consideration of the human eye, so the constant data rates and constant illumination of light may do not cause the effect on the human eye[27] See Figure 3.3. In the case of security, controlling the optimal signal can reduce the communication range, which is available at a specific range only

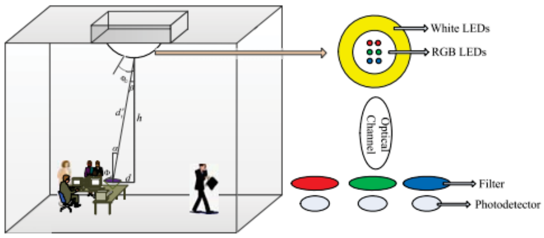

Figure 3.3: The scenario and light source model [27]

There is one more research paper[12] which describes the APD detection of the transmitting light power transmitting and calculates the bit error rates and probability of bit errors for a single room with AGC modeling OOK. In this paper, the OOK modulation technique is used, and the output obtained is BER rates at an average signal and background photon count and in this simulation[12].

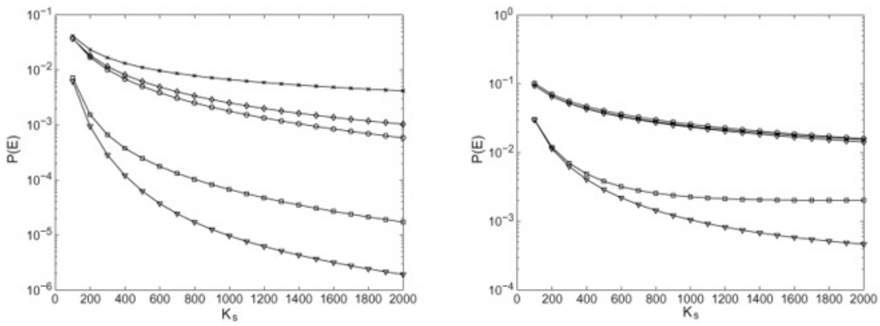

Figure 3.4: BERs obtained at average signal photon count and average background photon count [12]

Chapter 4

Method

This section describes on combination of research methods used in order to answer RQs.

4.1 Literature Review

4.1.1 Study selection criteria

A literature study has been done on related work, which has scientific publications related to visible light communications. Digital libraries IEEE Explore, Google Scholar, and ACM digital library have been used.

4.1.2 Search string

We are using different databases for study selection, among them the main data bases are

- IEEE Explore
- Google scholar
- ACM digital library

We are incorporating 'OR' and 'AND' boolean expressions in searching various papers from the above databases. The following keywords (or) terms are using for searching.

("Visible light communication" OR "Optical communication")
("Indoor visible light communication" AND "OOK modulation technique")
("Photo detection technique" OR "APD detector")
("VLC behaviour" AND "small scale dimensions ")
("VLC behaviour" AND "large scale dimensions")

4.2 Inclusion & Exclusion criteria

This criterion has been used to make our process easy to have the papers related to this work. Half of these criteria have been met to include a paper.

Inclusion criteria

- Published papers and are peer-reviewed

- Consisting clear statements on the goal of our research
- Explanations on answering research questions

Exclusion criteria

- Papers not addressing RQs
- Papers not focusing on search string and strategy.

Process	Results
Literature Review	80 papers
Inclusion and Exclusion criteria	54 papers
Date Extraction and Synthesis	39 papers
Total	29 papers

Table 4.1: Papers obtained after search strategy

4.3 Data extraction and Synthesis

Data extraction The relevant information has been extracted from papers that focus on concepts of visible light communications.
Data Synthesis Data synthesis has been used to figure out relevant data and these papers have formulae and tabular values to design the system and observe the outputs.

4.4 Simulation

Consider an indoor VLC system having two rooms, as shown below (see Figure4.1). The rooms have tables in them. The rooms consist of one LED at a fixed position and one PD at different positions. The two-room sizes are considered as5x5x3. In two rooms, the LEDs and PDs are placed in the room's ceiling and top on the table, respectively, and vice-versa. The system parameters are shown in table 4.2

Few simulation parameters have been referred from the respective papers to observe the behavior with similar inputs for large dimensional spaces, i.e., for two rooms. Whereas, Spectral power distribution has been calculated as shown below to obtain the transmitted power of White LEDs inside rooms.

4.4.1 Inputs of Transmitter

The LED, which is an important component of the Tx side, is placed in the position of the desk (2.375,2.375,0.85) in room1 as shown in figure 4.3. In the room2, the LED

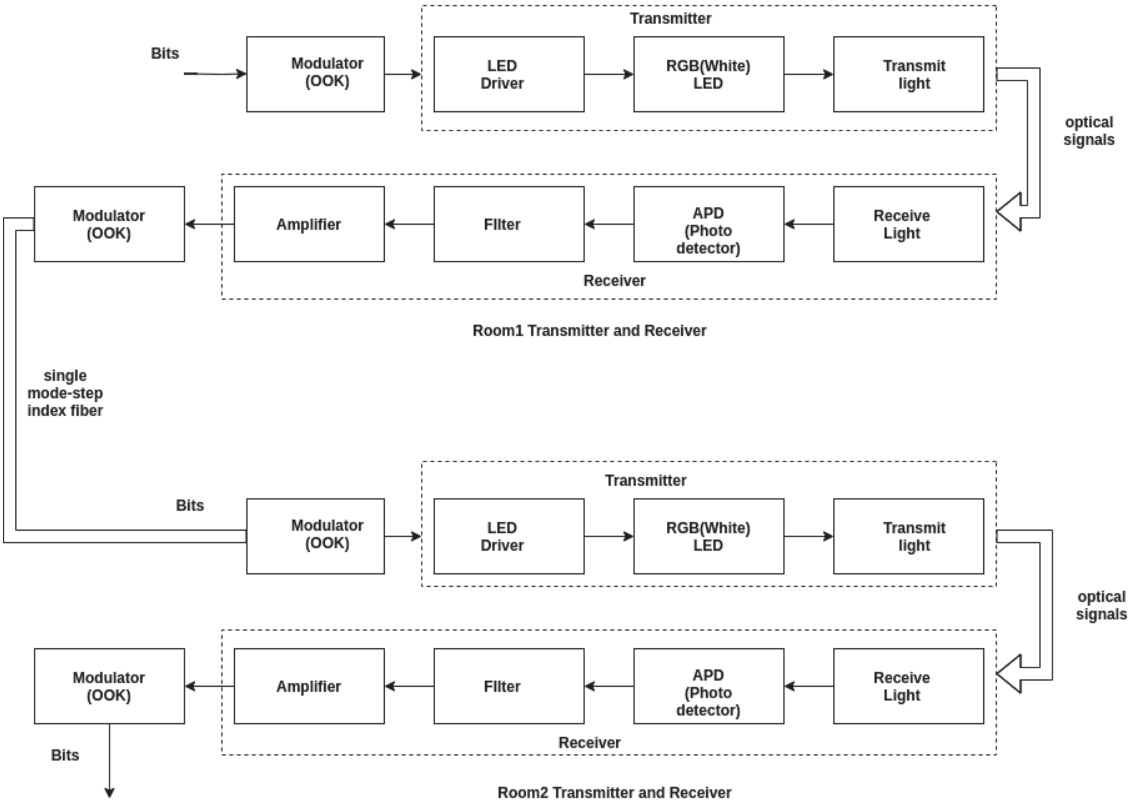

Figure 4.1: System model of two rooms VLC

is placed on the position $room_c$ (2.5,2.5,3) as shown in figure 4.4. The white light-producing LEDs are using as Txs[25][13]. RGB narrow line phosphor emitter LEDs are used as white light LEDs[25][13]. We are using a Gaussian function equation to determine the spectral power densities (SPDs) of RGB phosphor emitter LEDs, respectively. The linear addition of these LEDs SPDs will form the SPD of the white light emitter LED, which is implemented by the eq(4.2). By using the values from the table 4.3 in the formula, we write a code in Matlab, which results in a mixing combination SPD curve of phosphor emitter LEDs[27] as shown in the above figure 4.2, which is a recreation from the source[25][13][16].

The general Gaussian function of any LED[25] [13][16] is given as

$$V\left(\lambda,\lambda_c\right) = I.e^{\frac{-(\lambda-\lambda_c)^2}{\sigma^2}} \tag{4.1}$$

V = relative Spectral Density
I = 1, intensity scaling factor (I>0)
λ = wavelengths of light(nm)
λ_c = peak wavelength, value is 555 nm
σ^2 = variance (18 nm^2)

In case, RGB LEDs[25][13][16] we use sum of SPDs

$$V_{RGB}\left(\lambda,\lambda_c\right) = V_R + V_G + V_B \tag{4.2}$$

Parameter	**values**
rooms size[32]	5x5x3
desks size	4.75x4.75x0.85
desk LED positions (room 1)	(2.375,2.375,0.85)
LED positions (room 2)	(2.5,2.5,3)
LEDs colour [16]	RGB(white)
centre luminance intensity of LED	0.73 cd
number of LEDs per array	60x60
half power semi angle in room1	60°
half power semi angle in room2	60°
half angle field of view (FOV)	50°
receiver plane height	0.85 m
PD surface area (A_d) [12]	$2.510^-5\ m^2$
elevation angle [12]	90°
an aperture lens of area (A) [12]	$10e^{-2}$
signal-noise ratio [6]	0.01(dbm)

Table 4.2: Simulation Parameters

LED type	Peak wavelength	FWHM (nm)
Red	625	16
Wide green	520	31
Blue	477	22
Narrow green	550	7

Table 4.3: RGB LED design Parameters[16]

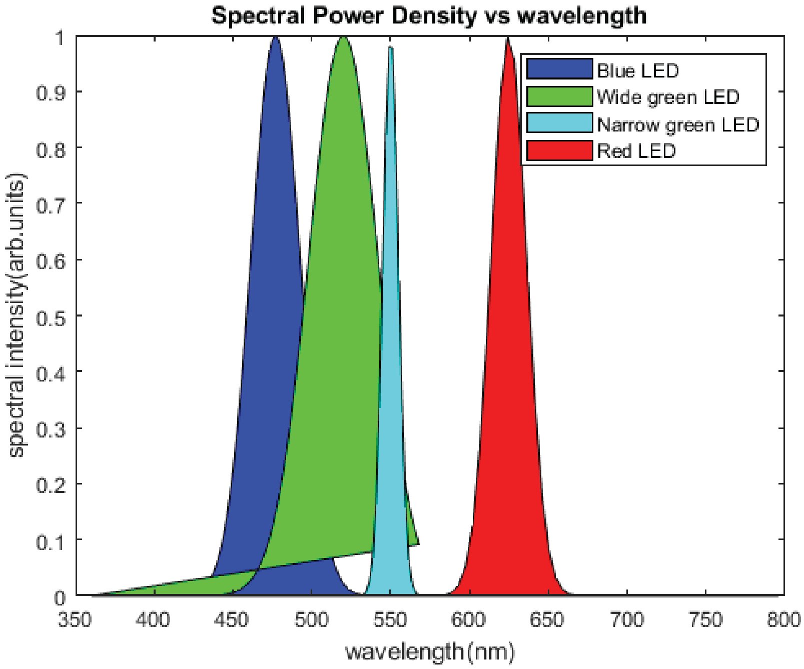

Figure 4.2: Spectral power density of RGB(white light) LED emitters

The SPD is not a complete characterization of a LED source because an eye vision of humans is not equally sensitive for all color specters of LEDs. The typical spectrum response of a human eye is indicated by the standard luminosity function $S(\lambda)$ developed by the International Commission on illumination. This function has maximum sensitivity at a wavelength of 555nm. To estimate light vision, we used an equation proposed by Agarwal [32].

$$S(\lambda) = exp(-88x^2 + 41x^3) \tag{4.3}$$

where $x = \lambda/555$ -1,
λ = wavelength (nm)

The luminous flux [25][13]equation is considered from eqn (4.2) and eqn(4.3)

$$\Phi = K_m \int_{380}^{780} S(\lambda) V_{RGB}(\lambda, \lambda_c)\, d(\lambda) \tag{4.4}$$

where, K_m = Maximum visibility (approximated 683 lm/W at wavelength equals to 555 nm)
$S(\lambda)$ = standard luminosity spectrum curve
$V_{RGB}(\lambda, \lambda_c)$, radiant power spectrum (or) SPD of white light

To obtain luminous flux, we are using the eq(4.4) in matlab. The area under the two functions $V(\lambda, \lambda_c)$ and S(λ) produces luminous flux. So, eye sensitivity curve is implemented from the eqn(4.3) as shown in the figure 4.5 below. The wavelength of

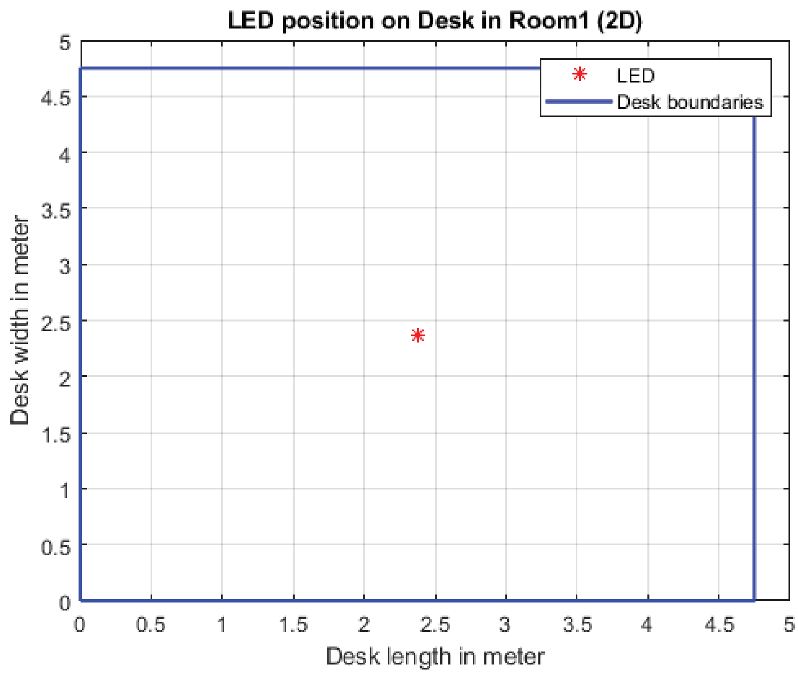

Figure 4.3: Room1 RGB LED position on desk

this spectral sensitivity curve and luminous flux are same, that are range from 380 to 780 nm.

The luminous intensity displays the lighting qualities of the needed LED sources in any direction in the room. It is the luminous flux (Φ) for the unit solid angle of omega (Ω).

$$I = \frac{d\Phi}{d\Omega} \tag{4.5}$$

Assume that an LED light source has a half-powered semi-angled ($\psi_{1/2}$) that is not equivalent to 60° in practice. The Lambertian radiation pattern is used in these LEDs. The light intensity at the Rx surface is taken as an

$$I(\phi) = I(0)\cos^m(\phi) \tag{4.6}$$

$\phi =$ irradiance angle of led with respect to axis to normal to receiver

$$m = -\frac{\ln(2)}{\ln\left(\cos\phi_{1/2}\right)} \tag{4.7}$$

$\phi_{1/2} =$ is the half power semi angle of Led.

The PD sensitivity curve limits are using to calculate the transmit power. So we are finding PD sensitivity curve limits from the Eqn (4.14). We observe the wavelengths range from 420 to 1120 nm. The transmit power value is obtained from the double integrals which are PD wavelengths and area of the power spectrum caused by light on the PD. Therefore, the Tx optical power P_t[32] is

$$P_t = K_m \int_{\Lambda_{min}}^{\Lambda_{max}} \int_0^{2\pi} \Phi d\theta d\lambda \approx 4mw \tag{4.8}$$

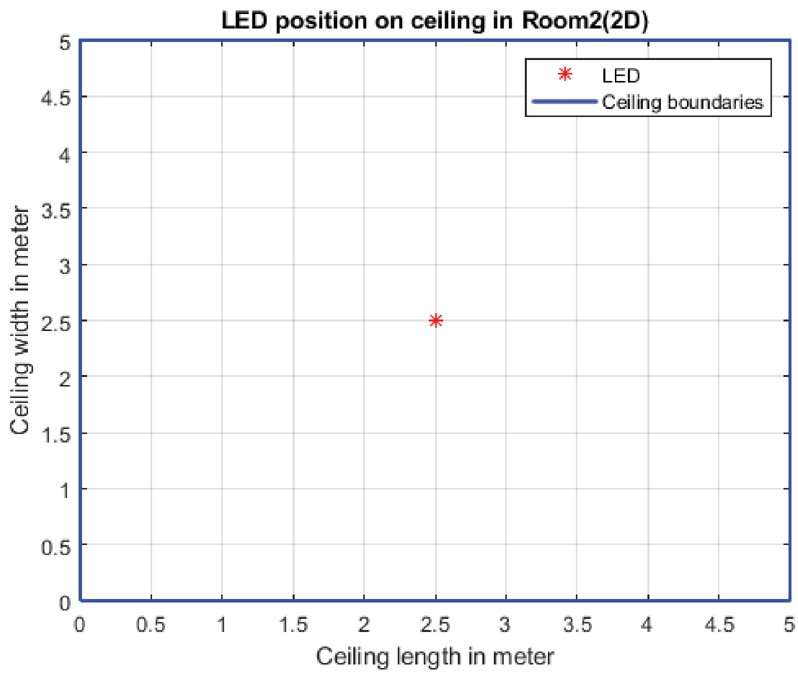

Figure 4.4: Room2 RGB LED position on desk

Where Λmin, Λmax are values calculated from PD sensitivity.

4.4.2 Channel model

For two rooms indoor VLC, there are two types of links available in between the Tx and Rx.
For LOS Links, We have to find direct current(DC) channel gain. To find the DC channel gain, we have to find the gain of the PD first by using the equation[19][5]

$$g(\psi) = \begin{cases} \frac{n^2}{sin^2\psi_{fov}}, & 0 \leq \psi \leq \psi_{fov}, \\ 0, & 0 \geq \psi_{fov} \end{cases} \tag{4.9}$$

n = refractive index, ϕ_{fov} = field of view angle from receiver plane
Then, DC channel gain of LOS links are estimated by Lambertian emission[19][5]

$$H_d(0) = \begin{cases} \frac{A_E(m_l+1)}{2\pi d^2} cos^{m_l}(\phi)T_s(\psi)g(\psi)cos(\psi), & 0 < \psi < \psi_{fov}, \\ 0, & 0 > \psi_{fov} \end{cases} \tag{4.10}$$

A_E = $Acos(\psi)$, for 0<ψ<90, effective area of PD, ϕ = irradiance angle of LED, ψ = angle of incidence of PD, $T_s(\psi)$ = transmission parameter of filter, d = distance between receiver and transmitter,

$$m_l = \frac{ln2}{cos\phi_h}, it\, is\, order\, of\, Lambertian\, emission \tag{4.11}$$

ϕ_h = semi angle at half power of LED,

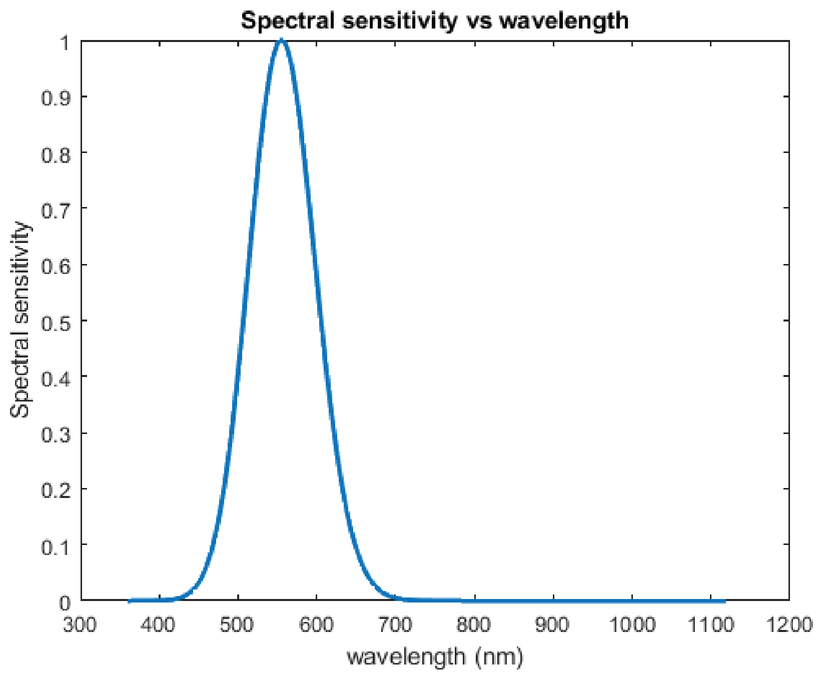

Figure 4.5: Eye sensitivity curve of visble light spectrum[32]

For NLOS links, we have reflections of so many orders, but here we are considering first-order reflections[19][5]. The DC channel gain of NON-LOS, only for first-order reflections are estimated by the equation[19][5]

$$H_{ref}(0) = \begin{cases} \frac{A_E(m_l+1)}{(2\pi d_1 d_2)^2} \rho dA_{wall} cos^{m_l}(\phi_r) cos(\alpha_{ir}) cos(\beta_{ir}) T_s(\psi) g(\psi) cos(\psi_r), & 0 \leq \psi_r \leq \psi_{fov} \\ 0, & \text{elsewhere } \psi_r \geq \psi_{fov} \end{cases} \tag{4.12}$$

$$\begin{aligned} d_1 &= \text{LED and reflective point distance,} \\ d_2 &= \text{reflective point and surface of detector distance,} \\ \phi_r &= \text{irradiance angle to reflective point,} \\ \rho &= \text{reflective factor 0.8,} \\ dA_{wall} &= \text{reflective area of small region on the wall} \\ \phi_r &= \text{reflective point irradiance angle,} \\ \alpha_{ir} &= \text{reflective point irradiance angle,} \\ \beta_{ir} &= \text{PD receiving point irradiance angle,} \\ \psi_r &= \text{reflective surface incidence angle} \end{aligned}$$

The single mode-step index optical fiber[4] is used to connect and transmit data from room1 to room2. The text data is sent from the ceiling(2.5,2.5,3), which is the APD position of the room1, to the ceiling(2.5,2.5,3), which is the LED position of the room2. Since the distance from room1 to room2 is (≤10 meters). We haven't observed any channel errors and data errors[21]. So, we are excluding the simulation of optical fibers in Matlab.

4.4.3 Receiver

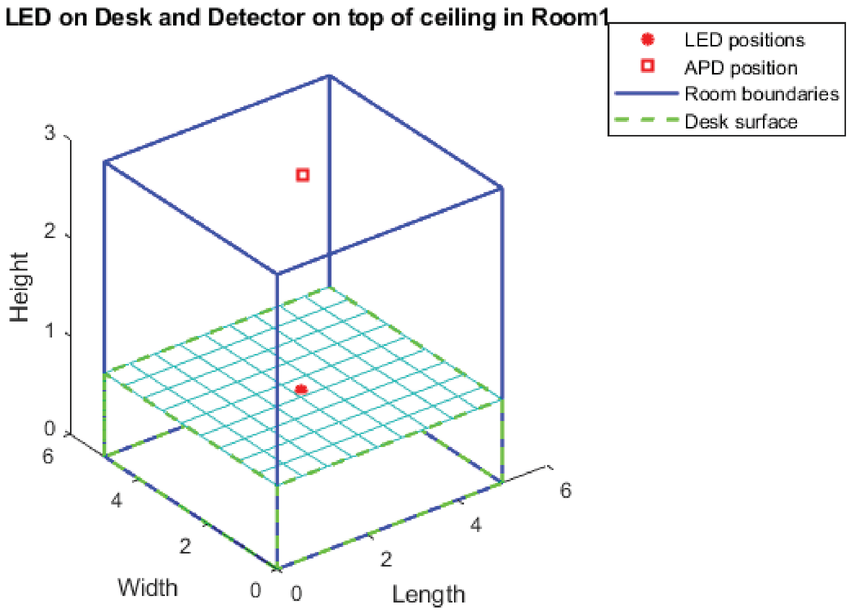

Figure 4.6: RGB LED and APD postions in Room1

The ceiling acts as a Rx plane in room1 as shown in figure 4.6. The dimension of Rx is $room_c$(x1,y1,z1), where $0 \leq (x1, y1, z1) \leq 5$. In the room2, desk(x2,y2,z2), where $0.125 \leq (x2, y2, z2) \leq 4.875$ acts as the Rx plane looks like figure 4.7. We assume the Rx has an aperture A(m^2)[12]. The area of PD is A_d (m^2) placed on the focal plane of an aperture lens having area A(m^2). The diameter and focal distance of the aperture lens are assumed to be identical. This results in diffraction-limited FOV[12]

$$\Omega_{dl} \approx (\frac{\pi}{4})^2 \frac{\lambda^2}{A} \tag{4.13}$$

λ = radiated wavelength (in meters)

For [12],

$$FOV = (\frac{\pi}{4})\frac{A_d}{A} \tag{4.14}$$

Photo detector power of background is[12]

$$P_b = P_0 \frac{\Omega_{fv}}{\Omega_{dl}} \approx P_0 \left(\frac{4A_d}{\pi\lambda^2}\right) inW. \left(\frac{4A_d}{\pi\lambda^2}\right) \tag{4.15}$$

Horizontal illumination of NLOS[19][5][18],

$$I_{\text{NLOS, Hor}} = \frac{\rho I_0 \cos^m(\alpha_{ir}) \cos(\beta_{ir}) \cos(\gamma) \cos(\delta) d\text{Awall}}{\pi(d1d2)^2} \tag{4.16}$$

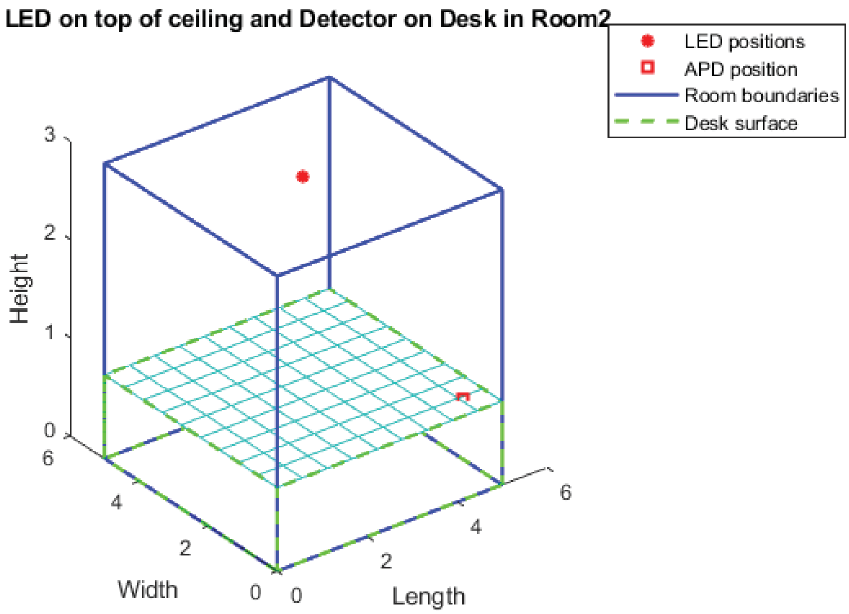

Figure 4.7: RGB LED and APD postions in Room2

Received power of LOS[19][5][18],

$$P_{LOS} = \begin{cases} \frac{(m_l+1)A_g}{2\pi d^2} P_t cos^{m_l}(\phi) T_s(\psi) g(\psi) cos(\psi), & \text{if } 0 < \psi < \psi_{fov}. \\ 0, & 0 > \psi_{fov}. \end{cases} \quad (4.17)$$

where, P_t = transmitter optical power $A_E = Acos(\psi)$, for $0<\psi<90$, effective area of PD, m_l = order of lambertian emission, ϕ = irradiance angle of LED, ψ = angle of incidence of PD, $T_s(\psi)$ = transmission parameter of filter, d = distance between receiver and transmitter, Received power of NLOS,

$$P_{NLOS} = \begin{cases} \frac{A_E(m_l+1)}{(2\pi d_1 d_2)^2} P_t \rho d A_{wall} cos^{m_l}(\phi_r) cos(\alpha_{ir}) cos(\beta_{ir}) T_s(\psi) g(\psi) cos(\psi_r), & \text{if } 0 < \psi_r < \psi_{fov}. \\ 0, & 0 > \psi_{fov}. \end{cases} \quad (4.18)$$

The total power received at Rx is obtained by combining eqn(5.55) and eqn(5.56)[19][5][18]

$$P_r = \sum^{LEDS} \left\{ P_{LOS} H_d(0) + P_{NLOS} H_{ref}(0) \right\} \quad (4.19)$$

We are using this received received power for sending text data and receive the data using OOK modulation as shown below[19][5][18].

4.4.4 Implementation of on-off keying modulation technique for LOS and NON-LOS

For visible light communications, on-off keying modulation is the most often used optical modulation for IM/DD methods[8][18].

$$p(t) = 2P_r \quad \text{for } t\varepsilon\,[0, T_b] \tag{4.20}$$

$$p(t) = 0 \quad \text{elsewhere} \tag{4.21}$$

We modulate the signal using Txs to achieve OOK keying in the system. At Rxs, RSS-based localization is used to determine the device's position based on signal route loss due to propagation[8][18]. The difference between the 1s and 0s in the transmitted optical power is determined by for OOK keying modulation[18].

$$P_{op} = \eta_{\text{ook}}\, P_{\text{t}} \tag{4.22}$$

At the Rx end, the optical gain is given as

$$P_R = H(0) \cdot \eta_{\text{ook}}\, P_{\text{t}} \tag{4.23}$$

For the case of NON-LOS where reflections are taken into consideration the equation is as follows[8][18].

$$P_R = \sum^{N_{LEDS}} \left\{ P_t H_d(0)\eta_{\text{ook}} + \int_{\text{Reflections}} p_t dH_{\text{ref}}\,(0)\eta_{\text{ook}} \right\} \tag{4.24}$$

4.4.5 Detection

We consider APD direct detection in presence of non thermal noises in the channels[12]. The output signal can be modelled as

$$x(t) = e \sum_{n=-\infty}^{\infty} g_n h\,(t - t_n) + \zeta(t), \tag{4.25}$$

where e = an electron charge ,
g_n = APD random gain with n th photon detection
h(t) = response of the APD to a photon

Average receiver photon count[12] (photons/sec)

$$\lambda_r(t) = \lambda_b + \lambda_s \eta d(t) \tag{4.26}$$

where, background wave length $\lambda_b = \frac{\alpha}{hf} P_b$
signal wave length $\lambda_s = \frac{\alpha}{hf} P_s$,
η, optical turbulence channel effect
P_s, input signal power
P_b, optical signal power
α, quantum efficiency of primary photon detection

We are using estimation process of channel estimation detection, in detail we are using average [12][26]signal level eqn =

$$\left(E\{\eta\}\frac{K_s}{2}+K_b\right) \tag{4.27}$$

where, K_s = average signal photon count , K_b = average background photon count channel effect[12] We then using optimum Rx architecture conditional[12] probability density function (pdf) of eqn

$$f(x \mid \eta, d=l)=\frac{1}{\sqrt{2\pi\sigma_l^2(\eta)}}\exp\left\{-\frac{(x-m_l(\eta))^2}{2\sigma_l^2(\eta)}\right\}$$
$$l \in \{0,1\}$$

where $m_1(\eta) = \eta K_s + K_b$, $m_0 = K_b$, $\sigma_1^2(\eta) = F(\eta K_s + K_b) + \sigma^2$, and $\sigma_0^2 = FK_b + \sigma^2$. Note that $\sigma_1^2(\eta) > \sigma_0^2$. In fact, since η can assume any value in $[0,\infty)$[12] Aided gain channel (AGC) estimation, uses channel gain with short term variation[12] $\hat{n}$

$$x_{ST-AGC}=\frac{x}{\hat{\eta}} \tag{4.28}$$

when $\hat{\eta} \approx \eta$ and $K_s >> K_b$ (as is in most cases)[12], $E\{x_{ST-AGC}\} \approx \frac{K_s}{2}$,
Dual threshold equation[12]

$$\frac{1}{\sqrt{2\pi\sigma_1^2(1)}}\exp\left\{-\frac{(\Gamma_{ST-AGC}-m_1(1))^2}{2\sigma_1^2(1)}\right\}=\frac{1}{\sqrt{2\pi\sigma_0^2}}\exp\left\{-\frac{(\Gamma_{ST-AGC}-m_0)^2}{2\sigma_0^2}\right\} \tag{4.29}$$

Then we are doing performance analysis by using BER formulas Now we are using the relation between BER and signal to noise ratio (SNR) of the channel[18][6]. In AWGN channel conditions, The BER relationship of OOK signal and SNR channel is depicted by the following equation[18][6].

$$BER = Q\left(\frac{P}{\sqrt{R_b N_0}}\right)=Q(\sqrt{SNR}) \tag{4.30}$$

Responsivity of APD is[26]

$$R=\frac{i_\lambda}{P_\lambda}==\frac{ne\lambda_0}{hc} \tag{4.31}$$

Chapter 5

Results and Analysis

In this chapter, we are going to discuss the results obtained from the Matlab simulation. Two important topics are discussing in this chapter, the BER distributions inside the two rooms when a text message is sending from one room to another room.

5.1 Output responsivity curves of optical photo diode in both rooms

5.1.1 Room 1

In room1 LED has been placed on the desk and this light transmission will be detected by a PD which is placed at maximum output power level.

From this ceiling point (2.5,2.5,3) the maximum power value is 15.256*10e^{-}06. Turbulence channel conditions have been selected for two scenarios which are type 1 and type 2 as shown in figure 5.1. Type 1 is considered as best-case scenario having carrier amplitude levels in between 1 and 2 range whereas Type 2 is considered a worst-case scenario which has minimum value 3 and maximum value of 10 We have used a single threshold equation to test the various test cases.

Result describes that in Type 1 we have minimum error rates occurred at test cases 2,8,9,10 in which most of them are zero values compared to Type 2 from table 5.1. And in remaining test cases for both Type 1 and Type 2 the error rates occurred to be constant which is around 0.43.

Figure 5.1: Simulation of error rates using different test cases in Room1

From figure 5.2 we have analyzed the performance analysis of the APD detector to find the probability of BERs. We have selected turbulence conditions for average signal photon count within the range of 0<Ks<1000 and the probability of BERs of Type 1 is less compared to Type 2 in room 1 as shown in table 5.2.

Type 1 value exponentially decreases from 10*e^{-}3 to 0 when Ks value increases and similar for Type2 which decreases from 14*e^{-}3 to 0 due to Ks value decrease. Hence Type 1 is proven best to transfer data in room1 from the selected point.

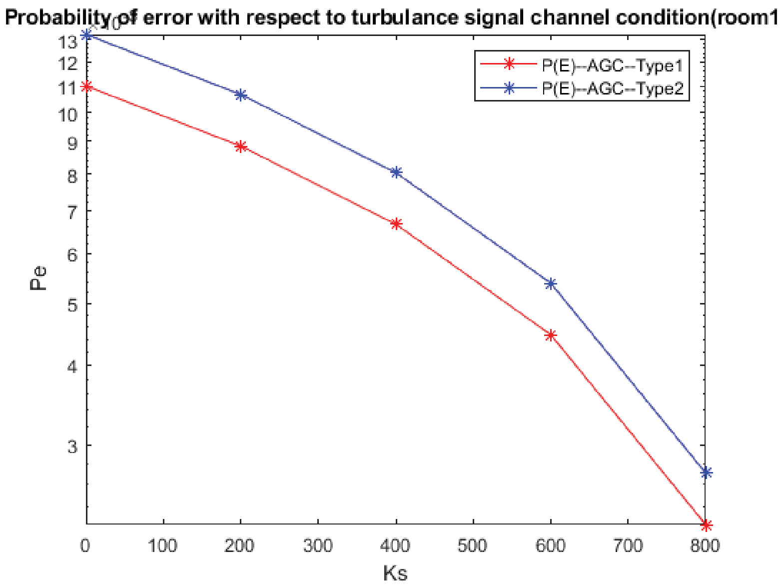

Figure 5.2: APD AGC-OOK type-1 and type-2 probability of errors in Room1

From the figure 5.3, the results we observed that the responsivity of the PD is dependent on received signal power. Rx signal power gradually increases with an increase in responsivity of the ADP diode. The output power values are reaching to 10^{31} mw.

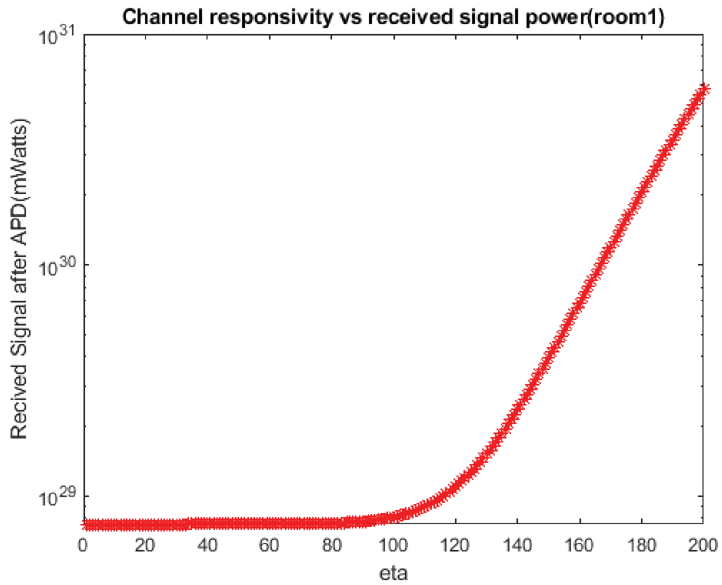

Figure 5.3: Reponsivity curve of APD detector Room1

5.1.2 Room 2

In room2 LED has been placed on the ceiling and this light transmission will be detected by a PD which is placed at the minimum output power level.

From this desk (4,5,0.5,0.85) the maximum power value is 7.97632*10e^{-}12. Turbulence channel conditions have been selected for two scenarios which are type 1 and type 2 as shown in figure 5.4.

Result describes that in Type 1 we have minimum error rates occurred at test cases 2,8,9,10 in which most of them are zero values compared to Type as shown in table 5.1. And in remaining test cases for both Type 1 and Type 2 the error rates occurred to be constant which is around 0.43

Figure 5.4: Simulation of Error rates using different test cases in Room2

From figure 5.5 we have analyzed the performance analysis of the APD detector to find the probability of BERs. We have selected turbulence conditions for average signal photons count within a range of 0<Ks<1000 and the probability of BERs of Type 1 is less compared to Type 2 in room2 as shown in table 5.2.

Type 1 value exponentially decreases from 10*e^{-}3 to 0 when Ks value increases and similar for Type2 which decreases from 14*e^{-}3 to 0 due to Ks value decrease. Hence Type 1 is proven best to transfer data in room 1 from the selected point.

From the results above we observed that the responsivity of the PD is dependent on received signal power. Rx signal power gradually increases with an increase in responsivity of the ADP diode. The output power values are above 10^{23} mw.

The goal of the simulation is observed by responsivity curves for room1 and room2 in which room2 has a high value compared to room1 since it is dependent on power transmitted to LED through PD.

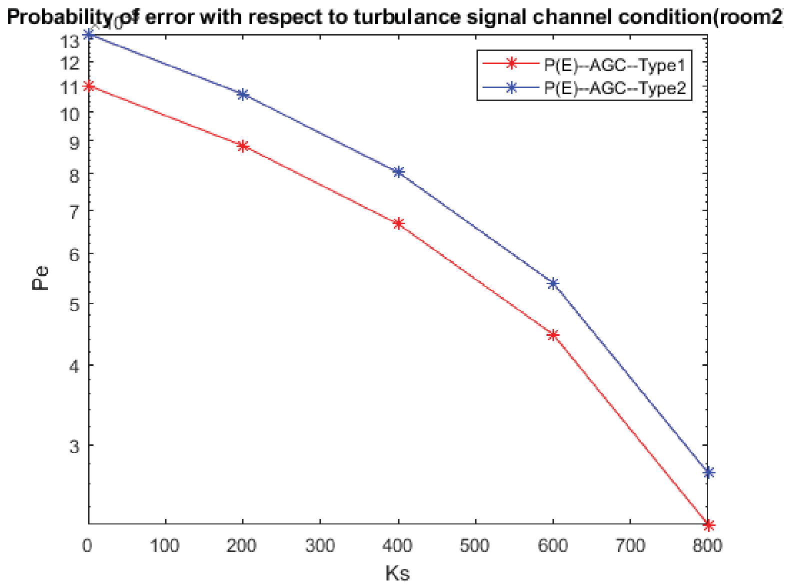

Figure 5.5: APD AGC-OOK type-1 and type-2 Probability of errors in Room2

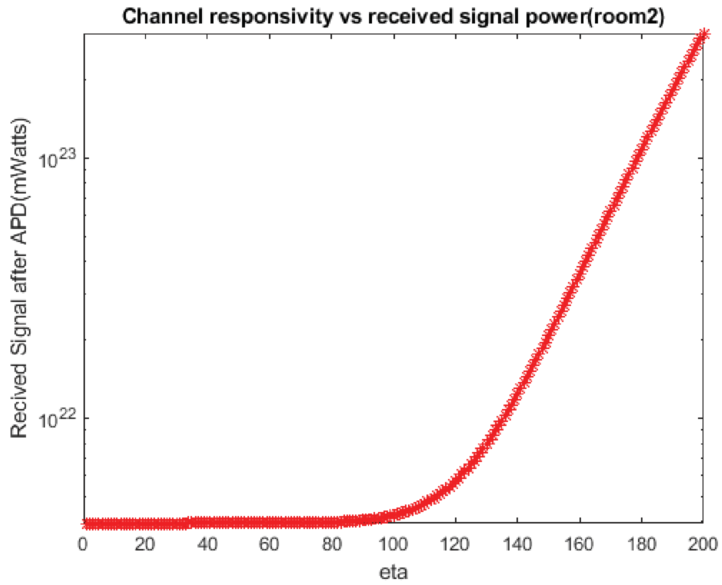

Figure 5.6: Reponsivity curve of APD detector Room2

5.2 Simulation output of BER distributions inside two rooms

The BER of PD at available positions while sending data in the two rooms of equal sizes 5x5x5 is calculated from the Eqn(4.24). The whole system simulation parameters are shown in the table 4.2. The white or RGB LEDs produce the power at different positions on top of the ceiling in room1. This power is used to transfer data in OWC. The figure 5.7 shows BER distribution of LED-PD combination in room1, which LED is placed on desk(2.375,2.375,0.85) and the PD is placed on different

Room 1 Type 1	Room 1 Type 2	Room 2 Type 1	Room 2 Type 2
0.422	0.422	0.422	0.422
0.359	0.422	0.359	0.422
0.422	0.422	0.422	0.422
0.422	0.422	0.422	0.422
0.420	0.422	0.422	0.422
0.422	0.422	0.422	0.422
0.422	0.422	0.422	0.422
0.412	0.422	0.412	0.422
0	0.422	0	0.422
0	0.422	0	0.422

Table 5.1: Single point BERs of Room1 and Room2

Room 1 Type 1	Room 1 Type 2	Room 2 Type 1	Room 2 Type 2
0.011	0.012	0.011	0.012
0.08	0.010	0.08	0.010
0.06	0.008	0.06	0.008
0.04	0.005	0.04	0.005
0.02	0.002	0.02	0.002

Table 5.2: Single point probability of BERs for Room1 and Room2

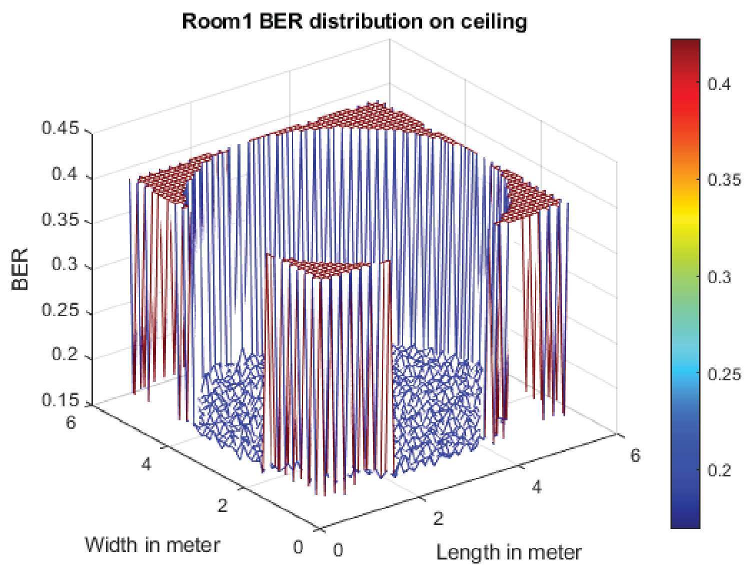

Figure 5.7: Multi point BER distrubtions (Room1)

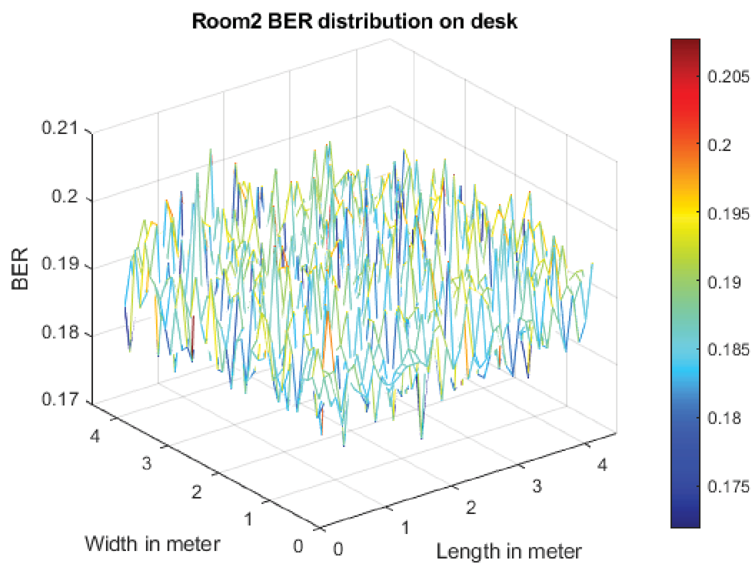

Figure 5.8: Multi point BER distrubtions (Room2)

length, width and same height on $ceiling(x1, y1, z1)$, where $0 < (x1, y1) \leq 5$,$z1 = 5$. The signal-to-noise ratio is $SNR = 0.1db$ used in the channel modeling of the system. The BER is maximum when we are moving the Rx from a center point to corners on the ceiling. The maximum BER value is 0.4. The minimum BER values form like a circle with the value 0.15. The other important observation is as we are considering the single RGB LED, the power is boundary-specific means limited to a specific region on the ceiling. After crossing that boundary we can observe neither the power nor the BER. We are selecting a $ceiling(2.5, 2.5, 3)$ point which is having the least BER in room1. The optical fiber is used as shown in the figure to transmit data between two rooms. In the room2, the data is sending from $ceiling(2.5, 2.5, 3)$ which is LED position to room2 PD placing on different positions on $desk(x2, y2, z2)$ where $0.5 < (x2, y2) \leq 4.5$,$z2 = 0.85$. The BER distribution is as shown in the figure. The BER distribution is as shown in the figure 5.8. There are an even distribution curve in-between values 0.16 to 0.2. There are some fluctuations in the BER values but there are no maximum errors that should make a note. This is because of the surface boundaries which we created to focus more light.

Chapter 6

Discussion

Simulation is an important research method used in our thesis to obtain BERs and their probability density functions. Under this simulation environment, two rooms have been connected via indoor advanced optical communications in which LEDs and PD have been placed in different locations for both rooms.

Another challenging task was to find out the responsivity curves which tell about PD output current w.r.t input optical power.

As shown in figure 7.1, the text message has been used to find out these responsivity curves and BERs. Depending on the turbulence channel effect efficiency η , average signal, and background photon count, K_s, K_b are used to find out the single threshold AGC and OOK for both Type 1 and Type 2 in which Type 1 behavior is stable and suitable compared to Type2 for both rooms. Due to this, we also observe that the responsivity is higher in room2 than that of room1.

Coming to BERs for both rooms, room2 again observes to have BERs in constant compared to room1 because the light spectrum is centrally focused on the desk whereas for room1 it seems to be widespread.

6.1 Threats to validity

Threats to validity is a study focusing on validating threats that are involved and their mitigating solutions.

6.1.1 Internal validity

This section describes the correctness of this research, and the simulation environment has been used to have several scenarios to observe BERs and responsivity. MATLAB is an essential tool used for this simulation environment to make sure proper data has been obtained with these scenarios

6.1.2 External validity

External validity measures and concludes on the worth of this study in which the results might be helpful for industries in the OWC field.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

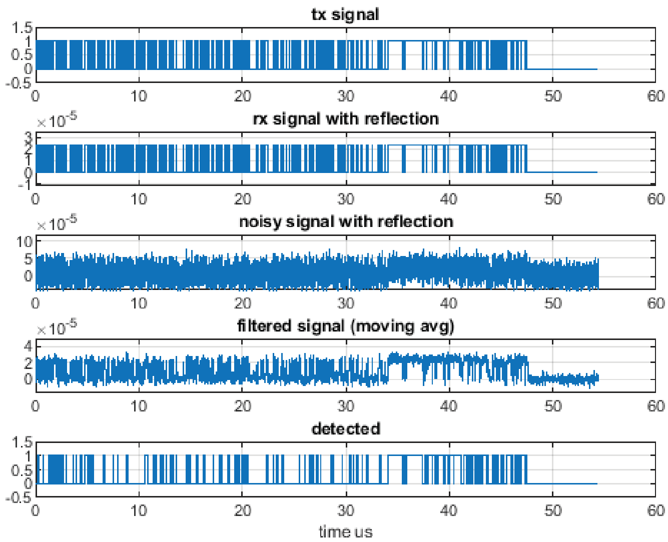

Figure 7.1: Modulation and demodulation graphs of text data

In this thesis, we researched calculating BERs for single-point and multi-point links. As mentioned in section 4.4, we have established both sender (RGB LED) and APD in the simulation environment. This was challenging to do this for both rooms, which have different light spectrums spread again.

To find out responsivity for the APD, we used the AGC OOK detection technique to find output data w.r.t channel efficiency, which is also a responsivity curve, we find that output of detected data is dependent on the responsivity.

Below are further explanations on modulation graphs and demodulated text data, and output text message printed in the console of MATLAB w.r.t to input from room1 to room2 see Figure 7.2.

7.1.1 Answers to Research Questions

RQ.1. Investigate the optical photo diodes responsivity inside the two rooms?

This question has been answered by conducting a simulation to find the responsivity inside two rooms of PDs. As discussed in section 4.4 about both sender and Rx, APD is an Rx in this case. To find responsivity for both rooms in a single point a text input data message has been sent as shown in figure 7.2, and it has been concluded that responsivity of room2 is stable and better compared to that of room1, which has been discussed in 5.1 section which is Results and Analysis.

RQ. 2. Investigate bit error rates vary from room to room for given LED power sources?

Similar to RQ1, this RQ has been answered again by conducting a simulation to find the BERs in all scenarios. BERs have been obtained for multi-point links in which room2 has minimum BERs compared to room1, and below are other graphs obtained, which are demodulation and modulation techniques and BERs obtained in different coordinates of each sender and Rx. The output obtained is shown in table 7.1.

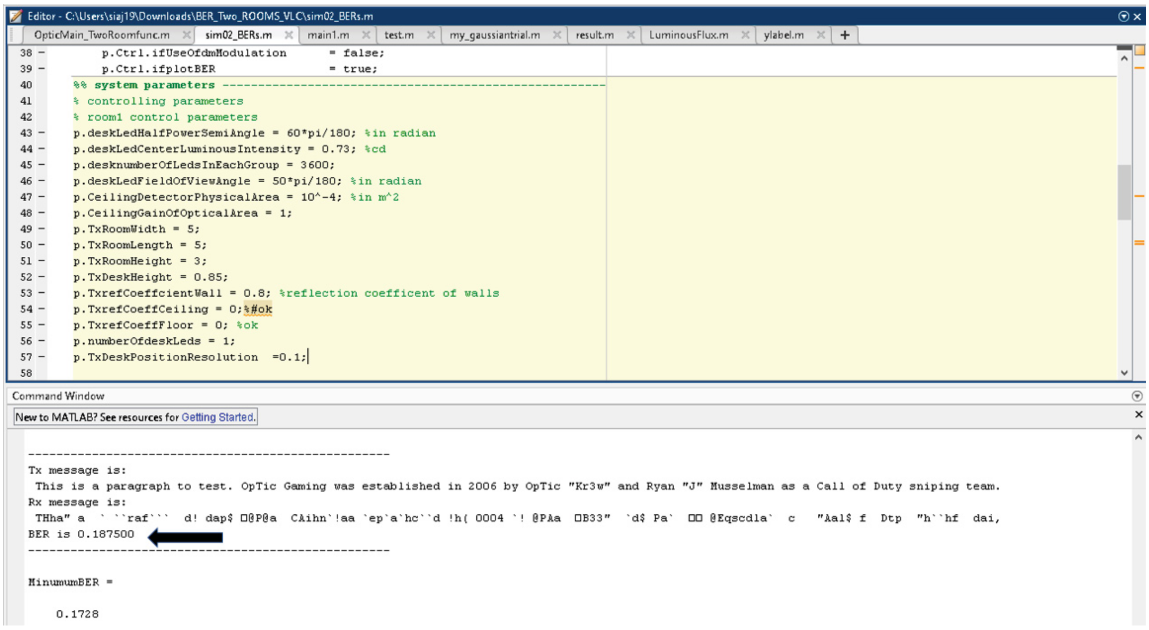

Figure 7.2: Transmitting and Receiving text message from Room1 to Room2 (command window)

7.2 Future Work

In this thesis, BERs and pdfs have been calculated using OOK modulation techniques for two rooms and the same with its responsivity curves. This is completely done in this simulation environment, which helped us place LEDs and PDs, acting as sender

Room 1 Coordinates (x,y,z)	Room 1 BERs	Room 2 Coordinates (x,y,z)	Room 2 BERs
(0.1,0.1,5)	0.422	(0.5,0.5,0.85)	0.18
(0.2,0.1,5)	0.422	(2.8,0.6,0.85)	0.18
(0.3,0.1,5)	0.422	(4.4,1,0.85)	0.181
(2.8,0.1,5)	0.18	(4.1,3.6,0.85)	0.177
(4.8,2,5)	0.186	(3.9,3.8,0.85)	0.19
(3.8,4.3,5)	0.181	(3.4,3.8,0.85)	0.188
(1.4,4.8,5)	0.422	(2.7,3.6,0.85)	0.185
(1.1,4.6,5)	0.422	(2.2,3.5,0.85)	0.18
(3.7,4.8,5)	0.422	(2,3.2,0.85)	0.182
(4.2,4.9,5)	0.422	(1.4,2.8,0.85)	0.187

Table 7.1: Multi point link BERs of Room1 and Room2

and Rx. It would be interesting to calculate these metrics with different modulation techniques like OFDM and its variations in future work.

Another interesting future work is carrying this research with multiple LEDs as sender and considering the room's whole area to calculate these metrics along with multi-point responsivities. The same can be used to do for complete networks with different lengths of optical cables.

We have used text data as input messages in our case, but it would be interesting to use audio or video streams as input to calculate these metrics.

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Appendix A

Supplemental Information

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