SIGNAL-TO-NOISE RATIO AND BIT ERROR RATE ANALYSIS OF INDOOR VISIBLELIGHT COMMUNICATION LINK USING NON-LINE-OF-SIGHT MODEL

SKRIPSI

TEKNIK ELEKTRO KONSENTRASI TELEKOMUNIKASI

Ditujukan untuk memenuhi persyaratan
memperoleh gelar Sarjana Teknik

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UNIVERSITAS BRAWIJAYA
FAKULTAS TEKNIK
MALANG
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LEMBAR PENGESAHAN

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Malang, 29 Januari 2016

Mahasiswa,

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"Dedicated with love to my lovely and great Mother Mrs. Sri Murni Utami, my dearest late Father Mr. Thontowi Djauhari, my father Mr Hadi Sugianto, My 3 funny and great brothers, Mas Ari, Mas Iwan, Mas Iman, And my 5 sisters Mbak Ulfa, Mbak Felli, Teh Ani, Teh Bella, and Teh Eli, my nephew and niece that I can't mention one by one and all my family…

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...Thank you for all, may Allah S.W.T bless you all..."

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Thanks to Allah S.W.T that finally I can complete this project and the thesis with title “Signal-to-Noise Ratio and Bit Error Rate Analysis of Indoor Visible Light Communication Link using Non-Line-of-Sight model” as it is today.

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LIST OF ABBREVIATIONS

FOV	-	Field of View
VLC	-	Visible Light Communication
μW	-	Microwatt
mW	-	Miliwatt
W	-	Watt
cm	-	Centimeter
Km	-	Kilometer
m	-	Meter
S	-	Siemens
K	-	Kelvin
Mbps	-	Megabit/second
Gbps	-	Gigabit/second
FOV	-	Field of View
OOK	-	On-Off Keying
OWC	-	Optical Wireless Communication
IR	-	Infrared
RF	-	Radio Frequency
Hz	-	Hertz
THz	-	Tera Hertz
GHz	-	Giga Hertz
MHz	-	Mega Hertz
IM/DD	-	Intensity Modulation / Direct Detection
SNR	-	Signal to Noise Ratio
BER	-	Bit Error Rate
LOS	-	Line of Sight
NLOS	-	Non Line of Sight
LED	-	Light Emitting Diode

RINGKASAN

Rifka Fahriza Jauhari, Jurusan Teknik Elektro, Fakultas Teknik Universitas Brawijaya, Januari 2016, *Signal-to-Noise Ratio and Bit Error Rate Analysis of Visible Light Communication Link Using Non-Line-of-Sight Model*, Dosen Pembimbing : Dr. Ir. Sholeh Hadi Pramono, MS dan Dr. Rahmat bin Talib.

Visible Light Communication (VLC) merupakan salah satu teknologi komunikasi nirkabel yang populer saat ini. Dengan keterbatasan frekuensi radio spectrum (*bandwidth*), *Visible Light Communication* (VLC) yang menggunakan LED (*Light Emitting Diode*) dengan panjang gelombang antara 380-700 nm untuk membawa informasi memiliki keuntungan lebih dibandingkan sistem komunikasi nirkabel menggunakan radio frekuensi. *Visible Light Communication* (VLC) memiliki kinerja yang lebih baik jika digunakan di dalam ruangan, karena VLC bekerja pada transmisi jarak dekat dan *noise* utama dari sistem ini berasal dari *background backlight* yang berasal dari sinar matahari. Untuk mengetahui performasi dari sistem VLC khususnya yang menggunakan *non-line-of-sight* model, program simulasi dibuat menggunakan program MATLAB. Dengan adanya refleksi yang ada dalam sistem, simulasi akan menunjukan hasil daya yang diterima oleh sistem. Pada thesis ini daya yang diterima oleh sistem VLC non-line-of-sight model dengan adanya pengaruh angle dari field of view dan pengaruh jarak akan ditampilkan. Untuk analisis kinerja, teknik modulasi yang digunakan pada proyek ini adalah OOK-NRZ. Simulasi analisis kinerja pada thesis ini menunjukkan pengaruh *bit rate* dan *receive power* terhadap nilai SNR dan BER pada sistem. Sebagai kesimpulan, pengaruh jarak, angle dari *field of view*, *received power*, dan *bit rate* telah berhasil dianalisis. Kami berharap *Indoor Visible Light Communication* akan dapat digunakan dalam waktu dekat ini.

Kata Kunci – Visible Light Communication, Field of View, Bit Error Rate, Received Power, Signal to Noise Ratio.

SUMMARY

Rifka Fahriza Jauhari, Department of Electrical Engineering, Faculty of Engineering, Universiy of Brawijaya, January 2016, Signal-to-Noise Ratio and Bit Error Rate Analysis of Visible Light Communication Link Using Non-Line-of-Sight Model, Academic Supervisor : Dr. Ir. Sholeh Hadi Pramono, MS and Dr. Rahmat bin Talib.

Visible Light Communication (VLC) as one of the wireless communication technology has become more popular nowadays. With the limited of radio frequency spectrum (bandwidth), the visible light communication that use LEDs (Light Emitting Diodes) with the wavelength between 380-700 nm to carry information has more advantages than Radio Frequency wireless communication system. Visible light communication has better performance specifically in indoor environment, because VLC worked in short-range transmission and the noise of this system comes from the background backlight due to sun-light. In order to know the performance of VLC system especially that used non-line-of-sight link, the simulation program have been developed using MATLAB programming. With the reflections that presents in the system, the simulation will calculate the received power of the system. This project shows the received power of VLC system with of NLOS model according of the influence of various distance and various angle of field of view. For the performance analysis, this project use OOK-NRZ as the modulation technique. The performance analysis simulation for this project show the performance of indoor VLC with various bit rate and received power have been characterized based on SNR and BER value. As the conclusions, the influence of the distance, the angle of field of view, received power, and bit rate has been successfully analyzed. We believe this Indoor Visible Light Communication can be implemented in this near future.

Keyword – Visible Light Communication, Field of View, Bit Error Rate, Received Power, Signal to Noise Ratio.

CHAPTER I
INTRODUCTION

1.1 Background of Study

These days, the information technology continues to grow, in line with the increasing number of human demand to getting information more easily, quickly, and accurately. In this case, the wireless communication technology is the most widely used communication technology right now. The wireless communication technology capable of providing communication facilities such as audio, image, video and data communication. But aside from this, the wireless communication also has advantages and disadvantages.

The advantages of wireless communication technologies are the technology allow users to communication with each other with their mobile devices anywhere and anytime. However, wireless communication technologies specifically that used radio frequency spectrum also have disadvantages in capacity, efficiency, cost, safety, and security.

Due to government regulations for the use of the frequency spectrum, made bandwidth for users became limited. Radio frequency spectrum is almost full now and it is made more difficult to find radio capacity to support the demand of wireless data transmissions for media applications (Osman, 2014: 1).

Therefore, it is now necessary to other wireless communication technologies to able to cover this shortfall. Visible light communication (VLC), is one of many other wireless communication technologies. This day many researchers doing research for this visible light communication system, so this technology can use in near future. VLC that used Light Emitting Diode (LED) as the transmission source has several advantages than using radio frequency or microwave communication.

Due to the absence of restrictions frequency spectrums, VLC has an unlimited bandwidth. With more bandwidth available, the ability of the system to accommodate more users will increase and also the potential to achieved higher transfer speeds for each user will increase accordingly.

Visible Light Communication (VLC) is basically a short-range optical wireless communication using LEDs for illumination and communication simultaneously. VLC is a data communication technology that uses visible light with wavelength between 380 nm and 780 nm. These wavelengths correspond to a frequency range of approximately 384 THz to 789 THz. VLC is the technology which can utilizes the visible light source as a signal transmitter, the air as a transmission medium, and the appropriate photodiode as a signal receiving component (M.H Mustafa, 2014).

VLC, for now, can be use better for an indoor environment, because VLC worked in short-range transmission and the noise for this technology comes from the background backlight due to sun-lighting. Recently, the indoor VLC technology using light-emitting diodes (LEDs) has become a new research field. Using LEDs for the source, there are a lot of advantages in viewpoints of lighting and wireless communication. The lighting equipment with LEDs is easy to install, nice looking and safe for human eye, low cost, low electric power consumption, and long life expectancy are the considerable advantages, also the possibility to achieved high-speed data communication is the indispensable characteristic for using LED infrastructure for lighting as communication devices. From these advantages, it is expected that the indoor optical wireless communication using LEDs will be used widely in the near future (Nguyen, 2010: 1).

This thesis will show how the performance of the system when information transmitted using VLC system in an indoor environment that has several path loss and reflection occurs during transmission.

There is some research for this indoor VLC system, the study discusses about the influence of interference and reflection. Based on numerical analyzes, they show that the system will expect as indoor communication of next generation (Komine, 2004: 1).

In this thesis the influences of the received power, bit rate, angle of field of view and distance to the performance of indoor VLC system using non-line-of-sight link will be discussed. The reflections that occur during the transmission also will be present on this study. The study based on simulation using MATLAB programming. In the simulation the SNR and BER value of the VLC system using non-line-of-sight model showed.

1.2 Problem Statement

The radio spectrum is highly congested now and the demand for wireless data is making this issue much worse. The bandwidth required for the RF communications is rapidly getting exhausted. In the current situation, more bandwidth is being found but it's clearly not enough. More nodes are being added, cell splitting has been done for years but this is expensive. Also, two nodes do not have double the capacity of one as due to interference issue, the law of diminishing returns is at play. Moreover, doubling the infrastructure will not double the revenue. Spectral efficiency also improved over the years, but recently the increase in wireless spectral efficiencies has slowed. Furthermore, research on hazards of RF has found that extreme RF radiation has adverse effect on the environment (P. Salian, 2013: 1).

To overcome this issue, there is another wireless communication. Visible Light Communication (VLC) is a wireless communication technology that can overcome this major issue. With the use of light, that can be seen humans as the source, VLC offers advantages that make it a great complement to established RF communications.

VLC has many advantages compared to RF-based wireless communications, it can potentially use existing local power line infrastructure for wireless communication as a backbone, the bandwidth is virtually unlimited, the security is very outstanding, that is, it is difficult for an intruder to pick up the signal from outside due to characteristic of light, transmitters and receivers using LEDs are cheap and there is no need for expensive radio frequency units, visible light radiations are free of any health concerns. Furthermore, no interference with RF based systems exists, so that the use in airplanes or hospitals is uncritical (Shin, 2011: 1).

In an indoor VLC system using line-of-sight link model is a definite advantage because the signal will be stronger. Visible light signals can be reflected but does not penetrate most of the objects in our daily life which can be a security advantage and perhaps a coverage disadvantage. This characteristic can be also considered as a disadvantage that preventing the signal from spreading among multiple rooms. And furthermore, reflection can absorb much energy so that the rate of communication without line-of-sight (LOS) between the transceivers is greatly limited. Not any optical spread signal under power regulation can be strong enough to let reflected signals still preserve enough power for communication. If light levels are low and VLC receiver can collect photons, it can receive data at a lower data rate. Like radio technology that indirect signals have a lower power and hence the data rate reduces (Mustafa, 2014: 4).

In indoor VLC system, the received power, bit rate, angle of FOV and distance have influence to the performance of the system. The reflection that occurs in the room also has influence to the performance of the system. This is why many researchers doing the research to know how to improve the performance of indoor VLC system using NLOS link.

On this thesis, by making a simulation using MATLAB programming, performance of the system will showed. The background of the problems in this thesis focused on:

1. How to develop the MATLAB code for indoor visible light communication based on non-line-of-sight model?
2. How the distance between the transmitter to the receiver and Field of View influence to receive the power of indoor visible light communication system?
3. How the bit rate, and the received power influence to the indoor visible light communication system performance by seeing the SNR and BER value?

1.3 Scope of Projects

The scope of this research is, this thesis used simulation program using MATLAB programming in order to know the performance of indoor VLC system using NLOS link based on the parameters that exist in the systems.

1. Performance of indoor VLC characterized based on SNR and BER.
2. The dimension of the room is 5.5x5.5x3 m. With the reflection occurs.
3. The simulation using MATLAB is made in accordance with the parameters existed.
4. The physical parameter is assumed for developing the simulation program.
5. The parameter for indoor VLC system and reflection between the transmitter and the receiver of the VLC system has been observed.
6. The modulation technique used in this thesis is On-Off Keying modulation.
7. Simulation based on non-directed NLOS link

1.4 Objectives

Based on the problem statement, the objectives of this research is.

1. Develop the MATLAB code for indoor visible light communication based on non-line-of-sight model.
2. Analyze SNR and BER performance of VLC with the influence of angle of field of view, distance, received power and bit rate parameter.

1.5 Thesis Outline

The thesis Outline for this thesis consists of five chapters which consist of an introduction, literature review, method of research, results and analysis, as well as a ending consisting of conclusions and recommendation.

Chapter 1:

This chapter explained the introduction of this project, background of study, problem statement, scope of project, objectives, and the thesis outline.

Chapter 2:

Chapter 2 explained the introduction to wireless communication, introduction to optical wireless communication, introduction to visible light communication, indoor visible light communication system, On-Off Keying modulation, and advantages and disadvantages of visible light communication.

Chapter 3:

This chapter discussed the method used to develop the visible light communication simulation using MATLAB programming for indoor visible light communication system. Development of performance analysis system simulation based on OOK modulation technique.

Chapter 4:

Chapter 4 provides the result and analysis of the simulation using MATLAB programming. This chapter will show the influence of the distance, field of view, bit rate, and receive power to performance of the indoor visible light communication system.

Chapter 5:

This chapter show the conclusion of the simulation and also the recommendation to the future work that is suggested for improving the proposed system in the future.

CHAPTER II
LITERATURE REVIEW

This chapter will examine the theories that support this thesis. Theories such as the introduction to wireless communication, introduction to optical wireless communication, introduction to visible light communication, indoor visible light communication system, and advantages and disadvantages of the system and.

2.1 Introduction to Wireless Communication

Wireless communication is the transfer of information between two or more points that are not connected by an electrical conductor. The most common wireless technologies use right now is RF communication. With radio frequency spectrum, transmitted audio, video, image, and data communication with long distance transmission can provides.

The rapid growth of wireless communication and access, together with the success of the internet, has brought a new era of mobile/wireless multimedia applications and services. Enormous recent developments have been undertaken by both academia and industry. The convergence of internet, wireless, and multimedia has created a new paradigm of research and development that enables multimedia content to move seamlessly between the internet and mobile wireless networks. With the benefit of the increase in bandwidth in wireless networks, new access capabilities including mobile visual phones and video streaming are pervading people's everyday life. Such capabilities, along with current readily accessible e-mails and mobile web services, provide us an enhanced ability to access to internet content anytime, anywhere, and from any device (Chen, 2002: 1).

But the issue is because of the many demands, the bandwidth required for the RF communications is rapidly getting exhausted. In the current situation, more bandwidth is being found but it's clearly not enough, it is finite. More nodes are being added, cell splitting has been done for years but this is expensive. Also, two nodes do not have double the capacity of one as due to interference issue, the law of diminishing returns is at play (P. Salian, 2013: 1).

The solution to solve this issue is the optical wireless technology. Rather than transmitting radio waves, optical wireless send data in modulated beams of white or infrared light. Optical systems can connect wireless digital devices to a data port on the infrastructure, which in turn can be hooked into whatever high-speed broadband data network serves a house or building. Compared with its radio wave counterpart, the optical wireless band is unlicensed and free of charge. The available bandwidth is much larger than that in traditional radio frequency communication systems and therefore, high data rate communication can be achieved. Besides, since the optical wireless communication utilizes carrier in the optical frequency band, which has no overlap with the traditional radio frequency band, no electromagnetic interference is introduced to the existing radio frequency communication systems (Cui, 2012: 1).

OWC systems operating in the visible band (390–750 nm) are commonly referred to as visible light communication (VLC). VLC systems take advantage of light emitting diodes (LEDs) which can be pulsed at very high speeds without noticeable effect on the lighting output and human eye. VLC can be possibly used in a wide range of applications including wireless local area networks, wireless personal area networks and vehicular networks among others.

2.2 Introduction to Optical Wireless Communication

Optical communication is any form of telecommunication that uses light as the transmission medium. Having originated in ancient times in the form of beacon fires and smoke signals that convey a message, optical wireless communication (OWC) has evolved to a high-capacity complementary technology to radio frequency (RF) communication. OWC systems utilize wavelengths in the infrared (IR) spectrum for IR communication and the visible light spectrum for visible light communication (VLC). Because of the availability of a huge license-free spectrum of approximately 670 THz, OWC has the potential to provide wireless links with very high data rates.

The recent advancements in OWC technology gained significant pace after the pioneering work of Gfeller and Bapst in 1979. They showed the potential of OWC for high-capacity in-house networks promising hundreds of THz bandwidth of the electromagnetic spectrum in the optical domain. One branch of OWC is targeted at outdoor FSO links over long distances which are generally realized through highly directional laser diodes as transmitters. At the receiver side, generally, a photodiode (PD) is employed. Another branch of OWC focuses on indoor mobile wireless networks, and it is realized through a diffuse light emitting diodes (LEDs) as the transmitter (Dimitrov, 2015: 1).

VLC is a stream of OWC. VLC is unique in nature than IR and UV because the light sources which used for illumination purpose are also used for communication purpose using same visible light energy. In VLC, the intensity of the LED light sources is modulated in such way that light flicker is imperceptible to the human eyes (Bhalerao, 2014: 1).

2.2.1 Comparison between Optical Wireless and RF systems

The optical wireless has several characteristics such as the optical waves are absorbed by dark objects, diffusely reflected by light-colored objects, and directionally reflected from shiny surfaces. Also, it could penetrate through glass, but not through walls or other opaque barriers. So the indoor transmissions are confined to a room. This signal confinement makes it easy to secure transmissions against casual eavesdropping and prevents interference between links operating in different rooms. Thus, the indoor communication systems can potentially achieve a very high aggregate capacity, and their design may be simplified since transmissions in different rooms need not be coordinated. Different from traditional RF systems where phase or frequency modulation with coherent detection is adopted widely, the short-range optical wireless communications systems focus on usually utilize intensity modulation / direct detection (IM/DD). The characteristics of radio and optical wireless links are compared in Table. 2.1.

Table 2.1 Characteristic comparison of radio and optical wireless link

Property of medium	**Radio**	**Optical wireless**
Bandwidth regulated?	Yes	No
Multipath fading	Yes	No
Multipath distortion	Yes	No
Path Loss	High	High
Input X(t) represents	Amplitude	Power

(Source: Kaiyun, 2012: 3)

By contrast, radio links are typically subject to large fluctuations in received signal magnitude and phase. Freedom from multipath fading greatly simplifies the design of the optical wireless links. However, the signal to noise ratio (SNR) of a direct detection receiver is proportional to the square of the received optical power, implying that IM/DD links can tolerate only a comparatively limited path loss.

Radio and optical wireless are complementary transmission media, with different applications favoring the use of one medium over the other. Radio is favored in applications where user mobility must be maximized or transmission through walls or over a long range is desired. Optical wireless is favored for short to medium-range applications in which per-link bit rate and aggregate system capacity must be maximized at minimal cost or receiver signal-processing complexity (Kaiyun, 2012: 4).

2.2.2 Typical Optical Wireless Links

An optical wireless link can be classified into two categories, as shown in Figure 2.1. The first category is the line-of-sight (LOS) link, where a transmitter is within the receiver field of view (FOV). The directed link design adopts narrow beam angle transmitter and small FOV receivers, maximizing the power efficiency by minimizing the path loss and reception of ambient light noise. On the other hand, the non-directed link design adopts wide beam angle transmitters and large FOV receivers, alleviating a need for accurate pointing as in the directed link, while at the expense of large path loss. The second category is the non-line-of-sight (NLOS) link, relying generally upon the reflection of the light from the ceiling or some other diffusely reflecting surfaces. Compared with the LOS link, the path loss of the NLOS link is generally much larger, while link robustness and ease of use increase, allowing the link to operate even when barriers, such as people or cubicle partitions, stand between the transmitter and receiver (Cui, 2012: 4).

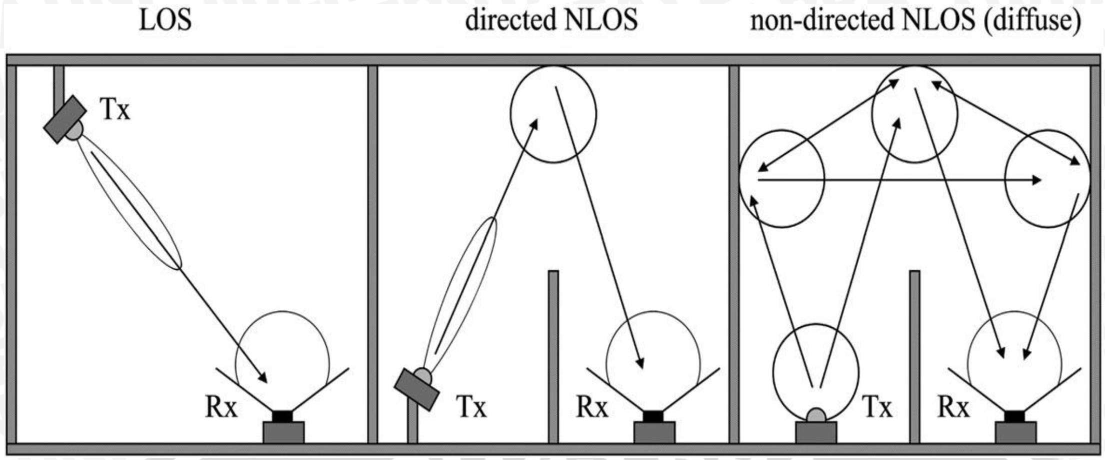

Figure 2.1 Optical wireless link

(Source: Harald Haas, 2015: 15)

2.3 Introduction to Visible Light Communication

The various communication technologies have been advanced to process the immense amount of data information at a very high speed. Among them, recently, visible light communication (VLC) technology is attracting much attention as short range communication means of high speed (Park, 2011: 1).

Visible light being a natural source of energy can be thought of has an alternative to the RF communication. The VLC refers to the communication technology which utilizes the visible light source as a signal transmitter, the air as a transmission medium, and the appropriate photodiode as a signal receiving component.

VLC is rapidly emerging as a compelling technology for supplementing traditional radio frequency communication and enabling new wireless device use cases that are uniquely achievable with this technology. The key property of LEDs that enables VLC is their susceptibility to amplitude modulation at frequencies high enough to achieve meaningful data rates while not affecting the LED’s primary illumination function (Jovicic, 2013: 1).

The VLC denotes a communication technology which uses visible light as an optical carrier for data transmission and illumination. Nowadays, LED at visible wavelengths (380 nm ~ 780 nm) has been actively developed.

The VLC system can be used as a communication source and, naturally, the silicon photodiode which shows good responsivity at visible wavelength region is used as receiving element. The transmission channel is the air, whether it is indoor or outdoor. Visible light is not injurious to vision. The technology uses fluorescent lamps (ordinary lamps, not special communications devices) to transmit signals at 10 kbit/s, or LEDs for up to 500 Mbit/s. Low rate data transmissions at 1 kilometer (0.6 mi) and 2 kilometers (1.2 mi) were demonstrated. RONJA achieves full Ethernet speed (10 Mbit/s) over the same distance thanks to larger optics and more powerful LED (Lee, 2011: 329).

VLC uses white LEDs as source, where the data are transmitted using intensity modulation (IM) technique. The detected intensity is converted as an electrical signal by a photodetector. This process is called direct detection (DD). IM/DD methods are advantageous over the other methods since they are simple and easy to implement. Figure 2.2 show the Visible Light Communication system (K. Shindubala, 2015: 1).

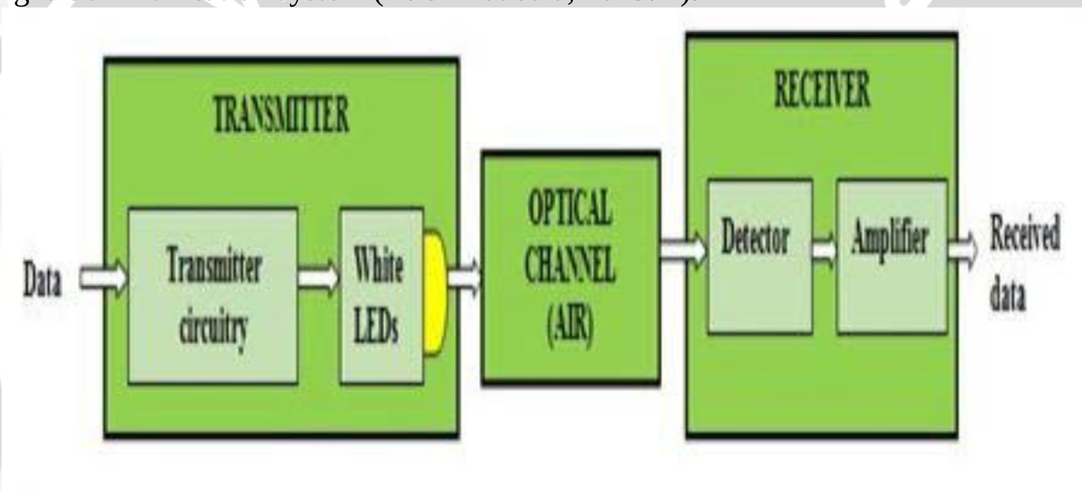

Figure 2.2 Visible light communication system

(Source: K. Shindubala, 2015: 1)

Visible Light Communication can be carried out using optical devices such as LED’s. Lighting reaches nearly everywhere, so communication can ride along for nearly free. LED communication offers an entirely new paradigm in wireless technologies in terms of communication speed, flexibility, usability, and security. An opportunity is arising by using the current state of the art LED lighting solutions for illumination and communication at the same time and with the same module. This can be done due to the ability to modulate LED’s at speeds far faster than a human eye can detect while still providing artificial lighting. While LED’s used for illumination, their secondary duty could be data communication onto lighting system (Prabhu, 2013: 1).

In the last couple of years, VLC research has shown that it is capable of achieving very high data rates (nearly 100 Mbps in IEEE 802.15.7 standard and up to multiple Gbps in research). The communication through visible light holds special importance when compared to existing forms of wireless communications. First, with the exponential increase of mobile data traffic in last two decades has identified the limitations of RF-only mobile communications. Even with efficient frequency and spatial reuse, the current RF spectrum is proving to be scarce to meet the ever-increasing traffic demand. Compared to this, the visible light spectrum which includes hundreds of terahertz of license-free bandwidth (see Figure 2.3) is completely untapped for communication.

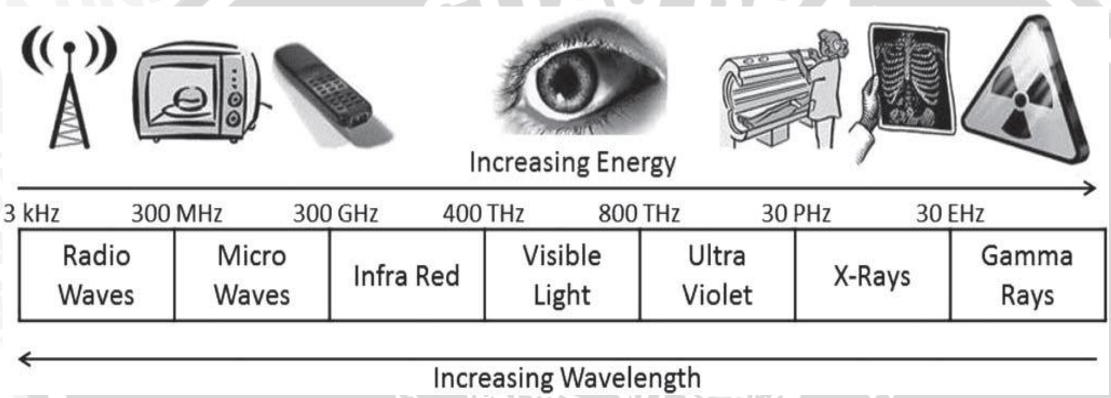

Figure 2.3 The electromagnetic spectrum.
(Source: Zafar, 2015: 1)

In an indoor VLC system, there is two typical VLC links, the line-of-sight (LOS) link and non-line-of-sight (NLOS) diffuse link, are characterized both experimentally and numerically (Lee, 2011: 328).

2.4 Indoor Visible Light Communication System Characteristic

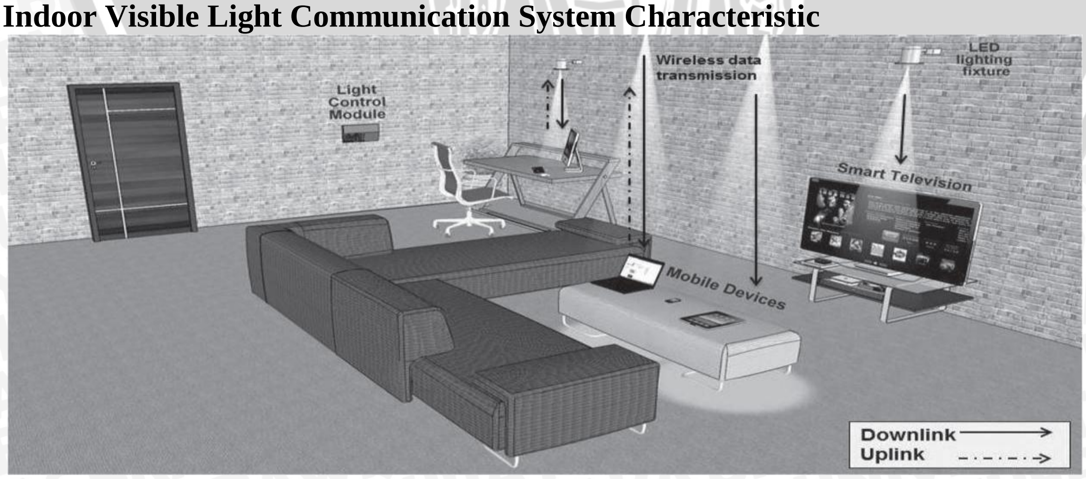

Figure 2.4 Indoor illumination integrated with VLC for next generation smart home lighting.
(Source: Zafar, 2015: 1668)

There exist diverse link connectivity scenarios for indoor visible light communication. For example, there is a single LOS link for point to point VLC between PDAs, multiple LOS links from multiple sources to a single spot, an NLOS link for indoor diffused lighting communication and mixed LOS/NLOS link for information broadcasting. In summary, two fundamental links comprising these diverse link connectivity scenarios are the line of sight link (LOS) and the non-line of sight (NLOS) diffuse link, which will be characterized in this section.

2.4.1 Line of Sight

Indoor VLC systems commonly use the intensity-modulation and direct-detection (IM/DD) scheme. There is a direct path without obstruction and spatial alignment between the radiation pattern of the transmitter and the detection pattern of the receiver. In the following, an LOS component of the light propagation is referred to as the portion of the light radiated by the transmitter that arrives directly within the field of view (FOV) of the receiver (Harald Haas, 2015:15), which could be written as:

$$P_{rm} = \sum_{i}^{N} P_{ri} \quad (3\text{-}1)$$

where *i* denote the single LOS link index and *N* is the number of single LOS links determined by the receiver FOV and the relative position and orientation of the transmitter and receiver.

2.4.2 Non Line of Sight

In indoor environments, the receive optical signal experiences dispersion due to reflection from walls and other objects. In this transmission using indoor VLC system, can be calculate the value of the received power after the reflection occurs. The calculation will be using existing formula.

From now, this will concentrate on the indoor application of VLC and non-directed, line-of-sight (LOS) link, since the indoor application is expected to be developed in a near future. Figure 2.5 show the geometry for indoor NLOS link system.

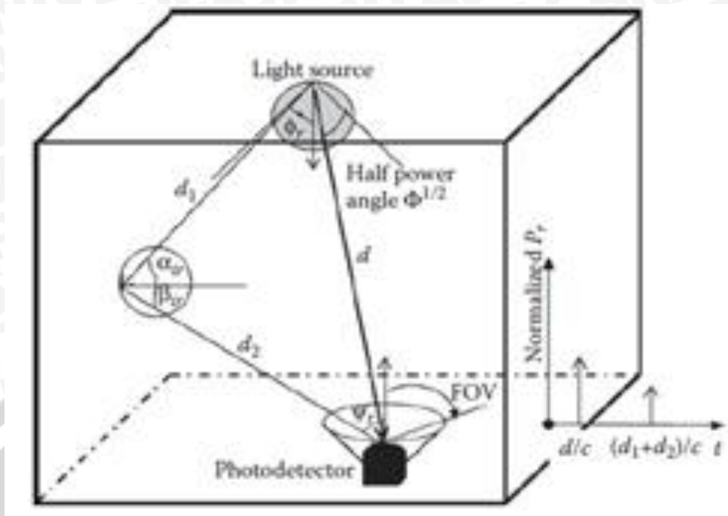

Figure 2.5 Propagation model of diffuse link
(Source: S. Rajbhandari, 2013: 460)

Due to VLC system uses the LED as the transmitter, many commercial lighting LEDs without any beam shaping component can be treated as Lambertian sources with spatial distribution function. Assuming that an LED lighting has a Lambertian radiation pattern, the radiation intensity at a desk surface is given by (Rajbhandari, 2013: 453).

$$I(\emptyset)=I(0)\cos^{ml}(\emptyset) \qquad (3\text{-}2)$$

where:

$\emptyset$ = the angle of irradiance with respect to the axis normal to the transmitter surface,

$I(0)$ = the centre luminous intensity and

ml = the order of Lambertian emission

$$ml = \frac{-\ln(2)}{\ln(\cos \Phi 1/2)} \qquad (3\text{-}3)$$

where:

ml = the order of Lambertian emission

$\Phi_{1/2}$ = the semiangle at half illuminance of an LED

In indoor visible light communication system, the reflectivity will present. The plaster wall has the highest reflectivity followed by floor and ceiling, respectively Considering reflection from the wall, the received power is given by the channel DC gain on directed path *H*d(0) and reflected path *H*ref (0)

$$Pr = \sum^{NLED}\{P_t H_d(0) + \int_{reflection} P_t dH_{ref}(0)\} \quad (3\text{-}4)$$

The DC channel gain of the first reflection is given by

$$H_{ref}(0) = \begin{cases} \frac{A_r(m_l+1)}{2(\pi d_1 d_2)^2}\rho dA_{wall}\cos^{m_l}(\Phi_r)\cos(\alpha_{ir}) \\ \times \cos(\beta_{ir})Ts(\Psi)g(\Psi)\cos(\Psi_r), & 0 \le \psi_r \le \psi_c \\ 0 & elsewhere\ \psi_r > \psi_c \end{cases} \quad (3\text{-}5)$$

where :

d_1 = the distances between an LED chip and a reflective point

d_2 = a receiver surface,

ρ = the reflectance factor,

dA_{wall} = a reflective area of small region,

ϕ_r = is the angle of irradiance to a reflective point,

α_{ir} = the angle of irradiance to a reflective point

β_{ir} = the angle of irradiance to a receiver,

ψ_r = is the angle of incidence from the reflective surface

2.4.3 The Parameters Affecting the Received Signal

In the design of the light distribution by LEDs, some other parameters to be thoroughly analyzed are the luminous spatial intensity distribution, the optical power, and the spectral density. Many parameters are likely to affect the communication link. Such as, the illumination related to the current intensity flowing in the LEDs, the external sources of light (interference), the order of the Lambertian emission, and the nature of the wall surface (multipath scenario and resolvable path). Hence, the bit error rate (BER), the symbol error rate (SER) and the signal to noise ratio (SNR) are functions of these parameters. This has previously been analyzed and summarized in Figure 2.6 (Ndjiorgue, 2015: 7).

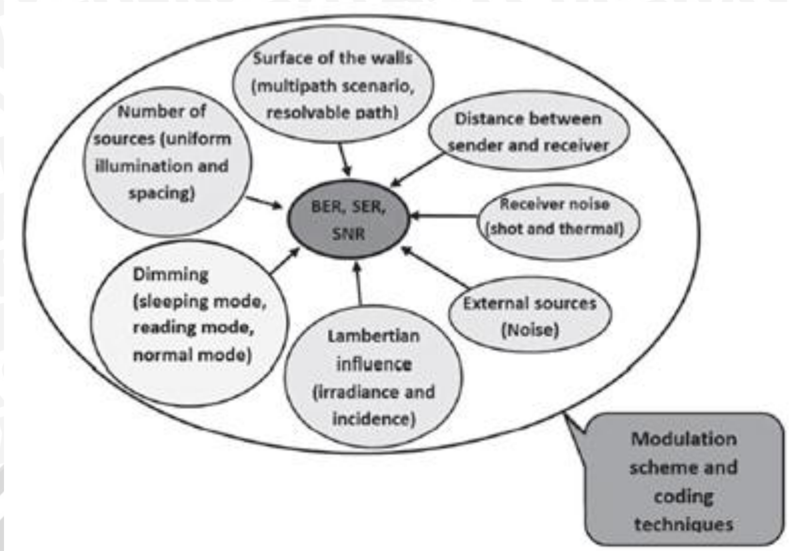

Figure 2.6 Factors influencing the VLC transmission link

(Source: Ndjiorgue, 2015: 7)

2.5 On-Off Keying Modulation

LED is having a special characteristic. LEDs can easily switch ON and OFF with logical 'l' & '0' and data can be sent serially. The simplest modulation use for optical communication is ON-OFF key (OOK) modulation. It represents digital data as the presence or absence of a carrier wave. The presence of a carrier for a specific duration represents a binary one while its absence for the same duration represents a binary zero. In fiber-optics communications, ON-OFF keying modulation is generally implemented in the baseband (Devi, 2014: 1).

In OOK, the data bits 1 and 0 are transmitted by turning the LED on and off respectively. In the OFF state, the LED is not completely turned off but rather the light intensity is reduced. The advantages of OOK include its simplicity and ease of implementation. OOK-like modulation is widely used in wireless communication (Feng, 2015: 1).

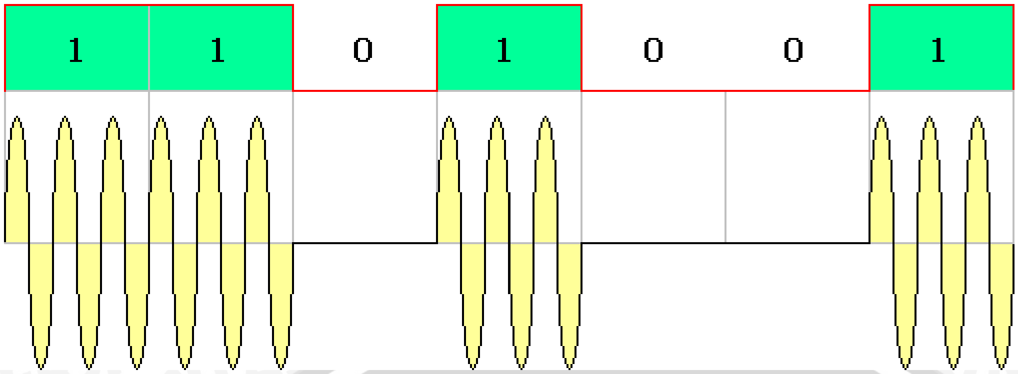

Figure 2.7 On-Off Keying modulation

(Source: Siletec.org)

2.6 Noise and Signal to Noise Ratio (SNR)

There are three major sources of noise in indoor visible light optical link ambient light noise due to solar radiation from windows and doors, noise due to other illumination sources such as incandescent and fluorescent lamps, shot noise induced in the photodetector by the signal and the ambient light and electrical pre-amplifier noise (also known as thermal noise) of the photodetector.

The ambient noise of solar radiation and artificial illumination sources such as lamps results in ambient noise floor which is a DC interference. The effect of such noise can be mitigated by using an electrical high pass filter at the receiver. Most of the previous studies assume that this ambient noise floor remains stationary over space and time. However, no systematic evaluation is present in the literature. For example, the indoor solar radiation changes at different places depending on windows and doors.

The radiation also changes depending on the time of the day (and year) and orientation of the windows/doors. Radiation from other illumination sources will also remain an unavoidable source of noise until it is completely transition to LED technology. It is required that exhaustive indoor measurements are carried out to accurately account for such noise. Once the noise due to solar radiation and artificial illumination sources is filtered, the SNR at the receiver can be calculated based on the shot noise and the thermal noise of the photodetector circuitry.

An SNR can express the quality of a communication system. Assume that the transmitter transmits the signal using on-off keying (OOK) modulation technique. Among all modulation techniques for VLC link, OOK is the simplest one and it is very easy to implement. In a single receiver, the average signal-to-noise ratio (SNR) is defined as the ratio of the received signal to the aggregated noise and it can be seen that when the shot noise is the dominant noise source, the SNR is proportional to the detector area

$$SNR = \frac{(R\mathrm{Pr})^2}{\sigma^2\mathrm{shot}+\sigma^2\mathrm{thermal}} \quad (3\text{-}6)$$

where:

R = photodetector responsivity

Pr = receive power

σ^2shot = shot noise

σ^2thermal = thermal noise

The shot and thermal noise variances are given by

$$\sigma^2\mathrm{shot}=2qR\mathrm{Pr}B+2qI_bI_2B \quad (3\text{-}7)$$

$$\sigma^2 thermal = \frac{8\pi\kappa T_k}{G_{ol}}C_{pd}AI_2B^2 + \frac{16\pi^2\kappa T_k\Gamma}{g_m}C_{pd}^2A^2I_3B^3 \quad (3\text{-}8)$$

where:

q = electron charge constanta

R = photodetector responsivity (A/W)

Pr = receive power (W)

B = bandwidth of the electrical filter that follows the photodetector represented (Hz)

κ = is the Boltzmann's constant (JK^{-1})

I_B = the photocurrent due to background radiation (µA)

T_k = absolute temperature (K)

G_{ol} = the open-loop voltage gain,

C_{pd} = the fixed capacitance of photodetector per unit area (pF/cm^2)

Γ = FET channel noisefactor,

g_m = FET transconductance and noise-bandwidth factors (mS)

I_2 = 0 562

I_3 = 0 0868

A^2 = detector area (cm^2)

For the calculation BER with OOK scheme, the formula

$$BER = Q\sqrt{SNR} \qquad (3\text{-}9)$$

where:

$$Q(x) = \frac{1}{2\pi}\int_{x}^{\infty} \bar{e}^{y2}/2_{dy} \qquad (3\text{-}10)$$

Notice that the received optical power is proportional to the square of the photodetector area (A^2). The shot noise variance is proportional to the detector area. Hence, if shot noise is the dominant noise source, the SNR is proportional to the detector area. The thermal noise is a complicated function of A and hence the noise variance is a complicated function of the photodetector area (Rajbhandari, 2013: 463).

2.7 The Advantages and Disadvantages of VLC System

In addition to the crowding of the frequency spectrum, interference is also a concern for many existing wireless systems. Any simultaneous use of a frequency band will cause interference due to the electromagnetic nature of most wireless devices, which could result in incorrect or loss of information for those users involved. A prime example of this is the use of mobile devices on planes, which directly affects safety.

VLC systems have more flexibility and integrity than other communication systems in many regards. Since the medium for transmission in VLC systems is visible light and not RF waves that can penetrate walls, the issue of security is inherently solved because light cannot leave the room, containing data and information in one location. There is no way to retrieve and access the information unless a user is in a direct path of the light being used to transmit the data. In addition, LEDs are highly efficient and becoming more durable, adding to the integrity of these systems (Ngatced, 2015: 1)

2.7.1 Advantages

Visible light should be considered as the medium for wireless transmission because it has a few advantages over other standard wireless transmissions.

1. The first reason to consider is visible light’s frequency spectrum bandwidth, which ranges from 430 THz to 750 THz.
2. The bandwidth is much larger than the radio frequency bandwidth, which ranges from 3 kHz to 300 GHz. With a larger bandwidth it is possible to accommodate more users and potentially achieve higher transfer rates because each user can be given a larger portion of the bandwidth to transfer information.
3. If the communication system will be used in hospitals, the transmissions will not occur in the Industrial, Scientific, and Medical (ISM) band, therefore not interfering with medical devices.
4. On top of having a higher bandwidth, the frequency spectrum has less regulation than the radio spectrum. With little regulation, the user will be able to choose any frequency to transfer information.
5. If visible light communication systems become more popular, regulations could be placed on these forms of data transmission for the same reasons that they were placed for the radio spectrum.
6. The next major advantage that visible light systems have over other communication systems is its abundance. Light sources are everywhere, and can be more efficiently used by increasing its simultaneous functionality by transmitting data in addition to lighting an area. On typical work days, company buildings, restaurants, grocery stores, etc. will have lights on for at least the duration of hours of operation, of which could be used for visible light communications.

There are also a few drawbacks to visible light in standard situations that could potentially be used as advantages for a visible light communication system. Unlike radio waves, light cannot propagate through walls. Since light cannot propagate out of an enclosed room, the only way to access the information is if the receiver is in the same room; thus, no outside sources will be able to acquire the information. Therefore, light sources are more secure than radio waves because they are not broadcasted for external sources to receive.

Visible light was chosen for a variety of reasons, but primarily because it will not add to the cluttering of the radio frequency spectrum, which is heavily regulated by the FCC, and also because it will avoid the issue of interference in sensitive settings such as hospitals and airplanes. Figure 2.8 shows the wavelength range of visible light.

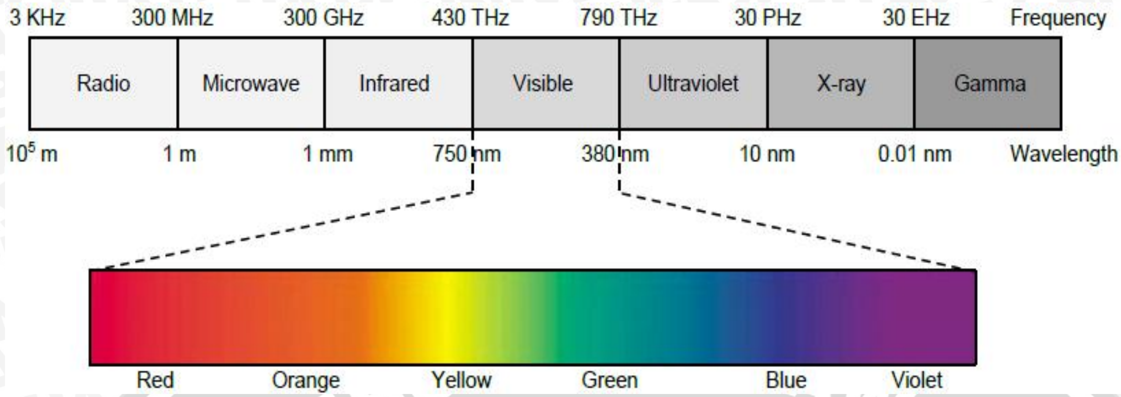

Figure 2.8 Visible light spectrum

(Source: Pathak, 2015:2)

From these wavelengths, the frequency range can be calculated by the following equation:

$$f = \frac{c}{\lambda} \qquad (3\text{-}11)$$

where:

f = the frequency,

c = the speed of light,

λ = is the wavelength.

Thus, it can be shown that the range of frequencies for visible light is around 400-800 THz (Ferreria, 2015: 18)

2.7.2 Disadvantages

Limitations and drawbacks that need to consider include noise from ambient light and the line-of-sight of the system. If the intensity of ambient light is greater than that of the light from our system, the signal-to-noise ratio (SNR) is low, which will distort transmitted data. To compensate for this, the SNR will be maximized by setting thresholds on the microcontroller based on voltage signals produced by the ambient light in conjunction with the transmitter signal.

Also, the system will only be maximized when the LEDs are directly facing the sensor. If the angle is changed even slightly, the maximum range of the system will decrease significantly. The easiest solution is to ensure that the transmitter and receiver are facing directly at each other (Ndjiorgue, 2015: 20).

CHAPTER III
METHOD OF RESEARCH

In order to show the performance of the indoor visible light communication system using non-line-of sight model, this chapter will explain about the method used for this thesis. For the performance analysis, this thesis used simulation method using MATLAB programming. The simulation shows the performances of the system by varying the distance, angle of field of view (FOV), bit rate and received power. The flow of this project has been discussed in this chapter. Figure 3.1 shows the flowchart about the methodology of MATLAB simulation development that will be used in this thesis.

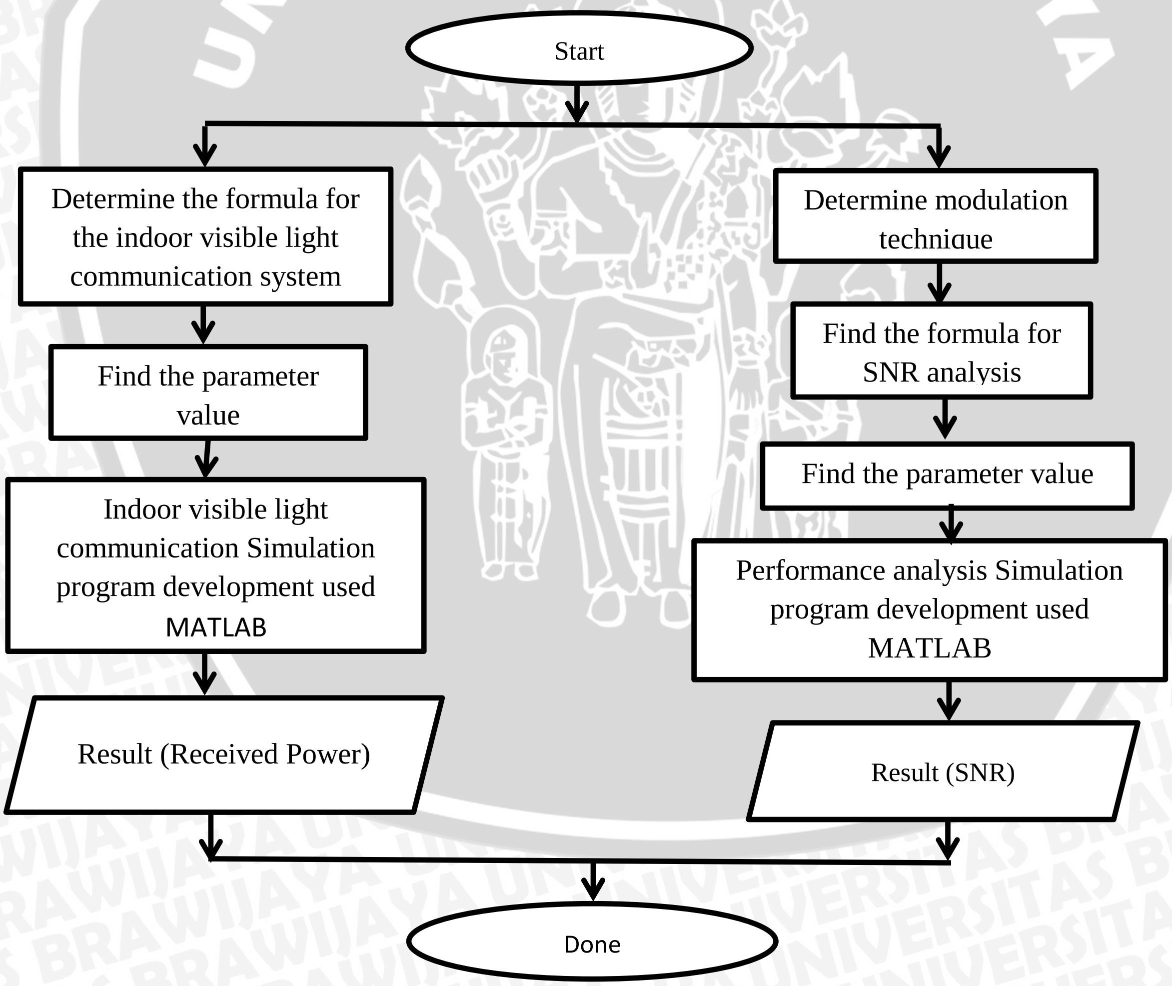

Figure 3.1 MATLAB simulation development
(Source: Design Configuration)

3.1 Non-Line of Sight Formula

In order to develop the simulation program, the formula that will use for simulation program must be determined. In indoor visible light communication, there are many formula that needed for the calculation. There are two link types in indoor VLC system, which are line of sight (LOS) link and non-line of sight (NLOS) link and both link types have different formula. For the NLOS link, the reflection that happened in the room is taken into account. Hence the calculation of the performance of the system for LOS and NOLS will be different. For this thesis the reflections that happened in the room assumed. The calculation for this simulation will add the reflections from 4 walls in the room. The formula will be added to MATLAB programming to create simulation program for indoor visible light communication system using NLOS model. Figure 3.2 shows the flowchart to create the simulation using MATLAB:

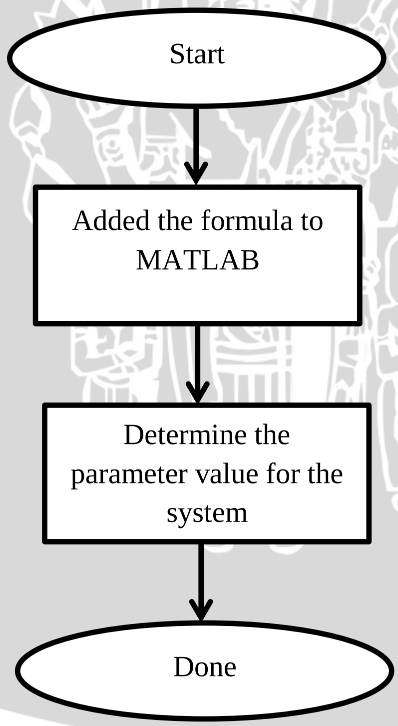

Figure 3.2 Flowchart to create simulation using MATLAB
(Source: Design Configuration)

3.2 Determine Parameter Value

Based on the VLC using NLOS model formula, there is some parameters that will be used in the simulation. The parameters for the room, transmitter and receiver are very crucial to get most reliable analysis for this system. For this project, the size of the room is 5.5x5.5x3 m the LEDs are installed on the ceiling, the height of the desk is 0.85 m and the receiver is placed on the working plane. This simulation used 5 LED and the power of each LED is 1 watt. The LED placed in one place. Figure 3.3 show the room size and position of transmitter and receiver:

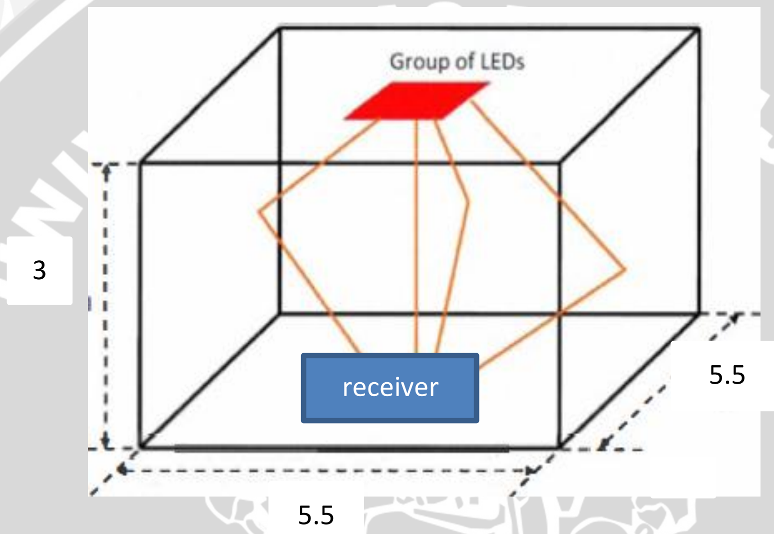

Figure 3.3 Room size and position of the transmitter and the receiver
(Source: Design Configuration)

Table 3.1 Parameter for visible light communication link

Parameters		Value
Room	size	5.5x5.5x3 m
	Reflection coefficient	0.8
Tranmsitter	Location (1 LEDs)	(2.5x2.5x3)m
	Semi-angle at half power (FWHM)	65°
	Transmitted power (per LED)	5x1watt
	Centre Luminous intensity	>450Lx
Receiver	Receive plane above the floor	0.85m
	Active are (A)	1 cm^2
	Half-angle FOV	70°
	Elevation	90°
	Azimuth	0°

(Source: Design Configuration)

3.3 Indoor Visible Light Communication System Simulation Program Development

The VLC using NLOS model simulation program development is based on MATLAB programming. In order to develop the simulation, the code must be created in MATLAB programming based on the formula that will use and then assign the parameter to the formula. In this simulation, the parameter will be same with the previous study first to make sure that the MATLAB code is correct.

For this thesis after make sure the MATLAB code is correct, the simulation will proceed by changes the parameter value. In this thesis, the parameters will be changed are room size, transmitter power, and angle of field of view. From Figure 3.4 shows the flowchart of Indoor VLC system simulation program development.

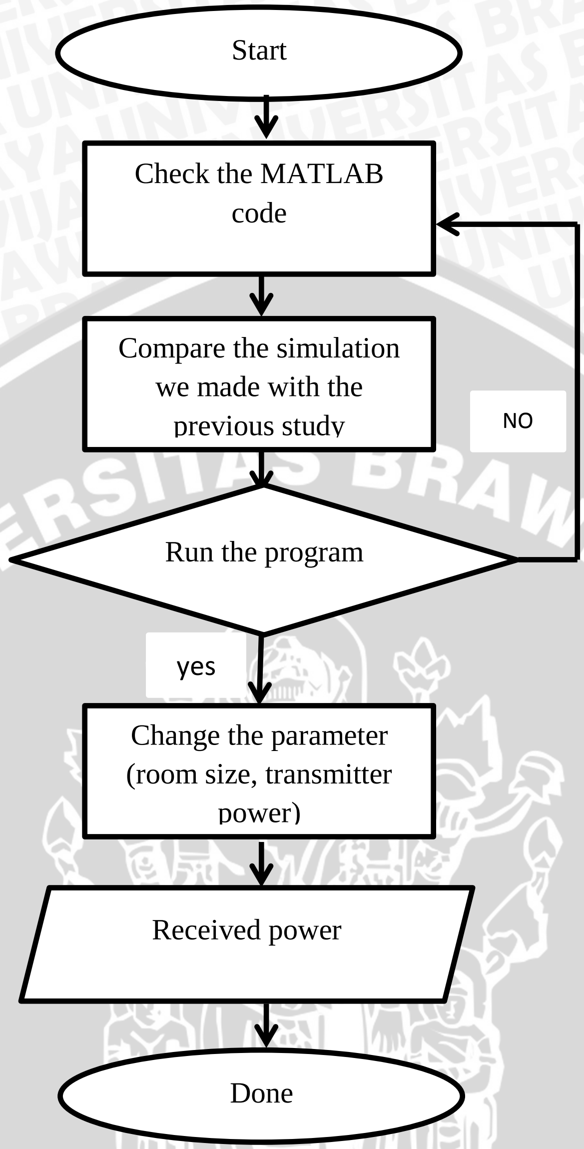

Figure 3.4 Flowchart indoor visible light communication system simulation program development

(Source: Design Configuration)

This simulation program will shows the received power value with reflection present in the system. From this simulation program, the result will show the influenced of the angle of field of view and distance between the transmitter and the receiver to the received power.

3.4 Determine Modulation Technique

For this simulation, the modulation technique will be used is on-off keying non-return to zero (OOK-NRZ). This is typical modulation technique for VLC system study. Based on this modulation technique, the formula to calculate the SNR value of the system is given as.

$$SNR = \frac{(RPr)^2}{\sigma^2 shot + \sigma^2 thermal} \qquad (3\text{-}1)$$

From this formula, it shows that the noise has the influence to the SNR of the system. For the parameters used for this analysis, some parameters will be same with the previous study. The received power value has been obtained from NLOS model simulation as discuss in previous section.

3.4.1 Determine the noise value

In general, noise is very crucial parameter to determine the system performance of communication including for VLC link. Therefore, determine the correct parameters in estimating the noise will influence the accuracy of performance analysis. In this project, in order to make sure the MATLAB code that have been created are right, a comparison with the previous work has been done. The validation comparison that has been checked is the thermal noise value and shot noise value. Figure 3.5 show the influence data rate on noise (T. Komine, 2004):

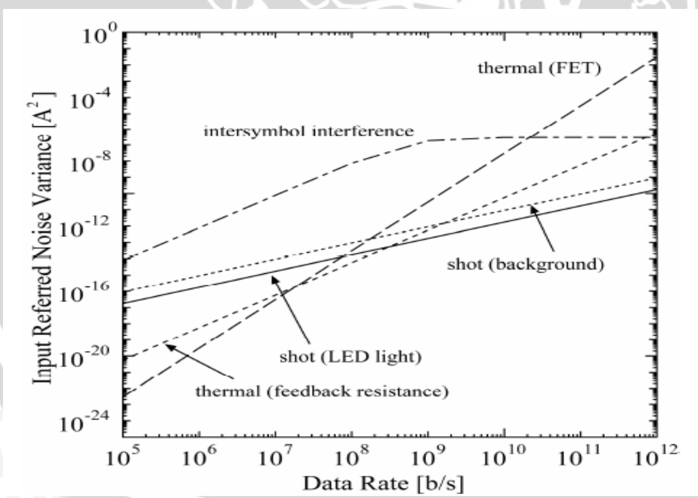

Figure 3.5 The influence of noise on data rate

(Source: Komine, 2004)

From Figure 3.5 the thermal noise in data rate of 10^7 bps is around $10^{-16} A^2$, and from the MATLAB simulation work in this project, the obtained thermal noise is 4.14×10^{-14} A^2

almost the same with the previous study. The differences because the previous study just mentions the B parameter with MB/s unit, on the other hand, the unit for B is Hz. Also from the previous study, did not mention if the bandwidth has intersymbol interference or not. Because the bandwidth can has different value with and without intersymbol interference. So the different from this project calculation and previous study are because the fixed value for B parameter not mention.

From this comparison, the created MATLAB code in this project is correct, the simulation can be proceed by changing some parameters in order to see the performance of the system. For this study the received power is obtained from the previous simulation work of the indoor visible light communication. Table 3.2 show the parameters value that will be used and Figure 3.6 shows how to develop MATLAB simulation for performance analysis in indoor VLC link.

Table 3.2 Parameters for performance analysis

Parameter	**Values**
Electron change (q)	$1.602177X10^{-9}$ c
The photocurrent due to background radiation (Ib)	$5.1X10^{-3}$ A
Bandwidth of the elctrical filter that follows the photodetector (B)	$75X10^{6}$ Hz
Noise bandwidth factor (I_2&I_3)	0.562 0.0868
The photodetector responsivity (R)	0.54 A/W
Power on the receiver (Pr)	$4X10^{-3}$ W
Boltzmann's constant (k)	$1.3806504X10^{-23}$ JK^{-1}
Absolute temperature (Tk)	295K
Fixed capacitance of photodetector/unit area (C_{pd})	112 pF/cm^2
Detector physical area (A)	1 cm^2
Open-loop voltage gain (G_{ol})	10
FET channel noise factor (Nfet)	1.5
FET transconductance (gm)	$30X10^{-3}$ S

(Source: Design Configuration)

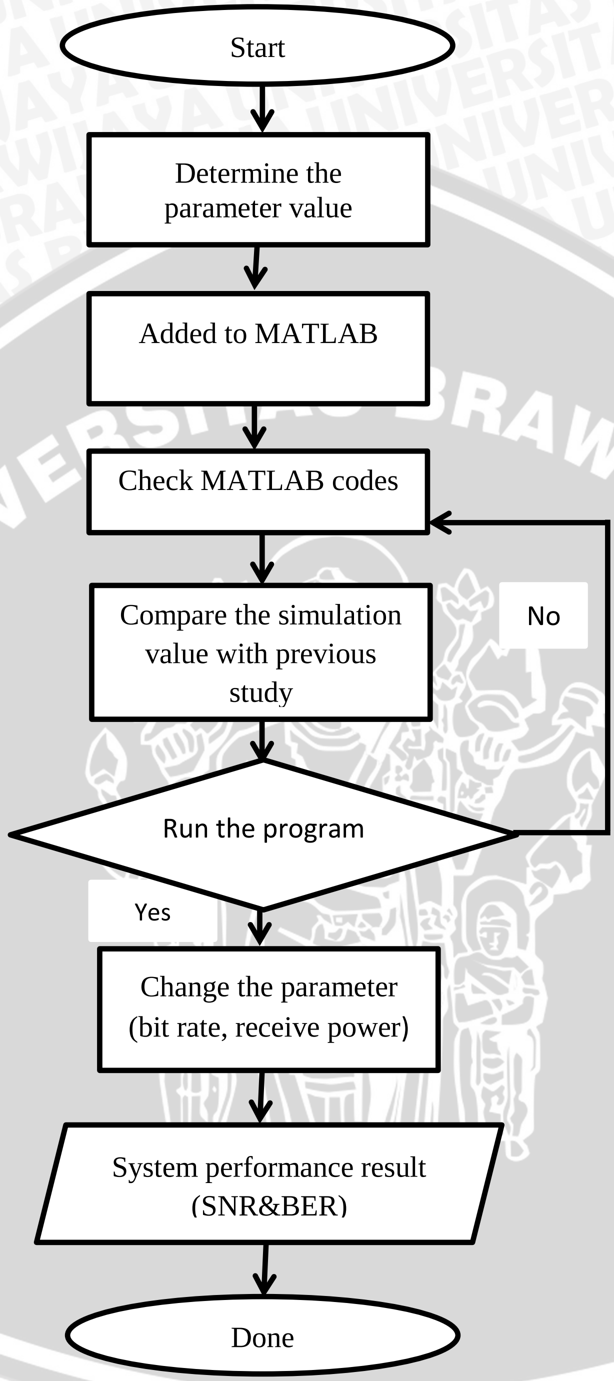

Figure 3.6 Flowchart of MATLAB simulation development for performance analysis

(Source: Design Configuration)

From this simulation of performance analysis, the influence of bit rate and received power to the indoor visible light communication system performance will be observed. In this project, performance of indoor VLC with various bit rate and received power have been characterized based on SNR and BER

CHAPTER IV
RESULT AND ANALYSIS

This chapter will describe the results and analysis of indoor visible light communication system based on MATLAB simulation that have been explained in CHAPTER 3. The data obtained throughout the simulation work were analyzed and interpreted. The analysis will be about the influence of the field of view (FOV) and distance to the received power. The influence of bit rate and received power to performance of the system will be determined by the signal-to-noise ratio (SNR) and bit error rate (BER) .

4.1 Influence of Field of View to Received Power of the System

The FOV of the photodetector usually can be found from the photodetector manufacturer specification. From the datasheet of typical photodiode, the FOV value usually around 25° to 70°. So for this analysis, the calculation FOV will start from 30° to 75° in order to see the influence to the received power. Figure 4.1 shows the simulation result based on this simulation.

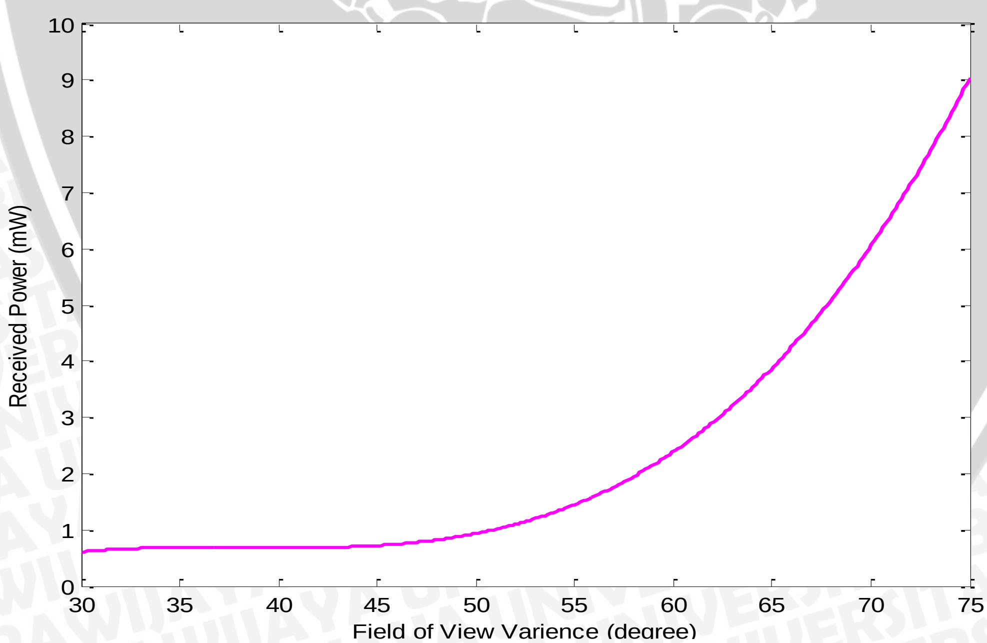

Figure 4.1 The influence of FOV to the received power of the system
(Source: Research)

The figure shows that no significant change of the received power when FOV value increase from 30° to 45°. However, there is drastically improvement of the received power for FOV above 45°. Generally, this trend shows that when FOV value is increased then the received power will also increase as well. By increasing the field of view, the photodetector capable to accept more light from the transmitter. Theoretically, the maximum FOV is 90° however typical FOV value is less than that. However, huge FOV is susceptable to other source of noise such as background sunlight. For this simulation, assuming the room is dark with no background sunlight.

Figure 4.2 shows the received power at room area using 3 dimension (3D) plot. The received optical power intensity is distributed over the room area with the middle room area has the maximum received power (red). The received power then reduced and reach the minimum value (blue) at edge of the room are.

From the simulation at FOV of 60°, the received power is around 1.7 mW.

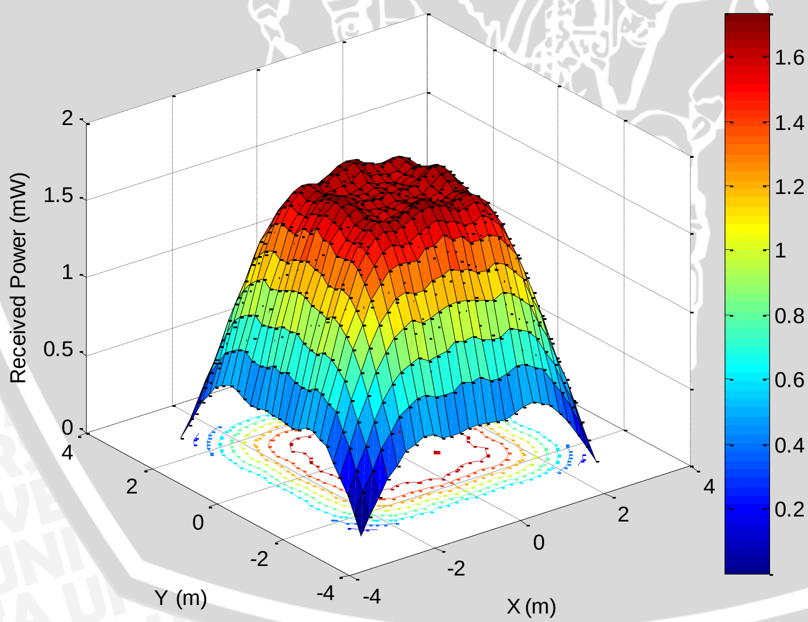

Figure 4.2 Simulation result with FOV of 60°

(Source: Research)

The conclusion from this simulation is when the angle of FOV increase the received power will be increased. The maximum value for FOV is at angle 70°, in this value, the results of the received power good and the performance of the system will be improved.

4.2 Influence of the Distance to Receive Power of the System

For this simulation, the results show how the distance between the transmitter and the receiver have the influence to the received power of the system. In this simulation work, the VCL transmitter is based on the commercial LED to provide suitable optical power for room application. Typically, the optical power of the VLC transmitter is around 5 watts.

Figure 4.3 shows the received optical power in 3 dimension (3D) plot when the transmitter is placed at the middle of ceiling. The simulation of NLOS model calculate the received power of room area at the middle of room height. In this simulation, the maximum received power is around 3 mW if the transmitter optical power of 5 watts is used.

```
TP1=[0 0 lz/2];
% TP2=[0 1 lz/2];
% TP3=[-1 0 lz/2];
% TP4=[0 -1 lz/2];
% transmitter position
%%%%%%%%%%%%%%%calculation for wall
1%%%%%%%%%%%%%%%%%%%
for ii=1:Nx
 for jj=1:Ny
  RP=[x(ii) y(jj) 0];
  % receiver position vector (W. Popoola, 2013)
```

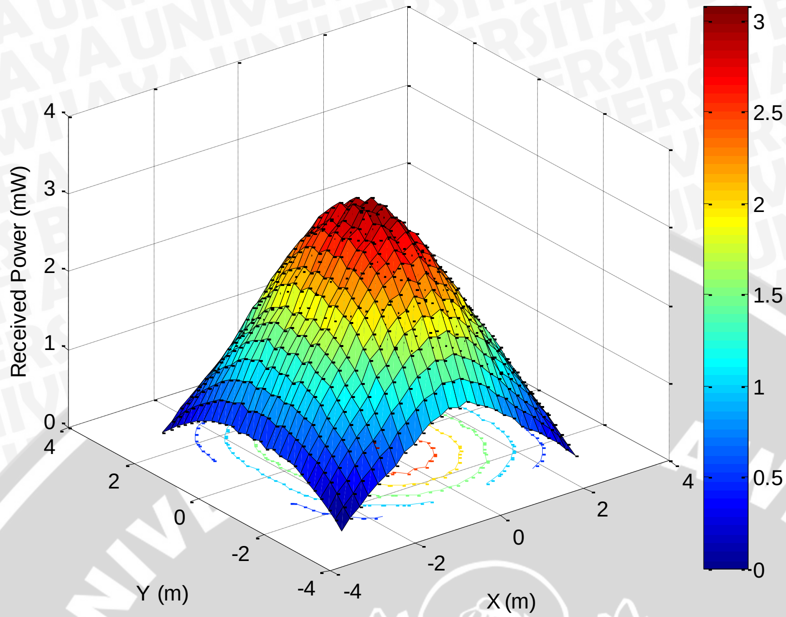

Figure 4.3 3D plot of the received power

(Source: Research)

In order to observe the influence of distance, the maximum received power will be used to plot the result when the distance is varied. Figure 4.4 shows the received power against distance. The received power decrease when the distance increase. The highest received power is around 6.5 mW when the receiver very close to transmitter. The received power reduces to around 3 mW for the receiver is located at 1.5 m away.

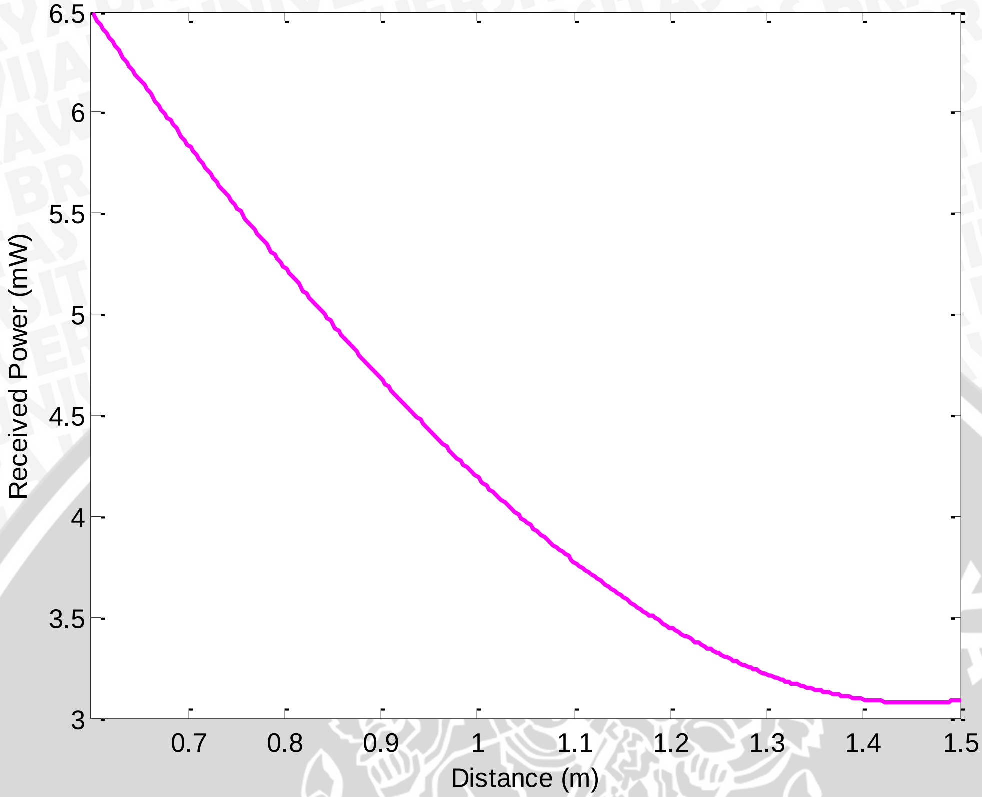

Figure 4.4 Influence of the distance to received power

(Source: Research)

4.3 Influence of Bit Rate to SNR and BER of the System

Based on the SNR formula for On-Off keying (OOK) modulation in Chapter 2, there are no parameters of bit rate involved directly. However, each modulation including OOK requires minimum bandwidth in order to avoid serious intersymbol interference in the transmission. Theoretically, the relation between bit rate or symbol rate with the signal bandwidth for OOK can be obtained using Fourier Transform. Based on typical implementation for OOK-NRZ, the bandwidth of 0.75 X bit rate is required so that no intersymbol interference problem on the transmitted signal in the system. Therefore, this bandwidth calculation has been used in this simulation in order to relate with the bit rate parameter

In this analysis, similar parameters as mentioned in Chapter 3 are used. The received optical power is fixed to 4 mW. The effect of the bit rate on SNR is simulated by varying the bit rate from 50 Mbps to 250 Mbps.

Figure 4.5 shows the simulation result for the influence of bit rate on SNR. The result shows that SNR is affected if the bit rate is increased. This is due to the thermal noise is bandwidth dependent. As bit rate increases, bandwidth also increases and produce more thermal noise. Consequently SNR becomes smaller as noise power increases.

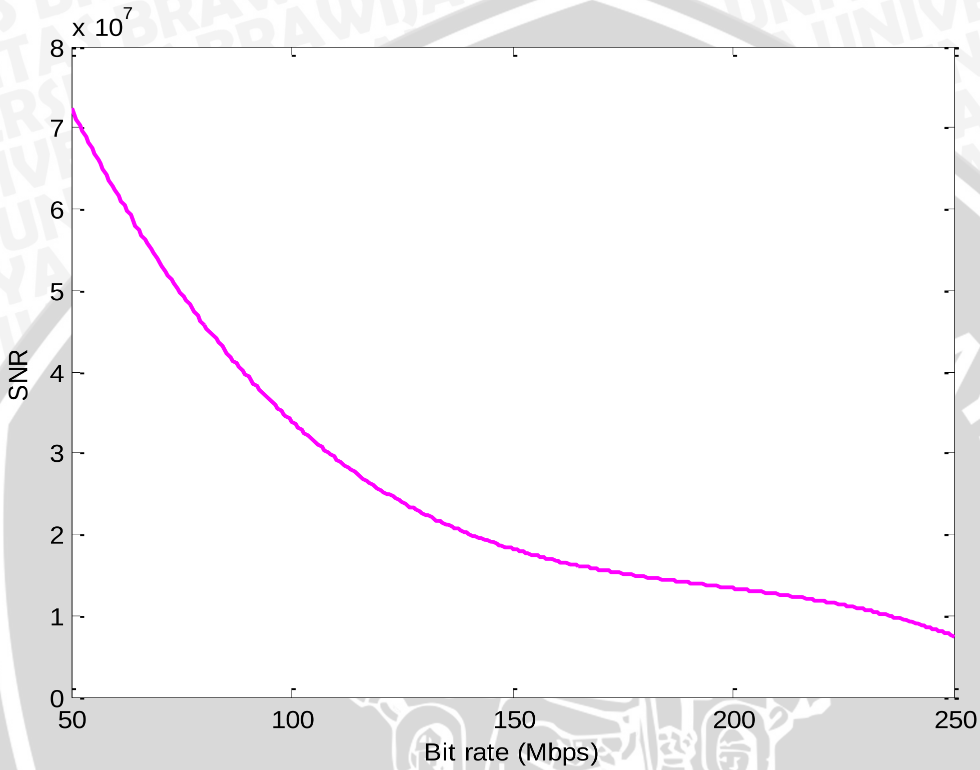

Figure 4.5 Influence of bit rate to the SNR of the system

(Source: Research)

For a digital communication, system performance is characterized by BER. BER of this system can be estimated using SNR value as discussed in Chapter 3. Based on previous analysis, SNR is very good if the parameters in Chapter 3 is used. Based on this SNR value, no BER for this condition. In order to observe the BER value, SNR therefore is further reduce by using higher bit rate. For the SNR value of 12.5021 dB, and BER value is 2.0324 X 10^{-4}. To obtain this BER performance, the bit rate must be around 2.9 X 10^{10} bps which is equivalent to bandwidth of 22 X 10^{9} Hz. This bit rate is for theoretical analysis only and not possible to be implemented using current VLC technology. The influence of the bit rate on

BER can be observed using data provided in Table 4.1. Based on this result, BER becomes worse if the bit rate is increased.

Table 4.1 BER at various bit rate

Bit rate (bps)	Bandwidth (Hz)	BER
2.9 X 10^{10}	22 X 10^{9}	2.0324X10^{-4}
2.6 X 10^{10}	20 X 10^{9}	2.2611X10^{-5}
2.4 X 10^{10}	18 X 10^{9}	8.8909X10^{-7}
2.1 X 10^{10}	16 X 10^{9}	5.9974X10^{-9}

(Source: Research)

4.4 Influence of Received Power to SNR and BER of the System

The purpose of this analysis is to investigate the influence of the received power on SNR and BER. Based on previous analysis, the received power in the room area is not equal. Therefore, it is very important to know the SNR and BER of VLC link for receiver at different position in the room. In this analysis, the receiver bandwidth is fixed based on OOK bit rate of 100 Mbps. Meanwhile, the received power is varied from -25 dBm to 34 dBm or 3μW to 3 W.

Figure 4.6 shows the simulation result of the influence of received power on SNR. The graph shows that SNR value increase steadily with the received power. Note that the noise power for this analysis is calculated based on the parameters given in Chapter 3. Since the received bandwidth is fixed, the noise power is also unchanged. Based on this analysis, SNR can be improved if more received power is provided.

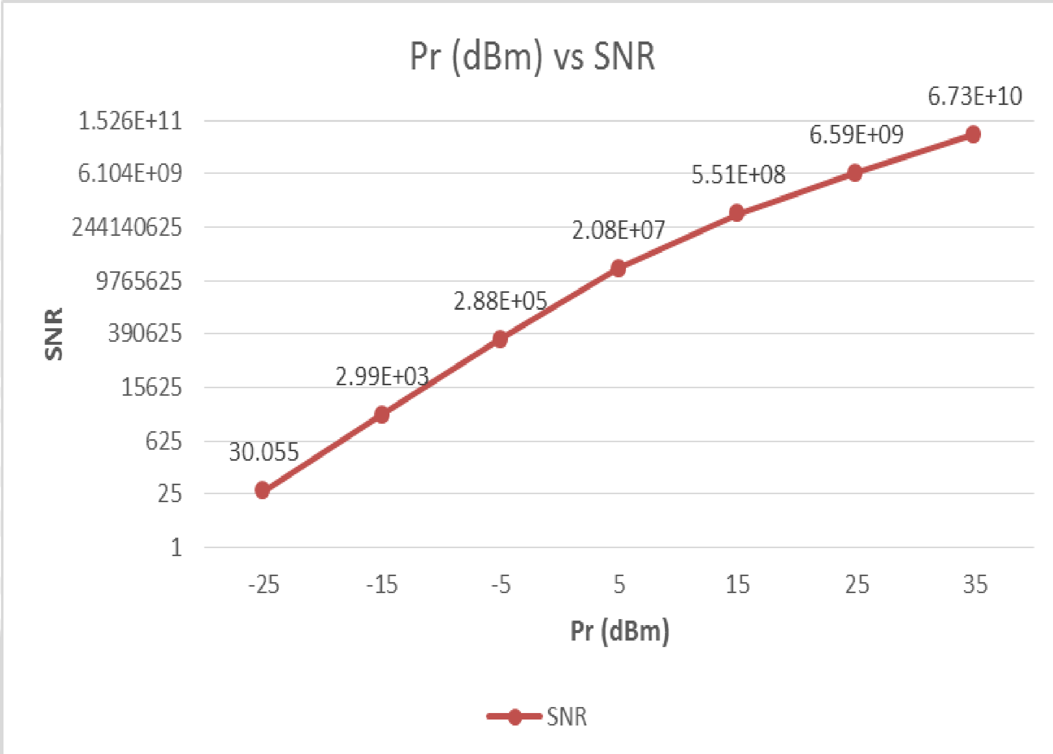

Figure 4.6 Influence of received power to SNR of the system

(Source: Research)

Table 4.2 shows the data for BER at various received power. The result shows that by increasing the received power from -27 dBm to -24 dBm, clear improvement of BER performance is achieved. In this case, when the received power is increased, SNR also increase as well because the noise power remain unchanged. The minimum received power or receiver sensitivity of the VLC system can be determined at particular BER target.

Table 4.2 BER at various received power

Received Power (dBm)	BER
-27	$1.2851X10^{-4}$
-26	$2.453X10^{-6}$
-25	$2.0989X10^{-8}$
-24	$7.9853X10^{-11}$

(Source: Research)

CHAPTER V
CONCLUSION AND RECOMMENDATION

This chapter describes the conclusion of the project based on simulation using MATLAB programming and to give recommendations for future work about this study.

5.1 Conclusions

In this project the objectives in chapter 1 has been successfully achieved. The simulation development of this project and analyzing have been done, this project confirm that the distance between transmitter and receiver, the angle of field of view, received power and bit rate had influenced to the performance of the indoor Visible Light Communication using NLOS link.

1. Based on the simulation, the influenced of the angle of field of view to the received power can be concluded as follows:
   - When the field of view value increase, the received power will be increased. By increasing the field of view, the photodetector capable to accept more light from the transmitter.
   - Theoretically, the maximum FOV is 90° however typical FOV value is less than that. However, huge FOV is susceptable to other source of noise such as background sunlight. For this simulation, assuming the room is dark with no background sunlight.
2. Based on the simulation, the influence of distance to the received power can be concluded as follows:
   - The received power decrease when the distance increase.
   - From the simulation, the highest received power is around 6.5 mW when the receiver very close to transmitter.

3. Based on the performance simulation, the influence of bit rate to SNR can be concluded as follows:
    - SNR is affected if the bit rate is increased. This is due to the thermal noise is bandwidth dependent. As bit rate increases, bandwidth also increases and produce more thermal noise. Consequently as SNR become smaller as noise power increases.
    - From the simulation we conclude that high bit rate is needed in order to get BER higher than 10^{-9}.
4. Based on the performance simulation, the influence of received power to SNR can be concluded as:
    - From the simulation result, SNR value increase steadily with the received power.
    - When power increased from -27 dBm to -24 dBm, the BER performance will improved.
    - Based on this analysis, SNR can be improved if more received power is provided.

5.2 Recommendation

Based on analysis of the simulation result which has been discussed in chapter 4, there are two suggestions that can be considered for future research.

- The future research can be used other modulation technique for indoor visible light communication, such as Pulse Position Modulation (PPM), Pulse Width Modulation (PWM) and etc.
- The other research can also use smaller transmitter power to see the system performance with small power.

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