MODELING AND PERFORMANCE TESTING FOR GENERAL VISIBLE LIGHT COMMUNICATION CHANNEL

BY

PIYAPHAT PHUKPHAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF MASTER OF
ENGINEERING (INFORMATION AND COMMUNICATION
TECHNOLOGY FOR EMBEDDED SYSTEMS)
SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
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PIYAPHAT PHUKPHAN

Submitted to

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Abstract

MODELING AND PERFORMANCE IMPROVEMENT FOR GENERAL VISIBLE LIGHT COMMUNICATION CHANNEL

by

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In this project, the visible light communication (VLC) modeling and enhancement has been implemented to see particular characteristics of light wave when it is being used as data transmission medium wirelessly. It consists of two main parts; general model testing and physical channel modeling. First, it starts with an observation of parameter for light propagation model. The system of data stream transmission started with a generation of binary data, and then it had to be modulated to be able to travel through a medium of air. On-Off Keying (OOK) was chosen as a mean to transfer because of its simple function as presence of fixed amplitude and frequency sinusoidal wave for `1` bits and absence for `0` bits. An ambient air always contains a random noise which can affect any electromagnetic wave such as sunlight, so a noise model of Additive White Gaussian Noise (AWGN) has been added into propagated OOK signal. At receiver side, interfered-transmitted signal has been recovered to be a digital binary data again. The efficiency of this system such as Bit Error Rate (BER) was observed by noise intensity and propagation delay variation. In the second part, an example of physical model, like an airplane cockpit, was used to make a clearer description with this VLC system model simulation due to the impacts to light wave from dispersion, reflection, and refraction caused by surroundings. The factors which can make error bits as investigated from the simulation are; noise intensity, number of noise path (multi-path), Standard Deviation (SD) of AWGN, and propagation delay. BER of VLC system using OOK may not be satisfied as the proper way of data transfer without any supportive means. Finally, BER could be concluded with average value from several samples of binary input in random pattern which made BER different at a time.

Keywords: Channel model, Visible light communication, On-off keying modulation, Additive white Gaussian noise, Multipath channel

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Chapter 1

Introduction

A visible light communication (VLC) is a method to wirelessly transfer a digital data without any solid medium like optical fiber. The light in this communication system is a visible light band, which is between infrared and ultraviolet. This visible light has a very small wavelength with a very narrow band, this property make a visible light appropriate for high speed data transmission. This capability does not depend on the speed of light but on an extremely high frequency of propagation as reversely proportional with its own wavelength, it means light signal can carry more data bit. The sources of visible light can be any kinds of illuminating light as seen in everyday life such as fluorescent, Light-Emitting Diode (LED), laser, etc. The visible light is based on a color capable to be seen by human eyes. Its primary colors are red, green, and blue, another colors are made from these primaries mixing. A natural light and general light source are usually white which is an all-combined of primary color, while an absence of all color is represented by black color. From this scheme, the visible light can be used as a data multiplexer, a module that can transmits several data stream at the same time. By multiple-colored light sources utilization, multiplexer can be done, it is like Frequency Division Multiplexing (FDM) of radio wave in light wave term. There are various advantages of VLC. First, it provides harmlessness to human body because it does not radiate effective energy which is a factor of sickness, like in Radio Frequency (RF) communication. Also, the light cannot travel through a wall or any other blocking, absorbing, or diffracting objects. So this characteristic of light can be used as a network security enhancement due to difficulty of eavesdropping. Finally, VLC can achieve a data throughput which has never been experienced before, like several Gb/s up to a thousand one compared to Wi-Fi. While VLC is an advanced way of communication, it still provides so many disadvantages. A possible propagation path is short with a nature of light that spread wider with a distance increment and this limits a data rate of VLC too. Some modules to help light travel and maintain data rate must be developed such as a relay-assisted system, multi-path propagation model, laser driver, etc. Additionally, VLC cannot be implemented in outdoor environment since there is a strong interference from sunlight that a transmitted signal may disappear suddenly along its path.

In this thesis, the detail of works has been separated into two parts; VLC model testing and VLC enhancement. The VLC modeling is a process of data transfer simulation, which is started by the simplest situation of transmitter (Tx) and receiver (Rx) direct transmission. There are many characteristic experiments those are necessary to be done; propagation delay impact, natural noise effect, and multi-path interference. As a result, a relation of these parameters versus BER is used as a reference to improve the system in the future. However, there is also a usage of physical structure to simulate how the light travel and react with surroundings as an instance in the next part. A method to improve data throughput and BER has been studied and implemented. Although the main composition of digital data transfer is how the data is modulated to transmit along certain medium, but it is also important to determine appropriate modules and variables such as sampling rate, receiver filter, binary reconstruction, compensation installment, etc.

1.1 Motivation

A typical and main signal category used to transmit digital data is a radio frequency since very long time ago. Now, this communication mean is bounded by its own limitation such as frequency, speed of transmission, high traffic bandwidth, regulation, network security, and etc. Therefore, there is a trend of using light wave as a carrier signal which provide better data rate. But the light has a nature of spread as it travels in long distance, an optical fiber has been developed to carry and control light signal as desired. The light can be easily adjusted its own path by altering texture, cross-section shape, or material of fiber to change reflection, refraction, polarization, or diffraction properties of light wave. However, the optical fiber system is still considered as a wired communication, which needs exclusive equipment with a little bit complex installation. Consequently, management and maintenance cost are high following required devices. As a result, an urge of visible light communication study is the interesting way to get out of these limitations. A regular wireless communication system using radio frequency in some settings may be able to be replaced with this VLC system in the near future.

1.2 Objective

The author`s intention is to develop the system of VLC with appropriate modules in both transmitter and receiver sides, so the suppression of BER is as strong as possible. From specifications of light wave, it can travel faster and contain higher frequency compared to regular RF communication. The light characteristics must also be investigated thoroughly to provide the most effective method of VLC implementation to be able to overwhelm RF system. However, VLC system is now capable only in indoor environment due to extremely strong sun ray interference outside. With this inevitable disadvantage, we have to boost a quality of VLC system as a smart communication grid inside every buildings instead with many advantages as mentioned before.

An expected output of this thesis is the visualization graph of light wave characteristics provided by several data communication parameters; signal delay, noise, and multi-path interference. This information can be a foundation to VLC system enhancement. By applying compatible modulation and carrier method from experiments, the best possible system can be constructed. The intended future work of author may be the development of VLC system as a whole in indoor setting, which utilizes traditional illuminating light source as a coupling module in building to also provide data transfer for every electronic devices without any wires.

1.3 Thesis Structure

This proposed project composes of four main chapters. In chapter 1, fundamental information of visible light band is explained with its properties and possible applications. Then chapter 2, literature review and background knowledge requirement to do this project are shown such as light theory, modulation technique, transmitter and receiver. Next is chapter 3, it is methodology part of the whole proposed VLC system which is introduced, i.e. light characteristics observation, system modeling, and system enhancement. There are also experiments and simulation details. Finally in chapter 4, results, discussions and conclusions on the current work is to be summarized with provision of possible further study and development.

Chapter 2

Literature Review

2.1 Visible Light Communication (VLC)

Visible light communication (VLC) is one method of data transfer in a subset of Optical Wireless Communication (OWC), which includes ultraviolet (UV) and infrared (IR) usage. VLC utilizes only a visible light frequency band as shown in Figure 2.1. Because illuminating light sources are abundant compare to UV and IR both natural and man-made means, it is more ideal to imply VLC as a common communication method. Typical lighting equipment in household or building is mainly fluorescent light which is not power-efficient, since it radiates harmful thermal energy with almost all of electrical input converted to this kind of wasteful power, not into its benefit of illumination. So it is a trend to replace these lighting with light emitting diode (LED) as in Figure 2.2 to lower power requirement, to improve output ratio with human health concern. By manipulation of LED intensity by electrical current variation to dim up and down, a binary signal modulation can be made to couple the digital data transfer system into LED. This scheme is neither detected by human eyesight nor has an effect to illumination role of LED; normal frequency of flickering in light wave is represented the mean of light modulation like amplitude modulation (AM) in radio frequency (RF) system. Then photo-sensitive detector is installed at the receiver end to encode and demodulate light signal back into electrical digital signal again. It usually requires a complex transceiver and antenna in RF system while VLC can perform direct transmission with simple devices. In comparison with traditional IR, VLC also achieves more data rate since IR is power-limited in a concern safety.

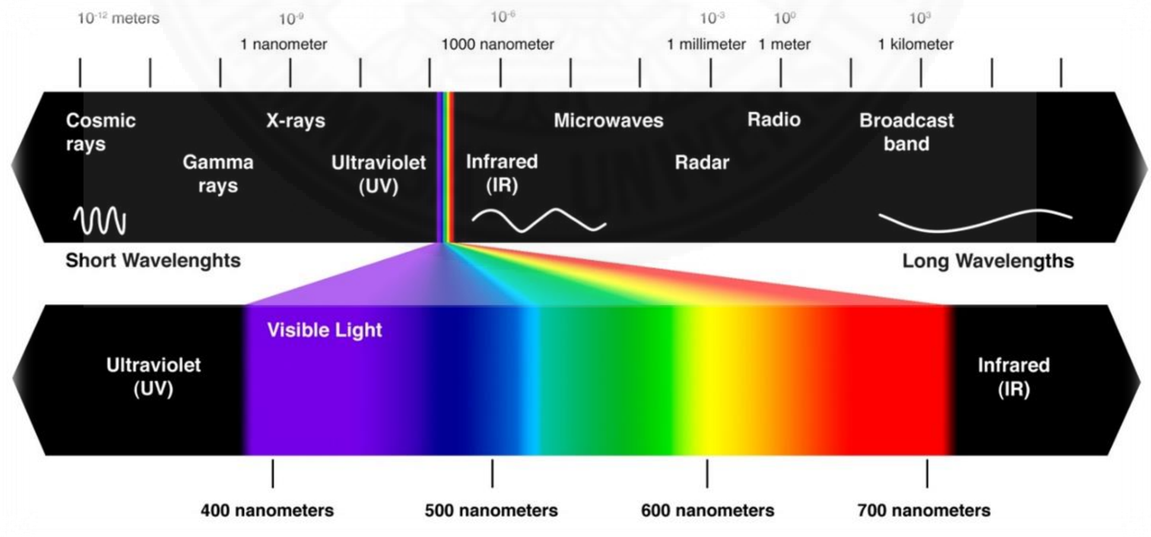

Figure 2.1 Visible light frequency band
from: http://www.energysquirrel.com

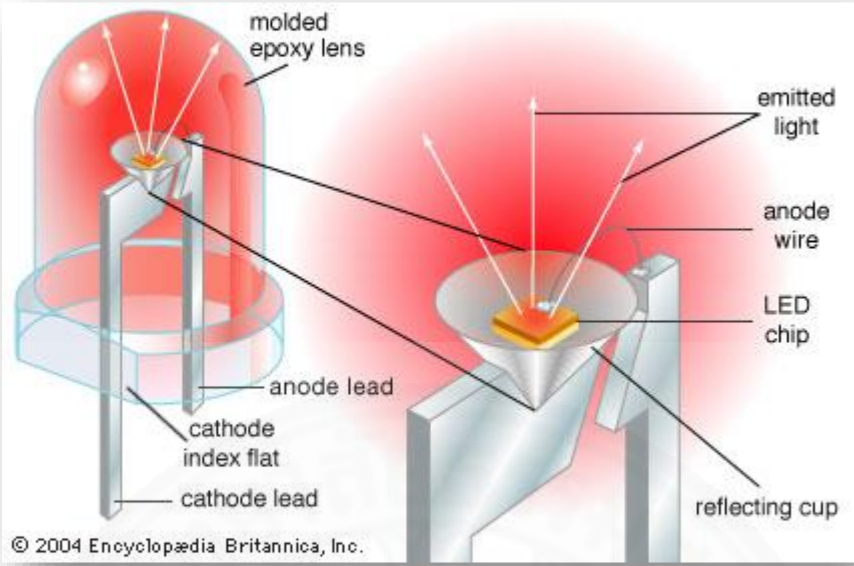

Figure 2.2 Light emitting diode structure
from: http://www.britannica.com/technology/LED

There are many advantages of VLC in comparison to typical RF system. **Capability** of VLC is higher in terms of short range data rate, like in office or home. Because of extremely high frequency of light, VLC can contain more data bit than RF. Due to bandwidth congestion of RF signal; it is more preference to use VLC which is free of cost and no regulation. The VLC system and propagation path could be easier to manage with lower interference; this is consequences from lighting visibility and simple obstruction, which limits the travel path of light. VLC also provides **safety and security** network, since RF transmission has a possibility to interfere with important transmission like in an airplane that passengers are not allowed to use wireless fidelity (Wi-Fi) for instance. Also, RF can be dangerous when it is placed in vicinity of chemical plant or hospital, which it can affect chemical reaction. All of these hazardous situations do not happen in VLC system. Moreover with light blockade and limited illumination area, it is easier to perform prevention to data leakage. The data direction can be controlled [1-2].

In application area of VLC, two examples of present system development are introduced in this thesis. First is a **smart lighting for home and office** as shown in Figure 2.3 of Boston University project [3]. The overall indoor VLC network can be implemented in any of lighting sources in the buildings as access points. With coupling an infrastructure of data control and transfer to lighting, any electronic communication devices such as, mobile phone, PC and peripherals, in proximity of light can interconnect together and access to internet. The second one is **VLC infrastructure for vehicle traffic control** in Figure 2.4 [4]. VLC technology is induced in headlamps and tail lamps of all vehicles, also in traffic light signals and signs. The implementation is in both vehicle-to-vehicle and vehicle-to-signs/signals schemes. Headlights of each vehicle have to detect a change of taillights of another one in front, if they detect red color they have to send a signal of braking indication to help in efficiently stop. This same algorithm can be used in vehicle-to-signal also. This system will provide significant well-management in traffic control and road safety.

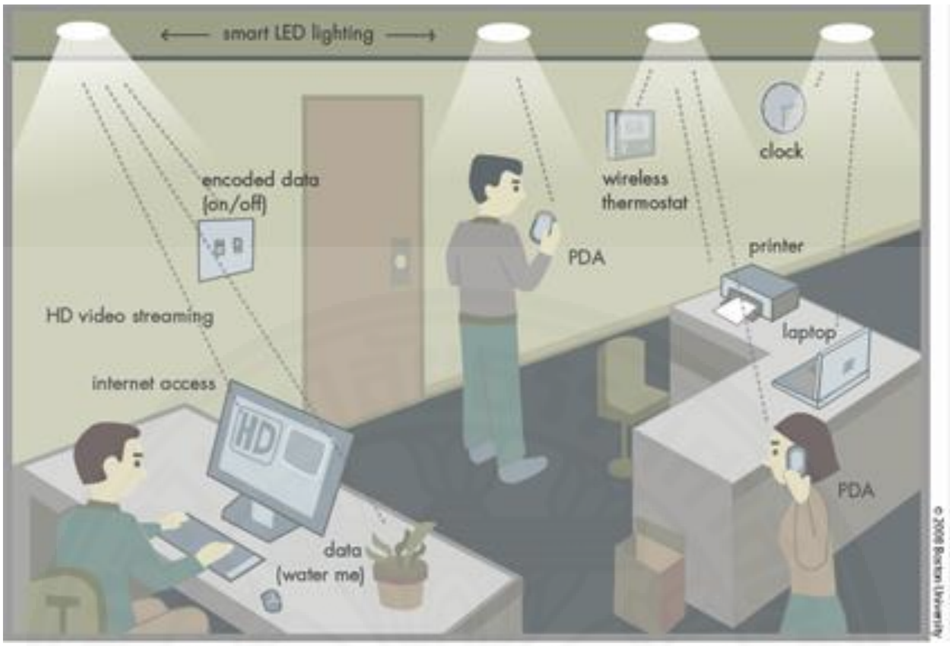

Figure 2.3 Smart lighting in building
from: https://www.techtalkthai.com/li-fi-is-100-times-faster-than-wi-fi

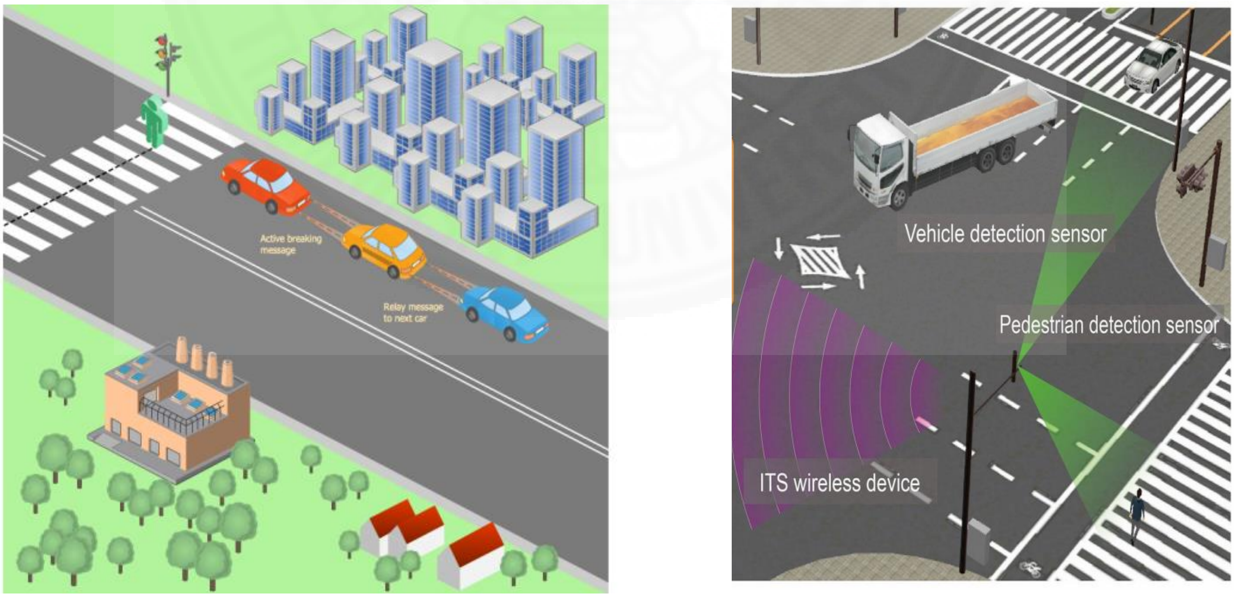

Figure 2.4 VLC for smart traffic management
from: www.conceptdraw.com, steeringnews.com

2.2 Digital Data Modulation Techniques

In this thesis, two main methods of digital data carrying have been performed. Amplitude shift keying (ASK) was taken first to test the general characteristics of VLC channel in the simplest point of view. Then pulse position modulation (PPM) was taken place after to improve the performance of the proposed VLC channel model in this thesis. The details of these two methods are described as the following:

2.2.1 Amplitude Shift Keying (ASK)

For nowadays data communication, sources and destination of the data are always in digital format and wireless; personal computer, mobile devices, or network access points for examples. But natural medium of signal such like the air cannot carry out a transmission role properly for digital data which is in binary form since all surroundings' behavior acts as an analog channel. Therefore a development of some certain methods to support digital data transmission have been created to help data stream travels through the air.

ASK is one way to convert any binary data into an analog signal carrier, it manipulates the amplitude of particular signal. This method works by assigning varied amplitude of sinusoidal wave to corresponding patterns of binary stream or discrete levels. The pattern of binary bits can be two or more depending on the system requirement. Figure 2.5 visualizes a complete picture of ASK of four levels which is formed by all possible combinations of two data bits, it can be called 4-ary ASK.

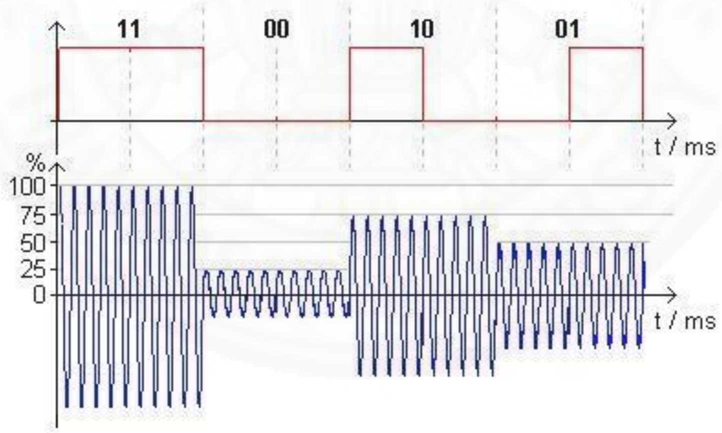

Figure 2.5 Four-levels amplitude shift keying
from: www.indiastudychannel.com

As it can be seen, there are four different levels of sinusoidal wave to send out in place of binary patterns. But there are several instant discontinuities when binary input travels past transition state, this makes the ASK signal contains wider bandwidth than its usual necessity. With wide band of frequency, the signal can be interfered easier with the signal from neighborhood band. Also, overall ASK signal is considered as non-linear since it contains abrupt change of signal power. An amplifier or attenuator can seriously impact because they require linearity.

However the main advantage of ASK is that it provides very simple demodulator to detect and recover data.

On-off keying modulation (OOK) is primarily used in this thesis as a basic form of ASK for carry a digital data wave through analog channel, such as air or any physical medium. It can be called binary ASK, is appropriate to implement in lighting source to send data with a modulation by light intensity manipulation. With fixed frequency and amplitude sinusoid signal, it is assigned to be on when binary data is '1' and off represents '0' as shown in Figure 2.6.

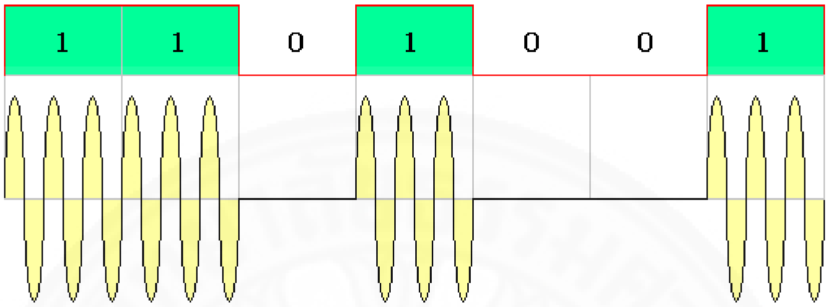

Figure 2.6 On-off keying modulation
from: electronics.stackexchange.com

2.2.2 Pulse Position Modulation (PPM)

This is a method of modulation by using a pulse with fixed duration and magnitude with a variation of its location in one time period. PPM can be applied to both analog-to-digital and digital-to-analog schemes, and also can be implemented for at least two to several levels of binary data like ASK, depends on a length of time period which is assigned for different bit combinations. While PPM gives a good power efficiency of transmitted signal and tolerance to external noises, it is easily severed by multipath interference and receiver time synchronization. Since PPM receiver requires the same clock pulse time as the transmitter to recognize transmitted signal correctly, multipath fading which is caused by self-interference of different delayed paths has much effect to PPM channel. A details of how PPM is working is expressed in Figure 2.7, it can be seen that location of pulses is realized by every rising edges clock detection. There is also more effective PPM called differential pulse position modulation, which omits unused slot of pulse to not depend on clock synchronization and boost data throughput at a time. [5]

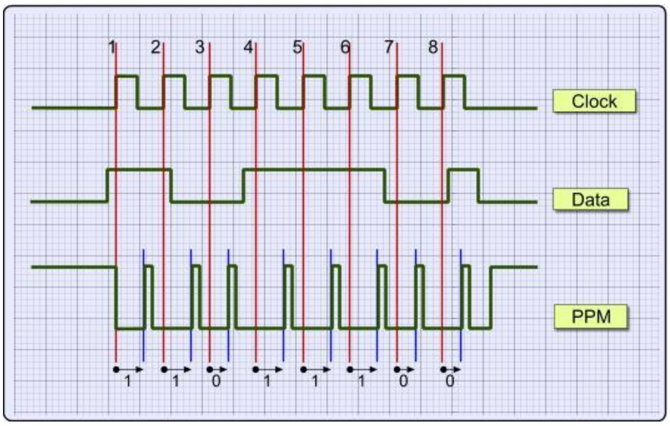

Figure 2.7 Pulse position modulation
from: www.pcbheaven.com

2.3 Wireless Communication Channel Model

In every communication channels, a method to determine the particular characteristics of any channel should be studied first to perceive some point of view in overall system. The model is needed to analyze the performance of system, also allows improvement and comparison among any different implementation on the same term. But it is not very precise when the model results are compared with the ones from experiment in actual environment or simulation, because the model has to be made from assumption. There are many communication model parameters which are often considered such as carrier frequency, signal power, propagation delay, system bandwidth, probability of error and etc. Communication models can be analyzed in both time and frequency domain, there is also a new trend of domain analysis in space-time. Wireless communication is a free-space signal transmission scheme, so there are many variations depend on how transmitter or receiver is located like moving or fixing location. This situation has an impact very much on a quality of transmitted signal since there is a possibility of several sources of interference.

There are two main categories of channel models; physical analysis and statistical analysis. Physical analysis gives rise of certain visible parameters like propagation path, delay, power ratio, temperature. This is important to implement to let us see how each single signal travels through the air, how it acts with any obstacle, and in what form of degradation it will be at the receiver end. Although it is very deterministic and assumptive to construct this kind of model, that is it cannot simulate actual real world behavior of an extremely complex signal wave. So physical model must be combined with statistical model all the way to show exact results which can be applied to the real world problems.

In this thesis, combination of multipath and additive white Gaussian noise (AWGN) channel has been created to simulate a free-space VLC model. The multipath channel occurs when several copies of the same propagated signal reach their destination with different propagation delays, this situation can interrupt the original transmitted signal in both additive and destructive means. The main original signal may not be able to travel directly to the receiver; this is called non-line-of-sight (NLOS) system, while there is the strong direct-path signal in this thesis which is called line-of-sight (LOS) system. LOS multipath channel provides a dominated power of direct signal path compare to any of its own copies of multipath reflection. Therefore an overall received power has no significant change, but the primary concern must be different propagation delays among them. From this delayed self-interference, which is called inter symbol interference (ISI), it make huge impact on the system additional with AWGN when moving through air medium. A simple diagram of multipath channel is illustrated in Figure 2.8.

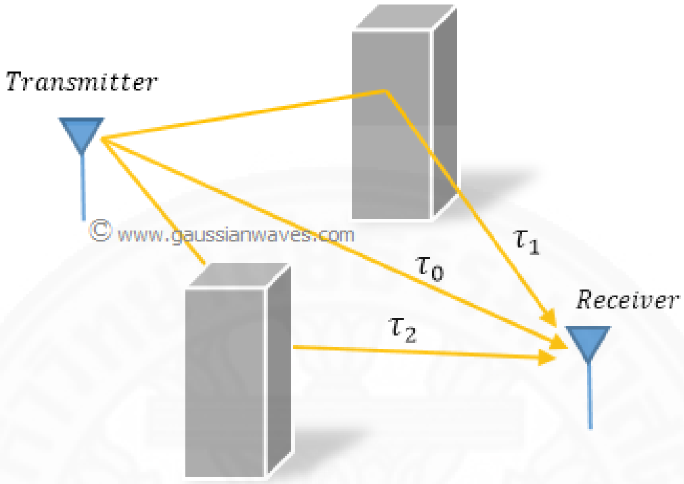

Figure 2.8 Multipath wireless communication channels

About AWGN, it is an assumption that every noise signal in an environment behaves within central limit theorem, which leads to normal-distributed probability. So AWGN is a noise produced in the air based from normal distribution curve along a time axis. Figure 2.9 shows AWGN waveform from this thesis. So at the receiver, it is very important to implement a module which contains a capability to filter out high frequency noise. From these situations overall, a diversity of signal can be occurred in three terms; time, space, and frequency. Mobile users that receive signal from broadcasting, obtain different signal power at a different time point because of transmitted signal is time-varying. Also, a position which users are located or move to, affect in abruptly change in signal detection. With various frequency bandwidths in present day, it can make diversity in signal of the same slot of time too.

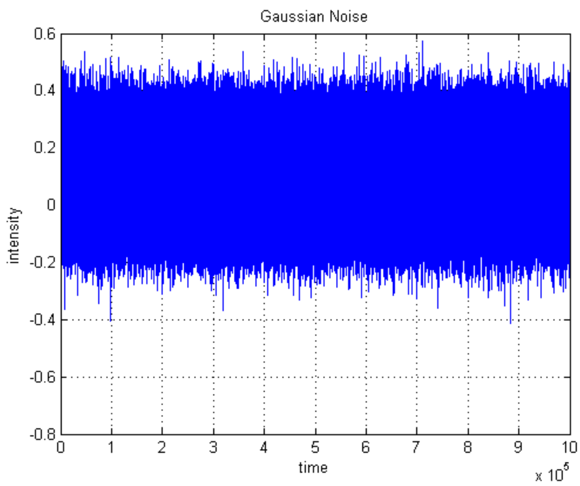

Figure 2.9 White Gaussian noise

There are many researches in order to overcome VLC wireless communication problem. In compensation of multipath fading, relay-assisted terminal can be added to the VLC system between transmitter and receiver to increase or attenuate and shift the severed signal to be able to recover better output [6]. Also, there is an attempt to improve performance of multiple-input-multiple-output (MIMO) VLC by image sensor based spatial modulation [7].

2.4 Physical Light Characteristics

Physical light is one form of an electromagnetic (EM) radiation which is in a small wavelength range of 380 to 750 nanometer (between infrared and ultraviolet) approximately; it is the only bandwidth of EM that can be visible by human eyesight. There are several color of light visibility derived from the different wavelengths of the light from natural white light such as the sunlight perceived through a prism. Usually the physical light moves and reacts as a propagated wave along a certain medium, but it can be considered as a particle also if total energy packet, called photon, is in a method of analysis. Light always travels at the speed of light about 300,000 kilometers per second; however, its typical speed can be reduced in various types of transmission medium and farther distance of propagation. Each medium contain various particles, pressure, and temperature distinguished from others, so the light can be impacted in a way of reflection, refraction, diffraction, and scattering of its own travel path and power.

In this thesis, two main properties of light are being considered:

2.4.1 Light Reflection/Refraction

Normally light wave has to travel in a straight pathway, but it can be bent or refracted when it travels past a specific connection between two or more different mediums. This situation also causes a light speed fluctuation. The refraction and reflection may occur one at a time or both at the same time depend on types and structure of medium surface. Figure 2.10 below, displays the typical scheme of light reflection and refraction.

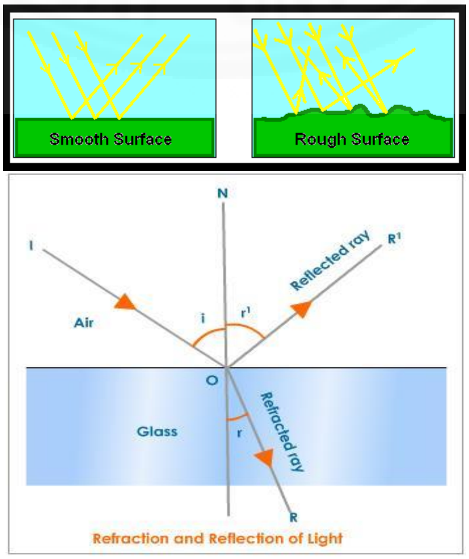

Figure 2.10 (above) Light reflections on different surfaces, (below) Refraction and reflection between mediums from: www.tutorvista.com, www.myschoolhouse.com

From the picture, smooth surface makes the original light at the same travel path reflected back altogether after its incidence while the while the coming back light is in chaos for the incidence of rough surface. Every time when there is a light reflection, reflected light travels at the same angle of originally incident one corresponding to a normal plane of medium surface. The refraction also happens which is the light that can go through from one medium to another with a bending angle referred to normal plane also. This refractive angle can be determined by a medium`s specific quantity called “refractive index”. Normally, full speed of light can be achieved when it moves in a vacuum state. It means that the vacuum refractive index is equal to one referred from a ratio of full speed of light over an actual speed of light at a time in medium:

$$\mathrm{n} = \frac{c}{v} \qquad (2.1)$$

Where; n = medium material refractive index,
c = full speed of light (300000 km/s),
v = actual speed of light in medium.

Refractive index is a value which is individually assigned to each type of the medium. Then the angle of incidence and angle of refraction can be determined by putting refractive index into the equation of Snell`s law:

$$\frac{\mathrm{n}_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} \qquad (2.2)$$

Where; n_1 = source refractive index,
n_2 = destination refractive index,
θ_1 = incident angle,
θ_2 = refractive (bent) angle.

From the above equation it can be concluded that larger refractive index for incident medium makes the refractive angle to be wider respect to normal plane, while smaller index in incident medium causes a vice versa result. There is an angle threshold which affects the incident light to be totally reflected back, called “critical incident angle”. A power of incident and reflected light wave can also be calculated by light reflectance which is a ratio of reflected power over incident power from Fresnel`s equation:

$$\boldsymbol{R_s} = \left|\frac{n_1\cos\theta_i - n_2\cos\theta_t}{n_1\cos\theta_i + n_2\cos\theta_t}\right|^2 = \left|\frac{n_1\cos\theta_i - n_2\sqrt{1-(\frac{n_1}{n_2}\sin\theta_i)^2}}{n_1\cos\theta_i + n_2\sqrt{1-(\frac{n_1}{n_2}\sin\theta_i)^2}}\right|^2 \qquad (2.3)$$

$$R_p = \left|\frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}\right|^2 = \left|\frac{n_1\sqrt{1-(\frac{n_1}{n_2}\sin\theta_i)^2} - n_2 \cos\theta_i}{n_1\sqrt{1-(\frac{n_1}{n_2}\sin\theta_i)^2} + n_2 \cos\theta_i}\right|^2 \quad (2.4)$$

Where; R_s = parallel polarization reflectance,
R_p = perpendicular polarization reflectance,
n_1 = source refractive index,
n_2 = destination refractive index,
θ_t = transmitted (refractive) angle,
θ_i = incident angle.

2.4.2 Light Scattering

The light scattering is a property which light propagating energy is scattered throughout some materials or surfaces. Light scattering can be considered as a deflection of light into all direction paths as much as possible, most of this kind of situation occurs when light has to travel along a medium that contain high density of irregular particles such as water vapor, dust, or aerosol of some chemical substances. These particles can cause a deviation from a typical reflective mean due to abnormality of texture or chemical on a surface. These abnormalities are in common in earth surface`s air so it can be indicated as a random process of interference in light propagation. If particles in the air perform a high density cloud, they can cause the transmitted light signal to be negated all the way through. Although this property may severe a quality of light transmission in huge level, but it can be useful to use light to determine characteristic of some unknown particles in a certain fields of science study. An example diagram of light scattering is shown in Figure 2.11.

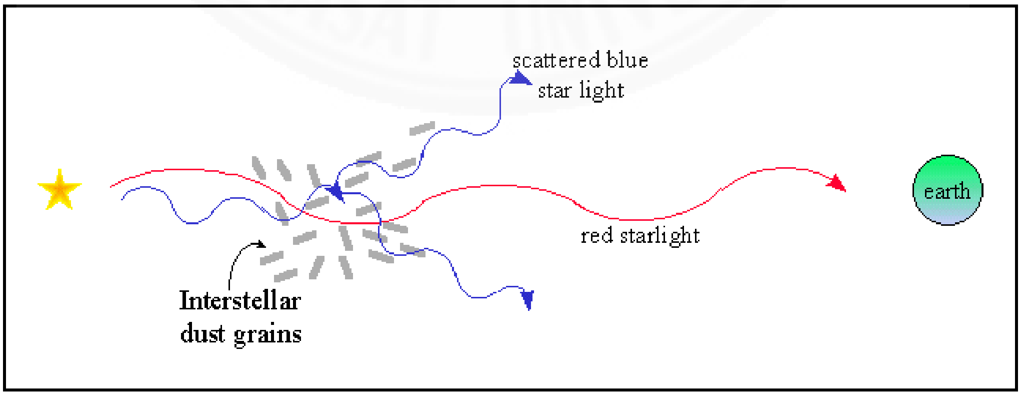

Figure 2.11 Light scattering from the sun to the earth
from: http://www.astro.cornell.edu

2.5 Optical Demodulator

In optical communication modules and visible light channel, it is a very important part to detect and reconstruct received data correctly. So a powerful and proper demodulator for optical channel is required to be able to take out unwanted signal from extremely severed transmitted signal travels through a medium. The prominent modulation schemes used for VLC are OOK and PPM since it can represent a light dimming of intensity modulation and light flickering for pulse modulation more easily than any other means. From a high fluctuation wave detected at the receiver end, there must be module to convert this chaos waveform first.

2.5.1 Optical Wavelength Mixer (Optical Heterodyne Detection)

Optical wavelength mixer is a module which mixes a transmitted signal wave with high frequency from noise or self-interference with a certain sinusoidal waveform at a fixed frequency. Most of them are used to reduce the received signal down to baseband again to give it a capability of further processing. A local oscillator produces a laser which contains a different frequency from the received signal, then combines them together at a photo detector. An instance of optical heterodyne receiver module is illustrated as in Figure 2.12.

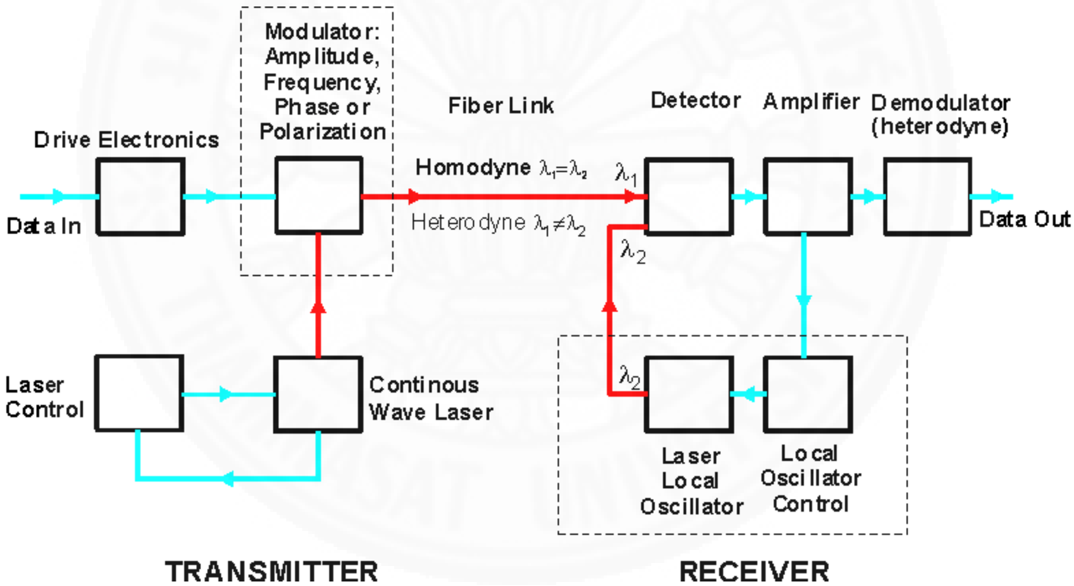

Figure 2.12 Optical heterodyne detection system
from: http://www.invocom.et.put.poznan.pl

As shown above, a data stream travels to light modulator first to be able to transmit with LED and be detected at the receiver's detector. The local light oscillator will play a role of light frequency production to combine with received at the detector, then transmit a detected light data to be converted to electrical output signal as a binary bits after this schemes. In this thesis, the light wavelength of the same as the light carrier signal at the transmitter was utilized to force the noise-mixed received signal to be into non-fluctuated form again. The oscillator must be in control by any further module in a process to ensure the wavelength that it makes to be appropriate with the received signal over a time.

2.5.2 Butterworth Low-pass Filter

Next step of optical demodulation from detection can be many methods to recover the data such as, amplification; when received data is attenuated to be very low which a reconstruction process may not be possible. A low-pass filter has been used in this thesis to filter out all unwanted components made from natural noise or delayed noise. A main process is to make the detected signal to be in before-transmit form of binary data as much as possible. Low-pass filter is usually made from a pulsed square-shape signal to be placed in low frequency band as desired in frequency domain to allow only low frequency signal to pass through, acts like a trap to high frequency noise. The filter can be set manually in frequency domain but it is simple way to determine how properly it can work on detected signal at a time. So Butterworth filter is one way of using sophisticated method to appropriately set the filter behavior to be corresponded with the desired wave form. Butterworth low-pass filter requires parameters; filter order, pass/stop band frequency, filter gain, and cut-off frequency. All of this is calculated using transfer function, different variation of these parameters give rise to different shape of filter. The ideal low-pass filter is flat-shaped with no transition band which is hard to implement in natural world. Figure 2.13 shows an overview on how to construct the Butterworth filter using various variables. With more filter order, the response of filter itself will be steeper in transition period but there is a trade-off of more complex calculation and more computation time.

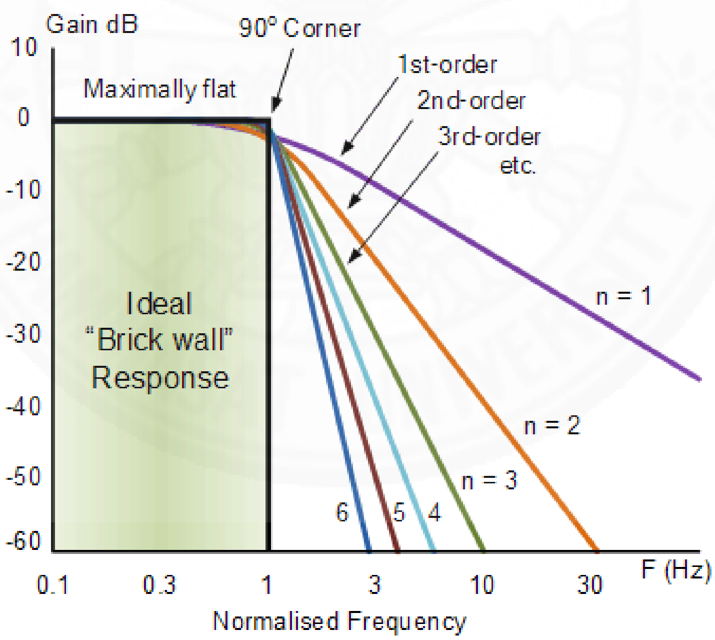

Figure 2.13 Butterworth low-pass filter with different order number
from: http://www.invocom.et.put.poznan.pl

2.5.3 Hard-Decision Coding Data Recovery

Data reconstruction is the last step of demodulation when there are still remaining interferences. The most basic form of data recovery is using one amplitude level set as a threshold value. If an input signal passes through this module at a time, has amplitude lower than the threshold, it will be assigned to a zero bit. On the other hand, if the signal is higher than threshold, it will be converted to a one bit. After this, the module will determine Hamming distance for all possible code words. Hamming distance is a number of bit differences of one sequence of binary data compared to a reference one. The bit sequence that contains minimum Hamming distance will be considered as a correct code word as the transmitter tries to communicate. This method can be called “Hard-Decision Coding”. These mentioned schemes are expressed in Figure 2.14 below.

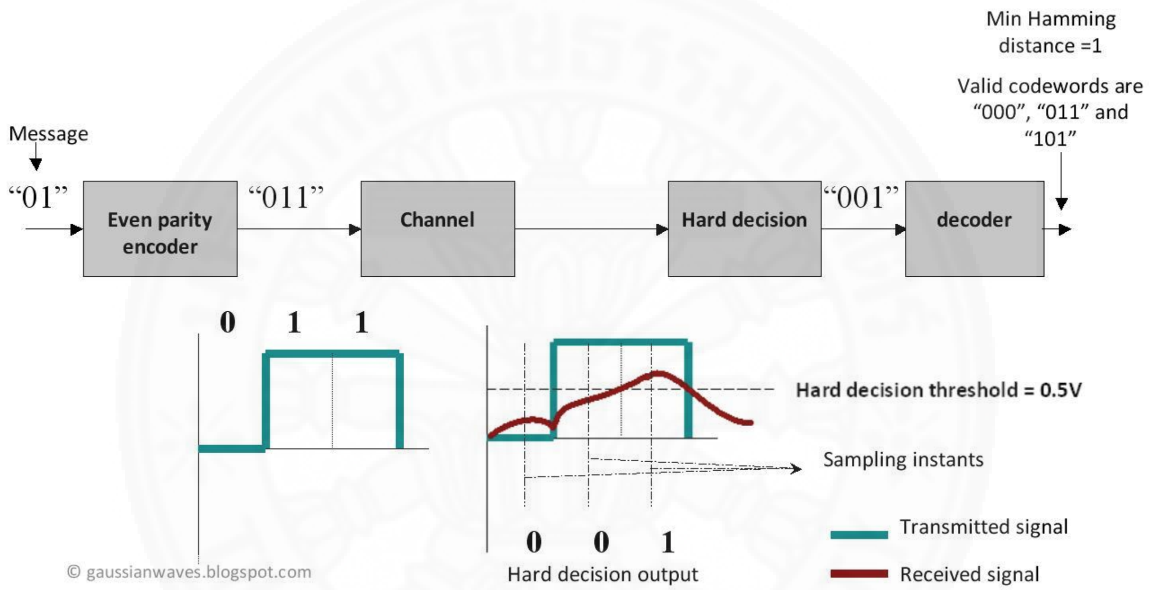

Figure 2.14 Hard-decision coding data reconstruction
from: http://www.invocom.et.put.poznan.pl

Chapter 3

Methodology

3.1 General VLC Channel Modeling

In the first step to model VLC channel in actual scheme, it is necessary to determine any general characteristic of light between transmitter and receiver beforehand. There are three main parameters which are considered to be observed in VLC general transmission; ambient noise intensity, propagation delay, and inter-symbol interference caused by multi-path wave. These mentioned variables are compared with bit error rate in average of the system. The general setting in simulation is illustrated in Figure 3.1.

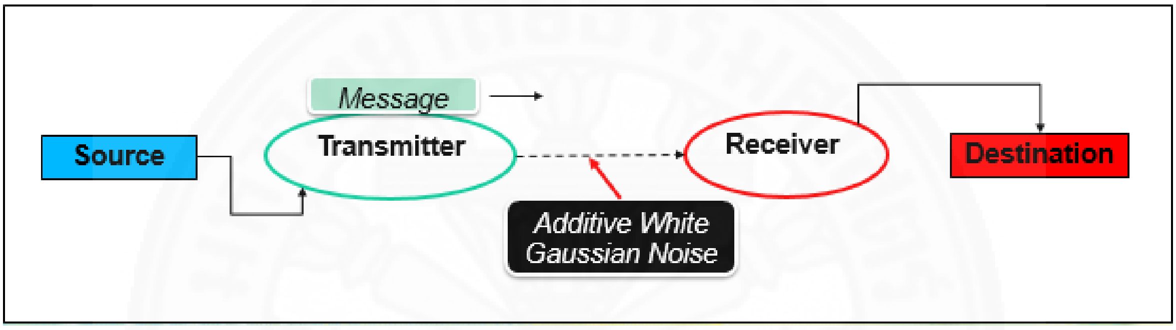

Figure 3.1 Generalized proposed communication model

From this figure, input data from electronic devices is sent to a transmitter end. Within this transmitter, it conveys a role of light signal modulation which will envelop digital data into analog data to form a message. Then light message travels through the air wirelessly. It is surely, at this point, severed with external interference from sunlight or man-made light. This interference is cumulatively considered as an additive white Gaussian noise, which adds random pulse into the message in additive mean within normal distribution range. So the received message at the receiver end will be much distorted at the moment of detection. It is certainly for a receiver to act as a demodulator of light signal. But with an unusual light characteristic compared to RF signal, there must be an additional function to compensate signal distortion better. To finish a transmission work, recovered digital data comes out from the receiver and be sent to a destination application or devices.

The first variable to be investigated is noise intensity which is considered as the most important factor to indicate channel efficiency. Normally, there are so many noises all around the air. So the signal can be interfered with air turbulence, man-made light or even temperature. But in this simulation, the used noise is considered only by natural light component, mostly sunlight. The natural light can be simplified by the model of additive white Gaussian noise, which proves most natural phenomenon to be limited within central limit theorem to form normal distribution.

For propagation delay, it is a time required for light to travel at some specific distance. Generally, light is in a top speed when it travels through a vacuum, with a bit slower when travels in the air. But it will decrease its speed drastically when it passes through glass, water, etc. This phenomenon causes alteration of light speed when we use it in some man-made application certainly and also causes a refraction/reflection. Consequently, it will bring an impact to propagation delay of light wave.

Inter-symbol interference can be described as self-inflicted noise caused by minor paths of original wave. They can be mixed into the direct and strongest light wave via multi-path reflection from surrounding obstacles, which can possibly be infinite paths. These waves come from the same source altogether but arrive at destination at different points of time. So they can make interference to the final output of desired signal in either constructive or destructive means. It is very important to implement some functions to counter this problem.

In the simulation, input signal generation must be realized first in terms of its form of data and proper modulation method. The general form of serial data in binary was used in this thesis' fundamental simulation, it is the most basic data utilization in any digital devices. By using MATLAB programming platform, a stream of binary data can be created from so many different function, but a pseudo-random function was used to create random numbers. These numbers was a base to calculate into binary number by thresholding algorithm. In this thesis, a length of a million bits of binary has been created with a certain rate of bits per symbol. Figure 3.2 shows the sample plot of a randomized million bits of binary data.

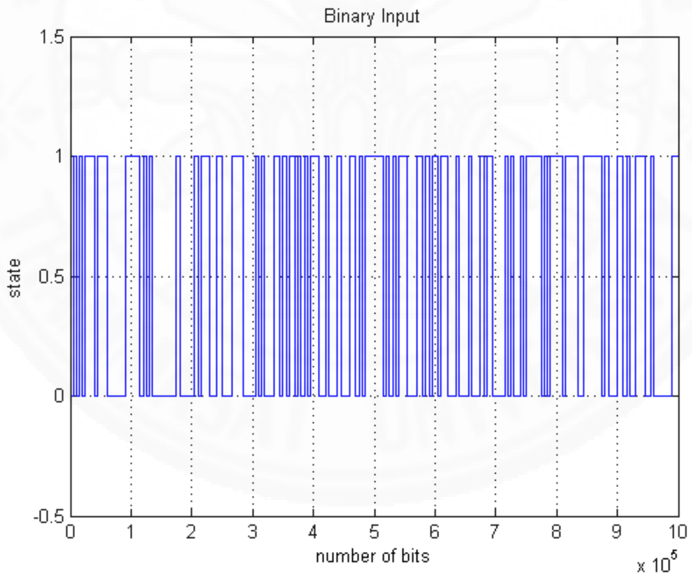

Figure 3.2 a randomized binary data

With the above data, it was fed in a transmitter as an input data from source devices, which can be either stationary or mobile. At a transmitter, there is a core module which does a particular task to ensure that the input data can be transmitted smoothly, this is called "modulation" part. It is the way to transform any input data into some logical forms which contain a high degree of certainty in transmission, depends on desired transmission scheme and environment. A concern of input and output format of data is the main factor to decide which modulation is appropriate. For digital to analog data transmission, binary amplitude shift-keying (B-ASK), as known as on-off keying (OOK), is the primary modulation that was implemented in this thesis. This is the simplest form of ASK which assigns a certain sinusoid wave to ‘1’ bits as “on”, and shows an absence of signal to ‘0’ bits as “off”. OOK can be easily manipulated by natural flickering of light source, only to be on and off at a time, so this method is good for VLC system. It is also proper to be sent via analog wireless channel. The graph of OOK signal to be transmitted is shown in Figure 3.3 below.

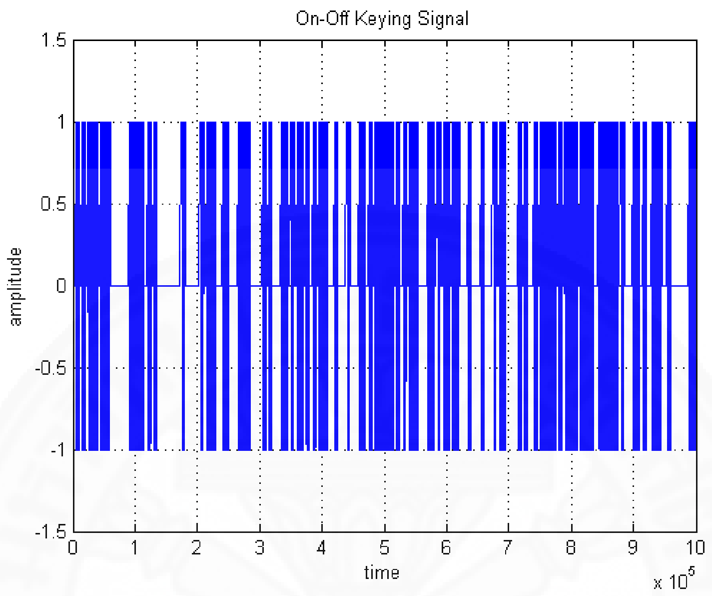

Figure 3.3 an on-off keying transmitted signal

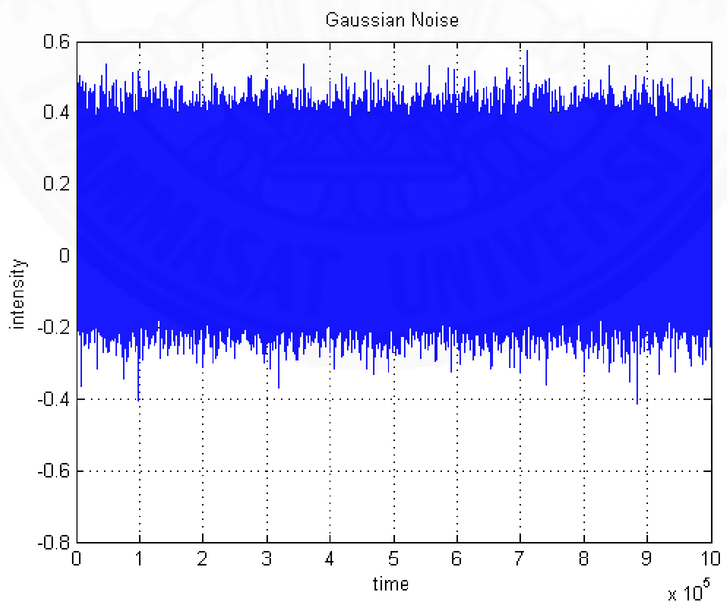

Figure 3.4 a natural Gaussian noise

The visualized graph above in Figure 3.4 is an example of additive white Gaussian noise. It is the noise generally presented in any kind of natural interference. It can be any form of signal wave in environment with normal distribution statistic. In this thesis, it is a role model represents sunlight noise or man-made light noise. It is unavoidable in wireless light transmission to be severely interfered as a distance is farther. This fuzzy noise will be added up to the transmitted signal, then a high frequency signal to a receiver is formed in midair. The result of disturbed signal before receiver will be very obscured and hard to directly detect or recover. Figure 3.5 expresses how distorted the signal can be at the receiver end.

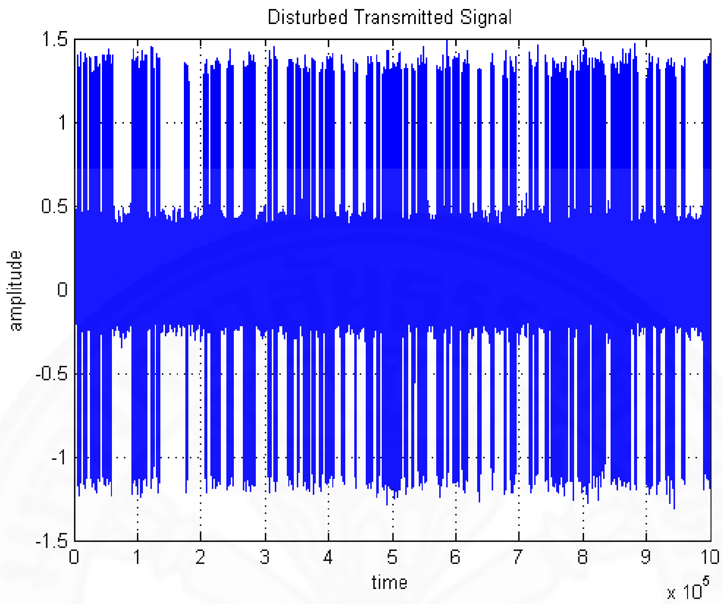

Figure 3.5 a disturbed message signal by AWGN

After the receiver got the travelling message signal into itself using a proper photo detector such as, photodiode with quite high sensitivity to be able to detect a short glimpse in light flickering from LED. The most needed module to be implement is demodulator or light signal decoder. It must change and rearrange the distorted signal into original message from source as close as possible according to some specific algorithms and relations with transmitter. For light transmission, there is the most proper method to modulate and demodulate, called intensity modulation/direct detection (IM/DD). As the mentioned name, it starts with light intensity modulation by some dimming property of LED at the transmitter. Then there is an algorithm to decide a disturbed message to be in fixed levels directly at the receiver. But in this thesis, light heterodyne detection has been used to primarily demodulate received light. This method works by mixing desired wavelength of light oscillator into an interfered message to easily separate original message from external noise.

After demodulation process, high frequency component may remain in the received signal at the flat slope. To take out this kind of noise completely, an effective low pass filter is necessary. The low pass filter is a filter in frequency domain that allows only low frequency component to pass through. Ideally, a shape of low pass filter must be square wave with indication of frequency limitation at its end. However, an actual electronic circuit cannot convey a perfect square filter directly due to its analog behavior. The real low pass filter depends on several parameters, response time, cut-off frequency for instances. Therefore it is better to select a filter type which can be easily adjusted via a few configurations. The Butterworth filter is the most probable choice with many variations. It can be modeled by cut-off frequency, response time, transient period, filter order and gain. With an appropriate order calculation, the low pass filter can be constructed as near as possible with an ideal filter without a heavy burden to hardware unit. As a result, any high frequency noise can be taken out precisely. The graphical result of light signal after experienced demodulation can be seen in Figure 3.6. Following by Figure 3.7, it expresses how an output reconstruction looks like.

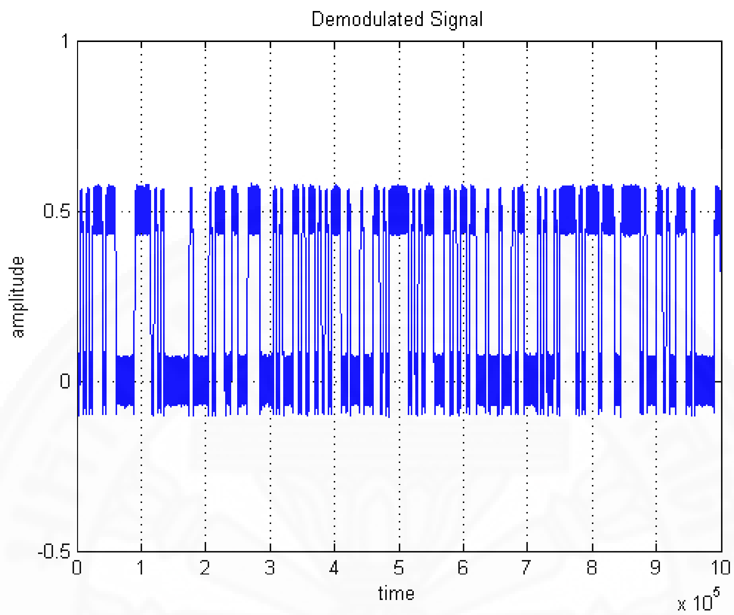

Figure 3.6 a demodulated message with noise remaining

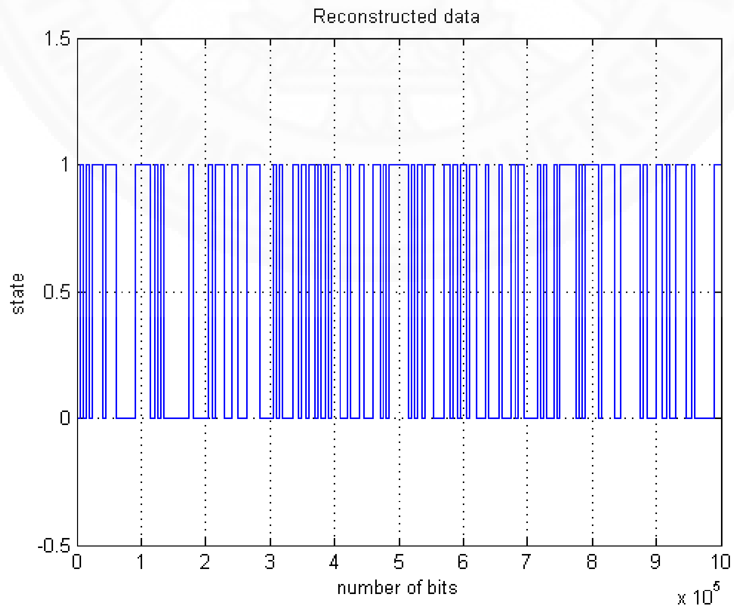

Figure 3.7 a reconstructed binary data

From above figure, it can be seen that the output binary to be sent to destination device is in a near-perfect state compares to the original data from source. This can be done by decision coding which decides which level of quantized data the distorted message would be in. Hard-decision coding has been used in this thesis as thresholding method to separate certain levels of received data and assign to the most probable output in accordance.

3.2 Physical Environment Modeling

In this section, an intention to model the mentioned general VLC model was being realized in an actual environment. Any kind of surroundings can be selected as long as VLC communication modules can be installed around those place. Typical type of model which has been mostly used are a simple office room with no obstacle, it provides extreme easiness to investigate VLC channel. But a model of a plane cockpit named Commander FAR-23 was chosen as a light medium to convey paths of light for communication among pilot devices and control panel. The picture of this model of plane is illustrated in Figure 3.8.

Figure 3.8 Commander FAR-23 private plane

When the actual environment is being considered, real dimensions of width/height/length are very important to analyze light paths. The exact location of obstacles such as, a chair or mirror, must also be considered as a mean to reflect and absorb light in order to see multi-path behavior of light. The main components to be used as a light transmission devices are mounted transmitter on a ceiling, above pilots, and mounted receiver on control panel. The transmitter can act as a notification of some emergency on the plane and then it can send an information directly to receiver at control panel to make a correct counter measure. However light source always transmits light in omni-direction, so there are nearly infinite path of light, some is absorbed into obstacle, some is reflected, and there is one direct light signal sending from transmitter to receiver. To simplify this case, only directed path and reflected paths from both sides of cockpit window was in consideration. The point that only two reflected light paths were used because there is only one major reflective impact in one reflection scheme, other minor paths can be neglected due to overwhelming power of major reflected path.

To calculate for direct path of light, the distance in vertical and horizontal line at the same plane between transmitter and receiver have to be known first. By taking Pythagorean Theorem, the direct distance of travelling can be found. But it is much harder to determine the proper distance for reflected paths, the distance from center plane to cockpit window must be known also. When it is combined with direct distance, both reflected distance and light incident angle to the window can be realized by Pythagorean and Trigonometry. These distance values are important factor to determine an absolute propagation delay, while incident angle determines power of light reflection. The exact location to install transmitter and receiver in the cockpit is shown in Figure 3.9, the red point is a transmitter and the blue point is a receiver. Followed by Figure 3.10, it shows distance and incident angle in this model before calculation.

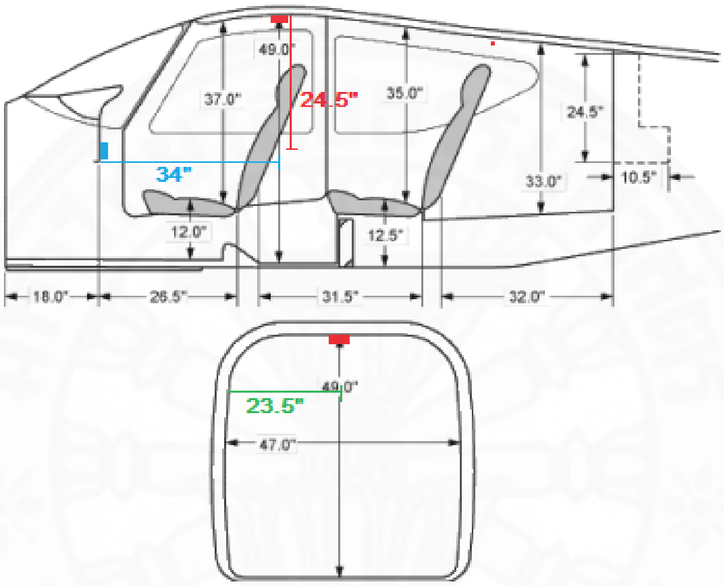

Figure 3.9 Locations of TX-RX mounting and cockpit dimension

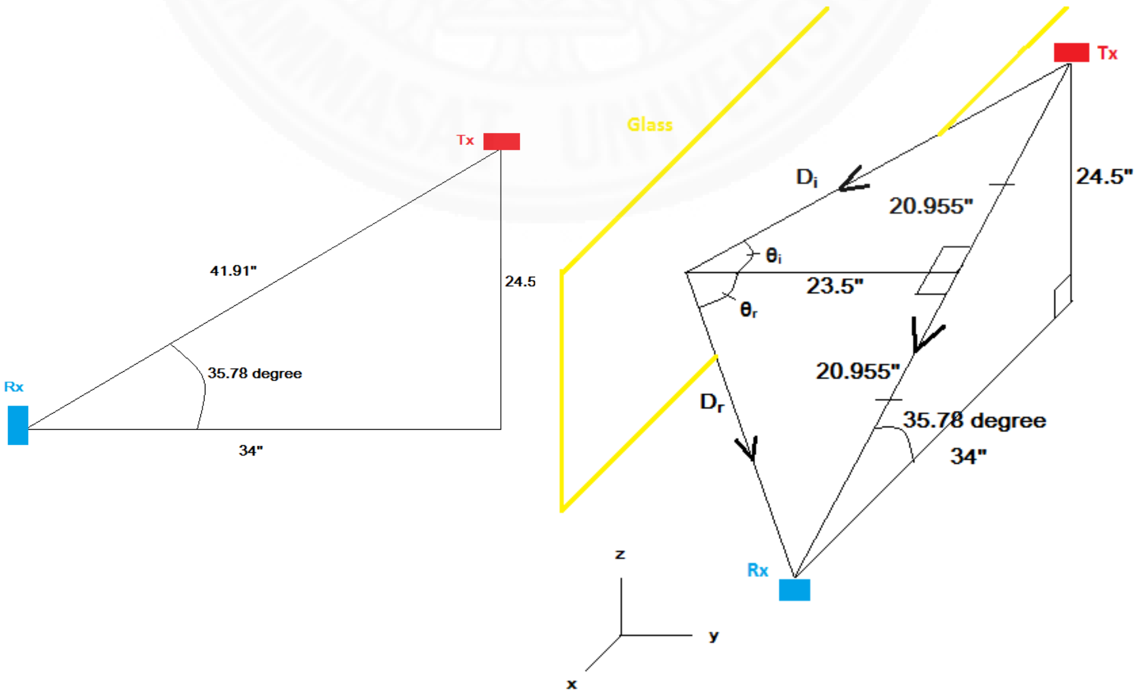

Figure 3.10 Direct light path (Left), Reflected light path for one side (Right)

The following equation is how we calculated for the specific light travelling distance and incident/reflective angle at the center point of cockpit window, noted that incident angle always equals to reflective angle;

$$\boldsymbol{D_i = \sqrt{(23.5)^2 + 20.955^2} = 31.486" = D_r} \quad (3.1)$$

$$\boldsymbol{\theta_i = tan^{-1}(\frac{20.955}{23.5}) = 41.72\,^{\circ} \ = \theta_r} \quad (3.2)$$

Next step, a power of light signal contains a major impact to determine a degree of interference and signal loss along a wireless transmission. The main cause of signal loss in multi-path wave is reflective material. In this simulation, cockpit window is considered as the main reflective obstacle. Therefore the material which this window is made of must be known first, to assign a right value of refractive index. This will lead to find an important parameter which is called reflectance. It is a ratio between a powers of reflected light over a power of an original light before it is incident at a material surface. Two required variables to compute reflectance are incident angle and refractive index. Angle of incident is very important for both refraction and reflection of light, it can directly determine direction of light input/output, whether the light is being absorbed, and its speed variation. Reflectance equation is separated into two versions depends on light polarization alignment, parallel and perpendicular. However, natural light usually have no exact polarization, i.e. sunlight travels in all direction as it propagates. So reflectance of parallel and perpendicular light are bounded to be average to obtain natural reflectance. The FAR-23 cockpit window is made from windshield glass of laminated layers [8], it is said that this kind of glass has refractive index around 1.4 to 1.6. In this thesis, the refractive index of 1.5 was taken into calculation. Propagation delay for both direct path and reflected path is also calculated from distance value which is already obtained from previous step. Equations below shows the method for computation of reflectance and propagation delay.

$$\boldsymbol{R_p} = \left|\frac{(1)\sqrt{1-\left(\frac{1}{1.5}\,sin\,41.72°\right)^2}-(1.5)\,cos\,41.72°}{(1)\sqrt{1-\left(\frac{1}{1.5}\,sin\,41.72°\right)^2}+(1.5)\,cos\,41.72°}\right|^2 = \boldsymbol{0.0123} \quad (3.3)$$

$$\boldsymbol{R_s} = \left|\frac{(1)\,cos\,41.72°-(1.5)\sqrt{1-\left(\frac{1}{1.5}\,sin\,41.72°\right)^2}}{(1)\,\cos 41.72°+(1.5)\sqrt{1-\left(\frac{1}{1.5}\,\sin 41.72°\right)^2}}\right|^2 = \boldsymbol{0.0818} \quad (3.4)$$

$$\boldsymbol{R_{unpolar}} = \frac{0.0818+0.0123}{2} = \boldsymbol{0.0471} \quad (3.5)$$

$$\boldsymbol{T_{p,direct}} = (\boldsymbol{2.54 \times 10^{-2}})\,\frac{41.91}{c} = \boldsymbol{3.55\ ns} \quad (3.6)$$

$$\boldsymbol{T_{p,reflect}} = (\boldsymbol{2.54 \times 10^{-2}})\,\frac{2(31.486)}{c} = \boldsymbol{5.33\ ns} \quad (3.7)$$

From the equations, they imply that the reflected power is quite insignificant, although the perpendicular polarization shows some impacts, compare to powerful direct signal. But with the propagation delay, the reflected signal certainly makes damage to overall received signal with its phase-shifting. Even if propagation delay is in nanoseconds, it takes an effect to VLC system because the light travels in only nanoseconds range.

Chapter 4

Simulation Result

The specific simulations that have been done in this thesis are based on theory and methodology, which are mentioned before in previous chapters. First, the graphical result of general VLC channel was generated and tested for multiple times. Even with strict constraints of the simulation, the output of BER is still varied in some significant degree. Therefore, a mean of BER from several simulations for at least five times were used to conclude an approximate BER over all VLC system performance. A relation between noise intensity from external source and bit error rate is expressed in Figure 4.1.

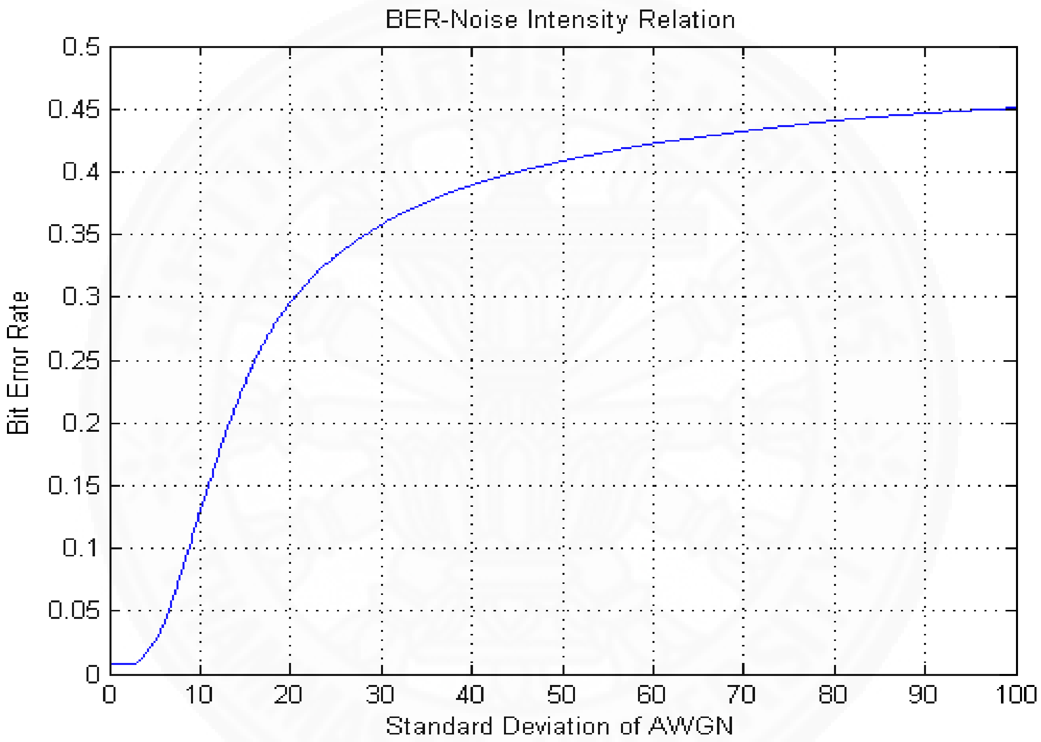

Figure 4.1 Bit error rate (BER) versus noise intensity relationship

As it can be seen from above, standard deviation of additive white Gaussian noise was used as an indication of noise intensity. Because standard deviation change can cause a broader range of random variable in randomized function when it is used to generate random noise. So it can make change in noise amplitude in the simplest way. With an increment of SD of AWGN, it is sure that BER will be rising up. At about SD value of four, BER is seen to be abruptly increased with the lowest point of around 0.01. Although BER is increasing dramatically, it appears that it contains a steady-state at 0.45 regardless of SD value. In this situation, a time with highly exposed light travels in a medium may be an impossible case to make VLC channel functional properly. Due to a high amplitude of light interference, output message will be extremely disturbed and may not be recovered at all. To summarize from this graph, indoor environment with minimal light noise is the perfect choice for system implementation with incoherent transmission.

Next, a varied distance between transmitter and receiver was observed whether how much impact it gives to a general VLC system. As the more distance is, more bit error usually be inflicted into data stream. Because phase shifting grows proportionally with propagation distance and delay, so this situation takes more effect when it happens in multi-path channel. Figure 4.2 below shows a plotting result of distance and BER relation.

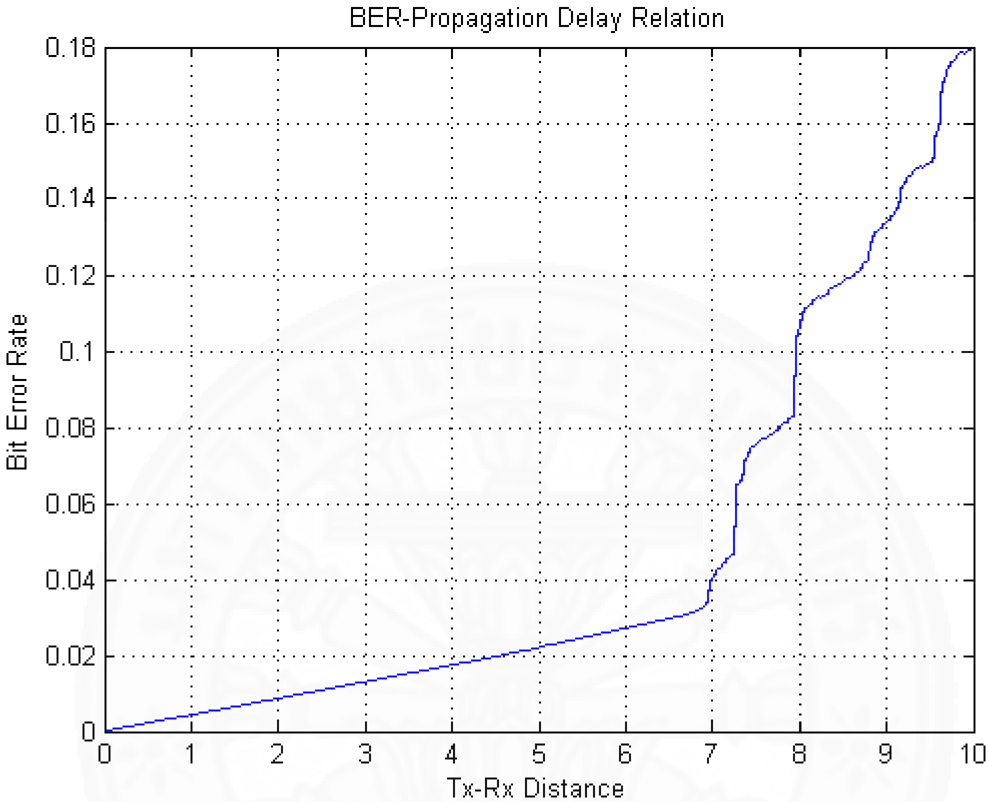

Figure 4.2 Transmission distance versus BER relationship

As it can be seen from the graph, the system respond to distance of propagation in such insensitive trend from the start. From zero to almost seven meters, BER is not more than 0.04 which is acceptable. However, this project has been tested in assumption of no power fading over a propagation, so BER may increase a little when the system works in actual situation. After the point of seven meters, BER rose up quite abruptly with average constant rate. Because light source was used as a mean to send information rather than radio frequency signal, there is a certain limited range of effect for light propagation. Therefore, almost all of optical power dispersed when traveled further than seven meters. At ten meters, BER increased itself up to 0.18 approximately. From BER numerical result, it may not express problem and may be acceptable rate overall, but there are many other factors which can give impact to a signal at further location. External noise is one major problem in a long propagation, it can severe quality of signal to the point that it is impossible to be recovered at a receiver. A demodulator is another cause of BER rising if it is not proper with the current VLC system. With accurate transmission delay calculation, phase delay is clearly determined and BER is in control so that bit error from noise only is tolerable at a receiver. Demodulator must produce bit error as less as possible.

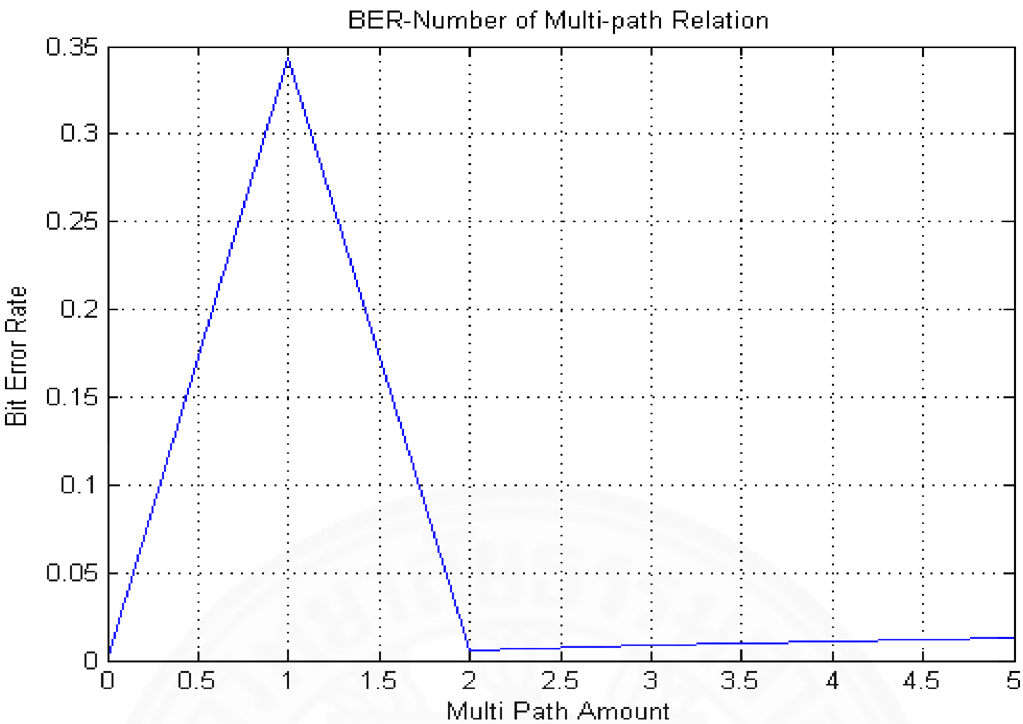

Figure 4.3 Number of multi paths versus BER relationship

Next parameter to be observed is an amount of multi-path wave to be self-interfered with the main light signal. From Figure 4.3 above, it expresses one path of inter-symbol interference (ISI) makes the result of maximum bit error rate. The cause of this activity may be one clearly phase-shifted path affects in definite destructive mean to the main signal, while ISI of at least two can randomly neglect among themselves. Consequently, there is a possibility that interference wave is reduced results in less bit error. But there is also a trend of bit error rate to rise a little after two paths of interference. In the plane cockpit simulation, there were also graphical results at some states shown in Figure 4.4 and 4.5.

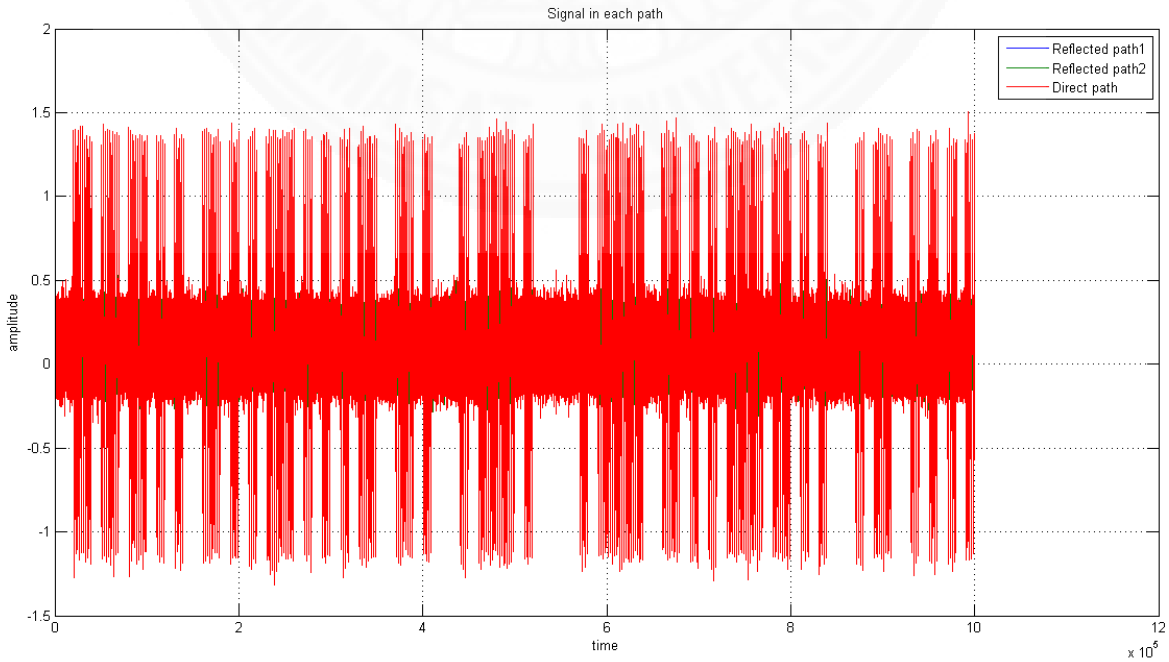

Figure 4.4 Direct and reflected path of light propagation

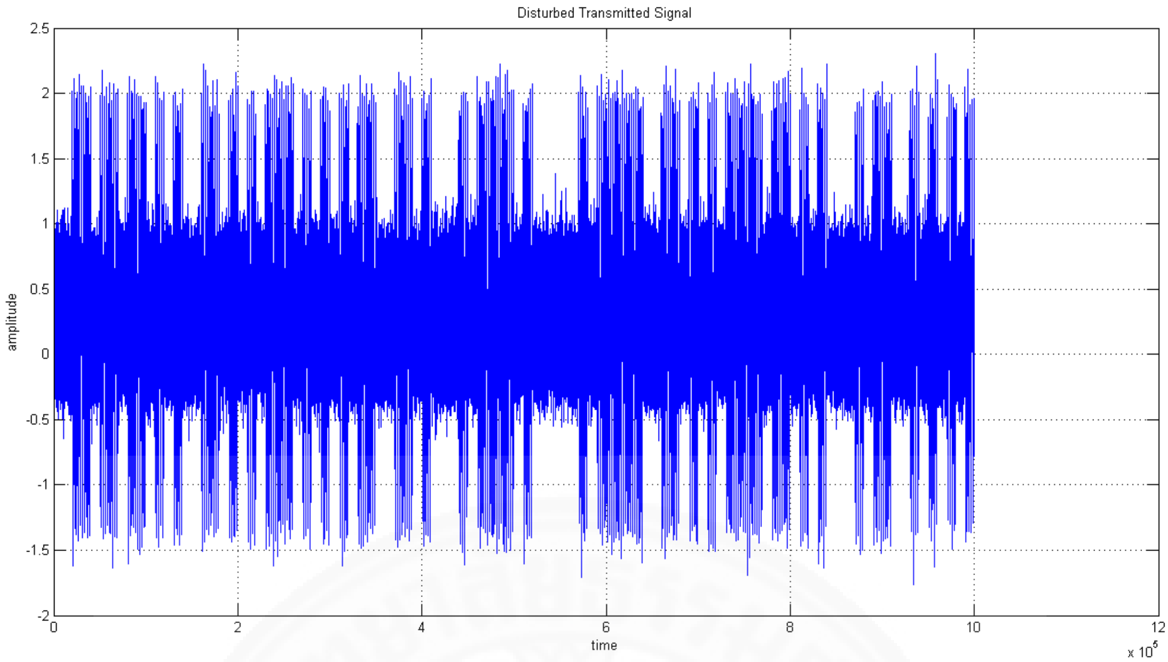

Figure 4.5 All-combined signal at a receiver with high disturbance

From Figure 4.4, the red signal is a primary direct signal that travels straight from transmitter to receiver. It contains original maximum amplitude of the transmitted signal. While the green one, which may be a little visible because of small magnitude, is the reflected waves from two sides of cockpit windshield glass. All of these signal shown in this figure are already distorted by AWGN in a medium. Then in Figure number 4.5, it is an overall signal detected at the starting point of receiver end. The direct signal, reflected signals and natural noise are mixed together and provide high frequency component to be hardly translated back to the original message. In the final step, several experiments were conducted with different pattern of binary input. Table 4.1 shows bit error rate result acquired from five samples of input, the average BER is around 0.01. From all of these results, it have been proved that there are two main causes of bit error; propagation distance and multi-path reflection. Therefore, an effective module to improve these issues must be implemented and adjusted thoroughly to reduce bit error as much as possible.

Table 4.1 Bit error rate from five inputs and average value

Input Sample	Bit Error Rate
1	0.010173
2	0.009668
3	0.010644
4	0.011010
5	0.009522
Average	*0.010203*

Chapter 5

Conclusion

To summarize overall thesis, generalized form of communication model was used and modified to be properly worked in visible light communication system. It started with an input data which we desire to send to the other end. The digital data is always in a binary form, this binary train then traveled to modulator part. The modulator worked as an encoder-like module to transform data according to transmission capability. This project utilized binary amplitude shift-keying as a modulator to transform digital data of zeros and ones into continuously analog signal. This transformed signal was assigned by fixed frequency and amplitude of sinusoidal wave, it overwrote binary signal as presence on ones and absence on zeros respectively. Digital data is not appropriate to be sent via physical medium. Therefore, this method was carried out. At a transmitter, LED unit was mounted on and acted as light data transmitter by manipulation of light flickering directly as modulator output. Afterward, a transmission medium that is air was considered as additive white Gaussian noise channel originated from another disturbance such as, lighting or sunray. This kind of channel is the simplest way to simulate how communication channel works in fundamental step. With all that noise, modulated light was fluctuated at a very high frequency domain. Consequently, an effective receiver was installed by high sensitivity photodiodes. These equipment helped very much in term of light detection even if there was only a little blink. At the receiver, complex demodulator was implemented to ensure decoding ability as perfect as possible for light wave communication. There were three steps of function in this demodulator. The first was light heterodyne detection to detect light wave using mixed adjunctive wavelength, followed by low-pass filter, to throw away unwanted high frequency signal, and decision coding to finally quantize the levels of disturbed signal into binary form. From all of these mentioned processes, an output of binary reconstruction referred from input data was sent to the destination with a bit error rate as low as possible. There were three relationships that tested how efficiently this VLC channel is. These mentioned tests were noise intensity, propagation distance, and number of self-interference path, all of them was observed respect with bit error rate of output signal compare to input one. The final result was moderately satisfied, noise induced more BER in gradual and normal mean, but propagation distance made BER rose up drastically with only small increase. This mistake might be caused by improper adjustment in the demodulator.

Another part was a physical environment simulation. The objective of this part was to convey the simple VLC simulation into a real world environment, so the certain boundary was taken in account. The model used Commander FAR-23 private plane cockpit as a setting for light transmission. It can be functional as a mean to communicate or to inspect a control device, by mounting transmitter and receiver in desired locations. Light influential material in this surrounding was considered as a factor of changing path of light, windshield glass around the cockpit in particular. Most windshield glasses are made of laminated silica in multiple layer and able to withstand considerate amount of force. Thick layers of this kind of glass made light traveled with less speed compared with the air. From this scheme, multi-path light model was taken place consequently from reflection light at the surface of windshield glass. There were direct light and reflected light transmission, direct light contained only propagation delay, reflected light carried both delay and power attenuation caused by reflectance ratio. This parameter was calculated from refractive index of two mediums and incident angle at reflection point, it contained a meaning of reflected power divided by original power of light. After the system found all unknown variables, it could create the efficiency testing chart like the one in generalized model.

There is a plan of possible future works to develop more contribution for this thesis. First of all, the VLC simulation must be revised to provide lossless or effective coherent transmission. Both external light noise, i.e. sunlight, and internal noise, i.e. inter-symbol interference, have to be reduced by some specific method to deal with VLC system. As the author has studied in several modulations, it is better to apply a combination of existing modulations. Therefore, it had been found that pulse position modulation (PPM) is one of the modulation process which tolerates abrupt change in signal amplitude. PPM can be implemented together with sub-carrier wave to ensure less data loss. With phase shifting is also the main problem for multi-path transmission, which mostly happens, phase tuning method may express prominent improvement on bit error rate caused by propagation delay if it is functioning in both transmitter and receiver. For demodulator part, adjustments like light direct detection, can provide much more effectiveness with light wave reception if it is implemented on a good photodiode.

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