

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO



# **A Dense And High Throughput WLAN System Using Emerging Light Communications Technology: Polarization Based Visible Light Communications**

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# Resumo

Visible Light Communications (VLCs) é uma tecnologia em crescimento com um vasto potencial para responder a muitas das questões sobre o futuro das comunicações de redes sem fio.

A pesquisa em VLCs foi motivada pela inovação no espaço de telecomunicações devido ao congestionamento de frequências radio e à crescente necessidade de conectividade mais robusta e rápida. Os VLCs encaixam-se perfeitamente nesse contexto, pois a luz visível faz parte da banda de frequência não restrita. Com o próximo standard (802.11bb), essa tecnologia tornar-se-á onnipresente. A polarização é uma propriedade inerente a luz que é ao mesmo tempo bem definida, compreendida e modulável.

Espera-se que a contribuição deste trabalho aumente o interesse na criação de novos usos da polarização da luz visível em sistemas VLC e propõe soluções novas e criativas que visa a melhoria dos sistemas já existentes.



# Abstract

Visible Light Communications (VLCs) is an emerging technology with vast potential for many of the unanswered questions of wireless network communication.

Research in VLCs has been motivated by innovation in the telecommunication space due to the ever-increasing frequency congestion and the ever-growing need for more reliable and fast connectivity. VLCs fit perfectly in this context as visible light is a part of the unrestricted frequency band. With the upcoming standard (802.11bb), this technology will become ubiquitous. Polarization is an inherent property of light that is well defined, understood, and modulatable.

Hopefully, the contribution of this work will build interest in the creation of new uses of visible light polarization in VLC systems and proposes new and creative solutions that improve already existing systems.



# Acknowledgments

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André Da Silva Reis



*"I don't stop when I'm tired. I stop when I'm done"*

David Goggins





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# Abbreviations and Symbols

|      |                                          |
|------|------------------------------------------|
| AP   | Access Point                             |
| AWGN | Additive White Gaussian Noise            |
| BCSK | Binary Color Shift Keying                |
| BER  | Bit Error Rate                           |
| CIE  | Commission Internationale de l'Eclairage |
| CSK  | Color Shift Keying                       |
| DC   | Direct Current                           |
| DD   | Direct-Detection                         |
| FEC  | Forward Error Correction                 |
| FOV  | Field of View                            |
| IM   | Intensity Modulation                     |
| LED  | Light-emitting Diode                     |
| LOS  | Line of Sight                            |
| LP   | Linear Polarizer                         |
| MIMO | Multiple-Input-Multiple-Output           |
| OOK  | On-Off Keying                            |
| PAM  | Pulse Amplitude Modulation               |
| PD   | Photodetector                            |
| PDM  | Polarization Division Multiplexing       |
| PPM  | Pulse Position Modulation                |
| QWP  | Quarter Waveplate                        |
| RF   | Radio Frequencies                        |
| SNR  | Signal to Noise Ratio                    |
| TDMA | Time Division Multiple Access            |
| TN   | Twisted Nematic                          |
| VLC  | Visible Light Communication              |
| WLAN | Wireless Local Area Network              |





# Chapter 1

## Introduction

### 1.1 Context

The world's rising demand for better means of communication has pushed for innovation in the telecommunication area. Visible Light Communications (VLCs) is amongst these innovations and our focus. As the name suggests, these systems utilize light modulation to carry data using light in the visible spectrum (380-750 nm). They also provide general illumination. VLCs tackle many different problems in the communication space. By not using radio frequencies (RFs), the issue of rising RF spectrum congestion does not arise. Many of the technologies for communication, such as Wifi-6, 5G, and Bluetooth, use the RF spectrum. It is increasingly difficult to operate such systems in high-density environments, such as sports venues, concerts, and airports, due to losing part of its Quality of Service. Furthermore, the visible nature of light, combined with the fact that it does not travel through most physical objects, makes it very difficult, if not impossible in most scenarios, for man-in-the-middle attacks. Ergo, it has an overall better physical layer of security than RF communications. It is also possible to create precise light positioning systems and other systems such as image-based, car-to-car, and underwater VLCs. The technological advancement in high-powered light-emitting diodes (LEDs) and the upcoming standard (802.11bb Light Communications Amendment) will make the adoption of VLCs straightforward and, therefore, relevant for the near future.

### 1.2 Motivation

Visible light is electromagnetic radiation composed of an electric field ( $\vec{E}$ ) and a corresponding orthogonal magnetic field ( $\vec{B}$ ). Light has many different properties such as speed, wavelength ( $\lambda$ ), direction ( $Z$ ), intensity, and last but not least, polarization, as shown in Figure 1.1, which will be the basis of this work. Polarization is the direction of oscillation of a wave whose motion is perpendicular to it; in the case of light, the polarization direction is the direction of its electrical field oscillation.

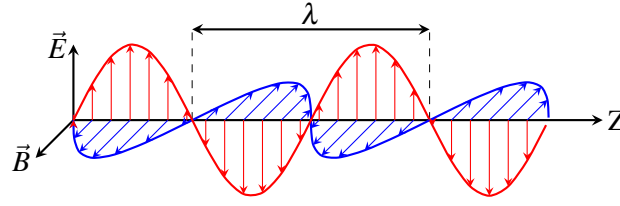


Figure 1.1: Electromagnetic wave.

Polarization manipulation is an established field of study in optics that has given us technologies such as sunglasses, 3D Televisions, and movies. The modulation of light polarization has the potential to enhance the performance of VLC systems, making it an excellent area of research to find new and renewed applications. So far, research for VLCs using the modulation of light polarization is lacking.

### 1.3 Problem Statement

The property of light polarization is not as widely used in VLCs as it is for monochromatic laser light. The issue is that its applications for monochromatic laser light do not always translate well for broad-spectrum light. The consequence is that a possibly very inexpensive and effective solution for VLCs problems considers using light polarization. The focus of this dissertation will be the proposal of new polarization-based VLC systems.

### 1.4 Objectives

Considering the statements above, the goal of this work will be, first and foremost, to gain a thorough understanding of the current state of the art of VLCs and explore the field of optics, specifically polarization manipulation. Secondly, it will be to merge these two fields to create VLC systems with enhanced characteristics, harnessed in a multitude of applications, at the same time; defining each possible scenario and how polarization affects the overall system in a better way. Finally, it will present a good case for polarization in VLC systems. Hopefully, this work will motivate other researchers to pursue this idea.

On a more specific note, it seems evident that polarization can decrease the overall interference in VLC systems that use multiple access points (APs), in this case, light sources. This work will also focus on improving that aspect of the system.

### 1.5 Contributions

The main contributions of this dissertation are:

- A brief, concise and simplified literature review on the existing concepts of VLCs and polarization of light

- Development, presentation, and analysis of new, modified, or hybrid VLC systems.

## 1.6 Document Structure

This document is structured in the following chapters:

- Chapter 2 [[Literature Revision](#)] - Revision of VLC concepts and polarization concepts
- Chapter 3 [[State of the art](#)] - State of the art of systems that use polarization in VLCs.
- Chapter 4 [[Developed work](#)] - Developed work, proposed solutions.
- Chapter 5 [[Simulations and Results](#)] - Simulations, results and findings.
- Chapter 6 [[Conclusion](#)] - A brief conclusion

## 1.7 Notes

In order to have the most pleasant and immersive reading experience, Adobe Acrobat Reader is recommended, as some figures are animated. These figures will give the reader a better visual representation of the topics discussed.



## Chapter 2

# Literature Review

A simple literature revision about two main topics, VLCs and Polarization, is presented, allowing the reader to understand better what is involved in this work and to develop intuition about the decision made further in this dissertation.

### 2.1 VLC Channel Modeling

Channel modeling of VLC systems is fundamental knowledge necessary to create and construct efficient, robust, and optimized systems. Channel modeling of VLC systems also helps to understand the limitations and drawbacks of such systems. This section will present information about the main characteristics of this channel and its effects.

#### 2.1.1 Propagation Modes

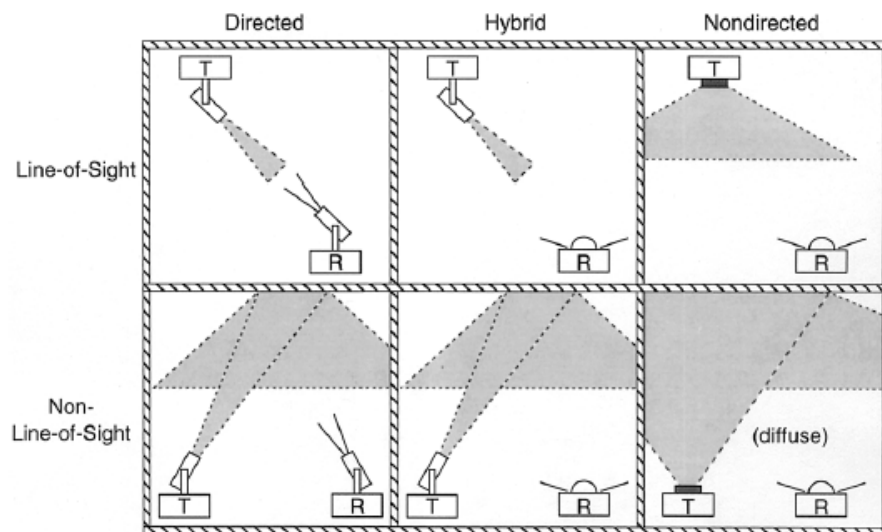


Figure 2.1: Infrared links classification according to the directionality of the Tx, Rx pair and the existence of a LOS path between them. [1, Fig. 1].

The contributions of [1] provides six different configuration modes for infrared wireless communications, as seen in Figure 2.1. As argued, "Infrared and visible light are close together in wavelength, and they exhibit qualitatively similar behavior." [1], making the same propagation modes relevant for VLC systems. For the interest of this dissertation, the non-directed line-of-sight (LOS) non-tracked configuration will be predominant as it better suits a realistic VLC system with illumination. The non-directed line-of-sight non-tracked configuration is ideal for a multi-user, low-cost system. It is suitable for indoor consumer use but comes at the cost of lower achievable data rates [2]. The low achievable data rates are due to the diffuse nature of this configuration, which lowers the received light intensity to the photodetector (PD).

### 2.1.2 Illuminance of Light Emitting Diodes

Light emitting diodes (LEDs) have a Lambertian radiation pattern. Let us consider a closed box of emitting light to understand the meaning of a Lambertian radiation pattern and its consequences. This box has no preference in the direction of emission of light.

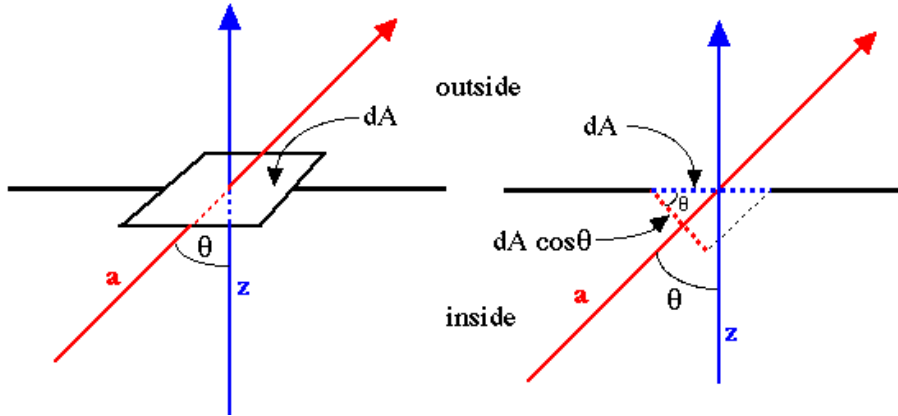


Figure 2.2: Photons approaching the window along the  $z$ -axis see a large cross-section of escape ( $dA$ ). Photons approaching the window along the vector  $a$  see a foreshortened cross-section of escape ( $dA \cos \theta$ ). [3, Fig.1].

Now let us open a small window on top of the box for light to escape. As depicted in Figure 2.2, even if the box of light emits light randomly, the number of photons exiting that small window will depend on the angle of approach  $\theta$ . The consequences of this pattern are simple. The emitted light of the LED will decrease the more angle  $\theta$  increases. If we suppose that a PD is on a plane surface below the emitting LED, then any deviation from the perfect alignment between LED and PD will decrease signal intensity for the same distance.

The illuminance intensity is given in terms of the spatial angle  $\Omega$  and the luminous flux  $\Phi$  as [4]:

$$I = \frac{d\Phi}{d\Omega} \quad (2.1)$$

The luminous intensity when illuminating a surface defined in terms of the angle of irradiance  $\phi$  is given as [1]:

$$I(\phi) = \frac{m+1}{2\pi} I(0) \cos^m(\phi) \quad (2.2)$$

Where  $I(0)$  represents the center luminous intensity of the LED and  $m$  indicates its Lambertian order, given by [5]:

$$m = \frac{-\ln(2)}{\ln(\cos(\Phi_{1/2}))} \quad (2.3)$$

Where  $\Phi_{1/2}$  is the semiangle at half illuminance of the Tx. Lambertian order is the value that defines the level of directionality of the emitted light of an LED. This effect is caused mainly by the optics of LEDs as a regular Planar LED follows a Lambertian radiation pattern closely, as described above, where  $m = 1$ .

### 2.1.3 LED Bandwidth Limitation

One of the main limitations of high data rate transmissions in VLC is inadequate LEDs. Although trichromatic LEDs have bandwidths of several hundred megahertz, they often are not used because they are expensive and present other issues such as complex modulation and color shift over time. White light LEDs (blue LED plus phosphorous layer) are envisioned for indoor lighting but present limited bandwidth to several MHz due to phosphor's slow time constant. Several solutions have been presented, such as pre-equalization of the driving circuitry, the use of multilevel modulation together with discrete multi-tone, and lastly, multiple-input, multiple-output (MIMO) architectures with spatial diversity. All solutions have drawbacks, whether cost, complexity, or both. In this dissertation, MIMO architecture together with polarization division multiplexing (PDM) will be used.

### 2.1.4 Single Source Channel

The following presentation of the equations that model the LOS Channel are made to understand how VLC systems are affected by hardware and physical geometry. Figure 2.3 illustrates a typical scenario with a single source and a single receiver design.

If we only account for LOS paths and assume an emitter with a generalized Lambertian radiation pattern, we have [6]:

$$P_R = H(0)P_E \quad (2.4)$$

where  $P_E$  is the emitted optical intensity,  $P_R$  is the received optical power, and  $H(0)$  is given as follows:

$$H(0) = \begin{cases} \frac{(m+1)A_{PD}}{2\pi d^2} \cos^m(\phi) T_s(\varphi) g(\varphi) \cos(\varphi), & 0 \leq \varphi \leq \varphi_c \\ 0, & 0 \geq \varphi_c \end{cases} \quad (2.5)$$

where  $A_{PD}$  is the PD surface area,  $\varphi$  is the incident angle,  $\varphi_c$  is the Rx Field of View (FOV) (semiangle), and  $d$  is the distance from LEDs to the Rx point. Also,  $T_s(\varphi)$  is the optical filter gain,

and the optical concentrator gain  $g(\varphi)$  is defined as [1]:

$$g(\varphi) = \begin{cases} \frac{n^2}{\sin^2 \varphi_c}, & 0 \leq \varphi \leq \varphi_c \\ 0, & 0 \geq \varphi_c \end{cases} \quad (2.6)$$

where  $n$  is the concentrator refractive index.

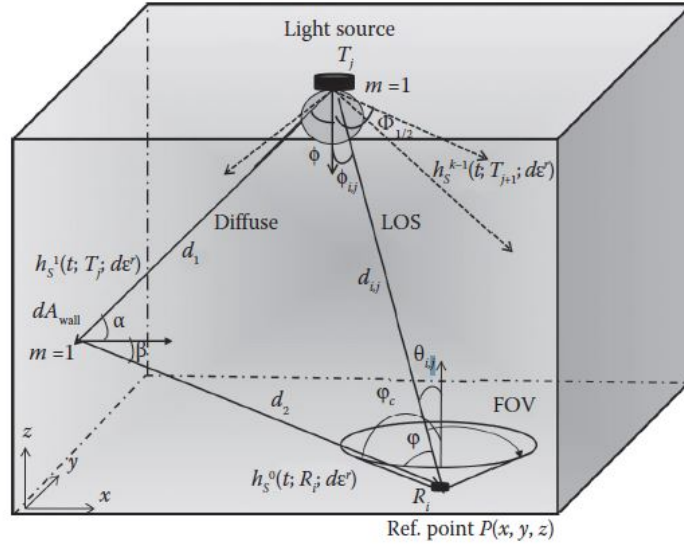


Figure 2.3: Geometry of optical Tx, Rx, and reflectors. [4, Fig. 3.4].

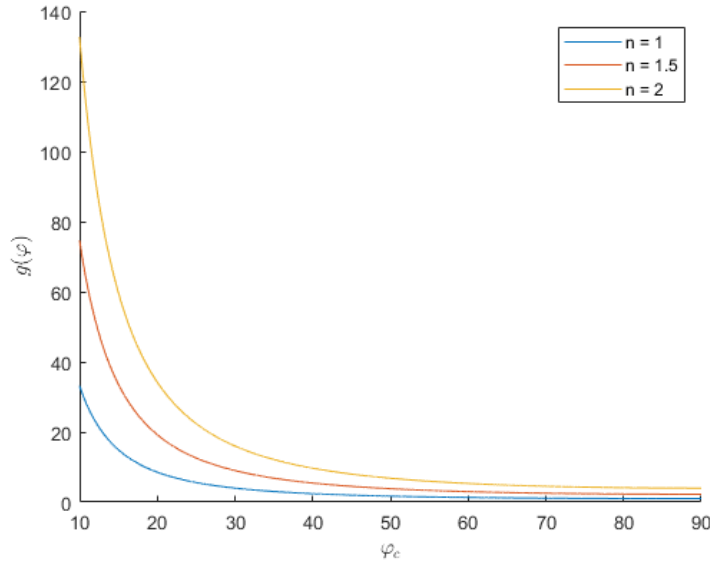


Figure 2.4: Concentrator gain vs. FOV for a each Refractive Index.

As seen in equation 2.5, multiple design choices can be made that will significantly affect the system's use case. The PD surface area proportionally increases the collector gain, but "photodiode



area is expensive, and tends to decrease receiver bandwidth and increase receiver noise." [1]. In terms of geometry, we want to decrease the distance  $d$  and the angle of irradiance  $\phi$ . The distance  $d$  and the angle of irradiance  $\phi$  are not controllable as the geometric structure of a space is already well defined, and the receiver should be able to move freely within the designed area. The optical filter gain  $T_s(\phi)$  should have little to no loss. Figure 2.4 shows a tradeoff between FOV and concentrator gain. Higher FOV will lead to a more coverage area, but at the cost of lower gain. Lower FOV will lead to blind spots and a more directed connection but work more efficiently when a direct connection is achieved. We can also conclude that the refractive index  $n$  should always be maximized as it benefits concentrator gain independently of FOV. Conclusion about concentrator gain can also be seen by signal to noise ratio (SNR) degradation in result [6], as can be shown in Figure 2.5:

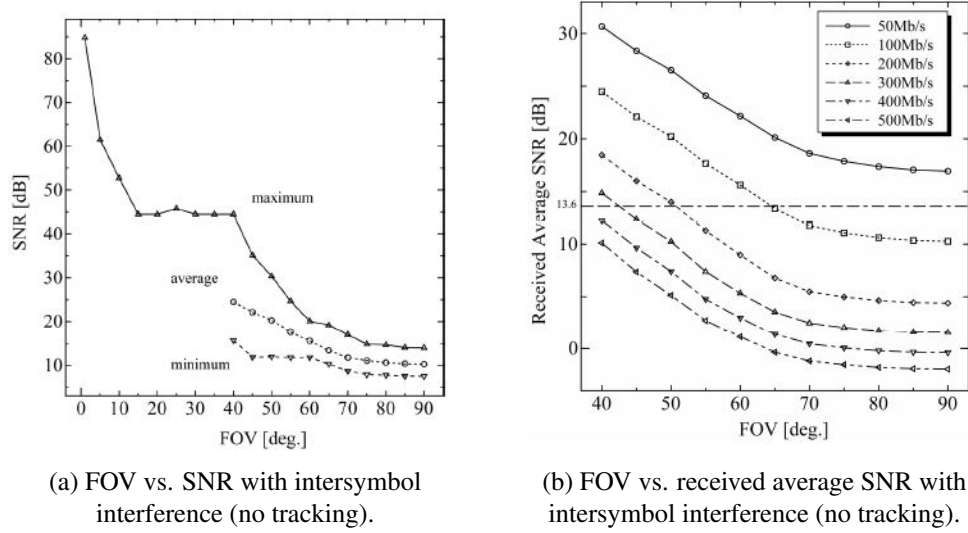


Figure 2.5: Performance results for model room [6, Fig. 11,12].

Lastly, Lambertian order  $m$  dictates the directionality of the LED. The higher the order, the worse performance is for a higher angle of irradiance, making the area of coverage smaller.

### 2.1.5 MIMO VLC Systems

Let us consider the general case of a MIMO VLC system with  $N_t$  transmitters and  $N_r$  receivers, as illustrated in Figure 2.6. This MIMO channel can be described by a matrix  $H$  of dimension  $N_R \times N_T$ , whose entries are the direct current (DC) channel gains between each Tx–Rx pair [4].

$$H = \begin{bmatrix} h_{11} & \dots & h_{1N_T} \\ \vdots & \ddots & \vdots \\ h_{N_R1} & \dots & h_{N_R N_T} \end{bmatrix} \quad (2.7)$$

where  $h_{ij}$  represents the channel gain between the  $i$ th PD and  $j$ th LED. The channel matrix includes the LOS component as well as the diffuse component arising from multipath reflections.

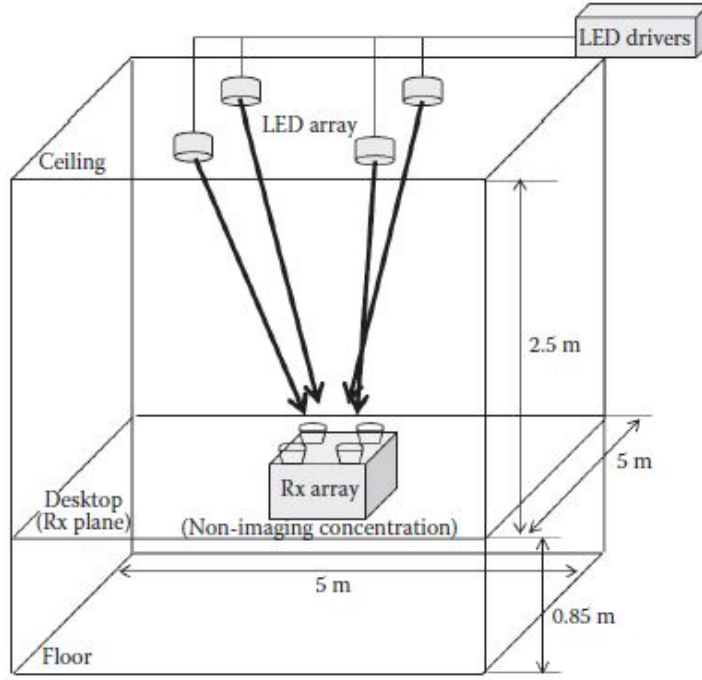


Figure 2.6: Nonimaging MIMO system. [4, Fig. 3.10].

Let us denote the vectors of transmitted and received signals at a given time reference by  $X = [x_1, \dots, x_{N_t}]^T$  and  $Y = [y_1, \dots, y_{N_r}]^T$ , respectively, we can write:

$$Y = RP_{LED}HX + n \quad (2.8)$$

where  $R$  is the detector responsivity,  $n$  is the noise, and  $P_{LED}$  is the average transmitted power. Then, the transmitted data are obtained, for instance, based on channel inversion:

$$\hat{X} = H^{-1}Y \quad (2.9)$$

where it is assumed that  $H$  is known at the Rx.

In order to estimate the transmitted signals from Equation 2.9, the channel matrix must be of full rank, which is mostly not the case with nonimaging MIMO systems. If the channel matrix is ill-conditioned or rank deficient, recovery of the transmitted signal range from difficult to recover with serious noise interference to impossible to recover [4]. As we will see later in this dissertation, the use of polarization will make a nonimaging system able to recover the transmitted signals.

## 2.2 VLC Modulation Schemes

VLC systems need to modulate and detect light properties to send data. That modulation/detection pair comes in various forms. The most well-known is intensity modulation and direct detection (IM/DD), which divides into three main categories:

- Baseband Modulations.
- Optical Orthogonal Frequency Division Multiplexing.
- Color-Shift Keying (CSK).

### 2.2.1 Baseband Modulations

"Baseband modulation techniques are so called because the spectrum of the modulated data is in the vicinity of DC" [7].

In the baseband modulation, data is coded in three distinct ways via light intensity (Pulse Amplitude), light timing (Pulse Position), and light interval (Pulse Interval) [4].

#### 2.2.1.1 Pulse Amplitude Modulation (PAM)

PAM "is one of the most popular signaling techniques for VLC system because of its simplicity." [4] and transmits data by modulating light's intensity. In L-PAM where  $L = 2^M$ ,  $M \in \mathbb{N}$ ,  $L$  number of symbols can be represented.

In a 2-PAM modulation scheme, or as it's also known, on-off keying (OOK), a data bit 1 (One) is represented by an optical pulse that lasts the entirety of the bit duration, and 0 (Zero) is represented by the lack of such optical pulse as shown in Figure 2.7. The consequence of this modulation is that it is very intuitive to understand. The circuits to realize this modulation is simple.



Figure 2.7: Time Waveform of OOK-NRZ.

In a 4-PAM modulation scheme, or any L-PAM the time waveform can be represented as:

$$s(t) = P_t \sum_{k=-\infty}^{\infty} b_k p(t - kT_{sym}) \quad (2.10)$$

where  $P_t$  is the average optical power,  $T_{sym}$  is the symbol duration and:

$$b_k = \{0, 1, 2, \dots, (L-1)\} \quad (2.11)$$

A more intuitive approach to understanding this modulation is to divide the maximum optical power ( $P_m$ ) by  $L-1$  and multiply it by the desired output bit, giving it the following representation in the case of 4-PAM Figure 2.8.

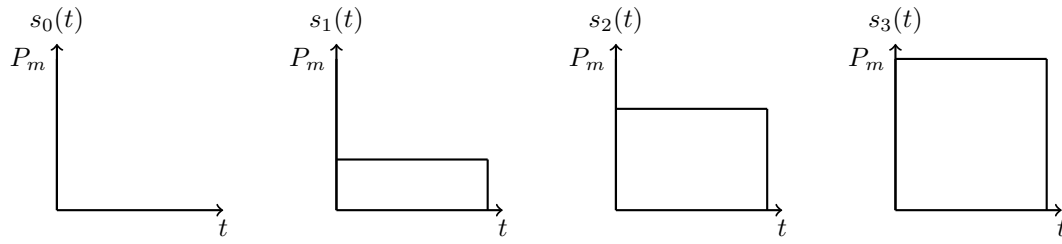


Figure 2.8: Time Waveform of 4-PAM.

### 2.2.1.2 Pulse Position Modulation (PPM)

In L-PPM, data is encoded in the position in time of the optical pulse. Similarly to L-PAM, the L is the number of symbols and also the number of time slots of equal duration. In this scheme, all time slots are empty except the data-carrying slot, as shown in Figure 2.9.

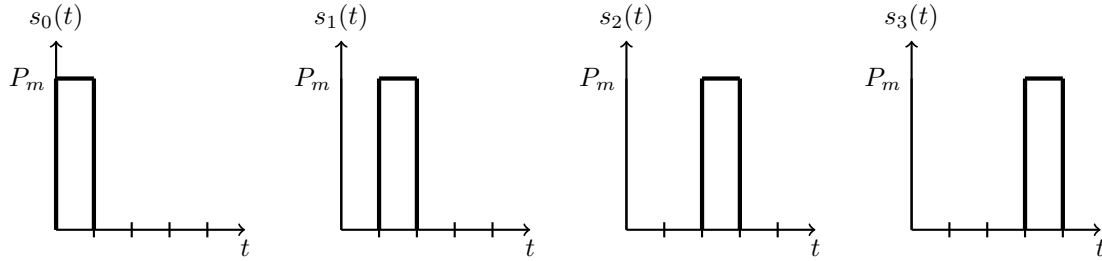


Figure 2.9: Time Waveform of 4-PPM.

The PPM signal can be represented by the following equation:

$$x(t) = \begin{cases} 1, & \text{for } t \in [(m-1)T_{sppm}, mT_{sppm}] \\ 0, & \text{elsewhere} \end{cases} \quad (2.12)$$

### 2.2.1.3 Hybrid and other schemes

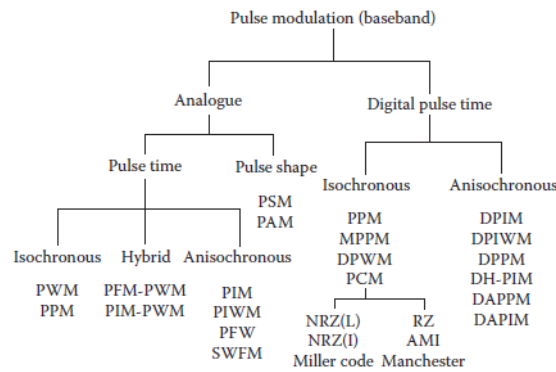


Figure 2.10: Baseband Modulation tree [7, Fig. 4.1].

As observable in Figure 2.10, many other baseband schemes exist, and some of them are hybrids between two or more schemes, for example, "DAMPPM, which is a combination of PAM and DPPM" [4]

### 2.2.2 Color Shift Keying

CSK uses the wavelength of light (Color) to transmit data. It is a special modulation as it circumvents the bandwidth limitation of white phosphor LEDs by using Red Green and Blue LEDs [8]. However, CSK is more complex and expensive to implement [4].

#### 2.2.2.1 Principle Of Function

The perception of color in humans is complex. In 1931 the Commission Internationale de l'Eclairage (CIE) identified a system that links the electromagnetic visible spectrum wavelength distributions and physiologically experienced colors in human color vision. All the perceivable human color space for a particular brightness is shown in Figure 2.11.

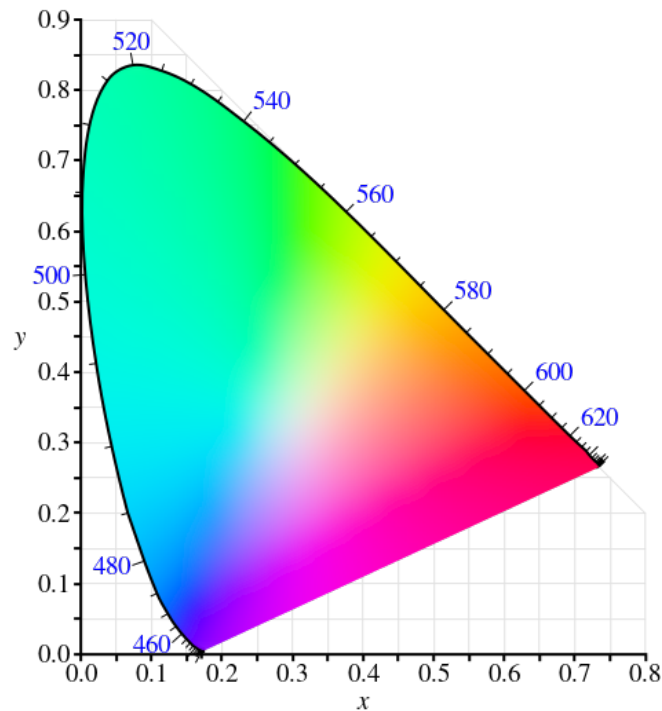


Figure 2.11: CIE 1931 XY color diagram.

CSK works by dividing this color space into a triangle where the edges are decided by the center wavelength of the three color bands chosen from Table 2.1 and illustrated in Figure 2.12. These bands, typically called bands i, j, and k, are carefully selected according to the rules defined by the Institute of Electrical and Electronics Engineers 802.15.7 and "The final output color (e.g., white) is guaranteed by the color coordinates" [8].

| Band (nm) | Code | Center (nm) | (x,y)          |
|-----------|------|-------------|----------------|
| 380–478   | 000  | 429         | (0.169, 0.007) |
| 478–540   | 001  | 509         | (0.001, 0.597) |
| 540–588   | 010  | 564         | (0.402, 0.597) |
| 588–633   | 011  | 611         | (0.669, 0.331) |
| 633–679   | 100  | 656         | (0.729, 0.271) |
| 679–726   | 101  | 703         | (0.734, 0.265) |
| 726–780   | 110  | 753         | (0.734, 0.265) |

Table 2.1: Color Bands.

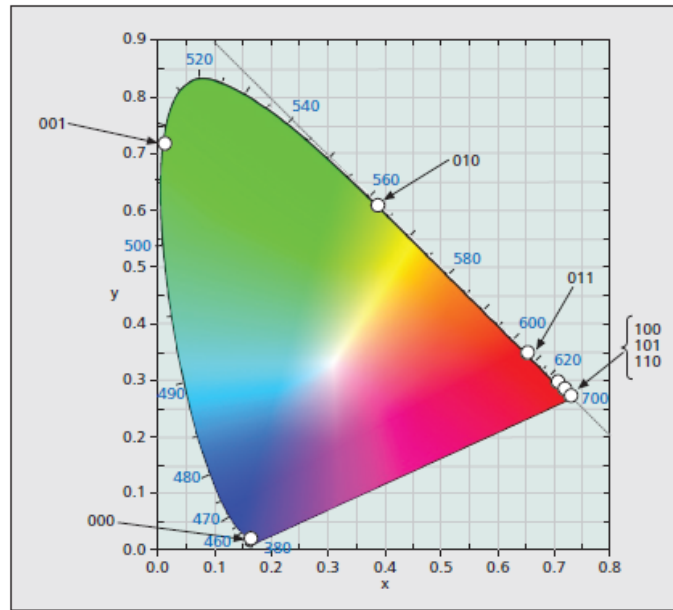


Figure 2.12: XY color coordinates of the seven bands and their position in the XY color diagram [8, Fig. 9].

As seen below in Figure 2.13, the symbol map of 4-CSK is defined by triangle edges and its centroid. Higher-order CSK modulation uses the division of triangles to map more symbols. Data transmission in this scheme is achieved by modulating the intensity of colored LEDs in order to represent a specific chromaticity symbol.

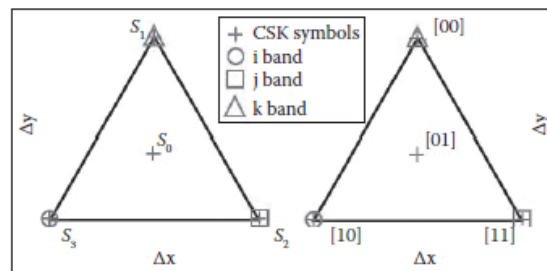


Figure 2.13: Design rule and the data mapping of 4-CSK. [4, Fig. 4.26].

## 2.3 Polarization

Light is a transverse electromagnetic wave; this means that light is a wave composed of its electric and magnetic fields that oscillate in a perpendicular plane to the direction of propagation. Polarization refers to the properties of the light in this transverse plane, describing whether the light is polarized or unpolarized and the orientation of this polarization. By convention, the polarization of electromagnetic waves refers to the direction of the electric field.

As discussed above, light polarization can be classified as unpolarized or polarized. Particular cases of significant polarizations can be further classified within the polarized category, as illustrated in Figure 2.14. This distinction will become relevant when discussing polarization manipulation.

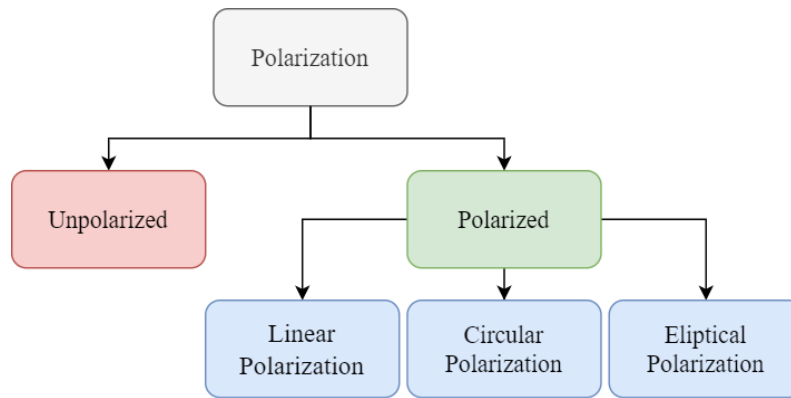


Figure 2.14: Polarization Categorization.

All polarized states can be represented in the Poincaré sphere, as shown in Figure 2.15. In the equirectangular projection of the Poincaré sphere, the entire top row is right circularly polarized, and the entire bottom row is left circularly polarized. In contrast, the middle row represents all the linearly polarized states.

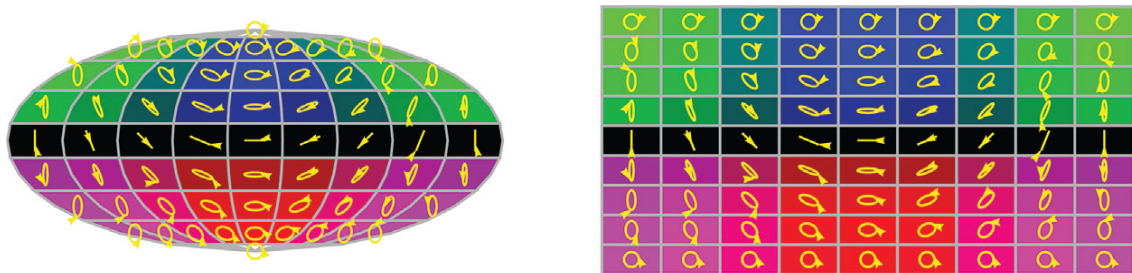


Figure 2.15: Mollweide and equi-rectangular projection of the Poincaré sphere. [9, Fig. 1.7].

For further intuition for the Poincaré sphere, use the interactive visualization tool in [10].

### 2.3.1 Unpolarized Light

Unpolarized light is the naturally occurring state of light emitted by any luminous object, such as the sun or LEDs. A light wave that presents an unpredictable and randomly evolving electrical field is considered unpolarized. In other words, "Unpolarized light has a randomly varying polarization state with no preference for any particular state." [9]

If we take unpolarized light with direction  $Z$  and trace its evolving electric field into the  $Z$  plane, we will obtain an illustration akin to Figure 2.16.

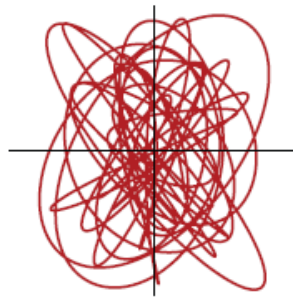


Figure 2.16: Electric field patterns for unpolarized light. [9, Fig. 3.2].

### 2.3.2 Linear Polarization

Light is linearly polarized when its electrical field oscillates only in one direction between positive and negative, causing the magnitude of the electric field to drop to zero twice per period. Figure 2.17 illustrates the oscillating electric field of a  $45^\circ$  linearly polarized light.

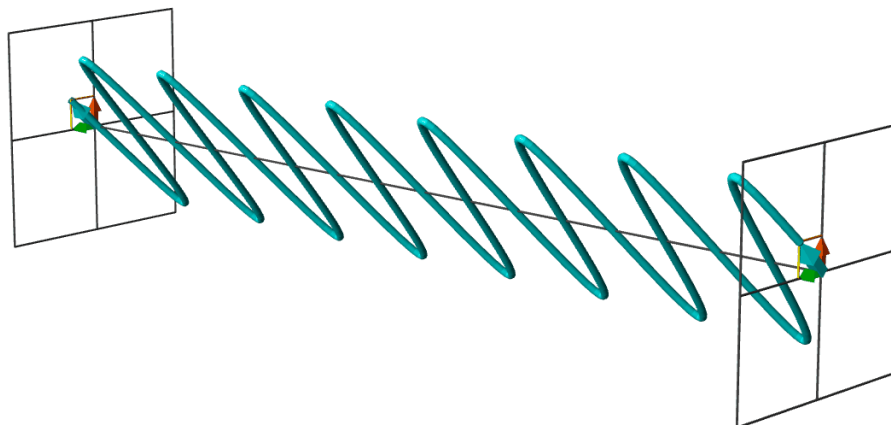


Figure 2.17:  $45^\circ$  linear polarized light.

Linearly polarized light can be viewed as the time-dependent vectorial superposition of two linear orthogonal components, as shown in Figure 2.18. These two components must be in or  $180^\circ$  out of phase for the resulting sum to be linearly polarized.



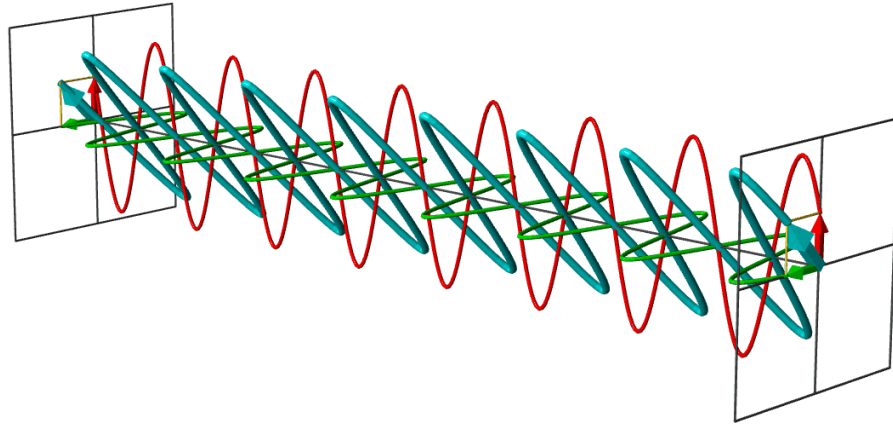


Figure 2.18: Decomposition of  $45^\circ$  linear polarized light (Cyan) into horizontal (Green) and vertical components (Red).

Any linear polarization with any direction is decomposable by these two components. For example, we eliminate the vertical component to obtain horizontal linear polarization. To get  $135^\circ$  linear polarization, we need to dephase one of the components by  $180^\circ$  or subtract a vectorial component equivalently. This decomposition will give an intuition for understanding Malus's law and any other phenomenon regarding light intensity.

### 2.3.3 Circular Polarization

Light is circularly polarized when the amplitude of its electrical field remains constant and its direction uniformly axially rotates. Circularly polarized light can also be viewed as the time-dependent vectorial superposition of two linear orthogonal components, as shown in Figure 2.19. These two components must be out of phase by  $90^\circ$  or  $-90^\circ$ , and each component's magnitude equals the other.

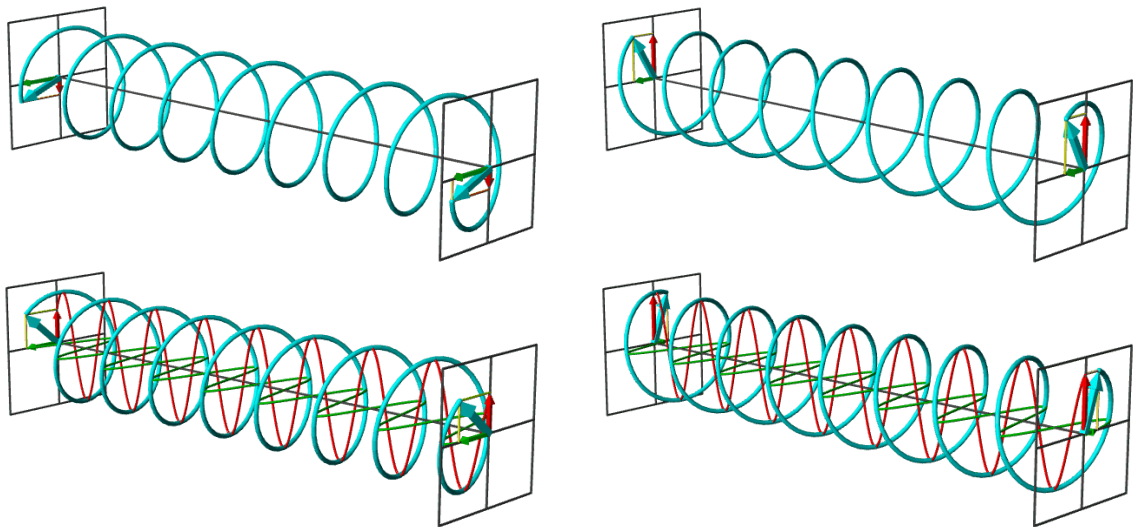


Figure 2.19: Left circular and Right circular polarized light and their respective decomposition.

Linearly polarized light has an infinity of states because it has an infinity of directions. Contrarily, circularly polarized light only has two states, right circular and left circular, depending on if the components are  $+90^\circ$  or  $-90^\circ$  out of phase.

## 2.4 Polarization Manipulation

As discussed in subchapter 1.2, the polarization of light can be altered or controlled in various ways. Some materials have properties of dichroism or birefringence or even both. Dichroism is the ability to absorb light from a specific polarization more strongly than light in its orthogonal polarization. On the other hand, birefringence is the property of a material to slow down the speed of light from a specific polarization more than light in its orthogonal polarization.

### 2.4.1 Diattenuation

Diattenuation is a metric for the strength of polarization-dependent amplitude change of a polarizer, and its equation is as follows: [9]

$$D = \frac{T_{max} - T_{min}}{T_{max} + T_{min}}, \quad 0 \leq D \leq 1 \quad (2.13)$$

where  $T_{max}$  is the maximal intensity transmittance and  $T_{min}$  is the minimal intensity transmittance.

### 2.4.2 Linear Polarizer (LP)

An ideal linear polarizer is a device that, when placed in an incident unpolarized beam, produces a beam of light whose electric field vector is oscillating only in one plane, with no component in the perpendicular plane. This phenomenon occurs because a polarizing filter has long-chain molecules aligned in the same direction. When light strikes the filter, the portion of waves polarized in the same direction as the long-chain molecules are absorbed. This phenomenon leaves only the waves polarized orthogonal to the filter's molecules to pass. An ideal linear polarizer has a perfect diattenuation of one.

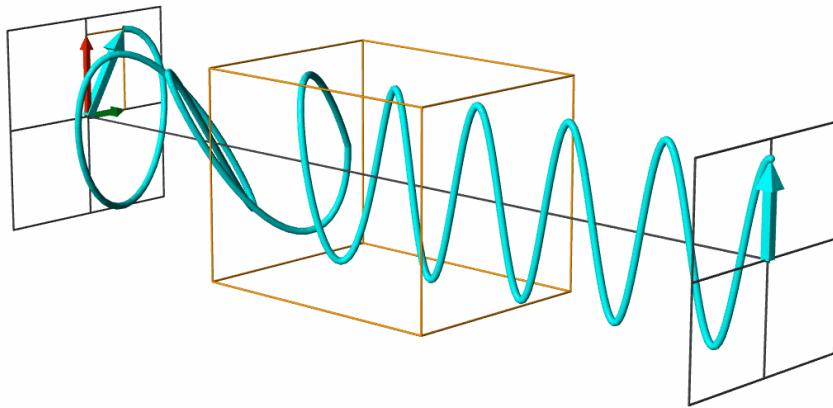


Figure 2.20: Effects of a linear polarizing filter on unpolarized light.

Figure 2.20 illustrates the effect of the linear polarization filter represented by the orange rectangle on unpolarized light.

### 2.4.3 Malus's Law and Light Intensity

An interesting effect occurs when we apply a linear filter to an already polarized light. The light intensity that passes through the filter varies by the angle  $\theta$  defined between the light polarization and the filter. This effect is known as Malus's law. The equation derived from this law is given by

$$I = I_0 \times \cos^2(\theta) \quad (2.14)$$

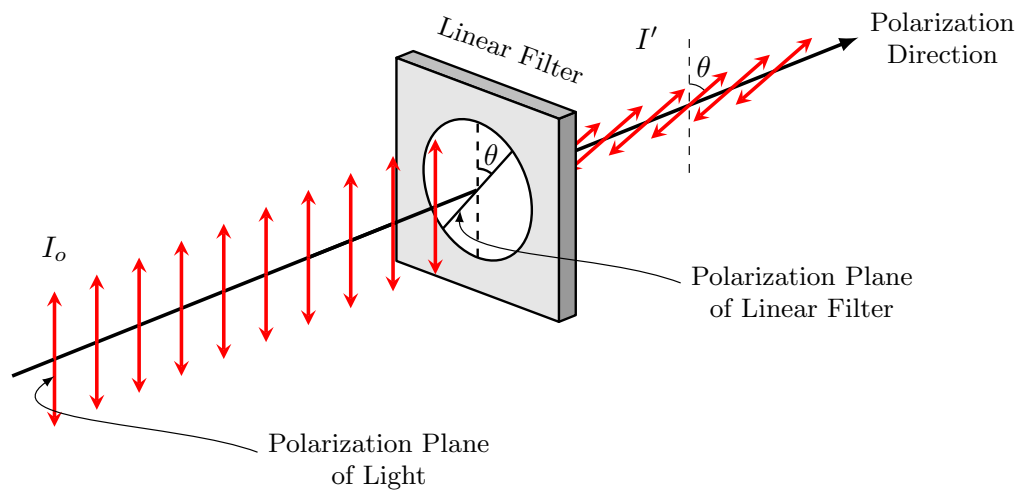


Figure 2.21: Illustration of Malus's law.

As seen in Figure 2.21, after the vertically polarized light passes through the linear polarizer, it becomes polarized with the same plane as the linear polarizer; however, the output light intensity is now a factor of cosine squared of the angle  $\theta$ . This law will become essential in chapter 4 to understand proposed solutions. Table 2.2 will present some of the most used and useful angles and intensity values.

| Angle $\theta$ (Degrees) | Angle $\theta$ (Radians) | Intensity I |
|--------------------------|--------------------------|-------------|
| 0°                       | 0                        | 1           |
| 22,5°                    | $\pi/8$                  | 0.8536      |
| 45°                      | $\pi/4$                  | 0.5         |
| 67.5°                    | $3\pi/8$                 | 0.1464      |
| 90°                      | $\pi/2$                  | 0           |

Table 2.2: Malus's law table of most used angles.

In the case of unpolarized light, this law can also help understand the output intensity when this type of light strikes a polarizing filter. As discussed in subchapter 2.3.1, unpolarized light is light

that presents an unpredictable and randomly evolving electrical field. Then it is fair to assume this light has a uniform distribution of all linear polarization states. Using clever mathematics, we can find out the output intensity by integrating Malus's law for all possible angles and dividing it by the range of all angles, effectively finding the mean value of the output light intensity.

$$I = \frac{I_0}{2\pi} \int_0^{2\pi} \cos^2(\theta) d\theta = \frac{I_0}{2} \quad (2.15)$$

Therefore, as seen in the equation above, the output intensity of a linear filter when it is struck with unpolarized light will always be half of the initial intensity.

Last but not least, when circularly polarized light strikes a polarizing filter, the output intensity will also be half of the initial intensity. This phenomenon can be explained in the following way. Let us assume two orthogonal linear polarized light beams with angle  $\theta$  and  $\theta + 90^\circ$ , respectively, relative to a polarizing filter. Also assume that the intensity of each light beam is only half the intensity of a circular polarized light beam. It is possible then to calculate the output intensity of the sum of the two linear light beams using Malus's law, as shown in the following equation

$$I = \frac{I_0}{2} \times \cos^2(\theta) + \frac{I_0}{2} \times \cos^2(\theta + 90^\circ) \quad (2.16)$$

we can simplify this equation due to the trigonometric identity

$$I = \frac{I_0}{2} \times (\cos^2(\theta) + \sin^2(\theta)) = \frac{I_0}{2} \quad (2.17)$$

As discussed in subchapter 2.3.3, circular polarization can be viewed as the superposition of two orthogonal linear components and, therefore, is analogous to two orthogonal linear polarized light beams striking a polarizing filter with a dephasing of  $90^\circ$ . The dephasing of these light beams is irrelevant to the polarizing filter; therefore, a circular polarized light striking a polarizing filter will always produce an output intensity of half the initial intensity.

#### 2.4.4 Retardance

Retardance, represented by the symbol  $\delta$ , is the optical path difference between eigenpolarizations. In other words, retardance is the phase shift between two orthogonal polarization that occur after passing through an optical element. There are multiple ways to represent retardance, as shown in Table 2.3

| Name      | Relative to wave                                                                    |
|-----------|-------------------------------------------------------------------------------------|
| Radians   | For one wave of retardance $\delta = 2\pi$                                          |
| Degrees   | For one wave of retardance $\delta = 360^\circ$                                     |
| Nanometer | For one wave of retardance $\delta = \lambda$ ; for 550 nm light, $\delta = 550$ nm |
| Waves     | For one wave of retardance $\delta = 1$                                             |

Table 2.3: Units for Retardance.

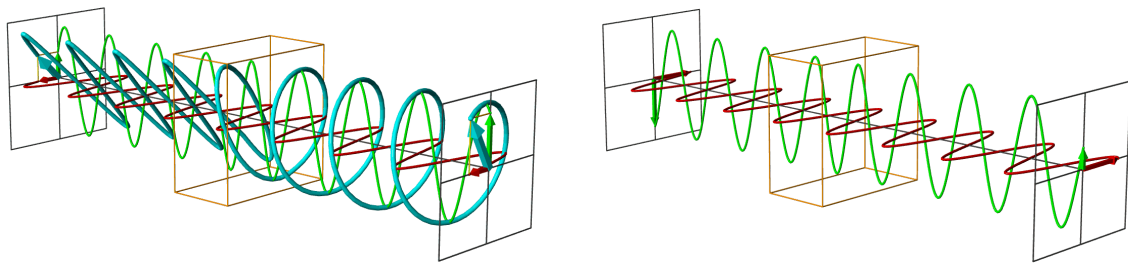


Figure 2.22: Illustration of retardance.

Figure 2.22 illustrates this concept. Looking carefully, we can see that the material shown in orange affects the vertical polarization component by slowing it down by a quarter of a wave, yet the horizontal polarization component remains unaffected. We have a quarter-wave retardance on the output because the vertical polarization component was retarded a quarter-wave relative to the horizontal polarization component. It also shows the transformation of linearly polarized light into circularly polarized light. This phenomenon will be studied more carefully in the following subchapter.

### 2.4.5 Waveplate

Waveplates, also known as retarders, are optical objects made of birefringent materials. Because of their birefringent property, waveplates have very precisely determined retardance. Waveplates can also be monochromatic, meaning that the desired retardance property works only in particular light wavelengths, or achromatic, meaning that the desired retardance property works in a broad range of light wavelengths. Typically they come in quarter-wave or half-wave plates. In Figure 2.23, we can see a picture of a typical waveplate. The white line in the periphery of the optics indicates the fast axis and is orthogonal to the slow axis. Light polarized with the same plane as the fast axis encounters a lower index of refraction relative to the slow axis; therefore, it travels faster through waveplates than light polarized along the slow axis hence their respective names.



Figure 2.23: Waveplate.

Let a linearly polarized light pass through a waveplate. Also, let that linearly polarized light have the same polarization plane as the fast or slow axes. In this case, since the decomposed

linearly polarized light does not have a component in the orthogonal axis, it will only be affected by one refractive index. The result is that the output polarization will be the same as the input as no retardation occurs. This effect is observable in any waveplates independently of its characteristics.

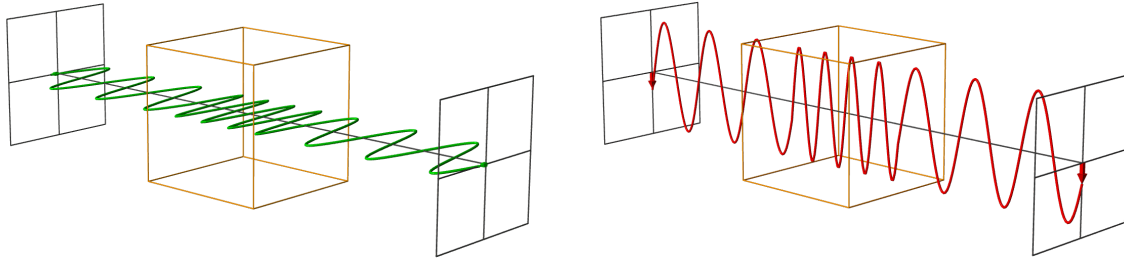


Figure 2.24: Effect of linear polarized light with the same plane as the fast and slow axis.

Figure 2.24 illustrates this phenomenon well. The orange box represents a waveplate with the fast axis aligned with the vertical axis. As can be seen, the horizontal and vertical polarized light does not suffer any changes in the output. The figure also shows that the light slowed down when passing the birefringent material.

As the name suggests, quarter-waveplates have retardance of a quarter-wave or  $90^\circ$ . This retardance allows it to transform linearly polarized light into circularly polarized light.

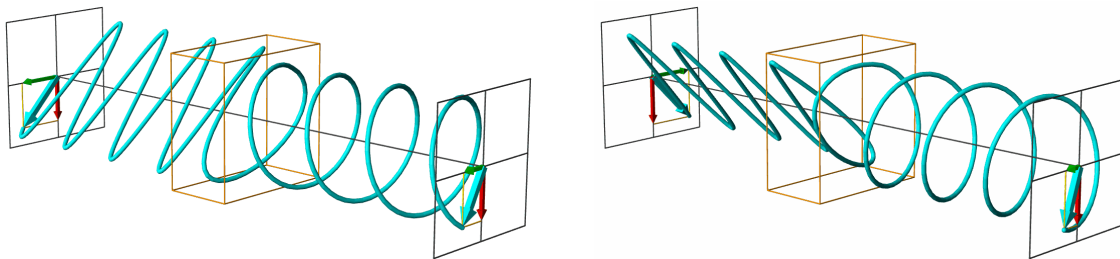


Figure 2.25: Quarter-Wave Plate Effects on Linear Polarization.

Looking at subchapters 2.3.2 and 2.3.3, notice that the only difference between linearly polarized light at  $45^\circ$  decomposed in the vertical and horizontal components from circularly polarized light is that one of the components is dephased by  $\pm 90^\circ$ . Because the quarter-wave plate does precisely this retardance of  $90^\circ$ . If the amplitude of components from the linear polarization decomposes with the same amplitude for the fast and slow axis planes, then the output will be circular polarization. This last requirement only occurs when the linear polarization input is at  $\pm 45^\circ$  relative to the fast axis of the quarter-wave plate. Figure 2.25 illustrates this phenomenon. The orange box represents a quarter-wave plate where the fast axis is in the vertical plane. Linear polarization at  $45^\circ$  to the fast axis will output right circular polarization, while linear polarization at  $-45^\circ$  will output left circular polarization.

Following the same thought process, it is possible to create linear polarized light from circularly polarized light using quarter-wave plates. The most exciting part of quarter-wave plates and circular polarization is that independently of the angle between itself and the circular polarization, the output will always be linear polarizer light at  $\pm 45^\circ$  (depending on the circular polarization handedness) relative to the fast axis of the quarter-waveplate. This phenomenon occurs because circular polarization presents axial symmetry in the direction of propagation. Figure 2.26 illustrates this phenomenon.

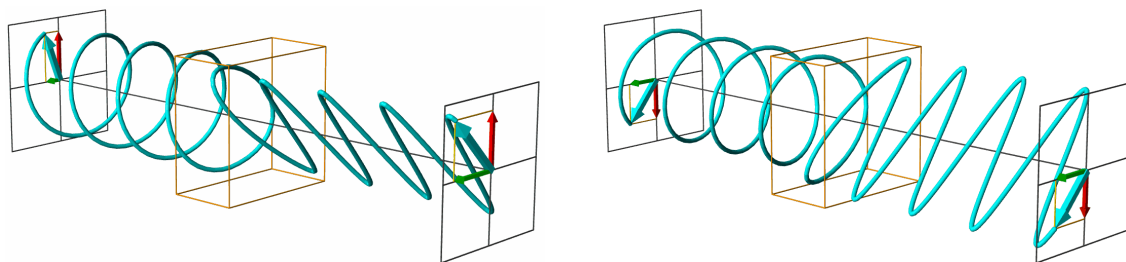


Figure 2.26: Quarter-Wave Plate Effects on Circular Polarization.

Half-waveplates have a retardance of  $180^\circ$ . This retardance allows it to transform left circular polarization into right circular polarization and vice versa. Because, as explained in subchapter 2.3.3, right and left circular polarization only differ by one of the components being  $\pm 90^\circ$  out of phase, then if we apply a  $180^\circ$  retardance to either, the output will be precisely the opposite circular polarization to the input because  $-90^\circ - 180^\circ = 90^\circ$  and  $90^\circ - 180^\circ = -90^\circ$ . Figure 2.27 illustrates this phenomenon.

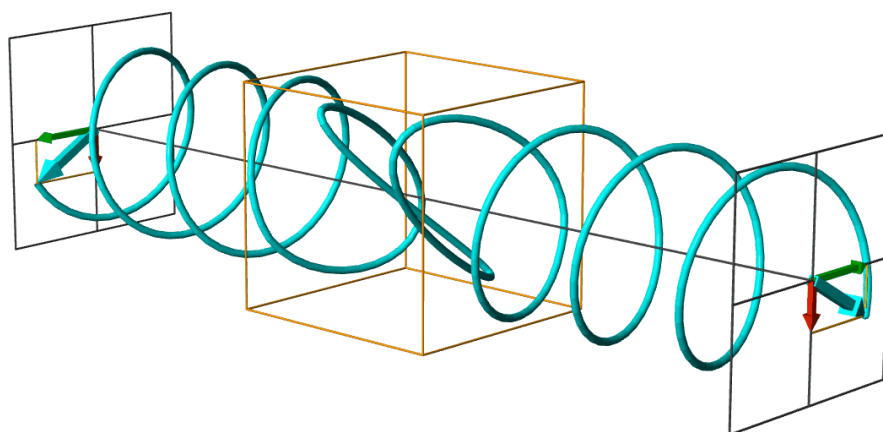


Figure 2.27: Half-Wave Plate Effects.

In summary, Table 2.4 presents some of the most widely used cases of quarter-wave and half-wave waveplates, where  $\theta$  is the offset from the fast axis of the waveplate.

| Input                        | Output                       |
|------------------------------|------------------------------|
| Quarter-Wave                 |                              |
| Linear, $\theta = 45^\circ$  | Right Circular               |
| Linear, $\theta = -45^\circ$ | Left Circular                |
| Right Circular               | Linear, $\theta = -45^\circ$ |
| Left Circular                | Linear, $\theta = 45^\circ$  |
| Half-Wave                    |                              |
| Linear, angle: $\theta$      | Linear, angle: $-\theta$     |
| Right Circular               | Left Circular                |
| Left Circular                | Right Circular               |
| Any Wave Plate               |                              |
| Linear, $\theta = 0^\circ$   | Linear, $\theta = 0^\circ$   |
| Linear, $\theta = 90^\circ$  | Linear, $\theta = 90^\circ$  |

Table 2.4: Common waveplate transformations.

The tables presented in this chapter are essential as they will help the reader understand what transformation is occurring quickly without the mental gymnastics of visualizing it, memorizing it, or resorting to any mathematical description of polarization.



## Chapter 3

# State of the art

### 3.1 Higher Bandwidth VLCs using Polarization Division Multiplexing

Contrary to polarization-based VLCs, where data transmission is encoded in the polarization state. PDM uses polarization to create multiple channels between receivers and transmitters.

Demonstrations in [11, 12, 13] show that it is possible to use a 2x2 PDM VLC system to double its throughput. The technique involves using two orthogonally oriented linear polarizing filters in front of the transmitting LEDs and the PD receivers. This configuration will form the following channel matrix:

$$H = \frac{1}{2} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (3.1)$$

This channel matrix is diagonal, making it very interesting for data transmission as a diagonal matrix represents independent channel transmission. 2x2 PDM is a cheap and effective way to double throughput without adding complexity to the demodulation system. 2x2 PDM allows light to use the same optical channel without interference on the receiving side. An Illustration of PDM subsystem architecture is shown in Figure 3.1.

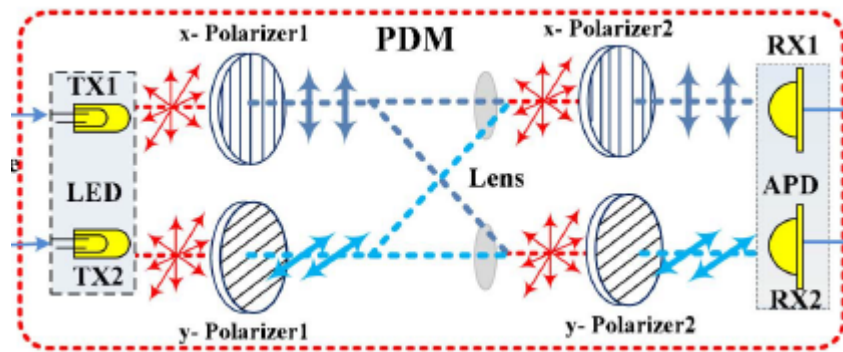


Figure 3.1: PDM subsystem architecture [12, Fig. 1].

In order to prove the independent channel communication, let us use  $TX_1$  and  $RX_2$  pair as an example. Notice that the linear polarizers between  $TX_1$  and  $RX_2$  are orthogonal, meaning  $\theta = 90^\circ$ . Calculating light intensity in  $RX_2$  that is transmitted by  $TX_1$  using Malus's law, as explained in subchapter 2.4.3, the following equation emerges:

$$I = I_0 \times \cos^2(90^\circ) = 0 \quad (3.2)$$

Therefore  $RX_2$  does not receive any data from  $TX_1$ . The same conclusion applies to  $RX_1$  and  $TX_2$ .

Theoretically, the linear polarizers can have almost any angle for PDM to function. This configuration will form the following channel matrix:

$$H = \frac{1}{2} \begin{bmatrix} \cos^2(a_{11}) & \cos^2(a_{12}) \\ \cos^2(a_{21}) & \cos^2(a_{22}) \end{bmatrix} \quad (3.3)$$

PDM is functional except when the following equation is true:

$$\cos^2(a_{11}) \cos^2(a_{22}) = \cos^2(a_{12}) \cos^2(a_{21}) \quad (3.4)$$

The matrix is rank deficient if the equation above is valid. As explained in subchapter 2.1.5 a MIMO VLC system cannot recover data unless the channel matrix is known and full rank.

In practice PDM is more efficient when the channel matrix is a diagonal matrix as it will lead to a more reliable performance in the presence of additive white Gaussian noise (AWGN).

It is essential to state that PDM is modulation independent, implying that any of the modulation presented in subchapter 2.2 can be used with PDM making it remarkably flexible in its implementation.

Chapter 4 of this dissertation shows that using more than two polarization states to create a 4x4 PDM MIMO VLC system is possible.

## 3.2 Polarization Based VLC

Demonstrations in [14] show that a polarization-based VLC Link is "32.6% more robust VLC link compared to the conventional transceiver under severe optical interference". In this system, two transmitter-receiver pairs are used. Data is sent in a complimentary way, signifying that a data bit 1 (one) is modulated by switching  $TX_1$  ON and  $TX_2$  OFF while a data bit 0 (zero) is modulated by switching  $TX_1$  OFF and  $TX_2$  ON. This modulation, coupled with the fact that the TX pair have each one a linear polarizing filter orthogonal to each other, as illustrated in Figure 3.2, effectively makes this system transmit data not by luminous intensity but by polarization state as the luminous intensity remains the same.

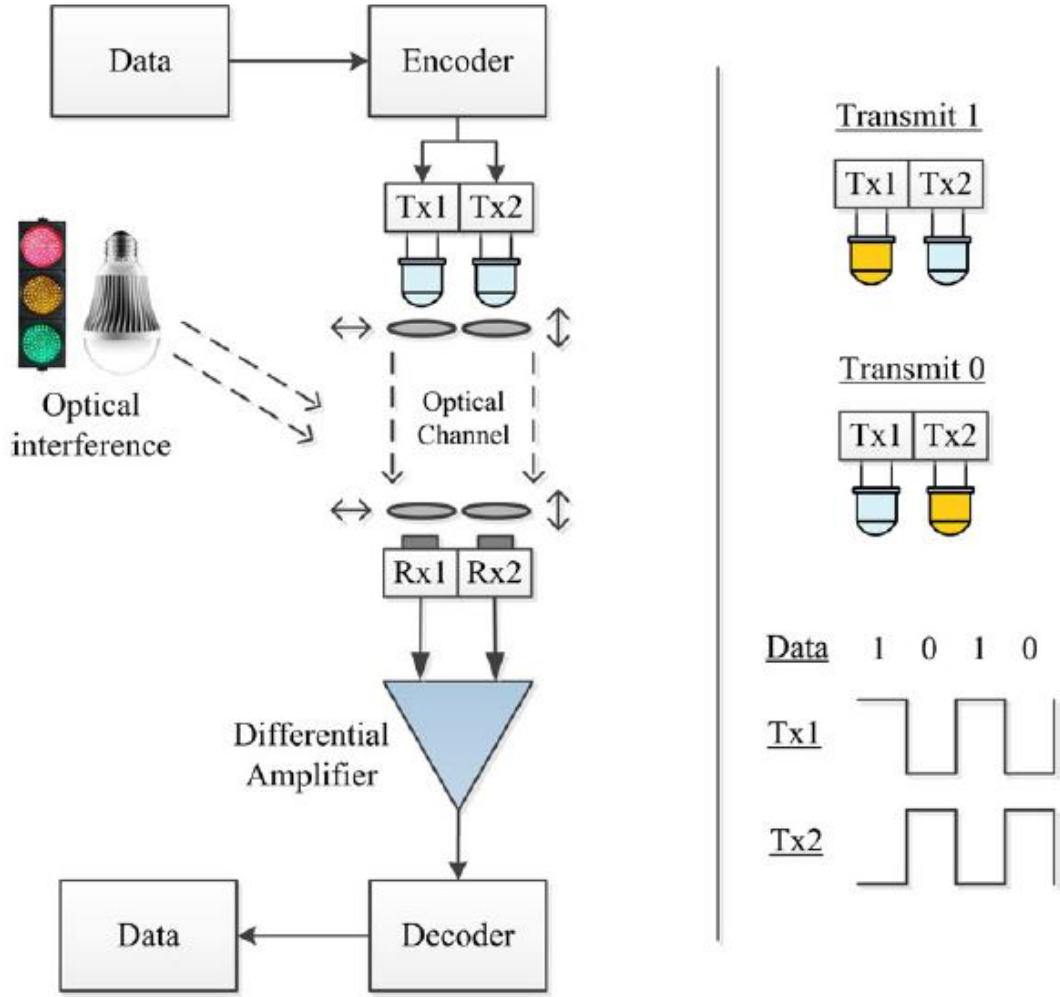


Figure 3.2: System architecture [14, Fig. 1].

The main idea behind this system is that when a  $TX_1$  sends data, only  $RX_1$  detects it.  $RX_2$  cannot detect it due to the properties of orthogonality of linear polarized filters. For  $TX_2$ , the conclusion is analogous. This effect is the same as PDM, but its application is different. It can also be explained by Malus's Law and equation 3.2. Because of the complementary modulation and the differential amplifier, this system will, by nature, remove any ambient source of light that might interfere with the data transmission. This effect occurs because, as explained in subchapter 2.3.1, natural sources of light are, for the most part, unpolarized and, therefore, the received intensity of this ambient source will be the same for  $RX_1$  and  $RX_2$  because both receive half of the initial light intensity. The differential amplifier will then promptly equation this interference out of the system. If we assume perfect linear polarizer alignment, then the system can be modeled the following way:

$$Y_1 = X_1 + I_1 + n_1 \quad (3.5)$$

$$Y_2 = X_2 + I_2 + n_2 \quad (3.6)$$

Where:

- $Y_i$  represents light intensity in the receiver  $RX_i$ .
- $X_i$  represents light intensity in the receivers, transmitted by  $TX_i$ .
- $I_i$  represents light intensity in the receiver  $RX_i$  produced by ambient light.
- $n_i$  represents AWGN.

Modeling the output of the differential amplifier:

$$Y_z = Y_1 - Y_2 \quad (3.7)$$

$$Y_z = X_1 - X_2 + I_1 - I_2 + n_1 - n_2 \quad (3.8)$$

Where  $Y_z$  is the output of the differential amplifier.

Since:

- $I_1 \approx I_2$
- $n_1 - n_2 \approx 0$

Then we conclude:

$$Y_z \approx X_1 - X_2 \quad (3.9)$$

As shown in the equation above interference from ambient light was effectively cancelled out.

This system presents many advantages compared to a more traditional IM/DD. The first is that the flickering effect is absent because data is effectively transmitted via the polarization state, and light intensity is kept equal at all times. It also implies that the need for a scrambler is unnecessary, making this system less complex than its counterpart. The second advantage is that this system can implement dimming support by adjusting both  $TX_1$  and  $TX_2$  LEDs intensities. This support is simple compared to other types of dimming support that rely on complex modulations and have tradeoffs between data rate and light dimming.

Further research into this system architecture was made in [15] where the rotation of the receivers was accounted for as shown in Figure 3.3. It was shown that in near to 45° angles SNR will decrease drastically making this system unusable as shown in Figure 3.4.

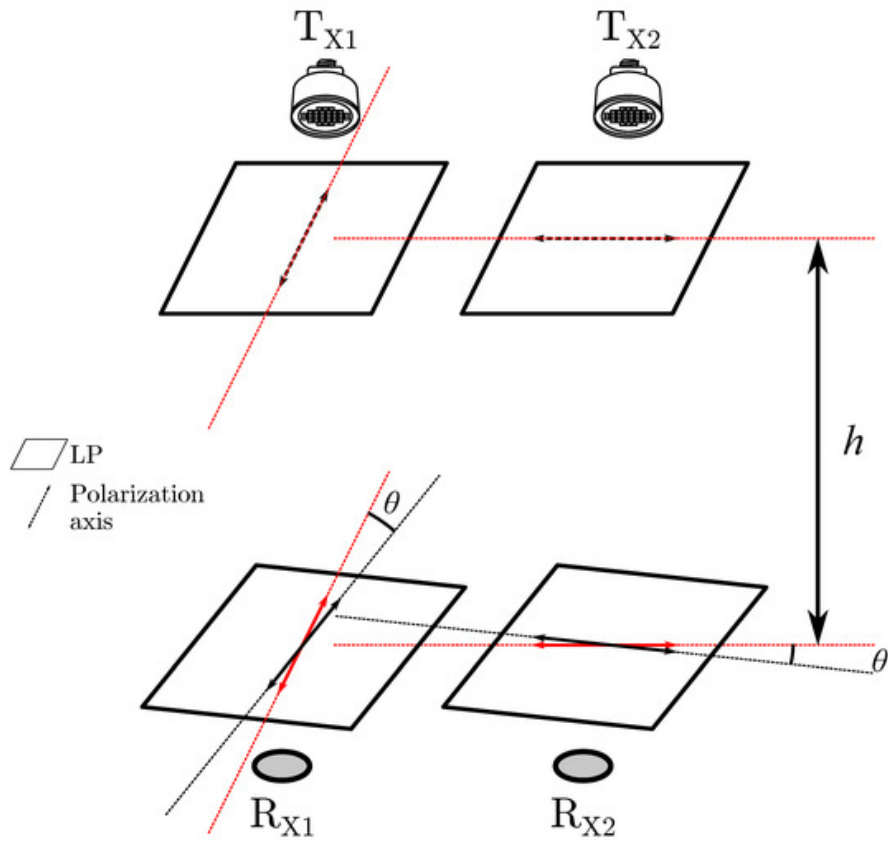


Figure 3.3: Rotation of the receivers [15, Fig. 1].

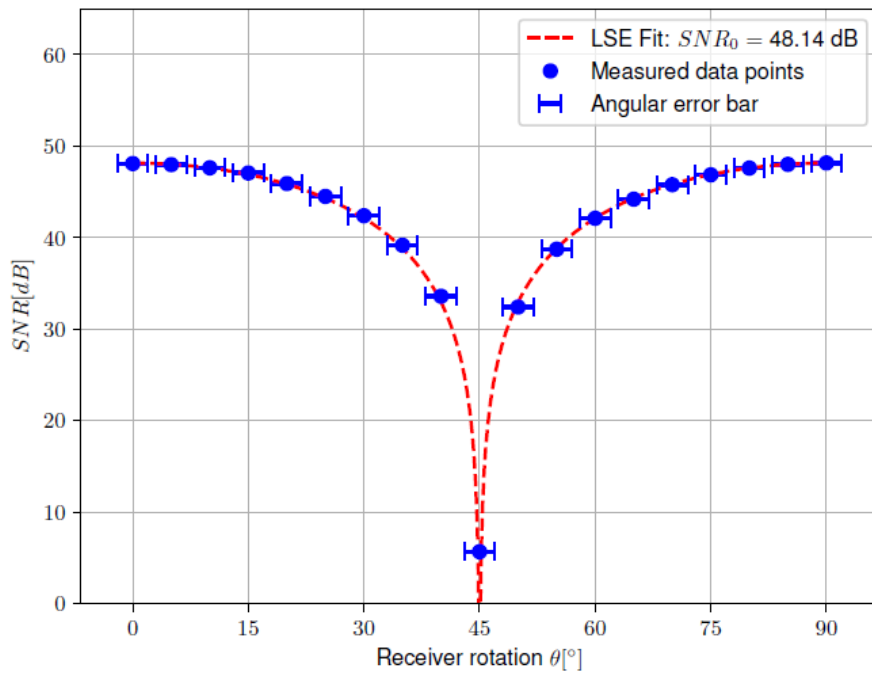


Figure 3.4: SNR vs. Receiver rotation [15, Fig. 11].

This drastic decrease is due to having no discernible differentiation between the transmitters at the receiver side. For example, if TX1 is switched on, the following Malus law equation will emerge:

$$Y_1 = X_1 \cos^2(45^\circ) = \frac{X_1}{2} \quad (3.10)$$

$$Y_2 = X_1 \cos^2(-45^\circ) = \frac{X_1}{2} \quad (3.11)$$

$$Y_z \approx 0 \quad (3.12)$$

Therefore it is impossible to recover the data.

The author's proposed solution is to add a second receiver pair with an orientation of  $45^\circ$  relative to the first pair, as depicted in Figure 3.5. This solution, in turn, will ensure that for any angle between the transmitter and receiver, differentiation of transmitters is always possible. The maximum achievable attenuation will be 3dB, as illustrated in Figure 3.6.

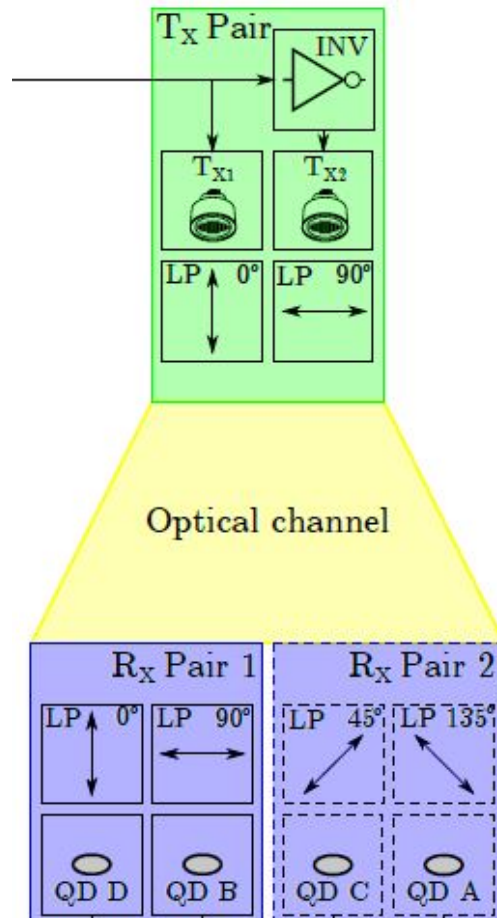


Figure 3.5: System architecture with rotation of the receivers [15, Fig. 7].

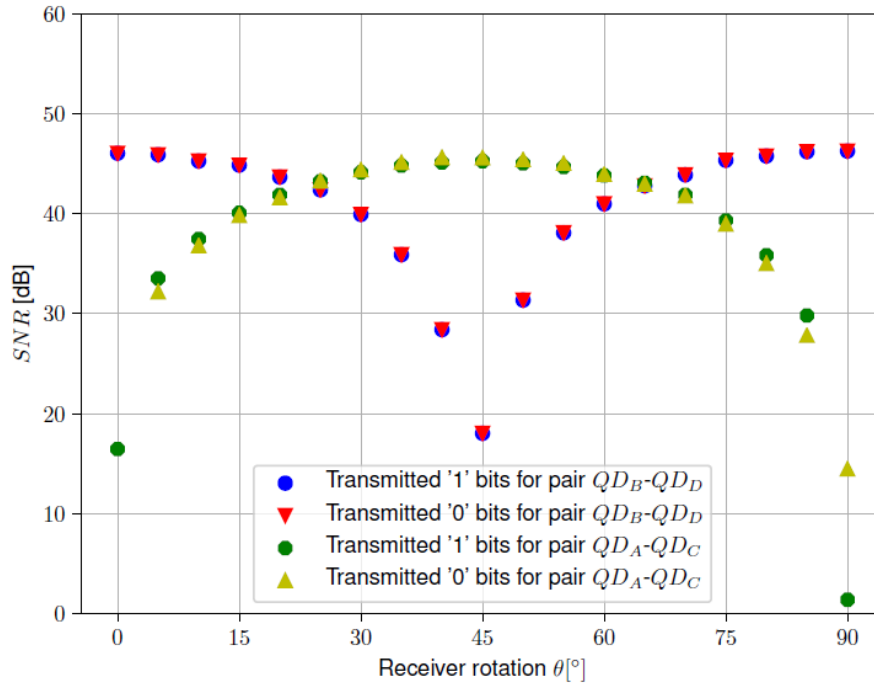


Figure 3.6: SNR vs. Receiver rotation of proposed solution [15, Fig. 13].

The authors mention using a stepper motor to align the transmitter and receivers. It would effectively yield the same, if not better. This idea of mechanically rotating receivers will be used in the proposed solution system discussed in chapter 4.

Demonstrations in [16] showed that it is possible to create a low bit-rate VLC system with the sole purpose of indoor positioning using proprieties of polarization.

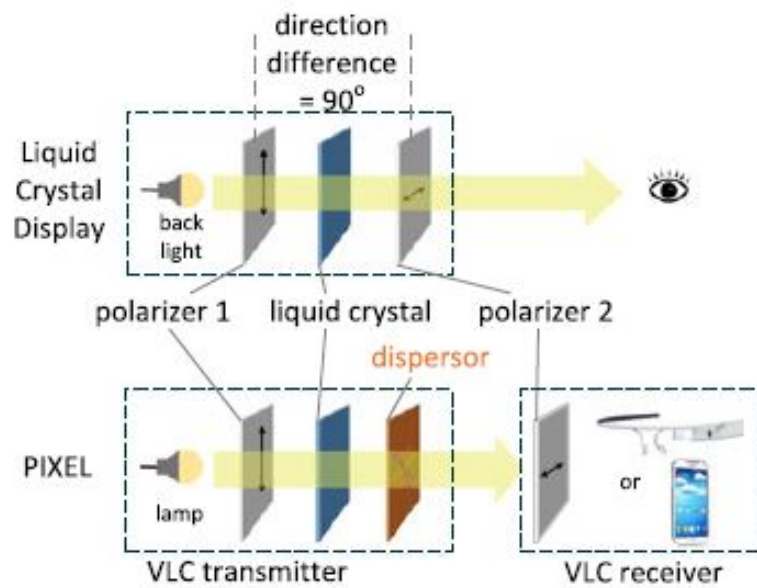


Figure 3.7: PIXEL and Liquid Crystal Display comparison [16, Fig. 3].

This system uses a technology called PIXEL, as shown in Figure 3.7, whereby passing light through a polarizing filter, liquid crystal, and dispersor makes it possible to create a modulation called Binary Color Shift Keying (BCSK).

This system works by first polarizing light from the backlight with the help of a polarizing filter, as explained in subchapter 2.4. Then using a dielectric liquid crystal, more specifically, a twisted nematic (TN) cell, either does not alter the direction of the polarized light or rotates it by  $90^\circ$  depending if a voltage is applied to it. Finally, using the dispersor, we can rotate the polarization again. However, contrary to liquid crystals, this rotation is wavelength-dependent, meaning that the rotation angle will depend on the color of light that is striking the dispersor. This phenomenon creates an effect in which each linear polarization direction only has a specific wavelength of light (color). Liquid crystals and dispersor are not explained in the literature revision because they are not used in the proposed solution of chapter 5. The receiver end is composed of a linear polarizing filter complemented with a camera capable of color differentiation.

The voltage control of the TN cell creates the modulation necessary to transmit data. If we want to transmit a data bit 1 (One), we activate the TN cell effects. This activation has, in turn, a causal implication for the receiver. It makes it receive a specific color. If we want to transmit a data bit 0 (zero), we deactivate the TN cell effects. This deactivation will, in turn, switch the initial color to another one. The color is dependent on the relative rotation between the transmitter and the receiver. Although this system is rather complex to understand, the illustration in Figure 3.8 is a simple diagram of the last stages of the system.

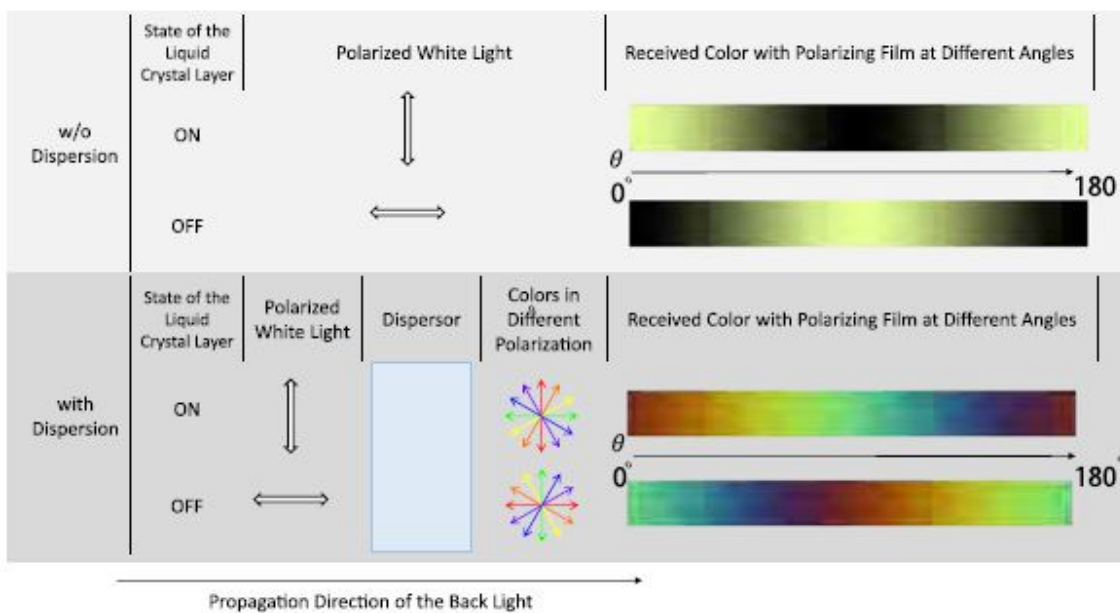


Figure 3.8: BCSK info-graphic [16, Fig. 5].



This system also solves the same problem of rotating the receiver because instead of using two orthogonal linear polarization that will be indiscernible at angles of  $\pm 45^\circ$ , it uses the dispersor that makes it impossible to find an angle where data transmission is indiscernible. This effect can also be seen in Figure 3.8.

In both [16, 14], the different modulations possible with polarization manipulation are interesting to take for further exploration. Likewise, it also demonstrates a lot of creative ways to solve VLC problems using polarization manipulation.



## Chapter 4

# VLC systems using polarization: concept development and analysis

### 4.1 MIMO VLC System

#### 4.1.1 Increasing Throughput

"In contrast to radio frequency or free-space optical communication, where MIMO systems are used to achieve increased link reliability by providing spatial diversity gain, in VLC systems we are concerned with a deterministic channel, and hence the only interest of MIMO architectures is for increasing the data throughput." [4]

As seen in subchapter 3.1, PDM is used to increase the throughput of the systems but usually only uses two polarization states in a 2x2 MIMO VLC. [11, 12, 13]. The proposed solution uses four polarization states to create a 4x4 MIMO system, theoretically quadrupling the original throughput. As explained in subchapter 2.1.5, a full rank H Matrix must be devised to create a viable MIMO system.

#### 4.1.2 Proposed Solution using PDM

Figure 4.1 shows a block diagram of the proposed 4x4 MIMO PDM VLC system. As explained in subchapters 2.3 and 2.4, when incoherent light from the transmitters LEDs passes through linear polarizers (LPs), the output, represented by the red, green, and cyan arrows in the diagram, will be linearly polarized. When linearly polarized light at 45° relative to the fast axis strikes a quarter-wave plate, the output, represented by the blue arrows in the diagram, becomes right circularly polarized. These signals will spread in the optical medium, where the receivers PDs detect them. Each  $RX_i$  ( $i = 1, 2, 3, 4$ ) is equipped with a polarizing filter at a specific angle, and  $RX_4$  also has a quarter-wave plate. This configuration will make the detected luminous intensity of an  $RX_i$  depend on the  $TX_i$  polarization output and light intensity. The H matrix can fully characterize these luminous intensities.

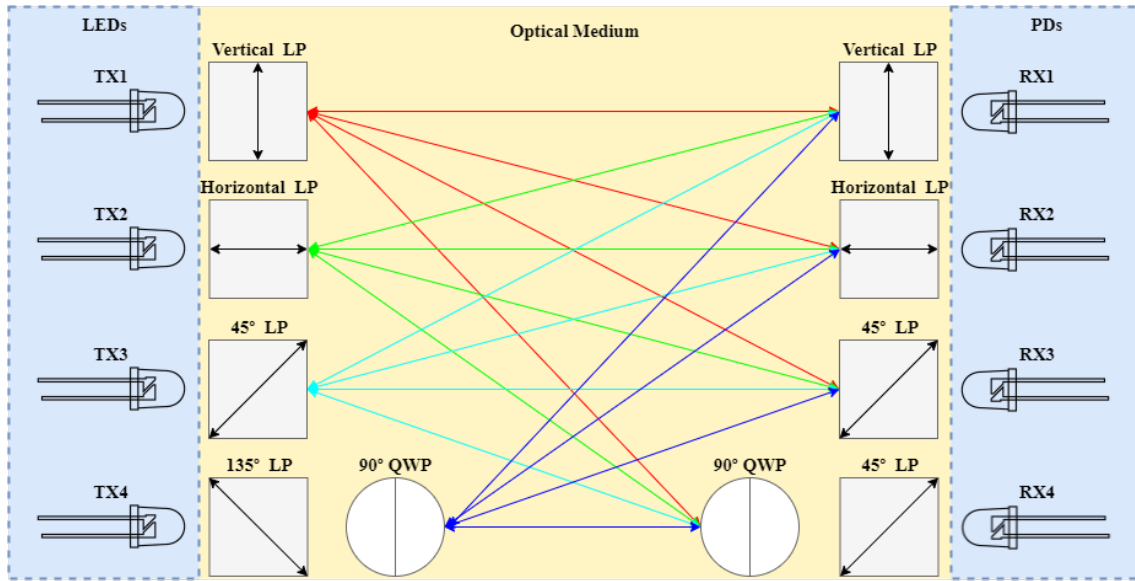


Figure 4.1: Block diagram of proposed PDM.

#### 4.1.3 Channel Matrix Characterization

Malus's Law and Light Intensity (subchapter 2.4.3) can fully explain the channel matrix. This characterization assumes that the angles between linear polarizers remain unchanged and that only LOS paths are considered.

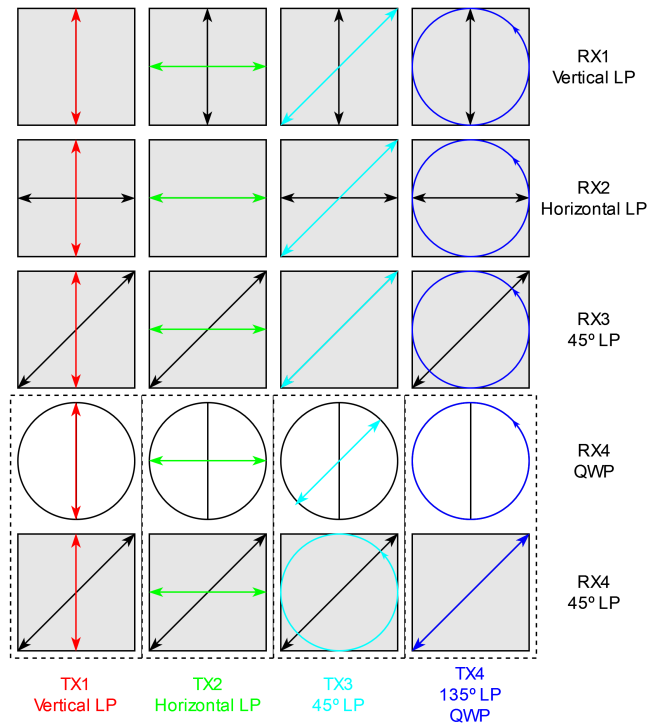


Figure 4.2: Channel Matrix Illustration.

To understand what the channel matrix gains represent, an illustration in Figure 4.2 was created. In it colored arrows and circles represent incident polarizations, squared grayed boxes with a black arrow represent linear polarizers and their respective polarization angle. Finally, a white circle with a verticle divider represent quarter-wave plates and their respective fast axis. This scheme result in the following equations:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \end{bmatrix} = H \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} + N \quad (4.1)$$

$$H = \frac{1}{2} \begin{bmatrix} 1 & 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & 1 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & 1 & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 1 \end{bmatrix} \quad (4.2)$$

of which matrix  $Y$  represents the received optical intensity at the  $RX$ s; meanwhile, the  $X$  matrix represents the emitted optical intensity of  $TX$ s.  $H$  and  $N$  denote the channel matrix and the noise, respectively.

This particular  $H$  channel matrix is full rank and therefore invertible where:

$$H^{-1} = \begin{bmatrix} 4 & 2 & -2 & -2 \\ 2 & 4 & -2 & -2 \\ -2 & -2 & 4 & 0 \\ -2 & -2 & 0 & 4 \end{bmatrix} \quad (4.3)$$

Based on channel inversion, we can fully obtain the transmitted data using the following equation:

$$X = H^{-1}Y \quad (4.4)$$

#### 4.1.4 Performance Comparison

Using a modified version of Program 8.4 shown in appendix A from [7], Bit Error Rate (BER) versus SNR is simulated using N-PAM modulation for a specific channel matrix. This simulation enables the comparison of the expected theoretical performance from a 2x2 PDM system used in [11, 12, 13] versus the proposed 4x4 PDM system. In Figure 4.3 the simulation results are shown alongside the Forward Error Correction (FEC) limit.

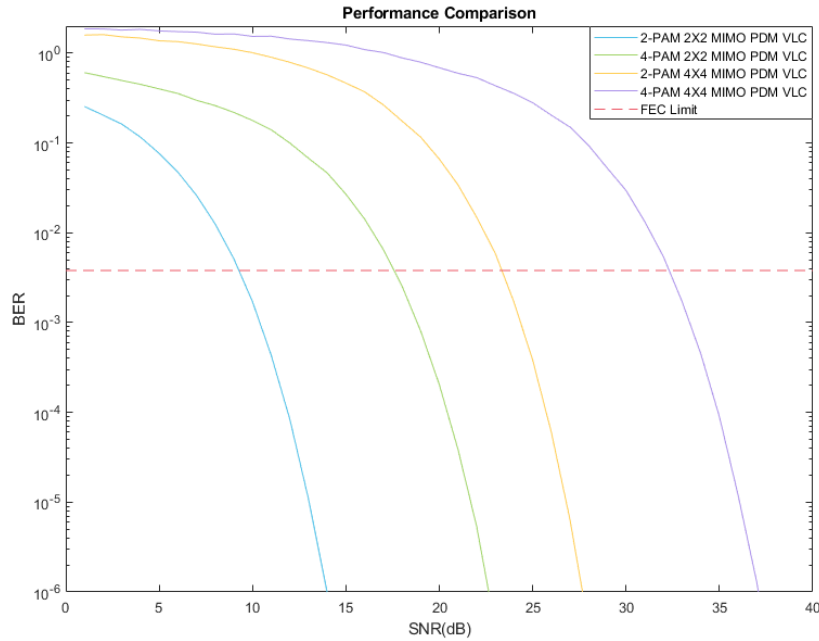


Figure 4.3: BER vs. SNR for N-PAM  $N \times N$  MIMO VLC system.

As shown, the BER of the 4x4 MIMO PDM VLC requires significantly more SNR to compare to the same modulated 2x2 MIMO PDM VLC. This is because contrary to the 2x2 system where the channel matrix is diagonal the 4x4 doesn't have the same proprieties, making it more susceptible to additive noise.

#### 4.1.5 Discussion

This system theoretically does not present any advantages. Let us, for example, compare 4-PAM 2X2 MIMO vs. 2-PAM 4X4 MIMO. They would have the same output data rate, but the 2-PAM 4X4 MIMO system requires about 5dB more SNR to function at the same BER as the 4-PAM 2X2 MIMO. Not only does it requires 5dB more, but it also uses two achromatic waveplates, which are expensive. The only actual use of this system would be if white phosphorous LEDs bandwidth limit were reached. In that case, switching to a 4x4 PDM system would increase the throughput twofold but would require a higher SNR meaning a higher current drive for the same LEDs. Nonetheless, it has been proven that a 4x4 MIMO PDM VLC can exist.

## 4.2 Multiple Access Points VLC Systems

### 4.2.1 Interference between Access Points

One of the differences between VLC and WLAN systems is that each VLC access point (AP) covers a relatively small area. This difference is advantageous in environments where many mobile devices must be connected simultaneously. In this case, when the amount of connected devices

is high TDMA-based WLAN systems do not excel because there are not sufficient time slots available for all devices covered in that respective areas. VLCs can be considered small area TDMA networks only if the multiple APs interference problem is avoided and fast switching between APs can be achieved.

### 4.2.2 Proposed Solution using Polarization

Figures 4.4 and 4.5 represent three separate transmitters and one receiver, respectively.

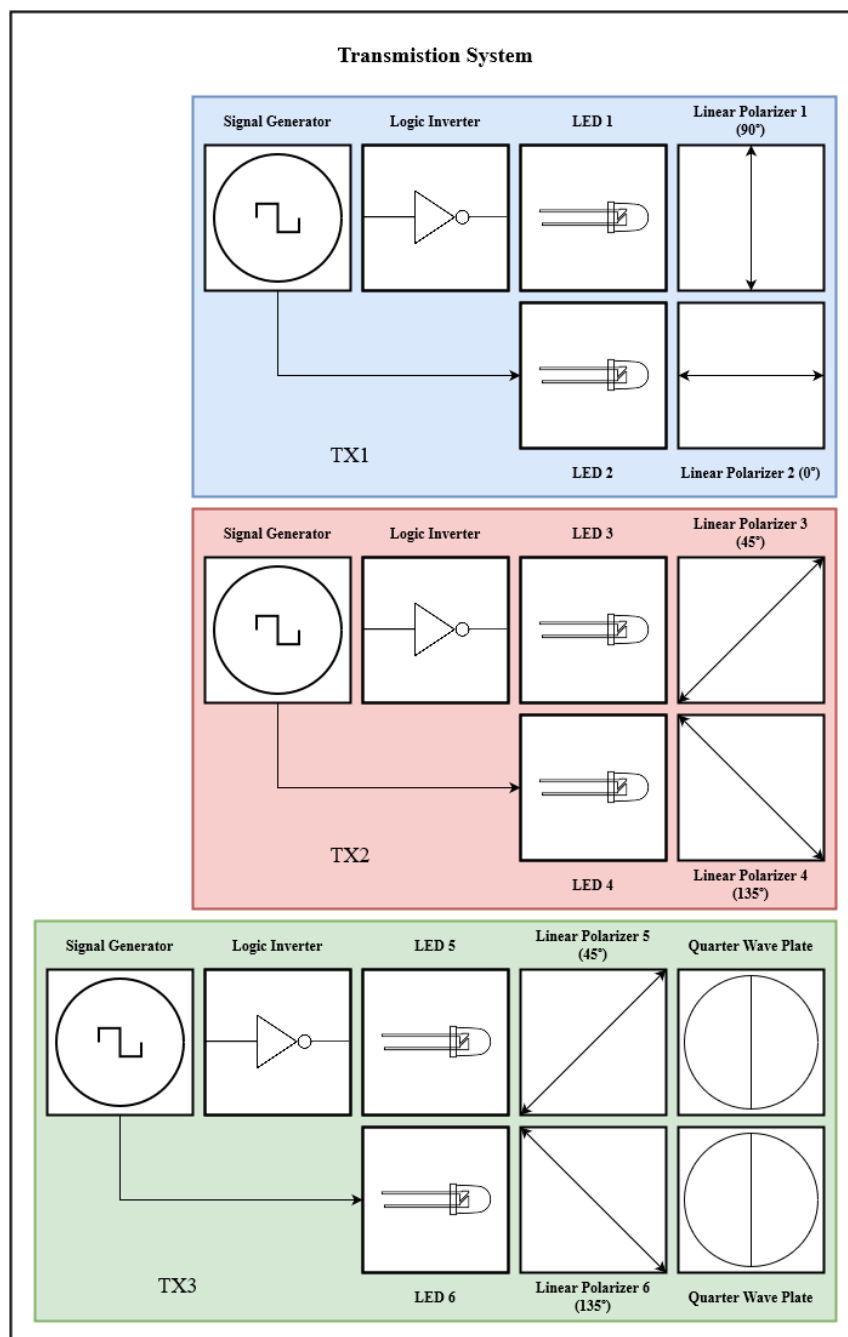


Figure 4.4: Block Diagram of Proposed Transmitter.

The developed system in [15] inspired this system; however, a significant difference is that this system uses the same properties of interference rejection to create three different transmitters. Also, the receiver has a mechanically rotating platform that, when aligned with a specific transmitter, will naturally reject light from other transmitters, ambient light, and other unpolarized sources.

Three independent transmitters constitute this system. Each transmitter generates orthogonally polarized light. In our case, horizontal and vertical linear polarization for TX1,  $\pm 45^\circ$  linear polarization for TX2, while TX3 produces right and left circular polarization. They achieve this by using two high-powered LEDs and two orthogonal polarizing filters, and in the particular case of TX3, also two quarter-wave plates (QWP). Each transmitter also has an inverter, essential for modulating the transmitted data.

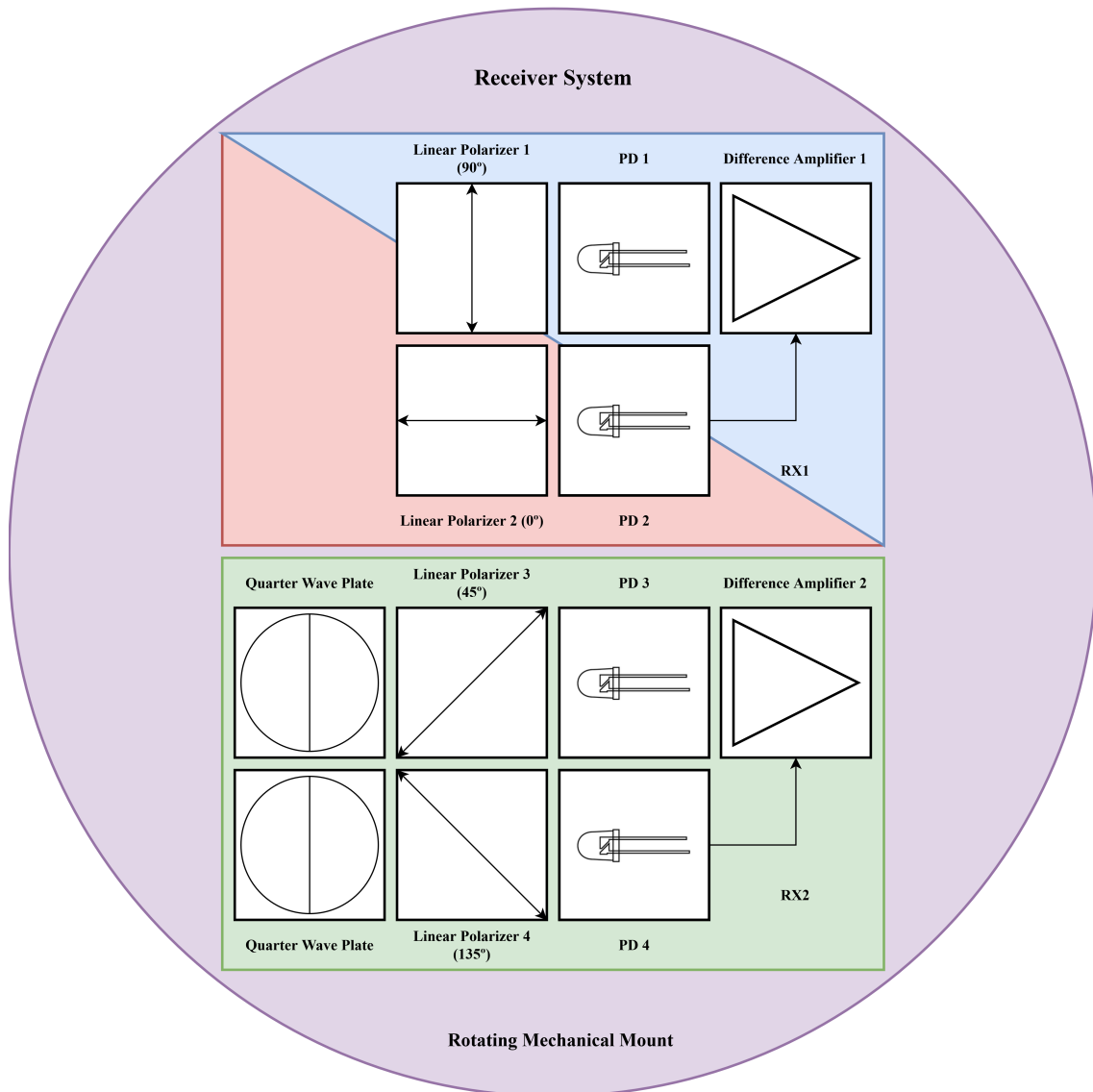


Figure 4.5: Block Diagram of Proposed Receiver.



The receiver is designed to detect six types of light polarization. Those six types are the ones generated by the transmitters. However, the receiver is not designed to detect all six types simultaneously. It is dependent on the alignment between the transmitter and receiver. The receiver achieves signal detection by employing four photodetectors, four polarizing filters, and two quarter-wave plates. RX1 is designed with the ability to detect the polarization from TX1 and TX2. This detection depends on the offset angle between transmitter-receiver linear polarizers. RX2 is designed with the ability to detect the polarization from TX3. The receiver also employs two differentiators, essential for demodulating the transmitted data.

### 4.2.3 System Functioning

This system's fundamental idea for its function is that when a RX is aligned with a particular TX, the other TXs will have the same light contribution to both PDs of that RX. Because this light contribution from other TXs will be the same, it will promptly be filtered out by the differential amplifier. Let us define correct alignment as the offset angle between an RX element and the desired TX element so that other TXs light contributions are equal for both PDs of RX. Let us define all the possible correct alignment cases and their respective offset angle between elements, as shown in Table 4.1.

| Case | RX  | TX  | Alignment                             | Offset Angle     |
|------|-----|-----|---------------------------------------|------------------|
| 1    | RX1 | TX1 | RX1 LP1 & TX1 LP1                     | $\psi = 0^\circ$ |
| 2    | RX1 | TX2 | RX1 LP1 & TX2 LP3                     | $\psi = 0^\circ$ |
| 3    | RX2 | TX3 | RX2 Fast Axis QWP & TX3 Fast Axis QWP | $\psi = 0^\circ$ |

Table 4.1: TX and RX correct alignments.

By examining case number 1, observe that RX1 and TX1 are aligned. This alignment implies that all light generated from TX2 and TX3 must strike PD1 and PD2 with the same intensity. Figure 4.6 illustrates all the combinations of the light polarizations generated by TX2 and TX3, represented by the colored arrows and circles, and the linear polarizing filters of RX1, represented by the gray boxes and respective arrows that indicate the polarization axis when RX1 is aligned with TX1.

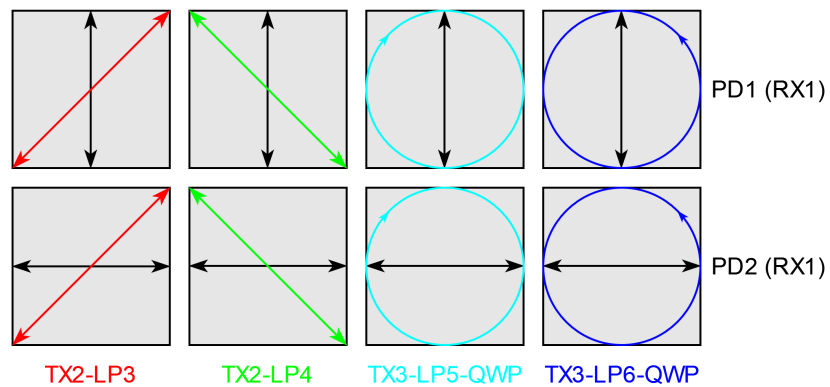


Figure 4.6: Combinations for RX1 - TX2 & TX3.

Regarding case number 2, the same reasoning is applicable. Observe that in case number 2, RX1 and TX2 are aligned. Figure 4.7 illustrates all the combinations of the light polarizations generated by TX1 and TX3 and the linear polarizing filters of RX1 when RX1 is aligned with TX2.

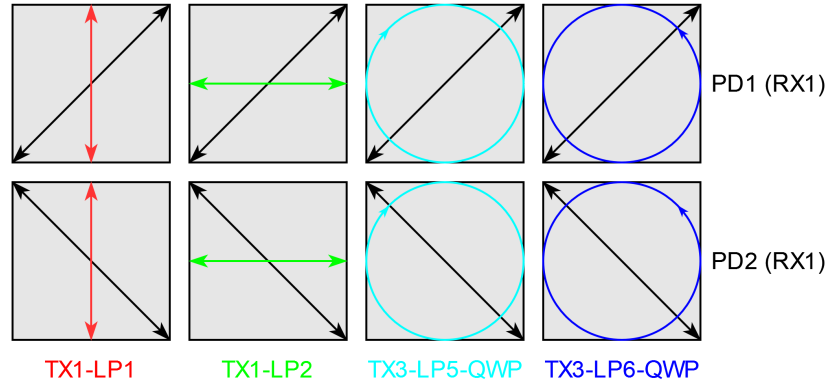


Figure 4.7: Combinations for RX1 - TX1 & TX3.

Finally, for case number 3, observe that RX2 and TX3 are aligned. Figure 4.8 illustrates all the combinations of the light polarizations generated by TX1 and TX2 and the optical elements of RX2 when RX2 is aligned with TX3.

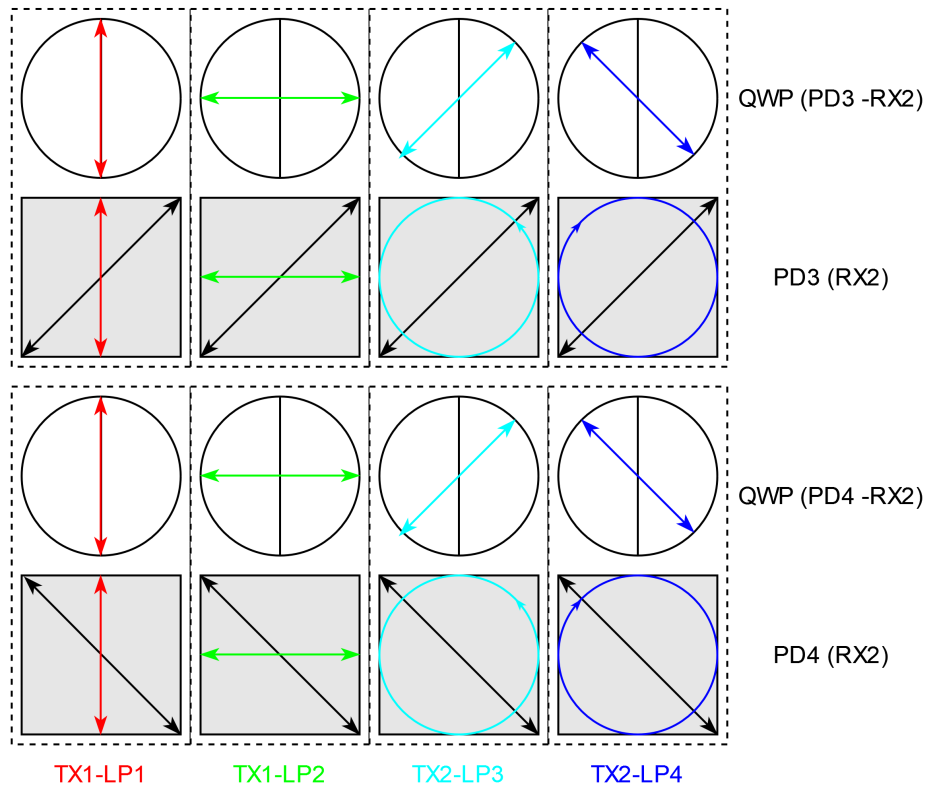


Figure 4.8: Combinations for RX2 - TX1 & TX2.

Notice that the light intensity after the polarizing filter will always be half the initial light intensity for any of the above combinations. Therefore the light intensity that reaches each PD pair will always be the same. Because of the differential amplifier, all contributions from the nonaligned transmitters to the PDs will promptly be filtered out. In case number 3, although the correct alignment is strictly defined, a mathematical proof expressed in a later subchapter will conclude that this effect will always be observable for any offset angle between elements. Therefore no alignment is required between RX2 and TX3.

Regarding the system response to interference light from ambient and active light sources, as explained in subchapters 2.3.1 and 2.4.3, ambient light and light from other sources are unpolarized. It is then clear that the output light intensity after the polarizing filter will always be half the initial light intensity for all combinations above. Therefore it will also be promptly filtered out by the differential amplifier.

This system's correct function is predicated on how the data transmitted from the aligned transmitter is discernable. For the transmitted data to be discernable when RX is aligned with a particular TX, the light intensity that reaches both PDs of RX must be distinctive. In case number 1, this implies that the light from vertical and horizontal polarization generated by TX1 must not have the same output for PD1 and PD2. Figure 4.9 illustrates all the combinations of the light polarizations generated by TX1 and the linear polarizing filters of RX1 when RX1 is aligned with TX1 and all the combinations of the light polarizations generated by TX2 and the linear polarizing filters of RX1 when RX1 is aligned with TX2.

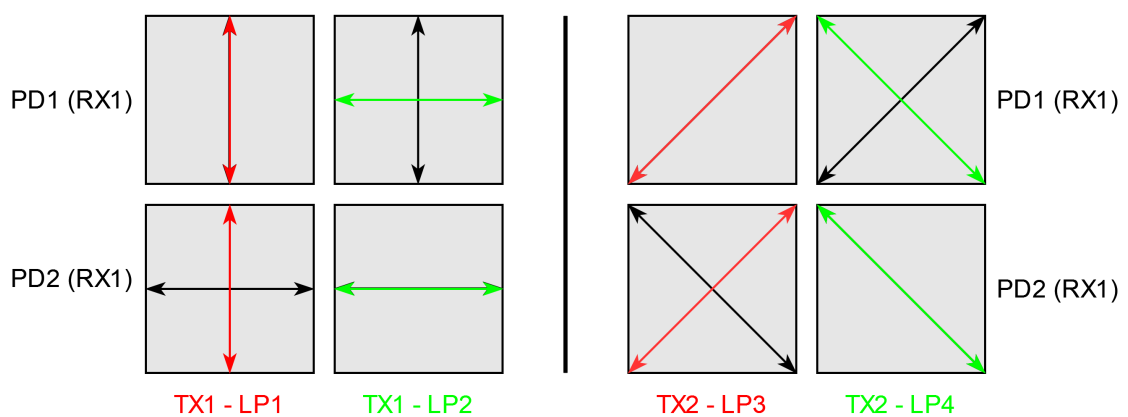


Figure 4.9: Combinations of light polarizations when RX1 is aligned with TX1 and with TX2.

Figure 4.10 Illustrates all the combinations of the light polarizations generated by TX3 and the optical elements of RX2 when RX2 is aligned with TX3.

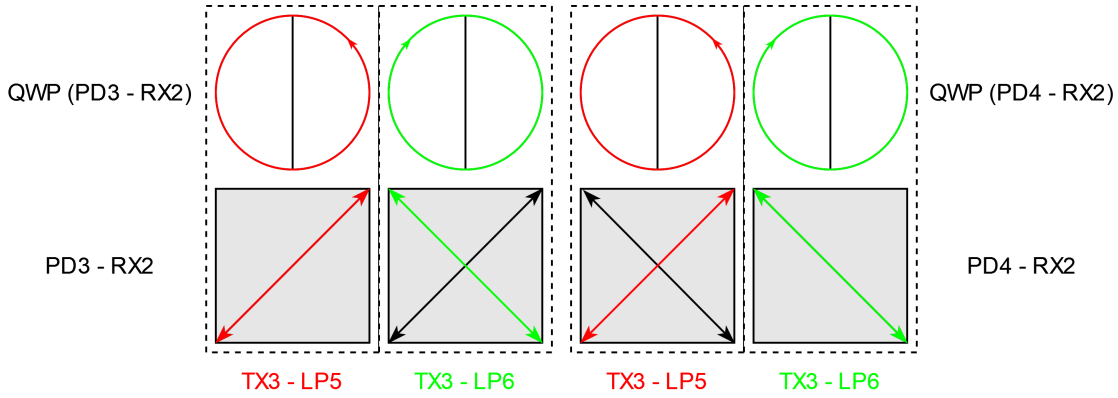


Figure 4.10: Combinations of light polarizations when RX2 is aligned with TX3.

Notice that each particular polarization that strikes a polarizing filter has either the same polarization direction as the polarization axis of the linear filter or is orthogonal to it. Furthermore, if a particular polarization has the same direction as the polarization axis of a linear filter, it will be orthogonal to the other filter. Therefore the light intensity that reaches a PD will either be equal to the initial light intensity or zero and will have the opposite light intensity for the other PD for each polarization. This phenomenon alone, however, does not explain how data is transmitted. The following subchapter will explain how these properties are used to transmit data.

#### 4.2.4 Modulation and Demodulation

The modulated signal of each transmitter is complimentary, meaning that, for example, in TX1, when LED 1 is ON, then LED 2 is OFF and vice-versa. Effectively, data is transmitted in the polarization state of light. When LED 1 is ON, TX1 outputs vertically polarized light that should be interpreted as a data bit '1'. When LED 2 is ON, TX1 outputs horizontally polarized light that should be interpreted as a data bit '0'. The same logic can be applied to each independent transmitter, although the orthogonal polarization states of each one are specific to each transmitter. Figure 4.11 illustrates an example of a transmitted complementary signal.

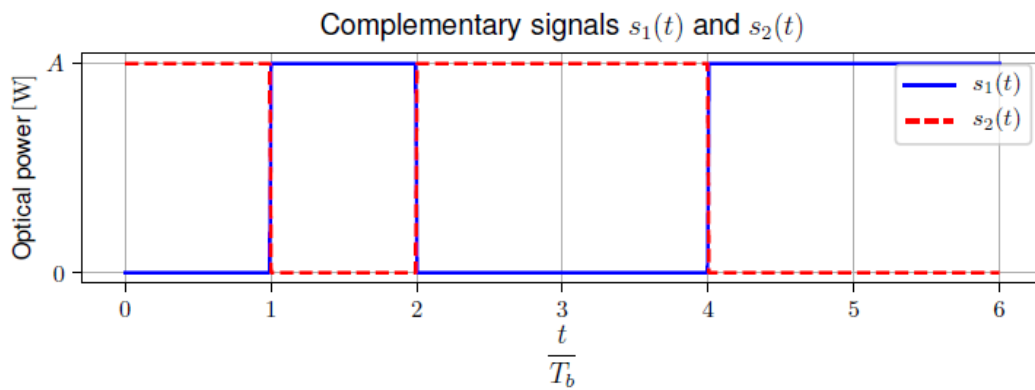


Figure 4.11: Complementary transmitted signals [15, Fig.2].

The demodulation is effectively realized using the properties described in the subchapter above. Notice that because of the complementary modulation, only one polarization state from the aligned transmitter is present. Therefore, only one PD will receive light from that transmitter, which consequentially will be demodulated as a data bit 1 or data bit 0, depending on which PD receives light. Since the electrical output is captured after the differential amplifier, the signal will be received as a positive or a negative electrical value of the same amplitude. Figure 4.12 illustrates this effect.

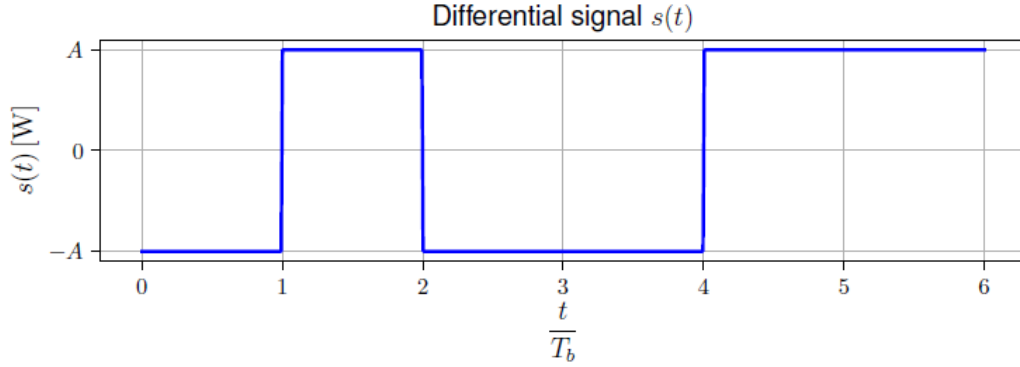


Figure 4.12: Differential signal [15, Fig.2].

#### 4.2.5 System Modeling

Before diving into the model's mathematics, let us understand what happens when Malus's law cannot effectively explain the light output intensity when it goes through a specific configuration of optical elements. Linearly polarized light striking a quarter-wave plate followed by a  $\pm 45^\circ$  linear polarizer and circularly polarized light striking a linear polarizer are the two cases of interest. The Jones matrices prove to be helpful for that understanding. For completeness, let us also prove that the right and left circular polarization that strikes a quarter-wave plate will always output  $-45^\circ$  and  $45^\circ$  linear polarization relative to the fast axis of the waveplate.

For linearly polarized light striking a quarter-wave plate followed by a  $\pm 45^\circ$  linear polarizer, let us first take the normalized Jones vector of vertically polarized light as shown in the equation below:

$$E_v = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (4.5)$$

This initial polarization vector can create a more general vector that considers all polarization directions. Name it  $E_\theta$ , where  $\theta$  is the offset angle from the vertical position.  $E_\theta$  is obtained by multiplying the rotation matrix with  $E_v$  as shown below:

$$E_\theta = R \cdot E_v = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} \quad (4.6)$$

The transfer function for this normalized Jones vector of a general linear polarization is composed of the Jones matrices of a quarter-wave plate with its fast axis on the vertical plane and a  $\pm 45^\circ$  linear polarizing filter:

$$A_{QWP} = \begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix} \quad (4.7)$$

$$A_{LP45} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \quad (4.8)$$

$$A_{LP135} = \frac{1}{2} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \quad (4.9)$$

The output polarization is calculated using the A matrices and the input polarization vector. For each described case, the following equation are used:

$$E_{o1} = A_{LP45} \cdot A_{QWP} \cdot E_\theta \quad (4.10)$$

$$E_{o2} = A_{LP135} \cdot A_{QWP} \cdot E_\theta \quad (4.11)$$

$$E_{o1} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix} \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} = \begin{bmatrix} \frac{\cos(\theta)}{2} - \frac{\sin(\theta)}{2}i \\ \frac{\cos(\theta)}{2} - \frac{\sin(\theta)}{2}i \end{bmatrix} \quad (4.12)$$

$$E_{o2} = \frac{1}{2} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix} \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} = \begin{bmatrix} \frac{\cos(\theta)}{2} + \frac{\sin(\theta)}{2}i \\ -\frac{\cos(\theta)}{2} - \frac{\sin(\theta)}{2}i \end{bmatrix} \quad (4.13)$$

The output polarization magnitude can now be calculated. Fortunately, the magnitude of both  $E_{o1}$  and  $E_{o2}$  are the same; therefore, the general magnitude  $E_o$  is:

$$\|E_o\| = \sqrt{\left(\sqrt{\left(\frac{\cos(\theta)}{2}\right)^2 + \left(\frac{\sin(\theta)}{2}\right)^2}\right)^2 + \left(\sqrt{\left(\frac{\cos(\theta)}{2}\right)^2 + \left(\frac{\sin(\theta)}{2}\right)^2}\right)^2} \quad (4.14)$$

This equation can be simplified using trigonometric identities in the following steps:

$$\begin{aligned} \|E_o\| &= \sqrt{\left(\sqrt{\frac{\cos^2(\theta)}{4} + \frac{\sin^2(\theta)}{4}}\right)^2 + \left(\sqrt{\frac{\cos^2(\theta)}{4} + \frac{\sin^2(\theta)}{4}}\right)^2} \\ \|E_o\| &= \sqrt{\left(\sqrt{\frac{\cos^2(\theta) + \sin^2(\theta)}{4}}\right)^2 + \left(\sqrt{\frac{\cos^2(\theta) + \sin^2(\theta)}{4}}\right)^2} \end{aligned}$$

$$\begin{aligned}
||E_o|| &= \sqrt{\left(\sqrt{\frac{1}{4}}\right)^2 + \left(\sqrt{\frac{1}{4}}\right)^2} \\
||E_o|| &= \sqrt{\left(\frac{1}{2}\right)^2 + \left(\frac{1}{2}\right)^2} \\
||E_o|| &= \frac{1}{\sqrt{2}}
\end{aligned} \tag{4.15}$$

Finally, the magnitude of the output polarization can express the output light intensity for any given normalized input polarization by the following equation:

$$I_o = ||E_o||^2 \times I_i \tag{4.16}$$

Therefore:

$$I_o = \left(\frac{1}{\sqrt{2}}\right)^2 \times I_i = \frac{1}{2} \times I_i \tag{4.17}$$

It is proved that the output intensity will always be half the initial intensity for any linear polarized light that strikes a combined quarter-wave plate with a vertical fast axis and a  $\pm 45^\circ$  linear polarizer.

In subsection 2.4.3, a creative explanation was conducted on the effects of light intensity when a circularly polarized light strikes a polarizing filter. The equations below formulate a more rigorous mathematical proof of it.  $E_{RC}$  and  $E_{LC}$  represent the right and left circular polarization.  $E_{RC\theta}$  and  $E_{LC\theta}$  represent the general right and left circular rotated polarization, respectively.

$$E_{RC} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ i \end{bmatrix} \tag{4.18}$$

$$E_{LC} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -i \end{bmatrix} \tag{4.19}$$

$$E_{RC\theta} = R \cdot E_{RC} = \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} 1 \\ i \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(\theta) - \sin(\theta)i \\ \sin(\theta) + \cos(\theta)i \end{bmatrix} \tag{4.20}$$

$$E_{LC\theta} = R \cdot E_{LC} = \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} 1 \\ -i \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(\theta) + \sin(\theta)i \\ \sin(\theta) - \cos(\theta)i \end{bmatrix} \tag{4.21}$$

Considering now the polarizer,  $A_{VLP}$  in equation 4.22 is the Jones matrix for a vertical linear polarizer. For this, subsequent calculations are shown in equations 4.23 to 4.27.

$$A_{VLP} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \tag{4.22}$$

$$E_{o1} = A_{VLP} \cdot E_{RC\theta} \quad (4.23)$$

$$E_{o2} = A_{VLP} \cdot E_{LC\theta} \quad (4.24)$$

$$E_{o1} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(\theta) - \sin(\theta)i \\ \sin(\theta) + \cos(\theta)i \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ \sin(\theta) + \cos(\theta)i \end{bmatrix} \quad (4.25)$$

$$E_{o2} = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(\theta) + \sin(\theta)i \\ \sin(\theta) - \cos(\theta)i \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ \sin(\theta) - \cos(\theta)i \end{bmatrix} \quad (4.26)$$

$$\|E_o\| = \frac{1}{\sqrt{2}} \times \sqrt{\sin^2(\theta) + \cos^2(\theta)} = \frac{1}{\sqrt{2}} \quad (4.27)$$

Using equation 4.16:

$$I_o = \left( \frac{1}{\sqrt{2}} \right)^2 \times I_i = \frac{1}{2} \times I_i \quad (4.28)$$

It is proved that the output intensity will always be half the initial intensity for any circularly polarized light that strikes any linear polarizer.

Lastly, let us calculate the polarization output of circular polarization that strikes a quarter-wave plate:

$$E_{o1} = A_{QWP} \cdot E_{RC\theta} \quad (4.29)$$

$$E_{o2} = A_{QWP} \cdot E_{LC\theta} \quad (4.30)$$

$$E_{o1} = \begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(\theta) - \sin(\theta)i \\ \sin(\theta) + \cos(\theta)i \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(\theta) - \sin(\theta)i \\ \cos(\theta) - \sin(\theta)i \end{bmatrix} \quad (4.31)$$

$$E_{o2} = \begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(\theta) + \sin(\theta)i \\ \sin(\theta) - \cos(\theta)i \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \cos(\theta) + \sin(\theta)i \\ -\cos(\theta) - \sin(\theta)i \end{bmatrix} \quad (4.32)$$

$$E_{o1} = \frac{1}{\sqrt{2}} \begin{bmatrix} e^{-i\theta} \\ e^{-i\theta} \end{bmatrix} \quad (4.33)$$

$$E_{o2} = \frac{1}{\sqrt{2}} \begin{bmatrix} e^{i\theta} \\ e^{i(\theta+180^\circ)} \end{bmatrix} \quad (4.34)$$

As shown above, right circular polarization striking a quarter-wave plate creates 45° linear polarization, which is -45° relative to the vertical fast axis of the waveplate, and left circular polarization



striking a quarter-wave plate creates  $-45^\circ$  linear polarization, which is  $45^\circ$  relative to the vertical fast axis of the waveplate.

Now that these proofs are achieved, a system model can be devised for the solution proposed in section 4.2.2, Figures 4.4 and 4.5. The system model is the following:

$$Y = \begin{bmatrix} \cos^2(\alpha) & \cos^2(\beta) & \cos^2(\gamma) & \cos^2(\delta) & \frac{1}{2} & \frac{1}{2} \\ \cos^2(\epsilon) & \cos^2(\zeta) & \cos^2(\eta) & \cos^2(\theta) & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 1 & 0 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & 0 & 1 \end{bmatrix} \cdot X + I + N \quad (4.35)$$

Where:

- $Y$  is the received light intensity matrix of the 4 PDs ( $Y = [Y_1 \ Y_2 \ Y_3 \ Y_4]^T$ )
- $X$  is the transmitted light intensity matrix of the LEDs ( $X = [X_1 \ X_2 \ X_3 \ X_4 \ X_5 \ X_6]^T$ )
- $I$  is the ambient or interference light matrix ( $I = [I_1 \ I_2 \ I_3 \ I_4]^T$ )
- $N$  is the AWGN matrix ( $N = [N_1 \ N_2 \ N_3 \ N_4]^T$ )
- $\alpha$  is the offset angle between receiver LP 1 and transmitter LP 1
- $\beta$  is the offset angle between receiver LP 1 and transmitter LP 2
- $\gamma$  is the offset angle between receiver LP 1 and transmitter LP 3
- $\delta$  is the offset angle between receiver LP 1 and transmitter LP 4
- $\epsilon$  is the offset angle between receiver LP 2 and transmitter LP 1
- $\zeta$  is the offset angle between receiver LP 2 and transmitter LP 2
- $\eta$  is the offset angle between receiver LP 2 and transmitter LP 3
- $\theta$  is the offset angle between receiver LP 2 and transmitter LP 4

Assuming a one-to-one ratio between electric gain and light intensity gain, and using the equations above, the electrical output of the differential amplifiers are the following:

$$D_1 = Y_1 - Y_2 \quad (4.36)$$

$$D_2 = Y_3 - Y_4 \quad (4.37)$$

$$D_1 = X_1(\cos^2(\alpha) - \cos^2(\epsilon)) + X_2(\cos^2(\beta) - \cos^2(\zeta)) + X_3(\cos^2(\gamma) - \cos^2(\eta)) \\ + X_4(\cos^2(\delta) - \cos^2(\theta)) + I_1 - I_2 + N_1 - N_2 \quad (4.38)$$

$$D_2 = X_5 - X_6 + I_3 - I_4 + N_3 - N_4 \quad (4.39)$$

To simplify the analysis it will be assumed now that:

- $I_1 - I_2 \approx 0$
- $I_3 - I_4 \approx 0$
- $N \approx 0$

These assumptions are not overly presumptuous. All photodetector's received ambient or interference light is approximately the same because the light source is unpolarized. As for the AWGN, if we assume high SNR, we can assume it is close to zero or relatively irrelevant. Therefore the equations above can be simplified as follows:

$$D_1 = X_1(\cos^2(\alpha) - \cos^2(\epsilon)) + X_2(\cos^2(\beta) - \cos^2(\zeta)) \\ + X_3(\cos^2(\gamma) - \cos^2(\eta)) + X_4(\cos^2(\delta) - \cos^2(\theta)) \quad (4.40)$$

$$D_2 = X_5 - X_6 \quad (4.41)$$

As shown in the above equations, the differential amplifiers eliminate the ambient light interference. Aligning RX1 with TX1, using the mechanical rotating platform,  $D_1$  will become:

$$D_1 = X_1(\cos^2(0^\circ) - \cos^2(90^\circ)) + X_2(\cos^2(90^\circ) - \cos^2(0^\circ)) \\ + X_3(\cos^2(135^\circ) - \cos^2(45^\circ)) + X_4(\cos^2(45^\circ) - \cos^2(135^\circ))$$

$$D_1 = X_1(1 - 0) + X_2(0 - 1) + X_3\left(\frac{1}{2} - \frac{1}{2}\right) + X_4\left(\frac{1}{2} - \frac{1}{2}\right)$$

$$D_1 = X_1 - X_2 \quad (4.42)$$

Aligning RX1 with TX2, using the mechanical rotating platform,  $D_1$  will become:

$$D_1 = X_1(\cos^2(135^\circ) - \cos^2(45^\circ)) + X_2(\cos^2(45^\circ) - \cos^2(135^\circ)) \\ + X_3(\cos^2(0^\circ) - \cos^2(90^\circ)) + X_4(\cos^2(90^\circ) - \cos^2(0^\circ))$$

$$D_1 = X_1 \left( \frac{1}{2} - \frac{1}{2} \right) + X_2 \left( \frac{1}{2} - \frac{1}{2} \right) + X_3(1 - 0) + X_4(0 - 1)$$

$$D_1 = X_3 - X_4 \quad (4.43)$$

As equations 4.42 and 4.43 illustrate, when using linear polarization, it is possible to have an interference-free channel by aligning the receiver RX1 to the transmitter TX1 or TX2. Relatively to the use of circular polarization, RX2 does not need any alignment to communicate with TX3 and be interference-free, being the recovered signal at the receiver always set by equation 4.41. This ability to be alignment-free is a tremendous advantage of circular polarization.

#### 4.2.6 Receiver Transmitter Alignment Theory

The alignment of this system might be the most challenging part because there are many different situations for it. Although RX2 and TX3 do not need an alignment, RX1 needs alignment with TX1 or TX2.

The receiver must be able to align itself to the transmitter without any communication. This passive alignment, although possible, is challenging. Notice the differential amplifier equation 4.40; due to the way the modulation for this system works, this equation is split into four cases, as shown in Table 4.2.

| Case | LED 1 | LED2 | LED 3 | LED 4 |
|------|-------|------|-------|-------|
| 1    | ON    | OFF  | ON    | OFF   |
| 2    | OFF   | ON   | ON    | OFF   |
| 3    | ON    | OFF  | OFF   | ON    |
| 4    | OFF   | ON   | OFF   | ON    |

Table 4.2: Modulation cases.

The resulting equations will be:

$$C_1 = X_1(\cos^2(\alpha) - \cos^2(\epsilon)) + X_3(\cos^2(\gamma) - \cos^2(\eta)) \quad (4.44)$$

$$C_2 = X_2(\cos^2(\beta) - \cos^2(\zeta)) + X_3(\cos^2(\gamma) - \cos^2(\eta)) \quad (4.45)$$

$$C_3 = X_1(\cos^2(\alpha) - \cos^2(\epsilon)) + X_4(\cos^2(\delta) - \cos^2(\theta)) \quad (4.46)$$

$$C_4 = X_2(\cos^2(\beta) - \cos^2(\zeta)) + X_4(\cos^2(\delta) - \cos^2(\theta)) \quad (4.47)$$

Where  $C_n$  represents the differential amplifier output  $D_1$  for case  $n$ . Because the linear polarizers in the transmitters are all fixed between each transmitter and each LED of the transmitter and the receiver linear polarizers are also fixed between each receiver LED, the equations above can replace all angle variables to a single one where:

- $\alpha = \lambda$
- $\beta = \lambda + 90^\circ$
- $\gamma = \lambda + 135^\circ$
- $\delta = \lambda + 45^\circ$
- $\varepsilon = \lambda + 90^\circ$
- $\zeta = \lambda$
- $\eta = \lambda + 45^\circ$
- $\theta = \lambda + 135^\circ$

A plot of the differential amplifier output for each case can now be devised and is shown in Figure 4.13.

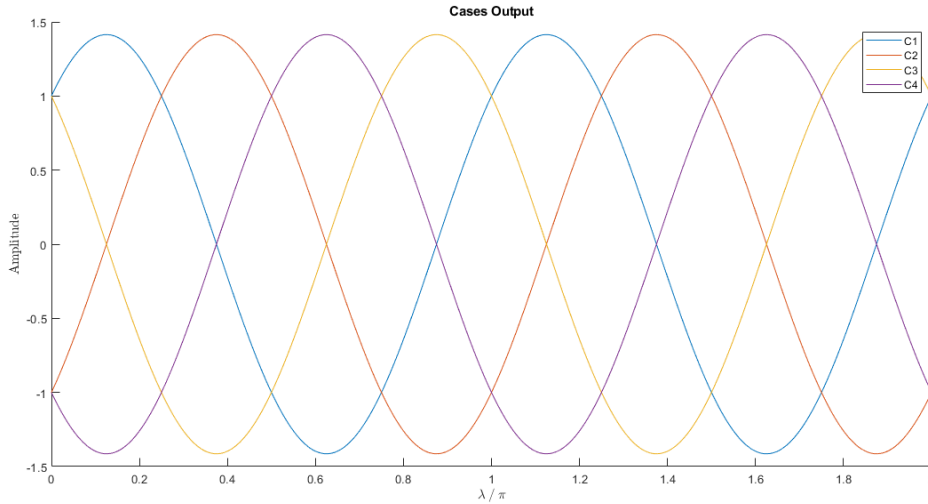


Figure 4.13: Differential amplifier output for each case.

Looking at the plot, notice that alignment occurs when particular cases have the same output amplitude, in particular, when  $C_1 = C_3$ ,  $C_1 = C_2$ ,  $C_2 = C_4$  and  $C_3 = C_4$ . However, there is a slight caveat to this rule. The alignment can also be  $90^\circ$  off, meaning in practical terms that the data received will be inverted. This caveat is not significantly problematic as a simple logic inverter

can solve this problem and is easily detectable. To further understand this effect, a mathematical description of each case is made below:

$$C_1 = C_3 \equiv \\ X_1(\cos^2(\alpha) - \cos^2(\epsilon)) + X_3(\cos^2(\gamma) - \cos^2(\eta)) = X_1(\cos^2(\alpha) - \cos^2(\epsilon)) + X_4(\cos^2(\delta) - \cos^2(\theta))$$

$$C_1 = C_2 \equiv \\ X_1(\cos^2(\alpha) - \cos^2(\epsilon)) + X_3(\cos^2(\gamma) - \cos^2(\eta)) = X_2(\cos^2(\beta) - \cos^2(\zeta)) + X_3(\cos^2(\gamma) - \cos^2(\eta))$$

$$C_2 = C_4 \equiv \\ X_2(\cos^2(\beta) - \cos^2(\zeta)) + X_3(\cos^2(\gamma) - \cos^2(\eta)) = X_2(\cos^2(\beta) - \cos^2(\zeta)) + X_4(\cos^2(\delta) - \cos^2(\theta))$$

$$C_3 = C_4 \equiv \\ X_1(\cos^2(\alpha) - \cos^2(\epsilon)) + X_4(\cos^2(\delta) - \cos^2(\theta)) = X_2(\cos^2(\beta) - \cos^2(\zeta)) + X_4(\cos^2(\delta) - \cos^2(\theta))$$

Simplifying the equivalences using only a single variable to represent all angles, the following emerges:

$$C_1 = C_3 \equiv \\ X_3(\cos^2(\lambda + 135^\circ) - \cos^2(\lambda + 45^\circ)) = X_4(\cos^2(\lambda + 45^\circ) - \cos^2(\lambda + 135^\circ))$$

$$C_1 = C_2 \equiv \\ X_1(\cos^2(\lambda) - \cos^2(\lambda + 90^\circ)) = X_2(\cos^2(\lambda + 90^\circ) - \cos^2(\lambda))$$

$$C_2 = C_4 \equiv \\ X_3(\cos^2(\lambda + 135^\circ) - \cos^2(\lambda + 45^\circ)) = X_4(\cos^2(\lambda + 45^\circ) - \cos^2(\lambda + 135^\circ))$$

$$C_3 = C_4 \equiv X_1(\cos^2(\lambda) - \cos^2(\lambda + 90^\circ)) = X_2(\cos^2(\lambda + 90^\circ) - \cos^2(\lambda))$$

Finally, knowing, in this context, that the amplitude of  $X_1 = X_2$  and the amplitude of  $X_3 = X_4$ , the inequalities are solvable for  $\lambda$ :

$$C_1 = C_3 \equiv \lambda = 0^\circ + k \times 90^\circ, k \in \mathbb{Z} \quad (4.48)$$

$$C_1 = C_2 \equiv \lambda = 45^\circ + k \times 90^\circ, k \in \mathbb{Z} \quad (4.49)$$

$$C_2 = C_4 \equiv \lambda = 0^\circ + k \times 90^\circ, k \in \mathbb{Z} \quad (4.50)$$

$$C_3 = C_4 \equiv \lambda = 45^\circ + k \times 90^\circ, k \in \mathbb{Z} \quad (4.51)$$

Therefore described above is a solid mathematical basis for the alignment of this system. This alignment theory is simple to grasp as it only requires some particular output cases to be the same. However, in a more general view of the solution, two different output cases must be equal and different from zero for alignment to exist.

This concludes the mathematical and conceptual approach of building these VLC systems on the next chapter this latter VLC system is going to be put to the test with simulation.

## Chapter 5

# Simulations and Results

### 5.1 Receiver Transmitter Alignment Real-World

As shown previously, although the theoretical approach to alignment is correct, in practical terms, other challenges arise. In this section, a pseudo-algorithm for alignment that considers real-world use will be devised and presented.

The idea of this pseudo-algorithm is relatively simple. It consists of turning the rotating mechanical mount from a random unknown starting point  $\sigma$  to  $\sigma + 45^\circ$ , which, as demonstrated before, will guarantee the existence of an alignment point when TX1 and TX2 are present. Data about the light intensity is collected for each angle of the rotating mechanical mount. It is essential in this stage to capture enough light intensity data to guarantee that the four different cases are present in the collected data. Unfortunately, the collected data about the light intensity does not indicate directly the case in which it falls. Thus an algorithm to distinguish the four distinct cases and categorize the intensity data is necessary. However, this distinction does not need to be so accurate as the equations found above, as will later be shown. After completing the categorization, the mean value of each category is saved. This process is repeated until the rotating mechanical mount has turned  $45^\circ$  in total. After the mean value of all categories is saved in arrays where the indices correspond to the turning angle, an alignment point is easily discovered by simply looking for the non-zero equal value in those arrays. The last part of the pseudo-algorithm consists in finding the best transmitter. This process is done by aligning the receiver to each transmitter, then averaging the power captured for each, and finally aligning with the one with the highest power. Figure 5.1 is a flowchart of the pseudo-algorithm described above.

An implementation of the proposed pseudo-algorithm was programmed in Matlab and can be seen in Appendix B. Most of the program is reasonably straightforward. However, the most challenging aspect of it was implementing a classification algorithm that would be able to discern four classes of data.

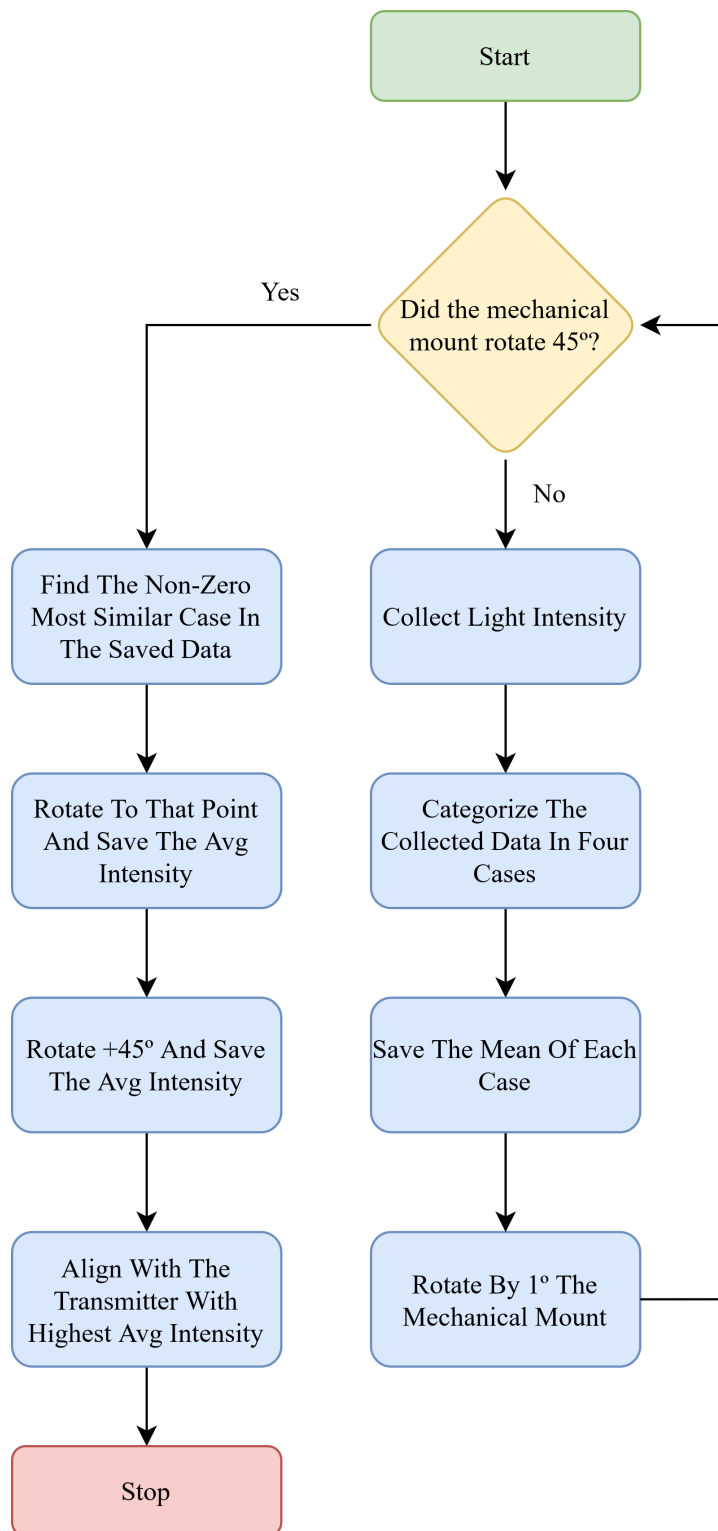


Figure 5.1: Algorithm Flowchart.

For this classification, the *kmeans* machine learning algorithm was used. Even though the *kmeans* algorithm is commonly used in problems with many variables, it can be used with only one variable and remains very effective in its classification. Therefore the *kmeans* algorithm was



chosen because it is easy to understand and is effective for the problem at hand. In the program, it is clear that each category was grouped in ascending order. This grouping strategy leads to a nonconforming classification to its original description. However, it does not affect the result of finding the alignment point, as seen in Figure 5.2.

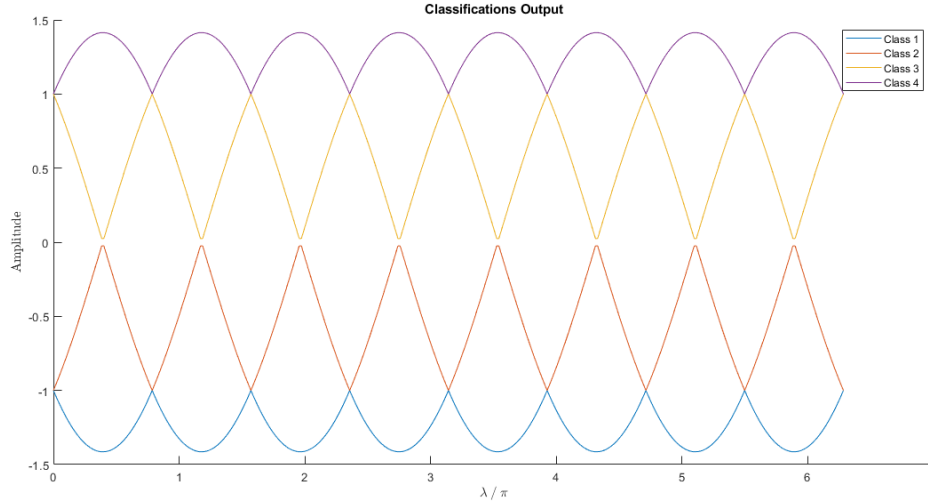


Figure 5.2: Light Intensity Classification.

## 5.2 Performance

The SNR for this system is equal to or similar to the one presented in [15]. Looking at the pairs RX1 with TX1 and RX1 with TX2, it is clear that the system is exactly equal to the one described in [15]. Therefore since SNR does not take into account interference from other transmitters, the SNR is:

$$SNR = \frac{(A^2 T_b \alpha R_p)^2}{\mathbb{E} \left[ \left( A \int_{T_b} w(t) dt \right)^2 \right]} \cos^2(2\theta) \quad (5.1)$$

Where:

- $A$  is the optical power in transmittance.
- $T_b$  is the bit period.
- $\alpha$  is the optical channel gain.
- $R_p$  is the photodiode responsivity.
- $w(t)$  is the noise contribution.
- $\theta$  is the offset angle.

The SNR for the RX2 - TX3 pair is similar but not equal. The only difference is that, as seen in the system modeling, RX2 - TX3 pair does require an alignment. Therefore, it does not depend on the angle  $\theta$ . The SNR consequently is:

$$SNR = \frac{(A^2 T_b \alpha R_p)^2}{\mathbb{E} \left[ (A \int_{T_b} w(t) dt)^2 \right]} \quad (5.2)$$

BER is directly correlated to SNR and can be calculated the following way:

$$BER = Q(\sqrt{SNR}) \quad (5.3)$$

Where:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-y^2/2} dy \quad (5.4)$$

## 5.3 Evaluation Environment

Now that the performance metrics are examined let us focus on why this system was developed. For this purpose, let us imagine a relatively big empty room where many devices are connected simultaneously. If, for instance, WLAN technology is used in the band of 2.4 GHz, eleven would be the maximum number of APs in the room (and subject to interference), since this is the number of channels allocated for this technology in that band. If each AP has a maximum device connection of 200, then the maximum overall connected devices in a relatively big empty room are about 2200 (this number can only increase if spectral reuse is made, but this implies distances greater than around 75 meters between APs in the same channel, i.e., approximately in spaces over 10,000 square meters). Let us then, create a comparable test to analyze our system with WLAN in the band of 2.4 GHz.

### 5.3.1 VLC Boundary Line

Looking at a VLC AP, it is understood that there is a maximum distance for a reliable, error-free connection between it and any device. This maximum distance heavily depends on the VLC AP hardware implementation, such as the semiangle of half illuminance and other design decisions. However, the drop in light intensity with distance is typically significant in VLC, as shown in Figure 5.3 (figure generated by a modified version 8.1 program from [7], as shown in Annex D). That said, assuming a device remains at a fixed plane, even when there is interference, a maximum circular radius exists at which a device can connect to that VLC AP. Let us name that line the *boundary line*. This line is essential for the results presented below.

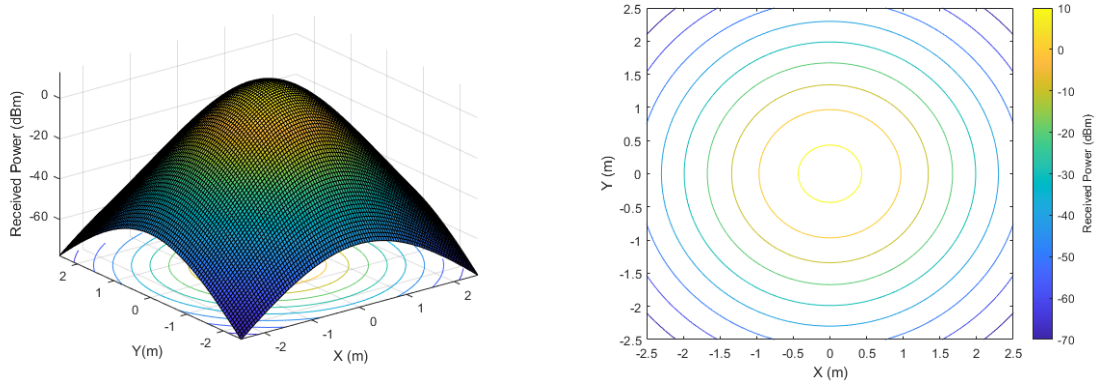


Figure 5.3: Receiver Optical Power In Space.

### 5.3.2 VLC AP Positioning

Now that the boundary line is defined and it is known that this system has three independent transmission modes, we must define the structure for placing various VLC APs in an established empty area. Figure 5.4 shows the AP positioning network where the black dots represent the APs. As is shown, the AP positioning has an equilateral triangular shape where AP\_Radius is the radius of the boundary line, and AP\_Dist is the distance between APs.

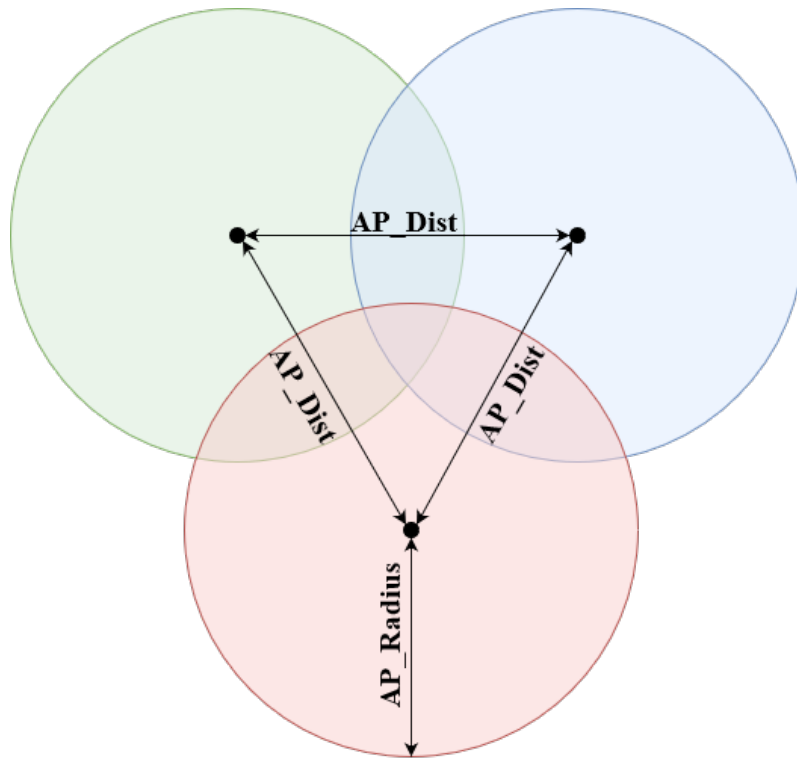


Figure 5.4: AP positioning.

As stated previously, the boundary line is heavily dependent on the physical implementation of the APs, and therefore, so is AP\_Radius. AP\_Dist is given by the equation:

$$AP\_Dist = \frac{2 \times AP\_Radius}{\sqrt{2}} \quad (5.5)$$

If we keep on repeating this basic triangular positioning shape, we get the pattern depicted in Figure 5.5 where the black dashed lines represent a potential wall of that space. All the area inside the black dashed lines is covered by at least one AP. This is guaranteed because of the way AP\_Dist is defined and calculated.

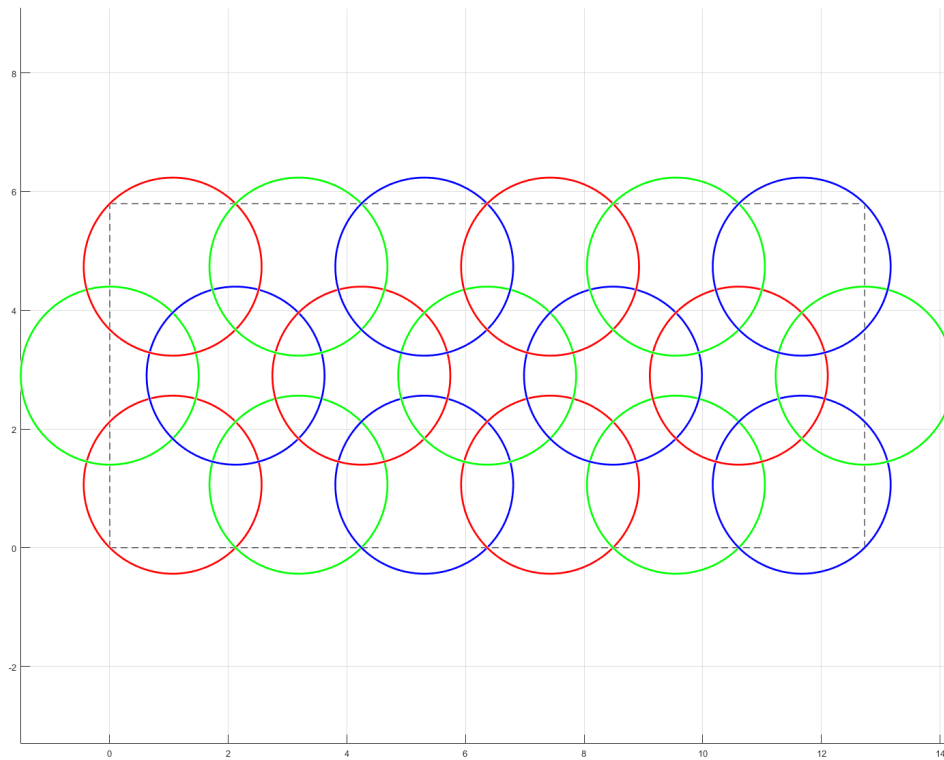


Figure 5.5: AP Coverage Pattern.

### 5.3.3 WLAN 2.4 GHz band

The WLAN operating in the 2.4 GHz frequency band can be compared to the VLC system described earlier, but solely under the circumstance where the WLAN employs channels 1, 6, and 11 exclusively. This is due to the inherent characteristics of each of the three channels, where they exhibit non-interference with one another [17]. This fact is used in site network planning because the mesh of AP that only use channels 1, 6 and 11 are ideal for non-interference network coverage as seen in Figure 5.6.

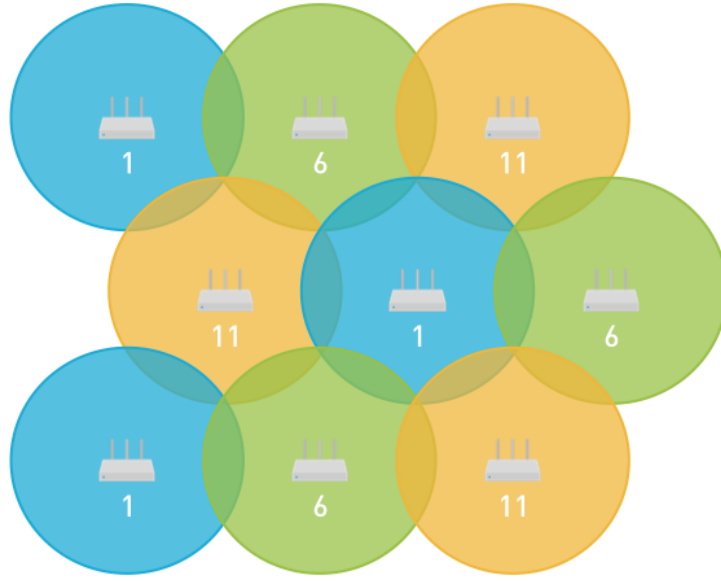


Figure 5.6: Channel Planning [17, Fig.5].

The positioning for our comparison purposes can also be the same as the VLC system however this system has a much bigger AP\_radius due to the nature of the technology. It is also important to mention that an additional variable is introduced, to represent the distance between APs, using the same radio channel. In this case, a distance of around 75 meters between APs is recommended. Figure 5.7 depicts the positioning of the system.

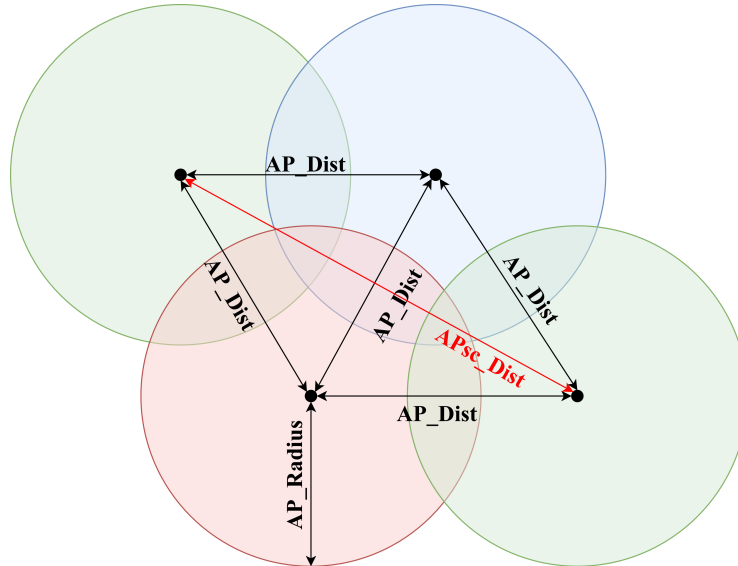


Figure 5.7: WLAN AP Positioning.

Each of the colors represent a different RF channel and APsc\_Dist is the distance between two APs, in the same channel, and can be calculated by the following equation:

$$AP_{sc\_Dist} = \sqrt{3} \times AP\_Dist = \sqrt{6} \times AP\_Radius \quad (5.6)$$

Finally, the signal strength drop with distance is also similar to the pattern found in VLC and information depicted by Figure 5.8 can be taken as an example (in this case representing the IEEE 802.11g characteristic, but other versions have similar behavior, exception made for the speeds).

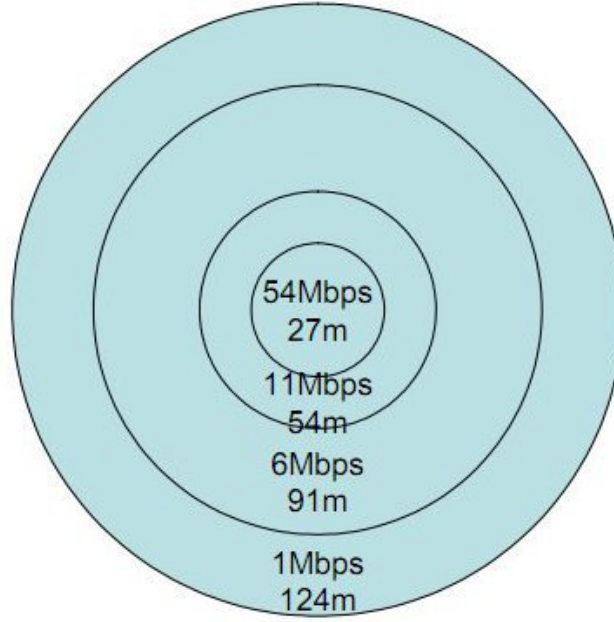


Figure 5.8: AP Signal Strength [18, Fig.3].

With this information in hand we can now proceed with a general comparison between the two systems using simulations.

## 5.4 Simulation Results

The Monte Carlo simulation of the Matlab program in Annex C helps analyze the number of connected devices per VLC AP or WLAN AP, where the principles explained above are modeled. The simulation starts by creating a space with a set-defined number of vertical and horizontal APs calculating the position of each AP using the value of AP\_radius where, the words "horizontal" and "vertical" mean a orientation according to the "X-axis" and the "Y-axis". After this process is concluded, it simulates the random positioning of connected devices, where MCON is the maximum number of possible connected devices per AP. The simulation stops when a randomly generated position of a device cannot connect with any of the APs present in that position. This simulation is repeated hundreds of times to determine the average number of connected devices in each parameterized scenario.

In the first set of simulation runs, N\_HAPS and N\_VAPS variables that represent the number of horizontal and vertical APs, respectively, progressively get bigger in a ratio of 2 to 1 between them. This variation is reflected in the covered area as more APs in use implies a larger area. AP\_radius is fixed at 1.5 meters for the VLC APs and 25 meters for WLAN APs. Also, multiple variations of this simulation run were performed where MCON is increased from 10 to 20 and 30 connectable devices per AP for the VLC system and 100, 200 and 300 for the WLAN system. The result of these simulation runs is shown in Figure 5.9 where, as expected, the increasing number of APs linearly increases the possible number of connected devices and the number of connected devices is always higher with the VLC system, even when MCON is one order of magnitude lower for the VLC system.

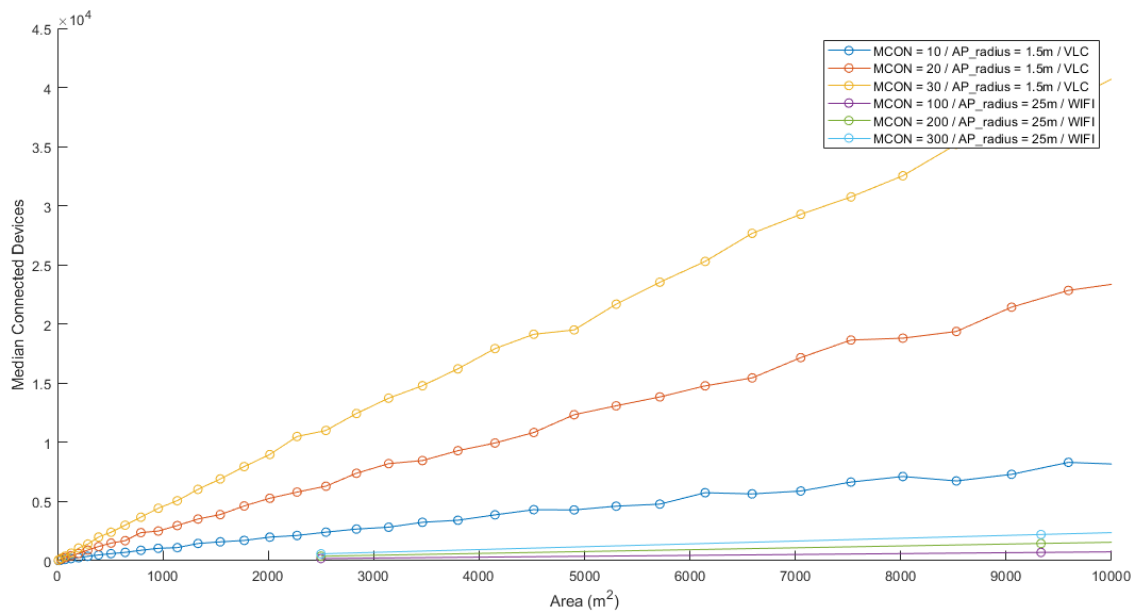


Figure 5.9: Number of connected devices for a given area with variation in MCON.

Similar to the first set, in the second set of simulations runs the number of horizontal and vertical APs progressively get bigger in a ratio of 2 to 1 between them. However, this time, instead of varying, MCON is kept constant and equal to 20 for VLC APs and 200 for WLAN APs and AP\_radius varies between 1, 1.5, and 3 meters for VLCs and 25, 30 and 35 meters for WLAN. This affects the overall density of APs but once again, as expected, the number of connected devices is always higher with the VLC system as shown in Figure 5.10.

As seen in the results of all simulations, the result heavily depends on the parameters given to the program. However, for all representative configuration values used, the, VLC system always performed better than the WLAN system. The results are, therefore, a good indicator of the performance of this system.

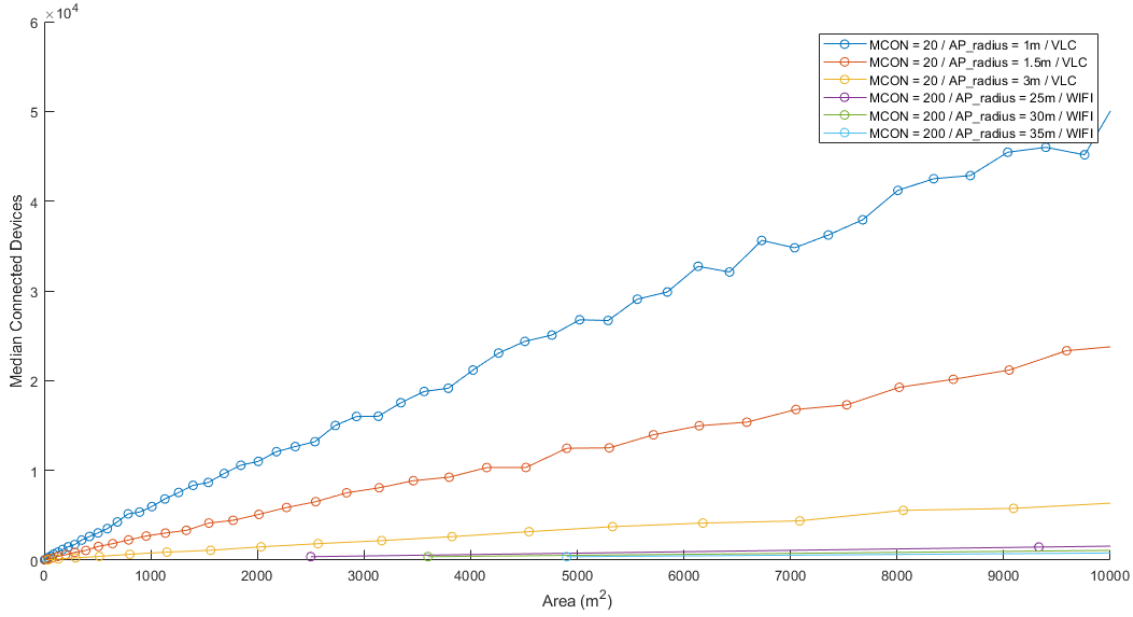


Figure 5.10: Number of connected devices for a given area with variation in AP\_Radius.

## 5.5 Discussion

Similarly to what was presented for [15] in chapter 3, this VLC system has the following advantages:

- Flicker free operation
- Scrambler free operation
- Simple dimming support
- Dense connectivity

This system also offers some unique benefits, such as the potential to be deployed in large areas and keeping the same properties of interference rejection and dense connectivity. This system also guarantees the best SNR possible because of its mechanical rotating mount, as it will always try to adjust itself to be aligned with the transmitter.

In terms of disadvantages, possibly, the most relevant one is that it uses achromatic waveplates. Achromatic waveplates are generally expensive, and this system requires them for RX2 to function. Although some promising attempts have been made to achieve similar polarization manipulation characteristics with liquid crystals, the research on the manufacturing cost of such devices is inconclusive. This system can efficiently work without RX2 and still provide relevant advantages. Still, it will lose a fundamental one as RX2 is the only RX where alignment is not required for optimal functionality.



Overall this system is a step forward in the full potential use of the properties of light polarization in VLCs.



## Chapter 6

# Conclusion

This dissertation focused on using polarization in VLCs for the applications of interference reduction and data throughput. Polarization manipulation isn't always easy. It requires specific and sometimes expensive optical elements. However, polarization employed in VLCs shows promise in its range of creative applications. In this dissertation, two new VLC systems were proposed alongside their respective use cases and viability. Simulations demonstrated that 4x4 PDM could improve data throughput, although it was also concluded that its use cases were limited due to lower SNR than other data throughput enhancements. In the case of interference reduction, it was demonstrated through mathematical modeling that it was possible to create a fully functional multiple AP system capable of being interference tolerant. With simulations it was also shown that it can support a large number of connected devices, although it was also concluded that the material to make such a system are, at the moment of writing, expensive. In a broader sense and although more subjective, this dissertation shows that the use of polarization in VLCs is a subject worthwhile researching.



## Appendix A

### Modified Program 8.4

```
1 clear
2 clc
3 close all
4
5 %% Simulation Parameters
6
7 TxN=2; % Number of transmitters
8 RxN=2; % Number of receivers
9
10 M=2; % bit resolutions bits/Hz/s/channel
11 L=2^M; % Average symbol length
12 nsym=1000; % number of symbols
13
14 min_BitsToTest = 1e8;
15 max_BitError = 3000 ;
16
17 SNR_dB=1:1:50; % SNR in dB
18
19 Hmat=[1 0
20        0 1];
21
22 Hmat=Hmat./sum(Hmat(:)); %Normalize H matrix
23
24
25 for jj = 1:length(SNR_dB)
26     total_nbit = 0; % initialise the loop variables
27     total_nerr = 0; % number of bits tested, errors
28
29     while total_nbit ≤ min_BitsToTest - 1 && total_nerr ≤ max_BitError
30
31         %% Generate Random data
32         DataSymbolIn=randi([0 L-1],TxN,nsym);% Generate data symbols
33     end
end
```

```

34     %% MIMO Encoding
35     % Generate modulated symbols
36     PAM_Symbol = pammod(DataSymbolIn,L,0,'gray');
37     % Only Consider the real part
38     PAM_Symbol_tx=real(PAM_Symbol);
39     % Adding a DC to make signal unipolar
40     Tx_signal=PAM_Symbol_tx+(L-1);
41
42     %% Received Data
43     Rx_bit=Hmat*Tx_signal; % received data
44     Rx_bit=awgn(Rx_bit, SNR_dB(jj)+3, 'measured'); % Add AWGN Noise
45
46     %% MIMO Decoding
47     received_signal=pinv(Hmat)*Rx_bit;
48
49     for Rx_index=1:RxN
50         received_signal(Rx_index,:)=received_signal(Rx_index,:) ...
51             -mean(received_signal(Rx_index,:));
52     end
53
54     DataSymbolOut = pamdemod(received_signal,L,0,'gray');
55
56     %% Calculate Errors
57     [nerr, bb] = biterr(DataSymbolOut , DataSymbolIn);
58     clc
59     total_nbit=total_nbit+nsym*M;
60     total_nerr=total_nerr+nerr
61 end
62
63 BER(jj) = total_nerr/total_nbit
64 if BER(jj) == 0
65     break;
66 end
67
68 figure;
69 semilogy(SNR_dB(1:length(BER)), BER)
70 xlabel('SNR(dB)'), ylabel('BER');

```

## Appendix B

# Alignment Algorithm

```
1 clear
2 clc
3 close all
4
5 % ----- %
6
7 I_X12 = rand() % Received luminous intensity of X1 & X2
8 I_X34 = rand() % Received luminous intensity of X3 & X4
9
10 Nbits = 100; % Number of random bits received per angle
11
12 D = [];
13
14 C1 = [];
15 C2 = [];
16 C3 = [];
17 C4 = [];
18
19 AC1 = [];
20 AC2 = [];
21 AC3 = [];
22 AC4 = [];
23
24
25 theta = 2*pi*rand() % Random inicial unknown angle
26
27 result = theta + pi/4 - mod(theta,pi/4) % The calculated expected next ...
    angle of alignment
28
29 inicialtheta = theta;
30
31 thetaarray = 0;
32
```

```

33 while theta < inicialtheta + pi /4 %We are guaranteed to find alignment ...
    within pi/4
34
35 for n = 1:Nbits % Nbits bits are transmitted for each Angle of the ...
    Mechanical rotating Device
36
37     % ---- Send Randomly Generated Bits ----%
38
39     X1 = round(rand()) * I_X12 ;
40     X2 = I_X12 - X1;
41     X3 = round(rand()) * I_X34;
42     X4 = I_X34 - X3;
43
44     X = [X1 , X2 , X3 , X4]';
45
46     % ----- Channel Matrix ----- %
47     ChM = [ (cos(theta)).^2 - (cos(theta+(pi/2))).^2 ;
48             (cos(theta+(pi/2))).^2 - (cos(theta).^2) ;
49             (cos(theta+(3*pi/4))).^2 - (cos(theta+(pi/4))).^2;
50             (cos(theta+pi/4)).^2 - (cos(theta+3*pi/4)).^2]';
51
52     D = [D; ChM * X]; % Differentiator output
53
54 end
55
56 D = [D , kmeans(D,4)]; % Runs Kmeans algorithm and saves the category
57
58 for n = 1:size(D,1)
59
60     switch D(n,2)
61         case 1
62             AC1(end+1) = D(n,1);
63         case 2
64             AC2(end+1) = D(n,1);
65         case 3
66             AC3(end+1) = D(n,1);
67         case 4
68             AC4(end+1) = D(n,1);
69     end
70 end
71
72 means = [mean(AC1),mean(AC2),mean(AC3),mean(AC4)]; % Calculate the ...
    means of each category
73 means = sort(means); % Sort each category to keep correct order
74
75 C1 = [C1 , means(1)];
76 C2 = [C2 , means(2)];
77 C3 = [C3 , means(3)];
78 C4 = [C4 , means(4)];

```



```
79
80     AC1 = [];
81     AC2 = [];
82     AC3 = [];
83     AC4 = [];
84
85     D = [];
86
87     thetaarray = [thetaarray , theta];
88
89     theta = theta + ((2*pi)/360); %Increments the mechanical rotating ...
        device
90
91 end
92
93 thetaarray = thetaarray(2:end);
94
95 %% Finds the angle of alignment
96
97 [M, I] = min(abs(C1 - C2));
98
99 calculated = thetaarray(I)
100
101 [M, I] = min(abs(C3 - C4));
102
103 calculated = thetaarray(I)
104
105 %-----%
106
107 hold on
108
109 plot(thetaarray,C1);
110 plot(thetaarray,C2);
111 plot(thetaarray,C3);
112 plot(thetaarray,C4);
```



## Appendix C

### Connections to APs

```
1 close all
2 clear
3 clc
4
5 %% Parameters
6 N_HAPS = 6; %Number of APs in the 1st Row
7 N_VAPS = 3; %Number of Rows
8
9 all = [];
10 average = [];
11 sqm = [];
12
13
14 AP_Radius = 3; %Distance of Posible ...
    Connection
15 AP_Dist = (2*AP_Radius)/sqrt(2); %Distance Between APs
16 M_CON = 20; %Max Number of Connections
17 Row_Offset = AP_Dist/2; %Even Rows Offset
18
19 % Room Dimensions
20 length = AP_Dist * (N_HAPS);
21 width = (2* AP_Radius)/sqrt(2) + ...
    (((2*AP_Radius)*sqrt(6))/4) * (N_VAPS -1);
22 Area = length * width;
23
24 fprintf('|-----|\n')
25 fprintf('| Dimensions |\n')
26 fprintf('|Length: %.2f M Width: %.2f M Area: %.2f ...
    M^2|\n',length,width,Area)
27 fprintf('|-----|\n\n')
28
29 %% Program
30
```

```

31     AP = [];
32     AUX = [];
33
34     AUX(1,4) = 3;
35
36     for i = 1: N_VAPS
37         for n = 1: N_HAPS
38
39             if AUX(1,4) == 1
40                 AUX(1,4) = 2;
41             elseif AUX(1,4) == 2
42                 AUX(1,4) = 3;
43             else
44                 AUX(1,4) = 1;
45             end
46
47             if mod(i,2) == 0
48                 AUX(1,1) = AP_Dist * (n-1) - Row_Offset + ...
49                     sqrt(AP_Radius^2/2);
50             else
51                 AUX(1,1) = AP_Dist * (n-1) + sqrt(AP_Radius^2/2);
52             end
53
54             AUX(1,2) = (i-1) * sqrt(AP_Dist^2 - ((AP_Dist/2)^2)) + ...
55                 sqrt(AP_Radius^2/2);
56             AUX(1,3) = 0;
57
58             AP = [AP;AUX];
59
60         end
61         if mod(i,2) == 0
62             N_HAPS = N_HAPS - 1;
63         else
64             N_HAPS = N_HAPS + 1;
65         end
66
67         if mod(i,2) == 0
68             AUX(1,4) = 3;
69         else
70             AUX(1,4) = 1;
71         end
72     end
73
74     hold on
75     axis equal
76     grid on
77
78     line([0 length],[0 0], 'Color', 'black', 'LineStyle', '--')
79     line([0 length],[width width], 'Color', 'black', 'LineStyle', '--')

```

```

78     line([0 0],[0 width],'Color','black','LineStyle','--')
79     line([length length],[0 width],'Color','black','LineStyle','--')
80
81     for n = 1 : size(AP,1)
82         if (AP(n,4) == 1)
83             color = 'r';
84         elseif (AP(n,4) == 2)
85             color = 'g';
86         else
87             color = 'b';
88         end
89         viscircles([AP(n,1), AP(n,2)], AP_Radius, 'Color', color);
90     end
91
92
93     % Generate Random Receiver
94
95     DIST = zeros(size(AP,1),2);
96
97     while(1)
98         x = rand * length;
99         y = rand * width;
100
101         %plot(x,y, 'x', 'color', 'black')
102
103         for n = 1:size(AP,1)
104             DIST(n,1) = sqrt((x - AP(n,1))^2 + (y - AP(n,2))^2) - 0.01;
105             DIST(n,2) = n;
106         end
107
108         DIST = sortrows(DIST);
109
110         for n = 1:size(AP,1)
111             if DIST(n,1) > AP_Radius
112                 impos = 1;
113                 break;
114             else
115                 if AP(DIST(n,2),3) < M_CON
116                     AP(DIST(n,2),3) = AP(DIST(n,2),3) + 1;
117                     impos = 0;
118                     break;
119                 else
120                     end
121             end
122         end
123
124         if impos == 1
125             break;
126         end

```

```
127
128     end
129
130     % Number of Devices Connected
131
132     fprintf(' |-----|\n')
133     fprintf(' |Number of Devices Connected: %d      ...
        |\n',sum(AP(:,3)))
134     fprintf(' |-----|\n')
```

## Appendix D

### Modified Program 8.1

```
1 %% opto-electrical parameters
2 theta=12.5; % the semi-angle at half power
3 m1=-log10(2)/log10(cosd(theta)); %Lambertian order of emission
4 P_LED=20; %the tranmist optical power by individual LED
5 nLED=60; % the total number of LED array in each cluster (nLED*nLED)
6 P_total=nLED*nLED*P_LED; %the total transmitted power
7 Adet=1e-4; %the detector physical area of a PD
8 Ts=1; %the gain of an optical filter; ignore if no filter is used
9 index=1.5; %the refractive index of a lens at a PD; ignore if no lens ...
    is used
10 FOV=70; %the FOV of the receiver
11 G_Con=(index^2)/(sind(FOV).^2); %the gain of an optical concentrator; ...
    ignore if no lens is used
12
13 %% room parameters
14 lx=5; ly=5; lz=3;% the room dimensions in meter
15 h=2.15; %the distance between the source and the receiver plane
16 [XT,YT] = meshgrid([0 0],[0 0]);
17 % the position of an LED; it is assumed that all LEDs are located at ...
    the same %point for the faster simulation
18 % for one LED simulation located at the centre of the room, use XT=0 ...
    and YT=0
19 Nx=lx*20; Ny=ly*20; % the number of grid in the receiver plane, larger ...
    the number, better is the approximation but takes longer time
20 x=linspace(-lx/2,lx/2,Nx);
21 y=linspace(-ly/2,ly/2,Ny);
22 [XR,YR]=meshgrid(x,y);
23
24 %% simulation for sournce one
25 D1=sqrt((XR-XT(1,1)).^2+(YR-YT(1,1)).^2+h^2); % the distance vector ...
    from the source 1
26 cosphi_A1=h./D1; % the angle vector
27 recevier_angle=acosd(cosphi_A1);
```

```

28 H_A1=(m1+1)*Adet.*cosphi_A1.^(m1+1)./(2*pi.*D1.^2); % the channel DC ...
    gain for source 1
29 P_rec_A1=P_total.*H_A1.*Ts.*G_Con;% the received power from source 1;
30 P_rec_A1(find(abs(recevier_angle)>FOV))=0;
31
32 %% assuming symmetric property, no need to calculate other power
33 % if the transmitter is not symmetrical, you need to calculate power ...
    for individual LEDs
34 P_rec_A2=fliplr(P_rec_A1);
35 %P_rec_A3=flipud(P_rec_A1);
36 %P_rec_A4=fliplr(P_rec_A3);
37 P_rec_total=P_rec_A1%+P_rec_A2+P_rec_A3+P_rec_A4;
38 P_rec_dBm=10*log10(P_rec_total);
39
40 %%
41 figure
42 %surf(x,y,P_rec_dBm);
43 contour(x,y,P_rec_dBm);hold on; % mesh(x,y,P_rec_dBm);

```



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