



**BOTSWANA INTERNATIONAL UNIVERSITY OF SCIENCE &
TECHNOLOGY**

MASTERS THESIS

**Design and Development of a Wireless
Colour-based Optical Modulation System**

by

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A thesis submitted to the **Faculty of Engineering & Technology** in partial fulfilment of the requirements for the award of the degree of **Master of Engineering in Computer and Telecommunications** of Botswana International University of Science & Technology

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“Learning is a basic skill, to be honed and cherished, yet innate. It’s teaching that comes hard, particularly teaching oneself.”

-Unknown

BOTSWANA INTERNATIONAL UNIVERSITY OF SCIENCE & TECHNOLOGY

Abstract

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In visible light communication (VLC), arrays consisting of a single or multi-colour light sources are employed for a dual purpose being: the provision of illumination and data transmission. Therefore, it is substantial to come up with efficient techniques for resource allocation. The aim of this thesis is to design and develop a multi-user colour-based optical spatial modulation VLC framework using a line-of-sight (LoS) model. An optimisation problem with the intention of minimising the total luminous intensities of the light emitting diode (LED) arrays subject to the transmitting LED array's optical power budget, minimum required illuminance level, LED-user channel conditions and latency intolerant users' (LITUs) quality-of-service (QoS) target constraints is proposed. With the adaptation of spatial modulation and convex optimisation, the design and development of a colour-based algorithm is carried out. Firstly, a coordinated algorithm for the selection of a transmitting array, maintenance of a particular illuminance and signal-to-interference-plus noise ratio (SINR) levels during symbol transmission is designed. Secondly, through computer simulations, a numerical analysis is carried out to demonstrate and evaluate the performance of the algorithm. The proposed scheme is capable of satisfying the user required SINR target for LITUs while reducing the optical power by approximately 20 % to 25 % during the transmission of symbols. Additionally, the system can provide adequate illuminance as per the users' requirement at all areas where users are located while there is low illuminance ranging from 100 lux to 250 lux at any other location. The proposed algorithm is capable of satisfying the user's required illuminance provided it is specified within the standardised levels of 300 lux to 1500 lux. Furthermore, the algorithm can meet the SINR targets for the LITUs while minimising the optical power of the LED arrays. However, fair SINR levels for the latency tolerant users (LTUs) are not guaranteed. The proposed system is able to achieve data rates of 5 Mbps to 25 Mbps using commercially-off-the-shelf LEDs.

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List of Abbreviations

5G	Fifth-Generation
6G	Sixth-Generation
APD(s)	Avalanche Photodiode(s)
AWGN	Additive White Gaussian Noise
CSK	Color-Shift Keying
DD	Direct Detection
FOV	Field-of-View
FSO	Free-Space Optical
IM	Intensity Modulation
IR	Infrared
IrDA	International Infrared Data Association
JIETA	Japan Electronics and Information Technology Industries Association
LD(s)	Laser Diode(s)
LED(s)	Light Emitting Diode(s)
LiFi	Light Fidelity
LoS	Line-of-Sight
MIMO	Multiple-Input Multiple-Output
NLoS	Non-Line-of-Sight
OMEGA	hOme Gigabit Access
OWC	Optical Wireless Communication
PC-LED(s)	Phosphor Converted-LED(s)
PD(s)	Photo Detector(s)
QoS	Quality-of-Service
RF	Radio Frequency
RGB	Red-Green-Blue
SINR	Signal-to-Interference-plus-Noise Ratio
SM	Spatial Modulation
SMP	Spatial Multiplexing
SSL	Solid-State Lighting
TLED(s)	Tri-chromatic-LED(s)
UV	Ultraviolet
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VLC	Visible Light Communication
VLCA	Visible Light Communication Associations
VLCC	Visible Light Communication Consortium
WiFi	Wireless Fidelity
WLED(s)	White Light Emitting Diode(s)

Mathematical Notations

$\mathbb{R}^{M \times N}$	The set of real-valued $M \times N$ matrices.
$\mathbb{R}_+^{M \times N}$	The set of non-negative real-valued $M \times N$ matrices.
$\mathbb{C}^{M \times N}$	The set of complex-valued $M \times N$ matrices.
$\mathbb{Z}_+^{M \times N}$	The set of non-negative integer $M \times N$ matrices.
$\mathbb{E}\{\mathbf{X}\}$	The mathematical expectation of a stochastic $\mathbf{X}$.
$\mathbf{X}^\top$	The transpose of $\mathbf{X}$.
$\mathbf{X}^*$	The conjugate of each element of $\mathbf{X}$.
$\mathbf{X}^H$	The conjugate transpose of $\mathbf{X}$.
$\mathbf{X}^{-1}$	The inverse transpose of $\mathbf{X}$.
$\log_a(x)$	The logarithm of x using the base $x \in \mathbb{R}_+$.

To my beloved wife and graceful mother.

Chapter 1

Introduction

The inception of wireless communication technology can be traced back to as far as the late 19th century when the renowned Alexander Graham Bell came up with the design and implementation of a photophone in 1880 [1]. He successfully transmitted a voice signal over a distance of 213 m by modulating the sun's radiation. In 1896, Guglielmo Marconi invented a wireless radiotelegraph system with which he subsequently transmitted the first wireless message successively across the Atlantic in 1901 [2]. Due to the successive research achievements during the late decades of the 20th century and the early years of the current century, wireless communication technologies have advanced rapidly and thus leading to the diversification of wireless systems and devices. As a result, wireless communication is now an essential part of our present-day lives.

1.1 Background

The embodiment of communication is constantly broadening from 'human-human' to embrace 'human-thing' and subsequently 'thing-thing', which is also referred to as 'machine-machine' (M2M). Through this expansion, a huge number of different things or objects are virtually being connected to the Internet and this creates what is known as the Internet of Things (IoT) [3–5]. The connected objects may be physical or digital. IoT will enable the inception of new smart systems and devices across a wide range of industries. An IoT environment with over a trillion number of communication nodes leads to data traffic growth. Predictions published by Cisco shows that in 2016, the global mobile data traffic grew at an estimated rate of 63% from 2015 [6]. Progressively, in 2017, the mobile data traffic grew at a rate of 71% from 2016. The global mobile data traffic is projected to increase seven fold to 77 exabytes monthly at a compound annual growth rate of 46% from 2017 to 2022 [7]. With this proliferation, the demand for data-intensive wireless services from end users continues to be one of the main factors escalating the exponential increase of mobile data traffic worldwide.

1.2 Motivation

Despite the introspective development and standardisation of wireless radio frequency (RF) technologies, the efforts are falling short in meeting the demand for the limited RF band. This shortfall leads to a bottleneck, which deprives the advancement of wireless devices and the provision of data-intensive services like; real-time video and audio, online-gaming, safe and secure online-financial transactions, and a lot more others. The provision of such services results in the scramble for RF spectrum bands which has the best propagation conditions. RF bands such as those in the orders of 1 GHz to 2 GHz have become jam-packed as they have been exploited to a point where there is limited or no potential to exploit them any further [8,9].

To improve the capacity, spectral and energy efficiencies of RF systems, there are various ongoing research efforts. These include; millimetre-wave (mm-Wave) [10–12], massive multiple-input multiple output (MIMO) [13–15], non-orthogonal multiple access (NOMA) [16–18], ultra-dense networks [19–21] and intelligent reflective surfaces (IRSs) [22–24]. However, licenses for using the RF spectrum as well as resource allocation and network management are very costly. Moreover, power consumption in RF systems remains relatively high despite the innovative counter measures such as low-power integrated circuits (ICs).

With the exponential growth in data traffic, existing technologies and resources might present difficulties to accomplish satisfactory mobile data services in the upcoming decades. Therefore, careful consideration must be given to the limited availability of the RF spectrum when designing wireless systems for the next networking generations. The above complications call for an urgent need for the development and implementation of optimum complementary technologies. To curb the RF impediments, many research institutions are shifting their focus to new research areas in the field. Researchers are investing time and economic resources into exploring the feasibility of exploiting other segments of the electromagnetic (EM) spectrum.

Currently, there is a swift expansion in the lighting and illumination sector. The developments in this sector have led to the commissioning of solid-state lighting (SSL) sources operating within the visible light band of the EM spectrum. These sources are gradually phasing out the incandescent and fluorescent sources in many applications and are predicted to become the predominant lighting sources [25,26]. In addition to general illumination using the SSL sources, a very high data-rate transmission can be achieved. The feasibility of modulating the optical source's intensity at rapid speeds greater than the human eye's response paves way for data transmission using visible light communication (VLC) technology [26–28]. A detailed introduction to VLC is given in section 1.3.

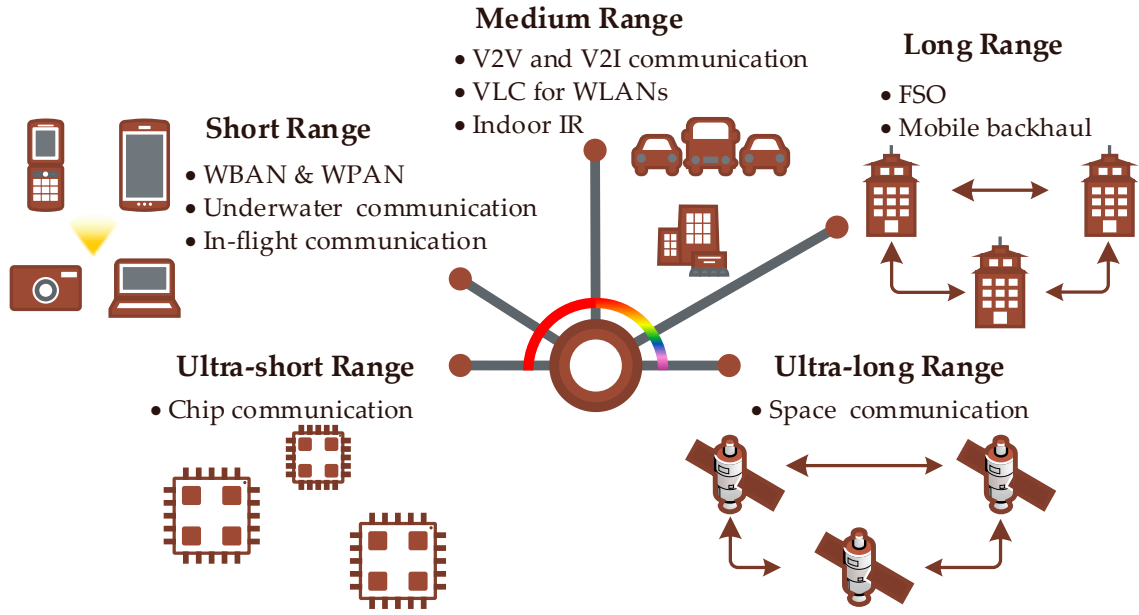


FIGURE 1.1: Classes of OWC based on propagation distance.

1.3 Introduction to visible light communication

The exploration of other frequency bands of the EM spectrum led to the discovery of a potential and favourable wireless communication technology using the visible light band. VLC is a sub-class of the optical wireless communication (OWC) technology. Over the past two decades, OWC has acquired a highly substantial interest. OWC is perceived as both an alternative and an auspicious interdependent for the RF technology, which has a regulated and licensed EM spectrum band spanning from 30 kHz to 300 GHz. OWC spectral band is between 300 GHz and 30 000 THz (wavelength between 1 mm and 10 nm) of the EM spectrum, covering the infrared (IR), visible light and ultraviolet (UV) light bands. Based on the scope of communication [29–31], the categories of OWC are shown in Figure 1.1.

The ultra-short range category of OWC (typically about 10 mm to 100 mm), is used for optical communication between and within chips of ICs. For the short range category (typically within 1 m distance), OWC is used to create communication links between the ever present electronic equipment for daily use. The said equipment form the wireless personal area networks. Additionally, the short range category may be deployed for the establishment of wireless body area networks. The medium range category (typically up to 10 m) is concerned with IR and VLC communications. Free-space optical (FSO) communication is an example of the long range category (about 10 km). FSO systems are a prospective solution to reduce the mobile backhaul bottleneck [29]. Lastly, the ultra-long range category (typically

4500 km to 10 000 km) is concerned with laser communication in space for inter-satellite links.

The initial standardisation for VLC was proposed in 2007 by the Visible Light Communication Consortium (VLCC) following its formation in 2003 by major companies in Japan [32]. The consortium presented two standards being; visible light communication system standard and visible light ID system standard. The Japan Electronics and Information Technology Industries Association (JEITA) later accepted these standards as JEITA CP-1221 and JEITA CP-1222 respectively [33]. The physical layer for IR communication by the International Infrared Data Association (IrDA) was adapted and incorporated by the VLCC in 2009. The hOME Gigabit Access (OMEGA) project [34] financially supported by the European Union (EU) also developed an optical communication network. The OMEGA project was planned to provide a data rate of 1 Gbps using indoor lighting fixtures.

In 2011, IEEE ratified the IEEE 802.15.7-2011 standard [35] as part of the WPAN standards. IEEE 802.15.7-2011 is now superseded by the IEEE 802.15.7-2018 [36] to cover a wider range of OWC from 10 000 nm to 190 nm (IR to UV). This standard comprise of the design specifications for both the physical and link layers. A successor of VLCC, referred to as Visible Light Communication Associations (VLCA) was formed in 2014 to advance the standardisation of VLC. The International Telecommunication Union (ITU) has also developed and approved their G.9991 VLC standard in 2019 [37]. The standard particularly defines three aspects for a high-speed indoor OWC transceiver based on the use of visible light. The said aspects are, system architecture, physical layer and data link layer.

VLC is anticipated to reduce a huge amount of traffic on the wireless RF band, which is heavily congested. VLC technology has an edge over the RF technology due to various factors as summarised in Table 1.1 [26]. Firstly, VLC is based on the industrial, scientific and medical (ISM) spectrum band, which is regulatory-free from international and local authorities. By this virtue, VLC offers license-free services with an enormous bandwidth and very high data rates. The bandwidth of VLC is approximately ten thousand folds more of the entire RF bandwidth.

Secondly, the luminaires used for VLC systems comes at low cost and energy efficient as they use less power despite their high light intensity. This makes VLC systems more economical as they are used for both illumination and data transmission. Thirdly, VLC systems are safer compared to RF systems in the sense that, there are minimal medical health complication caused by visible light on humans.

In VLC systems, there is no requirement for sophisticated antennas to transmit data from the light source. One more factor which makes VLC systems attractive is that, they have intrinsic security. The control of transmitted data in the physical

Table 1.1: Summarised properties of RF and VLC.

Property	VLC	RF
Bandwidth	approx. 400 THz	approx. 300 GHz
Licensed	No	Yes
Power consumption	Low	Medium
Coverage	Limited	Wide
Mode of connection	Illumination	Access point
Safety	Unregulated	Intensity regulated
EM interference	No	Yes
Complexity	Low	High
Security	High	Limited
Noise	High	Little
Multipath	High	Low

layer is simple as communication is commonly in line-of-sight (LoS). This, at least to some extent, avoids invasion of the communication system by unauthorised persons. Moreover, in contrast to RF, visible light is not capable of penetrating solid surfaces such as walls. The incapability of wall penetration also enables the creation of small cells (attocells) to transmit without interference between cell locations.

A number of different research outputs on VLC technology have been presented either for integration with existing technologies or for operating purely on OWC technological competence. A thorough survey for indoor VLC has been provided in [38] with a focus on its novel applications of VLC and diverse practical aspects of the system design. These aspects include channel modeling and propagation characteristics, modulation techniques as well as their capability to provide dimming with minimal flicker to avoid degradation of spectral efficiency. In [39], the authors provided an overview of VLC technology entailing the physical attributes, system architecture, predominant applications and recent research challenges. Besides, current research platforms as well as the predicted advancements of the field are detailed. A survey of OWC providing an overview of VLC, light fidelity (Li-Fi), optical camera communication and FSO among others is provided in [40].

1.3.1 Applications of VLC

Many sectors ranging from household level to factory level such as personal area networks, tracking, localisation and vehicular communication can benefit from VLC. It is however worth mentioning that with VLC, the intention is not to supersede the existing technologies, it is rather explored as an augmentation of existing technologies [27, 38, 41–43]. This offers an alternate wireless data link in areas where there is no desire, no possibility, or less sufficiency for wireless radio transmission.

Radio wave transmission is known to interfere with some RF-sensitive health care equipment such as magnetic resonance imaging (MRI) scans and electrocardiograph (ECG) machines. In such cases, VLC can be utilised to offer data and monitoring services in areas where radio waves are not desirable. On the other hand, there is desire for the provision of flight safe and high speed data transmission in the aviation sector during flight. Some service providers offer aircraft-to-earth data link whereas some provide wireless fidelity (WiFi) solutions which are compatible with flight equipment. These provisions are well founded and safe, however, they are not economical to implement and the baud rate per individual user is exceedingly low [44]. The provision of VLC would be an ideal alternative for the aviation industry to provide wireless data services at low costs [45]. The use of VLC will also reduce the effects of RF interference on the cockpit communication systems.

In addition to quality and reliable transportation services, human beings desire more adhoc features for inland vehicles. Such features include, in-vehicle internet access, forward collision warning, emergency brake lights, blind-spot warning & lane change warning, among others [26, 46]. It is envisioned that by 2025, 90% of vehicles being sold will have the capability of communicating with each other and the infrastructure [47]. There is a requirement for a large bandwidth and low latency for reliable reach-ability, therefore, high speed VLC technology can be easily adapted because of the improved vehicular lights and traffic light infrastructure.

Furthermore, it is well known that under certain conditions and circumstances, RF transmission may possibly cause explosions in hazardous areas such as mines, production plants for petrochemical and explosive devices [48]. Thus, it is very imperative that the installation of wireless RF networks be planned and executed with expertise to reduce the potential risk. However, it is rare for instances of ignition to occur [48, 49]. RF techniques like leaky wave antennas have been found to be very useful in spatial constrained environments (underground mines) [50]. Nonetheless, equipment for such technologies require separate deployment. Thus, VLC may be the most suited form of wireless communication in hazardous areas.

VLC technology has already been commercialised by various entities. Acuity Brands offers indoor localisation based on VLC technology to some retail stores [51]. Philips Lighting also has a similar system to that of Acuity brands featuring LEDs and smartphones. A system for retail stores developed by Fujitsu which mimics the quick response (QR) code technology features VLC technology to embed product data for customers to scan the invisible data using their smartphones [52].

1.3.2 Challenges of VLC

The most predominant drawback in VLC is that, an increase in the link distance sharply decreases the maximum achievable data rate since VLC is a non-coherent communication technique. One other key challenge in VLC is the limited modulation bandwidth of the white phosphor LEDs. Majority of the existing luminaires constitute of white phosphor LEDs with about 2 MHz of bandwidth [53].

Most of the newly rolled out devices are equipped with economical optical components, which may be used for uplink and downlink [54–57]. Be that as it may, these components are not suitable for being used for VLC systems. Frequent flashing of such components waste a lot of energy and it causes flickering which is perceptible to the human eye. The use of complementary technologies viz. RF or IR has been investigated to be used for the development of an uplink in VLC to promote efficiency. Anyhow, the use of RF for an uplink leads to a very complex system design and network management. The complexity is driven by the use of heterogeneous networks (HetNets) which imposes a lot of challenges including link layer design and reliable handover from one technology to the other.

An important question is, “what happens when the lights are switched off, since this technology is intended to perform a dual purpose?”. The literature suggest that in HetNets, this can be addressed easily by switching to either RF or IR technologies in the event that the user only requires data services. Although that is the case, the problem persist in scenarios where the system uses VLC technology only. This poses a very difficult challenge since the transmission of data is dependent on the luminous intensity of the light sources [58].

1.4 Problem statement

The provision of illumination and data transfer comes with widespread difficulties emanating mainly from the functional aspects of both lighting and communication systems. In VLC, the modulating signals are carried by the luminous intensity of the light source, for instance, an LED. To directly modulate the intensity of such a source, the data carrying signal is required to be real and positive valued [28,31,59].

Flickering and dimming continue to be cumbersome to tackle for VLC modulation schemes used in VLC and this affects the quality of service (QoS). The fluctuations of the luminous intensity during modulation, termed flicker, poses a hazard to the human eye [9,60]. Modulation related issues may continue to be persistent, however, it is of great importance to find ways of enhancing the overall performance of a system [61]. In this treatise, the design, development and optimisation of a hybrid

modulation scheme is considered. To define the main research problem addressed in this thesis, firstly the generic optimisation problem is stated and denoted as [62]

$$\begin{aligned} & \underset{\mathbf{g}}{\text{maximise}} && f(\mathbf{g}), \\ & \text{subject to} && \mathbf{g} \in \mathbf{G} \subseteq \mathbb{R}^n, \end{aligned} \tag{1.1}$$

where $f : \mathbb{R}^n \mapsto \mathbb{R}$ is the objective (cost) function, $\mathbf{g}$ is the optimisation variable and $\mathbf{G}$ is a set of feasible solutions.

1.4.1 Problem Description - Part one

Firstly, the optimisation variables are considered to be the luminous intensities of the luminaries of LED arrays while satisfying the user signal-to-interference-plus-noise ratios (SINR) and taking into consideration the illuminance. In this case, equation (1.1) is transformed into a non-convex mixed-integer non-linear programming problem. Collaborative use of colour-shift keying (CSK) modulation and optical spatial modulation (OSM) is exploited. OSM uses only one of the available luminaires to transmit at a given symbol time period while CSK modulation reduces the illuminance during symbol transmission. This work aims to develop an algorithm where the objective of the system is to minimise the luminous intensities of the transmitters subject to the user SINR target, illuminance and luminous intensity constraints.

1.4.2 Problem Description - Part two

In the last part of this thesis, the user worst-case SINR targets are taken to be the optimisation variables. In this scenario, equation (1.1) becomes a max-min problem. The network under consideration consists of heterogeneous users being, the latency intolerant users (LITUs) and the latency tolerant users (LTUs). The LITUs require service provision of latency-free data services and their SINR target is unequivocal. On the other hand, the LTUs require latency tolerant services and they do not have a specific SINR target, they rather accept the best disposable SINR from the network. Here, the aim is to develop an algorithm with an objective of maximising the worst-case SINR of the LTUs, subject to the standard illuminance level constraints, and the SINR constraints of the LITUs.

1.5 Research aim and objectives

The aim of this thesis is to design, develop and optimise an algorithm for a LoS multi-user colour-based OSM indoor VLC system using optimisation techniques. The specific objectives for the addressed research problem are listed below;

1. To design, mathematically model and integrate all functional units of an indoor VLC system based on the collaborative use of CSK and OSM techniques.
2. To improve system performance through the exploitation of optimisation techniques to satisfy the minimum required illuminance levels.
3. To enhance the data transmission fairness by maximising the SINR of the LTUs subject to the SINR target of the LITUs, the LED power constraint and the desired illuminance levels.

1.6 Research Publications

The contribution of this thesis is mainly on the design, development and optimisation of a modulation scheme for VLC communication networks. This contribution is supported by various international journal publications.

1. **G. A. Mapunda**, R. Ramogomana, L. Marata, B. Basutli, A. S. Khan, and J. M. Chuma, "Indoor Visible Light Communication: A Tutorial and Survey," *Wireless Communications and Mobile Computing*, vol. 2020, pp. 146, Dec. 2020.
2. A. Sanenga, **G. A. Mapunda**, M. T. L. Jacob, L. Marata, B. Basutli, and J. M. Chuma, "An Overview of Key Technologies in Physical Layer Security," *Entropy*, vol. 22, no. 11, pp. 133, Nov. 2020.
3. **G. A. Mapunda**, A. Sanenga, B. Basutli and J. M. Chuma, "Optimisation of a Colour-based Spatial Modulation Scheme for VLC Under Illuminance and SINR Constraints," submitted to *IEEE Access* (under review).

1.7 Thesis outline

The remaining part of this thesis is structured into four (4) chapters. Chapter 2 provides the architecture of a VLC system. A brief background on the use of light sources and photodetectors (PDs) as constituents of a VLC system is presented in

this chapter. Fundamentals of radiometry and photometry as well as the basics of illumination are addressed in Chapter 2. Introduction to LED driver circuitry is also given in this chapter. Additionally, the framework of a VLC system together with VLC propagation models are over-viewed. A detailed outline and description of the characteristics as well as the design of LoS and non-LOS (NLoS) link topologies.

In Chapter 3, both basic and advanced modulation as well as dimming schemes for VLC systems are discussed. The same chapter also discusses the concept of dimming and how it is affected by data modulation. This chapter gives an overview of MIMO techniques and how they may provide an improved system capacity. The concepts of multiple access schemes for VLC systems are also covered in Chapter 3.

Chapter 4 presents the framework for conceptualisation, design and the numerical analysis of a colour-based OSM VLC scheme. A scenario of the LoS model in an indoor environment where users are mobile in a heterogeneous user network is defined and outlined in this chapter. The optimisation of the system using optimisation techniques is addressed in section 4.2. Chapter 4 also presents the analysis and the discussion of the numerical results.

Finally, in Chapter 5, a summary and conclusion of the thesis are presented. Problems which may be of interest for future research works are also outlined. Furthermore, an investigation on the potential of incorporating VLC technology into a number of emergent and future wireless techniques such as 5G and sixth-generation (6G) is carried out, specifically in sectors where VLC is applicable.

Chapter 2

Architecture of a VLC System

This chapter aims to introduce and discuss elementary segments of VLC transceiver systems as well as the propagation models. Light sources suited for communication systems based on optical technology are adamantly required to possess various and appropriate properties in relation to; modulation bandwidth, radiance, wavelength, reliability and long life. There exists an assortment of light sources, but the most widely used sources for optical communication systems are LEDs and laser diodes (LDs). Both the LEDs and LDs depend on the semiconductor material's ability to be electronically excited to radiate light. For VLC receiver systems, suitable PDs or imaging sensors are put to use.

2.1 Optical transmitters and receivers

Illumination sources evolved from back in the days when illumination was mainly achieved by the utilisation of fire and wax candles. Illumination evolution is shown in Figure 2.1. Through the years, since the moonlight, fire and candle era until today, the illumination sector has substantially advanced and we have seen developments that have led to the inception of solid-state LEDs. During the evolution, fluorescent lamps have been used with efforts to replace the most widely used incandescent lamps, which consumes a lot of energy. As of present, the illumination industry is shifting towards the use of solid-state LED lamps. This is owing to a variety of factors such as; higher power conversion efficiency, higher luminous efficacy [64], durability, safety, size [65, 66], longer mean time to failure (MTTF) and free from dangerous elements like mercury. This is relative to the conventional illumination technologies. In this thesis, a detailed discussion on the theory of light sources, generation of white light using LEDs, operation of a photodiode (PD), selected aspects of radiometry, which are relevant to the discussion of photometry is given. All of the above elements and aspects are studied with regards to their significance as elements of VLC systems.



FIGURE 2.1: Evolution of illumination showing various sources with improved luminous efficacy at each stage [63].

Relative to the incandescent sources, during optical radiation, the LEDs and LDs do not exhibit thermal radiation because of the low temperatures of the semiconductor materials. Furthermore, LEDs and LDs come in smaller sizes with low forward voltage, low drive current, higher brightness which is within the visible wavelengths and light can be emitted at one or variable wavelengths. Different applications and their features including but not limited to; optical power versus current attributes, speed and the beam profile dictates the choice of the appropriate source. The light emitted by the LEDs and LDs can be outspread in a range of various wavelengths depending on how the source was fabricated.

The emission of light, generally, is caused by electrons' transition from an excited state to a lower energy state. The transition of an electron creates an energy difference and this brings about a radiative or a nonradiative process. The latter produces heat, whereas the former leads to the production of light hence optical sources. With regards to conventional light sources, the photon flux is provided by means of the recombination of the carrier. For solid state sources, there are three methods in which the photon interrelate with an electron to produce photons [67].

The first method is whereby the electron in a filled valence band attains the energy transferred by the photon. The electron then transits to the conduction band which is an empty state. The solar cell is fundamentally associated with this kind of photon-electron interaction. One other way is that, from a filled conduction band, an electron can spontaneously go back to the valence band, which is an empty state. During this process, termed spontaneous radiative recombination, as illustrated in Figure 2.2a, a photon will be released. This process is associated with the light produced by LEDs. The third method involves the invigoration of radiative recombination, where the incident photon makes the emission of a second photon with the same phase as the incident photon i.e the photons are coherent. The fundamentals of a laser are based on this type of photon interaction.

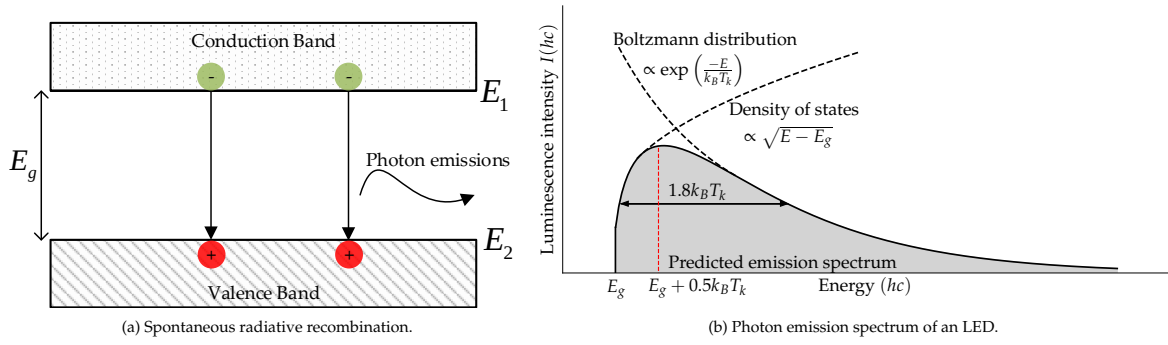


FIGURE 2.2: The process of photon emission and the emission spectrum of an LED.

For radiative recombination, it is conventionally assumed that the emitted photon has the same energy as the band-gap energy of the material. However, the additional thermal energy due to temperatures beyond the absolute zero makes the electrons in the conduction band to reside just above the band edge and the holes in the valence band to reside just below the band edge. This phenomena creates a photon energy level which is a bit higher than the band-gap energy. The generated photon's frequency and wavelength are related to the energy level E , given as

$$E = E_2 - E_1 = hf = \frac{hc}{\lambda}, \quad (2.1)$$

where E_2 and E_1 are the two energetic states, $h = 6.626 \times 10^{-34}$ Js, represents the Planck's constant, $c = 2.998 \times 10^8$ m/s, is the speed of light, f is the radiation frequency and λ is the wavelength of the emitted or absorbed energy.

Depending on the energy of the band-gap of the semiconductor material, the light emission could fall in the UV, visible, or IR part of the EM spectrum. The semiconductor chip is the main component of an LED under the condition that the chip forms a p-n junction. Forward biasing the LED results in the emission of photons due to energy bursts. Human eyes perceive the emitted photons with wavelengths from 780 nm to 380 nm. This phenomena is referred to as electroluminescence [68].

The energy of the released photon is equivalent to the energy that results as the difference of energy levels between the conduction and valence bands, i.e the band-gap energy. The rate at which photons are emitted together with its wavelength are respectively given by equations (2.2) and (2.3).

$$I(E = hf) \propto \sqrt{E - E_g} \exp\left(-\frac{E}{k_B T_k}\right), \quad (2.2)$$

$$\lambda = \frac{hc}{E \text{ (eV)}} \quad \mu\text{m}, \quad (2.3)$$

Table 2.1: Characteristics of LED types [26].

	Intricacy	Efficacy(lm/W)	Bandwidth (MHz)	Cost	Application
RGB LED	Moderate	65	10 to 20	High	Illumination
PC-LED	Low	130	2 to 3	Low	Illumination
OLED	High	45	≤ 1	Lowest	Display
μ -LED	Highest	-	≥ 300	High	Bio-sensors

where E_g is the band-gap energy, k_B is the Boltzmann constant and T_k is the absolute temperature in kelvins (K). As depicted in Figure 2.2b, for the photons to be emitted, the energy should be at least equal to the band-gap energy with a half-power width of $1.8k_B T_k$. The half-power spectral width is given by [67]

$$\Delta\lambda = \frac{1.8k_B T_k}{hc}. \quad (2.4)$$

The transition and the resulting photon emission occurs randomly without a mutual phase relationship between the radiated photons. This consequently generates what is commonly known as an incoherent light source [31, 67]. Typical LEDs operating at wavelengths of 850 nm and 1300 nm have $\Delta\lambda$ of approximately 60 nm and 170 nm respectively [67]. Higher temperatures causes a decline in the band-gap energy. Since the photon energy emission is directly proportional to the band-gap energy, it means that an increase in temperature decreases the peak photon energy. There are different types of LEDs, each type has distinct characteristics which makes it suited for a specific application. Properties and applications of different LEDs are shown in Table 2.1 [26]. For realisation of VLC transmitters, multi-chip (mostly RGB) LEDs and phosphor converted LED (PC-LEDs) are the most preferable candidates for the provision of both illumination and data transmission in VLC systems since they are capable of producing white light.

2.1.1 Generation of White Light for Illumination

With the aid of LEDs, there are two main approaches which are widely used for generation of white light. The first approach involves the use of PC-LEDs, this approach produces light which is known as phosphor-converted white light. PC-LEDs are made up of a blue Indium Gallium Nitride (InGaN) chip. Illuminating this chip with blue light produces Yttrium Aluminum Garnet (YAG) phosphor coating. Part of the blue light is converted into yellow segment of the spectrum by the phosphor layer coating. Appropriately mixing the remaining blue light and yellow light produces white light. Colour temperatures of the resulting light, being neutral white,

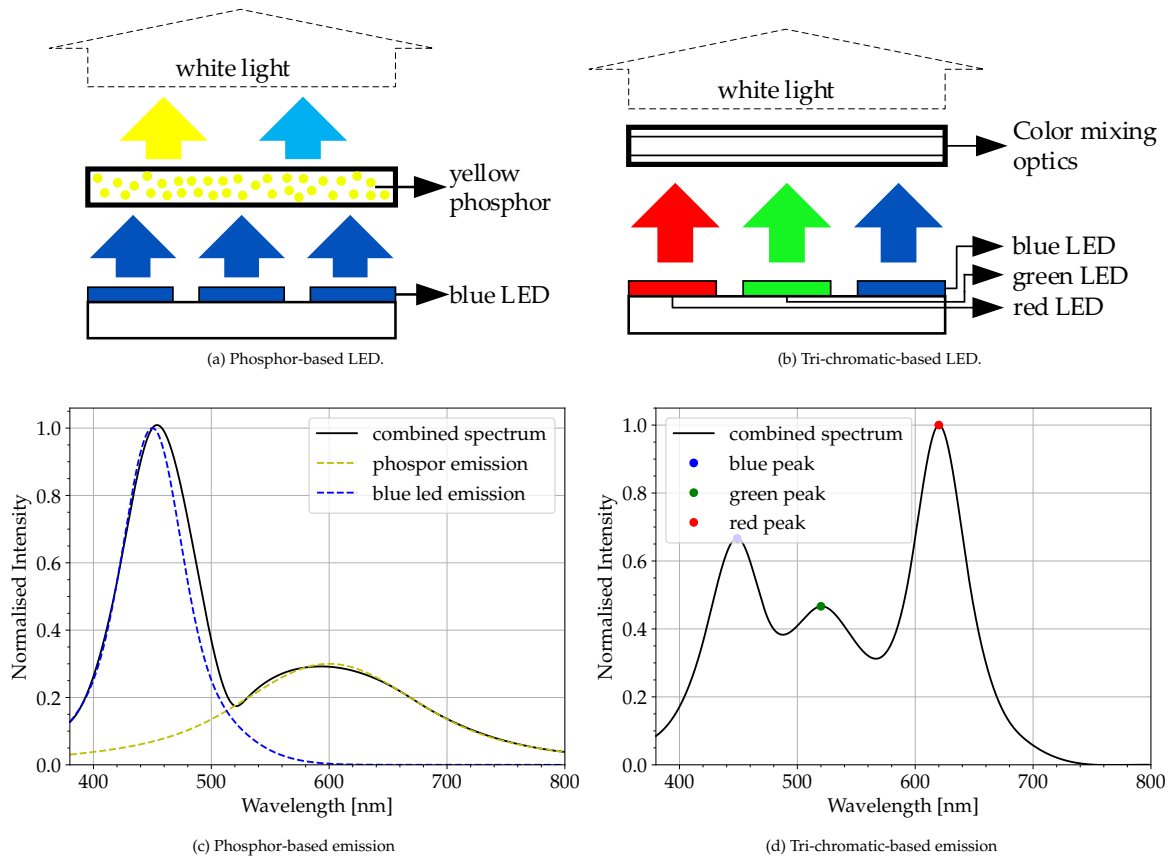


FIGURE 2.3: Generation of white light using LEDs and white light emission spectra.

cool white and warm white depends on the thickness of the phosphor layer [69]. The process of producing white light using blue light and a phosphor material as well as the spectrum of the produced light are shown in Figures 2.3a and 2.3c respectively. On the other hand, RGB LEDs conventionally consists of three or more LED chips which typically emits the red, green and blue light. The second approach produces white light when the light of the RGB chips are selected and combined using colour mixing optics. This process as well as the spectrum of the produced white light are shown in Figures 2.3b and 2.3d respectively. Suitable wavelengths for white light production are, 625 nm for red, 525 nm for green and 470 nm for blue. Colour rendering is relatively easy to accomplish when using this approach because the colour of each chip can be adjusted separately.

By reason of a simplified implementation and cost effectiveness of PC-LEDs, in contrast to RGB LEDs, PC-LEDs are the most preferred type for producing white light. Nonetheless, they have a low response time due to the phosphor coating leading to a provision for the narrowly limited bandwidth as seen in Table 2.1 [70]. This poses a limitation for communication as this will negatively affect the modulation speed. However, the use of blue filters at the receiver to suppress the slow phosphorescent components may increase the bandwidth to about 20 MHz. On the other

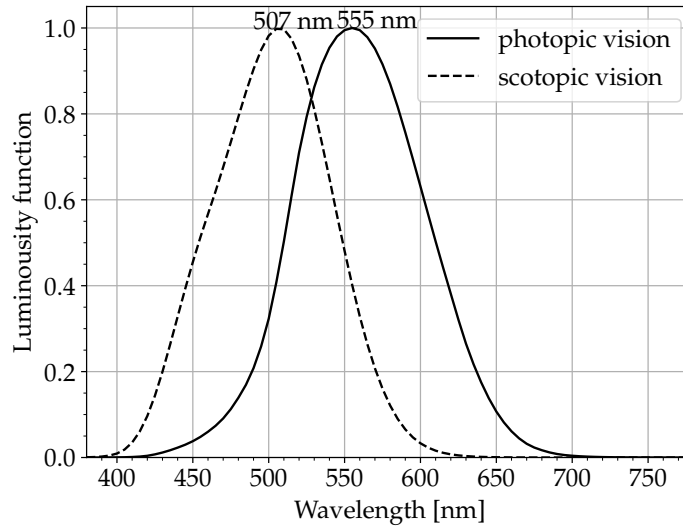


FIGURE 2.4: CIE luminosity functions for scotopic and photopic vision.

hand, RGB LEDs may be more suitable for communication because of their ability to provide data modulation through three different colour wavelengths. The property of having more than one wavelength instigates throughput which is three times higher than that of a single chip LED. Lighting units normally have a driver circuit which is used to alter the light intensity by controlling current that flows through the LEDs. For these sources to be used in VLC systems, an amendment to the driver circuitry is required to allow data modulation using the emitted light [38].

2.1.2 Perception of Colour and Light

The cone and rod receptor cells in the retina of the human eye are responsible for the perception of colour and light intensity. The cones aid with both the comprehension of colour and identification of fine details, while the rods are very responsive to light. When there is little light intensity, the rods provide monochrome vision. There are three mechanisms of vision in which the human eye has the ability to adapt its vision relative to the light levels. One of these mechanisms is the photopic vision, it comes about when the light levels are high, for example, during the day. Scotopic vision is one other mechanism, this type occurs when the light levels are low. In the scotopic vision colour comprehension is lost because the rod receptor cells are highly sensitive to light and are the ones controlling this vision while the cones are less sensitive and they control the photopic vision. The third mechanism is referred to as the mesopic vision and it comes about in between the first two mechanisms. In this vision the human eye can still perceive colour with less distinction when compared to the photopic vision. The luminosity functions for the photopic and the scotopic vision are shown in Figure 2.4.

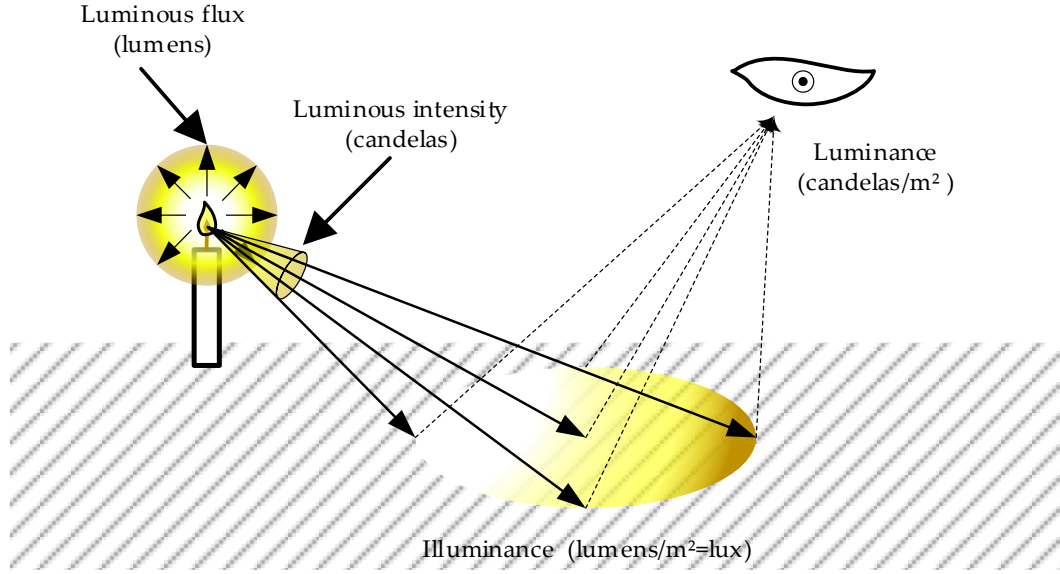


FIGURE 2.5: Graphical representation of photometric parameters.

2.1.3 Radiometry and Photometry

Radiometry is concerned with the measurement of optical radiation for a wider optical spectrum from UV to IF. On the contrary, photometry involves the examination of optical radiation which is only visible to the human eye as opposed to radiometry which does not consider the human eye's sensitivity. The parameters of photometry only look into and evaluate the alterations for various wavelengths of the visible light band [71]. Stereotypical parameters of radiometry include radiant power flux, irradiance, radiant intensity and radiance. VLC is a wireless communication technology that relies on the conversion of light energy into electricity, therefore it is a necessity to convert between radiometric and photometric parameters. This conversion takes into consideration the relative visibility of light for a specific wavelength. The relative visibility of light is given by the eye sensitivity curve which is also known as the luminous efficiency curve (see Figure 2.4) [31]. This curve represents the ratio of all photometric parameters to their equivalent radiometric parameters. The correlation between photometric and radiometric parameters is given by

$$[1 \text{ lux}] = [1 \text{ W}] \times 683 \left(\frac{\text{lm}}{\text{W}} \right) \times V(\lambda), \quad (2.5)$$

where $V(\lambda)$ is the relative spectral sensitivity function at wavelength λ . The photopic luminosity function is practically used even if scotopic or mesopic visions are suggested by the light levels [72]. Typical aspects of photometry to be understood with regard to VLC systems are luminous flux, luminous intensity, illuminance and luminance. Figure 2.5 graphically depicts these parameters.

The total quantitative amount of power emitted per second by an optical source and within the visual sensation of the human eye is referred to as luminous flux. SI unit for luminous flux is lumen (lm) or candela steradian ($\text{cd} \cdot \text{sr}$). In general terms, luminous flux may mathematically be given as

$$\Phi_v = I_v \cdot \Omega, \quad (2.6)$$

where I_v is the light intensity in candela and Ω is the angular span (in steradian) over which the light is emitted. With respect to isotropic sources, equation (2.6) may be re-written as

$$\Phi_v = 4\pi I_v. \quad (2.7)$$

The sensitivity of human eyes due to various visible light wavelengths changes notably when adjusting the luminous flux. The photopic spectral sensitivity function as shown in Figure 2.4 depicts that the human eye is capable of comprehending colours due to variations of wavelengths between 780 nm to 380 nm. The human eye have a maximum sensitivity of 683 lm/W at 555 nm wavelength which is the yellow-green region of the visible light spectrum. For sources that emit light through various wavelengths over the visible light spectrum, the luminous flux can be denoted in terms of the radiant flux Φ_e by

$$\Phi_v = k_m \int_{380 \text{ nm}}^{780 \text{ nm}} \Phi_e(\lambda) \cdot V(\lambda) d\lambda, \quad (2.8)$$

where $k_m \approx 683 \text{ lm/W}$ at a wavelength of 555 nm. The total optical power can be determined by integrating the radiant flux in all directions. The denotation is therefore given as

$$P_t = k_m \int_{\Lambda_{\min}}^{\Lambda_{\max}} \int_0^{2\pi} \Phi_e d\theta d\lambda, \quad (2.9)$$

where $\Lambda_{\max}$ and $\Lambda_{\min}$ are the maximum and the minimum operation wavelengths of the PD obtained from the sensitivity curve of the PD.

The intensity of the power radiated per unit time from an optical source is known as luminous intensity. In simpler terms it is the luminous flux per solid angle in a given direction. The units are lm/sr or as commonly known candela (cd). The intensity may be given as [73,74]

$$I_v = \frac{d\Phi_v}{d\Omega} = \frac{d \left(k_m \int \Phi_e(\lambda) \cdot V(\lambda) d\lambda \right)}{d\Omega}. \quad (2.10)$$

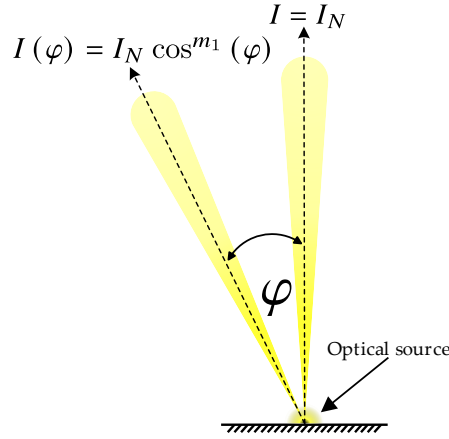


FIGURE 2.6: Lambert radiator.

The amount of irradiance on a given surface, i.e the luminous flux per unit area is referred to as illuminance. Illuminance is measured in lm/m^2 or lux [73,74], hence given by

$$E_s = \frac{d\Phi_v}{dS} = \frac{d \left(k_m \int \Phi_e(\lambda) \cdot V(\lambda) d\lambda \right)}{dS}, \quad (2.11)$$

where dS is the illuminated area. In an instance where the illuminated area is large, the illuminance is simply the ratio of the luminous flux to the total area S . The amount of radiance on a given surface area and a given solid angle in a given direction, i.e the luminous flux per unit area per unit solid angle is referred to as luminance. Luminance is measured in $\text{lm}/\text{m}^2\text{sr}$ or cd/m^2 and it is expressed by equation (2.12) [73,74]. Of all the three parameters dependent on the flux intensity, luminance is the most significant parameter. This is on account of the fact that the light energy is radiated from an extended source instead of a point source. Moreover it is the only parameter which is conserved during the propagation of light [74].

$$E_v = \frac{d\Phi_v}{dS d\Omega} = \frac{d \left(k_m \int \Phi_e(\lambda) \cdot V(\lambda) d\lambda \right)}{\cos(\theta_s) dS d\Omega}. \quad (2.12)$$

The estimation of power transfer for a radiant source having a uniform radiance across its surface and uniformly emitting in an isotropic manner is very useful in optics. Such a source is said to be a Lambertian source [74,75]. Ideally, a Lambertian source conforms to Lambert's cosine law, which states that, the luminous intensity viewed from an ideal diffuse radiator varies directly with the cosine of the angle between the surface normal and the incident light ray [31,76]. This is graphically depicted in Figure 2.6 and mathematically represented by equation (2.13). Lambert's law is of significance in the measurement of light. To obtain worthwhile radiance

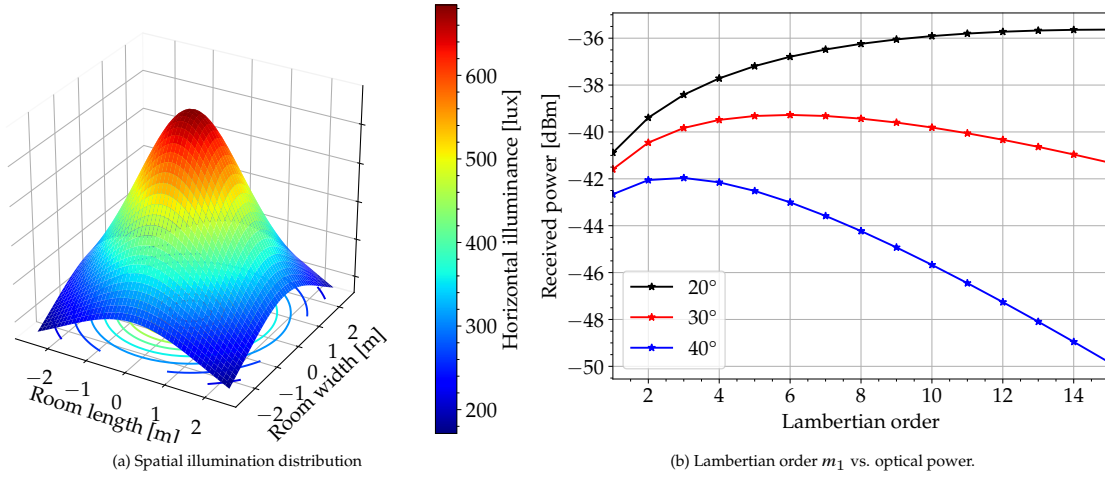


FIGURE 2.7: Illuminance distribution and variation of the received optical power against Lambertian order.

measurements of an object that has a large or uncertain angular distribution, cosine receptors on detectors are a requirement. As a consequence, a commonly used model for radiance estimation is the Lambert radiator [77]. Take luminous intensity with an arbitrary direction of a Lambertian radiator to be denoted as

$$I(\varphi) = I_N \cos^{m_1}(\varphi) = I_N k_d (\vec{N} \cdot \vec{L}), \quad (2.13)$$

where φ is the angle between the surface normal and the incident light ray, I_N is the maximum intensity of the light source in the normal direction, m_1 is the order of Lambertian emission, k_d is the diffuse reflection coefficient $\vec{N}$ is the unit normal vector and $\vec{L}$ is the unit light vector.

The luminance of such a radiator is independent from the orientation angle φ despite different levels of the luminous intensity at different viewpoints. This means that, the luminance from any point of view is equal. VLC light sources can be estimated using the Lambert radiator. The CIE states that different levels of illuminance are required depending on the type of environment. Typically, any level from 30 lux to 100 lux is adequate for visualisation tasks in public places. As for residential and corporate places, a wider range with higher levels, ideally from 300 lux to 1000 lux is indispensable. Figure 2.7a depicts the illuminance distribution of an LED array with a 60° semi-angle. From Figure 2.7b, it is observed that narrow semi-angle at half-power yields higher received power for a fixed Lambertian order.

One other element which is of significance to the realisation of VLC systems is photodetection. Light detection is normally achieved through the use of a PD, which are also known as non-imaging receivers. A PD is a square-law optoelectronic transducer sensor that detects and responds to the EM radiation (EMR), specifically light,

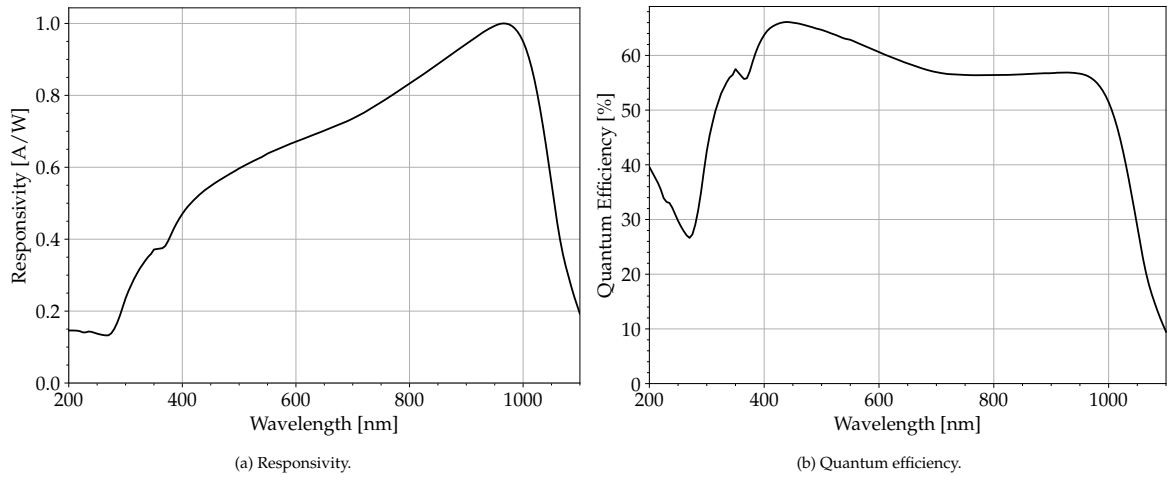


FIGURE 2.8: Typical responsivity and quantum efficiency of a PIN PD.

which is incident to its surface. They respond to the impinging EMR signals by converting the light photons into current which is proportional to the square of the received radiation. Alternatively, photodetection can be done by the utilisation of imaging sensors also referred to as camera sensors. An imaging sensor is a matrix of multiple PDs. Such sensors are found in many of the existing mobile devices including smartphones. This makes it possible for the mobile devices with imaging sensors to be easily adapted as VLC receivers. These sensors need to be converted because of a very high number of PDs, which facilitates high-resolution imaging. Having numerous PDs notably decreases the rate at which frames are being captured by the sensor. This consequently gives rise to limited data rates in the range of a few kbps due to low sampling rates of the sensor. On the other hand, non-imaging sensors offer higher data rates in the range of hundreds Mbps.

In a VLC channel, a PD must have precise and uncompromising performance requirements because the received optical signal is conventionally weak. The said performance requirements include, a sufficient bandwidth to satisfy the desired data transfer rate, a very low noise level, a very high sensitivity in the range of wavelengths which the PD operates. Sensitivity of a PD may be defined in terms of its responsivity or quantum efficiency. The quantum efficiency is given by [78]

$$\eta_{qe} = \frac{\text{electrons out}}{\text{photons out}} = (1 - R) \xi (1 - e^{-\alpha d}), \quad (2.14)$$

where R is the reflection coefficient at the interface of air and the semiconductor, ξ is the fraction of the electron hole pairs, α is the absorption coefficient and d is the distance between the transmitter and the receiver. Figure 2.8 depicts typical plots of both responsivity and quantum efficiency of a PIN PD.

Table 2.2: Typical performance Characteristics for various PDs [31].

Parameter	Silicon		Germanium		InGaAs	
	PIN	APD	PIN	APD	PIN	APD
Wavelength range (nm)	400-1100		800-1800		900-1700	
Peak (nm)	900	830	1550	1300	1550	1550
Responsivity $\mathcal{R}$ (A/W)	0.6	77-130	0.65-0.7	3-28	0.75-0.97	
Quantum efficiency (%)	65-90	77	50-55	55-75	60-70	60-70
Gain	1	150-250	1	5-40	1	3-10
Excess noise factor	-	0.3-0.5	-	0.95-1	-	0.7
Bias voltage (-V)	45-100	220	6-10	20-35	5	<30
Dark current (nA)	1-10	0.1-1.0	50-500	10-500	1-20	1-5
Capacitance (pF)	1.2-3	1.3-2	2-5	2-5	0.5-2	0.5
Rise time (ns)	0.5-1	0.1-2	0.1-0.5	0.5-0.8	0.06-0.5	0.1-0.5

The most critical compatibility and performance requirements for detectors have a number of properties in which they are defined. Firstly, a large surface area to allow for a wider detection field of view (FOV) and a large collection aperture are required. In applications which require high-speed, it is more appropriate and best to have PD arrays that bears a small surface area. Secondly, the PD's sensitivity and responsivity at the desired wavelength must be high. One other property is that the PD must have a low noise which in turn yields a high signal-to-noise ratio (SNR). Lastly, the PD must have a fast response time as well as high reliability, small size and low cost. Performance characteristics for PDs made of various semiconductor materials are given in Table 2.2 as adapted from [31].

The most common types of PDs used for optical receivers are the avalanche PD (APD) and positive-intrinsic-negative (PIN) PD, photoconductors and metal-semiconductor-metal PD. Due to their properties, PIN and APD PDs meet all of the aforesaid requirements, hence them being popularly used for VLC systems. A PIN PD is made up of two semiconductor materials with p-type and n-type regions, which are detached by an intrinsic and sparingly n-doped region. An adequately large reverse bias voltage has to be applied across the device to facilitate operation. For the conversion of an impinging photon into an electric current, the energy of the incident photon has to be equal to or greater than the band-gap energy. An electron from the valance band is excited by the energy of the incident photon to the conduction band, during this excitation process, an electron-hole pair is generated.

Concentration of impinging light is under conventional conditions directed to the depleted intrinsic region. After the separation of the generated charge carriers because of the high electric field in the depleted region, the charges accumulate across the reverse biased junction. In-turn, there is a current flow along the load resistor.

The upper cut-off wavelength, which is determined by the type of semiconductor material used may generally be computed by equation (2.3). PIN PDs have the capability of functioning at extremely high bit rates over 100 Gbps [79–85]. Nevertheless, in view of the constraints posed by the packaging, the PD based devices currently available in the market only have a bandwidth not exceeding 20 GHz. The APD differs with the PIN PD in the sense that the APD inherently supplies current gain using repeated electron ionisation process. This results in an elevated sensitivity of the device because of photocurrent multiplication prior to its encounter with the thermal noise of the receiver circuitry. The gain factor of the APD is therefore

$$G = \frac{I_T}{I_{ph}} = \frac{I_T hc}{\lambda \eta_{qe} q_e P_r} = \frac{I_T}{\mathcal{R} P_r}, \quad (2.15)$$

where I_T is the total output photocurrent (average) in the APD, I_{ph} is the primary instantaneous photocurrent of the PD, q_e is the electronic charge, P_r is the impinging average power of the optical radiation per time period and $\mathcal{R}$ is the responsivity of the optical detector in A/W and it is denoted by

$$\mathcal{R} = \frac{\lambda q_e \eta_{qe}}{hc} = \frac{\lambda \eta_{qe}}{1.24}. \quad (2.16)$$

Note that the value of I_{ph} is equal to that of I_T in an instance where G is unity and λ is measured in μm . The APD's responsivity value can be higher than unity as the standard gain values are between 50 and 300. This means that the sensitivity of the APD is greater than that of the PIN PD since the PIN PD has a gain value of unity. However, it is worth mentioning that there is an omnipresent multiplication noise when it comes to the APD following the ionisation process which is of a statistical nature [86]. In addition, the ionisation process is highly sensitive to temperature. When an APD is used in a VLC system, it is advisable to take into account these factors as they are very significant to the performance of the system.

2.2 Driver circuitry of an LED

There exist various ways in which the constituents of the LED driver are arranged and these are classified according to the LED's regulatory requirement, application, performance, power rating and energy storage. Generally, LED drivers are categorised into two main categories, viz. passive and active [26, 38, 87]. LEDs are distinctly quick to respond to photometric, thermal and electrical variations. Therefore, to fully acquire the precise potential and exhaustive benefits of an LED for optimal design and operation of LED-based systems, an in-depth understanding of complex

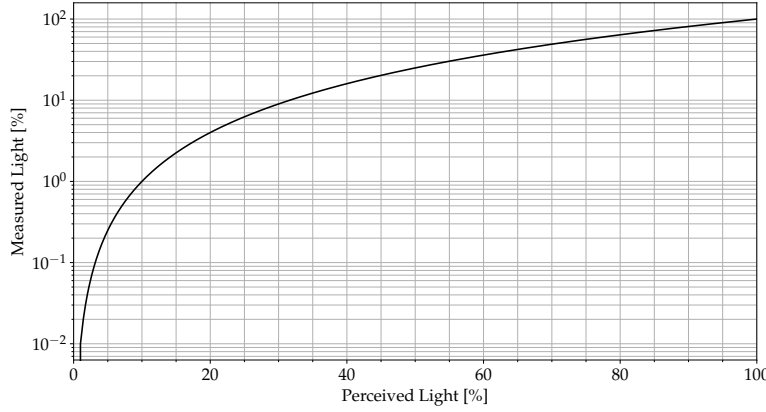


FIGURE 2.9: Human eye light perception versus measured light.

interactions of these three aspects is crucial. The mathematical description of the interactions of the aforementioned aspects has been described in the photo-electro-thermal (PET) theory framework [88,89]. PET theory can be used for optimisation of LED-based systems to meet practical constraints of technical specifications including but not limited to; international regulations, form factors, reliability and costs.

2.2.1 Controlling and Dimming Using LED Drivers

As opposed to ordinary LED drivers, VLC driver circuitry must cater for data modulation and other associated features without negatively impacting the lighting controls like dimming and flicker mitigation. Dimming of an LED to a particular level has an impact on the light perception of the human eye. Humans are able to adapt to low levels of illumination, thanks to the contraction of the pupil which enable supplemental light to get into the eye. The relationship between perceived and measured light is given by [90]

$$P_L = 100 \times \sqrt{\frac{M_L}{100}}, \quad (2.17)$$

where P_L is the perceived light in percentage form and M_L is the measured light. As depicted in Figure 2.9, various sources have shown that there is a non-linear correlation of the perceived light and the measured light. This correlation implies that the human eye perceives the light to be dimmed to approximately 32% for an illumination source that has been dimmed to 10% of the actual measured light output. This property is very crucial for VLC systems because dimming level should not disturb communication even when the user selects any dimming level [91].

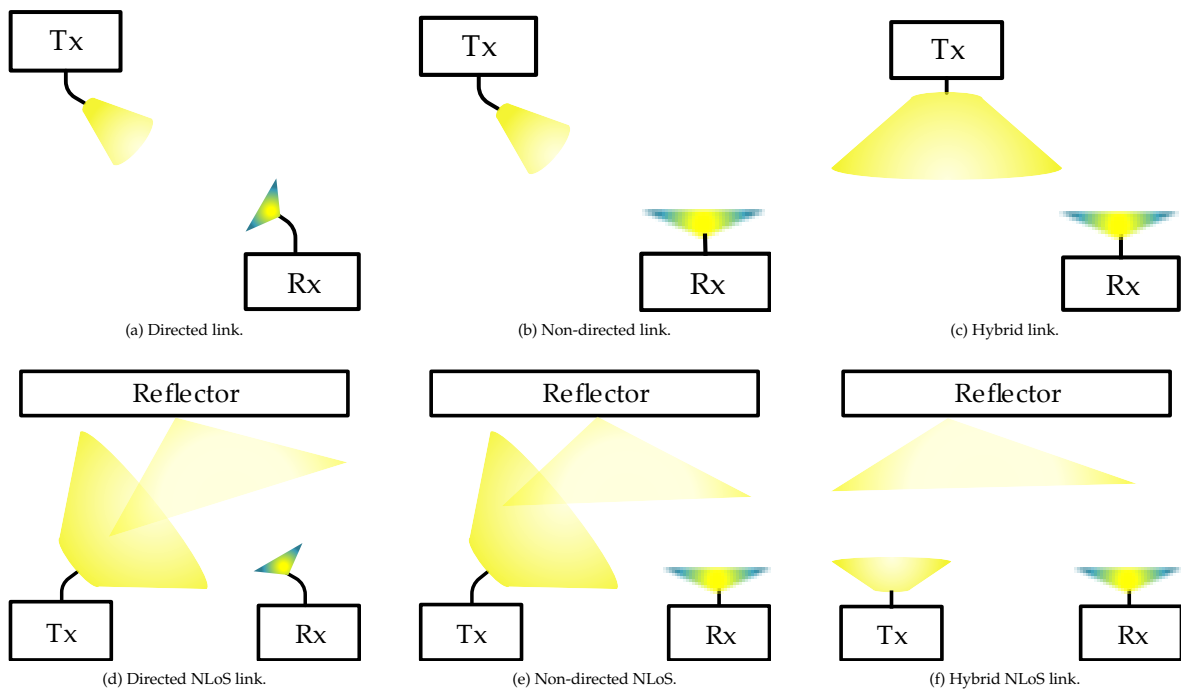


FIGURE 2.10: Classes of link configurations based on transmitter-receiver pair.

2.3 Framework of a VLC System

The structure of VLC channel may be categorised into two, depending on the way in which the link configuration between the transmitter and the receiver is set up [27,31,75,77,92]. Figure 2.10 depicts the classes of link configurations. For the degree of directionality channels category, the link may be established by means of having a directed or non-directed transmitter-receiver pair. Extending this category, there are three different feasible classes regarding directionality and they are; directed, non-directed and hybrid links. In the class of directed links, the transmitter and the receiver are directed and aimed towards each other. Moreover, the transmitter's beam angle and the receiver's FOV angle are very narrow. With this class, power efficiency and immunity to distortion due to environmental culminations such as ambient light are substantially enhanced. This is suitable for low data transfer point-to-point communication applications with no obstacles between transmitter receiver pair. However, such a link is not capable of providing mobility in a typical indoor environment since they are easily affected by blocking/shadowing and it does not cater for broadcast applications [75,77,92].

In the non-directed links class the transmitter and the receiver are not specifically directed to a specific point. Transmitters with wide beams and receivers with a wide FOV are a fundamental requirement for the transmission of signals for this class. The requirement of high power levels to strive for the reduction of elevated optical

path loss and multipath-induced malformation are the major pitfalls for this second class owing to a wider beam divergence [31,92]. On the other hand, it allows user mobility and it also decreases the effects of shadowing as it is suited for broadcast applications. A case whereby the transmitter and the receiver may assume divergent levels of directionality leads us to another class commonly known as a hybrid class. As an example for this class, consider a scenario whereby the transmitter with a narrow beam is directed towards a certain point and the receiver with a wide FOV are not arranged to align towards a specific direction or vice versa. Systems based on this class suffer from multipath propagation [31,92].

The availability of a line-of-sight pathway between the transmitter and the receiver yields the second category being the line-of-sight channels category. This category may also be extended into three classes and they are; directed NLoS, non-directed non-LoS and hybrid non-LoS links. The directed NLoS class features a scenario whereby the transmitter-receiver pair have do not have any obstruction between them. This configuration simplifies the path loss calculation owing to the the fact that there is no consideration of the reflections.

The NLoS systems with a non-directed transmitter and receiver are also referred to as diffuse systems. For this class, the transmitter-receiver pair do not have to be directed, neither do they need to have a clear path to establish a communication link. Signals arrive at the receiver indirectly from the transmitter due to the nearly uniform distribution of the optical signal by the reflecting panels such as walls and ceilings. Diffuse systems are considered to be the most robust, easy to design and implement, predominantly for the mobile communication systems [27,31,75]. This class paves way for effortless use as they allow the transmitter and the receiver to operate even when there are obstacles in between them. In the hybrid NLoS configuration, the transmitted signals are reflected from various objects and are received at different time intervals. The hybrid NLoS architecture is prone to multipath distortions. The distortions make it very difficulty to estimate the path loss and hence a complex and very costly implementation.

It is worth noting, with regard to the transmission speed only, that VLC channels may be categorised into two categories. One category is a case where the use is for high data rate and the other category is case where the requirement is for low data rate [93]. For utilisation where there is a need for high data rate, high-speed PD receivers are required. As for low data rate cases, the existing hardware found on our day to day lives such as mobile devices may form part of the system. A downlink communication to mobile devices in an office or flight cabin from the general omnipresent illumination lamps is one of the most promising high data rate VLC applications [94]. Other applications for high data rate include cases where

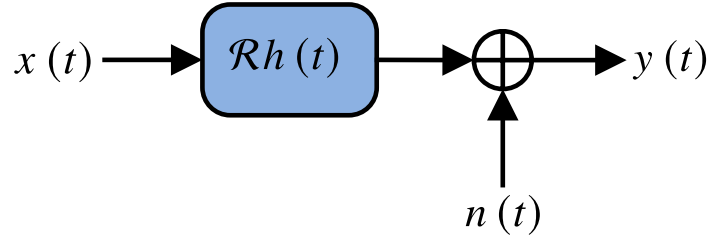


FIGURE 2.11: OWC system baseband model.

files are being transferred between devices and streaming from a device to a display. Augmented reality (AR), V2V, V2I, underwater communications, indoor localisation systems, just to mention a few, are examples of low data rate applications [95].

2.3.1 Indoor VLC Structure

Due to the intrinsic nature of the LEDs producing incoherent light intensity, the most convenient modulation employed for indoor VLC systems is intensity modulation (IM). Moreover, this technique is easy to implement and highly cost effective. With IM technique, the optical power emitted by the LEDs is changed with respect to a certain attribute of the baseband signal. For demodulation, direct detection (DD) is employed as apposed to heterodyning as in RF and optical laser communication where coherent detection is possible [27, 28, 75, 96, 97]. The IM/DD technique however poses a hazard to human health due to flicker, which affects the human eyes.

Optical wireless systems based on the IM/DD technique have an analogous baseband model which conceals the natural optical carrier's high-frequency [98]. The model is illustrated in Figure 2.11, where $h(t)$ is the impulse response of the baseband channel and $n(t)$ is the shot noise. This shot noise is modeled with a double-sided power spectral density (PSD) of $N_0/2$ and it is the additive white Gaussian noise (AWGN) [31]. A general system structure block diagram based on IM/DD is depicted in Figure 2.12. IR or RF are typically used for the uplink on VLC systems. The supremacy of using different frequencies is that, interference is greatly minimal. Furthermore, this avoids visual distress [38, 66].

NLoS indoor VLC links are subject to be negatively affected by the inter-symbol interference (ISI) as a result of dispersion. Impulse response, $h(t)$, of the channel, taken as a linear baseband channel is used to model the dispersion. For a specified locality of the transmitter, receiver and any other object capable of reflecting light, the channel characteristic of a VLC link does not change. The channel characteristic will only change when any of the above mentioned elements are moved by the order of a few centimetres to a different locality [31]. Simulation and analysis of the effects

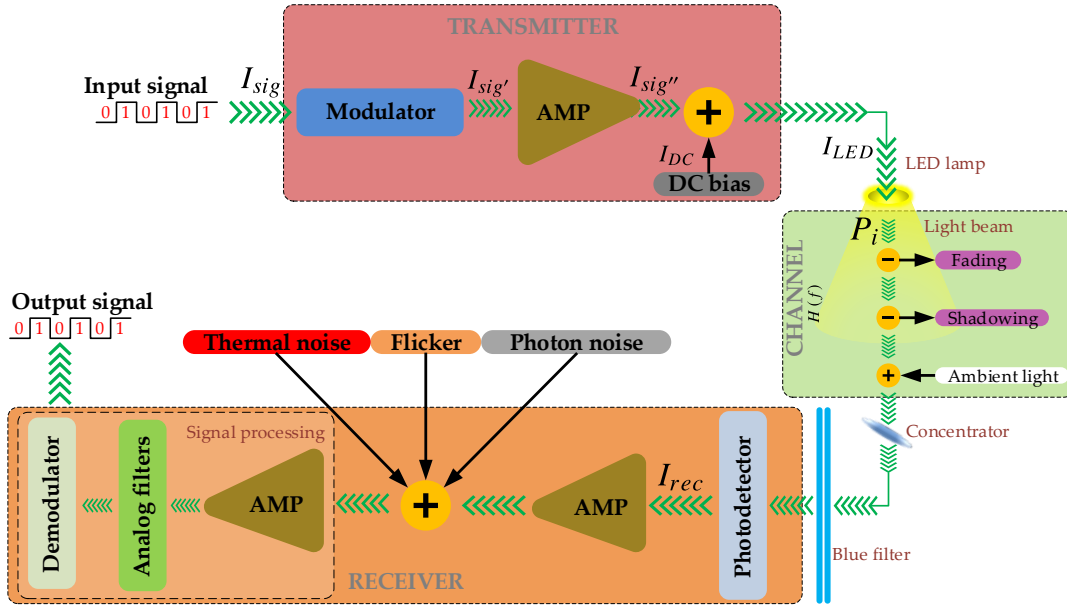


FIGURE 2.12: Indoor VLC channel propagation model.

of dispersion can be performed by utilising $h(t)$ defined by [1]

$$h(t) = \begin{cases} \frac{2t_0}{t^3 \sin^2(FOV)}, & t_0 \leq t \leq \frac{t_0}{\cos(FOV)} \\ 0, & \text{otherwise} \end{cases}, \quad (2.18)$$

where t_0 is the minimum delay. Hence, the corresponding baseband model is

$$\begin{aligned} y(t) &= \mathcal{R}x(t) \otimes h(t) + n(t) \\ &= \int_{-\infty}^{\infty} \mathcal{R}x(\tau) \otimes h(t - \tau) d\tau + n(t), \end{aligned} \quad (2.19)$$

where the character $\otimes$ represents circular convolution. In contrast to electrical and RF systems, $x(t)$ in equation (2.19) is represented as a power signal instead of amplitude signal. That being said, this inevitably yields two restrictions on the transmitted signal. Firstly, $x(t)$ has to be strictly greater or equal to zero. Owing to the safety of the human eye safety, the second constraint is that, the mean value of $x(t)$ must not be greater than the standard maximum power value given by

$$P_{\max} = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T x(t) dt. \quad (2.20)$$

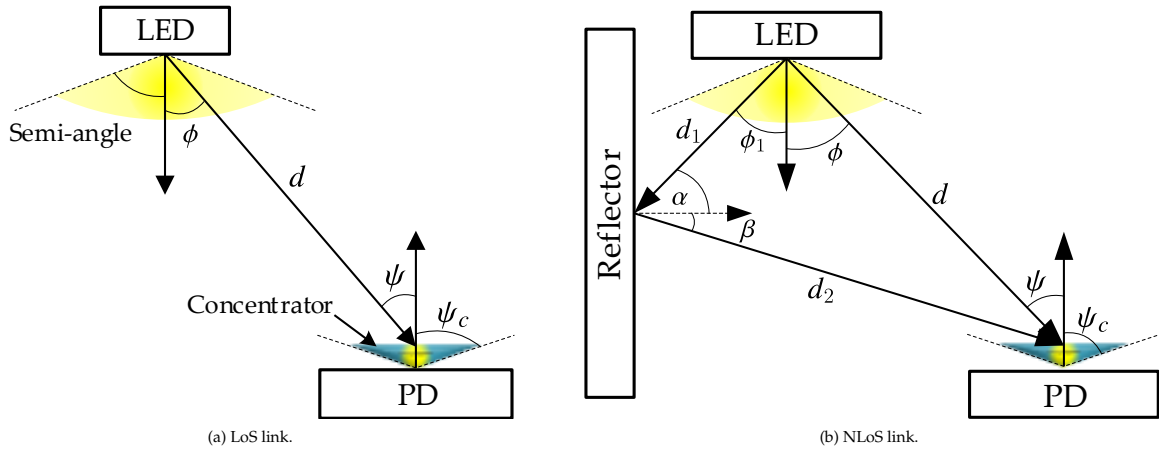


FIGURE 2.13: Ideal link configurations for propagation models.

2.3.2 Line-of-Sight Propagation Model

The radiation intensity pattern for the LED's angular distribution, as depicted in Figure 2.13a is based on Lambertian approximation and it is defined by

$$R_0(\phi) = \begin{cases} \frac{m_1 + 1}{2\pi} \cos^{m_1}(\phi), & \phi \in [-\pi/2, \pi/2] \\ 0, & \phi \geq \pi/2, \end{cases} \quad (2.21)$$

where $\phi = 0$ is the maximum power's radiation angle, Φ is the semi-angle of the LED and m_1 is expressed in terms of semi-angle at half-power by

$$m_1 = \frac{-\ln(2)}{\ln(\cos(\Phi_{1/2}))}. \quad (2.22)$$

An LED's radiant intensity, defined in terms of irradiance angle is given by

$$P_i = \frac{(m_1 + 1) P_t \cos^{m_1}(\phi)}{2\pi}, \quad (2.23)$$

where P_t is the total transmitted power of the LED. The effective collecting area A_e of the PD, in terms of the active collection area A_r , at angle ψ is expressed as

$$A_e(\psi) = \begin{cases} A_r \cos(\psi), & 0 \leq \psi \leq \pi/2 \\ 0, & \psi > \pi/2 \end{cases}. \quad (2.24)$$

Detectors with large areas of collection are preferable for indoor applications so as to allow for collection of the maximum available power from the source. However, practically this poses challenges because of various economical and technical constraints such as costs, low bandwidth and high noise. As a counter measure, a

non-imaging concentrator is put to use as a way of improving the effective collection area. The optical gain of the concentrator is defined by

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2(\psi_c)}, & 0 \leq \psi \leq \psi_c \\ 0, & \psi > \psi_c, \end{cases} \quad (2.25)$$

where n is the internal refractive index of the concentrator and ψ_c is the detector's FOV. As per the constant radiance theorem [99], the relationship between the lens' collection area and the system receiver's FOV is given by

$$A_{col} \sin\left(\frac{\psi_c}{2}\right) \leq A_r. \quad (2.26)$$

From equation (2.26), it is noticeable that a small FOV give rise to an increased concentrator gain. The direct current (DC) channel gain between the LED and the receiver is mathematically estimated using [75]

$$H_{LoS}(0) = \begin{cases} \frac{A_r (m_1 + 1) \cos^{m_1}(\phi)}{2\pi d^2} \times T_s(\psi) g(\psi) \cos(\psi), & 0 \leq \psi \leq \psi_c \\ 0, & \psi \geq \psi_c, \end{cases} \quad (2.27)$$

where T_s is the optical filter's gain. Thus, the received power is expressed by as

$$P_{r-LoS} = H_{LoS}(0) P_t \quad (2.28)$$

Multipath dispersion is sporadically a challenge in LoS links that have shorter distances between the source-receiver pair. The path loss of optical links is dependent on the square of distance between the transmitter-receiver pair because the links are non-frequency selective. The link is generally modeled as linear attenuation and delay [31]. Hence, the impulse response is expressed by

$$h_{LoS}(t) = \frac{A_r (m_1 + 1) \cos^{m_1}(\phi) T_s(\psi) g(\psi)}{2\pi d^2} \times \cos(\psi) \delta\left(t - \frac{d}{c}\right), \quad (2.29)$$

where δ is the Dirac function, $\delta\left(t - \frac{d}{c}\right)$ is the propagation delay, $\phi < 90^\circ$, $\psi < \text{FOV}$ and $d \gg \sqrt{A_r}$.

2.3.3 Non-Line-of-Sight Propagation Model

Various aspects such as the orientation and positioning of the transmitter-receiver pair, room dimensions, window size, the reflectivity of the walls, ceiling, and objects

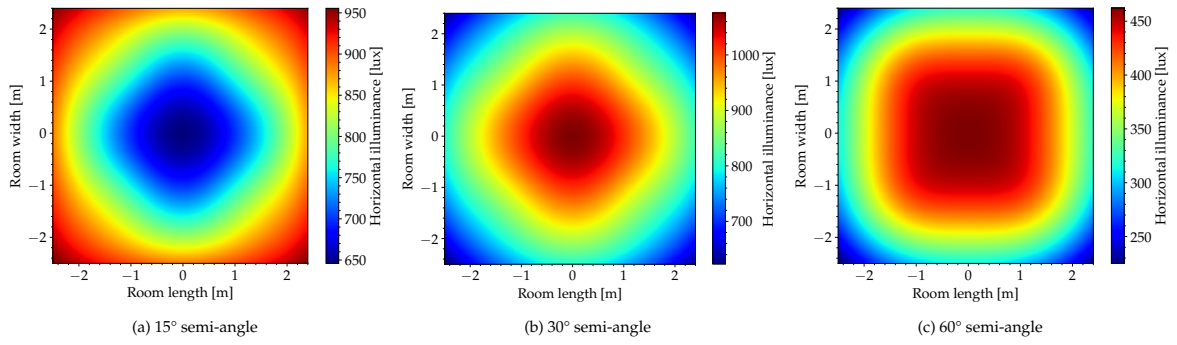


FIGURE 2.14: Optical power dispersion of four LED arrays with different semi-angles.

in the room makes the computation of optical path loss not easy to predict and analyse. The power received is conventionally given by

$$\begin{aligned}
 P_{r-NLoS} &= \left(H_{LoS}(0) + H_{NLoS}(0) \right) P_t \\
 &= \left(H_{LoS}(0) + \sum_{REFL} H_{REFL}(0) \right) P_t,
 \end{aligned} \tag{2.30}$$

where $H_{REFL}(0)$ is the channel DC gain of the path of the reflecting object/surface and may be defined by

$$H_{REFL}(0) = \begin{cases} \frac{A_r \rho dA (m_1 + 1) \cos^{m_1}(\phi) T_s(\psi) \cos(\beta) \cos(\alpha) g(\psi) \cos(\psi)}{(2\pi d_1 d_2)^2}, & 0 \leq \psi \leq \psi_c \\ 0, & \psi \geq \psi_c \end{cases}, \tag{2.31}$$

where d_1 and d_2 represents the distance between and the reflecting object respectively, dA is the reflective area of a small region, ρ represents the reflective factor, β is the angle of irradiance to the receiver and α is the angle of incidence to the reflecting object. The geometrical NLoS model is as shown in Figure 2.13b.

It is very crucial to evaluate the dispersal of the optical power for a particular setup to estimate the path loss for non-directed LoS and diffuse links. Several experimental attempts have been made in [77, 100–111] to precisely delineate indoor optical channels. To model and evaluate the optical power distribution for non-directed LoS and diffuse links, a similar approach as in [106] was adapted. Figure 2.14 depicts the impinging power distribution patterns. The simulation of the radiation pattern using a set of four LED arrays with each consisting twenty LED chips was considered. The four LED arrays are assumed to be located within a room that has dimensions of $5 \times 5 \times 3 \text{ m}^3$. With reference to the centre of the room as $(0, 0, 3)$, the lamps are positioned at coordinates $(x, y, z) = (-1.25, -1.25, 3), (1.25, 1.25, 3)$,

$(-1.25, 1.25, 3)$ and $(1.25, -1.25, 3)$. The semi-angles are varied from 15° to 30° and lastly to 60° . An interesting phenomenon to note in Figure 2.14 is that, the power dispersion pattern of four LED arrays is equal to that of a single LED that has the same illuminance level with a semi-angle of 60° .

The impulse response of an OWC channel is mathematically determined by integrating the power of all the constituents that impinges their radiation on the receiver of the system post multipath propagation [112]. The signals impinging the receiver consists of diverse elements from different paths. These elements have dissimilar path lengths with respect to the room design and therefore they lead to the broadening of the pulse. As opposed to an LoS element, which its channel gain satisfy a modified gamma distribution, the channel gain of NLoS channel together with all the reflections for the majority of transmitter-receiver pair distances, the channel gain satisfy a modified Rayleigh distribution [111]. To evaluate the time-dispersive characteristics for a certain multipath channel, the root mean square delay spread (D_{RMS}) is utilised and it can be computed using [31, 109]

$$D_{RMS} = \sqrt{\frac{\int (t - \mu)^2 h^2(t) dt}{\int h^2(t) dt}}, \quad (2.32)$$

where μ is the mean delay spread and is expressed by

$$\mu = \frac{\int t h^2(t) dt}{\int h^2(t) dt}. \quad (2.33)$$

Calculations for basic power budget can be adequately satisfied by the determination of optical power distribution of an entire room, however, this does not take into consideration the multiple reflections. With this being said, power loss on account of multipath propagation can not be estimated unambiguously. When a channel has more than one reflection, the optical power associated with the reflections is fairly small. The signal reaches the receiver at a later time compared to the time of when there is a single reflection. Therefore, for non-directed LoS and diffuse links that operate at high-speed, this delay needs to be taken into account. In [77], the authors established a ray-tracing algorithm capable of producing an impulse response that takes into account higher order reflections. The algorithm evaluates the path loss as well as the time delay for all the paths having a specific number of reflections. The impulse response for a specific unique source (S) and receiver (R_x)

in a room can be expressed as

$$h_{NLoS}(t, S, R_x) = \sum_{k=0}^{\infty} h_{NLoS}^{(k)}(t, S, R_x), \quad (2.34)$$

where $h_{NLoS}^{(k)}(t, S, R_x)$ is the impulse response because of exactly k reflections of light. Modification of equation (2.34) to satisfy multiple sources yields

$$h_{NLoS}(t, S, R_x) = \sum_i^K \sum_{k=0}^{\infty} h_{NLoS}^{(k)}(t, S, R_x). \quad (2.35)$$

After the k^{th} reflection, the recursive algorithm can be used to calculate $h^{(k)}(t, S, R_x)$ and the algorithm is defined by [75,77,113]

$$h_{NLoS}(t, S, R_x) = \frac{m_1 + 1}{2\pi} \sum_{j=1}^K \frac{\rho_j \cos^{m_1}(\phi_j) \cos(\Psi)}{d_{Sj}^2} \text{rect}\left(\frac{2\Psi}{\pi}\right) h_{NLoS}^{(k-1)}\left(t - \frac{d_{Sj}^2}{c}, S, R_x\right) \Delta A, \quad (2.36)$$

where ΔA is the area of the reflecting elements, K is the number of reflecting objects, ρ_j is the reflecting coefficient of the reflecting object, d_{Sj} is the distance between the source and a specific reflector and $h^{(k-1)}(t, S, R_x)$ is the impulse response of order $(k-1)$ between a particular reflector and the receiver.

As the magnitude of $\|h^{(k)}(t, S, R_x)\|$ approaches zero, k approaches infinity. Thus, “the impulse response of the channel can be approximated using only the first $\mathfrak{R}$. A very good channel estimation can be obtained by considering only the first ten (10) reflections in a case where iterative methods are employed. When evaluating the initial reflections, room surfaces are divided by $\mathfrak{R}$ reflecting elements having an area of ΔA ” [31]. A channel can be described by considering all elements of the surface which has a surface area of ΔA as individual receivers. On the other hand, all of the elements are considered to be point sources that re-emits the collected signal which is scaled by the reflecting coefficient ρ_j . The channel response for an individual reflection can be estimated using

$$h_{NLoS}^1(t, S, R_x) = \sum_{j=1}^{\mathfrak{R}} \frac{(m_1 + 1) \rho_j A_r \Delta A \cos^{m_1}(\phi_{Sj}) \cos(\Psi_{Sj}) \cos(\Psi_{Rj})}{2\pi (d_S d_{Rsj})^2} \delta\left(t - \frac{d_{Sj} + d_{Rj}}{c}\right). \quad (2.37)$$

For indoor OWC systems, the impulse response of a channel is dependent on

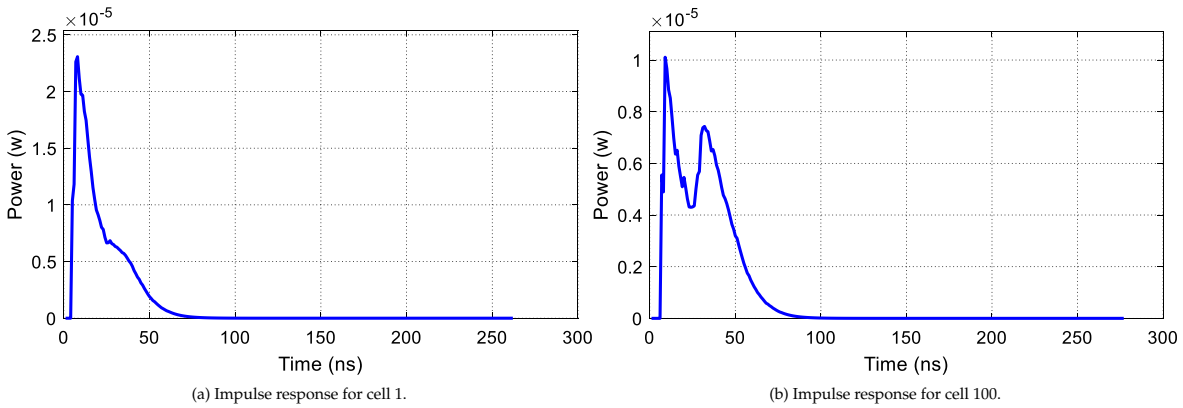


FIGURE 2.15: Empty room simulations for detector 5.

the receiver's location as it varies when the receiver is moved from one position to the other. The most significant component is the first reflection since it impacts the limits of the data rates. It should be noted that this model satisfies a specific room arrangement. Shadowing and the layout of furniture are not taken into account. A modification of this model by Abtahi and Hashemi [114] took into consideration the effects of the objects (i.e, furniture and people) inside rooms of uniform and non-uniform shape. A neural network was utilised by Pakravan and Kavehrad [115] to increase the speed of the algorithm that was developed in [77]. With the neural network, just a small number of the total points that needs to be calculated is computed and then the network learns the remaining points. Lomba *et. al* [113, 116], considered a signal which is being reflected more than once and proposed a simulation model which is more efficient for indoor channels. The approaches that improve the simulation efficiency are the 'time-delay agglutination' and 'time and space indexed tables'. Effects of multipath reflections in the receiver were simulated using the iterative site-based model suggested by Carruthers *et. al* [110]. The study in [110], suggests that, fully diffuse and LoS channels must be separately modelled.

In [117, 118], the authors designed reference channel models for various indoor environments by considering an empty room, conference room, living room and office space. The simulations for channel response for an empty space of $6\text{ m} \times 6\text{ m}$ and nine LED luminaires with their positioning as defined in [117, 118] are shown in Figure 2.15. The room is divided into 10×10 cells which are equally spaced by 0.6 m in x and y directions. Using the same channel parameters, LED and PD specifications as well as user descriptions as outlined in [117, 118], the impulse responses from all of the nine luminaires with the user located at cell 1 and cell 100 using the code developed by [119] is modelled. The PD is considered to be located at detector number five (D5 (see [117, 118])) on the user's cellphone. Figure 2.15a depicts the overall impulse response when the user is located at cell 1 whereas Figure 2.15b

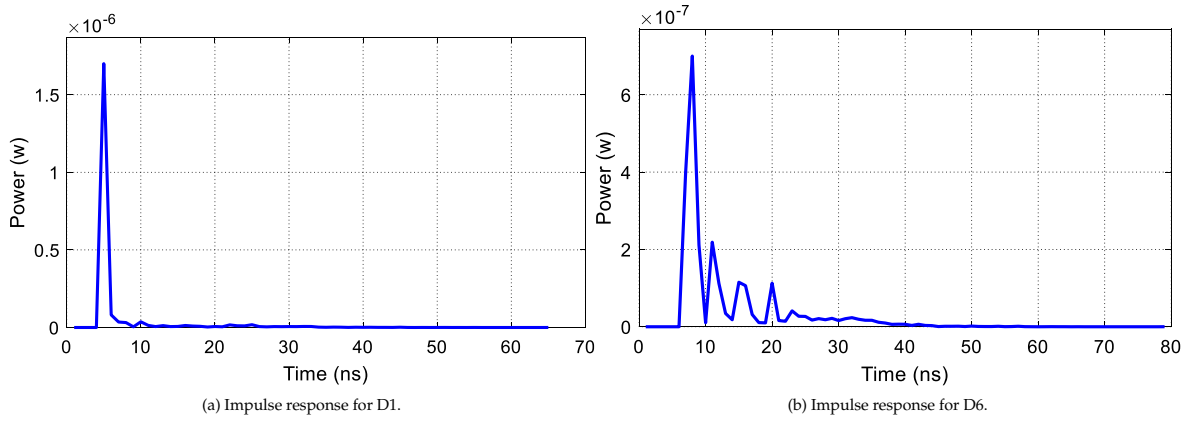


FIGURE 2.16: Conference room simulations.

depicts the overall impulse response when the user is at cell 100. For both of these responses, the impact of LED response with 20 MHz cut-off frequency was taken into account.

Using the room dimensions, furniture arrangement, luminaire setup and the positioning of all detectors as outlined and shown in [117, 118], simulations for the impulse response for a conference room environment. Using the same code, channel parameters, LED and PD specifications as outlined in [117, 119], the system was configured to show the overall impulse responses from all of the ten luminaires to only D1 and D6 respectively. The channel response from all luminaires to detector D1 is shown in Figure 2.16a and Figure 2.16b depicts the response for detector D6. For both of these impulse responses, the impact of LED response was not considered.

The above mentioned channel models are founded on the Monte-Carlo ray tracing algorithm and Lambert's model of reflection. It should be noted that a different impulse response of the same channel can be obtained when using Phong's model. This is with respect to Lambert's model in a scenario where a surface depicts a high specular component [120]. Primary and higher order reflections from the decomposed signal can be used to model the impulse response [112]. The impulse response of the primary reflections is quantified using the gamma probability density function (pdf). The spherical model as defined in [121], is used to simulate the higher order reflections impulse response.

Chapter 3

Modulation and Dimming Schemes

In VLC, the modulating signals are carried by the luminous intensity of the illuminating source, for instance, an LED. Directly modulating the intensity of such a source carrying signal requires both a real and positive valued signal [28, 31, 59]. Therefore, amplitude and phase modulation techniques are not feasible for VLC. Dimming support is crucial as it paves way for high energy efficiency and power saving. Moreover, dimming enables users to be able to communicate even when they require to reduce the brightness level of the occupied space.

It is conventionally a standard practice to make use multi-luminaires for the provision of adequate levels of illuminance for various environments. In most cases, at least as of recent, the luminaires have several LEDs which have the capability of being used as transmitters to facilitate the design and implementation of optical MIMO systems for VLC. This chapter discusses the different types of modulation, dimming and multiple access schemes.

3.1 Intensity modulation/Direct detection

When employing IM/DD to modulate and retrieve the information, it is imperative for the transmitted information to have certain attributes. These attributes associates the data with the transmitted field's intensity variations. The performance of a VLC channel is influenced by noise sources together with the frequency bandwidth and distortions induced on the link. Like any other communication systems, noise source identification at the front-end of the receiver is crucial. The optical front-end is normally made up of a pre-amplifier for amplification of the electrical current produced in the PD. The diagram of the optical receiver front-end is depicted in Figure 3.1. The main source of noise in VLC channels is the photo-generated shot noise which is radically caused by the PD's discontinuous energy and charge. The resistive component of the front-end produces thermal noise. This noise is not dependent on the received signal and it has a Gaussian distribution.

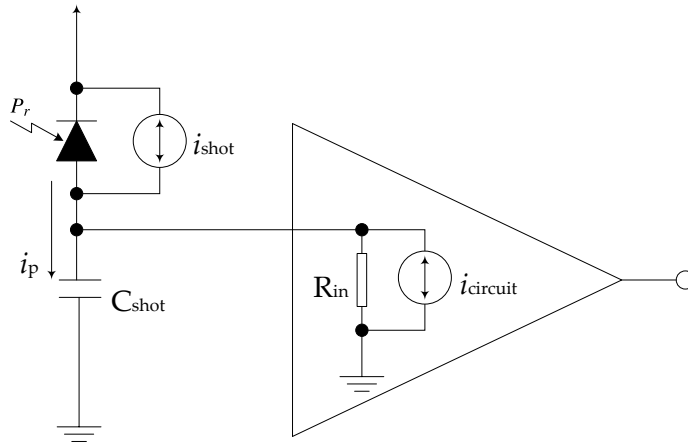


FIGURE 3.1: Optical receiver front-end with a PD and noise sources [31].

There exists three classes of amplifiers used for optical receivers and they are; trans-impedance amplifiers (TIA), low impedance amplifiers and high impedance amplifiers. Speed and sensitivity are the two factors that determine the design of the front-end on account of the balance required between these two factors [122]. In the event that a high impedance amplifier is utilised, there is a great reduction of thermal noise, thus enhancing the sensitivity but this also reduces the bandwidth. Low bandwidth on a high impedance front-end can be mitigated by the use of an equaliser. A low impedance front-end is not a practical technique for VLC systems due to the prevalence of the thermal noise. A balance between a desirable bandwidth and sensitivity is crucial for systems with a TIA-based front-end. The design of VLC systems using TIAs has been on the rise for the past few years [123–125].

The aggregate of the radiated photons is never constant for a given time. This is caused by the discrete nature of light impinging the receiver. Thus, the performance of an ideal PD is affected by nothing besides the noise. With regard to optical sources that produce continuous power, the number of actual photons produced per unit time have a Poisson distribution despite the source producing a constant mean number of photons per unit time. This phenomenon leads to quantum noise which is also termed photon noise. This type of noise is prevalent in every photon detector. Quantum noise is a shot noise with variance given by equation (3.1) for the PIN PD and APD.

$$\sigma_{q-PIN}^2 = 2q_e \langle i \rangle B, \quad (3.1a)$$

$$\sigma_{q-APD}^2 = 2q_e \langle i \rangle B F G^2, \quad (3.1b)$$

where $\langle i \rangle$ is the average current over an instance of time, B is the bandwidth (in Hz) of the filter that follows the PD and F is the excess noise factor.

There is always a small amount of current at the output of the PD even when there is no incident light. This current is termed dark current, it is a composite current made up of the bulk and surface leakage currents. Dark current is generated by the movement of electrons into the conduction band from the valence band. PD materials with a large band-gap exhibit values which are tremendously low for the dark current. The variance of the surface leakage current noise and the bulk dark current noise are given as

$$\sigma_{DS}^2 = 2qI_L B, \quad (3.2a)$$

$$\sigma_{DB}^2 = 2qI_D G^2 B, \quad (3.2b)$$

where I_D is the detector's dark current and I_L is the detector's leakage current.

All conducting materials are susceptible to thermal noise which is also referred to as Johnson noise. This type of noise is caused by thermal instability of the electrons in the receiver circuitry. The load resistance (R_L) contributes to thermal noise. Thermal noise has a Gaussian distribution with zero mean and a variance of

$$\sigma_{TH}^2 = \frac{4k_B T_k B}{R_L}. \quad (3.3)$$

3.1.1 Signal-to-noise ratio

In contrast to RF-based communication systems, which their SNR is proportional to the received average RF power, the electrical SNR, SNR_e , of VLC links is proportional to the square of the average received optical power and it is denoted by

$$\text{SNR}_e = \frac{\left(\mathcal{R}H(0) P_r \right)^2}{\sigma_{TH}^2 + \sigma_q^2}. \quad (3.4)$$

Furthermore, the optical SNR, SNR_o , is expressed by

$$\text{SNR}_o = \frac{\mathcal{R}H(0) P_r}{\sigma_{TH} + \sigma_q}. \quad (3.5)$$

In a scenario where the dominant noise source is the shot noise, the SNR is analogous with the area of the PD as a result of the proportionality of the shot noise variance and the received electrical power to the area of the PD and to the square of the area of the PD respectively. Thus, it is advantageous to have a PD which has a large area for single element receivers. However, an increase in the surface area of the detector in turn reduces the transmission capacity as a result of increased capacitance, hence a trade-off between high bandwidth and high power efficiency.

Typically, different types of noise have different weights, in most cases, thermal noise and quantum noise are the most significant. In an occurrence where the power of the optical signal is quite high, the thermal noise is far much less than the shot noise. Thus, the SNR is referred to as quantum noise limited. Under the conditions where the power of the optical signal is low, the shot noise is dominated by the thermal noise and the SNR is now said to be thermal noise limited.

3.2 Modulation and dimming schemes

Mitigation measures to address flicker and dimming problems must be taken into consideration when designing modulation schemes to constrain fluctuations of the light intensity within a certain time period [60]. Flicker frequency of approximately 200 Hz is widely considered to be safe as it is not perceivable by the human eye. To safely and fully support illumination and communication, modulation techniques should reckon with issues that are associated with dimming and flickering [9]. As a way of curbing flicker, run length limited (RLL) coding is employed to prevent long sequences of ones and zeros. Moreover, the RLL strings are used for clock and data recovery. Error correction may be executed by the adoption of forward error correction (FEC) techniques like Reed Solomon (RS) [26, 36, 38, 91, 126].

3.2.1 On-Off keying

On-off keying (OOK) is one of the most straightforward modulation scheme easy to implement. It is based on switching the LEDs between on and off states to modulate data. The former represents a high data bit (1) whereas the latter represents a low data bit (0). The presence of an optical pulse that takes on all or part of the bit duration corresponds to a high data bit and the unavailability of an optical pulse corresponds to a low data bit. Non-return-to-zero (NRZ) and return-to-zero (RZ) are the two types of OOK. For OOK-RZ schemes, a pulse that its period is only a fraction of the bit duration is transmitted as a high data bit whereas in OOK-NRZ the pulse is transmitted as a high data bit if its period is equal to the bit duration.

During the early stages of VLC, a demonstration of 10 Mbps data rate using OOK-NRZ and white LEDs (WLEDs) was carried out in [127]. With efforts to exhibit an improved system in terms of performance, a blue filter was used to increase the bandwidth by removing the yellow component of the PC-LED. As a result, an improved overall data rate of 40 Mbps was achieved. Consolidation of blue-filtering and equalisation techniques at the receiver for OOK based systems results in improved system data rates, this was validated by [128] and [129] with each attaining

a data rate of 100 Mbps and 125 Mbps respectively. The use of a different type of a PD and OOK-NRZ also results in higher data rates. A data rate of 230 Mbps using an APD instead of a PIN PD was demonstrated in [130]. Instead of using all of the three RGB-LED chips for data transmission, authors in [131] used only the red chip for data transfer while the other two were for the provision of illumination. The achievable data rate was recorded to be 477 Mbps using OOK-NRZ.

Using OOK-NRZ, an overall data rate of 1.5 Gbps through the realisation of GaN based μ -LED array system inside a CMOS was accomplished by [132]. The array consisted of four μ -LEDs which were modulated concurrently with each μ -LED pixel providing a bit rate of 375 Mbps. Recently, the demonstration of a VLC system based on the exploitation of just one phosphor LD in [133] depicted data rates that are in the range of 1062.5 Mbps to 1250 Mbps. This was accomplished over a distance range of 1 m to 1.5 m within an indoor setting with an illuminance level of over 500 lux. Blue filtering technique was not applied and it is anticipated that higher data rates could be achieved if an array of LDs was to be used.

Dimming support for VLC systems that adopts OOK modulation may be facilitated in two ways as defined in [36]. One of the methods is redefining the ON and OFF levels by assigning one of the levels to have a lower intensity. Alternatively, compensation periods may be used. These periods are dependent on the desired dimming level. However, compensation periods give rise to low data rates when the lights are dimmed. The former method is able to maintain a constant data transfer rate but decreased levels of dimming leads to a shorter communication range.

3.2.2 Pulse modulation techniques

The world has seen the inception of alternate modulation techniques of OOK and they solely rely on the width and position of a pulsating signal. In PWM, the duration of pulses is altered according to the required level of brightness and the individual pulses encode the modulated signal. In PWM applications, at least one bit of data may be transmitted during longer single pulses while maintaining the exhaustive brightness of the luminaire. This property makes PWM more efficient compared to OOK where each pulse transmits a single bit of data. In PWM, the data transmission rate of the system is determined by the desired level of dimming. PWM is advantageous in the sense that brightness reduction does not affect the level of intensity for the pulses. Therefore, the effects of colour shifting as in OOK schemes are eliminated. A major shortfall of PWM is limited data rates [38].

When pulse position modulation (PPM) is applied in VLC, a transmitted data bit corresponds to the positioning of a pulse within one of the predetermined time

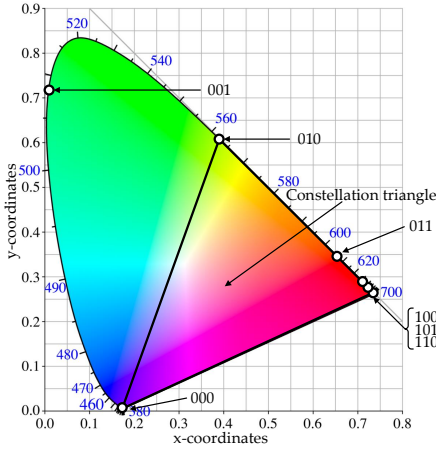


FIGURE 3.2: CIE 1931 colour space chromaticity diagram.

TABLE 3.1: M -ary CSK bands

Band (nm)	Center (nm)	Code	xy -coordinate
380 – 478	429	000	(0.169, 0.007)
478 – 540	509	001	(0.011, 0.733)
540 – 588	564	010	(0.402, 0.597)
588 – 633	611	011	(0.669, 0.331)
633 – 679	656	100	(0.729, 0.271)
679 – 726	703	101	(0.734, 0.265)
726 – 780	753	110	(0.734, 0.265)

frames of a symbol period. All of the frames have the same length of time. The complexity of PPM systems is elevated due to the accuracy of the synchronisation process of the data bit and symbol at the receiver [36, 38]. On the other hand, both the average power efficiency and the signal bandwidth of PPM is higher. In spite of this good performance of PPM, there exist several variations of PPM modulation such as VPPM, pulse position modulation-pulse width modulation, pulse interval modulation (PIM), and the dual header PIM [9, 26, 75].

VPPM technique is based on the amalgamation of PPM and PWM. Varying the pulse width of the transmitted data bits controls the brightness of the LED based on the required dimming ratio. The distinction between a low data bit and a high data bit is characterised by the positioning of the pulse per symbol period. Simplicity as well as the robustness of PPM are maintained with this technique whilst it allows the variation of the duty cycle to enable diversified dimming levels [126, 134].

3.2.3 Colour-shift keying

In a CSK system, the transmitted data bit patterns are mapped into the colour space of the colour (wavelength) band combinations of the luminaires made up of the tri-chromatic LEDs (TLEDs) or the quad-chromatic LEDs. TLED CSK scheme is standardised by the IEEE 802.15.7 to solve problems of lower data transmission rates and restricted dimming provision faced by other schemes [36, 91]. CSK is based on the CIE 1931 colour space chromaticity diagram depicted in Figure 3.2 [135]. Figure 3.2 also shows all seven colour band centres in Table 3.1, together with a valid constellation triangle for the ($[100]$, $[010]$, $[000]$) colour band combination.

The IEEE 802.15.7 standard in [36] describes the guidelines for the design and implementation of CSK symbol constellations. With reference to the block diagram of

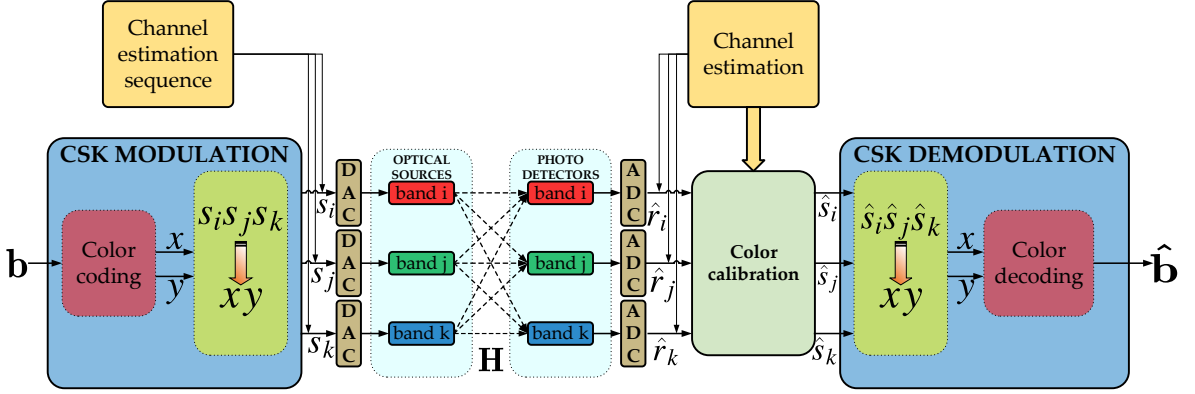


FIGURE 3.3: M-ary CSK functional system block diagram.

an M -ary CSK modulation shown in Figure 3.3, a binary stream of data denoted as $\mathbf{b}$ modulates the CSK symbols, where M is the constellation size. In CSK modulation, one symbol is used to map one group of $N_b = \log_2 M$ incoming bits. A combination of different wavelengths of the multi-coloured luminaires is used to modulate the CSK symbols. For TLED CSK, a three-dimensional vector, which contains the intensities of the individual constituents of the produced white light, is used to represent a CSK symbol. A CSK symbol denoted by $\mathbf{s}$, can be defined by $\mathbf{s} = [s_i, s_j, s_k]$, $\mathbf{s} \in \mathcal{S}$. Each element of $\mathcal{S}$ symbolises the power of the matching multi-coloured luminaire LED chip and $\mathcal{S} = \{s_0, s_1, s_2, \dots, s_{M-1}\}$ represents a cluster of all valid symbols.

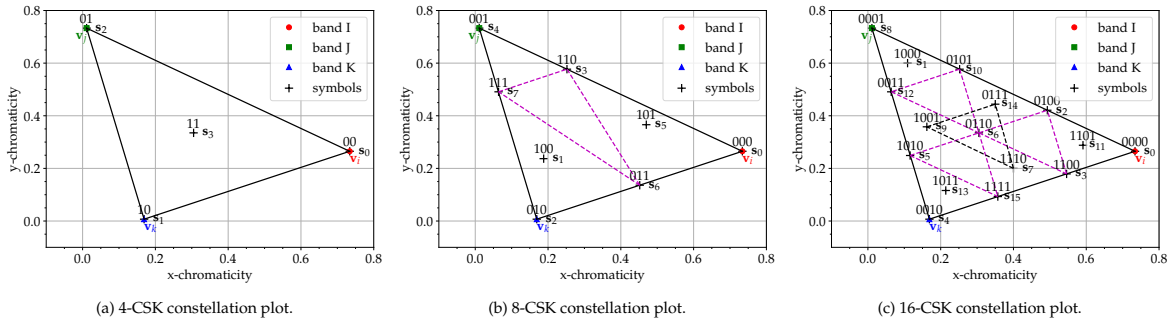
Solving an optimisation problem is required for the determination of the location of the symbols on the xy -plane [36]. Various works such as those of [136–138] have studied and evaluated this optimisation problem. Describing this problem, with reference to IEEE 802.15.7 standard, the output luminous intensity I of the multi-coloured luminaire LED chips must be restricted to $0 < s_p < I$ for $p = i, j, k$, i.e. distance between the symbols must be maximised to minimise the ISI. Due to the need for a constant luminous intensity of the CSK symbol, which is expressed by

$$\sum_{p=i,j,k} s_p = I, \quad (3.6)$$

valid CSK symbols in a three dimensional space must be equally spread and confined to a triangular area on the $\sum_p s_p = I$ plane so that the combined light is perceived as white [36]. The boundaries of the constellation plane are defined by [139]

$$\begin{cases} s_j + s_k = I \\ s_i = 0 \end{cases}, \quad \begin{cases} s_i + s_k = I \\ s_j = 0 \end{cases} \quad \text{and} \quad \begin{cases} s_i + s_j = I \\ s_k = 0 \end{cases}. \quad (3.7)$$

The intensity boundary I is conventionally set to unity for normalisation of the symbol intensities s_p . From equation (3.6) it can be seen that the three-dimensional

FIGURE 3.4: M -ary CSK constellation diagrams.

representation of the CSK symbols can independently be represented only in two ways without violating any of the above mentioned constraints. As a result, it is then suited and desirable to represent symbol s using the CIE 1931 colour space which uses a two dimensional vector denoted by $\mathbf{q} = [x, y]$. For CIE representation, the colour bands of the individual LED chips for the multi-coloured luminaire are combined to establish the vertices of the triangular area which will have all of the valid CSK symbols. These wavelength bands are then mapped into new coordinates of $\mathbf{v}_i = [x_i, y_i]$, $\mathbf{v}_j = [x_j, y_j]$ and $\mathbf{v}_k = [x_k, y_k]$. The new two-dimensional CSK symbols can now be defined by equations (3.8a) and (3.8b).

$$x = s_i x_i + s_j x_j + s_k x_k, \quad (3.8a)$$

$$y = s_i y_i + s_j y_j + s_k y_k. \quad (3.8b)$$

Equations (3.8a) and (3.8b) can be re-written to yield

$$\mathbf{q} = s_i \mathbf{v}_i + s_j \mathbf{v}_j + s_k \mathbf{v}_k, \quad (3.9)$$

which subsequently paves way for all s vectors to be mapped into unique $\mathbf{q}$ vectors. The two-dimensional triangle vertices, $\mathbf{v}_i = [x_i, y_i]$, $\mathbf{v}_j = [x_j, y_j]$ and $\mathbf{v}_k = [x_k, y_k]$ represents the chromaticity values for the centre of the wavelength bands for the luminous intensity. Furthermore, these unique vectors also represents three of the constellation points at the vertices (band centres) of the CSK domain.

The design rules and guidelines of the IEEE 802.15.7 standard specifies the nine band combinations for the construction of a valid constellation triangle. CSK symbols are created by modulating the intensities of various colours of the valid band combinations of the multi-colour luminaire. For instance, depending on the chosen M -ary CSK modulation¹, the elements of each symbol are then mapped into the

¹For this example, the band code combination selected is ([110], [001], [000]) and deduced the chromaticity points in Tables A.1 to A.3

red, green, and blue transmitters as shown in Figure 3.3. According to the standard, three of the symbols are mapped to the vertices of the constellation triangle while the other remaining symbols are mapped to positions within the triangle. For the three symbols positioned at the vertices, only one of the LED chips of the multi-luminaire is activated for each vertex i.e. $\mathbf{v}_i$, $\mathbf{v}_j$ and $\mathbf{v}_k$ whilst the other symbols are activated by weighted colour intensities of the symbols.

The design rules for 4-CSK, 8-CSK and 16-CSK are graphically visualised in Figure 3.4. For 4-CSK mapping, as observed in Figure 3.4a, symbols s_0 , s_1 and s_2 are mapped to vertices $\mathbf{v}_i$, $\mathbf{v}_j$ and $\mathbf{v}_k$ of the constellation triangle whilst symbol s_3 is mapped to the centroid of the triangle. With 4-CSK specification, the Euclidean distances of the CSK symbols is maximised. From the graphical depiction of 8-CSK mapping shown in Figure 3.4b it can be seen that symbols s_0 , s_4 and s_2 are mapped to vertices $\mathbf{v}_i$, $\mathbf{v}_j$ and $\mathbf{v}_k$ of the constellation triangle while s_3 and s_7 are respectively mapped to the xy -chromaticity points that divide each of the $\mathbf{v}_i\mathbf{v}_j$ and $\mathbf{v}_j\mathbf{v}_k$ sides of the triangle into two lengths with a ratio of 1:2. Symbol s_6 is mapped to the mid-point of side $\mathbf{v}_k\mathbf{v}_i$ while symbols s_1 and s_5 are mapped to the centroids of triangles $s_6s_7s_2$ and $s_6s_3s_0$ respectively.

Figure 3.4c displays constellation mapping for the design of 16-CSK modulation. Like the previous two specifications for 4-CSK and 8-CSK, three symbols, being s_0 , s_8 and s_4 are mapped to vertices $\mathbf{v}_i$, $\mathbf{v}_j$ and $\mathbf{v}_k$ of the constellation triangle while s_2 & s_{10} , s_{12} & s_5 and s_3 & s_{15} are mapped to the xy -chromaticity points that divide each of the $\mathbf{v}_i\mathbf{v}_j$, $\mathbf{v}_j\mathbf{v}_k$ and $\mathbf{v}_k\mathbf{v}_i$ sides into three lengths with a ratio of 1:3. Symbols s_{11} , s_{14} , s_1 , s_9 , s_{13} and s_7 are the centroids of the six smaller triangles sharing one or two sides with the main constellation triangle. Additionally, joining symbols s_7 , s_9 and s_{14} results in another small triangle, which is congruent with nine other small triangles as shown in Figure 3.4c. With that in mind, the 16-CSK symbols can be mapped to the vertices and centroids of four small and congruent triangles with the same settings as those of 4-CSK design [139].

The two dimensional vector $\mathbf{q} = [x, y]$ of symbol s is created by the intensities of the TLED. The intensity vector $\mathbf{s}$, can be easily obtained from the two dimensional vector $\mathbf{q}$ using any of the band combinations specified in [36]. An example of this conversion using the same band combination used in Table A.2 is demonstrated by considering the 8-CSK modulation. The symbols are as mapped in Figure 3.4b using the CIE 1931 colour space chromaticity values. Given a band code combination of ($[110]$, $[001]$, $[000]$), the fundamental RGB coordinates to employ for deducing the elements of all the $\mathbf{s}$ vectors are given as $\mathbf{q}_R = \mathbf{v}_i = [0.734, 0.265]$, $\mathbf{q}_G = \mathbf{v}_j = [0.011, 0.733]$ and $\mathbf{q}_B = \mathbf{v}_k = [0.169, 0.007]$. For instance, take symbol s_5 which is represented by $(x, y) = (0.470, 0.366)$ in Figure 3.4b, its intensity vector is

determined by solving a system of linear equations given by

$$\begin{cases} 0.734s_i + 0.011s_j + 0.169s_k = 0.470 \\ 0.265s_i + 0.733s_j + 0.007s_k = 0.366 \\ s_i + s_j + s_k = 1 \end{cases} \quad (3.10)$$

Solving the system yields $\mathbf{s} = [0.610 \ 0.278 \ 0.112]$. All other intensity vectors of the constellation points are obtained by repeating the same procedure. Intensity vectors for 4-CSK, 8-CSK and 16-CSK are listed in Tables A.1 to A.3. The conversion and mapping process for M -ary CSK modulation is summarised as follows:

1. Define the constellation triangle with reference to the centre wavelength of the chips used for the multi-colour luminaire as specified in [36].
2. Map the data stream to xy -chromaticity values using the constellation triangle to determine the positioning of the symbols.
3. Determine the intensities of the LED chips using equations (3.6) and (3.9) to pave way for transmission of symbols by varying the intensities.

The symbols are received by three different PDs with in-built RGB filters. The optical channel depicted in Figure 3.3 constitutes a noisy multipath model which characterises the channel-instigated aggravations, some of which are the ambient light noise, device noise, multi-colour interference and multi-colour imbalance. The received symbol $\mathbf{r} = [\hat{r}_i, \hat{r}_j, \hat{r}_k]$, which is corrupted by AWGN can be expressed by

$$\mathbf{r} = \mathbf{R}\mathbf{H}\mathbf{s}^T + \mathbf{n}^T, \quad (3.11)$$

where $\mathbf{H}$ is a 3×3 element matrix denoted by

$$\mathbf{H} = \begin{bmatrix} h_{ii} & h_{ji} & h_{ki} \\ h_{ij} & h_{jj} & h_{kj} \\ h_{ik} & h_{jk} & h_{kk} \end{bmatrix}. \quad (3.12)$$

The individual entries of $\mathbf{H}$ define the channel gain between a certain pair of the multi-luminaire LED chip and a PD. For instance, h_{ki} is the channel gain between LED chip k and PD i , which constitute for the band imposed interference. In essence, the diagonal elements equate to the channel gain of the matching band whereas the interference instituted by other bands is represented by other elements of the matrix [140, 141]. For this explanation, consider the CSK system to have an ideal non-dispersive AWGN channel in a point-to-point transmission model. Moreover, $\mathbf{n} = [n_i, n_j, n_k]$ corresponds to the AWGN noise vector. The noise vector $\mathbf{n}$ has a noise

variance of σ^2 at the receiver and each element has a zero mean and a variance of $\sigma_0^2 = \sigma^2/3$.

The variance of the AWGN at each detector may be modelled as a summation of the shot noise and thermal noise [138] given by equations (3.1) and (3.3) respectively. The $\langle i \rangle$, in equation (3.1) may be split into two to denote the two components impinging the PD. The said components are the received instantaneous optical power P_r from the source and the atmospheric indoor power P_{sun} from the diffuse sunlight. According to [138], the value of P_{sun} may be approximated to only be 11% of the mean value of P_r . The optical SNR of an M -ary CSK system may be expressed as $\gamma_0 = E_b/\sigma^2$, where E_b is the average power of all legitimate M -ary CSK symbols and is defined by $E_b = \mathbb{E} \{ \|s\|^2 \}$. An estimate of s , defined by $\hat{s}$ as seen in Figure 3.3, is obtained by means of colour calibration, and it is denoted by [36]

$$\hat{s} = \mathcal{R}\mathbf{H}^{-1}\mathbf{r}. \quad (3.13)$$

Having obtained $\hat{s}$, the signal is converted back to the xy -chromaticity coordinates, upon which the decoding module will retrieve data $\mathbf{b}$ denoted by $\hat{\mathbf{b}}$. To take full advantage of the modulated information for decoding, the a posteriori probability of symbol $\hat{s}_m, \hat{s}_m \in \mathcal{S}$ must be obtained. This probability may be denoted by [139]

$$\begin{aligned} \Pr(\hat{s}_m|\mathbf{r}) &= p(\mathbf{r}|\hat{s}_m) \frac{\Pr(\hat{s}_m)}{p(\mathbf{r})} \\ &= \frac{\Pr(\hat{s}_m)}{2\pi\sigma p(\mathbf{r})} \exp\left(-\frac{\|\mathbf{r} - \mathcal{R}\mathbf{H}\hat{s}_m\|^2}{2\sigma^2}\right), \end{aligned} \quad (3.14)$$

where $\Pr(\hat{s}_m)$ is the a priori probability of symbol $\hat{s}_m$. Equation (3.14) may be represented in the log domain by

$$\text{lr}(\hat{s}_m|\mathbf{r}) = A - \left(\frac{\|\mathbf{r} - \mathcal{R}\mathbf{H}\hat{s}_m\|^2}{2\sigma^2}\right), \quad (3.15)$$

where $A = \ln[\Pr(\hat{s}_m)] - \ln[2\pi\sigma p(\mathbf{r})]$. If there is no a priori information provided, A is the same for all symbols and $\text{lr}(\hat{s}_m|\mathbf{r})$ is defined by $\ln[\Pr(\hat{s}_m|\mathbf{r})]$. Symbol $\hat{s}_m$ can now be estimated using equation (3.15) as the maximum-likelihood (ML) function and the maximum a posteriori probability (MAP) estimate defined by equation (3.16) [139]

$$\begin{aligned} \hat{s} &= \arg \max_{\hat{s}_m \in \mathcal{S}} [\text{lr}(\hat{s}_m|\mathbf{r})] \\ &= \arg \min_{\hat{s}_m \in \mathcal{S}} \|\mathbf{r} - \mathcal{R}\mathbf{H}\hat{s}_m\|^2. \end{aligned} \quad (3.16)$$

The symbol $\hat{s}_m$, with the least distance from the received symbol $\mathbf{r}$, can now be regarded as the legitimate symbol $\hat{s}$ which is the result of the MAP detection. The symbol $\hat{s}$ in the end is then decoded and mapped into data bit $\hat{b}$.

In CSK, dimming is achieved by employing amplitude control. This technique controls the brightness of the LEDs by modulating the driving forward current of the RGB chips of the multi-luminaire light source [36,91]. In different circumstances when there is an inappropriate control of the forward current for amplitude dimming, colour shift of the light source may arise and become a hindrance in the performance of the system. For any of the appropriate dimmer control setting, the optical power of the optical source is unchanged which suggest that the colour of the band centre for the constellations is constant. There are no severe negative impacts due to flickering in CSK because there is no amplitude variation as opposed to other schemes like OOK [91,142].

3.2.4 Optical orthogonal frequency division multiplexing

This multi-carrier modulation scheme is an up-and-rising modulation scheme for OWC technologies that facilitate the realisation of some high-speed optical systems [143] and it has in the past recent years gained momentum for use in VLC. Optical OFDM (OOFDM) is an adaptation of the conventional OFDM which is widely used for RF technologies due to its clear-cut benefits [92]. By reason of the need for real valued and non-negative signals for IM/DD, the modulating signal should be a real time-domain signal. Such a signal is commonly obtained by firstly making the frequency-domain signal $\mathbf{Q}$ conform to the Hermitian symmetry constraint. Secondly, the Hermitian imposed signal is converted to a unipolar signal.

There are many ways in which the Hermitian symmetry conforming signals can be converted to unipolar signals and the most prominent are the DC-biased OOFDM (DCO-OFDM) and asymmetrically clipped OOFDM (ACO-OFDM) [26,38,92,144]. However, the conversion of signals to unipolar consequently degrades the spectral efficiency since the available bandwidth is reduced by half [145,146]. In the case of DCO-OFDM, all of the initial OFDM sub-carriers are combined with an appropriate positive DC-bias. An appropriate DC bias value would be a value that results in the mean value of the positive signal that lies at the midpoint of the optical source's linear range [144]. The negative part of the combined signal is clipped in order to remain with only the positive unipolar sub-carriers [59]. Nonetheless, clipping is known to pose non-linear distortions which leads to performance degradation as it was investigated in [147]. As an addition, this method is less energy efficient due to its high power consumption at optimal levels which is achieved by bit and power

loading [26]. For ACO-OFDM, the even sub-carriers are replaced by zeros while only the odd sub-carriers are modulated and this results in anti-symmetrical real-valued signals [147]. With this, it is safe to clip the negative part of the OFDM signal without any distortions [145]. Despite the higher energy efficiency of the ACO-OFDM, it has lower spectral efficiency because it uses only half of the sub-carriers in comparison with DCO-OFDM with double the spectral efficiency of the former.

With reference to the conventional frequency division multiplexing, the spectrum of the sub-carriers do not overlap with each other. In OOFDM however, the sub-carriers are overlapped with one another in order to allow for an improved spectral efficiency. For distortion free recovery, the sub-carriers should be orthogonal for the period length of the signal. Non-linearity of the LED luminaires and the limited availability of dimming support techniques are the two major drawbacks of OOFDM [38, 143, 148]. The effects of non-linearity which have been found to most likely affect systems with a higher dynamic range since they have a high peak-to-average power ratio (PAPR) were investigated in [59, 148]. Higher PAPR has been found to be mitigated in different ways and some of the said ways can be found in [148]. In spite of all the challenges, OOFDM is still a highly regarded modulation scheme with staggering data rates in the range of several Gbps through the use of just a single LED [149–151]. Recently, there has been a few contributions to the state of the art for high-speed VLC systems based on OFDM such as those in [152–154]. Other experimental works of high-speed VLC based on the use of multi-colour LEDs and OFDM can be found in [155, 156].

The three physical layers for VLC are specified by the IEEE 802.15.7 standard as PHY I, PHY II and PHY III. PHY I, which typically yields data rates in the range of 11.67 kbps to 266.6 kbps operates at an optical clock rate not exceeding 400 Hz. In addition, PHY I is designed for just one light source which makes it suitable for single-carrier modulation schemes being the OOK and VPPM. PHY I is found mainly in outdoor applications since outdoor light sources switch at a slow rate. PHY II is operational at an optical clock rate of less or equal to 120 MHz yielding data rates of 1.25 Mbps to 96 Mbps. Typical applications for PHY II are those of indoor scenery where there are mobile and portable devices that uses fast switching LEDs. Just like the PHY I, PHY II also supports single-carrier modulation schemes and single light sources. As defined in [36], the third layer operates at an optical clock rate of at most 24 MHz. This clock rate happens to be the maximum clock rate for TLED multi-luminaire sources [38, 91]. The achievable data rates for PHY III are from approximately 12 Mbps to 96 Mbps. Specific data rates within the specified ranges of the three physical layer mode are determined by four metrics which are the optical clock rate, modulation scheme, the use of the RLL and FEC codes [36, 38, 91].

The revision of [35] in [36] resulted in the addition of three more layers for OCC [157–160]. The said layers are defined as PHY IV, PHY V and PHY VI. The use case for PHY IV is when discrete light sources are used and the maximum achievable data rate is 22 kbps, depending on the modulation scheme selected as per Table 79 in [36]. PHY V is developed with the intention to be used in scenarios where there is availability of diffused surface light sources. The maximum achievable data rate is 5.71 kbps, depending on the modulation scheme selected as per Table 79 in [36]. PHY IV, is intended for use with video displays and with varying data rates in the scale of a few kbps as per the modulation schemes defined in Table 79 by [36].

3.3 Multiple-input multiple-output schemes

With a similar objective as in RF MIMO systems, optical MIMO utilizes multiple LEDs to significantly improve the performance of VLC systems from the transmission point of view [26, 161]. Normally these enhancements come about the utilisation of spatial multiplexing which increases the system's throughput or by the use of spatial diversity which decreases the bit error rate (BER) [162]. The spectral efficiency is greatly enhanced due to the fact that there is an establishment of parallel communication platform. This platform is created when transmitters with multiple light sources are used in conjunction with receivers which have multiple detectors [38]. Consequently this results in augmented data transmission capacity in contrast to when there is a single transmitter-receiver pair. Furthermore, the use of optical MIMO technique makes it easy to come up with mobile optical wireless schemes where there is no need for stringent alignment of the transmitter and receiver [163, 164]. However, it has been shown in the literature that, the use of spatial multiplexing for optical MIMO is not an effective technique for enhancing the data transmission rates for non-imaging receivers [163].

In comparison with RF MIMO, design and implementation of optical MIMO systems for VLC is not easy by reason of limited spatial diversity [38, 165]. This limitation is mostly prevalent in indoor applications where the paths taken by the impinging signals from the transmitter to the receiver are less diverse as opposed to naturally diverse paths in RF MIMO systems. Works on spatial diversity with reference to optical MIMO are given in [164, 166–168]. Another issue faced in VLC MIMO is attributed to the design of the optical MIMO system receiver which are commonly designed as either non-imaging or imaging receivers [163, 169]. For a non-imaging receiver, a group of PD are arranged without any dependence on each other and each of the PDs have its own optical concentrator [170]. This kind of receiver is favourable in systems where there is a need for very high gain which can

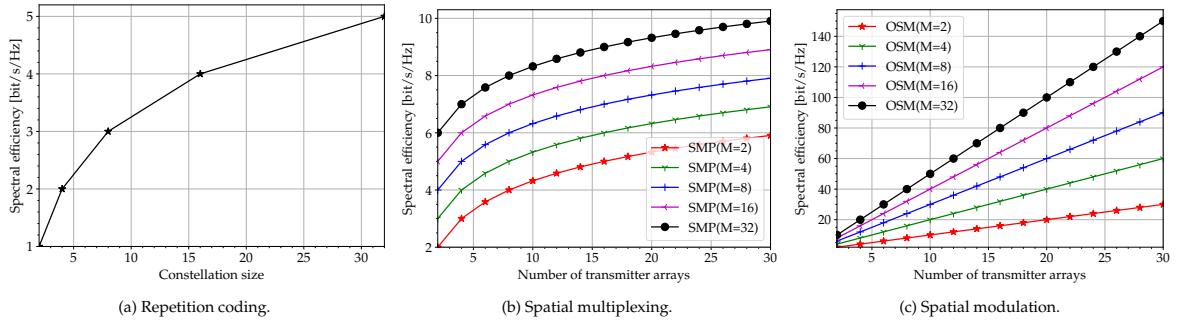


FIGURE 3.5: Variations of the spectral efficiencies of VLC MIMO schemes.

be easily provided because of the narrow FOV of the individual PDs. Nonetheless, this technique comes with a shortfall of a very tight requirement for the alignment of a transmitter-receiver pair on account of the narrow FOV. A slight misalignment of this pair will drastically reduce the spectral capacity of the system [38, 165].

In the case of imaging receivers, image sensors are employed as constituents of the receiver. An image sensor is basically a composite of an imaging optical device such as a projection lens as well as a large array of PDs. Such a sensor subsequently creates an adequate FOV which greatly reduces the need for the tight alignment of transmitter-receiver pair [164, 170, 171]. The limitation of such receivers is that there is the need for exceptional image processing for the creation of a MIMO channel that has a high level of efficiency and as an addition, each of the PDs have a constrained gain. Another factor which reduces the throughput of systems based on imaging sensors is the low sampling rate of the sensors [38].

There are three types of algorithms for VLC MIMO which have been implemented by various researchers in the literature and these are repetition coding (RC), spatial multiplexing (SMP) and optical spatial modulation (OSM) [172–174].

3.3.1 Repetition coding

The most elementary and easy technique is the RC in which all the transmitters are simultaneously transmitting the same data signal. The spectral efficiency and the computational complexity of RC algorithm are given by $\log_2(M)$ bit/s/Hz and $M(2N_t N_r + N_r - 1)$ respectively [172]. N_t is the total number of transmitters and N_r is the total number of PDs. This algorithm performs well when designed for FSO schemes due to its transmit diversity [29]. Moreover, the transmitted signals add up constructively on the receiver, hence an increase in the overall gain of the system. The spectral efficiency for different constellation sizes is depicted in Figure 3.5a.

3.3.2 Spatial multiplexing

In SMP, all the transmitters are simultaneously transmitting different data signals. The spectral efficiency and the computational complexity of SMP algorithm are given by $N_t \log_2(M)$ bit/s/Hz and $M^{N_t} (2N_t N_r + N_r - 1)$ respectively [172]. SMP creates parallel multiple single-input single-output (SISO) data streams. With this type of transmission, there is a challenge since it is highly mandatory for the transmitter-receiver pair to be accurately aligned with one another so that inter-channel interference (ICI) may be mitigated [38]. Variation of the spectral efficiency for different constellation sizes as well as the number of transmitters is depicted in Figure 3.5b.

3.3.3 Optical spatial modulation

In the OSM MIMO technique, only a single LED transmitter array is activated for the entire transmission duration of one data symbol while all other arrays are in idle mode. To all intents and purposes, the constellation diagram of the signal is broadened by introducing an extra dimension referred to as the spatial dimension. The individual transmitters of the transmitting array are only activated one at a time when their pre-assigned unique spatial symbol is harmonious with the random spatial data symbol to be transmitted [167, 172, 175].

On the transmitter side, the data bits are classified into data symbols. Eventually the bits of each data symbol are delineated into two data carrying domains being the spatial and signal constellation domains [172, 176]. Both the spatial and signal domains are used to transmit the information at the same time. Thus, OSM yields a higher spectral efficiency of $\log_2(MN_t)$ bit/s/Hz with a computational complexity of $MN_t (3N_r - 1)$. The spectral efficiency of this scheme is shown in Figure 3.5c. The most significant bits of each data symbol are mapped by the spatial modulator into the spatial domain and the point at which the symbol is mapped is the one that decides on which LED is selected. The remaining least significant bits are then mapped into the signal domain and this symbol dictates the level of the luminous intensity that is emitted by the activated LED [172, 176]. The symbol point mapped into the signal domain propagates the channel through any of the digital modulation schemes including PAM, OOFDM and CSK. However, some modulation schemes such as PAM need to be modified to avoid the transmission of signals that have their intensities set to zero as they would lead to the loss of spatial information.

The path for a specific transmitter-receiver pair is characterised by its channel impulse response as defined by equation (2.18). The spatial placement of each LED determines the channel conditions of the optical signal which are unique for any given LED [31]. To that end, the receiver estimates the transmitted data symbol

based on the channel experiences of each signal on the corresponding transmitter-receiver path independently. With that being said, prior knowledge of $h(t)$ of all the propagation paths for each transmitter-receiver pair is essential on the receiver side. Normally the ML criterion is exploited for this estimation, therefore, the estimation of the received data symbol can be performed in a similar manner as specified in section 3.2.3 by equation (3.16). Here the smallest Euclidean distance is computed between the received signal and a set of all legitimate combinations in the spatial and signal domains [172, 176]. Hence enabling the possibility of spatial domain symbol detection. Due to the property of having only one transmitter emission per symbol duration, OSM is completely robust to ICI and this makes it less complex to decode the transmitted symbols [167, 176].

Some schemes, such as in [177, 178] allow the activation of more than one transmitter per symbol duration instead of just one. These schemes are termed generalised spatial modulation techniques. Activating more than one LED leads to improved spectral efficiency but at the expense of a complex design.

3.4 Multiple access schemes

Link layer services such as media access control are vitally important when there are more than one LED transmitters. The IEEE standard in [36] details link layer topologies as peer-to-peer, star and broadcast. Typical schemes used for MAC are; optical orthogonal frequency division multiple access [179, 180], optical carrier sense multiple access [181, 182] and optical code division multiple access (OCDMA) [183, 184]. OCDMA can be divided into two methods and they are synchronous OCDMA and asynchronous OCDMA.

Chapter 4

Design and Optimisation of a Colour-based Downlink OSM Scheme

This chapter presents the framework for the design and functionality of the proposed scheme's elements. The thesis particularly focuses on the conflicting interests between illuminance and signal transmission. This work is motivated by [89]. Unlike the work in [89], this work considers the optimisation of a multi-user system under various constraints in a heterogeneous user network (i.e users have different QoS requirements). The system is configured as an indoor LoS model based on the collaborative use CSK and OSM with IM/DD.

4.1 Functional Model

Joint utilisation of CSK and OSM is capable of meeting data rate specifications with low-order complexity. On the other hand, the integration of the two techniques yields an improved system performance as it reaps the benefits of elevated data rates from the colour domain and the spatial gain from the spatial domain [185,186]. An overview of the proposed system is depicted by the block diagram in Figure 4.1.

4.1.1 Signal Modulation

The core block diagram of the proposed scheme based on CSK is shown in Figure 4.2. Let $\mathbf{X}$ denote the input binary data carrying matrix block. This input block is defined by $N_b \times N$, where, N represents the total number of symbols in a colour-based OSM whereas N_b is the total number of bits transmitted per symbol and it is defined by

$$N_b = \log_2 M + \log_2 N_T, \quad (4.1)$$

where N_T is the total number of optical transmitter arrays. The vectors of $\mathbf{X}$, given by $[\mathbf{x}_0, \mathbf{x}_1, \dots, \mathbf{x}_{N-1}]^T$ are individually mapped to the available LED arrays and also to

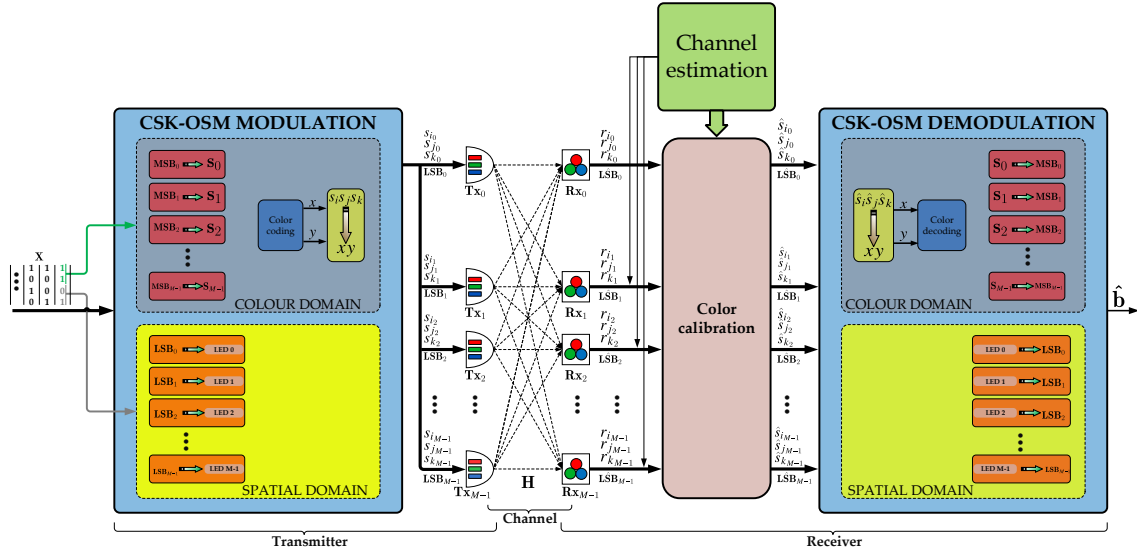


FIGURE 4.1: Architecture of the proposed system model. Adapted from [36, 185, 187]

the different constellation points in the colour (signal) domain. The most significant bits (MSBs) of the data symbol are mapped to CSK constellation points in the colour domain while the least significant bits (LSBs) of the data symbol are each mapped to the indices of the LED arrays for the selection and activation of the transmitting LED array in the spatial domain according to the pre-defined mapping table. The activated array will in-turn simultaneously illuminate the room and transmit data to all users. Like the colour domain, the spatial domain is also carrying data just like the signal domain. An illustration of the mapping procedure of the colour-based OSM using 8-CSK and four LED transmitter arrays is shown in Figure 4.2. During the mapping process, X is transformed into a new chromaticity mapping matrix Z , defined by $(N_T \times 2) \cdot N$. Subsequently, Z is transformed into an intensity matrix U with dimensions $(N_T \times 3) \cdot N$.

To delineate the mapping process, consider the first symbol $x_0 = [1 \ 1 \ 1 \ 0 \ 1]^T$ as depicted in Figure 4.2. The MSBs (first three bits) of this transmission symbol are mapped to one of the points in the 8-CSK signal domain, which in this case is expressed by s_7 . CSK constellation points are determined based on their xy -chromaticity coordinates as defined in [36] with reference to the CIE 1931 chromaticity diagram shown in Figure 3.2. The LSBs (last two bits) are used to select and activate one of the LED transmitter arrays, which in this case is array one denoted as LED 1. The same procedure is then followed for the next symbol $[0 \ 1 \ 0 \ 1 \ 1]^T$ until all N symbols have been transmitted [167].

Upon completion of the X conversion, the non-zero xy -chromaticity coordinates contained in the column vectors of the sub-matrices in Z can now be converted into their weighted x and y luminous intensity (chromaticity) values. This conversion is

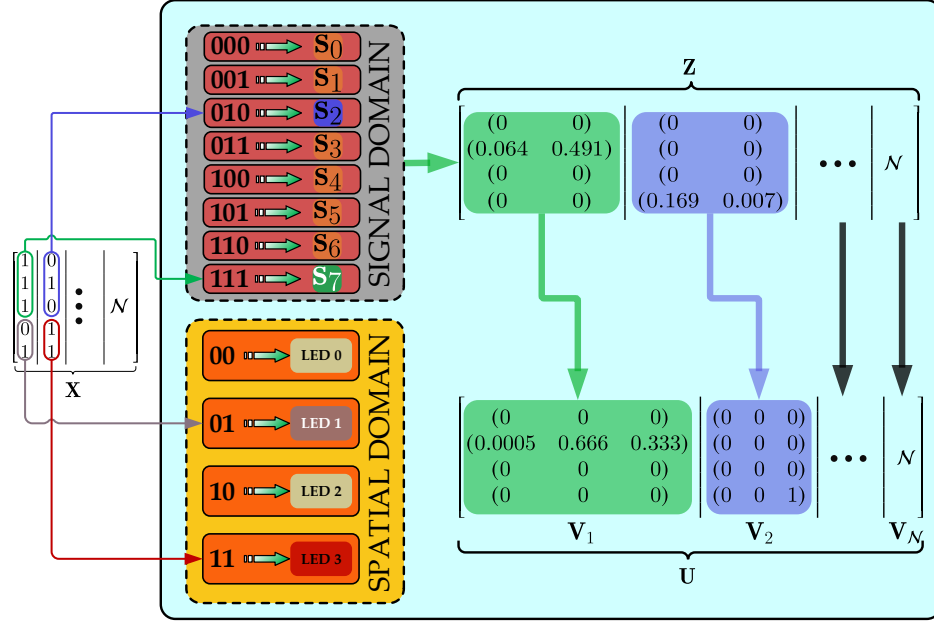


FIGURE 4.2: Colour-based OSM mapping procedure using 8-CSK and four LEDs.

facilitated by equation (3.10). As shown in Figure 4.2, all rows of the sub-matrices in $\mathbf{U}$ have only one non-zero row and this row corresponds with the LED number that is activated during symbol transmission. Detailed guidelines of CSK modulation are given by the IEEE 802.15.7 standard in [36]. The modulated intensities are then used to control the light emission of the transmitter following the same concept of OSM as defined in [167].

4.1.2 Optical Channel

An optical channel is characterised by the DC channel gain between the transmitter and receiver as defined by equation (2.27) [31]. In this thesis, a LoS model as described in section 2.3.2 is considered. Without consideration of the diffuse components that propagates through the reflecting surfaces of the room, the total instantaneous optical power at the receiver is expressed as

$$\mathbf{p}_r = \mathbf{H} \mathbf{p}_t^{\max}, \quad (4.2)$$

where $\mathbf{p}_t^{\max}$ is the maximum transmitting optical power. $\mathbf{H}$ is a $N_R \times N_T$ channel gain matrix, with N_R being the total number of receivers. The individual entries of $\mathbf{H}$ define the channel gains between the pairs of the multi-luminaire LEDs chip and the PD. For instance, $\mathbf{h}_{ij}$ is the channel gain between the RGB transmitter i and the RGB receiver j with the dimension of $(N_T \times 1) \cdot 3$.

4.1.3 Receiver

During one time interval T , of a colour-based OSM data symbol, one sub-matrix of $\mathbf{U}$ i.e. $\mathbf{V}_k$, is transmitted through a channel with N_T transmitters until all N symbols are transmitted. All transmitters have an array of RGB LED chips. The k -th received signal $\mathbf{r}_k$ at each receiver is expressed by equation (4.3).

$$\mathbf{r}_k = \mathcal{R}\mathbf{h}_{ij}^T \mathbf{V}_k + \mathbf{n}_k, \quad (4.3)$$

where $\mathbf{n}_k$ is the AWGN vector at the receiver. The noise vector has a variance of σ^2 and contains three independent and identically distributed elements with mean value of 0 and a noise variance of $\sigma_0^2 = \sigma^2/3$. The variance σ_0^2 of the AWGN at each detector is modelled as a summation of the shot noise and thermal noise [138]. The shot noise is defined by equation (3.1) and the thermal noise is defined by equation (3.3). Therefore, the SNR may be expressed as

$$\gamma_0 = \frac{\mathbb{E} \left\{ \|\mathcal{R}\mathbf{p}_k\|^2 \right\}}{\sigma^2}, \quad (4.4)$$

where $\mathbb{E} \{ \cdot \}$ is the operation for the expected value defining the average received power and $\mathbf{p}_k$ is the received power of all legitimate colour domain symbols.

4.1.4 Signal Demodulation

Due to the concurrent use of CSK and OSM modulation techniques, there is a need for joint demodulation of the CSK and OSM modulated symbols. The concatenated demodulation technique [185] or alternatively the joint ML based demodulation [188] are the two methods that could be used to demodulate the received signal. On account of improved performance and the ability to achieve demodulation of the colour-based OSM modulated symbols with a single attempt, the use of joint ML-based demodulation is taken into consideration. With this technique, as opposed to its counterpart, both the transmitter index and CSK signal points are detected at once. In order to demodulate the CSK-modulated signals, each receiver must constitute three PDs with each having a narrowband optical colour filter among other components. The filters must have different colours of red, green and blue.

A simple estimate of symbol $\mathbf{x}_k$, defined by $\hat{\mathbf{x}}_k$ can be done by the use of colour calibration to compensate for any impairments induced during signal propagation and the estimated symbol is defined by [36]

$$\hat{\mathbf{x}}_k = \mathcal{R}\mathbf{H}^{-1}\mathbf{r}_k. \quad (4.5)$$

In the event that $\mathbf{H}$ does not have a full rank, matrix inversion cannot be performed. Under such a circumstance, the pseudo inverse of $\mathbf{H}$ can be used. On the other hand, detection techniques such as the maximum likelihood-aided detectors and lattice-reduction-aided detectors may be used. In this work, an estimate of $\mathbf{x}_k$, is obtained by means of determining the *a posteriori* probability of each symbol $\mathbf{x}_{t,c}$, $\mathbf{x}_{t,c} \in \mathbf{X}$. Symbol $\mathbf{x}_{t,c}$ is expressed by

$$\mathbf{x}_{t,c} = \mathcal{R}\mathbf{H}\mathbf{V}_{t,c}, \quad (4.6)$$

where $\mathbf{V}_{t,c}$ is a $N_T \times 3$ matrix. The t -th row of matrix $\mathbf{V}_{t,c}$ contains the light weighted intensities (s_i , s_j and s_k) of the RGB LED chips while all other rows of the matrix contains values of zero signifying that there is only one specific transmitter activated during the transmission time interval of one symbol. The intensities of the RGB LED chips are obtained from the c -th point of the M -ary CSK constellation point. Hence the *a posteriori* probability is denoted by [139,188]

$$\begin{aligned} \Pr(\mathbf{x}_{t,c}|\mathbf{r}_k) &= p(\mathbf{r}_k|\mathbf{x}_{t,c}) \frac{\Pr(\mathbf{x}_{t,c})}{p(\mathbf{r}_k)} \\ &= \frac{\Pr(\mathbf{x}_{t,c})}{2\pi\sigma p(\mathbf{r}_k)} \exp\left(-\frac{\|\mathbf{r}_k - \mathbf{x}_{t,c}\|_{\mathbb{F}}^2}{2\sigma^2}\right), \end{aligned} \quad (4.7)$$

where $\Pr(\mathbf{x}_{t,c})$ is the *a priori* probability of symbol $\mathbf{x}_{t,c}$. Equation (4.7) may be represented in the log domain by

$$\text{lr}(\mathbf{x}_{t,c}|\mathbf{r}_k) = A - \left(\frac{\|\mathbf{r}_k - \mathbf{x}_{t,c}\|_{\mathbb{F}}^2}{2\sigma^2}\right), \quad (4.8)$$

where $A = \ln[\Pr(\mathbf{x}_{t,c})] - \ln[2\pi\sigma p(\mathbf{r}_k)]$. If there is no *a priori* information provided, A is the same for all symbols and $\text{lr}(\mathbf{x}_{t,c}|\mathbf{r}_k)$ is defined by $\ln[\Pr(\mathbf{x}_{t,c}|\mathbf{r}_k)]$. Symbol $\mathbf{x}_{t,c}$ can now be estimated using equation (4.8) as the ML function and the MAP estimate defined by [139,188]

$$\begin{aligned} \hat{\mathbf{x}}_k &= \{\hat{t}, \hat{c}\} = \arg\max_{t,c} [\text{lr}(\mathbf{x}_{t,c}|\mathbf{r}_k)] \\ &= \arg\min_{t,c} \|\mathbf{r}_k - \mathbf{x}_{t,c}\|_{\mathbb{F}}^2. \end{aligned} \quad (4.9)$$

The symbol $\mathbf{x}_{t,c}$, with the least distance from the received symbol $\mathbf{r}_k$, can now be regarded as the legitimate symbol $\hat{\mathbf{x}}_k$. The demodulated index of the LED is expressed as $\hat{t}$ and the constellation point is denoted by $\hat{c}$. Subsequently, the constellation point is converted back to the xy -chromaticity coordinates and finally the decoding module is used to retrieve the bit stream of symbol $\mathbf{x}_k$.

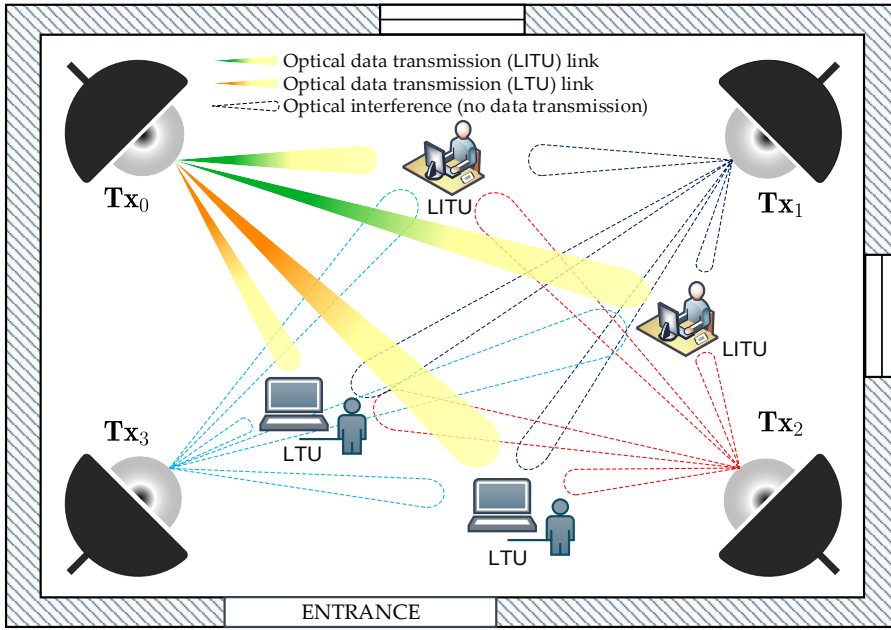


FIGURE 4.3: Colour-based OSM network with multiple transmitters, LITUs and LTUs.

4.2 System Optimisation Model

Consider a typical multicast and coordinated downlink indoor VLC system configured with a LoS model with L transmitters, G groups of users and U users. All transmitters have an array of RGB LED chips. The sets of transmitters, groups and users are denoted by $\mathcal{L} = \{1, \dots, L\}$, $\mathcal{G} = \{1, \dots, G\}$, and $\mathcal{U} = \{1, \dots, U\}$, respectively. As depicted in Figure 4.3, at any given instance of a data symbol transmission, only one of the L transmitters is selected and activated for data transmission as well as illumination while the other transmitters are strictly activated for illumination.

The number of groups that are served by transmitter l is defined as G_l , where the corresponding set of groups is given by $\mathcal{G}_l$. The number of users in group g is represented by U_g and the corresponding set of users is denoted by $\mathcal{U}_g$. It is worth noting that each user can be a member of only one group. Therefore, the sets of users who are members of different groups have no elements in common, i.e. they are disjoint and this is defined by $\mathcal{U}_a \cap \mathcal{U}_b = \emptyset, \forall a, b \in \mathcal{G}, a \neq b$. Each of the optical transmitter arrays have maximum and equal transmission power of $p_l^{\max}$.

Given a data symbol from the l -th transmitter to the u -th user, the transmitted signal, which is inferred to be non-negative for intensity modulation suitability, is defined by [162]

$$\mathbf{x}_l = \frac{\tau \mathbf{V}_g}{\sqrt{T}}, \quad (4.10)$$

where τ is the optical source conversion factor for intensity modulation in W/A and $\mathbf{V}_g \in \mathbb{R}^{L \times 3}$ is the data symbol matrix. The signal received by user u is given by

$$y_u = \mathcal{R} \mathbf{h}_{l,u}^\top \mathbf{x}_l + \sum_{j \in \mathcal{L} \setminus \{l\}} \mathbf{h}_{j,u}^\top \mathbf{p}_j + \mathbf{n}_u, \forall l \in \mathcal{L}, \forall u \in \mathcal{U}_g \quad (4.11)$$

where $\mathbf{h}_{l,u}^\top \in \mathbb{R}^{1 \times L}$ is the channel gain vector between the l -th transmitting LED array and the u -th user, $\mathbf{h}_{j,u}^\top \in \mathbb{R}^{1 \times L}$ is the channel gain vector between the j -th non-transmitting LED array and the u -th user. The noise vector of the u -th user is denoted by $\mathbf{n}_u \in \mathcal{CN}(0, \sigma^2)$ and it has the same properties as defined for equation (3.11) [169]. The notation $\mathcal{L} \setminus \{l\}$ represents a set $\mathcal{L}$ excluding member l . It now follows that, the SINR of user u belonging to group g is defined by

$$\text{SINR}_u = \frac{\left(\mathbf{h}_{l,u}^\top \mathbf{p}_l \right)^2}{\sum_{j \in \mathcal{L} \setminus \{l\}} \left(\mathbf{h}_{j,u}^\top \mathbf{p}_j \right)^2 + \sigma_u^2}. \quad (4.12)$$

The horizontal illuminance on surface $\mathbf{s}$, during symbol transmission is linearly dependent on the luminous intensities of the LED arrays [169], hence it is defined by

$$\mathcal{E}_s^{\text{tx}} = \underbrace{\frac{\mathcal{I}_{N_{l,u}} \cos^{m_1}(\phi)}{d_{l,u}^2 \cos(\psi)}}_{\mathcal{E}_{\text{TX}}} + \underbrace{\sum_{j \in \mathcal{L} \setminus \{l\}} \frac{\mathcal{I}_{N_{j,u}} \cos^{m_1}(\phi)}{d_{j,u}^2 \cos(\psi)}}_{\mathcal{E}_{\text{nTX}}}, \quad (4.13)$$

where $\mathcal{I}_{N_{l,u}}$ and $\mathcal{I}_{N_{j,u}}$ are the combined (i.e white) maximum luminous intensities of the transmitting array and non-transmitting arrays in the normal direction respectively. $\mathcal{E}_{\text{TX}}$ and $\mathcal{E}_{\text{nTX}}$ represent the illuminance of the transmitting and non-transmitting arrays respectively. For every work area, at any given instance, there is a minimum level of illuminance required for safety and visual efficiency without any form of visual strain. The minimum required illuminance at each work station is denoted by $\mathcal{E}_{r_u}$.

The illuminance distribution across the working area must conform to a certain factor which is termed as illuminance uniformity. It is defined as the ratio of the lowest illuminance level to the average illuminance of uniformly distributed N sensors in the room [189]. It is therefore denoted as

$$\epsilon = \frac{\min_n(\mathcal{E}_n)}{\frac{1}{N} \sum_{n=1}^N \mathcal{E}_n} \quad (4.14)$$

4.2.1 Assumptions

For this work, a few assumptions were made as follows:

- for each receiver, there is an uplink of either IR or RF.
- each transmitter array can determine the location of each mobile receiver.
- illuminance sensors with no decoders are distributed across the room.
- the variance of the AWGN at each detector is modelled as a summation of the shot and thermal noises.

4.3 Problem Formulation

In this thesis, one optimisation problem is formulated to minimise the luminous intensities of the transmitting arrays while fulfilling the SINR target for LITUs and taking into consideration the required minimum horizontal illuminance. Furthermore, the maximisation of the minimum SINR of LTUs while maintaining the SINR target for LITUs is taken into consideration. For simplicity, the optimisation problem is firstly formulated with the consideration of the SINR targets of the LITUs only. Since the human eye perceives illuminance logarithmically, the problem is cast as

$$(\mathbf{P1}) : \underset{\mathcal{I}_{Nl,u} > 0, \mathcal{I}_{Nj,u} \geq 0}{\text{minimise}} \quad \max_{\mathbf{s}} |\log \mathcal{E}_s^{\text{tx}} - \log \mathcal{E}_{r_u}|, \quad (4.15a)$$

$$\text{subject to} \quad \mathcal{I}_{Nl,u} \leq \mathcal{I}_{Nl,u}^{\text{csk}}, \quad \forall l \in \mathcal{L}, \quad (4.15b)$$

$$\mathcal{I}_{Nj,u} \leq \mathcal{I}_{Nj,u}^{\text{max}}, \quad \forall j \in \mathcal{L} \setminus \{l\}, \quad (4.15c)$$

$$\mathcal{E}_s^{\text{tx}} \geq \mathcal{E}_{r_u}, \quad \forall u \in \mathcal{U}_g, \quad (4.15d)$$

$$\frac{(\mathbf{h}_{l,u}^T \mathbf{p}_l)^2}{\sum_{j \in \mathcal{L} \setminus \{l\}} (\mathbf{h}_{j,u}^T \mathbf{p}_j)^2 + \sigma_u^2} \geq \gamma_u, \quad \forall u \in \mathcal{U}_g, \quad (4.15e)$$

where $\mathcal{I}_{Nl,u}^{\text{csk}}$ represents the CSK modulated intensities of the transmitting array and γ_u is the user SINR target.

4.3.1 Problem Solution: Part One

The formulated optimisation problem is a non-convex mixed-integer non-linear programming problem. **P1** becomes intricate with an increasing number of users and they are moving around the room [190]. As different symbols are transmitted and

the user's location coordinates changes, the SINR levels changes and the optimisation problem will have to be repeated with every change. To reduce the complexity of solving **P1** due to the aforementioned changes, the problem is solved in two parts following a pragmatic (i.e heuristic) approach.

To simplify the complexity of the problem, the CSK-OSM scheme is firstly re-configured to re-assign the transmitting LED array based on the distance from the centre of the transmitter to the centre of the receiver. If the selected LED array is furthest from the user, the algorithm re-assigns transmission to the LED array closest to the user.

Secondly, it is noted that the objective function presented in (4.15a) is non-convex and this makes it difficult to solve it efficiently. Nonetheless, this problem can easily be transformed into its convex equivalent based on the properties of logarithmic functions. To describe the transformation procedure, let $\max_s |\log (\mathcal{E}_s^{\text{tx}} / \mathcal{E}_{r_u})|$ be represented by $\max |\log (A/B)|$, then, it follows that

$$\begin{aligned} \max |\log (A/B)| &= \begin{cases} \log (A/B), & A/B \geq 1 \\ -\log (B/A), & A/B \leq 1 \end{cases}, \\ &= \begin{cases} \arg \max (|\log (A/B)|) = \arg \max (\log (A/B)), & A/B \geq 1 \\ \arg \max (|\log (B/A)|) = \arg \max (\log (B/A)), & A/B \leq 1 \end{cases}. \end{aligned} \quad (4.16)$$

Based on equation (4.16), the objective function can now be turned into a convex form and hence re-formulate **P1** for the determination of a global solution. Hence the problem **P1** in equation (4.15) can now be cast as

$$(\mathbf{P2}): \underset{\mathcal{I}_{N_{l,u}} > 0, \mathcal{I}_{N_{j,u}} \geq 0}{\text{minimise}} \quad \max_s f(\mathcal{E}_s^{\text{tx}} / \mathcal{E}_{r_u}), \quad (4.17a)$$

$$\text{subject to} \quad \mathcal{I}_{N_{l,u}} \leq \mathcal{I}_{N_{l,u}}^{\text{csk}}, \quad \forall l \in \mathcal{L}, \quad (4.17b)$$

$$\mathcal{I}_{N_{j,u}} \leq \mathcal{I}_{N_{j,u}}^{\text{max}}, \quad \forall j \in \mathcal{L} \setminus \{l\}, \quad (4.17c)$$

$$\mathcal{E}_s^{\text{tx}} \geq \mathcal{E}_{r_u}, \quad \forall u \in \mathcal{U}_g, \quad (4.17d)$$

$$\frac{(\mathbf{h}_{l,u} \mathbf{p}_l)^2}{\sum_{j \in \mathcal{L} \setminus \{l\}} (\mathbf{h}_{j,u}^T \mathbf{p}_j)^2 + \sigma_u^2} \geq \gamma_u, \quad \forall u \in \mathcal{U}_g, \quad (4.17e)$$

where $f(x) = \max\{x, 1/x\}$. Now it is noted that the objective function $f(x)$ is non-linear, non-differentiable, and convex due to the monotonic increase of a logarithmic function. It is also noticed that equation (4.17e) is non-convex neither is it concave.

For problem **P2** to be solved efficiently through the utilisation of the available convex optimisation techniques, the constraint stated in equation (4.17e) should be converted into a convex function. One way to achieve convexity of equation (4.17e) is to firstly re-write the constraint as

$$\left(\mathbf{h}_{l,u}^\top \mathbf{p}_l\right)^2 \geq \gamma_u \sum_{j \in \mathcal{L} \setminus \{l\}} \left(\mathbf{h}_{j,u}^\top \mathbf{p}_j\right)^2 + \sigma_u^2, \quad (4.18)$$

it then follows that, taking the square root on both sides, makes the constraint a convex second order cone constraint denoted by [191]

$$\mathbf{h}_{l,u}^\top \mathbf{p}_l \geq \sqrt{\gamma_u \sum_{j \in \mathcal{L} \setminus \{l\}} \left(\mathbf{h}_{j,u}^\top \mathbf{p}_j\right)^2 + \sigma_u^2}. \quad (4.19)$$

Problem **P2** can now be efficiently solved, it is however worth noting that, this optimisation problem may highly likely not satisfy the solution with equality based on the fact that the proposed algorithm aims to satisfy two objectives, being the light intensity and the SINR targets. For instance, in the event that the SINR target threshold is low, the target will be satisfied with a high SINR as compared to a higher SINR target threshold, which may likely not be satisfied due to elevated interference from the non-transmitting LED arrays. To maintain the desired illuminance while satisfying the user SINR target, Algorithm 1 is proposed.

4.3.2 Problem Solution: Part Two

The second problem, which is a sub-problem of **P2**, involves the maximisation of the minimum SINR of a group of LTUs while guaranteeing and maintaining the SINR target for a group of LITUs. The SINR targets for LITUs are defined by $\{\xi_u\}_{u \in \mathcal{U}}$ and those of LTUs are defined by $\{\delta_u\}_{u \in \mathcal{U}}$. This problem entails SINR balancing subject to distinct power of the optical transmitter. Therefore, the problem is cast as

$$(\mathbf{P3}) : \underset{I_{Nl,u} > 0, I_{Nj,u} \geq 0}{\text{maximise}} \quad \min. \delta_u, \quad (4.20a)$$

$$\text{subject to} \quad \gamma_u \geq \xi_u, \quad \forall u \in \mathcal{U}_g, \quad (4.20b)$$

$$I_{Nl,u} \leq I_{Nl,u}^{\text{csk}}, \quad \forall l \in \mathcal{L}, \quad (4.20c)$$

$$I_{Nj,u} \leq I_{Nj,u}^{\text{max}}, \quad \forall j \in \mathcal{L} \setminus \{l\}, \quad (4.20d)$$

$$\mathcal{E}_s^{\text{tx}} \geq \mathcal{E}_{r_u}, \quad \forall u \in \mathcal{U}_g. \quad (4.20e)$$

Following the same conversion procedure for the constraint in equation (4.17e), the constraint stated in equation (4.20b) can be converted to a convex second order cone constraint. The solution for this problem can be realised by the adapting the mixed QoS distributed algorithm proposed in [192]. For this work, due to the time constraints and the fact that the main objective of this work is already satisfied, this part of the problem is left out for future works.

Algorithm 1: Algorithm for optimal illuminance and symbol transmission with the required SINR for LITUs

Input: $\mathcal{I}_{N_{l,u}}^{\max}, \forall l \in \mathcal{L}, \gamma_u, \mathcal{E}_r, s_l$
Initialisation: Set $0 \leq \mathcal{I}_{N_{l,u}} \leq \mathcal{I}_{N_{l,u}}^{\max}, \forall l \in \mathcal{L}$
Result: Maintain $\mathcal{E}_r$ and ensure γ_u

- 1 Set $\mathcal{E}_r$ using (4.13); ▷ Required illuminance without transmission
- 2 Compute $\mathcal{E}_s^{\max}$ using (4.13); ▷ Maximum illuminance without transmission
- 3 **for** $l = 1$ **to** $\mathcal{L}$ **do**
- 4 **for** $u = 1$ **to** $\mathcal{U}$ **do**
- 5 Compute $d_{l,u}$; ▷ Distance between LED array l and user u
- 6 Append $d_{l,u}$ to an array;
- 7 **for** $u = 1$ **to** $\mathcal{U}_g$ **do**
- 8 Extract $d_{l,u}$ from an array in step 6; ▷ For LITU users only
- 9 **if** $d_{l,u}$ is the shortest to the LITU **then**
- 10 Set l as the transmitting LED array;
- 11 **else**
- 12 Re-assign l to the LED array with the shortest distance to the LITU.
- 13 Solve (P2) with the constraint in (4.19);
- 14 Update $\mathcal{I}_{N_{l,u}} = s_l \mathcal{I}_{N_{l,u}}^*$; ▷ Optimal intensity for the transmitting array
- 15 Set $\mathcal{I}_{N_{j,u}}^*, \forall j \in \mathcal{L} \setminus \{l\}$; ▷ Optimal intensities for non-transmitting arrays
- 16 Compute $\mathcal{E}_s^{\text{tx}*}$ using (4.13); ▷ Optimal illuminance during transmission
- 17 Update $\mathcal{E}_r = \mathcal{E}_s^{\text{tx}*}$
- 18 **repeat**
- 19 Step 3
- 20 **until** All symbols are transmitted;

Table 4.1: LED simulation parameters.

Parameter	LED Chip		
	Red	Green	Blue
Peak wavelength (nm)	620	520	450
Luminous flux (lm)	140.60	230.20	60.20
Forward voltage (V)	2.30	3.70	3.50
Forward current (mA)	700	700	700
Semi-angle (°)	60	60	60

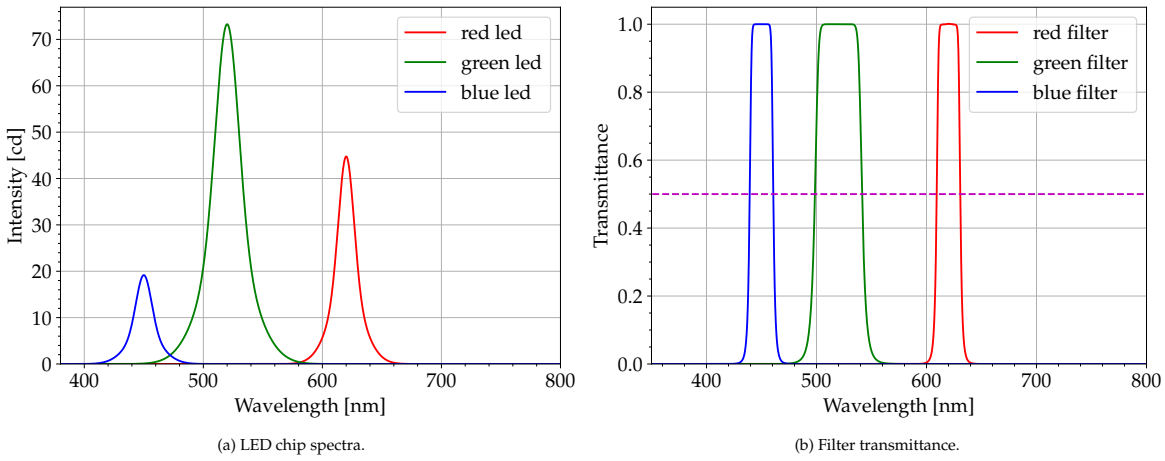


FIGURE 4.4: The combined RGB LED spectra and optical filter transmittance curves.

4.4 Setup and Simulation Parameters

To analyse the performance of the system, some computer-based simulations based on different configurations as described in this subsection were carried out. All computations for the simulation plots presented herein were carried out using Python version 3.8.5 and CVXPY version 1.0.31 [193, 194], which are both open source. Transmitters are mounted to flush with the surface of the ceiling of a general indoor working space measuring $(5 \times 5 \times 3) \text{ m}^3$. The receiving plane is 1 m above the floor and the receivers are positioned facing the ceiling. There are four light fixtures which are each made up of an array of twenty (4×5) RGB LEDs. These fixtures are positioned at $(1.25, 1.25)$, $(-1.25, 1.25)$, $(1.25, -1.25)$ and $(-1.25, -1.25)$. Each user is equipped with a receiver made up of three PDs, each with a responsivity of 0.6 A/W , refractive index of 1.5, FOV of 60° and an active area of 3 cm^2 . Each PD is preceded by either a red, green or blue optical filter with optical gain of unity.

A selected set of parameters of the RGB LED used for simulations are tabulated in Table 4.1. The LED spectra of the RGB chips making up the transmitters is shown in Figure 4.4a. Figure 4.4b shows typical transmittance curves for the RGB optical filters.

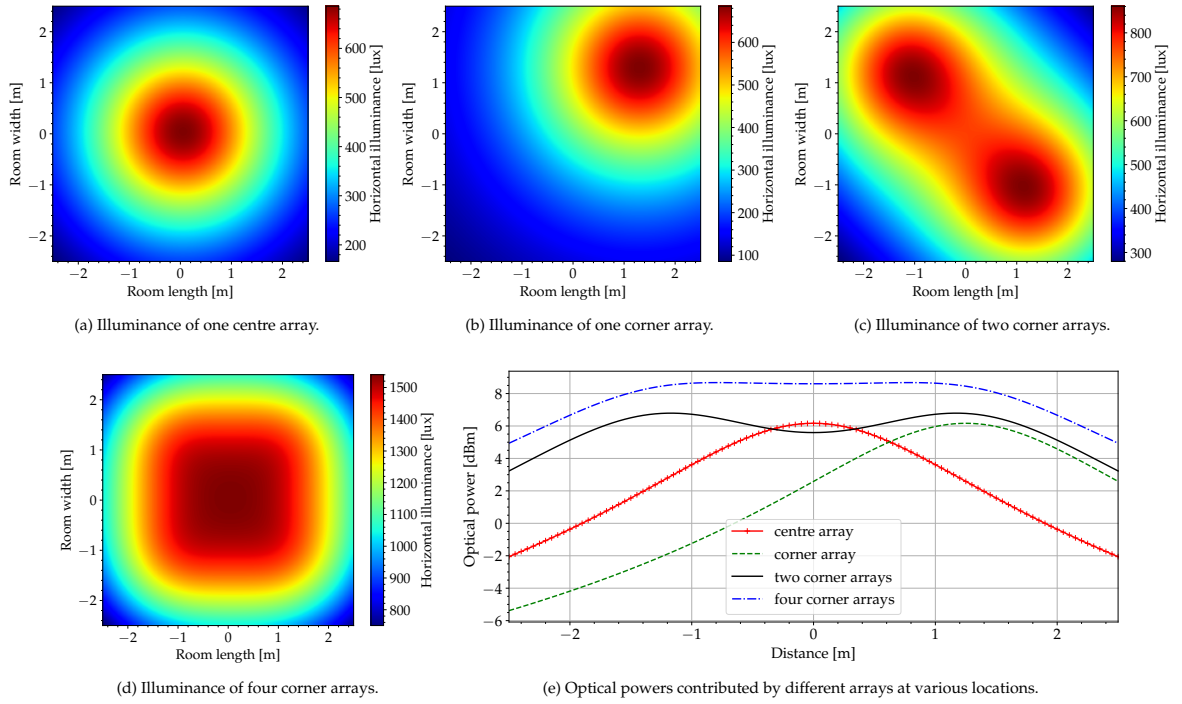


FIGURE 4.5: Illuminance levels and power distribution of various array configurations without symbol transmission.

4.5 Numerical Results

According to the International Organisation for Standardisation (ISO), the illuminance level of an indoor space should be from 300 lux to 1500 lux, depending on the tasks being carried out. Using the parameters in Table 4.1, the illuminance patterns as well as the plots of the received optical power at different points of the room for various LED array configurations are shown in Figure 4.5. Figure 4.5a depicts the illuminance patterns for one array located at the centre of the room. Figure 4.5c depicts the illuminance patterns for two arrays located at the opposite corners of the room whereas Figure 4.5d show the illuminance pattern for four arrays located at the corners of the room. Figure 4.5e shows the plots of the received power across the room under different array configurations. As expected, configurations where a single LED array is used, low levels of illuminance are experienced, hence low optical power levels at the receiver whereas the use of numerous arrays yields higher levels of illuminance, resulting in increased optical power as seen in Figures 4.5d and 4.5e. Adequate and uniform levels of illuminance are in accordance with ISO standards for configurations of at least two LED arrays.

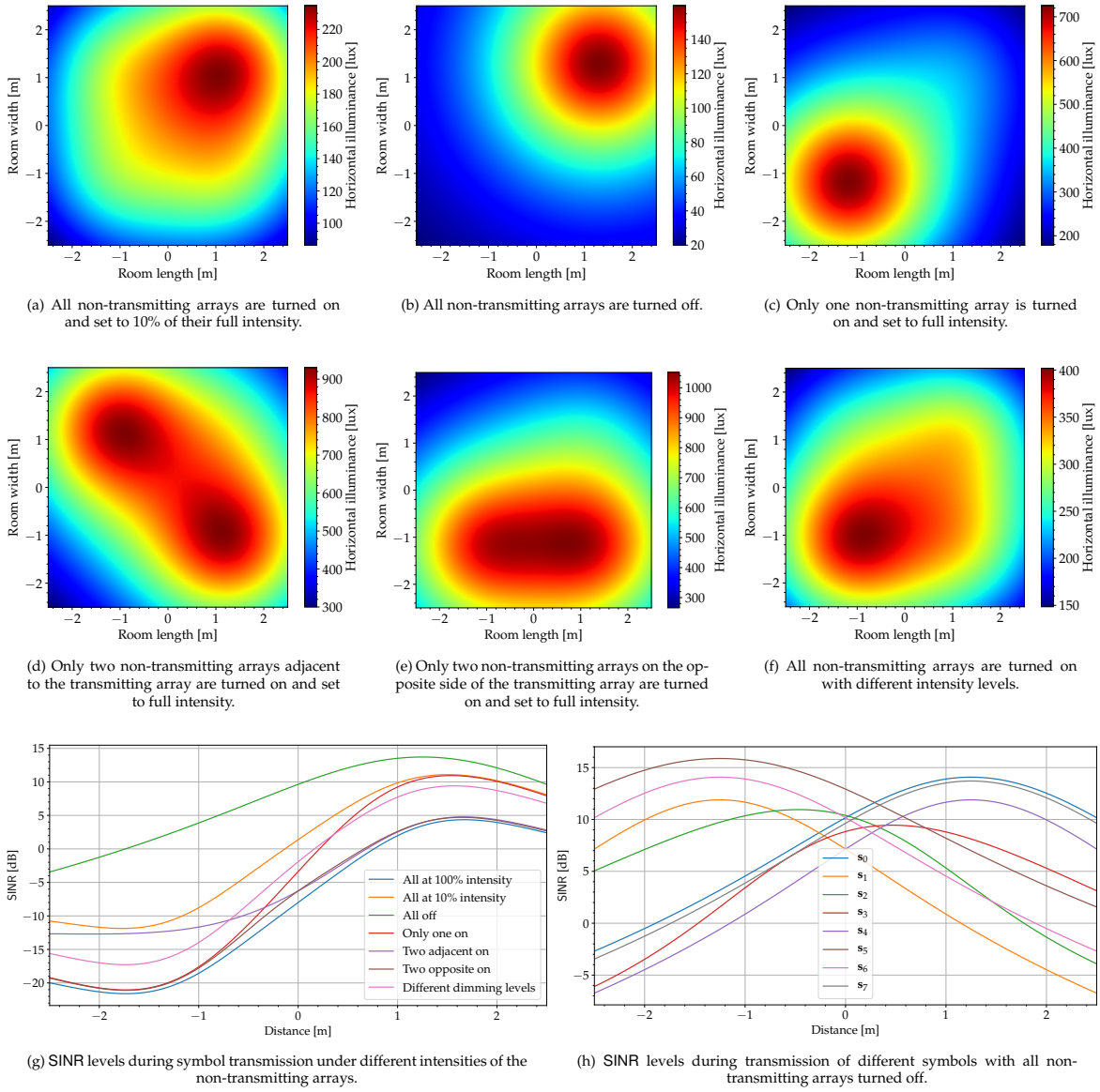


FIGURE 4.6: Heat-maps of the illuminance and SINR plots across the room with varying intensities of the non-transmitting arrays during one symbol transmission using 8CSK-OSM: Figures 4.6a to 4.6f show the illuminance plots for different array configurations. Figure 4.6g shows the SINR variations for one symbol under varying intensities. Figure 4.6h shows the SINR variations for different symbols.

Figure 4.6 shows the heat-maps depicting indoor illuminance levels during signal transmission under distinct intensities of the non-transmitting arrays. It is observed in Figure 4.6a to Figure 4.6f that the illuminance distribution depicted in Figure 4.5d is altered differently when the intensity combinations differ, subsequently affecting the SINR (see Figure 4.6g). Comparing Figures 4.5b and 4.6b, illuminance levels are drastically reduced when non-transmitting arrays are off. The depictions in Figure 4.6, clearly show that different settings for intensity levels of the transmitting and non-transmitting arrays may lead to some challenges in relation to the

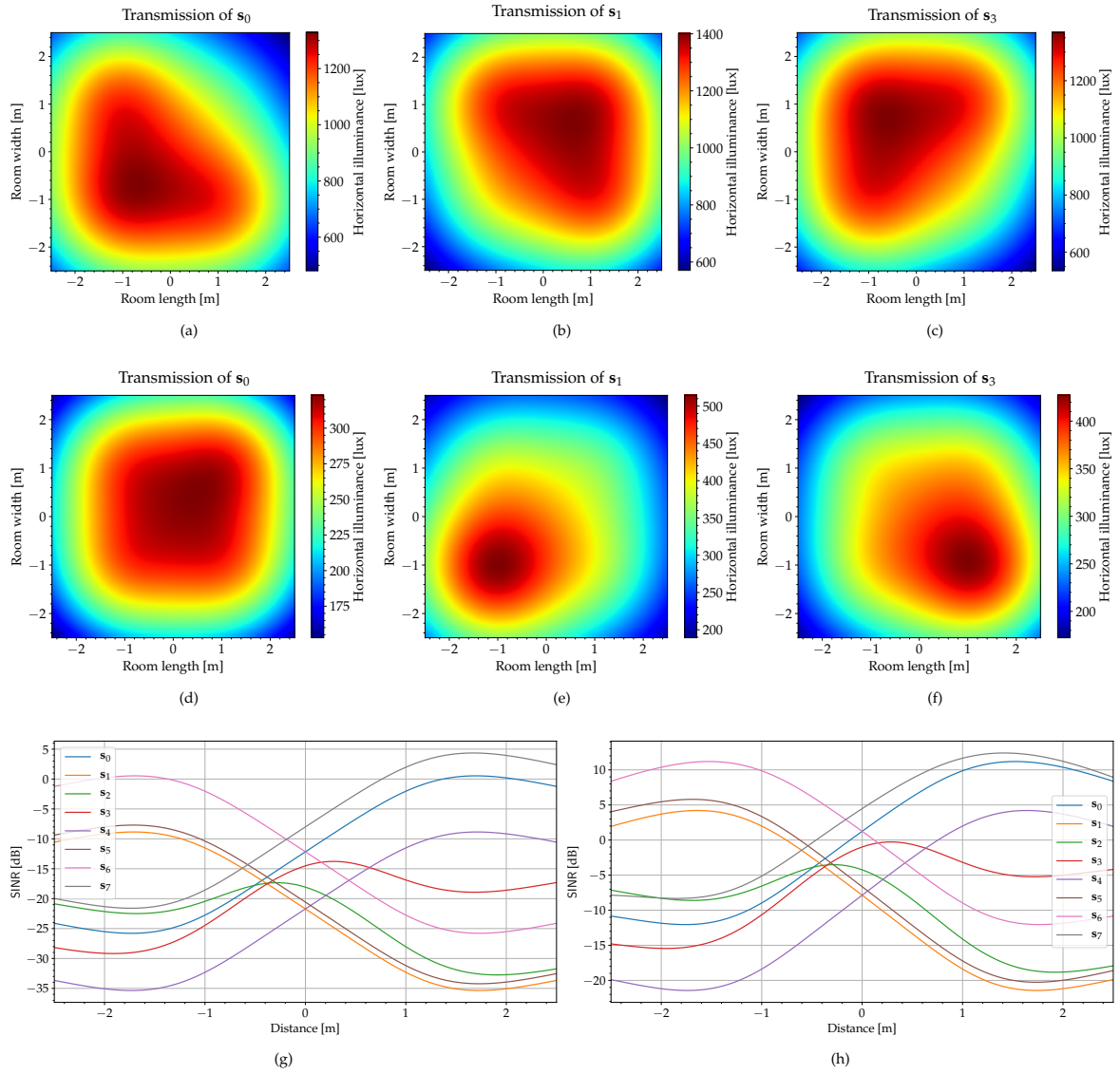


FIGURE 4.7: Heat-maps of the illuminance and SINR plots across the room without and with dimming of the non-transmitting arrays during the transmission of different symbols using 8CSK-OSM: Figures 4.7a to 4.7c show the illuminance without dimming for transmission of s_0 , s_1 and s_3 . Figures 4.7d to 4.7f show the illuminance with dimming for transmission of s_0 , s_1 and s_3 . Figure 4.7g shows the SINR variations for all symbols without dimming the non-transmitting arrays. Figure 4.7h shows the SINR variations for all symbols with dimming of all the non-transmitting arrays by 80%.

minimum illuminance and signal transmission. These challenges, among others, include; high energy consumption, under utilisation of resources, high levels of interference leading to poor QoS and visual disturbance during transmission owing to varying levels of illuminance¹. The proposed system adapts the configuration in Figure 4.5d and the intensities of the non-transmitting arrays are not equally

¹The equivalent 3D patterns and SINR plots for 4CSK-OSM and 16CSK-OSM of Figure 4.6 are shown in Appendix B Figure B.1.

dimmed or brightened during transmission.

The illuminance distribution patterns during symbol transmission are shown in Figures 4.7a to 4.7c. During the transmission of s_0 , as seen in Figure 4.7a, the illuminance levels are higher for the working areas under non-transmitting arrays while there is very little illuminance for areas under the transmitting array located at (1.25, 1.25). During the transmission of the subsequent symbols, the same phenomenon exists and this is depicted in Figure 4.7b for s_1 and Figure 4.7c for s_3 using the transmitters located at $(-1.25, -1.25)$ and $(1.25, -1.25)$ respectively². Although, illuminance levels are within the standardised levels during symbol transmission, it will be very difficult if not infeasible for the receiver to decode the transmitted symbols due to high interference levels. Figure 4.7g depicts very low SINR for all symbols compared to Figure 4.6h, where all non-transmitting arrays are turned off.

The illuminance patterns during the transmission of the same symbols as in Figures 4.7a to 4.7c when the non-transmitting LED arrays are providing only 20% of their total intensities are shown in Figures 4.7d to 4.7f. Comparing Figures 4.7g and 4.7h, it shows that the SINR improves significantly when the non-transmitting arrays are dimmed. Nonetheless, this may drastically decrease the illuminance levels to below the required values at other room locations. From Figures 4.7d to 4.7f, it is observed that the illuminance levels at the furthest point from the transmitter are at most 200 lux during the transmission of any symbol.

With the aid of the proposed algorithm, the optimised illuminance and SINR level plots are depicted in Figures 4.8 to 4.11. In Figure 4.8, the simulations were initially done with only the consideration of illuminance without the SINR constraint. In all of these maps and plots, the LITU is considered to be placed at Rx_0 while the LTU is considered to be placed at Rx_1 . Comparing Figures 4.7a to 4.7c with all of the sub-figures in Figure 4.8, it is clear that when considering only the illumination constraint after transmitter re-assignment, the proposed algorithm is capable of satisfying the required illuminance levels (in this case, the required illuminance was set to 550 lux) at different user locations with no need to perform manual dimming. It is worth noting however that the algorithm provides the required illuminance to the LTU mostly from the non-transmitting arrays. This means that there is a high likelihood of very poor SINR levels for latency tolerant users. This is the motivating factor for the introduction of part two of the formulated problem. However, the solution to reduce the impacts of the said interference is not considered in this work and it forms part of the future work to be carried out. For a possible solution to the aforementioned problem, the reader is directed to the work in [192], which

²The equivalent 3D patterns and SINR plots for 4CSK-OSM and 16CSK-OSM of Figure 4.7 are shown in Appendix B Figures B.2 and B.3.

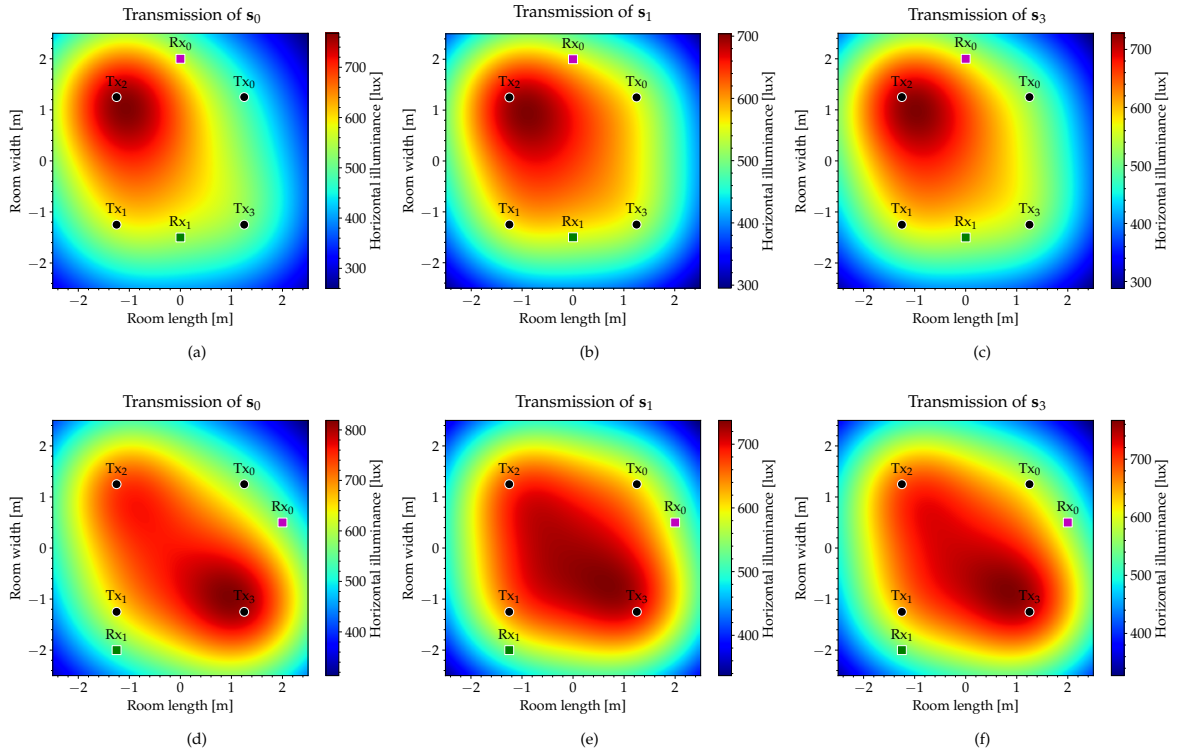


FIGURE 4.8: Heat-maps of the optimised illuminance offering the required illuminance of 550 lux (after transmitter re-assignment but without the SINR constraint) during transmission of different symbols using 8CSK-OSM with receivers at different positions: Figures 4.8a to 4.8c shows the illuminance with the LITU and LTU located at (0, 2) and (0, -1.5), respectively. Figures 4.8d to 4.8f shows the illuminance with the LITU and LTU located at (2, 0.5) and (-1.25, -2), respectively, during transmission of s_0 , s_1 and s_3 .

deals with mixed-QoS SINR balancing between LITUs and LTUs. Adaptation of the work in [192] as part of the solution to problem part two may result in the capability of providing fairness for all types of network users.

Figure 4.9 shows the SINR levels per symbol with and without transmitter re-assignment for different user configurations during symbol transmission³, respectively. From these plots, it suggests that the target SINR should be bounded to the maximum and minimum system values due to the varying SINR levels of the individual symbols. Moreover, the satisfaction of the SINR target largely depends on the location of the user, therefore user stations may need to be pre-defined in a practical real-time application. For mobile users, the mobile range needs to be restricted to the locality of the transmitting LED array during the transmission of a symbol.

It is observed in Figures 4.10a to 4.10f, by way of comparison with Figures 4.8a to 4.8f that the consideration of the SINR constraint does not affect the illuminance levels in an undesirable manner because the desired illuminance level is met in all

³The equivalent SINR plots for Figure 4.9 using 4CSK-OSM and 16CSK-OSM are shown in Appendix B Figures C.1 and C.2.

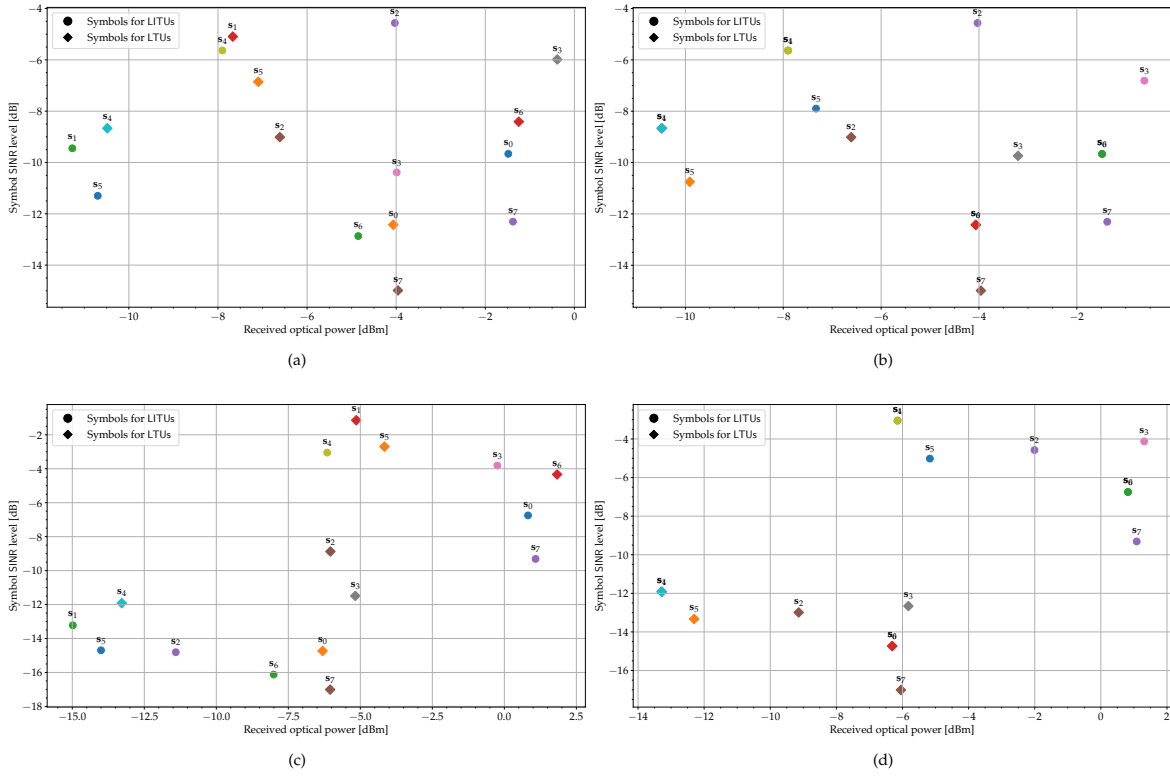


FIGURE 4.9: SINR levels (without the SINR constraint) during transmission of different symbols using 8CSK-OSM with receivers at different positions: Figure 4.9a shows the SINR levels against received power for each symbol at (0, 2) (LITU location) and at (0, -1.5) (LTU location) before transmitter re-assignment and Figure 4.9b shows the same plot after transmitter re-assignment. Figure 4.9c shows the SINR levels against received power for each symbol at (2, 0.5) (LITU location) and at (-1.25, -2) (LTU location) before transmitter re-assignment and Figure 4.9d shows the same plot after transmitter re-assignment.

cases. On the other hand, the simulations in Figure 4.11 shows that the SINR target, which was set to -10 dB for this simulation is met for all of the LITU transmitted symbols⁴. It is seen that, the SINR levels for LTU are below the SINR target and the best disposable levels from the system are provided. However, some of CSK symbols may result in an infeasible solution in the event that the desired illuminance is very high and the transmitting power is very low. This is likely to occur during the transmission of symbols with very low optical power due to the principle of CSK modulation technique, which reduces the optical intensity of the RGB chips.

The minimum and average data rate for the types of network users are depicted in Figure 4.12. With reference to Figures 4.10 and 4.12, it is observed that with an increase in the number of LITU or LTU, the data rates significantly decreases due to the amount of interference from the non-transmitting arrays as they compensate

⁴The equivalent SINR plots for Figure 4.11 using 4CSK-OSM and 16CSK-OSM are shown in Appendix B Figures C.3 and C.4.

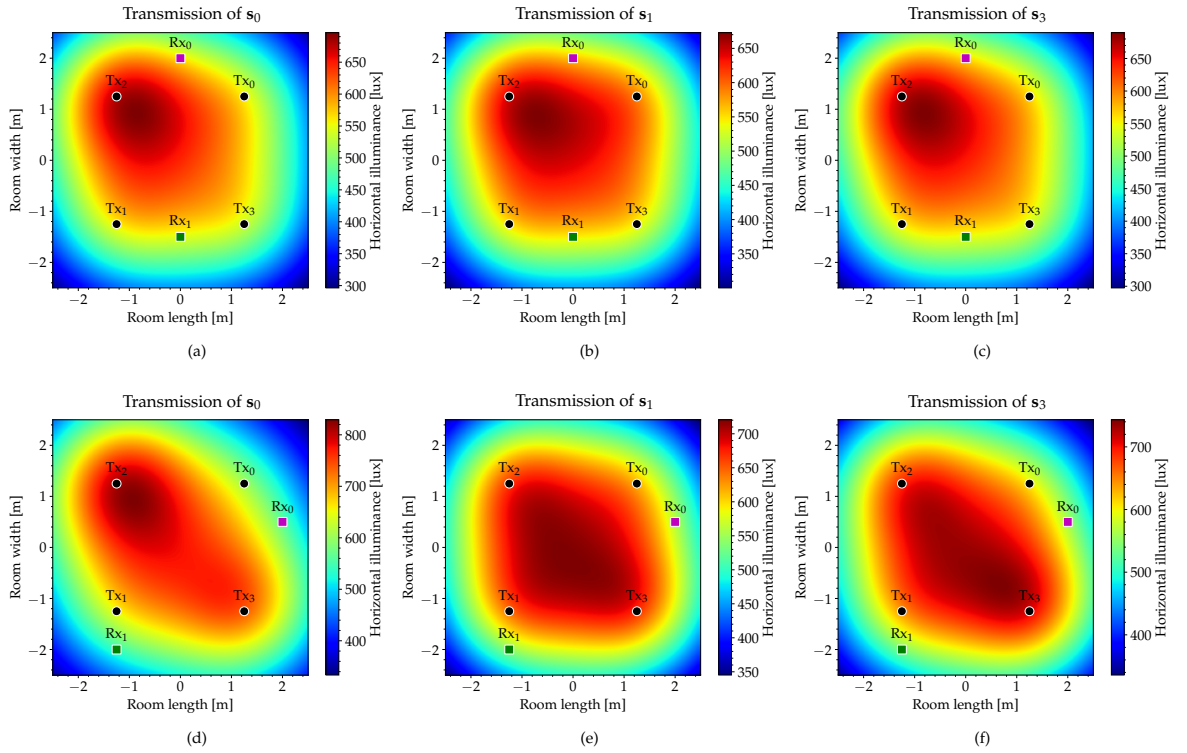


FIGURE 4.10: Heat-maps of the optimised illuminance offering the required illuminance of 550 lux and meeting the SINR level target of -10 dB during transmission of different symbols using 8CSK-OSM with receivers at different positions: Figures 4.10a to 4.10c shows the illuminance with the LITU and LTU located at $(0, 2)$ and $(0, -1.5)$, respectively. Figures 4.10d to 4.10f shows the illuminance with the LITU and LTU located at $(2, 0.5)$ and $(-1.25, -2)$, respectively, during transmission of s_0 , s_1 and s_3 .

for illuminance. However, with the obtained SINR levels shown in Figures 4.9a and 4.9b, the average data rate in worst case scenarios for both types of users for the defined room dimensions can be met with bounded SINR targets for LITUs. So, in general, the proposed algorithm (at least for the first part of the problem without SINR balancing) is capable of providing the desired illuminance at all user positions with a satisfactory SINR level for LITUs, which is the main aim of this work.

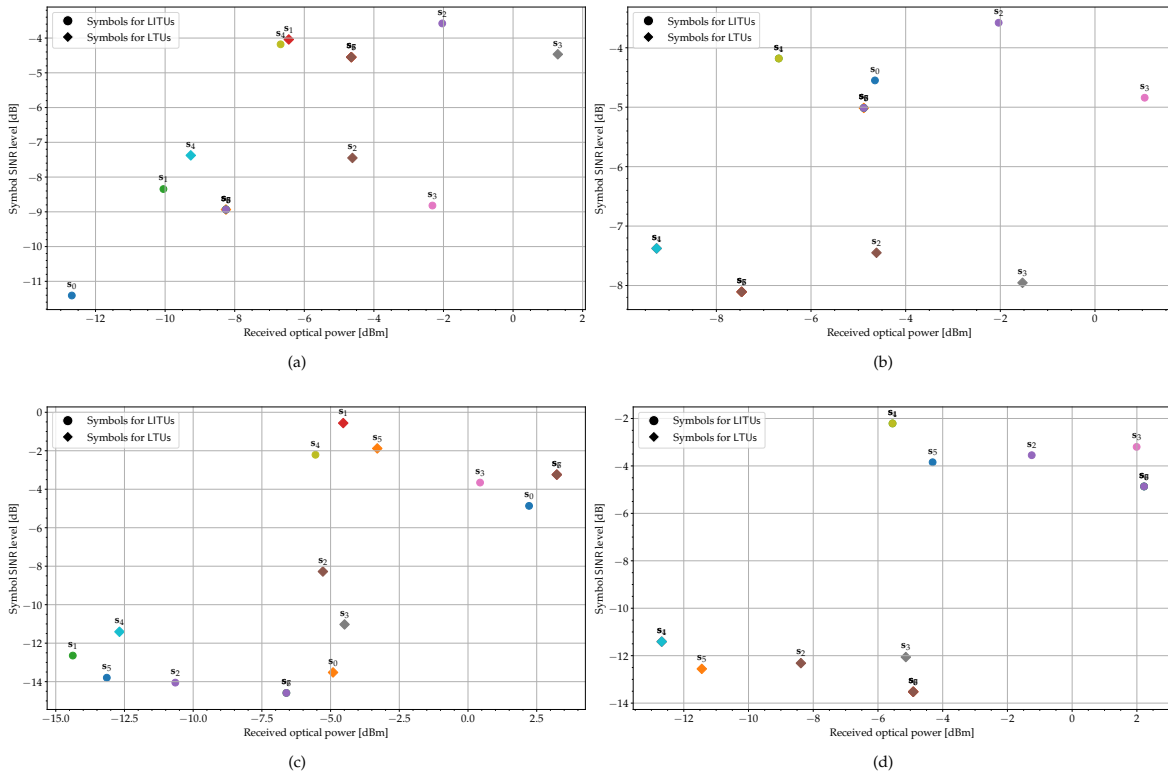


FIGURE 4.11: SINR levels (with the SINR constraint) during transmission of different symbols using 8CSK-OSM with receivers at different positions: Figure 4.11a shows the SINR levels against received power for each symbol at (0, 2) (LITU location) and at (0, -1.5) (LTU location) before transmitter re-assignment and Figure 4.11b shows the same plot after transmitter re-assignment. Figure 4.11c shows the SINR levels against received power for each symbol at (2, 0.5) (LITU location) and at (-1.25, -2) (LTU location) before transmitter re-assignment and Figure 4.11d shows the same plot after transmitter re-assignment.

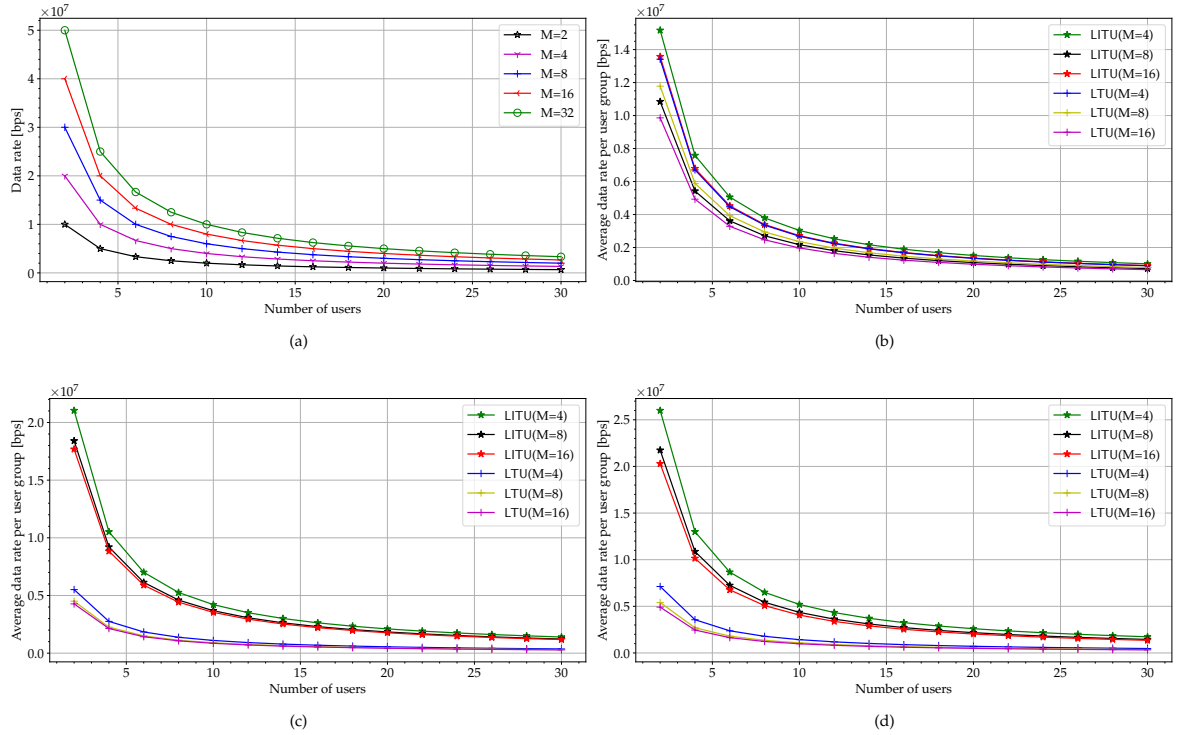


FIGURE 4.12: Effects of the CSK modulation order, transmitter re-assignment and SINR constraint on the data rates for LITUs and LTUs: Figure 4.12a depicts the ideal data rates against the number of (LITUs) and (LTUs) for various CSK modulation orders. Figure 4.12b shows the average data rates against the number of (LITUs) and (LTUs) for various CSK modulation orders without both transmitter re-assignment and SINR constraint. Figure 4.12c depicts the average data rates against the number of (LITUs) and (LTUs) for various CSK modulation orders after transmitter re-assignment and without SINR constraint. Figure 4.12d shows the average data rates against the number of (LITUs) and (LTUs) for various CSK modulation orders with both transmitter re-assignment and SINR constraint.

Chapter 5

Conclusions and Future Directions

5.1 Conclusion

The aim of this research was to design, develop, optimise and analyse a modulation scheme for an indoor LoS VLC system. Optimal VLC technology can be easily deployed due to the advancements of solid-state lighting. The use of VLC can solve many problems such as energy efficiency, relief of the spectrum crunch from the congested RF band. Furthermore, with this technology, it is feasible to provide data transmission where other communication technologies are known to cause problems such as electromagnetic interference. The contributions and findings of this thesis are:

- In Chapter 4, a colour-based optical spatial modulation scheme with two types of users based on latency tolerance was designed and developed. Additionally, an optimisation algorithm for the simultaneous provision of the desired illuminance and SINR target was also developed.
- In comparison to other VLC works where the conventional spatial modulation is applied, this thesis proposed a low-complexity algorithm with the consideration of heterogeneous network users. The proposed algorithm is capable of satisfying the user's required illuminance level provided it is specified within the recommended levels as per the ISO standards. Furthermore, the algorithm can meet the SINR targets for the LITUs while minimising the optical power of the LED arrays without affecting the required illuminance level. This finding addressed both the first and second objectives while partially addressing the third objective.
- The simulations for the solution proposed in section 4.3.2, which fully addresses SINR balancing were not carried out in this research and it was left out as part of future works since the main aim of the project was achieved and time resources were not allowing to fully optimise the system.

- Intensive research input is needed for the realisation of VLC-based networks. The consolidation of VLC with other technologies comes with impediments that needs to be addressed before the wide deployment of practical systems.

5.2 Future Works

During the undertaking of this research work several challenges and other ideas which are worth consideration emerged. Some of the notable challenges and future research ideas are listed as follows;

- There is need for robust optimisation algorithms which are capable of addressing multiple objectives with little trade-off between the conflicting interests of illumination and SINR targets of network users.
- In this thesis, the optimisation algorithm considers the satisfaction of the standard illuminance levels in areas where the users are located instead of the entire room. The satisfaction of illuminance at all points may be achieved by the introduction of another constraint of uniformity to the optimisation problem. The introduction of illumination uniformity will aid with the provision of the standard illuminance levels at all indoor positions. However, this constraint comes at a penalty of either low SINR or low illuminance, therefore, future optimisation systems will have to adapt to the challenging trade-off between illuminance and data transmission.
- To improve the SINR levels, it is worth investigating the possibility of optical intensity scaling for the RGB LED chips after modulation. The scaling of the RGB intensities will lead to elevated data rates without affecting the CSK modulated symbol intensities.
- The re-assignment of the transmitting LED array may lead to very poor SINR levels for the latency-tolerant network users even when the max-min fairness approach is applied. Therefore, it is of significance to investigate other spatial modulation techniques such as the generalised spatial modulation.

5.3 Consolidation of VLC with other technologies

Most of the current and emerging wireless communication trends including 6G among others are shifting to the right of the electromagnetic spectrum to employ higher frequency bands [195]. With this, VLC is one of the fairly advancing trends

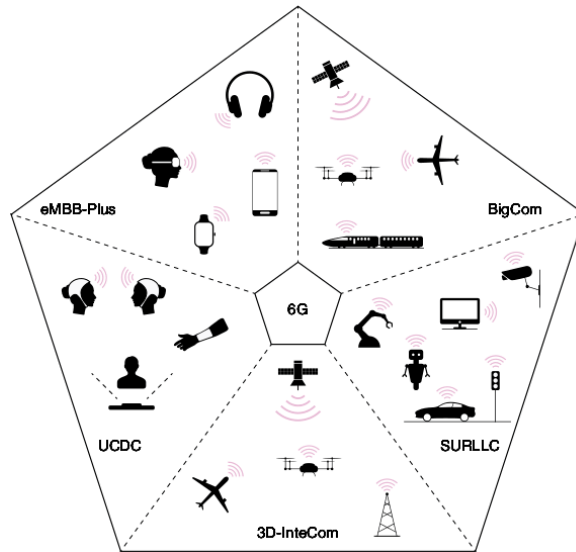


FIGURE 5.1: Supported use cases of a 6G network [199].

becoming more relevant for the establishment of some of the pipelined wireless communication techniques. Specifically, the properties of VLC, its objectives as well as those of the recently developed and upcoming techniques qualifies the amalgamation of VLC with present and future cutting edge technologies [196].

5.3.1 Fifth (5G) and Sixth Generation (6G) Networks

5G networks have the capability of supporting an enormous amount of data traffic for a very large number of wireless connections with diverse QoS requirements [197]. A complete 5G system is designed to meet the specifications of three use cases of 5G [198]. During the development of 5G technology, which is as of present being rolled out for commercialised use around the world [199], VLC was and still is anticipated to be a complementary technique to the mm-Wave technique for short range indoor-based communication in 5G networks.

Following the deployment of 5G, the development and standardisation of 6G will take place between 2020 and 2030 [196]. Different countries around the globe are setting up research initiatives, which will enable the development and inception of 6G. Some of the prominent initiatives towards 6G are the 6G flagship project in Finland [200] and the establishment of a 6G research centre by South Korea. Since 6G networks will be expected to operate optimally while accommodating a very huge amount data traffic, the most feasible way in which this can be achieved is the use of different non-congested frequency bands. Unlike 5G, 6G is expected to concurrently support all of the three use cases as well as some additional use cases [199]. The use cases of 6G are shown in Figure 5.1.

It is imperative for this use case to be highly competent in optimisation of cellular networks with regard to big data transmission, handover and interference mitigation. For instance, there will be accurate indoor positioning, which could be provided by the use of VLC, which currently has a very high accuracy in the range [201]. Moreover, cellular coverage using VLC for indoor scenery is one area which could be directed towards 6G development. More research efforts will be aimed at the development of new hardware, algorithms for NLoS systems if VLC is considered for inclusion in beyond 5G technologies [202].

As opposed to the RF technology, which is expensive, heavily regulated and congested, OWC technologies are capable of meeting the requirements of a wide range of use cases in 6G. This allows different kinds of communication including but not limited to point-to-multipoint, chip-to-chip, point to point, machine-to-machine and vehicle-to-infrastructure to be supported with ease [203].

Appendix A

Color-shift Keying Mapping Tables

Table A.1: 4-CSK symbol mapping.

Band centre (nm)	4-CSK		
	b	q	s
753	[0 0] $\Rightarrow$ (0.734, 0.265)		[1 0 0]
509	[0 1] $\Rightarrow$ (0.011, 0.733)		[0 1 0]
429	[1 0] $\Rightarrow$ (0.169, 0.007)		[0 0 1]
	[1 1] $\Rightarrow$ (0.305, 0.335)		[0.334 0.333 0.333]

Table A.2: 8-CSK symbol mapping.

Band centre (nm)	8-CSK		
	b	q	s
753	[0 0 0] $\Rightarrow$ (0.734, 0.265)		[1 0 0]
509	[0 0 1] $\Rightarrow$ (0.011, 0.733)		[0 1 0]
429	[0 1 0] $\Rightarrow$ (0.169, 0.007)		[0 0 1]
	[0 1 1] $\Rightarrow$ (0.452, 0.136)		[0.501 0 0.499]
	[1 0 0] $\Rightarrow$ (0.188, 0.237)		[0.111 0.277 0.112]
	[1 0 1] $\Rightarrow$ (0.470, 0.366)		[0.610 0.278 0.112]
	[1 1 0] $\Rightarrow$ (0.252, 0.577)		[0.333 0.667 0]
	[1 1 1] $\Rightarrow$ (0.064, 0.491)		[0.0005 0.666 0.333]

Table A.3: 16-CSK symbol mapping.

Band centre (nm)	16-CSK		
	b	q	s
753	[0 0 0 0] $\Rightarrow$ (0.734, 0.265)		[1 0 0]
509	[0 0 0 1] $\Rightarrow$ (0.011, 0.733)		[0 1 0]
429	[0 0 1 0] $\Rightarrow$ (0.169, 0.007)		[0 0 1]
	[0 0 1 1] $\Rightarrow$ (0.064, 0.491)		[0.0005 0.666 0.333]
	[0 1 0 0] $\Rightarrow$ (0.493, 0.421)		[0.667 0.333 0]
	[0 1 0 1] $\Rightarrow$ (0.252, 0.577)		[0.333 0.667 0]
	[0 1 1 0] $\Rightarrow$ (0.305, 0.335)		[0.334 0.333 0.333]
	[0 1 1 1] $\Rightarrow$ (0.350, 0.444)		[0.445 0.444 0.112]
	[1 0 0 0] $\Rightarrow$ (0.109, 0.600)		[0.111 0.777 0.112]
	[1 0 0 1] $\Rightarrow$ (0.162, 0.358)		[0.112 0.444 0.445]
	[1 0 1 0] $\Rightarrow$ (0.116, 0.249)		[0 0.336 0.667]
	[1 0 1 1] $\Rightarrow$ (0.214, 0.116)		[0.111 0.111 0.779]
	[1 1 0 0] $\Rightarrow$ (0.546, 0.179)		[0.667 0 0.333]
	[1 1 0 1] $\Rightarrow$ (0.591, 0.288)		[0.778 0.111 0.112]
	[1 1 1 0] $\Rightarrow$ (0.400, 0.200)		[0.440 0.110 0.451]
	[1 1 1 1] $\Rightarrow$ (0.357, 0.093)		[0.333 0 0.667]

Appendix B

3D Illuminance During Transmission

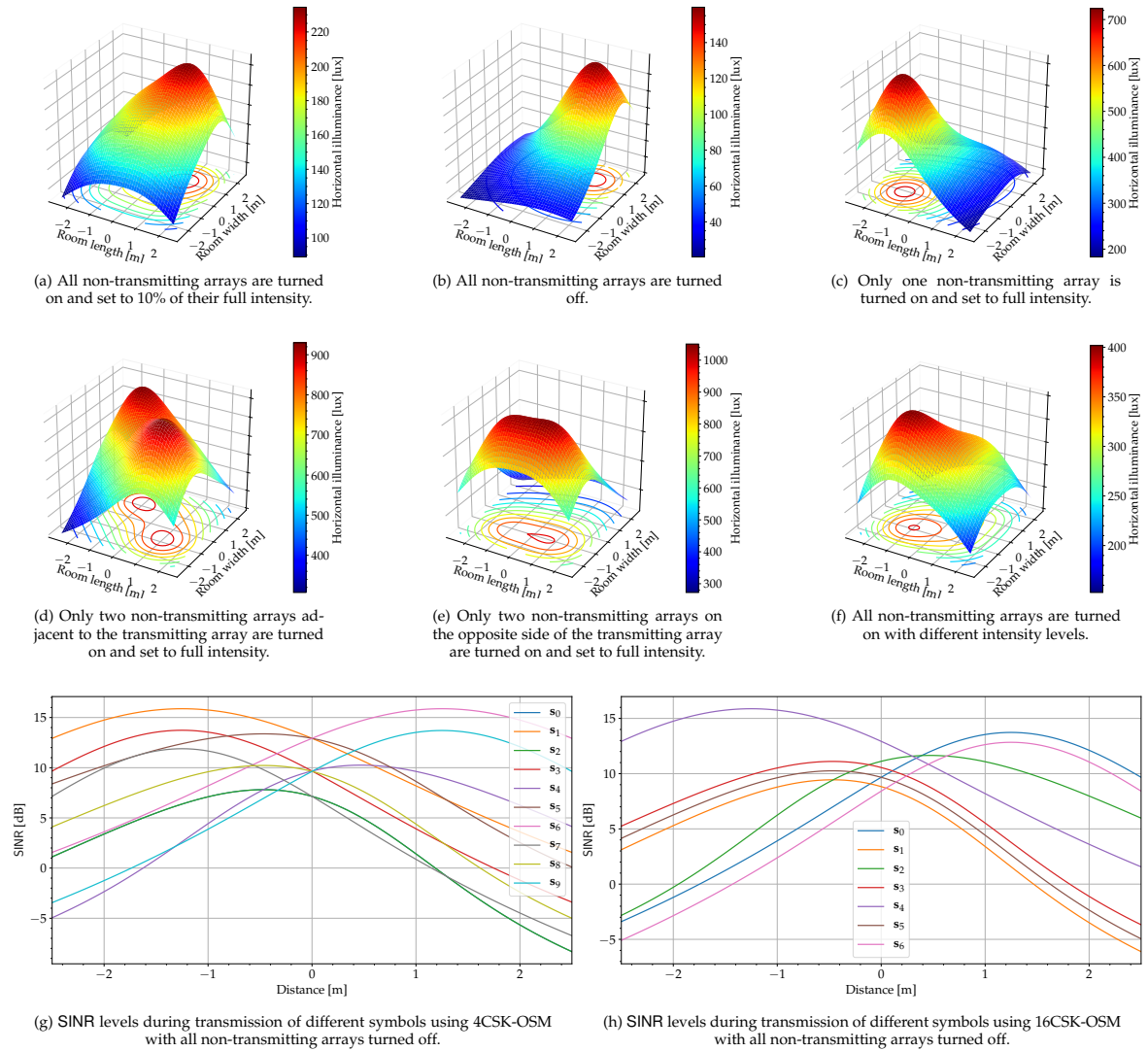


FIGURE B.1: 3D illuminance views and SINR plots across the room with varying intensities of the non-transmitting arrays during one symbol transmission: Figures B.1a to B.1f shows the illuminance plots for different array configurations. Figure B.1g shows the SINR variations for different symbols using 4CSK-OSM with non-transmitting arrays turned off. Figure B.1h shows the SINR variations for different symbols using 16CSK-OSM with non-transmitting arrays turned off.

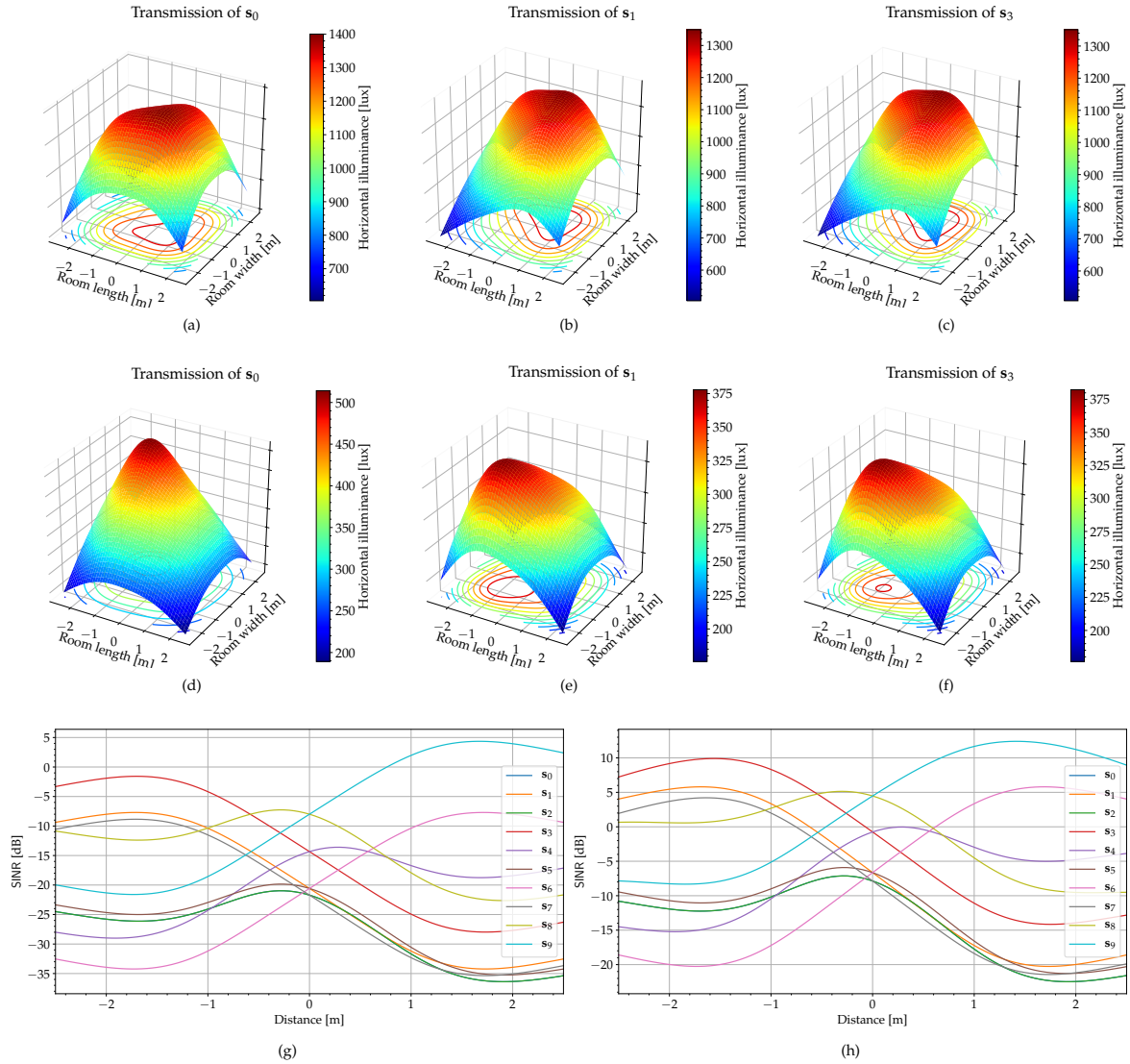


FIGURE B.2: 3D plots of the illuminance and SINR plots across the room without and with dimming of the non-transmitting arrays during the transmission of different symbols using 4CSK-OSM: Figures B.2a to B.2c show the illuminance without dimming for transmission of s_0 , s_1 and s_3 . Figures B.2d to B.2f show the illuminance with dimming for transmission of s_0 , s_1 and s_3 . Figure B.2g shows the SINR variations for all symbols without dimming the non-transmitting arrays. Figure B.2h shows the SINR variations for all symbols with dimming of all the non-transmitting arrays by 80%.

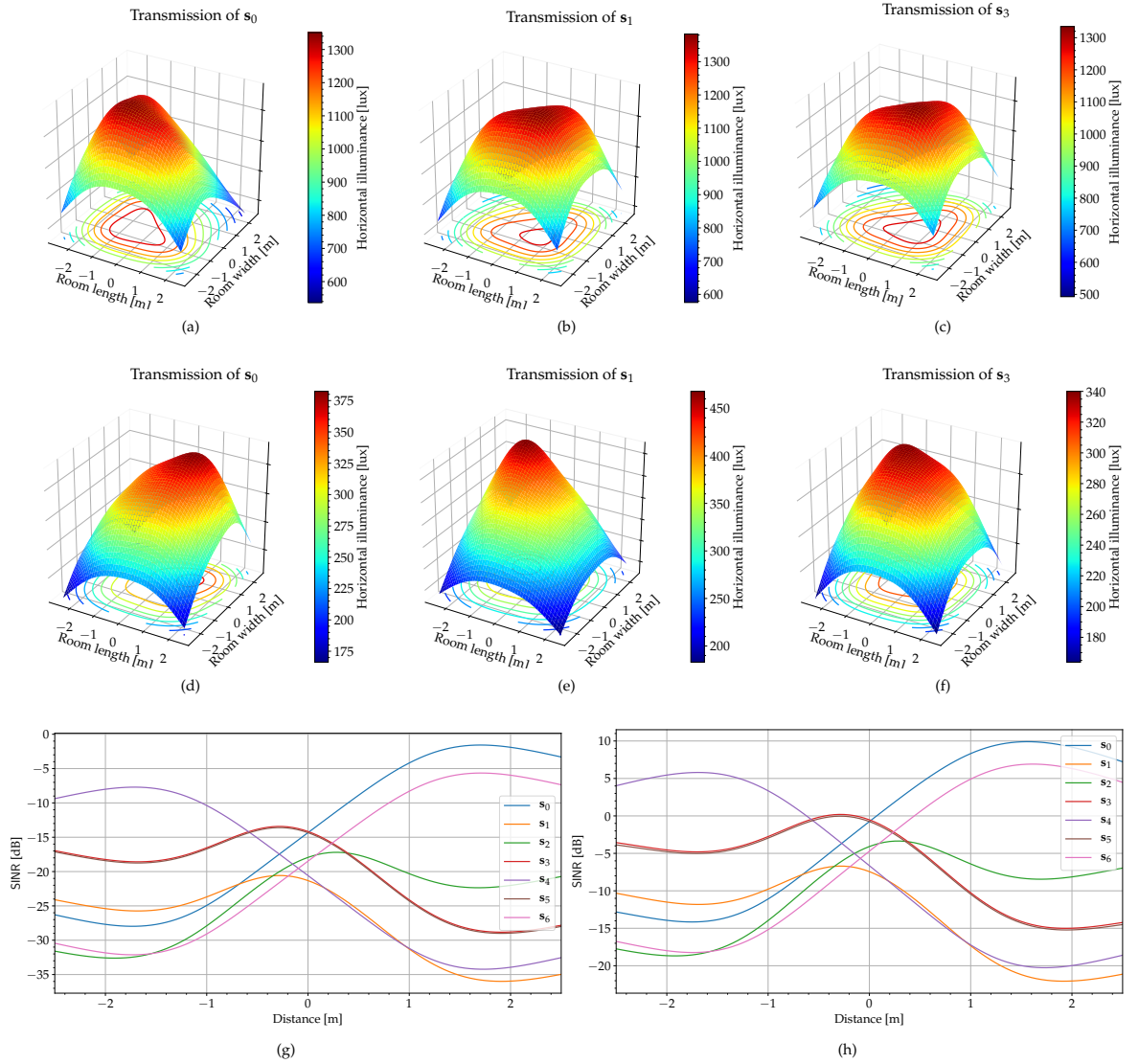


FIGURE B.3: 3D plots of the illuminance and SINR plots across the room without and with dimming of the non-transmitting arrays during the transmission of different symbols using 16CSK-OSM: Figures B.3a to B.3c show the illuminance without dimming for transmission of s_0 , s_1 and s_3 . Figures B.3d to B.3f show the illuminance with dimming for transmission of s_0 , s_1 and s_3 . Figure B.3g shows the SINR variations for all symbols without dimming the non-transmitting arrays. Figure B.3h shows the SINR variations for all symbols with dimming of all the non-transmitting arrays by 80%.

Appendix C

Signal-to-noise-ratio Levels

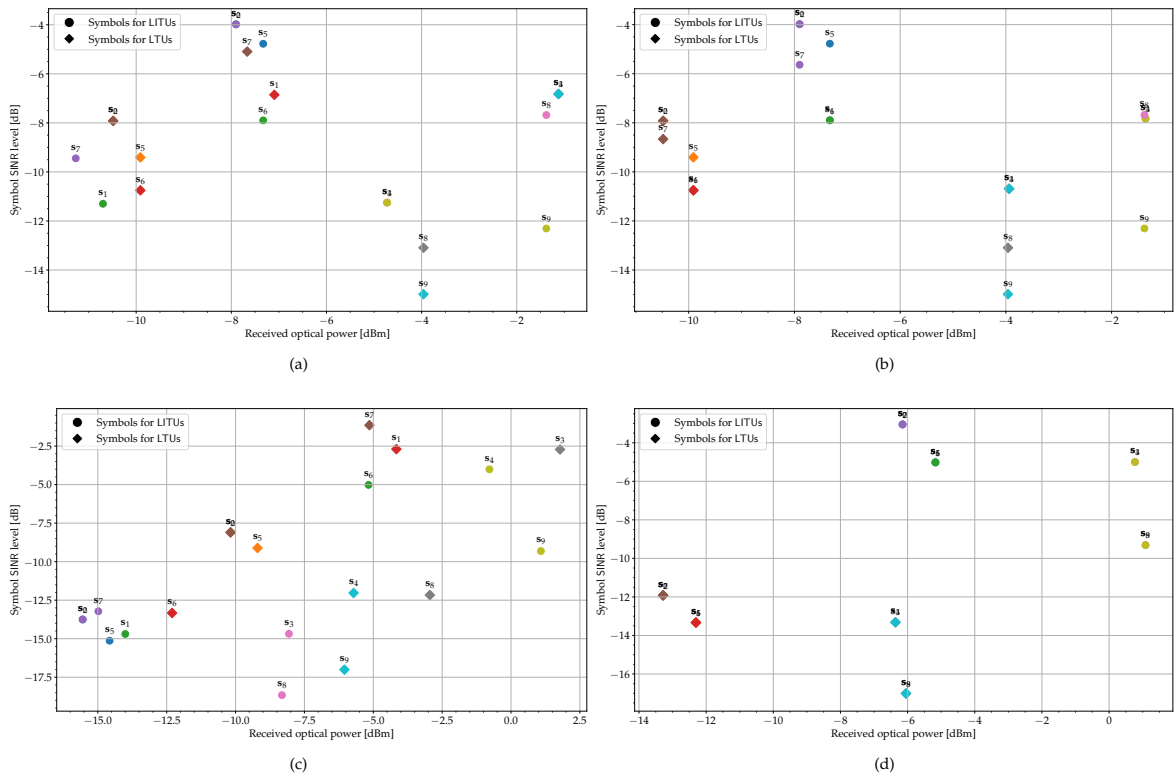


FIGURE C.1: SINR levels (without the SINR constraint) during transmission of different symbols using 4CSK-OSM with receivers at different positions: Figure C.1a shows the SINR levels against received power for each symbol at (0, 2) (LITU location) and at (0, -1.5) (LTU location) before transmitter re-assignment and Figure C.1b shows the same plot after transmitter re-assignment. Figure C.1c shows the SINR levels against received power for each symbol at (2, 0.5) (LITU location) and at (-1.25, -2) (LTU location) before transmitter re-assignment and Figure C.1d shows the same plot after transmitter re-assignment.

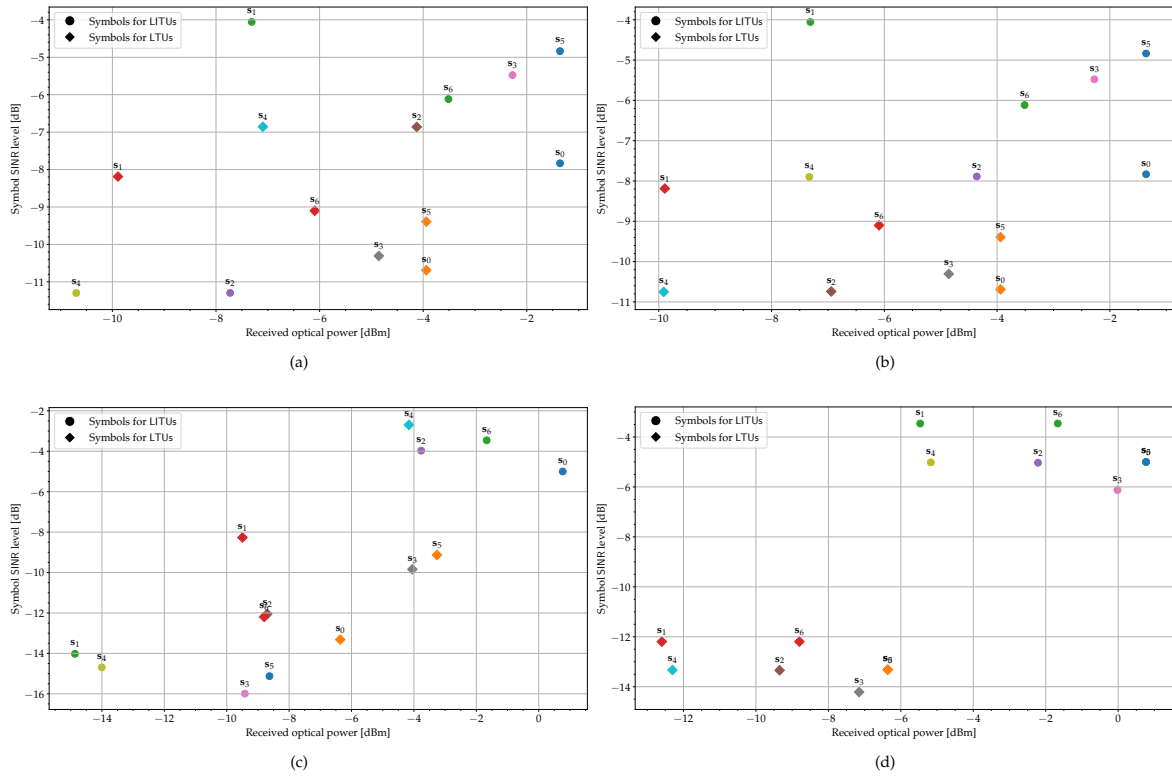


FIGURE C.2: SINR levels (without the SINR constraint) during transmission of different symbols using 16CSK-OSM with receivers at different positions: Figure C.2a shows the SINR levels against received power for each symbol at (0, 2) (LITU location) and at (0, -1.5) (LTU location) before transmitter re-assignment and Figure C.1b shows the same plot after transmitter re-assignment. Figure C.2c shows the SINR levels against received power for each symbol at (2, 0.5) (LITU location) and at (-1.25, -2) (LTU location) before transmitter re-assignment and Figure C.2d shows the same plot after transmitter re-assignment.

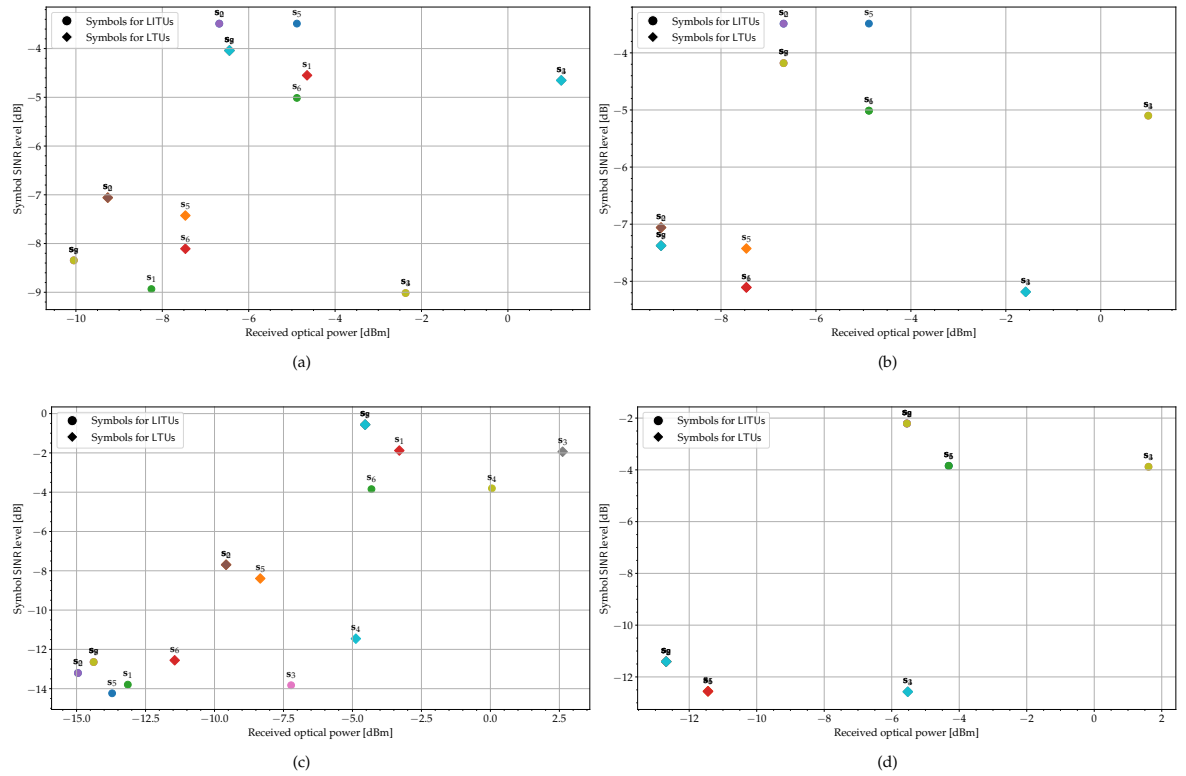


FIGURE C.3: SINR levels (with the SINR constraint) during transmission of different symbols using 4CSK-OSM with receivers at different positions: Figure C.3a shows the SINR levels against received power for each symbol at (0, 2) (LITU location) and at (0, -1.5) (LTU location) before transmitter re-assignment and Figure C.3b shows the same plot after transmitter re-assignment. Figure C.3c shows the SINR levels against received power for each symbol at (2, 0.5) (LITU location) and at (-1.25, -2) (LTU location) before transmitter re-assignment and Figure C.3d shows the same plot after transmitter re-assignment.

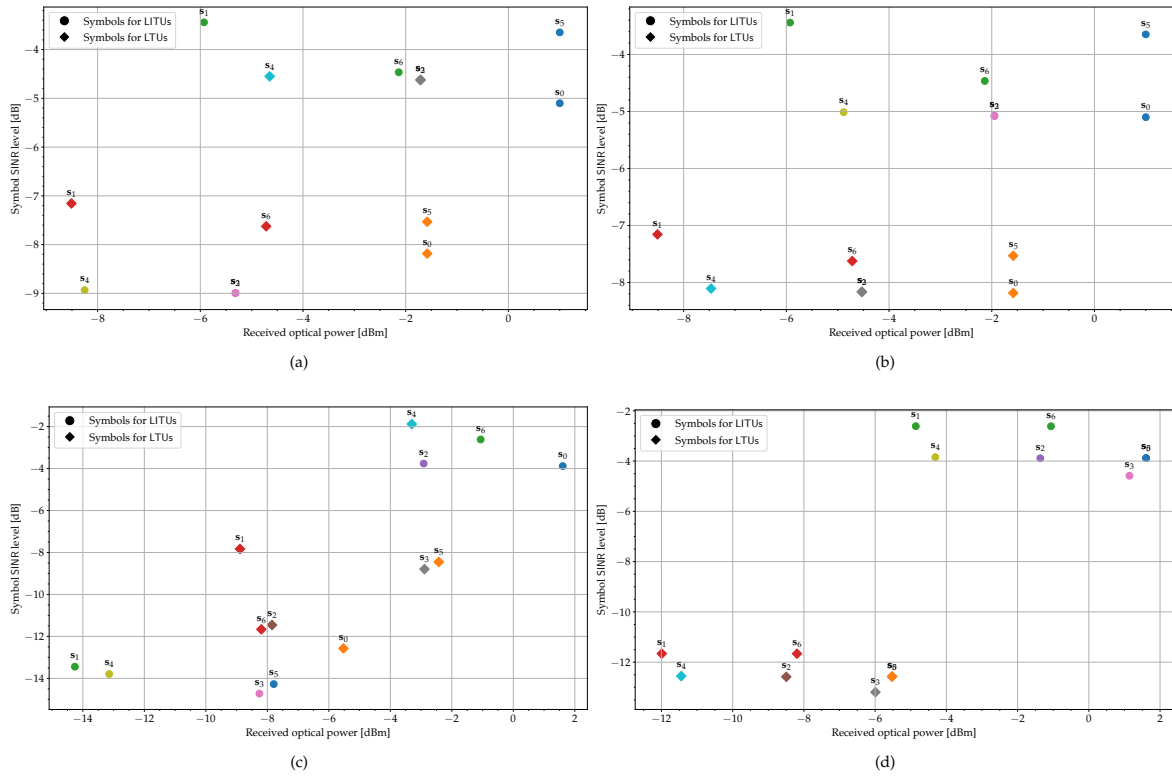


FIGURE C.4: SINR levels (with the SINR constraint) during transmission of different symbols using 16CSK-OSM with receivers at different positions: Figure C.4a shows the SINR levels against received power for each symbol at (0, 2) (LITU location) and at (0, -1.5) (LTU location) before transmitter re-assignment and Figure C.4b shows the same plot after transmitter re-assignment. Figure C.4c shows the SINR levels against received power for each symbol at (2, 0.5) (LITU location) and at (-1.25, -2) (LTU location) before transmitter re-assignment and Figure C.4d shows the same plot after transmitter re-assignment.

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