MULTIPLE INPUT MULTIPLE OUTPUT VISIBLE LIGHT COMMUNICATION SYSTEM SUB-OPTIMIZATION USING POWER ALLOCATION SCHEMES

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by

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LIST OF SYMBOLS

BW	Bandwidth
r	Current user position to the Center
R	Radius of system coverage
r/R	Normalized Offset
ξ	Modulation index
$\boldsymbol{\gamma}$	Responsivity of PD
$\boldsymbol{P_{opt}}$	The average optical power of the LED
$\boldsymbol{\mu}$	The gain of the optical filter
$\boldsymbol{\eta}$	The gain of the optical lens
$\boldsymbol{\psi_{\frac{1}{2}}}$	The semi-angle at half power of LED

LIST OF ABBREVIATIONS

4QAM	4-Ary Quadrature Amplitude Modulation
5G	Fifth Generation
ADCO	Asymmetrically DC-Biased
AP	Access Point
BC	Broadcast Channel
BER	Bit Error Rate
BLAST	Bell Laboratories Layered Space-Time
BPSK	Binary Phase-Shift Keying
BS	Base Station
BTS	Base Transceiver Stations
CCI	Co-Channel Interference
CDMA	Code Division Multiple Access
CFO	Carrier Frequency Offset
CSI	Channel State Information
DCO	DC-Biased
DHT	Discrete Hartley Transformation
FOV	Field of View
FPA	Fixed Power Allocation
FWHT	Fast Walsh-Hadamard Transformation
GPS	Global Positioning System
GRPA	Gain Ratio Power Allocation
HCM	Hadamard Coded Modulation
I2V	Infrastructure to Vehicle

ICI	Interchannel Interference
ICT	Information and Communication Technology
IM/DD	Intensity-Modulated/Direct-Detected
ImR	Imaging-Based Receiver
IoT	Internet of Things
ISI	Inter Symbol Interference
ITS	Intelligent Transportation System
IUI	Inter-User Interference
LBS	Location-Based Services
LED	Light Emitting Diode
Li-Fi	Light Fidelity
LOS	Line-of-Sight
LPS	Light Positioning System
MAC	Multiple Access Channel
MAI	Multiple Access Interference
MAI	Multiple Access Interference
MCM	Multi-Carrier Modulation
MIMO	Multiple-Input Multiple-Output
M-NGDPA	Modified - Normalized Gain Difference Power Allocation
MPA	Message Passing Algorithm
M-PAM	M-ary Pulse Amplitude Modulation
MPPM	Multiple Pulse Position Modulation
M-QAM	M-ary Quadrature Amplitude Modulation
MS	Mobile Station
MSI	Multi-Stream Interference

MUSA	Multiuser Shared Access
NGDPA	Normalized Gain Difference Power Allocation
NImR	Non-Imaging Receiver
NOMA	Non-Orthogonal Multiple Access
NRZ	Non-Return-To-Zero
OCDMA	Optical Code-Division Multiple-Access
OFDM	Orthogonal Frequency Division Multiplexing
OMA	Orthogonal Multiple Access
OOK	On-Off Keying
OWC	Optical Wireless Communication
PAM	Pulse Amplitude Modulation
PAPR	Peak-To-Average Power Ratio
PD	Photodiode
PDMA	Pattern Division Multiple Access
PSK	Phase Shift Keying
PWM	Pulse Width Modulation
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
SCFDE	Single-Carrier Frequency-Domain Equalization
SCM	Single-Carrier Modulation
SCMA	Sparse Code Multiple Access
SISO	Single Input Single Output
TDMA	Time Division Multiple Access
UVLC	Underwater Visible Light Communication
V2I	Vehicle-to-Infrastructure

V2V	Vehicle-to-Vehicle
VLC	Visible Light Communication
VPPM	Variable Pulse Position Modulation
WDM	Wave Division Multiplexing
WLAN	Wireless Local Area Network
WPDM	Wavelet Packet Division Multiplexing

LIST OF APPENDICES

SUB-PENGOPTIMUMAN SISTEM KOMUNIKASI CAHAYA NAMPAK PELBAGAI INPUT PELBAGAI OUTPUT DENGAN SKEMA PERUNTUKAN KUASA

ABSTRAK

Penggunaan kuasa yang rendah dan kadar bit yang tinggi adalah ciri terpenting sistem komunikasi cahaya nampak (VLC). Ciri-ciri ini sentiasa menjadi sasaran utama mana-mana sistem komunikasi. Kajian ini menumpukan pada meningkatkan kadar data dan mengoptimumkan penggunaan tenaga dalam sistem VLC. Untuk meningkatkan kadar data, pendekatan pelbagai input pelbagai output (MIMO) telah digunakan kerana keupayaannya untuk menggabungkan aliran data dan menggandakan kadar data. Sistem ini dinaik taraf daripada konfigurasi 2×2 kepada 4×4 MIMO-VLC. Bagi mengoptimumkan penggunaan tenaga, dua skim peruntukan kuasa, peruntukan kuasa nisbah gandaan (GRPA) dan peruntukan kuasa beza gandaan ternormal (NGDPA), telah diaplikasikan pada sistem 4×4 MIMO-VLC. Selain itu, satu skim baru yang dinamakan NGDPA-diubahsuai (M-NGDPA) dicadangkan, yang berjaya memperluaskan kawasan liputan daripada 3.14 m^2 kepada 4.52 m^2 dan meningkatkan kadar jumlah di sempadan liputan. Model matematik sistem yang dicadangkan juga telah dibentangkan. Keputusan simulasi menunjukkan bahawa sistem 4×4 MIMO-VLC mencapai kadar jumlah sebanyak 268 Mbps menggunakan lebar jalur 10 MHz dalam kawasan liputan berbentuk bulat dengan jejari 1 m (3.14 m^2). Hasil simulasi juga menunjukkan bahawa walaupun NGDPA memberikan kadar jumlah yang lebih tinggi, GRPA menunjukkan kecekapan tenaga keseluruhan yang lebih baik. M-NGDPA mengatasi kedua-dua skim ini dari segi kawasan liputan dan prestasi di sempadan

liputan. Berbanding dengan kaedah terkini dalam literatur, sistem M-NGDPA yang dicadangkan menunjukkan keputusan yang lebih baik, menjadikannya penyelesaian yang menjanjikan untuk rangkaian VLC masa depan yang berkelajuan tinggi dan cekap tenaga.

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ABSTRACT

Low power consumption and high bit rate are the most important features of visible light communication (VLC) systems. These features are always the main target of any communication system. This study focuses on enhancing data rates and optimizing power consumption in VLC systems. To improve the data rate, multiple-input multiple-output (MIMO) has been employed and this technique has an inherited property of combining the data streams and multiplying the data rate. The system was upgraded from a 2×2 to a 4×4 MIMO-VLC configuration. To optimize power consumption, two power allocation schemes, Gain Ratio Power Allocation (GRPA) and Normalized Gain Difference Power Allocation (NGDPA), were applied to the 4×4 MIMO-VLC system. Additionally, a novel Modified-NGDPA (M-NGDPA) scheme was proposed, extending the coverage area from 3.14 m^2 to 4.52 m^2 and enhancing the sum rate at the coverage boundaries. The mathematical model of the proposed system was presented. The simulation result shows that the 4×4 MIMO-VLC system achieves a sum rate of 268 Mbps over a 10 MHz bandwidth within a circular coverage area of 1 m radius (3.14 m^2). Simulation results indicate that while NGDPA provides a higher sum rate, GRPA demonstrates better overall energy efficiency. The M-NGDPA outperforms both schemes in coverage area and boundary performance. Compared to existing state-of-the-art methods, the proposed M-NGDPA system achieves superior results, making it a promising solution for future high-speed, energy-efficient VLC networks.

CHAPTER 1

INTRODUCTION

1.1 Background of Research

Visible light communication (VLC) is relatively a new telecommunication technology that has its applications in various walks of life. VLC utilizes a non-RF band, and its spectrum lies in the visible region concerning the human eye i.e. 380 nm to 780 nm. This spectrum is virtually unlimited and presently license-free. VLC is classified as a special case of free-space optical communication. VLC enjoys many benefits over RF technology such as its green technology, huge spectrum, immunity to electromagnetic interference, environmental and human friendly, harvesting of ambient light, and can work in areas where RF is non recommended such as the petrochemical industry and hospitals. VLC also supports high data rates and the development of techniques that enable VLC to support even higher data rates is a popular research area nowadays.

The transmitter in VLC can be either a laser or a light-emitting diode (LED). On the other hand, the receiver in VLC is the photodiode working in Infrared and visible light regions. Both transmitter and receiver have limitations in terms of switching speed and data handling capabilities. When the link is established between a single transmitter and a single receiver, the system is called single input single output (SISO) VLC. On the other hand, if more than one transmitter and receiver are being used, the system is considered to be multiple-input multiple-output (MIMO). The MIMO-VLC system is proposed to increase the system sum rate capacity and at the same time the system reliability.

Like any technology, VLC has some limitations and problems. Provision of uplink, multipath distortion, and mobility are the most of VLC challenges. VLC would be the optimum solution if these limitations and problems are minimized, mitigated, or avoided. In conclusion, trying to take the benefits of MIMO-VLC advantages and control its challenges will allow the MIMO-VLC system to be applied in different indoor applications such as classrooms, conference halls, hospitals, aircraft, and enterprise offices as well as outdoors, however, for outdoor VLC, lasers are used instead of LEDs with the typical application of back-haul network.

Visible light communication (VLC) systems with more than one transmitter and receiver or multiple-input multiple-output (MIMO) are attracting attention due to their numerous advantages. Compared with conventional single input single output (SISO) VLC systems, the overall system sum rate can exponentially increase. Other than that, the MIMO system has other advantages such as improved spectral efficiency, enhanced reliability and coverage, and improved spectral efficiency to name a few. As a result of the increase in the system sum rate, more users can be added to the system. Besides that, the system coverage area can also be increased, and the same bit rate for all users at any position within the system coverage area can also be maintained. This is because the MIMO system utilizes more than one transmitting and receiving point. Consequently, the MIMO system provides better reliability, privacy, and safety features over its best competitor, i.e., the wireless radiofrequency system. These advantages allow the MIMO-VLC system to be applied in different indoor applications such as classrooms, conference halls, hospitals, aircraft, and enterprise offices.

1.2 Problem Statement

The rapid penetration of information and communication technologies (ICT) has forced telecommunication service providers and regulators to develop mechanisms to support high-speed and reliable data communication both for indoor and outdoor environments. The prime functions of modern communication systems are to enhance their capacity in terms of the number of served subscribers (users), improve link distance, and coverage area, and improve privacy, and overall system reliability. A good telecommunication system has the features of improved signal-to-noise ratio (SNR) and bit error rate (BER). Furthermore, power optimization in the era of billions of connected devices is also an area of concern. All the above-listed parameters are interconnected and there is a trade to improve on certain parameters. For example, increasing the system power will directly improve the system SNR, but the trade-off is on increased power consumption by the system. In conclusion, the aim is to build a communication system that achieves acceptable Quality of Service (QoS) while utilizing the least resources.

VLC has many advantages over RF communication as mentioned in Section 1.1 and indoor is a promising communication technology. Integration of VLC with MIMO can substantially increase data rates, throughput, coverage, and reliability. Like any other technology, MIMO VLC also has some drawbacks and challenges that need to be addressed to fully explore the potential of MIMO VLC. One such aspect is the power allocation schemes in MIMO-based VLC systems. There is a lack of in-depth studies on power allocation strategies specifically focusing on MIMO-based VLC systems. The main objective of this research is to observe the impact of a 2×2 and a 4×4 MIMO VLC system on the sum rate and compare its data rate with a SISO system. The selection of such MIMO configuration is because a typical indoor home environment is considered for this study. In addition to that, investigating novel power allocation schemes for the MIMO VLC system.

The journey of the VLC system started around two decades back and gradually we are witnessing improvement in the system in terms of increased data rates, development of novel materials for the realization of transmitters and receivers, enhanced spectral efficiency, and lower energy consumption per transmitted bit. The inclusion of MINO in the VLC system is less than a decade old. In 2015, K. Sindhubala proposed a VLC system with one transmitter and one receiver. The system managed to transmit a signal over 10 m, but the transmission rate was only 0.01 Mbps. Later, in another study by Chen in 2018, they proposed a 2x2 MIMO-VLC system. The system managed to cover 12.5 m per square with a transmission rate of 112 Mbps. Chen's proposed system could maintain the same sum rate for all users in the coverage area. In this study, the prime goal revolves around achieving the highest possible sum rate, serving the largest number of users, and maintaining the same bit rate for all users within the coverage area. The study also investigates power consumption by applying two power allocation schemes. Applying a power allocation scheme would improve power consumption and ensure that the other targeted performance indicators are achieved. Gain ratio power allocation (GRPA) and normalized gain difference power allocation (NGDPA) are the most common power allocation schemes that have been used in MIMO-VLC systems. Therefore, in this thesis, both power allocation strategies are applied to the 4×4 MIMO-VLC system to optimize the system power consumption by ensuring a high sum rate, a large number of users, and a large possible coverage area.

1.3 Research Objectives

The main aim of this research work is to design a new VLC system that addresses the following points:

1. Develop a comprehensive understanding of the characteristics of MIMO VLC systems, including channel modeling, system performance metrics, and its implementation in a simulation environment considering realistic parameters.
2. Investigate the impact of upgrading an existing MIMO-VLC system from 2×2 to 4×4 in terms of the overall system sum rate the maximum number of served users, and the received bit rate of each user within the system coverage area.
3. Design, implement, and evaluate the performance of the proposed power allocation schemes through extensive simulations in realistic VLC deployment scenarios. In addition to this, a novel power allocation, M-NGDPA, is presented and compared with the aforementioned power allocation algorithms.

1.4 Scope of Study

The scope of this thesis begins with an extensive exploration of the literature review on VLC, its channel models, techniques to enhance data rates and power allocation strategies in VLC-based systems. This study identifies the gaps and challenges within the current research in the said field. The study will encompass the MIMO-based VLC system, the performance metrics, and the effect of increasing the size of the MIMO system for a typical indoor domestic environment. The prime focus of this research will be to enhance the sum rate for a better user experience. Last but not least, the study will also focus on the power allocation strategics (which are GRPA and NGDPA) for MIMO-based VLC systems and their impact on the sum rate. All this work will be carried out in a realistic simulation environment.

Additionally, the study delves into power allocation strategies, specifically GRPA and NGDPA, to evaluate their influence on the sum rate of MIMO-based VLC systems. A novel power allocation scheme, M-NGDPA, will also be introduced and analyzed in this thesis. M-NGDPA builds upon the foundation of NGDPA by refining the power allocation process to sustain higher sum rates, particularly at the boundaries of the system's coverage area, making it a significant contribution to the field. All investigations and analyses will be conducted in a realistic simulation environment to ensure practical relevance and applicability.

1.5 Research Work Contribution

In this section, the key contributions of the thesis are summarized. First, a thorough literature review was conducted on the VLC, its applications, system architecture, MIMO-based VLC systems, modulation schemes, and power allocation strategies. Simulations were performed by setting up a realistic MMO-based VLC environment for a 2x2 system. In order to enhance the sum rate, the system was upgraded to 4x4. For both the systems, we observed achievable sum rate vs normalized offset, and user average bit rate vs normalized offset. Two power allocation strategies, namely GRPA and NGDPA were applied on 2x2 and 4x4 MIMO NOMA-based VLC system and the sum rate was observed for all these scenarios. In addition to that, another significant contribution of this thesis is the presentation of Modified Normalized Gain Differential Power Allocation (M-NGDPA) scheme along with its performance evaluation. By these means, a better understanding of the optimal power allocation schemes for 4x4 MIMO-VLC systems can be gained, which can inform future developments in the field of indoor VLC systems.

1.6 Thesis Outline

The thesis is organized into five chapters. The literature review is presented in Chapter 2. The literature review chapter covers VLC, its applications, system architecture, MIMO-based VLC systems, modulation schemes, and power allocation strategies. Chapter 3 presents the mathematical details of the VLC systems and the MIMO along with the introduction to Gain Ratio Power Allocation and Normalized Gain Difference Power Allocation and newly presented M-NGDPA algorithm. Chapter 4 presents the details regarding the upgradation of a 2x2 MIMO-based VLC system to a 4x4 system. Achievable sum rate and user average bit rate vs normalized offset were investigated for up to 6 number of users followed by the effect of two power allocation schemes on the proposed architecture terms of sum rate gain. The final chapter (chapter 5) provides the conclusion and suggestions for future research work that can be realized from this work.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The visible optical wireless communication system carries the information by modulating within the visible spectrum (380 - 790 nm), and it is called visible light communication (VLC) [1]. Recently, VLC has drawn the attention of many research groups for data transmission, indoor localization, and secure and green communication. Thus, there have been many experiments and studies on this technology.

2.2 VLC Applications

Many applications can use VLC technology. Examples of where VLC might be applied: indoors and outdoors Light Positioning System (LPS), Light Navigation Systems, hospital and healthcare (by allowing mobility and data communications), hazardous environments (where RF is considered harmful like in Oil and Gas fields), and commercial aviation (by using wireless data communications for in-flight entertainment and personal communications). The VLC also applied for corporate and organizational security (where Wi-Fi is considered a security risk), relief in Wi-Fi spectrum (through supplying additional bandwidth for unlicensed communication bands in congested environments), defense and military applications (by providing military vehicles and aircrafts with high data rate wireless communications), and underwater communications that occur between divers and/or vehicles. Some of these applications will be discussed in the following subsections.

2.2.1 Light positioning system (LPS)

Indoor positioning, or as referred to as indoor localization, is one of the most promising applications in real life to use VLC technology. For example, the development of this technique, with the increased use and development of mobile computing systems like smartphones and tablets, will make it possible for accurate location-based services (LBS). Therefore, this field is attracting the interest of many researchers. Currently, with the increased research on VLC technology, commercial high-quality indoor positioning systems were approached [2].

VLC systems can be used to exchange data between rooms, offices, or any indoor sections. User location can be predicted in an indoor area using traditional white LEDs with a unique user ID. Figure 2. 1 shows a navigation system prototype or visually impaired users [3].

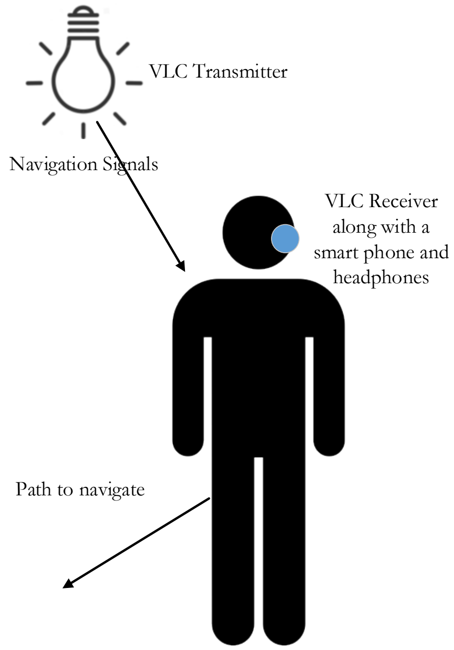

Figure 2. 1 Indoor VLC navigation system for visually impaired users

There are many benefits from using indoor positioning for many industries and customers. For example, indoor positioning can be applied in large warehouses for location sensing and management of products inside. Another example, in large buildings such as shopping malls and museums, location-based services (LBS) might be provided to pedestrians for indoor navigation services and advertisements for consumers, see Figure 2. 2.

In outdoor environments, such as in some downtown and urban locations, the need to precisely locate a vehicle requires a reliable navigation system, where the most widely used Global Positioning System (GPS). However, GPS sometimes performs poorly due to link blockage or multipath [4]. In addition, GPS encounter many challenges such as the expense and time required to measure its received power through the use of high gain antenna dishes, the lack of availability of high-quality absolute power calibration systems for commercial GPS receivers, and no possibility to recover the full transmitted antenna pattern from all the 32 GPS satellites due to the limited number of ground stations [5].

Figure 2. 2 How the 3D tracking for indoor navigation will look like [3]

2.2.2 Intelligent Transportation Systems (ITS)

Intelligent transportation systems (ITS) applications are developed in the field of information and communication technology (ICT) and ITS combines the collected data about transportation systems [6]. The collected data then is organized and analyzed to make the construction and operation of transportation systems more effective and economical. Some intelligent equipment has to be installed in the transportation infrastructure. Different schemes of vehicular communication are developed to make the roads safer and, of course, to minimize the number of accidents. Some of these schemes like vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V) [7].

VLC systems play a significant role in ITS, from broadcasting real-time traffic information to V2V, V2I, and I2V schemes. LED traffic lights were used to send and receive traffic information to and from different communication facilities schemes. Researchers in [8] proposed a traffic information system using existing LED traffic lights. They designed a service area without interfering with other service areas and analyzed its basic performance, such as the suitable modulation and the amount of receivable information. Some researchers have discussed road-to-vehicle communication systems using LED traffic lights [9], [10]. A parallel optical wireless communication system based on LED traffic lights as the transmitter and the camera as the receiver was suggested. Independently modulating each LED was considered, and a receiver will be linked to a camera.

2.2.3 VLC Applications in Aviation

In-flight entertainment and personal communications enable wireless data communications using VLC, which is another promising application. In recent years, this technique, through the employment of LED reading lamps, has been gaining attention for its inexpensive and green access to high-speed internet. In addition, in comparison to the existing low-bandwidth Wi-Fi-based infrastructure, VLC provides an inexpensive and scalable alternative for entertainment and multimedia services. To serve the passengers' terminals, a VLC-based solution (either added into or externally to laptops, smartphones, tablets, etc.) acts as a femtocell system by using the LED reading lamps present with the presence of point-to-point wireless downlink Intensity-Modulated/Direct-Detected (IM/DD) visible light communication [11]. Moreover, an aeronautical network architecture was proposed based on VLC technology which enables in-flight entertainment services [12]. Two different methods were investigated using the LEDs within an aircraft cabin with the VLC technique. The first one reduces intra-cell and inter-cell interferences by using Wave Division Multiplexing (WDM) and direct sequence Optical Code-Division Multiple-Access (OCDMA) system techniques. The second one allows the efficient sharing of resources between users using a two-dimensional OCDMA scheme.

2.2.4 Underwater Applications

Another application for VLC is underwater for underwater communications or water pollution investigations [13]. It can be operated between divers and/or remote-operated vehicles. Underwater communication began during World War II for military purposes. However, in recent years, it has attracted interest in several civilian applications, such as underwater archaeology, environmental monitoring, and underwater disaster prevention and analysis. Underwater visible light communication (UWVLC) vertical links have been proposed and evaluated [14]. It has considered the inhomogeneous nature of the underwater environment. An equivalent N layer is proposed based on the variations in refractive index and attenuation profiles due to underwater depth. A path loss expression is formulated to estimate the vertical link loss before the design of the link. Also, it was found that underwater VLC allows us to assess the quality of the transmission medium and not only for communication purposes.

2.3 Integration of MIMO with VLC

This section discusses another approach applied to enhance the capabilities of VLC through multiple-input multiple-output (MIMO) schemes [15]. VLC in conjunction with MIMO increases the performance of VLC, particularly when transmitting data over long distances [16]. However, the MIMO VLC system has also encountered some difficulties. For instance, the MIMO VLC channel is only available under static Line of Sight (LOS) situations. The correlation caused by static LOS is connected with the characteristics of the LED array and the PD array, respectively. The considerable correlation in the channel matrix significantly affects the transmission performance [17].

To date, a range of schemes has been introduced to boost efficiency and expand the VLC system coverage [18]. The most common and efficient method is the MIMO scheme with arrays of illuminating LEDs [19], [20]. Meanwhile, 150 Mbps over 6 m using on-off keying and 100 Mbps over 0.6 m using orthogonal frequency-division multiplexing (OFDM) modulation with a 2×2 MIMO was demonstrated [20], [21]. Also, a MIMO-OFDM-based VLC system with four separated LEDs and a 3×3 receiver array as a detector transmitting with 1 Gbps was reported [21]. Many different techniques and schemes have been applied to the VLC system architectures to enhance their performance by increasing the transmission bit rate and enlarging the capacity by adding more users. MIMO-VLC systems are also suffering from different types of interference, such as inter-cell interference (ICI), inter-user interference (IUI), co-channel interference (CCI), or inter-symbol interference (ISI) [22], [23]. Some other schemes and devices are used to eliminate or mitigate these interferences or their effects on VLC systems. In order to mitigate both IUI and ICI in multi-user multi-cell MIMO VLC systems, a joint precoder and equalizer design based on interference alignment were used. Their proposed system design achieved a sum rate enhancement of up to 18.2% and 28.7% [23].

The MIMO-VLC system for data rate enhancement was introduced by Hsu et al. [24]. It included the 3x3 MIMO-VLC system for data rate enhancement. The pre-equalizer circuit can increase the LED transmitter bandwidth while communicating across VLC networks. The construction of the channel matrix is easier by using a

MIMO training sequence dependent on time multiplexing. The signal-to-noise ratio (SNR) determines the modulation sequence during the data transmission in VLC. OFDM also has the additional benefit of increasing spectrum efficiency. VLCs are possible using phosphor LEDs. However, it has a restricted modulation bandwidth and causes problems in high-speed transmission. The advantages and disadvantages of using MIMO based VLC system are as follows.

- Introduction of an Optical Adaptive Precoding (OAP) strategy for MIMO-VLC downlink systems to enhance the signal-to-interference-plus-noise ratio (SINR) [25].
- It is possible to ensure a wide range of high-quality, high-rate services while consuming the least amount of spectrum, power, and hardware complexity in MIMO-based VLC system [26].
- The diversity gain and coding gain can be realized using MIMO based VLC system [27] over a classic single-input single-output (SISO) system.
- Surprisingly, MIMO spatial multiplexing systems exploit channel unpredictability, but MIMO space-time-coded systems counteract it [28]. It has been discovered that using numerous antennas in a multiuser environment provides more flexibility in dealing with multiuser interference and permits simultaneous high-rate, multiuser communications while giving spatial multiplexing and diversity advantages [29], [30].

As a result, MIMO systems have emerged as a potential transmission topology for achieving the objective of future wireless networks [31].

2.4 Overview of VLC and optical MIMO

With the increasing use of energy-efficient white LEDs, VLC is emerging as a promising dual-use technique for indoor illumination and high-speed data transmission [32], [33]. LED luminaires installed on the ceiling are used to illuminate the room and transmit data to the user devices (e.g., smartphone, laptop, TV). The most viable optical modulation and demodulation technology for VLC is IM/DD [34]. In IM/DD, the transmitted information is modulated on the intensity of the light. Unlike conventional incandescent and fluorescent lights, the intensity of the light emitted from LEDs can be modulated at frequencies up to several megahertz [35]. The wide modulation bandwidth has the potential to support high data rate communication. Multiple luminaires are installed on the ceiling in most indoor environments to provide sufficient illumination. Thus, a range of novel VLC MIMO systems can be developed using ceiling lights to transmit multiple data streams [36]. These can be detected using multiple PDs. MIMO communication is already a well-established and widely implemented radio frequency (RF) communication technique. It can provide multiplexing gain to boost the data rate and/or diversity gain to improve reliability [28]. However, it is difficult to design an effective MIMO system for VLC because of the properties of IM/DD channels. Figure 2.3 shows the how the indoor VLC using LEDs for both illumination and data transmission looks like.

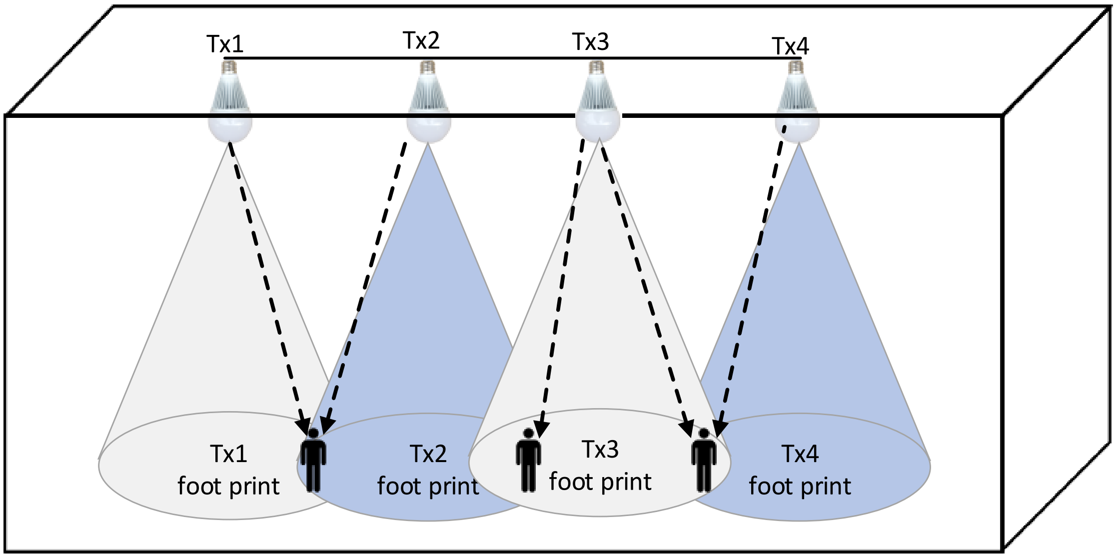

Figure 2. 3 Indoor VLC using LEDs for both illumination and data transmission

Unlike RF MIMO systems in which the channels provide a rich scattering environment, and the channel matrix is typically full rank, IM/DD channels lack diversity because the optical power varies slowly with the receiver position [35]. Different forms of optical MIMO receivers, based on either spatial diversity [37] or angular diversity [38], have been studied to overcome this problem. Several optical MIMO receivers using angular diversity have been described, but most have significant drawbacks, such as bulky construction or limited field of view. In Figure 2. 4 VLC block diagram is introduced. In sub-section 2.5.1, VLC data transmission is discussed. The VLC transmission link design is explained in subsection 2.5.2. While in subsection 2.5.3, the primary VLC receiver's components are discussed in detail.

2.5 VLC System Block Diagram

In Figure 2. 4, a block diagram of an indoor VLC system is presented. The system consists of a receiver incorporating a photodetector, a VLC link or channel, and a transmitter utilizing either visible light lasers (LD) or white LEDs.

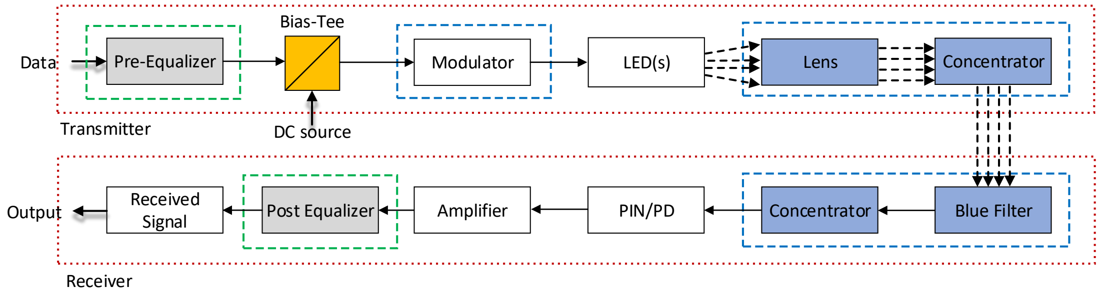

Figure 2. 4 Block Diagram of an Indoor VLC System

The elements presented in grey blocks are optional, while those in blue blocks are designed to enhance the performance of the VLC system. The remaining components are essential for ensuring the proper functionality of the system [39].

2.5.1 VLC Data Transmitters

The primary function of the VLC transmitter is to convert electrical signals into optical signals and transmit them through the free-space link using LEDs. White LEDs are also perceived as eye-safe. They are available at low cost even at relatively high powers, since they have a broader surface area that emits light in a larger spectral range [1].

Commercial white LEDs are well known to emit light in semi-angles. They are reliable and affordable, unlike incandescent light bulbs. Despite LEDs having various advantages, they remain the best light source for indoor VLC applications; however, they have certain drawbacks, including:

- Nonlinearity.
- Low electro-optic power translation efficacy (mostly ten to forty percent).
- Low modulation bandwidth.

In contrast, white LD may be taken as other options to LEDs in VLC systems because of their various benefits which include:

- Linear electric to visual signal change features [40].
- High electro-optic power change efficacy.

- Wide modulation bandwidth

Although LD requires a complex drive circuit, they are more expensive than LEDs. Furthermore, they have strict eye safety standards and generally suitable for point-to-point communication.

2.5.2 VLC Transmission Links Design

VLC links can be categorized based on two criteria: (i) the presence of a direct path between the transmitter and receiver, where the optical signal travels directly without passing by any obstacles or walls, and (ii) the degree of directionality between the receiver and transmitter. These categorizations are based on two factors: (a) the radiation pattern design of the transmitter that specifies the transmitter coverage area, and (b) the scope of the receiver to read the received signal, which is called the receiver field of view (FOV). The main types of VLC links are demonstrated in Figure 2. 5.

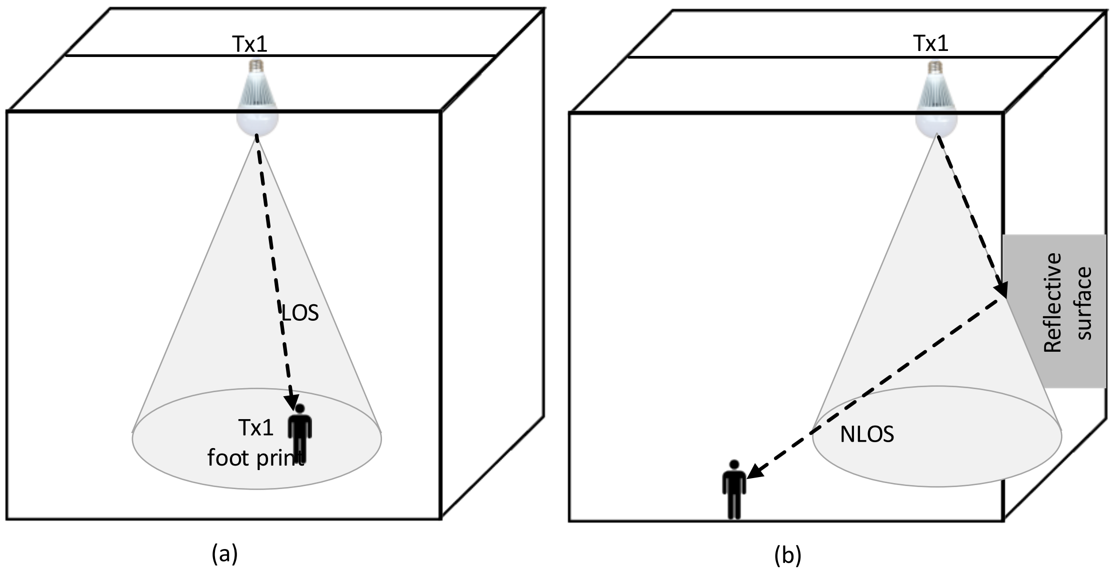

Figure 2. 5 Types of VLC Links (a) Line-of-Sight (LOS) (b) Non-Line-of-Sight (NLOS)

The two primary categories of indoor VLC links are Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) transmission configurations [41], [42], [43]. These systems can also be classified as diffuse, hybrid, or directed, based on the alignment between the receiver and transmitter [44], [45]. In contrast, the LOS links give a direct pathway between the receiver and transmitter, minimizing the multipath dispersal, and it enhances the VLC communication system's power efficiency. On the other side, NLOS link efficiency depends on the optical signals after many reflections because of walls or other objects. The NLOS links offer protection and strong links against signal blockage and shadowing; however, they are massively impacted by multipath diffusion, which leads to pulse spreading and ISI [41].

2.5.3 Receiver Components

The received optical signal is converted to an electrical signal by the VLC receiver, which composes a preamplifier and a photodetector circuit behind the anterior end [46]. The role of the optical filter is to reduce the ambient light amount captured through the removal of the signal's optical spectral band. In contrast, the role of the concentrator is to increase the quantity of the established signal power at the receiver [47], [48].

2.5.3(a) Concentrator

The primary role of an optical concentrator, and from its name, is mainly to concentrate light rays from a broader area to a light ray that emerges from a tiny part. An optical concentrator can be employed to boost the collected signal power by increasing the effective collecting area. Expanding the photodiode's active area enhances the received optical power. However, this also increases capacitance, which may limit transmission rates and reduce the receiver's bandwidth [49].

Concentrators are generally classified as imaging and non-imaging types. Imaging concentrators are commonly used in long-range systems such as free-space optics, while non-imaging concentrators are widely employed in indoor optical wireless links, including VLC. The effective signal collection area can be determined by [40]:

$$A_{eff}(\delta) = \begin{cases} A\cos(\delta), & 0 \leq \delta \leq \frac{\pi}{2} \\ 0 & \delta > \frac{\pi}{2} \end{cases} \quad (2.\ 1)$$

where: A is the physical area of the detector and δ is the angle of incidence. The following formula describes the ideal relation between the receiver FOV and gain. [35]:

$$\mathrm{g}(\delta) = \begin{cases} \frac{N^2}{\sin^2 \psi_c}, & 0 \leq \delta \leq \psi_c \\ 0 & \delta > \psi_c \end{cases} \quad (2.\ 2)$$

Where ψ_c is the concentrator FOV semi-angle and N is an interior refractive guide (normally $\psi_c \leq 90°$). The shown formula depicts an inverse relation between FOV and the receiver's gain. The gain is increased If the receiver's FOV is reduced.

2.5.3(b) Optical Filters

Optical wireless systems are vulnerable to sunlight and ambient light. Hence, an optical filter is used before detection by the photodetector to decrease the impact of unnecessary optical noise elements in the received electric signal [50], [51]. The available modulation bandwidth in LED transmitters is usually smaller than the bandwidth of the VLC channel, meaning that this reduces transmission rates. A blue optical filter is a cost-effective and straightforward approach to increase data rates [52].

2.5.3(c) Photodectors

The photodetector transducer produces an electric wavelength proportionate to the incident light. The photodetector must meet vital performance specifications because the optical wireless system's established light is usually weak. Some of these performance specifications should be minimized, like cost and noise level. On the other side, reliability, sensitivity, responsivity, and conversion rate are to be increased. Two categories are typically utilized in optical wireless systems: the avalanche photodiodes and PIN photodiodes. PIN photodiodes are cheaper and less complex to manufacture; they need reduced multifaceted predetermining than APDs [53]. To make the PIN photodiode a good choice, it should have high responsivity and as large a bandwidth as possible. Responsivities of silicon photodiodes, which operate between 430 nm to 655 nm bands, are in the range of 0.21 A/W to 0.46 A/W [54]. The main parameter is responsivity in photodiode models and is determined at the central optical frequency of operation.

2.5.3(d) Preamplifiers

The preamplifiers are categorized into three categories. The first one is the low impedance which provides a wide bandwidth with high noise and thus causes a low receiver sensitivity. The second one is the high-impedance preamplifiers, which provide high sensitivity. However, an equalizer must be added to avoid the limitations imposed on the frequency response by the front-end time constant. Moreover, due to their high input impedance, they also have a limited dynamic range [53]. The third one is the trans-impedance preamplifiers (TIA). TIA is implemented by more than one operational amplifier (Op-Amp) [55].

2.6 MIMO-VLC

Multiple LED luminaires installed at intervals on the ceiling illuminate most indoor environments. Light can be received from more than one source at most positions within the room. When these LED luminaires are used as data transmitters, VLC MIMO transmission can be achieved. The most common VLC MIMO systems are SMP [56], OSM [57], and indoor VLC cellular systems [58]. In this section, the structures of these three VLC MIMO systems are first described. Next, the optical MIMO channel is explained. Finally, a review of the existing optical MIMO receivers is presented, and their limitations are also explained.

2.6.1 VLC Cellular System

An indoor VLC cellular system can be constructed where the data intended for a given user is transmitted by the nearest luminaire [59]. As shown in Figure 2. 6, the possible position of the user is divided into different cells, and each cell has one corresponding LED luminaire. The luminaire transmits signals to the users within its cell. For example, the user User1 receives the desired signal from the luminaire located above, and User2 receives the desired signal from a different luminaire. Each cell can support multiple users by using multiplexing techniques, e.g., time division multiple access (TDMA), code division multiple access (CDMA), and orthogonal frequency-division multiple access (OFDMA).

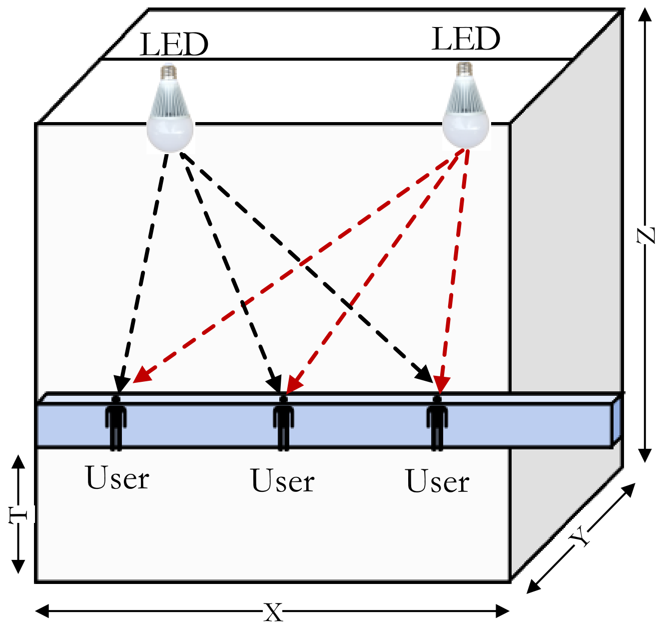

Figure 2. 6 Indoor optical cellular system

A particular VLC system, termed "LiFi," has been described [60]. This is an example of a VLC system that uses an indoor VLC cellular configuration. “LiFi” is also the term used in the related draft standard, IEEE 802.15.7r1 [61].

2.6.2 MIMO-VLC Channel

In all the optical MIMO systems that have been described, multiple transmitters are configured to transmit data, and multiple detectors are used to receive the transmitted signals, as shown in Figure 2. 7.

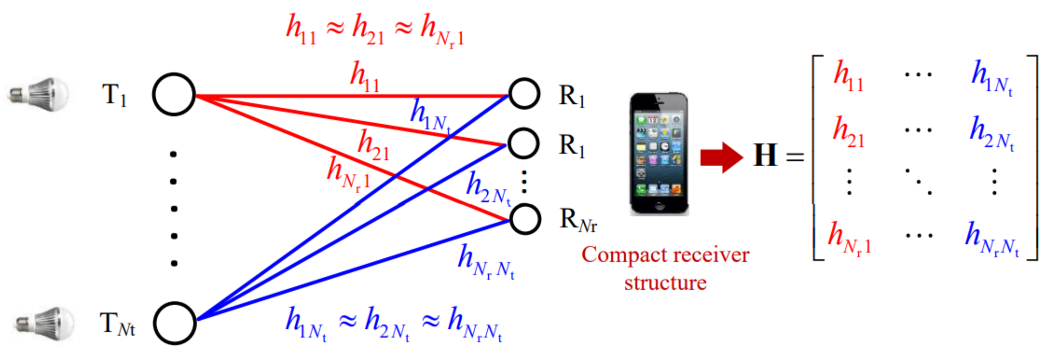

Figure 2. 7 Optical channel between multiple LED transmitters and photodetectors

Regardless of the optical MIMO type, the channel of a MIMO system can be described by a matrix, H:

$$H = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \vdots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN_t} \end{bmatrix} \tag{2. 3}$$

where h_{ij} is the channel gain between the j_{th} transmitter and i_{th} detector, N_t is the number of LED transmitters, and N_r is the number of PD detectors. When only a LOS channel is considered, h_{ij} is given by:

$$h = \frac{(m+1)}{2\pi d^2} cos^m(\emptyset).\cos(\varphi) \tag{2. 4}$$

Here, *m* is the Lambertian emission order. This equation shows that channel gain depends on the properties of both the LED transmitter and the PD receiver. It is also a function of the distance, *d*, the emergence angle, φ, the incident angle, ϕ. It can be seen that the relative position between the LED and PD not only affects the distance, *d* but also influences both the emergence and incident angles of the light. Thus, the relative position between the LED and the PD significantly influences the channel gain.

2.6.3 VLC-MIMO Receivers

In this section, a review of the existing optical MIMO receivers is presented. As shown in the previous sections, the signals transmitted from different LED sources need to be separated without significant noise enhancement for all three different optical MIMO systems. Thus, a good MIMO channel condition is required [62]. These receiver structures are shown in Figure 2. 8 summarized as follows.

In the conventional non-imaging MIMO receiver, multiple bare PDs are used to detect the intensity of the light [63]. The performance of this receiver is related to the separation between these PDs. When the PDs mounted on the receiver are far apart, the light transmitted from a given transmitter will result in light being received with different intensities at different PDs, and thus the similarity between the channel gains will be reduced. Imaging optical MIMO receivers typically use a lens that projects an image onto an imaging plane. A straightforward approach is to use a camera to detect the intensity of the light. This can fully use the existing smartphone camera technology [66]. However, the speed of reading information from the pixels is limited. To overcome the problem of limited FOV, an optical wireless receiver using a hemispherical lens was developed [67]. The optical power density of the projected images was derived. From the simulated optical power density and the channel gains, it can be seen that the optical signals transmitted from different luminaires are distinguishable. In [68], a compact optical receiver structure based on a prism array is described. This receiver uses angular diversity to achieve an excellent optical MIMO channel condition. It was shown that the received optical power from a specific luminaire is related to the orientations of the prisms. However, the drawback of this receiver design is that not all the light from the