A NEW OPTIMIZATION UNIFORMITY FOR INDOOR VISIBLE LIGHT COMMUNICATION SYSTEMS USING OPTICAL ATTOCELLS CONFIGURATION

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A thesis submitted in
fulfillment of the requirement for the award of the
Doctor of Philosophy in Electrical Engineering

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I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

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PROF. DR. MOHAMMAD FAIZ LIEW BIN ABDULLAH

I dedicate this thesis to my beloved family, my dear father and mother. To my lovely wife Esra and my Son Feras. To my brothers Musab, Musa and Abdallah. To my sisters Halima, Hanaa and Arafa. For their pure love and prays that helped me along the way. To all my friends.

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ABSTRACT

The demand for high data rate, capacity, increasing user mobility as well as low power consumption is increasing daily, where it is considered as main the challenges facing the radio frequency (RF) technology. Therefore, an alternative technology called visible light communications (VLC) was adopted to overcome these challenges. This technology is expected to support 5G and beyond due to its high and free frequency offered, as well as robust security. The main problem of this research is, the distribution of a few numbers of optical attocells on the ceiling have caused multiple blind areas in the room, and resulted in nonuniformity distribution. Besides that, employing large numbers of optical attocells has caused a severe ISI, which degrades the system performance, and produced large RMS delay. Therefore, to avoid this problem, a new arrangement of optical attocells, in addition to optimizing the VLC system parameters is proposed. In this research, the proposed arrangement of optical attocells configuration models will improve the uniformity in terms of received power and SNR. The SAAHP, FOV, and CV are used to study the behavior of the two proposed models. The average received power of 2.85 dBm is obtained for the proposed Model $_{\text{Basic 2}}$ that consists of 13 optical attocells, which varies from -0.57 to 4.92 dBm. Moreover, the average SNR of 75.37 dB is obtained for the proposed Model $_{\text{Basic 2}}$, which varies from 68.52 to 79.5 dB. The maximum of received power and SNR is obtained at the center of the room. The better uniformity (CV) of 0.374 and 0.0283 are obtained for the received power and SNR respectively. Additionally, six various modulation techniques are studied to evaluate the proposed models, all modulations produced better BER ($\leq 10^{-6}$) at data rate 30 Mbps, while the higher order modulations (L-PPM and M-PAM) produced higher data rate reaching up to 100 Gbps with a BER $\leq 10^{-6}$. This research also investigated an industrial warehouse model with different heights level, where a data rate of 30 Mbps is achieved with acceptable received power and SNR respectively. A BER $\leq 10^{-6}$ is obtained with L-PPM and M-PAM modulation techniques.

ABSTRAK

Permintaan untuk kadar data yang tinggi, kapasiti, peningkatan mobiliti pengguna serta penggunaan kuasa yang rendah meningkat setiap hari, di mana ia dianggap sebagai cabaran utama yang dihadapi teknologi frekuensi radio (RF). Oleh itu, teknologi alternatif yang disebut komunikasi cahaya tampak (VLC) digunakan untuk mengatasi cabaran ini. Teknologi ini diharapkan dapat menyokong 5G dan seterusnya kerana menawarkan frekuensi tinggi dan percuma, serta keselamatan yang kuat. Masalah utama kajian ini adalah, kedudukan lokasi beberapa bilangan attocells optik di siling telah menyebabkan banyak kawasan buta di dalam bilik, dan mengakibatkan pembahagian bukan keseragaman. Selain itu, menggunakan sejumlah besar attocell optik telah menyebabkan ISI teruk, yang menurunkan prestasi sistem, dan menghasilkan kelewatan RMS. Oleh itu, untuk menyelesaikan masalah ini, penyusunan semula attosell optik, selain mengoptimumkan parameter sistem VLC dicadangkan. Dalam penyelidikan ini, susunan model konfigurasi attocells optik yang dicadangkan akan meningkatkan keseragaman dari segi kuasa yang diterima dan SNR. SAAHP, FOV, dan CV digunakan juga untuk mengkaji tingkah laku dua model yang dicadangkan. Purata kuasa yang diperolehi adalah 2.85 dBm untuk Model $_{\text{Basic 2}}$ yang terdiri daripada 13 attosel optik, yang bervariasi dari -0.57 hingga 4.92 dBm. Di samping itu, purata SNR yang diperolehi adalah 75.37 dB untuk Model $_{\text{Basic 2}}$ yang dicadangkan, iaitu berbeza dari 68.52 hingga 79.5 dB dimana maksimum kuasa dan SNR yang diperolehi adalah di tengah bilik. Keseragaman yang baik iaitu (CV) 0.374 dan 0.0283 masing-masing diperoleh untuk kuasa yang diterima dan SNR. Selain itu, enam pelbagai teknik modulasi dikaji untuk menilai model yang dicadangkan, semua modulasi menghasilkan BER yang lebih baik ($\leq 10^{-6}$) pada kadar data 30 Mbps, sementara modulasi pesanan yang lebih tinggi (L-PPM dan M-PAM) menghasilkan kadar data yang lebih tinggi sehingga 100 Gbps dengan BER $\leq 10^{-6}$. Penyelidikan ini juga mengkaji model gudang industri dengan tahap ketinggian yang berbeza, di

mana kadar data 30 Mbps dicapai dengan kuasa yang diterima dan SNR masing-masing. BER $\leq 10^{-6}$ diperolehi dengan teknik modulasi L-PPM dan M-PAM.

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LIST OF SYMBOLS

$h^{(0)}(t)$	-	Direct impulse response
$h^{(1)}(t)$	-	First reflection impulse response
h_{ij}	-	Channel coefficient
$A_{position}$	-	Position of optical attocells in the ceiling
BER_{Mod}	-	Bit error rate using different modulation techniques
B_{req}	-	Required bandwidth
CV_{SNR}	-	Coefficient of variation for SNR (uniformity)
CV_{power}	-	Coefficient of variation for the received power (uniformity)
D_d	-	Direct distance from transmitter to receiver
D_{rms}	-	root mean square (RMS) delay (ns)
$E_{hor}(x, y, z)$	-	Horizontal illuminance
G_{max}	-	Maximum traditional gain of optical concentrator
I_{bg}	-	Background noise current
$L_{receiver}$	-	Number of receiver in the room
N_0	-	Noise spectral density
$N_{LED-chip}$	-	Number of led chips in optical attocell
N_{OA}	-	number of optical attocells in the typical room model
P_T	-	Total power consumption (W)
P_r	-	Received power (dBm)
P_{rISI}^2	-	Received interfering power
P_{single}	-	Transmitted power per led chip (mW)
$P_t(\lambda)$	-	Power spectrum depend on the wavelength
R_b	-	Bit rate (Mb/s)
S_{sur}	-	Sum area of reflected surface
$T_s(\psi)$	-	Optical filter gain

$\bar{X}$	-	Average or mean of received power/ SNR
θ_{max}	-	Maximum acceptance angle
ξ_i	-	Decision of threshold
σ_I^2	-	Variance
σ_c^2	-	Variance of overall noise
σ_{shot}^2	-	Shot noise
$\sigma_{thermal}^2$	-	Thermal noise
ψ_c	-	Semi-angle at half power (SAAHP) (radian)
$\phi_{\frac{1}{2}}$	-	Semi-angle of half illumination (radian)
B	-	Data rate (Mb/s)
D_{rx}	-	Distance from the wall to the receiver
D_{tx}	-	Distance from the transmitter to the wall
E [.]	-	Expectation operator
G	-	Open-loop voltage gain
$g(\psi)$	-	Gain of an optical concentrator
$h(t)$	-	Impulse response
$I(0)$	-	Centre luminous intensity
I_2	-	Noise bandwidth factor
k	-	Number of optical attocells in the room
m	-	Order of Lambertian emission
Φ	-	Luminous flux
Q	-	Electronic charge
Z	-	System constraints
γ	-	Channel noise factor of the field-effect transistor (FET)
λ	-	Wavelength
σ	-	Standard deviation
ϕ	-	Angle of irradiance
ψ	-	Angle of incident
ψ	-	Field of view (radian)
I	-	Luminous
N	-	Total noise

$P(\lambda)$	-	Spectral power distribution
SNR	-	Signal to noise ratio (dB)
$V(\lambda)$	-	Receiver sensitivity that measured during the experiments
c	-	Speed of light
dA_{wall}	-	Reflective area of a tiny region
dP	-	Overall radial flux
n	-	Number of side detectors
α	-	Angle of irradiance to reflective point
$\alpha°$	-	Tilt angle along $x - z$
β	-	Angle of irradiance to the receiver
γ	-	Decision vector involving all the system variables
μ	-	Mean excess delay
ρ	-	Reflectance coefficient

LIST OF ABBREVIATIONS

5GB	-	5G and beyond
AP	-	Access Point
AWGN	-	Additive White Gaussian Noise
ADR	-	Angle Diversity Receiver
APs	-	Avalanche PDs
BS	-	Base Station
BPSK	-	Binary Phase Shift Keying
BER	-	Bit Error Rate
B2B	-	Building to Building
CIR	-	Channel Impulse Response
CSI	-	Channel State Information
CCI	-	Co-Channel Interference
CV	-	Coefficient Of Variation
CSK	-	Color Shift Keying
CAGR	-	Compound Annual Growth Rate
CPC	-	Compound Parabolic Concentration
CS	-	Cuckoo Search
DME	-	Device Management Entity
D2D	-	Device to Device
DPSK	-	Differential Phase Shift Keying
E/O	-	Electrical to Optical Conversion
EA	-	Evolutionary Algorithm
FOV	-	Field of View
5G	-	Fifth Generation
FC	-	Fluorescent Concentrator
4G	-	Fourth Generation
FDMA	-	Frequency Division Multiple Access

PRBS	-	Pseudorandom Binary Sequence
GA	-	Genetic Algorithm
GPS	-	Global Positioning System
OMEGA	-	Home Gigabyte Access
ICN	-	Industrial Communication Network
IR	-	Infrared
ICI	-	Inter-Cell Interference
ISO	-	International Organization for Standardization
IoT	-	Internet of Things
ISI	-	Intersymbol interference
JEITA	-	Japan Electronics and Information Technology Industries Association
LD	-	Laser Diode
LED-ID	-	LED-Identification
LEDs	-	Light Emitting Diodes
Li-Fi	-	Light Fidelity
LSD	-	Lighting Shape Diffuser
LOS	-	Line of Sight
LAN	-	Local Area Network
Lx	-	Illumination Level
MAC	-	Media Access Control
MIMO	-	Multiple Input Multiple Output
MPAPM	-	Multiple Pulse Amplitude and Position Modulation
NSD	-	Noise Spectral Density
Non-LOS	-	Non-Line of Sight
OOK-RZ/NRZ	-	On-Off Key-Return/Non-Return-to-Zero
OA	-	Optical Attocell
OCC	-	Optical Camera Communication
O/E	-	Optical to Electrical Conversion
OWC	-	Optical Wireless Communications
OFDM	-	Orthogonal Frequency Division Modulation
PER	-	Packet Error Rate
PAPR	-	Peak to Average Power Ratio

PDAs	-	Personal Digital Assistant
PD	-	Photo-Detector
P2P	-	Point-to-Point
PSD	-	Power Spectral Density
M-PAM	-	Pulse Amplitude Modulation
PPM	-	Pulse Position Modulation
PWM	-	Pulse Width Modulation
QPSK	-	Quadrature Phase Shift Keying
QoS	-	Quality of Service
RF	-	Radio Frequency
RLS	-	Recursive Least Square
RGB	-	Red, Green and Blue
RMS	-	Root Mean Square
SAAHP	-	Semi-Angle at Half Power
SINR	-	Signal to Interference Plus Noise Ratio
SNR	-	Signal to Noise Ratio
STD	-	Standard Deviation
UV	-	Ultraviolet
UIR	-	Uniformity Illuminance Ratio
UEs	-	User Equipment
V2V	-	Vehicle to Vehicle
VL	-	Visible Light
VLC	-	Visible Light Communication
VLP	-	Visible Light Positioning
VLCC	-	VLC Consortium
Wi-Fi	-	Wireless Fidelity

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CHAPTER 1

INTRODUCTION

1.1 Prefaces

This chapter presents an introduction and historical background for the visible light communication system; it shows the basic backbone information for this research, which contains problem formulation, the objectives as well as the scope and significance of the research. The summary of all chapters is contextualized at the end of the chapter.

1.2 Background

Optical wireless communication (OWC) has become an emerging alternatives band to the radio frequency (RF) in the electromagnetic spectrum, and this is due to the vast spread of solid-state lighting technology. Visible light communications (VLCs) employing light emitting diodes (LEDs) are expected to be the prime source of illumination as well as communication in the future. It can be used in direct communication (point-to-point) as well as broadcasting (Bairagi & Chakroborti, 2016; Pathak, Feng, Hu, & Mohapatra, 2015). Furthermore, the VLC has gained great care recently and become a promising supplementary technology for the short-range scenarios in the upcoming fifth generation (5G) and beyond. VLC system has employed for the indoor and outdoor environments due to the great advantageous that comprises unregulated huge (Terahertz) bandwidth, license-free operation, low power consumption, low-cost front-ends, long life expectancy, friendly to the environment as well as safety for the human eye (Aziz, Anuar, Rashidi, Aljunid, & Endut, 2020; H Burchardt, Serafimovski, Tsonev, Videv, & Haas, 2014; Buzzi et al., 2016; Hranilovic, 2005; Hranilovic, Lampe, Hosur, & Roberts, 2014). In addition to its immunity to electromagnetic interference as well as high security where the optical signals cannot penetrate the walls.

The optical band was suggested as complementary techniques used to convey the signal (i.e., data, voice, etc.) with high data rates as well as a lower bit error rate (BER). this optical band was divided into three sub-bands which contains an infrared (IR), visible light (VL), and ultraviolet (UV). On 11 February 1800, the W. Herschel was discovered the Infrared light, and he discussed the spectrum of sunlight with the prism and determined the temperature of all colors (Uysal & Nouri, 2014). IR communication is a short range application applied to convey the information from devices. Such as mobile phones, personal digital assistants (PDAs), notebooks, and medical devices to each other with the standard data rate, which fluctuated from 9.6Kbps to 16Mbps (Borah, Boucouvalas, Davis, Hranilovic, & Yiannopoulos, 2012). Furthermore, the UV radiation and its properties were discovered earlier in three phases gradually by three scientists in 1614, 1777, 1801 by Sala, Scheele, and Ritter respectively (C.-W. Chow, Chen, & Chen, 2015).

The VL is a unique in natural than IR and UV technologies, this is due to the dual function of communication and illumination simultaneously, it was known earlier and the first experiment was achieved by Graham Bell in 1880 through the development of a photo phone system to transmit the speech wirelessly by modulating the reflected sunlight (Elgala, Mesleh, & Haas, 2011; L. Feng, Hu, Wang, Xu, & Qian, 2016). An indoor VLC system using white LEDs was introduced in (K. Qiu, Zhang, & Liu, 2015), and the room model of multiple optical attocells (i.e. transmitter) was depicted as in Figure 1.1.

The integration between VLC and RF technologies has been investigated to produce a new smart infrastructure for communication (Kumar, Mihovska, Kyriazakos, & Prasad, 2014). Moreover, the connectivity should be required in order to provide effective communication systems. Furthermore, different integration methods were introduced to enhance the security solutions, guarantee the communication link as well as support 5G and beyond (5GB) requirements.

Currently, many trends are suggested to improve the VLC system performance, which includes the design and distribution of optical attocells (i.e. LEDs lighting or transmitter) in the room, channel characteristics, and receiver configuration (Y. Qiu, Chen, & Meng, 2016). Most of the investigated optimization techniques for improving the performance of VLC system were reviewed in (Obeed, Salhab, Alouini, & Zummo, 2019), where it contained power allocation, security issues, energy harvesting, maximizing sum rate and others. Also, the author has discussed the influence of VLC limitations on performance.

The demand for access to broadband data services in high-speed indoor environments is increasing as more people are moving within the indoor environment. The introduction of laptops, tablets, and high-end handsets onto mobile networks is a significant source of traffic because these devices offer consumer content and applications not supported by the previous generation of mobile devices. As shown in Figure 1.1, a single laptop can generate as much traffic as 515 basic-feature phones, and a smartphone transmits as much traffic as 24 basic-feature phones.

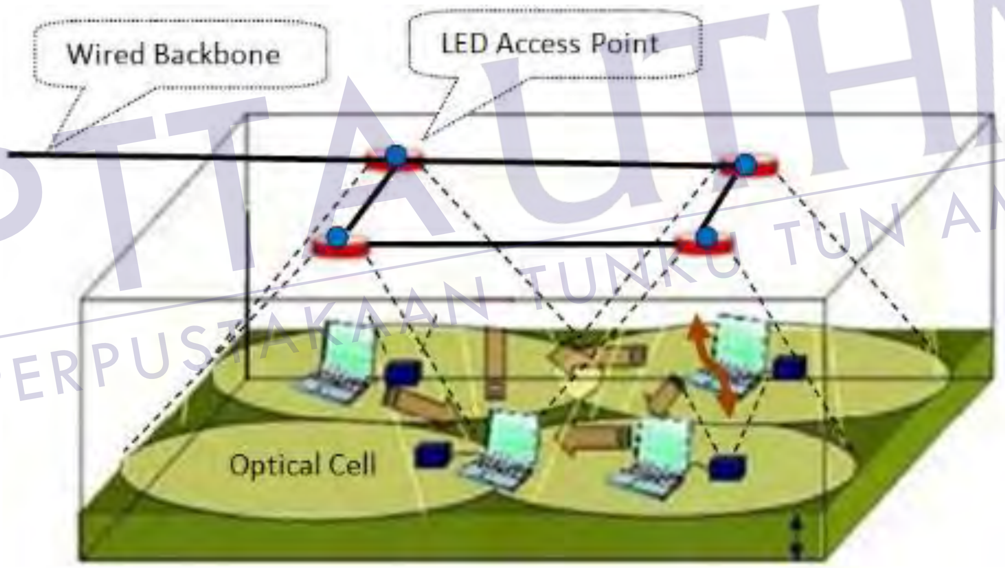

Figure 1.1: VLC system model (Dehao Wu, Ghassemlooy, LeMinh, Rajbhandari, & Kavian, 2011)

VLC has dual functionally, which can be used in communication and illumination simultaneously, and it could be adopted to provide higher data rates and more uniform data services to users moving in indoor environments (typical room). Also, VLC is capable for supporting higher data rates that reach to multiple Gigabits/second for both indoor and outdoor environments.

1.3 Problem Statement

The demand for high data rate, capacity, increasing user mobility as well as low power consumption are increasing daily (Morley, Widdicks, & Hazas, 2018), in which are considered as main the challenges facing the radio frequency (RF) technology. Moreover, the mobile data traffic is expected to increase at a compound annual growth rate (CAGR) of 53% from 2015 to 2020, besides 30.6 exabytes per month via 2020 as illustrated in Figure 1.2, according to CISCO (Cisco, 2016).

Nowadays the challenges of exchanging data traffic in the indoor environments become one of the exciting areas for the academic and industrial researchers, and it gets massive care because more than 70% of communication traffic originated in the indoor environment (Miramirkhani & Uysal, 2015; Tombaz, Zheng, & Zander, 2013).

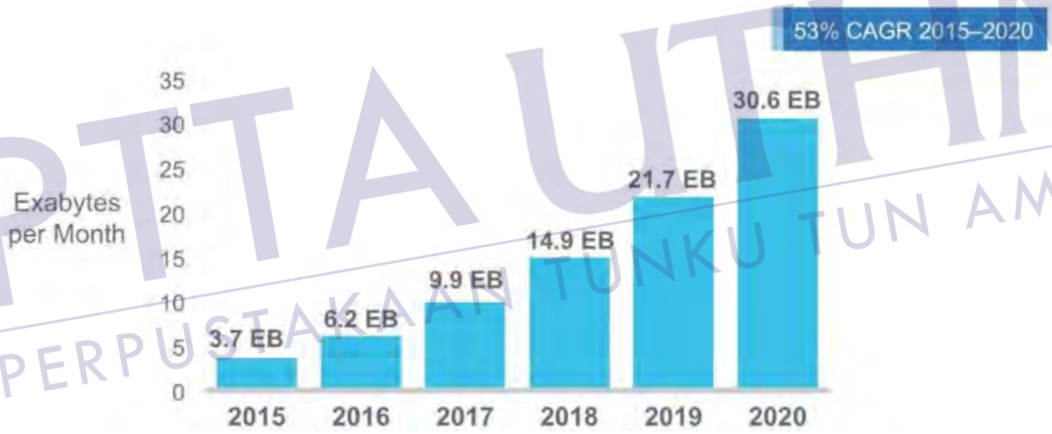

Figure 1.2: Expected Mobile Data Traffic by 2020 (Cisco, 2016)

Numerous efforts have placed to reduce power consumption, interference, increasing data rate and security. In addition to improving the uniformity distribution and link quality of communication, where users can connect to the internet in any position in the indoor environments. However, the current RF technologies suffer from the capacity crunch and bandwidth bottleneck, besides interference, power consumption, cost, and other constraints. Therefore, RF becomes unsuitable to fulfill the communication requirements in many applications today and in the future as well. The current VLC systems in the typical room model provide a lower data rate (below 100 Mbps). Furthermore, the design of a general optical attocells configuration model in the typical room has considered as one of the prospective future research directions, which takes the number of optical attocells and layout of the room into account (Y. Qiu et al., 2016).

The performance improvement of indoor environments by deploying multiple optical attocells on the ceiling of the typical room has presented in (T.-H. Do & Yoo, 2014; T. H. Do, Hwang, & Yoo, 2013; Ghassemlooy, Popoola, & Rajbhandari, 2019; M. Khadr, Abd El Aziz, Fayed, & Aly, 2019; T. Komine & Nakagawa, 2004; Li, Wu, Zou, & Chen, 2016; Mahfouz, Fayed, Abd El Aziz, & Aly, 2018; H. Q. Nguyen et al., 2010; M. T. Niaz, Imdad, Kim, & Kim, 2016; Priyanka & Singh, 2019). These previously presented works by other reseachers are insufficiency, and only a few parameters were discussed.

The main problem of this research according to the previously achieved works is as follows, the improveing of VLC system (i.e. received power, SNR, BER, data rate) by distribution of a few numbers of optical attocells on the ceiling have caused multiple blind areas in the room, and resulted in nonuniformity distribution. While employing large numbers of optical attocells has caused a severe ISI due to adjacent interference (Vegni & Biagi, 2019), which degrades the system performance in terms of RMS delay and bit rate as well. Therefore, the design of the optimal VLC system can be achieved by proposing an adequate number of optical attocells in which provides uniformity distribution in the entire room as well as producing higher VLC system performance under the illumination requirements.

Moreover, in spite of the great deal of research in VLC for the upcoming 5G applications, a clear gap for using VLC in industrial application exists. Only recent work for utilizing VLC in the warehouse model has been performed by (Almadani, Ijaz, Rajbhandari, Adebisi, & Raza, 2018), and it was evaluated in terms of illumination, received power and SNR as well. However, data rate doesn't exceed 10 Mbps, in addition to blinds areas at the room and poor uniformity in terms of illumination, received power as well as SNR distribution.

1.4 Research Objectives

This research study is aimed at designing and performance evaluation of the VLC system in indoor environments. It aims to develop optical attocells arrangement and configuration models for the typical room model and warehouse (industrial) model. These models are investigated for the several numbers of optical attocells, receiver positions as well as modulation techniques. The outcomes of this analysis will be beneficial in determining the link quality in terms of the data rate and BER performance. In addition to the required number optical attocells that would be utilized to produce a sufficient uniformity distribution in the indoor environment over each configuration model. Therefore, the objectives of this research are as follow:

(i). To propose a new optical attocells configuration models for the indoor typical room and warehouse models.

(ii). To formulate a multi-objective optimization equations for different parameters in indoor visible light communication (VLC) system.

(iii). To analyze the proposed configuration models in terms of illumination level, received power, SNR, RMS delay, bit rate, BER, data rates as well as uniformity distribution, where different modulation techniques are considered.

1.5 Research Scope and Limitations

The scope of this research is to develop an indoor VLC system by proposing a novel optical attocells configuration models, which is utilizing a fair number of optical attocells in the typical room of different scenarios. These proposed models are expected to improve uniformity distribution in terms of received power and SNR distribution. In addition to satisfying the illumination requirements of the typical room model based on the international organization for standardization (ISO). A different modulation techniques are studied to evaluate the proposed optical attocells configuration models in terms of BER performance as well as data rates. Therefore, to achieve the scope of this research, the following steps are adopted:

(i). Develop an indoor VLC system using multiple optical attocells on the ceiling of the room as well as the warehouse.

(ii). The dimension of the typical room is $5 \times 5 \times 3\ m^3$, while the typical warehouse size is $20 \times 20 \times h\ m^3$, where h is set as a variable, which varies from 4 to 20 m.

(iii). Simulate model with different modulation techniques, which include OOK-RZ/NRZ, BPSK, QPSK, DPSK, L-PPM, and M-PAM in order to observe the BER performance.

(iv). The LOS and Non-LOS VLC propagation links are considered.

(v). Characterize the proposed models using SAAHP, FOV, distance as well as the CV (i.e. standard deviation and coefficient of variation).

(vi). The MATLAB software program is used in the simulation and analyses.

(vii). Comparisons and validation the results of the proposed models with the previously research studies.

1.6 Significance of the research

This research significantly begins in an effort to employ LEDs for the VLC system through a new layout of optical attocells configuration models. Most of the previous studies on indoor VLC systems are concentrated more on either channel modelling such as LOS and Non-LOS propagations, receiver configuration as design smart receiver, equalization, and optimization algorithms. In addition to improving optical attocell parameters such as the number of LEDs chip in each optical attocell and optimization of SAAHP. However, this research is looking for designing a universal optical attocells configuration model, which could be improved and optimized the overall performance parameters that highlighted by the green color in Figure 1.3 for the typical room model and warehouse as well.

This research proposes a new optical attocells configuration models, where multiple optical attocells with different configurations have been employed to obtain high performance with improved data rates and enhanced uniformity distribution at various SAAHP, in which improving the users mobility. Furthermore, FOV has been optimized, where received power, SNR, RMS delay spread, and bit rate have been improved. The BER performance of the proposed configuration models has been improved by utilizing different modulation techniques. Thus, it expected that these proposed configuration models would revolutionize the VLC system and can find a wide range of applications in the indoor and outdoor environments as well as industrial fields.

Lastly, the K-chart is established as a monitoring and planning tool because it provides a more comprehensive micro level planning. Besides that, it constructed with the aim to provide an obvious design of the total work and granting a micro level of planning.

As illustrated in Figure 1.3, the parameters and existing steps adopted in this research are represented using different colors. In this research, two approaches are utilized to perform the evaluation and analysis of the proposed optical attocells configuration models. The simulation is created using MATLAB, and similar theory and analysis are built for the theory part. Several parameters are used to evaluate and study the comparison and validation between current and previous simulation in terms of received power, SNR, data rates, CV, bit rate, and RMS delay spread as well. The proposed optical attocells configuration is extended to the industrial applications (warehouse), and the wide room scenarios of different heights levels are studied. Finally, several modulation techniques are studied to evaluate the typical room models and warehouse model in terms of BER performance.

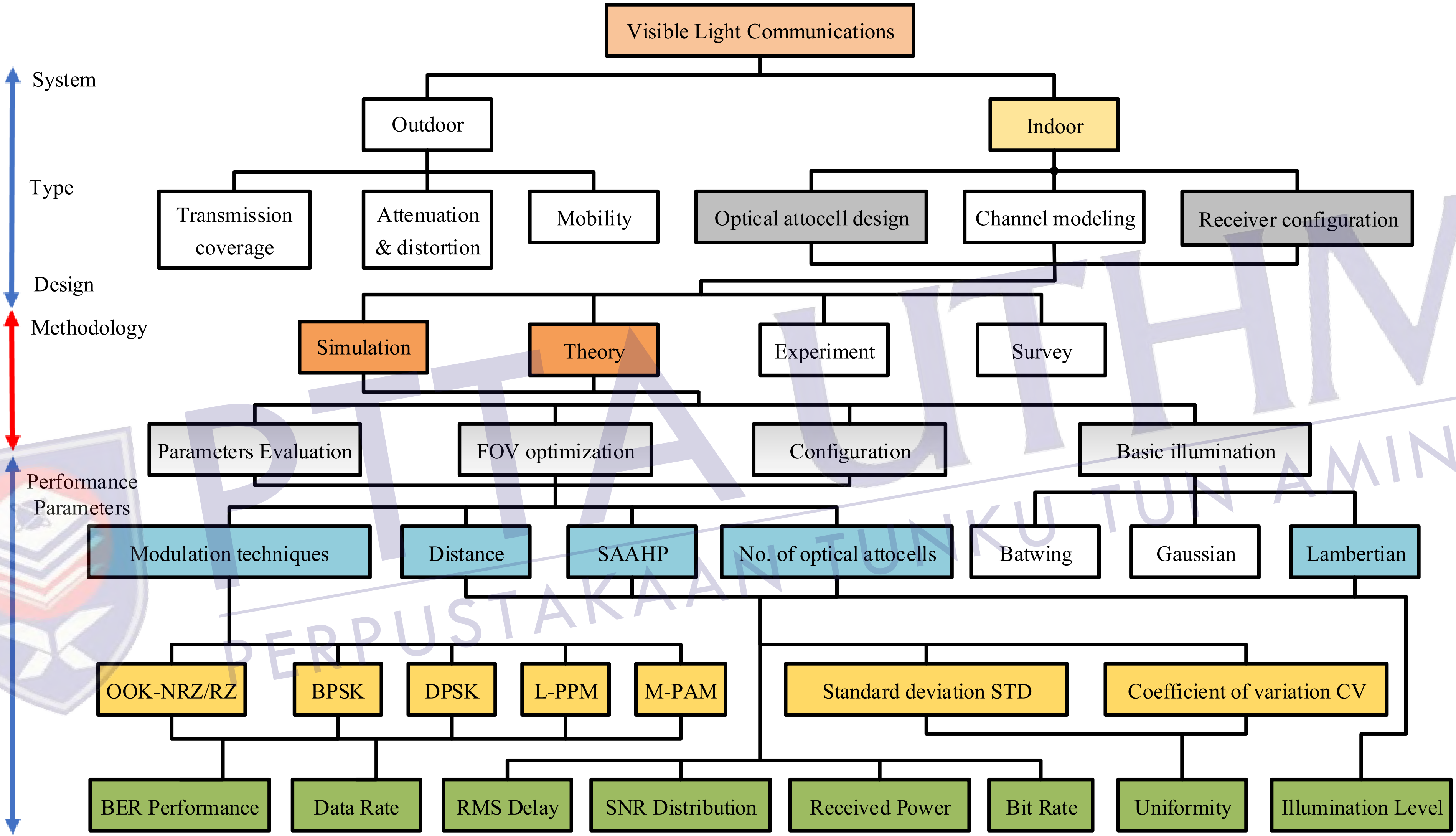

Figure 1.3: Modeling and evaluation of the proposed models in the typical room and warehouse model K-Chart

1.7 Research Structure outline

The proposed outline for this research is given in this section. The whole structure of the thesis includes five main chapters, comprising this introductory chapter. The elaborated elements of this research have been documented in these five chapters, such as follows:

(i). Chapter 1: Introduction:

This chapter presenting a historical background, and the introduction of the research equally establish the problem statement and research objectives. Furthermore, the scope, limitations and significance of this research are also within the context of this chapter.

(ii). Chapter 2: Literature Review:

This chapter presents an overview about the previous studies pertaining to the OWC system and especially the VLC system indoor environments, VLC standardization, and basic channel structure, in addition to the possibilities, advantages, features, and applications. Moreover, different optical attocells configuration models are introduced, where the illumination characteristics with radiation patterns are presented. Additionally, the general block diagram of the VLC system is introduced, where the functions of all parts are highlighted. Furthermore, various evaluation metrics were presented to shows the performance of the VLC system in the typical room model. The relevant related works are investigated and summarized in order to highlight the research gaps at the end of the chapter.

(iii). Chapter 3: Methodology:

This chapter represents the core of this study. The chapter will present the overall methodological process used in this research which including the theory, computational methods, and research procedure. The proposed optical attocells configuration models in the typical room and the proposed optical attocells configuration model for the warehouse model (industrial application) are discussed.

The different evaluation metrics employed to analyze and evaluate the proposed models are explained throughly in this chapter.

(iv). Chapter 4: Results and Discussion:

This chapter presents the outcome of this research from the methodological methods proposed in Chapter 3. The results of the simulation study are discussed and analyzed. The results are divided into two parts for a better understanding and clarity of the reader. The first part of this chapter starts with extensive discussion and presentation of the simulation work for the typical room models. The warehouse results are presented and analyzed in the second part of this chapter. The comparison and validation of the results of this research work with the previous related studies are discussed in this chapter, to prove the reliability and accuracy of the proposed optical attocells configuration model.

(v). Chapter 5: Conclusion and Recommendation:

This chapter presents a summary of the main simulation findings demonstrated in Chapter 4. The main contributions of this research work are highlighted in this chapter. Additionally, this chapter suggests future research trends for additional improvement and development of VLC system in the indoor environment applications.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter offers an extensive overview of the previous studies and research on the new technologies that contain solid state light emitting diodes (LEDs), visible light communications (VLC). Which included performance analysis of power consumption, illumination level, received power, SNR distribution, BER, and data rate analysis. This chapter also introduces the solid state lightings (LEDs) characteristics, channel characteristics (propagation links) and modulation techniques.

2.2 Background of VLC system

The optical band was suggested as supplementary technology to the RF in short range scenarios, in order to convey data with high rates. It has been divided into three sub-bands, which contained infrared (IR), visible light (VL) and ultraviolet (UV) (Uysal & Nouri, 2014). VL has a unique in features compared to IR and UV, due to its dual functionality that it could be utilized in illumination and communication simultaneously.

The visible light (VL) wavelengths vary from 400 to 700 nm, and it could be a supplementary technology supporting the era of internet of things (IoT) at the indoor environment. Besides, different LEDs array (optical attocell) has been employed to create a secure zone for the physical layer in the VLC system. Hence, higher transmission security has been produced as reported in (C.-W. Chow, Liu, et al., 2015; Kocharoen, 2016; Mat, Rashidi, Aljunid, Endut, & Ali, 2020).

5G networks aim to offer a 1000-fold rise in the total throughput, also, to increase the individual link throughput to 10 fold as compared to 4G wireless networks (Nawaz, Sharma, Wyne, Patwary, & Asaduzzaman, 2019). A novel physical technology such as VLC has been suggested to deliver these high data rates, where the huge bandwidth could support higher data rates. Figure 2.1 illustrates the development of mobile communication networks, which involved the generations, technology, systems, and standardizations. According to the current and expected requirements of communication networks, VLC could be a promising candidate technology to fulfil these requirements based on its valuable features and advantages illustrated previously in Chapter 1.

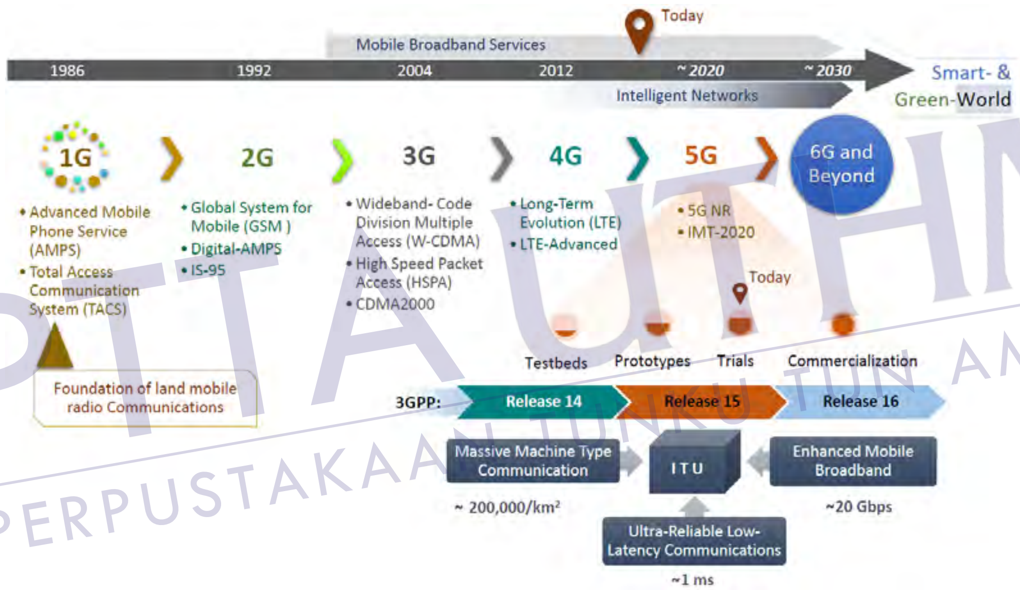

Figure 2.1: Development in the generations of mobile radio communication networks (Nawaz et al., 2019).

There are many techniques and approaches have been implemented to satisfy the increasing demand of the network capacity. New modulation techniques, signal processing and spectrum allocation techniques have been employed to improve spectral efficiency and link capacity respectively. However, the distribution of many small optical attocells (base stations) in the indoor environments has been required, in order to meet the requirements of the upcoming 5G and beyond applications, through improving the channel capacity, transmission rate, BER performance as well as SNR. These improvements are leading to increasing the total spectral efficiency and bandwidth density as well (Ghassemlooy, Alves, Zvanovec, & Khalighi, 2017; Kamel, Member, Hamouda, & Member, 2019). Figure 2.2 has depicted the growth of cellular coverage network in term of cell size.

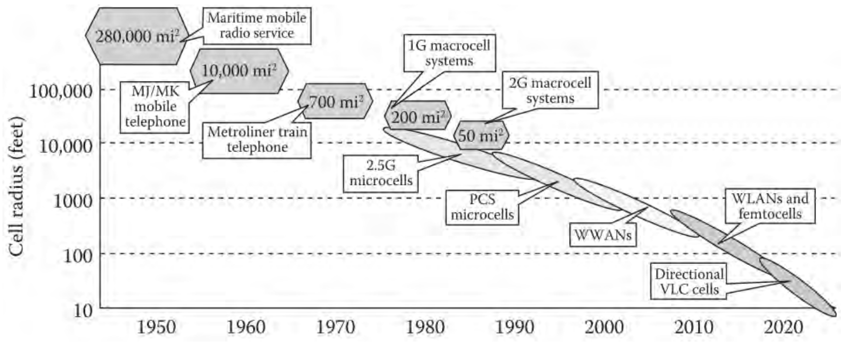

Figure 2.2: Development of cellular coverage size for wireless communication system (Ghassemlooy, Zvanovec, Khalighi, Popoola, & Perez, 2017)

The employing of multiple optical attocells in indoor environments would improve the uniformity as well as guarantee users mobility, and this could be accomplished by utilizing a VLC coordinator. VLC coordinator has a physical switch connected with an optical element in all optical attocells and controlled by a device management entity (DME), which facilitate the mobility. Figure 2.3 illustrated optical attocells configuration with the VLC coordinator, where UL and DL were referred to the uplink and downlink, respectively.

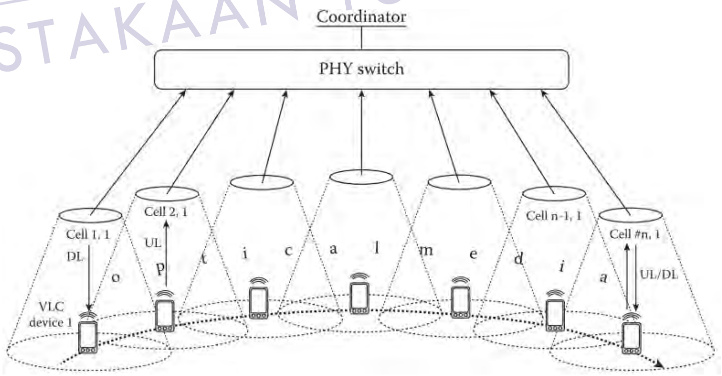

Figure 2.3: VLC optical attocells configuration (Ghassemlooy, Zvanovec, et al., 2017)

Currently, VLC has been considered as the key candidates to resolve the capacity crunch being experienced by RF. Also, VLC has many advantages as mention previously; however, the comparison with RF in terms of different parameters has been summarized in Table 2.1 (Harald Burchardt, Serafimovski, Tsonev, Videv, & Haas, 2014; Fidelity, 2014; Ma'ruf, Othman, & Sholeh, 2015).

Table 2.1: Comparison between VLC and RF communication technology (Harald Burchardt et al., 2014; Fidelity, 2014)

Parameters	VLC	RF
Spectrum band	~ 400 THz to ~ 780THz	~ 3GHz to ~ 300 GHz
Spectrum allocation	unlicensed	Licensed
applications	Communication & illumination	Communication
Power consumption	Low	Medium
Infrastructure	Illumination	hotspot point
complication	Low	High
Multipath fading	No	Yes
Coverage Area	bounded	Wide
Safety	Unregulated	Intensity regulated
Electromagnetic Interference	No	Yes
Security	High	Bounded
Information delivery	carried on optical intensity	carried on electric field
Signal	real valued	complex valued

Alternatively, the VLC requirement, advantages in terms of capability, productivity, safety and security, as well as challenges in indoor environments have been introduced in (Bhalerao & Sonavane, 2014). In addition to recent developments projects, in which include home gigabyte access (OMEGA) that supported by the European Commission, this project aims to deliver high bandwidth services with high transmission speed up to (Gb/s).

2.3 Modeling and characteristics of VLC system

The modeling and characteristics of VLC system have been considered various issues, in which included the power consumption, illumination features, and characteristics of optical attocells (LEDs) in terms of LED chips, number of attocells in the room model as well as configuration topologies. Many issues could degrade the transmitted signal in the channel such as propagation links, intersymbol interference (ISI), multipath fading and shadowing. Additionally, the receiver gain, RMS delay and user mobility decrease the received signal at the receiver end. All these issues are presented in the following subsections.

2.3.1 Power consumption

The power consumption was considered as one of the main problems facing the upcoming applications in communication networks, the reduction strategies of power consumption in various types of networks were introduced in (Vereecken et al., 2011). In case of low demand, the adaptive network was designed to switch devices off, and low power consumption has been obtained. The optimization of power consumption for fixed-line as well as wireless access networks has been concerned with fully shift toward the optical networks (wired and wireless communication). Figure 2.4 demonstrated different wired and wireless networks.

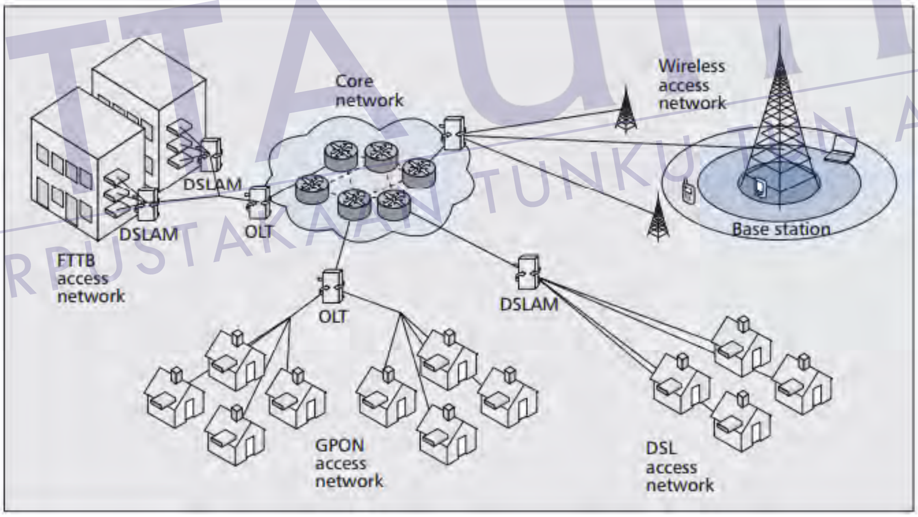

Figure 2.4: Overview of different wire and wireless networks (Vereecken et al., 2011)

One of the main challenges in 5G and beyond generation is to reducing the power consumption, increasing the network capacity and data rate, as well as the spectral efficiency. The conventional RF was reached the bottleneck to satisfy these requirements. Moreover, the innovation of a new low-power integrated circuit will be required in order to mitigate power consumption, which still represents a challenge for RF communication. The white LED lighting has a lower voltage requirement as well as lower power consumption as compared to the incandescent and fluorescent brightness in indoor environments (room and office) (Toshihiko Komine, Lee, Haruyama, & Nakagawa, 2009). The minimum power consumption represents an important factor in the design of any communication system.

Recently, the researchers are concern with the energy-saving to reduce the energy consumption of light, and approximately 20% of the total generated electricity was used for lighting purposes as presented in (Halonen, Tetri, & Bhusal, 2010). The wide spreading of LEDs has used as an emerging method for reducing lighting energy consumption. In (Din & Kim, 2014), an optimization problem was investigated based on subcarrier PPM scheme to improve the energy efficiency in the VLC system, and high energy efficiency was obtained. Where the recommended illumination level for the typical room, office, and laboratories have fluctuated from 400 to 500 Lx.

The main reason for substituting the fluorescent and incandescent lamps with the optical attocells (i.e. LEDs array) in the lightings is to producing lower energy cost, as well as providing higher energy efficiency. The illumination level should be taken into account in order to avoid any influence on the communication performance because lower brightness level leading to a decrease in the transmission power. Therefore, degrading the SNR distribution (S. Wu, Wang, & Youn, 2014). The authors (Fan, Tian, & Liang, 2016) have investigated the minimizing of power consumption and maximizing the illumination uniformity simultaneously. Various parameters were studied to provide acceptable illumination and communication distribution. The design of multi-user full-duplex VLC system was proposed for indoor environments, to improve the BER performance and data rates as illustrated in Figure 2.5, while reducing the cost and power consumption as well (M. Niaz, Imdad, & Kim, 2017).

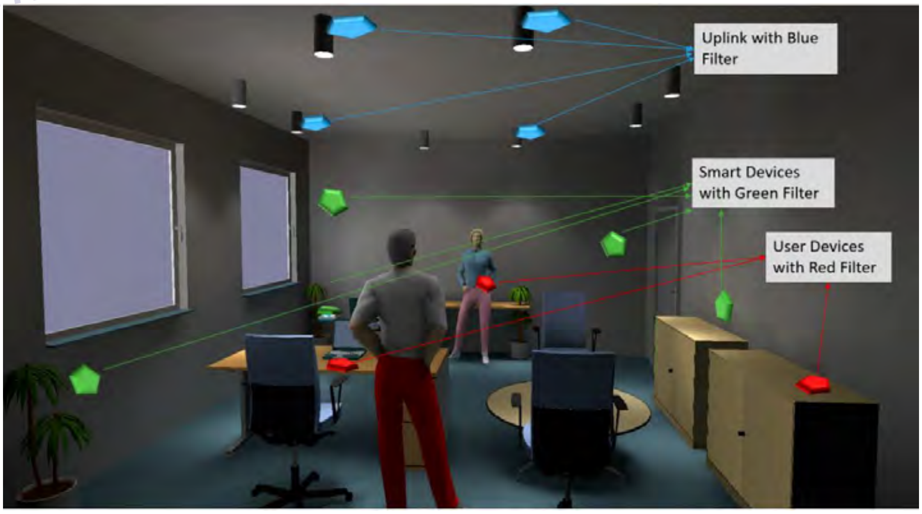

Figure 2.5: Multi-user full-duplex (VLC) system (M. Niaz et al., 2017)

The results of the designed VLC system showed that higher energy efficiency and cost savings had been obtained, which could be employed for the upcoming 5G and beyond networks.

In (Zhang, 2016), the impact of optical attocells position on the power savings for VLC system was investigated, and the more uniformity distribution can be achieved through utilizing more optical attocells in the indoor communication system. The design of energy-efficient optical attocells configuration, which is meeting the illumination constraints was introduced in (Ali & Elgala, 2016). Also, the optimization problem of illumination constraints was formulated to reduce power consumption. Where the optimal power consumption has been considered as an important factor in the design of optical attocells in the indoor environment (Praneeth Varma, Kumar, Sushma, Sharma, & Sharma, 2017).

Alternatively, a system model of optical attocells based on the color separation was presented to optimize the transmitted power. The power optimization has applied for the device to device (D2D) and broadcast connection schemes, the increases of transmission power for D2D connection has constrained due to eye safety considerations (Gong, Li, Gao, & Xu, 2015). Also, signal to interference plus noise ratio (SINR) influence the received signals of broadcast connection, which causes degradation in the quality of service (QoS). Therefore, analytical design for the new structure of power optimization was introduced in (Gong et al., 2015), which was solved the problem.

The light concentration of LEDs array (optical attocells) was controlled to alleviate the harmful effects mentioned in (Gong et al., 2015). The evolutionary algorithm (EA) with the optimized system has been proposed to mitigate the power of the transmitted signals. Further, 16 LED bulbs (optical attocells) within an empty room were considered as in (It Ee Lee et al., 2014). The proposed algorithm was simulated and practically implemented. The result showed that the transmitted power was reduced, and the illumination level satisfied the requirements, in addition to providing an adequate SNR distribution and low BER respectively. The conventional local search algorithm (LSA) was compared with EA, and the result showed that LSA had provided a suboptimal solution, while EA had produced an optimal solution (J. Ding, Huang, & Ji, 2012).

The discussion of LEDs lighting characteristics as an illumination tool is required to control the optical emitted power in the room. In addition to determining a minimum SNR that required to guarantee the communication link, as well as enhance the quality of the VLC system (Zixiong Wang, Wen-De Zhong, Changyuan Yu, & Jian Chen, 2011).

Lastly, the power of LEDs (optical attocells) characteristics depends mainly on the VLC system application. Recently, manufactories produced LEDs with high luminance, long lifetime as well as small driving voltage. Additionally, LED optical power of different wavelengths has been demonstrated in (Y. Qiu et al., 2016), and the power can be expressed as follows.

$$P_t = \int_{\lambda_L}^{\lambda_H} P_t(\lambda) d\lambda \tag{2.1}$$

where, $P_t(\lambda)$ is the optical power at different wavelengths. The average optical power of LEDs can be calculated theoretically as follow:

$$P_t = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t) dt \tag{2.2}$$

Where $X(t)$ refers to a transmission signal, generally, LED can propagate light energy in whole directions without causing any problem to the human eye as in laser diode (LD) transmitter. Many characterizations and modelling for indoor VLC system were analyzed in details (Y. Qiu et al., 2016).

2.3.2 Cellular coverage optimization

The VLC was suggested to offer extra capacity, bandwidth and enhancing spectral efficiency in the indoor environment, and different applications scenarios with simulation supports were studied in (Harald Burchardt et al., 2014). Moreover, the small cells sizes concept has been introduced to improve system capacity 1000 times or more in the future of OWC in indoor applications.

Additionally, small optical attocells configuration has been applied in an indoor environment in order to produce better spectral efficiency. However, the main obstacles to applying a massive number of small optical attocells are the interference and cost as well. The optimization techniques were investigated to reduce the effect of co-channel interference, increasing network capacity as well as improve the data rate. Referring to the authors (Seguel et al., 2017), two different methods of optimization were proposed based on the Cuckoo Search algorithm (CS) to improve spectral efficiency. The simulation analysis showed that acceptable results were achieved at various FOV angle.

The design of optical attocells in indoor environments should meet the illumination requirements and authoritative data transmission simultaneously. Figure 2.6 illustrated different cellular cells networks which included optical attocells distributed in a typical room model.

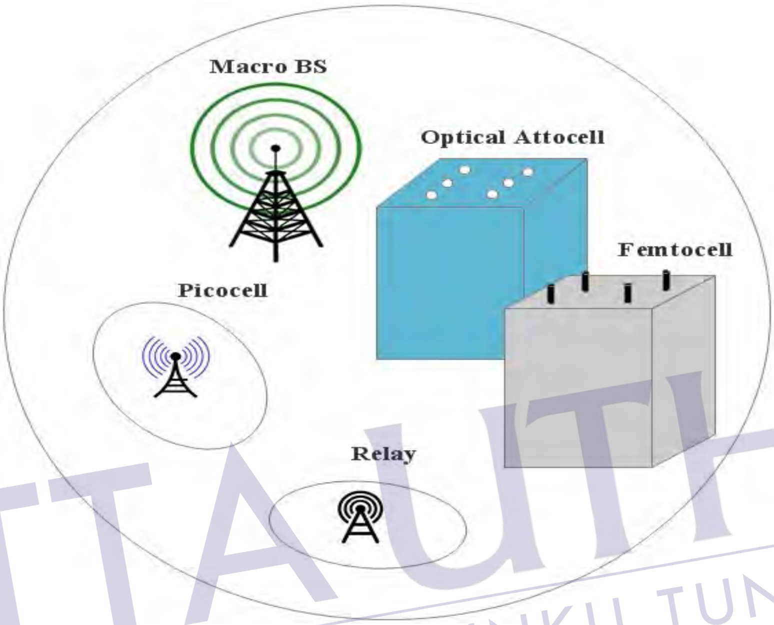

Figure 2.6: Optical attocells in the context of a heterogeneous network (Tsonev, Videv, & Haas, 2014)

The aim of optimizing VLC coverage area in an indoor environment is to guarantee that both received power and SNR are uniformly distributed at all receiver planes (entire room), in addition, to guarantee the fairness of illumination and communication around the room. The new improved CS algorithm has been introduced to optimize the power coverage in indoor VLC system (Sun et al., 2017). The simulation results of the improved algorithm shows an increased in the coverage efficiency, meanwhile convergence speed of solution. Also, the uncovered area was significantly improved. The optical attocells can be used in the construction of MIMO in OWC system in order to increase the capacity.

According to authors (Madani, Baghersalimi, & Ghassemlooy, 2017), three topologies of optical attocells were designed to improve the cellular coverage area in terms of the SNR distribution for a single transmitter and receiver, as well as multiple transmitters with a single receiver scenario. The authors have studied the FOV, transmitter locations, number of LED chips in optical attocell as well as a variable SAAHP to improve the SNR distribution. Authors observed that the SNR and received power were degraded as SAAHP increase, and the wide SAAHP could expand the light beams, which causes ISI and multipath fading (Madani et al., 2017).

2.3.3 Field of view (FOV)

The field of view (FOV) is the viewing angle of the receiver which is adjusted to improve the received signal, whereas the applying of small or either wide FOV could be effect the received signal performance.

According to authors (Burton, Le Minh, Ghassemlooy, Rajbhandari, & Haigh, 2012), FOV has been considered in the design of a new smart receiver, which could be used to reduce the shadowing effects and to improve user mobility as well. The concept of this smart receiver is to design optical antennas from the arrays of PDs, where PDs could be able to receive the light signal from all directions, as shown in Figure 2.7.

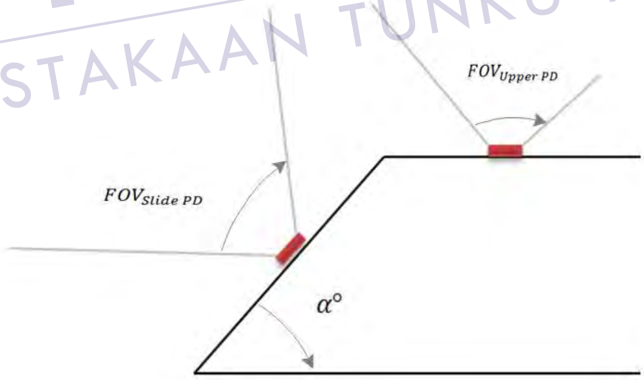

Figure 2.7: Side view of the receiver geometry (Burton, Le Minh, Ghassemlooy, et al., 2012)

The smart receiver needs a 180° and 360° view over the axis $x - y$ and $x - z$ respectively, and at most three sides for the receiver. The FOV of every side detector required to satisfy the following condition in equation (2.3)

$$FOV_{Side} = \frac{360°}{n} \quad (2.3)$$

Where n represents number of side detectors, $\alpha°$ is tilt angle along $x - z$, and it could be computed using the FOV of side detector as follow:

$$\alpha° = \frac{FOV_{Side}}{2} \tag{2.4}$$

There is a trade-off between bandwidth and PD active area in the VLC system. Small PDs has tiny capacitance, therefore, produces higher bandwidth and vice versa. When the signal failed at small PDs, the optical concentrator can be employed to collect the light from a large area to small PDs as demonstrated in Figure 2.8. Furthermore, the optical concentrator in the receiver has been employed to improve the gain based on the FOV angle.

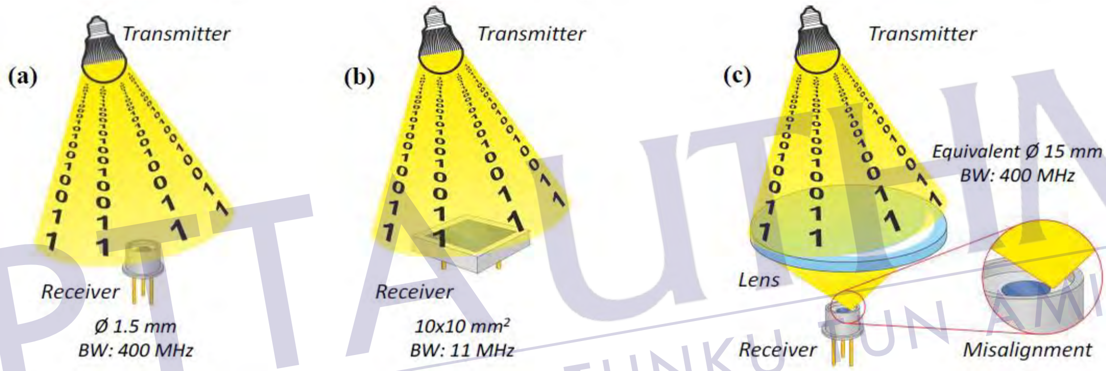

Figure 2.8: Trade-off between BW and PD active area: (a) high BW receiver at small active area (b) low BW receiver at large active area(c) large active with high BW using concentrator but it is prone to non-LOS (Mulyawan et al., 2017).

A comparison study between the traditional optical concentrator (Compound Parabolic Concentration-CPC) and Fluorescent Concentrator (FC) was studied based on the FOV and optical gain performance in (Mulyawan et al., 2017). The maximum traditional gain of optical concentrator (G_{max}) was computed by maximum acceptance angle θ_{max} as well as refractive index n using Snell law as given in equation (2.5). Moreover, the relationship between FOV and light configuration design was introduced in (Ji & Ding, 2012).

$$G_{max} = \frac{n^2}{sin^2\theta_{max}} \tag{2.5}$$

The angle diversity receiver has been studied to reduce the interference, in which utilizing various PD receivers with small FOV. The severe impact of inter-cell interference (ICI) has decreased throughput and SINR at the cell edge of the communication system. A novel network configuration based on soft frequency reuse (SFR), and two FOV angles were proposed to reduce the effect of ICI as introduced in (Jang, 2012). Thereafter, performance evaluation of SFR has been computed in terms of SINR and BER performance as well. Authors have pointed out that SFR reduced ICI effect and improved the communication system as compared to conventional approaches.

Additionally, co-channel interference (CCI)/ICI and ISI come from the neighbour optical attocells and multipath reflections respectively are limit the performance of the downlink VLC channel. Therefore, the FOV angle has optimized to eliminate the CCI and reduce the ISI in the typical indoor scenario. Also, the constraint FOV angular diversity receiver (CFOV-ADR) was proposed to reduce these limitations in (Eldeeb, Selmy, Elsayed, & Badr, 2018). Figure 2.9 shows the geometrical model of the proposed CFOV-ADR. The results showed that the CFOV-ADR was produced a better SINR as compared to conventional ADR and ADR-ZF as well.

Figure 2.9: Shape of ADR with seven PDs for the proposed CFOV-ADR (Eldeeb et al., 2018)

According to authors (Y. Liu, Peng, Liu, & Long, 2015), the Genetic Algorithm (GA) approach proposed to optimize the optical concentrator at the receiver, which can increase the optical received power distribution in the room. The simulation results of the proposed algorithm showed that the ratio of summit power deviation was decreased without degrading the illumination as compared to other optimization approaches; further, the optical received power had improved.

REFERENCES

Ali, R. E., & Elgala, H. (2016). Energy efficient LED layout optimization for near-uniform illumination. *Fifteenth International Conference on Solid State Lighting and LED-Based Illumination Systems*, *9954*(December 2017), 995406.

Almadani, Y., Ijaz, M., Rajbhandari, S., Adebisi, B., & Raza, U. (2018). Application of Visible Light Communication in an Industrial Environment. *2018 11th International Symposium on Communication Systems, Networks and Digital Signal Processing, CSNDSP 2018*, 1–6.

Aziz, N. A., Anuar, M. S., Rashidi, C. B. M., Aljunid, S. A., & Endut, R. (2020). Medical healthcare M2M system using the VLC system. In *AIP Conference Proceedings* (Vol. 2203, p. 20058).

Azizan, L. A., Ab-Rahman, M. S., Hassan, M. R., Bakar, A. A. A., & Nordin, R. (2014). Optimization of signal-to-noise ratio for wireless light-emitting diode communication in modern lighting layouts. *Optical Engineering*, *53*(4), 45103.

Bairagi, A. K., & Chakroborti, D. (2016). Trust based D2D communications for accessing services in Internet of Things. *2015 18th International Conference on Computer and Information Technology, ICCIT 2015*, 50–54.

Berenguer, P. W., Hellwig, P., Schulz, D., Hilt, J., Kleinpeter, G., Fischer, J. K., & Jungnickel, V. (2018). Real-Time Optical Wireless Communication : Field-Trial in an Industrial Production Environment. *Ecoc*, (1), 1–3.

Berenguer, P. W., Schulz, D., Fischer, J. K., & Jungnickel, V. (2017). Optical wireless communications in Industrial production environments. *30th Annual Conference of the IEEE Photonics Society, IPC 2017*, *2017–Janua*, 125–126.

Bhalerao, M. V., & Sonavane, S. S. (2014). Visible light communication: A smart way towards wireless communication. In *Proceedings of the 2014 International Conference on Advances in Computing, Communications and Informatics, ICACCI 2014*.

Borah, D. K., Boucouvalas, A. C., Davis, C. C., Hranilovic, S., & Yiannopoulos, K.

(2012). A review of communication-oriented optical wireless systems. *EURASIP Journal on Wireless Communications and Networking*, *2012*(1), 91.

Bui, T. C., Kiravittaya, S., Sripimanwat, K., & Nguyen, N. H. (2016). A Comprehensive Lighting Configuration for Efficient Indoor Visible Light Communication Networks. *International Journal of Optics*, *2016*.

Burchardt, H., Serafimovski, N., Tsonev, D., Videv, S., & Haas, H. (2014). VLC: Beyond point-to-point communication. *Communications Magazine, IEEE*, *52*(7), 98–105.

Burchardt, H., Serafimovski, N., Tsonev, D., Videv, S., & Haas, H. (2014). VLC: Beyond point-to-point communication. *IEEE Communications Magazine*, *52*(7), 98–105.

Burton, A., Le Minh, H., Ghasemlooy, Z., & Rajbhandari, S. (2012). A study of LED lumination uniformity with mobility for visible light communications. *2012 International Workshop on Optical Wireless Communications, IWOW 2012*, (October).

Burton, A., Le Minh, H., Ghassemlooy, Z., Rajbhandari, S., & Haigh, P. A. (2012). Smart receiver for visible light communications: Design and analysis. *Proceedings of the 2012 8th International Symposium on Communication Systems, Networks and Digital Signal Processing, CSNDSP 2012*, (July 2012).

Buzzi, S., Chih-Lin, I., Klein, T. E., Poor, H. V., Yang, C., & Zappone, A. (2016). A survey of energy-efficient techniques for 5G networks and challenges ahead. *IEEE Journal on Selected Areas in Communications*, *34*(4), 697–709.

Chen, Z., & Haas, H. (2015). A simplified model for indoor optical attocell networks. *2015 IEEE Summer Topicals Meeting Series, SUM 2015*, *3*, 167–168.

Choi, S. Il. (2012). Analysis of VLC channel based on the shapes of white-light LED lighting. *ICUFN 2012 - 4th International Conference on Ubiquitous and Future Networks, Final Program*, 1–5.

Chong, J. X. J., Saon, S., Mahamad, A. K., Othman, M. B., Rasidi, N., & Setiawan, M. I. (2020). Visible Light Communication-Based Indoor Notification System for Blind People. In *Embracing Industry 4.0* (pp. 93–103). Springer.

Chow, C.-W., Chen, C.-Y., & Chen, S.-H. (2015). Enhancement of signal performance in LED visible light communications using mobile phone camera. *IEEE Photonics Journal*, *7*(5), 1–7.

Chow, C.-W., Liu, Y., Yeh, C.-H., Chen, C.-Y., Lin, C.-N., & Hsu, D.-Z. (2015). Secure communication zone for white-light LED visible light communication. *Optics Communications*, *344*, 81–85.

Chow, C. W., Liu, Y., Yeh, C. H., Sung, J. Y., & Liu, Y. L. (2015). A practical in-home illumination consideration to reduce data rate fluctuation in visible light communication. *IEEE Wireless Communications*, *22*(2), 17–23.

Chvojka, P., Zvanovec, S., Haigh, P. A., & Ghassemlooy, Z. (2015). Channel Characteristics of Visible Light Communications Within Dynamic Indoor Environment. *JOURNAL OF LIGHTWAVE TECHNOLOGY*, *33*(1).

Cisco. (2016). Cisco Visual Networking Index: Global Mobile Data, 39. Retrieved from https://www.cisco.com/c/dam/m/en_in/innovation/enterprise/assets/mobile-white-paper-c11-520862.pdf

Davis, C. C. (2006). Design and Analysis of Advanced Free Space Optical Communication Systems. *Sugianto Trisno*.

Din, I., & Kim, H. (2014). Energy-Efficient Brightness Control and Data Transmission for Visible Light Communication. *IEEE Photonics Technology Letters*, *26*(8), 781–784.

Ding, D., Ke, X., & Xu, L. (2007). An optimal lights layout scheme for visible-light communication system. *2007 8th International Conference on Electronic Measurement and Instruments, ICEMI*, 2189–2194.

Ding, J., Huang, Z., & Ji, Y. (2012). Evolutionary algorithm based power coverage optimization for visible light communications. *IEEE Communications Letters*, *16*(4), 439–441.

Dixit, V., & Kumar, A. (2020). Performance analysis of non-line of sight visible light communication systems. *Optics Communications*, *459*(September 2019), 125008.

Do, T.-H., & Yoo, M. (2014). Optimization for link quality and power consumption of visible light communication system. *Photonic Network Communications*, *27*(3), 99–105.

Do, T. H., Hwang, J., & Yoo, M. (2013). Analysis of the effects of LED direction on the performance of visible light communication system. *Photonic Network Communications*, *25*(1), 60–72.

Eldeeb, H. B., Selmy, H. A. I., Elsayed, H. M., & Badr, R. I. (2018). Interference mitigation and capacity enhancement using constraint field of view ADR in downlink VLC channel.

Elgala, H., Mesleh, R., & Haas, H. (2011). Indoor optical wireless communication: Potential and state-of-the-art. *IEEE Communications Magazine*, *49*(9), 56–62.

Elganimi, T. Y. (2013). Studying the BER performance, power- and bandwidth-efficiency for FSO communication systems under various modulation schemes. *2013 IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies, AEECT 2013*, 0–5.

Eroglu, Y. S., Sahin, A., Guvenc, I., Pala, N., & Yuksel, M. (2015). Multi-Element Transmitter Design and Performance Evaluation for Visible Light Communication. *IEEE Globecom Workshops (GC Wkshps)*.

Fan, B., Tian, H., & Liang, S. (2016). Energy Efficient Illumination Optimization for Indoor Visible Light Communication. *2016 19th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, (c), 183–187.

Feng, J., Yang, C., Hou, J., Long, H., & Chen, S. (2020). Performance enhancement for indoor visible light communication system with an improved inter-symbol interference model using optimized hemispherical optical-angle-diversity-receivers. *Optics Communications*, *454*(September 2019), 124488.

Feng, L., Hu, R. Q., Wang, J., Xu, P., & Qian, Y. (2016). Applying VLC in 5G Networks: Architectures and Key Technologies. *IEEE Network*, *30*(6), 77–83.

Fidelity, L. L. (2014). Li-Fi (Light Fidelity), 1–23.

Fuada, S., Putra, A. P., & Adiono, T. (2017). Analysis of Received Power Characteristics of Commercial Photodiodes in Indoor Los Channel Visible Light Communication, *8*(7), 164–172.

Fuchtenhans, M., Grosse, E. H., & Glock, C. H. (2019). Literature review on smart lighting systems and their application in industrial settings. In *2019 6th International Conference on Control, Decision and Information Technologies (CoDIT)* (pp. 1811–1816). IEEE.

Ghassemlooy, Z., Alves, L. N., Zvanovec, S., & Khalighi, M.-A. (2017). *Visible Light Communications: Theory and Applications*. CRC Press.

Ghassemlooy, Z., Popoola, W., & Rajbhandari, S. (2012). Introduction. In *Optical Wireless Communications* (pp. 1–33). CRC Press.

Ghassemlooy, Z., Popoola, W., & Rajbhandari, S. (2019). *Optical wireless communications: system and channel modelling with Matlab®*. CRC press.

Ghassemlooy, Z., Zvanovec, S., Khalighi, M. A., Popoola, W. O., & Perez, J. (2017). Optical wireless communication systems. *Optik*, *151*, 1–6.

Gong, C., Li, S., Gao, Q., & Xu, Z. (2015). Power and rate optimization for visible light communication system with lighting constraints. *IEEE Transactions on Signal Processing*, *63*(16), 4245–4256.

Gupta, A., & Garg, P. (2018). Statistics of SNR for an Indoor VLC System and its Applications in System Performance. *IEEE Communications Letters*, *PP*(c), 1.

Haas, H., Elmirghani, J., & White, I. (2020). Optical wireless communication. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2169), 20200051.

Haas, H., Sarbazi, E., Marshoud, H., & Fakidis, J. (2020). Visible-light communications and light fidelity. In *Optical Fiber Telecommunications VII* (pp. 443–493). Elsevier.

Haas, H., Yin, L., Chen, C., Videv, S., Parol, D., Poves, E., … Islim, M. S. (2020). Introduction to indoor networking concepts and challenges in LiFi. *Journal of Optical Communications and Networking*, *12*(2), A190–A203.

Halonen, L., Tetri, E., & Bhusal, P. (2010). Guidebook on energy efficient electric lighting for buildings. *Espoo, Finland: Department of Electrical Engineering, Aalto University*.

Hamkins, J. (2011). Pulse Position Modulation. *Handbook of Computer Networks*, *1*, 492–508.

Hranilovic, S. (2005). *Wireless Optical Communication Systems*.

Hranilovic, S., Lampe, L., Hosur, S., & Roberts, R. D. (2014). Visible light communications: The road to standardization and commercialization (Part 2). *IEEE Communications Magazine*, *52*(7), 62–63.

Ip, E., & Kahn, J. M. (2006). Power spectra of return-to-zero optical signals. *Journal of Lightwave Technology*, *24*(3), 1610–1618.

Jang, V. V. H. N. T. L. N. S. M. Z. C. Y. M. (2012). Inter-cell Interference Mitigation Using Soft Frequency Reuse with Two FOVs in Visible Light Communication. *2012 International Conference on ICT Convergence (ICTC)*, *1*, 141–144.

Ji, Y. F., & Ding, J. P. (2012). Evolutionary algorithm-based optimisation of the signal-to-noise ratio for indoor visible-light communication utilising white light-emitting diode. *IET Optoelectronics*, *6*(6), 307–317.

Kamel, M., Member, S., Hamouda, W., & Member, S. (2019). Ultra-Dense Networks : A Survey. *Ieee Communications Surveys & Tutorials*, *18*(4), 2522–2545.

Khadr, M., Abd El Aziz, A., Fayed, H., & Aly, M. (2019). Bandwidth and BER Improvement Employing a Pre-Equalization Circuit with White LED Arrays in a MISO VLC System. *Applied Sciences*, *9*(5), 986.

Khadr, M. H., Fayed, H. A., Aziz, A. A. El, & Aly, M. H. (2016). Bandwidth extension of an enhanced SNR with a higher light uniformity of a phosphorescent white LED based visible light communication system. *2016 10th International Symposium on Communication Systems, Networks and Digital Signal Processing, CSNDSP 2016*.

Kocharoen, P. (2016). Visible Light Communication: Importance and Thai Preparations. *Procedia Computer Science*, *86*, 51–54.

Komine, T., Lee, J. H., Haruyama, S., & Nakagawa, M. (2009). Adaptive equalization system for visible light wireless communication utilizing multiple white led lighting equipment. *IEEE Transactions on Wireless Communications*, *8*(6), 2892–2900.

Komine, T., & Nakagawa, M. (2004). Fundamental analysis for visible-light communication system using LED lights. *IEEE Transactions on Consumer Electronics*, *50*(1), 100–107.

Kumar, A., Mihovska, A., Kyriazakos, S., & Prasad, R. (2014). Visible light communications (VLC) for ambient assisted living. *Wireless Personal Communications*, *78*(3), 1699–1717.

Le Minh, H., Liaw, S.-K., Aslam, N., Bentley, E., Ghassemlooy, Z., & Burton, A. (2014). Experimental demonstration of a 10BASE-T Ethernet visible light communications system using white phosphor light-emitting diodes. *IET Circuits, Devices & Systems*, *8*(4), 322–330.

Lee, I. E., Chung, G. C., Pang, W. L., Anas, S. S., & Cheong, M. Y. (2020). Design of a hybrid free space optical and visible light communication system for indoor wireless data broadcasting. *Journal of Physics: Conference Series*, *1432*, 12065.

Lee, I. E., Law, J. C., Chung, K. Y., Fong, K. Y., Liew, Y. Q., Quan, S. Y., … Tan, C. K. (2014). Design and development of a portable visible-light communication transceiver for indoor wireless multimedia broadcasting. In *2014 2nd International Conference on Electronic Design (ICED)* (Vol. 7, pp. 20–24). IEEE.

Li, F., Wu, K., Zou, W., & Chen, J. (2016). Analysis of energy saving ability in dimming VLC systems using LEDs with optimized SAHP. *Optics Communications*, *361*, 86–96.

Little, T. D. C., Dib, P., Shah, K., Barraford, N., & Gallagher, B. (2008). Using LED lighting for ubiquitous indoor wireless networking. *Proceedings - 4th IEEE International Conference on Wireless and Mobile Computing, Networking and Communication, WiMob 2008*, (October 2008), 373–378.

Liu, H., Lin, Z., Xu, Y., Chen, Y., & Pu, X. (2019). Coverage uniformity with improved genetic simulated annealing algorithm for indoor Visible Light Communications. *Optics Communications*, *439*(January), 156–163.

Liu, Y., Peng, Y., Liu, Y., & Long, K. (2015). Optimization of receiving power distribution using genetic algorithm for visible light communication. In Y. Liao, W. Zhang, D. Jiang, W. Wang, & G. Brambilla (Eds.) (Vol. 9679, p. 96790I).

Ma'ruf, M. I., Othman, M. B., & Sholeh, H. P. (2015). Audio transmission using visible light communication (VLC). *ARPN Journal of Engineering and Applied Sciences*, *10*(20), 9835–9838.

Madani, F., Baghersalimi, G., & Ghassemlooy, Z. (2017). Effect of transmitter and receiver parameters on the output signal to noise ratio in visible light communications. In *2017 Iranian Conference on Electrical Engineering (ICEE)* (pp. 2111–2116). IEEE.

Mahfouz, N. E., Fayed, H. A., Abd El Aziz, A., & Aly, M. H. (2018). Improved light uniformity and SNR employing new LED distribution pattern for indoor applications in VLC system. *Optical and Quantum Electronics*, *50*(9), 350.

Mat, N. R. N., Rashidi, C. B. M., Aljunid, S. A., Endut, R., & Ali, N. (2020). Enrichment of wireless data transmission based on visible light communication for triple play service application. In *AIP Conference Proceedings* (Vol. 2203, p. 20066).

Miramirkhani, F., & Uysal, M. (2015). Channel Modeling and Characterization for Visible Light Communications. *IEEE Photonics Journal*, *7*(6), 1–16.

Morley, J., Widdicks, K., & Hazas, M. (2018). Digitalisation, energy and data demand:

The impact of Internet traffic on overall and peak electricity consumption. *Energy Research and Social Science*, *38*(August 2017), 128–137.

Mulyawan, R., Gomez, A., Chun, H., Rajbhandari, S., Manousiadis, P. P., Vithanage, D. A., … O'Brien, D. (2017). A comparative study of optical concentrators for visible light communications. In B. B. Dingel, K. Tsukamoto, & S. Mikroulis (Eds.) (p. 101280L).

Mushfique, S. I., & Yuksel, M. (2016). Optimal multi-element VLC bulb design with power and lighting quality constraints. *3rd ACM Workshop on Visible Light Communication Systems, VLCS 2016*, *03–07–Octo*, 7–12.

Nawaz, S. J., Sharma, S. K., Wyne, S., Patwary, M. N., & Asaduzzaman, M. (2019). Quantum Machine Learning for 6G Communication Networks: State-of-the-Art and Vision for the Future. *IEEE Access*, *7*(Ml), 46317–46350.

Nguyen, H. Q., Choi, J., Kang, M., Ghassemlooy, Z., Kim, D. H., Lim, S., … Lee, C. G. (2010). A MATLAB-based simulation program for indoor visible light communication system. *Communication Systems Networks and Digital Signal Processing (CSNDSP), 2010 7th International Symposium on*, *3600*(April 2016), 537–541.

Nguyen, H. Q. Q., Choi, J.-H., Kang, M., Ghassemlooy, Z., Kim, D. H. H., Lim, S.-K., … Lee, C. C. G. (2010). A MATLAB-based simulation program for indoor visible light communication system. *Ieee*, *3600*(April 2016), 537–541.

Niaz, M., Imdad, F., & Kim, H. (2017). Power Consumption Efficiency Evaluation of Multi-User Full-Duplex Visible Light Communication Systems for Smart Home Technologies. *Energies*, *10*(2), 254.

Niaz, M. T., Imdad, F., Kim, S., & Kim, H. S. (2016). Deployment methods of visible light communication lights for energy efficient buildings. *Optical Engineering*, *55*(10), 106113.

Nuwanpriya, A., Ho, S. W., & Chen, C. S. (2015). Indoor MIMO Visible Light Communications: Novel Angle Diversity Receivers for Mobile Users. *IEEE Journal on Selected Areas in Communications*, *33*(9), 1780–1792.

Obeed, M., Salhab, A. M., Alouini, M. S., & Zummo, S. A. (2019). On Optimizing VLC Networks for Downlink Multi-User Transmission: A Survey. *IEEE Communications Surveys and Tutorials*, *21*(3), 2947–2976.

Pathak, P. H., Feng, X., Hu, P., & Mohapatra, P. (2015). Visible light communication, networking, and sensing: A survey, potential and challenges. *IEEE Communications Surveys & Tutorials*, *17*(4), 2047–2077.

Praneeth Varma, G. V. S. S., Kumar, A., Sushma, R., Sharma, V., & Sharma, G. V. V. (2017). Power allocation for uniform illumination with stochastic LED arrays. *Optics Express*, *25*(8), 8659.

Priyanka, & Singh, M. L. (2019). Simulation and Analysis of Uniformity of Illuminance in Indoor VLC System. *2018 6th Edition of International Conference on Wireless Networks & Embedded Systems (WECON)*, *1*, 142–147.

Qiu, K., Zhang, F., & Liu, M. (2015). Visible light communication-based indoor environment modeling and metric-free path planning. In *2015 IEEE International Conference on Automation Science and Engineering (CASE)* (Vol. 17, pp. 200–205). IEEE.

Qiu, Y., Chen, H., & Meng, W. (2016). Channel modeling for visible light communications-a survey. *Wireless Communications and Mobile Computing*, *16*(14), 2016–2034.

Sacko, D., & Kéïta, A. A. (2017). Techniques of Modulation : Pulse Amplitude Modulation , Pulse Width Modulation , Pulse Position Modulation, (2), 100–108.

Seguel, F., Firoozabadi, A. D., Adasme, P., Soto, I., Krommenacker, N., & Azurdia-Meza, C. (2017). A novel strategy for LED re-utilization for visible light communications. *Optik*, *151*, 88–97.

Shaaban, R., & Faruque, S. (2017). A survey of indoor visible light communication power distribution and color shift keying transmission. In *2017 IEEE International Conference on Electro Information Technology (EIT)* (pp. 149–153). IEEE.

Sun, G., Liu, Y., Yang, M., Wang, A., Liang, S., & Zhang, Y. (2017). Coverage optimization of VLC in smart homes based on improved cuckoo search algorithm. *Computer Networks*, *116*, 63–78.

Teli, S. R., Zvanovec, S., & Ghassemlooy, Z. (2019). Optical internet of things within 5g: Applications and challenges. *Proceedings - 2018 IEEE International Conference on Internet of Things and Intelligence System, IOTAIS 2018*, 40–45.

Tombaz, S., Zheng, Z., & Zander, J. (2013). Energy efficiency assessment of wireless access networks utilizing indoor base stations. *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio*

Communications (PIMRC), 3105–3110.

Tronghop, D. (2012). Modeling and Analysis of the Wireless Channel formed by LED Angle in Visible Light Communication. *International Conference on Information Networking (ICOIN)*, (2010), 354–357.

Tsonev, D., Videv, S., & Haas, H. (2014). Light fidelity (Li-Fi): towards all-optical networking. In *Broadband Access Communication Technologies VIII* (Vol. 9007, p. 900702). International Society for Optics and Photonics.

Uysal, M., Miramirkhani, F., Narmanlioglu, O., Baykas, T., & Panayirci, E. (2017). IEEE 802 . 15 . 7r1 Reference Channel Models for Visible Light Communications. *IEEE Communications Magazine*, *55*(January), 212–217.

Uysal, M., & Nouri, H. (2014). Optical wireless communications—An emerging technology. In *Transparent Optical Networks (ICTON), 2014 16th International Conference on* (pp. 1–7). IEEE.

Vanderka, A., Hajek, L., Latal, J., Vitasek, J., & Koudelka, P. (2014). Design, simulation and testing of the OOK NRZ modulation format for free space optic communication in a simulation box. *Advances in Electrical and Electronic Engineering*, *12*(6), 604–616.

Vegni, A. M., & Biagi, M. (2019). Optimal LED placement in indoor VLC networks. *Optics Express*, *27*(6), 8504.

Vereecken, W., Heddeghem, W., Deruyck, M., Puype, B., Lannoo, B., Joseph, W., … Demeester, P. (2011). Power consumption in telecommunication networks: overview and reduction strategies. *IEEE Communications Magazine*, *49*(6), 62–69.

Vitturi, S., Zunino, C., & Sauter, T. (2019). Industrial Communication Systems and Their Future Challenges: Next-Generation Ethernet, IIoT, and 5G. *Proceedings of the IEEE*, *107*(6), 944–961.

WANG, J., ZOU, N., Dong, W., Kentaro, I., Zensei, I. H. A., & NAMIHIRA, Y. (2012). Experimental study on visible light communication based on LED. *The Journal of China Universities of Posts and Telecommunications*, *19*, 197–200.

Wang, Y., Lan, T., Wang, H., & Ni, G. (2017). A new design of light source arrangements for indoor visible light communication. *2016 3rd International Conference on Systems and Informatics, ICSAI 2016*, (Icsai), 705–709.

Wilke Berenguer, P., Schulz, D., Hilt, J., Hellwig, P., Kleinpeter, G., Fischer, J. K., &

Jungnickel, V. (2018). Optical Wireless MIMO Experiments in an Industrial Environment. *IEEE Journal on Selected Areas in Communications*, *36*(1), 185–193.

Wu, D., Ghassemlooy, Z., LeMinh, H., Rajbhandari, S., & Kavian, Y. S. (2011). Power distribution and q-factor analysis of diffuse cellular indoor visible light communication systems. In *Networks and Optical Communications (NOC), 2011 16th European Conference on* (pp. 28–31). IEEE.

Wu, D., Ghassemlooy, Z., Rajbhandari, S., & Le Minh, H. (2012). Channel characteristics analysis and experimental demonstration of a diffuse cellular indoor visible light communication system. *The Mediterranean Journal of Electronics and Communications*, *8*, 1–7.

Wu, S., Wang, H., & Youn, C.-H. (2014). Visible light communications for 5G wireless networking systems: from fixed to mobile communications. *IEEE Network*, *28*(6), 41–45.

Yang, H., Bergmans, J. W. M., Schenk, T. C. W., Linnartz, J. P. M. G., & Rietman, R. (2009). Uniform illumination rendering using an array of LEDs: A signal processing perspective. *IEEE Transactions on Signal Processing*, *57*(3), 1044–1057.

YoussefElganimi, T. (2013). Performance Comparison between OOK, PPM and PAM Modulation Schemes for Free Space Optical (FSO) Communication Systems: Analytical Study. *International Journal of Computer Applications*, *79*(11), 22–27.

Zhang, J. (2016). Influence of lamp placement on power saving efficiency for indoor visible light communication systems. *2016 China International Conference on Electricity Distribution (CICED)*, (Ciced), 1–4.

Zheng, H., Chen, J., Yu, C., & Gurusamy, M. (2017). Inverse design of LED arrangement for visible light communication systems. *Optics Communications*, *382*, 615–623.

Zheng, H., Yu, C., Chen, J., You, X., & Ghassemlooy, Z. (2015). LED arrangement optimization for visible light communication systems. *2015 Opto-Electronics and Communications Conference, OECC 2015*.

Zixiong Wang, Wen-De Zhong, Changyuan Yu, & Jian Chen. (2011). A novel LED arrangement to reduce SNR fluctuation for multi-user in visible light communication systems. In *2011 8th International Conference on Information, Communications & Signal Processing* (pp. 1–4). IEEE.