HIGH CAPACITY OF OPTICAL CODE DIVISION MULTIPLE ACCESS IN VISIBLE LIGHT COMMUNICATION SYSTEM USING CATENATED OFDM MODULATION TECHNIQUE

by

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LIST OF ABBREVIATIONS

5G	Fifth Generation
APD	Avalanche Photodiode
ASK	Amplitude Shift Keying
BER	Bit Error Rate
CSK	Color Shift Keying
DMT	Discrete Multi-Tone
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FOV	Field-of-View
FSO	Free Space Optic
IEEE	Institute of Electrical and Electronics Engineers
IM/DD	Intensity Modulation and Direct Detection
IoT	Internet of Thing
IR	Infrared
ISI	Inter-symbol Interference
LED	Light Emission Diode
Li-Fi	Light Fidelity
LOS	Line of Sight
MAI	Multiple Access Interference
MZM	Mach-Zehnder Modulator
NLOS	Non Line of Sight
NRZ	Non Return to Zero
OCDMA	Optical Code Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On-Off-Keying
OPL	Optical Path Loss
OTDMA	Optical Time Domain Multiplexing
OWC	Optical Wireless Communication
PIIN	Phase Induced Intensity Noise
PIN	Positive-Intrinsic-Negative
PPM	Pulse Position Modulation

PWM	Pulse Width Modulation
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RF	Radio Frequency
RGB	Red-Green-Blue
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
VLC	Visible Light Communication
VLCC	Visible Light Communications Consortium
VLD	Visible Laser Diode
VPPM	Variable Pulse Position Modulation
WDM	Wavelength Division Multiplexing
ZCC	Zero Cross Correlation

Pembahagian Kod Berbilang Capaian Optik Berkapasiti Tinggi dalam Sistem Komunikasi Cahaya Terlihat Menggunakan Teknik Modulasi Baharu

ABSTRAK

Sistem komunikasi cahaya terlihat (VLC) adalah teknologi baru sebagai alternatif kepada kesesakan komunikasi tanpa wayar yang menggunakan spektrum frekuensi radio. Teknologi ini menawarkan jalur lebar tiada kawalan, tidak berlesen dan tanpa had untuk memenuhi permintaan yang semakin meningkat dalam sistem komunikasi di dalam bangunan pada masa depan. Sehingga kini, cabaran utama dalam sistem VLC ialah dalam meningkatkan kelajuan penghantaran sistem VLC dengan optimum kapasiti jalur lebar. Salah satu cara untuk meningkatkan penggunaan spektrum adalah menggunakan format modulasi termaju seperti pemultipleksan pembahagian frekuensi orthogonal (OFDM). Dalam kajian ini, pendekatan baharu untuk teknik modulasi berdasarkan pengubahsuaian konvensional OFDM telah dibangunkan dalam sistem VLC yang mampu meningkatkan kecekapan spektrum dan mengoptimumkan kadar data. Kajian ini juga menyumbang kepada pembangunan model matematik bagi pembahagian kod berbilang capaian optik (OCDMA) berdasarkan kod penghubung silang sifar (ZCC) menggunakan teknik modulasi baharu. Kombinasi ini menunjukkan kawalan akses yang cekap dalam reka bentuk dasar rangkaian untuk meningkatkan kapasiti saluran, untuk menaik taraf kadar data sistem dan pada masa yang sama untuk meningkatkan kepekaan pengesan cahaya. Secara khususnya, kajian ini bermula dengan pembinaan teknik modulasi baharu, iaitu catenated-OFDM yang dibangunkan berdasarkan beberapa spektrum OFDM. Untuk memenuhi permintaan generasi akan datang untuk sistem kadar data yang lebih tinggi, konvensional OFDM-VLC diubahsuai untuk mendapatkan prestasi yang optimum. Rangka kerja matematik baru teknik modulasi ini untuk menganalisa prestasi SNR dan BER dalam sistem VLC telah dibangunkan. Simulasi dijalankan untuk menilai beberapa parameter yang tidak termasuk dalam pengiraan matematik. Pemilihan nilai parameter yang berbeza seperti kadar bit, bilangan kumpulan jalur, kuasa yang berkesan dan jarak penyebaran akan mempunyai kesan yang berbeza terhadap prestasi sistem. Pengesahan keputusan teori dan keluaran simulasi juga dijalankan. Pengiraan matematik menunjukkan bahawa prestasi catenated-OFDM melebihi konvensional OFDM sebanyak lima kali dan lapan kali peningkatan kecekapan spektrum pada lima dan lapan kumpulan band masing-masing. Ia juga menunjukkan bahawa rekabentuk yang dicadangkan, catenated-OFDM, berfungsi dengan baik walaupun pada kadar bit yang tinggi iaitu 15 Gbps. Dalam gabungan sistem OCDMA-VLC menggunakan catenated-OFDM, pengiraan teori dan model simulasi juga dibangunkan untuk menilai dan menganalisis prestasinya. Sistem ini secara teorinya menunjukkan bahawa peningkatan kardinaliti dengan peningkatan dua kali ganda, tiga kali ganda dan empat kali ganda bilangan pengguna untuk (Band = 2), (Band = 5) dan (Band = 8) masing-masing berbanding dengan sistem OCDMA ZCC-VLC sebelumnya. Hasil ini mendedahkan peningkatan dalam sensitiviti penerima yang penalti kuasa 7.3 dB berbanding hasil kerja sebelumnya. Disamping itu, integrasi ini memberikan sensitiviti penerima yang lebih tinggi; kira-kira -17.7 dBm dengan 8 bilangan berat dan panjang kod ditetapkan kepada 20. Juga didapati bahawa, untuk menampung lebih ramai pengguna, sistem memerlukan kuasa berkesan yang lebih tinggi pada bahagian penerima. Hasil ini menunjukkan kemungkinan sistem ini akan menjadi satu teknik modulasi yang hebat sebagai calon untuk

rangkaian akses masa depan. Oleh itu, dengan kapasiti yang lebih besar, kadar data yang tinggi dan keselamatan yang dipertingkatkan, OCDMA-VLC berdasarkan catenated-OFDM dijangka menjadi pertimbangan baharu untuk rekabentuk sistem komunikasi mudah alih OCDMA-VLC yang akan datang.

High Capacity of Optical Code Division Multiple Access In Visible Light Communication System using New Modulation Technique

ABSTRACT

Visible light communication (VLC) system is a new technology as an alternative for crowded wireless communication using radio frequency spectrum. This technology offers unregulated, unlicensed and huge bandwidth to meet the growing demand in future indoor communication system. To date, the major challenge in VLC systems has been in improving transmission speed of VLC system with optimize bandwidth capacity. One of the method to improve spectral usage is using advanced modulation formats such as orthogonal frequency division multiplexing (OFDM). In this work, a new approach for modulation technique based on modification of conventional OFDM has been developed in VLC system which capable to improve the spectral efficiency and optimize the data rate. This work also contributes to the development of mathematical model of optical code division multiple access (OCDMA) based on zero cross correlation code (ZCC) using a new modulation technique. This combination demonstrates an efficient access control in backbone design network to enhance the channel capacity, to upgrade the system data rate and at same time to improve sensitivity of photodetector. In particular, this thesis begins with the construction of a new modulation technique, namely catenated-OFDM that is developed based on multiband OFDM. In order to fulfill the next generation demand for higher data rate system, conventional OFDM-VLC is modified to get the optimum performance. A new mathematical framework of this modulation technique to analyze SNR and BER performance in VLC system has been derived. Simulation are carried out to evaluate some parameters that are not included in the numerical analysis. Different selection of parameter values such as bit rates, number of bands, effective power and propagation distance will have different effect on the system performance. Validation of theoretical results and simulation results are also conducted. Numerical analysis shown that the catenated-OFDM outperforms conventional OFDM by five times spectral efficiency improvement and eight times spectral efficiency improvement at their five and eight number of bands respectively. It is also shown that the proposed catenated-OFDM design is working well even at very high bit rate of 15 Gbps. In the combination of OCDMA-VLC using catenated-OFDM, the theoretical analysis and simulation model are also developed to evaluate and analyze its performance. This system theoretically demonstrates cardinality enhancement with double-fold, triple-fold and quadruple increase in number of user for (Band=2), (Band=5) and (Band=8) respectively compared to previous OCDMA ZCC-VLC system design. This result reveals improvement in term of receiver sensitivity which the power penalty of 7.3 dB compared to previous work. In addition, this integration provides higher receiver sensitivity; an approximately –17.7 dBm with 8 number of weight and fixed code length of 20. It is also found that, to accommodate more user, the system requires higher effective power at the receiver. This results exhibit the feasibility of the scheme to be one powerful modulation technique as a candidate for future access network. Thus, with a larger capacity, high data rate and enhanced security the OCDMA-VLC based on catenated-OFDM is predicted to be new considerable for upcoming OCDMA-VLC mobile communication system design.

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CHAPTER 1 : INTRODUCTION

1.1 Project Background

The very rapid growth of internet-connected of smart devices and high speed networks shapes the internet of things (IoT), where 'things' refer to the devices ranging from very simple sensors to highly complex cloud servers such as smart phones, tablets, laptops, body sensors, smart tags, wearable devices, embedded objects, and traditional electronic gadgets (Ammar, Russello, & Crispo, 2018). The IoT interconnected different devices with ubiquitous accessibility and built-in intelligence. It has gained wide acceptance, growth popularity and predicted to reach seven billion IoT transmission devices in the forthcoming fifth generation (5G) environments by 2025 (Farris, Orsino, Militano, Iera, & Araniti, 2018). According to CISCO, there will be sevenfold increase in mobile data traffic in 2021 compared to 2016 as shown in Figure 1.1. The increase in the number of devices accessing the mobile networks is the primary reason for the drastic increase in mobile data traffic. Along with this, the development of online social services (such as facebook, instagram and twitter) has further increased the mobile data traffic. The proliferation of these devices has created a huge pressure on the currently established third generation (3G) and fourth generation (4G) mobile communication networks. These technologies become unable to cope with the tremendous growth of the mobile service demands. Therefore, the research and industrial communities are targeting that the new standard of mobile technology in 5G environments will improved the security, enhanced the capacity and transmission performance by 1000 times compared to the existing technologies (Abdallah & Boudriga, 2016). To overcome this issue, the research community has suggested that 5G concept will not only based on single technology but the researchers have to consider higher ranges of the electromagnetic spectrum.

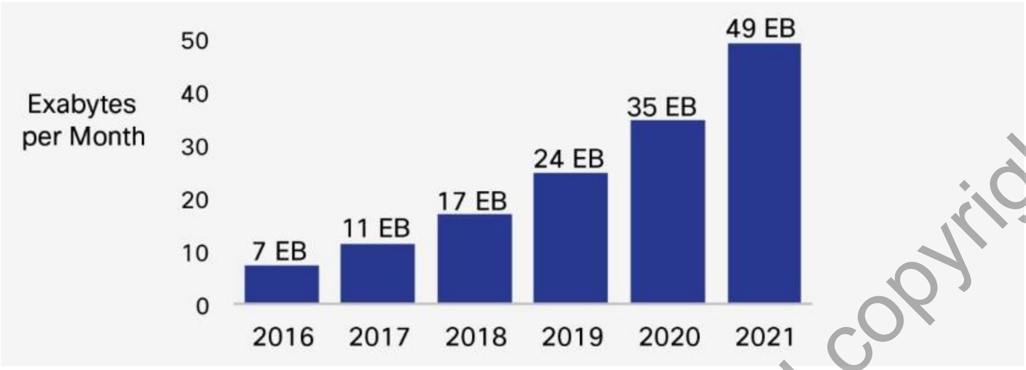

Figure 1.1 Global mobile data traffic (Cisco, 2017)

Recently, optical wireless communication (OWC) came along taking the attention because of several importance characteristics such as large bandwidth, high security, low cost, and license free operation. Although OWC has only recently been gaining interest in transmission system, it has a long history of existence. OWC have been used long before radio communications were first considered. The first implementation of OWC started in 1880, when Alexander Graham Bell and his assistant invented wireless optical technology in the form of photo-phone (Dimitrov, 2013; Ndjiongue, 2015). This instrument was used to transmit a human voice hundreds of meters by modulating the sunlight. However, over the last century the communication through radio frequency medium has been the preferred choice to transmit data wirelessly. Recently, when there are shortages in capacity for wireless data communications, it is necessary to explore and consider other alternatives like OWC as a candidate for widespread wireless communications applications (Ndjiongue, Ferreira, & Ngatched, 2015).

Optical wireless especially visible light communication (VLC) can be a potential candidate solution for 5G networks. The VLC system has been investigated for about one and half decade and received a lot of interest (O'Brien, 2011). VLC system has more flexibility and integrity than other communication systems in many regards. Since the medium for transmission in VLC system is visible light and not radio waves that can penetrate walls, the issue of security is inherently solved. It is because light cannot leave the room, containing data and information in one location. There is no way to retrieve and access the information unless a user is in a direct path of the light being used to transmit the data.

The standardization of the visible light communication research is strongly supported by the Visible Light Communications Consortium (VLCC) in Japan. In 2011, the Institute of Electrical and Electronics Engineers (IEEE) published a standard for VLC, IEEE Std 802.15.7−2011, "IEEE Standard for Local and Metropolitan Area Networks, Part 15.7: Short-Range Wireless Optical Communication Using Visible Light" (Dimitrov, 2013; O'Brien, 2011).

1.2 Problem Statements

VLC technology encounters several challenges in the implementation level. One of the major challenge in VLC system has been in improving transmission speed with high spectral efficiency. Similar to other broadband wireless access network, VLC is aimed to allow high data rate communication between users. A maximum speed of 662 Mbps of on-off-keying (OOK) VLC system was reported in (Fujimoto & Yamamoto, 2014) using a high power red-green-blue (RGB) type of light emission diode (LED) with post-equalizing technique for an optical receiver. Unfortunately, the VLC with OOK data formatting approaches still leads to poor efficiency of optical wireless communication for future broadband access network (Y. C. Chi et al., 2015). The single-carrier modulation schemes did not handle inter-symbol interference (ISI) properly which resulted in nonlinear frequency response of VLC (A. Khalid & Asif, 2017). Hence, a suitable and good modulation technique may lead to increase the speed (> 1 Gbps) of the overall system. Compared with non-return-to-zero (NRZ) OOK modulation, orthogonal frequency division multiplexing (OFDM) modulation attracts much attention due to its advantage of high spectral efficiency, reduced the complexity in equalizers (Jiang, Deng, Xiao, Tao, & Zhu, 2015) and might be a promising alternative for high-speed VLC systems (Y. C. Chi et al., 2016). On the other hand, the visible laser diodes (LDs) reveal high direct modulation speed and high pumping efficiency with the absence of efficiency droop effect, which becomes a research spotlight for developing alternative VLC system (Y. C. Chi et al., 2015). Hence, there are still room of improvement in modulation scheme that could improve bandwidth efficiencies of the existing modulation scheme while maintaining the high data rates system.

Although OFDM is an attractive modulation technique that can achieved the requirement for 5G standard performance, another issue to enable VLC system suited for future 5G networks is access control in this multiuser environment (Abdallah & Boudriga, 2016). Therefore, the efficient backbone design network to support higher capacity distribution of connectivity between VLC access points are needed. Optical code division multiple access (OCDMA) is one of the promising technique that offers multiple access control based on optical encoding technique that can enable the OFDM access in the VLC network. OCDMA is a networking technique that provides multiple access and offers various advantages such as large effective bandwidth utilization, asynchronous transmission with low latency access ability to provide privacy and security (Kaur & Bal, 2017) and soft capacity in demand. The unprecedented increasing of traffic volumes in wireless network, the data privacy and confidentiality is becoming more important. Therefore, hybrid OCDMA-VLC system is useful to envision the most promising candidate for future mobile communication.

Motivated by the advance contribution in modulation technologies, this thesis aims to explore and embed a new modulation scheme into OCDMA-VLC domain based on multiband OFDM to achieve large bandwidth efficiencies while maintaining the high data rates system. Then, the combination of OCDMA and VLC system based on this new modulation is developed theoretically and in simulation to investigate the overall system performance. Thus, with a larger capacity, the OCDMA visible light spectrum is the next best thing for the purpose of high speed data transmission.

1.3 Research Objectives

1. To design and develop a new modulation technique at higher data rate of VLC system.
2. To design and develop a new OCDMA-VLC system based on the newly proposed modulation technique with Zero Cross Correlation (ZCC) code.
3. To evaluate and analyze the theoretical and simulation performance of:
    i) a new modulation technique of VLC system.
    ii) a new combination OCDMA-VLC based on new proposed modulation technique.

1.4 Research Scope

The research scope to develop a new modulation technique is illustrated in Figure 1.2. This can be effectively guide the direction of research and focus on the research contribution. The main challenges in VLC system are providing an uplink to send information back to the transmitter, increasing the transmission rate with high spectral efficiency and subject to regulation challenges from non-communications standard (eye-safety standard, illumination regulation or an automotive standard). This thesis engaged toward increasing transmission rate of VLC system. In order to increase the transmission rate of the system, five methods can be implemented. The first method is to create a detector arrays at receiver (multi-input multi-output (MIMO) system) in order to ensure the necessary alignment between array of detectors and array of optical sources. The second method is to use an advanced modulation technique such as OFDM and the third method by using transmitter devices with high modulation bandwidth (visible laser diode). The fourth method by using pre/post-equalization and lastly, by implementing an optical filtering to combat the effects of ambient light. A new proposed modulation technique in this work is based on advanced modulation technique, OFDM and using visible laser diode.

In details, this thesis involves simulation and theoretical analysis of a new modulation technique for OCDMA-VLC system. In order to achieve the research objectives, the scope of work start with thorough study and review other related works on modulation in VLC which focus on OFDM modulation and OCDMA-VLC system design. This proposed modulation technique is then combined with OCDMA-VLC network system to ensure the reliability and compatibility of the technique in high capacity network design. The OCDMA-VLC system is developed based on ZCC code. All designs and simulations of a new modulation technique in VLC and OCDMA-VLC are performed by *Optisystem* simulation tool version 11. Mathematical analysis of a new modulation technique is derived for VLC and OCDMA-VLC system in term of signal to noise ratio (SNR) and bit error rate (BER). The theoretical and simulation performances for all designs are evaluated and analyzed.

1.5 Contributions

The contributions of this research work is listed as follows:

i. The development of a new mathematical SNR and BER derivation for a new modulation scheme in VLC system, which has high spectral efficiency while maintaining the high bit rate performance of the system.
ii. A new design of modulation technique in VLC using *Optisystem* simulation tool.
iii. A new mathematical SNR and BER derivation for OCDMA-VLC based on ZCC code using the newly proposed modulation technique. The new proposed system application offers high cardinality and reliable to operate at high data rate transmission.
iv. A new design of OCDMA-VLC based on ZCC code with a newly proposed modulation technique using *Optisystem* simulation tool.

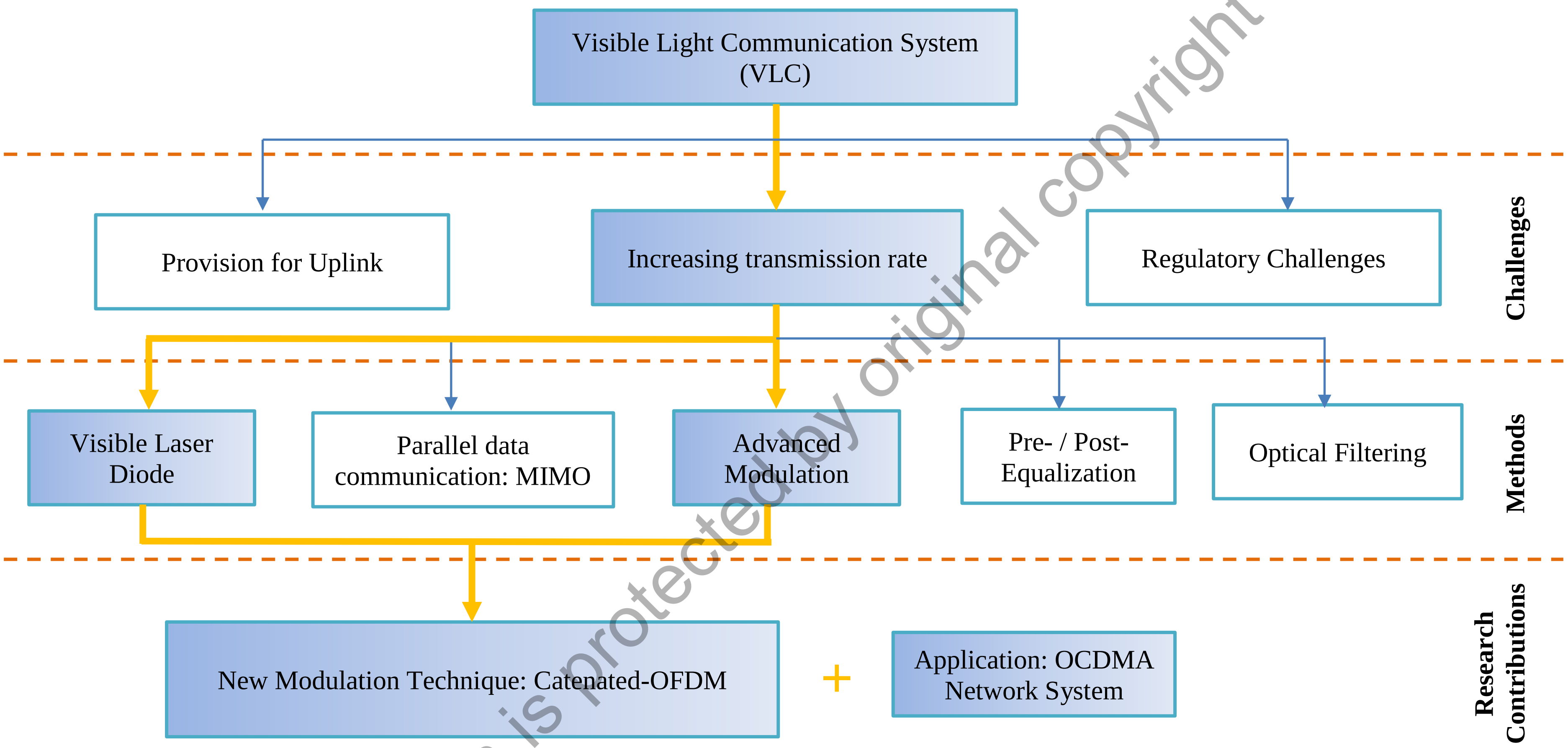

Figure 1.2 Scope of Work

1.6 Thesis Outlines

This thesis consists of five chapters and is organized as follows:

Chapter 1 provides an overview of the research field and direction, includes the background information of the project and the motivations for the research topic. It also presented the research objectives, research scopes and contributions together with the thesis outlines.

Chapter 2 begins with a review of contemporary research on OWC, emphasis on VLC system. The purpose of this review is to link between the VLC theory and the main exploratory objectives of the study. This includes a history perspective of communication via visible light spectrum and a brief discussion on its comparison with radio wave communication. The chapter also track the development of VLC transmission system, the components involved and its modulation technique are discussed. In addition, a review on OFDM modulation technique including a brief history, OFDM transceiver system and its basic mathematical formulation. Literature on OCDMA strengths and issues will be provided at the end of this chapter including description on ZCC coding scheme.

In the Chapter 3, the methodology of the research is discussed. The initial focus is on the development of VLC based on catenated-OFDM modulation technique. Its included discussion on the parameters study, simulation and noise detection analysis. The second part will be focused on the development of catenated-OFDM modulation with ZCC code for VLC system. Moreover, the BER equations for catenated-OFDM VLC and catenated-OFDM ZCC VLC are detail explained.

Chapter 4 provides the results and discussions, which is divided into two part; the numerical results of theoretical analysis and simulation result analysis. The *Optisystem* simulation tool version 11.0 is used to fully implement and simulate the system. This chapter also included the comparison between theoretical and simulation results for validation.

Finally, Chapter 5 gives a conclusion and summarization of the whole research work and proposed a recommendation of possible future research direction.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

This chapter reviews contemporary research on optical wireless communication (OWC) system, focusing on visible light communication (VLC) system that is one of the branch of OWC. The purpose of this review is to link between the VLC theory and the main exploratory objective of the study. The chapter introduced the reader to a brief history of the communication via visible light spectrum, and its comparison with radio wave spectrum. It comprises the discussion on features, advantages and applications of the VLC system. The chapter also tracks the development of VLC transmission system that discussed all the components involved in this construct. The study also reviews on the previous modulation scheme used in this area. As this study is exploring the modulation technique, this chapter will review on theory and principle of an orthogonal frequency division multiplexing (OFDM) modulation technique in OWC system. Next, a review on optical code division multiple access (OCDMA) included a brief description on zero cross correlation code is presented. Finally, the last section is a summarization of the whole chapter is provided.

2.2 Optical Wireless Communication (OWC)

OWC system is a complementary technology to radio wave system which use free space transmission medium as another solution to the short and longer-range interchange links. This concept has seen growing popularity in recent years for indoor and outdoor applications. It compromises flexible networking solutions that offer low cost, safe from biological effects to humans by the electromagnetic field, and allows acceptance to enable the OWC in hospitals and airports since no interference with radio frequency (RF) circuits electronics. Moreover, OWC offers high speed unlicensed wireless broadband connectivity for a number of applications, including voice, data and video transmission, entertainment, illumination and data communications at the same time, enterprise connectivity, disaster recovery and many others. Using optical signal with unique properties, a footprint can precisely define and hence can linked more devices within a small boundary.

OWC can be classified into two types: free space optic (FSO) communication and visible light communication (VLC) and summarized in Figure 2.1. Data transfer by using the infrared portion of the spectrum is called free space optic communication. FSO system can be characterized by having a longer distance of several kilometers and always refer to outdoor optical wireless communication at infrared region while indoor OWC is called wireless infrared communication. Infrared systems use wavelengths in the near IR region, in the range of from 780 to 1400 nm (Perrin & Souques, 2012) that are invisible to the human eye. VLC is the transmission of information through visible light of the electromagnetic radiation spectrum ranges from 400 to 780 nm (Perrin & Souques, 2012) and the frequencies are comprised between 430 THz and 750 THz which commonly used for indoor OWC. Over the past few years, VLC has attracted increasing attention and also has been considered for outdoor applications. The earliest research (Gfeller & Bapst, 1979) for indoor wireless optical communications use diffuse links can provide flexible and efficient data transmission.

In 2003, the idea of illumination and data communication via visible spectrum has been initiated by Nakagawa et al. in Keio University (Nakagawa Laboratory), Japan (Cevik & Yilmaz, 2015; Ndjiongue, 2015a). Since then, more research began on VLC in various area such as characterizing indoor and outdoor channels, modelling transmitter and receiver parts for communication system design, and also developing a new channel topology. The most interesting on wireless networking is Light Fidelity (Li-Fi) system introduced in Europe by Harald Haas in 2011. Li-Fi offers high data rates system that was developed using enhanced modulation schemes incorporate with standard light emission diode (LED) bulbs.

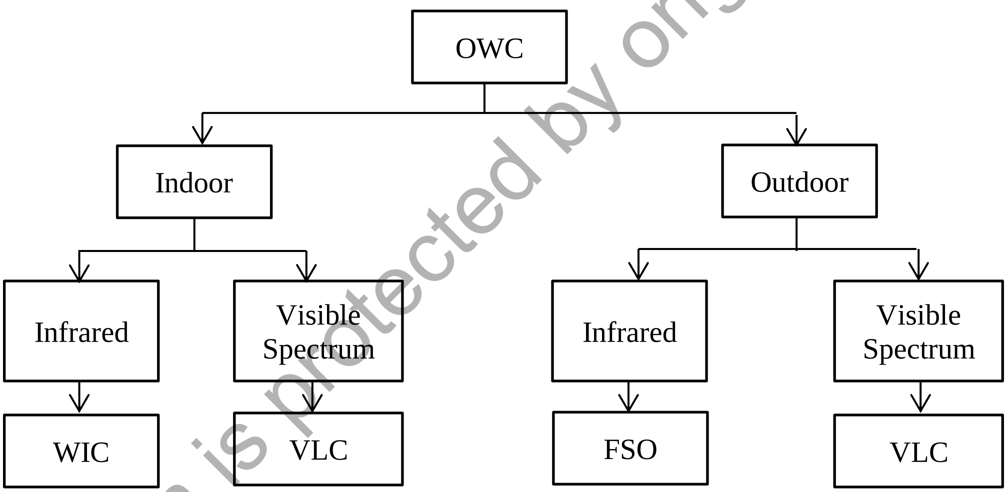

Figure 2.1 Classification of OWC

A system based on commercial 16 light emitting diodes (16-LEDs) array at data rate of 40 Mbps has been reported in 2008 (Minh et al., 2008b). The data signals are modulated using resonant driving technique implemented based on non-return-to-zero (NRZ) on-off-keying (OOK) via visible spectrum. Same group of researchers demonstrated enhancement in data rate achieving 80 Mbps of NRZ-OOK-VLC system by implementing single pre-equalizer (Minh et al., 2008a). This technique can increase data signal but limits the distance to only 10 cm. The approach proposed in Vucic et al. (2009), obtain higher transmission speed of 125Mbps by combining a phosphorescent white LED with commercial PIN photodiode. However, this experiment required filtering the low speed phosphorescent component to increase the bandwidth of the VLC system. A maximum speed of 662 Mbps of OOK-VLC system was reported by Fujimoto & Yamamoto (2014) using a high power RGB-type of LED with post-equalizing technique for an optical receiver.

The low modulation bandwidth of the transmitter devices and inter symbol interference (ISI) due to multipath propagation are the major challenges impeding the VLC system development (A. T. Hussein & Elmirghani, 2015; Minh et al., 2008b). The LEDs modulation bandwidth at transmitters is usually less than the bandwidth of visible light channel, its consequently limits the system propagation rates. To date there are several solutions have been proposed in order to attain high data rates VLC system. Using optical filters, pre-equalization or post-equalization (or both) (Minh et al., 2008a), complex multiple access and modulation schemes (A. M. Khalid, Cossu, Corsini, Choudhury, & Ciaramella, 2012) are among the most prominent solutions that have been suggested to achieve high data rate transmission system. Surveys such as that conducted in X. Zhang, Cui, Zhang, & Xu (2012) advocated to use parallel communication such as optical multiple input multiple output (MIMO) while combination of transmitter devices of red, green, and blue (RGB) LEDs has been reported in Kottke, Hilt, Habel, Vucic, & Langer (2012).

Study by Butala, Elgala, & Little (2013) has revealed that there is an improvement in data rate by embedding the MIMO technique in VLC system under illumination constraints. MIMO incorporated with pulse position modulation (PPM) approach has found to enhance the data rates without reducing the reliability of the link (Biagi, Vegni, Pergoloni, Butala, & Little, 2015). High data throughput was reported by Pergoloni et al. (2015) using Color shift keying (CSK) where LEDs' instantaneous output color was used to encode the data. A 1.25 Gbps system with RGB LEDs was stated in Kottke et al. (2012), and 1.5 Gbps has been achieved using non-return-to-zero on–off keying (NRZ-OOK) modulation technique incorporates with a new micro LED (μLED) array light source architecture (Leds et al., 2013). The wavelength division multiplexing (WDM) with RGB LEDs design capable to achieve higher data rate system. Reported in (Cossu, Khalid, Choudhury, Corsini, & Ciaramella, 2012) the highest throughput (3.4 Gbps) was achieved using combination of discrete multitoned (DMT) modulation, WDM, and RGB LEDs. However, the main concern in this system is the design complexity which lead to complicated implementation.

Previous discussion concerning on the VLC systems that have used LEDs and RGB LEDs as transmitter devices. However, due to their low modulation bandwidth, the highest VLC throughput (3.4 Gbps) achieved by LEDs reported in (Cossu et al., 2012). Therefore, substantial research efforts are being engaged toward increasing the LEDs' modulation bandwidth. One method is implemented using micro LEDs. These type of transmitter sources have been proposed by Tsonev et al. (2014) and manage to achieve 3 Gbps VLC systems. Potentially, 10 Gbps data rates could be delivered with an RGB triplet in such devices.

High data rate VLC systems can be achieved using transmitter devices with high modulation bandwidth. As a result, several studies have suggested the use of laser diodes (LDs), which be able to operate at the Gbps data rate (Y. C. Chi et al., 2016; Chun et al., 2015; Oubei et al., 2015). This means that LDs can be attractive VLC transmitters. However, generally LDs have limitation and not popular to be used for illumination purposes due to potential health hazards, cost, color mixing complexity, the spectral emission profile of a typical LD (on the order of 2–3 nm), and a very narrow spot size compared to LEDs. Nevertheless, a previous study has demonstrated that diffused laser light does not compromise the user experience compared with conventional LEDs (Neumann et al., 2011). Later, Denault et al. (2013) had discovered the different types of RGB-LD lights to generate white light for illumination. One of the main potential issues associated with using laser lighting is that lasers can be dangerous to human eyes, and the original sources indeed have laser source properties. However, once laser sources have been combined and had the beam scattered and diffused, the light no longer has the characteristics of laser light, but resembles white light (Basu, Meinhardt-Wollweber, & Roth, 2013), which meets illumination safety standards. This white light has exactly the same characteristics (e.g., color rendering) of the white light produced from LEDs, as experimental results have shown (Neumann et al., 2011).

The authors in (Denault et al., 2013) have experimentally proven that RGB-LDs have comparable characteristics to white LED sources. An illumination infrastructure (a communication network and control systems) can be used to support a number of LD light engines in a building, and their illumination can be controlled via plastic fiber optic cables that can be run along the ceiling. A combination of RGB visible lasers with a diffuser can be used to generate white light that has high quality color rendering and efficiency (Soltic & Chalmers, 2013). Therefore, it is expected that visible LDs can be used as a source of illumination instead of LEDs due to their high efficiency, especially in high power applications (Wierer, Tsao, & Sizov, 2013). Gancarz, Elgala, & Little (2013) had projected that laser-produced illumination, if cost effective, could enable significant performance gains in VLC systems due to the high frequency modulation capabilities of lasers.

Alternatively, OFDM as a practical implementation of multi-subcarrier modulation techniques can effectively mitigate multipath induced ISI (Hany Elgala, Member, Mesleh, & Haas, 2009). It is an effective solution to inter symbol interference (ISI) caused by a dispersive channel. A second major advantage of OFDM is that it transfers the complexity of transmitters and receivers from the analog to the digital domain. For example, while the precise design of analog filters can have a major impact on the performance of serial modulation systems, in OFDM any phase variation with frequency can be corrected at little or no cost in the digital parts of the receiver. While many details of OFDM systems are very complex, the basic concept of OFDM is quite simple (Armstrong, 2009). Data is transmitted in parallel on a number of different frequencies, and as a result the symbol period is much longer than for a serial system with the same total data rate. Because the symbol period is longer, ISI affects at most one symbol, and equalization is simplified. In most OFDM implementations any residual ISI is removed by using a form of guard interval called a cyclic prefix (Armstrong, 2009). OFDM offers high bandwidth efficiency, and allows for simple equalization at the receiver. The possibility to apply higher order digital modulation schemes to provide high data rates and the possibility to easily combine OFDM with multiple access schemes such as TDMA (time division multiple access) and FDMA (frequency division multiple access), makes it a promising choice for indoor OWC systems. For broadcasting applications, different broadcasting channels can be easily realized through assigning the OFDM symbols and the subcarriers to each channel based on the required data rate and quality of service (QoS).

2.3 Comparison of VLC and radio wave

For future demand, wireless broadband transmission system is desirable. The VLC is one of that system that offers license-free operation, high available bandwidth, high spatial diversity and innate security in comparison to the existing radio frequency (RF) technology (Rajbhandari et al., 2017). The VLC also offers the potential for the alternative besides high data rates. The main reasons are as discussed in the next sub-sections.

2.3.1 VLC Features and Advantages

VLC technology give an alternative solution where RF communication faces limitations (Uddin, Cha, Kim, & Jang, 2011; Z. Wu, Chau, & Little, 2011). Several advantages of VLC systems compared with radio wave communication are discussed as in Table 2.1.

Table 2.1 Advantages of VLC technology

1	Bandwidth	The bandwidth of VLC offers a large frequency band of approximately of 400 THz and virtually not limited compared to RF system
2	Efficiency	VLC provides high efficiency technology since data communication and illumination are done simultaneously
3	Data rates	VLC can achieve high data rates (hundreds of Mbps) and it can therefore be used for high speed wireless communications.
4	Less expensive	Optical devices such as light emitters and detectors in OWC can operate at high speed are readily available at low cost.
5	Human safety	Visible spectrum VLC is not injurious to the human eye and the effects of electromagnetic fields on human health can be avoided.
6	Security	Since visible light is used and not RF waves that can penetrate walls, the issue of security is inherently solved because light cannot

		leave the room, containing data and information in one location.

2.3.2 VLC Applications

There are many applications in which data transfer via VLC systems could be useful including aviation system, smart lighting, defense and security, hospitals, hazardous environments, vehicle and transportation, and underwater communications.

a) Aircrafts

As radio wave is not possible to be used by passengers in aircrafts, VLC transmitter is an alternative to provide media services for passengers.

b) Smart Lighting

Smart lighting with VLC provides the infrastructure for both lighting and communication and reduces the circuitry and energy consumption within an organization.

c) Defence and Security

VLC can enable secure and high data rate wireless communications within military vehicles and aircraft.

d) Healthcare

Some medical equipment is prone to interference with radio waves and this situation is undesirable in some parts of hospitals, especially around scanners and in operation theatres. VLC technology consequently is the promising technology that can be used in hospitals owing to the fact that the VLC spectrum is free from electromagnetic interference.

e) Hazardous Environments

VLC can be used in environments such as petro-chemical plants, mines, etc., as it is a safe technology (no explosion risks as in RF).

f) Transportation

Cars can communicate with each other to prevent accidents and also traffic lights can communicate with the car to ensure road safety.

g) Underwater application

The propagation of RF signals is not efficient in underwater environments. However, communications between divers or remote operated vehicles are possible using visible spectrum. VLC may support high data rates beneath the water.

2.4 Visible Light Communication System

The VLC technology which respects the communication principle in which three main parts are considered: transmitter part, channel model and receiver part is presented in Figure 2.2. It illustrates two electrical domains (blue arrows) and one optical domain (red arrows.). The modulated signal combines with light source to contributes transmitter. The primary duty of transmitter is to modulate the electrical source data into the optical carrier, which then propagates through the free space channel to the receiver. On the other hand, the receiver has to convert back the optical carrier into electrical carrier to form received data. The light source in the transmitter can be either light emitting diode and laser diode.

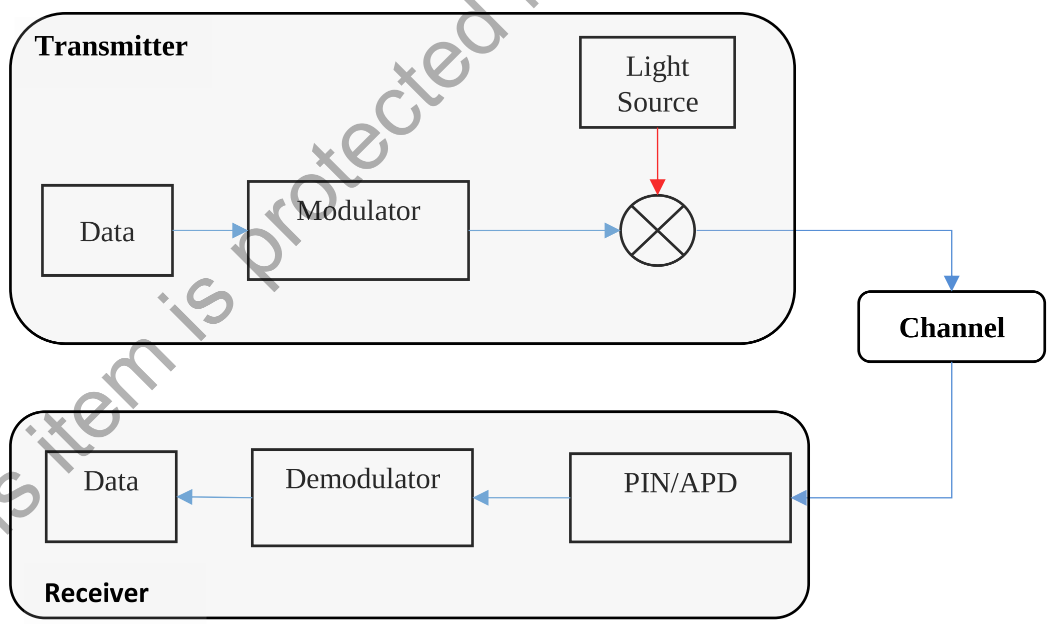

Figure 2.2 Basic VLC transmission system block

The goals of selecting appropriate components for VLC transmitter and receiver for indoor OWC depending on the application and can be various. The visible solid state emitter for VLC optical light source is LED or visible laser diode (VLD). Both VLDs and LEDs have been used for data communications, but white light LEDs can be used as an illumination source as well which gives VLC communication system acts as dual function; data transmission and illumination at the same time.

2.4.1 Optical Transmitter

The structure of optical transmitter is the first thing to consider in designing optical communication system. Its function to convert the electrical signal to an optical signal before pass through the medium. Generally, optical transmitter can be classified into two types: direct modulation transmitter and an external modulator transmitter.

2.4.1.1 Direct Modulator Transmitter

The components of direct modulation transmitter design are shown in Figure 2.3. Direct modulation occurs when modulated electrical data stream is applied directly to laser diode to modulate optical density or optical power. Therefore, 1 and 0 bits are created based on laser turn 'ON' and 'OFF' respectively (Agrawal, 2002; Alatawi, 2013). Direct modulation is suitable for data rates of 2.5 Gbps or less.

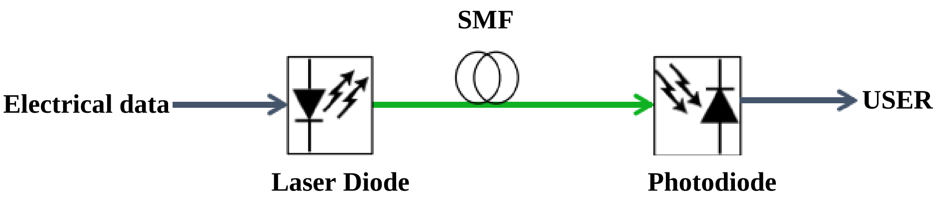

Figure 2.3 Direct Modulation

The main limitation of direct modulation is the broadening in the line width of the laser because of the laser on and off process. This results from the electrical signal that drives the laser source. The broadening of the line width is called chirp, and it will lead to degradation in the system performance. Therefore, direct modulation is not suitable for data rates greater than 2.5 Gbps (Agrawal, 2002; Alatawi, 2013).

2.4.1.2 External Modulator Transmitter

An alternative scheme eliminates the laser-chirp problem completely by operating the laser continuously and using an external modulator to generate the bit stream. In external modulation, the laser source emits a constant amplitude signal that enters the external modulator such as a Mach-Zehnder modulator (MZM) as shown in Figure 2.4 (Agrawal, 2002; Alatawi, 2013). The electrical signal then enters the external modulator to change the optical power level that the external modulator will transmit, but not change the amplitude of the light that comes originally from the laser to produce optical signal with time variance (Agrawal, 2002). The constant amplitude signal from the laser source will help to avoid the chirp of the pulses which will reduce the dispersion and make this process more effective for systems with high data rates of 10 Gbps and greater, and for the long-haul communication systems (Agrawal, 2002; Alatawi, 2013).