การพัฒนาระบบระบุตำแหน่งภายในด้วยการสื่อสารทางแสงที่มองเห็นได้

นายมูฮัมหมัด ซาดิ

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DEVELOPMENT OF INDOOR LOCALIZATION SYSTEMS USING VISIBLE LIGHT COMMUNICATION

Mr. Muhammad Saadi

A Dissertation Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy Program in Electrical Engineering
Department of Electrical Engineering
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Thesis Title	DEVELOPMENT OF INDOOR LOCALIZATION SYSTEMS USING VISIBLE LIGHT COMMUNICATION
By	Mr. Muhammad Saadi
Field of Study	Electrical Engineering
Thesis Advisor	Associate Professor Dr. Lunchakorn Wuttisittikulkij, Ph.D.
Thesis Co-Advisor	Dr. Yan Zhao, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Doctoral Degree

_______________________ Dean of the Faculty of Engineering
(Professor Dr. Bundhit Eua-arporn, Ph.D.)

THESIS COMMITTEE

_______________________ Chairman
(Associate Professor Dr. Watit Benjapolakul, Ph.D.)

_______________________ Thesis Advisor
(Associate Professor Dr. Lunchakorn Wuttisittikulkij, Ph.D.)

_______________________ Thesis Co-Advisor
(Dr. Yan Zhao, Ph.D.)

_______________________ Examiner
(Assistant Professor Dr. Pasu Kaewplung, Ph.D.)

_______________________ Examiner
(Assistant Professor Dr. Chaiyachet Saivichit, Ph.D.)

_______________________ External Examiner
(Dr. Keattisak Sripimanwat, Ph.D.)

มูฮัมหมัด ซาดิ : การพัฒนาระบบระบุตำแหน่งภายในด้วยการสื่อสารทางแสงที่มองเห็นได้ (DEVELOPMENT OF INDOOR LOCALIZATION SYSTEMS USING VISIBLE LIGHT COMMUNICATION) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ลัญฉกร วุฒิสิทธิกุลกิจ, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม: เหยียน จ้าว, 96 หน้า.

เมื่อไม่นานมานี้ *การสื่อสาร*ด้วยแสงที่มองเห็นได้ (Visible light communication: VLC) เป็นงานวิจัยหนึ่งที่ได้รับความสนใจเป็นอย่างมาก ทั้งนี้เนื่องมาจากการประยุกต์ใช้งานที่แพร่หลาย วิทยานิพนธ์นี้แสดงให้เห็นว่า *การสื่อสาร*ด้วยแสงที่มองเห็นได้สามารถนำมาในทางปฏิบัติได้อย่างไรสำหรับ (1) การระบุตำแหน่งภายในอาคารโดยการใช้ประโยชน์จากไดโอดเปล่งแสง (Light emitting diodes: LEDs) และ (2) การสื่อสารที่น่าเชื่อถือได้และปลอดภัย

ในการระบุตำแหน่งภายในอาคาร ผู้เขียนพัฒนาอัลกอริทึมจำนวน 4 อัลกอริทึม ได้แก่ (1) การระบุตำแหน่งโดยใช้การแบ่งกลุ่มข้อมูลแบบเคมีน (Indoor positioning using k-means clustering) (2) การระบุตำแหน่งโดยใช้การสแกนลำแสง (Indoor positioning using beam scanning) (3) การระบุตำแหน่งบนพื้นฐานของความแรงของสัญญาณที่ได้รับและการทำซ้ำคู่ (Indoor positioning based on received signal strength and bi-literation) (4) การได้รับตำแหน่งโดยใช้การแก้ปัญหาแบบศึกษาสำนึก (Achieving localization using a heuristic approach) อัลกอริทึมที่ถูกพัฒนาขึ้นทั้ง 4 อัลกอริทึมอยู่บนพื้นฐานของไดโอดเปล่งแสง (LEDs) อัลกอริทึม 2 อันแรกถูกตรวจสอบความสมเหตุสมผลผ่านการทดลองและผลลัพธ์ที่ได้แสดงความถูกต้องที่ได้รับ ในหลักสิบเซนติเมตร (นั่นคือ 37 เซนติเมตรสำหรับเทคนิคแรกและ 10 เซนติเมตรสำหรับเทคนิคที่สอง) ซึ่งสามารถเปรียบเทียบได้กับเทคนิคการระบุตำแหน่งต่างๆ ที่มีอยู่แล้ว ยิ่งไปกว่านั้น คณะผู้เขียนเป็นกลุ่มคนกลุ่มที่แรกที่แนะนำการเรียนรู้ของเครื่อง (Machine learning) เพื่อให้ได้การระบุตำแหน่งสำหรับ*การสื่อสาร*ด้วยแสงที่มองเห็นได้

ความปลอดภัยถูกนำมาพิจารณาในระบบ*การสื่อสาร*ด้วยแสงที่มองเห็นได้ซึ่งถูกพัฒนาขึ้น ผ่านการส่งสัญญาณแบบไดเวอร์ซิตีเชิงที่ว่าง (Spatial diversity) โดยการใช้ตัวส่งเชิงแสง (Optical transmitter) จำนวน 2 ตัวและความน่าเชื่อถือในการเชื่อมต่อ สามารถได้รับจากวิธีการใหม่ที่ถูกนำเสนอสำหรับการสร้าง พาริตีเช็กเมตริกซ์ (Structured parity check matrix) สำหรับรหัสพาริตีเช็กความหนาแน่นต่ำแบบไบนารี (Low density parity check: LDPC) ผลการทดลองที่ได้แสดงให้เห็นว่า เทคนิคใหม่ที่ถูกนำเสนอทำให้ระบบ*การสื่อสาร*ด้วยแสงที่มองเห็นได้มีความปลอดภัยและมีการเชื่อมต่อที่น่าเชื่อถือระหว่างเครื่องส่งและเครื่องรับ

ภาควิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อ อ.ที่ปรึกษาหลัก	....
ปีการศึกษา	2558	ลายมือชื่อ อ.ที่ปรึกษาร่วม	....

5471465621 : MAJOR ELECTRICAL ENGINEERING
KEYWORDS: VISIBLIE-LIGHT-COMMUNICATIONS / LOCALIZATION / SECURITY / SPATIAL-DIVERSITY / CLUSTERING

MUHAMMAD SAADI: DEVELOPMENT OF INDOOR LOCALIZATION SYSTEMS USING VISIBLE LIGHT COMMUNICATION. ADVISOR: ASSOC. PROF. DR. LUNCHAKORN WUTTISITTIKULKIJ, Ph.D., CO-ADVISOR: DR. YAN ZHAO, Ph.D., 96 pp.

Visible light communication (VLC) has recently been the focus of research due to its widespread applications. This thesis practically demonstrates how VLC can be used for: (i) Indoor localization utilizing light emitting diodes (LEDs) and (ii) Secure and reliable communication.

In the domain of indoor localization, the author has developed four algorithms namely (i). Indoor positioning using k-means clustering (ii). Indoor positioning using beam scanning (iii). Indoor positioning based on received signal strength and bi-literation and (iv). Achieving localization using a heuristic approach. All the developed techniques are based on LEDs. The first two approaches have been validated through experiments and the results show an accuracy of tens of centimeters (37 cm for the first technique and up to 13 cm for second technique) is achieved which are comparable to the state of the art indoor localization techniques available in the literature. Furthermore, to the best of author's knowledge, they are the first one to introduce machine learning to achieve localization for VLC.

Security is brought into the developed VLC system through spatial diversity based transmission using two optical transmitters and the reliability in the link is achieved by a newly proposed method for the construction of structured parity check matrix for binary Low Density Parity Check (LDPC) codes. Experimental results show that a successful secure and reliable link between the transmitter and the receiver can be achieved by using the proposed novel technique.

Department:	Electrical Engineering	Student's Signature	....
Field of Study:	Electrical Engineering	Advisor's Signature	....
Academic Year:	2015	Co-Advisor's Signature	....

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At the end I would like to acknowledge the financial support from NECTEC and 90th Anniversary of Chulalongkorn University Scholarship.

Muhammad Saadi

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List of Abbreviations

APD	Avalanche Photo-diode
AWG	Arbitrary Waveform Generator
VLC	Visible Light Communication
VLP	Visible Light Positioning
PWM	Pulse Width Modulation
OWC	Optical Wireless Communication
LDPC	Low Density Parity Check
LED	Light Emitting Diode
SSL	Solid State Lighting
RSS	Received Signal Strength
RF	Radio Frequency
IR	Infrared
FSO	Free Space Optics
CDMA	Code Division Multiple Access
LoS	Line of Sight
GPS	Global Positioning System
FEC	Forward Error Correction
WDM	Wavelength Division Multiplexing
WEP	Wired Equivalent Privacy
TIA	Trans-Impedance Amplifier
VLCC	Visible Light Communication Consortium
VCO	Voltage Control Oscillator
OFDM	Orthogonal Frequency Division Multiplexing
DSP	Digital Signal Processing
OSI	Open System Interconnection
BER	Bit Error Rate
WOSS	Wireless Optical Spread Spectrum
DSSS	Direct Sequence Spread Spectrum
OCDMA	Optical Code Division Multiple Access
QPSK	Quadrature Phase Shift Keying
FFT	Fast Fourier Transform
NRZ-OOK	Non-Return to Zero – On Off Keying
SSL	Solid State Lighting
ICT	Information and Computer Technology
IPS	Indoor Positioning System
TDOA	Time Difference of Arrival
TOA	Time of Arrival
AOA	Angle of Arrival

Chapter 1

1 Introduction

1.1 Summary

Recent advancements in the solid state lightning (SSL) has enabled the researchers to use light emitting diodes (LEDs) not only for illumination but also for communication. This gives an opportunity to overcome the bandwidth scarcity issue in radio frequency (RF) communication. In addition to bandwidth limitation, another serious concern about RF is that it suffers from its open nature of RF propagation which introduces significant challenges in security issues especially when considering two scenarios: next generation wireless networks with large-scale decentralized features in public areas and point-to-point communications on top-secret issues by very important persons or intelligent agencies as example.

The goal of this research is to propose a scheme for secure and reliable data transmission for Visible Light Communication (VLC) and also introduce a Visible Light Positioning (VLP) system and to develop such a system which can ensure security and link reliability. For achieving the first goal i.e. localization, the author has proposed four techniques namely (i). Indoor positioning using k-means clustering (ii). Indoor positioning using beam scanning (iii). Indoor positioning based on received signal strength and bi-literation and (iv). Achieving localization using heuristic approach.
In order to achieve the second goal i.e. secure and reliable data transmission, a novel method for establishing a secure and reliable communication link using optical wireless communication (OWC) has been proposed. For security, spatial diversity based transmission using two optical transmitters are used and the reliability in the link is achieved by a newly proposed method for the construction of structured parity check matrix for binary Low Density Parity Check (LDPC) codes.

1.2 Overall Scenario

With the advancement in the domain of Information and Communication Technologies (ICT), the demand for bandwidth has increased rapidly. Around a decade ago, internet users were happy if they were able to download an audio song of few Mbps but now users want high definition (HD) video streaming, online gaming, and social networking in addition to other bandwidth hungry application usage. This has forced the scientists to find other ways for communication, besides RF, to meet this demand. Furthermore, the RF spectrum is getting congested with the every passing day and time is not far when current RF spectrum will not be able to accommodate more users. Thus it is a matter of grave concern by the researchers to find other means of communication.

With the emergence of light emitting devices for solid-state lighting, VLC has given a chance to achieve secure data transmission at low cost with power efficiency in addition to lighting. Indoor VLC provides a built-in security feature as light cannot pass through the walls. However, the system may become potentially less secure when the intruder is located within the same locality, nonetheless, confidentiality and integrity of data must be maintained in such situations as well. For example, very important persons (VIPs) including prime minister, minister, ambassadors, and military officers need to exchange information securely at public places such as an airport and convention venues.

Indoor positioning system is gaining a lot of attention these days as it has its applications in number of ways for example augmented reality, store navigation, guided museum tours, navigation assistance to special people, warehouse, targeted advertising etc. Global Positioning System (GPS), which is the best candidate for outdoor localization, fails to provide sufficient accuracy for indoor localization. Furthermore, other RF localization techniques such as Wi-Fi, Bluetooth, sensor network etc. also don’t have very precise location estimation. However, if we look around, one can find ceiling lights everywhere. Generally they are distributed in all indoor environments where indoor localization is required. Exploiting this lighting, localization can be performed using the same (or with little modification) light fittings. To-date, this is the most economical, environmental friendly and accurate method for indoor localization.

1.3 Thesis Motivation

GPS fails to provide good estimation of location for an indoor environment because of poor satellite coverage, multipath effect, signal attenuation etc. Some theoretical/simulation based works have achieved very high accuracy. However such high level of accuracy have never been achieved so for experimentally. Therefore need arises for the development of system which can provide security, reliability and precise location estimation in a practical environment.

In the domain of high data rate and link accuracy, researchers have achieved quite remarkable milestones but not enough work has been done in terms of security, link reliability and precise location estimation. As light cannot pass through the concrete structure therefore gives inbuilt security but intruder can be in the same locality where data transmission is going on. One of the theoretical work has been done in Waseda University, Japan [1] but still there exists no practical system achieving security. Reliability in communication literature is used with several meanings such a link failure, redundancy etc. Here by link reliability author means that transmitted message in encoded in such a way that it can minimize the effect of channel degradations and the received message can be decoded correctly by the receiver with good bit error ratio performance.

1.4 Methodology and Contribution to Literature

The main objective of this research is to develop an accurate positioning system develop in addition to secure and reliable communication system. Development of such a system requires diverse work thus the work was structured in three different phases.

In the first phase, development of OWC based secure communication was devised. This step requires the design of transmitters and the receiver. In the developed system, two transmitters are used with a static receiver. For uplink, the infrared (IR) link is used and for downlink the visible light (white light) is used. Security is brought into the system by incorporating a well-established position diversity transmission scheme. In the second phase, reliability in the link is established. Today, LDPC codes are considered as the most eligible channel codes for future generation high data rate communications and various practical applications. A newly proposed method for the construction of structured parity check matrix for LDPC codes is introduced in the link to ensure link reliability. In the last (third) phase, four visible light positioning systems are developed namely (i). Indoor positioning using k-means clustering (ii). Indoor positioning using beam scanning (iii). Indoor positioning based on received signal strength and bi-literation and (iv). Achieving localization using a heuristic approach. All the developed techniques are based on LEDs. Designing and implementing the above mentioned system requires many software tools and resources. Before integrating any design in hardware, it is important to test the system using simulations. For analogue electronic design, MultiSim and PSpice are used for designing the transmitter and the receiver. They were simulated for desired response. For implementing the channel code i.e. an LDPC code, data generation and data split, Wiring programing language is used. MATLAB is used for demodulation, reconstruction and signal analysis at the receiver side. MATLAB is also used for examining the illumination pattern and LEDs characterization and implementation of machine learning algorithms.

List of journal and conference papers published by the author can be found in Appendix I. Here is the overview of the major work done by the author in the field of VLC. Following are the contributions to the literature in the VLC domain by the author.

The author experimentally demonstrated a way to have a secure and reliable communication using optical wireless communication. The previous works (in the literature) are mostly based on simulation. Security in the link is achieved by spatial diversity and for the reliability in the communication link, the author developed a new method for the construction of parity check matrix for LDPC codes. A novel method for indoor localization using k-means clustering is also developed and to the best of author's knowledge, he is the first one to introduce machine learning for localization and the localization results achieved by this approach outperforms all other existing algorithms.

Other than these major contributions mentioned in the above paragraph, the researcher also introduced concepts of adaptive threshold detection and transmission placement planning for VLC. Link performance of VLC and IR are also analyzed and the performance is also evaluated based on pulse width modulation (PWM). These contributions are discussed in Appendix-II and Appendix-III.

1.5 Thesis Organization

The organization of thesis is as follows.

In chapter 2, an introduction to visible light communication is given. A brief history about VLC is described followed by the major milestones achieved in this area. How VLC system can be modeled and what are the recent advancements in the field of visible light communication are also mentioned. Various well established prototypes of VLC system are described and discussion on existing localization techniques is also done. Lastly, the chapter concludes by mentioning the applications of VLC.

Chapter 3 discusses the various indoor localization techniques developed by the author namely (i). Indoor positioning using k-means clustering (ii). Indoor positioning using beam scanning (iii). Indoor positioning based on received signal strength and bi-literation and (iv). Achieving localization using a heuristic approach. Chapter 4 introduces a proposed system for secure and reliable communication using optical wireless communication.

In the last section, Chapter 5, conclusion has been drawn for this dissertation and the possible future research work is discussed to improve the position estimation, security and reliability for indoor OWC.

Chapter 2

2 Introduction to Visible Light Communication and Visible Light based Positioning System

This chapter gives an overview of VLC starting from its evolution. Like any other wireless channel, the main entities of a VLC system are the transmitter, the receiver and the channel. System modeling for these entities have been described in this chapter followed by the major contributions by various research groups. Various well established VLC systems are described in detail followed by one of the most important application i.e. localization has been reviewed. The chapter concludes by mentioning the applications of VLC.

2.1 Introduction

The concept of using light as a source of communication is not a new one. In fact VLC can be considered as an oldest method for telecommunication. People use mirrors to reflect the sun light towards a particular direction to gain the attention of the some person. Light houses are being used since ages to guide the ships. People in the tribes have been lighting fire to invite people from the villages for some gathering and the same technique is being used for emergency help. The examples mentioned here reveal that using light as a source of communication is not a new technique. However, if one talks about modern and sophisticated techniques for communication then VLC is a very new communication technologies. The phenomenal developments in optoelectronics especially SSL have given a re-birth to VLC.

SSL refers to the generation of light via solid state electroluminescence. First high brightness LEDs were introduced in early 90s and the intention for the development was illumination only. With the passage of time, tremendous improvement in terms of luminous efficacy (from 0.1 lm/W to 260 lm/W) has been observed which is very good in comparison with traditional incandescent (52 lm/W) and fluorescent lamps (90 lm/W) [2]. It is expected that soon researchers will be able to achieve the theoretical limit of 425 lm/W as well for white LEDs. Other advantages of LEDs includes;

- Green technology (mercury free);
- Higher Mean Time Before Failure (MTBF);
- Higher tolerance to humidity;
- Energy efficient and lower power consumption;
- Fast switching speed.

LEDs can serve dual purpose i.e. they can be used for lighting up an indoor/outdoor environment as well as for data transfer simultaneously.

2.1.1 Definition

Optical wireless communication (OWC) refers to data transmission using Infrared Wireless Communication (IrWC), ultraviolet wireless communication, VLC as well as Free Space Optics (FSO) in contrast to radio waves. Visible light spectrum falls within the OWC and is defined from 380 nm to 780 nm. If visible light is used for the purpose of communication then it is called as visible light communication [3],[4].

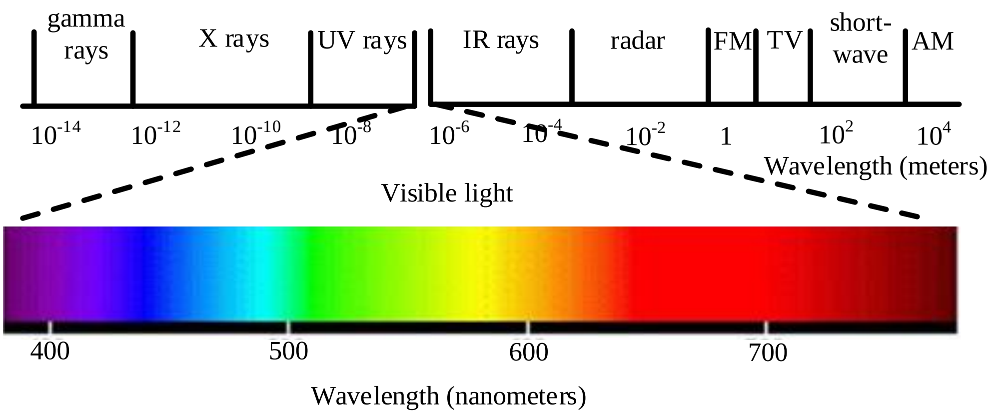


Figure 2-1: The electromagnetic spectrum highlighting VLC spectrum

2.1.2 How LEDs Emit White Light

For any typical indoor environment, white light is the most commonly used for illumination purpose. White LEDs also perform very well in communication. There are two commonly used approaches for making white LEDs. One method is to combine red, green and blue (RGB) lights in a proper proportion which results in the emission of white light. However this is not a popular technique for the reason that the junctions that produce red, green and blue lights are not equally efficient i.e. efficiency of blue light (80%), red (60%) and green (30%). Also this method has certain packaging and electronic complexities which make it a less favorable. Second method to implement white-light LEDs is known as phosphor based white LED. A single blue LED is coated with a layer a phosphor that emits yellow light. Some yellow light is absorbed by phosphor and is made to mix with non-absorbed blue light to produce desired white light color [5], [6].

2.1.3 Comparison between RF and VLC Technologies

Table 2-1 gives a detailed comparison between RF and VLC communication technologies [7], [8].

Table 2-1: Comparison between RF and VLC communication technologies

Attributes	VLC	RF
Spectrum	(380nm to 780 nm) Virtually unlimited	Regulated and limited
Licensing	Free	Very expensive
Electromagnetic interference	No	Yes
Environment friendliness	Yes	No
Co-channel and adjacent channel interference	No	Yes
Cell planning	Simple	Complex
Line of sight (LoS)	Yes	No
Multipath propagation problem	No	Yes

Distance	Short	Short to long
Security	Good	Poor
Services	Illumination and communication	Communication
Noise source	Sun light and ambient light sources	All electrical and electronics appliance
Power consumption	Low	Medium
Mobility	Very limited	Fair enough
Coverage	Small	Wide

2.1.4 Visible Light Communication Channel Model

VLC channel model can be summarized as in Table 2-2.

Table 2-2: Summary of VLC channel model

Entity	**Equations**	**Comments**
Transmitted Power	$P_T = \int_{\Delta_{min}}^{\Delta_{max}} \int_{0}^{2\pi} \phi_e d\theta \, d\,\lambda$	$\boldsymbol{\Delta_{max}}$ and $\boldsymbol{\Delta_{min}}$ should be selected based on photo detector $\boldsymbol{\phi_e}$ is energy flux
Lambert Radiation Pattern	$R(\phi) = \frac{n+1}{2\pi} P_T cos^n(\phi)$	$\boldsymbol{n}$ is the mode number of radiation lobe. ϕ is the angle of irradiance with respect to transmitter perpendicular axis
Channel DC Current Gain	$H(0) = \frac{R(\phi)\, cos(\theta) A}{d^2}$	$\boldsymbol{d}$ is the distance between LED and the photo detector. $\boldsymbol{\theta}$ is the angle of incidence. $\boldsymbol{A}$ is the physical area of photo detector

Received Power	$P_r = \sum^{LEDs} \left\{ P_T H_d(0) + \int_{walls} P_T dH_{ref}(0) \right\}$	$\boldsymbol{H_d(0)}$ is the direct path and $\boldsymbol{H_{ref}(0)}$ is the reflected path.

2.2 Related Work for Link Security and Reliability

In this section, related work in terms of link security and reliability will be discussed and related work in terms of position estimation/localization will be discussed in Section 2.6.

2.2.1 Related Work for Link Security

Wireless networking intensifies the tractability in home and office environments to connect the Internet without wires. This luxury is attained at the cost of risks associated with stealing the data or threat of loading malicious code with the intention of harming the network. Implementation of security protocols can reduce the threat to large extent. However security is still a major concern for digital and ICT society. RF wireless communications suffer from its open nature of RF propagation. This introduces significant challenges in security especially when considering two scenarios: next generation wireless networks with large-scale decentralized features in public areas and point-to-point communications on top-secret issues by very important persons or intelligent agencies as example. While current classical security of wireless network communications relies on classical network cryptography techniques, next generation wireless networks, which possess large-scale decentralized features naturally, will experience high overhead and computational complexity. Several techniques adopted in the standards have been developed in some protocol layers modeled in Open System Interconnection (OSI) layer with less focus given on the physical layer (PHY). Therefore, new technique in physical layer security has been introduced, in this thesis, to be an alternative for such a circumstance. Instead of being based on computational mathematical complexity like others in higher layers such as

Wired Equivalent Privacy (WEP) protocols in Wi-Fi in data (2nd) layer, it enables two wireless entities to communicate data securely in the presence of an eavesdropper through the use of physical layer properties of its inherit channels. There are demands on the development of systems with highly secure, affordable, and efficient features.

The most vulnerable point in wireless communication for intruder attack is the transmission channel. The techniques available in literature to overcome this problem are either encryption based or modulation based. Encryption method could be applied to solve this security problem; however, it is possible that attackers can decrypt the signal and obtain the confidential information. Moreover, in encrypted Code Division Multiple Access (CDMA) optical transmission codes, the cross-correlations of the encrypted codes determine the Bit Error Rate (BER) performance and limit the maximum data rate.

Modulation schemes based on spread spectrum techniques are commonly used. Spread spectrum performs a data encryption in the modulation process. Wireless Optical Spread Spectrum (WOSS) system is done by using the conventional OWC devices with some added circuitry which is responsible for applying the spreading technique. Direct Sequence Spread Spectrum (DSSSS) and Time hopping codification in VLC have been presented in [9], [10] respectively. Optical Code Division Multiple Access (O-CDMA) is the most prevalent technique used in VLC for security as well as for multiple access. O-CDMA have advantages like it provides format independent security in physical layer in addition to the easy-to-implement and de-centralized control network, improved spectrum efficiency and so on [11]. Another conceptual work on optical wireless communication link for telephone networks has been proposed in [12] which validates that quantum cryptography, quantum teleportation, and quantum coding and decoding which can be implemented using OWC link.

A position-based diversity transmission scheme for indoor OWCS was simulated to enhance the security of optical wireless transmission by transmitting $\boldsymbol{I}$ (in-phase) and $\boldsymbol{Q}$ (Quadrature) waveforms of quaternary phase-shift keying (QPSK) modulation separately in an optical wireless channel. The input serial data stream is arranged into the word size needed for transmission which is 2 bits/word for QPSK, and shifted into a parallel format by a Serial to Parallel (S/P) converter. The data is then transmitted in parallel assigning each data word to one carrier in the transmission. The in-phase signal is multiplied by $cos(\omega t)$ whereas the quadrature signal is multiplied by and $sin(\omega t)$. Two LEDs, the $\boldsymbol{I}$ transmitter and the $\boldsymbol{Q}$ transmitter, are used up for transmitting an $\boldsymbol{I}$ and a $\boldsymbol{Q}$ signal, respectively. The advantage of this scheme is that the users which stay in the area where both $\boldsymbol{I}$ and $\boldsymbol{Q}$ signals can be received simultaneously can obtain the correct information

2.2.2 Related Work for Channel Codes

Channel coding is a hot area of research in order to make the communication link reliable. Today, LDPC codes are considered as the most eligible channel codes for future generation high data rate communications and various practical applications. The milestones LDPC research begin in 1962, introduced by R. Gallagar [13] in his PhD thesis. Since then these codes were ignored almost next 30 years due to complexity and less analytical tools available at that time. Later these codes were rediscovered by Mackay and Neal in 1996 [14]. Enormous potential research has been carried out on channel coding since Shannon's theory of mathematical constraints for channel capacity. LDPC codes can be represented in two basic forms. One way is that all linear block codes in matrices form and another illustrative way of presentation is graphical form and most commonly known as Tanner graph. LDPC codes, are the class of linear block codes which is defined by a parity check matrix ($\boldsymbol{H}$), which is sparse. A regular(j, k), $\boldsymbol{H}$ matrix is a $M \times N$ binary matrix having j ones in each column and exactly k ones in each row, where $j < k$ and $\{j, k\}$ are small as compared to N for sparse matrices. The code rate will be $R = 1 - \frac{M}{N}$ which can equivalent then $= 1 - \frac{j}{k}$, assuming the M rows are linearly independent.

Development of most optimized and efficient constructed LDPC codes have been studied widely in the current decade. LDPC codes can provide lower error probabilities than the equivalent conventional codes. Struggle is for designing such algorithms which can efficiently encode the data using existing parity check matrix and can recover the original information even when the noise level is high. Literature reveals that the random generated parity check matrix performs inferior to structured $\boldsymbol{H}$ matrix. Implementation complexity of LDPC codes can be significantly reduced if an appropriate structured $\boldsymbol{H}$ matrix is defined [15]. Various researchers have tried to create an efficient ***H*** matrix which can outperform the random generated ***H*** matrix. Progressing Edge Growth (PEG) [16] algorithm is one of the promising algorithms for the generation of suitable ***H*** matrix with high girth. Fan et al. [17] introduced array structured ***H*** matrix that offers comparable performance when compared to random generated ***H*** matrix with low noise floor and no existence of cycle of 4. Eleftheriou et al. [18] proposed a Modified Array Structure (MAC) by applying cyclic shift to Fan's array which offers superior performance to Fan's array by reducing number of '1's' in lower triangle. Chutima et al. [19] work is based on MAC in which number of '1's' were reduced in upper triangle by applying matrix transpose, and row and column swap which give rise to two new structured ***H*** matrix. Singhaudom et al. [20] introduced the Interleaved Modified Array (IMAC) by introducing quasi cyclic matrix into the cyclic shift Fan's array.

2.3 Major Achievements in VLC from Various Research Groups

Summary of the work from different research groups around the globe is given below. In this table, only the most significant works with the maximum speed have been mentioned and indeed each group has many other contributions in the VLC domain.

Table 2-3: Important achievements summary in VLC

Group	**Work**	**BER**	**Speed (Mbps)**	**BW (MHz)**	**Distance**
Northumbria University	[21]	10^{-6}	10	-	0.7m
Boston University	[22]	10^{-6}	20	20	-
University of Edinburgh	[23]	10^{-6}	80	20	1.75m
Oxford University	[24]	10^{-6}	75	25	2.15m
	[25]	10^{-6}	80	45	10cm
	[26]	10^{-9}	100	50	10cm
Nakagawa/ Keio University	[27]	10^{-9}	100	-	3m
	[28]	10^{-6}	400	-	2.5m
Taiwan NTUT	[29]	10^{-9}	500	600	10m

OMEGA	[30]	2×10^{-3}	513	-	-
Scuola Superiore Sant'Anna	[31]	1.5×10^{-3}	1000	-	-
Oxford/llmenau/France Telecom	[32]	$<10^{-9}$	1250	-	3m
Scuola Superiore Sant'Anna	[33]	2×10^{-3}	3400	280 MHz	-

Japan is pioneer in this technology and was the first one to introduce two VLC standards in 2007 by Visible Light Communication Consortium (VLCC). There are many research groups within Japan who are actively working in this area. Their contributions can be summarized as in Table 2-4 [34].

Table 2-4: Contributions from various organizations from Japan in the field of VLC

Organization	**Contributions**
Shimizu Corporation, Japan	• Communication using LED spotlight
NEC and Matsushita Electric Works	• Information broadcast system using VLC • Global location service that uses visible light ID system
VLCC	• VLC applications in the domain of ITS • VLC applications in light house
Keio University	• Multiple transmission using multiple colors • Standardization of format of location information • High speed parallel wireless VLC system with the help of image sensor and LED transmitter • Accurate position detection of a transmitter or a receiver
Nakagawa Laboratory	• Flow planning survey system for a store • 100Mbps full-duplex multi-access visible light communication system
Casio Computer	• Augmented reality

Joint Projects	• 3D location estimation system using visible light communication by Keio University and Nakagawa Laboratory • Underwater VLC by Rise, Keio University, Nakagawa Laboratory

2.3.1 IEEE 802.15.7 Standard on VLC

In 2011, IEEE released standard on VLC which is IEEE 802.15.7. This standard can be briefly summarized as in Table 2-5 [35].

Table 2-5: Summary of IEEE 802.15.7 standard

Entity	**Characteristics**
MAC Supported Topology	Star, P2P, Broadcast
Addressing	16 bit, 64 bit
Collision Avoidance Scheme	Yes (Scheduled and Slotted random access with collision avoidance)
Acknowledgement	Yes
Device Classification	Infrastructure, Mobile, Vehicle
Modulation Scheme	OOK, VPPM, CSK
PHY Frame Structure	|Preamble|PHY Header| HCS| Optional Fields| PSDU|
Multiplexing	FDM
Data Transfer Model	03
Clock Rate Selection	Multiple from 200 KHz to 120 MHz
Cryptographic Mechanism	Symmetric Key Cryptography
MAC Protocol Specifications	Generating and Synchronizing Network Beacon, Supporting VPAN Association, Color Function, Visibility, Dimming, Visual Indication, Device Security Mobility and Reliable Link
Contention Period	Contention Access Period and Contention Free Period
Channel Scan	Active and Passive
Synchronization	With Beacon and Without Beacon
Multiple Channel Usage	Supported

MAC Frame Format	|Frame Control| Sequence No.| Destination VPAN Identifier| Destination Address| Source VPAN Identifier| Source Address| Auxiliary Security Header| Frame Payload| FCS|
Max. Error Tolerance for Multiple Optical Source	Not more than 12.5% of the clock period
Clear Channel Assessment (CCA)	Mode 1: Energy Above Threshold Mode 2: Carrier Sense Mode 3: Carrier Sense with Energy Threshold
Data Mode of PHY	Single, Packed, Burst, Dimmed OOK

2.4 Prototypes on Visible Light Communication Systems

The first contribution in the area of VLC system was published in 1999 when G. Pang et al. [36] and his team described a VLC based an audio system which is well suited for heterogeneous audio transmission in a small area. The transmitter is constructed by using LEDs and the current fed to those LEDs were modulated and encoded with audio information. The main component of the transmitter is the voltage controlled oscillator (VCO) for changing the frequency of the LED. A square wave oscillator is used for the reason that it has only two states. The carrier frequency was kept to be 100 kHz with the maximum frequency deviation of 50 kHz. The switching frequency was kept high enough that it doesn't bother human eyes. Thus output of the transmitter is a frequency modulated audio signal by switching the LEDs through a driving circuits. The transmitter is shown the Figure 2-2.

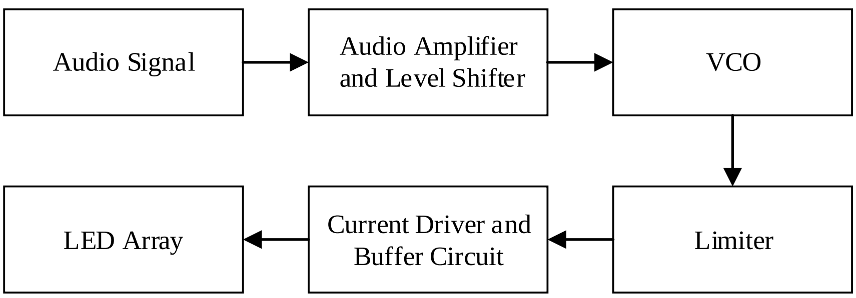


Figure 2-2: An audio system with multiple transmitters

The handheld receiver which has the ability to demodulate the transmitted signal in free space and can reproduce the information with the car jack. Line of sight communication was done. The receiver consists of a photo detector which detects the frequency variations in the received signal and then fed to the amplifier. Pulse shaping and detection circuits are used to construct a square wave which is then differentiated and its negative tailing edges are clipped. A pulse generator is used to convert the pulses from differentiator into sharp pulses which is then fed to integrator and envelope detector to demodulate the signal. A band pass filter is used to create an appropriate waveform followed by an amplifier. Such audio systems have their applications where multiple audio sources are in small area. Block diagram for the receiver is shown in Figure 2-3.

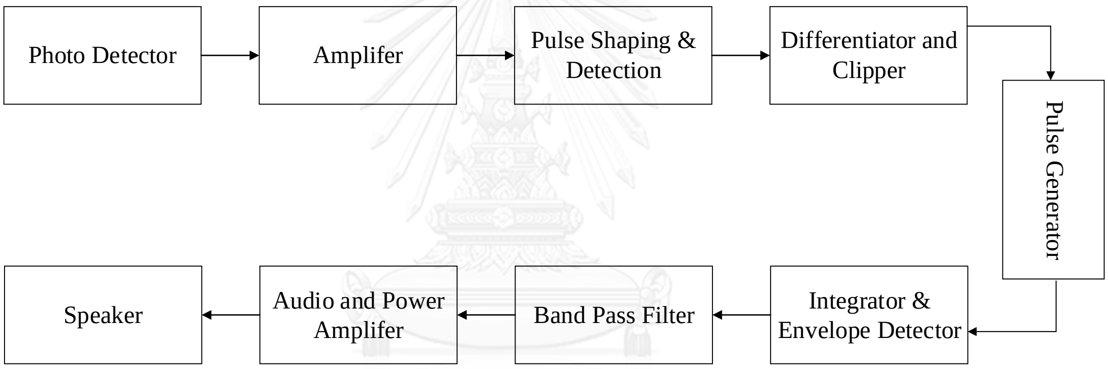


Figure 2-3: Block diagram for the receiver

Orthogonal Frequency Division Multiplexing (OFDM) is a strong candidate in wireless communication technology and its acceptability can be judged from IEEE 802.16 standard. H. Elgala [37] used OFDM in visible light communication. Other researchers [38] also used OFDM for the white LED broadcasting. In H. Elgala's work, he evaluated the channel performance with the help of an experimental setup as no well-defined channel model was available at that time. The transmitter and receiver of their proposed model is shown in Figure 2-4. Digital signal processing (DSP) board was used for the implementation of fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) algorithms. Forward error correction (FEC) coding was implemented on OFDM Tx board. At the receiver, Viterbi decoding with hard decision was used.

Results show that the bit error rate (BER) of 2×10-5 can be achieved over a distance of 90 cm using QPSK modulation and a single LED.

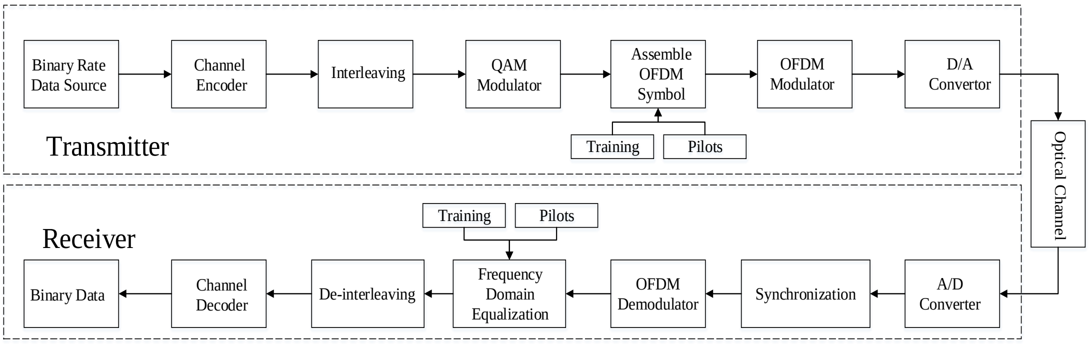


Figure 2-4: Visible light OFDM transmission model

Research team from Taiwan [39] developed a 10 Mbps white LED VLC system. By using pre-distortion and first order RC equalization, a 10Mbps VLC link was established by maintaining a BER of < 10^{-10} using 1 MHz bandwidth white light LED. Experimental setup consists of modeling LED by a 10 Mbps pseudo-random binary sequence (PRBS). The modulated white light is passed through the focusing lens and then it falls on a PIN PD which is amplified for further processing. The proposed equalization circuit consists of a resistor and a capacitor with optimized values. Their experimental setup is shown in Figure 2-5.

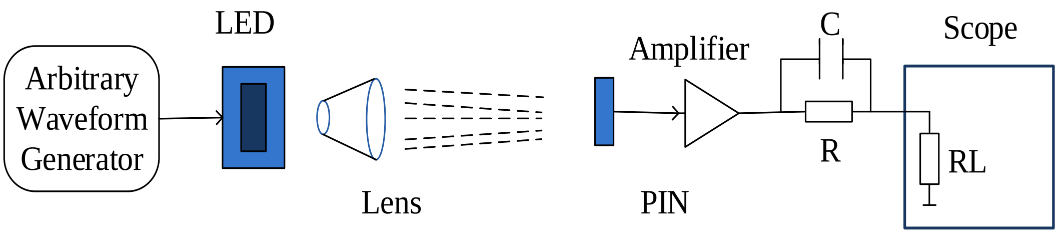


Figure 2-5: Experimental setup of LED based communication system

In another experiment [29], the same group used red and green laser pointer lasers (LPLs) and demonstrated a 500 Mbps Wave Division Multiplexing (WDM) VLC system. The system has the capability to maintain a BER of 10^{-9} at a distance of 10m. Red and green LPLs were directly modulated to 500 Mbps PRBS. The receiver consisting of a PIN Photo-diode (PD), pre-amplifier (with low noise figure), adaptive filter and multiplexer which was placed at a distance of 10 meters. Adaptive filter consists of amplitude and phase comparator with feedback paths to store amplitude/phase values. From this experiment, they concluded that employing LPLs in VLC system is a primary option in accelerating the VLC deployment. System block diagram for the above experiment is shown in Figure 2-6.

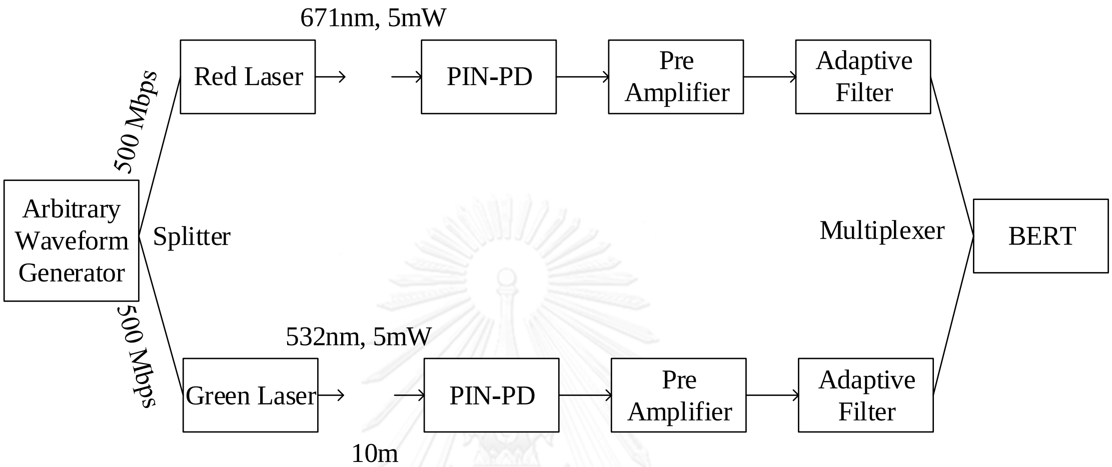


Figure 2-6: Experimental configuration of a WDM based VLC systems

Researchers from Oxford University reported that when an equalization is applied at the receiver, the data rate significantly improved from 16 Mbps to 32 Mbps using Non-return to zero on off keying (NRZ-OOK) with a BER of 10-6 [40]. The represented the LED response as in the Eq. (2.1).

$$h_{LED}(t) = e^{-w_c t} \tag{2.1}$$

Taking its Laplace transform, we get;

$$H_{LED}(S) = \frac{1}{S + w_c} \tag{2.2}$$

So first order equalizer response was designed as;

$$H_{equ}(S) = \frac{1}{H_{LED}(S)} = S + w_c \tag{2.3}$$

To overcome the low bandwidth issue of VLC, same group from Oxford University, used 16 LEDs which are modulated by a resonant driving technique which gives a 25 MHz bandwidth. NRZ-OOK is then applied to establish a 40 Mbps link which gives low BER [41]. Using pre-equalization, the group achieved a data rate of 80 Mbps and by detecting only the blue component of the LED and using a simple first-order analogue post equalizer, a data rate of 100 Mb/s was achieved.

Researchers from Italy have demonstrated a VLC link of 1 Gbps using a rate-adaptive discrete multi-tone modulation (DMT). A phosphor-based white LED was used as an optical source which is responsible for generating a luminous flux with Lambertian emission. 512 subcarriers were used with the bandwidth was 190 MHz which were uploaded to an Arbitrary Waveform Generator (AWG). A power amplifier (PA) was used to amplify the signal which is coming out from an AWG which helps in obtaining a good level of modulation index of the LED light. The electrical DMT signal was then superimposed on the LED with dc bias current via a bias-T. LOS link was established between the transmitter and the receiver. On the other hand, the receiver consists on an APD module which have an Avalanche Photo-diode (APD) along with the Trans-Impedance Amplifier (TIA) which is integrated with the APD. In order to filter out the slow phosphorus components, a dichroic optical band pass filter was placed in front of the APD. Furthermore, a bi-convex glass lens was placed to focus the light onto the APD active area. The output signal from the APD module was then sampled and saved by means of a real-time (RT) oscilloscope.

2.5 Indoor Visible Light Positioning System

An Indoor Positioning System (IPS) is a network of devices used to locate objects or people inside a building wirelessly. Indoor localization has many potential applications in the robotic industry, indoor navigation service and for public safety [42]. Outdoor position system mostly rely on GPS but this system is not fit for indoor positioning mainly because of the poor satellite coverage, signal attenuation, multipath effect and obstacles. To date, a number of techniques have been proposed and studied for the indoor location sensing. Most of them are using a positioning technique based on triangulation, finger printing, scene analysis or proximity [43]. There are two major categories of indoor position system. The first one is based on microwave links i.e. radio frequency identification (RFID), wireless local area network (WLAN), ultra-wide band (UWB) and Bluetooth. In these techniques, the position accuracy is decreased to tens of centimeters because of electromagnetic interference, noise, stability etc. The other category is based on optical tracking and imaging which gives a good accuracy [44]. Details regarding the techniques which are widely used in visible light positioning system are mentioned in the sub-sequent section.

2.5.1 Triangulation and Multilateration

Triangulation in reality is a generalized name of localization technique in which the geometric properties of triangles are used for the estimation of the location. Triangulation can further be classified into two main classes i.e. lateration and angulation. In Lateration technique, estimation of the target location is done by measuring the distances from multiple reference points. For this case (i.e. VLC based localization system) the proposed method in the literature uses light sources as a reference points and the optical receivers is co-located with the target. As it is not possible to have the measurement of the distance directly, therefore other parameters such as time of arrival (TOA), received signal strength (RSS), time difference of arrival (TDOA) etc. are measured and corresponding algorithms are applied to estimate the distance. Angulation alternatively, measures the angle relative to different reference points. In order to have the estimation for the location, determination of the intersection of direction lines is done, which are radii range from the reference points (light sources) to the target (receiver) [45].

Multilateration is a location estimation technique which is based on the measurement of the difference in the distance between/among two or more stations at known locations that broadcast signals at known times. Disparate measurements of the absolute distance or angle, measuring the difference in distance results in a countless number of locations that fulfills the measurement. When these possible locations are plotted, they form a hyperbolic curve. To locate the exact location along the curve, a 2nd measurement is taken with a different pair of stations to produce a second curve, which intersects with the first. When these two intersections are compared, a small number of possible locations are revealed which can be further processed for location estimation.

2.5.2 Received Signal Strength

Three receivers are needed to find the position of the object of interest by obtaining the information from the signal strength of the received signal. RSS-based systems measure the RSS and determines the loss in the signal strength as it propagates from the transmitter to the receiver. Range estimation is done by using a path loss model. Then, trilateration is applied to measure the target's position. At-least three reference points are needed to realize 2-D or 3-D positioning same as TOA and TDOA based methods. The pros of this technique is that the accuracy is not dependent on system bandwidth and choice of modulation scheme.

A LED based indoor positioning system architecture and algorithm has been proposed [46]. In the proposed method, four LED lamps installed at the ceiling were used and they radiate their light in each assigned time slot which helps in distinguishing the signals from four different LED lamps. To determine the location under LED illuminating lamps, received signal strength ratio (RSSR) method is applied. The system parameters of LED optical wireless channel are shown in Figure 2-7.

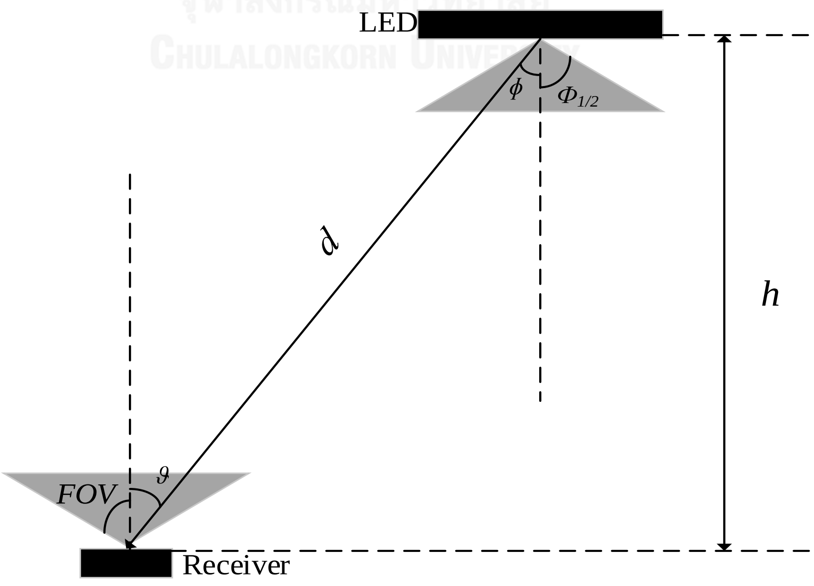


Figure 2-7: System parameters for the optical wireless channel

More than four LED lamps are required for proposed localization system and time division multiplexing can be used to distinguish each light signal from the LED lamps. Using power ratio between the received signals from each LED lamp, the location of the object can be estimated.

2.5.3 Time of Arrival (TOA)

This technique is time access method which measures the elapsed time for a transmission between a transmitter and a receiver. TOA utilizes the exact time difference between transmitter and receiver so synchronization between the transmitter and the receiver is very important. In TOA-based systems, time of arrival measurements are required from the three reference points to determine the target (giving intersection point of three circles for 2-D positioning, or three spheres for 3-D scenario respectively). TOA based systems have many applications in current world however there are few problems associated with it. Synchronization of all the clocks which are used as a reference points must be done as well as the target point's clock must also be synchronized. Any inconsistence in synchronization would be directly transformed into positioning errors. Secondly, there has to be a time stamp included inside the transmitted signal which potentially requires extra cost in terms of data rate. Due to these two problems, TOA-based localization technique is not a very good approach for indoor localization.

2.5.4 Time Difference of Arrival (TDOA)

Different from TOA, TDOA-based systems calculate the difference in time at which signals from various reference points are received. These signals are supposed to be transmitted simultaneously. For this reason, all the transmitters need to be synchronized in time. The advantage as compared to TOA is that the receiver need not to be synchronized with the transmitter since it is not taking measurements of the absolute time of arrival. Furthermore, there is no need for the time stamp in the transmitted signal.

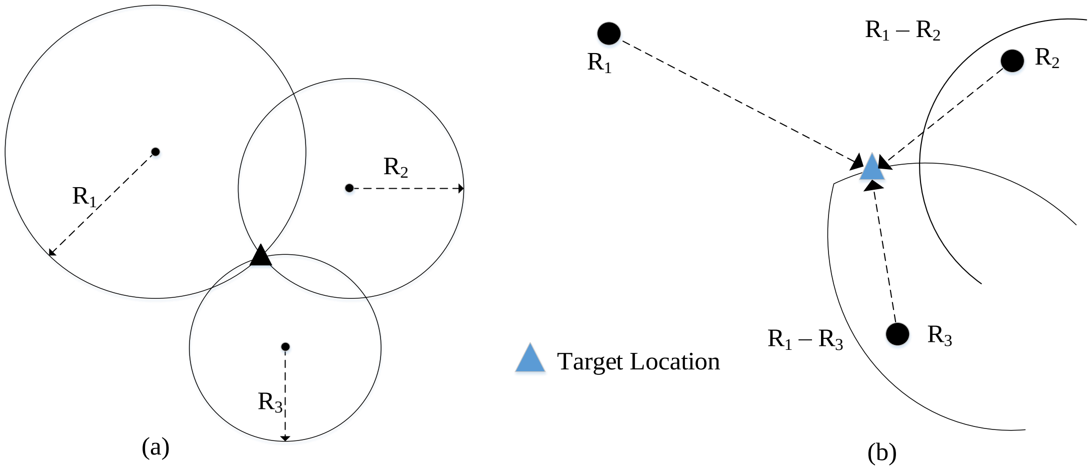


Figure 2-8: Multilateration using (a) TOA or RSS and (b) TDOA measurements

Soo Yong [47] proposed an optical wireless indoor localization using LEDs and demonstrated the system using simulation. Unique frequency addresses (F-IDs) were given to each LED and that address is transmitted via light which is radiated by the LED. Using the phase difference, TOA positioning algorithm is applied. The results show that the location accuracy of 1 cm can be achieved using this algorithm. It is assumed that there is no distortion in the channel. In order to calculate the position of the object for an indoor environment, three LED lamps were used and each LED lamp has a unique F-ID based on the characteristics that the LED can modulate signals while being used as lighting device, each LED lamp transmits its assigned F-ID. Noticing the phase difference between the Tx signals, time difference of arrival is estimated. The system is shown in Figure 2-9.

Computer simulations were done with the dimensions of room as 5.0 m × 5.0 m × 3.0 m. The LED celling lamps are located in (1.5, 1.5, 3), (1.5, 3.5, 3) and (3.5, 1.5, 3). The proposed positioning system proves the usefulness of LED based localization for an indoor environment.

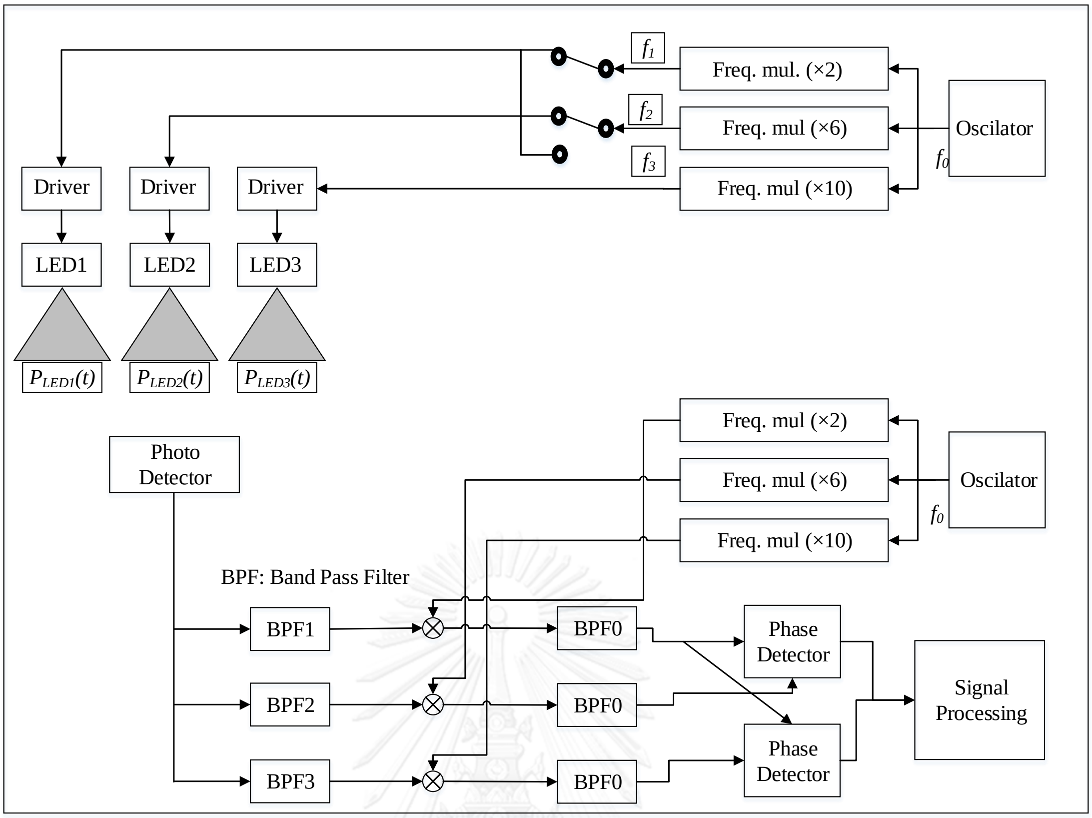


Figure 2-9: Proposed indoor localization scheme using TDOA

2.5.5 Angle of Arrival (AOA)

Angle of arrival (AOA) measurement is a method for determining the direction of propagation of a signal incident on an antenna array AOA determines the direction by measuring theTDOA at individual elements of the array. From these delays the AOA can be calculated.

Seongsu [48] proposed an angle of arrival (AOA) method to find the location of a LED using circular-PD-array. AOA estimation is an important technique for realizing the location awareness services. They propose truncated weighting method for enhancing the accuracy of AOA estimation. Via simulations, it was observed that the number of PDs in circular-PD-array influence the estimation error of a LED and truncated weighting scheme shows better estimation performance than those of simple average and MAX schemes. By adopting AOA algorithms for an indoor environment, proposed truncated scheme also shows better location estimation performance.

System model is described in Figure 2-10. It can be seen from the figure that multiple PDs are deployed at the receiver are distributed in a circular fashion.

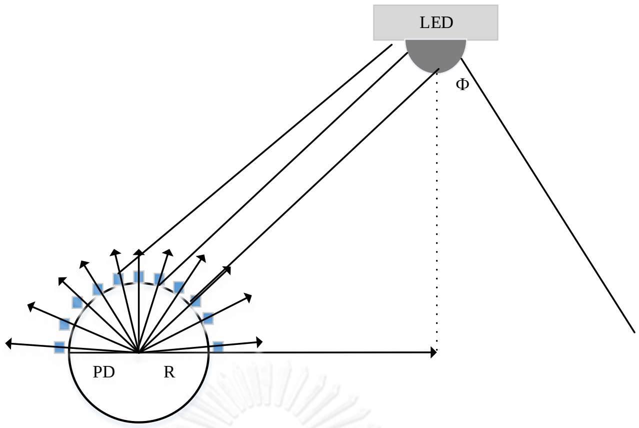


Figure 2-10: System model for estimating AOA based on circular PD array

2.5.6 Scene Analysis

Scene analysis states to a categories of localization algorithms which first gather fingerprints related with every position in a scene. Target's location is then determined by matching real-time measurements to these fingerprint readings. Parameters which can be used as fingerprints include TOA, TDOA, RSS and AOA. RSS is the most popular method for creating a finger printing map because of the simplicity in VLC systems. For using fingerprints, the time required to calculate the single position estimation is less than the position estimation using trilateration methods. A quick computation also helps in saving the power. However there are also some corns associated with this technique. It requires precise system pre-calibration for a specific scenario and thus cannot be deployed instantly inside a new environment.

2.5.7 Proximity

The operational principle of the proximity technique is straight forward and simple. It depends on a dense grid of reference points, and all the reference points have well known positions. When a mobile target gets the signal from a single reference point, it is assumed to be co-located with it. The shortcoming for the system is that the proximity grid will determine the accuracy of the location. If the grid is less dense, the accuracy will not be enough. To increase the accuracy, more light sources are needed which will result in not only cost issue but also lighting problems.

2.6 Applications

Visible light communication have their applications in various aspects of life. Following are the few promising applications of VLC.

VLC uses LED as transmitter and as mentioned before that the LEDs have many advantages over incandescent and florescent lighting so it can be stated that VLC promises smart lighting. High speed data transmission is possible using VLC with an advantage of inherent security and the achieved data rate is far higher than Bluetooth and Wi-Fi. As light cannot pass through the concrete structure, this gives an in-built security system so VLC has a potential application in communication domain where data privacy is a major concern.

It is not safe to use RF communication in mines and petro-chemical plants. VLC is a green technology with no harm to humans or the environment. RF communication technologies are also undesirable in hospitals and health care units especially around magnetic resonance imaging (MRI) scanners, Intensive Care Units (ICUs) and other sensitive equipment. VLC can fill the gap and provide an opportunity to have safe communication.

With the mushroom growth of mobile users in the last decade, the Wi-Fi spectrum is getting congested with every passing day. VLC spectrum is considered to be virtually unlimited and can accommodate large number of users. Therefore, VLC can provide a relief to Wi-Fi spectrum. RF communication has an extremely poor response for underwater networks. VLC can work well for short range underwater communication

Modern cars are now equipped with the LED headlight and backlights. Furthermore, the traffic and street lighting are also using LEDs. This creates an opportunity for the development of vehicle to vehicle and intelligent transportation system (ITS). Last but not the least – VLC most promising application is the location based services. VLC can be used for localization and many techniques have already been developed for the VLC based localization.

Chapter 3

3 Developed Localization Techniques for Indoor Environment

In this section, the author will discuss the developed localization techniques for indoor environment using light emitting diodes. The author has developed four techniques to achieve localization which are: Indoor localization using k-means clustering, a beam scanning based indoor localization, a heuristic approach for indoor localization, indoor localization using RSS and bi-literation. Details about each proposed technique will be discussed as follows.

3.1 Indoor Localization using k-means Clustering

Localization in VLC has been discussed in detail in chapter 2. Before the proposed localization approach is discussed it is worth investigating what about scholars have achieved in terms of location accuracy. Results can be classified based on either it's a simulation based work only or the actual design which enables the author to compare the proposed algorithm accuracy with the already available approaches in the literature.

Some theoretical works based on simulations have achieved high accuracy in location estimation. For instance, in Kavehrad et al., an accuracy of 0.5 mm is reported by analytically solving the Lambertian transmission equations. A mean error of 4.5mm was reported by Jung et al., in which a localization method based on TDOA using three LED ceiling lamps was proposed by assigning a unique frequency address to each LED lamp. In theory, indoor localization using LEDs and image sensors can achieve a level of accuracy in tens of centimeters. However such a high level of accuracy has never been achieved experimentally so far. One experimental work is Pharos [49] in which BFSK and channel hopping are adopted to achieve reliable beaconing from multiple and uncoordinated light sources over a shared light medium. Reported results reveal that the localization accuracy of 0.4 m and 0.7 m for two typical indoor environments (5 m × 8 m and 3.5 m × 6.5 m) are achieved respectively. Experimental results from Epsilon [50] reports that using a single LED, an accuracy of 1.1 m can be achieved.

3.1.1 Proposed Design and Implementation

The transmitter consists of two LEDs which are 12 W each and are modulated to 1 kHz and 2.5 kHz respectively. The reason for choosing 1 kHz and 2.5 kHz is that higher harmonics of the 1 kHz sinusoidal signal does not have a significant amplitude at 2.5 kHz. At the receiver side, the block diagram is shown in Figure 3-2 (a) and the implementation details are given in Figure 3-2 (b). In the first part of the receiver, a photodiode is used to convert modulated light signals into electric current which is then fed to a trans-impedance amplifier (TIA) to further convert into voltage signals. The output of TIA is the input to the differential amplifier for adaptive minimum voltage cancellation. The purpose of the minimum voltage cancellation circuit is to remove the DC component and interference from ambient light sources from the received signal [51]. Information from the amplifier is received by the microcontroller and then sent to the computer for RSS recovery. The overall scenario of localization is shown in Figure 3-1.

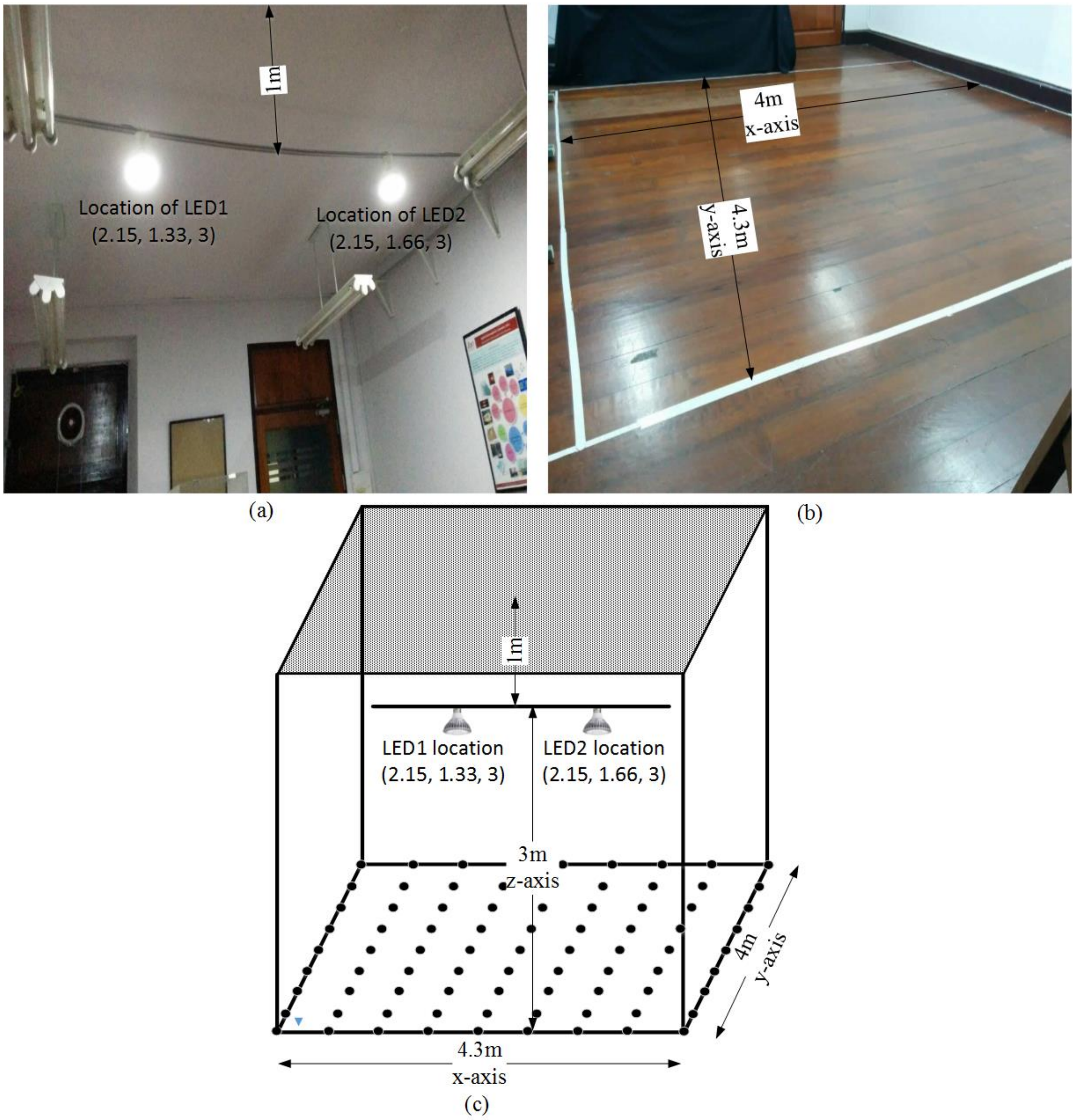
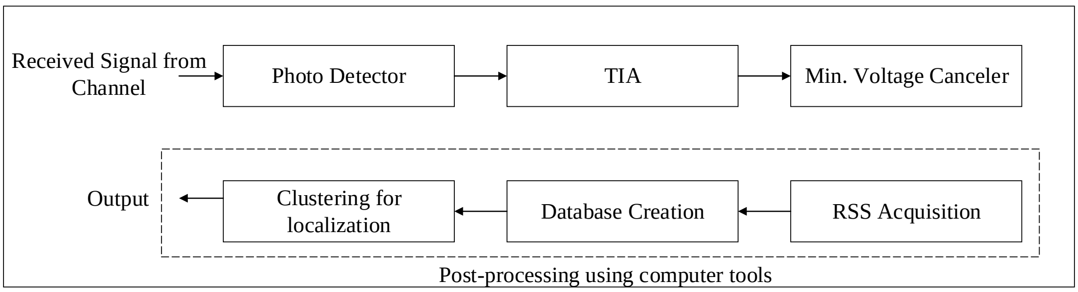
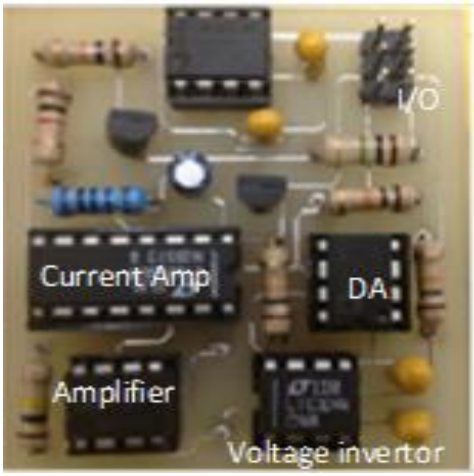


Figure 3-1: Placement of LEDs on the ceiling (b). Floor area for experimentation (c). 3D visualization of the overall scenario



(a)



(b)

Figure 3-2: (a). Proposed receiver for localization (b). Implementation details

The database is created manually by recording the actual RSS readings from LEDs at various locations. These readings are collected in a symmetric manner instead of random as the former one is well suited for machine learning algorithms. The database creation is essentially the generation of a finger print map during the offline stage (i.e. the stage in which RSS information is collected, processed, and recorded as a reference in database). The end result of this step is a sparse map. Then sparse map is converted into a dense map through interpolations.

As the first step to check the map, validation of the map is performed. The locations of transmitters are known and fixed thus one can validate whether the distribution of LED lights follow the position of transmitters. Figure 3-3 shows the two dimensional (2-D) grid of a dense fingerprint map in which the brightest spot corresponds to the positions of LEDs as seen in Figure 3-1. The Z = 73 identifies a 2D slice taken from the dense 3D cube at the largest height of the cube.

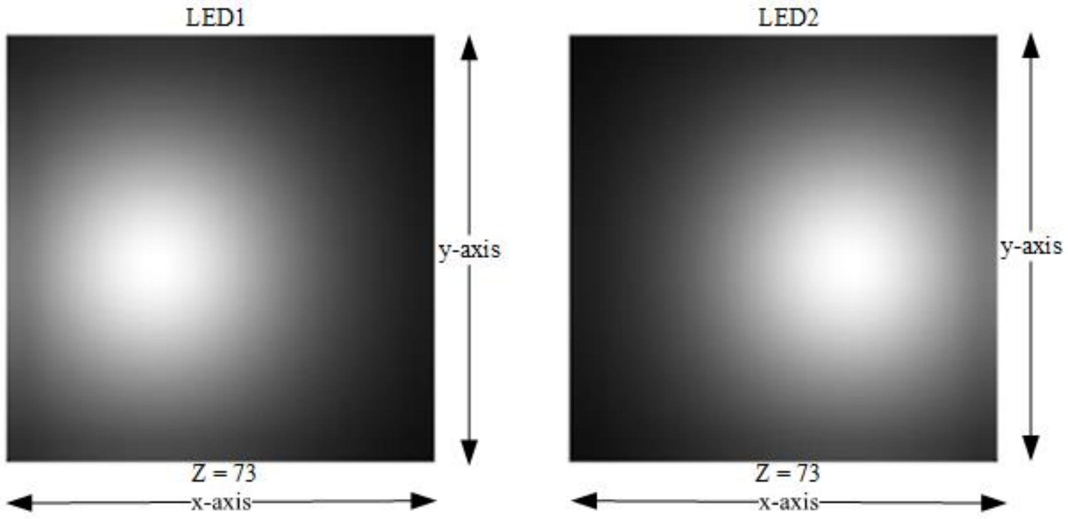


Figure 3-3: Light intensity map indicating the locations of transmitters (LEDs)

3.1.2 Proposed Localization Algorithm

Details of the proposed localization algorithm inspired by the general concepts of image processing and machine learning are outlined as follows.

(A). Bilinear Interpolation to Generate a Dense Intensity Map

Interpolation has been excessively used for various signal and image processing applications [52] and is the process of generating new data points synthetically by using the already available real data points. Author define a dense grid/cube for fingerprint map which has sparse measures available from a manual uniform sampling, i.e. the fingerprint map created in the previous section. These manually collected readings are used in a recursive fashion to interpolate new values for each location on fingerprint grid /cube. Figure 3-4 shows various iterations of grid filling by using fingerprint map readings from the neighbors. Only a 2-D grid is shown for demonstration purposes and the actual experiments involve filling up a dense cube equal to the dimensions of the room for each LED.

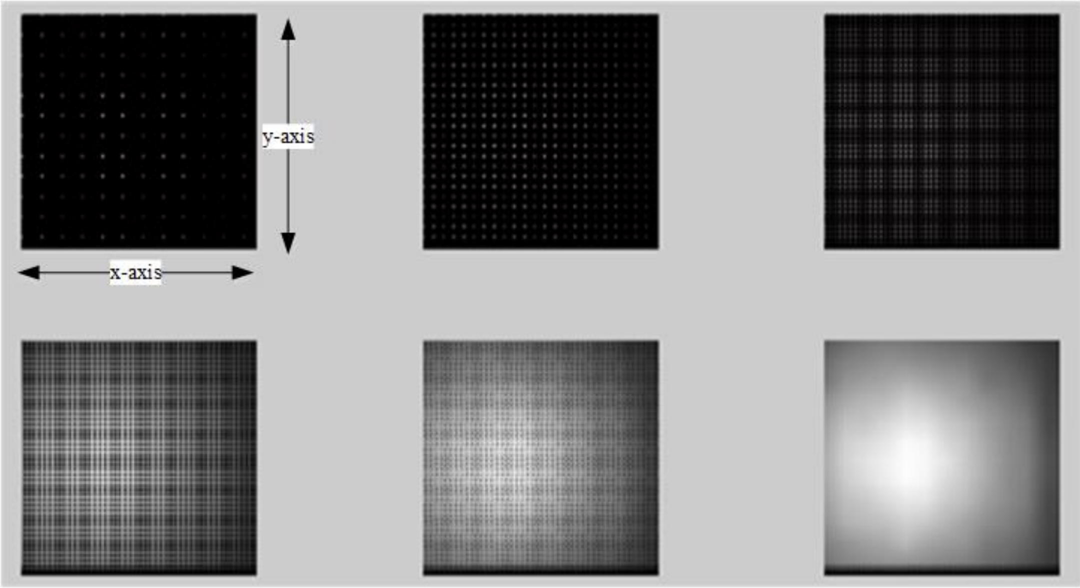


Figure 3-4: Recursive generation of dense LED readings grid for LED1

The author further smoothen RSS grid/cube by applying a median filter of 3 × 3 (for grid) or 3 × 3 × 3 (for cube). The final output of this process would be two three-dimensional arrays $L_1(i,j,k)$ and $L_2(i,j,k)$ for fingerprint maps from LED1 and LED2 respectively, where i,j and k are indices and vary from $1-M, 1-N$ and $1-O$ respectively, i.e. the resolution of the cube in *x*, *y* and *z* dimensions.

Using RSS arrays L_1 and L_2 we prepare a $D\times 5$ array A; where we concatenate fingerprint maps for both LEDs X,Y and Z dimensional indices for each of the $D = M\times N\times O$ data points in a row fashion of the form $\left[L_1(i,j,k), L_2(i,j,k), i, j, k\right]$. Mathematically,

$$A = \begin{bmatrix} L_1(1,1,1) & L_2(1,1,1) & 1 & 1 & 1 \\ L_1(1,1,2) & L_2(1,1,2) & 1 & 1 & 2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ L_1(1,1,O) & L_2(1,1,O) & 1 & 1 & O \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ L_1(M,N,O) & L_2(M,N,O) & M & N & O \end{bmatrix} \tag{3.1}$$

Once matrix A is constructed, we use it for k-means clustering as described below.

(B). Training: k-means Clustering

Clustering is an un-supervised machine learning approach where entities are grouped together based on their naturally similar characteristics such that entities belonging to a group are more similar as compared to entities belonging to another group. For example, if we have a data base of animals [dog, cat, rat, sparrow, crow, eagle]; based on their natural capacity of being able to fly or not, they would be clustered into two groups [Cluster1: dog, cat, rat] and [Cluster2: sparrow, crow, eagle]. Various clustering algorithms have been proposed over the years and can majorly be grouped as hierarchy based algorithms, centroid based algorithms and distribution and density based algorithms. The k-means clustering is a basic unsupervised learning algorithm which belongs to the category of centroid-based algorithms [53]. It has been successfully used for image segmentation and multi-class classification [54].

Author uses k-means clustering to train a system which can be used to estimate the unknown positions given the RSS readings i.e. LED based localization. For this approach, two layers of clusters are used so that it can accurately estimate the position in a coarse-to-fine manner. First the given grid/cube is segmented into $\boldsymbol{K}_1$ number of chosen clusters at layer 1, then all the data points allocated to cluster $\boldsymbol{j}$ at layer1 are further clustered into $\boldsymbol{K}_2$ number of chosen clusters. The centroids of these clusters at layer1 and layer2 are used to estimate the location of a query RSS reading as described in the next section.

Figure 3-5 shows the segmentation found by k-means clustering for a 2-D grid of fingerprint map, where only LED readings are used as features for the k-means clustering. The segmentation on the left shows the partitioning of the 2-D grid into 8 segments highlighted by a color coding. At layer 2, each of these clusters is further partitioned into three clusters. An example for the 2nd layer clustering is shown in Figure 3-5 (right) where the black cluster from level1 is partitioned into three different clusters at level2 highlighted by the color coding.

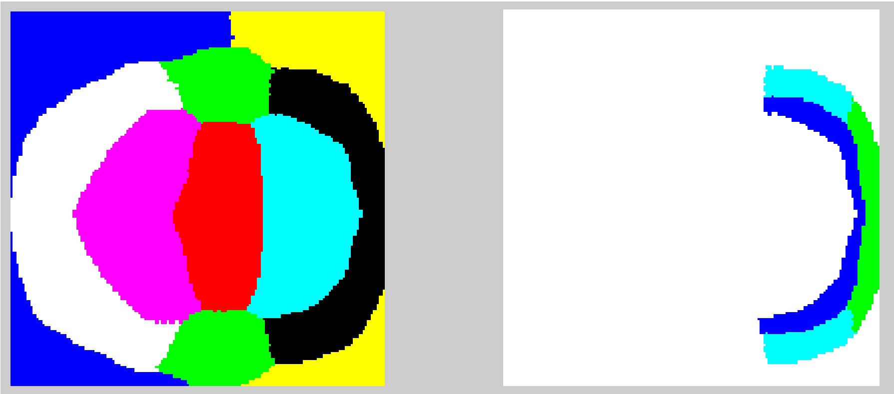


Figure 3-5: Clustering data points on a grid into 8 clusters (left) at level1, taking all the points in one of the clusters and further clustering these points into 3 clusters (right) in level2

Here the clustering is done only for a 2D grid and based only on the fingerprint map for demonstration and highlighting the problem that arises when only RSS maps are used for clustering. In actual experiments, author uses five features i.e. author also include indices of the data points because the clustering solely based on LED readings can result in disjoint clusters (green cluster at level1 and cyan cluster at level2) which would cause problems at testing.

Mathematically, k-means can be considered as a function which takes a data matrix $\boldsymbol{A}$ and the number of clusters $\boldsymbol{k}$ to be found as parameters and returns the centroids $\boldsymbol{C}$ for the clusters and allocation vector $\boldsymbol{I}$ which contains the cluster identification (ID) for each example in the data matrix $\boldsymbol{A}$. At level1, mathematically, this formulation can be written as,

$$[\boldsymbol{I}_1, \boldsymbol{C}_1] = \textbf{k-means}(\boldsymbol{A}, \boldsymbol{k}_1) \tag{3.2}$$

where, $\boldsymbol{k}_1$ is the number of clusters at level1, $\boldsymbol{A}$ is the data matrix as constructed in Eq. 3.1, $\boldsymbol{C}_1$ is the $\boldsymbol{k}_1 \times \boldsymbol{5}$ vector of the cluster centroids and $\boldsymbol{I}_1$ is the $\boldsymbol{D} \times \boldsymbol{1}$ vector of cluster IDs to which each data example is assigned to.

Next, each of the clusters from level1 is further clustered into $\boldsymbol{k}_2$ clusters with $\boldsymbol{C}_{i2}$ centroids. For every cluster $\boldsymbol{i}$ from level1, the k-means function would be called for only those data points from the original data set $\boldsymbol{A}$ which were assigned to that particular cluster i and the process would be repeated for k_1 times i.e. the number of clusters at level1. A mathematical function F can be defined which returns a data vector A_i comprising of only those data points in A which have been assigned with the cluster label i at level1;

$$A_i = F\left(A, I_1, i\right) \tag{3.3}$$

Mathematically, each call to k-means function can be described as;

$$\left[I_{i2}, C_{i2}\right] = \textbf{k-means}\left(A_i, k_2\right) \tag{3.4}$$

To conclude at the end of the training phase, we will have a $k_1 \times 5$ dimensional matrix C_1 and $k_1\, k_2 \times 5$ dimensional matrices $C_{12}, C_{22}, C_{32} \cdots, C_{k12}$ of centroids which are essential for testing i.e. localization of an unknown point using LED readings.

(C). Testing: Estimating Position for Query LEDs Reading

Author use LED readings for a query point to find the location of the point by minimizing the Euclidean error of the given LED readings with that of cluster centroid LED readings of clusters at level1 and level2. The first two columns in each of the matrices $C_1, C_{12}, C_{22}, C_{32} \ldots$ etc. correspond to the centroid LED readings. First at level1, author find the cluster with which the given LED readings have the lowest Euclidean distance.

$$i^* = \textbf{arg}\,\textbf{min}_i\left(\sqrt{\left(C_1\left(i,1\right) - L_{q1}\right)^2 + \left(C_1\left(i,2\right) - L_{q2}\right)^2}\right) \tag{3.5}$$

where i^* is the cluster from level1 which has the minimum Euclidean distance from the given query LED readings from LED1 (L_{q1}) and LED2(L_{q2}). Next the cluster identified at level1 is used to identify clusters at level2 to which the distance of the query LED readings should be minimized.

$$j^* = \arg\min_j \left(\sqrt{\left(C_{i*2}(j,1) - L_{q1}\right)^2 + \left(C_{i*2}(j,2) - L_{q2}\right)^2} \right) \tag{3.6}$$

And the x, y and z indices of this cluster at level2 are taken as the approximate location of the query LED point.

$$\left[X_q Y_q, Z_q\right] = \left[C_{i*2}(j,3), C_{i*2}(j,4), C_{i*2}(j,5)\right] \tag{3.7}$$

Table 3-1: Details of various parameters used in the experimental setup

Entity	**Parameters**	**Value**
Transmitter	Number of LEDs	02
	Power emitted by each LED	12W
	Semi angle at half power	70°
	Location of LEDs	(2.15, 1.33, 3) (2.15, 1.66,3)
	Mounting height	3m
Receiver	Active area of photodiode	4.48 mm^2
	Angle of half sensitivity	60°
Others	Dimension of room	4 × 4.3 × 4m^3
	Samples in sparse grid	81
	Samples in sparse cube	486
	Samples in dense grid	21025
	Samples in dense cube	1534825

3.1.3 Results and Discussion

The collection of samples is conducted in a 4.3 × 4 ×4 m^3 room. Shadowing effect is also considered which is caused by the objects present in the room. There was no reflecting object present in the area of interest. Results of the proposed algorithm are shown in Figure 3-6. The graph is plotted for the samples and their corresponding errors. The mean localization error is found to be 37 cm. The accuracy of the algorithm is better in the center of the room and poor at corners of the room mainly because of the shadowing effect from objects. However this can be overcome if more samples are taken at the corners but in this experiment, samples are taken uniformly. If the accuracy of the proposed algorithm is compared with existing method, it can be observed that the proposed algorithm has an excellent performance.

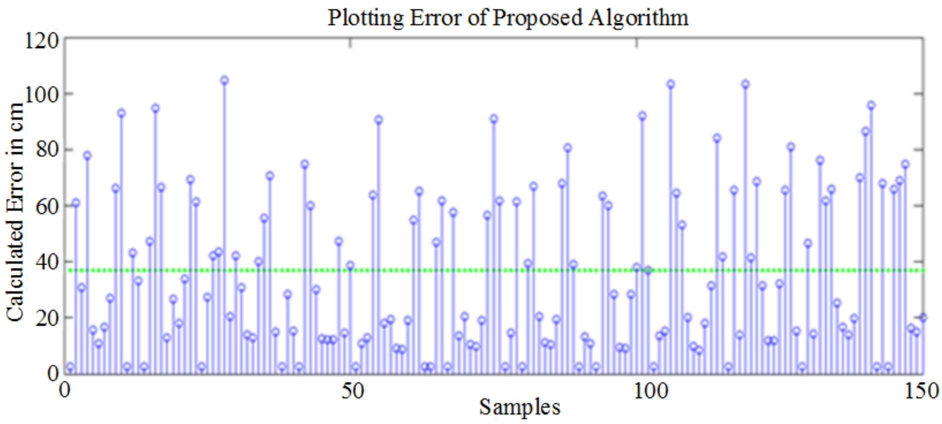


Figure 3-6: Plotting errors of the proposed algorithm

The error for each query point is computed by taking the Euclidean distance of LED readings from the closest centroid at level2 as shown in the Eq. 3.8,

$$\boldsymbol{E_q} = \left(\sqrt{\left(\boldsymbol{C_{i*2}(j*,1) - L_{q1}}\right)^2 + \left(\boldsymbol{C_{i*2}(j*,2) - L_{q2}}\right)^2} \right) \tag{3.8}$$

where, $\boldsymbol{i*}$ and $\boldsymbol{j*}$ are the clusters at level1 and level2 found by Eqs. (3.5) and (3.6) described above.

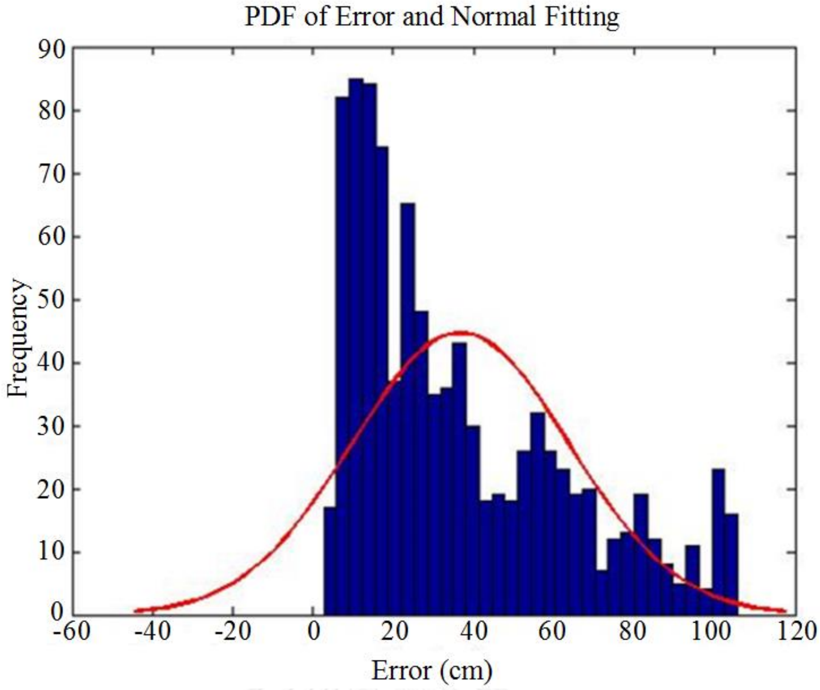


Figure 3-7: Power distribution function of error and normal fitting

In Figure 3-7, probability distribution function (PDF) is shown for the error distances and a normal distribution fitting to it. It is quite clear that error PDF is concentrated between 30 cm to 40 cm mark and only limited localization errors exceed 60 cm. To the best of author's knowledge, this is the best accuracy achieved in any practical environment utilizing LEDs. Furthermore, it is also important to mention that, in this approach, only two transmitters are required to achieve accurate localizations.

3.2 A Beam Scanning-Based Indoor Localization System Using Light Emitting Diodes

In literature, there exists several techniques for indoor localization [55], [56], [57], [58], [59], [60]. In this work, location of the object is determined by scanning two LEDs at pre-defined angles which are modulated at different frequencies. During scanning process, for each LED, two maximum values of received signal strength (RSS) are recorded and this information is used to calculate the position of the object. Time division multiplexing (TDM) is used to incorporate angle information of the receiver. A bicubic spline interpolation is applied to calculate the position of the object.

3.2.1 System Modeling

In order to establish a communication system, transmitter, channel and the receiver need to be modeled. Light emitted from an LED follows a Lambert emission pattern which is governed by Eq. 3.9.

$$R(\phi)=\frac{n+1}{2\pi}P_T\cos^{n_l}(\phi) \tag{3.9}$$

where P_T is the power transmitted from the LED, ϕ is the angle between the source orientation vector and the vector pointing from source to the receiver, n is the mode number of the radiation lobe which is $n=-\ln 2/\ln(\cos\Phi_{1/2})$ where $\Phi_{1/2}$ is the LED view angle at half power. It is assumed that the receiver is facing vertically upwards. Furthermore, for a typical VLC channel, the distance (d) between the transmitter and the receiver is quite large as compared to the photodiode detector area (A_R), which makes the received signal irradiance constant over the photodiode detector area. With these assumptions, the VLC channel impulse response $h(t)$ can be approximated as a scaled and delayed Dirac delta function from LED_i for $\theta_i \le FoV$ is given by Eq. 3.10.

$$h_i(t)=\left\{\frac{n+1}{2\pi}\frac{\cos^n(\phi_i)\cos(\theta_i)A_R}{d_i^2}\delta(t-\frac{d_i}{c})\right\} \tag{3.10}$$

where θ_i is the angle between the receiver orientation vector and vector pointing from receiver to the source, FoV is the field of view of the receiver and c is the speed of light. The received signal can be expressed by Eq. 3.11.

$$P_R(t)=P_T\sum_{i=1}^{k}s_i(t)\otimes h_i(t)+\mathrm{n(t)} \tag{3.11}$$

where $s(t)$ is the modulated signal and $\mathrm{n(t)}$ is the noise from the channel. In order to distinguish between the signals from each angle of the LED, time division multiplexing (TDM) is used and frame structure for one period is shown in Figure 3.8. At the end of each frame, the receiver will have the information about the received signal strength

(RSS) of an LED for each angle. In order to distinguish between the LED1 and LED2, different frequencies (i.e. 1 kHz and 2.5 kHz) are used.

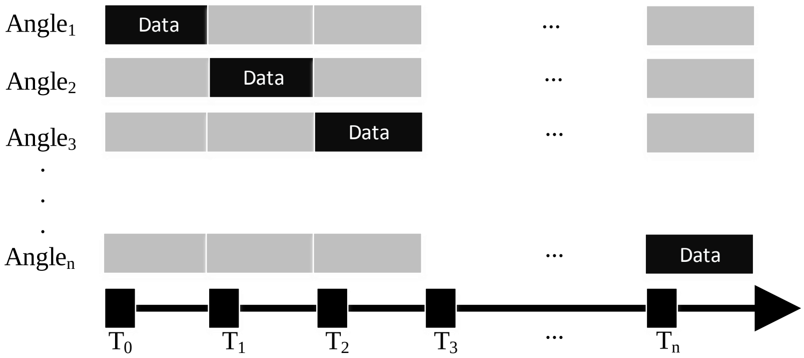


Figure 3-8: Frame structure for one time slot

3.2.2 Transmitter Design

The block diagram of transmitter is shown in Figure 3.9. It primarily consists of two units. The first part is the motor control unit and the second part is the data transmission unit. The motor control unit consists of stepper motor driver and stepper motor which is controlled by a microcontroller unit (MCU). The motor is connected to the LED lamp with the help of motor shaft. The data transmission part consists of signal generator which is responsible for modulating the signal. Angle information (as per Figure 3.8) coming from MCU becomes one of the inputs of the multiplier and the other input is from the signal generator. The output of the multiplier is amplified with the help of an amplifier, which is fed to the LED driver circuit, followed by the LED lamp.

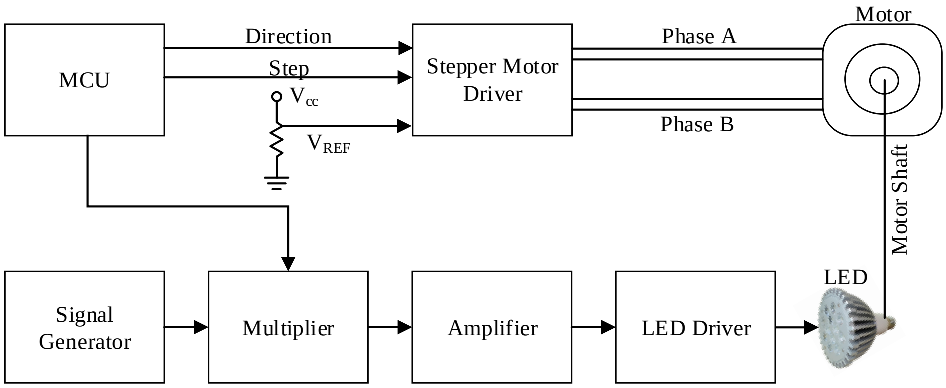
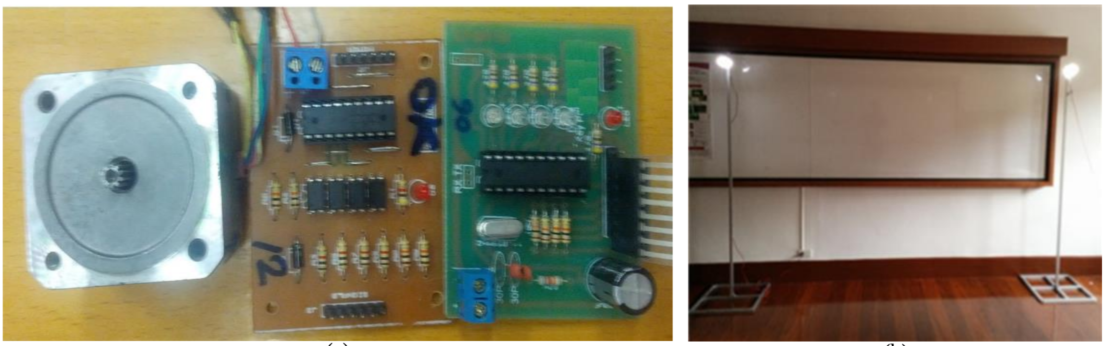


Figure 3-9: Block diagram of transmitter

Figure 3-10 shows the implementation details of the motor control unit and the experimental setup.



(a) (b)

Figure 3-10: (a). Motor control unit (b). Experimental setup

3.2.3 Receiver Design

Block diagram of the proposed receiver is shown in Figure 3-11 and the implementation details are the same as that of Figure 3-2. The first part of the receiver is a photodiode which is used to convert the modulated light signals into electric current which is then fed to a trans-impedance amplifier (TIA). TIA converts the electric signal into voltage. The output of the TIA becomes the input to the differential amplifier for adaptive minimum voltage cancellation. The purpose of the minimum voltage cancellation circuit is to remove the DC component and interference from the ambient light sources from the received signal. Information from the minimum voltage canceler is received by the microcontroller and then sent to the computer for further processing.

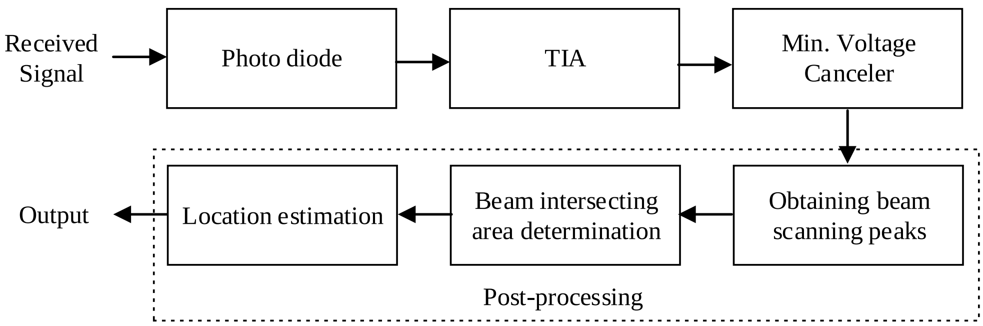


Figure 3-11: Block diagram of the receiver circuit

3.2.4 Proposed Algorithm

For this work, two-dimensional (2-D) localization scenario is considered. Two transmitters (LED1, LED2) are used. Each LED L_i is mounted above the localization area with the center of the LED emission focused at $(x\_axis_{MAX}/2, 0)$ for LED1 and $(x\_axis_{MAX}/2, y\_axis_{MAX})$ for LED2 which are used as reference angles. The LEDs are pointed downwards facing the area with the elevation angle of $\theta_{e,i}$. The beam emitted with $\theta_{e,i}$ will have its projection in a conical geometry on 2D plane and its vertex is defined as a location of a virtual point source. The scenario is shown in Figure 3-12.

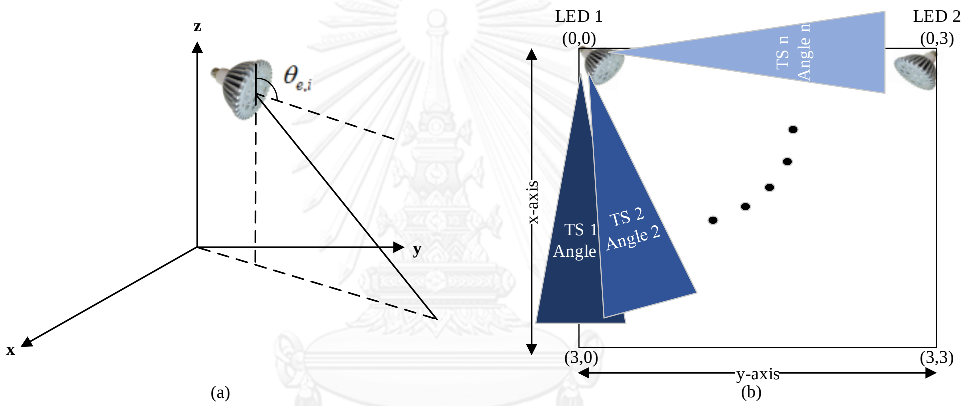


Figure 3-12: (a). Parameters of LED (b). Beam scanning process

The proposed algorithm is explained in the following three steps.

<u>(A). Beam scanning and higher peaks recording</u>

In the first step, the LED1 is moved with a step of few degrees (8° to 20°) from a reference point to an end point. 0° refers to the data transmission at first time slot (TS) and 90° refers to last TS data transmission which is shown in Figure 3-12(b). During the scanning process, LED records the highest and the second highest intensity with their respective time slots which tells the information about the angle of the LED. The same procedure is repeated for LED2 as well.

(B). Finding an intersecting area

When the receiver has the knowledge at which angle of the LED, the receiver receives the maximum values, the intersecting area between the two LED beams can be found. The two RSS values from each LED will always be consecutive and the four points (two highest readings from LED1 and two from LED2) will correspond to a specific region in a 2D plane where the object needs to be localized. This area refers to the intersecting area of the beams from LED1 and LED2 which is depicted in Figure 3-13

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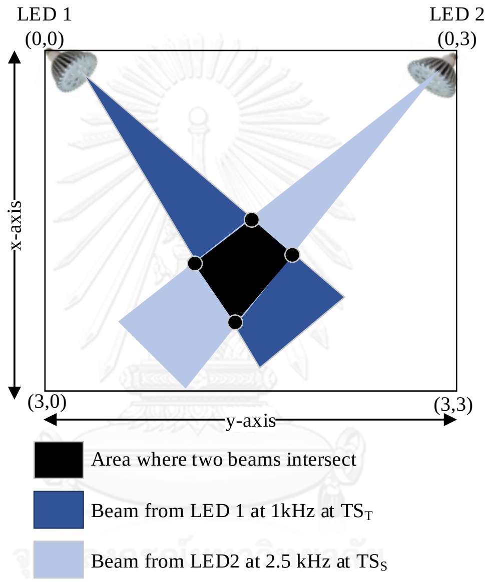


Figure 3-13: Determining intersecting area of two beams

(C). Finding the location of an object

When the area under the intersecting beams is known, the next step is to find the location of an object. For position estimation, the bicubic spline interpolation is used. The intensity at the corners of the intersecting area are known to the receiver (during the offline stage, these readings are measured and recorded in the lookup table of the receiver). The advantage of using bicubic spline interpolation is that instead of using four intensity values to estimate the position, bicubic spline interpolation gives 16 points which can be processed to approximate the position. To understand this, one can consider Figure 3-14.

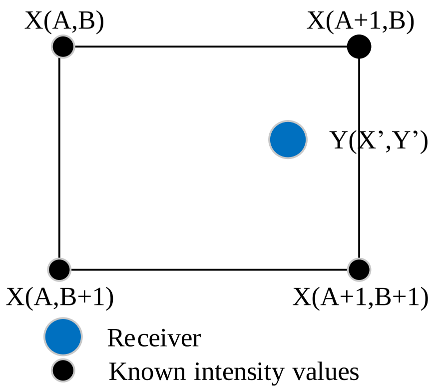


Figure 3-14: Bicubic spline interpolation for our case

The original intensity values are $f(A,B), f(A+1,B), f(A,B+1), f(A+1,B+1)$. By taking the partial derivatives along the x-axis, y-axis and cross derivatives of each of these will give 16 points in total. It is worth mentioning here that a VLC channel is comparatively static and light intensity is changed in a known fashion with respect to the distance. Furthermore, ignoring the effect of multipath, reflection and shadowing (which is insignificant for a typical official environment), the equations for bicubic spline interpolation can be modified to the following set of equations.

$$\begin{aligned} f(x,y) &= \sum_{i=1}^{4}\sum_{j=1}^{4} x^i y^j \\ \partial_x f(x,y) &= \sum_{i=1}^{4}\sum_{j=1}^{4} i x^{i-1} y^j \\ \partial_y f(x,y) &= \sum_{i=1}^{4}\sum_{j=1}^{4} j x^i y^{j-1} \\ \partial_{xy} f(x,y) &= \sum_{i=1}^{4}\sum_{j=1}^{4} ij x^{i-1} y^{j-1} \end{aligned} \tag{3.12}$$

With the help of these 16 points, the position of an object is estimated.

3.2.5 Results and Discussion

For experimental demonstration, two off-the-shelf, narrow beam, 12 W LED lamps were taken with viewing angle of 25°. A high speed photo diode is used with angle of half sensitivity equals to + 65° and the radiant surface area of $7.5mm^2$. Each LED lamp is composed of 12 LEDs which are arranged in a circular fashion. The height of the LED lamps were fixed at 2m and room dimensions are kept to be $3\times3\times2\ m^3$. The horizontal distance between the LEDs is 3m and the position of the LED lamps are fixed and known. For the given scenario, performance of the proposed localization algorithm is evaluated for noisy and noise-free environment. We also investigate the effect of LED rotation step size on location estimation.

.

(A). Performance evaluation under noise-free and noisy environment

For the first case, light from all the ambient light sources such as sun light, fluorescent and incandescent light sources etc. are not allowed to enter in the experimental area and only the lights from the LEDs contributing to this experiment are turned on. LEDs are moved at fixed step sizes and the mean location estimation error is plotted against each step size. It can be observed from Figure 3-15 that as the step size increases, the accuracy of location estimation decreases implying inverse relation between step size and localization errors. For this experiment, the minimum step size for LED movement is kept at 8° however it can be further reduced. At 8°, the position estimation error for noise-free case is 13 cm which is superior to conventional RF and VLC localization techniques.

The second graph (green line) in Figure 3-15 is for the case when receiver is placed in an environment where sun light can enter in the room (not direct sun light) and ambient light sources are also present which results in generation of shot noise. For moderate conditions, the value of shot noise is typically around 160 dbm W considering low data transmission which is true for our case. Under this condition, for 8° step size, the localization error is 18 cm and for 20° the localization error is approximately 45 cm.

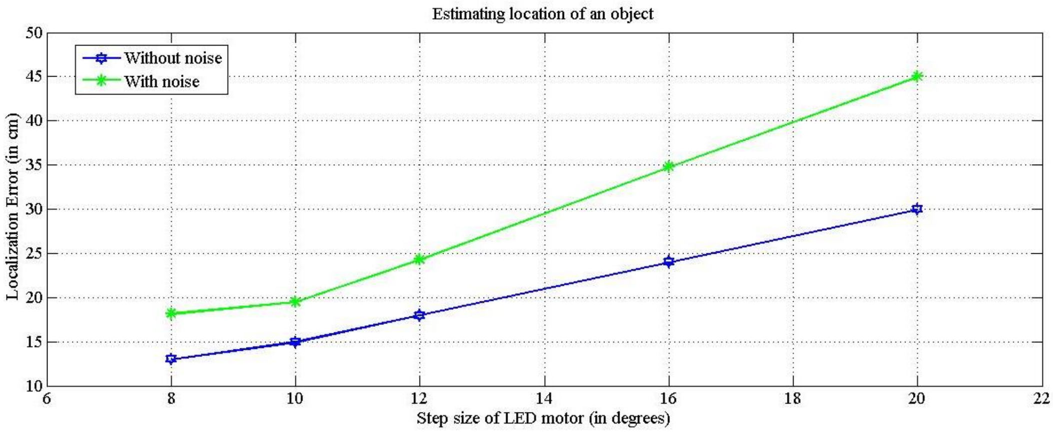


Figure 3-15: Localization error at different step sizes for a no noise and noisy environment

(B). Location-wise Positioning Estimation Error

Further analysis is done for the location estimation error with respect to the coordinates of the room. It has been observed that the location estimation error at the corners is more as compared to the center of the room which is because of the directionality of Lambert emission transmission. When the receiver is near to the corner, the received intensity from the diagonal source can be considerably degraded and is susceptible to noise interferences. However for the proposed algorithm, the location estimation error primarily depends on the overlapping area of the beams of the two LED lamps. If the intersecting area (as shown in Figure 3-13) is bigger, then the error will also be more and vice versa. The corners which are near the LEDs will have small intersecting area and as the beam goes farther, the intersecting area increases which results in un-even location estimation errors at the corners. Figure 3-16 shows the positioning error for a specific case when the step angle of the LEDs is 8° and the system is noise-free (no sunlight or ambient light sources).

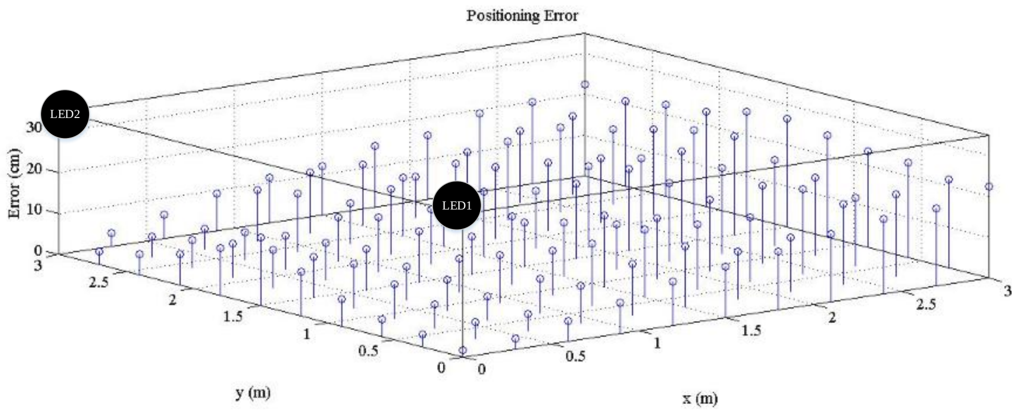


Figure 3-16: Location-wise positioning estimation error

3.3 A Two Dimensional Localization Technique using Received Signal Strength and Bi-literation

In this section, a novel two dimensional visible light positioning system based on received signal strength and bi-literation is presented.

3.3.1 System Modeling

VLC system modeling consists of modeling the transmitter, receiver and the channel like other RF based wireless communication technologies but the light emission pattern from LED is different from RF antenna. The equations governing the VLP environment are given in Eqs. 3.9 to 3.11. The overall scenario is shown in Figure 3-17.

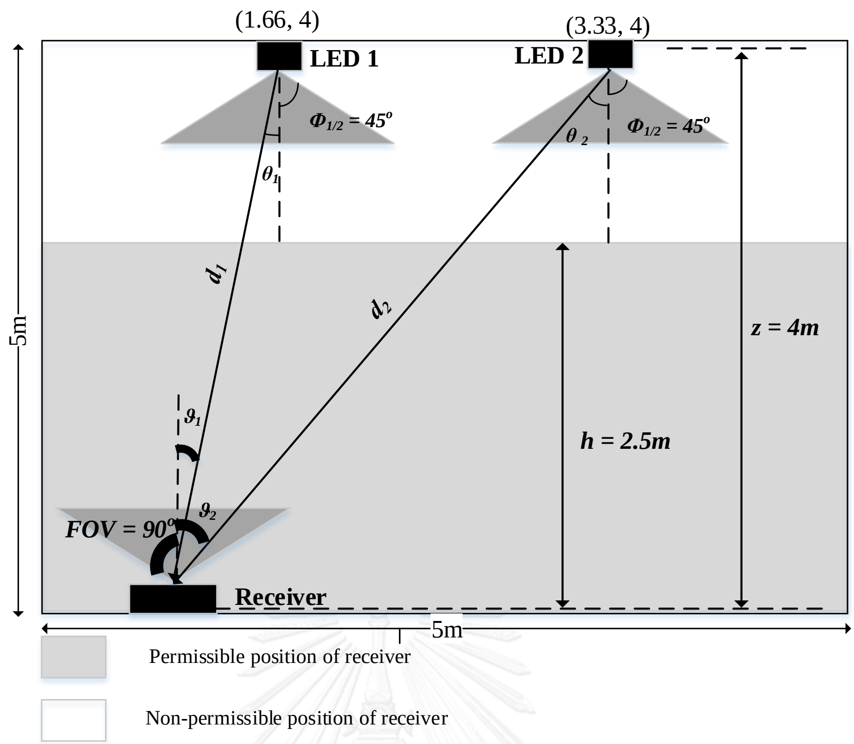


Figure 3-17: Simulation environment for the VLP system

3.3.2 Proposed Localization Algorithm

The proposed localization algorithm can be explained in the following steps:

(A). Declaration

First of all, author created a VLP environment as per the details mentioned in Figure 3-17 which include the dimensions of the room, transmitter, channel and receiver characteristics.

(B). Receiver Placement and Intensity Measurement

In second step, the receiver is placed randomly within the permissible area of the room as shown in Figure 3-17. Light intensity is measured at the receiver for the two cases. In first case, LED1 is ON and LED2 is OFF and in the second case LED2 is ON and LED1 is OFF. From these two measurements, one can determine in which half of the room the receiver is by simple comparison. If the receiver is exactly in the central plane then both measurements will be the same.

(C). Fingerprint Map Creation

The third step is to create a fingerprinting map. In the proposed localization algorithm, attention is given to create a very compact and efficient fingerprinting map. To measure the RSS at all possible locations in the room is not an efficient way. RSS is measured in a straight line perpendicular to LEDs.

(D). Finding K-Nearest Neighbor (k-nn)

Four nearest neighbors from the two databases created in step two are found with the measured RSS at the receiver. For the known RSS at the receiver, one can calculate how close each observation X_i is to x using the Euclidean distance $\|x\| = (x'x)^{1/2}$ and the distance D_i is:

$$\boldsymbol{D_i = \|x - X_i\| = \left((x - X_i)'(x - X_i)\right)^{\frac{1}{2}}} \tag{3.13}$$

(E). Bi-Literation

Utilizing the property of Lambart emission of light from the LED, it is known that if the distance between the LED and the point obtained from k-nn, one can draw a circle. Along with that circle, intensity of light will remain the same. The center point of the circles is the position of LEDs of the ceiling which in this case is known and fixed. The details can be better understood from Figure 3-18 and the relations used in two circle intersection scenario are as follows:

$$\boldsymbol{z = \frac{D^2 - R_1^2 + R_2^2}{2D}} \tag{3.14}$$

$$\boldsymbol{s = \frac{1}{D}\left(\sqrt{4D^2R_1^2 - \left(D^2 - R_2^2 + {R_1^2}^2\right)}\right)} \tag{3.15}$$

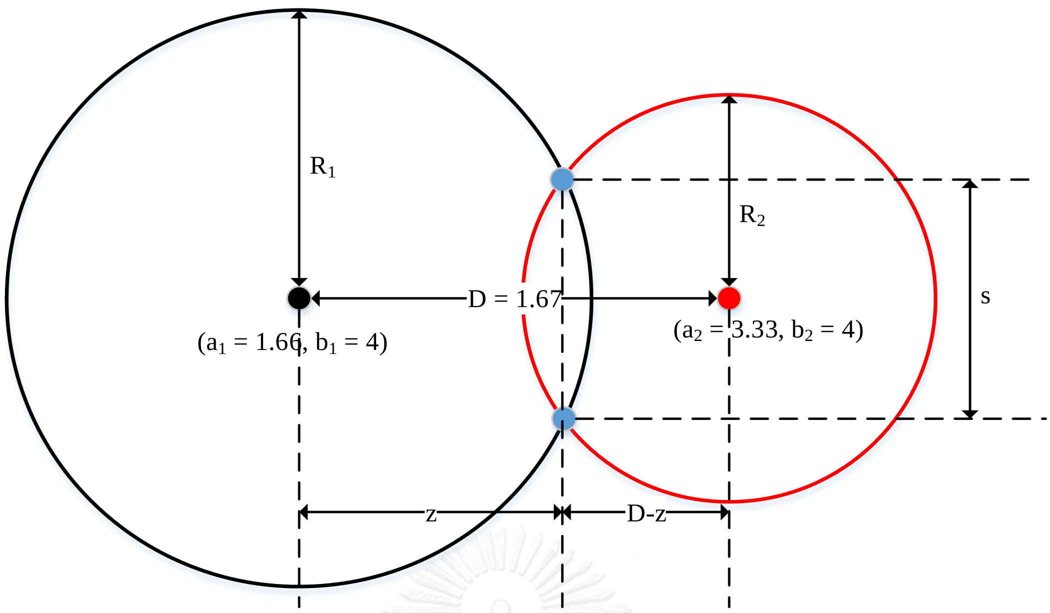


Figure 3-18: Bi-literation for the scenario

3.3.3 Position Estimation

At the end of bi-literation process, two points of intersection will be obtained. One of the two intersection points is the estimated position of the receiver. The point of intersection, which is not in the permissible area for the position of receiver will be canceled out and the remaining point is the estimated position. If both point of intersection lies within the permissible area of the receiver then by training the data (the values obtained by intensity measurements), determination the right point of intersection is possible. Furthermore, data is also trained for handling the extreme sides of the room which intersection of the circles might not be possible. Finally the error between the actual position and estimated position is calculated.

3.3.4 Results and Discussion

In order to have a fair results, simulation is tested for 10,000 times i.e. placed receiver 10,000 times randomly in the permissible area and try to calculate the position. Results show that on an average, accuracy of 1 mm can be achieved using the proposed algorithm. The accuracy of the algorithm is better in the central area and poor at the edges of the room. Figure 3-19 shows is a simulated scenario. The blue shadowed line shows the real dimensions of the room. It can be seen that the second point of intersection goes out of the room. Blue circles represents the position of LEDs in the room. While green and red stars represents the estimated and actual position of the object respectively.

It is very interesting to see the accuracy of the proposed algorithm at each point. Figure 3-21 shows the result of location error which is plotted for 500 random locations of the receiver and then calculating its position (for the sake of visualization). From the Figure 3-21, it can be seen that the location of error is more dominant at the corners of the room while in other points it's very nominal.

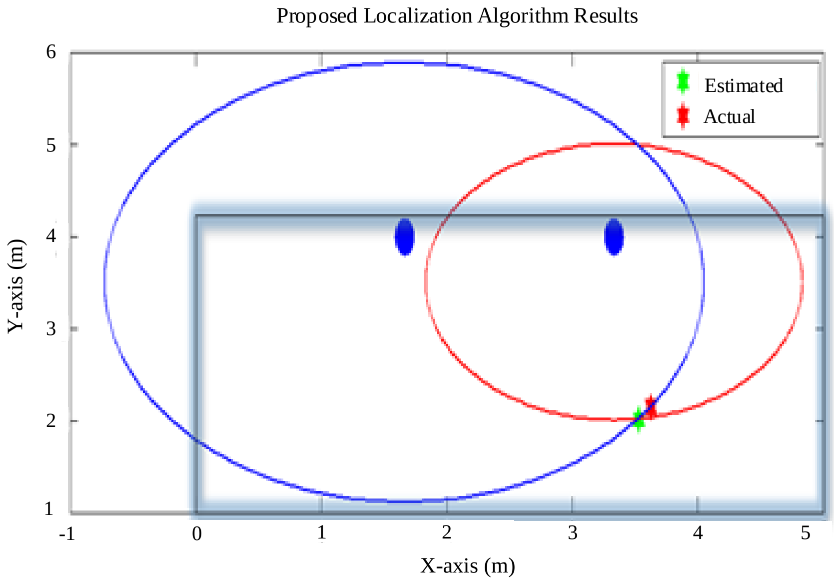


Figure 3-19: Proposed algorithm localization result

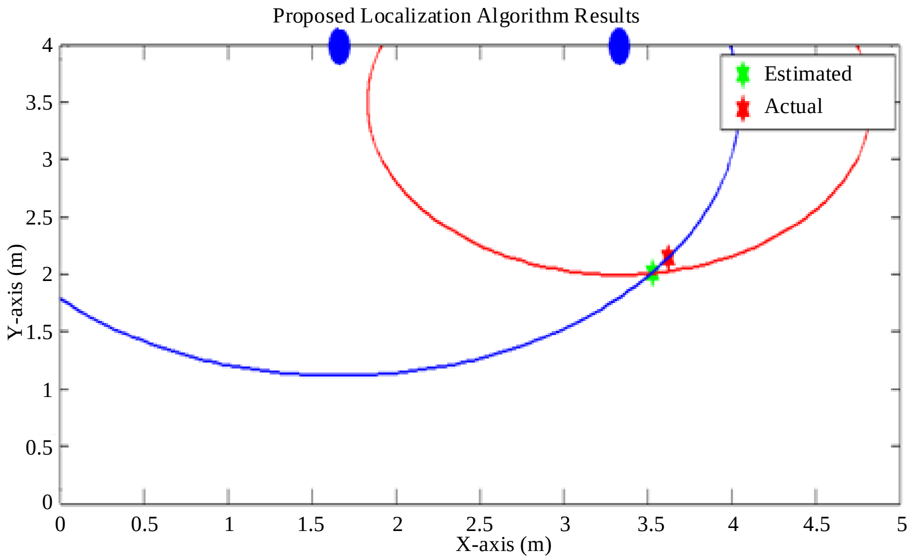


Figure 3-20: Considering the room area only for plotting

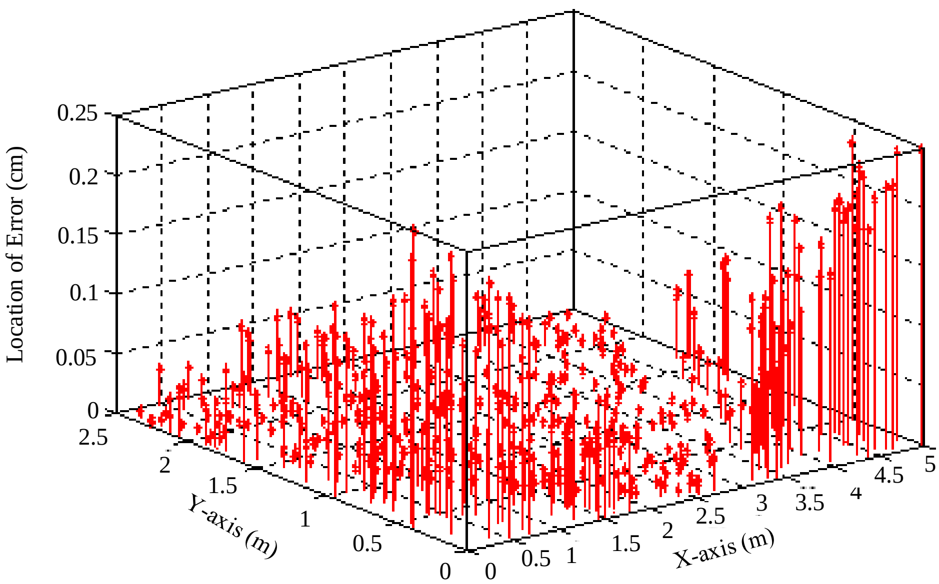


Figure 3-21: Location of the error in x-y plane

3.4 A Heuristic Approach to Indoor Localization Using Light Emitting Diodes

In this work, author present a heuristic approach for indoor localization using LEDs and validate the proposed system using simulations. Furthermore, a new type of clustering named as portion clustering is introduced, which is applied to the received signal in order to have accurate location estimations.

3.4.1 System Modeling and Transmitter Design

The equations governing the visible light communication system are described in Eqs. 4.9-4.11. The overall scenario is shown in Figure 3-22.

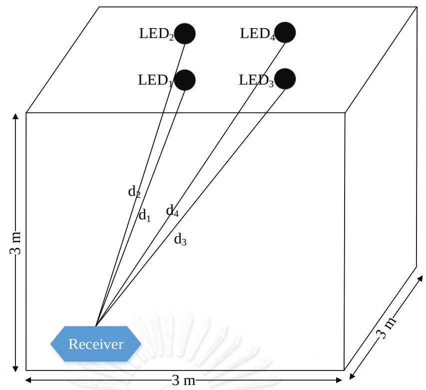


Figure 3-22: Elementary units of visible light positioning system

In order to distinguish between the signals from each LED, time division multiplexing (TDM) is used and frame structure for one period is shown in Figure 3-23. At the end of each frame, the receiver will have the information about the received signal strength (RSS) from each LED. Based on the information received from the LEDs, the location of the object of interest is estimated by using a heuristic approach and proposed portion clustering technique which will be discussed in later section.

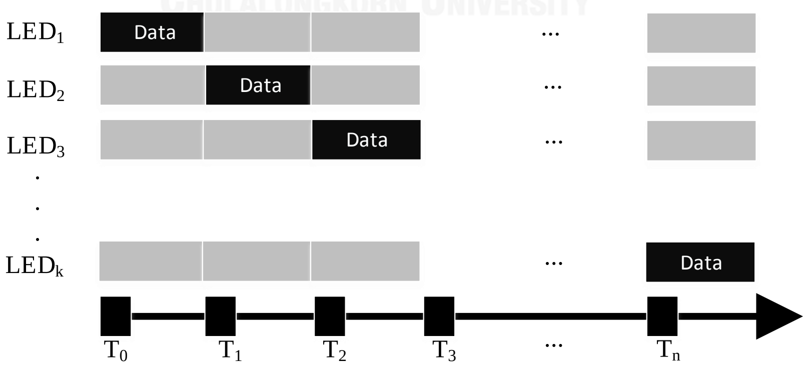


Figure 3-23: Frame Structure for k transmitters

In order to test the proposed algorithm, author placed the transmitters in various layouts i.e. triangular, symmetric square with uniform power from LEDs and symmetric square with non-uniform power from LEDs. The placement of LEDs are shown in Figure 3-24 where black stars represent the positions of the LED.

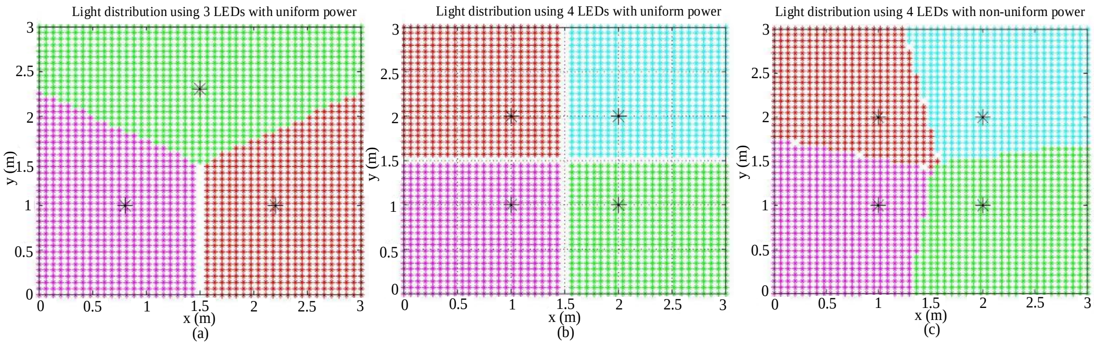


Figure 3-24: LED placement with their footprints based on the maximum intensity (a) 3 LEDs in triangular geometry (b) 4 LEDs in a square geometric with uniform power (c) 4 LEDs in a square geometry with non-uniform power from each LED

3.4.2 The Proposed Algorithm

Our proposed localization algorithm consists of two levels of clustering. The first level of clustering is through heuristic approach and the second level of clustering is through newly proposed clustering scheme. The key idea for the proposed algorithm is that the classification of the room can be done with respect to the maximum intensity of each LED for every location.

(A). Level 1 Clustering

We place the transmitters in various positions as shown in Figure 3. Depending upon the number of LEDs used, there will be $k!$ patterns in which the receiver can receive light from the LEDs and the ‘greater than’ condition is true. For instance, if there are four LEDs, then there will be certain areas where the intensities from the LEDs satisfy the following condition: $LED_{1_{Int}} > LED_{2_{Int}} > LED_{3_{Int}} > LED_{4_{Int}}$. In addition to these $k!$ patterns, there will be $(k-1)!$ additional number of areas in which two LEDs will have the same distance (i.e. same intensity) and the remaining LEDs have different distances. Furthermore, there will be k number of areas where three LEDs have same distance from the receiver and other LED(s) will have different distances. Finally, there will be a single point on the surface where all the transmitters have an equal distance to the receiver. So, if we have four LEDs, then in total there will be the following possible pattern as given by Eq. (3.16).

$$Total_{patt\_4LED} = k! + (k-1)! + k + 1 \tag{3.16}$$

However, when we consider symmetric placement of four LEDs then out of 24 conditions, there will be only 8 conditions which will be true thus reducing the number of portions for the next clustering and ultimately reducing the localization accuracy. There are two possible ways to overcome this issue. One is the asymmetric placement of LEDs i.e. LEDs are not placed at an equidistant from each other but in a random and planned fashion. Another way is to have non-uniform power emission with respect to each LED while keeping the symmetric placement. The first approach is not suitable as per its appearance is concerned, therefore, we consider non-uniform power emission to break the symmetric pattern. We can clearly see from Figure 3-24(c) that non-uniform power emission helps in avoiding the conditions where the receiver is receiving the same light from multiple LEDs. Thus by carefully selecting the power emitted from each LED can help creating $k!$ unique patterns of light.

(B). Level 2 Clustering

From level 1 clustering, it can be observed that the symmetric LEDs with non-uniform power give the maximum number of valid combinations in which the ‘greater than’ condition (i.e. signal strength of one transmitter is stronger than the others at a given location) is true. Then, for each valid combination, a portion clustering is applied. For a given received signal from k transmitters, the received signal will contain components of signal from each source. Based on the portion of each source contributing to the signal, clustering is done. From the readings of level 1 clustering, range is determined which is divided into p portions. For this study, p is taken to be 5.To have a better understanding of level 2 clustering i.e. the portion clustering, let’s consider Figure 3-25.

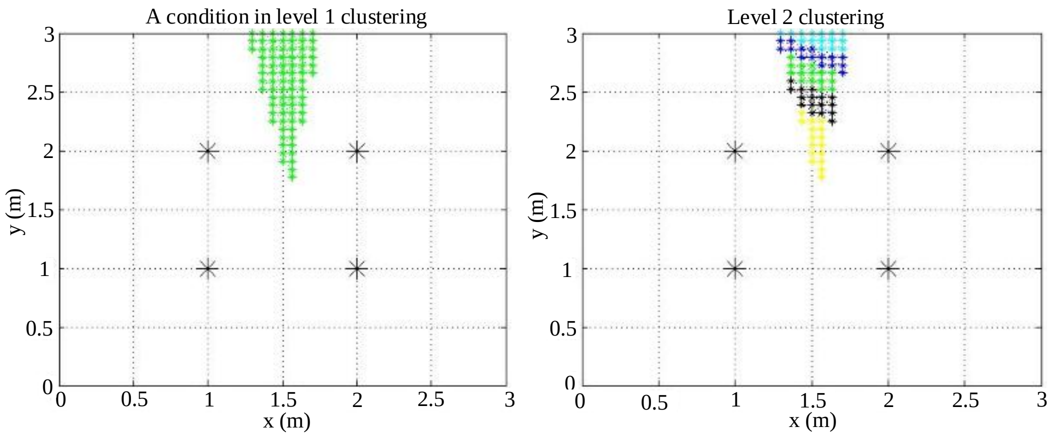


Figure 3-25: Clustering levels (a). Level 1 clustering (b). Level 2 clustering

Figure 4-25(a) is one of the 24 cases of level 1 clustering and for this specific case $LED_{4_{Int}} > LED_{1_{Int}} > LED_{3_{Int}} > LED_{2_{Int}}$ is true. The area in green color is the area where the intensity of LED4 is the brightest one and the intensity of LED2 is the weakest. Intensity of LED1 is less than LED4 and intensity of LED3 is less than LED1. Figure 3-25(b) shows how level 1 is portioned into 5 sub-portions based on the level of intensity of the LEDs. Following are the three steps by which portion clustering is achieved.

1. Data from the cluster level 1 is processed for level 2 clustering. Average weighted sum (AWS) of $k-1$ least bright LEDs for a specific region is calculated.
2. Average weighted sum is compared with the brightest LED at the specific level 1 cluster. Based on the range (the difference between the brightest intensity level and the AWS), data is further partitioned into p smaller portions.
3. For a given query LEDs reading; the trained clusters are used for position estimation assuming the object to be at the center of level 2 cluster.

3.4.3 Simulation Parameters for Performance Evaluation

To validate the proposed algorithm, we tested it using simulation for various conditions as aforementioned. Room dimensions are taken to be 3 × 3 ×3 m^3. Shadowing effect is not considering while simulating the environment and it is also assumed that there is no reflecting object present in the area of interest. For the first case (i.e. 3 LEDs arranged in triangular geometry) the LEDs were placed on the ceiling at fixed locations (0.8 m, 1 m, 3 m), (2.2 m, 1 m, 3 m), (1.5 m, 2.3m, 3 m). The reason for this selection is the uniform light intensity at the corners of the room. All the LEDs emit 12 W power. For the second and third case the LEDs are placed at (1 m, 1 m, 3 m), (1 m, 2m, 3 m), (2 m, 1m, 3 m), (2 m, 2 m, 3 m). For the second case, the power for all four LEDs is kept at 12 W, however, we choose LEDs with different power for the third case i.e. 11W, 11.5W, 12W and 12.5W. The LEDs are modulated by different addresses of [1 0 0], [0 1 0], [0 0 1] for case 1 and [1 0 0 0], [0 1 0 0], [0 0 1 0], [0 0 0 1] for case two and three, so that TDM can be applied. Each LED transmit data only in the time slot assigned to it which helps the receiver to differentiate the signals from each LEDs.

3.4.4 Discussion and Results

(A). Location Estimation Errors for Three Scenarios

Consider the case when the transmitters are placed in a triangular geometry. With only 6 combinations at level 1 clustering, the level 2 clustering gives 30 portions in total for the given area of interest which results in significant errors. The average error for the location estimation is 38.73 cm. The results are shown in Figure 3-26.

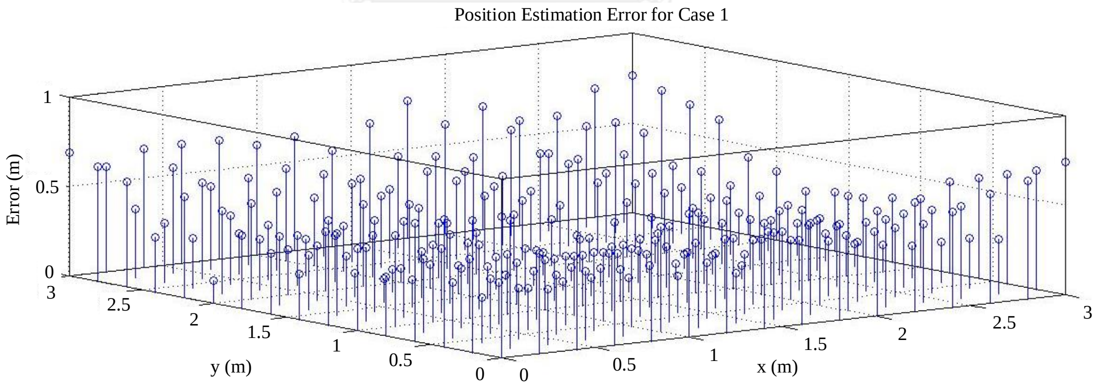


Figure 3-26: Plotting error when 3 LEDs having same light intensity

For the second case, the first level of clustering gives 24 combinations but due to the symmetric placement in conjunction with uniform power emission from all the LEDs, only 8 combinations are unique on which level 2 clustering can be applied resulting in 40 unique portions corresponding to an area. The average position estimation error is 33.54 cm. The results are shown in Figure 3-27.

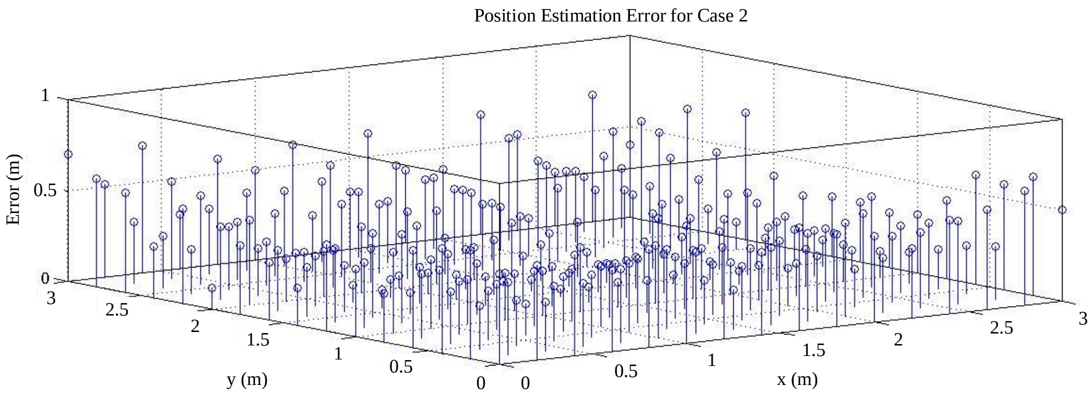


Figure 3-27: Plotting error when 4 LEDs having same light intensity

For the last case, four transmitters are used and placed in a symmetrical manner, transmitting different intensities. As the power emitted from each LED is of different intensity, level 1 clustering will yield 24 combinations. When level 2 clustering is applied on these 24 combinations, it will give 120 unique portions corresponding to an area. The average error for location estimation is 19.36 cm. The results are shown in Figure 3-28.

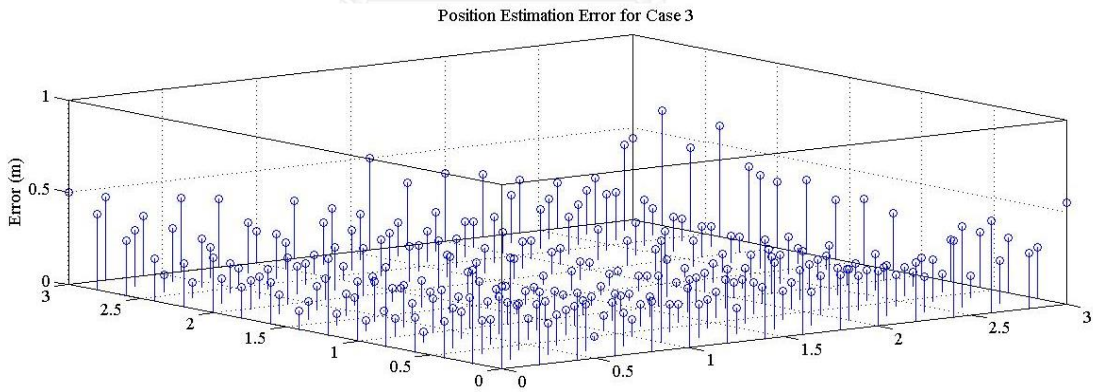


Figure 3-28: Plotting error when 4 LEDs having non-uniform light intensity

While plotting the error, the error limit value (i.e. the *z* axis) for Figures 3-26-3-28 is kept in between 0 to 0.4 which gives a fair comparison for the accuracy for all three scenarios. It can be seen that the error is the least for case 3 and worst for case 1. Furthermore, the accuracy of the algorithm is better in the center of the room and poor at corners because the directionality of Lambert emission transmission. When the receiver is near the corner, the received intensity from the diagonal source can be considerably degraded and is susceptible to noise interferences.

(B). Effect on Location Estimation by Varying Level 2 Portions

From the results, it is evident that when 4 LEDs are used with non-uniform light intensity, the location estimation error is the least, therefore, we further analyze the results for this case by varying the number of portions p in level 2 clustering. Initially p was taken to be 5 and for this section, the author vary p from 2 to 7 and observe the effect on location estimation. Figure 3-29 is plotted against varying p and average location estimation error.

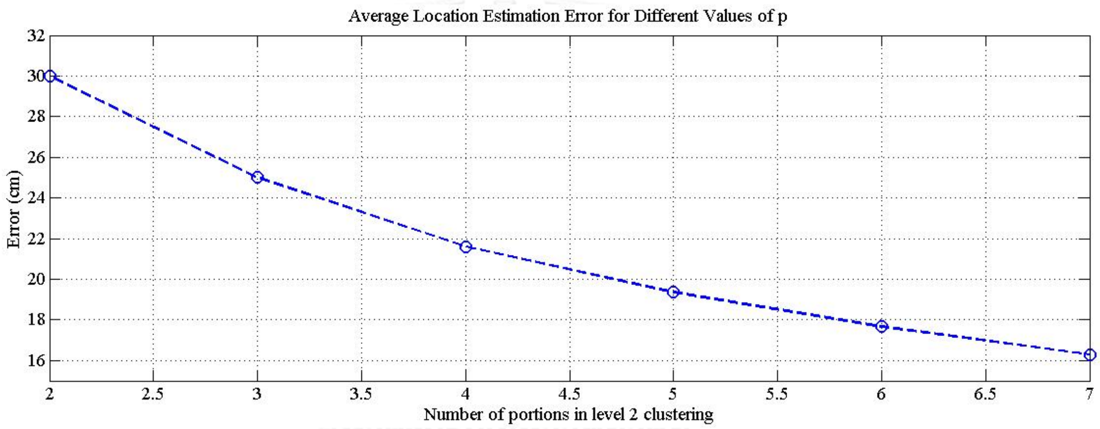


Figure 3-29: Average location estimation error for different values of p

From Figure 3-29, it can be seen that when the value of p increases, the accuracy of location estimation is improved.

(C). Effect of Noise on Location Estimation

Performance is evaluated for the positioning algorithm under different noise level. When the area of the optical receiver is large then thermal noise can be ignored and noise is primarily associated with shot noise which can be modelled as Gaussian with power spectrum density (PSD) of $N_o = 2qI_{bg}$ where q is the charge on the electron and I_{bg} is the background light induced current. As the localization bandwidth requirements are very modest so it is fair to assume a low speed data transmission communication system. Typically the shot noise varies between -140 dbm W (direct sunlight) to -180 dbm W (artificial light only).

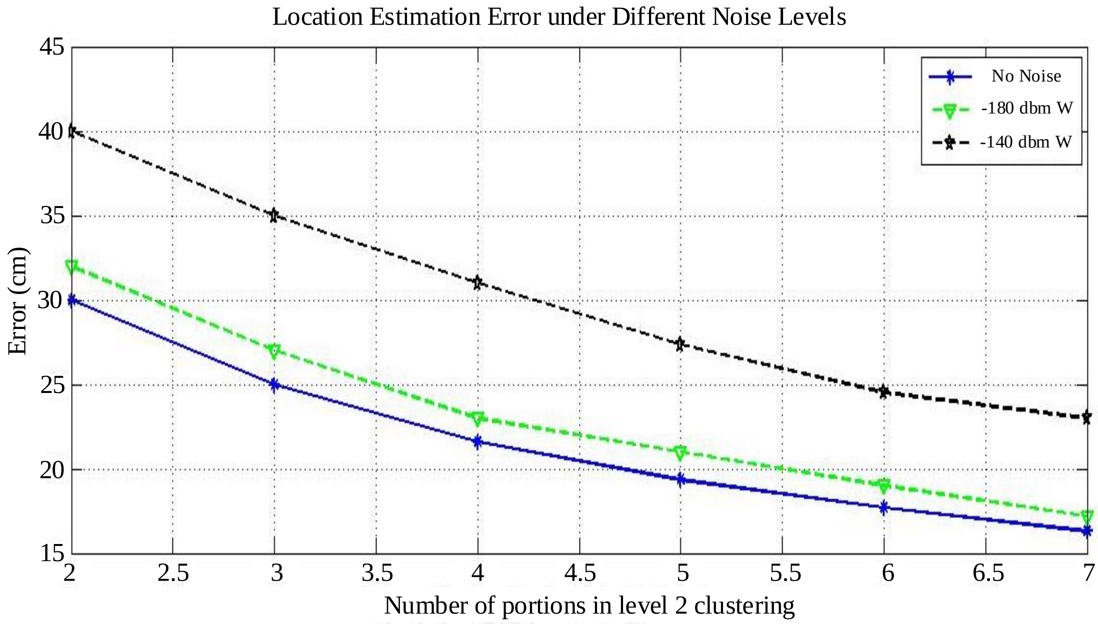


Figure 3-30: Effect of noise on location estimation

When there is only artificial light sources in the field of view of the receiver, there is a minor effect on overall performance of the algorithm. Such light is not strong enough to disturb the symmetry of light distribution i.e. increase or decrease the light intensity of one source from one to another. However, in the presence of direct sunlight, the performance is significantly degraded.

Chapter 4

4 System Design for Secure and Reliable Communication

In this chapter, the author discuss about the developed system for secure and reliable communication using optical wireless communication. Designing such system requires two major sub-systems i.e. devising a mechanism for secure communication and implementation of channel coding for bringing reliability into the system. Although wireless networking intensify the tractability in the home and office environment to connect the internet without wires but at the cost of risks associated with stealing the data or threat of loading malicious code with the intention of harming the network. To overcome the issue of security, the researcher has used an approach for spatial diversity based transmission using two optical transmitters. One of the widely adopted way for bringing reliability in the link is the use of channel codes. Low density parity check (LDPC) codes are considered to be the most favorable channel coding scheme for future generation networks such as wireless LAN, Digital Television Broadcasting (DVB), hard-disk data storage etc. For this work, a newly proposed method for the construction of structured parity check matrix for binary LDPC code have been introduced and its performance is compared with the well-established LDPC codes. Lastly, indoor localization is a very active area of research these days because of its numerous applications in everyday life.

4.1 Establishing a Secure Communication Link

Security concerns in VLC are not that serious as in the case of RF as light cannot pass through the concrete objects. This brings an in-built security in VLC. However, it is a possibility that the intruder is inside the same locality where secure transmission is required. In this research, the communication system is designed in such a way that can cater above mentioned security concern. By using spatial diversity based transmission, physical layer security has been achieved. The overall picture of the designed system is shown in Figure 4-1.

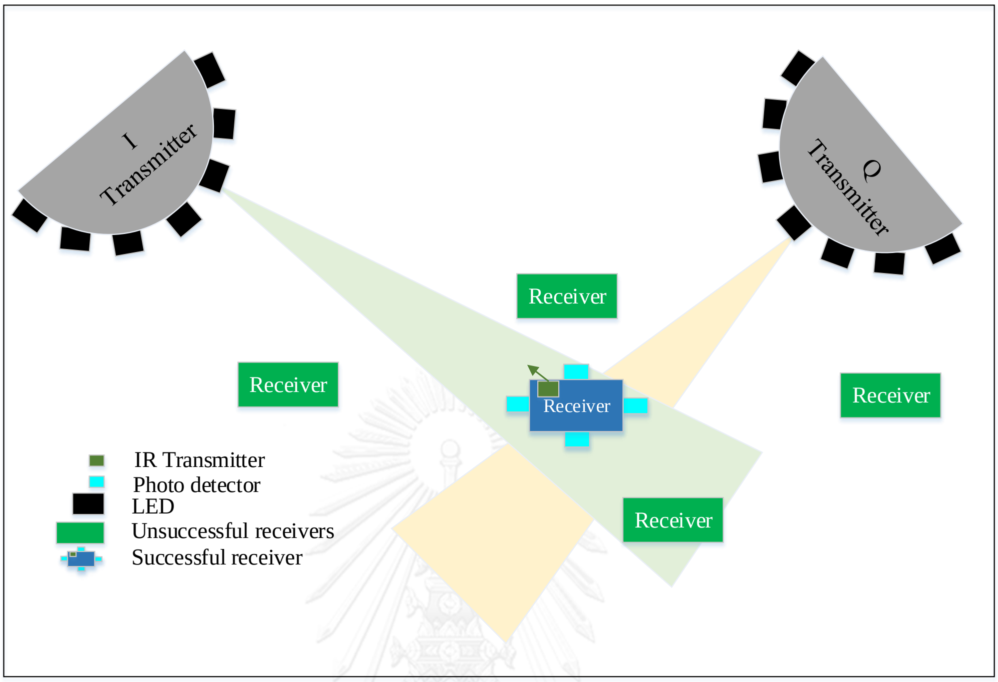


Figure 4-1: Position based reception to ensure secure data communication. Only the blue colored receiver can receive successfully

Two transmitters (***I*** & ***Q***) are used to transmit the information instead of one transmitter. The information is split between the two transmitters evenly. If the receiver is in the coverage area of ***I*** and ***Q*** transmitter, only in that case, receiver will be able to reconstruct the original information. If the receiver is within the coverage area of one of the two LEDs or none of the LED, then it will not be able to reconstruct the signal. Thus, it is possible to establish a secure communication link with the desired receiver. For acknowledgement (from receiver to the transmitter), IR is used.

The block diagram of the transmitter (only downlink design) is shown in Figure 4-2. Uplink design is quite straight forward consisting of an IR transmitter and a receiver which needs not to be explained here.

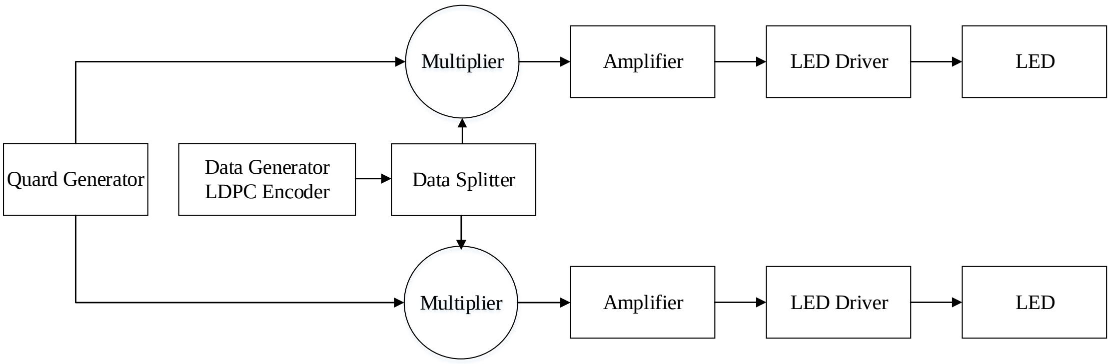
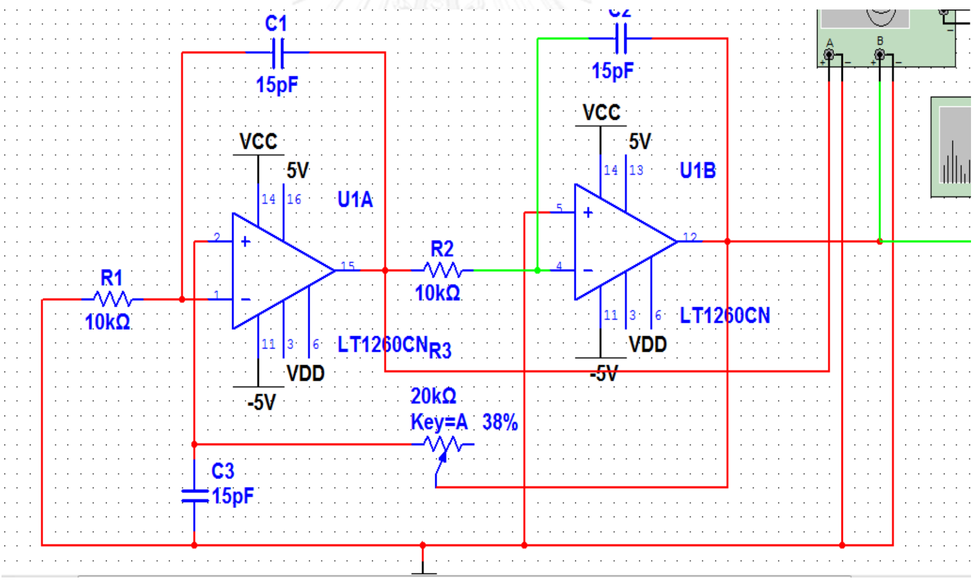
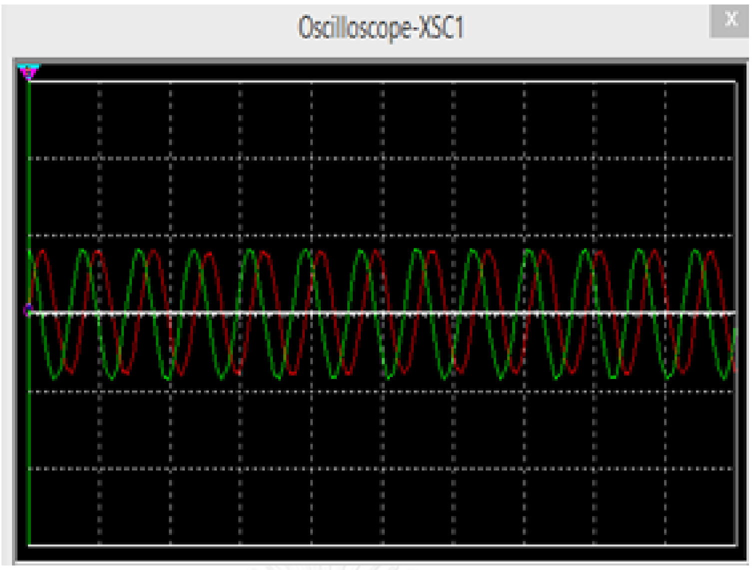


Figure 4-2: Block diagram of the transmitter (downlink design only)

A quadrature generator is used to generate cosine wave (***I*** signal) and sine wave (***Q*** signal) at a specified frequency. LT1260 is used for this purpose. The schematic diagram for the quadrature generator is shown in Figure 4-3. By tuning the values of the resistors and the capacitors, the desired frequency can be achieved.



(a)



(b)

Figure 4-3: (a). Design of the quadrature generator (b). Simulation results

The output of the quadrature generator will become the input of the multipliers. Multiplier is used with null scaling factor configuration. Random data is generated using a high speed Arduino board. Let's assume that we have a binary data stream which can be expressed by the Eq. (4.1).

$$\boldsymbol{d_k(t) = d_0, d_1, d_2, d_3, \dots, dn} \tag{4.1}$$

where $\boldsymbol{d_k(t)}$ is either +1 or 0. In order to overcome the effect of the channel, channel coding using an LDPC is implemented and the details will be discussed in the next section. Applying an LDPC coding on $\boldsymbol{d_k(t)}$, we get:

$$\boldsymbol{b_k(t) = d_k(t) + d_{LDPC}(t)} \tag{4.2}$$

where $\boldsymbol{d_{LDPC}(t)}$ are the additional bits which are added in the binary data stream due to the channel coding scheme. Furthermore within the Arduino board, the even and the odd indexes of $\boldsymbol{b_k(t)}$ are separated which are made accessible through the digital pins. Separated data stream in even and odd indexes can be expressed by the Eq. 4.3 and Eq.4.4.

$$b_I(t) = b_0, b_2, b_4, \ldots (even\ bits) \tag{4.3}$$

$$b_Q(t) = b_1, b_3, b_5, \ldots (odd\ bits) \tag{4.4}$$

where data rate of $b_I(t) = b_Q(t) = \frac{b_k(t)}{2}$. I signal is the product of even indexes of channel coded bits with the cosine wave and the Q signal is the product of odd indexes of channel coded bits with the sine wave. Output of the multiplier is actually the combination of sinusoidal wave and the data which can be represented by the Eq. 4.5 and Eq. 4.6.

$$s_I(t) = \frac{1}{\sqrt{2}} b_I(t) \times \cos(2\pi f_0 t) \tag{4.5}$$

$$s_Q(t) = \frac{1}{\sqrt{2}} b_Q(t) \times \sin(2\pi f_0 t) \tag{4.6}$$

The next stage is the amplification and LED driver stage and signals can be expressed as:

$$s_I(t) = A \times \frac{1}{\sqrt{2}} b_I(t) \times \cos(2\pi f_0 t) = \mathrm{B} \times b_I(t) \times \cos(2\pi f_0 t) \tag{4.7}$$

$$s_Q(t) = A \times \frac{1}{\sqrt{2}} b_Q(t) \times \sin(2\pi f_0 t) = B \times b_Q(t) \times \sin(2\pi f_0 t) \tag{4.8}$$

where A is the amplification factor. In order to control the current flowing through the LED, a transistor is used in the LED driver stage. Off-the-shelf high bright LEDs (HBLEDs) were used and the built-in control circuit of the HBLED lamp was removed to enhance its switching speed.

$$s_{CHANNEL\_I}(t) = B \times b_I(t) \times \cos(2\pi f_0 t) + n_1(t) \tag{4.9}$$

$$s_{CHANNEL\_Q}(t) = B \times b_Q(t) \times \sin(2\pi f_0 t) + n_2(t) \tag{4.10}$$

$$R(t) = B \times \left[b_I(t) * \cos(2\pi f_0 t) + b_Q(t) \times \sin(2\pi f_0 t)\right] + n_T(t) \qquad (4.11)$$

where $n_T(t) = n_1(t) + n_2(t)$ is the accumulative noise.

Information from both the LEDs will be received by the receiver which consists of a photodiode, amplifiers, Arduino board, and a computer (for post-processing) as shown in the Figure 4-4. Light falling on the photo diode will generate a current in proportion to the intensity of light. Due to the channel behavior, the signal will be attenuated and weak, thus the trans-impedance amplifier (TIA) with a standard well known design is used [61]. The output of TIA will be fed to the differential amplifier for adaptive minimum voltage cancellation. The purpose of minimum voltage canceler is to remove the DC component and the ambient light sources signal from the received signal. Then, the signal goes to the Arduino board which records the received information. The last stage is the data processing stage in which MATLAB is used as a tool. The received signal is actually a modulated signal which needs to be demodulated and decoded. For that purpose, the received signal will be first multiplied by the sine wave and then by the cosine wave of the same frequency as used at the transmitter side. As sine and cosine are orthogonal in nature, $\boldsymbol{I}$ and $\boldsymbol{Q}$ signals can be easily separated. Demodulation can be mathematically represented by the Eq. 4.12 and Eq.4.13.

$$R_I(t) = R(t) \times \cos(2\pi f_0 t) \qquad (4.12)$$

$$R_Q(t) = R(t) \times \sin(2\pi f_0 t) \qquad (4.13)$$

After filtering, these separated signals are now combined together with proper indexing to get the binary data. LDPC decoding is also performed at this stage. The received signal is then compared with the transmitted signal in order to calculate the block error rate (BLER).

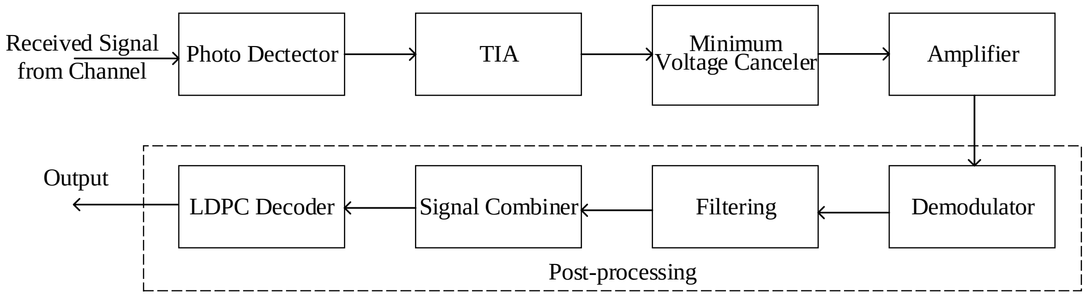
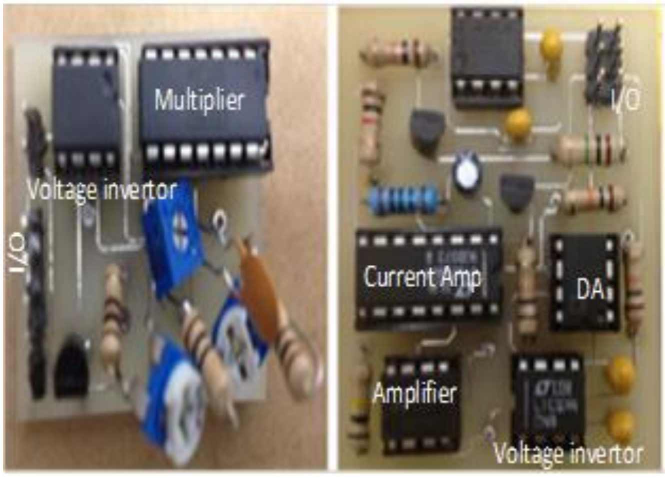


Figure 4-4: The downlink receiver circuit

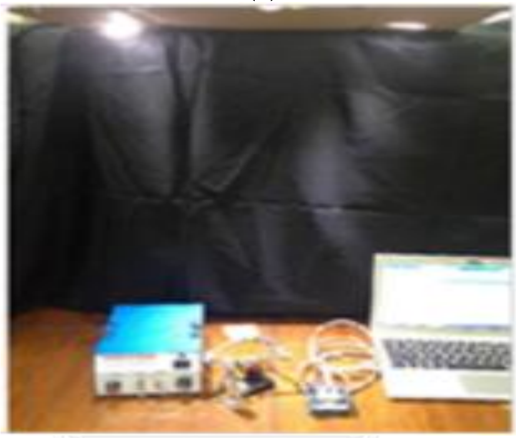
The block diagram of the receiver is shown in Figure 4-4. If the receiver is receiving information from both LEDs, the receiver will be able to recover the information correctly. Table 4-1 gives a quick summary of the components characteristics used in this experiment and the actual figure for implementation of hardware is shown in Figure 4-5.

Table 4-1: Summary of the components used

Components	**Characteristics**
Quadrature Generator	90MHz Bandwidth, 0.1 dB gain flatness
Processor Board	32 bit processor, Cortex-M3 MCU, 84 MHz CPU
Multiplier	10 MHz bandwidth,
LED	3×1 Watt, White color
Transmitter Amplifier	55 MHz gain bandwidth product, open loop gain of 140 dB
Photo diode	Angle of half sensitivity = $\pm 65^{\circ}$, switching time = 20ns, a radiant surface area = $7.5mm^2$
Receiver Amplifier	120 MHz bandwidth
Tx and Rx Distance	0.8 m



(a)



(b)

Figure 4-5: (a). The transmitter module (left side), the receiver's module (right side) (b). A complete system diagram

4.2 Design of Parity Check Matrix

This work is based on the optimization of Chutima's [19] work by introducing quasi cyclic matrix into the Chutima structured ***H*** matrix. By doing so, further reduction in the number of '1's' in ***H*** matrix can be obtained leading to a new-sparse ***H*** matrix. In order to evaluate the performance of proposed ***H*** matrix, we compared it with PEG, Fan, MAC, IMAC and Chutima ***H*** matrix. 6×12 binary ***H*** matrix was taken for each algorithm in order to provide a fair comparison. Sum product algorithm was used for LDPC decoding. Generalized form of Fan, MAC, Chutima, IMAC and proposed 6×12 ***H*** matrix is shown in Table 4.2. The generalized form of proposed algorithm is given as follows:

Table 4-2: Generalized form of structured H matrix algorithms

Algorithm	**Mathematical Form**	**Comments**
Fan	$\begin{bmatrix} \boldsymbol{I} & \boldsymbol{I} & \boldsymbol{I} & \boldsymbol{I} \\ \boldsymbol{I} & \boldsymbol{\alpha} & \boldsymbol{\alpha^2} & \boldsymbol{\alpha^3} \end{bmatrix}$	Low noise floor and no existence of cycle of 4
MAC	$\begin{bmatrix} \boldsymbol{I} & \boldsymbol{I} & \boldsymbol{I} & \boldsymbol{I} \\ \boldsymbol{0} & \boldsymbol{I} & \boldsymbol{\alpha} & \boldsymbol{\alpha^2} \end{bmatrix}$	Cyclic shift to Fan's array
Chutima	$\begin{bmatrix} \boldsymbol{I} & \boldsymbol{\alpha} & \boldsymbol{\alpha^2} & \boldsymbol{\alpha^3} \\ \boldsymbol{0} & \boldsymbol{I} & \boldsymbol{I} & \boldsymbol{0} \end{bmatrix}$	Matrix transpose, row and column swap to MAC for reducing number of 1's
IMAC	$\begin{bmatrix} \boldsymbol{I} & \boldsymbol{I} & \boldsymbol{I\omega} & \boldsymbol{I\omega^2} \\ \boldsymbol{0} & \boldsymbol{I} & \boldsymbol{\alpha\omega} & \boldsymbol{\alpha^2\omega^2} \end{bmatrix}$	Quasi cyclic matrix to Fan
Proposed algorithm	$\begin{bmatrix} \boldsymbol{I} & \boldsymbol{\alpha\omega} & \boldsymbol{\alpha^2\omega^2} & \boldsymbol{\alpha^3\omega^3} \\ \boldsymbol{0} & \boldsymbol{I} & \boldsymbol{I} & \boldsymbol{0} \end{bmatrix}$	Introduced Quasi cyclic term in Chutima algorithm

where

$$\boldsymbol{\alpha\omega} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \boldsymbol{\alpha^2\omega^2} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \boldsymbol{\alpha^3\omega^3} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

$$H_{PROPOSED} = \begin{bmatrix} I & \alpha\omega & \alpha^2\omega^2 & \alpha^3\omega^3 & \cdots & \alpha^{k-1}\omega^{j-1} & \alpha^k\omega^j \\ 0 & I & \alpha^2\omega & \alpha^3\omega^2 & \cdots & \alpha^{(k-1)}\omega^j & 0 \\ 0 & 0 & I & \alpha^3\omega^2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & I & \cdots & \cdots & \vdots \\ 0 & 0 & \cdots & 0 & I & \cdots & 0 \end{bmatrix} \tag{4.14}$$

4.3 Results and Discussion

As described in the previous section that the LDPC coded binary data will be separated into $\boldsymbol{I}$ and $\boldsymbol{Q}$ channels which will be multiplied by their respective sinusoids. Figure 4-6 shows the result for this case. This signal is the output of the LED driver which will be fed to the LED for transmission over the channel.

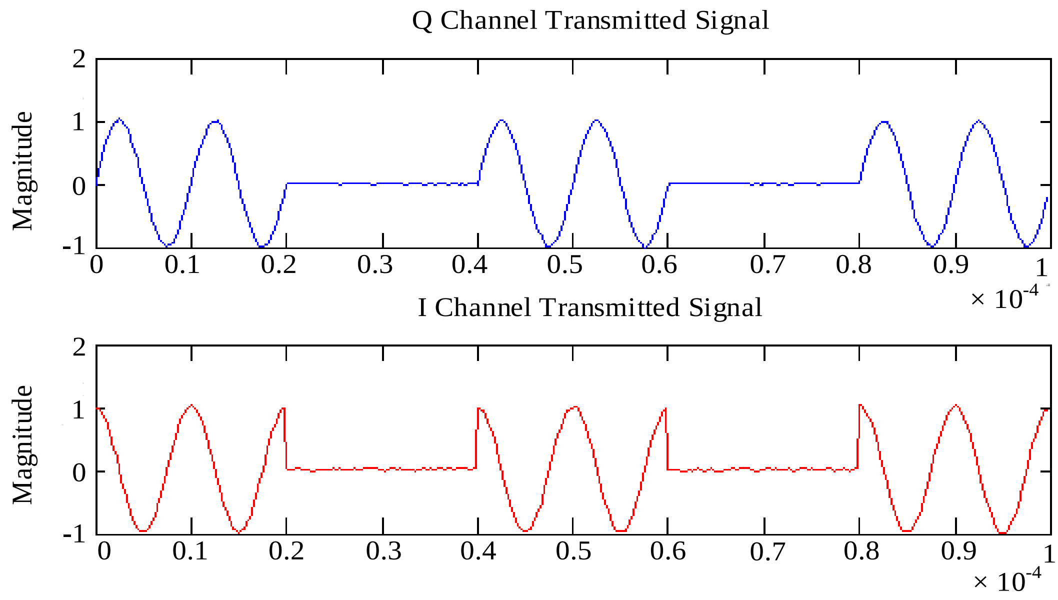


Figure 4-6: Signals fed to the LEDs

First, we demonstrate if we transmit single channel and then, how we can recover the signal. For example, a square wave is modulated by a sine wave. Figure 4-7 shows the received signal by the photo diode which will be post-processed to recover the original data.

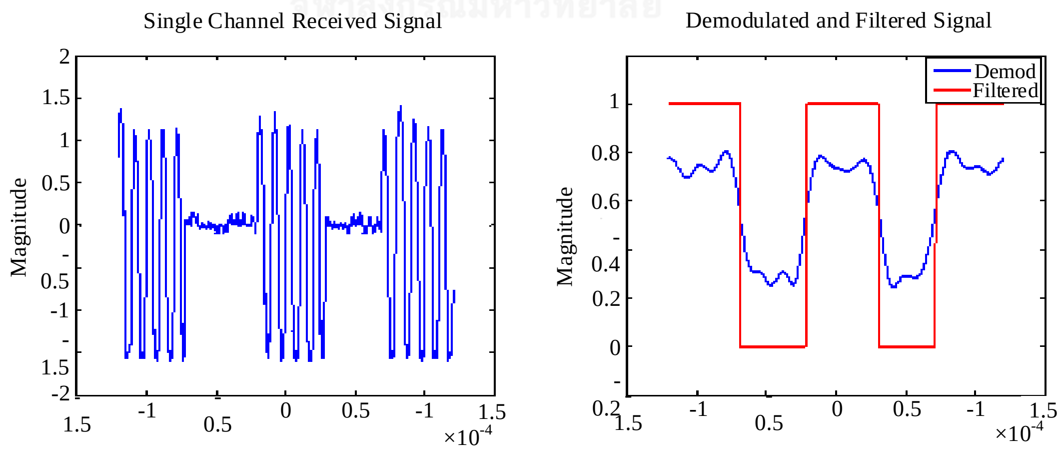


Figure 4-7: Single channel received signal

I and ***Q*** channel signals will be received by the photodiode and after amplification will be recorded by the Arduino board and finally fed to the computer for further processing which includes demodulation, filtering, decoding and re-arrangement of bits. Figure 4-8 shows the received signal at the photodiode after amplification and adaptive minimum voltage cancellation.

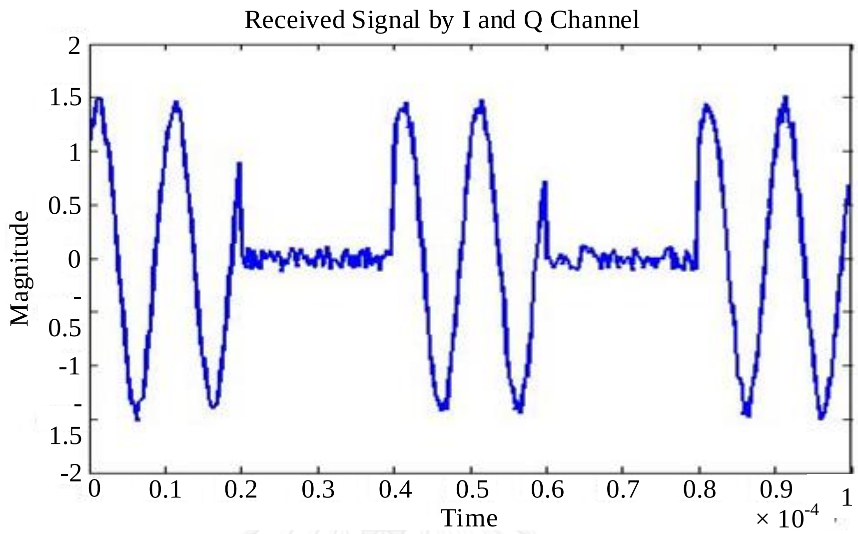


Figure 4-8: I and Q signal received by the photodiode

Output of the photodiode consists of both the sine wave and the cosine wave. However due to their orthogonal nature, we can separate them out using demodulation.

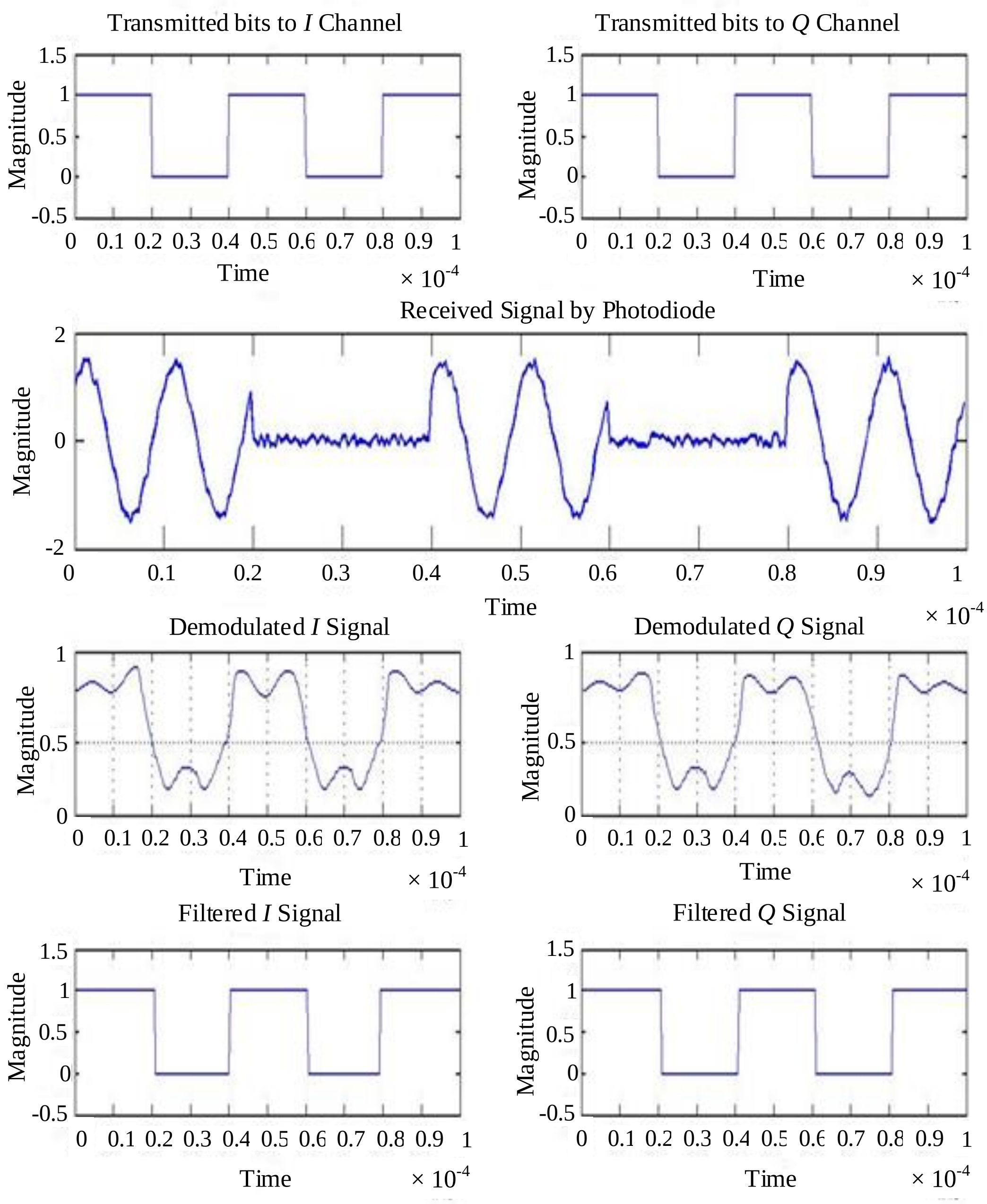


Figure 4-9: Received and recovered signals

Investigating the performance of the proposed ***H*** matrix, results show that appropriate quasi cyclic shift to ***H*** matrix have better performance than structured and random generated methods of ***H*** matrix construction. Performance of proposed ***H*** matrix is superior to PEG, Fan and MAC ***H*** matrix and have comparable performance to IMAC. Comparing the performance with Chutima’s work, the performance of the proposed $\boldsymbol{H}$ matrix is superior especially at higher SNR but for low SNR, performance is quite similar. Figure 4-10 shows the simulation results for block error rate (BLER) against $\boldsymbol{Eb/No}$ under AWGN channel.

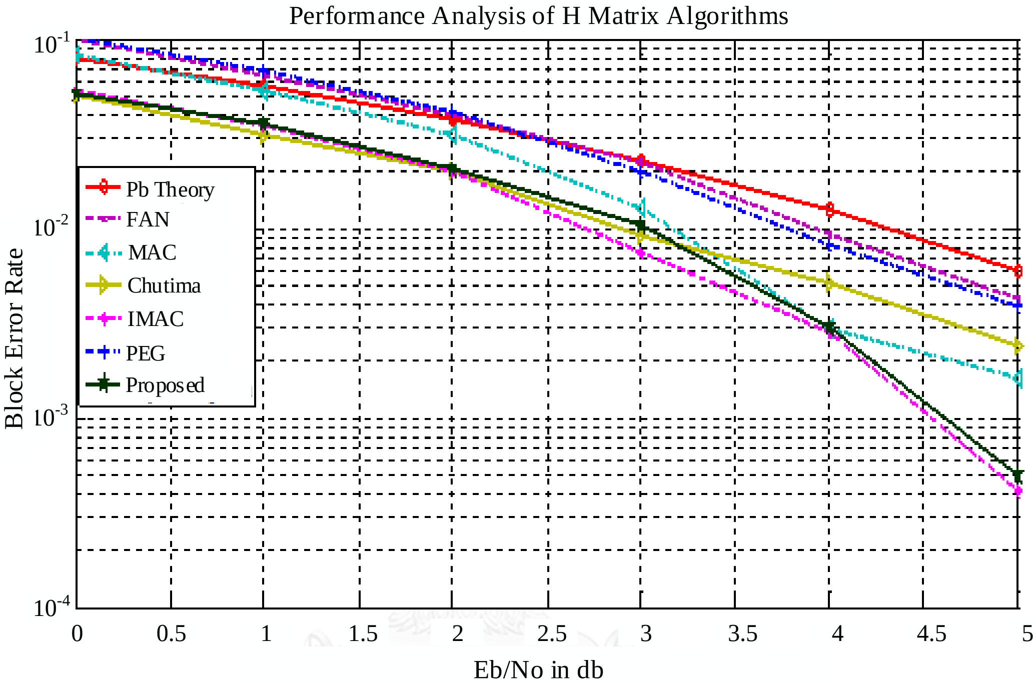


Figure 4-10: Performance analysis of H matrix generation algorithms

Chapter 5

5 Conclusions and Future Works

5.1 Conclusion

Indoor localization is an active area of research because of its diverse applications in various ways of life. In this dissertation, the author has proposed four new techniques for indoor localization using visible light communication. In the first approach, an LED based indoor localization system using k-means clustering is described in which transmitters consist of two light-emitting diodes (LEDs) which are modulated with 1 kHz and 2.5 kHz sinusoidal signals respectively. At the receiver, the received signal strength (RSS) is calculated and a sparse grid is constructed by recording light intensity readings at different locations uniformly. An interpolation is then applied to create a dense grid of readings which is used for the training of a hierarchical k-means clustering system. For a given query LEDs reading; the trained clusters are used for position estimations by minimizing the distances between the reading and cluster centroids. From the results, it can be seen that location estimation accuracy of 0.37m can be achieved for a room with dimensions 4.3 × 4 ×4 m^3. To the best of author's knowledge, to date, this is the best accuracy achieved in any practical environment utilizing LEDs.

In second approach, location of the object is determined by scanning two LEDs at pre-defined angles which are modulated at different frequencies. During scanning process, for each LED, two maximum values of RSS are recorded and this information is used to calculate the position of the object. TDM is used to incorporate angle information the receiver. A bicubic spline interpolation is applied to calculate the position of the object. Simulations are performed for a typical indoor environment with dimensions of (3 × 3 × 2 m^3) and results are validated using by experiments. The experimental results confirm that beam scanning can be used to determine the location of an object precisely up to 13 cm. In third developed technique, author presented a heuristic approach to localization employing clustering for an indoor environment using light emitting diodes (LEDs). Depending upon the number of LEDs used, level 1 clustering is achieved by simply comparing the signal strength for each combination of transmitter's light intensities at the receiver. Moreover, a new technique of clustering is proposed, named the portion clustering, is applied to further partition and narrow down the area where the object of interest can be located. From the simulation results, it can be observed that the location estimation up to few centimeters m can be achieved for an indoor environment with the dimensions of $3 \times 3 \times 3\,m^3$.

The author also presented a simulation based work on 2D localization using RSS and bi-literation. RSS at the receiver is matched with the table generated by fingerprinting. Then bi-literation technique is applied in order to estimate the position of the object of interest. From the measurements, the least error is found to be less than 1 mm and the maximum error is 24 cm. The simulation results are in good enough to be compared with the existing literature in this domain.

Wireless communication is now a vital part of our everyday life. It is hard to imagine a life without mobile devices as they keep us connected to the world along with other countless activities. However, this luxury brings some security concerns i.e. the wireless signal can be intercepted by the intruder with the intention of stealing the information or harming the network. Thus secure and reliable communication is a critical issue in wireless applications when people depend on wireless networks for the transmission of confidential information. Visible light communication is an alternative technology to RF which can help easing the congestion of RF spectrum in addition to providing virtually unlimited bandwidth and in-built security. In this dissertation, a physical layer secure and reliable communication using optical wireless communication is presented. Results show that a secure communication link can be established using spatial diversity based transmission. Two transmitters are used for transmitting the information which is equally divided into $\boldsymbol{I}$ and $\boldsymbol{Q}$ channels to obtain a secure position based transmission. Enhanced security is achieved by establishing a demodulation area in which the signal can be demodulated accurately while in all other regions, the signal cannot be demodulated accurately. Channel degradations can be overcome by implementing suitable channel codes and for this work, a new method for the construction of parity check matrix for LDPC codes have been presented. The investigations presented in this dissertation are limited for static receiver and tested for binary LDPC codes only. However the proposed method for $\boldsymbol{H}$ matrix generation can also be applied for non-binary LDPC codes for further improvement in BER but at the cost of increased complexity.

In a nutshell, it can be concluded that visible light communication is an emerging technology which can be used in conjunction with RF to facilitate communication and humans can employ VLC in a number of applications to make their life more comfortable.

5.2 Future Works

In this dissertation, four localization approaches are discussed and in both approaches RSS measurement is used as a tool to further processing the information for localization. RSS is a simple to extract however, newly introduced objects (after creating a fingerprinting map) will degrade the accuracy of location estimation. Other techniques such as TDOA, TOA, AOA, can be used to construct the fingerprinting map and then the performance of location estimation can be noted. Furthermore, the author has investigated, k-means clustering and interpolation technique to estimate the position of the object however there are many other techniques available in machine learning which can be applied and its comparison with k-means clustering will be very interesting.

Future works include the investigation of other potential techniques to improve the performances of the schemes. In the current work, for secure and reliable communication, only static receiver is considered however, some applications require users to move freely. Therefore, how to improve users' mobility in the proposed model is still an open topic For bringing the reliability in the link, more complex channel coding algorithms can be used For instance, in this thesis, the author has proposed a new method for the construction of ***H*** matrix use an LDPC code. Non-binary LDPC codes, generally guaranties better performance and it is worth investigating.

In the current research, microcontroller based communication system is analyzed. Using field programmable gate array (FPGA) enables the communication to be occur at higher speed. It will be worth nothing what will be the effect on link accuracy, reliability and overall performance when low speed data communication is replaced by high speed data communication.

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APPENDIX

Original Contributions

On the way to realize the end to end system, various contributions have been made in the form of journal and conference papers. Here is the list of contribution by the author in the domain of visible light communication/optical wireless communication:

1. **Muhammad Saadi**, Touqeer Ahmad, Yan Zhao, Lunchakorn Wuttisittikulkij. "**An LED based Indoor Positioning System using k-means Clustering**" submitted to Journal of Machine Learning and Cybernetics (under review).

2. **Muhammad Saadi**, Oumair Naseer, Yan Zhao, Lunchakorn Wuttisttikulkij. "**A Beam Scanning-Based Indoor Localization System Using Light Emitting Diodes**" submitted to Journal of Ambient Intelligence and Humanized Computing (under review).

3. **Muhammad Saadi,** Yan Zhao, Lunchakorn Wuttisttikulkij. "**A Heuristic Approach to Indoor Localization Using Light Emitting Diodes**" submitted to Journal of Theoretical and Applied Information Technology (under review).

4. **Muhammad Saadi**, Ambar Bajpai, Yan Zhao, Paramin Sangwongngam, Lunchakorn Wuttisittikulkij. "**Design and Implementation of Secure and Reliable Communication using Optical Wireless Communication**" in Frequenz 2014; 68(11–12): 501 – 509

5. **Muhammad Saadi**, Lunchakorn Wuttisittikulkij, Yan Zhao, Paramin Sangwongngam; **"Visible Light Communication: Opportunities, Challenges and Channel Models"**.In International Journal of Electronics and Informatics (IJEI)

6. **Muhammad Saadi**, Ambar Bajpai, Pollawat Vonlopvisut, Yan Zhao, Lunchakorn Wuttisittikulkij. **"A Novel Two Dimensional Visible Light Positioning System based on Received Signal Strength and Bi-literation"** *In 29th International Technical Conference on Circuit/System, Computers and Communication, 2014*.

7. **Muhammad Saadi**, Pollawat Vonlopvisut, Yan Zhao, Paramin Sangwongngam, Lunchakorn Wuttisittikulkij. **“Transmitter Placement Planning for Visible Light Communication**” *In 29th International Technical Conference on Circuit/System, Computers and Communication, 2014.*

8. **Muhammad Saadi**, Lunchakorn Wuttisittikulkij, Yan Zhao, Kittisak Panlek, Kampol Woradit, and Paramin Sangwongngam. **"Performance Analysis of Optical Wireless Communication System using Pulse Width Modulation."** In *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2013 10th International Conference on*, pp. 1-5. IEEE, 2013.

9. **Muhammad Saadi**, Thiti Sittivangkul, Yan Zhao, Lunchakorn Wuttisittikulkij, and Paramin Sangwongngam. **"System Demonstration for Visible Light Communication using Adaptive Threshold Detection for Low Data Rate Applications**." In *Electron Devices and Solid State Circuit (EDSSC), 2012 IEEE International Conference on*, pp. 1-3. IEEE, 2012.

10. **Muhammad Saadi**, Paramin Sangwongngam, Suvit Nakpeerayuth, Pisit Vanichchanun, Yan Zhao, Lunchakorn Wuttisittikulkij. **"Global Efforts in Realizing Visible Light Communication Systems and its Comparison with other Short Range Wireless Communication Networks".** *In National Broadcasting and Telecommunication Committee (NTBC) end year conference 2011, December 15-16, 2011*.

System Demonstration for Visible Light Communication using Adaptive Threshold Detection for Low Data Rate Applications

Muhammad Saadi, Thiti Sittivangkul, Yan Zhao, Lunchakorn Wuttisittikulkij
Department of Electrical Engineering
Chulalongkorn University
Payathai, Patumwan, Bangkok, 10330, Thailand
muhammadsaadi@gmail.com

Paramin Sangwongngam
Optical & Quantum Communications Lab
National Electronics and Computer Technology Center
Klong Luang, Pathumthani, 12120, Thailand

Abstract— **With the materialization of light emitting devices for solid state lighting, visible light communication (VLC) has provided a prospect to realize low cost, high speed, power efficient and secure data transmission in addition to lighting. Incandescent and fluorescent light sources are being replaced by light emitting diodes (LED) which are not only energy efficient but also help in reducing carbon dioxide CO_2 emission. In this paper, experimental results are being presented using a new protocol for VLC and the optimum placement of the LEDs within the transmitter to maximize the transmitter foot prints.**

Keywords-Light Emitting Diode; Geometry; Visible Light Communication, Adaptive Threshold Detection

I. Introduction

Use of infrared or visible light for the purpose of communication is classified as wireless optical communication. Optical carriers are used to transmit information using optical wireless channel from host to the destination [1]. Optical wireless has large spectrum and unlicensed band available for the purpose of communication thus providing high speed network. VLC is basically a short range optical wireless communication using LED's for illumination and communication simultaneously. [2]. Modern lighting system will employ white LED's instead of incandescent and fluorescent lamps because of their better mean time before failure (MTTF), high lighting efficiency, specific spectrum and environmental friendliness. In VLC, intensity of light is used to transmit information which gives rise of digital base band signal. Change in amplitude is so small for a naked human eye that it is un-noticeable [3-4].

It has been observed that nearly 33% of the total electrical energy consumed is for lighting purpose [5]. Therefore it is a must that efficient lighting source must be used in order to reduce this proportion. Other than water, electrical energy is also generated from coal, gas, oil and nuclear products which are responsible for emission of CO_2 and other gases. By replacing all lighting source with LED's, 50% of the total global power consumption for lighting will be reduced. In United States only, 760GW can be saved over a period of 20 years using LED. It has been estimated by Ministry of International Trade of Japan that if half of all incandescent and fluorescent lamps are replaced by LEDs in Japan then six midsized power plants will be available for providing electricity for more productive purpose in addition to the reduction of greenhouse gases [6]. In this paper we investigate the performance of new prototype which in-cooperates adaptive threshold detection (ATD) scheme which is applied to visible light communication system. Furthermore, experimental results regarding optimum placement of LEDs within the transmitter are also being presented.

II. Frame Structure

Due to the dynamic and mobile nature of office environment, light intensity at particular location changes very quickly. Using visible light as a mode of data communication is affected dominantly by the variations in the light intensity. Light from the Sun, ambient light sources, monitors light etc. are the major sources of noise in visible light communication. To overcome this problem, we develop a prototype using ATD scheme. In this scheme, we consider size of the frame to be of one thousand bits. First twenty bits are used for threshold detection, next 8 bits are used for synchronization and remaining bits are used for data transfer. It is assumed that the communication link between transmitter and receiver has been established. The ATD bits contain all zeros which help in measuring the non-data communication light sources intensity. Synchronization bits contains all 1's so when the receiver receives eights 1's, it will treat the next 972 bits as data bits. Frame structure is shown in Figure 1.

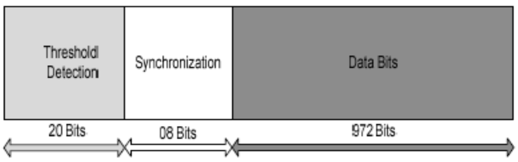

Figure 1. Frame Structure for Adaptive Threshold Detection Scheme

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III. Experimental Setup

Two experiments were conducted in order to analyses the performance of visible light communication system. In the first experiment, transmitter was kept stationary and the receiver was moved from 1 meter to 3 meter distance and data transmission accuracy was recorded. 10 frames were sent repeatedly in order to normalize the results. The experiment was performed under three conditions which are: Case 1: Ceiling lights are on and sunlight is allowed to enter the room. Case 2: Ceiling lights are partially on and sunlight is also allowed to enter the room partially. Case 3: Ceiling lights are off and no sunlight is allowed to enter the room. Data was generated using MATLAB. This experiment primarily focuses on the successful transmission of data from transmitter to the receiver. The design of transmitter and receiver for both experiments is the same other than LED panels. The second experiment primarily investigates the optimized placement design of the LEDs for the transmitter. For this purpose, four geometric shapes were selected i.e. triangle, square, hexagon and circle. Each LED panel consists of 12 LED. LEDs were placed at the boundaries of the geometry only and area for all the geometries was kept the same shown in equation as follows.

$$1.3*R_{TRI}^2 = 2*R_{SQU}^2 = 2.6*R_{HEXA}^2 = 3.14*R_{CIR}^2 = 150cm^2$$

LED panel is connected to the dimming control circuitry followed by the transistor (used as a switch) and an opto-coupler. Signal information is sent through the Arduino board. Function of opto-coupler is to isolate voltage supply from rest of the circuit thus preventing microcontroller from high voltage.

Different LED panels were used to record the reading at the receiver which consists of a photodiode, followed by the trans-impedance amplifier and another Arduino board. MATLAB was used to plot the results. The block diagram of the system is shown in Figure 2.

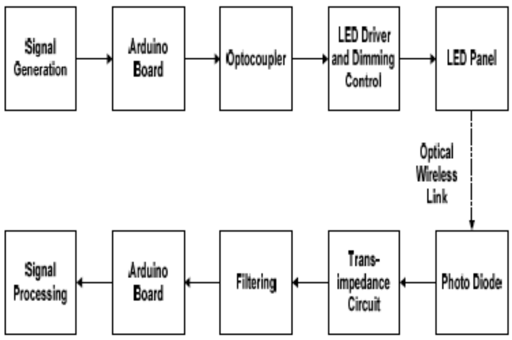

Figure2. Block Diagram of VLC Communication System

The second experiment was tested for mild sunlight entering the room and partial ceiling lights on. It is worth mentioning here that time required to read the serial port using MATLAB is a slow process as compared to writing on the serial port. In addition, time also varies with the processing speed of the computer. Therefore higher data rates are not achievable using this technique as MATLAB and the time consumed reading the serial port are the bottlenecks to data transfer rates. Synchronization between the transmitter and the receiver is a challenging task.

IV. Results and Discussion

For the first experiment, results are shown in Figure 3. From the results, it can be seen that when only LED lights are on which are participating is communication, the system performance is the best. At a distance 1 and 2 meter, the link is 100 percent reliable and at 3 meter distance, the link is 99% reliable. For the case 2, link performance is also reasonable with a 97% reliable link at 3 meter distance. However, the performance for case 1 is not satisfactory. System performance degrades to 89% successful transmission at a distance for 3 meters.

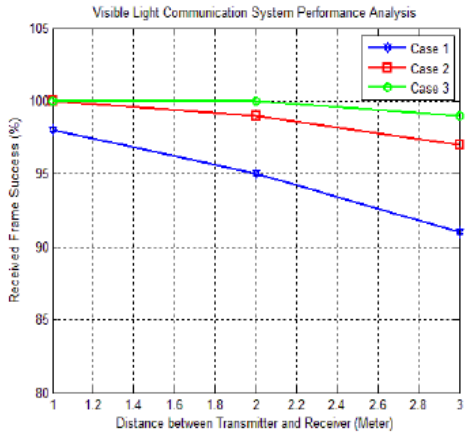

Figure 5: Measurement of Link Reliability for VLC System

Room light intensity level was measured by sending header bits and then voltage level at the receiver was measured at various positions for Line of Sight (LOS) horizontal movements of the receiver for all LED panels. The graph shown in Figure 4 is plotted against distance between the transmitter (in meters) and the receiver versus difference voltage level i.e. impact of transmitter light on photodiode minus ambient light level.

Receiver was moved from zero meters to 4 meters and the reading was recorded. All the panels have same response at zero meters because at the position only one LED is effective and gives the same reading for all. From the results, it is evident that square geometry performs the worst. However, circular and hexagonal panels perform better than the triangular and square one. Circular and hexagonal panel's response is quite similar. Results show that the non-coherent light emission nature of LEDs results in no significant difference by arranging LEDs in different geometries. All LED panels emit light in a similar fashion when the distance is of 1m.

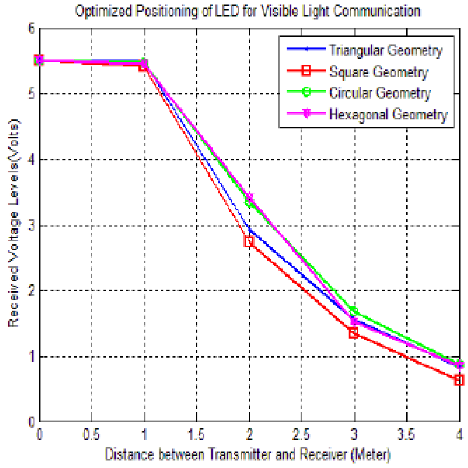

Figure 4. Comparison between different geometry transmitters

V. Conclusion

From the above results, it can be concluded that inherit non-coherent light emission nature of LED cannot be strongly influenced by the arrangement of LEDs within the transmitter. If the receiver is close to the transmitter, all LED panel behavior reflected at the receiver is similar. However circular and hexagonal geometry pushes the light to more distance than others so best results can be achieved by arranging the LEDs in theses geometries. Microcontrollers are not a good choice if we want to go beyond few hundred kilobits/sec. Adaptive Threshold Technique is quite useful to overcome the dynamic variation of light intensity at the receiver. Further investigation can be done by different orientation of LEDs, using high bright/super bright LEDs and the photodiode with faster response time.

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Performance Analysis of Optical Wireless Communication System using Pulse Width Modulation

Muhammad Saadi, Lunchakorn Wuttisittikulkij, Yan Zhao
Department of Electrical Engineering
Chulalongkorn University
Bangkok, Thailand

Kittisak Panlek, Kampol Woradit
Department of Electrical Engineering
Srinakharinwirot University
Nakhonnoyok, Thailand

Paramin Sangwongngam
Optical and Quantum Communication Laboratory.
NECTEC
Pathumthani, Thailand

***Abstract*— Optical wireless communication has emerged as a promising complementary technology for Radio Frequency technology. Reliability and survivability of solid state lighting devices has attracted researchers and is gaining attention as they provide synergistically illumination and communication. Furthermore optical wireless communication is environmental friendly and also helps in energy conservation. In this paper various parameters for visible light and infrared link such as link accuracy, noise immunity have been studied. A simple algorithm has been described for localization and tracking for a full duplex optical wireless communication system.**

***Keywords*— Light emitting diodes, optical wireless communication, pulse width modulation, synchronization, localization, tracking**

I. Background

Use of light as a source of communication perhaps starts with human evolution. Igniting the fire to gain the attention of the natives and building light houses for ship navigation system are the typical examples which testify the use of light as a mode of communication since ages. Optical Wireless Communication (OWC) using Infrared (IR) was proposed in the late 1970s and during the 1990s Infrared Wireless Communication (IrWC) received considerate attention. Using LED as a source of voice and data communication history is not very long and is given in the following Table 1.

II. Introduction

Radio Frequency (RF) is facing problems like bandwidth limitation, frequency scarcity, security loopholes, frequency hazards, electromagnetic interference. These problems have triggered the researchers to focus on alternative techniques which can not only solve the problems related with RF but can also well fit in Next Generation Network (NGN).

Optical radiations which convey information in free space or air within the wavelength ranging from infrared to ultraviolet (UV) frequencies are classified as Optical Wireless Communication. This range also includes the visible light spectrum and the communication using visible light wavelength (380nm to 780 nm) is known as Visible Light Communication. An optical source includes Light Emitting Diode (LED) and Laser Diode (LD). LEDs are typically used for indoor applications and LD is used for outdoor applications. LEDs posses many advantages such as quick response time, longer Mean Time before Failure (MTBF), high frequency modulation capability, energy efficiency and cost effectiveness over conventional fluorescent lamps which makes them an excellent choice for NGN and also for their common use in domestic applications [5-6].

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TABLE I
KEY ACHIEVEMENTS IN VISIBLE LIGHT COMMUNICATION

Year	Major Milestone
1998-1999	Realizing that LED can be used as a source of data communication and experimentation begins [1]
2001	Contributions from Keio University for broadband VLC using White LED
2003	Formation of Visible Light Communication Consortium (VLCC) [2]
2005-2006	Wireless World Research Forum (WWRF) initiation [3]
2007	- VLCC publishes two VLC standards namely *JEITA CP – 1221 and JEITA CP – 1222* - Global Recognition – Scientific America publishes paper on VLC
2008	US and Europe funded research projects on VLC
2009	Call for contributions on IEEE 802.15.7
2011	IEEE publishes IEEE 802.15.7 standard [4]

This paper deals with the indoor Optical Wireless Communication System (OWCS) consisting of Visible and IR link. It is therefore interesting to know pros and corns of visible light communication and infrared communication [7] before going into details of the whole communication system. Comparison between these two links is given in Table II.

In this paper, a full duplex OWCS has been developed and various performance parameters like link reliability, link accuracy, effect of duty cycle of Pulse Width Modulation on link performance have been investigated. For uplink IR is used and for downlink visible light (white color) is used. An overall comparison between the visible light link and infrared has also been discussed.

The aim of this paper was to analyze the performance of visible light and IR communication and draw a comparison between them. Furthermore, a simple technique has been described to achieve localization and tracking using simple algorithm and inexpensive hardware. The rest of the paper has been organized in the following way. Section III discusses Pulse Width Modulation (PWN). Section IV deal with overall system description and component parameters. Section V is about the testing parameters and conditions. Section VI discusses the results followed by the conclusion in Section VII.

TABLE III
COMPARISON BETWEEN VISIBLE LIGHT AND INFRARED COMMUNICATION

Parameter	**Visible Light**	**Infrared**
Wavelength	380nm to 780nm	850nm
Spectrum	Virtually unlimited	Lower
Thermal Radiation	No	Yes
Sun Spectrum	Yes	Yes
Achievable Data Rate	>800Mbps	16Mbps
Standardization	IEEE 802.15.7	Infrared Data Association (IrDA)
Technique	Relatively new	Old
Acceptable Eye Safety Level	High power	Low power
Services	Communication and illumination	Communication
Link Distance	LED in meters LD in Km	Up to 3 meter
Applications	Indoor and outdoor applications	Mainly indoor and point to point application
Unregulated	Yes	Yes

The aim of this paper was to analyze the performance of visible light and IR communication and draw a comparison between them. Furthermore, a simple technique has been described to achieve localization and tracking using simple algorithm and inexpensive hardware. The rest of the paper has been organized in the following way. Section III discusses Pulse Width Modulation (PWN). Section IV deal with overall system description and component parameters. Section V is about the testing parameters and conditions. Section VI discusses the results followed by the conclusion in Section VII.

III. PULSE WIDTH MODULATION

Optical systems work at higher frequencies. Coherent demodulation is a difficult choice in terms of implementation at such higher frequency. In non coherent schemes, intensity modulation with direct detection is popular technique used in optical communication. Other popular modulation techniques include On-Off Keying (OOK), Color Shift Keying (CSK), Orthogonal Frequency Division Multiplexing (OFDM) and Pulse Time Modulation (PTM) [8-9].

Pulse Width Modulation (PWM) is a type of PTM in which digitally encodes analogue signal levels. Let $f(t)$ be a pulse waveform then average value of the waveform can be represented by

$$\dot{x} = \frac{1}{T}\int_0^T f(t)dt \qquad (1)$$

The value of pulse waveform can either be maximum or minimum. The value of the pulse is maximum for time t_{max} and is minimum for time t_{min} then average value of the pulse can be expressed as in equation (2).

$$\dot{x} = \frac{1}{T}\left(\int_0^{t_{max}} x_{max}dt + \int_{t_{max}}^{T} x_{min}dt\right) \qquad (2)$$

Where $T - t_{max} = t_{min}$. If t_{max} is more than t_{min} in a duty cycle D then we can say that the pulse is on for more time having more energy and vice versa. Mathematically we can express the PWM signal as follows

$$x(t) = \begin{cases} 1 & 0 \le t \le t_{max} \\ 0 & t_{max} \le t \le T \end{cases} \qquad (3)$$

IV. SYSTEM DESCRIPTION

Fig. 1 is the block diagram of whole communication system. The system has a capability to do full duplex communication. For uplink IR is used and for downlink visible light (white color) is used. The purpose of choosing different frequencies for uplink and downlink is to avoid Inter symbol Interference (ISI). Typical utilization for downlink is more as compared to uplink and from Table II analysis, the choice of uplink and downlink becomes justified. Furthermore, the downlink LED will do illumination purpose in a better way. For an indoor environment, it is not convenient to have lighting from down to top.

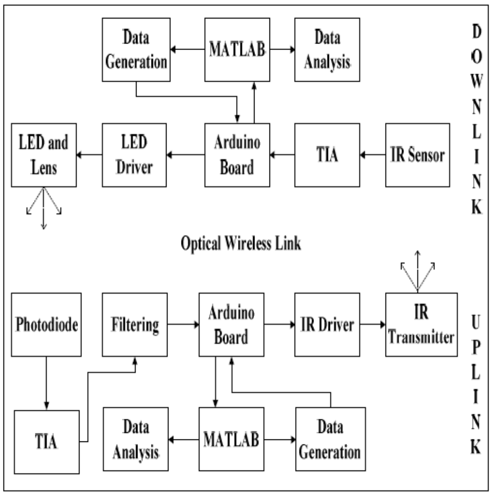

Fig. 1 System Block Diagram for Optical Wireless Communication System.

Considering the downlink system first, for transmission purpose, MATLAB is used for generation of the data. Data is then fed to the Arduino board which is connected to the LED driver circuit consisting of a dimming control circuitry followed by the transistor (used as a switch) and an opto-coupler. LED will be responding to the signal received from LED driver but turning it on and off which will be then propagated through the optical channel. Lens is used to focus the light and make the beam emission narrow. For the reception of IR signal from the uplink, IR sensor is used which is connected to the Trans-Impedance Amplifier (TIA). Output of TIA is fed to the Arduino board which is connected to MATLAB for data analysis purpose.

The uplink system consists of a photodiode which is receiving signals from the LED through an optical wireless link. Based on the intensity of the light fallen on the active area of photodiode, current will be generated. Current signal will be fed to TIA and filtering is done as ambient light sources (sunlight, incandescent lamps, TV screens etc.) are the sources of noise. After filtering, the signal is fed to the Arduino board which is connected with the MATLAB for data processing and analysis. For uplink transmission, data is generated through MATLAB which is transmitted through IR transmitter.

V. Testing Parameters and Conditions

Fig. 1 gives the complete picture of the overall communication system. Here are some details about the transmitter and receivers used for uplink and downlink followed by some testing conditions

TABLE III
COMPONENT SPECIFICATIONS

Element	Specifications
IR	- Peak Wavelength= 940nm - Spectral Bandwidth = 45nm - View Angle = 20°
LED	- Luminous Flux (lm) = 105-150 - View Angle = 120° - Peak Wavelength= 475nm
Photodiode	- Spectral response 430 nm to 1080 nm - Rise/Fall time 10µsec

A. Pulse Width Modulation Duty Cycle Variation

In order to evaluate the effect of duty cycle variation on the performance of IR and Visible link, duty cycle was varied from 50% to 100%. 100% duty cycle corresponds to all time high signals with no variation i.e. a DC signal which carries no information.

B. Link Reliability and Accuracy

For measuring the link reliability and accuracy, the transmitter is first kept line of sight with the receiver and transmitted bits were recorded to measure the link accuracy. Then receiver was moved in steps of 5 degrees in order to observe the link reliability and accuracy.

C. Localization and Tracking

Need for Location Based Services (LBS) is increasing which triggered research in the domain of localization techniques for indoor environment [10]. Differe technologies and products are available for indoor positioni and navigation, such as infrared, computer vision, ultrasoun laser, radio frequency, cellular communication, and so on [1 12]. In this paper, localization and tracking is implement with the help of bit patterns. For experimental purpose, fo LEDs are placed at the ceiling representing four rooms. Ea room will be transmitting a packet containing header b along with data and parity bit. When receiver will receive t pattern, it will match the pattern with the pre-programm memory to determine the location of the room. F visualization, MATLAB GUI is developed.

For tracking purpose, when a user knows about t location, packet will be uplinked via IR to the receiver on t roof. The data packet size is of 5 bits containing two head bits, two data bits and one parity bit. Program will check da and display on admin terminal about tracking information the user. Experimental setup is shown in Fig 2.

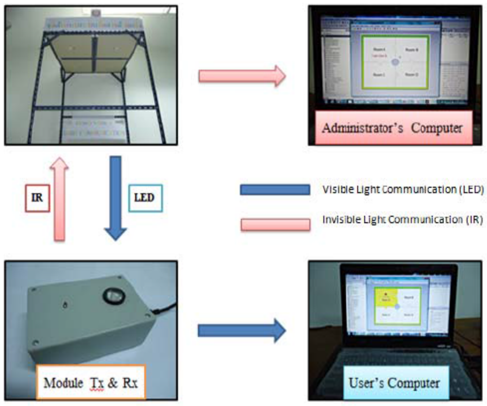

Fig. 2 Localization and Tracking for users

Flow chart for localization and tracking is shown in Fig 3.

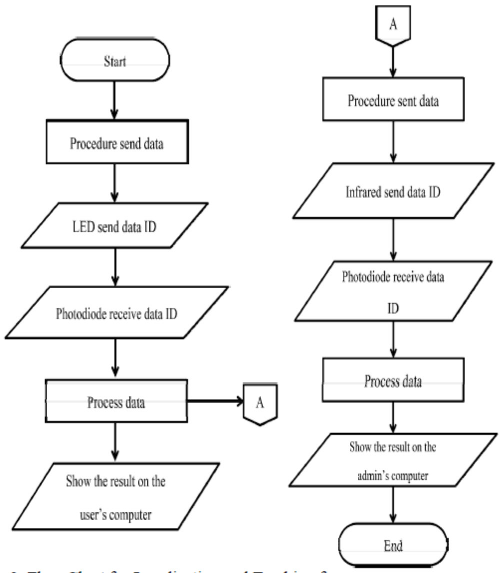

Fig. 3 Flow Chart for Localization and Tracking for users

VI. Results

Results from the experimentation mentioned in Section V are as follows.

A. Pulse Width Modulation Duty Cycle Variation

In order to evaluate the performance of IR and visible link with the change in the duty cycle, the duty cycle was varied from 50% to 100% and the effect was observed by looking into the accuracy of the link. The distance between transmitter and receiver was set to be 1 meter. From the graph, it can be observed that the link accuracy for both is very good when the duty cycle is at higher side. IR link performs better as compared to visible light link with 80% of duty cycle is giving nearly 100% accuracy.

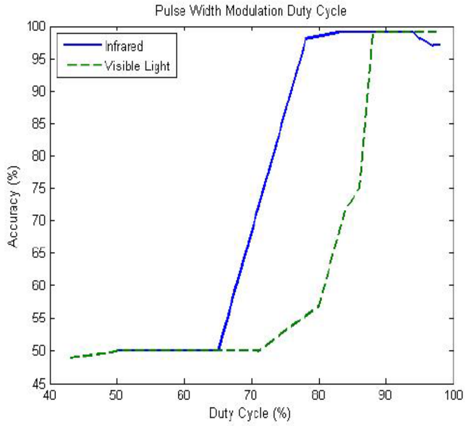

Fig. 4 Effect of changing duty cycle on link performance

B. Link Reliability and Accuracy

For Line of Sight (LOS) communication, both LED and IR link performs accurately. But when the transmitter and receiver becomes Non Light of Sight (NLOS), the performance starts to degrade. However we can see from the Fig. 5 that visible link has a better performance than IR.

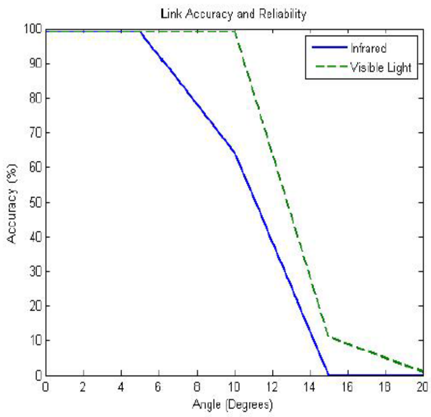

Fig. 5 Measuring accuracy of the link when transmitter and receiver goes NLOS

C. Localization and Tracking

As localization and tracking works with the visible light and IR communication so the accuracy is same as described in Fig 6. At the admin terminal, MATLAB based Graphical User Interface (GUI) will display the location of the user.

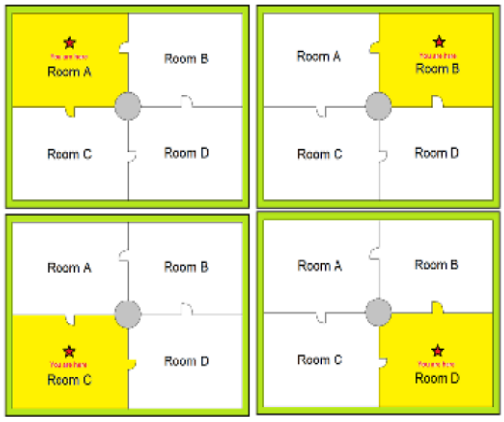

Fig. 6 Admin Panel to Monitor Localization and Tracking

VII. Conclusion

From the above discussion, it can be concluded that optical communication using LED and IR is a promising technique which can be used in conjunction with other communication technology. VLC link can go beyond the IR and are more accurate and reliable than IR links. However IR links have the potential to work with low duty cycle i.e. low power better as compared to the visible link. Furthermore localization and tracking using these inexpensive components can be achieved.

Acknowledgment

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VITA

Mr. Muhammad Saadi is a Pakistani national and was born on 5th August, 1985 in the city of Multan, Pakistan. He has done his Bachelor degree from National University of Computer and Emerging Sciences, Pakistan in 2007 in the field of Telecommunication Engineering. He started working as an Associate Engineer in a mobile operator company Mobilink, Pakistan before he started his Master degree from National University of Malaysia (UKM) and graduated in 2009 as the top student of the class. He returned to his homeland and started his career as university lecturer in University of Management and Technology (UMT), Pakistan.

Mr. Saadi started his PhD in semester II of year 2011 from Department of Electrical Engineering, Chulalongkorn University, Thailand. During his PhD, he got various opportunities to work for industrial project like Digital Television Broadcasting project from National Broadcasting and Telecommunication Corporation (NBTC), Thailand. He was also the team member of Optical and Quantum Communication Laboratory, National Electronics and Computer Technology Center (NECTEC) where he was involved in the development of 100 Mbps Visible Light Communication link. Furthermore, he also worked as a part time lecturer in King Mongkut University of Technology North Bangkok (KMUTNB).

Author has successfully published journal and conference papers. He also had an opportunity to serve as a reviewer of ITC-CSCC 2014. His research interest includes Visible Light Communication, Localization and Channel Coding. Author is also the recipient of the prestigious 90 years Chulalongkorn Scholarship, UKM Dean Honor List, ITC-CSCC-2014 Best Paper Award, ITC-CSCC-2014 student travel grant, WEC-2011 travel grant and ICESS-2011 travel grant.

The career objective of the author is to become a research leader in the area of short range wireless communication technologies and transfer my knowledge and skills to the future generation of engineering/IT professionals through innovative, research-based teaching. Saadi is keen of watching and playing Cricket, Table Tennis and Badminton.