BACHELOR OF SCIENCE IN ELECTRONIC AND TELECOMMUNICATION ENGINEERING

Design and Simulation for Increasing the range of Li-Fi

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October, 2022

DEDICATION

This thesis work is dedicated to all of our honorable teachers and parents.

CERTIFICATE OF APPROVAL

The thesis entitled as “Design and Simulation for Increasing the range of Li-FI.” Submitted by Nafiz Omar Abtahi, bearing ID No: T-173036, to the Department of Electronics and Telecommunication Engineering (ETE) of International Islamic University Chittagong (IIUC) has been found as satisfactory for the partial fulfillment of the requirements for the Degree of Bachelor in Electronic and Telecommunication Engineering and approved as to its style and contents for the examination held on 18th October 2022.

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CANDIDATES DECLARATION

It is hereby declared that the work presented in this thesis has not been submitted elsewhere for the award of any degree or diploma, does not contain any unlawful statement.

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ACKNOWLEDGEMENT

In the name of Allah, the Most Merciful of All, the Most Merciful of All. All credit and glory goes to Allah (SWT) for providing us with numerous opportunities and pouring His mercy and wisdom on us throughout our lives. And may Allah's peace and blessings be upon Prophet Muhammad (pbuh), who has been a source of guidance and inspiration in our lives. We are grateful and appreciative to **Engr. Md. Jashim Uddin**, our thesis supervisor, for his effort in this field of research, useful assistance, and encouragement throughout the research process. We thank **Sayed Zahidur Rashid**, Head of the Department of Electronic and Telecommunications Engineering at IIUC, for providing us with the greatest facilities in the department as well as timely recommendations. We also appreciate **Engr. Abdul Gafur**, our thesis convener, for his devotion and sacrifice. We also want to thank all of our teachers for putting up their best effort during our academic careers. And we remember our parents for their unwavering support throughout our lives. We also want to thank our friends and well-wishers for their direct or indirect contributions to the completion of this thesis.

ABSTRACT

With the demand for faster and secure communication technologies to make our lives better, innovative technologies like Li-Fi (Light Fidelity) are becoming increasingly popular. Li-Fi utilizes Light Emitting Diodes (LEDs) for accomplishing data transmission. This research concentrates around handover algorithms and performance evaluation of a Li-Fi network. Accordingly, the work is outlined in two parts.

Firstly, this research work evaluates the performance of handover algorithms in Li-Fi network. Two handover algorithms are investigated namely, the closest-AP based algorithm (AP: Access Point) and maximum-channel-gain-based algorithm. Monte Carlo simulations using MATLAB tools are conducted to evaluate handover algorithms and show the impact of User Equipment (UE)'s rotation and movement on handover performance.

Secondly, this research evaluates the performance of a Li-Fi network with multiple beams LEDs on moving UEs. The network performance is investigated in the case of the maximum channel gains. The simulated results show that when the beam angle is 30°, the Li-Fi system has the best performance in terms of channel gain (hence throughput) by considering its mean and standard deviation (SD) values.

Thirdly, in this research I used concave mirror and the algorithm of cone to increase the range of Li-Fi.

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Abbreviation

ADC	Analogue to Digital Converter
ADR	Angle Diversity Receiver
AF	Amplify-and-Forward
AP	Access Point
APS	Access Point Selection
BS	Base Station
CCI	Co-Channel Interference
CCU	Central Controller Unit
CSI	Channel State Information
DAC	Digital to Analogue Converter
DF	Decode-and-Forward
DD	Direct Detection
EGC	Equal Gain Combining
FL	Fuzzy Logic
FOV	Field of View
FR	Frequency Reuse
FSO	Free-Space Optical
IB	In-Band
IM	Intensity Modulation
IR	Infrared
IrDA	Infrared Data Association
JOA	Joint Optimization Algorithm

LAC	Light Fidelity Attocell
LB	Load Balancing
LD	Laser Diode
LED	Light Emitting Diode
Li-Fi	Light Fidelity
LOS	Line of Sight
MAC	Medium Access Control
MIMO	Multiple-Input Multiple-Output
MRC	Maximum Ratio Combining
OBS	Optical Base Station
OPC	Optimum Combining
OWC	Optical Wireless Communications
PD	Photodiode
PDF	Probability Density Function
PF	Proportional Fairness
PPP	Poisson Point Process
QoS	Quality of Service
RF	Radio Frequency
RGB	Red, Green and Blue
SBC	Select Best Combining
SD	Standard Deviation
SDMA	Space-division Multiple Access
SIR	Signal to Interference Ratio
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SOA	Separate Optimization Algorithm
SSL	Solid State Lighting

SSS	Signal Strength Strategy
TDMA	Time Division Multiple Access
UE	User Equipment
VL	Visible Light
VLC	Visible Light Communication
Wi-Fi	Wireless Fidelity

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Chapter 1

Introduction

1.1 Li-fi Technology:

Transfer of data from one place to another is one of the most important day-to-day activities. The current wireless networks that connect us to the internet are very slow when multiple devices are connected. As the number of devices that access the internet increases, the fixed bandwidth available makes it more and more difficult to enjoy high data transfer rates and connect to a secure network. But radio waves are just a small part of the spectrum available for data transfer. A solution to this problem is by the use of Li-Fi. Li-Fi stands for Light-Fidelity. Li-Fi is transmission of data through illumination by taking the fiber out of fiber optics by sending data through an LED light bulb that varies in intensity faster than the human eye can follow. Li-Fi is the term some have used to label the fast and cheap wireless communication system, which is the optical version of Wi-Fi. Li-Fi uses visible light instead of Gigahertz radio waves for data transfer.

The idea of Li-Fi was introduced by a German physicist, Harald Hass[4], which he also referred to as ―data through illumination‖. The term Li-Fi was first used by Haas in his TED Global talk on Visible Light Communication. According to Hass, the light, which he referred to as D-Light, can be used to produce data rates higher than 10 megabits per second which is much faster than our average broadband connection Li-Fi can play a major role in relieving the heavy loads which the current wireless systems face since it adds a new and unutilized bandwidth of visible light to the currently available radio waves for data transfer. Thus, it offers much larger frequency band (300 THz) compared to that available in RF communications (300GHz) [1].

Also, more data coming through the visible spectrum could help alleviate concerns that the electromagnetic waves that come with Wi-Fi could adversely affect our health. Li-Fi can be the technology for the future where data for laptops, smart phones, and tablets will be transmitted through the light in a room. Security would not be an issue because if you can‘t see the light, you can ‘t access the data. As a result, it can be used in high security military areas where RF communication is prone to eavesdropping.

Figure1.1. Li-Fi Bulb [19]

1.2. CONSTRUCTION OF Li-Fi SYSTEM:

Li-Fi is a fast and cheap optical version of Wi-Fi. It is based on Visible Light Communication (VLC). VLC is a data communication medium, which uses visible light between 400 THz (780 nm) and 800 THz (375 nm) as optical carrier for data transmission and illumination. It uses fast pulses of light to transmit information wirelessly. The main components of Li-Fi system are as follows:

a) a high brightness white LED which acts as transmission source.
b) a silicon photo diode with good response to visible light as the receiving element.

LEDs can be switched on and off to generate digital strings of different combination of 1s and 0s. To generate a new data stream, data can be encoded in the light by varying the flickering rate of the LED. The LEDs can be used as a sender or source, by modulating the LED light with the data signal. The LED output appears constant to the human eye by virtue of the fast-flickering rate of the LED. Communication rate greater than 100 Mbps is possible by using high speed LEDs with the help of various multiplexing techniques. VLC data rate can be increased by parallel data transmission using an array of LEDs where each LED transmits a different data stream. The Li-Fi emitter system consists of 4 primary sub-assemblies:

a) Bulb
b) RF power amplifier circuit (PA)
c) Printed circuit board (PCB)
d) Enclosure

The PCB controls the electrical inputs and outputs of the lamp and houses the micro controller used to manage different lamp functions. A RF (radio-frequency) signal is generated by the solid-state PA and is guided into an electric field about the bulb. The high concentration of energy in the electric field vaporizes the contents of the bulb to a plasma state at the bulb 's center; this controlled plasma generates an intense source of light. All of these sub assemblies (shown in Fig. 1.2) are contained in an aluminum enclosure.

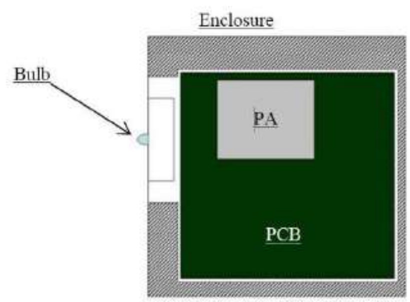

Figure1.2.1 Block diagram of Li-Fi sub-assemblies

The bulb sub-assembly is the heart of the Li-Fi emitter. It consists of a sealed bulb which is embedded in a dielectric material. This design is more reliable than conventional light sources that insert degradable electrodes into the bulb. The dielectric material serves two purposes. It acts as a wave guide for the RF energy transmitted by the PA. It also acts as an electric field concentrator that focuses energy in the bulb. The energy from the electric field rapidly heats the material in the bulb to a plasma state that emits light of high intensity and full spectrum. Figure 1.2.2 shows the bulb sub-assembly.

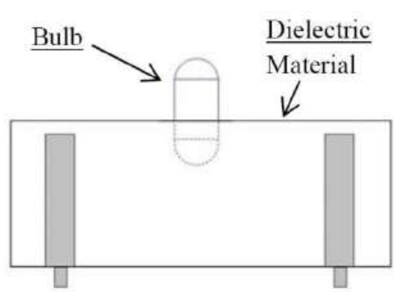

Figure1.2.2 Bulb sub-assembly

There are various inherent advantages of this approach which includes high brightness, excellent color quality and high luminous efficacy of the emitter in the range of 150 lumens per watt or greater. The structure is mechanically robust without typical degradation and failure mechanisms associated with tungsten electrodes and glass to metal seals, resulting in useful lamp life of 30,000+ hours [3]. In addition, the unique combination of high temperature plasma and digitally controlled solid state electronics results in an economically produced family of lamps scalable in packages from 3,000 to over 100,000 lumens [4].

1.3 WORKING OF Li-Fi:

A new generation of high brightness light-emitting diodes forms the core part of light fidelity technology. The logic is very simple. If the LED is on, a digital 1 is transmitted. If the LED is off, a digital 0 is transmitted. These high brightness LEDs can be switched on and off very quickly which gives us a very nice opportunities for transmitting data through light The working of Li-Fi is very simple. There is a light emitter on one end, for example, an LED, and a photo detector (Light sensor) on the other. The photo detector registers a binary one when the LED is on; and a binary zero if the LED is off. To build up a message, flash the LED numerous times or use an array of LEDs of perhaps a few different colors, to obtain data rates in the range of hundreds of megabits per second [4]. The block diagram of Li-Fi system is shown in Fig. 1.3.1.

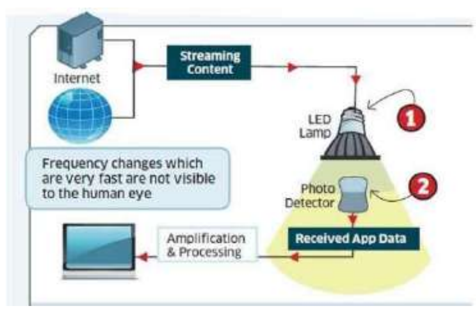

Figure1.3.1Block diagram of Li-Fi system[4]

The data can be encoded in the light by varying the flickering rate at which the LEDs flicker on and off to generate different strings of 1s and 0s. The LED intensity is modulated so rapidly that human eye cannot notice, so the light of the LED appears constant to humans. Light-emitting diodes (commonly referred to as LEDs and found in traffic and street lights, car brake lights, remote control units and countless other applications) can be switched on and off faster than the human eye can detect, causing the light source to appear to be on continuously, even though it is in fact, 'flickering'. The on-off activity of the bulb which seems to be invisible enables data transmission using binary codes: switching on an LED is a logical '1', switching it off is a logical '0'[19]. By varying the rate at which the LEDs flicker on and off, information can be encoded in the light to different combinations of 1s and 0s. This method of using rapid pulses of light to transmit information wirelessly is technically referred to as Visible Light Communication (VLC), though it is popularly called as Li-Fi because it can compete with its radio-based rival Wi-Fi. Figure 1.3.2 shows a Li-Fi system connecting devices in a room.

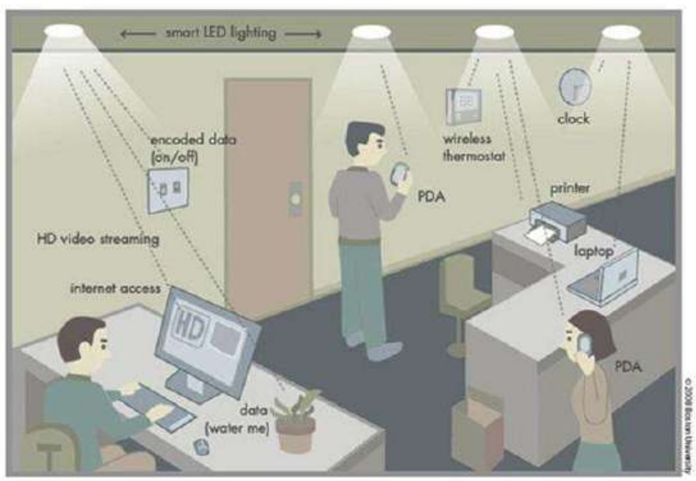

Figure1.3.2 Li-Fi system connecting devices in a room[19]

Many other sophisticated techniques can be used to dramatically increase VLC data rate. Teams at the University of Oxford and the University of Edinburgh are focusing on parallel data transmission using array of LEDs, where each LED transmits a different data stream. Other groups are using mixtures of red, green and blue LEDs to alter the light frequency encoding a different data channel.

1.4 RECENT ADVANCEMENTS IN Li-Fi:

Using a standard white-light LED, researchers at the Heinrich Hertz Institute in Berlin, Germany, have reached data rates of over 500 megabytes per second. Using a pair of

Casio smart phones, the technology was demonstrated at the 2012 Consumer Electronics Show in Las Vegas to exchange data using light of varying intensity given off from their screens, detectable at a distance of up to ten meters. A consortium called ‗Li-Fi Consortium ‘was formed in October 2011 by a group of companies and industry groups to promote high-speed optical wireless systems and overcome the limited amount of radio based wireless spectrum. According to the Li-Fi Consortium, it is possible to achieve more than 10 Gbps of speed, theoretically which would allow a high-definition film to be downloaded in just 30 seconds. Researchers at the University of Strathclyde in Scotland have begun the task of bringing high-speed, ubiquitous, Li-Fi technology to market.

1.5 COMPARISON BETWEEN Li-Fi & Wi-Fi:

Li-Fi is the name given to describe visible light communication technology applied to obtain high speed wireless communication. It derived this name by virtue of the similarity to Wi-Fi. Wi-Fi works well for general wireless coverage within buildings, and Li-Fi is ideal for high density wireless data coverage inside a confined area or room and for relieving radio interference issues. Table I shows a comparison of transfer speed of various wireless technologies. Table II shows a comparison of various technologies that are used for connecting to the end user. Wi-Fi currently offers high data rates. The IEEE 802.11.n in most implementations provide up to 150Mbit/s although practically, very less speed is received.

TABLE 1.1. COMPARISON OF SPEED OF VARIOUS WIRELESS TECHNOLOGIES

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Technology	**Speed**
Wi-Fi – IEEE 802.11n	150 Mbps
Bluetooth	3 Mbps
IrDA	4 Mbps
Li-Fi	>1Gbps

TABLE 1.2. COMPARISON OF TECHNOLOGIES USED FOR CONNECTING TO THE END USER

Technology	Connection	Security	Reach	Impact	Cost	Bandwidth Expansion
Wi-Fi	Wireless EMF	Good	Excellent	Unknown	Good	Limited
Hardwired	Cables	Excellent	Fair	None	Good	Limited
Li-Fi	Wireless Light	Excellent	Excellent	None	Good	Exceptional

1.6 Problems in Wi-Fi:

The following are the basic issues with radio waves:

- **Capacity:** Wireless data is transmitted through radio waves which are limited and expensive. It has a limited bandwidth. With the rapidly growing world and development of technologies like 3G, 4G and so on we are running out of spectrum.
- **Efficiency:** There are 1.4 million cellular radio base stations that consume massive amount of energy. Most of the energy is used for cooling down the base station instead of transmission. Therefore, efficiency of such base stations is only 5%.
- **Availability:** Availability of radio waves is a big concern. It is not advisable to use mobile phones in aero planes and at places like petrochemical plants and petrol pumps.
- **Security:** Radio waves can penetrate through walls. They can be intercepted. If someone has knowledge and bad intentions, they may misuse it. This causes a major security concern for Wi-Fi.

1.7 Advantages of Li-Fi:

Li-Fi technology is based on LEDs or other light source for the transfer of data. The transfer of the data can be with the help of all kinds of light, no matter the part of the spectrum that they belong. That is, the light can belong to the invisible, ultraviolet or the visible part of the spectrum. Also, the speed of the communication is more than sufficient for downloading movies, games, music and all in very less time. Also, Li-Fi removes the limitations that have been put on the user by the Wi-Fi.

- **Capacity**: Light has 10000 times wider bandwidth than radio waves. Also, light sources are already installed. So, Li-Fi has got better capacity and also the equipment's are already available.

- **Efficiency**: Data transmission using Li-Fi is very cheap. LED lights consume less energy and are highly efficient.
- **Availability**: Availability is not an issue as light sources are present everywhere. There are billions of light bulbs worldwide; they just need to be replaced with LEDs for proper transmission of data.
- **Security**: Light waves do not penetrate through walls. So, they can 't be intercepted and misused.

With the advent of Li-Fi, now it is not mandatory to be in a region that is Wi-Fi enabled to have access to the internet. One can simply stand under any form of light and surf the internet as the connection is made if light is present. Figure 6 gives a description of Li-Fi along with its advantages.

1.8 Disadvantages of Li-Fi:

One of the major demerits of this technology is that the artificial light cannot penetrate into walls and other opaque materials which radio waves can do. So, a Li-Fi enabled end device (through its inbuilt photo-receiver) will never be as fast and handy as a Wi-Fi enabled device in the open air. Also, another shortcoming is that it only works in direct line of sight. Still, Li-Fi could emerge as a boon to the rapidly depleting bandwidth of radio waves. And it will certainly be the first choice for accessing internet in a confined room at cheaper cost.

1.9 APPLICATIONS OF LI-FI:

There are numerous applications of this technology, from public internet access through street lamps to auto-piloted cars that communicate through their headlights. Applications of Li-Fi can extend in areas where the Wi-Fi technology lacks its presence like medical technology, power plants and various other areas. Since Li-Fi uses just the light, it can be used safely in aircrafts and hospitals where Wi-Fi is banned because they are prone to interfere with the radio waves. All the street lamps can be transferred to Li-Fi lamps to transfer data. As a result of it, it will be possible to access internet at any public place and street.

Some of the future applications of Li-Fi are as follows:

1.9.1 Education systems:

Li-Fi is the latest technology that can provide fastest speed internet access. So, it can replace Wi-Fi at educational institutions and at companies so that all the people can make use of Li-Fi with the same speed intended in a particular area.

1.9.2 Medical Applications:

Operation theatres (OTs) do not allow Wi-Fi due to radiation concerns. Usage of Wi-Fi at hospitals interferes with the mobile and pc which blocks the signals for monitoring equipment's. So, it may be hazardous to the patient's health. To overcome this and to make OT tech savvy Li-Fi can be used to accessing internet and to control medical equipment's. This can even be beneficial for robotic surgeries and other automated procedures.

1.9.3 Cheaper Internet in Aircrafts:

The passengers travelling in aircraft's get access to low speed internet at a very high rate. Also, Wi-Fi is not used because it may interfere with the navigational systems of the pilots. In aircraft's Li-Fi can be used for data transmission. Li-Fi can easily provide high speed internet via every light source such as overhead reading bulb, etc. present inside the airplane.

1.9.4 Underwater applications:

Underwater ROVs (Remotely Operated Vehicles) operate from large cables that supply their power and allow them to receive signals from their pilots above. But the tether used in ROVs is not long enough to allow them to explore larger areas. If their wires were replaced with light — say from a submerged, high-powered lamp — then they would be much freer to explore. They could also use their headlamps to communicate with each other, processing data autonomously and sending their findings periodically back to the surface. Li-Fi can even work underwater where Wi-Fi fails completely, thereby throwing open endless opportunities for military operations.

1.9.5 Disaster management:

Li-Fi can be used as a powerful means of communication in times of disaster such as earthquake or hurricanes. The average people may not know the protocols during such disasters. Subway stations and tunnels, common dead zones for most emergency communications, pose no obstruction for Li-Fi. Also, for normal periods, Li-Fi bulbs could provide cheap high-speed Web access to every street corner.

1.9.6 Applications in sensitive areas:

Power plants need fast, inter-connected data systems so that demand, grid integrity and core temperature (in case of nuclear power plants) can be monitored. Wi-Fi and many other radiation types are bad for sensitive areas surrounding the power plants. Li-Fi could offer safe, abundant connectivity for all areas of these sensitive locations. This can save money as compared to the currently implemented solutions. Also, the pressure on a power plant 's own reserves could be lessened. Li-Fi can also be used in petroleum or chemical plants where other transmission or frequencies could be hazardous.

1.9.7 Traffic management:

In traffic signals Li-Fi can be used which will communicate with the LED lights of the cars which can help in managing the traffic in a better manner and the accident numbers can be decreased [1]. Also, LED car lights can alert drivers when other vehicles are too close.

1.9.8 Replacement for other technologies:

Li-Fi doesn't work using radio waves. So, it can be easily used in the places were Bluetooth, infrared, Wi-Fi, etc. Are banned.

1.10 Hybrid Li-Fi – Wi-Fi

To tackle the rapidly growing number of mobile devices and their expanding demands for Internet services, network convergence is envisaged to integrate different technology domains. A recently proposed and promising approach to indoor wireless communications is integrating light fidelity (Li-Fi) and wireless fidelity (Wi-Fi), namely a hybrid Li-Fi - Wi-Fi. This type of network combines the high-speed data transmission of Li-Fi and the ubiquitous coverage of Wi-Fi.

1.11 Hybrid Wi-Fi - Li-Fi Network and It's Structure

Wi-fi (Wireless Fidelity) Network is a wireless (no wires) network that connects to your Internet router and wireless-enabled devices (such as laptops, smartphones and printers) in your home using a wireless radio signal. An alternative short-range wireless communication technology is visible light communication and its networking variant, light fidelity (Li-Fi). In Li-Fi, light-emitting diode (LED) lamps act as access points (APs). and light is used as a medium to carry information bits via intensity modulation and direct detection. At the receiver, a photon diode (PD) is employed to collect photons and convert them into electric current. Unlike the radio-frequency (RF) techniques including Wi-Fi, Li-Fi does not experience interference from other sources because it is contained within a specific area. And light is not transferred through opaque objects such as walls. Li-Fi is capable of offering high-speed data transmission in the GBPs range. But Li-Fi has a smaller coverage area than Wi-Fi, around 2-3 m diameter. In order to provide enhanced coverage, we can use a hybrid Li-Fi and Wi-Fi network, which combines the high-speed data transmission of Li-Fi and the relatively large coverage of Wi-Fi. Such a hybrid network can achieve a greater throughput than a single Wi-Fi or Li-Fi network. In this case, all of the users are first connected to the Li-Fi network, and then those of low achievable data rates are switched to Wi-Fi. This network may fail to take into account when required data rates might vary with users. Hybrid network is more complicated than homogeneous network. For homogeneous networks, a straightforward access point method is to select from which the user can receive the strongest signal. This method is called the signal strength strategy (SSS), which is widely used in the current wireless networks. In homogeneous network, access points are deployed in a way with little coverage overlap to avoid inter-cell interference. In this situation, unbalanced load occurs when the required data rates of users are unequally distributed among the coverage areas of the access point. But in hybrid network, the coverage areas of different networks overlap each other. If the traffic demands are equally distributed Wi-Fi still faces more traffic load than Li-Fi due to a larger coverage area. This makes the signal strength strategy infeasible for a hybrid network, and load balancing is an important factor here. Consider a generalized hybrid Li-Fi and Wi-Fi network for indoor downlink communications, where a number of rooms or compartments are taken into account, as in the following Fig.

Here, each room has a number of ceiling LED lamps, each lamp is enabled as a Li-Fi access point covering a fixed area. Also, there is a Wi-Fi access point in each room, providing coverage for the entire room. Though the access points may be irregularly placed in room, we assume Li-Fi access points to be arranged in a rectangular shape and Wi-Fi access points at the center of room for the purpose of simplicity. Carrier sense multiple access with collision avoidance (CSMA/CA) is used in the Wi-Fi system, and therefore no interference occurs among Wi-Fi access points. And in Li-Fi system, all of the Li-Fi APs reuse the same bandwidth. Since light does not penetrate walls, interference only exists between those Li-Fi access points in the same room. At each Li-Fi access point, time-division multiple access (TDMA) is adopted to serve multiple users.

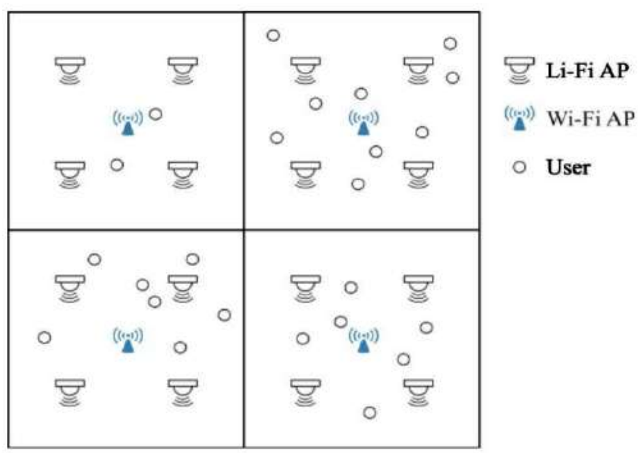

Fig 1.11: Li-Fi and Wi-Fi AP

1.12 Mirror-Assisted Li-Fi Range Expansion

As mirrors reflects light comes from an object, we may use the mirror by setting them in an efficient angle, so that the mirrors can reflect the light which came from LED and that can be received by another mirror and so on. But there are some problems in this method as finding the right angle and it is complicated to calculate intensity of light increased in the area. For that we can use spherical mirrors such as convex mirror & concave mirror.

1.13 Research Problem

Although Li-Fi can offer many advantages there are some disadvantages as well. For starters, Li-Fi doesn't work under direct sunlight because the sunlight blocks the path of the ray of light given by the LED lamp. Furthermore, it can't go through bricks or walls, so it can only be used in a single room. If you want to move to another location, you have to make sure there is also an LED bulb to make the connection to the receptor. Another disadvantage is that it doesn't work with the LED lights turned off (the lights need to be on in order to transmit data but they can be dimmed down), this being an issue and also a concern on the power bill and usage. It only works on those devices (tablets, smartphones, etc.) that have a Li-Fi receptor. Li-Fi entails line of sight (LOS) and the receiving device can't be shift in indoors. Li-Fi entails line of sight (LOS) and the receiving deceives can't be shifted in indoors. A key challenge is how the receiving device LI-Fi technology will transmit the data back to transmitter. Another significant issue is intrusion from external light sources like normal bulbs, sun light; dense materials in the path of transmission will cause disruption in the communication. Another disadvantage is Li-Fi doesn't work in the dark. As light can't pass through objects, so if the receiver is inadvertently blocked in any way, then the signal will instantly cut out. And the signal might be easily blocked by someone simply walking in front of the LED source.

1.14 Objectives

The aims of the research are:

- Expand the LED's range
- To reduce costs.
- To prevent losing efficiency.

1.15 Thesis Organization

This thesis is organized in the following way.

Chapter 1 introduces the significance of the research, research contributions, research aims, and objectives, research methodology, thesis layout, and summary. Chapter 2 provides background information about the Li-Fi networks which comprises of, the definition, evolution, system operation, system architecture, advantages and disadvantages of Li-Fi network, LAC network, downlink transmission and handover description.

Chapter 3 presents the literature review of handover algorithms, load balancing, multiple beams and inter cell interference.

Chapter 4& 5 presents the modelling and simulation results including Li-Fi and Wi-Fi hybrid model and Mirror-Assisted Li-Fi Range Expansion

Chapter 6 describes the conclusions, limitations and future works.

Chapter 2

Literature Review

2.1.1 Simulation and Evaluation of Li-Fi data Transmission and Reception using LED and Photodiode

A PC-to-PC data transmission in terms of Li-Fi visible light communication has been reviewed and Li-Fi transmitter and receiver circuits have been simulated using a simulation tool. The LED was acting as a light emitting source which was used to transmit the data from a PC and the photodiode was used as a receiver of the light signals. A simple data transmission and reception can be replaced by the image files or video files transmission. The simulation results were observed by transmitting and receiving the data which are examined and encouraged. As a future work, the Li-Fi technology can be implemented using the real-time hardware system. The system can be tested by transmitting and receiving various medical images within a hospital premises so that a huge amount of time will be saved by the physicians. Also, if the Li-Fi facility is carefully designed and placed in public and commercial areas, it will be substituting and replacing a Wi-Fi hotspot. [3]

2.1.2 Implementation of Li-Fi Technology in Classrooms

As the technology is expanding, the students have to be educated well to understand these things. Some topics cannot be explained by the conventional system of teaching so we need an interactive place so that the students can have a clear insight of the knowledge. Evolving technologies like 3D printing and nanotechnology can be easily understood visually. Traditional teaching methods cannot give a deeper insight about it. So, digital technology is much needed to make students understand well. An efficient data transmission technology can easily accomplish a difficult task of transmitting heavy data. There is a continuous development happening in communication method in many areas, so to keep it up with the time we also need to implement these new methods in education field as well. Also, traditional method of teaching required very skilled teachers so that the student can have better knowledge. Which visual technology teachers with a little less knowledge can also teach students efficiently? Hence, it does not give much work load to the staff as well. We hope that the design proposed in this paper will be implemented and will work efficiently. [5]

2.1.3 Design and analysis of Li-Fi system

The purpose of presented work was to project a Li-Fi based data communication arrangement from transmitter to receiver system. The designed system discussed in this work is suitable in parameters such as cost, speed, and data transfer capability. The arrangement, design, implementation, and simulations of presented work has been performed in research lab. The idea of Li-Fi is of a boundless interest because it offers an efficient substitute against RF wireless communication system. The present work is majorly software based. We are targeting for hardware-based systems capable of communicating with larger data. Achieving more distance of communication and better power efficiency will be targeted for future work. Using the better configuration of devices and arrayed structure the data rates as well as efficiency of data transfer can be improved. From analysis point of view, the angle between the transmitter and receiver followed by optical rays also places a crucial role in the speed and bandwidth of data transmission. We will be targeting to analyze the factor of angle in our future work. [6]

2.1.4 Testbed for a Li-Fi System integrated in Streetlights

In this paper, a Li-Fi system prototype implementing was shown. All the operating modes of the physical layer according to the specifications of the IEEE 802.15.7 standard are implemented. This development is based on FPGAs. Besides, the prototype includes a circuit. The testbed is proposed for a scenario with streetlights, for which the results have been validated. The transmitter and the channel have been tested. The effect of the ambient light has been observed. Future works are focused on improving the achieved rates using more sophisticated modulation scheme such as OFDM. As well as, performing the same work with the receiver. [7]

2.1.5 Design and Performance Evaluation of Large-Scale VLC-based Indoor Positioning Systems under Impact of Receiver Orientation

In this paper, we proposed and investigated the performance of the VLC-based IPS using the RSS-based triangulation method and OOCs. We also proposed a localization enhancement method to minimize the LE under the impact of receiver orientation. Simulation results showed that the polar and azimuth angle have different effects on LE. In particular, the increase in LE was mainly caused by the change of the polar angle while the impact of azimuth angle was not significant. In addition, a simple proof-of-concept was developed to confirm the effectiveness of the link layer design with the use of Golay code. Experimental results showed that the proposed system achieved an acceptable ID detect ability for practical scenarios of user mobility. [9]

2.1.6 Potentialities and challenges of VLC based outdoor positioning

In this paper, we explain difficulties in outdoor positioning based on VLC. It is shown that the ambient light, especially sunlight is the biggest problem causing many indoor VLC positioning function less in outdoor environment. Then we survey existing VLC based positioning techniques including: trilateration, triangulation, and collinearity condition based. Both trilateration and triangulation-based techniques use PD as receiver and thus are vulnerable to ambient light in outdoor environment. Collinearity condition-based techniques, in the other hand, employs image sensor as receiver. Although collinearity condition-based techniques suffer from many sources of error including ambient light noise, sensor resolution, lens distortion, and lens FOV, the capability of standing against even sunlight noise makes it become the most promising technique for outdoor positioning-based VLC. [11]

2.1.7 Visible Light Communications: improving data rate, link margin and field of view

The combination of visible light and communications offers the potential for extremely high data rate wireless transmission to augment the available RF wireless approaches. This will become increasingly important, as the predicted growth in demand for wireless data far outstrips the RF spectrum available to fulfill this. As the results presented here show, multi-Gbit/s communications is possible with LEDs, and there are promising approaches to ‘engineer’ these to the point where they can be applied in ‘real-world’ situations. [12]

2.1.8 Performance Limits of Visible Light-Based Positioning for Internet-of-Vehicles: Time-Domain Localization Cooperation Gain

In this paper, the performance limits of vehicular VLP for mobile UEs are comprehensively studied. Specifically, a closed-form CRLB for the UE location and orientation, respectively, is obtained, which can give insights into the informative contribution of prior knowledge, UE mobility and observation information to the overall VLP performance. Moreover, the time-domain evolution of the VLP error is studied, which sheds light on the long-term VLP performance and helps understand the essence of time-domain localization cooperation. The obtained closed-form CRLBs on UE location and orientation errors can not only serve as a performance benchmark for practical vehicular VLP systems, but also give insights into how system parameters and LED deployment affect the UE location and orientation estimate performance. [13]

2.1.9 LED Based Indoor Visible Light Communications: State of the Art

The spectral and bandwidth drawbacks of RF communication motivate the use of visible band for communication purposes. LEDs have emerged as one of the most energy efficient and promising lighting infrastructure; with the unit prices expected to decrease, the market adoption and domination of LED light sources is inevitable. The fast-switching capability of LEDs allow them to be used as an optical source in VLC. In this paper, VLC link structure as well modulation schemes and dimming methods were discussed elaborately. Different modulation and dimming schemes have different characteristics and are expected to be chosen based on the functional requirements of the application they are used in. Recent progress amongst various research groups associated with VLC, enabled communication speeds of above 1 Gb/s. There are various system level issues VLC is currently facing such as interference, noise, shadowing etc. which is preventing its rapid growth. By the efforts initiated by the related research communities, these issues are foreseen to be countered, making way for VLC to be a promising communication technology for indoor applications. The future prospects of VLC look bright, primarily with the ever-increasing popularity of LEDs. With LEDs anticipated to rapidly replace traditional lighting technology, VLC is foreseen to be readily implemented into general lighting infrastructures which will give rise to several beneficial applications. By turning on a switch, broadband internet can be accessed by the same fixture which is providing illumination. VLC together with PLC can be part of a ‘Smart grid’, capable of controlling and keeping track of any device connected to the grid. The user could communicate with the ‘home network’ through VLC. [15]

2.1.10 Cooperative Load Balancing in Hybrid Visible Light Communications and Wi-Fi

In this paper, various VLC cell formation schemes and a heterogeneous system constituted by WLANs and VLC networks were investigated. We studied the regular design concept borrowed from cellular networks relying on different FR factors in VLC environments as well as of merged multi-AP cells employing either CT or ZF-based VT. To solve the essential LB problem in the context of our VLC/Wi-Fi hybrid system, both centralized and distributed algorithms were invoked for implementing a PF scheduler. We analyzed the MBE of different VLC cell formations as well as the throughput and fairness of the hybrid VLC/Wi-Fi system. By employing a sophisticated VT among all the 16 VLC APs, the VLC network becomes capable of providing a higher MBE, while the hybrid system is capable of providing a higher average throughput without any sacrifice of the fairness, when the Wi-Fi data rate is modest.[16]

2.1.11 A Hybrid Radio Frequency and Broadcast Visible Light Communication System

In this paper, we have proposed and analyzed a hybrid system that integrates directional broadcast VLC channels with an omnidirectional RF channel. Through analytical and simulated analysis, we have shown that our system provides additional aggregate capacity and alleviates contentions on the RF channel. The dynamic allocation of users between downlink channels has been investigated and we provided potential results of an optimal allocation scheme and potential VHO mechanism. In summary, the proposed system represents an opportunity to bring VLC to market without acting as a competitor to conventional RF devices. Developing VLC systems that supplement Wi-Fi allows the aggregate capacity to increase linearly as the number of VLC channels increases. This scalability offers benefits in overall system throughput that will be needed as we trend towards the forecasted increases in wireless network traffic. [17]

2.1.12 Two-stage Access Point Selection for Hybrid VLC and RF Networks

In this paper, a novel two-stage APS method was proposed for hybrid VLC and RF networks. Based on the concept of FL, the proposed method first determines which users should be served by the RF system, and then assigns the remaining users to the VLC network. Compared with the conventional two-stage APS that assigns all of the users to VLC and then migrates some to RF, the new method intelligently exploits the limited resource of RF and hence improves the overall network performance. Also, the proposed method takes different required data rates into account. Simulation results show that our method can greatly outperform SSS, LB and the conventional two-stage APS. Future research will involve a comprehensive analysis of optimality and complexity for the proposed method, in comparison with the optimization method. [18]

2.1.13 Light Fidelity (Li-Fi) Technology

The possibilities are numerous and can be explored further because the concept of Li-Fi is currently attracting a lot of eye-balls because it offers a genuine and very efficient alternative to radio based wireless. It has a good chance to replace the traditional Wi-Fi because as an increasing population is using wireless internet, the airwaves are becoming increasingly clogged, making it more and more difficult to get a reliable, high-speed signal. In the future, data for laptops, smart phones and tablets can be transmitted through light in the room by using Li- Fi. Researchers are developing micron sized LED which are able to flicker on and off around quicker than larger LED. If this technology can be put into practical use, every bulb can be used as a Wi-Fi hotspot to transmit wireless data and we will proceed toward the cleaner, greener, safer and brighter future. This concept promises to solve issues such as the shortage of radio-frequency bandwidth and boot out the disadvantages of Wi-Fi. Li-Fi is upcoming and on growing technology acting as competent for various other developing and already invented technologies. Hence the future applications of the Li-Fi can be predicted and extended to different platforms and various walks of human life [19]

2.1.14Li-Fi Technology Transmission of data through light

There is a plethora of possibilities to be gouged upon in this field of technology. If this technology becomes justifiably marketed then every bulb can be used analogous to a

Wi-Fi hotspot to transmit data wirelessly. By virtue of this we can ameliorate to a greener, cleaner, safer and a resplendent future. The concept of Li-Fi is attracting a lot of eye-balls because it offers a genuine and very efficient alternative to radio based wireless. It has a bright chance to replace the traditional Wi-Fi because as an ever-increasing population is using wireless internet, the airwaves are becoming increasingly clogged, making it more and more difficult to get a reliable, high-speed signal. This concept promises to solve issues such as the shortage of radio-frequency bandwidth and boot out the disadvantages of Wi-Fi. Li-Fi is the upcoming and on growing technology acting as competent for various other developing and already invented technologies. Hence the future applications of the Li-Fi can be predicted and extended to different platforms and various walks of human life. [20]

2.1.15 Li-Fi: The Future Technology in Wireless Communication

If this technology can be put into practical use, every bulb can be used something like a Wi-Fi hotspot to transmit wireless data and we will proceed toward the cleaner, greener, safer and brighter future. The concept of Li-Fi is attracting a lot because it offers a genuine and very efficient alternative to radio based wireless. This concept promises to solve issues such as the shortage of radio-frequency bandwidth and boot out the disadvantages of Wi-Fi. [21]

2.1.16 Downlink System Characterization in Li-Fi Attocell Networks

This paper addressed multi-point joint transmission in indoor optical atto-cell networks in order to achieve seamless coverage, high data rate and multiple access. The performance of a cellular system that applies joint transmission was compared to the performance of a full frequency reuse system and a static resource partitioning system with a reuse factor of three. The results showed that the joint transmission systems achieved higher cell edge SINRs compared to a full frequency reuse system in addition, a joint transmission system also achieved 67.6% improvement in terms of median system throughput compared to a static resource partitioning system. However, the downside of joint transmission systems is that they need extra signaling overhead. [22]

2.1.17 Handover Modeling for Indoor Li-Fi Cellular Networks: The Effects of Receiver Mobility and Rotation

Handover modeling for indoor Li-Fi cellular networks is proposed for the first time. It is found that the receiver rotation has a significant effect on the handover performance based on the receiver tipping and tilting angles, β and γ, respectively. For a network area of 10 × 10 m2, the highest handover probability due to the receiver movement is observed for 60◦ ≤ β, γ ≤ 80◦. Also, assuming that the user moves with a typical speed of 1 m/s, it is found that the effect of tilting the UE toward right (or left) on the handover rate is more than tipping the UE toward (or away from) the user. Future works will consider extended analysis of the RSI-based and bandwidth-based handover mechanisms in Li-Fi networks. [23]

2.1.18 A guide to wireless networking by light

With the popularity of smart devices, there is a growing demand for wireless communications resulting from new applications such as virtual reality and high-definition TV. In addition, it is predicted that the IoT and Industry 4.0 will create an explosion in the number and diversity of devices. All these new trends will require new means of providing wireless communications in a wide range of environments. A crucial aspect of this is the allocation of a new spectrum for additional capacity. Li-Fi networks, using visible light communications, have the potential to provide this with high capacity in the environments with very high user and device density. This paper highlights the challenges of providing wireless communications networks using light, including interference and deployment strategies, and introduces a framework for determining the key parameters in their performance. Specifically, it has shown that an integrated and holistic approach is needed to address these challenges. Optical devices, and their arrangement in an optical transceiver, affect the performance of networking techniques such as interference mitigation algorithms and multiuser access techniques. Similarly, optimum networking performance imposes specific requirements on optical devices and optical sub-systems. Therefore, the techniques that have led to record data rates in fixed point-to-point link-level VLC systems may only be sub-optimum in Li-Fi network deployments. Therefore, further work in this area from researchers in devices and networks is required. [24]

2.1.19 Access Point Selection in Li-Fi Cellular Networks with Arbitrary Receiver Orientation

One of the main problems of the signal strength technique for AP selection is that the load of APs is not taken into account. Thus, users may connect to an overloaded AP and leave other APs idle. By considering the load balancing among APs and to provide a better user's QoS, a new metric for AP selection in Li-Fi cellular networks with arbitrary receiver orientation was proposed. The orientation of users was modeled and the performance of randomly rotated and perpendicular PDs for both proposed and conventional AP selection metric was evaluated. The performance was assessed in terms of user average throughput, satisfaction level and fairness index. The simulation results show a better performance for the proposed method compared to the signal strength technique, especially when the number of users or the requested data rate increases. [26]

2.1.20 In-House Data Communication via Diffuse Infrared Radiation

We have analyzed the physical aspects of the diffuse optical channel and demonstrated technical feasibility. With the wireless transmission scheme great flexibility in terminal arrangement may be achieved. An experimental PCM baseband link and a PSK link, operating at 125 kbit/s and 64 kbit/s, respectively, have been built. The channel is suitable for low to medium speed transmission at low error rates and free from EMI. With present low-cost state-of-the-art LED's, the maximum transmission speed is around 100 kbit/s due to the limited modulation capability of the LED. Higher transmission speeds up to 1 Mbit/s appear feasible if increased optical power raises no objection. There is scope for improving the performance and reducing the cost of the satellite and terminal interfaces. Current trends indicate a decrease of hardware costs for optical components and circuitry, whereas costs of copper cables and labor for pulling cables are not likely to be reduced. Expenditure for fiber optics is still relatively high and the present state of development favors individual point-to-point links rather than distributed systems with a large population of users. There is, therefore, a challenge in identifying new applications of local area networks where the wireless optical link can offer distinct advantages. [27]

2.1.21 Performance Modeling of the IrDA Protocol for Infrared Wireless Communications

Using an analytical model based on the concept of the "virtual transmission time," we show that it can be successfully applied to the IrL AP protocol, which is based on HDLC in NRM mode. The results of the model are also successfully verified using a network simulation package. We present results for throughput efficiency against data message length, bit error rate, and minimum turnaround time. We indicate possible limitations and improvements of the present IrDA protocol in supporting higher bit rates (e.g., 10 Mb/s and above. We show that the link turnaround time must be minimized, and the maximum window size should be increased for improved highspeed performance. [29]

2.1.22 Practical considerations for indoor wireless optical system implementation using OFDM

Practical implementations of an OW communication system based on OFDM are discussed in this paper. Due to the low channel delay spread for indoor OW applications, it is shown that the CP has insignificant impact on power and bandwidth efficiencies. It is also shown that Doppler frequency results in a very small shift to the actual peak wavelength which corresponds to insignificant SNR variations. The main time and frequency distortions in OW communication is mainly due to the sampling offsets. Another major challenge is the nonlinear behavior of the LED due to the high PAPR of the OFDM signal. The optical receiver frontend is the dominant source of noise which determines the overall system performance and SNR. Finally, OFDM is promising solution for indoor OW communication systems; however, several issues need to be further considered. [30]

2.1.23 OFDM-Based Optical Spatial Modulation

In this paper, two of the major OFDM-based optical SM techniques, namely FD-SM and TD-SM were investigated. The spatial symbols are encoded in the subcarrier level in FD-SM which brings ICI, TX/RX complexity and spectral efficiency loss. Conversely, in TD-SM technique, the spatial symbols are encoded in the time domain as suggested by conventional SM. It has been shown that TD-SM inherits all the merits of conventional SM. Moreover, TD-SM techniques achieve significantly higher spectral efficiency compared to FD-SM. Both systems have been validated in terms of BER performance by Monte Carlo computer simulations as well as, for the first time ever, experimental results. It has also been shown by using extensive simulations and demonstrating the proof-of-concept experimental results that the TD-SM with an optimal MAP detector outperforms FD-SM in terms of the BER performance. Consequently, the experimental results verify and suggest that TD-SM is a viable candidate for next generation OFDM-based SM. [31]

2.1.24 Access Point Selection for Hybrid Li-Fi and Wi-Fi Networks

In this paper, a two-stage APS method was proposed for hybrid Li-Fi and Wi-Fi networks, by exploiting the distinguishing characteristics between those two networks. The proposed method at first determines the users that need service from Wi-Fi, and then assigns the remaining users as if in a homogeneous Li-Fi network. The concept of fuzzy logic is applied in the first stage to rank the user's priority of accessing Wi-Fi. In the second stage the SSS or LB can be employed, and the proposed method is named the FL-SSS or FL-LB correspondingly. Based on experimental results and complexity analysis, it is shown that compared to the optimization method, the proposed method achieves a near-optimal throughput at significantly reduced complexity. In addition, the FL-LB marginally outperforms the FL-SSS with a slight increase in complexity. Compared with the SSS and LB, results show that FL-LB can improve the network throughput by 24% and 11%, respectively. Future research will involve cellular network in the context of a hybrid network. [33]

2.1.25 A Wireless Backhaul Solution Using Visible Light Communication for Indoor Li-Fi Attocell Networks

A novel wireless VLC backhaul solution is proposed for indoor optical attocell networks. The FR and IB bandwidth allocation methods are introduced to apportion the system bandwidth to the access and backhaul links for both AF and DF relaying protocols. By studying the average downlink spectral efficiency performance of the network, it is identified that the performance depends on the emission semi angle, Φb, of the auxiliary LEDs used for the AP-to-AP links. It is found that the FR backhaul outperforms the IB backhaul over a broad range of values for Φb. This highlights the benefit of the FR method due to the exploitation of the entire system bandwidth for the access and backhaul links, despite the higher interference compared with the IB method. It is also found that for either FR or IB methods, DF relaying outperforms AF relaying for $\Phi b \geq 25^\circ$. Future research will consider an extended analysis for the performance of optical attocell networks with wireless backhaul and will study the effects of downlink LED semi-angle, vertical separation and cell radius. [34]

2.1.26 IJERT-SNR Analysis for Visible Light Communication Systems

In this paper we proposed the use of multiple input multiple output system for indoor optical wireless communication systems as compared to single input single output systems. The simulations are done for SISO, 2x2 MIMO and 4x4 MIMO systems. It is seen that 4x4 MIMO gives better results as compared to the other two systems at higher data rates and large field of view angles. The 4x4 system also provides better illuminance as compared to the other two systems. [36]

2.1.27 Li-Fi is a paradigm-shifting 5G technology

In this paper we have shown that there has been a clear trend in wireless communications to use ever higher frequencies. This is a consequence of the limited availability of RF spectrum in the lower frequency bands of an exponential growth in wireless data traffic that we have been witnessing at the same time during the last decade. This growth will continue. It is, therefore, inevitable that other spectrum than the RF spectrum must be used for future wireless communication systems. We, therefore, forecast a paradigm shift in wireless communications when moving from mm-wave communication to nm-wave communication which consequently involves light – i.e., Li-Fi. There has been significant research in physical layer technologies for Li-Fi during the past 15 years and data rates have increased from a few Mbps in around 2002 to 8 Gbps from a single LED in 2016. In the last five years there has been increasing research in Li-Fi networking techniques such as multiuser access, interference mitigation and mobility support, and in parallel Li-Fi products have entered the market which have enabled wireless networking with light. Therefore, Li-Fi has become a reality and this technology is here to stay for a long time. [37]

2.1.28 A Low-Cost Indoor Positioning System Using Bluetooth Low Energy

In this work, we proposed a low cost BLE sensing based system for person localization in the home. A BLE beacon is used as the tracking object that attached on the target user. Our BLE sensing based system localizes the position of the BLE beacon through two proposed algorithms. One method used the trilateration algorithm to track the position of the BLE beacon in a known coordinate reference frame. Another method used the fingerprinting-based method to locate the BLE beacon in one of the 36 1m2grids or one of Location-of Interest. The smoothing method has been proposed in order to remove the noise of from the raw RSSI values. Our experimental results have shown good accuracy in indoor positioning. From our results, it can be seen that high accuracy can be obtained in localizing around key areas/stay points (table, bed, etc.). Our fingerprinting-based method demonstrated that as even with low-cost sensors, a high accuracy (>90%) achieved. Our results have shown this is consistently true for different devices in different home settings. In our experiments, we had collected large datasets for evaluation. However, in real world testing, there is no need to collect so many samples. Based on our results from dynamic testing, only 5mins data collection at each labelled location will suffice. The cost of the overall system is around USD$200 making it scalable for a wide range of people who would benefit from monitoring even if they are only mildly at risk (e.g., people at the early stages of dementia). This may enable longer independent living with beneficial impact to both the individual, their relatives, and the national health system. In addition, Wi-Fi passive sensing approaches shares the similar working principle with the above BLE sensing approach. It locates the target by tracking the RSSI changes in the tracked object (a Wi-Fi device, usually a smartphone). It can be useful if the mobile phone is the tracked object. There are Wi-Fi modules available that have a smaller size and can be attached to human body as that of a BLE beacon. However, a Wi-Fi device usually consumes more battery than a BLE device (a BLE beacon or a smart watch). As for future work, we will implement our system in real world applications to investigate the indoor pattern for people with significant physical disabilities and for those with neurological conditions e.g., people living with dementia, people affected by stroke, Parkinson's disease, epilepsy, etc. This could help the clinicians and doctors understand and diagnose the individuals in home rehabilitation. [38]

2.2 Summary

By reviewing the papers mentioned above, I came to the conclusion that there has been significant advancement regarding Li-Fi technology, they used, a two-stage APS method was proposed for hybrid Li-Fi and Wi-Fi networks, by exploiting the distinguishing characteristics between those two networks, OFDM-based optical SM techniques, namely FD-SM and TD-SM were investigated. The spatial symbols are encoded in the subcarrier level in FD-SM which brings ICI, TX/RX complexity and spectral efficiency loss, The FR and IB bandwidth allocation methods are introduced to apportion the system bandwidth to the access and backhaul links for both AF and DF relaying protocols, but one of the massive lacking was on the increasement of Li-Fi range, which will be the main motive of this research.

Chapter 3

Methodology

3.1 Load Balancing (LB)

Some studies about load balancing (LB) methods in Li-Fi were conducted in [25], [26], [27], [28] and [29].

Load balancing technique is applied when there are more than one networks covering the same areas in order to avoid overlapping between these networks [25]. In, in order to maximize the proportional fairness (PF) index of all users to solve the problems related to the resource allocation and coordination, there is a need for optimizing the power allocation of the hybrid Li-Fi/Wi-Fi network under the constraint of common backhaul. The Li-Fi and Wi-Fi backhaul system model is shown in the Fig. 3.1.1

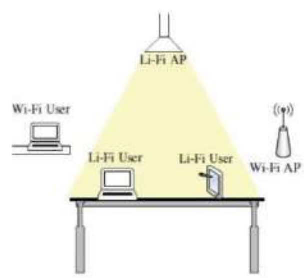

Figure 3.1.1: Li-Fi and Wi-Fi backhaul system model [25]

More specifically, the rate and power allocation algorithms are used to guarantee the maximized values of PF among all users are applied in the downlink scenarios only. In the case of low backhaul capacity, similar data rates can be shared among Li-Fi and Wi-Fi users. Otherwise, the Li-Fi users might have higher data rates than the Wi-Fi users by taking advantages of this condition. Two dynamic LB schemes in Li-Fi and RF hybrid network are proposed: Joint Optimization Algorithm (JOA) and Separate Optimization Algorithm (SOA). These algorithms are used to jointly and separately optimize the AP assignment and resource allocation, respectively. The following figure shows the schematic diagram of this proposed model. Both algorithms provide optimized fairness coefficient and data threshold to achieve the maximized QoS. The research work in [26] shows that in a typical indoor environment, over 90% of users in JOA achieve the maximum QoS which is 1.3 times larger than that in SOA and the JOA also provides the medium data rate 1.5 times higher than the SOA does. In terms of LB, SOA has a better trade-off between performance and complexity than JOA.

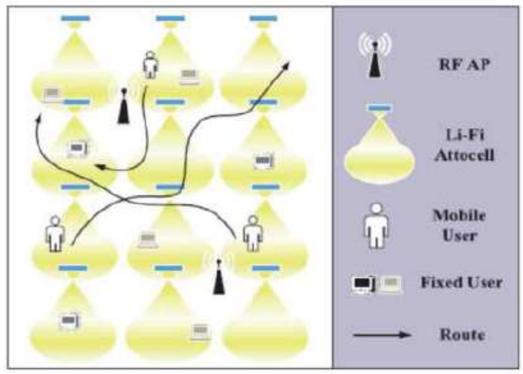

Figure 3.1.2: Schematic diagram of the system model.[26]

The Fuzzy Logic (FL) was used to determine a user's throughput based on CSI [27]. A two-stage Access Point Selection (APS) method was suggested for Li-Fi and Wi-Fi hybrid networks, which is shown in Fig. 3.1.3. Firstly, the algorithm determines which users require service from Wi-Fi, and then assigns the remaining users to a homogeneous Li-Fi network. In this stage, the priority of access the Wi-Fi of users is ranked by applying the Fuzzy Logic (FL) concept. Secondly, the Signal Strength Strategy (SSS) or LB is applied with the proposed method named the Fuzzy Logic-SSS (FL-SSS) or Fuzzy Logic-LB (FL-LB) correspondingly [27]

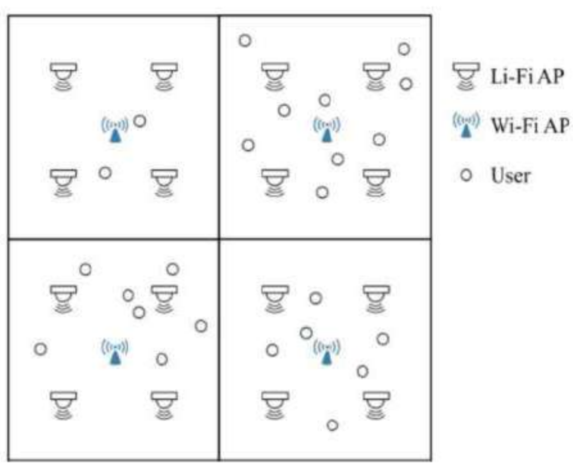

Figure 3.1.3: Schematic diagram of the system model.[27]

Based on the experimental results, it is shown that the proposed method achieves a near-optimal throughput with the complexity was reduced significantly [28]. And the FL-LB outperforms the FL-SSS with a slight increase in complexity and the FL-LB can improve the network throughput by 24% and 11% when compared to SSS and LB respectively. A dynamic LB scheme which is based on FL was proposed to prevent the handover effects in Li-Fi/RF hybrid network (Fig. 3.1.4)

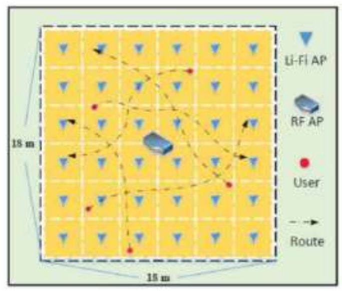

Figure 3.1.4: Simulation Scenario of Li-Fi/RF Hybrid Network [28]

In the proposed algorithm, the speed and average Signal to Interference Noise Ratio (SINR) of users who are measured in order to allocate users which have high speed or are experiencing transient shadowing effect to suitable APs, and also reduce the ping-pong handover pattern. The research work shows that this dynamic LB scheme which is based on FL has lesser data rate loss than the traditional LB algorithms, and both QoS and data rate of users have improved 40%. A two-stage APS method was proposed for hybrid Li-Fi and RF networks [29]. This model is shown in Fig. 3.1.5.

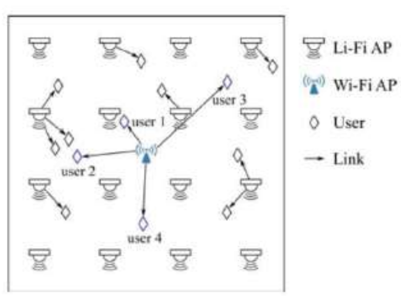

Figure 3.1.5: Paradigm of an indoor hybrid Li-Fi/RF network [29]

Firstly, users are served by the RF system and then the remaining users are assigned to the Li-Fi network [30]. By applying this method, the limited resource of RF system is exploited and the overall network performance is also improved. The arbitrary receiver orientation is considered to determine the user's SINR and traffic of Aps

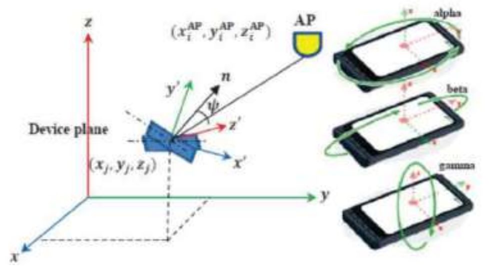

Figure 3.1.6: Modelling of device orientation based on rotations in three axes [30]

A new metric for the selection of APs to provide a better QoS for users with arbitrary receiver orientation is proposed in Li-Fi cellular networks by applying the LB among APs. The performance is evaluated based on three different metrics: user average throughput, satisfaction level, and fairness index in the models of users' orientation. The research work shows that the proposed method has a better performance compared to the signal strength technique, especially when the number of users or the requested data rate rises.

3.2 Multiple Beams

There are several studies related to multiple beams in the Li-Fi network [31]. The angle diversity transmitters are researched to improve coverage areas and this network is shown in the following figure

By applying an angle diversity transmitter, the research work shows that when transmitters have multiple LED elements (37 elements), the spectral efficiency is times higher. It also shows that the optical Space-division Multiple Access (SDMA) system outperforms the optical Time Division Multiple Access (TDMA) benchmark system when considering system performance. It was also proved [31] that the optical SDMA system is good in terms of the user positioning errors (about 14%) compared with other practical state-of-the-art indoor positioning techniques.

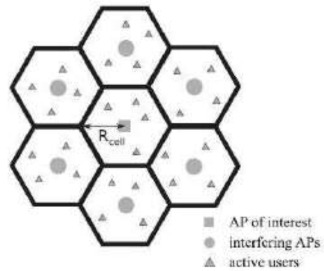

Figure 3.2.1: The layout of a 7-cell attocell network [31]

In order to increase the AP coverage range, the dynamic beam and luminaire control is applied (Fig. 3.2.2)

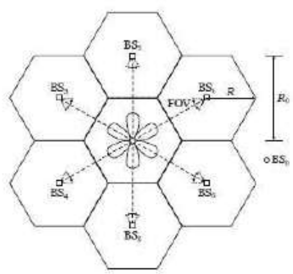

Figure 3.2.2: Hexagonal cellular layout of seven attocells [32]

Two bandwidth allocation methods, including the Frequency Reuse (FR) and In-Band (IB)) are used to divide the system bandwidth into two parts: the access and backhaul links for both relaying protocols [32]: Amplify-and-Forward (AF) and Decode-and-Forward (DF). The research work shows that the performance depends especially on the emission semi-angle of the auxiliary LEDs which are used for the AP-to-AP links in the downlink. It also shows that for either FR or IB methods, DF relaying outperforms AF relaying when the emission semi-angle is larger than 250.

3.3 Intercell Interference

There are several studies related to inter-cell interference [33], a very close approximation to co-channel interference is reachable by applying the Fourier analysis (Poisson summation) in attocell networks. It applies for both single and two dimensions. In addition, in order to provide upper bounds for interference, a high degree of accuracy in calculating interference power is proposed when applying this characterization in attocell networks with any given height to inter-LED separation ratio. In addition, the Fourier analysis method can be applied for the case of the user PDs that have limited FOVs by using the interference characterization. The statistical-equivalent transformation of the SINR is applied to determine the coverage probability for saving energy and minimizing the co-channel interference in multi-user VLC networks (Fig. 3.3)

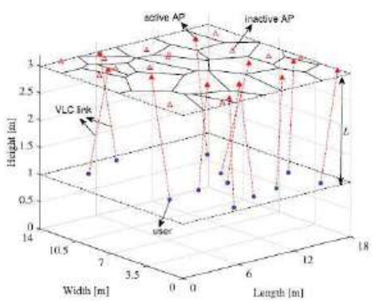

Figure 3.3: Three-dimensional Voronoi cell formation in the Li-Fi network [34]

In this case, by operating the AP sleep strategy in under loaded and general networks, the APs' idle probability is evident. When the AP density is smaller than the user density, the homogeneous Poisson Point Process (PPP) applied for active APs is valid. In addition, the PPP also produces the close coverage results to the exact ones. In the multi-user VLC network, if the noise level of the typical receiver is approximately −117.0 dBm [34], the SINR values are approximated by the SIR when analyzing the simplified coverage performance. The Angle Diversity Receiver (ADR) is used to mitigate interference based on four methods: Select Best Combining (SBC), Equal Gain Combining (EGC), Maximum Ratio Combining (MRC) and Optimum Combining (OPC). The research work concluded that in terms of SIR performance, by using OPC to nearly achieve the interference-free systems, the system using ADR outperforms a single PD receiver system. However, the knowledge of CSI is required in all-optical APs in the network while applying OPC. In contrast, MRC and SBC only require the knowledge of CSI from the desired cell and both of them also have better performance than a single-PD receiver [34]. In addition, MRC and SBC can provide better SINR performance in the double-source cell configuration mode.

3.4 Li-Fi & Wi-Fi Bandwidth Aggregation at the Physical Layer

Any phenomena that can vary in nature and can be received by some sensor can be used as a medium to transmit data, even something as simple as a piano. In the piano example, a 2-FSK system was described where one key (or frequency) represents a 0 and another key represents a 1. As more keys on the piano are used, more bits can be sent simultaneously. In fact, the precise number of bits that can be represented equals $[log2(k)]$ where k is the number of keys involved in the encoding scheme [35]. This can be scaled up, only limited by the number of different modulations possible and the sensitivity of the sensor, or its ability to distinguish one key from another. This scaling up process will be referred to as increasing the number of levels. As the number of levels are increased, more bits can be sent in the same time period than another scheme with less levels. The data rate is subsequently increased as well, which is a crucial metric in computer networks and significantly impacts user QoS. Naturally, the goal of increasing the number of levels translates directly to Li-Fi and Wi-Fi, where finding ways to increase the number of levels will increase data rates and therefore, is an important area of research. To represent different levels to send bits, state-of-the-art Li-Fi uses MM as discussed in chapter 1 and Wi-Fi systems typically use quadrature amplitude modulation (QAM), which is essentially a combination of ASK and phase shift keying (PSK). Previous works have researched leveraging multiple forms of networks or connections when both are available to increase data rate and improve user QoS through a process called bandwidth aggregation (BWA). Most of the research in this realm has focused on aggregating signals from Wi-Fi and broadband cellular. BWA can be done at several levels of the Transmission Control Protocol/Internet Protocol (TCP/IP) stack and to the knowledge of the author, prior research has explored BWA at the data link layer, the network layer, and the transport layer for cellular and Wi-Fi. For hybrid Li-Fi & Wi-Fi networks, only a few works are known to have studied BWA, all of which were implemented at the transport layer where the algorithm essentially serves different requests independently by either Li-Fi or Wi-Fi, but services requests simultaneously. However, no prior research has been found that looked into doing BWA at the physical layer, combining the modulations received through different mediums (radio frequencies and light) into one stream of bits. This concept, termed "bandwidth aggregation at the physical layer," (BWAPL) is the focus. In order to properly explain BWAPL, several assumptions must be made and requirements must be met. Firstly, it is assumed that all other layers of the TCP/IP stack operate as usual. No protocols are modified and no changes are made to existing state-of-the art operations of the other four layers of the model. BWAPL focuses exclusively on bits to signal at the transmitter and signal to bits at the receiver. Additionally, it is assumed that for BWAPL to work, both Li-Fi and Wi-Fi must be available to the UE. This means that the position and orientation of the UE must be one such that the PD is visible and the RF signal is strong enough. If this is not the case, then BWA is not the right choice to transmit/receive data and the UE will be serviced as usual either through Li-Fi or Wi-Fi exclusively depending on which signal is not available. Prior to applying BWA, both sender and receiver must be aware that BWA is being used so the transmitter and receiver know to emit and detect both types of signals, respectively. As previously mentioned in chapter 3, it is fairly easy to quickly calculate the position and orientation of UE and whether or not Li-Fi & Wi-Fi will be available. Based on this determination, the UE's CPU can determine that it is in a pose where both Li-Fi and Wi-Fi can be received simultaneously. When data is requested by the UE [35]; it will begin by sending an uplink request for BWA via IR, which will be received by the CU. A response will be given on downlink via Li-Fi confirming that the UE will be serviced by a BWA composition of signals, or on WiFi declining the request. After the IR uplink request for BWA, the UE will be sensing for a Li-Fi signal and a Wi-Fi signal so it can receive the verdict of its request. After the request is confirmed, the transmitter will service the request via the BWA signals and the receiver will continue to listen over both mediums. This handshake is crucial so the transmitter knows to encode the intended bits in two signals and the receiver knows to decode both signals for that particular stream of packets. A simple encoding scheme will be discussed as an example to clarify this concept. Lastly, it is critical that synchronization between Li-Fi & Wi-Fi is prioritized, since the bit stream for a particular grouping of signals depends on both signals received. There are many ways to synchronize the two, and this will largely depend on the baud rates of the mediums. However, for simplicity, it will be assumed that Li-Fi and Wi-Fi either have the same baud rate or the faster of the two will be slowed to match that of the slower one, so they have the same symbol rate. Other possibilities for mismatched baud rates will be discussed.

BWAPL is, to the knowledge of the author, a novel technique for increasing the number of levels in a computer network and subsequently increasing data rates [35]. As mentioned, it requires that both Li-Fi and Wi-Fi are available to the UE and that RF/light signals are sent simultaneously. Rather than servicing requests independently through one medium, the combination of the two signals received is another way to increase the number of levels and offer great potential to increase data rate. The process begins with the user requesting data. The CPU of the UE then determines the device's position and orientation using methods developed. Based on UE configuration and the availability, the CPU will determine whether or not Wi-Fi and/or Li-Fi are available. If one of the two is not available, the device will send its uplink request via IR or Wi-Fi and be serviced as usual in a hybrid network system. However, if both Li-Fi and Wi-Fi are available, meaning the PD will be visible to the LAP and a strong enough Wi-Fi signal is available, a BWA request will be sent via IR uplink. From this time until the UE receives communication back from the AP, the UE will be detecting for signals over both Li-Fi and Wi-Fi. This request for BWA is received by the AP, and processed by the CU. If the CU is not able to serve both Li-Fi and Wi-Fi, then a decline message will be sent via Wi-Fi downlink to the device and it will be serviced as usual in a hybrid network system. If the CU deems it is able to serve over both mediums, a confirmation message will be sent via Li-Fi downlink and the UE will be serviced by both signals simultaneously. An encoding scheme must be standardized to translate bits to signal at the transmitter and signal to bits at the receiver. There are many options for how this can be done, and they depend on the different levels of MM and QAM available to the network. A very simple encoding/decoding scheme will be presented to anchor this concept. At some point, either Li-Fi or Wi-Fi will likely become unavailable and the communications will need to revert to exclusively one or the other. Again, there are many ways to detect this and determining the best method to do so is an area for future research. However, two potential methods include detecting when the UE is no longer in a position to receive both signals or cutting off the BWA format when a certain number of signals for one medium is missed in a period of time. In order to determine whether or not a user can be serviced through BWA to begin with, calculations are done to determine the UE position and orientation. These calculations can continue throughout the process of servicing the UE and if it is found that they are in a position where Li-Fi or Wi-Fi would not be available, the UE can revert to typical hybrid network service. However, this idea is vulnerable to what is known as the "ping pong effect" where users bounce between two forms of networks due to over sensitivity. As a result, it would be important to have some delay period where a network would have to be unavailable for a certain number of steps or period of time before reverting. This would reduce the sensitivity compared to a system that switches immediately between the BWA Li-Fi & Wi-Fi and typical hybrid network service when a signal is not received. When hybrid networks were first developed and the idea formed to switch between Li-Fi and Wi-Fi when one loses signal, the phenomena of the "ping pong effect"[35] was discovered and many papers focused exclusively on solving this problem. If the community adopts the idea of BWAPL, this will surely be a challenging problem to solve and an important area for future research, although past research on hybrid Li-Fi & Wi-Fi network handovers would be a good starting point. Another concern, although minor, is that it is computationally expensive to calculate the UE position and orientation every time a signal is received. The other idea for detecting if BWA should revert to usual hybrid network operations is much less complex. Instead of calculating the pose of the UE, it is simply detected whether or not both signals were received at a particular time step. If one of the signals are not received, then the system can revert. Again, this idea is sensitive to the "Ping pong effect" [35] and would require research into determining when the appropriate time is to switch between BWA and exclusively Li-Fi or Wi-Fi. Both of the methods for reverting from BWA involved a decision made either at the time of signal receipt or after it. With advances in ML, in particular RL, an interesting area of future research is to predict in advance how UE will translate or rotate and whether or not both light and radio signals will be able to be received. Regardless of the method to decide whether or not to revert from BWA, at some point this decision will be made by the UE's CPU or the CU. If the UE's CPU recognizes that both Li-Fi and Wi-Fi are not available, it will send a request via IR uplink to return to purely Li-Fi or Wi-Fi, specifying which one to transition to. The AP will receive this communication and notify the CU, which will send a downlink confirmation of the agreement via the available medium. If the CU decides that it cannot service over 56both Li-Fi and Wi-Fi, it will only send over the available medium. Eventually, per the previous few paragraphs, the UE CPU will recognize that it is not receiving one of the necessary signals and it will then send the request to transition to pure Li-Fi or Wi-Fi. Another significant concern of BWAPL is synchronization. Li-Fi and Wi-Fi often have different baud rates, or number of signals modulated per second. In order to combine both signals into one bit stream, they must be synchronized in a manner that can be standardized. For example, if the baud rate of Li-Fi is twice that of Wi-Fi, an encoding scheme could be used to decode at the rate of Wi-Fi, but the mapping of signals to bits would involve two Li-Fi signals and one Wi-Fi signal. While the baud rate of one medium could be slowed to match that of the other, this would not make the best use of the maximum possible data rate, as more levels can be achieved through the receipt of three signals (two Li-Fi, one Wi-Fi) than two. If the baud rate of one signal does not divide evenly by the baud rate of the other, the problem becomes a bit more difficult, as 1.5 signals are received over one medium to one signal over the other, for example. However, it is possible to develop a modulation scheme that accounts for this and it would still be beneficial to increasing data rates. The primary concern with synchronization is simply consistency in the baud rate of each signal independently. If either is not perfectly consistent, they will become more and more offset over time until signals begin to overlap with preceding or following signals and errors occur. This issue can be solved by ensuring that Li-Fi and Wi-Fi are independently synchronized to the same clock of the CU. State-of-the-art synchronization schemes such as Manchester Encoding or a non-return to zero (NRZ) variant are easy choices to do so.

3.5 Concave Mirror

This research seeks to improve the range of existing Li-Fi technology. So, the research topic refers to applied research or action research category. To improve the range, the proposal is to use concave mirror to develop the visible light range by increasing the distance and the angle. That indicates our background knowledge should be electromagnetic waves, light properties, mirrors and lens. There are no existing techniques of increasing Li-Fi range. We will propose a new technique. For implanting the system, we propose to use concave mirror which is able to reduce the number of LEDs as well as increase their range efficiently. From various resources done in literature review chapter it was mentioned that if the intensity of LEDs is increased, it increases the range as well. So, we focused on intensity and found some ways as –

- Supplying more current to the LEDs
- Supplying more voltage to the LEDs

But both these methods decrease the LED life. Other ways to increase the intensity are

- Using lens
- Using mirrors

We choose mirror over lens because of its availability and less cost

Ideas of using mirror in various way**:**

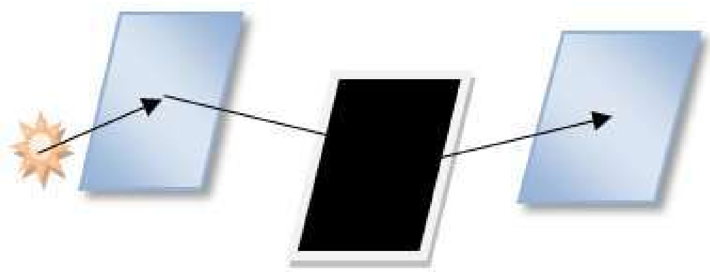

Fig.3.5.1. Reflection of light- mirror to mirror [25]

As mirrors reflects light comes from an object, we may use the mirror by setting them in an efficient angle, so that the mirrors can reflect the light which came from LED and that can be received by another mirror and so on.

But there are some problems in this method as finding the right angle and it is complicated to calculate intensity of light increased in the area. Another way is to use the spherical mirrors. which are

- Convex mirror.
- Concave mirror

Convex mirror never gives any real image

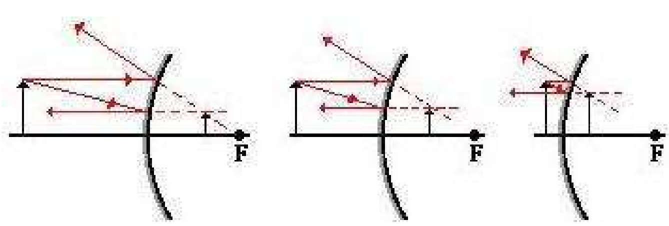

Fig.3.5.2. Image of Convex mirror [25]

The diagrams above show that in each case, the image is located behind the convex mirror, a virtual image, an upright image, reduced in size. Concave mirror gives real and extended image when object is located between center of curvature and main focus. The diagrams above show that in each case, the image is located front the concave mirror. A real image. A downright image. Increased in size. Electromagnetic wave: Light

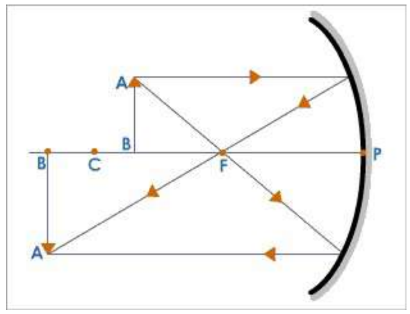

Fig.3.5.3. Image of Concave mirror [25]

The intensity of light is given by pointing vector. It defines the power output per unit area (w/m2) of the electromagnetic wave. Simply it is the changing rate of energy per unit area of any electromagnetic wave.

Luminous Flux and Luminous intensity:

Luminous flux is the measure of perceived power of visible light [25]. Unit is lumens (lm). Simply it is the quantity that tells us how much power a certain light wave carries. 683lm = 1watt of power carried by light of wave length 555nm.Luminous intensity defined as the luminous flux per solid angle. Luminous intensity expresses the directionality of the energy emitted by the light. Solid angle: This is defined as two-dimensional angle define using units knows as steadies.

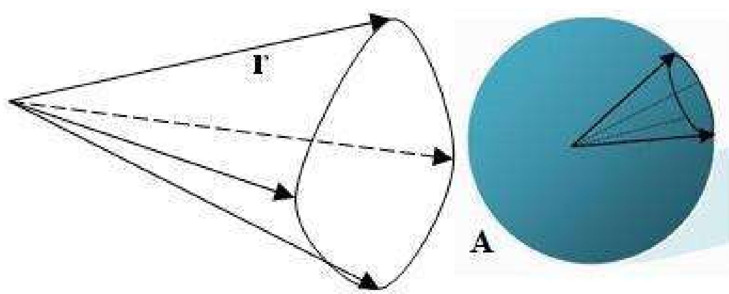

Fig.3.5.4 Solid angle and solid angle in a sphere [25

$$\text{Solid angle} = \frac{Area}{r^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

Where **A** is the surface area on a sphere with radios **r** Luminous intensity can be defined as luminous flux/solid angle.

Light Projection*:*

It is well known that, visible light projects as a cone. And the more is the distance is less the intensity. Now, considering a light source without a mirror behind. The source. So simply we can consider it as a cone. With the use of a mirror, we may able to expand the angle.

Fig.3.5.5. Light Projection [25]

Now there are 2 things to be concerned,

- What happened if the angle is expended
- How the angle can be expended

As we know from the definition of solid angle,

$$\text{Angle} = \frac{Area}{r^2} \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

$$\text{or, } Area = angle \times r^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

So, from equation we can say area increases when the angle increases. That means if angle can be expanded, then it is possible to cover more area. To expand the angle, we propose to use concave mirror. As mentioned before when the object is situated in between center of curvature and main focus, it gives inverted but a real image which is increased in size. So, if we place the LED in between center of curvature and main focus of the mirror, it will give an expanded real image of the LED. As a bigger LED has more intensity as well as the angle of its light projection is bigger, this automatically increases the range of normal LED. Increasing Range by Changing Position of LED: According to the usual setup of household lights Li-Fi might be set in the ceiling connected to the Li-Fi router. Concept of light projection tells that it will make cone shape from the ceiling

Fig.3.5.6. Light projection as a cone from ceiling [25]

We propose another way to set the light connected with the router. The lights must be set on the vertical wall of a regular rectangular room so that less LED can cover the whole room by projecting same amount of light.

How method of expanding angle can be a better solution [25]: As we saw if LEDs are set in the optimistic way, number of LED is decreased. Now according to the properties of concave mirror we get a real increased image as well as greater angle than the real LED, so using concave mirror we will get greater angle. As mentioned before

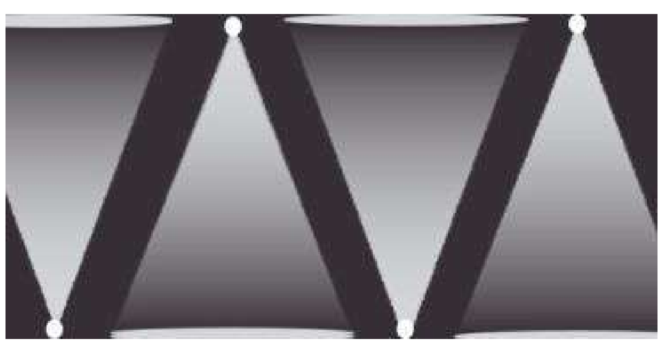

Fig 3.5.7. Number of LED can be reduced by positioning them in optimistic way- A view from the ceiling [25]

$$Area = angle \times r^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

That means greater the angle is, greater the area will be. So, expanding the angle and area it reduces the number of LED again.

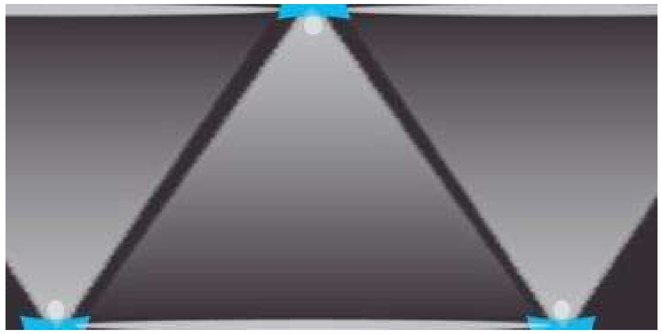

Fig.3.5.8. Angle and area are increased using concave mirror-A view from the ceiling [25]

Now the same area can be covered by using lesser number of LEDs than before. Though according to the theory, light projects as shown in the figures, but in real life the darker areas beside the cone remains no longer dark because of reflection from surroundings.

Chapter 4

Result Analysis

4.1 Li-Fi Channel

The irradiance distribution of a LED source is illustrated in Fig. 4.1.1:

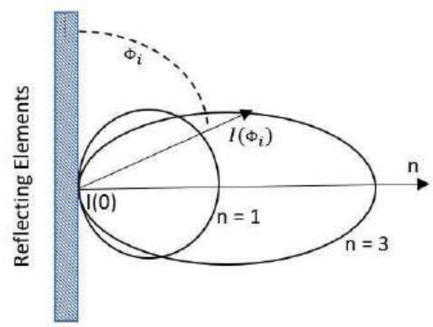

Figure 4.1.1: Lambertian emission pattern for mode n [36]

The Lambertian irradiance is defined as [37]

$$I(\varphi_i) = I(0)cos^n(\varphi_i) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

were

- I (0) is the Lambertian irradiance at the center of the beam in W/m^2
- φ is the viewing angle of irradiance
- n is the Lambertian irradiance order and it is calculated as follows

$$n = -\frac{1}{log_2 \cos(\emptyset_{1/2})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where $\emptyset_{1/2}$: the half power angle.

Lambertian radiation pattern is expressed as

$$R_0(\emptyset) = cos^n(\emptyset)\frac{n+1}{2\pi} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The average power ratio between received and transmitted signal is defined as

$$H_{LOS}=\begin{cases}\frac{A}{d^2}R_0(\emptyset)\cos(\varphi_i)\cos(\varphi_i) & 0\leq\varphi_i\leq\varphi_c\\ 0 & \varphi_i>\varphi_c\end{cases} \qquad \text{……………………. (8)}$$

And the channel gain at the receiver includes the optical fifilter gain $T_s$and optical concentrator g(φ_i) integrated in the photodetector

$$H_{(receiver)}=\begin{cases}\frac{A(n+1)}{d_i^2 2\pi}cos^n(\emptyset_i)T_s g(\varphi_i)\cos(\varphi_i) & 0\leq\varphi_i\leq\varphi_c\\ 0 & \varphi_i>\varphi_c\end{cases} \qquad \text{………… (9)}$$

were

- A: the effective photo detector area (m2)
- n: Lambertian order
- di: the Euclidean distance between APi and UE (m)
- φ_i: the radiance angle with respect to the z-axis (vertical) on the transmitter plane for APi
- $\emptyset_i$: the incidence angle with respect to the z-axis (vertical) on the receiver plane for APi
- T_s: optical filter gain of the receiver
- φ_c: Field of View (FOV) of the receiver
- $g(\varphi_i)$: the receiver's optical concentrator gain

4.1.2 Geometric Orientation Model

Three angles: α, β and γ are used to specify the receiver orientation along the z, x and y-axis respectively [5]. Fig. 4.1.2 describes the UE orientation model using the three axes in a cartesian coordinate system [36]. The angle α describes rotation around the z-axis, and because UE is assumed to be always on the ground plane, the angle α takes a value between 0*o* and 360*o*.The angles β and γ (both range from -90*o* to 90*o*) are the rotation angles around the x-and y-axis respectively. The range of angles is chosen so as to ensure that the UE is able to communicate with at least one AP [36]. These values are similar to the angles used in [5]. Another parameter is the distance vector

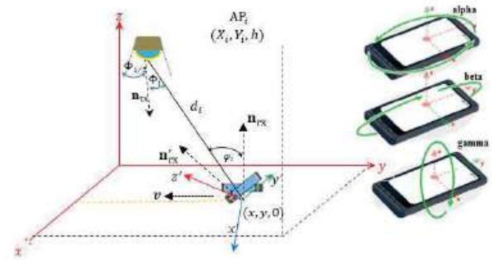

Figure 4. 1.2: Modelling of the receiver's orientation based on rotations around three axes [3]

between a UE (x, y, z) and every AP_i(*Xi*, *Yi*, *Zi*) and the magnitude of this vector is called the Euclidean distance between AP_i and the UE and it is calculated as follows [36]:

$$d_i = ||d_i|| = \sqrt{(Xi - x)^2 + (Yi - y)^2 + (Zi - z)^2} \text{ .... (10)}$$

There are two angles of interest between the UE and AP. They are φ_i and ϕ_i which are the angles of radiance with respect to the z-axis (vertical) on the transmitter plane and the receiver plane for AP_i , respectively. The angles φ_i and ϕ_i are described mathematically in the following equations using the rules of geometry:

$$cos\varphi_i = d_i.n_{tx}/||d_i|| \text{ .... (11)}$$

$$cos\phi_i = -d_i.n_{rx}/||d_i|| \text{ .... (12)}$$

were

- n_{rx} and n_{tx}: the normal vectors of the receiver and transmitter planes respectively
- || || and.: the Euclidean norm operators and inner product respectively.

  The optical concentrator gain of the receiver is given by

$$g\ (\varphi_i) = \begin{cases} \frac{m^2}{sin(\varphi_c)^2} & 0 \le \varphi_i \le \varphi_c \\ 0 & \varphi_i > \varphi_c \end{cases} \text{ .... (13)}$$

were

• m is the refractive index

4.2 Simulation Model

In this research, UE moves within the room at a constant speed in a rectangular spiral pattern. The rectangular spiral pattern is chosen due to its full coverage around the whole area in order to have a proper evaluation. UE starts moving from the point (-5, -5) in an easterly direction until reaching the edge of the simulation area. After completing one round, the UE moves one meter inward and this cycle is repeated until the UE reaches the center of the room. The numbers on the spiral pattern represent the moving time in seconds and it takes 1200 seconds to complete this spiral path.

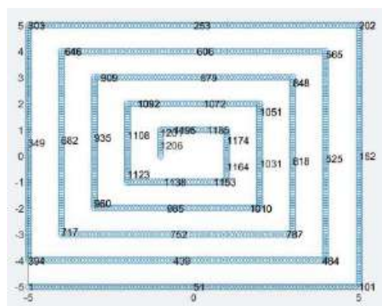

Figure 4.2: UE mobility modelling [36] [38]

4.3 Single Beam LEDs Model

The overview of the indoor optical system which contains four LED transmitters in the center of the four quarters of the room's ceiling

4.3.1 Single Beam LEDs Li-Fi System Configuration

Fig. 4.3.1 shows the overview of the indoor optical system which contains four LED transmitters in the center of the four quarters of the room's ceiling, and a UE device plays the receiver role on the floor. In this research, the Way Point Model was applied for user movement within a square area of dimensions of b x b (m^2).

The assumptions in this single beam LED model are:

i. LED transmitters follow "the Lambertian emission patterns and operate within the linear dynamic range of the current-to-power characteristic curve to reduce effects of nonlinear distortion".

ii. These LED transmitters emit light vertically downwards.
iii. UE can be rotated in any direction.
iv. All LED transmitters have the same transmit power, and one unique AP is chosen for serving the UE depending on its orientation and location.
v. Reflection on the wall, ceiling, and floor surfaces will not be considered.
vi. Line-of-sight (LOS) communication channel is considered in this research only.
vii. UE device is always on the ground plane of the network area

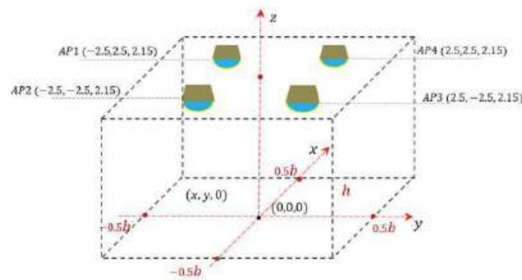

Figure 4.3.1: The simulated optical network system [36]

4.3.2 Single Beam LEDs Li-Fi System Parameters

The parameters that have been used in this research are given in the following table:

Table 4.1: Simulation single beam LED set up [36]

Name of Parameters	Value
Network space (L×W×H)	10m × 10m × 2.15m
Number of APs	4
Location of AP1	(-2.5, -2.5, 2.15)
Location of AP2	(-2.5, 2.5, 2.15)
Location of AP3	(2.5, -2.5, 2.15)
Location of AP4	(2.5, 2.5, 2.15)
LED half-intensity angle $\phi_{1/2}$	60°
Receiver FOV ψ_c	90°
Optical filter gain T_s	1
Effective photodetector area A	1×10^{-4}
Refractive index m	1

4.3.3 Single Beam LEDs Li-Fi System Flowchart

This modelling is conducted based on Fig. 4.3.3:

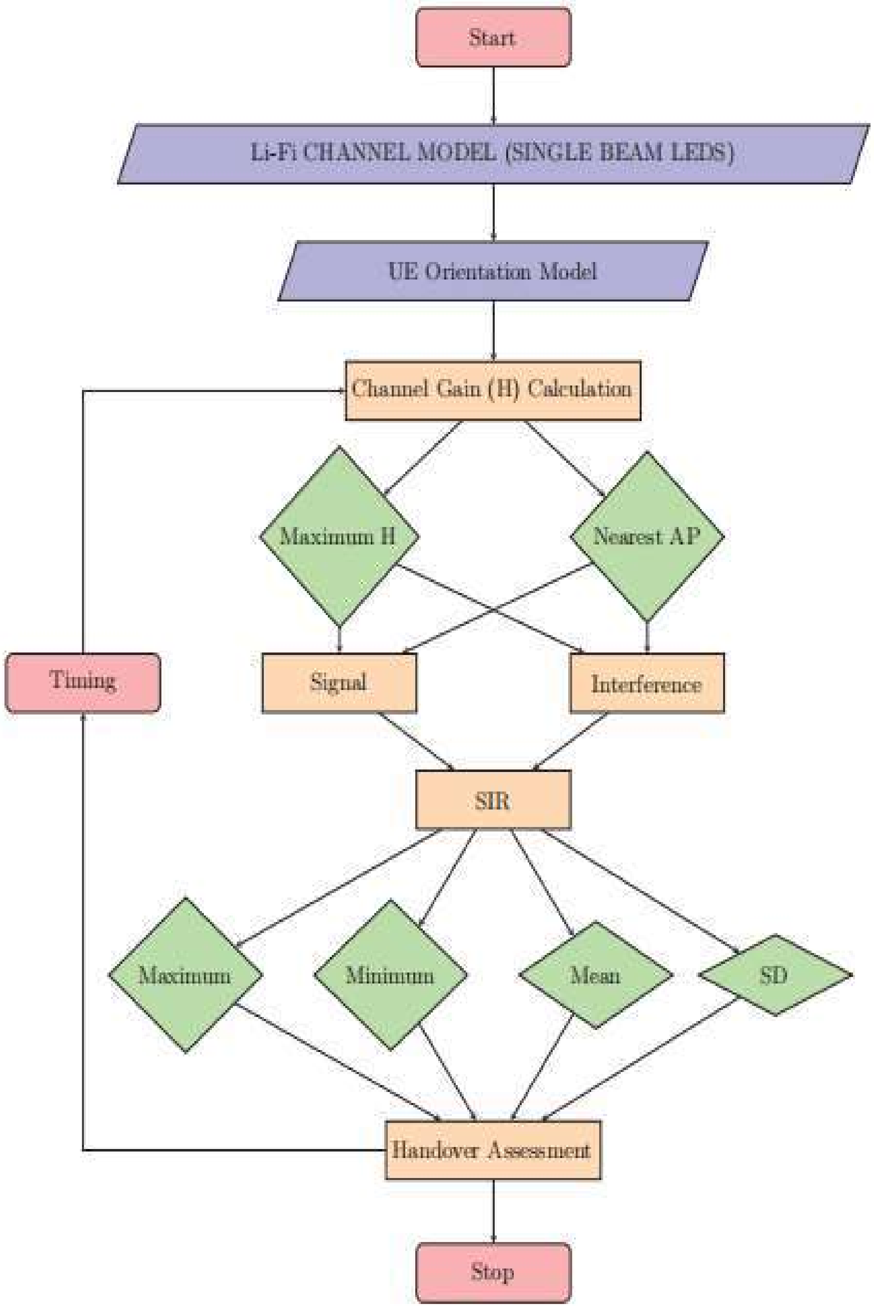

Figure 4.3.3: Single Beam LEDs Li-Fi System Flowchart

4.4 Multiple Beams LEDs Model

4.4.1 Multiple Beams LEDs Li-Fi System Configuration

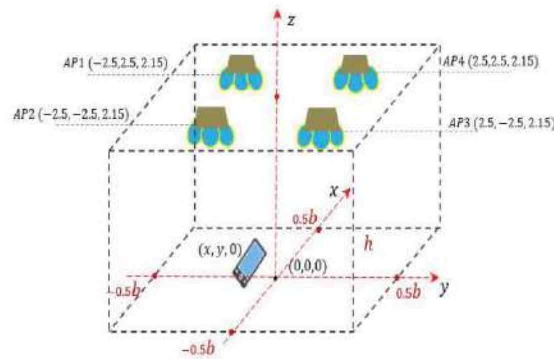

Figure 4.4.1: Multiple beams LED optical network system [38]

The overview of the indoor multiple beams LED system is shown in the Fig. 4.4.1 which contains four multiple beams LED transmitters in the four quarters of the room's ceiling, and a UE device plays the receiver role on the floor. Multiple beams LEDs are considered as the multiple beams Access Point (AP). The Way Point Model [7] was applied in this research for user movement within a square area of dimensions of b x b (m^2). The multiple beams LED is described in the following figure (Fig. 4.4.2) where four beams from one LED have been configured. The vertical inclination angle between each beam and vertical axis are equal.

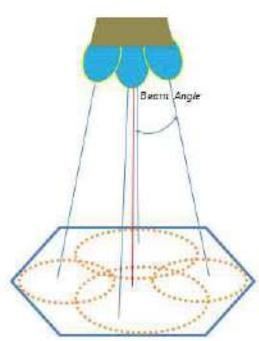

Figure 4.4.2: The layout of the optical scenario with an angle diversity optical transmitter [38]

The layout from the top is shown in Fig. 4.4.3. Each beam has its own coverage area and maybe overlapped with the coverage area of other beams depending on beam width and angle.

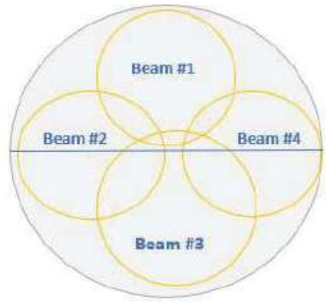

Figure 4.4.3: The layout of a 4-element angle diversity transmitter [38]

4.4.2 Multiple Beams LEDs Li-Fi System Parameters

The parameters that are used in this research are given in Table 4.2

Table 4.2: Simulation parameters in multiple beams environment [38]

Name of Parameters	Value
Network space (L×W×H)	10m × 10m × 2.15m
Number of APs	4
Location of AP1	(-2.5, -2.5, 2.15)
Location of AP2	(-2.5, 2.5, 2.15)
Location of AP3	(2.5, -2.5, 2.15)
Location of AP4	(2.5, 2.5, 2.15)
LED half-intensity angle $\phi_{1/2}$	60°
Receiver FOV ψ_c	90°
Optical filter gain T_s	1
Effective photo detector area A	1×10^{-4}
Refractive index m	1

The assumptions in this multiple beams LED model are:

1) All LED transmitters emit light in four directions of four beams.
2) The rotation of UE device can be random in three directions x, y and z.
3) All beams emit the same power and only one beam is considered for serving
4) the UE based on its rotated angle and location.44
5) Reflection on any surface: wall, ceiling & floor will not be considered.
6) Only line-of-sight (LOS) channel are considered.

7) UE device is always held by a person at one meter height from the floor in the
8) simulated area.

4.4.3 Multiple Beams LEDs Li-Fi System Flowchart

This modelling is conducted based on the following flowchart:

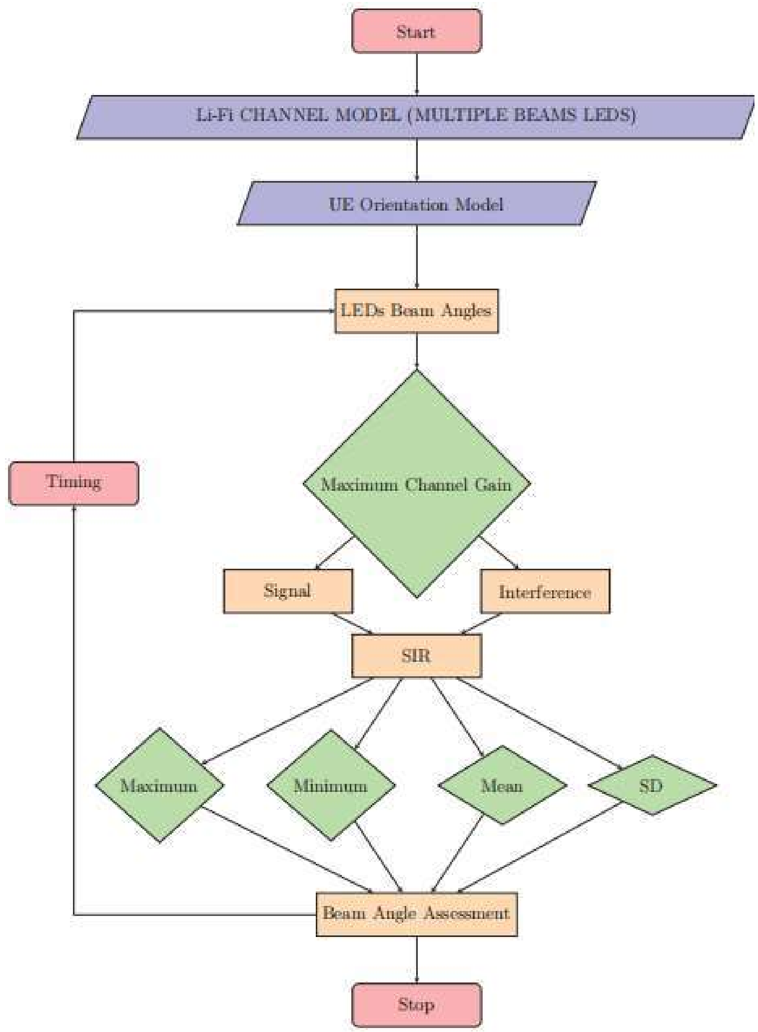

Figure 4.4.4: Multiple Beams LEDs Li-Fi System Flowchart

4.5 Channel Gain Assessment

When a UE is moving along the rectangular spiral path with fixed values of α, β and γ for each cycle, the channel gain values vary as shown in the following figure

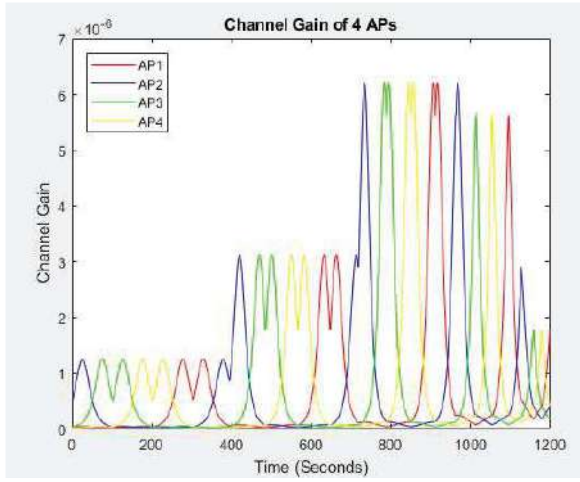

Figure 4.5.1: Channel gain of four APs when $\alpha = 0$, $\beta = 0$ and $\gamma = 0$

Fig. 4.5.1 shows the channel gain observed by the UE as it moves in the spiral path facing the default direction ($\alpha = 0$, $\beta = 0$ and $\gamma = 0$). Each color represents channel gain from each of the four APs in the room. Initially, when the UE is moving on the perimeter of the rectangle in an anticlockwise direction, the UE is furthest away from the APs and hence the channel gain observed are small from all APs. At time t = 0, the UE is at the location (-5, -5) (Fig. 4.2) and it is closest to AP2 at (-2.5, -2.5) (Fig. 4.3) and hence the signal from AP2 (shown in blue) is the strongest signal. Thereafter, between times t = 51 seconds and t = 100 seconds, the UE is closest to AP3 at (2.5, -2.5) and hence the signal from AP3 shown in green has the strongest channel gain. At time t = 400 seconds, the UE has almost completed a full rotation and returned close to the start point and the signal from AP2 shown in blue is the strongest signal. The channel gain at t = 400 seconds is higher than at t = 0 because the UE is now closer to AP1. From 0 to 1200 seconds, there are five different patterns because there are five anticlockwise cycles in that spiral path. On each cycle, the UE has nearly equal channel gain values from each AP. When UE is on 1*st,* 2*nd,* 3*rd* and 5*th* cycle, its channel gain is smaller because its distance to the APs is furthest. In contrast, in the 4*th* cycle, its channel gain is highest due to the nearest distance between UE and Aps After changing values of β to 450 (Fig. 4.5.2), the four APs' channel gain values reduce slightly.

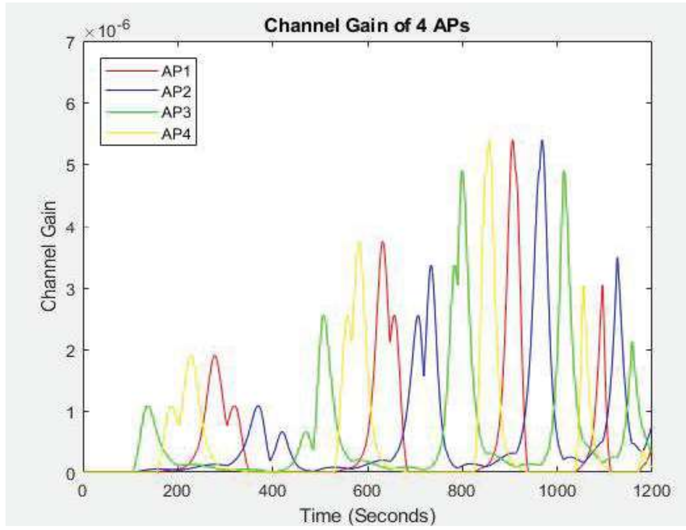

Figure 4.5.2: Channel gain of four APs when $\alpha = 0$, $\beta = 450$ and $\gamma = 00$

Moreover, the values are minimal after the first 100 seconds which is close to zero. Similarly, the channel gain values are small in the outer rounds and become larger when getting closer to the room center

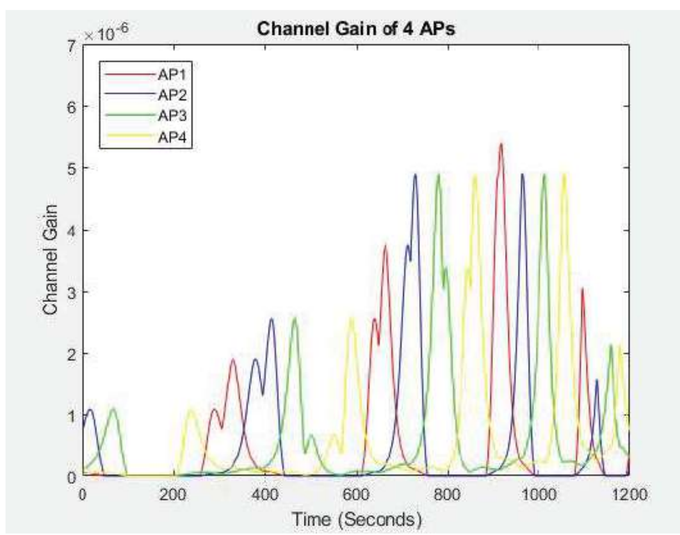

Figure 4.5.3: Channel gain of four APs when $\alpha = 0$, $\beta = 0$ and $\gamma = 450$

Repeating the same test with γ of 450 (Fig. 5.3), the channel gains are almost matching the values in Fig. 5.2, but the minimal values are from 100 to 200 seconds. The channel gain values have similar patterns - small in the outer paths and larger when getting closer to the APs in the room center.

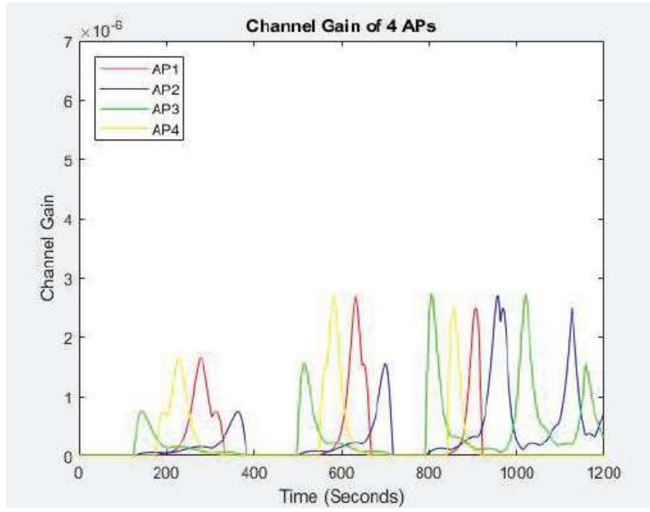

Figure 4.5.4: Channel gain of four APs when $\alpha = 0$, $\beta = 800$ and $\gamma = 0$

In Fig. 4.5.4, there is a symmetry between channel gain of AP4 and AP1, AP3 and AP2 within three-time frames when the values of β are changed to 800. They are increased when UE moves to the room center where it comes closer to the light source.

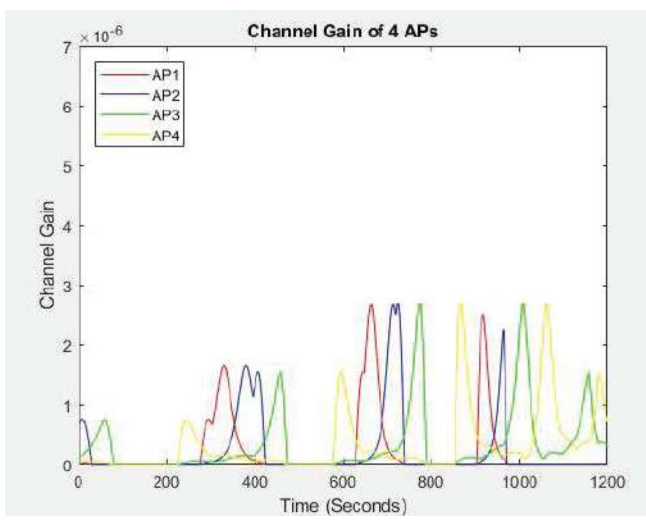

Figure 4.5.5: Channel gain of four APs when $\alpha = 0$, $\beta = 0$ and $\gamma = 800$

There is a similarity between Fig. 4.5.4 and Fig. 4.5.5 because there is symmetry for measurements in one cycle. However, signal values in Fig. 4.5.5 are advanced by 50 seconds compared to Fig. 5.4 due to the difference between values of rotating angles about x- and y-axis.

4.6 Maximum-channel-gain-based Handover Decision

In order to find the serving AP among four APs on the ceiling, the maximum values of channel gain are selected so that the received signal is continuous while the UE moves around the network area. These values are plotted in the following figure

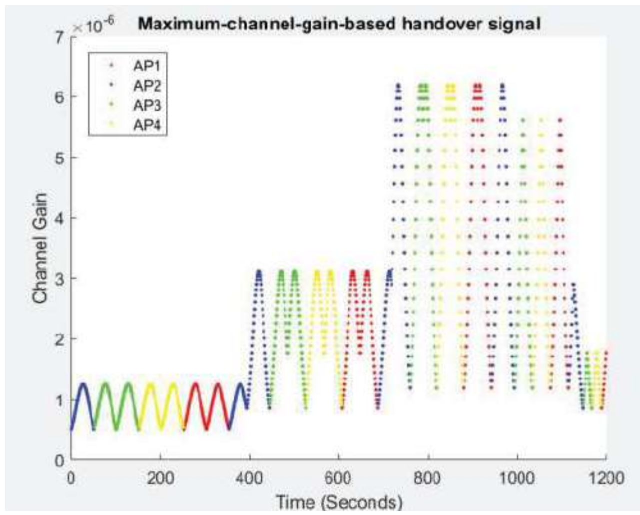

Figure 4.6.1: Maximum-channel-gain-based signal when $\alpha = 0$, $\beta = 0$ and $\gamma = 0$

If the UE is served by one AP which is considered as desired signal, then the other three APs would be considered as interference. Fig. 4.6.1 shows the total interference of the other three APs when UE is served by any AP. When UE is served by AP2, the blue graph shows the total interference of all AP1, AP3 and AP4. And then when it is served by AP3, the channel gain from AP1, AP2 and AP4 will be considered as the interference. In this case, the communication is possible during 94.71% of the whole path (Table 5.2). However, the maximum value of SIR is 13.13 and the average value is 8.4 which is suitable for light communication channel (Table 4.6.1)

Table 4.6.1: Maximum-channel-gain-based handover decision

Maximum-channel-gain-based handover	Maximum	Minimum	Mean	Standard deviation
Gain value (10^{-6})	6.20	0.50	1.71	1.57
Interference value (10^{-6})	1.49	0.08	0.38	0.35
SIR (dB)	13.13	-2.16	8.4	7.11

From Table 4.6.1, we could see that communication is possible for 94.71% of the time and this percentage reduces approximately 25% when requirements of SIR are 3dB (77.93%) and 7dB (56.20%). There is only 23.47% of the time where SIR is larger than 10dB.

Table 4.6.2: The overall system performance of maximum-channel-gain-based handover decision

	SIR>0 dB	SIR>3 dB	SIR>7 dB	SIR>10 dB
Percent of time (%)	94.71	77.93	56.20	23.47

Fig. 4.6.2 shows the received signal of UE when the handover decision is based on the maximum channel gain between four APs at one time. The signal is zero at the period from 0 to 100 seconds and then it was chosen among four APs' signals to find UE's signal

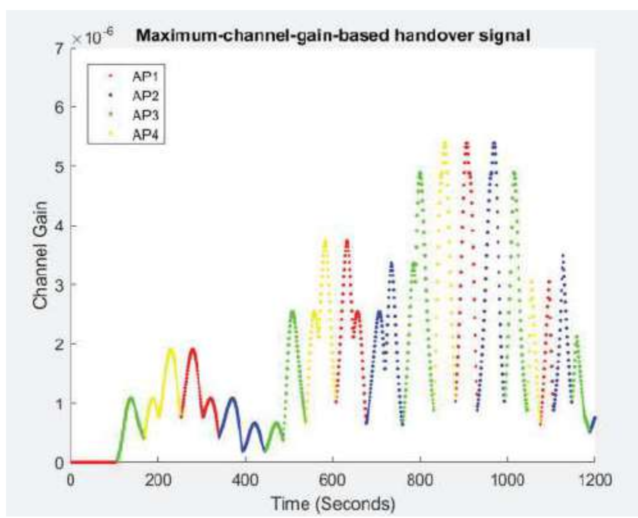

Figure 4.6.2: Maximum-channel-gain-based signal when $\alpha = 0$, $\beta = 450$ and $\gamma = 0$

The interference in Fig. 4.6.3 is quite small when compared to the received signal so it does not have much effect on the communication channel when UE is tipping at 450 around x-axis. For 8.8% of the time, there is no communication during this path. Although the maximum value of SIR is quite high (51.22) (Table 4.6.3) when compared to the previous case but the average value is lower (5.21)

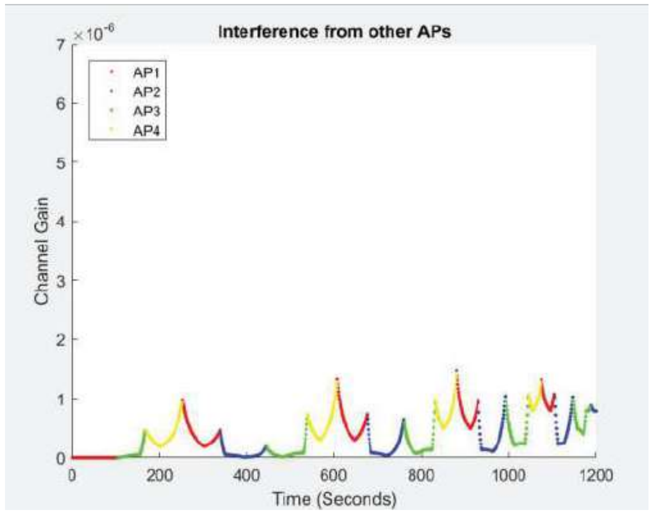

Figure 4.6.3: Maximum-channel-gain-based interference when $\alpha = 0$, $\beta = 450$ and $\gamma = 0$

Table 4.6.3: Maximum-channel-gain-based handover decision

Maximum-channel-gain-based handover	Maximum	Minimum	Mean	Standard deviation
Gain value (10^{-6})	5.4	0	1.31	1.32
Interference value (10^{-6})	1.47	0	0.25	0.32
SIR (dB)	51.22	0	5.21	12.99

Table 4.6.4: The overall system performance of maximum-channel-gain-based Handover

	SIR>0 dB	SIR>3 dB	SIR>7 dB	SIR>10 dB
Percent of time (%)	86.02	74.44	51.12	32.42

When the UE is inclined at 450 along y axis (Fig. 4.6.4), the signal is minimal from 100 to 200 seconds. The received signal value is similar to Fig. 5.8 and the maximum and minimum values remain the same (5.4 x 10−6 and 0) which are shown Table4.6.3and 4.6.4

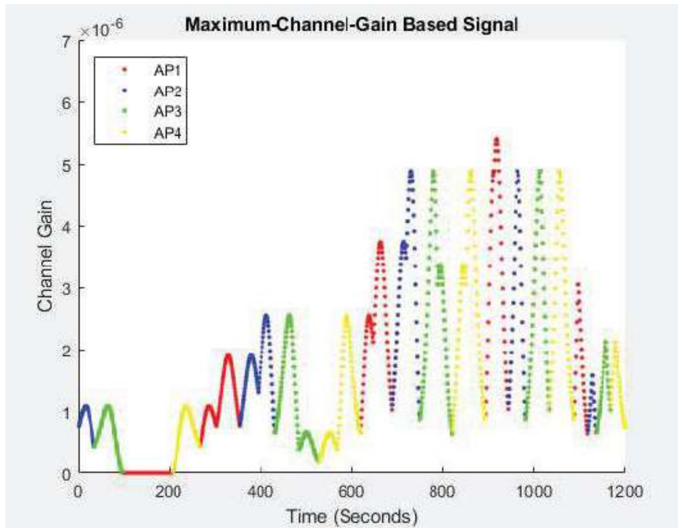

Figure 4.6.4: Maximum-channel-gain-based signal when $\alpha = 0$, $\beta = 0$ and $\gamma = 450$

The interference signal from 100 to 200 seconds is quite small when compared to the receiving signal (Table 4.6.5). There is no communication for 9.14% of the time during this test. Similarly, the maximum, minimum and mean values of SIR remain when UE's rotation is changed from around x-axis to y-axis.

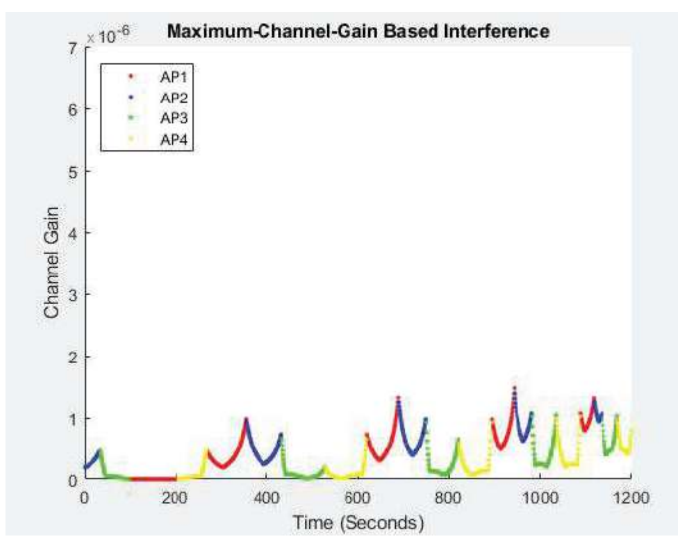

Figure 4.6.5: Maximum-channel-gain-based interference when $\alpha = 0$, $\beta = 0$ and γ= 450

Table 4.6.5: maximum-channel-gain-based handover decision

Maximum-channel-gain-based handover	Maximum	Minimum	Mean	Standard deviation
Gain value (10^{-6})	5.4	0	1.32	1.31
Interference value (10^{-6})	1.47	0	0.249	0.321
SIR (dB)	51.22	0	5.27	12.98

When the angles of β and γ increase to 800, the difference in level could be seen in 60 Fig. 4.6.6 to 4.6.9 There was the same pattern of signal and interference between two cases: β = 800, γ = 0 and β = 0, γ = 800 (α = 0 for both cases). However, the values in the second case (α = 0, β = 0 and γ = 800) have moved 70 seconds forward compared to the first case (α = 0, β = 800 and γ = 0).

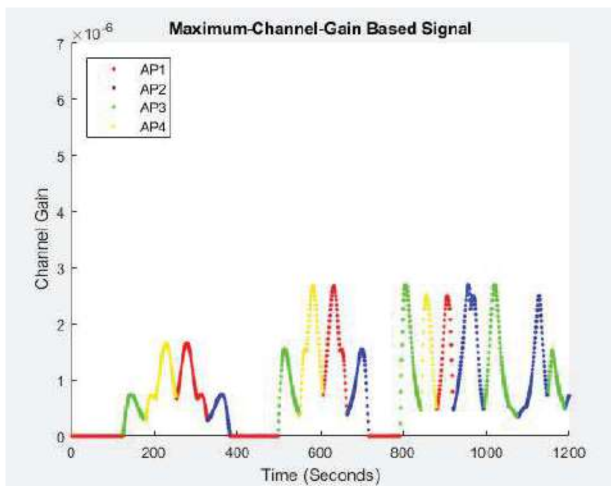

Figure 4.6.6: Maximum-channel-gain-based signal when α = 0, β = 800 and γ = 0

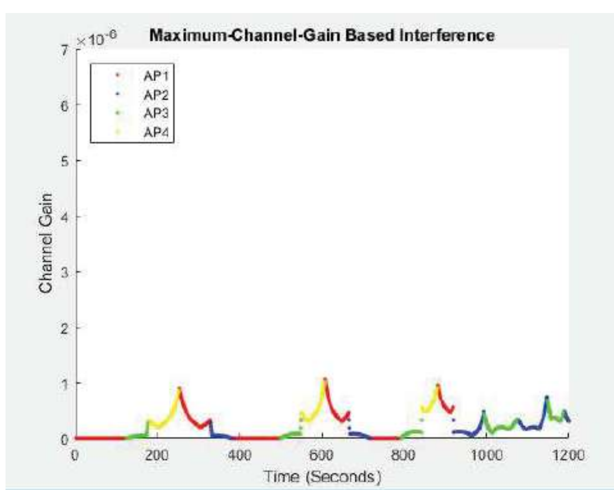

Figure 4.6.7: Maximum-channel-gain-based interference when α = 0, β = 800 and γ = 0

Table 4.6.6: Maximum-channel-gain-based handover decision

Maximum-channel-gain-based handover	Maximum	Minimum	Mean	Standard deviation
Gain value (10^{-6})	2.7	0	0.715	0.078
Interference value (10^{-6})	1.06	0	0.012	0.022
SIR (dB)	51.22	0	3.32	11.08

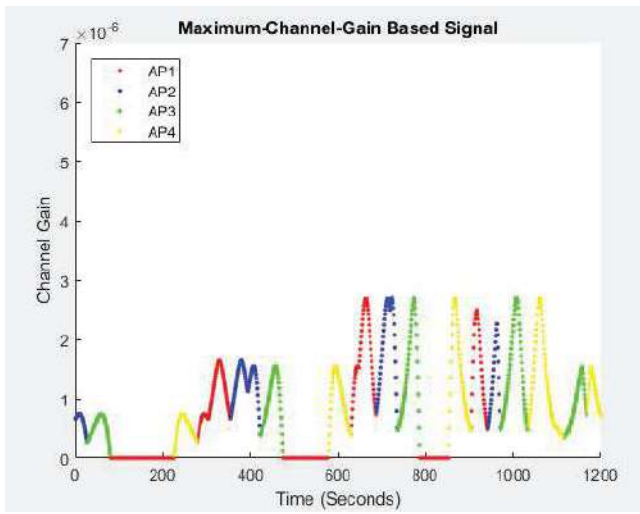

Figure 4.6.8: Maximum-channel-gain-based signal when $\alpha = 0$, $\beta = 0$ and $\gamma = 800$

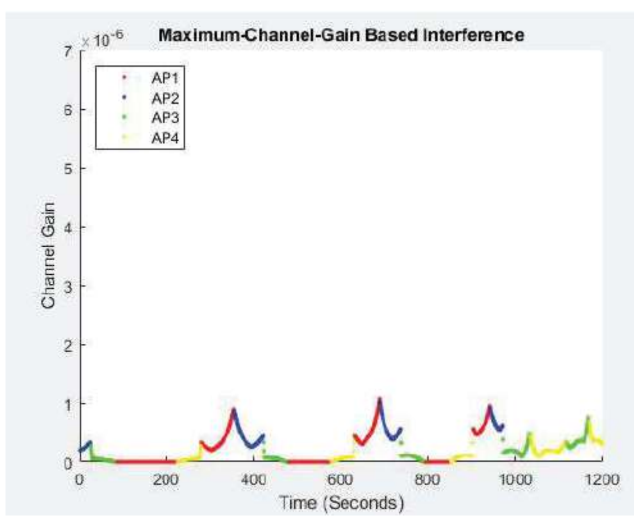

Figure 4.6.9: Maximum-channel-gain-based interference when $\alpha = 0$, $\beta = 0$ and $\gamma = 800$

In both cases ($\alpha = 0, \beta = 80$ and $\gamma = 0$ and $\alpha = 0, \beta = 0$ and $\gamma = 800$), for 26% of the time there is no communication during this test. Although the maximum value is quite high (51.22) but the mean value is quite low (3.32), and hence there are two cases considered as the worst-case scenario when UE is tipping 800 around x and y axis.

Table 4.6.7: Maximum-channel-gain-based handover decision

Maximum-channel-gain-based handover	Maximum	Minimum	Mean	Standard deviation
Gain value (10^{-6})	2.7	0	0.717	0.078
Interference value (10^{-6})	1.06	0	0.016	0.0223
SIR (dB)	51.22	0	3.32	11.32

In summary, Fig. 4.6.1 and 4.6.2 show the received signal and interference based on the maximum channel gain when UE is in a normal direction. It can be seen that the Signal to Interference ratio (SIR) is quite low in the first quarter of the path. However, this ratio was increased gradually in the remainder of the UE path. When the angles (β and γ) are changed to 450, both signal and interference values were small (Fig. 4.6.3 to 4.6.5) due to different paths between APs and photo detector. However, when these two angles are changed to 800, the SIR was quite high as shown in the Fig. 4.6.6 to 4.6.9. The selection of maximum channel gain values for indoor Li-Fi network was conducted in this research. When the user moved closer to the center of the room where the high values of channel gain exist, the handover process performs better due to the large density of transmitted signals from four LEDs. The receiver rotation has a significant impact on the channel gain values when UE is moving around the network area.

4.7 Beam Angle Assessment

For each beam angle (0, 15°, 30°, 45°, 60°&$75°$), the statistics in Table 4.7.2 shows the percentage of time that UE has specific range of SIR value. It is seen that most of the time (during the 1200 seconds), UE has the SIR values between 0 and 11.5. The SIR values of UE are between 0.5 and 1 most of the time and accounts for 89.2%, 80.3%, 62.8%, 44.7%, 30.5% and 49.8% of the total moving time for the case of beam angles are 0°, 15°, 30°, 45°, 60° and 75°, respectively

Table 4.7.1: Percentage of each Signal to Interference Ratio (SIR) range for each beam angle set

SIR	0°	15°	30°	45°	60°	75°
0.0 < SIR ≤ 0.5	1.7	7.2	7.9	12.1	25.8	33
0.5 < SIR ≤ 1.0	89.2	80.3	62.8	44.7	30.5	49.8
1.0 < SIR ≤ 1.5	1.3	7.9	8.1	9.9	15.8	13.9
1.5 < SIR ≤ 2.0	1.9	0	6	6.7	13.2	3.3
2.0 < SIR ≤ 2.5	1.3	0	4	6	8.8	0
2.5 < SIR ≤ 3.0	0	1.3	4	4.6	1.3	0
3.0 < SIR ≤ 3.5	1.3	0	2.6	9.3	1.3	0
3.5 < SIR ≤ 4.0	1.3	0	0	2.7	3.3	0
4.0 < SIR ≤ 4.5	1.3	0	0	2	0	0
4.5 < SIR ≤ 5.0	0.7	1.3	0	0	0	0
5.0 < SIR ≤ 5.5	0	0	0	2	0	0
5.5 < SIR ≤ 6.0	0	0	1.3	0	0	0
6.0 < SIR ≤ 6.5	0	1.3	0	0	0	0
6.5 < SIR ≤ 7.0	0	0.7	0	0	0	0
7.0 < SIR ≤ 7.5	0	0	0	0	0	0
7.5 < SIR ≤ 8.0	0	0	0	0	0	0
8.0 < SIR ≤ 8.5	0	0	1.3	0	0	0
8.5 < SIR ≤ 9.0	0	0	0	0	0	0
9.0 < SIR ≤ 9.5	0	0	0	0	0	0
9.5 < SIR ≤ 10	0	0	0	0	0	0
10 < SIR ≤ 10.5	0	0	0	0	0	0
10.5 < SIR ≤ 11	0	0	1.3	0	0	0
11 < SIR ≤ 11.5	0	0	0.7	0	0	0
TOTAL	100%	100%	100%	100%	100%	100%

In the case of beam angle of 300, the SIR values are distributed along the range from 0 to 11.5, result in the highest value of Standard Deviation (SD) (1.91) and the second highest of mean SIR (0.8), coming after the case of the beam angle is 45°. Over the six cases of different beam angle values, Table 6.2 shows the maximum, minimum, mean and standard deviation of SIR values when changing beam angles. When UE is being served by one light beam, the signals from the other three APs are considered as interference. The SIR values are calculated by using Equation (10).

Table 4.7.2: Signal to Interference Ratio (SIR) of UE (User Equipment) when changing beam angles

Beam angles	Maximum	Minimum	Mean	Standard deviation
0	4.2	0	0.2	0.7
15°	6.2	0	0.3	0.9
30°	11.4	0	0.8	1.91
45°	5	0	0.9	1.2
60°	3.5	0	0.7	0.8
75°	1.2	0	0.2	0.3

Fig. 4.7 is the Probability Density Function of the data taken from Table 6.3, it is shown that the SIR values when the beam angles are 0°, 15°, 45°, 60°&75° have its standard deviation smaller than the beam angle of 300 (gray color). In addition, in the case of beam angle of 300, there is less interference between 16 beams of the Li-Fi network. Hence, a beam angle of 300 (gray color) was chosen due to the considerably higher values of SIR.

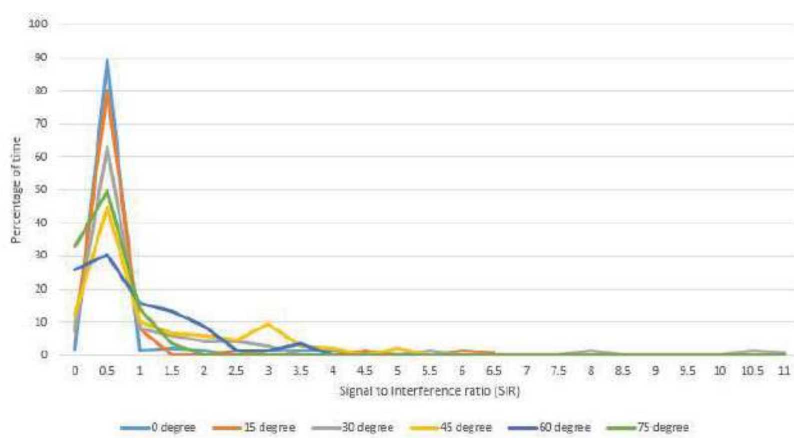

Figure 4.7: Probability Density Function (PDF) when changing beam angles

4.8 Li-Fi & Wi-Fi Bandwidth Aggregation at the Physical Layer

In order to anchor this concept with an example BWA system, it is useful to establish a very simple simulation and state further assumptions. Next, it is assumed that the Wi-Fi network operates under a basic 2-FSK scheme using the signal to bit translations shown in table 4.8.1

Table 4.8.1: Wi-Fi 2-FSK Signal to Bits Encoding Scheme.

Frequency (Hz)	Bits
500	0
1000	1

Additionally, it is assumed that the Li-Fi network utilizes a 2-IM/ASK scheme with the mapping shown in table 4.8.2 where two luminous intensity values represent different bits.

Table 4.8.2: Li-Fi 2-ASK Signal to Bits Encoding Scheme.

Luminous Intensity (lm)	Bits
300	0
400	1

Furthermore, for simplicity in this simulation it is assumed that the baud rate for both Li-Fi and Wi-Fi will be identical of value 1 symbol/second, although as explained in section 5.3 the two would likely be different and regardless of each medium's baud rate, an encoding scheme can still be developed using BWAPL. With this combination of synchronized signals available from the 2-FSK Wi-Fi and 2-IM/ASK Li-Fi, they can be encoded and decoded at the physical layer with simultaneous transmissions using the scheme in table 4.8.3.

Table 4.8.3: Li-Fi & Wi-Fi BWAPL Between 2-FSK and 2-IM/ASK Signal to Bits Encoding Scheme.

Luminous Intensity/Frequency	Bits
300/500	00
300/1000	01
400/500	10
400/1000	11

Table 4.8.3 shows that two bits can now be sent simultaneously rather than just one, thus, increasing the number of levels of the network as a whole, because BWA does not

require any level increase from Li-Fi or Wi-Fi independently [37]. Figure 4.8 portrays a simulation of communicating the message "I love BWA" over a combination of Li-Fi and Wi-Fi using the table 4.8.3 encoding scheme. It shows the result of this compared to transmitting the message purely over one network or the other and it should be noted that the BWA message required half as many signals as the independent networks each did in this case.

Figure 4.8: Simulation Result of Transmitting "I love BWA" over Wi-Fi, Li-Fi, and BWAPL Li-Fi & Wi-Fi.

In a real commercialized system, many more steps would occur prior to transmitting this message at other layers of the TCP/IP stack and the bit stream would be longer due to things like hamming bits and heads/tailers. However, for simplicity and proof-of-concept, after establishing a handshake between the transmitter and receiver, to send the message this simulation took plain text, used either ASCII or Base64 encoding, converted to bits, and converted the bits to signals based on the encoding schemes in tables 4.8.1, 4.8.2, and 4.8.3 for Wi-Fi, Li-Fi, and BWA Li-Fi & Wi-Fi, respectively. This transmission was received and the signals were decoded back to bits using the inverse of the mapping of the tables, then to plaintext again as shown in the final line of figure 4.8. The phase of the networking process occurring in each line of the output is shown in figure 4.8 and is labeled and grouped to the right of the step. At the end of the transmission, statistics for data rates are shown.

4.9 Concave Mirror

A. Concave mirror gives increased image located ahead of actual LED:
Let us assume a concave mirror of focal length f = 10cm So that the distance of center of curvature

$$C = 2f = 2 \times 10 = 20\text{cm} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

According to the properties of concave mirror, to get real and bigger image, LED has to be set in between the center of curvature and the main focus, Let the distance of LED is placed u = 18cm. LED size h = 9cm.So if the image size is h' and the distance of image is v, then from magnification we know

$$m = \frac{h}{h} = -\frac{v}{u} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

Now, to find the distance v, we know

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

$$\text{Or, } \frac{1}{v} = \frac{1}{f} - \frac{1}{u}$$

$$\text{Or, } \frac{1}{v} = \frac{1}{10} - \frac{1}{18}$$

$$\text{Or, } \frac{1}{v} = 0.0444$$

$$v = 22.50$$

So, the distance of image is 22.5cm which is 4.5cmahead of the LED

Now, placing the value of v, u and h we get,

$$\frac{h'}{h} = -\frac{v}{u} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(17)}$$

$$\Rightarrow h' = -\frac{vh}{u}$$

$$\Rightarrow h' = -\frac{22.50 \times 9}{18}$$

$$\Rightarrow h' = -11.30$$

Here the −(minus) sign represents that the image in inverted. So, the Image height is 11.30cm which is 2.30cm bigger than the real LED. As we know a bigger LED can project light with a greater angle than the smaller one. Also, a bigger LED has more intensity than a smaller one. So, the increased image of LED will give more angle and intensity.

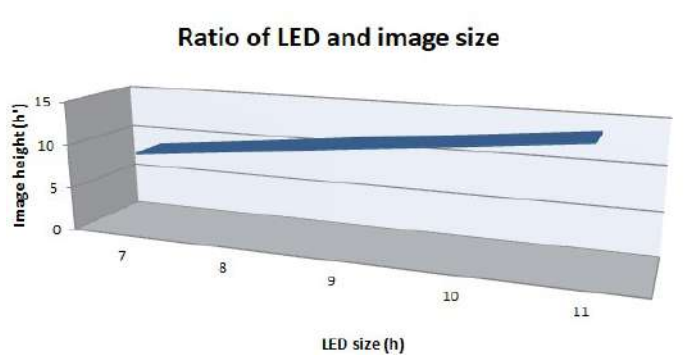

Fig.4.9.1. Ratio of LED and Image size

From the graph we can see the height of the image remains larger than the actual LED size. Also, here the increased image is built 3.5 cm ahead of the real LED, so it also increased the distance covered by the LDE. Simply it increases the range.

From the graph we can see the concave mirror always gives greater distance than the place where LED is placed. As it is known from the characteristics of light and light projection, it is a cone shape inside a sphere of radius R which is also the side of the cone.

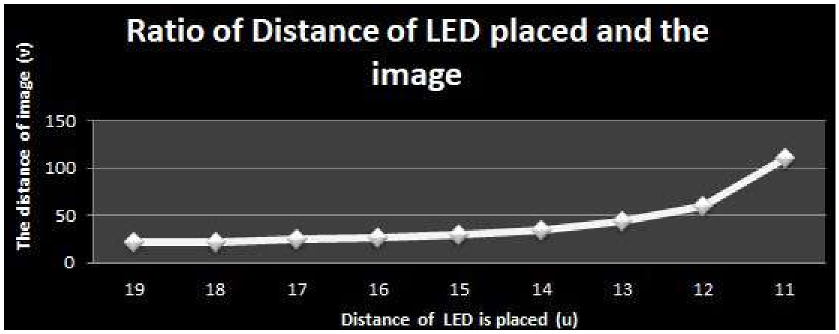

Fig.4.9.2. Ratio of distance of LED placed and the image

If the height of the cone is **h** and the radius of the base is **r**, then the volume of cone

$$v = \frac{\pi r^2 h}{3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(18)}$$

Base area of a cone is a 2D circle of radius r. If the angle increases, so does the radius of the base. Let's assume 2 cones with the same height but different angle, that means different base radius.

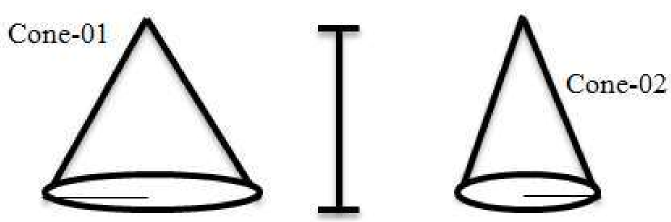

Fig.4.9.3. Two cones with different angle

For cone 01, let's assume,

Height h = 14cm

Base radius r = 5cm

$$A=\pi r^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(19)}$$

$$\Rightarrow A= 3.1416\times 5^2$$

$$\Rightarrow A= 78.84\ cm^2$$

$$\text{And volume } v = \frac{\pi r^2 h}{3}$$

$$v = \frac{3.1416 \times 5^2 \times 14}{3}$$

$$\Rightarrow v = 366.52cm^3$$

Again, for cone 02, as the height remains the same, so

Height h = 14cm

Base radius r = 2.5cm

$$\text{So, area } A = \pi r^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

$$\Rightarrow A = 3.1416 \times 2.5^2$$

$$\Rightarrow A = 19.635cm^2$$

$$\text{And volume } V = \frac{\pi r^2 h}{3}$$

$$V = \frac{3.1416 \times 2.5^2 \times 14}{3}$$

$$\Rightarrow V = 91.63cm^3$$

From this calculation we can see if the angle is increased, area as well as the volume both also increases. That means, if we use mirror to get greater angle then when the angle increases, it covers more area or in 3D it covers more space of a room. It automatically increases the range of Li-Fi.

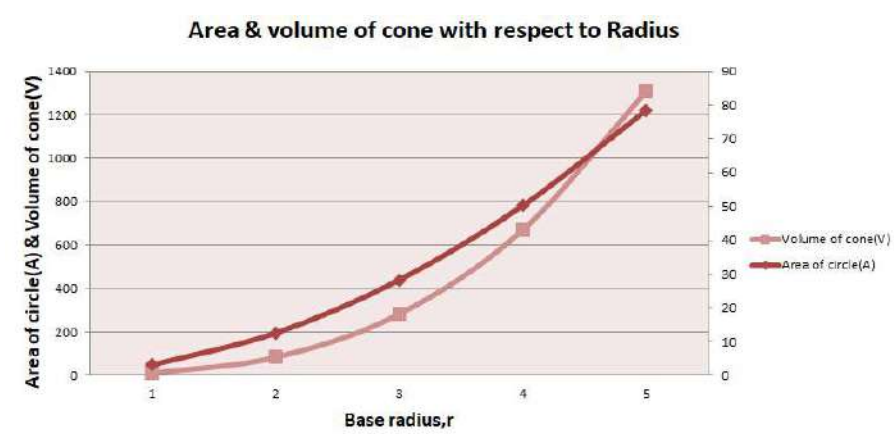

Fig.4.9.4. Area and volume of cone with respect to surface radius

From the graph above we can see area and volume increases when radius so that the angle increases. So, it is clear if we increase angle, it can cover more area.

Chapter 5

Conclusion

In present Li-Fi technology uses light that cannot go outside of any room or cannot pass any solid object that stops light. In future research this limitation can be considered, and a solution can be found regarding this. Also, our proposal of increasing the range of light can be proved by implementing in real life. Also, it can be tested that if our inverted image of LED gives any distorted data or not. Combination of lens and mirror might make the intensity more than only use of mirrors. As the range of Li-Fi is limited now days and soon it will be the broadly used technology, it is really important to increase the range of Li-Fi. As we proposed to use a concave mirror and the placing position of LED it will increase the range of each LED individually. Smarter way of positioning of light gives better coverage of light that increases the range of LED. Concave mirror gives larger image with greater angle which increases area that is covered by the light and the image created ahead of the LED which also increases the horizontal range of the light. Though it may not possible now days to increase the range from one room to another, but the method will help us to cover an enormous sized room. The impact of UE rotation and movement are considered in this research for two types of handover decision: closest-AP-based and maximum-received-signal-based. Overall, we could see that maximum-received-signal-based handover decision performs better than closest-AP-based handover decision: the average channel gain value is 12.7 times larger for the normal case of UE's rotation (see Table 5.1 and 5.8) and 1.31dB higher for the case of β = 45o (see Table 5.3 and 5.10). The UE's rotation and movement also have some effects on handover decision causes the received signal to be reduced slightly; however, the percentage of possible communication to be degraded considerably: 8.69% for the handover decision based on maximum received signal (see Table 5.2 and 5.4) and 2.6 times lower for the handover decision based on closest AP (see Table 5.9 and 5.11) [36]. In addition, in the case of multiple beams LED environment, the beam angles and rotation of UE have some effects on UE channel gains. When the beam angle is 30o, we could get the best value for SIR of 11.4, which is 1.5 times higher than in the other beam angles (see Table 6.3)

In this thesis work, we summarized and concluded the research on increasing the range of Li-Fi. The main findings are highlighted and conclusions are drawn. Finally, limitations and future work related to Li-Fi is presented.

5.1 Achievements

I used Handover Algorithm. Two handover algorithms are investigated namely, the closest-AP-based algorithm and maximum-channel-gain-based algorithm. Monte Carlo simulations using MATLAB tools are conducted to evaluate handover algorithms and show the impact of User Equipment's rotation and movement on handover performance. This research evaluates the performance of a Li-Fi network with multiple beams LEDs on moving UEs. The network performance is investigated in the case of the maximum channel gains. The simulated results show that when the beam angle is 30°, the Li-Fi system has the best performance in terms of channel gain by considering its mean and standard deviation values.

I also used the Concave Mirror to increase the range of the light, I used equations of solid area and cone to prove that if the angle is greater then the range will increase.

By using these techniques, I managed to gain the goal of this Thesis Research which was increasing the range of Li-Fi.

5.2 Limitation

Although I managed to increase the range of Li-Fi but there are some limitations to it. The multiple beams LEDs consume much of the energy resources, also it might become costly in some regards. The data transmission may also be interrupted due to sunlight.

5.3 Further work

Future research will focus on finding the best handover algorithm applied in Li-Fi multiple beams environment. While Li-Fi has been studied for many years, it is critical to remain open-minded and continue to consider outside-of-the-box ideas that could prove useful in the future.

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