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A SOFTWARE-DEFINED MULTI-ELEMENT VLC ARCHITECTURE FOR HIGH SPATIAL REUSE

A Thesis Submitted in Partial Fulfillment

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by

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ABSTRACT

Visible light communication (VLC) is an emerging wireless technology that offers a promising set of possibilities for applications that need more capacity than legacy radio frequency (RF) can offer. Free-space-optical (FSO) communication is VLC's general form spanning infrared bands, and it has an upper hand on traditional RF systems due to license-free spectrum, inherent security and containment of beams, energy efficient communications, and high transmission rates. In this work, we consider a hybrid RF/FSO mechanism to transmit multiple data streams over multi-element VLC modules. We evaluate a novel model of multi-element hemispherical design that can provide good lighting and communication coverage across a room. Simulation results are presented to evaluate the link quality performance of the hemispherical design with hundreds of LED transmitters, organized in different configurations.

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Chapter 1

Introduction

Radio frequency (RF) technology is the predominant and evolving approach for wireless communications, which will continue being the mainstream for the foreseeable future. Even though it has appealing features for handling mobility and capacity, RF's adequacy is in danger due to recent trends, such as the increasingly scarce RF spectrum resources, exponentially growing number of RF-enabled equipment, and ever-increasing spectrum licensing fees. It has been observed that RF interference [14] is one of the top issues that contribute to wireless network performance problems. In the long run, it is questionable if RF spectrum will be sufficient to address the exploding demand for wireless data [15].

Fortunately, several alternative wireless mechanisms are being developed that can complement RF in different contexts and applications. A promising such technology is free-space-optical (FSO) (a.k.a. optical wireless) communication which uses infrared and visible optical spectrum bands [18]. Visible light communication (VLC) is the FSO technology that uses visible optical band and effectively carries bits on visible light. Since solid-state lights such as light emitting diodes

(LEDs) can be switched faster than the human eye can respond, they can be modulated at high data rates without causing noticeable degradation to the illumination. This offers communications capabilities while simultaneously providing illumination. Due to the solid-state technology in the backend, these lighting systems have longer lifetime and cheap production costs. Moreover, the technology utilizes the license-free spectrum, provides indoor communication security and generates no radio interference, thus making them very attractive for use in RF-challenged environments such as hospitals and aircrafts.

To counter these advantages, the VLC technology heavily relies on highly directional line-of-sight (LOS) communication, which has to be maintained consistently, and also works within a limited range. The directional beams, while requiring LOS connectivity, open up great opportunities for spatial reuse of optical spectrum resources. As the number of wireless devices around us is increasing, highly directional wireless beams are needed to alleviate the RF interference, and attain higher spatial reuse. Multi-element VLC modules can significantly improve the efficiency of data transmission as they can take full advantage of the directionality of light by modulating each transmitter (e.g., an LED) with a different data stream. By designing these multi-element modules conformal to spherical shapes, one may also provide uniform light coverage across the room. The additional nice feature of the spherical shapes is that each transmitter emits the light in a different direction and hence attain an evenly scattered lighting.

Most of the existing VLC research is focused on increasing the field-of-view (FOV), range, and rate of communication, and significant advances have been attained in increasing what is possible with a *single* element, i.e., a transmitter (an LED), receiver (a photo-detector (PD)), or transceiver (an LED-PD pair) [34, 20, 25].

Recently, in [11, 23, 17, 31, 28], multi-element receiver approaches are introduced to improve system performance. There has also been earlier works that jointly study illumination and communication aspects of multi-element VLC systems [29, 5, 24, 36, 30, 12]. The focus of these efforts have been to increase reception gain by using a customized version of multi-input multi-output (MIMO) techniques. A mix of time and frequency techniques have been leveraged, in these efforts, to maximize the gain from a MIMO transfer of a single data stream, where LEDs have large divergence angles and photo-detectors have large FOV.

The key contribution of this thesis is to explore designs using *many* elements with *narrow* divergence angles and FOV. In particular, we *use multi-element VLC modules for simultaneous transfer of multiple data streams and attain higher spatial reuse in short ranges*, e.g., a room. We design an architecture around a multi-element "bulb" that has highly directional LEDs on it, as shown in Figure 3.1. We take a software-defined approach to managing LOS alignment to multiple receivers, e.g., laptops, in the room. We introduce a hybrid RF/FSO scheme to figure out which transmitter(s) on the bulb is in LOS alignment with which laptop in the room, and steer the data streams to corresponding transmitter(s) accordingly.

In this thesis, we have simulated a hemisphere with multiple LEDs that can serve as a source of light as well as IP-enabled communication system. Using this architecture, we have tried to address two issues:

1. Design of the bulb (hemispherical structure)
2. Analysis of the effectiveness of the bulb (hemispherical structure)

The bulb acts both as the source of light and access point for communication between the indoor receivers and internet. The results show that one "bulb" with at least three layers of LEDs on it can easily serve a 6x6 meter room in terms of lighting and communication capabilities. Even though the average light intensity across the room degrades as we move away from the bulb, it is evenly distributed across the room. The SNR is maintained at reasonably high values on a 4m circumference of the bulb. The measured SNR values can sustain an effective download optical link without significant disruption.

Apart from plotting the average light intensity in a room we were able to map the floor coverage area corresponding to each LED on the bulb. It was also observed that the pattern corroborate with Lambertian pattern [37], on the basis of which the bulb was designed, thereby proving the genuineness of this model. This simulation model work is very critical as it provides more insight into the development of actual structure. This model can be improved upon to test future modifications in the hemispherical structure. An interesting observation was the response of the model with respect to divergence angle of each layer of LED on the bulb. The simulations prove that divergence angle plays an important role in the coverage area and SNR making the model flexible enough for optimization problems. The simulations also show that the angle of placement of the LEDs on the bulb also has a significant effect on the interference and effective SNR values. It was observed that certain places on the floor gets very high SNR values and this scenario has a direct relation with the angle of placement of LEDs on the bulb.

We have also defined a partitioning algorithm which is aimed at improving the efficiency of download from the bulb to the receivers. It is a simple but novel algorithm that divides the LEDs into sections based on the positions of the receivers on the floor. The tests showed that maintaining an ideal distance between the receivers will benefit laptops with a stronger signal reception and less interference from one another. We also describe an algorithm to maintain the mobility of the receivers in the room. The toy prototype that we have demonstrated in this work projects our idea and the intended method of implementation.

The rest of the thesis is organized as follows: Chapter 2 surveys the relevant work and describes the motivation behind our work on multi-element bulb. We then propose the architecture of the bulb and describe the proposed RF/FSO hybrid Line-Of-Sight(LOS) management scheme in Chapter 3. In Chapter 4, the bulb is described in detail including the angular placement of the transmitters on the bulb. The simulation setup along with the results and the partitioning algorithm is described in Chapter 5. The work is summarized and future work is laid out in Chapter 6.

Chapter 2

Literature Survey

2.1 Related Work

Multi-Element visible light structures are a relatively new field of study in VLC systems. A large body of work exists on VLC systems with a focus on improving characteristics such as speed, range, and intensity of illumination because of the wide range of applications associated with these systems. Most of the works on FSO can be generally classified into five main categories:

- High Speed Free-Space-Optical Communication
- Indoor Free-Space-Optical Communication
- Hybrid Free-Space-Optical Communication
- LED-to-LED Communication

2.1.1 High Speed Free-Space-Optical Communication

Optical communication has been used for more than 3 decades in various forms to serve fast communication links in remote locations. Fiber optic communication has the most acceptance as a wired technology and it is capable of high speed transmission. Even though FSO communication systems use the same principle and similar transmitters and receivers, this technology is still considered to be in its infancy. However, years of research have been taking this technology one step ahead to commercial deployment. In the world of communication, datarate of data transfer is an important factor. However the datarate depends on several factors such as bandwidth, collisions, area of coverage, interference, modulation, mode of communication etc. Several schemes have been implemented by varying one or more of the above factors to increase the data rate. In [22], the authors demonstrate a bidirectional 1.25 Gbit/sec indoor Home Access Network project using power line communication in the back bone and RF/VLC as front-end. In this case the VLC is used as a broadcast medium to support multiple users. Also the receiver has three different elements directed in three directions, motivated from the concept of angle diversity described in [9], to facilitate handover between the elements depending on signal strength. The implementation uses infra-red front end instead of LEDs, while the authors claim that the system is compatible with LEDs. Speeds upto 1.28 Terabit/s has also been achieved using WDM transmission techniques on laser beams[13]. Orthogonal Frequency Division Multiplexing(OFDM)takes advantage of high peak to average power ratio of the signal thereby allowing high-speed data transmission . Multiple Input Multiple Output(MIMO) has also been used in conjunction with OFDM to generate a transmission rate of 220 Mbps at a Bit Error Rate(BER) of 10^{-3} over a range of 1 m [4]. The demonstration in ,[4] involves 2×9

imaging MIMO system sending OFDM coded symbols that is received effectively by 3×3 photodetector array over a distance of 100 cm. Subcarrier multiplexing has has also been used in MIMO-OFDM transmission scheme for simple realization of multiple-input transmitter.

2.1.2 Mobile Free-Space-Optical Communication

Line Of Sight (LOS) property of optical communication is a critical issue that needs to be addressed in any VLC system. In LOS communication an optical link has to be established, by aligning the transmitter and receiver, and maintained to facilitate communication. Some of the mechanisms developed to address the LOS issue is described in this section. In [35], the authors propose two protocols: (i) a peer-to-peer protocol where the receiving elements provide a multi-hop path among them, and (ii) a peer-to-host protocol where the multi-hop path is provided within the base stations. The latter is proved better in a scenario with fewer number of user devices and the former in the scenario with more user devices. Instead of using a light source with wide FOV, [6] suggests using multiple spot light sources. According to the authors the concept of ideal spot light results in an ideal cone of light which is focused and directed to provide both high datarate VLC signal and bright light covering a small surface. It reduces multi-path distortion due to reflection of the signal off walls and objects. It is to be noted that these light sources are designed to be completely independent light sources. IP enabled smart VLC systems can bridge the gap between the wired and optical communication systems . One such example is found in [10] where authors demonstrate a control module, based on Gumstix embedded MCU, that integrates the optical transceivers with Internet. Light dimming is an interesting indoor VLC application as described in

[7]. They define the ”lights off” mode as level that satisfies humans that the lighting is effectively ”off”. This is implemented by maintaining the surface area of the emitter large and the brightness of the emitter matching with current brightness of the room. The results show that the ”lights off” mode can maintain data rates of several Nm/s with low light emission. Optical communication is being used as replacement or complement to RF in many outdoor applications. In [3], the potential of introducing FSO into inter-vehicle safety communication is discussed. The property of directionality and smaller range, that was considered to be deterrent about VLC technology, have been put to good use thereby gaining an upper hand on RF communication in high density scenarios of inter-vehicular communication.

2.1.3 Hybrid Free-Space-Optical Communication

Optical communication was initially developed as a replacement for constrained RF technology. However, hybrid RF/FSO communication systems has become a hot topic where the advantages of both technologies are integrated. The advantages of RF include non-requirement of Line Of Sight, wider area of coverage and multi-user support. On the other hand, advantage of VLC include ”illuminication”, secure in an indoor setting, cheaper, easy to setup and less overall power consumption compared to RF. As an example,a work by [19] involves using a hybrid RF/FSO system in backbone networks as FSO links provide high bandwidth and security and RF links offer reliability. They propose a routing framework which enables traffic engineering on the incoming traffic by integrating traffic engineering and bandwidth management at an offline computing unit. This information is then used at ingress routers for traffic engineering and routing when the network is online. Ultraviolet has also been used as an uplink mechanism thereby creating a hybrid ultraviolet/FSO communication system [1]. Other recent studies on hybrid RF/FSO networks include [21, 27]. These works consider that in the downlink, each user is served only by a single LED, while in the uplink, an RF technology such as WiFi is used for communication.

2.1.4 LED-to-LED Communication

LED-to-LED communication is a very recent VLC technology that eliminates the use of a photodiode to receive data transmissions. The authors of [16] use narrow-band LEDs in low complexity applications and with low PHY rate using a single LED and micro-controller per device. It focuses mainly on communications and visual/emotion feedback. The LED is supplied in forward bias at a constant voltage when transmitting symbol +1, such that current flows from the anode to the cathode. However for transmitting a zero, the LED is reverse biased instead of removing the forward bias. This mechanism also helps in implementing the reception of data from another LED. Another group has taken the same concept further into development of a flexible software-defined platform,OpenVLC that helps in easily building PHY and MAC protocols in VLC setups using BeagleBone Black board(BBB) [33].

It can be observed from the above mentioned works that most research goes into either improving the properties of VLC systems or working a way around to make communication feasible. Our research differs from the recent works in the integration of multiple spotlighting mechanism onto a single light source (base station), thereby creating an apparently large FOV which makes handover easier and also serves the purpose of illumination. Instead of developing a VLC-based broadcast system, our research focuses on specific data stream from individual spotlight from the overhead light source.

Chapter 3

The Architecture

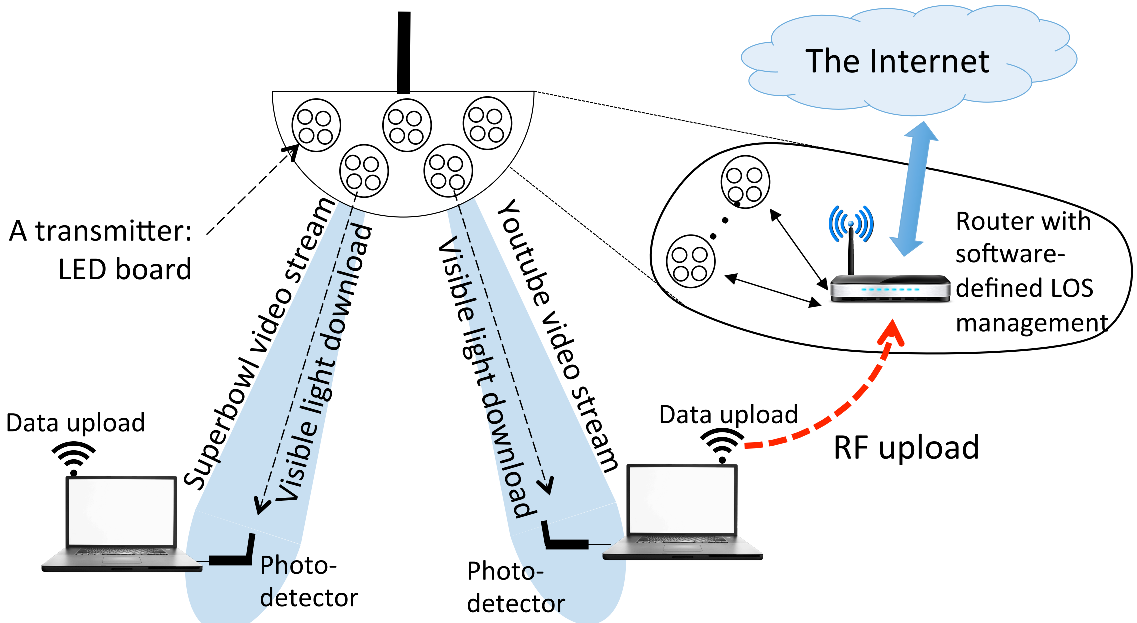


Figure 3.1: Architecture for multi-element VLC structure.

3.1 Multi-Element VLC Architecture

Two key aspects of our multi-element VLC approach are its (i) *high spatial reuse* by using transmitters with narrow divergence angle, and (ii) *seamless handling of mobility* of receivers by using software protocols that steer of data transmissions to mobiles. Unlike the traditional view of LEDs/transmitters with large divergence angles, we use narrow divergence angles and still perform an acceptable illumination by using hundreds of LEDs on a “bulb”. Since LEDs are getting cheaper, we believe this design direction will prove fruitful.

Another ramification of narrow divergence angles is the lack of coverage. Even when we use hundreds of LEDs, we still have the problem of steering the data transmission to the corresponding LED as the mobile receiver is moving. We tackle this problem with an enhanced version of our electronic steering concept [26]. Our architecture takes advantage of spatial reuse and seamless steering which, essentially, are untapped sources of efficiency in VLC. We detail the architecture by describing three key components below: The bulb, mobile receiver units, and an RF/FSO LOS management protocol.

3.1.1 The Bulb

The bulb is a hemispherical structure that acts as an access point for the room. It consists of multiple transmitters to facilitate *simultaneous downloads* to multiple receivers. These transmitters are intended to provide light coverage and facilitate communication in the room. As shown in Figure 3.1 the bulb consists of multiple transmitters directed at different directions. Each transmitter is placed in a layer that has constant angle with the normal. Within each layer the transmitters maintain an angle of 45 degree between them. A coverage area is defined for each transmitter. More mathematical details on calculation of coverage is provided in 4.1. Depending on the positioning of the transmitter there can be interference between the lights from neighboring transmitters. This will generate hot spots on the floor having combined received signal strengths from the two transmitters. These hot spots were found out to be advantageous to receivers when two neighboring transmitters are assigned to the same receiver using the partitioning theorem.

Each transmitter consists of multiple LEDs that transmit a single data stream. The LEDs on the board are all modulated by the same signal, and hence the purpose of having multiple LEDs on a transmitter board is to allow tuning of tradeoffs between source power, communication range, and illumination quality. It is possible to use just one LED instead of a board of them to find a good balance. For instance, for a large room with high ceiling, using smaller number of LEDs may result in a better performance in terms of illumination-communication balance. For our architecture, the important property is that each transmitter is looking at a different angle with respect to the other transmitters on the bulb. Overall, the bulb's spherical multi-element design coupled with highly directional LEDs allows higher spatial reuse in communication. However, it also presents the challenge of seamless steering of data transmissions to corresponding transmitters. To address this issue, we connect each transmitter (via Ethernet) to a router embedded in the bulb and run a software protocol for managing LOS alignment (detailed in Section 3.1.3).

Coexistence of spatial reuse with seamless steering of data transmissions is a larger problem that exists in multi-element directional communication systems. Many

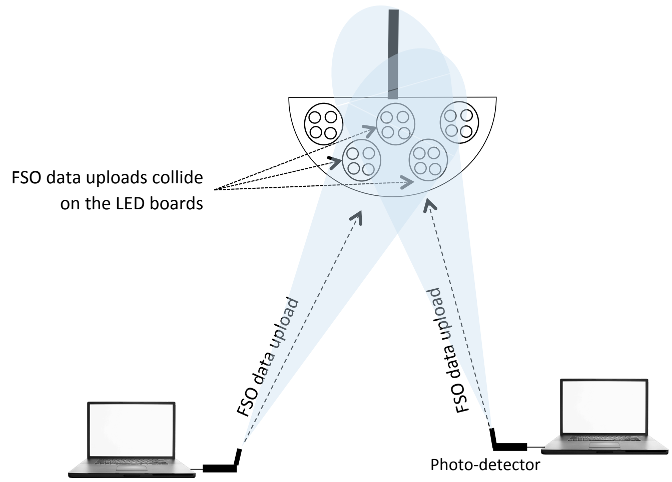


Figure 3.2: Collision in bidirectional communication.

research works tries to achieve either seamless steering or spatial reuse. In [32] authors propose a mechanism to handover communication from one access point (AP) to another. This approach attains seamless communication across APs, but falls behind in exploiting the full advantage of spatial reuse in VLC and FSO.

Another challenge is that using bidirectional VLC can cause significant collisions as shown in Figure 3.2. In our proposed architecture we resolve this issue by using a hybrid RF/FSO approach coupled with LOS alignment protocol [26]. In hybrid RF/FSO approach the data download is conducted through FSO/VLC and upload is carried out using RF. This approach significantly reduces the collision that can be caused by bidirectional VLC communication. In hybrid approach, the upload and download of data streams are completely decoupled. In [27], the authors also proposed to solve this issue via a RF/FSP hybrid network design. However, our approach is different in that we handle all the RF/FSO communication *within the same AP* and thus prevent any routing and transport protocol issues pertaining to asymmetric upload and download paths.

3.1.2 Mobile Receiver Units

The receiver unit is mobile and equipped with a photo-detector (PD). We envision the PD(s) to be conformal to the surface of the unit with additional apparatus like lenses as appropriate. These mobiles also need the ability to upload using legacy RF transmitters. They receive the download data from the LED transmitter(s) with which they are in LOS alignment. The design of these units is a big research undertaking and requires joint work of solid-state device and packaging as well as protocols. For instance, multi-element conformal PDs can be designed that covers a smartphone's or laptop's surface. We assume that these mobiles have one PD receiver and one RF transmitter.

3.1.3 RF/FSO Hybrid Management of LOS

In our hybrid architecture, the multi-element bulb manages the LOS management between the transmitters and *mobile* receivers. The bulb takes a software-defined approach in order to keep track of which receiver is best aligned with which transmitter LED on the bulb. This includes establishing an optical link by assigning/associating transmitter(s) to a receiver, maintaining the optical link with mobility of the receiver across the room, partitioning the transmitters so that multiple transmitters can serve a receiver, and cease the optical link once the receiver is offline. We group these functionality into three basic *bulb-mobile* association mechanisms as detailed below. Note that mobile-AP association is an old problem in Wi-Fi protocols. However, an overhaul of the association framework is needed due to the VLC complexities arising from the directionality of LEDs, the LOS alignment requirement.

Join with LED-RAT

In order to search for new mobiles in the room, the bulb periodically sends SEARCH frames via its LEDs. Each LED on the bulb has a local ID, k, which is included in the SEARCH frames being sent from that LED k. These SEARCH frames are analogous to the Ethernet's RTS messages, with a key difference that they are augmented with the local ID of the LED they are being sent from. A mobile receiver X, entering the room, receives these SEARCH frames. X might receive multiple of them depending on its position with respect to the bulb. We assume that the receivers have the capability to filter the SEARCH frame with strongest light intensity. Such a capability can easily be implemented in hardware level by using trans-impedance amplifiers, comparators and micro-controllers. A measure of the received signal strength indication (RSSI) can be fed into the micro-controller where the decision is made over which input has the strongest signal. [8]

Once the receiver filters and receives the SEARCH frame with the strongest intensity, it extracts the local ID of the LED, say k, from which it was transmitted. The receiver sends back an ACK frame (like a CTS in classical Ethernet) via its RF transmitter. This ACK includes the Ethernet address of the receiver and the local ID k of the LED from which the SEARCH frame was received. The ACK verifies to the bulb that X is aligned with the transmitter LED k. After receiving the ACK from X, the bulb assigns the LED k or a group of LEDs around the LED k to X, and maintains this information as an *LED-receiver association table* (LED-RAT).

When there are multiple receivers in the room, the bulb needs to partition the

LEDs and associate each partition to a separate receiver. LED-RAT will need to be updated accordingly. For every data frame to be sent, the bulb performs a reverse lookup to LED-RAT with the Ethernet address the frame destined to. In this manner, the bulb steers the data stream destined for receiver *X* onto the transmitters that just got assigned/associated to *X*. The partitioning of the LEDs across the receivers will be crucial in the overall spatial reuse performance. We will detail some heuristics to this partitioning problem in Section 4.1.

There is a well-known tradeoff in this approach of sending SEARCH frames periodically to detect new receivers in the room. Frequent transmission of SEARCH frames will deteriorate the optical download capacity as more time will be spent in "receiver detection". On the other hand, too infrequent SEARCH frames will increase the time taken by the receiver to connect to the bulb. This tradeoff exists in the AP-mobile association protocols of legacy WiFi as well. We expect to use sub-second frequencies (e.g., every 500ms) for periodic broadcast of the SEARCH frames, so that the connection time is reduced. The fine tuning of this timer is future work.

Maintain

Once the optical link is established between the receiver and the LEDs on the bulb, it is maintained by periodic exchange of SEARCH-ACK messages as described above. When there is a change in the LED-receiver association, the bulb will need to update LED-RAT and re-partition the LEDs. Since such changes can happen frequently, it is crucial to keep the complexity of the LED-RAT update and partitioning of LEDs small. Further, as we are envisioning hundreds of LEDs on the bulb, the re-partitioning operation should be performed in a manner independent of the number of LEDs on the bulb.

Leave

When a receiver leaves the room or powers down, the bulb needs to update LED-RAT and re-partition LEDs. We consider two possibilities. *Graceful Leave*: The receiver Y lets the bulb know that it is powering down by sending a CLOSE frame via its RF transmitter. *Ungraceful Leave*: The receiver Y simply leaves the room without letting the bulb know about his departure. Then, the bulb will keep sending its SEARCH frames, and will timeout on Y after t SEARCH frames without an ACK from Y. Either graceful or ungraceful, after the bulb finds out that Y is not responsive, it will release the LEDs associated to Y and re-partition.

3.1.4 A Toy Prototype for Proof-of-Concept

To explain the overall idea of the multi-element bulb in our VLC architecture, we have built a proof-of-concept toy prototype using off-the-shelf materials. As shown in Figure 3.3, the prototype portrays the communication between the bulb and two receivers, R_1 and R_2. The bulb consists of two LEDs L_1 and L_2, placed at a circular angle as envisioned in our architecture. The receivers go through the initial association mechanisms, Join with LED-RAT and Maintain, to establish and maintain the VLC link with the LEDs. Once established, the router's switching algorithm learns that L_1 is aligned with R_1 and L_2 is aligned with R_2. Then, the LEDs transmit two different Youtube streams to their corresponding receivers. The data received at each receiver is then delivered to corresponding laptops/clients via Ethernet. On the other hand, a message that needs to be delivered to the bulb from the receivers will be sent via RF to the router in the bulb. Mobility can be portrayed by moving and aligning laptop R_1 with LED L_2 and laptop R_2 with L_1, while the Youtube streams are being downloaded. After this change, The LOS alignment algorithm kicks in and updates the LED-RAT when the next set of SEARCH messages are sent from the transmitters. This process reassigns the datastreams corresponding to each of those laptops. This is just a simple presentation of our architecture and several challenges need to be tackled to develop a full-fledged prototype.

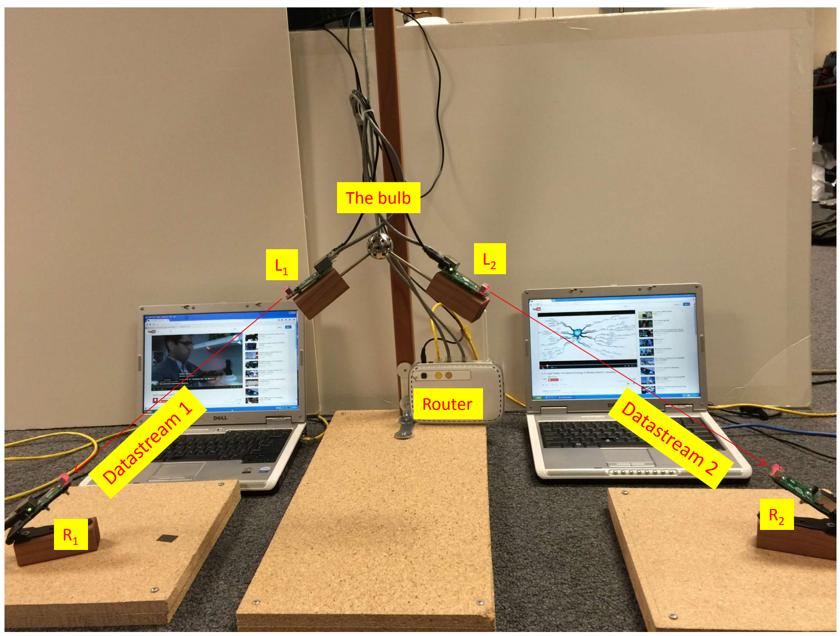


Figure 3.3: Proof-of-concept demo of multi-element bulb for more spatial reuse.

Chapter 4

The Bulb

4.1 Multi-Element Hemispherical Bulb Design

The design of the multi-element bulb is of utmost importance as it should provide an effective spatial reuse without noticeably affecting the lighting across the room. The bulb is a hemispherical structure that controls the light distribution and dataflow between the LED transmitters and receivers. The design of this structure is based on optical antenna prototype proposed in [26]. In order to maximize the coverage in the room, the transmitters are arranged in layers of circles with each layer at a different elevation angle. Transmitters in each circular layer are placed 45° apart. Figure 4.3 provides a perspective of the hemispherical model being evaluated in this paper. A more efficient arrangement of the transmitter LEDs is within itself an optimization problem that is not discussed in this paper (see e.g. [37] for further discussions on a special case of this problem). Several factors such as radius and divergence angles of the LEDs, and height of the room can affect the

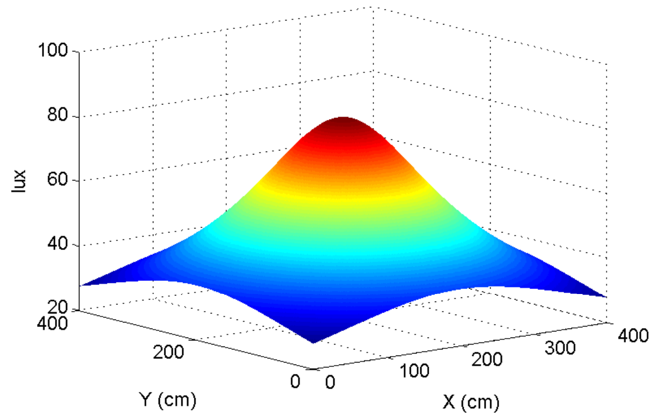


Figure 4.1: Average light distribution across the room.

light distribution and communication pattern in a room. An optimized placement should jointly improve the light distribution and communication in the room and this will be part of our future work. In our model we place the first, second, and third layers at 30, 45, and 70 degrees, respectively. Figure 4.1 shows the average light intensity on the room floor.

4.1.1 Partitioning Algorithm

In order to take full advantage of the multi-element bulb structure, we need to partition the LEDs into groups, each corresponding to a mobile receiver in the room. To put this into perspective, consider a scenario where the multi-element bulb has 10 transmitters that can serve up to 10 receivers in an indoor environment. If the room has just two receivers, without the partitioning algorithm, only two transmitters (that are the most aligned with the two receivers) will be serving the respective receivers. With the partitioning algorithm, the 10 transmitters can now be divided into two partitions, each of which, consisting of multiple transmitters, can now serve the two receivers. This can reduce the load on LOS alignment algorithm by providing a wider FOV for each receiver.

The algorithm is explained with respect to above scenario with two receivers. Let receivers 1 and 2 be placed at (X_1, Y_1) and (X_2, Y_2), respectively, on the floor. An imaginary partition line is considered such that it is perpendicular to and passes through the midpoint of the line connecting (X_1, Y_1) and (X_2, Y_2). The transmitter LEDs are then divided into two groups based on the positioning of their signals' projection on either side of the line on the floor. If the partition line intersects with an LED's projection on the floor, the LED is categorized into the side that includes the majority of the LED's projection. Once the LEDs are partitioned, all the LEDs in a partitioned are modulated with the same transmission signals, which means that the receiver for that partition now can enjoy a reception quality arising from the sum of all the light intensity coming from the LEDs of its partition. It is to be noted that the receiver will be able to receive from an LED only if it is within divergence angle of the corresponding LED.

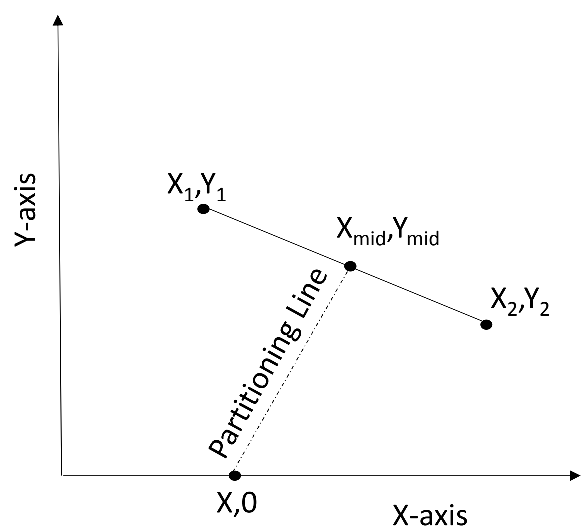


Figure 4.2: Partition line in a room.

In this section, we detail how we simulated the partitioning algorithm, given two completely random receiver positions, $(X_1, Y_1), (X_2, Y_2)$, in the room as shown in

Figure4.2. We find the mid point, (X_{mid}, Y_{mid}), of the two positions in the room. An imaginary partitioning line is drawn perpendicular to the line connecting the two random receiver positions. The perpendicular line is drawn between (X_{mid}, Y_{mid}) and the point, $(X, 0)$, at which the line meets the X-axis. The X-coordinate is calculated using the following equation:

$$X = -(Y_{mid} - (\tan(\arctan(m) + \pi/2)) * X_{mid}) \tag{4.1}$$

where m is the slope of the line connecting the two random receiver positions. This algorithm partitions the transmitters into different sections depending on the position of the receivers. This algorithm is executed every time when a new mobile device establishes connection with a transmitter. The algorithm reassigns all the transmitters giving new space for the new connection while maintaining the old connections.

4.1.2 Coverage of a Single Transmitter LED

The coverage area of a transmitter LED is defined as the area in which the receiver can align and/or reach the transmitter so as to receive data from the transmitter. In 3D, the coverage looks like a cone and the power received at any point within the cone is dependent on factors [37] such as source transmission power, divergence angle and surface area of the transmitter, sensitivity threshold and surface area of the photo-detector(s), geometric attenuation, and reflections from walls. Assuming that there is no atmospheric attenuation, a simplified model of the received light intensity at a point within the LOS of the transmitter is a function of the transmitter's source power P (dBm), the radius of the transmitter γ (cm), and the divergence angle of the transmitter θ (Rad). [34]

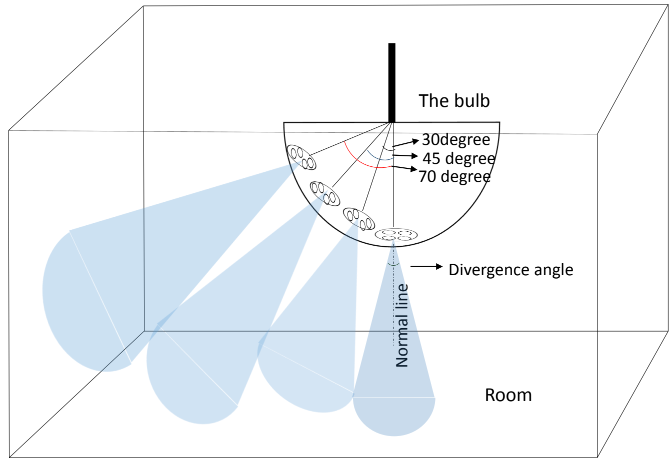


Figure 4.3: Angular placement of transmitters on the bulb.

The light distribution pattern of an LED follows the Lambertian law [34], which means that the intensity of light received on the floor from the LED is proportional to the cosine of the angle from which it is viewed. If P_Z is the received power along the beam at a distance Z, then the intensity at an arbitrary angle α from the beam at a distance Z would be: $P_{\alpha,Z} = P_Z \cos(\alpha)$ [37]. Considering a typical photo-detector sensitivity of $S = -43$ dBm, we obtain the maximum range of a transmitter from the following inequality [34]:

$$-(P + 43) < 10 \log(e^{\sigma R}) + 10 \log \left(\frac{\delta}{\gamma + 200R\theta} \right)^2 , \tag{4.2}$$

where P is the source power of transmitter in dBm, σ is the attenuation coefficient consisting of atmospheric absorption and scattering, R is the possible communication range, γ is the radius of the transmitter in cm, δ is the radius of the receiver in cm, and θ is the divergence angle of transmitter in mRad.

Chapter 5

Simulation and Results

5.1 Simulation Setup

The coverage area and signal strength were calculated by using MATLAB simulations. The simulation is based on an indoor setting in which a room contains a multi-element bulb at the ceiling center of the room. We detail the simulation setup and calculation methods used in the simulation.

5.1.1 Transmitter Coverage Model

The bulb consists of multiple transmitters to facilitate multiple streams of communication. Each transmitter is placed at an angle, θ, from the perpendicular normal and has a defined coverage area. Each coverage area takes the shape of a cone in 3 dimensions as shown in Figure 5.1. The figure depicts the coverage area of one LED board. The board is attached to the main unit by a connector and is held

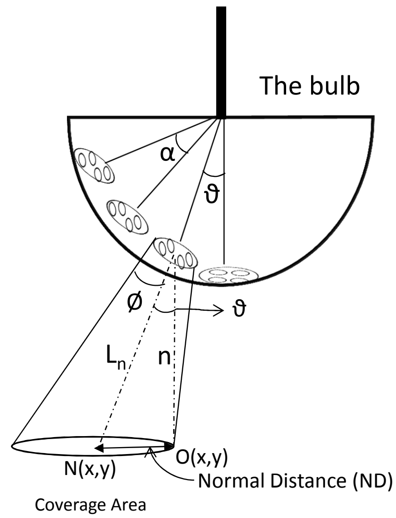


Figure 5.1: Angular placement of transmitters on the bulb.

at a height Z. Following the shape of a cone the coverage area of the floor will form a circle. As the angle from the normal increases the spread of the cone increases leading to elliptical formation replacing the circular coverage area on the floor. Maximum light coming out of the transmitter is concentrated on the normal point on the floor point perpendicular with respect to the transmitter. The slanted normal, L_n, connecting the normal point on the floor and center of the transmitter defines the distance between the two. This distance is directly proportional to the height of the transmitter. The normal point on the floor, $N(x, y)$ can be calculated from the following equation,

$$Nx = X \pm ND * cos(\alpha) \tag{5.1}$$

$$Ny = Y \pm ND * sin(\alpha) \tag{5.2}$$

where X and Y are the 2D coordinates of the transmitter position on the bulb. The Z coordinate is neglected as it will be 0 in all cases. Normal Distance(ND) is the distance between $N(x, y)$ and $O(x, y)$ where $O(x, y)$ is the point at which the perpendicular normal n meets the floor. Normal Distance can be calculated from,

$$ND = Z * tan(\theta) \tag{5.3}$$

where Z is the z coordinate or height of the corresponding transmitter and θ is the angle of the transmitter from the normal. α is the angular distance between the transmitters on a layer. We use (4.2) to find the maximum signal power received at the normal point. The distance between the normal point $N(x, y)$ and origin point of the transmitter gives the range R that is used in (4.2). This distance is calculated from the equation,

$$R = \sqrt{Z^2 + ND^2} \tag{5.4}$$

5.1.2 Divergence Angle

Divergence angle of an LED defines the angular spread of the light. The divergence angles in most optoelectronic transmitters could vary from less than 1 degree to around 30 degrees. Narrow divergence angles are associated with lasers and are used in applications requiring high signal in a concentrated area. The applications include Lunar laser ranging, barcode scanners, Heat treatment so and so forth. On the other hand light sources with high divergence angles are used in floating buoys that require more light to be distributed in larger area. In our simulation we choose three instances of divergence angles: 1°, 20°, 45°. The changes in the coverage area of each transmitter can be explained effectively with these divergence angles.

5.2 Results

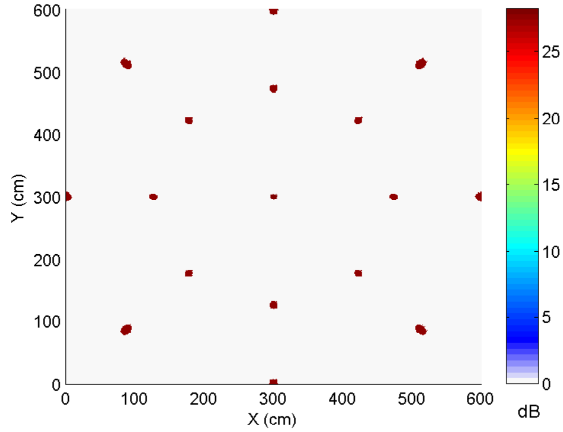
In this section, we detail how we simulated the partitioning describe the results obtained through the MATLAB simulations. In order to get a glimpse of what is possible in terms of download efficiency and illumination efficiency, we perform an initial evaluation of our VLC architecture with the partitioning algorithm discussed in Section 4.1.1. For simulation experiments, we consider a room of size 6 m × 6 m × 3 m. The multi-element bulb is placed at the center of the room ceiling which is considered as the origin point of the hemisphere. The hemisphere bulb consists of three layers of transmitters. Each layer is distinguished by the elevation angle between the normal of the hemisphere and the transmitter. In our model, layers 1, 2 and 3 are placed at an elevation angle of 30, 45 and 70 degrees, respectively. Each transmitter will have a certain number of LEDs that decide the signal strength in the coverage area of the respective transmitter. A divergence angle is assigned to each transmitter. In our experiment we are checking for the optimum arrangement that provides a good signal-to-noise ratio (SNR).

We randomly position two receivers on the room floor and divide the LEDs on the bulb into two partitions P_1 and P_2 following the heuristic described in Section 4.1.1. We assume that the photo-detector(a) at a receiver is conformal to the surface of the receiver and can receive the light coming from a partition on the bulb.The photodetector is facing upward to the transmitter and has a radius of 0.3 cm. So, a receiver is considered to be within the coverage of an LED if it lies within the divergence angle of the LED. A receiver can be in the coverage of one LED or multiple LEDs of the same partition or multiple partitions. Thus, the signals arriving to a receiver i from partitions other than P_i need to be considered as noise. For the simpler case of two receivers, let $S_{1,1}$ be the total signal received at receiver 1 from LEDs of P_1 and let $S_{1,2}$ be the total signal received at receiver 1 from LEDs of P_2. Then, SNR for receiver 1 is $\text{SNR}_1 = S_{1,1}/S_{1,2}$. Following the same symbolization, SNR for receiver 2 is $\text{SNR}_2 = S_{2,2}/S_{2,1}$. A photodetector with higher radius can have better SNR values.

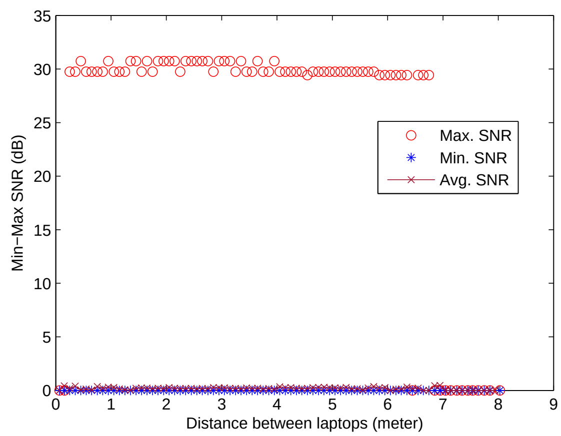
We evaluate at three different divergence angles. In the first two cases, we check the extreme scenarios with very small and and very large divergence angles to test the correctness of the model. In the third case, we experiment with other parameters to optimize the lighting and signal strength. We assume that there are 500 LEDs/transmitters (each with 20 mW of source power) on each transmitter board of each circular layer on the bulb. Each LED board will consume 10W power. A combined power of 250 W will be consumed by the entire bulb. It might be unreasonable for 6m x 6m x 3m room. However, the power consumption can be adjusted to keep the illumination and communication still high. A plausible solution would be to dim down the LEDs with higher divergence angles at the top layers of the bulb. We repeat the simulation 80K times for different random placements of the receivers.

5.2.1 Case I: Divergence Angle: 1°

A divergence angle of 1°corresponds to a laser or VCSEL. The minimum divergence angle that can be theoretically achieved by most lasers (e.g., Nd:YAG and He-Ne lasers) are 0.02014°and 0.03607°, respectively [2]. A small divergence angle concentrates the light in a small concentrated area thereby providing strong signal strength in that area. Figure 5.2, shows the signal intensity map at the room floor.



(a) Signal Coverage



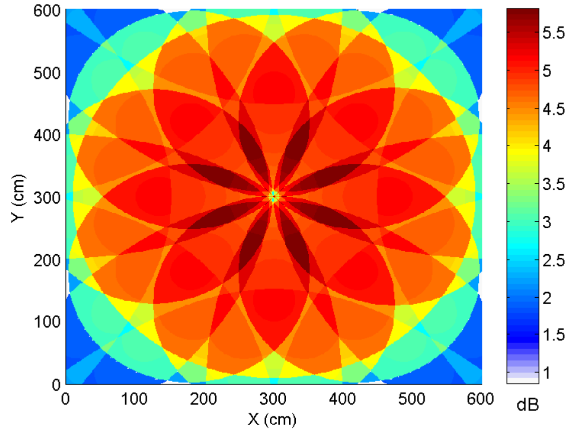
(b) SNR

Figure 5.2: Divergence angle: 1°

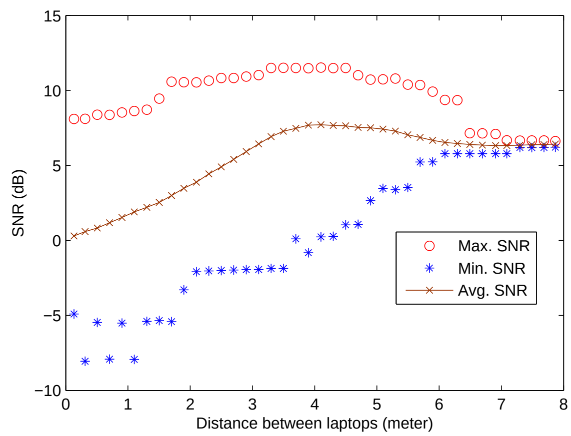
It can be observed that the signal availability is limited to some very concentrated areas. As a result the SNR is sporadic and uneven as shown in Figure 5.2 (b). The receiver under observation can receive the signal from the transmitter irrespective of the distance from the other receiver. The graph looks uneven as we are averaging the value over large number of observations. The results show that the receiver was within the coverage area of a transmitter once every 150-200 observations with distance between laptops being less than 0.2 m. This can be easily deduced from Figure 5.2 (c) where maximum and minimum at each averaging point were measured. Every averaging point has at least one position where the laptop will be within the coverage area of a transmitter and receive the maximum signal from the corresponding transmitter. The same results are observed for all other distances as well. At the same time, there are huge gaps in the room, represented with blue color, without any signal coverage. This case is an extreme for us to observe that too narrow divergence angles cause a highly intermittent connectivity as well as a too uneven lighting in the room.

5.2.2 Case II: Divergence Angle: 45°

This is another extreme case of LED transmitters used in the bulb. A high divergence angle increases the distribution of light across the room but can create sizable interference as well. In Figure 5.3 (a), it can be observed that the signal distribution is more uniform across the room. As in Figure 5.5, compared to Case I, the average SNR is high enough to maintain high throughput even for cases when the receivers are closer to each other. The distribution of light across the room is almost even. However, this positive factor was achieved at a price of reduction in SNR values. The number of LEDs and LED boards as well as the transmission power of LEDs may be tuned to increase the SNR. The average SNR value increases and then decreases slightly from the maximum, which will be explained in the next case where it occurs more prominently. The max and min SNR values in Figure 5.3 (c),show a different picture compared to case I. The gap between the maximum and minimum values are initially high, which then gradually decrease and finally almost merges around distance of 8 meters. In other words, result clearly shows the effect of interference with respect to distance between the receivers. The interference is very high in the middle regions whereas it decreases towards the corners of the



(a) Signal Coverage



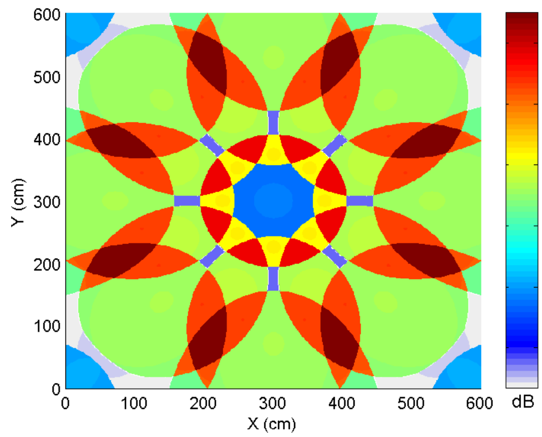
(b) SNR

Figure 5.3: Divergence angle: 45°

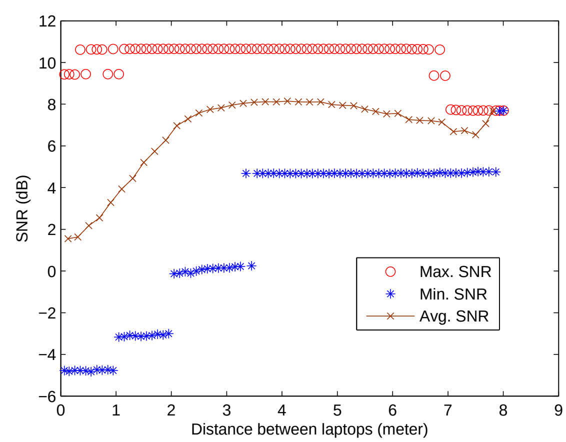
room. When the receivers are close to each other they are more likely to be somewhere in the center of the room. Likewise, when they are far from each other, they are more likely to be at the opposite corners of the room.

This result reveals three regions where three different factors dominate the SNR value. When the receivers too close (e.g., distance is 1-2m), the interference dominates and reduces the SNR achieved. When the receivers are too far from each other (e.g., distance is 6-8m), the signal strength dominates the resulting SNR as the receivers are now at farther corners of the room and hence receive the signal from the bulb at a farther location with a smaller strength. Finally, in the middle region (e.g., distance 2-6m) the spatial reuse dominates and increases the resulting SNR. This is a promising picture since the receivers more likely to be in these "middle" regions in general.

5.2.3 Case III: Divergence Angle: 20°



(a) Signal Coverage



(b) SNR

Figure 5.4: Divergence angle: 20°

Typically, divergence angle of LEDs varies from 15 to 20 degrees. So, to capture the common case, we consider LEDs with a divergence angle of 20°. From Figures 5.4 (a) and 5.4 (b), it can be observed that the signal distribution remains fairly even, and provides reasonably higher SNR compared to Case II even for shorter separation of the receivers. This means spatial reuse is better as expected from narrower divergence angles.

However, it can also be observed that the average SNR dips around distance of 5 meters. The reason for this can be explained based on Lambertian law. According to this law the intensity of light decreases with angle from the normal. The layered approach that we follow in the placement of transmitters on the bulb should also be taken into account here. Each layer of transmitters are placed at an angle from the normal. Therefore the signal strength received for a straight beam from a transmitter placed at an angle is less than the signal strength received by a straight beam from a transmitter placed in line with the normal of the bulb. In addition to this, we have the reduction in strength associated with Lambertian law. The two reasons mentioned above causes the dip in SNR. This can be resolved by adding more transmitters with LEDs that have larger divergence angle on the outer layers of the bulb. Adding more transmitters on the outer layer will help match the signal strength of transmitters that are in line with a legacy bulb.

Figure 5.4 (c), shows that the interference reduces in steps with increase in distance between the receivers. The reduction in interference, compared to case II, is obvious from the graph as the receiver is able to achieve the highest SNR at least at one point consistently over the range of distance from 0 to 8 meters.

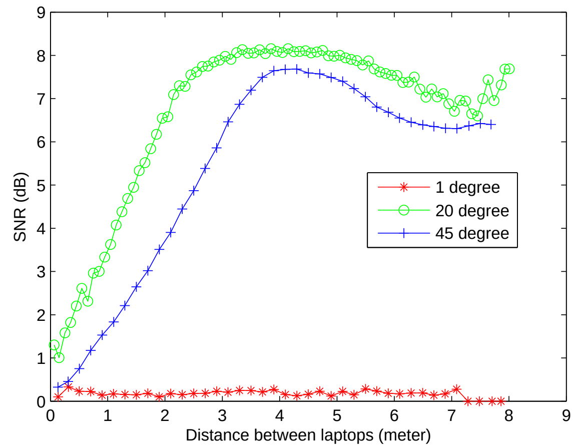


Figure 5.5: Average SNR for one receiver.

5.2.4 Effect of Divergence Angle

In this section we compare the SNR results from the three cases discussed above. In case I the divergence angle was set to 1° resulting in a few high SNR regions leaving the rest of the floor without any signal. The average SNR is very low as receiver is present within the coverage of a transmitter very few times. For most part of the observations of this case the receiver is out of coverage area of any transmitter in the bulb. This scenario rejects LEDs with very narrow divergence angles as a potential transmitter on the bulb. In case II we consider LEDs with high divergence angles, 45°, which gives more coverage across the room but produces sizable amounts of interference. The result shown in Figure 5.5 clearly shows the effect of interference. The SNR steadily increasing from 0 to a maximum value. This increase can be related with decrease in the interference with distance. Another reason associated with this steady increase is the angular placement of LEDs in each circular section. The received signal keeps reducing as the angle of placement increases. So the effect of interference reduces with distance as effective signal strength gets reduced. This case can be used to increase the SNR values at the outer section, sections where LEDs are placed at higher angles from the normal, so that there is more coverage at the outer sections. However, we will have to increase the number of LEDs to compensate for the decrease in received signal power. In the final scenario with LEDs with divergence angles of 20° we observed that the interference is within an optimum level which will be helpful in implementing the partitioning algorithm. From the figure it can be observed LEDs achieve the maximum SNR much faster than case II which shows that the interference levels are less compared to case II.

5.2.5 Effect on Varying Room Size and Transmit Power

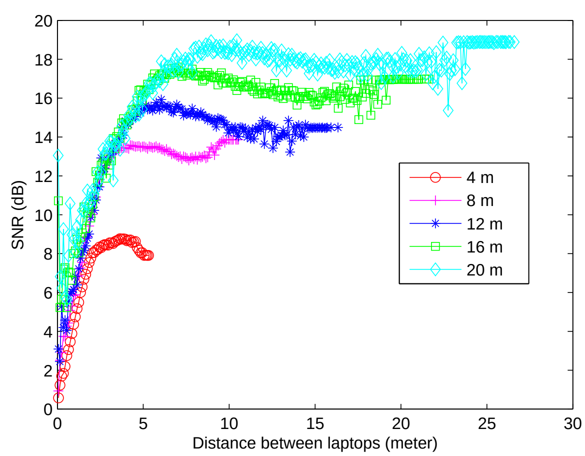


Figure 5.6: SNR for different room sizes

We extended our experiment to larger room sizes using LEDs of higher power. The results are shown in Figure5.6. This extended experiment is to show the effectiveness of the model over a bigger room. The experiment involved extending the room size from 4 meter to 20 meter along with a relative increase in the transmit power from the LEDs with divergence angle of 20°. The results show that the pattern of SNR graphs remains the same in all the cases. However, the graph extends to longer distances and to higher SNR values as expected.

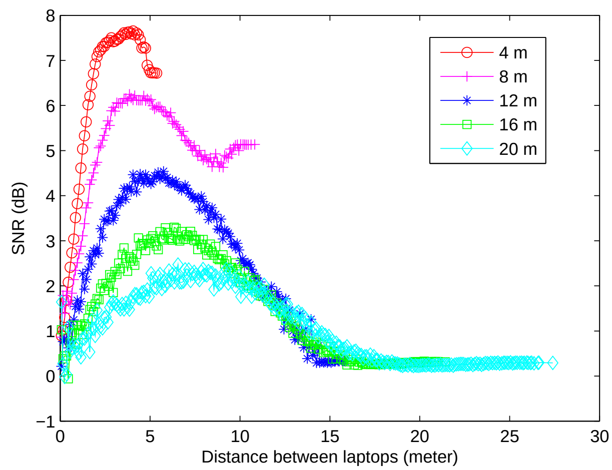


Figure 5.7: Variation in coverage of multi-element VLC bulb for different room sizes and constant transmit power.

In the second experiment the transmit power was kept constant while the room size was increased by m times for every iteration from 4 meter to 20 meter. The result shows that the Signal to Noise Ratio deteriorates for every increase in room size.

5.2.6 Divergence Angle Optimization

Divergence angle has a significant effect on the coverage area of each transmitter. To find the optimum divergence angle we ran experiments varying divergence angle from 5°to 40°over various power values of 5W, 10W, 20W, 25W and 50W. The SNR results for each power value were averaged per divergence angle. The results are depicted in Figure 5.8. As observed from the figure the optimum divergence angle is obtained within the range of 11°and 15°.

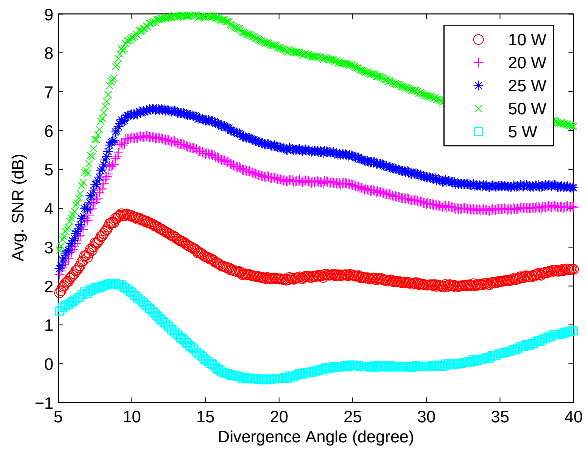


Figure 5.8: Divergence angle optimization at different transmit power

Chapter 6

Summary and Future Directions

In this thesis we introduced a multi-element VLC architecture that employs a multi-element hemispherical bulb design. The mobile receivers use VLC/FSO for download and RF for upload, and the multi-element bulb uses a software-defined approach to manage LOS alignment with receivers. We modeled the hemispherical multi-element bulb structure that simultaneously provides and showed, with initial results, that the architecture can offer high spatial reuse while keeping illumination of a room at acceptable levels. Our preliminary model follows Lambertian law and corroborates with expected results. This model also indicates the effectiveness and significant of potential in using a multi element communication structure for simultaneous lighting and communication.

Several future work items are inline. We assumed one AP in a room, and multiple APs can significantly improve the results. Future work also includes optimizing the number of LEDs and layers in the bulb. The algorithm for partitioning LEDs among receivers need further enhancements to better balance time complexity and higher spatial reuse opportunities. We do not consider the reflections from the surrounding walls in the model. This will also be a part of the future work.

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