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JOINT OPTIMIZATION OF ILLUMINATION AND COMMUNICATION FOR A MULTI-ELEMENT VLC ARCHITECTURE

by

SIFAT IBNE MUSHFIQUE B.S. Bangladesh University of Engineering and Technology, 2011

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Electrical and Computer Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

Spring Term 2018

Major Professor: Murat Yuksel

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ABSTRACT

Because of the ever increasing demand wireless data in the modern era, the Radio Frequency (RF) spectrum is becoming more congested. The remaining RF spectrum is being shrunk at a very heavy rate, and spectral management is becoming more difficult. Mobile data is estimated to grow more than 10 times between 2013 and 2019, and due to this explosion in data usage, mobile operators are having serious concerns focusing on public Wireless Fidelity (Wi-Fi) and other alternative technologies. Visible Light Communication (VLC) is a recent promising technology complementary to RF spectrum which operates at the visible light spectrum band (roughly 400 THz to 780 THz) and it has 10,000 times bigger size than radio waves (roughly 3 kHz to 300 GHz). Due to this tremendous potential, VLC has captured a lot of interest recently as there is already an extensive deployment of energy efficient Light Emitting Diodes (LEDs). The advancements in LED technology with fast nanosecond switching times is also very encouraging. In this work, we present hybrid RF/VLC architecture which is capable of providing simultaneous lighting and communication coverage in an indoor setting. The architecture consists of a multi-element hemispherical bulb design, where it is possible to transmit multiple data streams from the multi-element hemispherical bulb using LED modules. We present the detailed components of the architecture and make simulations considering various VLC transmitter configurations. Also, we devise an approach for an efficient bulb design mechanism to maintain both illumination and communication at a satisfactory rate, and analyze it in the case of two users in a room. The approach involves formulating an optimization problem and tackling the problem using a simple partitioning algorithm. The results indicate that good link quality and high spatial reuse can be maintained in a typical indoor communication setting.

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TABLE OF CONTENTS

LIST O	F FIGU	RES	ix
LIST O	F TABL	ES	xi
CHAPT	ER 1 :	INTRODUCTION	1
1.1	Thesis	Contribution	4
1.2	Thesis	Organization	6
CHAPT	ER 2:	RELATED WORK	7
2.1	Impro	ving Data Rates in VLC	7
2.2	Mainta	aining LOS Property in VLC	9
2.3	Modul	ation Schemes and Dimming Support in VLC	10
	2.3.1	On-Off Keying (OOK)	11
	2.3.2	Pulse Position Modulation (PPM)	11
	2.3.3	Color Shift Keying (CSK)	12
	2.3.4	Orthogonal Frequency Division Multiplexing (OFDM)	13

	2.3.5 Dimming Support	14
2.4	Hybrid VLC Schemes	14
СНАРТ	ER 3: MULTI-ELEMENT BULB ARCHITECTURE	18
3.1	The Bulb	19
3.2	Mobile Receiver Units	20
3.3	RF/FSO Hybrid LOS Management	20
	3.3.1 Establishing the Link	21
	3.3.2 Maintaining the Link	22
	3.3.3 Terminating the Link	23
3.4	Design of the Bulb	24
СНАРТ	ER 4: OPTIMAL MULTI-ELEMENT BULB DESIGN FOR HIGH SIGNAL-TO-	
INTERF	FERENCE RATIO AND SMOOTH LIGHTING	26
4.1	Parameters	26
4.2	Link Model and SIR Calculation	
4.3	Placement of Layers and LEDs	30
4.4	Optimization Objective	32
4.5	MAX_SIR: Maximum SIR Problem	33
4.6	MAX_SIR_LQ: Maximum SIR with Lighting Quality (LQ) Constraint	35

4.7	Heuris	stic Design for Nonlinearity	36
4.8	Simul	ation Results	38
	4.8.1	Calculation Method	38
	4.8.2	Solution for Best Bulb Configuration	40
	4.8.3	Effect of Power Constraints	41
	4.8.4	Effect of Divergence Angle	43
	4.8.5	The Three-Region Behavior	46
СНАРТ	ER 5:	SUMMARY AND FUTURE DIRECTIONS	49
APPEN	DIX A	LIST OF ABBREVIATIONS	51
APPEN	DIX B	LIST OF SYMBOLS	54
LIST O	F REFE	RENCES	57

LIST OF FIGURES

Figure 1.1	Inefficient use of spatial resources in a single-element architecture	2
Figure 3.1	Sample design of a multi-element VLC architecture.	19
Figure 3.2	Placement of transmitters in the bulb.	24
Figure 3.3	Partitioning algorithm.	25
Figure 4.1	Transmitter and receiver angles.	29
Figure 4.2	LED placements in multi-element bulb for different number of layers	31
Figure 4.3	Flow diagram of the optimization.	33
Figure 4.4	Nonlinearity of the obj. function: SIR against divergence angle and number of	
layers		37
Figure 4.5	Convergence of I_s values for $k_1 = 11$, $k_2 = 14$ and $\theta_d = 26$ degrees	38
Figure 4.6	SIR and I_s values versus power constraint for MAX_SIR and MAX_SIR_LQ.	40
Figure 4.7	Objective function output versus power constraint.	41
Figure 4.8	Obj. function vs. divergence angle for two layers of LEDs	42
Figure 4.9	Avg. SIR vs. divergence angle for two layers of LEDs	43

Figure 4.10	Illumination variation vs. divergence angle for two layers of LEDs	44
Figure 4.11	Obj. function output versus Divergence angle for different number of layers.	45
Figure 4.12	Effect of divergence angle comparison between 2 and 6 layers	46
Figure 4.13	The 3-region behavior.	47

LIST OF TABLES

Table 4.1	Parameters	26
Table 4.2	Best results for MAX_SIR and MAX_SIR_LQ	39

CHAPTER 1 INTRODUCTION

In the past few decades, the worldwide demand for wireless broadband data has been increasing exponentially [1] because of the popularity of smart-phones, laptops and tablets. As Light Emitting Diodes (LEDs) appropriation is on an ascent [2] it is expected that a large portion of the enlightenment will be given by LEDs in the following 10-15 years utilizing these LEDs, Visible Light Communication (VLC) is expected to be one of the primary wellsprings of communication in the near future. This change is driven by several characteristics of VLC - such as non-interference Radio Frequency (RF) signals, enhanced security (unlike RF signals, light can't pass through walls, and thus the chance of eavesdropping is virtually nonexistent), spatial reuse (with the help of highly directional light beams), safety (visible light does not have any health hazard unlike IR), energy efficiency (LEDs are highly controllable and energy efficient light sources), easy implementation into existing infrastructure as LEDs are already getting widely deployed, and low cost since only a few upgrades of existing lighting infrastructure is needed rather than the initial set up cost of an entire communication system.

In the current circumstances, LEDs are ending up being more accessible and solid-state circuitry to drive the LEDs is becoming lower in cost. Lighting is transitioning to solid-state lighting technologies and visible light is offering an excellent opportunity for combining both lighting and mobile wireless communications, particularly at indoor settings [3, 4].



Figure 1.1: Inefficient use of spatial resources in a single-element architecture.

Recent work showed the potential for VLC using LEDs in civilian indoor settings with sizable attention to issues on access [5, 6, 7]. The vast majority of the work has concentrated on diffuse optics [8] and diversity combining [9, 10] for downloading a data stream to devices in a room. At the modulation level, OFDM [11, 12] and Multi-Input-Multi-Output (MIMO) [13, 14] techniques were explored to increase the VLC link capacities. In contrast to the diffuse optics, Multi-element VLC enables different data streams to be transmitted simultaneously with the help of several LED transmitters with narrow divergence angles.

Multi-element VLC has been recently receiving extensive interest as a new paradigm that can simultaneously maintain desirable communication properties such as high speed and long range,

as well as high and even intensity of illumination. The directional beams in VLC systems, while requiring (Line-of-Sight) LOS connectivity, open up great opportunities for spatial reuse of optical spectrum resources. Multi-element VLC modules can significantly improve the efficiency of data transmission as they can take full advantage of directional property of light by modulating each LED transmitter 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 existing work in the literature related to multi-element VLC are on expanding 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) [15]. In [16, 17], multi-element receiver approaches are introduced to improve system performance. There have been earlier works that jointly study illumination and communication aspects of VLC systems [18], optical beamforming [19] where devices such as micromirrors are used to dynamically improve an optical wireless communications link, and hybrid RF/FSO networks [20] that consider VLC in the down-link and RF communication (such as WiFi) in the up-link. Also, in [2, 21], the main concept of the VLC architecture is presented in a way where light emitted from a single LED is focused in a specific target direction using Spatial Light Modulator (SLM) [22]. However, in a single-element architecture, it is not possible to take advantage of LED directionality to achieve spatial reuse as shown in Figure 1.1, which can be achieved using multi-element transceiver architectures.

Considering the limited functionality and efficiency of the single element VLC architecture, the goal of this work is to explore designs using many elements with narrow 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), due to the dense grid formed by the narrow FOV LEDs. Unlike the works in the literature that focus on integrating multiple spotlighting mechanism into a single light source and creating an apparently large FOV, our research focuses on unicast data stream from individual spotlight at an overhead light source [23]. This approach will likely be more practical for the emerging Internet-of-Things (IoT) applications that involve closely placed receivers accessing the VLC resources. Further, since most of these IoT receivers will not be highly mobile, handover across spotlights will not be prohibitively costly.

In our work, we deal with the problem of optimizing the design of our multi-element VLC architecture so that we can have a decent overall Signal-to-Interference Ratio (SIR) in average for the receivers, with as uniform lighting as possible across the room floor at the same time. We formulate this as an optimization problem where we vary the placement and divergence angle of the LEDs under power and illumination constraints and analyze the results.

1.1 Thesis Contribution

This thesis makes the following contributions and findings, some of which were published in our previous works [24, 25].

• We explore the trade-off between using small and large divergence angles by considering multi-element bulbs covered by multiple LEDs with relatively narrow divergence angles.

The bulb is supported with an LOS alignment protocol to steer the data streams to individual or group of LED boards corresponding to a particular receiver in the room [26].

- We formulate the LED placement on the bulb as an optimization problem under power constraints. Specifically, these constraints are applied as the maximum power that can be assigned to each LED.
- We analyze the performance of the multi-element bulb architecture based on several metrics such as the positions of the receivers, divergence angle of the transmitters with the help of this optimization problem which takes both uniformity of lighting and signal strength indicated by SIR across the room into consideration.
- Our framework enables optimizing the number of LEDs/transmitters on each layer of the bulb for maximizing the SIR while respecting the evenness of the lighting on the room.
- Considering the power constraint on the bulb, we find out that no matter how much we increase the power constraint or the number of LEDs on the multi-element bulb, maximum SIR saturates after a certain point which is detailed in Subsection 4.8.3.
- We study the effect of divergence angle of the LEDs over the objective function of the optimization problem. Furthermore, we find out that based on the SIR, we can divide the room into three separate regions which demonstrate different communication characteristics. These discoveries are detailed in Section 4.8.

1.2 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 2 surveys the relevant work and describes the motivation behind our work on multielement VLC bulb. The related works on VLC are elaborated based on the several things like improvement on data transmission speed, modulation schemes, maintaining LOS property, hybrid RF-VLC architectures.

We then propose the multi-element bulb and describe in detail about the components of the whole architecture. We also describe the proposed RF/FSO hybrid LOS management scheme along with the partitioning algorithm in Chapter 3.

In Chapter 4, we present a detailed discussion on the bulb design optimization problem along with a detail formulation of the problem. We also describe the simulation setup with detail explanation of the results.

Finally, we summarize our work and discuss briefly about the current progress on the expansion plus lay out some possible future work plans in Chapter 5.

CHAPTER 2 RELATED WORK

Optical communication can be utilized in different structures to serve quick correspondence interfaces in remote areas. Fiber optic communication has the most acknowledgment as a wired innovation and it is able to do rapid transmission. Despite the fact that FSO communication frameworks utilize a similar convention and same type of transmitters and receivers, this innovation is as yet thought to be in its early childhood. In any case, years of research have been making this innovation one stride ahead to deploy it commercially. Related research works on VLC can be categorized on some important factor, which are described below.

2.1 Improving Data Rates in VLC

In the realm of communication, data rate of information transfer is an imperative factor. However, the data rate relies on many factors, such as transmission capacity, impacts, region of scope, impedance, adjustment and method of communication. In [5], the authors demonstrate a bidirectional 1.25 Gbits/sec indoor Home Access Network project using power line communication in the backbone and RF/VLC as front-end. In this case, the VLC is used as a broadcast medium to support multiple users. In [10], the receiver has three different elements directed in three directions, motivated from the concept of angle diversity 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. The LOS system uses angle-diversity transceivers enabling discrete beam steering. Three transmitting and receiving elements are used in each transceiver giving an overall field of view of 25 x 8 degrees and a transmission range of 3 meters. Measurements show that the system can operate at a bit error rate below 10^{-9} without channel coding and the handover between cells is 400 ns. A detailed demonstration of high-definition (HD) video embedded in gigabit Ethernet stream using this system is presented as well.

Speeds upto 1.28 Terabit/s has also been achieved using Wavelength-division Multiplexing (WDM) transmission techniques on laser beams [27]. A novel FSO framework is reviewed representing a noteworthy achievement in FSO communications. The framework incorporates a couple of novel terminals, which enable immediate and straightforward optical association with basic single mode fibers and incorporate a dedicated electronic control unit that adequately tracks the signal beam wandering because of atmospheric turbulence and mechanical vibrations. Assist change in the flag control adjustment is accomplished by methods for saturated Erbium-doped Fiber Amplifiers (EDFAs). These arrangements permit to understand another FSO framework, which is tried in a double pass FSO link between two towers in Pisa, Italy. At the point when the terminals are bolstered by normal WDM signals they permit enough power spending plan and edges to help a record high limit transmission (32 x 40 Gbits/sec), with a gigantic change of steadiness (six hours with no mistake burst). Amid day-long transmission, the framework conduct has been profoundly portrayed to associate any expansion of Bit Error Rate (BER) to the FSO control parameters.

All of these mentioned works are done on the basis of improving the data speed, although the architecture used in them is either single element with large FOV or the beams are highly directional like laser, so basically they neither consider simultaneous transmission of multiple data streams nor the uniformity of lighting across the room. Our work takes both of these into consideration and tries to optimize the design of the architecture based on that.

2.2 Maintaining LOS Property in VLC

The 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 ongoing communication. We cover some of the mechanisms developed to address the LOS issue in this section. In [28], 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 peer-to-peer protocol consists of a narrow beam and field of view from the proposed device and thereby can have good performance in terms of speed without a central host. The peer-to-host protocol, in contrast, is simpler and easy to implement; but, due to its diffuse link model and interference, it is less manageable for high data rates and requires an accessible host. 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, the work in [29] 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 data-rate 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. By focusing the light, large signal strength are obtained with fewer or smaller LEDs, which potentially simplifies the driver circuitry and reduces transmitter capacitance, leading to increased amount of bandwidth in result. The paper uses the concept that of a spotlight typically having all its LEDs in a small space, and if they are switched simultaneously, the LOS light from all the LEDs to all transmitter locations is synchronized, which is not case for uniform lighting. Joint optimization of illumination of communication has been studied in [30], where the authors compared two different LED driver schemes, analyzed the ripple effect on the filter of the receiver, and proposed two approximations to model the ripple interference. However, in our work, we emphasize on finding an optimum design for the multi-element architecture that is proposed for high spatial reuse.

2.3 Modulation Schemes and Dimming Support in VLC

In VLC, the modulating signals can be used to switch LEDs at desired frequencies which contains information to be transmitted. Several modulation schemes are tried in VLC, which are discussed below -

2.3.1 On-Off Keying (OOK)

On-off Keying (OOK) is one of the simplest modulation techniques used to switch an LED between a high (bit 1) and low (bit 0) transmit power levels to modulate data. Run-Length Limited (RLL) codes such as Manchester coding may be used for DC balance [31]. In Non-return-to Zero (NRZ) OOK, 0s and 1s are represented by positive and negative voltages. This technique had been widely used in VLC and can carry more information since there is no rest state. Fujimoto *et al.* demonstrated the simplest NRZ-OOK system with a single Red Green Blue (RGB) LED (only red to transmit) achieving a bit rate of 477 Mbits/sec [32] and also employed duo-binary technique with bandwidth enhancement (using transmitter and receiver equalization) to achieve 614 Mb/s. A single commercially available red LED is used with a low-cost PIN-PD by adopting a proposed practical LED driver with a basic pre-emphasis circuit. They have also confirmed 456 Mbits/sec error-free operation of the proposed simple and low-cost high-speed VLC system that requires a single LED drive circuit with a single RGB-type white LED and one optical receiver with a low-cost PIN PD and no optical filter.

2.3.2 Pulse Position Modulation (PPM)

In L-Pulse Position Modulation (L-PPM), a pulse corresponding to a certain bit is transmitted in one of L time slots within a symbol period. The average power requirement for PPM is lower than OOK since it avoids the DC and lower frequency component of the spectrum, but it is less bandwidth efficient. System complexity is increased on PPM compared with OOK, as it requires stricter bit and symbol synchronization at the receiver. Variable PPM (VPPM) and Multiple PPM (MPPM) are the schemes amongst PPM generally used for dimming control as well as transmitting data. In [33], an 80W smart LED module is used to integrate communication and power management functions. The luminaire provides high-efficiency programmable ambient lighting and can also act as a networked sensor node to gather a variety of local measurements, which leads to improved safety, comfort and efficiency in future lighting systems. A dimmable LED driver based on the Logic Link Control (LLC) resonant DC-DC converter topology is proposed using VLC. The digitally controlled LLC converter operates in constant-current burst mode, where the burst is sequenced to autonomously control the dimming and data transferring using the VPPM modulation scheme. A receiver circuit is designed to demodulate and decode the visible light signal. The 50 kbits/sec system is successfully demonstrated on a 308 LED luminaire with a digitally controlled LLC DC-DC converter.

2.3.3 Color Shift Keying (CSK)

In the new IEEE 802.15.7 standards published in 2011, using multi-chip LEDs for VLC has been introduced. In the CSK modulation scheme, the color point for each symbol is generated by modulating the intensity of RGB chips. However, CSK cannot be used in a VLC system where the source is a pc-LED (which is one of the most common sources of light in an illumination system) and implementation of CSK requires a complicated circuit structure. In [34], some modifications

so as to include multiuser capabilities provided by a time-based multiplexing scheme are proposed with the modulation constellation symbols being adapted to encode data with the luminux powers of the red, green and blue color bands respectively. A simple and low-complexity time-based pulse signals structure is employed to separate the users data symbols, while a three-dimensional signal constellation design is merged to ameliorate the data throughput. To assess the performance of the architecture, numerical simulations are performed, and it is observed that the statistical properties of the transmitted RGB signals ensure dimming capabilities and that the illumination function is unaffected by flickering.

2.3.4 Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) is spectrally efficient, and is robust against channel dispersion. It is used extensively in RF applications such as Wi-Fi and Terrestrial Digital Video Broadcasting (DVB-T). Since VLC uses visible light to transfer data, a real and unipolar valued signal needs to be produced. Therefore, the conventional OFDM scheme used in RF communications should be modified. To achieve a real valued output signal, Hermitian symmetry is used on the parallel data streams into the Inverse Fast Forrier Transform (IFFT) input. In [35], an experimental demonstration of indoor VLC transmission at 1 Gb/s using MIMO OFDM is reported. The system consists of a four-channel MIMO link that uses white LED sources, each transmitting signals at 250 Mb/s using OFDM. A nine-channel imaging diversity receiver is used to detect the signals, and an average bit error rate of 10^{-3} is achieved at the room illumination level of approximately 1000 lux at 1m range.

2.3.5 Dimming Support

Light dimming is an interesting indoor VLC application as described in [36]. The authors 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. Investing VLC with limits on transmit power, this result is an important step toward ensuring acceptance and adoption of VLC technology.

2.4 Hybrid VLC Schemes

Optical communication was at first created as a substitution for constrained RF innovation. Be that as it may, hybrid RF/FSO communication frameworks has gotten to be a hot topic where the preferences of both technologies are integrated. The points of interest of RF incorporate non-requirement of Line Of Sight, more extensive range of coverage and multi-user support. On the other hand, advantages of VLC incorporate illumination and communication at the same time, secure communication in an indoor setting, cheaper, simple to setup and less in general control utilization compared to RF etc. As an illustration, a work by [37] includes utilizing a crossover

RF/FSO framework in backbone networks as FSO links give tall transmission capacity and security and RF links offer unwavering quality. They propose a directing system which empowers traffic engineering on the oncoming traffic by integrating traffic engineering and transfer speed administration at an off-line computing unit. This data is at that point utilized at ingress routers for traffic engineering and routing when the network is online.

Another recent study done on such a hybrid scheme showed that a hybrid system outperforms single standalone VLC system in terms of user connectivity and energy consumption [38]. It has analyzed the feasibility and possible benefits of using hybrid radio-optical wireless systems. Potential benefits are identified as service connectivity and energy efficiency of battery operated device in indoor environments. Moreover, cooperative communication using optical relays are also introduced in order to increase the coverage and energy efficiency of battery operated devices. The connectivity and energy efficiency of such hybrid radio-optical cooperative communications are characterized by optical LOS channel model, relay selection algorithm, mobility of user, semi angle at half power of the LED and the FOV of the photo detector. Simulations have been performed in order to evaluate the connectivity and energy efficiency performance of such homogeneous and hybrid networks. Simulation results reveal that user connectivity and energy efficiency depend on user density, coverage range ratio between single-hop and multi-hop, relay probabilities and mobility of the user. Finally, it has been claimed that hybrid radio-optical wireless systems have a positive impact on the performance of user connectivity and energy consumption. There have been some more recent studies on hybrid RF-VLC schemes. In [39], a hybrid Wi-Fi and FSO network consisting of femtocells is described a novel location-assisted coding technique is introduced,

based on which, the number of novel rate allocation algorithms is proposed to increase throughput and reduce interference for multiple users in a dense array of overlapped femtocells. In [40], a hybrid RF and VLC system is considered, where multiple RF and VLC access points are analyzed. The authors have proposed in order to improve the per usage data rate performance to support the standalone VLC network. It is assumed that the VLC system resources are fixed, and this paper quantifies the minimum spectrum and power requirements for a RF system. The hybrid RF/VLC system achieves certain per user rate coverage performances after the exposure to the VLC system. In another work [41], the authors have proposed and implemented two heterogeneous systems, one of which is a hybrid Wi-Fi/VLC system. It uses VLC for the downlink and Wi-Fi for the uplink. This approach helps to solve the optical uplink challenges and gets the benefit of the full-duplex VLC communication. The authors have shown theoretical proof of improvement on average system delay. The experiment result shows that the hybrid system performs better than conventional Wi-Fi in terms of throughput. In [42], the authors have proposed PLiFi, which is a hybrid VLC/Wi-Fi system using power line communication. It provides high speed interconnection between LEDs along with VLC/WiFi integration. The Wi-Fi access point connects to the power line using an Ethernet-PLC modem. For the downlink transmission, the packets received from the Internet are first forwarded to the power line network by the WiFi access point, and then to LED transmitters which deliver the packets to the end devices. On the uplink, the end-devices directly connect to the WiFi Access point. Preliminary results show that this PLC architecture provides sufficient data and coverage. An extension of ns3 network simulator is proposed in [43] in order to investigate the characteristics of hybrid RF/VLC networks. the VLC downlink and the RF (WiFi) uplink are

connected using the combination of the proposed ns3 VLC component and existing ns3 RF modules. Simulations show how this situation can be analyzed in terms of VLC signal to noise ratio (SNR) and bit error rate (BER) parameters, and in the resulting network performance measured as goodput. All 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.

It can be observed from the previously 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 MULTI-ELEMENT BULB ARCHITECTURE

We focus on two main objectives of our multi-element VLC approach: 1) *high spatial reuse* by fully utilizing the directionality of LEDs, and 2) *seamless handling of mobility* of receivers by using software protocols that steer the data transmissions to mobiles. Unlike the traditional design of LEDs/transmitters with large divergence angles, we propose to use narrow divergence angles and still perform an acceptable illumination by using a large number of LEDs on a "bulb". In particular, our work - 1) presents an architecture with LEDs having narrow divergence angles to reap the rewards of high spatial reuse; 2) uses software protocols for efficiently tackling the mobility issues such as LOS discovery, alignment maintenance, and receiver association; and 3) utilizes software-based heuristic optimizations to solve interference problems between simultaneous VLC links, which is significantly different from the concepts described in [2, 21].

Even when we use hundreds of LEDs, we still have the problem of steering the data transmission to the corresponding LED when the mobile receiver is moving. We tackle this problem with a software-defined and enhanced version of electronic steering [3]. Our architecture takes advantage of spatial reuse and seamless steering which are untapped sources of efficiency in VLC. We detail the architecture in Figure 3.1 by describing three key components below.



Figure 3.1: Sample design of a multi-element VLC architecture.

3.1 The Bulb

The bulb is a hemispherical structure, which will act as an access point for the room. There are multiple transmitters in the bulb to provide *concurrent downloads* to multiple receivers. A transmitter is basically an LED board which has a chunk of LEDs for transmitting a particular data stream. The LEDs on the same transmitter are all modulated by the same signal. For that reason, having multiple LEDs on a transmitter board allows operating in a wide range of configurations involving source power, communication range, and illumination quality. However, there remains the challenge of seamless steering of data to the corresponding transmitters. To address this issue, we connect each transmitter to a controller device embedded in the bulb and run a software protocol for managing LOS alignment.

3.2 Mobile Receiver Units

The receiver unit can be mobile and needs to be equipped with a PD. It is assumed that the PD(s) are conformal to the surface of the unit with additional apparatus like lenses as appropriate (something like in [44]). These mobiles also need the capability of uploading using legacy RF transmitters. We are assuming that these mobile devices have one PD receiver and one RF transmitter such as WiFi. They receive the download data from the transmitter(s) with which they are in LOS alignment. The design of these units requires joint work of solid-state device and packaging as well as communication protocols. For example, multi-element conformal PDs can be designed so that they cover the surface of a smart-phone or laptop.

3.3 RF/FSO Hybrid LOS Management

We are using a hybrid RF/FSO approach in our architecture, as bidirectional VLC can cause significant interference near the bulb. In hybrid RF/FSO approach the data download is administered through FSO/VLC and upload is handled using RF. This approach considerably reduces the collision that can be caused by bidirectional VLC communication. Also, we are using RF - the slower communication between the two - for data uploading as typically there is much less traffic in case of data uploading compared to data downloading. In our hybrid architecture, the multi-element bulb follows a software-defined approach to find the best receiver-transmitter link. In order to achieve this, we firstly establish the optical link and then maintain this link taking into consideration the receiver mobility. For this, establishing an optical link by associating transmitter(s) to a receiver and maintaining this link with mobility of the receiver across the room is needed. The controller device also has to partition the transmitters so that multiple transmitters can serve a receiver, and cease the optical link once the receiver is off-line. The transmitters located close to each other (that are in the same partition) are assigned to the same receiver and transmit the same data stream. When a receiver moves slightly, a handover will not be immediately necessary as it will still be receiving the data signal from the neighboring transmitters in the same partition. Thus, this design will require a handover (or a redoing of the receiver-transmitter association) only when the receiver makes abrupt movements, which is unlikely inside a room. This protocol allows smooth and continuous mobility for the receivers by electrically steering the data transmission in accordance with the position of the receiver. We group these functionality into three basic bulb-mobile association mechanisms as detailed below.

3.3.1 Establishing the Link

To search for new receivers in the room, the bulb periodically sends SEARCH frames via its transmitter 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 like 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 i, entering the room, receives these SEARCH frames. The receiver might receive multiple of the SEARCH frames 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. A measure of the received signal strength indication (RSSI) can be fed into the controller where the decision is made over which input has the strongest signal. [45]

Once the receiver receives the SEARCH frame, it sends back an ACK frame (like a CTS in Ethernet) via its RF transmitter. This ACK includes the Ethernet / MAC 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 i is aligned with the transmitter LED k. After receiving the ACK from i, the bulb assigns the LED k or a group of LEDs around the LED k to i, and maintains this information as an LED-receiver association table (LED-RAT). When there are multiple receivers in the room, the bulb partitions the LEDs and associates each partition (see Section 3.4) to a separate receiver. The LED-RAT needs to be updated accordingly. For every data frame to be sent, the bulb does a reverse lookup to the LED-RAT, with the Ethernet address the frame is destined to. In this manner, the bulb steers the data stream destined for receiver i onto the transmitters that just got associated to i. The partitioning of the LEDs across the receivers will be crucial in the overall performance of the spatial reuse.

3.3.2 Maintaining the Link

Once an 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 in the previous subsection. When there is a change in the LED-receiver association, the bulb will need to update LED-RAT and repartition 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. Furthermore, the re-partitioning operation should be performed in a manner independent of the number of LEDs, as there will be hundreds of LEDs on the bulb.

3.3.3 Terminating the Link

When a receiver leaves the room or powers down, the controller in the bulb needs to update LED-RAT and re-partition the LEDs. There are two possibilities for achieving this:

- *Graceful Leave*: The receiver *i* lets the bulb know that it is powering down by sending a CLOSE frame via its RF transmitter.
- Ungraceful Leave: The receiver *i* simply leaves the room without informing the bulb about its departure. Then, the bulb will keep sending its SEARCH frames, and will timeout on *i* after N_t SEARCH frames without an ACK from *i*. N_t actually indicates the number of search frames without acknowledgement from a receiver after which the bulb will consider the connection between that receiver and itself is timed out. Therefore, N_t can be changed under various circumstances.



Figure 3.2: Placement of transmitters in the bulb.

3.4 Design of the Bulb

The transmitters of our multi-element hemispherical bulb are arranged in layers of circles to maximize the coverage in the room. We consider a bulb with multiple layers as shown in Figure 3.2. Efficient arrangement of the transmitter LEDs is within itself an optimization problem that is not discussed in this thesis (see [46] 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 light distribution and communication pattern in a room.

An optimized placement should jointly improve the light distribution and communication in the room. A heuristic algorithm is devised to partition the LEDs into groups, each corresponding to a mobile receiver in the room, which takes full advantage of the multi-element bulb for higher spatial reuse. This reduces the load on LOS alignment algorithm by providing a wider FOV for
each receiver. Further, all LEDs in a partition are modulated with the same transmission signal, and hence, the receiver for that partition can enjoy an aggregate reception quality from the LEDs of its partition.



Figure 3.3: Partitioning algorithm.

For two receivers positioned at (X_1, Y_1) and (X_2, Y_2) on the room floor, we find the mid point, (X_{mid}, Y_{mid}) and draw an imaginary partitioning line perpendicular to the line connecting the two receiver positions (Figure 3.3). Once the partitioning line is settled, then we split the LEDs on the bulb into two categories based on which side of the line their projections fall. This procedure has to be executed every time when a new mobile device establishes connection with a transmitter on the bulb. In that case, the algorithm will reassign all the transmitters giving new space for the new association while keeping up the old associations.

CHAPTER 4 OPTIMAL MULTI-ELEMENT BULB DESIGN FOR HIGH SIGNAL-TO-INTERFERENCE RATIO AND SMOOTH LIGHTING

4.1 Parameters

We will mainly optimize the multi-element bulb design with respect to the *divergence angle of the LEDs* (θ_d) and the *number of LED Boards in each layer* ($k_1, k_2, ..., k_i$). All the needed parameters for the model are described in table 4.1.

Parameter Name	Symbol
Visibility (km)	v
Optical signal wavelength (nm)	λ
Particle distribution constant	q
Coefficient of absorption and scattering	σ
Divergence angle (radian)	$ heta_d$
Transmitter radius (cm)	r _t
Radius of the bulb (cm)	R

Parameter Name	Symbol
Layer <i>i</i> 's angle with the normal (radian)	$ heta_i$
Vector between <i>i</i> th LED board on the bulb and its normal point on the	$\overrightarrow{LP_i}$
floor	
Vector of the central LED facing down	$\overrightarrow{LP_0}$
Power on the normal for LEDs in <i>i</i> -th layer (W)	$P_L(i)$
Receiver radius (cm)	r _r
Slanted normal length for LEDs in <i>i</i> -th layer (cm)	H_i
Number of receivers in the room	N _{rcv}
Array of LED count in each layer	$k_{i=1l}$
Source power of each LED (W)	P _{LED}
Total power generated by the bulb (W)	P _{total}

4.2 Link Model and SIR Calculation

We assume that the transmitters on the bulb are grouped into sections so that each section is associated with a particular receiver. For example, if there are two receivers in the room, the LED boards (or transmitters) are grouped into two sections each corresponding to one of the receivers. So, we assume that the transmitters are grouped such that they are associated with the receiver closest to (or in the best LOS alignment with) their Lambertian beam. Given this, the normal component of the power generated by LED board *i* will be [15]:

$$P_L(i) = P_{LED} + 10\log(e^{-\sigma H_i}) + 20\log\left(\frac{r_r}{r_t + 200H_i\theta_i}\right)$$
(4.1)

where P_{LED} is the source power of each LED, σ is the atmospheric absorption and scattering coefficient. The expression for σ is:

$$\sigma = \left(\frac{3.91}{V}\right) \left(\frac{\lambda}{550}\right)^{-q} \tag{4.2}$$

Here q is particle distribution constant, where:

$$q = \begin{cases} 1.6, & \text{if } V > 50km \\ 0.5, & \text{if } V \ge 6km \text{ and } V \le 50km(1) \\ 0.585V^{1/3} & \text{if } V < 6km \end{cases}$$

with visibility V = 0.5km and optical wavelength $\lambda = 600$ nm [47]. And, after the grouping of the transmitters is complete, if a receiver *i* is located at partition *j* and the number of LED boards in partition *j* is N_j , then the average signal received by that receiver from that partition is:

$$S_{ij} = \sum_{m=1}^{N_j} P_L(m) \cos \phi_m$$
 (4.3)

where *m* refers to the IDs of LEDs in partition *j*. Similarly, the average power of the signals received by that receiver from a partition other than *j* (which will be treated as interference) is:

$$S_{il} = \sum_{m=1}^{N_l} P_L(m) \cos \phi_m \tag{4.4}$$

where P_L is the received power at the normal of the layer of the respective LED boards of that particular partition.



Figure 4.1: Transmitter and receiver angles.

Further, the angle between the LED board's normal and the normal of the receiver's field-ofview (FOV), ϕ_m , is defined as:

$$\phi_m \Longrightarrow \tan^{-1} \left(\frac{|\overrightarrow{RP} \times \overrightarrow{LP}|}{|\overrightarrow{RP} \cdot \overrightarrow{LP}|} \right)$$
(4.5)

where \overrightarrow{RP} is the distance vector from the origin point of the LED board to the receiver point in the X-Y plane, and \overrightarrow{LP} is the LED vector for that particular LED board. Essentially, ϕ_m is the angle between \overrightarrow{RP} and \overrightarrow{LP} in Figure 4.1. Then, for receiver *j*, the average Signal-to-Interference Ratio (SIR) is

$$SIR_{j} = \frac{S_{ij}}{\frac{1}{N_{s} - 1} \sum_{l=1..N_{s}, l \neq j} S_{il}}$$
(4.6)

Finally, the average SIR of the system will be:

$$SIR_a = \frac{1}{N_{rcv}} \sum_{j=1}^{N_{rcv}} SIR_j$$
(4.7)

Our main goal is to maximize this average SIR with minimum costs. The result of the optimization is the bulb configuration values (e.g., bulb radius, number of LED boards, divergence angle of LEDs, and radius of the transmitters) that maximize SIR under certain constraints.

4.3 Placement of Layers and LEDs

To find the maximum number of layers L and maximum possible number of LED boards in a layer, K, we assume the LED boards to be spaced as closely as possible. Depending on the shape of the bulb and LED boards, L and K can have different upper limits. First, we calculate how many LEDs can possibly be placed on the surface of any one half on the hemispherical bulb when looking from the x-z plane (y=0). So, each LED board (on the same layer) will create the same angle with the center point of the bulb (since their radius is the same) which can be defined as:

$$\theta_{LB} = 2\sin^{-1}\left(\frac{r_t}{R}\right) \tag{4.8}$$

where r_t is the radius of the LEDs and R is the radius of the bulb. Then, the maximum number of layers for a particular r_t and R can be expressed as:

$$N = \left\lfloor \frac{90^o}{\theta_{LB}} \right\rfloor \tag{4.9}$$

where θ_{LB} is measured in degrees.



(a) LEDs in 4 layers for R = 40cm and $r_t = 5.5$ cm.

(b) LEDs in 4 layers for R = 40cm and $r_t = 3.5$ cm.

Figure 4.2: LED placements in multi-element bulb for different number of layers.

Next, we calculate the upper limit of the number of LED boards in a particular layer *i*. If the angle between the *i*-th layer and the perpendicular normal is θ_i , then the radius of circle created by the LED boards in the *i*-th layer will be:

$$r_{li} = R\cos\theta_i \tag{4.10}$$

Then, the angle created by each LED board with the center of this circle will be:

$$\theta_{li} = 2\sin^{-1}(\frac{r_l}{r_{li}})$$
(4.11)

Lastly, the maximum number of possible LED boards in the *i*-th layer can be calculated as:

$$K_i = \left\lfloor \frac{360^o}{\theta_{li}} \right\rfloor \tag{4.12}$$

where θ_{li} is measured in degrees.

While searching for the best bulb configuration, we have varied the number of LEDs in each layer (i.e., k_i) up to these maximum values (i.e., K_i) for their corresponding layer. This is detailed

further in Section 4.8. In Figure 4.2 placement of layers and LEDs is displayed for 4 layers and 7 layers.

4.4 Optimization Objective

The goal of this work is to optimize the SIR of the system while considering the illumination quality at an indoor settings. So, the optimization objective could be formulated as to maximize SIR while taking into consideration the illumination quality and aggregate power consumption. We explore optimum bulb configurations for a particular number of layers by varying the number of LED boards in each layer to see which combination produces the maximum SIR under an aggregate power constraint.

We also used the divergence angle of the LEDs as another variable parameter for the optimization problem. Then, we update the optimization problem by adding a constraint on the illumination quality, which is defined by the standard deviation of luminance on the room floor, referred as illumination variation. We, then, compare the two results to analyze the effect of the illumination requirement on the overall optimization problem. The flow diagram with input parameters, intermediate values to calculate the SIR and the illumination variation, and the output parameters are shown in Figure 4.3.



Figure 4.3: Flow diagram of the optimization.

4.5 MAX_SIR: Maximum SIR Problem

We first formulate the problem of finding maximum SIR under a power constraint, i.e., the MAX_SIR problem. At a high level, MAX_SIR aims to find the best placement of LED boards on each layer of the bulb and the best divergence angle for the LEDs. We detail the variable and fixed parameters below:

Variable Parameters:

• k_i , Number of Transmitters in Layer i: Intuitively, given a fixed number of LED boards, they can be placed in layers in many different ways, depending on the size of the LED boards and

the bulb radius. Considering all the parameters involved, we vary the number of LED boards per layer by adjusting the spacing between them on each layer.

θ_d, *Divergence Angle of LEDs:* Divergence angle of the LED is one of the key factors in the source power and illumination quality. While large divergence angles yield better lighting (small variation of the illumination across the room floor), narrow ones are beneficent for increasing the spatial reuse and higher SIR. Thus, we try different divergence angles (in degrees) to find the configurations yielding maximum SIR.

Fixed Parameters: We assume that the following parameters are constant:

- *Room Size:* We are assuming a fixed room dimension of 6m x 6m x 3m for width, length and height, respectively.
- R, Radius of the Hemispherical Bulb: 40cm
- *r_t*, *Radius of the LED/Transmitter*: 3.5cm
- *Number of Layers:* Depending on *R* and r_t , different number of layers are possible in the hemispherical bulb. Given *R* and r_t , we calculate the maximum possible number of layers in the bulb. We are considering the minimum number of layers to be 2. For a specific number of layers between this minimum and maximum value, we have varied the number of LED boards in each layer to find the optimum layering combination.

Now, we formulate the MAX_SIR problem as follows:

$$\max_{k,\theta_d} \quad SIR_{avg}(k,\theta_d) \tag{4.13}$$

subject to

$$2 \le k_i \le K_i \tag{4.14}$$

$$P_{LED}\sum_{i=1}^{l}k_i \le P_{total} \tag{4.15}$$

$$l \le L \tag{4.16}$$

where *l* is the number of layers in the bulb, *L* is the maximum possible number of layers, and K_i is the maximum possible number of LED boards in the *i*-th layer. Further, $k = k_1, k_2, ..., k_L$ is the array of the number of LED boards in each layer. P_{LED} is the source power of a single LED board and P_{total} in (4.15) is the total power constraint, which we have assumed to be 25 Watts unless otherwise said.

4.6 MAX_SIR_LQ: Maximum SIR with Lighting Quality (LQ) Constraint

Although the communication quality has been considered to be the major goal in VLC, recent studies point to potentially significant health concerns of solid-state lighting. Both link quality metrics such as SIR and lighting quality must be considered in future designs. The hallmark of our multi-element design is the relatively smaller divergence angles of LEDs (to attain higher spatial reuse). But, these narrow angles can cause uneven lighting in the room. Thus, we focused on maximizing SIR while keeping the illumination variation on the floor, I_s under a limit.

We update the MAX_SIR problem (by scaling the SIR_{avg} with respect to I_s and adding a constraint on I_s) and define the MAX_SIR_LQ problem as follows:

$$\max_{k,\theta_d} \quad SIR_{avg}(k,\theta_d)/I_s \tag{4.17}$$

subject to

$$2 \le k_i \le K_i \tag{4.18}$$

$$P_{LED}\sum_{i=1}^{l}k_i \le P_{total} \tag{4.19}$$

$$l \le L \tag{4.20}$$

$$0 < I_s \le I_s^{max} \tag{4.21}$$

where I_s^{max} is the maximum allowed I_s .

The updated objective (4.17) and the additional constraint (4.21) significantly change the dimension and complexity of the problem, as there might be designs which can produce a better SIR but an uneven lighting. For simplicity, we are using $I_s^{max} = 5$, which could be varied for better exploration in future studies.

4.7 Heuristic Design for Nonlinearity

To observe the overall effects and the complexity of the search space, we calculated SIR_{avg} against the divergence angle and the number of layers – placing as many LED boards as possible in each layer. Both the line plot and the surface plot are shown in Figure 4.4(a) and Figure 4.4(b). The line plot is done for 3 divergence angles, and as expected, in all the cases after a certain point, the average SIR decreases, which indicates non-linearity, as it increases in the beginning.



(a) SIR against divergence angle. (b) SIR against number of layers.

Figure 4.4: Nonlinearity of the obj. function: SIR against divergence angle and number of layers.

From the surface plot we can also observe the nonlinear nature of the problem as several local maxima and minima can be spotted from the surface. Since the search space is pretty large for finding an optimum bulb configuration (detailed in Subsection 4.8.2), we followed a heuristic similar to Recursive Random Search [48]. In particular, we started the optimizer at 20 different random points and took the best local maxima resulting from these searches. Then we centered the search space around the best local maxima and shrunk it by halving each parameter range. We repeated this step until majority of the local maxima pointed to the same result, which we assumed to be the best result.



Figure 4.5: Convergence of I_s values for $k_1 = 11$, $k_2 = 14$ and $\theta_d = 26$ degrees.

4.8 Simulation Results

4.8.1 Calculation Method

To find solutions to the MAX_SIR problem, we used MATLAB's mixed nonlinear constrained optimizer. Before calling the optimizer, we first fixed the number of layers *l*. We called the optimizer with variable parameters $k = k_1, k_2, ..., k_l$ and θ_d . Then, the optimizer called our user-defined objective function SIR_{avg} with different combinations of *k* and θ_d to search for the bulb configuration maximizing SIR.

Objective	l	k_1	<i>k</i> ₂	<i>k</i> ₃	θ_d
MAX_SIR	2	19	2	_	39.5°
	3	16	26	2	47.2 ^o
MAX_SIR_LQ	2	6	28	_	16 ⁰

Table 4.2: Best results for MAX_SIR and MAX_SIR_LQ

Each time SIR_{avg} is called, the optical power received at each coordinate of the room floor needs to be calculated in order to calculate I_s , the illumination variation across the floor.

To reduce the computation time, we have chosen random points on the floor and calculated I_s for those random coordinates, and then iteratively added more random points to the previous ones until the I_s value becomes stable, that is, the value of I_s in the current iteration is within one percent of the value in the previous iteration. Figure 4.5 shows such a convergence in the case of $k_1 = 11$, $k_2 = 14$ and $\theta_d = 26$ degrees.

Further, upon each call to SIR_{avg} , two random points on the room floor are chosen for receivers, which are assumed to have a radius of 3.75cm and be facing upwards.

We then use these receiver locations to calculate the SIR for the two receivers. We repeated this random selection of locations for pairs of receivers 100 times to calculate the average SIR.



Figure 4.6: SIR and I_s values versus power constraint for MAX_SIR and MAX_SIR_LQ.

4.8.2 Solution for Best Bulb Configuration

We ran our heuristic to solve various cases of MAX_SIR and MAX_SIR_LQ. Table 4.2 shows the results for 2 and 3 layers cases. We observe that, in MAX_SIR, the best bulb configuration has much fewer LED boards in the higher layer. This is expected since the normal points for the LED boards in the higher layers go outside of the boundary of the room floor, so they contribute much less towards the SIR. When lighting quality is considered, in MAX_SIR_LQ, the best bulb configuration places more LED boards to the higher layers with the goal of attaining even lighting across the floor. Putting more LED boards to bottom layers would result in a high SIR spot in the center of the room but have dark areas towards to corners. As expected, MAX_SIR_LQ balances this tradeoff.



Figure 4.7: Objective function output versus power constraint.

4.8.3 Effect of Power Constraints

We also looked at the effect of the power constraints on the results. Figure 4.6 shows optimum SIR versus the total power constraint, which shows a rise at the beginning, but as expected, the best achievable SIR saturates as the power constraint increases.

It is also observed that the optimum SIR is significantly lower when there is an illumination constraint, again confirming our expectations. For the illumination variation, in case of MAX_SIR_LQ it gradually decreases as the power constraint increases, since better configurations are possible at higher power constraints. As we can see from the figure, the value of illumination variation is much lower in case of MAX_SIR_LQ, which results in higher objective function for lower SIR values. In Figure 4.7, the objective function also gets saturated; because, when the power constraint is increased (i.e., the number of LED boards in a configuration can be increased), it means that the signal strength also increases. Since we cannot have unlimited number of transmitters on the bulb, after a certain value of the power constraint, we cannot get any more improvement in the SIR. Even with maximum possible number of LED boards in each layer, we cannot achieve the best SIR because of higher interference coming into action. Therefore, after that threshold value the objective function value remains the same.





(b) Obj. function vs. θ_d for $k_1 = 19$ and $k_2 = 31$.

Figure 4.8: Obj. function vs. divergence angle for two layers of LEDs.

Since the main objective is to find a good balance between the SIR and the lighting quality, this is clearly evident from Figure 4.6. We can see that from every value of the power constraint, SIR considering the illumination constraint is lower than the SIR without considering the constraint because of the low value of the variation (which indicates better quality of lighting), and that is why the value of objective function is the highest.



(a) Avg. SIR vs. θ_d for $k_1 = 12$ and $k_2 = 15$. (b) Avg. SIR vs. θ_d for $k_1 = 19$ and $k_2 = 31$.

Figure 4.9: Avg. SIR vs. divergence angle for two layers of LEDs.

To observe the more interactions between the power constraint and the number of layers, more layers must be considered similar to the results in Figure 4.4(a) and Figure 4.4(b).

4.8.4 Effect of Divergence Angle

We have observed the effect of divergence angle of the LEDs on the objective function for two layers of LEDs in the bulb.

From the simulation we found the values of K_1 and K_2 as $K_1 = 19$ and $K_2 = 31$. Within this bound, we have plotted objective function vs. divergence angle for different combinations of k_1 and k_2 . Figure 4.8(a) shows the plot for $k_1 = 12, k_2 = 15$ and Figure 4.8(b) shows the plot for $k_1 = 19, k_2 = 31$. In both cases, we can see that the optimum value of divergence angle (for which the objective function value is the highest) is at around 53 degrees. For lower values of angles, the objective function is lower because of the overall low signal reception for the receivers, and for higher values of angles the objective function is lower as well because of the increased amount of interference. Also in Figure 4.9 and Figure 4.10, where we have plotted SIR and illumination variation respectively, we can see the best value of divergence angle at around the same region.



(a) Illumination variation vs. θ_d for $k_1 = 12$ and $k_2 = 15$. (b) Illumination variation vs. θ_d for $k_1 = 19$ and $k_2 = 31$. Figure 4.10: Illumination variation vs. divergence angle for two layers of LEDs.

We have also studied this effect for more number of layers in the bulb. In Figure 4.11, plots of objective function versus divergence angle for 2,3,4,5 and 6 layers are shown. As expected, with increasing number of layers, the optimum value for divergence angle decreases as more LEDs are placed in the bulb for more number of layers which can result the best communication coverage and uniformity of illumination across the room.

As we can see the optimum divergence angle value is lower in case of more number of layers, we wanted to see whether a higher SIR value (better spatial reuse) or a lower I_s value is the reason behind this.



Figure 4.11: Obj. function output versus Divergence angle for different number of layers.

To observe this, we plot both SIR and I_s against the divergence angle for 2 and 6 layers cases which is shown in Figure 4.12. We can see that optimum divergence angle value is lower for 6 layers case in both plots, but the difference is more significant in the plot of SIR against divergence angle. So, the higher SIR value is the main reason behind the lower value of optimum divergence angle in the case of more layers of LEDs.





(b) I_s against divergence angle for 2 and 6 layers.

Figure 4.12: Effect of divergence angle comparison between 2 and 6 layers.

4.8.5 The Three-Region Behavior

Figure 4.13(a) shows the contour plot of average SIR of receivers 1 and 2 (i.e., $\frac{1}{2}(\gamma_1 + \gamma_2)$) versus distance between each of the two receiver laptops and the floor center, which shows an interesting behavior. The SIRs are averaged over a large number of user locations, each of which satisfy the considered Euclidean distances to the center of the room as in Figure 4.13(a).

If the laptops are placed in region 1 (the center region of the room) then the distances between them and the center of the room floor is small, and if we place them in region 3 (in the corners), then this distance has to be large. In the surface plot we can see relatively low values of SIR for small and large distances between the laptops and the center of the room floor and higher values for the medium distances, so this indicates region 2 (the middle region between the center and the corner) to be the most favorable one. In the regions shown in Figure 4.13(b), it is assumed that both of the laptops are inside that region. The areas outside the red dotted circles in Figure 4.13(a) indicate cases where one receiver is close to the room center and the other is distant, which also produce low SIR.



(a) Contour plot of SIR. $k_1 = 11, k_2 = 17, \theta_d = 45^{\circ}$.

(b) Top view of the room floor.

Figure 4.13: The 3-region behavior.

The top view of the surface plot is shown in Figure 4.13(a) which more vividly points out the 3 regions (the red dotted circles), since the blue squares indicate low values and the yellow/green squares indicate high values of SIR. The 3 regions in the room floor are shown in Figure 4.13(b). Also in Figure 4.13(b) which illustrates the 3-region behavior in the SIR distribution across the room surface, it can be observed that SIR in the high interference region 1 reduces much slower

than the floor area, and in region 3, SIR decreases along with the floor size. This behavior can act as a useful guide in organizing the room layout for the placement of the receivers.

CHAPTER 5 SUMMARY AND FUTURE DIRECTIONS

We introduced a multi-element VLC architecture that employs a hemispherical bulb with multiple narrow FOV LEDs. The mobile receivers use VLC 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 bulb structure, and presented preliminary results showing that the architecture can offer high spatial reuse while keeping a desired illumination level. Also, we presented a framework for optimizing the multi-element bulb design not only taking the signal quality into consideration but also the evenness of lighting across the room. We believe that the software-defined VLC framework will greatly contribute to the field of VLC, particularly for the IoT applications.

The presented framework can serve as a basis for future studies for better understanding and further improvement. For instance, the optimization could be done over different room sizes and bulb parameters. We are considering the hemispherical shape of the bulb, but experimenting with some other shapes (triangular, square etc.) can be an interesting future work as well. Further, multiple such bulbs in a room could be considered to optimize the overall room's SIR as well as lighting quality. We are currently working on designing an efficient bulb partitioning algorithm for more than two users which can provide a reliable emulation of practical scenarios. And, the last but not the least, a proof-of-concept prototype of the architecture can surely ameliorate the understanding of the optimally designed bulb characteristics.

APPENDIX A LIST OF ABBREVIATIONS

BER	Bit Error Rate
CSK	Color Shift Keying
FOV	Field Of View
FSO	Free Space Optics
IFFT	Inverse Fast Forrier Transform
IM	Instant Messaging
IoT	Internet of Things
LED	Light Emitting Diode
LLC	Logic Link Control
L-PPM	L-Pulse Position Modulation
LOS	Line Of Sight
MCU	Microcontroller Unit
MIMO	Multi Input Multi Output
NRZ	Non-return-to Zero
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On-Off Keying
PD	Photodiode
PPM	Pulse Position Modulation
RF	Radio Frequency
RGB	Red Green Blue
RLL	Run-length Limited

- SIR Signal-to-Interference Ratio
- SLM Spatial Light Modulator
- VLC Visible Light Communication
- VPPM Variable Pulse Position Modulation
- WDM Wavelength-division Multiplexing
- Wi-Fi Wireless Fidelity

APPENDIX B LIST OF SYMBOLS

V Visibility (km)

- λ Optical signal wavelength (nm)
- σ Coefficient of absorption and scattering
- θ_d Divergence angle (radian)
- r_t Transmitter radius (cm)
- *R* Radius of the bulb (cm)
- θ_i Layer *i*'s angle with the normal (radian)
- \overrightarrow{LP}_i Vector between *i*th LED on the bulb and its normal point on the floor
- $\overrightarrow{LP_0}$ Vector of the central LED facing down
- $P_L(i)$ Power on the normal *i*th LED (W)

 r_r Receiver radius (cm)

- H_i Slanted normal length of LED *i* (cm)
- N_t The number of search frames without acknowledgment from a receiver after which the bulb will consider the connection between that receiver and itself is timed out
- N_{rcv} Number of receivers in the room
- S_{ij} Average power received for receiver i at section j
- *SIR*_{*j*} Average Signal-to-Interference-Ratio at section j
- *SIR_a* Average Signal-to-Interference-Ratio of the two receivers
- $k_{i=1..l}$ Array of LED count in each layer
- $K_{i=1..l}$ Array of maximum possible LED count in each layer
- θ_{LB} Angle created with the center point of the bulb by all the LEDs in the same layer

- r_{li} The radius of circle created by the LEDs in the *i*-th layer
- θ_{li} The angle created by each LED with the center of the circle created by its respective layer
- P_{LED} Source power of each LED (W)
- P_{total} Total power generated by the bulb (W)

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