RESOURCE OPTIMIZATION IN VISIBLE LIGHT COMMUNICATION USING INTERNET OF THINGS

by

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ABSTRACT

In the modern day, there is a serious spectrum crunch in the legacy radio frequency (RF) band, for which visible light communication (VLC) can be a promising option. VLC is a short-range wireless communication variant which uses the visible light spectrum. In this thesis, we are using a VLC-based architecture for providing scalable communications to Internet-of-Things (IoT) devices where a multi-element hemispherical bulb is used that can transmit data streams from multiple light emitting diode (LED) boards. The essence of this architecture is that it uses a Line-of-Sight (LoS) alignment protocol that handles the hand-off issue created by the movement of receivers inside a room. We start by proposing an optimization problem aiming to minimize the total consumed energy emitted by each LED taking into consideration the LEDs' power budget, users' perceived quality-of-service, LED-user associations, and illumination uniformity constraints. Then, because of the non-convexity of the problem, we propose to solve it in two stages: (1) We design an efficient algorithm for LED-user association for fixed LED powers, and (2) using the LED-user association, we find an approximate solution based on Taylor series to optimize the LEDs' power. We devise two heuristic solutions based on this approach. The first heuristic solution, called the Low Complexity Two Stages Solution (TSS), optimizes the association between the LEDs and the mobile users before and then the power of each LED is optimized. In the second heuristic, named the Maximum Uniformity Approach, we try to improve the illumination uniformity first and then adjust the power values for each LED so that they do not go above a certain value. Finally, we illustrate the performance of our method via simulations.

To all my loved ones

ACKNOWLEDGMENTS

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CHAPTER 1: INTRODUCTION

VLC is a newly emerging technology that has a noteworthy potential of providing complementary wireless access at high speeds [2]. The significant increase in the number of Internet-of-Things (IoT) devices and the need for more aggregate wireless access capacity are calling for VLC solutions as legacy RF bands are getting saturated [3]. Nowadays, multi-element architectures in VLC systems are gaining attention by optical wireless communications researchers [4,7,24]. These VLC networks can increase the aggregate throughput via simultaneous wireless links, which is how they may attain higher spatial reuse. The efficiency of the downlink data transmission can be improved remarkably by multi-element VLC modules using the directionality of the light beam where each LED transmitter is modulated using a different data stream. There is a serious need for higher spatial reuse in wireless access because of the increasing number of devices that are present in a room or a building. These IoT devices in future 5G networks may require very high aggregate download speeds at tens of gigabit-per-seconds and WiFi alone is incapable of providing such high speed data rates to all these devices.

In this thesis, in a VLC system composed of multiple LEDs and mobile IoT receiver devices, we are trying to optimize the power required for each LED by minimizing the power to such extent that constraints on both illumination (e.g., uniformity of the lighting in the room) and communication (e.g., throughput per receiver) efficiency are maintained, and also keeping in mind that each LED can be associated with at most one IoT receiver at a given time.

There have been significant amount of research concerning the constellation design for LED-based VLC in [8–12]. The main objective of optimization in these techniques is to find a set of constellation points for LEDs' placement so as to maximize the minimum distance to receivers in the room, given the lighting constraint and corresponding transmission power constraint.

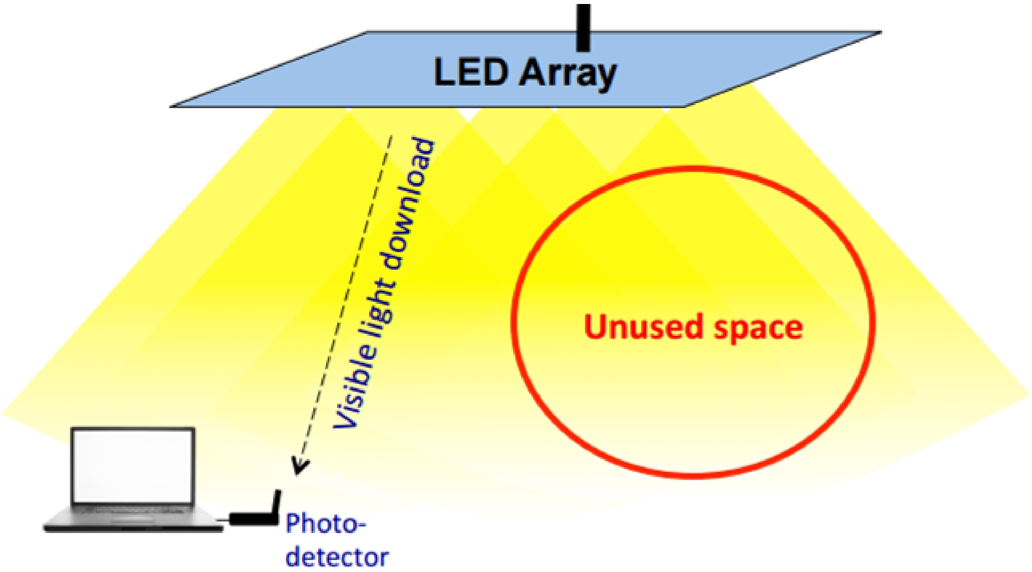


Figure 1.1: Inefficient use of space in a single-element VLC architecture [5]

The challenge of improving data rate has been addressed in works relating to VLC architecture. In [13], the authors proposed transmitter diversity and sub-carrier reuse techniques to improve the VLC data rate in a multi-user environment, but illumination uniformity was not considered. The problem of maximizing the transmission rate for both broadcast and point-to-point communication system was addressed in [20], where several convex optimization problems were derived and the best performance was found using an optimal symbol modulation power allocation scheme. [25] focused on providing uniform illumination levels under minimum Bit Error Rate (BER) and illumination constraints by developing a novel algorithm known as harmony annealing (HA), which was claimed to be performing better than the conventional search algorithms.

The concept of using VLC in an IoT environment has also been researched. In [14], a VLC communication system named 'Retro-VLC' has been proposed which can provide duplex communication via a device without needing a battery which can be merged in mobile IoT devices like sensor nodes. In [15], a VLC system over UART suitable for IoT networks has been proposed and demonstrated which can monitor temperature, humidity, and illuminance in real time utilizing the suggested VLC link. In another work [16], the performance of a smart IoT indoor lighting system is examined that uses time-slotted coordinated communications and binary Manchester coding to encode information, where a method is introduced to approximate optical channels gain and daylight at each lighting structure. However, the problem of minimizing the transmit power of each LED to optimize the overall power of a VLC system while taking both acceptable level of illumination and satisfactory data rate in to consideration has not been addressed before and this is what we propose to do in this paper. The main aim of this thesis is to build a framework of the transmission power and rate optimization based on certain lighting constraints. We provide an LED-based VLC transceiver system model, with the power, association and data rate constraints. We aim to minimize the total transmission power subject to certain transmission rate and lighting constraints for all receivers across the room.

1.1 Contributions of the Thesis

The main contributions of our thesis are as follows:

- Investigating a spherical multi-element bulb architecture for downlink VLC transmission, where each LED can be assigned to a receiver for data transmission and/or used for increasing the uniformity of illumination.
- Formulating an optimization problem aiming to minimize the total consumed energy taking into consideration, LEDs' transmit peak power, users' quality-of-service (QoS), LED-user associations, and illumination uniformity constraints.

- Due to the non-convexity of the problem, we solve it in two stages. Firstly, we propose an efficient algorithm to solve LED-user association for given LEDs' power. Then, given the LED-user association, we find an approximation solution based on Taylor series to find the optimal LEDs' power allocation. We use this approach in our proposed heuristic solutions and analyze our results.

1.2 Thesis Organization

The rest of the thesis is organized as follows:

- In Chapter 2, the relevant works and past contributions are described which lays the foundation for the proposed framework.
- In Chapter 3, the architecture of the multi-element hemispherical bulb used in our framework is detailed.
- In Chapter 4, the optimization problem along with the heuristics formulation is described and the simulation results are chronicled.
- In Chapter 5, the total work is summarized and the path is laid out for the future work.

CHAPTER 2: LITERATURE REVIEW

Optical communication is a method of communicating using light as a mode for carrying information from one place to another. The method typically uses some electronic equipment or vision to accomplish the task. This type of communication system is made up of three components: a transmitter, a channel and a receiver. The first component, that is the transmitter, has the task of encoding a given message in to an optical signal. The work of the channel is to deliver that message to its required destination. Finally, the receiver decodes the message from the optical signal that it received to its respective destination. Now, a form of optical communication in the wireless domain is the optical wireless system of communication which basically uses both the visible and the invisible part of the light spectrum to deliver signal from its source to its destination. The part of the optical wireless communication system that operates in the visible region of the light spectrum is called visible light communication (VLC). There is a lot of work happening in the VLC domain which uses Internet of Things (IoT). Some of the related works on VLC are described below.

2.1 LOS Maintenance in VLC

One of the main properties of optical communication is its line of sight (LOS) property. It is in fact a very evaluative issue that, in a VLC environment, needs addressing. The process of LOS communication involves creating an optical link between a transmitter and a receiver by aligning them and is kept that way to continue the communication between each other. [31] discusses a couple of protocols to adress this LOS issue. The first one is a peer-to-peer protocol in which a multi-hop path is provided among the receiving devices and the second one is a peer-to-host arrangement that uses the base station where the multi-hop path is provided. The former described protocol involves a field of view and a narrow beam of light, which does not require a central host, gives a very good performance when speed is considered and thus can be used in scenarios with very large number of devices. The latter, on the other hand, have an advantage of simplicity and implementation. However, since it has a diffuse link model and suffers from interference, it is not able to attain high data speeds and also requires an accessible host. So, this is mostly used in environments with fewer number of devices.

[32] proposes to use various light sources in the indoor environment which has narrow field of view (FOV) instead of using a single source light with a wide FOV. Actually, what the authors stated is using multiple spot light sources with narrow FOV results in a perfect light cone that is both focused and well directed providing sufficient bright light and higher data speeds which covers a compact area. The advantages of this approach also includes minimizing of the distortion that occurs from multi-path light propagation which basically arises when the signals gets reflected from the walls and objects inside a room. Since these light sources are completely independent from each other, the focusing of light results in an amplified signal strength that are obtained with lesser number of LEDs thereby reducing the complexity of the driver's circuit and lessens the capacitance of the transmitters resulting in an higher bandwidth. However, the spotted lighting brings the issue of illumination uniformity. [33] discusses about the performance of joint optimization of illumination of a VLC system in which two contrasting LED driver schemes are collated. Also, the effect of ripple on the receiver's filter is examined and a couple of approximations are suggested to model their interference. In contrast, our work mainly focuses on optimizing the power of each LED keeping in mind the association, uniformity and data rate constraint.

2.2 Data Rate Improvement in VLC

The speed at which data is transferred is a very important factor in the field of both wired and wireless communication. Several factors such as the region of scope, impedance, transmission capacity, communicating method and adjustment effects the data rate.

Although the above mentioned researches have done significant work in improving the data rate of the system, there are a few disadvantages. Firstly, they use large FOV where there remains a large number of unused space in the environment. Secondly, they use high directional beams, such as laser, and so light uniformity in the room is not maintained and simultaneous transmission does not take place. In contrast, our work takes in to consideration both of these things and our architecture design of the bulb in the room is established on that.

2.3 Hybrid Architectures Including VLC

A hybrid RF/FSO communication architecture has gained significant popularity in the recent days because it takes in factor advantages of both the communication technologies at hand. The main advantages of the RF technology are that they do not require LOS communication between the transmitter and the receiver, they have a wider range of coverage and the fact that they support multiple users. The advantages of FSO, or more specifically VLC in our context, are including communication and illumination simultaneously, enabling a secure connection in an indoor space, easier and cheaper to set up and reduced general control utilization as compared to its counterpart RF technologies. In [36], a hybrid scheme involving RF/FSO architecture is described where the RF links provides relentless quality and FSO does the job of giving increased security and high transmission capability. The authors put forth a directing system where they allow approaching traffic combining transfer speed administration and traffic engineering on a computing unit which is available offline. This information is then used by access routers for traffic engineering and routing when the system is online.

[37] discusses how a hybrid architecture performs better than simple VLC scheme when energy

consumption and user connectivity are taken in to consideration. Various calculations and observations have been done in this work to check the advantages of using a hybrid RF/FSO system. Some of the advantages include service connectivity and efficient use of energy of devices that include a battery in an indoor setting. On top of that, cooperative communication that utilizes optical relays are used to expand the coverage and the energy efficiency of these devices. This framework is mostly denoted by algorithms involving relay selections, the movement of the user in the room, LOS optical channel model, semi angle at half-power of the LED and the photo detectors' FOV and various simulations are conducted to calculate the performance of the efficient use of energy and connectivity of this hybrid architecture. These results disclose that the connectivity of the user and their energy efficiency depends on various factors which includes the number of users, the probabilities of the relays, coverage range ratio between single-hop and multiple hops and the mobility of the user. So, in this work, it has a positive effect on the performance of the users' connectivity and their efficiency. A hybrid FSO and Wi-Fi framework has been illustrated in [38]. Here, a novel location-based coding system is presented, in view of which, the quantity of new rate designation algorithms is proposed to expand throughput furthermore and decrease for different clients in a thick exhibit of overlapping femtocells. [39] discusses a hybrid VLC and RF architecture various access points for RF and VLC are examined and this is done so as to improve the data rate of each individual user thereby supporting the VLC system. The resources used in a VLC environment is presumed to be fixed and so the main objective of this paper is to measure the amount of power and minimum amount of spectrum required for an RF system. Thus, this hybrid system is able to achieve certain threshold for the data rate after being exposed to the VLC environment. The authors in [40] have suggested and executed a hybrid VLC/RF system which utilizes VLC for the process of downlink and Wi-Fi for the uplink process. The experimental results obtained in this work depicts that the hybrid system used outperforms the standalone Wi-Fi system when throughput is considered. A hybrid Wi-Fi/VLC system is proposed using power line communication called PLiFi [41]. This framework provides very fast data connection among the LEDs where the Wi-Fi access point establishes a connection to the power line with the help of Ethernet-PLC modem. In the downlink transmission process, the packets obtained from the web are initially moved further by the Wi-Fi access point to the power line network. After that, they are sent to the LED transmitters where the packets are dispatched to the end devices. These end devices are head on connected to the WiFi access points during the uplink process. An introductory report depicts that this PLC framework present sufficient network coverage and data speeds. An augmentation of ns3 network simulator is suggested in [42] so as to research the attributes of hybrid RF/VLC systems. The amalgamation of the proposed ns3 VLC and the already existing ns3 RF components are used in this work to connect the VLC downlink and RF or WiFi uplink. The resulting simulations have depicted how the system is examined regarding the VLC signal-to-noise ratio (SNR) and the bit error rate of the system in which the results for the network performance turns out to be goodput. In this process, one single user is served by only one LED during downlink and a RF technology (WiFi) utilized for communication during the uplink.

All these works described above focus on either enhancing the features of the VLC architecture or to make a viable communication network. In our work, we have used various spotlighting techniques from a large single bulb containing multiple LEDs in different layers serving as the base station making the handover between different mobile users in the indoor environment easier and also making sure of the required illumination. The main focus of our research is to minimize the power used by these LEDs so that an higher efficiency of the overall system is obtained.

2.4 Schemes of Modulation and Dimming Support in VLC

The modulation of signals in a VLC framework means switching the LEDs to the desiring frequency so that the encoded information can be communicated. There are several modulation techniques and some of them are described below:

- **Pulse Position Modulation (PPM):** In this technique of pulse modulation, a single pulse analogous to a specific bit is transferred in one of the total L given time slots inside a particular symbol period. Therefore, it is known as L-Pulse Position Modulation (L-PPM). The mean requirement for power of PPM is low as it steers clear of the DC component of the current and lower component of the frequency of the spectrum and is also less bandwidth efficient. PPM has a higher system complexity because of its need for a specific bit and synchronization of symbol at the users' end. Some PPM schemes, such as Variable PPM (VPPM) and Multiple PPM (MPPM), are there which are utilized normally for dimming control and transmission of data. [44] discusses an 80 W smart LED module utilized to consolidate the functions of power management and communication. It gives increased efficiency ambient lighting that is programmable and is able to work as a network sensor node capable to collect a huge variation of local measurements leading to increased safety, efficiency and comfortness of the lighting systems in the future. VLC is proposed to be utilized by a dimmable LED driver which is based on the Logic Link Control (LLC) resonant driver topology in this work. Here, the LLC converter, controlled digitally, works in constant current burst mode and these bursts are ordered to independently control the dimming of the light and the transmission of data applying the principle of VPPM modulation. At the receiver end, a circuit is present for demodulation and decoding of the light signal. The work depicts a 50 Kbits/sec system illustrated on a 308 LED luminaire using a digitally controlled LLC DC-DC converter.

- **On-Off Keying (OOK):** It is one of the most straightforward modulation technique that has ever been used. The process works when LEDs are switched on and off simultaneously where the 'on' state corresponds to the high bit rate, i.e. 1, and the 'off' state corresponds to the low bit rate, i.e. 0, and thereby modulating data. Run-Length Limited codes (RLL), for example Manchester coding, can be utilized to balance DC power [45]. Another modulation scheme namely the Non-Return-to-Zero OOK (NRZ-OOK) has been widely utilized in VLC. In this technique, the 0 and 1 are depicted by negative and positive voltages respectively, and there is no ‘rest’ state. A very simple NRZ-OOK system is exhibited using one Red Green Blue (RGB) LED in which only the red LED was used to transmit the data and it acquired a bit rate of 477 Mbits/sec. It also engaged a technique called the duo-binary technique alongwith bandwidth enhancement utilizing transmitter and receiver equilization thereby achieving 614 Mbits/sec. For this process, one red LED is used which is easily available commercially. This LED along with a cheap PIN-PD is used similar to a practical LED driver and a simple pre-emphasis circuit. It is asserted in the work that a data rate of 456 Mbits/sec is achieved using the method stated above.

- **Orthogonal Frequency Division Multiplexing (OFDM):** The main advantage of this technique is that it is both spectrally efficient and tough against channel dispersion. It is utilized substantially in applications relating to RF like Terrestrial Digital Video Broadcasting (DVB-T). VLC utilizes the light from the visible spectrum to carry data where a real and a unipolar value need to be generated and so the normal OFDM technique utilized in RF communication needs to be modified. Therefore, Hermitian symmetry is utilized on parallel data stream so as to achieve a real valued output signal using the Inverse Fast Fourier Transform (IFFT) input. An experimental illustration of an indoor VLC transmission operating at 1 Gbit/sec utilizing MIMO OFDM is discussed in [46]. In this system, MIMO link involving four channels that uses white LED sources is used where each and every LED transmits signals at 250 Mbits/sec. In this process, a nine channel imaging diversity receiver is utilized to identify the signal where 10^{-3} of average bit error rate is obtained at 1000 lux illumination level considering 1m distance.

- **Color Shift Keying (CSK):** Multi-chip LEDs in VLC architecture are introduced by the new IEEE 802.15.7 standards which was published in 2011. In this scheme, each symbol’s color point is created by adjusting the intensity of the RGB chips. Nonetheless, this scheme cannot be utilized where a VLC architecture is concerned because the source point in a VLC system is a pc-LED that is one of the most mundane light sources and CSK implementation is necessitates a complicated circuitry. [47] discusses some adjustment that are done to carry out multi-user capabilities using a time based multiplexing scheme where the modulation symbols are being utilized to encode data with the red, green and blue LEDs' power respectively. In this process, a pulse signal which is simple and time-based is used to split up the data symbol of the users and a three-dimensional signal constellation configuration is converged to improve the information throughput. Various simulations are performed to analyze this performance and it has been seen that the statistical characteristics of the RGB signals verifies the dimming capabilities of the system and flickering does not affect the illumination uniformity.

- **Dimming Support:** In a VLC application in an indoor setting, light dimming is a very engrossing factor [48]. In this work, the 'light off' mode is depicted as the extent that humans consider that the light is really turned 'off'. Basically, this is achieved by sustaining a large surface area of the emitter and equalling the emitter's brightness with that of the room and the outcome displays is actually capable of sending data at high Nm/s involving very reduced light emission. Thus, this work, in fact, shows how to use VLC in reduced lightning environment effectively and thereby limiting the transmitting power.

CHAPTER 3: THE VLC ARCHITECTURE

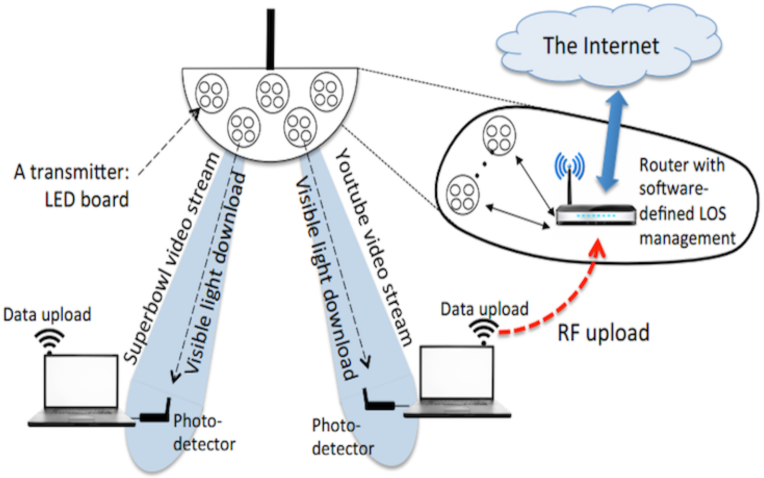


Figure 3.1: Design of a multi-element VLC architecture [5]

In our work, we have focused mainly on two objectives of the VLC architecture. They are (1) *high spatial reuse* by utilizing the LEDs' directionality and (2) *consistent handling of users' mobility* by utilizing software protocols to direct the data transmissions to mobile users. In our work, narrow divergence angles of transmitters/LEDs are used instead of large divergence angles as was used normally in the literature. This is done to attain high spatial reuse as it becomes possible to establish multiple download links from different LEDs. We likewise utilized software protocols from [5] to effectively handle the portability issues like maintenance of alignment between the LEDs and the users, LOS discovery and LED-user association and utilized heuristics optimization to efficiently explain interference issues between concurrent VLC links.

The main challenge comes when the receiver is not static and is moving. Though we have hundreds of LEDs in our bulb architecture, the problem still persists in which we have to steer the transmission of data to the corresponding LED, especially because of this mobility. Therefore, we assume this problem to be solved by using software-defined and seamless steering as was shown in [5], which can be of high efficiency in VLC. The detail of the architecture is shown in Figure 3.1). For better understanding, we briefly describe below this Hemispherical Bulb architecture and how it is modeled next.

3.1 The Hemispherical Bulb

In our design, we assume that the bulb acts as the access point for all the devices present in the room. The hemispherical bulb is provided with multiple transmitters to serve multiple users. The bulb is covered with LED boards containing multiple LEDs, which transmit a particular data stream and the LEDs belonging to the same board are modulated by the same data signal. The advantage of having multiple LEDs on a single transmitter board is that it allows to be designed for a variety of operational targets that include the range of communication, the quality of illumination and the power source. The main idea here is to establish connection between a transmitter and a controller device in the bulb and running a software protocol for properly managing the alignment of LOS between the LED boards and the mobile users in the room. The obstacle of seamlessly channelling the data to the corresponding transmitters can be effectively dealt with this software-based method. The details of this software-defined multi-element VLC technique are given in [5].

In this thesis, we consider a single hemispherical bulb for an indoor VLC system consisting of M LEDs serving U users. Each LED is powered at a different level of P_m Watt, $\forall m = 1, .., M$. The bulb is a hemispherical structure with two functions: illumination of the room and wireless data download to mobile users. First, it acts as an access point for the room. It consists of multiple transmitters (LEDs) to facilitate simultaneous downloads to multiple receivers (users) as shown in Figure 3.2. These LEDs are attached to the surface of the bulb in several layers pointing towards different directions so that they can illuminate different parts of the room. Second, the LEDs are intended to provide light coverage while facilitating wireless communication in the room. The uniformity of lighting is a key goal of the system. For IoT settings, the number of (mobile) receivers can be quite large. To provide a minimum data transfer rate to each of these receivers while attaining an acceptable uniformity of illumination is the joint objective of our system.

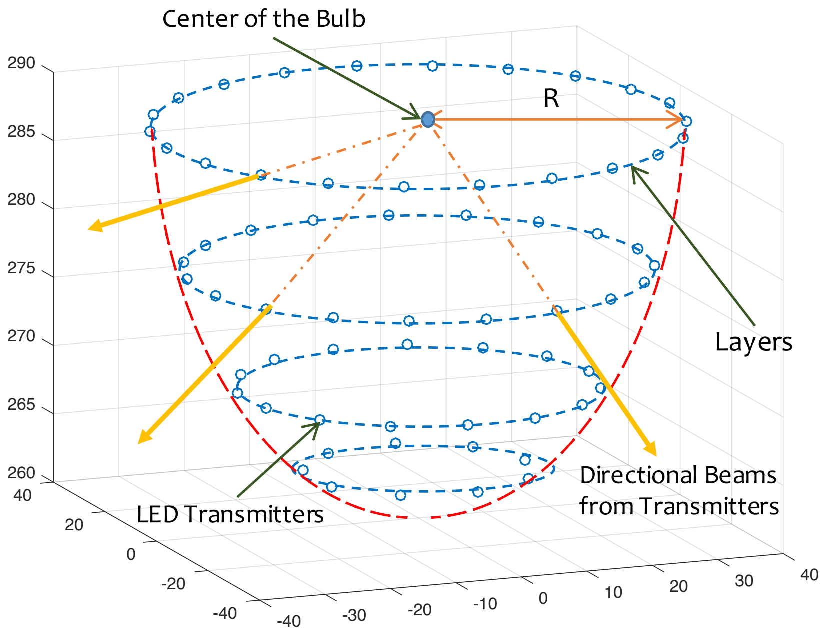


Figure 3.2: Placement of transmitters [5]

The LED boards on the hemispherical bulb are placed in different layers as depicted in Figure 3.2. If P is the maximum number of layers that are possible and M_i is maximum number of LED boards that are possible in the i-th layer, then, according to the shape of the LED boards and the bulb, P and M can have separate upper limits. We presume the LED boards in the bulb to be placed as closely as possible to determine the maximum number of layers P in it. Further details of how these upper limits are calculated and the positions of LED boards are determined are available in [24].

The main intuition is that more LED boards should be placed on the lower layers of the bulb to achieve a higher data rate and so, accordingly, we place the maximum number of LED boards in the lower layer and and go to the higher layers if required.

3.2 Mobile Users

We envision mobile users which are equipped with a collection of photo-detectors (PDs) conformal to the surface [43] of the receiver with additional apparatus like lenses. These users also need the capability of uploading using legacy RF transmitters. They receive the download from the LEDs with which they are in LOS alignment. These devices should be designed so that they contain a solid-state device, communication protocols and packaging like in smart-phones and laptops where the PDs cover the whole surface.

CHAPTER 4: MINIMAL ENERGY VLC FOR IOT

In this chapter, we are taking into account the large number of mobile users in an IoT environment and formulating an optimization problem that aims to minimize the total power consumed by each LED respecting a satisfactory level of illumination and data rate. First, we are using the Nearest User Assignment approach to associate each LED to at most one user. In our problem, the minimum data rate requirement to each IoT device/user imposes a constraint that makes the optimization a non-convex one. Hence, we use Taylor series approximation to make it a convex function so that our problem is solvable. Next, we are using our heuristic solutions to optimize the power of each LED which was our goal in the first place. Finally, we are depicting the simulation results that we obtained to show the performance of our proposed algorithms.

4.1 Assumptions

The following assumptions were made in this work:

- Inside the room, each mobile user has one PD receiver and one RF transmitter, and this user is able to extricate the desired signal from the optical transmitters.
- Locations of the mobile users are known to the controller running inside the bulb.
- There are N fixed sensors uniformly distributed inside the room. These are not equipped with decoders and are only used for measuring the illumination uniformity in the room. The light intensity received at these sensors determine how uniform the lighting is inside the room. It is possible to place these sensors at a place of interest, however, we assume that they are uniformly distributed, in a lattice placement pattern, to the room floor.

4.2 LED-user Association

A binary variable ϵ_{mu} is introduced that signifies the association between the LED m and the user u that is shown below:

$$\epsilon_{mu} = \begin{cases} 1, \text{if LED } m \text{ is associated with user } u. \\ 0, \text{otherwise.} \end{cases} \tag{4.1}$$

$$\sum_{u=1}^{U} \epsilon_{mu} \leq 1, \forall m. \tag{4.2}$$

Here, we assume that user u can be associated to many LEDs at the same time. In contrary, an LED is not allowed to associate with more than one user simultaneously as implied in (4.2).

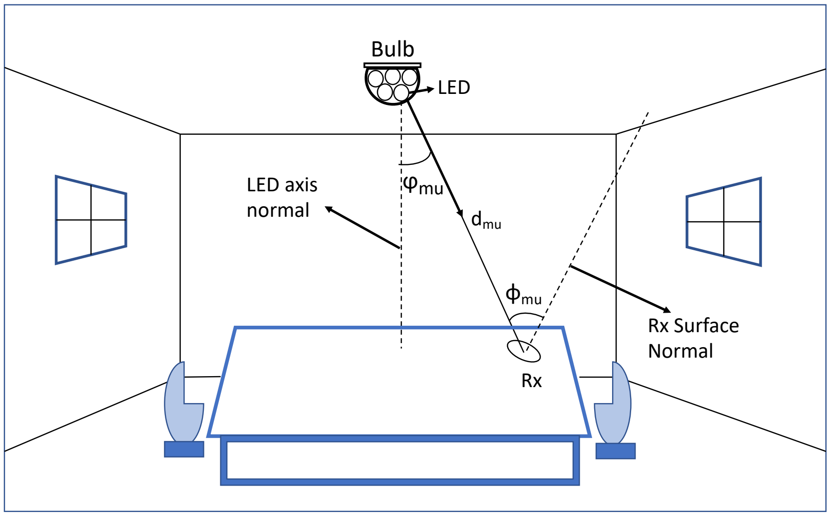


Figure 4.1: Transmitters and receivers in a VLC channel model

4.3 Channel Model

In our channel model, the multi-path propagation due to the reflections are neglected and only LOS channel propagation is considered. So, the downlink communication channel model between LED m and user u can be expressed as [1]:

$$h_{mu} = \begin{cases} \frac{A_u}{d_{mu}^2} Q_0(\varphi_{mu}) \cos(\phi_{mu}) & , \ 0 \leq \phi_{mu} \leq \phi_c \\ 0 & , \quad \phi_{mu} \geq \phi_c \end{cases} \tag{4.3}$$

where A_u is the user PD area and d_{mu} is the distance between LED m and user u. φ_{mu} and ϕ_{mu} are the irradiance and incidence angles respectively (shown in Figure 4.1). ϕ_c is the FOV angle of the PD. We have assumed that no optical filter is used. $Q_0(\varphi_{mu})$ is the Lambertian radiant intensity and expressed as

$$Q_0(\varphi_{mu}) = \frac{(q+1)}{2\pi} \cos^q(\varphi_{mu}), \tag{4.4}$$

where $q = -\ln(2)/\ln(\cos(\varphi_{1/2}))$ is the order of Lambertian emission and $\varphi_{1/2}$ is the transmitter semi-angle at half power.

4.4 SINR Calculation

We assume that each LED is either associated with one user or used for lighting only. Therefore, SINR at user u can be expressed as [28]

$$\Gamma_u = \frac{\beta_u^2}{N_0 B + \sum\limits_{\substack{k=1 \\ k \neq u}}^{U} \beta_k^2} \tag{4.5}$$

where $\beta_i = \sum\limits_{m=1}^{M} \epsilon_{mi} h_{mi} P_m$, and B and N_0 are the total power received by user i from its assigned LEDs, the communication bandwidth and the spectral density of the Additive White Gaussian Noise

(AWGN), respectively.

4.5 Illumination Uniformity

An important factor to be considered in VLC is illumination intensity distribution across the room floor. Specifically, the illumination uniformity, ϑ, can be defined as the ratio between the minimum and the average illumination intensity among all N sensors and is given as [29]

$$\vartheta = \frac{\min\limits_{n}(\sigma_n)}{\frac{1}{N}\sum\limits_{n=1}^{N}\sigma_n} \tag{4.6}$$

where $\sigma_n = \sum\limits_{m=1}^{M} \alpha_0 P_m h_{mn}$ is the received total power at sensor n. α_0 is the luminous efficiency that depends on the LED color wavelength, e.g., $\alpha_0 = 60$ lumen/Watt for white LED [30]. $\min(.)$ is the minimum function.

4.6 Problem Formulation

We formulate an optimization problem aiming to minimize the total energy consumption of LEDs while satisfying a certain rate threshold for users and taking into consideration the association and illumination uniformity constraints. So, the optimization problem can be written as:

$$\textbf{(P0):} \quad \underset{\epsilon_{mu}\in\{0,1\}, P_m \geq 0}{\text{minimize}} \quad \sum_{m=1}^{M} P_m \tag{4.7}$$

subject to:

$$P_m \leq \bar{P}, \quad \forall m, \tag{4.8}$$

$$\sum_{u=1}^{U} \epsilon_{mu} \leq 1, \quad \forall m, \tag{4.9}$$

$$\frac{\min\limits_{n}(\sigma_u)}{\frac{1}{N}\sum\limits_{n=1}^{N}\sigma_u} \geq \bar{I}_{\text{min}}, \quad \forall u. \tag{4.10}$$

$$B\log_2\left(1 + \frac{\beta_u^2}{N_0 B + \sum\limits_{\substack{k=1\\k\neq u}}^{U} \beta_k^2}\right) \geq \bar{R}_u, \quad \forall u. \tag{4.11}$$

where (4.8) and (4.9) represent the LEDs' power budget and association constraints. (4.10) represents the illumination uniformity constraint, where $\bar{I}_{min}$ is defined as the minimum acceptable illumination uniformity threshold which we set to be 0.7 [29]. Finally, (4.11) represents the minimum rate QoS, where $\bar{R}_u$ is the minimum rate expected for each IoT device.

4.7 Problem Solution

The formulated optimization problem given in (4.7)-(4.11) is a non-convex and mixed-integer non-linear programming problem. In our first solution, we propose a low complexity two stages heuristic solution. In the latter solution, in the first stage, we propose a 'Nearest User Assignment' approach to determine the value of ϵ_{mu}. Then, given the LED-user associations, we optimize the

LEDs' power allocations in the second stage.

4.7.1 Low Complexity Two Stages Solution (TSS)

Optimizing ϵ_{mu} and P_m at the same time makes our problem really complex specially for IoT scenarios where we have large number of users U and large number of LEDs M. In a practical scenario, IoT devices or users will be moving in the room, and every time users' locations change the optimization will need to be re-performed. Therefore, we propose a Two Stages Solution (TSS) as a practical and efficient solution with low complexity.

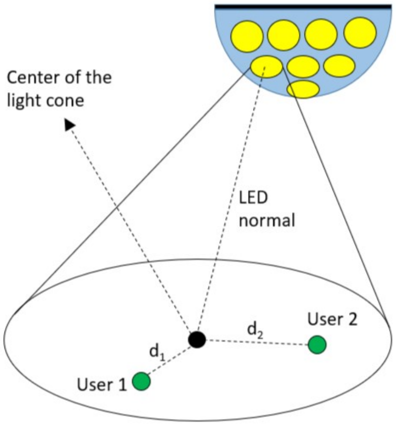


Figure 4.2: Nearest User Assignment Approach in case of interference for an LED on the bulb: Two users are within the code of the LED. When the LED is assigned to one of the users, the light beam of this LED will become interference to the other user's downlink.

In order to simplify the problem **P0**, we propose to optimize $\epsilon_{mu}, \forall m, u$ first, then use ϵ_{mu} values to optimize P_m. To do this, we firstly propose to use a heuristic 'Nearest User Assignment' approach to determine the value of ϵ_{mu}. We then optimize $P_m, \forall m$ by applying a Taylor series approximation to convert the problem into convex one. Finally, Successive Convex Approximation (SCA) approach is used to find the best approximation.

4.7.1.1 LED-User Association

In our ‘Nearest User Assignment’ for obtaining the value of LED-user association matrix ϵ_{mu}, we propose to find the user which is most aligned for each LED m. That is, for each LED m under consideration, we firstly find the light cone of LED m (Figure 4.2). After that, knowing the coordinate of each user, we can determine which user is the closest to the center of light cone of LED m. Let us assume this nearest user to be u, where the user u is in the LOS of LED m, then LED m gets assigned to user u (that is, we let $\epsilon_{mu} = 1$) and $\epsilon_{mu'} = 0, \forall u' \neq u$. In this way, no LED is assigned to more than one user. Finally, we use this LED-user association matrix value while optimizing the LEDs’ power, which is discussed in the next subsection.

4.7.1.2 Power Optimization

For given LED-user association, the optimization problem **P0** (with some term arrangements) that optimizes LEDs' power can be written as:

$$\textbf{(P1):} \quad \underset{P_m \geq 0}{\text{minimize}} \quad \sum_{m=1}^{M} P_m \tag{4.12}$$

subject to:

$$P_m \leq \bar{P}, \quad \forall m, \tag{4.13}$$

$$\frac{\bar{I}_{\min}}{N} \sum_{n=1}^{N} \sigma_u \leq \min_n(\sigma_u), \quad \forall u. \tag{4.14}$$

$$B \log_2 \left(1 + \frac{\beta_u^2}{N_0 B + \sum\limits_{\substack{k=1 \\ k \neq u}}^{U} \beta_k^2} \right) \geq \bar{R}_u, \quad \forall u. \tag{4.15}$$

Notice that in **P2**, the objective function is a convex function and all constraints are convex functions except (4.15). This constraint is neither concave nor convex with respect to the LED transmit power P_m. Hence, the goal is to convert constraint (4.15) into a convex one in order to solve the problem efficiently. Thus, from (4.15), we derive the convex function as follows:

$$\log_2\left(1+\frac{\beta_u^2}{N_0B+\sum\limits_{\substack{k=1\\k\neq u}}^{U}\beta_k^2}\right)\geq\frac{\bar{R}_u}{B}, \tag{4.16}$$

$$1+\frac{\beta_u^2}{N_0B+\sum\limits_{\substack{k=1\\k\neq u}}^{U}\beta_k^2}\geq 2^{\frac{\bar{R}_u}{B}}, \tag{4.17}$$

$$\frac{\beta_u^2}{N_0B+\sum\limits_{\substack{k=1\\k\neq u}}^{U}\beta_k^2}\geq 2^{\frac{\bar{R}_u}{B}}-1, \tag{4.18}$$

$$\tag{4.19}$$

Now, putting $C_u = 2^{\bar{R}_u/B} - 1$, we get

$$\frac{\beta_u^2}{N_0B+\sum\limits_{\substack{k=1\\k\neq u}}^{U}\beta_k^2}\geq C_u, \tag{4.20}$$

Then, the equation changes to

$$\beta_u^2 \geq C_u\left(N_0B+\sum_{\substack{k=1\\k\neq u}}^{U}\beta_k^2\right) \tag{4.21}$$

Then, by taking square root of both sides and substituting β_u and β_k with their expanded expressions including P_m, constraint (4.15) can be re-written as

$$\sum_{m=1}^{M}\epsilon_{mk}h_{mk}P_m \geq \sqrt{C_uN_0B+C_u\sum_{\substack{k=1\\k\neq u}}^{U}\left(\sum_{m=1}^{M}\epsilon_{mk}h_{mk}P_m\right)^2} \tag{4.22}$$

The RHS of (4.15) is non-convex. To approximate the RHS of (4.15) using Taylor series expansion, we first take its partial derivative and then apply first-order Taylor series approximation. The partial derivative of the RHS with respect to P_m is

$$\frac{\partial}{\partial P_m}\sqrt{C_u N_0 B + C_u \sum_{\substack{k=1\\k\neq u}}^{U}\left(\sum_{m=1}^{M}\epsilon_{mk}h_{mk}P_m\right)^2}, \tag{4.23}$$

$$\frac{1}{2}AC_u\frac{\partial}{\partial P_m}\sum_{\substack{k=1\\k\neq u}}^{U}\left(\sum_{m=1}^{M}\epsilon_{mk}h_{mk}P_m\right)^2 \tag{4.24}$$

where A = $\left(C_u N_0 B + C_u \sum\limits_{\substack{k=1\\k\neq u}}^{U}\left(\sum\limits_{m=1}^{M}\epsilon_{mk}h_{mk}P_m\right)^2\right)^{-0.5}$. So, the derivative of RHS becomes

$$AC_u\sum_{\substack{k=1\\k\neq u}}^{U}\left(\sum_{m=1}^{M}\epsilon_{mk}h_{mk}P_m\sum_{m=1}^{M}\epsilon_{mk}h_{mk}\right), \tag{4.25}$$

$$\frac{C_u \sum\limits_{\substack{k=1\\k\neq u}}^{U}\left(\sum\limits_{m=1}^{M}\epsilon_{mk}h_{mk}P_m\sum\limits_{m=1}^{M}\epsilon_{mk}h_{mk}\right)}{\sqrt{\left(C_u N_0 B + C_u \sum\limits_{\substack{k=1\\k\neq u}}^{U}\left(\sum\limits_{m=1}^{M}\epsilon_{mk}h_{mk}P_m\right)^2\right)}}. \tag{4.26}$$

Using the partial derivative from (4.26), we use first-order Taylor expansion approximation in order to convert the RHS of (4.22) into a convex one. For a function $f(x)$, the first-order Taylor series approximation can be written as:

$$f(x) = f(a) + f'(a)(x-a). \tag{4.27}$$

Using the same technique as in equation (4.27) on the RHS of (4.22), we get the following:

$$\beta_u \geq \sqrt{C_u N_0 B + C_u \sum_{\substack{k=1 \\ k\neq u}}^{U} \beta_k(r)^2} + \frac{C_u \sum\limits_{\substack{k=1 \\ k\neq u}}^{U} \left(\beta_k(r) \sum\limits_{m=1}^{M} \epsilon_{mk} h_{mk} \right)}{\sqrt{C_u N_0 B + C_u \sum\limits_{\substack{k=1 \\ k\neq u}}^{U} \beta_k(r)^2}} \left(P_m - P_m(r) \right) \tag{4.28}$$

where $\beta_k(r) = \sum\limits_{m=1}^{M} \epsilon_{mk} h_{mk} P_m(r)$. After this approximation, the optimization problem **P1** becomes a convex optimization problem and it can be solved using standard convex optimization techniques.

Algorithm 1 Algorithm for TSS

```
Let $\epsilon_{mu} = 0$ for $m = 1..M$ and $u = 1..U$.
Let $d \to 0, d_{min} \to 0, n \to 0$
for $m$ = 1 to $M$ do
    for $u$ = 1 to $U$ do
        if user $u$ is inside the cone of LED $m$ then
            if $d$ == 0 then
                $d \to$ distance between center of the cone and user $u$
                $d_{min} \to d$
                $n \to u$
            end if
        else
            $d \to$ distance between center of the cone and user $u$
            if $d < d_{min}$ then
                $d_{min} \to d$
                $n \to u$
            end if
        end if
    end for
    if $n! = 0$ then
        $\epsilon_{mn} \to 1$
        $n \to 0$
    end if
end for
Select feasible initial values $P_m^{(0)}$.
repeat
    r=1.
    Solve the optimization problem with calculated $\epsilon_{mu}$ using the interior-point method to determine the
    new approximated solution $P_m^{(r)}$.
until Convergence ($|\chi^{(r+1)} - \chi^{(r)}| \leq \xi$).
```

4.7.2 Maximum Uniformity Approach (MUA)

In MUA, we try to improve the illumination uniformity first by our heuristic algorithm and then adjust the power values for each LED so that they do not go above a certain value. This heuristic algorithm reduces the complexity of our original algorithm. The approach is described as below:

1. We first formulate a quasi-convex optimization problem that is efficiently solvable using bisection so that the power values that have been assigned for the individual LEDs can be

obtained using the maximum uniformity that is possible, given that a minimum value is obtained for the data rate. This problem can be formulated as:

$$\underset{P_m, I_{\min} \geq 0}{\text{minimize}} \quad \frac{\frac{1}{N}\sum_{n=1}^{N} \sigma_n}{I_{\min}} \tag{4.29}$$

subject to:

$$P_m \leq \bar{P}, \quad \forall m, \tag{4.30}$$

$$I_{\min} \leq \sigma_n, \quad \forall n \tag{4.31}$$

$$B \log_2 \left(1 + \frac{\beta_u^2}{N_0 B + \sum_{\substack{k=1 \\ k \neq u}}^{U} \beta_k^2} \right) \geq \bar{R}_u, \quad \forall u. \tag{4.32}$$

Again, we make constraint (4.32) into a convex one using Taylor series approximation just like in TSS. Then, after solving subproblem (4.29), we denote the resulting P_m values as intermediate power values which are P_{1i}, P_{2i}, ... P_{Mi} for M LEDs.

2. In case of one or no user in the LED m's cone (as shown in Figure 4.2), we assign the $\max(P_{mi}(1+\tau), P_{max})$ power to the LED m, where τ shows the deviation of the allocated power of LED m from its intermediate value P_{mi}. From this, we try different values of τ ranging from 0.1 to 0.7.

3. Whenever there is more than one user in an LED's cone, we use the Nearest User Approximation (Figure 4.2) to assign the user nearest to the center of the LED's cone with fractional power because interference will prevail in this case. Now, we calculate this fraction by taking the distances of the nearest and second nearest user from the center of the LED cone into account. For example, if the distance of the nearest user from the center of the cone is d_1 and the distance of the second nearest user from the center of the cone is d_2, then the allocated

power to LED m would be P_m = $(1 - d_1/d_2)P_{max}$. When the second nearest user is much closer to the nearest user, the ratio of d_1 and d_2 is higher, and that makes the value of P_m to be lower to minimize the effect of interference. Therefore, the power allocated to LED m becomes $P_m = (1 - d_1/d_2)P_{mi}$, which makes sure that the P_m is within the pre-configured limit making it $P_m \geq (1 - \tau)P_{mi}$. Here, we again use the Taylor series approximation to sustain the minimum rate constraint in (4.32).

4.8 Simulation Results

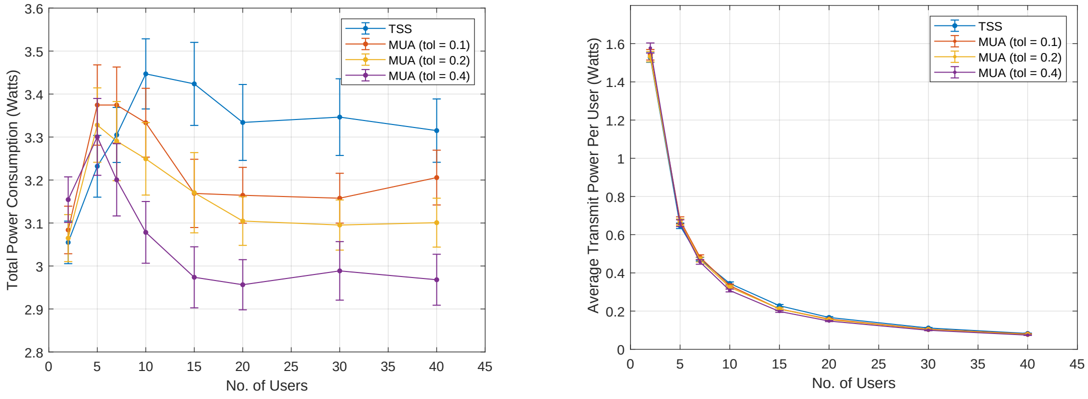
In order to understand the performance of our heuristics, we perform extensive simulations in MATLAB. Table 4.1 shows the default input parameters used in our simulation setup. The room size corresponds to a small size conference room or a large office with a 6 m × 6 m floor and 3 m of height. We consider a hemispherical bulb with radius R = 40 cm and the total number of LEDs used is 65 in 6 layers where $m_{1..6}$ = [11 14 17 10 7 5] and 1 LED exactly at the center point of the bulb. We assume the radius of the LED boards to be r_t=1.5 cm and the radius of the photo-detector receiver at the users to be r_r=3.75 cm.

Table 4.1: Simulation Parameters

Parameter	**Value**
Room Size	6 m × 6 m × 3 m
Radius of the transmitter, r_t	1.5 cm
Radius of the receiver, r_r	3.75 cm
No. of sensors, N	100
AWGN spectral density, N_0	2.5 x 10^{-20} W / Hz
Modulation bandwidth, B	20 MHz
Minimum uniformity, $\bar{I}_{min}$	0.7 [29]
Minimum data rate, $\bar{R}_u$	1 Mbps

We plot the effect of total power consumption, minimum rate utilized by each user, average rate used by the users, with the total number of users in the system, U. We increase the number of users U from 2 to 40 to observe the effect of dense IoT deployments. Similarly, to observe the effect of narrow or wide divergence angles on the illumination quality and data rates the IoT users receive, we vary the divergence angle of LED boards θ_d from 20^o to 120^o. We assume 20 MHz of bandwidth, which is very conservative for VLC bands and operational limitations since LEDs and PDs can work with much larger bandwidth than this. Finally, in terms of target illumination and communication efficiency, we target a minimum uniformity of $\bar{I}_{min}$ = 0.7 [29] and minimum data rate per user of $\bar{R}_u$ = 1 Mbps.

To gain confidence in the results, we run the simulations at least 100 times with randomly chosen user locations within the room. For seeding the random number generator in our simulations, we used the prime numbers starting with 11. We show the results with 95% confidence intervals.



(a) Total Power Consumption vs. No. of users.

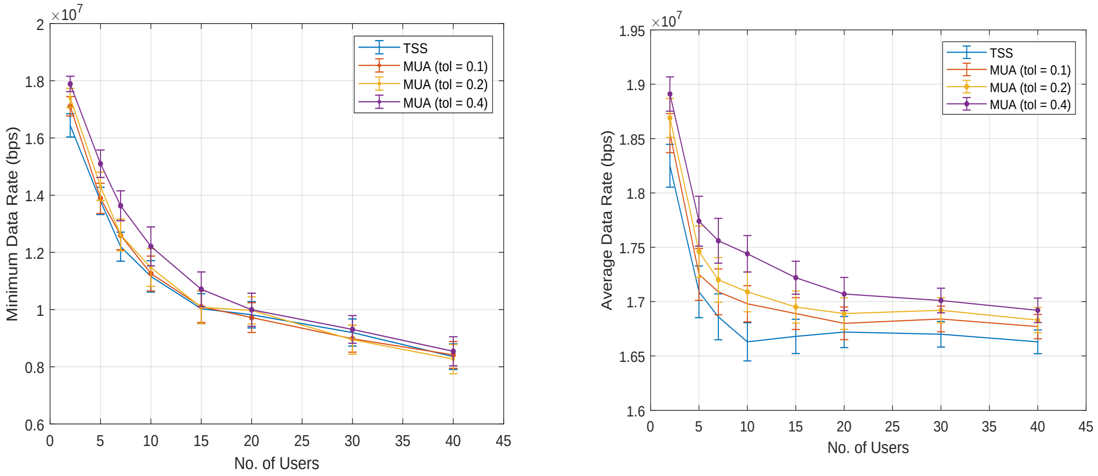
(b) Average Power Consumption vs. No. of users.

Figure 4.3: Effect on Power Consumption of the System.

4.8.1 Effect on Total Power Consumption of the System

We observe the effect on total power consumption of the system, which is the objective function in our optimization problem, with increasing number of users. The plots for total power consumed by the bulb and average transmit power spent for each user versus the total number of users in the room are shown in Figure 4.3(a) and 4.3(b), respectively. As we can see, the total power consumption of the bulb is increasing with the number of users, though not too much. This indicates that, as more users are admitted to the room, the LED-user associations are tuned to maintain the minimum data rate a user gets and the illumination uniformity constraint.

The average transmit power spent for each user (Figure 4.3(b)) significantly decreases for large number of users in the system. This reveals that more LEDs could be assigned to a user when there are few users in the room, but, as the number of users increases, the LEDs available for a user reduces which causes the aggregate transmit power spent for a user to reduce significantly. So, overall, our algorithm is able to keep the total power consumption to a satisfactory level which is the main objective of this work, and the cost-effectiveness is improved significantly for a very high number of users, as the amount of average transmit power spent for each user becomes very low while satisfying the minimum data rate and illumination uniformity constraints.



(a) Minimum Data Rate vs. No. of users.

(b) Average Data Rate vs. No. of users.

Figure 4.4: Effect on User Data Rate of the System.

4.8.2 Effect on Data Rate

Another important goal of our optimization problem is to provide a minimum data rate to each user of the system to maintain a good QoS, and for that we analyze the minimum and average throughput of the system with respect to the number of users, which is demonstrated in Figure 4.4(a) and 4.4(b). From these plots, we can see that our approach can maintain a very good data rate, both average and minimum, even for a large number of users, though both of these rates drop with increasing number of users, which is expected.

Interestingly, we can observe a clear tradeoff between the interference caused by large divergence angles and the high data rate opportunities when the number of users is low. We observe that 80^o provides notably higher minimum and average data rates for up to 20 users, but it cannot maintain a good data rate for more users. On the other hand, narrower divergence angles offer lower data rates for few-users cases but can maintain a good data rate even though the number of users increases.

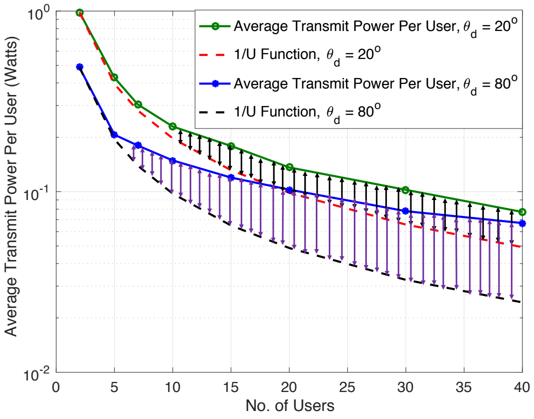
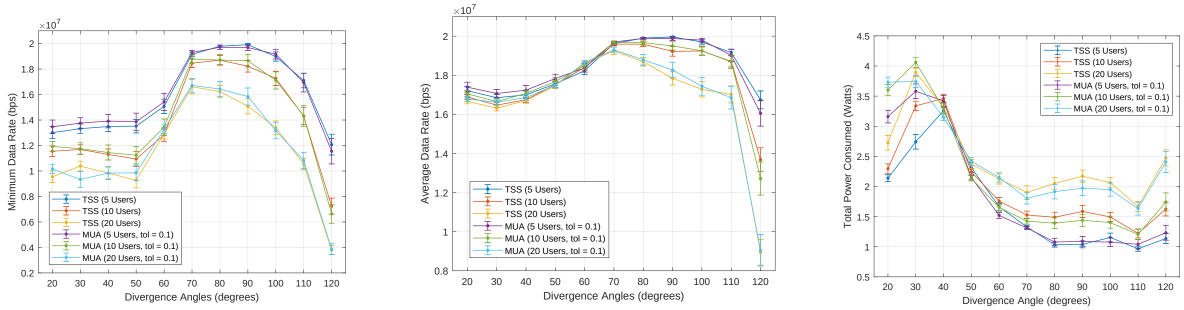


Figure 4.5: Average Transmit Power Decay Per User for $\theta_d = 20^o$ and $\theta_d = 80^o$

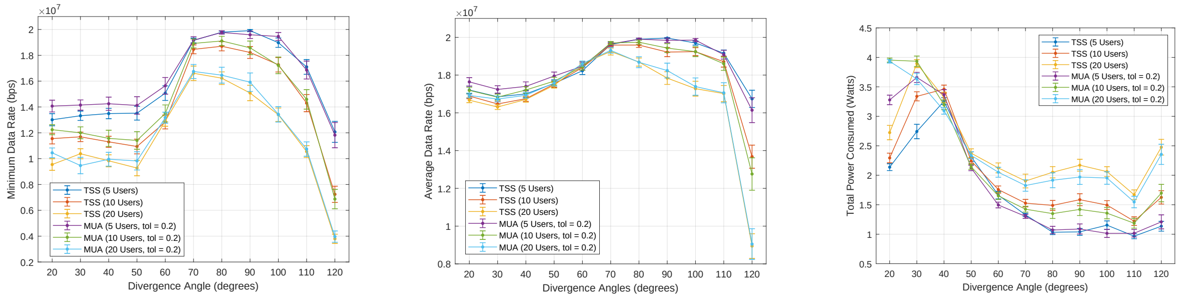
For a stronger analysis on the decays of average transmit powers per user with increasing number of users, we plot the $\frac{1}{U}$ function along with them for the cases of $\theta_d = 20^o$ and $\theta_d = 80^o$ in log scale. Although in both cases the power decays are slower than their respective $\frac{1}{U}$ functions, the decay for $\theta_d = 80^o$ is much slower than the decay for $\theta_d = 20^o$ (Figure 4.5). As we know, the possibility of interference is much higher for wider divergence angles as there is more possibility of having more than one user in an LED's beam. To counter this extra interference, more transmit power is needed to increase the signal portion of SINR and the average transmit power needed is also higher as a result.



(a) Minimum rate vs. Divergence Angle. $U = 5, 10, 20.$ and tolerance = 0.1

(b) Average Rate vs. Divergence Angle. $U = 5, 10, 20.$ and tolerance = 0.1

(c) Power Consumption vs. Divergence Angle. $U = 5, 10, 20.$ and tolerance = 0.1



(d) Minimum rate vs. Divergence Angle. $U = 5, 10, 20.$ and tolerance = 0.2

(e) Average Rate vs. Divergence Angle. $U = 5, 10, 20.$ and tolerance = 0.2

(f) Power Consumption vs. Divergence Angle. $U = 5, 10, 20.$ and tolerance = 0.2

Figure 4.6: System Analysis for Different LED Divergence Angles: A Comparative Study between TSS and MUA.

4.8.3 System Analysis for Different LED Divergence Angles: A Comparative Study between TSS and MUA

We also look at different divergence angles of the LEDs to see the effect on total power consumption, and minimum and average data rates. We look at this case for U = 5,10 and 20 and tolerance values of 0.1 and 0.2 (for MUA) to compare the data rate for different number of users and obtain total power consumption, minimum rate and average rate for θ_d from 20^o to 120^o in 10^o intervals which is shown in Figure 4.6. We observe that after a certain point (with divergence angle 60^o), less power is needed for maintaining the required data rate for the users. Also, the average data rate is increasing with angles more than 40^o, more specifically at 70^o. That indicates the improvement of the overall system performance if the system is designed with LEDs having divergence angle more than 60^o. However, with divergence angle greater than 90^o, the system performance reduces signifying that our algorithm works best with divergence angle in the range 60^o to 90^o.

CHAPTER 5: CONCLUSION

In this thesis, we have proposed two heuristic solutions that successfully minimize the total energy consumed by each LED on a hemispherical bulb, considering the LEDs' power budget maintaining certain illumination uniformity constraints, considering the users' QoS and the LED-user association. We used the Taylor series approximation to optimize the total power of the LEDs. We have successfully built a framework which corresponds to transmission power and rate optimization based on a certain lighting uniformity constraint. The main contributions that are addressed in this thesis include the use of each LED for transmission of data to a receiver as well as for increasing the illumination uniformity and formulation of the optimization problem that successfully minimized the total energy consumed taking into factor some important constraints.

The key insight of this thesis is that, by using low complexity heuristics, we were able to optimize the transmit power and also maintain a very good QoS while satisfying illumination uniformity requirements. Both the minimum data rate and the average data rate was satisfactorily high during the process and, in our simulation experiments, for divergence angles greater than 60^o, our system system performance showed remarkable improvement. From the simulations, we observed that our algorithm performs the best with 70^o divergence angle. Both the minimum and the average rate needed to maintain a good QoS is very high which we can see from the simulations. However, after that, a drop is noticed in both these cases which means that, as the divergence angle increases, interference between the users becomes more dominant as many of them come under the light cone of one LED. Also, the total power consumption of the system for the 70^o divergence angle is maintained at a low level which is the main objective of our optimization problem. Thus, we suggest using 70^o divergence angle to maintain a good throughput and all the while minimizing the total power used.

For future works, one should consider scenarios such as larger room size with users (as in airports or hospitals) and compare them. There is room for improving our heuristic algorithms to get closer to the optimum system performance. The changes in the behavior of our algorithms with changed system parameters, such as the size of the room, a very large number of users in the room and radius of transmitters and receivers are also worth exploring. Also, it will be interesting to see whether these parameters are related to each other and, if so, how. Since visible light communication is getting more attention and is in demand, our work will prove to be more fruitful in the designing of multi-element VLC architecture in the future.

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
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
WDM	Wavelength-division Multiplexing
Wi-Fi	Wireless Fidelity

APPENDIX B: LIST OF SYMBOLS

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)
r_r	Receiver radius (cm)
U	Number of users in the room
N	Number of sensors in the room
N_0	Additive White Gaussian Noise spectral density
B	Modulation Bandwidth
$\bar{I}_{min}$	Minimum Illumination Uniformity
$k_{i=1..l}$	Array of 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
h_{mu}	Communication Channel Model
A_u	User Photo Diode Area
φ_{mu}	Irradiance Angle
ϕ_{mu}	Incidence Angle
d_{mu}	Distance between LED m and user u
q	order of Lambertian emission
$Q_0(\varphi_{mu})$	Lambertian radiant intensity
$\varphi_{1/2}$	Transmitter semi-angle at half power
β	Total power received by user from its assigned LEDs
σ	Total power received at sensor
$\bar{R_u}$	Minimum rate expected for each IoT device

ϵ	Association binary variable between the LED and user

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