

# Resource Optimization in Visible Light Communication for Internet of Things

Sifat Ibne Mushfique\*

*Department of ECE*

*University of Central Florida*

Orlando, FL, USA

sifat.im@knights.ucf.edu

Akash Dey\*

*Department of ECE*

*University of Central Florida*

Orlando, FL, USA

akash@knights.ucf.edu

Ahmad Alsharoa

*Department of ECS*

*Virginia State University*

Petersburg, VA, USA

aalsharoa@vsu.edu

Murat Yuksel

*Department of ECE*

*University of Central Florida*

Orlando, FL, USA

Murat.Yuksel@ucf.edu

**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 paper, 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 a heuristic solution based on this approach. Finally, we illustrate the performance of our method via simulations.

**Index Terms**—Visible Light Communication; Illumination Uniformity; Joint Optimization;

## I. INTRODUCTION

VLC is a newly emerging technology that has a noteworthy potential of providing complementary wireless access at high speeds [1]. 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 [2]. Nowadays, multi-element architectures in VLC systems are gaining attention by optical wireless communications researchers [3]–[6]. 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 paper, 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 [7]–[11]. 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.

The challenge of improving data rate has been addressed in works relating to VLC architecture. In [12], 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 [13], where several convex optimization problems were derived and the best performance was found using an optimal symbol modulation power allocation scheme. [14] 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 [15], 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 [16], 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

\* These two authors have equal contribution in this paper.

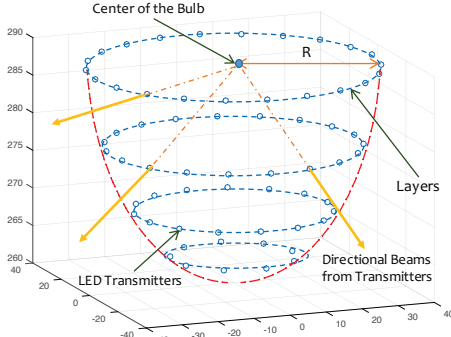


Fig. 1. Placement of transmitters in the multi-element bulb with 4 layers.

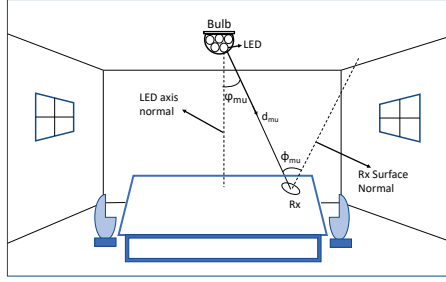


Fig. 2. Transmitters and Receivers in a VLC channel model.

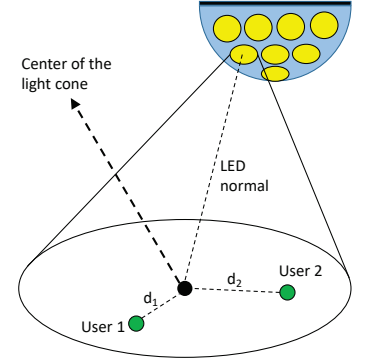


Fig. 3. Nearest User Assignment Approach in case of interference for an LED on the bulb.

VLC link. In another work [17], 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 paper 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.

The main contributions are summarized as follows:

- Investigating a hemispherical 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 solution and analyze our results.

## II. SYSTEM MODEL

We consider a single hemispherical bulb for an indoor VLC system consisting of  $M$  LEDs serving  $U$  users using power of

$P_m$  Watt,  $\forall m = 1, \dots, M$ . 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 Fig. 1. 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 and facilitate communication in the room.

We consider mobile users which are equipped with a single photo-detector (PD) or a collection of PDs, whichever is appropriate. These users also use legacy RF transmitters so that they can upload to their corresponding LEDs. They receive the download data from the LED(s) with which they are in LOS alignment.

### A. Assumptions

We make the following assumptions in this study:

- Inside the room, each mobile user can have 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.
- 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.

### B. LED-User Association

We propose to use a binary variable  $\epsilon_{mu}$  that indicates the association between LED  $m$  and user  $u$  which is given as follows:

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

$$\sum_{u=1}^U \epsilon_{mu} \leq 1, \forall m. \quad (2)$$

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 (2).

### C. Channel Model

In our channel model, the multi-path propagation due to the reflections are neglected and only LOS channel model is considered. So, the downlink communication channel model between LED  $m$  and user  $u$  can be expressed as [18]:

$$h_{mu} = \begin{cases} \frac{A_u}{d_{mu}^2} Q_0(\varphi_{mu}) \cos(\phi_{mu}) & , 0 \leq \phi_{mu} \leq \phi_c \\ 0 & , \phi_{mu} \geq \phi_c \end{cases} \quad (3)$$

where  $A_u$  is the user PD area and  $d_{mu}$  is the distance between LED  $m$  and user  $u$ .  $\varphi_{mu}$  and  $\phi_{mu}$  are the irradiance and incidence angles respectively (shown in Fig. 2).  $\phi_c$  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

$$Q_0(\varphi_{mu}) = \frac{(q+1)}{2\pi} \cos^q(\varphi_{mu}), \quad (4)$$

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.

### D. Signal-to-Interference and Noise Ratio (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 [19]

$$\Gamma_u = \frac{\beta_u^2}{N_0 B + \sum_{\substack{k=1 \\ k \neq u}}^U \beta_k^2} \quad (5)$$

where  $\beta_i = \sum_{m=1}^M \epsilon_{mi} h_{mi} P_m$ .  $\beta_i$ ,  $B$  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.

### E. Illumination Uniformity

An important factor to be considered in VLC is illumination intensity distribution across the room floor. Specifically, the illumination uniformity,  $\vartheta$ , can be defined as the ratio between the minimum and the average illumination intensity among all  $N$  sensors and is given as [20]

$$\vartheta = \frac{\min(\sigma_n)}{\frac{1}{N} \sum_{n=1}^N \sigma_n} \quad (6)$$

where  $\sigma_n = \sum_{m=1}^M \alpha_0 P_m h_{mn}$  is the received total power at sensor  $n$ .  $\alpha_0$  is the luminous efficiency that depends on the LED color wavelength, e.g.  $\alpha_0 = 60$  lumen/watt for white LED [21].  $\min(\cdot)$  is the minimum function.

## III. 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:

$$(\mathbf{P0}): \text{minimize}_{\epsilon_{mu} \in \{0,1\}, P_m \geq 0} \sum_{m=1}^M P_m \quad (7)$$

subject to (2) and:

$$P_m \leq \bar{P}, \quad \forall m, \quad (8)$$

$$\vartheta \geq \bar{I}_{\min}, \quad (9)$$

$$B \log_2(1 + \Gamma_u) \geq \bar{R}_u, \quad \forall u. \quad (10)$$

where (2) and (8) represent the LEDs' power budget and association constraints. (9) 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 [20]. Finally, (10) represents the minimum rate QoS, where  $\bar{R}_u$  is the minimum rate expected for each IoT device.

## IV. PROBLEM SOLUTION

The formulated optimization problem given in (7)-(10) is a non-convex and mixed-integer non-linear programming problem. So, we propose a low complexity two stages heuristic solution. In the first stage, we propose a 'Nearest User Assignment' approach to determine the value of  $\epsilon_{mu}$ . Then, given the LED-user associations, we optimize the LEDs' power allocations in the second stage.

### A. Low Complexity Two-Stage Solution (TSS)

Optimizing  $\epsilon_{mu}$  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-Stage Solution (TSS) as a practical and efficient solution with less complexity.

In order to simplify the problem **P0**, we propose to optimize  $\epsilon_{mu}, \forall m, u$  first, then use  $\epsilon_{mu}$  values to optimize  $P_m$ . To do this, we firstly propose to use a heuristic 'Nearest User Assignment' approach to determine the value of  $\epsilon_{mu}$ . 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.

1) *LED-User Association*: In our 'Nearest User Assignment' for obtaining the value of LED-User association matrix  $\epsilon_{mu}$ , we propose to find the user which is most aligned for each LED  $m$ . That is, for each LED  $m$  into consideration, we firstly, find the light cone of LED  $m$  (Fig. 3). 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

**Algorithm 1** Algorithm for TSS

---

```

1: Let  $\epsilon_{mu} = 0$  for  $m = 1..M$  and  $u = 1..U$ .
2: Let  $d \rightarrow 0, d_{min} \rightarrow 0, n \rightarrow 0$ 
3: for  $m = 1$  to  $M$  do
4:   for  $u = 1$  to  $U$  do
5:     if user  $u$  is inside the cone of LED  $m$  then
6:       if  $d == 0$  then
7:          $d \rightarrow$  distance between center of the cone and user  $u$ 
8:          $d_{min} \rightarrow d$ 
9:          $n \rightarrow u$ 
10:      end if
11:    else
12:       $d \rightarrow$  distance between center of the cone and user  $u$ 
13:      if  $d < d_{min}$  then
14:         $d_{min} \rightarrow d$ 
15:         $n \rightarrow u$ 
16:      end if
17:    end if
18:  end for
19:  if  $n \neq 0$  then
20:     $\epsilon_{mn} \rightarrow 1$ 
21:     $n \rightarrow 0$ 
22:  end if
23: end for
24: Select feasible initial values  $P_m^{(0)}$ .
25: repeat
26:    $r=1$ .
27:   Solve the optimization problem with calculated  $\epsilon_{mu}$  using
   the interior-point method to determine the new approximated
   solution  $P_m^{(r)}$ .
28: until Convergence ( $|\chi^{(r+1)} - \chi^{(r)}| \leq \xi$ ).

```

---

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.

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

$$\begin{aligned}
 \text{(P1): } & \underset{P_m \geq 0}{\text{minimize}} \quad \sum_{m=1}^M P_m \\
 & \text{subject to (8), (9) and (10).}
 \end{aligned} \tag{11}$$

Notice that in **P1**, the objective function is a convex function and all constraints are convex functions except (10). This constraint is neither concave nor convex with respect to the LED transmit power  $P_m$ . Hence, the goal is to convert constraint (10) into a convex one in order to solve the problem efficiently. Therefore, constraint (10) can be re-written as

$$\sqrt{C_u \left( N_0 B + \sum_{\substack{k=1 \\ k \neq u}}^U \beta_k^2 \right)} \leq \beta_u \tag{12}$$

where  $C_u = 2^{(\bar{R}_u/B)} - 1$ . It can be seen that the RHS of (12) is a linear function, thus we only need to approximate the LHS. Therefore, we propose to use same first order Taylor

expansion approximation in order to convert the LHS of (12) into a convex one as the following:

$$\frac{\sqrt{C_u N_0 B + C_u \sum_{\substack{k=1 \\ k \neq u}}^U (\beta_k(r))^2} + \left[ C_u \sum_{\substack{k=1 \\ k \neq u}}^U \epsilon_{mk} h_{mk} \beta_k(r) \right] (P_m - P_m(r))}{\sqrt{C_u N_0 B + C_u \sum_{\substack{k=1 \\ k \neq u}}^U (\beta_k(r))^2}} \leq \beta_u \tag{13}$$

where  $\beta_k(r) = \sum_{m=1}^M \epsilon_{mk} h_{mk} P_m(r)$ . After the approximation, the optimization problem **P1** becomes a convex optimization problem and it can be solved using standard convex optimization techniques. Finally, we propose to use SCA approach to find the best Taylor series approximation (in the end of Algorithm 1).

## V. SIMULATION RESULTS

In order to understand the performance of our heuristics, we perform extensive simulations in MATLAB. Table I 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  $\times$  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.

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  $\bar{I}_{min} = 0.7$  [20] 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. 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 for different divergence angles are shown in Figure 4(a) and 4(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

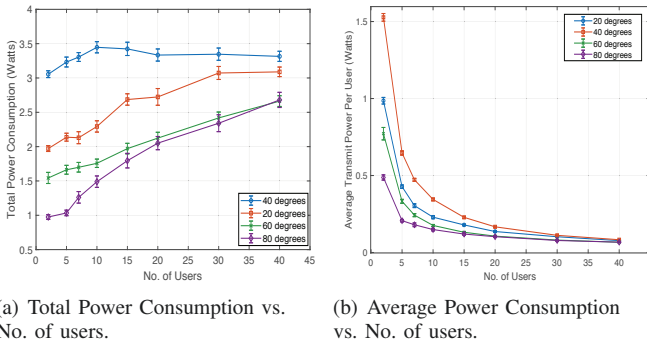


Fig. 4. Effect on Power Consumption of the System.

minimum data rate a user gets and the illumination uniformity constraint.

TABLE I  
SIMULATION PARAMETERS

Parameter	Value
Room Size	6 m x 6 m x 3 m
Radius of the transmitter, $r_t$	1.5 cm
Radius of the receiver, $r_r$	3.75 cm
Divergence angle of the LEDs, $\theta_d$	40°
No. of users, $U$	2-40
No. of sensors, $N$	100
AWGN spectral density, $N_0$	$2.5 \times 10^{-20}$ W / Hz
Modulation bandwidth, $B$	20 MHz
Minimum uniformity, $\bar{I}_{min}$	0.7

The average transmit power spent for each user (Figure 4(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.

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  $\theta_d = 20^\circ$  and  $\theta_d = 80^\circ$  in log scale. Although in both cases the power decays are slower than their respective  $\frac{1}{U}$  functions, the decay for  $\theta_d = 80^\circ$  is much slower than the decay for  $\theta_d = 20^\circ$  (Figure 6). 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.

### B. 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

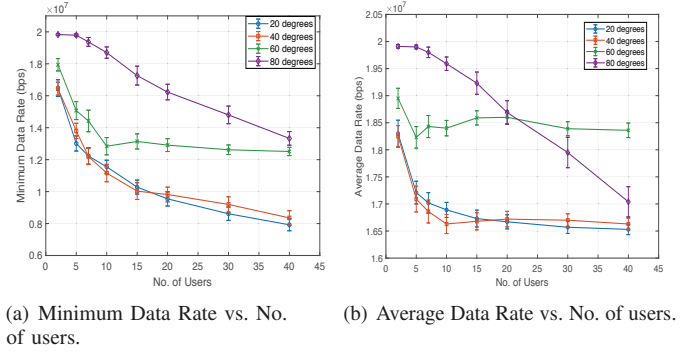


Fig. 5. Effect on User Data Rate of the System.

average throughput of the system with respect to the number of users, which is demonstrated in Figure 5(a) and 5(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 trade-off between the interference caused by large divergence angles and the high data rate opportunities when the number of users is low. We observe that  $80^\circ$  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.

### C. System Analysis for different LED Divergence Angles

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 to compare the data rate for different number of users and obtain total power consumption, minimum rate and average rate for  $\theta_d$  from  $20^\circ$  to  $120^\circ$  in  $10^\circ$  intervals which is shown in Figure 7. We observe that after a certain point (with divergence angle  $60^\circ$ ), less power is needed for maintaining the required data rate for the users. Also, the average data rate is increasing with angles more than  $40^\circ$ , more specifically at  $70^\circ$ . That indicates the improvement of the overall system performance if the system is designed with LEDs having divergence angle more than  $60^\circ$ . However, with divergence angle greater than  $90^\circ$ , the system performance reduces signifying that our algorithm works best with divergence angle in the range  $60^\circ$  to  $90^\circ$ .

## VI. SUMMARY AND FUTURE WORK

In this paper, we have proposed an optimization problem that successfully minimizes the total energy consumed by each LED bulb considering the LED's power budget maintaining certain illumination uniformity constraints, considering the users' QoS and the LED-user association and used the Taylor series approximation to optimize the total power of the LEDs. We have successfully built a framework in this paper which corresponds to transmission power and rate optimization based on a certain lighting constraints. The main contributions that

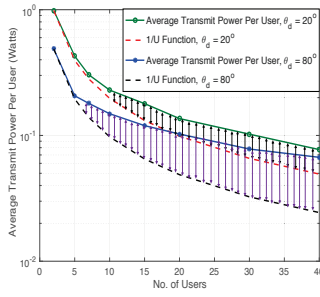
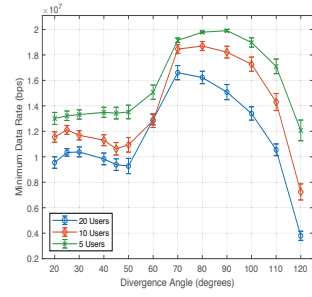
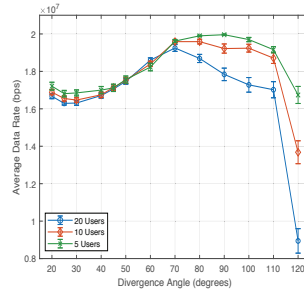


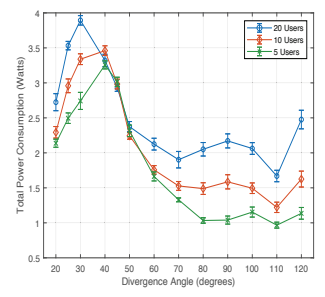
Fig. 6. Average Transmit Power Decay Per User for  $\theta_d = 20^\circ$  and  $\theta_d = 80^\circ$ .



(a) Minimum rate vs. Divergence Angle.  $U = 10$ .



(b) Average Rate vs. Divergence Angle.  $U = 10$ .



(c) Power Consumption vs. Divergence Angle.  $U = 10$ .

Fig. 7. System Analysis for different LED Divergence Angles.

are addressed in this paper 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 while taking some important constraints into consideration.

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 algorithm to get closer to the optimum system performance. The changes in the behavior of our algorithm 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.

## VII. ACKNOWLEDGMENT

This work was supported in part by NSF awards 1836741 and 1663764.

## REFERENCES

- [1] Z. Li, C. Zhang, D. Sun, H. Yang, and J. Song, "A real-time high-speed visible light communication system based on rgb-leds," in *2017 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. IEEE, pp. 1–4.
- [2] J. Chapin and W. Lehr, "Mobile broadband growth, spectrum scarcity, and sustainable competition," TPRC, 2011.
- [3] P. Palathingal, M. Yuksel, I. Guvenc, and N. Pala, "A multi-element VLC architecture for high spatial reuse," in *Proc. of the 2nd International Workshop on Visible Light Communications Systems (VLCS), Paris, France*. New York, NY, USA: ACM, Sept. 2015, pp. 21–26.
- [4] S. I. Mushfique and M. Yuksel, "Optimal multi-element VLC bulb design with power and lighting quality constraints," in *Proc. of the 3rd ACM Workshop on Visible Light Communication Systems (VLCS), New York, USA*, 2016, pp. 7–12.
- [5] M. S. Mossaad, S. Hranilovic, and L. Lampe, "Visible light communications using OFDM and multiple LEDs," *IEEE Transactions on Communications*, vol. 63, no. 11, pp. 4304–4313, 2015.
- [6] S. I. Mushfique, P. Palathingal, Y. S. Eroglu, M. Yuksel, I. Guvenc, and N. Pala, "A software-defined multi-element VLC architecture," *IEEE Communications Magazine*, vol. 56, no. 2, pp. 196–203, 2018.
- [7] B. Bai, Q. He, Z. Xu, and Y. Fan, "The color shift key modulation with non-uniform signaling for visible light communication," in *2012 1st IEEE International Conference on Communications in China Workshops (ICCC)*. IEEE, pp. 37–42.
- [8] R. J. Drost and B. M. Sadler, "Constellation design for color-shift keying using billiards algorithms," in *2010 IEEE Globecom Workshops*. IEEE, pp. 980–984.
- [9] E. Monteiro and S. Hranilovic, "Constellation design for color-shift keying using interior point methods," in *2012 IEEE Globecom Workshops*. IEEE, pp. 1224–1228.
- [10] R. You and J. M. Kahn, "Average power reduction techniques for multiple-subcarrier intensity-modulated optical signals," in *2000 IEEE International Conference on Communications*, vol. 3. IEEE, pp. 1620–1627.
- [11] Q. Gao, J. H. Manton, G. Chen, and Y. Hua, "Constellation design for a multicarrier optical wireless communication channel," *IEEE Transactions on Communications*, vol. 62, no. 1, pp. 214–225, 2014.
- [12] D. Bykhovsky and S. Arnon, "Multiple access resource allocation in visible light communication systems," *Journal of Lightwave Technology*, vol. 32, pp. 1594–1600, 2014.
- [13] C. Gong, S. Li, Q. Gao, and Z. Xu, "Power and rate optimization for visible light communication system with lighting constraints," *IEEE transactions on signal processing*, vol. 63, no. 16, pp. 4245–4256, 2015.
- [14] Z. Yao, H. Tian, and B. Fan, "Joint illumination-communication optimization in visible light communication," in *Proceedings of the 2nd International Workshop on Visible Light Communications Systems*. ACM, 2015, pp. 15–20.
- [15] J. Li, A. Liu, G. Shen, L. Li, C. Sun, and F. Zhao, "Retro-VLC: enabling battery-free duplex visible light communication for mobile and iot applications," in *Proceedings of the 16th International Workshop on Mobile Computing Systems and Applications*. ACM, 2015, pp. 21–26.
- [16] C.-W. Chen, W.-C. Wang, J.-T. Wu, H.-Y. Chen, K. Liang, L.-Y. Wei, Y. Hsu, C.-W. Hsu, C.-W. Chow, C.-H. Yeh *et al.*, "Visible light communications for the implementation of internet-of-things," *Optical Engineering*, vol. 55, no. 6, p. 060501, 2016.
- [17] K. Warmerdam, A. Pandharipande, and D. Caicedo, "Connectivity in iot indoor lighting systems with visible light communications," in *IEEE Online Conference on Green Communications (OnlineGreenComm)*. IEEE, 2015, pp. 47–52.
- [18] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical wireless communications: system and channel modelling with Matlab®*. CRC press, 2017.
- [19] Y. S. Eroglu, I. Guvenç, A. Şahin, Y. Yapıcı, N. Pala, and M. Yuksel, "Multi-element VLC networks: LED assignment, power control, and optimum combining," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 1, pp. 121–135, 2017.
- [20] I. Standardization, "Lighting for work places part 1: Indoor (ISO: 8995-1: 2002 E)," *International Commission on illumination, Vienna*.
- [21] B. music Netherlands. (2017) Lite gear LED PAR 30 7w lamp WW Edison 45gn. [Online]. Available: <https://www.bax-shop.nl/producten-uit-assortiment/lite-gear-led-par-30-7w-lamp-ww-edison-45g>