Optimal Multi-Element VLC Bulb Design with Power and Lighting Quality Constraints

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ABSTRACT

In the modern era of radio frequency (RF) spectrum crunch, visible light communication (VLC) offers a promising alternative. Thanks to its unlicensed and large bandwidth, VLC technology can deliver high throughput, energy efficient and low cost data communications. In this paper, we consider a VLC architecture with a novel multi-element hemispherical bulb, which can transmit multiple data streams over multiple LED boards. Simulations considering various VLC transmitter configurations and topologies show that good link quality and high spatial reuse can be maintained in typical indoor communication scenarios. We develop the characteristics of an optimum multi-element bulb design in terms of both illumination and communication under various constraints.

1. INTRODUCTION

The need for high speed wireless access is becoming more pronounced. Several devices in a room download high definition videos these days. Legacy WiFi speeds will not be sufficient when these speed-hungry wireless devices go alongside with many Internet-of-Things (IoT) devices being envisioned in a room or building. We need much more wireless capacity, reaching gigabit-per-second download speeds.

LEDs are becoming more available and solid-state circuitry to drive the LEDs is low in cost. As LED adoption is on a rise and it is expected that most of the illumination will be provided by LEDs by the next 10-15 years, VLC is going to be one of the main sources of communication for the near future. Lighting is transitioning to solid-state lighting technologies and visible light is offering an excellent opportunity for combining both lighting and mobile wireless communications, particularly at indoor settings [10, 1]. Recent work showed the potential for VLC using LEDs in civilian indoor settings with sizable attention to issues on access [7, 13, 4] and co-existence with legacy WiFi [11]. Most of the work has focused on diffuse optics [15] and diversity combining [12, 3] for downloading a data stream to devices in a room. At the modulation level, OFDM [6, 17] and MIMO [8, 2] techniques were explored to increase the VLC link capacities.

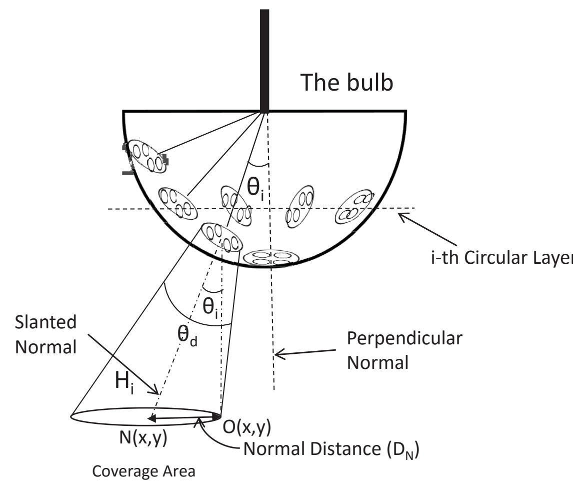

Figure 1: Multi-element bulb configuration.

There have been good reasons for using both small and large values of divergence angles. The typical assumption has been to use LEDs with large divergence angles – mainly for the goal of keeping good quality lighting. Large divergence angles result in smaller deviation in the illuminance across a room floor. Yet, reducing LED divergence angles can increase the spatial reuse and attain better communication performance and high SNRs. Little effort went into exploring the trade-off between these conflicting goals of illumination (i.e., high and smooth lighting) and communication (i.e., high SNR and high aggregate download rates for multiple devices).

In this paper, we explore this trade-off by considering multi-element bulbs covered with many LEDs with relatively narrow divergence angles. The bulb is supported with an LOS alignment protocol [9] to steer the data streams to individual or group of LED boards corresponding to a particular receiver in the room. We formulate the problem of placing the LED boards on the bulb as an optimization and find solutions under various constraints such as power and cost.

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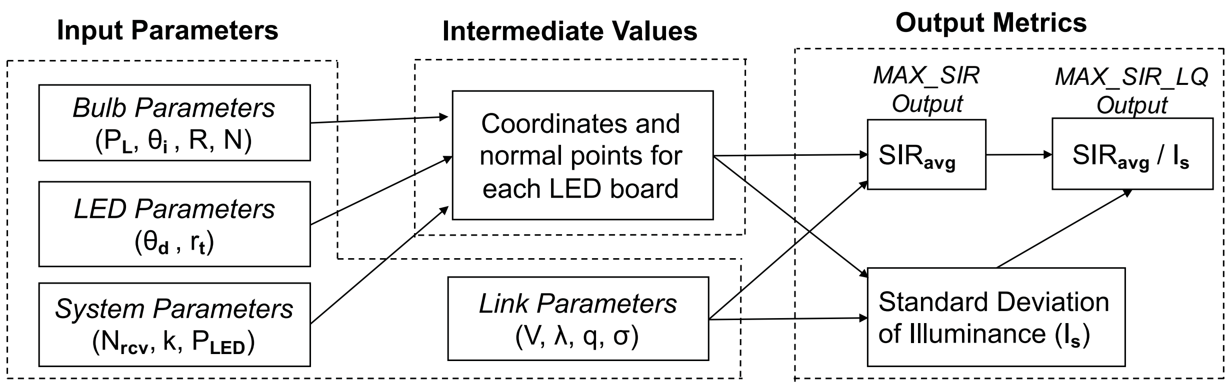


Figure 2: Flow diagram of the optimization.

2. SYSTEM MODEL

In contrast to the conventional design of LED transmitters with large divergence angles, our model tries to use relatively narrow divergence angles and still perform a satisfactory amount of illumination by using a large number of LED boards on a *bulb*. This bulb is a hemispherical structure, which acts as an access point inside the room. There will be several transmitters (LED boards)[1] on the bulb to provide concurrent downloads to multiple receivers. A transmitter has a collection of LEDs which will be designated to transmit a particular data stream.

Since the bulb is hemispherical in shape, the LED boards on the bulb will be placed in circular layers as shown in Fig. 1. All LEDs on the same transmitter are modulated by the same signal. The multi-element design for the bulb's spherical structure along with highly directional LEDs allows higher spatial reuse in communication. The receiver units can be mobile and they will need to be equipped with a photo detector (PD). Depending upon the number of receivers present in the room, the multi-element bulb maintains track of which receiver is best aligned with which transmitter(s). For this, establishing an optical link by associating transmitter(s) to a receiver is needed, and the optical link with mobility of the receiver across the room also needs to be maintained. There will be a controller device, which will partition the transmitters in a way they can best serve the receivers, and cease the optical link when a receiver becomes off-line. More details on this hybrid architecture for multi-element VLC architecture were published in our previous work [9].

2.1 Optimization Objective

The primary target of this work is to optimize the Signal-to-Interference Ratio (SIR) of the system. However, since the illumination quality is also another crucial part of a VLC system, we have to keep that part in consideration as well. Thus, the optimization objective is to maximize SIR as well as the illumination quality in a given room. We explore the bulb designs for optimizing these objectives while considering practical constraints such as aggregate power consumption and cost of the bulb.

First, we will explore optimum bulb configurations for a particular number of layers by varying the number of LED boards in each layer to see which combination produces the maximum SIR under an aggregate power constraint. We will also use the divergence angle of the LEDs as another variable parameter for the optimization problem. Next, we will update the optimization problem by adding a constraint on the illumination quality, which is defined by the standard deviation of luminance on the room floor. We will, then, compare the two results to analyze the effect of the illumination requirement on the overall optimization problem. The flow diagram with input parameters, intermediate values to calculate the SNR and the illumination variation, and the output parameters are shown in Figure 2. Before we give the detailed formulations of the problems, we will list and categorize the system parameters next.

2.2 Parameters

We will mainly optimize the multi-element bulb design with respect to the *divergence angle of the LEDs* (θ_d) and the *number of LED Boards in each layer* (k_1, k_2, ... k_i). All the needed parameters for the model are described in Tables 1-4 below:

Table 1: Link Parameters

Parameter Name	Symbol
Visibility (km)	V
Optical signal wavelength (nm)	λ
Coefficient of absorption and scattering	σ

Table 2: LED Parameters

Parameter Name	Symbol
Divergence angle (radian)	θ_d
Transmitter radius (cm)	r_t

2.3 Link Model and SIR Calculation

We assume that the transmitters on the bulb are grouped into sections so that each section is associated with a particular receiver. For example, if there are two receivers in the room, the LED boards (or transmitters) are grouped into two sections each corresponding to one of the receivers. We assume that the transmitters are grouped such that they are associated with the receiver closest to (or in the best LOS alignment with) their Lambertian beam. Given this, the

[1]We will use the words "transmitter" and "LED board" interchangeably throughout the paper.

Table 3: Bulb Structure Parameters

Parameter Name	Symbol
Radius of the bulb (cm)	R
Layer i's angle with the normal (radian)	θ_i
Vector between ith LED board on the bulb and its normal point on the floor	$\overrightarrow{LP_i}$
Vector of the central LED facing down	$\overrightarrow{LP_0}$
Power on the normal ith LED board (W)	$P_L(i)$

Table 4: System Parameters

Parameter Name	Symbol
Receiver radius (cm)	r_r
Slanted normal length of LED board i (cm)	H_i
Number of receivers in the room	N_{rcv}
Array of LED board count in each layer	$k_{i=1..l}$
Source power of each LED board (W)	P_{LED}
Total power generated by the bulb (W)	P_{total}

normal component of the power generated by LED board i will be [14]:

$$P_L(i) = P_{LED} + 10\log(e^{-\sigma H_i}) + 20\log\left(\frac{r_r}{r_t + 200H_i\theta_i}\right) \quad (1)$$

where P_{LED} is the source power of each LED Board, σ is the atmospheric absorption and scattering coefficient [5] with V = 0.5km and λ = 600nm. And, after the grouping of the transmitters is complete, if a receiver i is located at section j and the number of LED boards in section j is N_j, then the average signal received by that receiver from that section is:

$$S_{ij} = \sum_{m=1}^{N_j} P_L(m)\cos\phi_m \quad (2)$$

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

$$S_{ik} = \sum_{m=1}^{N_k} P_L(m)\cos\phi_m \quad (3)$$

where P_L is the received power at the normal of the layer of the respective LED boards of that particular partition. Further, the angle between the LED board's normal and the normal of the receiver's field-of-view (FOV), ϕ_m, is defined as:

$$\phi_m \Longrightarrow \tan^{-1}\left(\frac{|\overrightarrow{RP} \times \overrightarrow{LP}|}{\overrightarrow{RP} \cdot \overrightarrow{LP}}\right) \quad (4)$$

where $\overrightarrow{RP}$ is the distance vector from the origin point of the LED board to the receiver point in the X-Y plane, and $\overrightarrow{LP}$ is the LED vector for that particular LED board. Essentially, ϕ_m is the angle between $\overrightarrow{RP}$ and $\overrightarrow{LP}$ in Figure 3. Then, for receiver j, the average SIR is

$$SIR_j = \frac{S_{ij}}{\frac{1}{N_s - 1}\sum_{k=1..N_s, k\neq j} S_{ik}} \quad (5)$$

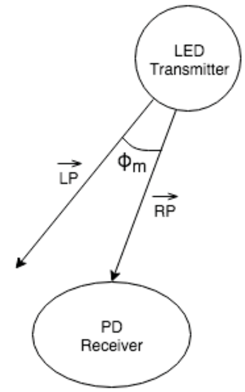


Figure 3: Transmitter and receiver angles.

Finally, the average SIR of the system will be:

$$SIR_{avg} = \frac{1}{N_{rcv}}\sum_{j=1}^{N_{rcv}} SIR_j \quad (6)$$

So, in our optimization, our main objective is to maximize this average SIR with minimum costs. The result of the optimization will be the bulb configuration values (e.g., bulb radius, number of LED boards, divergence angle of LEDs, and radius of the transmitters) that maximize SIR under power and cost constraints.

3. MAX_SIR: MAXIMUM SIR PROBLEM

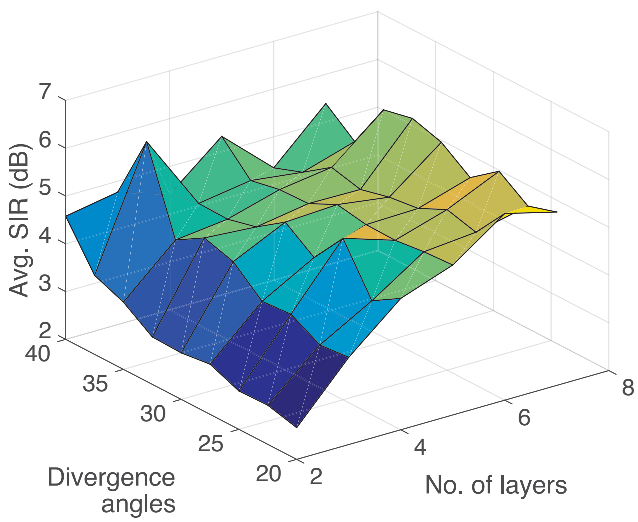
We first formulate the problem of finding maximum SIR under a power constraint, i.e., the MAX_SIR problem. At a high level, MAX_SIR aims to find the best placement of LED boards on each layer of the bulb and the best divergence angle for the LEDs. We detail the variable and fixed parameters below:

Variable Parameters:

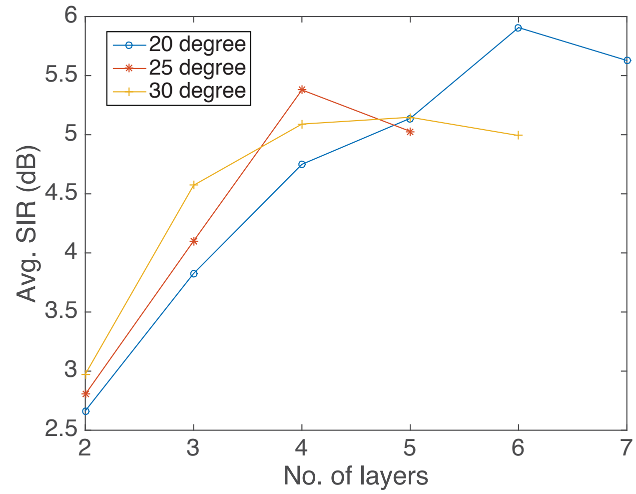
- k_i, *Number of Transmitters in Layer i:* Intuitively, given a fixed number of LED boards, they can be placed in layers in many different ways, depending on the size of the LED boards and the bulb radius. Considering all the parameters involved, we vary the number of LED boards per layer by adjusting the spacing between them on each layer.
- θ_d, *Divergence Angle of LEDs:* Divergence angle of the LED is one of the key factors in the source power and illumination quality. While large divergence angles yield better lighting (small variance of the illumination across the room floor), narrow ones are beneficient for increasing the spatial reuse and higher SIR. Thus, we try different divergence angles (in degrees) to find the configurations yielding maximum SIR.

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

- *Room Size:* We are assuming a fixed room dimension of 6m x 6m x 3m for width, length and height, respectively.
- *R, Radius of the Hemispherical Bulb:* 40cm
- r_t, *Radius of the LED Board/Transmitter:* 3.5cm



(a) SIR against divergence angle.



(b) SIR against number of layers.

Figure 4: Nonlinearity of the objective function: SIR against divergence angle and number of layers.

- *Number of Layers:* Depending on R and r_t, different number of layers are possible in the hemispherical bulb. Given R and r_t, we calculate the maximum possible number of layers in the bulb. We are considering the minimum number of layers to be 3. For a specific number of layers between this minimum and maximum value, we are going to vary the number of LED boards in each layer to find the optimum layering combination.

Now, we formulate the MAX_SIR problem as follows:

$$\max_{k,\theta_d} \quad SIR_{avg}(k, \theta_d) \tag{7}$$

subject to

$$2 \leq k_i \leq K_i \tag{8}$$

$$P_{LED} \sum_{i=1}^{l} k_i \leq P_{total} \tag{9}$$

$$l \leq L \tag{10}$$

where l is the number of layers in the bulb, L is the maximum possible number of layers, and K_i is the maximum possible number of LED boards in the i-th layer. Further, $k = k_1, k_2, ..., k_L$ is the array of the number of LED boards in each layer. P_{LED} is the source power of a single LED board and P_{total} in (9) is the total power constraint, which we assume to be 25 Watts unless otherwise said.

3.1 Placement of Layers and LED Boards

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

$$\theta_{LB} = 2\sin^{-1}\left(\frac{r_t}{R}\right) \tag{11}$$

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

$$N = \left\lfloor \frac{90^o}{\theta_{LB}} \right\rfloor \tag{12}$$

where θ_{LB} is measured in degrees.

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

$$r_{li} = R\cos\theta_i \tag{13}$$

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

$$\theta_{li} = 2\sin^{-1}\left(\frac{r_t}{r_{li}}\right) \tag{14}$$

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

$$K_i = \left\lfloor \frac{360^o}{\theta_{li}} \right\rfloor \tag{15}$$

where θ_{li} is measured in degrees. While searching for the best bulb configuration, we will vary the number of LEDs in each layer (i.e., k_i) up to these maximum values (i.e., K_i) for their corresponding layer. This is detailed further in Section 5.

3.2 Objective Function, SIR_{avg}

In addition to k and θ_d, the objective SIR_{avg} is a function of several other constants. To calculate the normal points and angles at which the LED boards face the room, the room size, R, and r_t are necessary. Further, for Lambertian propagation calculations, P_{LED}, V, λ, and q are needed. The description of these constants are explained in Tables 1-3.

4. MAX_SIR_LQ: MAXIMUM SIR W/ LIGHTING QUALITY (LQ) CONSTRAINT

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

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

$$\max_{k,\theta_d} \quad SIR_{avg}(k,\theta_d)/I_s \tag{16}$$

subject to

$$2 \le k_i \le K_i, \quad P_{LED}\sum_{i=1}^{l} k_i \le P_{total}, \quad l \le L \tag{17}$$

$$0 < I_s \le I_s^{max} \tag{18}$$

where I_s^{max} is the maximum allowed I_s. The updated objective (16) and the additional constraint (18) significantly change the dimension and complexity of the problem, as there might be designs which can produce a better SIR but an uneven lighting. For simplicity, we are using $I_s^{max} = 5$, which could be varied for better exploration in future studies.

5. PERFORMANCE EVALUATION

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

Each time SIR_{avg} is called, the optical power received at each coordinate of the room floor needs to be calculated in order to calculate I_s, the standard deviation of illumination intensity across the floor. To reduce the computation time, we have chosen random points on the floor and calculated I_s for those random coordinates, and then iteratively added more random points to the previous ones until the I_s value converges.

Further, upon each call to SIR_{avg}, two random points on the room floor are chosen for receivers, which are assumed to have a radius of 3.75cm and be facing upwards. We then use these receiver locations to calculate the SIR for the two receivers. We repeated this random selection of locations for pairs of receivers 100 times to calculate the average SIR.

5.1 Heuristic Design for Nonlinearity

To observe the overall effects and the complexity of the search space, we calculated SIR_{avg} against the divergence angle and the number of layers – placing as many LED boards as possible in each layer. Both the line plot and the surface plot are shown in Figure 4a and Figure 4b. The line plot is done for 3 divergence angles, and as expected,

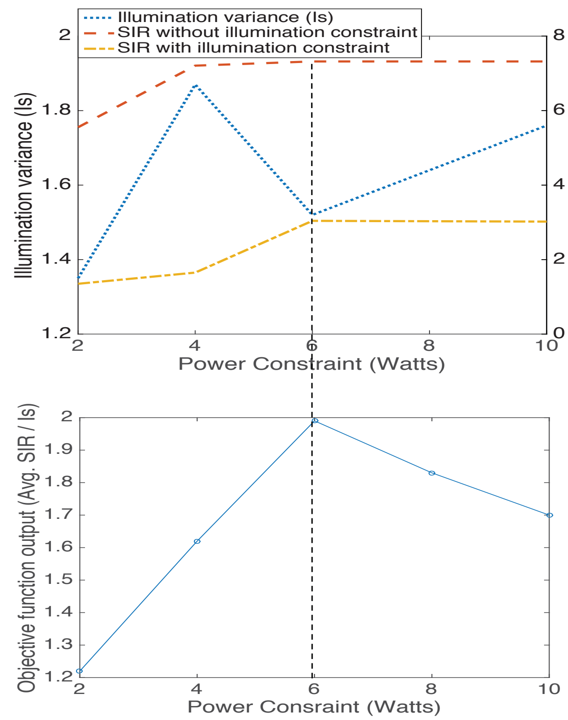


Figure 5: Comparison of SIR with and without the illumination costraint: MAX_SNR_LQ finds a good balance between the SIR and Lighting Quality.

Table 5: Best results for MAX_SIR and MAX_SIR_LQ

Objective	l	k_1	k_2	k_3	θ_d
MAX_SIR	2	19	2	–	39.5^o
	3	16	26	2	47.2^o
MAX_SIR_LQ	2	6	28	–	16^o

in all the cases after a certain point, the average SIR decreases, which indicates non-linearity, as it increases in the beginning. From the surface plot we can also observe the nonlinear nature of the problem as several local maxima and minima can be spotted from the surface.

Since the search space is pretty large, we followed a heuristic similar to Recursive Random Search [16]. In particular, we started the optimizer at 20 different random points and took the best local maxima resulting from these searches. Then we centered the search space around the best local maxima and shrunk it by halving each parameter range. We repeated this step until majority of the local maxima pointed to the same result, which we assumed to be the best result.

5.2 Results

We ran our heuristic to solve various cases of MAX_SIR and MAX_SIR_LQ. Table 5 shows the results for 2 or 3 layers cases. We observe that, in MAX_SIR, the best bulb configuration has much fewer LED boards in the higher layer. This is expected since the normal points for the LED boards in the higher layers goes outside of the boundary of the room floor, so they contribute much less towards the SIR.

When lighting quality is considered, in MAX_SIR_LQ, the best bulb configuration places more LED boards to the higher layers with the goal of attaining even lighting across the floor. Putting more LED boards to bottom layers would result in a high SIR spot in the center of the room but have dark areas towards to corners. As expected, MAX_SIR_LQ balances this tradeoff.

We also looked at the effect of the power constraints on the results. We varied P_{total} from 2 to 10 Watts, as the maximum power consumption possible for 2 layers for these particular bulb parameters is 10 Watts. Figure 5 shows a rise at the beginning, but as expected, the best achievable SIR saturates as the power constraint increases. We can clearly observe that the optimum SIR is significantly lower in MAX_SIR_LQ, again confirming our expectations. Also, as we have discussed earlier, the objective of MAX_SIR_LQ is to find a good balance between the SIR and the lighting quality. This is also clearly evident from Figure 5. In the bottom part of the figure, we can see that the maximum value of the objective function is found for a power constraint of about 6 watts. And in the top part, though the optimum SNR value is nearly the same from 4 to 10 watts, but the illumination variance starts to rise from 6 watts (which resembles to deteriorated quality of lighting), and the value of objective function of MAX_SIR_LQ starts to fall from the same point. So, MAX_SIR_LQ indeed finds a fine balance between the SIR and the quality of lighting.

To observe the more interactions between the power constraint and the number of layers, more layers must be considered similar to the results in Figure 4a and Figure 4b.

6. CONCLUSION

We have introduced a framework to optimize a multi-element bulb design for both illumination and communication quality of VLC in a room. The framework enables optimizing the placement of LED boards/transmitters on the bulb for maximizing the signal-to-interference ratio (SIR) while respecting the evenness of the lighting on the room floor. We also considered a power constraint on the bulb and observed that maximum SIR saturates as the power constraint as well as the number of layers and LED boards on the bulb increase. In the future, many promising studies can be performed within the framework. For instance, the optimization could be done over different room sizes and bulb parameters. We are considering the hemispherical shape of the bulb, but experimenting with some other shapes (triangular, square etc.) can be an interesting future work as well. Further, multiple such bulbs in a room could be considered to optimize the overall room's SIR as well as lighting quality.

7. ACKNOWLEDGMENT

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