A Multi-Element VLC Architecture for High Spatial Reuse

Prabath Palathingal, Murat Yuksel
University of Nevada, Reno
{ppalathingal,yuksem}@unr.edu

Ismail Guvenc, Nezih Pala
Florida International University, Miami, FL
{iguvenc,npala}@fiu.edu

ABSTRACT

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

Keywords

Free-Space-Optics;Visible Light Communication

1. INTRODUCTION

Multi-element visible light structures are a relatively new field of study in VLC systems. A large body of work exists on VLC systems with a focus on improving characteristics such as speed, range, and intensity of illumination because of the wide range of applications associated with these systems. The directional beams in FSO, while requiring LOS connectivity, open up great opportunities for spatial reuse of optical spectrum resources.

Multi-element VLC modules can significantly improve the efficiency of data transmission as they can take full advantage of directional property of light by modulating each transmitter (e.g., an LED) with a different data stream. By designing these multi-element modules conformal to spherical shapes, one may also provide uniform light coverage across the room. The additional nice feature of the spherical shapes is that each transmitter emits the light in a different direction and hence attain an evenly scattered lighting.

Most of the existing VLC research focused on increasing the field-of-view (FOV), range, and rate of communication,

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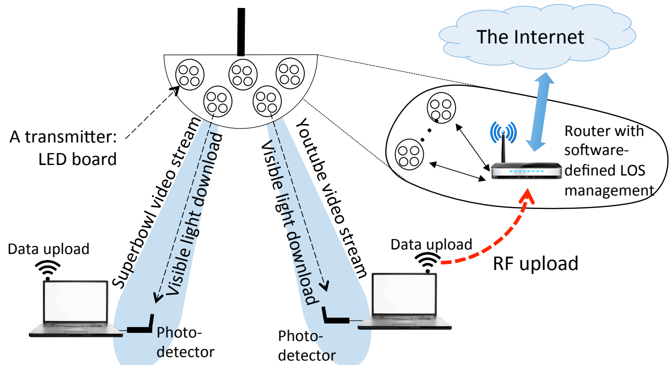


Figure 1: Architecture for multi-element VLC.

and significant advances have been attained in increasing what is possible with a *single* element, i.e., a transmitter (an LED), receiver (a photo-detector (PD)), or transceiver (an LED-PD pair) [6,11,19]. In [3,5,9,14,17], multi-element receiver approaches are introduced to improve system performance. There has also been earlier works that jointly study illumination and communication aspects of VLC systems [1, 4, 10, 15, 16, 20]. Other recent studies on hybrid RF/FSO networks include [7,13]. These works consider that in the downlink, each user is served only by a single LED, while in the uplink, an RF technology such as WiFi is used for communication.

The key contribution of this work is to explore designs using *many* elements with *narrow* FOV. In particular, we *use multi-element VLC modules for simultaneous transfer of multiple data streams and attain higher spatial reuse in short ranges*, e.g., a room. Our research differs from the recent works in the integration of multiple spotlighting mechanism onto a single light source (base station), thereby creating an apparently large FOV which makes handover easier and also serves the purpose of illumination. Instead of developing a VLC-based broadcast system [8], our research focuses on specific data stream from individual spotlight from the overhead light source. The rest of the paper is organized as follows. Section 2 describes our multi-element VLC architecture for both illumination and high spatial reuse communication within a room, and our hybrid approach to handling LOS for it. In Section 3, we explore the design of a hemispherical bulb needed for our architecture and present preliminary simulation results. Finally, we summarize our work in Section 4.

2. MULTI-ELEMENT ARCHITECTURE

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

Another ramification of narrow divergence angles is the lack of coverage and mobility. Even when we use hundreds of LEDs, we still have the problem of steering the data transmission to the corresponding LED as the mobile receiver is moving. We tackle this problem with an enhanced version of our electronic steering concept [12]. Our architecture takes advantage of spatial reuse and seamless steering which, essentially, are untapped sources of efficiency in VLC. We detail the architecture by describing three key components below.

2.1 The Bulb

The bulb is a hemispherical structure that acts as an access point for the room. It consists of multiple transmitters to facilitate *simultaneous downloads* to multiple receivers. These transmitters are intended to provide light coverage and facilitate communication in the room. A transmitter is an LED board with multiple LEDs transmitting a single data stream. The LEDs on the board are all modulated by the same signal, and hence the purpose of having multiple LEDs on a transmitter board is to allow tuning of trade-offs between source power, communication range, and illumination quality. Overall, the bulb's spherical multi-element design coupled with highly directional LEDs allows higher spatial reuse in communication. However, it also presents the challenge of seamless steering of data transmissions to corresponding transmitters. To address this issue, we connect each transmitter (via Ethernet) to a router embedded in the bulb and run a software protocol for managing LOS alignment (detailed in Section 2.3).

Coexistence of spatial reuse with seamless steering of data transmissions is a larger problem that exists in multi-element directional communication systems.Prior research addressed this issue by solving handover across multiple access points (APs) [18], however, handover across transceivers of a single multi-transceiver AP has not been addressed.

Another challenge is that using bidirectional VLC can cause significant collisions as shown in Figure 2(a). In our proposed architecture we resolve this issue by using a hybrid RF/FSO approach coupled with LOS alignment protocol [12]. In hybrid RF/FSO approach the data download is conducted through
FSO/VLC and upload is carried out using RF. This approach significantly reduces the collision that can be caused by bidirectional VLC communication. In hybrid approach, the upload and download of data streams are completely decoupled. In [13], the authors also proposed to solve this issue via a RF/FSO hybrid network design. However, our approach is different in that we handle all the RF/FSO communication *within the same AP* and thus prevent any routing and transport protocol issues pertaining to asymmetric upload and download paths.

2.2 Mobile Receiver Units

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

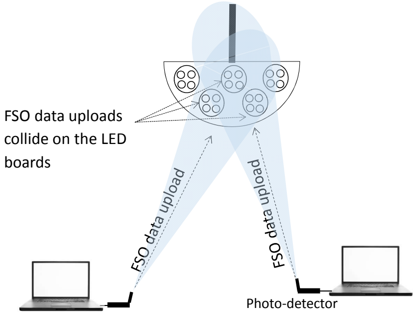
2.3 RF/FSO Hybrid Management of LOS

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

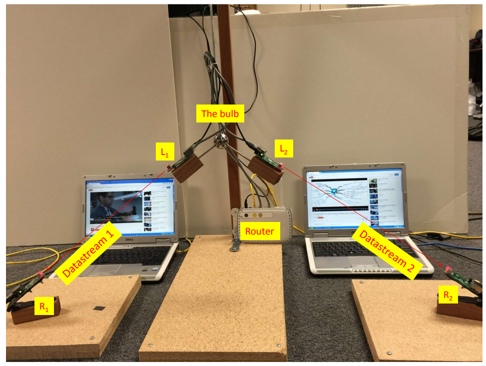
2.4 Establishing the Link

To search for new mobiles in the room, the bulb periodically sends SEARCH frames via its LEDs. Each LED on the bulb has a local ID, k, which is included in the SEARCH frames being sent from that LED k. These SEARCH frames are analogous to the Ethernet's RTS messages, with a key difference that they are augmented with the local ID of the LED they are being sent from. A mobile receiver X, entering the room, receives these SEARCH frames. X might receive multiple of them depending on its position with respect to the bulb. We assume that the receivers have the capability to filter the SEARCH frame with strongest light intensity. Such a capability can easily be implemented in hardware level by using trans-impedance amplifiers, comparators and micro-controllers. A measure of the received signal strength indication (RSSI) can be fed into the micro-controller where the decision is made over which input has the strongest signal. [2]

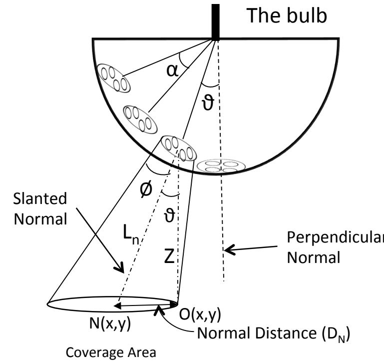
Once the receiver receives the SEARCH frame, it sends back an ACK frame (like a CTS in Ethernet) via its RF transmitter. This ACK includes the Ethernet address of the receiver and the local ID k of the LED from which the SEARCH frame was received. The ACK verifies to the bulb that X is aligned with the transmitter LED k. After receiving the ACK from X, the bulb assigns the LED k or a group of LEDs around the LED k to X, and maintains this information as an *LED-receiver association table* (LED-RAT). When there are multiple receivers in the room, the bulb partitions the LEDs and associates each partition (see Section 3) to a separate receiver. LED-RAT will need to be updated accordingly. For every data frame to be sent, the



(a) Collision in bidirectional VLC.



(b) Proof-of-concept demo of multi-element bulb for more spatial reuse.



(c) Placement of LEDs on the bulb.

Figure 2: Multi-element bulb architecture.

bulb performs a reverse lookup to LED-RAT with the Ethernet address the frame is destined to. In this manner, the bulb steers the data stream destined for receiver X onto the transmitters that just got associated to X. The partitioning of the LEDs across the receivers will be crucial in the overall spatial reuse performance.

2.5 Maintaining the Link

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

2.6 Terminating the link

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

2.7 A Prototype for Proof-of-Concept

To explain the overall idea of the multi-element bulb in our VLC architecture, we have built a proof-of-concept prototype using off-the-shelf materials. As shown in Figure 2(b), the prototype portrays the communication between the bulb and two receivers, R_1 and R_2. The bulb consists of two LEDs L_1 and L_2, placed at a circular angle as envisioned in our architecture. The receivers go through the initial association mechanisms, Join with LED-RAT and Maintain, to establish and maintain the VLC link with the LEDs. Once established, the router's switching algorithm learns that L_1 is aligned with R_1 and L_2 is aligned with R_2. Then, the LEDs transmit two different Youtube streams to their corresponding receivers. The data received at each receiver is then delivered to corresponding laptops/clients via Ethernet. On the other hand, a message that needs to be delivered to the bulb from the receivers will be sent via RF to the router in the bulb. Mobility can be portrayed by moving and aligning laptop R_1 with LED L_2 and laptop R_2 with L_1, while the Youtube streams are being downloaded. After this change, The LOS alignment algorithm kicks in and updates the LED-RAT when the next set of SEARCH messages are sent from the transmitters. This process reassigns the datastreams corresponding to each of those laptops. This is just a simple presentation of our architecture and several challenges need to be tackled to develop a full-fledged prototype.

3. MULTI-ELEMENT HEMISPHERICAL BULB DESIGN

To maximize the coverage in the room, the transmitters of our multi-element hemispherical bulb are arranged in layers of circles. We consider a bulb with layers at elevation angles of 30, 45, and 70 degrees as in Figure 2(c).

A more efficient arrangement of the transmitter LEDs is within itself an optimization problem that is not discussed in this paper (see e.g., [21] for further discussions on a special case of this problem). Several factors such as radius and divergence angles of the LEDs, and height of the room can affect the light distribution and communication pattern in a room. An optimized placement should jointly improve the light distribution and communication in the room and this will be part of our future work.

3.1 Partitioning Algorithm

To take full advantage of the multi-element bulb for higher spatial reuse, we devise a heuristic algorithm to partition the LEDs into groups, each corresponding to a mobile receiver in the room. This reduces the load on LOS alignment algorithm by providing a wider FOV for each receiver. Further, all LEDs in a partition are modulated with the same transmission signal, and hence, the receiver for that partition can now enjoy an aggregate reception quality from the LEDs of its partition. For two receivers positioned at (X_1, Y_1) and (X_2, Y_2) on the room floor, we find the mid point, (X_{mid}, Y_{mid}) and draw an imaginary partitioning line perpendicular to the line connecting the two receiver positions. Once the partitioning line is settled, then we split the LEDs on the bulb into two categories based on which side of the line their projections fall. If the partition line intersects with an LED's projection on the floor, the LED is categorized into the side that includes the majority of the LED's projection.

This heuristic has to be executed every time when a new mobile device establishes connection with a transmitter on the bulb. In that case, the algorithm will reassign all the transmitters giving new space for the new connection while maintaining the old connections. Although our heuristic partitions based on the position of the receivers, designs using various other parameters (e.g., room size, signal strength received at each receiver) are possible.

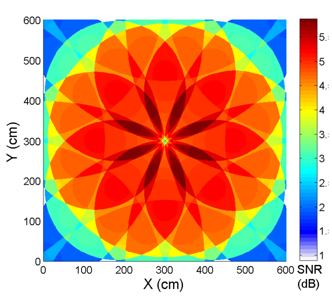
3.2 Hemispherical Coverage

The coverage of an LED forms a conical shape based on the Lambertian law [19]. We use the optical wireless propagation model [19] to calculate the received light intensity at a point within the LOS of the transmitter as a function of the transmitter's source power P (dBm), the radius of the transmitter γ (cm), the divergence angle of the transmitter θ (mRad), attenuation coefficient consisting of atmospheric absorption and scattering, and the radius of the receiver. Then, assuming a typical photo-detector sensitivity of S=-43 dBm, we obtain the maximum communication range.

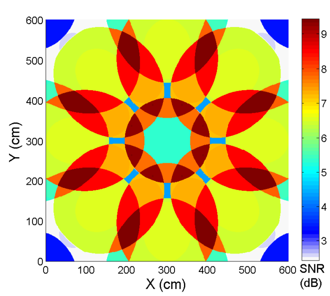
The bulb consists of multiple LED boards, each placed at an angle, ϑ, from the perpendicular normal as shown in Figure 2(c). Each LED board on the bulb generates a conical coverage following the LEDs' divergence angle θ, and is attached to the main unit at a height Z. Following the shape of a cone, the coverage area on the floor forms a circle. As ϑ increases, the spread of the cone increases leading to an elliptical formation. Maximum light coming out of the transmitter is concentrated on the normal point on the floor point perpendicular with respect to the transmitter. The slanted normal, L_n, connecting the normal point on the floor and center of the transmitter defines the distance between the two. The normal point on the floor, $N(x, y)$ is:

$$N_x = X \pm D_N \cos\alpha \qquad N_y = Y \pm D_N \sin\alpha \qquad (1)$$

where X and Y are the 2D coordinates of the transmitter position on the bulb and α is the angular distance between the layers of transmitters. The Normal Distance, D_N, is $D_N = Z\tan\vartheta$. We, then, use the communication range $R = \sqrt{Z^2 + D_N^2}$ to figure out if a receiver on $N(x, y)$ will receive the data or not.

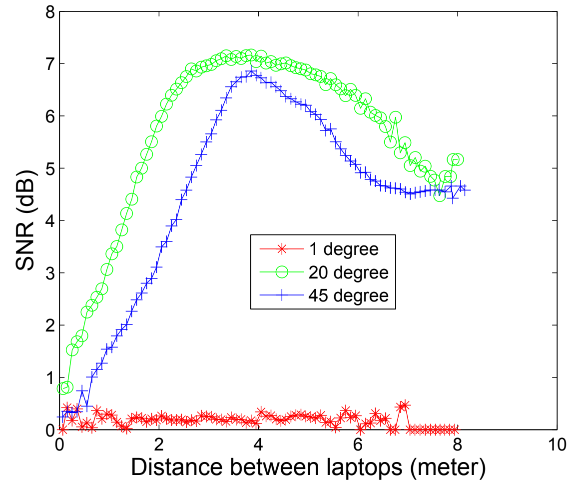


(a) θ=45°.

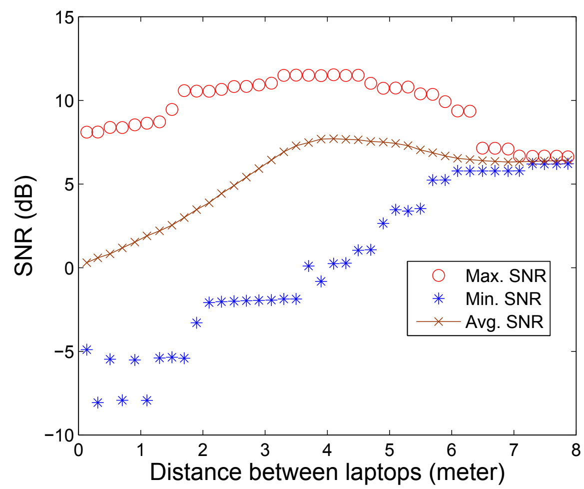


(b) θ=20°.

Figure 3: Coverage of multi-element bulb.



(a) Average SNR.



(b) Max & min SNR, θ=45°.

Figure 4: SNR for various divergence angles.

3.3 Simulation-Based Evaluation

In order to get a glimpse of what is possible in terms of download and illumination efficiency, we perform an evaluation of our VLC architecture with the partitioning algorithm and coverage model above. For simulation experiments, we consider a room of size 6 m × 6 m × 3 m, where dimensions are ordered as l x w x h respectively. The multi-element bulb is placed at the center of the room ceiling which is considered as the origin point of the hemisphere. The hemisphere bulb consists of three layers of transmitters. Each layer is distinguished by the elevation angle between the normal of the hemisphere and the transmitter. In our model, layers 1, 2 and 3 are placed at an elevation angle of 30, 45 and 70 degrees, respectively. An azimuth angle of 45°is assumed between transmitters. The transmitter is of radius 4cm. A divergence angle is assigned to each transmitter. The optimization of this divergence is described in later section. In our experiment we are checking for the optimum arrangement that provides a good signal-to-noise ratio (SNR).

We randomly position two receivers on the room floor and divide the LEDs on the bulb into two partitions P_1 and P_2 following the heuristic described in Section 3.1. We assume that the photo-detector(a) at a receiver is conformal to the surface of the receiver and can receive the light coming from a partition on the bulb. The photodetector is facing upward to the transmitter and has a radius of 3.75cm. So, a receiver is considered to be within the coverage of an LED if it lies within the divergence angle of the LED. A receiver can be in the coverage of one LED or multiple LEDs of the same partition or multiple partitions. Thus, the signals arriving to a receiver i from partitions other than P_i need to be considered as noise. For the simpler case of two receivers, let $S_{1,1}$ be the total signal received at receiver 1 from LEDs of P_1 and let $S_{1,2}$ be the total signal received at receiver 1 from LEDs of P_2. Then, SNR for receiver 1 is $\text{SNR}_1 = S_{1,1}/S_{1,2}$. Following the same notation, SNR for receiver 2 is $\text{SNR}_2 = S_{2,2}/S_{2,1}$. The noise considered in SNR calculation is from the light coming from the neighboring transmitters in the bulb. We are not considering any external noise factors.

We evaluate at three different divergence angles. In the first two cases, we check the scenarios with small and and very large divergence angles to test the correctness of the model. In the third case, we experiment with other parameters to optimize the lighting and signal strength.

3.4 Large Divergence Angle, θ=45°

This is an extreme case of LED transmitters used in the bulb. A large divergence angle increases the distribution of light across the room but can create sizable interference as well. In Figure 3(b), it can be observed that the signal distribution is more uniform across the room. As in Figure 4a, the average SNR is high enough to maintain high throughput even for cases when the receivers are closer to each other. The average SNR value increases and then decreases from the maximum, which will be explained in the next case where it occurs more prominently. When the receivers are close to each other they are more likely to be somewhere in the center of the room. Likewise, when they are far from each other, they are more likely to be at the opposite corners of the room.

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

3.5 Medium Divergence Angle, θ=20°

Typically, divergence angle of LEDs varies from 10 to 20 degrees. So, to capture the common case, we consider LEDs with a divergence angle of 20°. From Figures 3(c) and 4a, the signal distribution remains fairly even and provides reasonably higher SNR compared to the case θ=45°even for shorter separation of the receivers. This means spatial reuse is better as expected from narrower divergence angles.

However, it can also be observed that the average SNR dips around distance of 4 meters. The reason for this can be explained based on Lambertian law. According to this law the intensity of light decreases with angle from the normal. Considering the layered approach and angular placement of transmitters, the signal strength received for a straight beam from a transmitter placed at an angle is less than the signal strength received by a straight beam from a transmitter placed in line with the normal of the bulb. In addition to this, we have the reduction in strength associated with Lambertian law. The two reasons mentioned above causes the dip in SNR. This can be resolved by adding more transmitters with LEDs that have larger divergence angle on the outer layers of the bulb. Adding more transmitters on the outer layer will help match the signal strength of transmitters that are in line with a legacy bulb.

3.6 Varying Room Size and Transmit Power

We extended our experiment to larger room sizes using LEDs of higher power. The results are presented in Figures 5(a) and 5(b). This extended experiment is to show the effectiveness of the model over a bigger room. The first experiment involved extending the room size (l x w) from 4 meter to 20 meter along with a relative increase in the transmit power from the LEDs with divergence angle of 20°. The room height was set to 3 meter and $l = w$. The transmit power was increased by m^2 times for every m increase in the room size. The results show that the pattern of SNR graphs remains the same in all the cases. However, the graph extends to longer distances and to higher SNR values as expected.

In the second experiment the transmit power was kept constant while the room size (l x w) was increased by m times for every iteration from 4 meter to 20 meter. The room height was set to 3 meter and $l = w$. The result shows that the Signal to Noise Ratio deteriorates for every increase in room size.

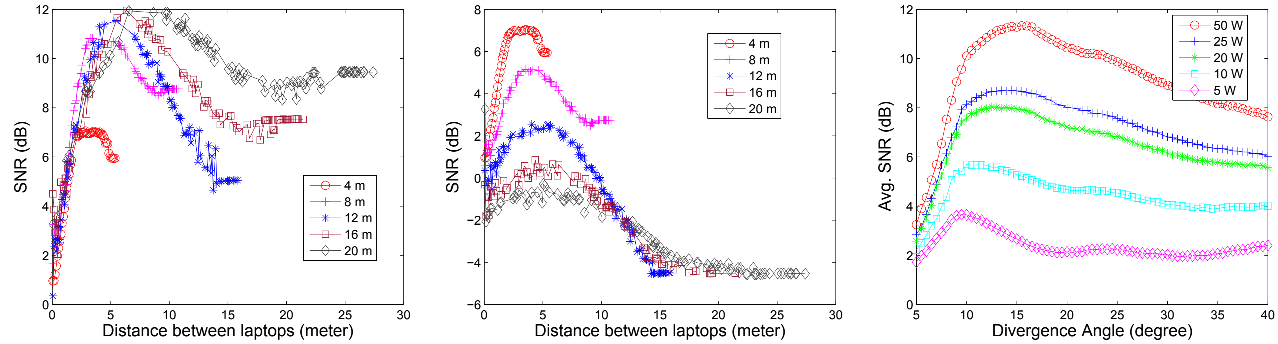
3.7 Varying Divergence Angle

Divergence angle has a significant effect on the coverage area of each transmitter. To find the optimum divergence angle we ran experiments varying divergence angle from 5°to 40°over various power values of 5W, 10W, 20W, 25W and 50W. The SNR results for each power value were averaged per divergence angle. The results are depicted in Figure 5(c). As observed from the figure the optimum divergence angle is obtained within the range of 10°and 16°.

4. SUMMARY AND FUTURE WORK

In this paper we introduced a multi-element VLC architecture that employs a multi-element hemispherical bulb design. The mobile receivers use VLC/FSO for download and RF for upload, and the multi-element bulb uses a software-defined approach to manage LOS alignment with receivers. We modeled the hemispherical multi-element bulb structure that simultaneously provides and showed, with initial results, that the architecture can offer high spatial reuse while keeping illumination of a room at acceptable levels.

Several future work items are inline. We assumed one AP in a room, and multiple APs can significantly improve the results. Future work also includes optimizing the number of LEDs and layers in the bulb. The algorithm for partitioning LEDs among receivers need further enhancements



(a) Varying room size & transmit power. (b) Varying room size. (c) Varying divergence angle.

Figure 5: SNR against various parameters.

to better balance time complexity and higher spatial reuse opportunities.

5. ACKNOWLEDGEMENT

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