

A novel hemispherical visible light transmitter design for multi-user beamforming in wireless communication

Tahesin Samira Delwar · Abrar Siddique · Jee Youl Ryu*

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Abstract This article presents a novel hemispherical visible light transmitter design for multi-user using optical beamforming (OB) in VLC communication. OB is a technique that uses specific selectivity to focus LED light on a specific point. By raising the SNR, OB helps to improve the VLC's data rate. We demonstrated the layout of a hemispherical visible light transmitter design. We developed a μ GOA optimization technique for power optimization and created a look-up table. The work is progressed by training the signal using μ GOA. μ GOA helps to find suitable LEDs to get maximum signal strength in any user position. We provide an efficient fully adaptive VLC system that can increase the receiver signal-to-noise ratio (SNR) and minimize the time necessary to estimate the VLC user position. Furthermore, we have tested the feasibility and robustness of the proposed system for various user positions. Simulation results show the bit error rate (BER) performance and high SNR characteristics of VLC. We can observe that the SNR at the 61 segment increases by 3 dB after beamforming. Furthermore, beamforming enhances the SNR at segments 1 and 121 by 4 dB and, 4.7 dB respectively. The VLC-based OB can benefit from smarter communication for multi-user beamforming in wireless communication.

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1 Introduction

Optical wireless communication (OWC) throughout the last decade has earned relatively considerable attention. OWC is seen as together a substitute and an opportune reliant communication approach for the standard radio frequency (RF) technique. OWC spectral band covers the infrared (IR), and ultraviolet (UV) spectrum are employed as propagation media. OWC systems operating in the visible light (VL) band are often classed as visible light communication (VLC). Figure 1, shows the VLC system, advantage, and application in one picture [1]. Meanwhile, among them, the development of LEDs' tremendous expansion led to VLC, identified as new wireless technology. VLC uses the spectrum within the (frequency range of 430–790 THz, wavelength range = 380–750 nm) [2]. VLC approaches dual functionality, such as illumination and communication. VLC has remarkable advantages. VLC enables vast bandwidths, low-cost, high-speed, extended life span, energy efficiency, switching to the varied light intensity at a very rapid pace, and high data rate. There is also no electromagnetic interference from other devices. Light waves cannot flow through concrete or VLC solid construction, so they benefit from an inherent safe transfer of information in the physical layer.

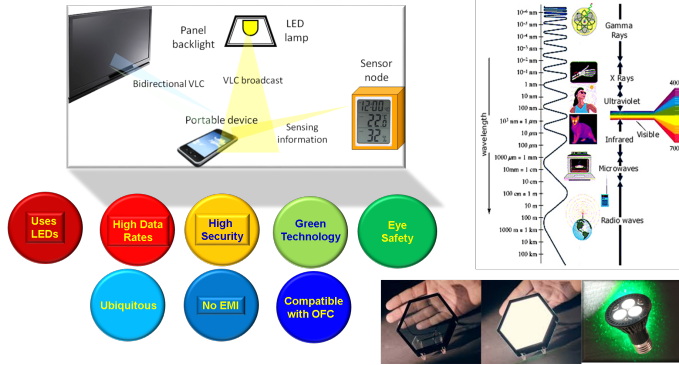


Fig. 1: Illustration of VLC system, advantage and features.

In contrast, VLC also has drawbacks. Although VLC has recently attracted significant interest, and a standard in the IEEE 802.15.7 [3], system was produced in 2011, VLC has yet to be widely commercialized. Another concern is also, following the traditional way signals in RF communication are modulated using amplitude, frequency, and phase modulation. But in VLC communication, due to the non-coherence of visible light, it employs intensity modulation.

Thus, it considers new problems in designing. In practice, all VLC demonstrations use the line-of-sight (LOS) method. In this case, if the LOS route is impeded by a barrier, the performance of VLC is not assured.

In previous research, authors have explored the impact of reflection in VLC. Hence, it is difficult to show acceptable VLC performance when using reflected or scattered light. The other major challenge is the interference of sunlight or other light sources. Although various studies have studied the effect of light reflection in VLC, they have typically regarded reflection as interference in the LOS path. Second, other lights or sunshine can cause VLC to malfunction. However, with the advancement of VLC technology, it is expected that this interference will be eradicated in the majority of interior scenarios. In the prior research, the author shows various methods to increase the VLC performance in two ways. One is the electrical domain and the other is the optical domain. Most electrical domain techniques were developed first for standard RF wireless communication and then applied to VLC. In a VLC system, author report an 8-QAM constellations, thus it achieve lower PAPR [4]. The author formulated [5], the energy and spectral efficiency for the conventional and hybrid OFDM-based VLC modulation, which assists in ensuring the QoS with affordable energy. The authors [6] present a MIMO system with several LEDs and photodetectors that use centralized or decentralized transmission power allocation methods. A VLC post-equalization circuit for increasing the bandwidth of a VLC system based on phosphor white LEDs [7]. On the other hand, optical-domain techniques include phosphor-based white LEDs [8], optical MIMO using several LED transmitters and image-sensor or photodiode (PD) array receivers [9], wavelength-division multiplexing (WDM) using RGB LEDs [10], polarization-division multiplexing (PDM) [11], optical beamforming (OB) [12], etc.

Optical beamforming (OB) has been extensively studied in communication systems to optimize SNR at the receiver. As a result, OB might be an appealing alternative to explore in VLC systems to improve system performance. An OB has recently been created for MIMO infrared optical wireless (IROW) systems with intensity modulation and direct detection. Furthermore, recent research has shown optical wireless energy transfer utilizing optical beamforming with a spatial light modulator (SLM). They employed optical beam steering and beam shaping to concentrate light on the intended target to convey optical wireless energy.

2 Published literature survey and motivation

Based on the VLC link, we have summarized the published papers which are related to OB. Considering the prior research, Shuang et al. [13] demonstrated a security zone considering the VLC scenario, and he approaches a PLS scheme based on OB to enable secure communications. Also, the author formulates a CSASPM optimization algorithm to maximize the signal power received. Another author, S. Ma et al. [14] described the minimization of the transmit

power and the maximization of secrecy rate issues. In this paper by Liu X. et al. [15], a secure MISO VLC network is investigated, where simultaneous light wave information and SLIPT are used to accommodate numerous energy-limited devices. Ayman et al. [16] In this paper, the author considered a VLC system in MISO linked to the design of transmitting beamformers to achieve the maximum secrecy rate. Furthermore, the author provides a solvable quasi-convex line search problem solution for the non-convex problem. Mostafa and Lampe [17] utilize large LEDs to conduct a vast assortment of optical patterns. However, the drawback of the paper is that the quantity of LEDs employed in the work is approximately 3600 LEDs, which seems difficult to install. In this study [18], the author proposed secure communications for a MISO VLC system with NOMA. To improve the security performance, the author applied beamforming technologies.

In addition, [19] an artificial noise-aided beamforming scheme is proposed for MISO VLC networks. This study demonstrated [20] the generation of robust beamformers in combination with spherical uncertainty sets for the eavesdropper's channel in the face of defective channel information. According to the author Yin and Haas's [21] research, optical beamforming is a viable method for realizing PLS in a 3D multiuser VLC network. In this paper [22], optimum and zero-forcing beamforming schemes, as well as robust beamforming strategies, were suggested for the MISO-VLC system assuming perfect and imperfect CSI. The results show that in the case of perfect CSI, the secrecy rate obtained by optimum beamforming is identical to that produced by zero-forcing beamforming, and the secrecy rate in the worst scenario may be greatly increased by utilizing robust beamforming. Furthermore, in [23], the authors integrated the NOMA into the cooperative VLC system and created a secure beamforming vector at the relay nodes to protect the needed information. This paper [24], shows an improved method with a superposed signal-based VLC system using MISO beamforming. The result demonstrates that a two-LED MISO-VLC system can attain a data rate of 1.0 Gbit/s. The notion of biased beamforming is introduced in this study [25] to fully use the potential of multicarrier multi-LED VLC systems. A coordinated beamforming (CB) [26] technique is presented for downlink interference minimization among co-existing VLC attocells using multi-luminaire transmitters. Also [27], it uses an LED array and OB to accomplish the PLS of a VLC system.

However, a large number of LEDs are still used in this study, and the authors do not explain in detail how to decipher the defined pattern synthesis optimization issue. In another paper, under the premise of LoS propagation, the authors of [28] investigated robust beamforming together with discrete uncertainty sets corresponding to erroneous knowledge about the eavesdropper's position. To increase SNR and transmission distance, a new wireless VLC technology using optical beamforming. Authors [29], [12] present a VLC system by employing time-division multiple access and space-division multiple access using optical beamforming to handle many user devices. However, the main problem is that they have used an SLM modulator. In practice, the installation of SLM is very costly to implement.

To the best of the author's knowledge, there is no complete framework that analyzes the integration of hemispherical visible light transmitter design for multi-user beamforming in VLC systems. In this context, the proposed scheme is likely to bring additional benefits to wireless communication, driven by the advantages afforded by μ GOA-based OB in multi-user systems. In particular, in this paper, we formulate an optimization algorithm to maximize the received signal strength in the VLC network. We have configured the hemispherical VLC transmitter design layout. The goal of this paper is to tackle this open problem.

Compared to the previously mentioned works, our work in this paper has the following key differences:

1. We propose a hemispherical visible light transmitter design layout.
2. We formulated a μ GOA optimization algorithm for power optimization and created a look-up table.
3. Using the μ GOA algorithm and with the help of a look-up table, we have shown the LEDs that are responsible for getting maximum signal strength.
4. Finally, we assess the possible performance of μ GOA-based OB, i.e., BER vs SNR performance after and before beamforming for the two user positions, using extensive computer simulations.
5. The results presented here provide important theoretical and real-world insights that are expected to be useful in the design and deployment of effective indoor VLC communication.

The remainder of the paper is organized as follows: Section 2, presents the proposed system model using optical beamforming. Then, Section 3, demonstrates a thorough overview of the working principle. Section 4 presents the corresponding numerical and simulation findings, as well as discussions. Finally, Section 5 finishes the paper with pertinent observations.

2.1 Proposed methodology for optical beamforming

In this paper, Figure 2, represents the traditional optical beamforming in the VLC link. Because LED light spreads out in all directions in traditional beamforming in VLC links, optical signal strength diminishes with transmission distance. This is also the fundamental reason why VLC performance degrades over time. To address this issue, in the earlier research, a VLC system was developed using OB with a spatial modulator (SLM). Using SLM is too costly to implement. To make it simple and cost-effective, in our proposed work we consider a hemispherical light-based OB technology to increase the VLC system SNR. To focus LED light on the desired target, we used a hemispherical shaped transmitter. Figure 3, shows the proposed hemispherical visible light based optical beamforming. Figure 4, depicts the fundamental requirements of the indoor VLC scenario of the proposed methodology. While Figure 5, describes the cross-sectional and side views of the proposed transmitter. For simplification, figure 6, shows the 2D cross-sectional view of the transmitter for the proposed methodology.

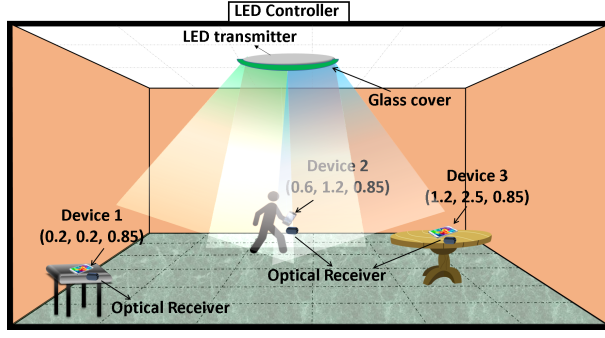


Fig. 2: Traditional optical beamforming in the VLC link.

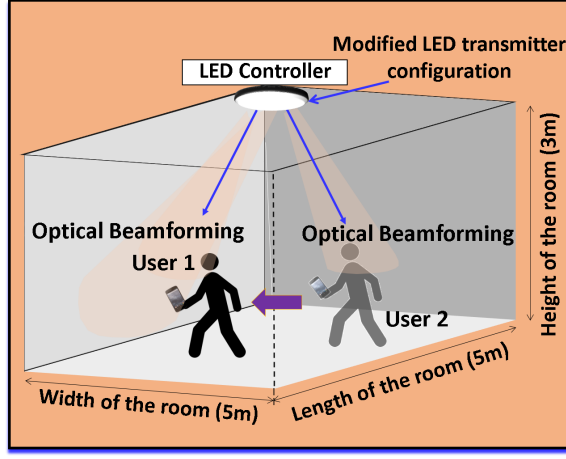


Fig. 3: Proposed hemispherical visible light based optical beamforming.

The working principle of the hemispherical transmitter design is we used bigger white LEDs on the outside surface for constant illumination. Besides, the small LEDs chosen in the centre for beamforming. The threshold taken into account when calculating the contribution of light output by larger white LEDs at the user position. The user location will be sensed first during the operation of the proposed approach, and all LEDs will be illuminated. All of the blazing LEDs, including the larger LEDs, will provide light intensity contributions to the user (PD). All LED received intensities will be ordered in increasing order. The median location of all the intensities of tiny LEDs will be picked after rearrangement (ordered ascending and rejecting the higher intensities owing to huge LED). LEDs with intensity levels greater than the median value will stay lit, while the remainder will turn off.

In the process, before real communication occurs, power optimization is done for the user locations of 1, 61, and 121. The median is computed for each locations throughout the μ GOA optimization process. As a result, at a certain

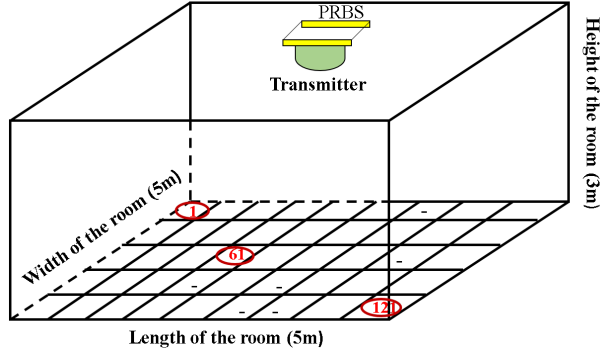


Fig. 4: Indoor VLC room configuration with hemispherical visible light OB.

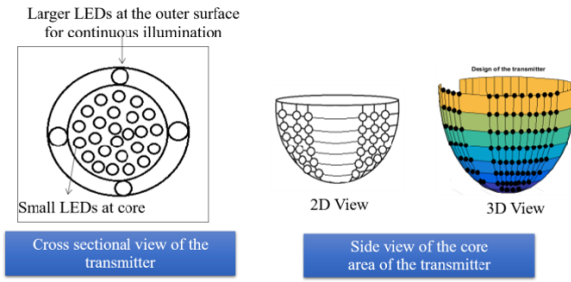


Fig. 5: Cross sectional and side view of the proposed transmitter.

place, LEDs with intensities more than or equal to the median intensity are chosen for transmission. The look up table is generated in this way. When the user position is known, the LEDs associated with that position (from the look-up table) are turned on.

2.2 Working principle for the proposed methodology

We evaluate a transmitter with 120 white LEDs at its center for our proposed methodology. For our proposed methodology, we consider a transmitter having 120 white LEDs at its core. To determine the user's location, the floor of the room is split into (11 rows by 11 columns = 121 segments). The power contribution of each LED is determined for each section. The simulated graphs in result section implies the light intensity distribution for beamforming. The median intensity is determined for each point. For communication, LEDs with intensities greater than or equal to the median are chosen for a certain user position. Figure 8, shows the look up table to simply understand the LED number which is glowing. Thus, a lookup database is kept for selecting the

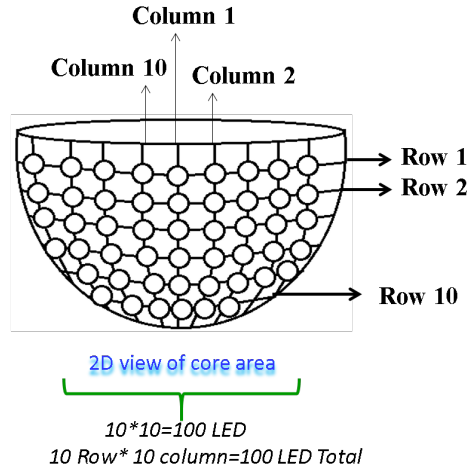


Fig. 6: 2D cross sectional view of the transmitter for the proposed system.

LEDs that provide intensity levels above the median for each place (segment). Figure 7, represents the proposed methodology's block diagram.

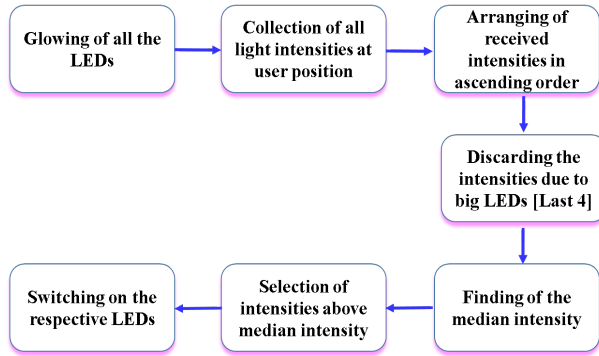


Fig. 7: Block diagram of the proposed hemispherical visible light OB.

2.3 Micro genetic optimization algorithm (μ GOA)

Evolutionary algorithms (EAs) refer to population-based combinatorial optimization algorithms that use phenomena similar to evolution in nature, such as reproduction, mutation, and recombination [30]. The working premise of EAs is based on Darwin's thesis of survival of the fittest.

Fig. 8: Look Up table [calculation of particular LED glow plot]

2) μ GOA with the promise of improved performance because it requires only a small population at a time (hence the name "micro").

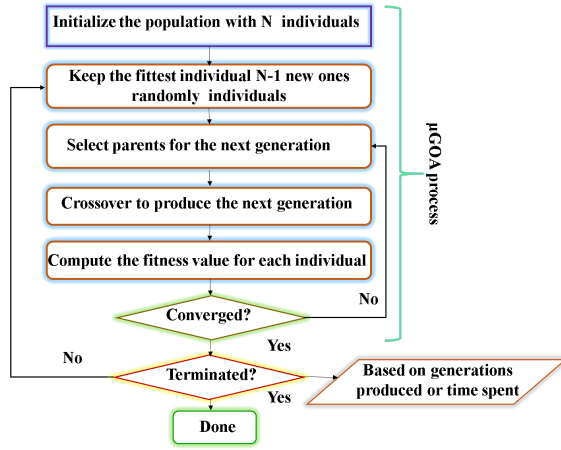


Fig. 9: Training of signal: μ GOA optimization algorithm

3) Given that the calculation of the fitness value is the most compute-intensive element of GA in most real-world applications.

4) A smaller population may result in fewer fitness calculations, allowing a better solution to be identified in less time.

The algorithm shows the process of the training of the signal in figure 10. To identify the optimization intensity of the proposed scheme, we have to follow the algorithm process in figure 11. Figure 12 illustrates the partitioning of the floor of the room into equal sizes. Figure 13 depicts the common floor mapping of the contribution of each LED in any segment.

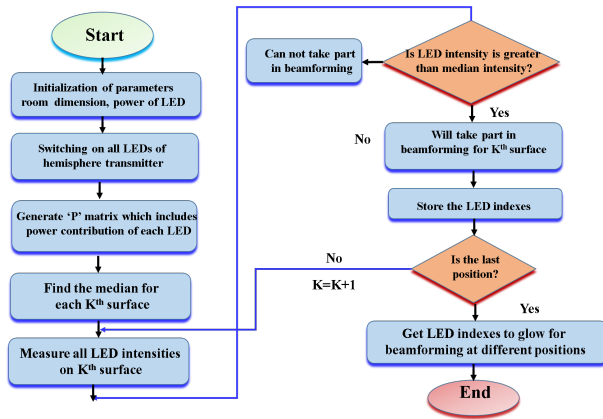


Fig. 10: Training of signal: μ GOA optimization algorithm

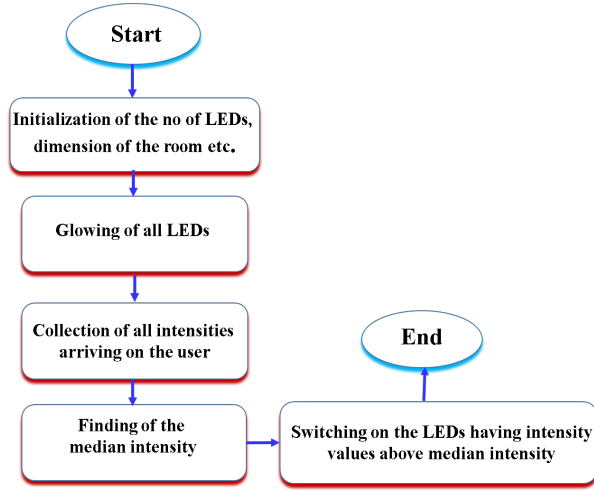
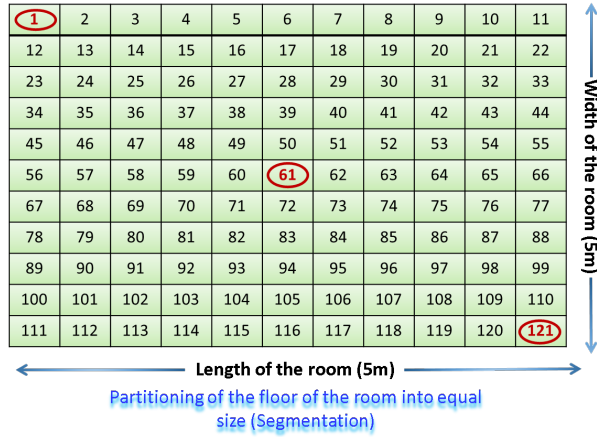
Fig. 11: Training of signal: μ GOA for optimization intensity.

Fig. 12: Partitioning of the floor of the room into equal size

2.4 Indoor Visible Light Communication Channel

This paper considers LED and Photodiode (PD) as transmitter (TX) and receiver (RX). The PD receives the optical signal from the VLC system's direct channel and converts it to an electrical signal. Figure 14, shows LOS configuration in VLC scenario. The output electrical power, P_e can be written as [32],

$$P_e = \begin{cases} [P_t \frac{\gamma A_r}{d^2} R(\varphi) T(\varphi) g(\varphi) \cos(\varphi)], & 0 \leq \varphi \leq FOV \\ 0, & \varphi \geq FOV \end{cases} \quad (1)$$

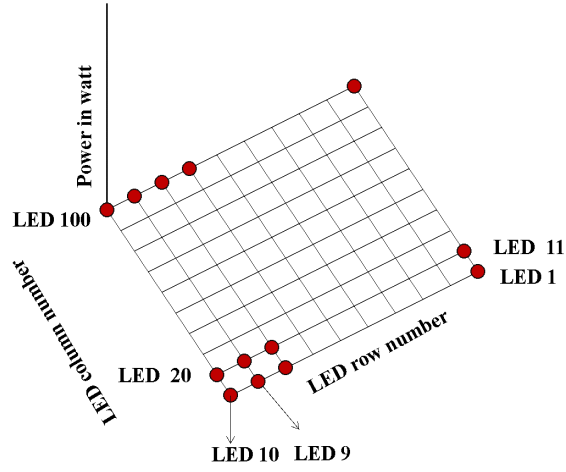


Fig. 13: Common floor mapping of contribution of each LEDs in any segment

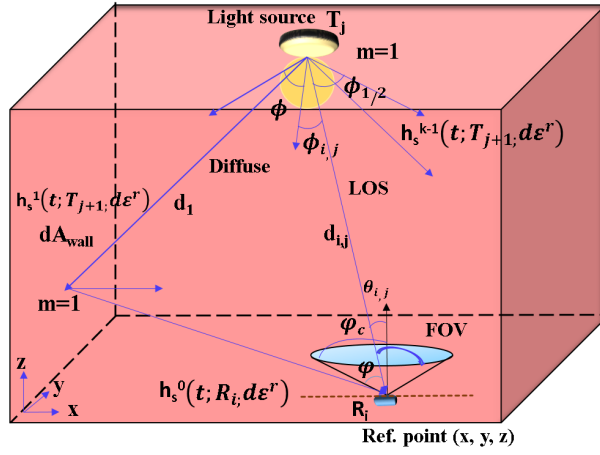


Fig. 14: LOS configuration in VLC scenario.

Here,

P_e = average transmitted power,

A_r = physical area of detector,

d = distance between the transmitter and the receiver,

$T(\phi)$ = optical filter gain,

$g(\phi)$ = concentrator gain,

FOV = field of view of the RX,

γ = response rate of the PD, and,

$R(\phi)$ = radiant angle intensity at radiation angle ϕ with respect to the RX.

As an LED is used as a transmitter in this system, the radiation pattern approximates the Lambertian model. So can be modeled as,

$$R(\phi) = R(\phi) = [(m+1)/2\pi] \cos^m(\phi) \quad (2)$$

Here m = number of mode and is related to the transmitter's semi angle at half-power $\phi_{1/2}$. Thus, the distance between the transmitter and the receiver can be expressed as,

$$d = \left\{ \frac{[\gamma P_t (m+1) A_r h^{m+1} T_f(\phi) g(\phi)]^2}{4\pi^2 P_e} \right\}^{1/6+2m} \quad (3)$$

h = vertical distance from the TX to the RX.

2.5 Calculations related to threshold

So, illuminance at this position, which is at different θ angle with every LEDs of the transmitter;

We are assuming that illuminance of Big LEDs are; L_1, L_2, L_3, L_4 [Pre-estimated] So, $L_{\text{threshold}} = L_1 + L_2 + L_3 + L_4$

At PD, received illuminance is [When all big and small LEDs are on],

$L(\text{total}) = L_{\text{threshold}} + L(\sum \text{small LED})$

As, $L_{\text{threshold}}$ is pre-estimated,

$L(\sum \text{small LED}) = L_{\text{total}} - L_{\text{threshold}}$

2.6 Calculations related to signal detection

Assuming all LEDs have Lambertian radiant intensity

$$R_0(\theta) = \frac{(m+1)}{2\pi} \cos^m(\theta) \quad (4)$$

Where m is the order of Lambertian emission.

Hence the total intensity received by the PD is given by,

$$P = \frac{A}{d^2} \sum_{i=1}^N R_0(\theta_i) \cos \Psi_i, \text{ for } 0 < \theta < \theta_c \quad (5)$$

$$L(x) = \frac{P(x; H_1)}{P(x; H_0)} > \gamma \quad (6)$$

$$\sum_{i=1}^N \int_{(x_i: L(x_i) > \gamma)} P(x_i, H_0) dx = \alpha \quad (7)$$

Where θ_i is the critical angle of incidence by the LED and Ψ_i is field of vision angle of Photo detector due to each LED.

The threshold to distinguish between two binary symbols can be found by using Likelihood Ratio Test (LRT).

Where, α is predefined false alarm value In this case, $\alpha=0.5$ P_{FA} is the probability of false alarm.

$$P(x_i, H_0) = \frac{(m+1)}{\pi} \cos^m(\theta) \quad (8)$$

Here, X is replaced by θ . So,

$$P(\theta_i, H_0) = \frac{(m+1)}{\pi} \cos^m(\theta_i) \quad (9)$$

So, γ is the value of intensity below which we will consider a '0' is transmitted and above γ , a '1' is transmitted.

In the receiver, the photo detector detects different intensities at different points and finds its maximum. Now that value is compared to γ , if it is less than γ , one '0' is considered, otherwise '1' is considered.

3 Results and Discussions

Most work on VLC channel modelling focuses on scenarios where transmitter and receiver are located at fixed points. In practice, user mobility should be taken into account because it will have important implications for system design. The complete simulation was carried out in the MATLAB environment using a white LED. We investigated three potential user positions for the practicality and robustness of the proposed system: user positions 1, 61, and 121. The intended positions specifically refer to the corner and middle positions of the room. Optical beamforming is shown to demonstrate the practicality of the proposed technology for those locations or segments. Table 2, presents the simulation parameter used in our work. And, table 3, shows the μ GOA simulation parameter used in our work.

As a case study, in figures 15, 18, and 21, we illustrate the light intensity distribution of the each considered user sections (1, 61, and 121) respectively. It is observed that as the user moves within the room, as compared to the corner locations 1 and 121, in the middle positions the received power, i.e., individual light intensity, is more approximately 11.04 dBm. Besides, figures 16, 19, and 22 represented the beamforming in the user positions 1, 61, and 121. On the other hand, in our working process we have considered the power contribution of each LED for each section. The graphs below 17, 20, and 23 depict the median intensity for each point. From the plotted graph, it helps to determine that for communication, LEDs with intensities greater than or equal to the median are chosen for a certain user position. Thus, a lookup database is kept for selecting the LEDs that provide intensity levels above the median for each place (segment) of the produced results. When the user approaches to

a luminaire, the signal strength increases. The maximum signal strength (i.e., the maximum value of channel gain) occurs when the user is right under the luminaire. When the user walks away, the signal strength decreases. Figure 24, shows the comparison level of the beamforming at 1,161 and 121 user positions. The result shows that mid-user position 61 achieved the maximum beamforming level of 29.14 dBm while the other two corner positions achieved 26.99 dBm and 24.62 dBm. To further investigate the effects of user locations in terms of BER performance, we have simulated the resultant BER performance before and after beamforming in figure 25. The BER performance result shows that after beamforming, the SNR at segment 61 improves by 3 dB, whereas beamforming improves the SNR by 4 dB at segment 1. And, at segment 121, it improves by 4.7 dB.

Table 1: Simulation parameter used in our work.

Parameters	Values
Room dimension	L-5m, W-5m, H-3m
Hemisphere radius (Tx radius)	100 Nos
Coordinate transformed from spherical to Cartesian	X= 0.05-x, Y= 0.05-y
Angle of irradiance in half (radian)	$\phi = (7.5 \prod) / 180$
Power of LED (small)	P LED=1 W
FOV of User (PD)	$\psi c=(20 \prod) / 180$
PD area	7.8E-7 m ²

Table 2: Parameters used for offline μ GOA computing.

Symbol	Parameters	Values
N_{pop}	Population size	50
$Iter_{max}$	Maximum iteration	300
$P_{crossover}$	Probability of crossover	0.5
$P_{mutation}$	Probability of mutation	0.1

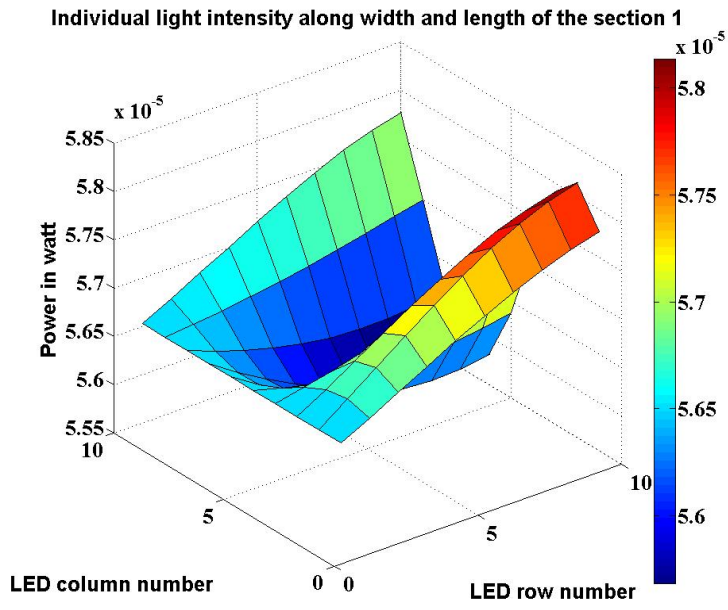


Fig. 15: Individual light intensity (section 1)

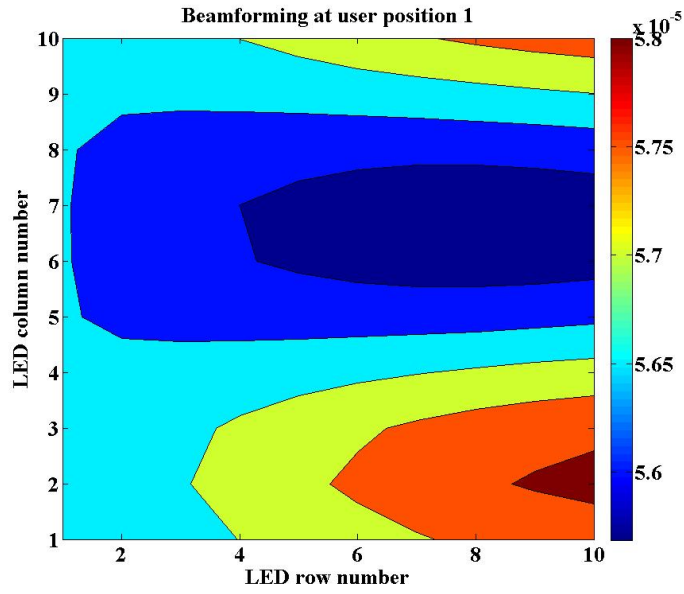


Fig. 16: Beamforming (section 1)

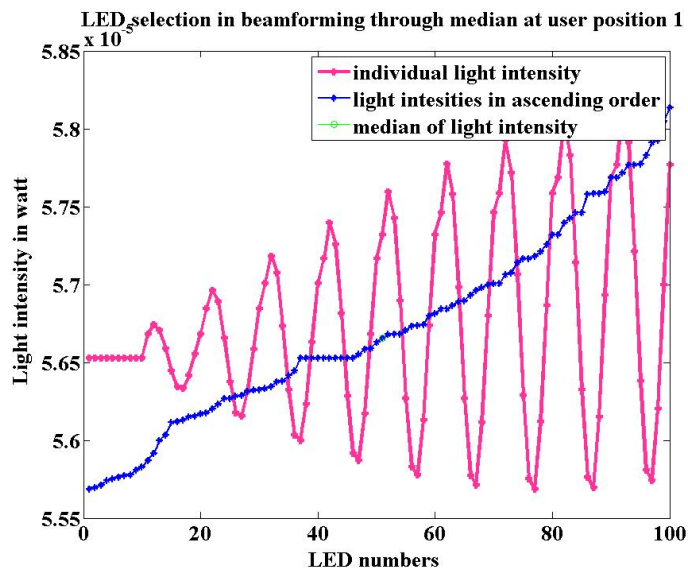


Fig. 17: LED selection in beamforming through median (section 1)

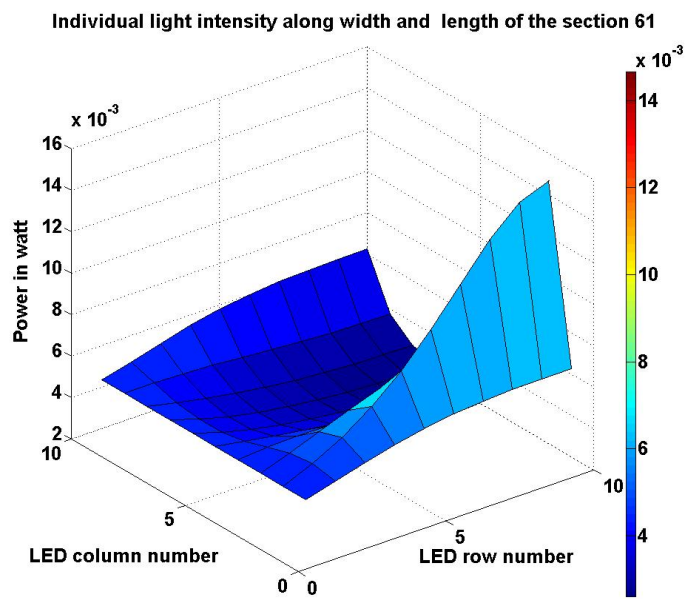


Fig. 18: Individual light intensity (section 61)

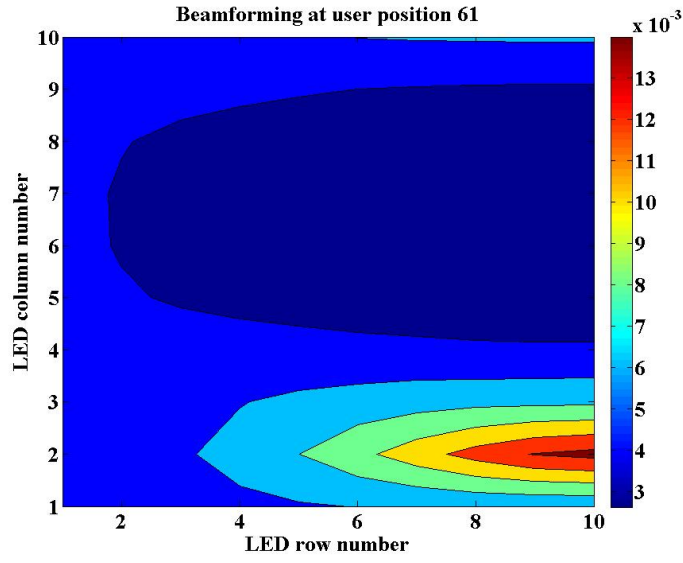


Fig. 19: Beamforming (section 61)

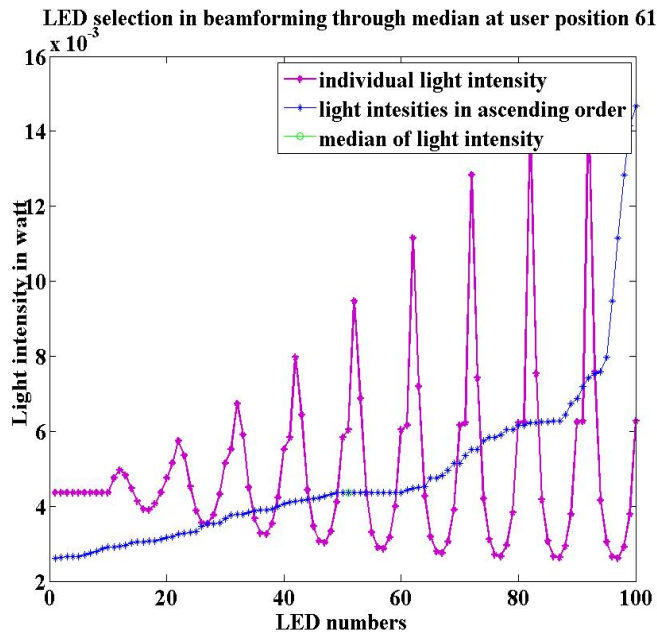


Fig. 20: LED selection in beamforming through median (section 61)

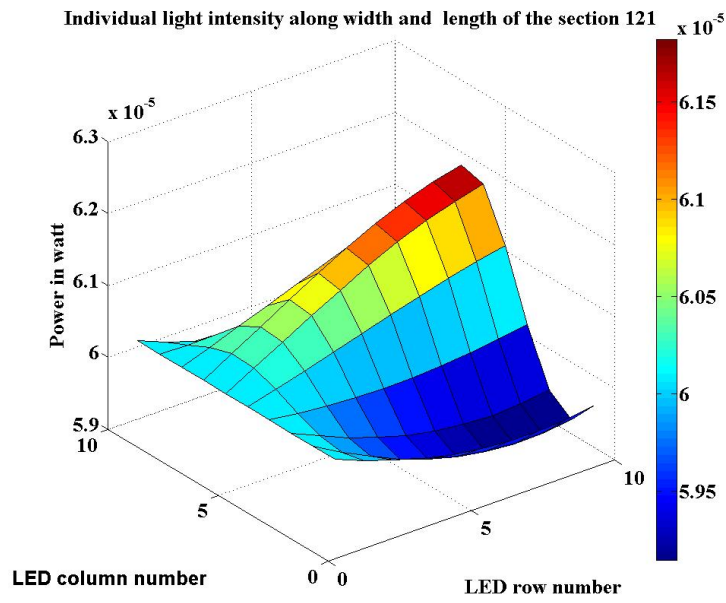


Fig. 21: Individual light intensity (section 121)

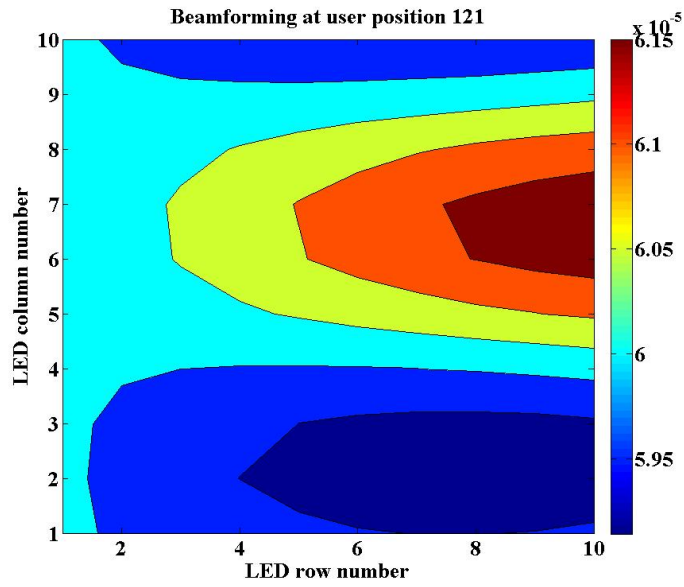


Fig. 22: Beamforming (section 121)

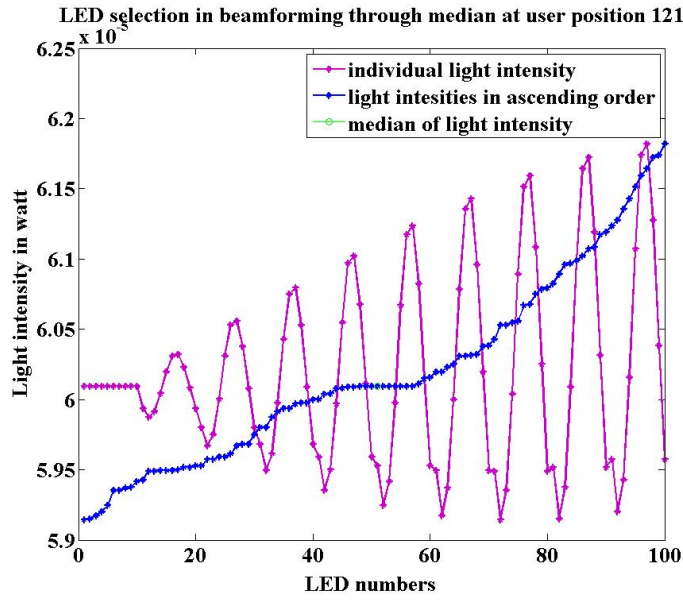


Fig. 23: User Position vs cumulative light intensity (section 121)

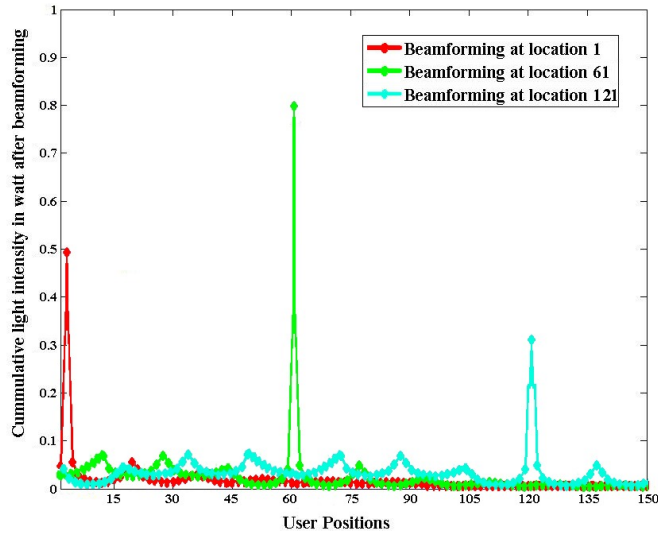


Fig. 24: BER performance section 1 vs 61 vs 121 (before and after beamforming)

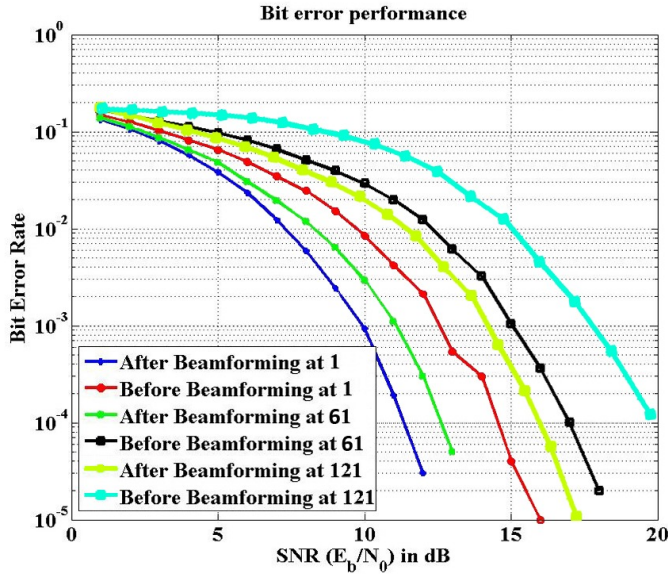


Fig. 25: BER performance section 1 vs 61 vs 121 (before and after beamforming)

4 Conclusion and Future Research

To support numerous users, we designed and demonstrated a hemispherical transmitter design layout for VLC that uses optical beamforming. We have shown the LEDs who are responsible to get maximum signal strength by using proposed μ GOA. We established a look up table and developed a μ GOA optimization method for power optimization. Finally, we assess the possible performance of μ GOA-based OB, i.e., BER vs SNR performance after and before beamforming for the three user positions, using extensive computer simulations. Our result shows the BER versus SNR comparison for three segments. We could see the after beamforming, the SNR at segment 61 improves by 3 dB. Furthermore, beamforming improves the SNR by 4 dB and 4.7 dB at segment 1, 121 respectively. The proposed technique is found to give precision during optical beamforming at user places while being system-independent. The findings presented here provide critical theoretical and practical insights that will aid in the design and execution of efficient indoor VLC communication.

Declarations

Ethical Approval

Not applicable

Competing interests

The authors declare that they have no competing interests.

Author Contributions

Conceptualization, methodology, formal analysis, writing—original draft preparation T.S.D. ; investigation, writing—review & editing, A.S.; visualization, J.Y.R.

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Availability of data and materials

This manuscript has no associated data.

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