A Simulation Analysis of LEDs' Spatial Distribution for Indoor Visible Light Communication

Ala’ Khalifeh1 · Karthikeyan Alakappan2 · Barath Kumar Sathish Kumar2 · Jayanth Srinivasan Prabakaran2 · Prabagarane Nagaradjane2

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Abstract
Visible light communication (VLC) is a promising technology that can jointly be used to accomplish the typical lighting functionalities of the light emitting diodes (LEDs) and data transmission, where light intensity is modulated with the aid of a high rate data that cannot be noticed by the human eye. In this paper, a VLC simulation framework to study the effect of LEDs’ distributions on different room dimensions is proposed by considering the performance metrics such as light intensity quality in accordance with the International Organization for Standardization (ISO) recommendation, and data transmission efficiency measured in terms of bit error rate (BER). To achieve that, a VLC communication system is designed that modulates the data, transmits it over the room utilizing the communication channel that is modeled using an accurate ray-tracing algorithm, and receives it. Our work is different from most of the published works, which studied either the data transmission efficiency or lighting quality but not both. In addition, our study investigates the effect of having different rooms dimensions and different number of transmitters on data transmission quality and light illumination. Consequently, this paper can be used as a methodological study to design an efficient VLC system that satisfies the ISO lighting requirement and the VLC application-specific BER requirements. Furthermore, a video transmission use case has been demonstrated, which shows how video quality can be significantly improved when the number of transmitters is increased. However, considering the ISO lighting requirements, one can put a limit on the number of LEDs that can achieve the required application BER and lighting requirements, thus achieving both objectives efficiently.

Keywords Visible light communication · Light engineering · BER · ISO lighting requirements · Video transmission

* Ala’ Khalifeh
ala.khalifeh@gju.edu.jo

Extended author information available on the last page of the article
1 Introduction

Nowadays, wireless networks have seen an unprecedented demand for increased data rate requirements. To facilitate realistic coverage with the data rate requirements, a considerable bandwidth is needed which remains a limiting factor due to the scantiness of radio frequency spectrum which bears the entire load of commercial and noncommercial wireless transmission applications. Most of the wireless communication systems are based on radio frequency (RF) communication technologies. The applications are numerous, that range from maritime radio navigation to satellite communications. The advancement in data streaming and multimedia has an adverse effect on the available radio spectrum, which is soon set to hit a roadblock. Consequently, of late, researchers across academia and industries have started exploring alternate wireless transmission technologies to meet the ever-increasing demand. The ultraviolet spectrum is too dangerous for humans, and hence, precludes its use in commercial applications. The infrared spectrum has also proved to be futile for commercial wireless transmission due to the power limitations and safety to the human eyes. In this context, the huge bandwidth available in the unlicensed electromagnetic spectrum in the optical domain is seen as a promising solution to the spectrum crunch. In view of this, research on wireless optical communications has seen an upsurge interest in the past decade [1]. Visible light communication (VLC) makes use of the higher frequencies in the visual band and extends the capabilities of data transmission using general light sources. It transmits data by high-speed switching or flickering at a rate that is not perceivable to the naked eye. VLC has been regarded as an appealing communication technology to fulfill the high data rate demands and as a new affiliate in the beyond, fifth-generation (5G) heterogeneous networks (HetNets). As 5G, networks are being deployed, VLC can aid in the design of hybrid systems that can utilize both the radio and visible spectrum to facilitate the high-speed data transmission without imposing much strain on the radio spectrum.

Additionally, significant research had been devoted to the optical spectrum specifically in the infrared region [2, 3]. Furthermore, advancements in illumination technology coupled with research efforts on high data rate have made VLC indoor optical wireless communications a reality [4]. The use of light emitting diodes (LEDs)-based transmitter and photo detector-aided receivers that are of low cost and highly energy-efficient when used in VLC, offers significant advantages in both lighting and wireless communications. An LED lighting equipment is easy to install and safe to the human eye. LEDs are available in different shapes to aid specific illumination and communication aspects, offer good modulation performance, longer life span, and excellent brightness. Moreover, the low-energy consumption and high-speed data communication that can be achieved by using LEDs along with the exploitation of huge bandwidth available in the unlicensed spectrum results in a new paradigm for data transmission. Besides, energy-efficient illumination and lighting functionality can also be attained.

Apart from the usage of the visible light spectrum by the VLC system, it offers several other advantages. To be specific, it offers secured communication, and thus provides protection against eavesdroppers and illegal tapping of data. To receive the data, the user or the receiver has to be in the field of view of LEDs, which will be noticed by the users in the room. The VLC system is also less hazardous to human health. In comparison to the infrared and ultraviolet communication, a VLC system can be implemented more comfortably and, consequently, a higher transmission power can be used to improve the communication link quality. In addition, VLC in the visible light spectrum is different from
the RF spectrum and does not interfere with the existing RF communication devices [1]. This allows the VLC system to easily satisfy the electromagnetic compatibility requirements, and hence, VLC systems can be used in environments, where the electromagnetic interference is deemed undesirable, for example, in places such as hospitals, airplanes, and chemical plants. VLC can also be used in many application scenarios such as underwater communications where short radio waves cannot penetrate through long distances in water and as indoor positioning systems for departmental stores. In addition, the huge indoor setups that require directions for efficient movement may use LED arrays placed few meters apart throughout the indoor setup. It also finds an interesting application in the automotive industry in the form of vehicular VLC, which enables the communication between cars, traffic signals, and road signs. Cooperative RF-VLC communications finds application in a typical cellular network, device-to-device communications, and in many other application scenarios as explained in [5–7].

The rest of the paper is organized as follows: Sect. 2 presents the most related work in the literature. Section 3 describes the indoor VLC system model. Section 4 demonstrates the LED spatial distribution simulation setup. Section 5 presents the simulation results and performance evaluation. Finally, Sect. 6 concludes the paper and presents the future work.

2 Literature Review

In [8], Cheng et al. presented a ray-tracing algorithm based on wavelength for modeling multisource indoor channel impulse response for VLC, and demonstrated that blue LED exhibits a larger bandwidth in a plastic wall room. In particular, this research contribution has analyzed the root-mean-square (RMS) delay spread and average delay for three wavelengths. This work has illustrated that blue LED has larger bandwidth than other LEDs. By contrast, in [9], authors have employed white LEDs for not only illuminating the rooms but also realizing VLC for indoor communications. Furthermore, with the help of numerical analysis, the influence of reflection and interference have been studied. A multi-user multi-input single-output (MU-MISO) VLC broadcast is delved into with zero forcing (ZF) and ZF-dirty paper precoding techniques and biasing model for an indoor scenario [10]. The authors here have addressed the optimization problems in order to maximize the throughput subject to the optical transmit power constraint. In the research article [11], authors have addressed few basic techniques and key issues related to VLC realization. In [12], a MATLAB-based simulation study has been reported which analyzes the distributions of illuminance and RMS delay-spread for an indoor VLC landscape. The simulation program considers the transmitters’ positions and reflections at each of the walls for an indoor VLC system. The authors in [13] have realized a digital transmission with the aid of RS-485 protocol. More specifically, the authors have exploited off-the-shelf white LEDs and demonstrated an indoor wireless VLC system that provides coverage of 2.5 m and7–10% bit error rate (BER). Zeyu et al. [14] have presented a new indoor VLC prototype that uses diffuse links to achieve acceptable data rates. This VLC system also supports mobility under line of sight (LOS) while at the same time, aiding illumination and transmission in excess of several meters. Additionally, it has been demonstrated that this VLC system is capable of delivering data rate excess of 1 Mbps.

In [15], the impact of different modulation schemes including multiple pulse position modulation is discussed. It also explored the performance of the different modulation schemes for VLC by comparing the BER, signal-to-noise ratio (SNR) and data rate. The
main aim was to perform the flickering improvement and dimming sustainability to offer optimal data rates for communication. The contribution in [16] reports a new constellation design called space-collaborative constellation for an indoor multi-input multi-output (MIMO) VLC. This new design has been shown to provide better BER under adverse operating condition than the conventional approaches that employ repetition code, spatial modulation and spatial multiplexing. In the research paper [17], the scope of the VLC to serve as a complementary technology to the current radio frequency standards is discussed. The paper includes a comprehensive survey of VLC, as well as the main concepts and challenges related to this emerging area. In [18] and [19], we have studied experimentally an indoor VLC system. In particular, in these contributions we have implemented, tested, and evaluated an indoor VLC setup. In [20], the performance of an indoor VLC system with randomly deployed LEDs is compared with fixed geometries such as circular and square. The SNR profile inside the room that changes with respect to LED placement as well as receiver’s position has been compared between different arrangements. Further, in [21], we have evaluated the potential utilization of VLC for car-to-car communication, and studied the effect of shadowing on VLC performance in [22]. Recently, we investigated the effects of shifting the LEDs transmitter and receivers positions on the communication performance in [23].

In [24], the authors introduced the application of machine learning in VLC and analyzed the performance of five deep learning algorithms in the VLC system. Specifically, the challenges and the possible prospects of machine learning (ML) in the context of VLC are addressed in [24]. Cen et al. [25], investigated the performance of an indoor multi-user VLC system aided by $2 \times 2$ multi input multi output non-orthogonal multiple access (MIMO-NOMA) with the aid of numerical simulations. In particular, the authors have employed NOMA to improve the sum-rate of a multiuser MIMO-VLC system. The contribution in [26], reports the performance of an indoor VLC system that endures multiple shadowing. This work, more specifically considered the room boundaries as well as the overlap between shadows. The impact of shadowing is analyzed in the context of throughput and outage probability by deriving mathematical expressions of the shadow region and position by considering the room dimensions. In [27], Windisch et al. have demonstrated the behavior of high efficiency LEDs in optical data transfer. Here, a detailed analytical framework is presented for the switch-on and switch-off transients of the LEDs under consideration. Also, the authors in [27] have combined thin active layer and surface textured thin-film LEDs in order to significantly improve the light extraction efficiency, with quantum-well LEDs, it is demonstrated that bit rates close to 2 Gbits/s is achieved.

The authors in [28], proposed a framework that offers a larger working area for an indoor VLC. Specifically, here, the authors have used a high power LED panel connected in series in conjunction with a low complexity modulation circuit that employs MOSFET to realize the largest working area at a data rate of 2 Mbps in a VLC setting. Additionally, it is showed that a communication distance of 5 m can be achieved in an area of $\sim 78.5 \text{ m}^2$ and a longitudinal distance of 3 m at 1 Mbps data rate. With 4-pulse Amplitude modulation (PAM), it has been demonstrated that double the data rate can be achieved with this proposal. In the work of [29], the authors have dwelled into the performance of a multi-user indoor VLC system by using Hadamard-coded modulation (HCM). It is found that optimally assigning code words to each of the users results in a significant improvement in terms of the achievable average throughput, almost twice the random assignment for a distinctive scenario. Moreover, this work utilized more than one codeword for each of the users in scenarios where the number of active users is less than the size of the Hadamard matrix in order to further improve the throughput of the
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This work also examined the diversity performance by transmitting the same data by multiple LEDs in an indoor communication scenario. In [30], Li et al., have assessed the feasibility of utilizing the existing indoor LED infrastructure (60×60 cm2 LED panel) to provide data communication. In this contribution, the authors have used all the modules of the LED panel and with minor modifications; they were able to implement the VLC. With this arrangement, it has been demonstrated that a data rate of 40 Mb/s can be obtained at a 2 m distance when multi-band carrierless amplitude and phase (CAP) modulation is used. Also, the authors have proposed a solution based on digital signal processing to take the edge off the flicker issue that precludes the achievement of the high data rate and quantified the effectiveness of the same through experimental validation.

The research contribution in [31], reports a novel ns3-based VLC system that can be readily used to investigate the performance of VLC-RF heterogeneous networks for an indoor scenario through simulation. The authors have tested the developed model and validated their proposal with the aid of a software-defined radio system, photodetector, white LEDs by considering phase shift keying (PSK) and quadrature amplitude modulation (QAM). Moreover, it has been demonstrated that how their proposed model can be employed to forecast the performance of a hybrid Wi-Fi/VLC network under different network loads. A modified evolutionary algorithm (MEA) is proposed to optimize the SNR in an indoor VLC in [32]. The SNR optimization is achieved by the selection of the LEDs in the LED array. It had been shown that this MEA attains faster convergence and at the same time yields larger SNR than the hyper-heuristic approach. In [33], the performance of a VLC system is studied for random location and orientation of the receivers. For the random location and orientation, exploiting the statistical nature of the channel, the authors have derived the closed-form expressions for outage probability and capacity and verified their accuracy. In addition, the impacts of optical intensity, receivers’ zone radius, transmitter height, Lambertian emission order, dimming target, and outage threshold have been analyzed in this work for the considered VLC system. In [34], the authors have exploited the advantages of meta heuristic approach in conjunction with enhanced gray wolf algorithm to improve the localization in the context of NLOS scenario in VANET and demonstrated that their approach has resulted in better message delivery rate and awareness of neighborhood. In addition, it has been shown that their proposal has resulted in reduced latency and MSE rate.

This work extends our previous works that aimed at designing and implementing a realistic yet efficient VLC transmission system. To be specific, compared with the work presented in the open literature and our earlier work reported in [23], the main contributions of this paper are summarized as follows:

- We present an expanded simulation analysis where the effect of the number of LEDs transmitters and their positions for different room sizes have been simulated and studied taking into consideration both the ISO office lightning recommendation and the performance evaluation of the communication channel measured in the BER.
- A realistic non-LOS channel model using a ray-tracing technique has been utilized in the simulation, which gives a more realistic result when compared with most of the presented works in the literature that utilize simplistic LOS channel model.
- The illumination analysis for the LEDs’ positions has been presented, thus giving a comprehensive study for both data transmission efficiency and light illumination quality according to the ISO standards.
• A video transmission use case of VLC utilizing different number of transmitters has been demonstrated where the effect of the number of LEDs on the received video quality and the room’s lighting quality are discussed and analyzed.

Furthermore, Table 1 summarizes our contributions compared with the literature work.

3 Indoor VLC System

A typical VLC system is depicted in Fig. 1. In what follows, a brief description of each block is provided.

3.1 Bit Stream Modulation

As depicted in Fig. 1, the data bit stream is input to a modulator where an on–off keying (OOK) modulation is utilized. There are number of modulation schemes, which can be used for VLC. A logical bit one is simply represented by an optical pulse that occupies the entire or part of the bit duration, while a logical bit zero is represented by the absence of an optical pulse. Both the return-to-zero (RZ) and non-return-to-zero (NRZ) schemes can be applied. In the paper, the OOK NRZ is used although it yields relatively low data rate compared to other modulation schemes, but the BER performance is the best for OOK modulation compared to other modulation schemes [35], which makes it a good candidate for applications that require high reliability than high data rates.

3.2 VLC Transmitter

In VLC, LEDs play the role of transmitters along with its usual role as a lighting device. LEDs are currently the best transmitters due to their long lifetime, cost effectiveness and energy efficiency. LEDs are normally modeled as Lambertian source where the luminance is distributed uniformly in all directions, whereas the luminous intensity is different in all directions.

The LED luminous intensity is given by Eq. (1).

\[ I = \frac{d\Phi}{d\Omega} \]  

(1)

where \( \Phi \) is the luminous flux, and \( \Omega \) is the spatial angle. Furthermore, the electric flux \( (\Phi_e) \) can be calculated using Eq. (2).

\[ \Phi_e = K_m \frac{780}{380} V(\lambda) \times \Phi_e(\lambda) d\lambda \]  

(2)

where \( K_m \) is the maximum visibility equals to 683 lm/W at \( \lambda = 555 \) nm. The optical transmitted power \( P_t \) is given by Eq. (3).

\[ P_t = \int_{\Lambda_{\min}}^{\Lambda_{\max}} \int_{0}^{2\pi} \Phi_e dA d\lambda \]  

(3)

where \( \Lambda_{\min} \) and \( \Lambda_{\max} \) are determined by the photo diode sensitivity curve. The luminous intensity for a Lambertian source in angle \( (\varphi) \) is given by Eq. (4) [9].
Table 1 A Comparison table with related works

| Related work       | LEDs’ transmitters spatial distribution analysis | Consider a realistic non-LOS communication channels | Evaluate lighting quality | Evaluate communication quality | Demonstrate a practical use case scenario |
|--------------------|-----------------------------------------------|--------------------------------------------------|--------------------------|-------------------------------|------------------------------------------|
| Cheng et al. [8]   | No                                            | Yes, presented a ray tracing analysis for VLC channel | No                       | Yes                           | No                                       |
| Komine et al. [9]  | Yes, but limited to one possible arrangement   | Yes                                              | Yes                      | Yes                           | No                                       |
| Nguyen et al. [12] | Yes, but limited to one possible arrangement   | Yes                                              | Yes                      | No                            | No                                       |
| Wu et al. [14]     | Yes, but limited to one possible arrangement   | Yes                                              | No                       | Yes                           | No                                       |
| Chen et al. [25]   | No                                            | No, only LOS channel is considered                | No                       | Yes                           | No                                       |
| Tang et al. [26]   | Yes, but limited to one possible arrangement   | Yes                                              | No                       | Yes                           | No                                       |
| Huang et al. [28]  | Yes, but limited to one possible arrangement   | No                                               | No                       | Yes                           | No                                       |
| Jie et al. [29]    | Yes, but limited scenarios                    | Yes                                              | No                       | Yes                           | No                                       |
| Li et al. [30]     | Yes, but limited scenarios                    | Yes                                              | No                       | Yes                           | No                                       |
| Fu et al. [33]     | Yes, but limited to one possible arrangement   | No                                               | No                       | Yes                           | No                                       |
| Kaviarasan et al. [34] | No                                           | Yes                                              | No                       | Yes                           | Yes, localization in vehicular networks |
| Our paper          | Yes                                           | Yes                                              | Yes                      | Yes                           | Yes, video transmission use case         |
where $\varphi$ is the angle of irradiance, $I(0)$ is the center luminance intensity that corresponds to the case, where $\varphi = 0$, and $n$ is the Lambert index calculated using Eq. (5) \[9\].

$$n = -\frac{\ln 2}{\ln \cos \varphi_{1/2}}$$

Figure 2 depicts the main parameters used in characterizing an LED source and a photodiode receiver such as the field-of-view (FOV), and $\varphi_{1/2}$ the transmitter’s semi-angle at half-power, $\theta$ is the angle between LOS path and the normal to the receiver mesh-grid.

### 3.3 NLOS Channel Model

Two channel types are commonly used to model a VLC system. The first one is the LOS model, while the other is the non-LOS model or sometime called as the diffused link channel model \[35\]. In case of the LOS channel, the transmitter and receiver communicate through direct LOS transmission using narrow beams, where no wall or surrounding reflections are considered. This type of channel can be used for high transmission rates. However, this type of transmission faces shadowing effect and blocking, and may not resemble the realistic scenarios where light beams undergo different paths and reflections before reaching the receiver. NLOS channel, on the other side, takes into consideration the possible reflections of the light beams from the walls and surrounding environments, and hence it is considered more realistic and practical. Clearly, this type of channel experiences multipath effects due to multiple reflections, but it does not experience the shadowing effect like the LOS channel. In this paper, we will be considering the NLOS channel in order to analyze the performance of the VLC system. The paper uses an enhanced Monte Carlo
ray-tracing algorithm to determine the impulse response of an indoor VLC channel based on the work presented in [36] and [37]. The paper utilized and modified the implementation MATLAB code of these algorithms, which is available in [38].

3.4 Channel Impulse Response Estimation

To generate a VLC indoor channel impulse response, the MMC algorithm is used. Several rays are generated from the emitter position with a distribution probability that equals to the emission profile or the angular optical intensity function. When the rays strike the obstacles along the path, the point where they strikes the obstacle is taken as an optical source from where a new ray is generated. This is because LEDs are considered Lambertian sources. The process continues until the time of flight. After every reflection, the power of the ray is decreased by the reflection coefficient of the obstacle. When a ray strikes a point, a new ray is generated and the reflected power contribution towards the receiver is calculated. In this paper, three reflections are considered as they contribute to most of the reflected power and rest of the reflected power contribution is ignored, as higher order reflections are negligible. This process is continued for all the rays generated from the source. Figure 3 shows a sample NLOS impulse response in time and frequency domains for an indoor room with a single transmitter and a receiver located at [3.5, 3.5, 3], [0.5, 1, 3] m, respectively, in a room of dimension [7, 7, 3] m.

![Fig. 3](https://example.com/figure3.png)

**Fig. 3** A NLOS impulse response in **a** time and **b** frequency domains for an indoor room of a single transmitter and a receiver located at [3.5, 3.5, 3], [0.5, 1, 3] m, respectively, in a room dimension of [7, 7, 3] m
3.5 VLC Receiver

The light pulse is transmitted through a multi-path diffuse channel and received at the photodetector. The received signal is passed through a matched filter. The detected signal at the input of the matched filter is given by Eq. (6).

\[ i(t) = I_p \ast h(t) + n(t) \]  

(6)

where \( h(t) \) is the NLSO channel impulse response which is estimated by the MMC algorithm, the symbol \( (\ast) \) represents the convolution operation, \( n(t) \) is the additive white Gaussian noise due to shot noise, ambient light and thermal noise. \( I_p \) is the peak photocurrent [36, 39]. The received bits are then demodulated, and the performance in terms of BER is evaluated for different number of LEDs transmitters, positions, and rooms’ dimensions as will be explained in the next section.

4 LEDs’ Spatial Distribution and Illumination Evaluation

In order to analyze the performance of VLC for different LEDs’ spatial distributions, different scenarios have been considered where the number of transmitters, their positions, the room dimensions have been varied. Furthermore, the number of rays used in modeling the channel, and simulating the spatial distribution of the LEDs, which are noticed to be affecting the performance of the system have been studied as well. A grid arrangement of LEDs has been used which is achieved by dividing the room into equal grids both horizontally and vertically depending on the number of LED transmitters, where one transmitter is allocated to each grid. Different room dimensions have been investigated as will be depicted in the simulation section. In order to simulate the grid arrangement, two mesh-grid functions in MATLAB tool have been used to simulate the transmitter and receiver planes. On the transmitter mesh-grid, the positions of the ceiling lamp arrays are set. On the other hand, the positions of the receivers are not fixed. Since the received light across the entire space is being measured, the receiver mesh-grid is assumed a continuous plane of photodiodes, with each point on the grid representing the received power of a photodiode at that location. However, due to the simulation limitation, the “continuous” plane of photodiodes is modeled as a set of discrete points on the mesh-grid. The resolution of the receiver mesh-grid could be increased at the cost of longer simulation runtime. To measure the effect of every array at each point on the receiver plane, the distance between each transmitter and every point on the receiver plane needs to be calculated as seen in Fig. 4. The distance is measured by using Eq. (7).

\[ d_{t-r} = \sqrt{(x_r - x_t)^2 + (y_r - y_t)^2 + h^2} \]  

(7)

where \( d_{t-r} \) is the distance between the transmitter and receiver. Following the calculation of the distance, the measurement of the angle \( \theta \) between LOS path and the normal to the receiver mesh-grid needs to be calculated. This is calculated using the simple trigonometry relation as given in Eq. (8).

\[ \theta = \cos^{-1} \left( \frac{h}{d_{t-r}} \right) \]  

(8)
To calculate the channel gain \( G \), we use Eq. (9) [40].

\[
G = \frac{(n + 1) \times DA \times \cos(\varphi)^{(n+1)}}{2\pi \times d_{t-r}^2}
\]  

(9)

DA is the photo-detector area. The calculation of the received power \( P_r \) must take into account the remaining parameters set at the beginning of the simulation for additional optional components. The power transmitted \( P_t \), the optical concentrator gain \( C \), the optical filter gain \( F \) as well as the calculated channel gain are all considered in Eq. (10) [40].

\[
P_r = P_t \times G \times C \times F
\]  

(10)

The received power has a direct effect on the performance of VLC. For instance, if we use a NRZ-OOK modulation scheme, then the probability of the error is given by Eq. (11) [10]:

\[
p(e) = Q\left(\sqrt{\text{SNR}}\right)
\]  

(11)

where \( \text{SNR} = \frac{P_r}{P_n} \), where \( P_n \) is the noise power at the receiver, and \( Q(.) \) is the Q-function calculated using Eq. (12).

\[
Q(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-y^2/2} dy
\]  

(12)

Finally, the photodiodes placed far enough from the light source that have a receiver angle higher than that of the initially set FOV value are assumed to receive no light. Therefore, a “find” function in MATLAB is called to find all the photodiodes with receiver angle that exceed the FOV angle so that their respective received power can be set to zero. Using the matrix properties in MATLAB, all the previously mentioned calculations can be performed for every point on the receiver mesh-grid. This will result in the power distribution for a single array of LEDs at a single point, i.e., one ceiling lamp. In order to evaluate the effectiveness of the grid arrangement on the illuminance intensity, the illuminance due to the positioning of LEDs is evaluated using the horizontal illumination \( E_h \) given by Eq. (13) [23].
Several experiments have been conducted to analyze the effects of changing the number of LED transmitters and their locations for various room dimensions. The main target of the simulation analysis is to study both the LEDs’ illumination efficiency and performance of the VLC systems. MATLAB is used to generate the simulation results. The simulation code is a modified version of the code presented in [12, 38]. The main simulation parameters used in this work is depicted in Table 2.

### Table 2 VLC main simulation parameters

| Parameter | Value/equation |
|-----------|----------------|
| $\varphi_{1/2}$ | 70° |
| Transmitted optical power by individual LED | equals to 20 dBm |
| NLED: Number of LEDs | 60 |
| Note: Number of LED array = | NLED×NLED |
| $P_t$: total transmitted power | NLED×NLED×PLED |
| $D_A$ | $10^{-4}$ m |
| $T_s$: gain of an optical filter | 1 |
| Index: refractive index of a lens at a PD | 1.5 |
| FOV | 70° |
| $l_x,l_y,l_z$: Room dimensions in meter | 5:5:3 m |
| $h$: the distance between the source and receiver plane | 2.15 m |
| $\theta$ | 30° |
| $n$ | 1 |
| Central luminance intensity ($I_o$) | 0.73 lx |
| Total luminance intensity | $60 \times 60 \times I_o$ |

An essential function of the VLC system is to provide efficient lighting. Hence, the LEDs’ illumination efficiency for different scenarios has been investigated. According to the International Organization for Standardization (ISO), the illuminance has to be between 300 and 1500 lx for office work [8].

Table 3 shows the coordinates and allocations of eight different LED transmitters for a 7×7×3 m³ room dimension. One can notice that whenever the number of LEDs is odd, a preference in terms of increasing the number of LEDs is given to the room center, where probably people are mostly residing most of the time. Furthermore, it is worth mentioning

$$E_h = \frac{I(0) \times \cos^n \varphi}{d_{i-r}^2} \times \cos \theta$$
that an array of LEDs as shown in Fig. 5 is typically used to satisfy the illumination requirement, which is used in our simulation. Thus, each dot in the LEDs arrangement of Table 3 consists of an array of LEDs.

Table 4 depicts the illumination results for a room of dimension $7 \times 7 \times 3 \text{ m}^3$ with different number of transmitters. From the results, it can be seen that even for a room of

| No. of LED transmitters | LEDs’ array arrangement |
|-------------------------|-------------------------|
| 1 Transmitter | coordinates: (3.5, 3.5) |
| 2 Transmitters | coordinates: (1.75, 3.5), (5.25, 3.5) |
| 3 Transmitters | coordinates: (1.75, 3.5), (3.5, 3.5), (5.25, 3.5) |
| 4 Transmitters | coordinates: (1.75, 1.75), (5.25, 1.75), (1.75, 5.25), (5.25, 5.25) |
| 5 Transmitters | coordinates: (1.75, 1.75), (5.25, 1.75), (3.5, 3.5), (1.75, 5.25), (5.25, 5.25) |
| 6 Transmitters | coordinates: (1.75, 1.75), (3.5, 1.75), (5.25, 1.75), (1.75, 5.25), (3.5, 5.25), (5.25, 5.25) |
| 7 Transmitters | Coordinates: (1.75, 1.75), (3.5, 1.75), (5.25, 1.75), (3.5, 3.5), (1.75, 5.25), (5.25, 5.25) |
| 8 Transmitters | coordinates: (1.4, 1.75), (2.8, 1.75), (4.2, 1.75), (5.6, 1.75), (1.4, 5.25), (2.8, 5.25), (4.2, 5.25), (5.6, 5.25) |
such large size, close to 100% illumination efficiency is attained which indeed satisfies
the ISO standards for number of transmitters that equals to 6 or more. Furthermore, this
result advocates the effectiveness of our proposed LED grid arrangement that is utilized
in the room ceiling. Additionally, Table 5 verifies the above results by showing a grey
colored figures, where areas that satisfy the ISO illumination standard are colored in
light grey, while the ones that do not satisfy it are colored in dark gray. Yet again, it is
clear that when the number of LEDs is increased to 6, illumination efficiency is satis-
fied in accordance with the ISO illumination standard. For further illustration, the table
shows the contour and mesh diagrams for various light distributions. It is noteworthy
that we have carried out the simulation experiments for different room sizes. From the
results, we infer that for each room size, we require a minimum number of LEDs to
satisfy the ISO illumination requirements, so that both the light illumination and data
transmission efficiency can be jointly obtained. Furthermore, this study will aid us to
decide on the minimum number of LEDs that will yield satisfactory light illumination
thereby resulting in improved data transmission efficiency. In the next section, the per-
formance evaluation in terms of light illumination and data transmission efficiency is
investigated for different light sources’ positions.

Table 4  Illumination results of different number of LEDs utilizing a grid arrangement for a room dimen-
sion of $7 \times 7 \times 3$ m$^3$

| Number of LED array transmitters | Average luminance of the room ($\ell_l$) | Percentage of room average illumination satisfying ISO standards (%) |
|---------------------------------|----------------------------------------|------------------------------------------------------------------|
| 1                               | 149.99                                 | 4.46                                                             |
| 2                               | 272.34                                 | 38.94                                                            |
| 3                               | 422.33                                 | 71.95                                                            |
| 4                               | 495.01                                 | 97.61                                                            |
| 5                               | 645.01                                 | 99.92                                                            |
| 6                               | 767.35                                 | 100                                                              |
| 7                               | 917.35                                 | 100                                                              |
| 8                               | 1009.5                                 | 100                                                              |
### Table 5  The effect of changing the number of transmitters on the room light illumination intensity

| Transmitters arrangement | Room light illumination showing areas satisfying and not-satisfying ISO standards, colored light and dark gray, respectively | Room Illuminance ($I_r$), contour diagram | Room illuminance ($I_r$), mesh diagram |
|--------------------------|----------------------------------------------------------------------------------------------------------------|------------------------------------------|----------------------------------------|

[Images of diagrams showing different transmitters arrangements and corresponding illumination maps]
5.2 LEDs’ Data Transmission Performance Evaluation

After studying the effect of changing the number of LEDs and their locations in a room light for illumination efficiency, it is important to study the performance of the data transmission ability, thus assuring that the LEDs can have an acceptable performance for both light illumination and data transmission. In particular, several design parameters such as the number of transmitters, receivers, and the room dimensions affect the data transmission performance. Hence, one of these parameters is kept fixed while the others are varied in our simulation, as will be discussed in the following scenarios. Table 6 shows the additional parameters used to simulate the VLC system.

5.2.1 The Effect of Number of LED Transmitters

The first scenario investigates the effect of LED transmitters distributed in a grid setup as described before for different room sizes. The room is designed with multiple receivers that are deployed in a grid formation with distance of 0.5 m between them. Figure 6a–d show the performance of the VLC communication system measured in terms of the attainable BER for different room sizes. As expected, it can be seen that the system performance is improved as the number of transmitter increases, especially when the SNR is low. However, at higher SNR, increasing the number of LEDs has small impact on improving the performance. One potential application scenario in this context can be transmitting the multimedia contents for the users who can tolerate small distortion in the multimedia content. As such for the case, increasing the number of LEDs is not going to result in a visible impact on the media content. Hence, the number of LEDs can be set to meet the ISO lighting standard (6 for the case of 7×7×3 m³ room dimensions).

5.2.2 The Effect of the Room Dimension

In order to have a closer look on the effect of changing the room dimension, here, for each experiment, the simulation setup that was used in the earlier setting is adopted. However, in this experiment, the number of transmitters and receivers are kept fixed while the room dimension is varied. Besides, note that we have employed the same receiver configurations used in the previous scenario. The system performance is measured for different SNR values. As depicted in Fig. 7a–d and Fig. 8e–h, regardless of the number of transmitters, the smaller room dimension has always resulted in a better performance than the larger dimensions. This is because the light path loss will be lower and the energy level will be higher in case of smaller room dimensions. Furthermore, the effect of multi-path will be insignificant.

| Table 6 Additional simulation parameters |
|------------------------------------------|
| Transmitter mode number | 1 |
| Emitting power | 1 |
| Receiver area | 0.0001m² |
| FOV | 85° |
| Reflections considered | 3 |
| Reflection coefficient | 0.8 |
| Number of rays used in the simulation | 1000 |
in the case of smaller room dimensions, which will not be the case in larger room dimension. In addition, when the SNR is low (<4 dB) and the number of transmitters is less than or equal, the system performance for all room dimensions is almost the same. However, increasing the number of transmitters more than 5 has a noticeable impact especially at low SNR values (from 4 to 6 dB). At higher SNR values (i.e., >8), the performance enhancement resulted from increasing the number of transmitters (>3) is more significant. This is apparent particularly for small room dimensions (4 × 4 × 3 m³ and 5 × 5 × 3 m³) than the cases of having larger room dimension (6 × 6 × 3 m³ and 7 × 7 × 3 m³) and higher number of transmitters (i.e., >3).

5.3 Video Transmission Over VLC Use Case

Multimedia transmission is one of the potential applications for using VLC where it can be used to transmit video and images containing promotions, ads, and coupons to potential customers while shopping and utilizing the shop lights. For example, a customer can position his/her smart phone under a product display, which uses the light to send an advertising signal. The mobile phone runs a special program capable of receiving and decoding the light signal and interpreting it as a coupon that can be used to get a discount on the displayed product. In order to assess the performance of the VLC system, we have used a normal video in AVI format for transmission purpose. It has 300 frames.

Fig. 6 The VLC system performance for different number of transmitters and receivers and different room dimensions: a 4 × 4 × 3 m³, b 5 × 5 × 3 m³, c 6 × 6 × 3 m³, and d 7 × 7 × 3 m³.
in the ratio of 4:3. The video obtained is then read as binary in our code. It is then transmitted through the designed channel. The received video after passing through the channel is obtained as binary and then written into AVI format video. Now, for every trial and case, we have the source and the received videos.

To check the quality of the received video, it has to be compared with the source video. There are two metrics for comparing the quality of the video: peak signal-to-noise ratio (PSNR) and structural similarity (SSIM) index [41]. We have used the SSIM for the quality evaluation, as it is more accurate in assessing the quality of the video file. SSIM has been designed to improve the traditional metrics like (PSNR) and mean-squared error (MSE) [42]. SSIM is used for measuring the similarity between two images. In SSIM, a distorted image is compared with the original uncompressed image as the reference. SSIM is an improved metric to the traditional PSNR. In order to calculate the SSIM value of two videos, both of them are separated into various frames. Each corresponding frames are compared and their SSIM value is calculated. Finally, the average of the entire SSIM value is taken to get the SSIM index for the compared videos. This process takes place for all the videos received. The SSIM index value varies from 0 to 1. The higher the value, the less is the distortion in the received video and the better is the quality and vice versa. Values 1, 0 represent the least and most distortion, respectively. Therefore, by transmitting the videos through the channel, we can check the efficiency of the VLC system and the effects related to different number of transmitters, receivers’ locations and different room dimensions. The SSIM metric is

Fig. 7 The VLC system performance while varying the room dimensions and changing the number of transmitters: a 1 b 2 c 3 d 4 transmitters
usually calculated on various windows of an image. The measure between two windows \( x \) and \( y \) of common size \( N \times N \) is described by Eq. (14).

\[
SSIM(x, y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}
\]

where

- \( \mu_x \): the average pixel values of a reference image \( (x) \)
- \( \mu_y \): the average pixel values of a reference image \( (y) \)
- \( \sigma_x^2 \): the variance of \( x \)
- \( \sigma_y^2 \): the variance of \( y \)
- \( \sigma_{xy} \): the covariance of \( x \) and \( y \)
- \( c_1 = (k_1L)^2 \)
- \( c_2 = (k_2L)^2 \)
- \( L = 2^8 \text{ bits per pixel} \)

\[ k_1 = 0.01, \quad k_2 = 0.03 \quad [41] \]

Fig. 8 The VLC system performance while varying the room dimensions and changing the number of transmitters: (a) 5, (b) 6, (c) 7, (d) 8 transmitters.
is the received video quality, which shows the efficiency of the proposed VLC system for multimedia transmission.

6 Conclusion and Future Work

In this paper, a simulation study is conducted to study the effect of the numbers and positions of LED transmitters for a VLC system in a room environment of different dimensions, on the lighting functionality and data transmission efficiency, measured in terms of the ISO light intensity standard metric and the BER, respectively. The outcome of our study can be used as a guideline to design an efficient VLC system capable of meeting the application BER requirements while keeping a good lighting quality according to the ISO standard. As a future course of work, we are working towards verifying the attained results and conclusions drawn to practically evaluate the quality of lighting and VLC application under consideration subjectively.

Authors’ Contributions Ala’ F. Khalifeh: Paper idea, writing, simulation coding and setup, Karthikeyan Alakappan: Paper writing, simulation coding and results’ analysis. Barath Kumar: Paper writing, simulation coding and results’ analysis, Jayanth Prabakaran: Paper writing, simulation coding and results’ analysis, Prabagarane Nagaradjane: Paper writing.

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Ala’ Khalifeh received the PhD degree in Electrical and Computer Engineering from the University of California, Irvine -USA in 2010. He is currently an Associate Professor in the Electrical Engineering department at the German Jordanian University. His research is in communications technology, and networking with particular emphasis on optimal resource allocations for multimedia transmission over wired and wireless networks, Quality of Service, Internet of Things and Wireless Sensor Networks.

Karthikeyan Alakappan received his Bachelor’s Degree in Electronics and Communication Engineering from Anna University, Chennai, India. He is currently pursuing a Master of Science in Electrical engineering from University of Southern California, Los Angeles, USA. His research is focused in wireless communications and networks with particular emphasis on multimedia transmission over wireless networks.

Barath Kumar Sathish Kumar Received his bachelor’s degree in Electronics and communication engineering from Anna University, Chennai, India. Currently he is pursuing his master’s degree in communication systems engineering, specializing in wireless communication from KTH Royal Institute of Technology, Stockholm, Sweden. His research interests are in the field of wireless communication and IoT.
Jayanth Srinivasan Prabakaran received his Bachelor’s in Engineering from Anna University, Chennai in 2020. He is currently a Master’s student at the University of Michigan, Ann Arbor, Department of Electrical and Computer Engineering. His research is in Wireless Communication Networks.

Prabagarane Nagaradjane is an Associate Professor with the Department of Electronics and Communication Engineering, SSN Institutions. His research interests include various aspects of wireless communications, especially with respect to signal processing for wireless and broadband communications. He is one of the founding members of Wireless Communications, Signal Processing and Networking (WiSP-NET) international conference technically co-sponsored by IEEE. He has guest-edited two special issues under the topic signal processing for 5G in Elsevier computers and electrical engineering journal and a special issue under the topic Future of Intelligent Wireless LANs in IET Communications journal. He also serves in the editorial board of Physical Communication and IET Communications journals as an area editor and associate editor, respectively.

Authors and Affiliations

Ala’ Khalifeh1 · Karthikeyan Alakappan2 · Barath Kumar Sathish Kumar2 · Jayanth Srinivasan Prabakaran2 · Prabagarane Nagaradjane2

Karthikeyan Alakappan
karthikeyan16048@ece.ssn.edu.in

Barath Kumar Sathish Kumar
barath16023@ece.ssn.edu.in

Jayanth Srinivasan Prabakaran
jayanth16045@ece.ssn.edu.in

Prabagarane Nagaradjane
prabagaranen@ssn.edu.in

1 Electrical Engineering Department, German Jordanian University, Amman, Jordan

2 Department of Electronics and Communication Engineering, Sri Sivasubramaniya Nadar College of Engineering, Chennai, India