

Enhancing signal reliability and illumination uniformity in indoor VLC systems via LEDs configurations

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With the ever-increasing realization of the limitations of the radio frequency (RF) spectrum in the evolution towards 5G and 6G communication systems, VLC has been recognized as a high-speed and secure communication system that supports gigabit-per-second data rates. However, in most cases, VLC communication systems are often hampered by issues related to line-of-sight (LOS) propagation and signal shadowing. This paper proposes the optimization of indoor VLC communication systems through the lighting geometry. Using the simulation environment set up in the $5\text{ m} \times 5\text{ m} \times 3\text{ m}$ indoor environment and carried out for different LED array patterns including single-centred patterns, square patterns, and circular patterns of 12-LEDs with a radius of 1.5 m, it was determined that the 12-LED array pattern with a radius of 1.5 m lead to an average SNR of 36.7 dB, a BER of 2.5×10^{-9} , and F_a of 8.24. The superiority of the proposed system was strictly observed in terms of significant improvement over the standard array patterns. Also, from the research carried out, it was ascertained that the proposed system can attain high-order modulation constellations of 256-QAM. The findings of the study clearly highlight that the collaboration of geometric organization and intelligent surfaces is critical in the design of future IoT-enabled communications and smart buildings requiring high spectral efficiency.

Keywords: visible light communication, 6G wireless networks, indoor illumination uniformity, signal-to-noise ratio, bit error rate, M-ary quadrature amplitude modulation, Internet of Things

1 Introduction

In recent years, the limitations of the radio frequency (RF) spectrum utilized in mobile communications have become more pronounced. This is a key difficulty to address regarding in terms of the traffic capacity requirements of fifth generation (5G) mobile communication with worrisome projections going past 5G and into the sixth generation (6G). This limitation leads to the densely populated deployment of RF access points, resulting in heavy competition for the available resources channels, which involves a degradation in service quality (QoS) [1-3].

Visible Light Communication (VLC) is a recent technological advancement that significantly improves traditional wireless communication systems. By utilizing visible light, which is largely generated by devices such as LEDs, VLC facilitates a highly effective and secure channel for the transmission of data in a wireless manner. Not only does this method make existing wireless networks more operative, but it also provides unparalleled benefits regarding data transmission rate, security measures, and spectrum availability [4, 5].

VLC offers numerous major advantages over traditional radio frequency (RF) communication technologies. VLC is based on a wide and open spectrum bandwidth of 430-750 THz, thus, it can potentially deliver data rates of gigabits per second (Gbps). It also has less latency because it needs a line of sight to propagate signals, and it is also less affected by electromagnetic interference [6, 7]. VLC does not utilize radio waves as RF systems do, making it more suitable for zones that require special care, like hospitals, factories, and defence areas. This technology does not allow signals to travel far, making it more secure, and it can make better use of the network by allowing signal reuse in small zones. Apart from that, VLC offers a two-in-one solution by combining data communication and lighting functionality. It uses already available lighting infrastructures to support modern wireless systems [8, 9]. One of the key benefits of VLC is that it can take advantage of the installed lighting infrastructure, given that LED technology serves a dual role in offering illumination and data transmission. This dual role not only increases energy efficiency but also helps in the adoption of environmental sustainability, especially when compared with conventional lighting systems [10, 11].

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Light Emitting Diode (LED) technology is employed in data transmission through VLC, leveraging its intrinsic benefits that include high efficiency, extended operational life, and low power usage. All these LEDs are excellently suitable for a variety of lighting and signalling applications. In Li-Fi (Light Fidelity) systems, LEDs act as multi-functional devices offering both light and data communication capabilities. The high switching and blocking capabilities of LEDs, accomplished at speeds imperceptible to the human eye, enable advanced data transmission. Furthermore, VLC has become a promising means of establishing wireless connections in the Internet of Things (IoT) network [12-15].

In Li-Fi technology, the incapability of light to penetrate opaque obstacles, such as doors and walls, is used to enhance network security and enable more controlled access. Secondly, if transparent objects are considered, the Li-Fi communication channel remains confined to devices placed within a targeted room, thus ensuring localized connectivity [12]. The economic benefit of Li-Fi technology to customers lies mostly in the fact that it uses an unlicensed spectrum, therefore not requiring permission from regulatory authorities. This aspect enables interference-free data transmission and promotes the use of Li-Fi where radio frequencies are unsuitable, for instance, underwater, where radio wave transmission is significantly limited. Li-Fi is particularly appropriate for application in sensitive contexts such as aircraft, hospitals, military bases, ships, and nuclear power plants, where the avoidance of electromagnetic interference is paramount. Besides, VLC achieves greater security from its inherent property of signal confinement because light signals cannot penetrate opaque obstacles such as walls. Due to this quality, VLC becomes the preferred technology for secure indoor environments such as medical centres, airplanes, underwater networks, and refineries where secure and interference-free communication upkeep is essential, some works have explored the application of VLC in different scenarios, including underwater communication, underground mining, and vehicular communication systems. VLC has also been researched for its application in positioning systems, for the transmission of 5G signals, and for IoT support, thereby facilitating Light-Fidelity (Li-Fi) networks [16].

This study investigates various luminaire distribution configurations to assess their effects on illumination uniformity and overall communication performance. In addition, the analysis examines the optimal luminaire count needed to ensure efficient system operation, while identifying the point at which increasing the number of luminaires provides limited improvement in both lighting consistency and communication reliability.

2 Literature review

This literature review examines a comprehensive array of issues related to VLC systems. LEDs are a basic part of many applications because they use less energy and last longer than other types of lighting [17, 18]. The main goal of this review is to look at different parts of VLC systems and use simulation to model their performance for more analysis. A thorough understanding of the basic principles, practical implementations, and unique challenges of VLC is essential for this investigation. The review also talks about things like system simulation tools, VLC-enabled audio and video transmission, LED-based light encryption methods, and using VLC technology for vehicle communication. In this scenario, some of the most important problems to think about are data rate limits, transmission range, line-of-sight (LOS) and non-line-of-sight (NLOS) conditions, uplink limits, regulatory frameworks, and electromagnetic interference in different VLC applications [4, 19].

The authors of [8] created an experimental setup for looking into both optical illumination and data transmission capabilities in VLC systems that use LED lighting. Their research evaluated the impacts of inter-symbol interference (ISI) and signal reflections in the communication environment. The authors examined attenuation caused by reflective surfaces and signal degradation stemming from inter-symbol interference (ISI). A significant finding of their research was the discovery of a correlation between the system's data rate and the field-of-view (FOV) utilized in VLC, underscoring the possibility of attaining high-speed data transmission rates of up to 10 Gb/s. Additionally, paper [20] examines the fundamental principles of VLC systems utilizing white LEDs, focusing on their incorporation with power line communication (PLC) for indoor broadband connectivity. The research investigated the viability of utilizing white LED infrastructure to enable both lighting and rapid data transmission. The authors used a VLC-based lighting system that could support strong data transmission to fill in coverage gaps and make sure that the indoor space always had a connection. In [21], the authors provided an overview of VLC, its basic principles, current challenges, and future scope. They discussed the rudimentary VLC system architecture and evaluated the performance based on some simple modulation techniques. From the results, it can be seen that LEDs can achieve SNRs greater than 40 dB and operate within bandwidths of the order of several MHz. They established equalization techniques as a method to extend the achievable data rates. Several techniques were assessed to support data rates in excess of 100 Mb/s. These included optical filtering, transmitter and receiver equalization, and optical MIMO transmission schemes. The authors discovered the technical difficulties involved in putting

high-speed VLC systems into place and examined how these parameters impacted the achievable data rates. Their findings illustrated the need for effective equalization, complex signal processing, sophisticated modulation schemes, or the use of parallel communication channels in order to achieve real-time data transmission at such high rates. These improvements, however, always add to the system's complexity, making deployment difficult.

In [21], the authors developed a simulation framework using MATLAB and Simulink to analyze the performance of indoor VLC systems. The developed simulation environment provides exhaustive transmitter positioning and wall reflections. The simulation environment can be used to study a series of parameters, which include light distribution, RMS delay spread, and the waveform of the received signal for different transmitter configurations and reflective 2 surfaces. First of all, this study focused on the illuminance distribution across the indoor environment, continuing with the RMS delay spread analysis, in single- and four-transmitter configurations.

Several studies have explored the application of VLC in multimedia transmission and intelligent transportation systems. In [22], VLC was demonstrated for simultaneous audio and video transmission over distances up to three meters, highlighting the relationship between illuminance distribution and light source placement, with potential for location-based services. Road-to-vehicle VLC systems were investigated in [23], where frequency-shift keying was employed to distinguish vehicle proximity, though the study did not account for environmental effects such as weather and multipath fading. Addressing this limitation, [24] evaluated vehicle-to-vehicle VLC performance under adverse atmospheric conditions and proposed a modified fixed decision threshold technique to improve signal detection in rainy environments. Further advancements include a road-to-vehicle VLC system utilizing LED arrays and high-speed cameras, as well as overlay coding techniques to significantly enhance data transfer rates for vehicular communication. Additionally, a cost-effective VLC system suitable for nighttime vehicular communication without the need for a service provider was presented in [25]. Finally, [26] proposed an efficient road-to-vehicle VLC system using LED traffic lights and high-speed cameras, achieving improved communication speed through advanced transmitter tracking and localization algorithms.

Several studies have addressed VLC channel modeling, tracking, security, and indoor applications. In [18], a simulation-based VLC channel model for automotive environments was developed using ray-tracing

techniques to evaluate V2V and V2I communication in urban and crossroad scenarios, demonstrating its relevance to intelligent transportation systems. Tracking and decoding challenges in vehicular VLC were investigated in [27], where LED array transmitters combined with M-sequence-based detection and inverted-signal tracking enabled reliable communication over distances of 25-80 m in dynamic driving conditions. Data security in VLC systems was addressed in [28-30], where novel and conventional encryption schemes including OFDM-based modulation and RSA encryption were shown to enhance secure data transmission with acceptable power penalties. Indoor VLC systems were comprehensively reviewed in [31, 32] highlighting algorithmic classifications, system design considerations, and the potential for high-accuracy positioning applications. Additionally, LED placement optimization for improved link reliability and illumination uniformity was examined in [33, 34] with results demonstrating notable improvements in signal-to-noise ratio and overall system performance.

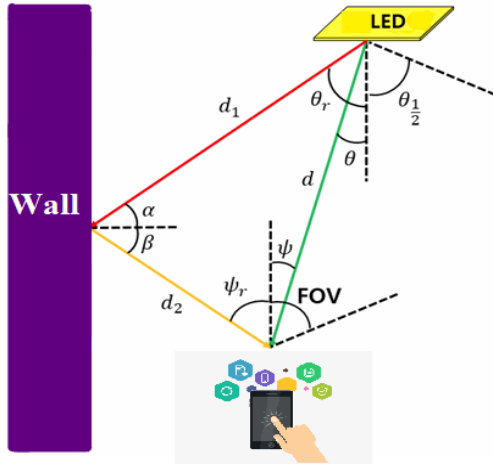
Recent research has explored the integration of reconfigurable intelligent surfaces (RIS) to enhance the performance of systems. In [35], a RIS-assisted parallel MIMO-VLC system was proposed to improve channel capacity by jointly considering line-of-sight and non-line-of-sight components under a Lambertian channel model. To address the resulting non-linear optimization problem, a low-complexity Relaxing Particle Swarm Optimization algorithm was developed, achieving significant capacity gains with reduced computational complexity. An integrated VLC and localization system employing liquid crystal-based RIS receivers was introduced in [36], where optimization of sum rate and energy efficiency demonstrated notable improvements in through-put, power efficiency, and positioning accuracy. Furthermore, [37] presented an indoor VLC system supported by both mirror-array-based RIS and liquid-crystal RIS receivers to mitigate line-of-sight blockages. By jointly optimizing mirror orientations and refractive indices using a sine-cosine optimization algorithm, substantial enhancements in data rate and energy efficiency were achieved compared to conventional and single-RIS-assisted VLC systems.

3 VLC system model

Herein, both line-of-sight and non-line-of-sight propagation mechanisms are considered to characterize the indoor communication channel. Figure 1(a) depicts the optical propagation mechanisms in an indoor VLC environment throughout LEDs configuration scenario communicate to different smart devices for IoT applications.



(a)



(b)

Fig. 1 (a) LEDs communication scenario communicates with IoT devices, and (b) Indoor VLC propagation mechanisms

The overall propagation channel is composed of two principal components: a direct line-of-sight (LOS) path and multiple non-line-of-sight (NLOS) paths. The LOS component, indicated by the green line, represents the direct optical link between the LED access point and the receiver as depicted in Fig. 1(b). In contrast, the NLOS components, illustrated by the red and yellow lines, arise from reflections off surrounding surfaces. Specifically, the NLOS propagation consists of an incident optical wave transmitted from the LED access point toward the wall (red line), followed by a reflected wave propagating from the wall to the receiver (yellow line). The channel characteristics associated with each of these propagation paths are analyzed in the following sections. The VLC channel follows a Lambertian radiation pattern, and the channel gain h for a line-of-sight (LOS) optical link is given by the following equation [35]:

$$h_{LOS} = \begin{cases} \frac{(m+1)A}{2\pi d^2} \cos^m(\phi) \cdot T_s(\psi) \cdot g(\psi) \cdot \cos(\psi), & 0 \leq \psi \leq \psi_c \\ 0, & \psi > \psi_c \end{cases}$$

$$h_{NLOS} = \frac{(m+1)A \cdot \rho}{2\pi d_1^2 d_2^2} \cos^m(\phi) \cdot \cos(\alpha) \cdot \cos(\beta) \cdot T_s(\psi) \cdot g(\psi) \cdot \cos(\psi) dA_{wall}$$
(1)

where m represents the Lambertian emission order, A is the photodetector active area, d denotes the distance between the transmitter and receiver, ϕ is the angle of irradiance, and ψ is the angle of incidence. $T_s(\psi)$ and $g(\psi)$ represent the optical filter gain and concentrator gain, respectively, while Ψ_c is the receiver field of view (FOV), ρ wall reflection coefficient, d_1 and d_2 are the distances from LED to reflector surface and receiver, α and β are incident and reflected angles and dA_{wall} is the differential reflective surface area.

$$m = \frac{-\ln(2)}{\ln(\cos(\phi_{1/2}))}$$
(2)

Here, $\phi_{1/2}$ is semi-angle at half optical power in radians. Using this channel model, the received optical power at the photodetector can be expressed as:

$$P_r = P_t \cdot (h_{LOS} + h_{NLOS})$$
(3)

where P_t is the transmitted optical power. The received optical power directly determines the signal-to-noise ratio (SNR) at the receiver and, consequently, the achievable communication performance of the VLC system. The signal-to-noise ratio (SNR) at the VLC receiver can be expressed as[36]:

$$SNR = \frac{(R \cdot P_r)^2}{\sigma_{total}^2}$$
(4)

Here, R denotes the responsivity of the photodetector, P_r is the received optical power, and σ_{total}^2 represents the total noise variance at the receiver. The total noise variance accounts for both shot noise and thermal noise contributions, which jointly limit the achievable system performance. To satisfy indoor lighting requirements in accordance with the European Standard EN 12464-1 [37], different indoor environments demand specific illuminance levels, such as 500 lux for office spaces, 300 lux for classrooms, and 100 lux for corridors. The illuminance distribution within a room equipped with multiple luminaires can be analytically evaluated using the following expression [38].

$$E = \frac{L \cdot (m + 1) \cdot \cos^m(\varphi) \cdot \cos(\psi)}{2\pi \cdot d^2} \quad (5)$$

Here, E denotes the total illuminance (in lux) at a given location, L represents the luminous flux (in lumens) emitted by the source, m is the Lambertian order of the light source (the LED in this work), which characterizes its radiation pattern, d is the distance between the transmitter and the receiver, φ is the angle of irradiance, and ψ is the angle of incidence.

After presenting the channel model, system performance is analyzed using three complementary evaluation metrics. Firstly, illumination uniformity (U) describes the spatial consistency of light distribution, that can be described by the following equation [39].

$$U = \frac{E_{min}}{E_{avg}} \quad (6)$$

Here, E_{min} denotes the minimum illuminance and E_{avg} represents the average illuminance. The resulting values range from 0 to 1, with higher values indicating greater illumination uniformity. Secondly, the quality factor (F_a) reflects the communication link quality through the SNR distribution that can be introduced with the following equation[40]:

$$F_a = \frac{\hat{\alpha}}{2\sqrt{\text{var}(\alpha)}} \quad (7)$$

Here, $\hat{\alpha}$ represents the average signal-to-noise ratio (SNR) and $\text{var}(\alpha)$ denotes the SNR variance across all receiving locations. Larger values reflect superior channel quality and enhance spatial uniformity of the SNR distribution. Finally, the coefficient of variation (CV_{RMSE}) measures the relative fluctuations of SNR within the indoor environment

$$CV_{RMSE} = \frac{\sqrt{\text{var}(\alpha)}}{\hat{\alpha}} \quad (8)$$

Lower metric values correspond to a more stable SNR distribution within the coverage region. Collectively, these metrics offer complementary insights, with illumination uniformity evaluating lighting performance, while F_a and CV_{RMSE} characterize communication robustness. Despite their mathematical interdependence, F_a and CV_{RMSE} convey different aspects of channel quality: F_a highlights performance gain through an increasing scale, whereas CV_{RMSE} emphasizes SNR stability via a decreasing scale. This dual perspective facilitates a comprehensive performance assessment across various luminaire arrangements.

4 VLC channel performance analysis and illumination distribution

In this section, a comprehensive simulation-based analysis is conducted to investigate the impact of different LED luminaire deployment strategies in a $5 \times 5 \times 3$ m³ indoor VLC environment. Four distinct lighting configurations are considered, namely: a single centrally mounted LED, a circular arrangement of 12 LEDs with a radius of 1.5 m, a circular arrangement of 12 LEDs with a radius of 2.5 m, and a square configuration comprising 12 uniformly spaced LEDs as illustrated in Fig. 2. These configurations are selected to evaluate various approaches for achieving efficient illumination coverage while maintaining reliable communication performance in indoor VLC systems.

The single-LED configuration represents a baseline scenario in which one luminaire is positioned at the center of the ceiling. Although this arrangement offers a simple and cost-effective solution, it typically results in non-uniform illumination and limited communication coverage, particularly toward the room edges. The circular configuration with a 1.5 m radius places 12 LEDs evenly distributed along a circumference centered on the ceiling, providing concentrated illumination in the central region while improving spatial symmetry. Expanding the circular radius to 2.5 m redistributes the luminaires closer to the room boundaries, enhancing edge illumination and mitigating coverage degradation at peripheral areas. This comparison enables an assessment of how radial spacing influences illumination, uniformity and channel quality. In contrast, the square configuration employs 12 LEDs arranged in a uniformly spaced grid across the ceiling plane. Although this layout is commonly adopted in commercial and office environments due to its structured deployment, ease of installation, and compatibility with standard lighting infrastructures, its performance is constrained by nonuniform spatial power distribution. Compared with the circular arrangement, the square configuration exhibits reduced central illumination and less efficient optical power concentration, which leads to lower SNR levels in key user regions. The circular LED distribution, by contrast, provides radially symmetric coverage that enhances received optical power and communication reliability, particularly in the central and high-usage areas of the room. Consequently, while the square layout ensures acceptable edge coverage, the circular configuration demonstrates superior overall illumination uniformity and VLC system performance the above configuration is illustrated in Fig. 3 with all the proposed design configurations.

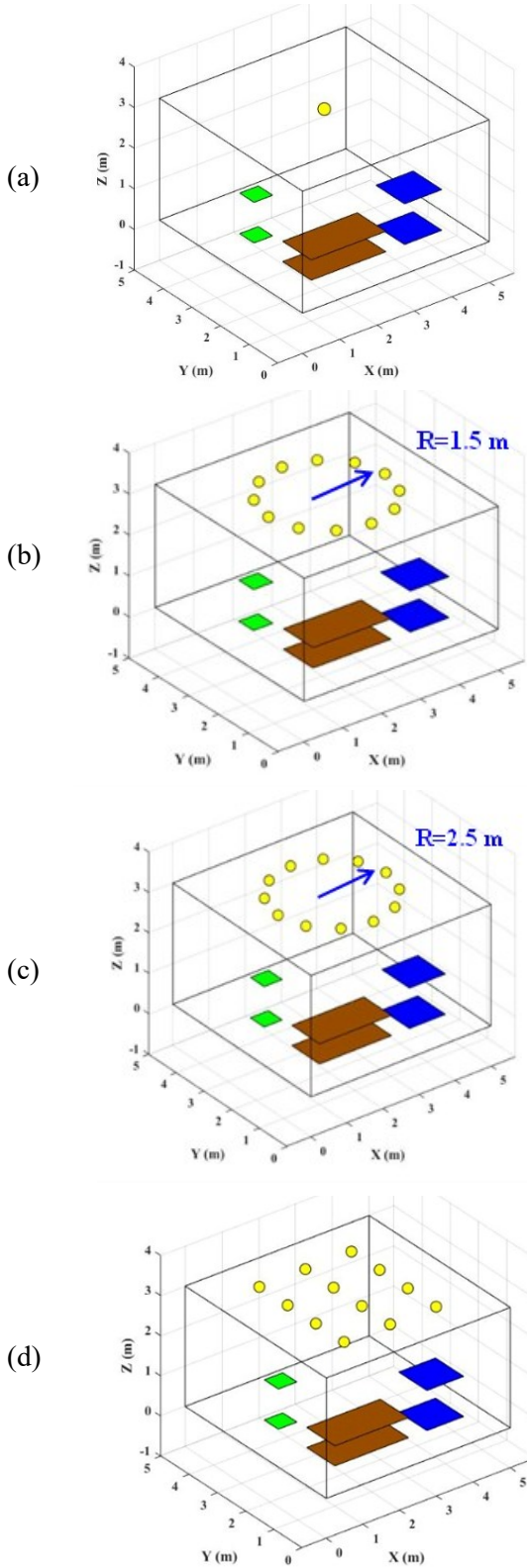


Fig. 2. VLC LEDs communication scenario (a) single LED, (b) 12 LEDs circular ($R=1.5$), (c) 12 LEDs circular ($R=2.5$) and (d) square 12 LEDs

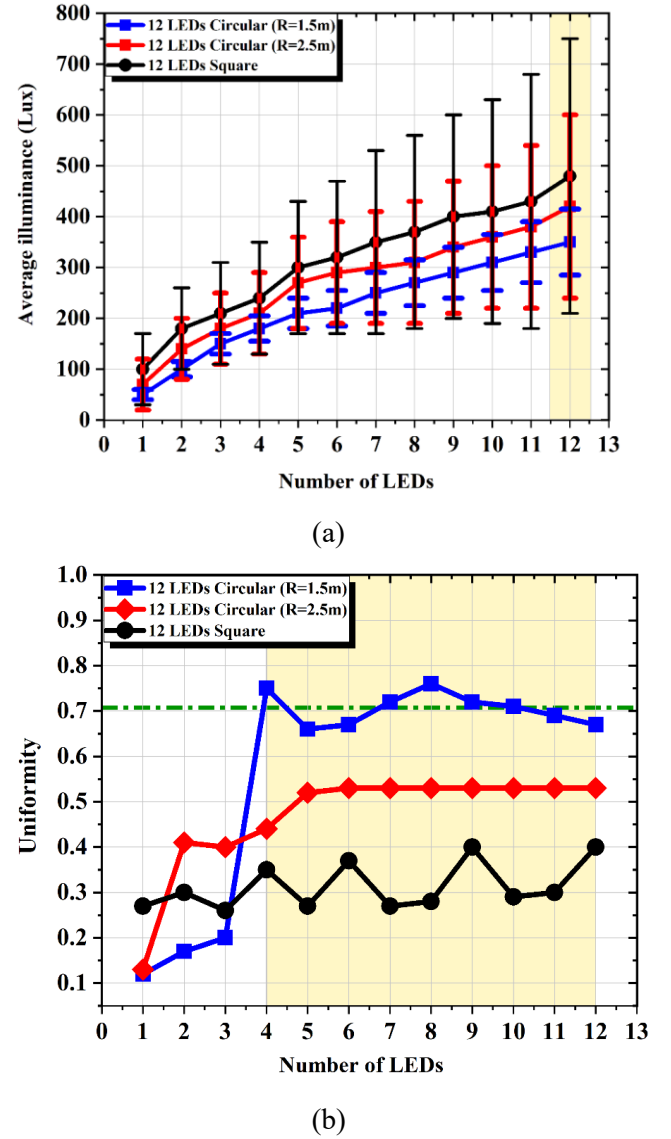


Fig. 3. (a) Average illuminance with the number of LEDs, and (b) illuminance uniformity at different LEDs configurations

For illumination performance, illustrated in Fig. 3(a), the curves depict the average illuminance as a function of the number of deployed LEDs, with vertical bars indicating the variation between the maximum and minimum illuminance values across the receiver plane. Among the evaluated configurations, the 12-LEDs circular arrangement with a radius of 1.5 m exhibits the highest average illuminance, increasing from low levels in the single-LED case to peak values approaching the upper illumination range as the number of LEDs increases. The 12 LEDs square configuration achieved the highest value at a single point of 12 luminaires with a value of 550 lux, while the 12 LEDs circular with a radius of 2.5 has the second highest value of 370 lux at 12 luminaires. The lowest value of the average illuminance is achieved by the 12 LEDs circular with a radius of 1.5 with a value of 160 lux. The uniformity performance, illustrated in Fig. 3(b), is evaluated against

the recommended threshold of approximately 0.7 specified by illumination standards [44]. The 12 LEDs circular with a radius of 1.5 maintains uniformity values above 0.6 from 4 to 12 LEDs distribution reaching with an average value of 0.73, while the other two configurations show a value ranging from 0.2 to 0.45 which falls below the recommended standards.

The results introduced in Fig. 3 demonstrate distinct trade-offs between illumination levels and uniformity. Although the 12 LEDs square configuration provides higher illumination levels, its uniformity introduced a value below the standers. 12 LEDs circular ($R=1.5$) configuration, providing lower average illumination maintains a better uniformity across the desired area. According to these values, 12 LEDs circular configuration offers the most balanced performance for the VLC systems. Following the illumination analysis, the channel performance is further evaluated using the quality metrics F_a and $CV(RMSE)$. Although these parameters are partially related to illumination uniformity through the received optical power, they primarily characterize the spatial distribution of the signal-to-noise ratio (SNR). This relationship stems from the proportionality between luminous flux and received optical power, which directly influences both the illumination intensity and the signal strength [45]. However, unlike illumination-based metrics alone, F_a and $CV(RMSE)$ additionally incorporate the effects of channel characteristics and noise components, thereby providing a more comprehensive assessment of communication reliability and link stability.

Figure 4 presents the performance of the quality factor F_a and $CV(RMSE)$ for the investigated luminaire configurations. The 12 LED circular ($R=1.5$) arrangement in Fig. 4(a) exhibits the most favorable channel characteristics. The quality factor increases from 0.97 to a maximum value of 6.8 with eight luminaires, followed by a small gradual reduction 6.5 from 9 to 12 luminaires are deployed. The corresponding $CV(RMSE)$ values in Fig. 4(b) decrease from 0.6 to 0.1, indicating a significant improvement in SNR uniformity. The peak performance observed from 8 to 12 luminaires suggests an optimal trade-off between spatial diversity and inter-luminaire interference.

The 12 LED circular ($R=2.5$) configuration Fig. 4(a) demonstrates moderate yet consistent channel improvement, with F_a steadily increasing from 0.5 to 3.4 as the number of luminaires increases. The associated $CV(RMSE)$ values decrease from 0.7 to a fluctuated response within the 4 to 12 luminaires with a minimum value of 0.2. In contrast, 12 LEDs square configuration in Fig. 4(a) exhibits comparatively limited performance,

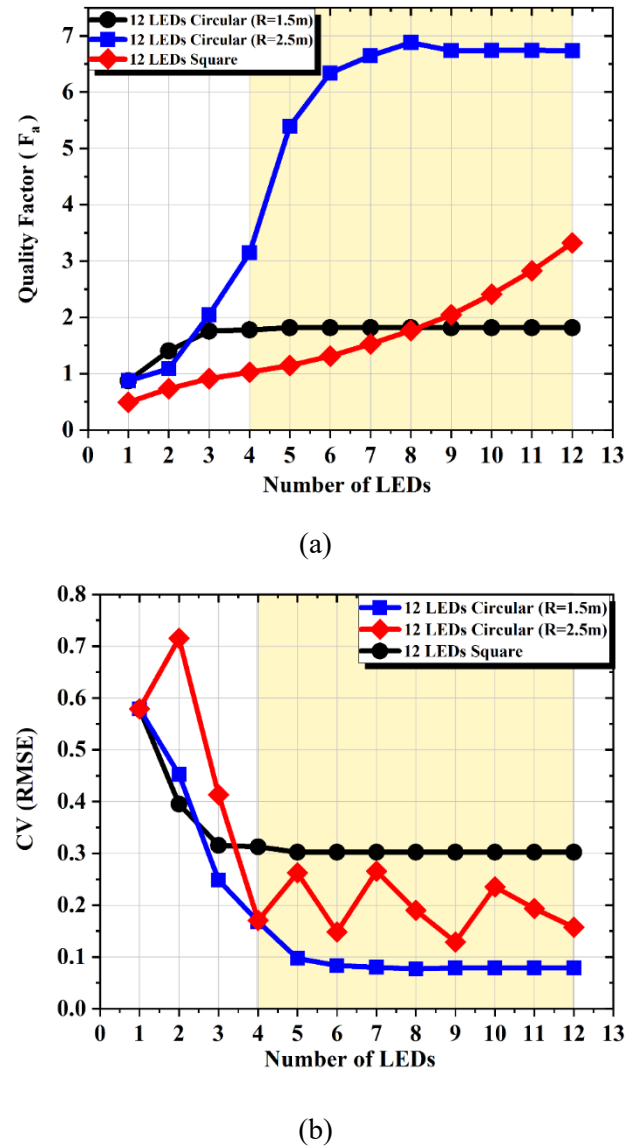


Fig. 4. (a) quality factor (F_a), (b) $CV(RMSE)$ for different LEDs configurations

with F_a ranging from 1 to 1.9 and $CV(RMSE)$ varying between 0.6 and 0.3, suggesting more pronounced SNR fluctuations within the coverage area.

Overall, the results confirm that luminaire geometry and spatial radius significantly influence both illumination uniformity and communication quality in VLC systems. While increasing the number of luminaires generally enhances performance, the improvement is strongly dependent on spatial distribution. The circular configurations, particularly with optimized radius, provide a better balance between illumination distribution and SNR stability compared to the square layout. These findings offer practical design guidelines for VLC systems, where both lighting uniformity and communication reliability must be jointly optimized according to room dimensions and application requirements.

$$\eta_{illum} = \frac{\text{uniformity} \times \text{average illuminance}}{\text{total power}} \quad (9)$$

Furthermore, to incorporate practical deployment considerations, an energy-efficiency metric is introduced to assess the overall performance of the VLC system. This metric enables the identification of configurations that achieve high operational effectiveness while maintaining reduced energy consumption. To this end, the illumination energy efficiency, denoted as η_{illum} , is defined to quantify the trade-off between illumination performance and the corresponding power expenditure. Specifically, this parameter characterizes the relationship between the achieved lighting quality and the electrical power consumed by the luminaire configuration.

In this formulation, the total power consumption is computed as the product of the number of deployed luminaires and the rated power per luminaire. In a similar manner, the energy efficiency associated with communication performance, denoted as η_{com} , is defined to evaluate the relationship between channel quality and the corresponding power consumption.

$$\eta_{com} = \frac{F_a}{\text{total power}} \quad (10)$$

To enable a comprehensive assessment of the VLC system performance, a unified energy efficiency metric, denoted as $\eta_{combined}$, is introduced to simultaneously account for both illumination and communication efficiencies. Since η_{illum} (expressed in lux/W) and η_{com} (dimensionless) possess different physical units, a normalization procedure is applied to ensure dimensional consistency and facilitate meaningful comparison. Specifically, each metric is normalized with respect to an appropriate reference value, yielding dimensionless quantities defined as follows [46]

$$\eta_{combined} = \left(\frac{\eta_{illum}}{\eta_{illum ref}} \right) \times \left(\frac{\eta_{com}}{\eta_{com ref}} \right) \quad (11)$$

where $\eta_{illum ref}$ and $\eta_{com ref}$ denote the maximum values of illumination energy efficiency and communication quality efficiency, respectively, obtained among all evaluated configurations.

Figure 5 presents the combined energy efficiency ($\eta_{combined}$) for different luminaire distribution configurations. In this evaluation, each luminaire operates at a constant electrical power of 20 W, corresponding to the typical consumption of commercial LED luminaires delivering approximately 2100 lumens. Accordingly, the total system power ranges from 20 W in the single-luminaire case to 240 W for configurations employing 12 luminaires.

Following the normalization of both illumination and communication efficiency metrics, the 12 LED circular ($R=1.5$) distribution consistently demonstrates superior overall energy efficiency compared to the other configurations across most luminaire counts, particularly in the range of 4 to 12 luminaires. The maximum efficiency is achieved with 8 luminaires in the 12 LED circular ($R=1.5$) configuration, reaching $\eta_{combined} = 0.85$. This result is consistent with the previously identified performance saturation point, where increasing the number of luminaires beyond a certain threshold produces diminishing returns not only in system performance but also in energy efficiency. In contrast, the 12 LED circular ($R=2.5$) configuration exhibits moderate performance, achieving $\eta_{combined} = 0.46$ at 8 luminaires, while the 12 LEDs square configuration consistently yields the lowest efficiency values, with $\eta_{combined} = 0.12$. These pronounced differences emphasize the critical role of luminaire spatial distribution in simultaneously optimizing illumination quality, communication reliability, and overall energy efficiency.

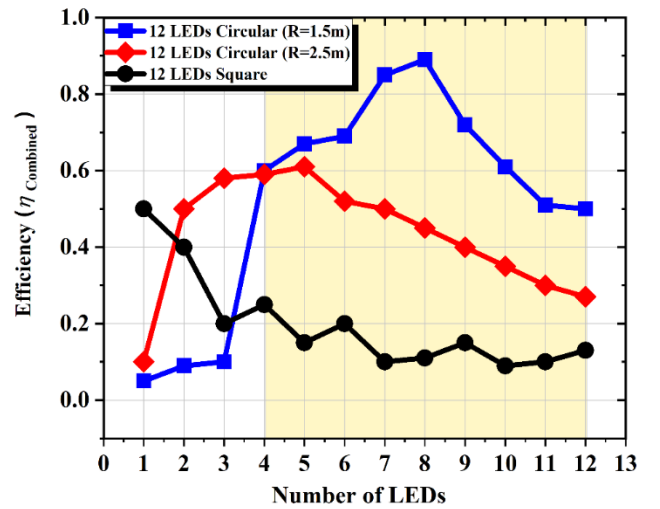


Fig. 5. Energy efficiency for different LEDs configuration with the number of LEDs

4.1 VLC model characteristics

A conventional VLC system, uninfluenced by Reconfigurable Intelligent Surfaces, depends exclusively on the inherent propagation characteristics of the channel for data communication. LEDs are often used in the system for two-way lighting and data transfer. They support intensity modulation with direct detection. The optical channel is mainly represented by a Lambertian transmitter, where the line-of-sight (LOS) component is represented as the main contributor to signal reception. One major problem with this situation is that the system is likely to get blocked or produce shadows because the signal won't go through an opaque surface. This means that the communication channel is limited to lighted

areas, and Bit Error Ratio (BER) depends a lot on how the lights are set up and where they are placed.

In our design, we utilize the basic parameters provided as illustrated in Tab. 1. The simulated system represents an indoor downlink VLC configuration in which optical signals are transmitted from ceiling-mounted LEDs to a photodetector placed on a horizontal receiving plane. The room size is $5 \text{ m} \times 5 \text{ m} \times 3 \text{ m}$. The LED transmitters are mounted on the ceiling, whereas the receiver plane is positioned 0.85 m above the floor, corresponding to desk level in a typical office setting. Although lighting placements, like a circular or square configuration around the room, will offer better lighting distribution, as well as reduce gaps, the absence of a changeable channel affects this communication system's adaptability to channel blockages as illustrated in Tab. 2.

Table 1. Simulation parameters for VLC system

	Parameters	Values
Room size	size	$5 \times 5 \times 3 \text{ m}^3$
	wall reflection	0.8
Transmitter	number of LEDs	12
	LED interval	0.01m
	size of LED light	$0.29 \text{ m} \times 0.29 \text{ m}$
	transmitted power per LED	20 mW
	half power angle	70°
	center luminous intensity	0.73 cd
Receiver	receiver from floor	0.85 m
	area	1 cm^2
	FOV	70°
	gain of filter	1

Table 2. Comparative analysis of the LEDs configurations

Configuration	Average illuminance (lx)	Max illuminance (lx)	Received optical power (mW)	Average SNR (dB)	Average BER	Average Q-factor
1 LED	650.3	1850.4	8.24	27.5	0.00023	3.15
12 LEDs ($R=1.5\text{m}$)	1012.6	1995.2	14.57	36.7	2.5×10^{-9}	8.24
12 LEDs ($R=2.5\text{m}$)	920.1	1873.5	13.01	34.2	3.1×10^{-8}	6.87
12 LEDs square	870.5	1930.5	10.82	30.6	2.1×10^{-8}	5.21

Comparative analysis shown in Tab. 2 proves that circular multi-LED configurations bring dramatic enhancements in light uniformity, optical power reception, and quality of communication. The two circular configurations prove that the 1.5 m radius performs slightly better due to perfect overlapping of LED beams. However, the 2.5 m configuration is to be selected in applications where edge illumination is a requirement. The outcomes highlight the importance of careful positioning of LEDs in achieving maximum VLC system design for both lighting and data transmission purposes.

The addition of the 12 LEDs square configuration is an indication that even a minor increase in LEDs significantly enhances lighting uniformity as well as communication performance in VLC systems. While the 12-LED circular design with radius 1.5 m remains the best in terms of average illuminance, SNR, and BER, the 12 LEDs square design offers an appealing performance and complexity trade-off. These findings vindicate the use of intermediate configurations in real-world VLC

applications where performance and uniformity must be balanced against installation issues.

The proposed 12-LED VLC system with different luminaire setups works under OOK modulation under additive white Gaussian noise (AWGN) conditions, which verifies that increased SNR levels improve the accuracy of data transmission. Figure 6 shows how BER relates to SNR for three different types of luminaires that use OOK modulation. The outcomes indicate an important and major effect of the geometric configuration on the communication reliability of the indoor VLC system

The results indicate that the circular LED array with a radius of 1.5 m consistently achieves the best performance, exhibiting the lowest BER across the entire SNR range. For instance, a BER on the order of 10^{-15} is achieved at approximately 20 dB SNR. This superior performance can be attributed to the geometric distribution of the LEDs, which enables a more uniform optical power distribution over the receiver plane.

The relatively small radius results in overlapping illumination regions, reducing low-illuminance areas and improving the overall SNR distribution, thereby enhancing communication reliability. In contrast, the circular array with a larger radius of 2.5 m demonstrates reduced performance and requires higher SNR values to achieve the same BER levels as the 1.5 m configuration. Although the larger radius improves spatial coverage, it reduces the optical power density, particularly near the center of the room. Consequently, the received optical power decreases, leading to higher average BER values for a given SNR, illustrating the trade-off between coverage area and signal strength. The square centered configuration exhibits the lowest performance among the arrangements considered. Due to its geometric layout, the illumination distribution is less uniform, with higher optical power directly beneath the luminaires and lower power levels in intermediate and corner regions. This uneven illumination results in a less favorable SNR distribution across the receiver plane, which is reflected in the higher BER performance compared with the circular configurations.

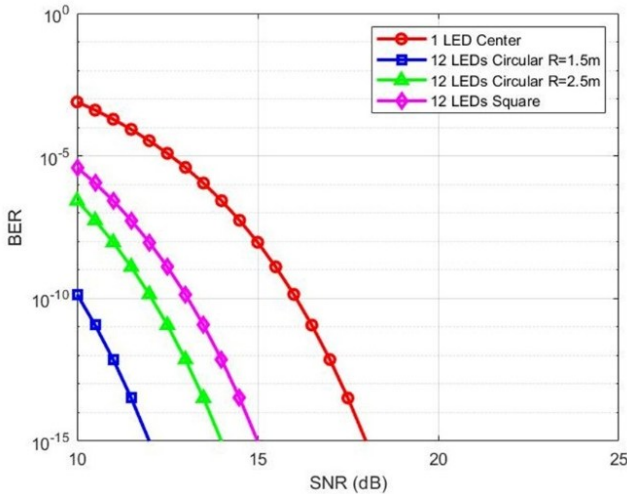


Fig. 6. SNR vs BER of the proposed design at different LEDs configuration

4.2 BER performance of DCO-OFDM with M-QAM

The VLC system employs intensity modulation and direct detection (IM/DD), where the transmitted optical signal must be real-valued and non-negative. To satisfy these constraints while maintaining high spectral efficiency, DC-biased optical orthogonal frequency-division multiplexing (DCO-OFDM) is adopted. In this technique, M-QAM symbols are first mapped onto

OFDM subcarriers, and Hermitian symmetry is applied to generate a real-valued time-domain signal. A suitable DC bias is then added to ensure that the transmitted waveform remains strictly positive before driving the LED for optical transmission. This approach enables efficient bandwidth utilization and supports high-data-rate VLC communication.

Figure 7 illustrates the BER performance of different M-QAM modulation orders implemented within the DCO-OFDM framework under the SNR conditions obtained from the VLC channel model. The BER evaluation assumes an additive white Gaussian noise (AWGN) environment at the receiver, including both shot noise and thermal noise components. For comparison, OOK modulation is considered as a base-line low-complexity IM/DD modulation scheme, while DCO-OFDM with M-QAM is utilized for high-throughput transmission scenarios. The results show that BER decreases as the SNR increases for all modulation orders. Lower-order modulation schemes such as 4-QAM achieve better BER performance due to the larger Euclidean distance between constellation points, making them more robust to noise and signal fluctuations. In contrast, higher-order schemes such as 64-QAM and 256-QAM provide higher spectral efficiency but require significantly larger SNR values to maintain reliable communication performance.

For the proposed circular LED configuration with $R = 1.5$ m, the achieved SNR of approximately 34 dB supports reliable operation of higher-order M-QAM schemes within the DCO-OFDM framework. These results demonstrate that the selected LED arrangement improves the optical channel quality and enables efficient high-speed VLC transmission. Moreover, the obtained BER characteristics confirm the fundamental trade-off between spectral efficiency and error performance in optical wireless communication systems. [41]

$$E_s/N_0 \text{ (dB)} = E_b/N_0 \text{ (dB)} + 10 \log(\log_2 M) \quad (12)$$

where E_b is the Energy per Bit and E_s is the Energy per Symbol calculated as

$$E_s = E_b \cdot \log_2 M \quad (13)$$

The plot indicates that an increase in order from 4-QAM to 256-QAM increases data rate but requires a higher SNR to attain a certain BER. The 256-QAM plot is 10-15 dB to the right of 4-QAM.

VLC operating points indicate that a circular configuration has the highest SNR and provides the best support for high-order modulations. 12-LED circular configuration with $R=1.5$ m has an SNR of 36.7 dB, 12-LED circular configuration with $R=2.5$ m has an SNR of 34.2 dB, 12-LED square configuration has an SNR of 30.6 dB, and a single LED has an SNR of 27.5 dB.

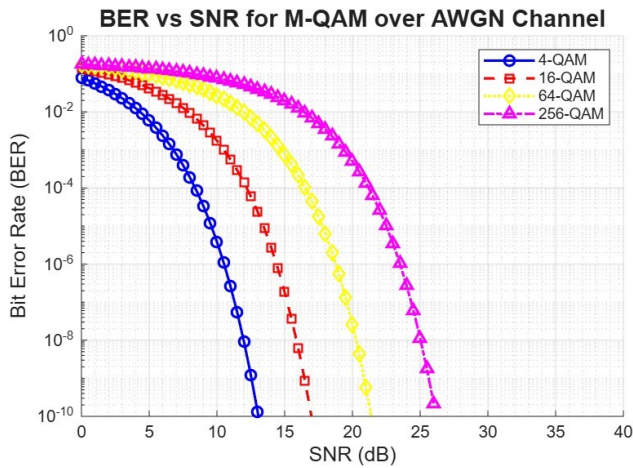


Fig. 7. BER vs SNR for M-QAM modulation

Table 3. BER for M-QAM at standard SNR at points (4, 8)

Modulation	SNR (dB)	BER (approx)
4-QAM	4	0.055
	8	0.005
16-QAM	4	0.24
	8	0.14
64-QAM	4	0.31
	8	0.23
256-QAM	4	0.36
	8	0.30

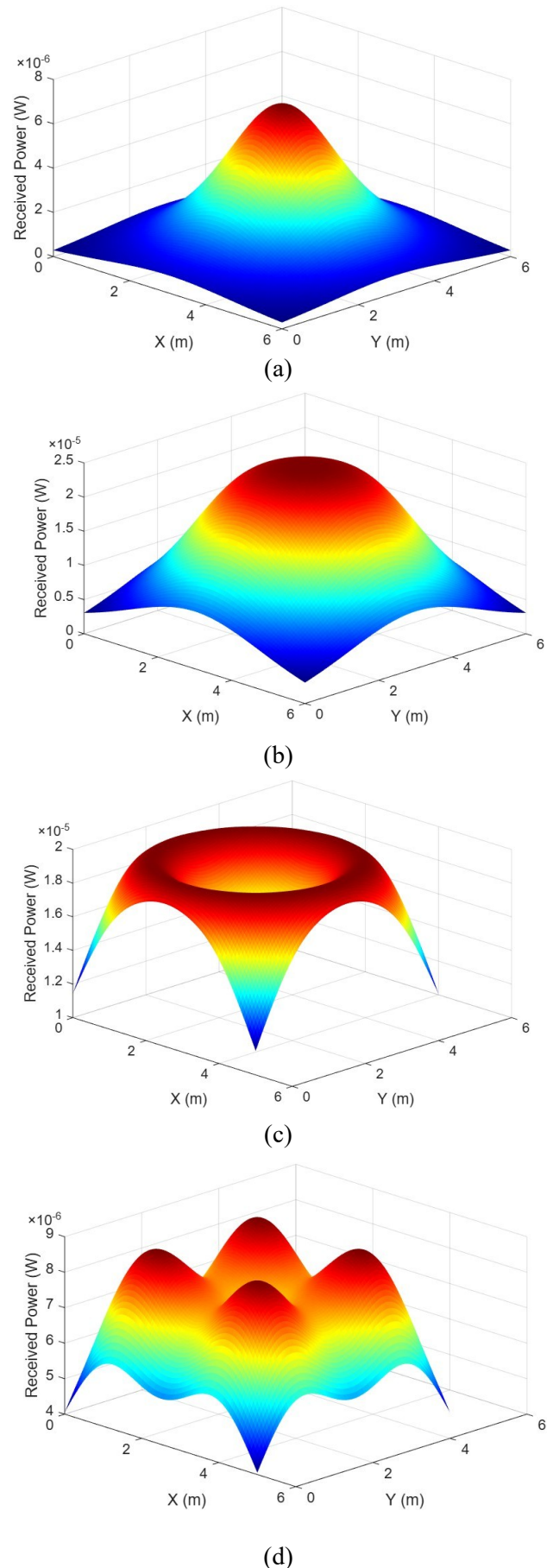


Fig. 8. LED spatial distribution on VLC system: (a) 1 LED, (b) 12 LEDs ($R=1.5$), (c) 12 LEDs ($R=2.5$), and (d) 12 LEDs square

The arrangement of LEDs plays a crucial role in determining the effectiveness of indoor VLC systems[43]. The evaluation centers on the resulting distribution of received optical power, signal-to-noise ratio (SNR), and bit error rate (BER). The received optical power. The results make it clear that how LEDs are arranged has a strong influence on the performance of an indoor VLC system. In simple terms, the placement of the light sources determines how the optical power is spread across the room, and this directly affects both the signal-to-noise ratio (SNR) and the bit error rate (BER). There are four different LED configurations namely, 1 LED, 12 LEDs ($R=1.5$), 12 LEDs ($R=2.5$), and 12 LEDs Square as illustrated in Fig. 8.

A single centrally placed LED provides maximum optical power directly beneath the source; however, the received power decreases significantly toward the room edges, resulting in lower SNR and higher BER for distant users. Although the square LED arrangement improves edge coverage by distributing optical power more effectively across the room, it may produce non-uniform ring-shaped power patterns, causing weaker performance in some central regions. Therefore, while

the square configuration enhances coverage compared to the single LED case, it does not completely achieve uniform illumination and communication performance.

The circular LED arrangement provides the most uniform optical power distribution by evenly covering the ceiling area, which results in more consistent received power across the room. This improves SNR uniformity and reduces BER variation compared to single and square configurations. The results show that uniform illumination is more important than maximizing peak power, making the circular layout the best trade-off between coverage and communication reliability for indoor VLC systems.

Table 4 demonstrates that the gain is achieved from a system-level design change rather than minor tuning. The proposed approach achieves SNR of 36.7 dB and BER of 2.5×10^{-9} in comparison with other studies that used more LEDs or partially reported results and achieves a compact deployment with a small number of LEDs (1 and 12 LEDs). The quality factor is 8.24, which is a cleaner signal and better than that achieved in [15, 18, 19]. The use of OOK and 256-QAM is a better solution in terms of spectral efficiency.

Table 4. Comparison of this work with previous works

References	Number of LEDs	Average SNR (dB)	Average BER	Average quality factor (Fa)	Modulation
[40]	16	30	-	7.6523 (Circle-Square)	Intensity modulation
[41]	12	-	8.40×10^{-4}	2.88	OFDM
[43]	16 to 64	20.11	-	1.0723	OOK
[44]	9	25.3	1.1×10^{-5}	4.91	OOK
[45]	16	28.7	3.2×10^{-6}	5.60	DCO-OFDM (16-QAM)
[46]	25	31.5	5.6×10^{-7}	6.42	OFDM / M-QAM
This work	12 circular ($R=1.5$ m)	36.7	2.5×10^{-9}	8.24	OOK and OFDM based M-QAM

5 Conclusion

This study shows what practitioners in indoor VLC have seen repeatedly in deployment-oriented design: luminaire geometry is not a secondary detail, but a first-order determinant of both link robustness and lighting quality. Among the simulated layouts, a 12-LED circular array with a 1.5 m radius offers the most credible engineering compromise, delivering an average SNR of 34.2 dB, a peak SNR of 36.7 dB, BER of 2.5×10^{-9} , and illumination uniformity with CV(RMSE) below 15%,

which provides sufficient SNR to support high-order modulation schemes within an OFDM-based IM/DD framework. The real value of this result is not just the numerical gain, but the balance it strikes between communication performance and practical lighting constraints. The next technical bottlenecks are predictable: blockage, shadowing, and user-induced channel instability. Moving forward, progress will depend on robust MIMO designs, better multi-user interference control, and tighter VLC-PLC integration for real indoor use.

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