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Optimizing Indoor Visible Light Communication Systems: A Comparative Analysis of Multi-LED Configurations

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Abstract; Visible Light Communication (VLC) utilizes LEDs to transmit data through visible light, offering an alternative to traditional RF systems. This study develops a model for indoor VLC environments, focusing on key factors such as illuminance distribution, received power, and signal-to-noise ratio (SNR) in both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. The research examines how different transmitter setups—single, four, and five LED configurations—affect system performance, with particular attention to the bit error rate (BER) for two modulation schemes: On-Off Keying (OOK) and Quadrature Amplitude Modulation (16-QAM). The findings show that multi-LED setups provide enhanced reliability, especially in diffuse propagation scenarios common in NLOS environments. Multi-LED configurations deliver better illuminance distribution and higher SNR, making them suitable for complex indoor environments. However, single-LED setups offer lower BER at higher SNR levels, demonstrating superior performance for simpler setups where direct communication paths are available. The study also compares modulation schemes, finding that OOK is more resilient to noise and achieves lower BER, particularly in single-LED configurations, while 16-QAM offers higher data throughput but is more susceptible to errors in lower SNR conditions. The trade-offs between wider coverage and increased BER in multi-LED setups indicate that configuration must be tailored to specific environmental conditions and system goals. This research contributes to the optimization of VLC systems, suggesting that while multi-LED setups are better suited for complex environments requiring broader coverage, single-LED configurations are more efficient in simpler scenarios where minimizing errors is crucial. The study's insights are expected to facilitate the wider adoption of VLC technology, particularly in secure indoor communication systems where RF signals face challenges like interference and limited bandwidth.

Keywords: *Visible Light Communication; LED; Line-of-Sight; Non-Line-of-Sight; Modulation*

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I. INTRODUCTION

Visible Light Communication represents a cutting-edge technology that leverages visible light to transmit data wirelessly, offering a promising alternative to traditional radio frequency (RF) communication systems [1]. VLC operates within the visible spectrum (approximately 400 to 700 nanometers) and utilizes light sources such as Light Emitting Diodes (LEDs) to deliver high-speed data transmission [2]. This form of communication is particularly advantageous in indoor environments where RF signals often suffer from limitations such as interference, congestion, and limited bandwidth. VLC, by contrast, can provide a high data transmission rate, robust security, and minimal interference, making it an ideal choice for a wide range of applications, including smart lighting systems, indoor navigation, and secure communication networks[3].

The necessity of VLC in indoor environments arises from its ability to seamlessly integrate with existing lighting infrastructure while offering enhanced communication capabilities[5]. Traditional RF systems can be prone to signal degradation and security vulnerabilities, especially in densely populated areas or in settings where multiple devices compete for bandwidth. VLC addresses these challenges by using light, a medium that is both abundant and already integrated into most indoor spaces through lighting systems[4]. Additionally, since light does not penetrate walls, VLC offers an inherent level of security, as the communication is confined to the room where the light is present. This makes VLC particularly suitable for environments that require high levels of data security, such as offices, hospitals, and government buildings[6].

The role of LEDs in VLC is crucial. LEDs are highly efficient light sources that can rapidly switch on and off, a

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capability that is essential for modulating data in VLC systems[7]. Unlike traditional incandescent or fluorescent bulbs, LEDs can operate at high speeds, enabling them to transmit data without noticeable flicker to the human eye[8]. Furthermore, LEDs offer the flexibility of dual functionality—they can illuminate spaces while simultaneously serving as communication transmitters, thereby optimizing energy use and reducing the need for additional hardware[9]. Therefore, this study aims to develop a comprehensive model for indoor VLC environments using LED technology. The research focuses on analyzing fundamental characteristics such as illuminance distribution, received power, and signal-to-noise ratio (SNR) to understand the impact of different propagation scenarios, including line-of-sight (LOS) and diffuse propagation. Specifically, the study explores the effects of diffuse transmission through walls and how this influences the bit error rate (BER) in VLC systems.

To achieve these objectives, the research has been structured around several key tasks:

- *Developing an Indoor VLC Model:*

This involves creating a model that accurately illustrates the distribution of illuminance for various transmitter configurations, including single, four, and five transmitter setups. The model also accounts for different receiver positions within the indoor environment to evaluate how the placement of both transmitters and receivers affects overall system performance.

- *Determining Received Power:*

The study establishes the relationship between brightness and illuminance to determine the received power at different points within the room. This analysis helps in understanding how the intensity of light impacts the effectiveness of VLC communication and the coverage area within an indoor setting.

- *Manipulating Signal-to-Noise Ratio (SNR):*

SNR is a critical factor in communication systems, affecting the quality and reliability of data transmission. This research manipulates SNR by accounting for various noise sources within the indoor environment and evaluating how different levels of noise influence the performance of the VLC system.

- *Demonstrating SNR Distribution for Diffuse and LOS Propagation:*

The study compares the SNR distribution in both diffuse and LOS propagation scenarios. It specifically investigates how diffuse propagation, including the transmission of light through white concrete walls, contributes to illuminance, received power, and SNR at the receiver. This analysis provides insights into how VLC systems can maintain high performance even in complex indoor environments with obstacles.

- *Calculating Bit Error Rate:*

Finally, the research calculates the BER for different propagation scenarios to assess the reliability of data transmission in VLC systems. The BER will be calculated for two modulation schemes: On-Off Keying (OOK), a simple modulation technique where data is represented by the presence or absence of light, and 16-bit Quadrature Amplitude Modulation (16-QAM), a more complex modulation scheme that uses different amplitude and phase shifts to encode data. The comparison of these two modulation techniques will provide a deeper understanding of how different modulation strategies impact the performance and reliability of VLC in indoor environments.

This study aims to advance the understanding of VLC technology in indoor environments by developing a detailed model that considers various factors affecting performance. The findings of this research are expected to contribute to the optimization of VLC systems, enabling their wider adoption in indoor communication networks.

II. LITERATURE REVIEW

The literature review on visible light communication (VLC) systems presents a range of methodologies and contributions from various researchers aimed at enhancing the performance and reliability of VLC in indoor environments. Younus et al. [11] explored multi-beam transmitters (MBTs) with wide field-of-view (W-FOV) and automatic device recognition (ADR) through experimental setups and simulations, demonstrating that MBTs significantly reduce signal fading, which is crucial for designing reliable indoor VLC systems. Similarly, Vipul Dixit et al. [12] employed simulation and analytical methods to evaluate adaptive diversity techniques (ADT) in indoor VLC systems, revealing that ADT can improve bit error rate (BER) by mitigating signal-to-noise ratio (SNR) variations and optimizing the transmitter semi-angle for enhanced performance.

Sheng-Hong Lin et al. [13] used a Lambertian emission model along with On-Off Keying (OOK) modulation to study input-dependent noise in VLC, proposing optimized receiver tilting angles that minimize BER, thereby improving system performance in noisy environments. JingyuanDuan et al. [14]focused on simplifying VLC system design using off-the-shelf technologies, enhancing mobility with a non-imaging concentrator, which advances the commercialization of VLC by addressing design complexity and integration challenges.

DebanjanaGhosh et al.[15] developed a Li-Fi transceiver using Arduino for data transmission, highlighting the potential of Li-Fi as a superior alternative to Wi-Fi in wireless communication. Khalifeh et al.[16], through simulations, emphasized the importance of strategic LED placement in VLC systems, showing that optimal positioning can enhance received power and minimize errors.

In another study, Mohammed S.M. Gismalla et al. [17] conducted a multi-variable evaluation of optical attocell models in VLC systems, analyzing different modulation schemes and identifying binary phase-shift keying (BPSK) as the most effective for optimal performance. TabishNiaz et al. [18] compared square array and circular LED deployments

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through simulations, proposing a circular LED deployment that improves coverage and reduces energy consumption, thereby enhancing system efficiency.

Mohammad F.L. Abdullah et al.[19] evaluated a VLC system with 13 optical attocells, optimizing for SNR and bit rate, and achieving significant communication quality improvements. Nguyen et al. [20] utilized MATLAB and Simulink simulations to analyze transmitter positions and wall reflections in VLC environments, providing valuable insights into illuminance and root mean square (RMS) delay spread distributions that enhance the understanding of VLC system performance.

Mahfouz etal.[21] compared a novel 16-LED array design with existing configurations, demonstrating that the new design reduces power and SNR fluctuations, ensuring uniform communication quality across the system. Manivannan et al. [22] combined practical measurements with a mathematical model to study LED behavior in VLC, contributing to a deeper understanding of power distribution and signal attenuation in these systems.

Sui-Il-Chol et al. [23] introduced a new LED lighting shape that optimizes both illuminance and data communication, even in the presence of obstacles, while Kominee et al. [24] conducted numerical simulations to analyze the use of white LEDs for room illumination and optical wireless communication, highlighting their effectiveness in providing reliable communication and energy-efficient lighting. These contributions collectively advance the field of VLC by addressing various challenges and proposing innovative solutions to improve system performance, efficiency, and reliability in indoor environments. Table 1 represents the recent studies of VLC systems using LED.

- *Research Gap*

The existing body of research on visible light communication (VLC) has significantly advanced our understanding of the technology's potential and limitations. However, several research gaps remain, particularly concerning the comprehensive modeling of indoor VLC environments with a focus on practical implementation and performance optimization. Many studies, such as those by Younus et al. [11]andVipul Dixit et al.[12], have concentrated on improving signal reliability and reducing bit error rates (BER) through advanced techniques like multi-beam transmitters (MBTs) and adaptive diversity techniques (ADT). While these studies have successfully demonstrated the benefits of these methods in minimizing signal fading and SNR variations, they often rely on idealized conditions and specific setups that may not fully capture the complexities of real-world indoor environments. Our study aims to bridge this gap by developing a more comprehensive model that incorporates various transmitter configurations and receiver positions, providing a more holistic understanding of how VLC systems perform in practical indoor settings. Sheng-Hong Lin et al.[13]and Mahfouz et al.[21] have explored the impact of noise and LED array designs on VLC system performance, proposing methods to optimize receiver angles and reduce SNR fluctuations. However, these studies primarily focus on specific aspects of VLC, such as noise management or LED configuration, without integrating these factors into a broader system model that considers multiple performance metrics simultaneously. Our research addresses this gap by analyzing illuminance distribution, received power, and SNR within a unified model, allowing for a more detailed examination of how these factors interact and influence overall system performance. JingyuanDuan et al. [14] and Khalifeh et al. [16] have contributed to the field by simplifying VLC system design and emphasizing the importance of LED placement. While their work has made strides toward practical VLC implementation, there is still a need for a detailed analysis of how these design choices affect system performance under different propagation scenarios, including both line-of-sight (LOS) and diffuse propagation. Our study fills this gap by specifically investigating the effects of diffuse transmission through walls and its impact on BER, which is crucial for understanding VLC's viability in more complex indoor environments. Furthermore, while research by Mohammed S.M. Gismalla et al. [17,19] and TabishNiaz et al. [18] has highlighted the benefits of specific modulation schemes and LED deployments, these studies often do not explore the trade-offs between different modulation techniques in a single, integrated model. Our research addresses this by comparing the BER of On-Off Keying (OOK) and 16-bit Quadrature Amplitude Modulation (16-QAM) within the same system model, providing insights into how different modulation strategies can be optimized for various indoor VLC scenarios. Studies like those by Sui-Il-Chol et al. [23] and Kominee et al.[24] have focused on optimizing LED designs and exploring the use of white LEDs for both illumination and communication. However, these studies typically do not account for the complex interactions between lighting design and communication performance, especially in environments with obstacles or varying illumination requirements. Our research seeks to bridge this gap by demonstrating how different propagation paths, including diffuse reflections through materials like white concrete walls, contribute to overall system performance, thereby offering a more comprehensive understanding of VLC in practical indoor environments.

- *Our Contribution*

While existing research has significantly advanced the field of visible light communication technology, there remains a pressing need for more integrated and comprehensive models that address multiple factors simultaneously within indoor environments. This study seeks to fill this gap by developing a detailed model for indoor VLC systems using LED technology. The research focuses on analyzing fundamental characteristics such as illuminance distribution, received power, and signal-to-noise ratio to better understand the impact of different propagation scenarios, including both line-of-sight and diffuse propagation. A particular emphasis is placed on exploring the effects of diffuse transmission through walls and its influence on the bit error rate in VLC systems. To achieve these objectives, the study is structured around several key tasks. First, it involves developing an indoor VLC model that accurately represents the distribution of illuminance across

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various transmitter configurations, such as single, four, and five transmitters, while also considering different receiver positions to evaluate how transmitter and receiver placement affects system performance. Second, the research aims to determine received power by establishing the relationship between brightness and illuminance at various points within a room, providing insights into how light intensity impacts the effectiveness of VLC communication. Third, the study manipulates SNR by accounting for various noise sources in the indoor environment, assessing how different noise levels influence VLC performance to optimize communication quality. Additionally, the research demonstrates SNR distribution under both diffuse and LOS propagation scenarios, specifically examining how diffuse propagation, including light transmission through white concrete walls, affects illuminance, received power, and SNR at the receiver. Finally, the study calculates the BER for different propagation scenarios, focusing on two modulation schemes: On-Off Keying and 16-bit Quadrature Amplitude Modulation. By comparing these modulation techniques, the research provides a comprehensive understanding of how different strategies impact the performance and reliability of VLC in indoor environments. Through this detailed analysis, the study aims to contribute valuable insights that will enhance the optimization and broader adoption of VLC technology in practical indoor communication systems.

Table 1 Recent Studies of VLC System Using LED

Paper	Methodology	Contribution	Research Gap
Younus et al. [11]	Experimental setups and simulations to assess MBTs with W-FOV and ADR in VLC systems.	Demonstrates that MBTs enhance VLC by minimizing signal fading, aiding in the design of reliable indoor systems.	Focuses on specific setups; lacks comprehensive analysis of multiple transmitter configurations and diverse receiver placements.
Vipul Dixit et al. [12]	Simulation and analytical methods to evaluate ADT in indoor VLC systems.	Shows that ADT improves BER by reducing SNR variations, optimizing transmitter semi-angle for better performance.	Does not consider the impact of diffuse propagation and wall reflections on overall system performance.
Sheng-Hong Lin et al. [13]	Lambertian emission model and OOK modulation to study input-dependent noise in VLC.	Proposes optimized receiver tilting angles to minimize BER, enhancing system performance in noisy environments.	Limited to specific noise management techniques; lacks integration with a broader system model considering multiple factors.
JingyuanDuan et al. [14]	Simplifies VLC system design using off-the-shelf technologies, enhances mobility with a non-imaging concentrator.	Advances VLC commercialization by addressing design complexity, mobility, and network integration challenges.	Does not explore the effects of multiple transmitter and receiver configurations on VLC performance in real-world environments.
DebanjanaGhosh et al. [15]	Li-Fi transceiver development using Arduino for data transmission.	Highlights Li-Fi's advantages over Wi-Fi, showing potential as a superior wireless communication alternative.	Focuses on Li-Fi; does not address the specific challenges of VLC in indoor environments, such as propagation and SNR issues.
Khalifeh et al. [16]	Simulations to explore LED positioning effects on VLC performance.	Emphasizes the critical role of strategic LED placement in optimizing received power and minimizing errors.	Lacks consideration of how diffuse reflections through walls affect overall system performance and BER.
Mohammed S.M. Gismalla et al. [17]	Multi-variable evaluation of optical attocell models in VLC systems, analyzing modulation schemes.	Introduces a novel attocell model, identifying BPSK as the most effective modulation scheme for optimal performance.	Does not compare multiple modulation schemes within the same system model to evaluate performance across different scenarios.
TabishNiaz et al. [18]	Simulations comparing square array and circular LED deployments for VLC.	Proposes a circular LED deployment that improves coverage and reduces energy consumption, enhancing system efficiency.	Focuses on LED deployment shapes; lacks a detailed examination of SNR distribution and BER in various propagation scenarios.
Mohammad F.L. Abdullah et al. [19]	Evaluation of a VLC system with 13 optical attocells optimized for SNR and bit rate.	Achieves significant communication quality improvements, demonstrating the model's effectiveness in VLC performance.	Does not address how different propagation paths, such as diffuse transmission through walls, impact system performance.
Nguyen et al. [20]	MATLAB and Simulink simulations to analyze transmitter positions and wall reflections in VLC environments.	Provides insights into illuminance and RMS delay spread distributions, enhancing	Limited focus on transmitter positions and reflections; lacks integration of BER analysis across different modulation schemes.

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		understanding of VLC system performance.	
Mahfouz et al. [21]	Comparison of a novel 16-LED array design with existing configurations in VLC systems.	Improves system performance by reducing power and SNR fluctuations, ensuring uniform communication quality.	Focuses on LED array design; does not explore the interplay between illuminance, SNR, and BER in different indoor setups.
Manivannan et al. [22]	Practical measurements and a mathematical model to study LED behavior in VLC.	Enhances understanding of LED performance in VLC systems, focusing on power distribution and signal attenuation.	Does not integrate findings into a broader model that accounts for multiple factors affecting overall system performance.
Sui-Il-Chol et al. [23]	Introduction of a new LED lighting shape for optimized illuminance and data communication.	Demonstrates how the new LED design enhances both illumination and data transmission, even with obstacles.	Limited to a specific LED design; lacks broader analysis of system performance under varying propagation and receiver configurations.
Kominee et al. [24]	Numerical simulations to analyze white LEDs for room illumination and optical wireless communication in VLC.	Highlights the effectiveness of white LEDs in providing reliable communication and energy-efficient lighting.	Does not address how white LEDs perform under different modulation schemes or the impact of diffuse propagation on system reliability.

III. METHODOLOGY

This study aims to develop a comprehensive indoor VLC model using LED technology, focusing on analyzing illuminance distribution, received power, and SNR to understand the impact of different propagation scenarios, including LOS and diffuse transmission through walls, on bit error rate.The proposed study is structured into four distinct phases. The first phase involves the development of a Visible Light Communication (VLC) system. The second phase focuses on exploring different transmitter configurations, including single, four, and five transmitters, to analyze their impact on the system. In the third phase, key characteristics such as illuminance distribution, received power, Signal-to-Noise Ratio (SNR) under both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions, and Bit Error Rate (BER) for On-Off Keying (OOK) and Quadrature Amplitude Modulation (QAM) will be evaluated. The fourth and final phase consists of a comparative analysis of the different transmitter configurations based on the evaluated parameters. The workflow diagram illustrating these phases is presented in Figure 1.

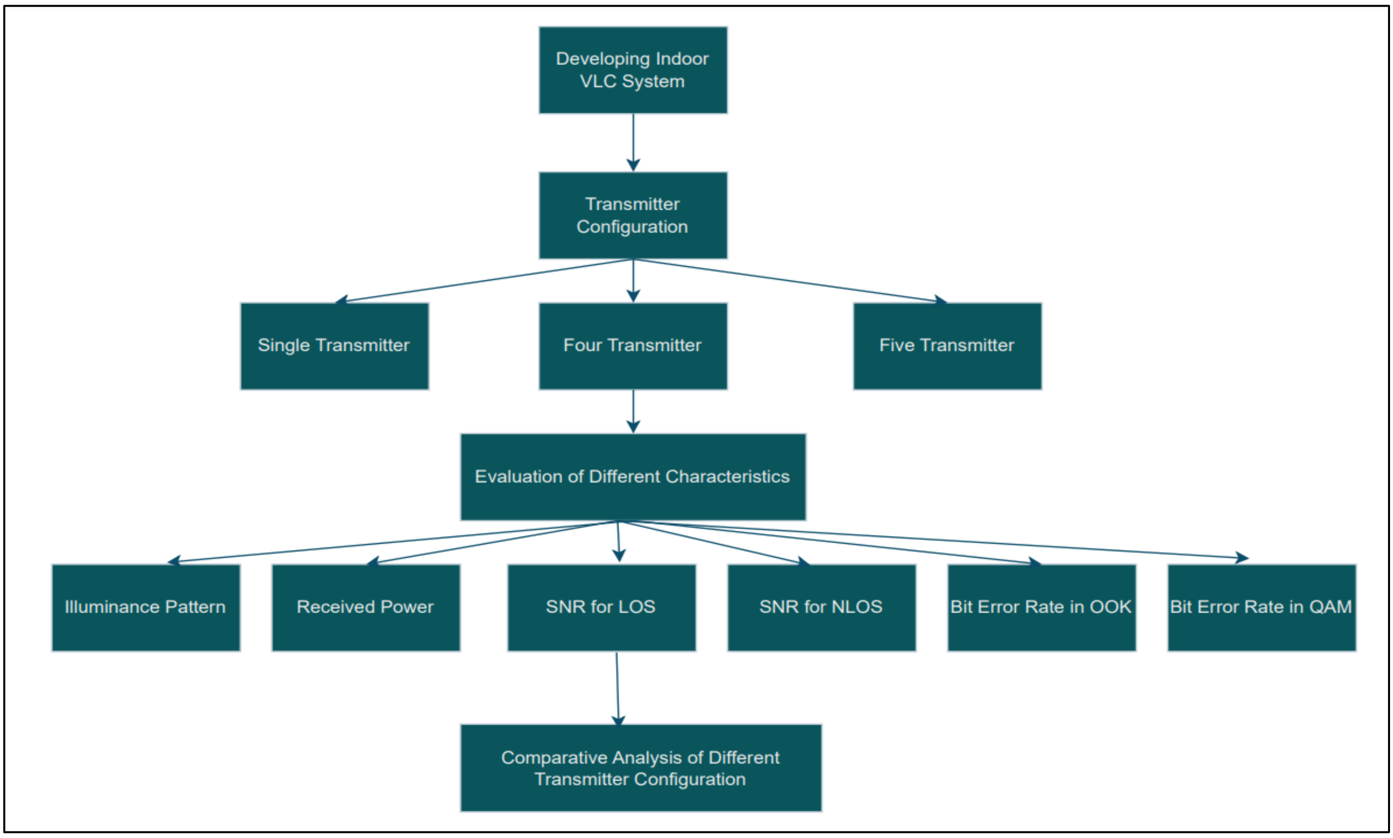

Fig 1 Workflow diagram of proposed system

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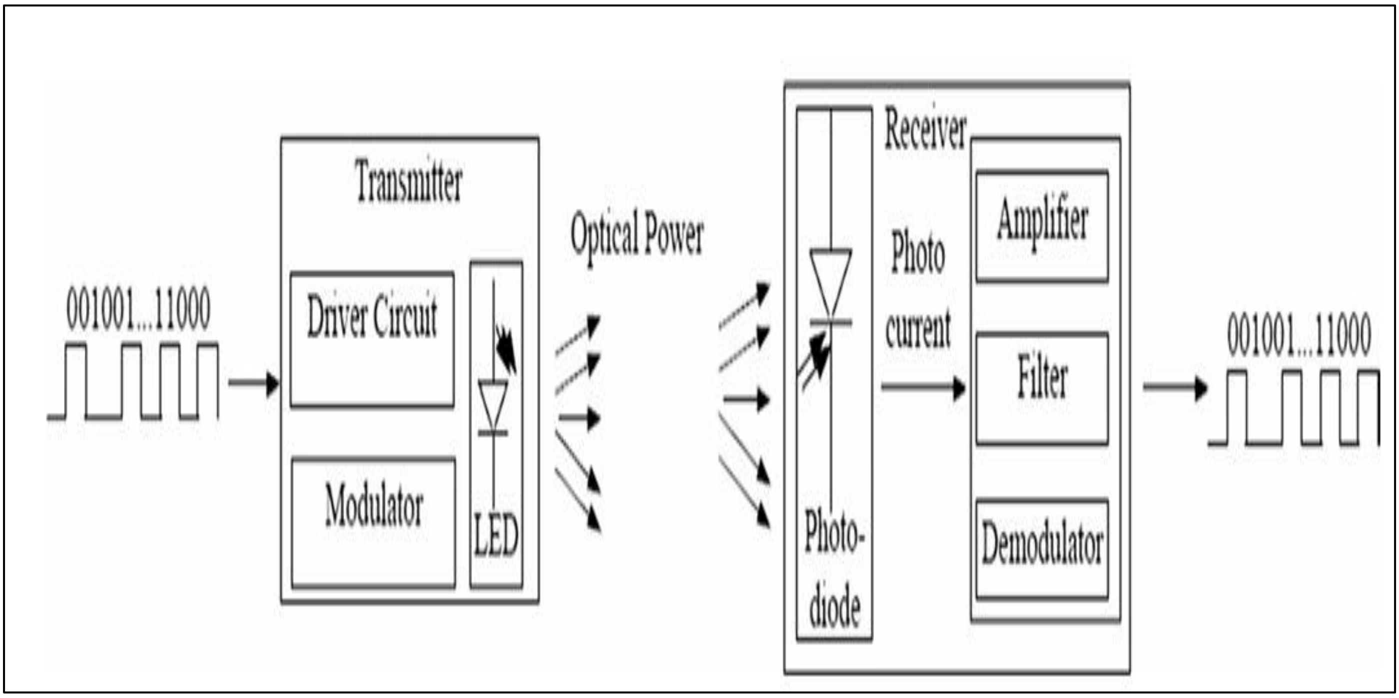
➢ *Developing Indoor VLC System*

This study developed a Visible Light Communication (VLC) system that involves the use of LED transmitters and photodetectors for wireless data transmission. Figure 2(a) presents the block diagram of the VLC communication process. The system begins with a modulated signal, which is fed into the driver circuit of the LED transmitter. The LED converts the electrical signal into optical power, transmitting it through the air to the receiver. The photodiode at the receiver end converts the optical power back into an electrical signal. This signal then passes through an amplifier, filter, and demodulator, ultimately reconstructing the original data stream. This figure encapsulates the entire VLC communication process, highlighting the roles of key components such as the LED, photodiode, and signal processing circuits. Figure 2(b) illustrates the spatial arrangement of LED transmitters and user receivers within an indoor environment. The LED transmitters are mounted on the ceiling, providing coverage to the receiver plane where multiple users (User 1, User 2, and User 3) are positioned. This configuration demonstrates the setup used to analyze the impact of different transmitter configurations and receiver positions on the VLC system's performance. The proposed VLC model is governed by several key parameters that influence the system's performance:

- Responsivity (0.289 A/W): This parameter indicates the photodetector's sensitivity, measuring the current generated per unit of optical power received.
- Path Loss (0.849): Path loss represents the reduction in power density of the optical signal as it propagates through the environment.
- Receiver Area (3): This refers to the effective area of the photodetector that captures the incoming optical signal.
- Noise Power Spectral Density: This parameter represents the power distribution of noise across the bandwidth, affecting the system's signal-to-noise ratio.
- Bandwidth (10 GHz): The bandwidth determines the range of frequencies over which the system can operate effectively, directly influencing data transmission rates.
- Room Area (25): This specifies the dimensions of the indoor environment where the VLC system is implemented.
- Reflectivity (0.78): Reflectivity measures how much of the incident light is reflected by the surfaces within the room, impacting the diffuse propagation of light.
- Half-Intensity Radiation Angle (2): This is the angle at which the intensity of light emitted by the LED is reduced to half of its maximum value, affecting the coverage area.
- Cut-Off Frequency (10 GHz): The cut-off frequency defines the maximum frequency at which the system can operate before the signal begins to attenuate.
- Field of View: This parameter indicates the angular range over which the receiver can effectively capture the incoming optical signal.
- Transmitted Optical Power (63 mW): This is the power level of the optical signal emitted by the LED transmitter.
- Lambertian Constant ($m = 1$): The Lambertian constant characterizes the LED's radiation pattern, assuming a uniform light distribution.
- Gain of Optical Filter ($Ts(\varphi) = 1$): The optical filter's gain represents the proportion of the incoming light that passes through the filter, affecting the overall signal strength.
- These parameters collectively define the operational characteristics of the VLC system, influencing its performance in terms of data transmission quality, coverage, and reliability.



(a) Block diagram of the VLC communication process

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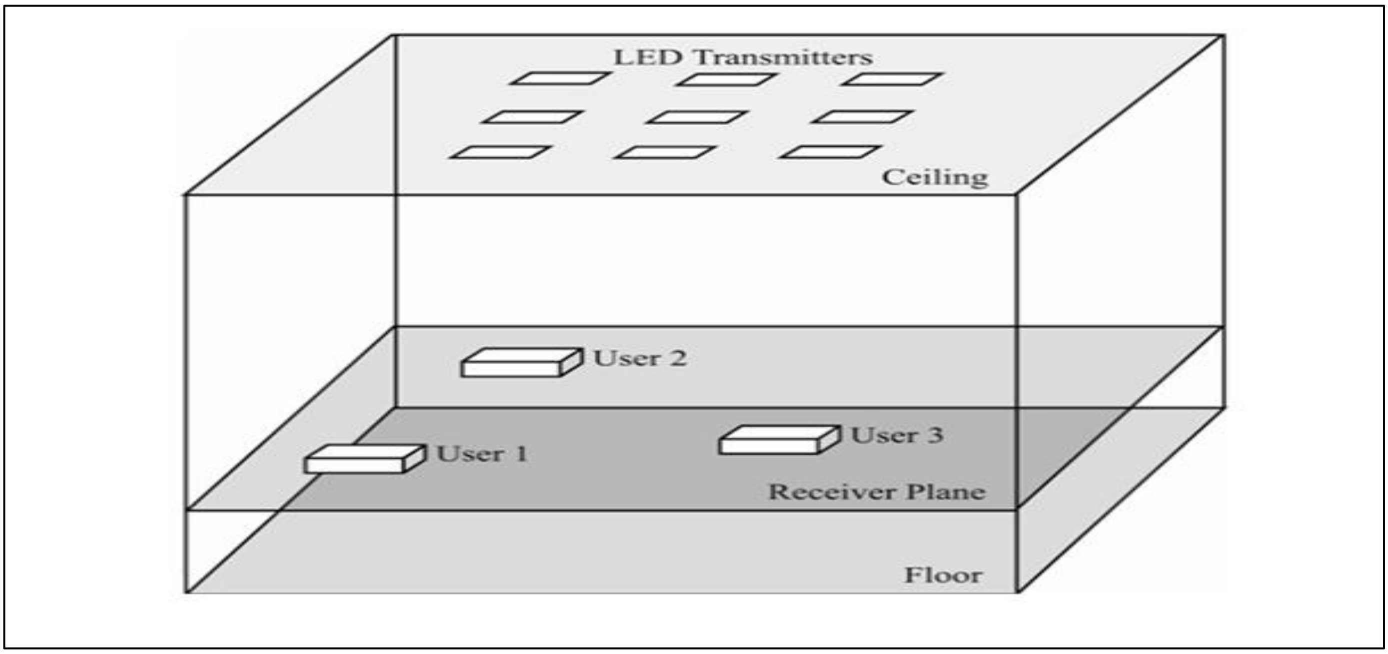

(b) Spatial arrangement of LED transmitters and user receivers within an indoor environment
Fig 2 Proposed VLC System [21]

Table 2 Parameters for VLC Model

Parameter	Symbol	Value
Responsivity	γ	0.289 A/W
Path Loss	α	0.849
Receiver area	A_R	$3\ cm^2$
Noise power spectral density	N_o	$10^{-15}\ A^2/Hz$
Bandwidth	B	10GHz
Room area	A_{Room}	$25\,m^2$
Reflectivity	ρ	0.78
Half intensity radiation angle	$2\theta_{max}$	120^0
Cut-off frequency	f_0	10GHz
Field of view	Φ	60^0
Transmitted optical power	P_T	63mW
Lambertian constant	m	1
Gain of optical filter	Ts(φ)	1

➢ *Transmitter Configuration*

This study employed three different transmitter configurations within the VLC system: single, four, and five transmitters, as depicted in Figure 3. Figure 3(a) illustrates the setup with a single transmitter positioned at the center of the area (coordinates 2.5, 2.5). This configuration represents the simplest form of deployment, focusing the light source centrally. In Figure 3(b), four transmitters are arranged symmetrically at the corners of the area, with coordinates (1.25, 1.25), (3.75, 1.25), (1.25, 3.75), and (3.75, 3.75). This arrangement is designed to provide more uniform coverage across the entire area by spreading out the light sources. Figure 3(c) shows the configuration with five transmitters, combining the central transmitter from the single setup with the four transmitters from the second configuration. The transmitters are positioned at coordinates (1.25, 1.25), (3.75, 1.25), (2.5, 2.5), (1.25, 3.75), and (3.75, 3.75). This configuration aims to enhance the uniformity and intensity of the illumination across the area by integrating a central light source with peripheral ones. These configurations are critical in evaluating the impact of different transmitter placements on the VLC system's performance, particularly in terms of illuminance distribution, received power, and signal quality across the coverage area.

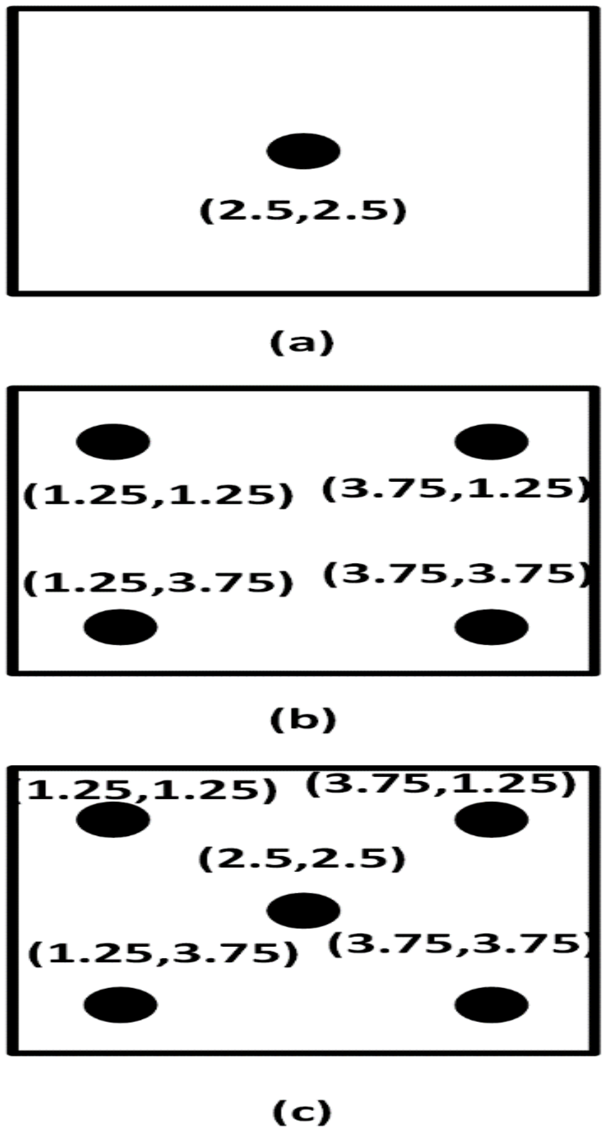

Fig 3 The Position of Leds When (A) Single Transmitter (B) Four Transmitter (C)Five Transmitter

➤ *Evaluation of Different Characteristics*

This study evaluates various characteristics of the VLC system, including illuminance distribution, received power, Signal-to-Noise Ratio (SNR) under both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions, and Bit Error Rate (BER) for different modulation schemes—On-Off Keying (OOK) and Quadrature Amplitude Modulation (QAM). These evaluations are conducted across different transmitter configurations, specifically with single, four, and five LED transmitters. This section provides a brief overview of these characteristics and their significance in assessing the performance and reliability of the proposed VLC system.

- *Illuminance Distribution*

This study calculated the illuminance pattern using Lambert's law and the associated equations to model irradiance formally.

The following radiometric quantities are employed to define the irradiance model:

Radiance intensity *(I)* is the radiant flux (Φ) divided by the elementary solid angle (*Ω):*

$$I = d\Phi / d\Omega \quad (1)$$

Irradiance (E) is the radiant flux incident on the elementary receiving area (A):

$$E = d\Phi / dA \quad (2)$$

According to the relations above, the elementary radiant flux is given by:

$$d\Phi = I * d\Omega \quad (3)$$

Therefore, the irradiance (E) can be expressed as:

$$E = I * d\Omega / dA \quad (4)$$

The solid angle (dΩ) is defined as:

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$$d\Omega = dA * \cos(\varphi) / R^2 \quad (5)$$

SS

$$E = I * \cos(\varphi) / R^2 \quad (6)$$

Consider n LEDs placed at points (x_1, y_1), (x_2, y_2), ..., (xn, yn), all on the same level z = 0. Each LED's intensity will contribute to the total irradiance of the LED system at a point (x, y) on the receiving surface:

$$E\ total = \Sigma(I_i * \cos(\varphi_i) / R_i^2) \quad (7)$$

To simplify the model, an intensity Lambert pattern will be considered:

$$I_i = I_0 * \cos^m(\theta_i) \quad (8)$$

where I_0 is the maximum intensity, m is the Lambertian order, and θ_i is the angle between the normal to the surface and the line-of-sight. The viewing angle φ_i is related to the line-of-sight:

$$\cos(\varphi_i) = |z| / R_i \quad (9)$$

Given $R_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + z^2}$, and assuming z = 0 and $\cos(\varphi_i) = z/R_i$, it results that $\cos(\varphi_i) = z$ and:

$$\cos(\varphi_i) = z / R_i \quad (10)$$

Combining equations (5), (6), and (8), we obtain the total irradiance as:

$$E\_total = \Sigma(P\_t,i * (m + 1) * \cos^m(\theta_i) * \cos(\varphi_i) / (2\pi R_i^2)) \quad (11)$$

This equation represents the irradiance model of the LED lighting system. Consider n LEDs placed at points (x_1, y_1), (x_2, y_2), ..., (xn, yn), all on the same level z = 0. The total illuminance at a point (x, y) on the receiving surface is the sum of the contributions from each LED:

$$I\_illum,total = \Sigma(P\_t,i * (m + 1) * \cos^m(\theta_i) * \cos(\varphi_i) / (2\pi R_i^2)) \quad (12)$$

Here:

P_t is the transmitted optical power from the LED.

m is the order of Lambertian emission, which characterizes the LED beam spread.

θ is the angle of emission from the LED.

φ is the angle of incidence at the receiver.

R is the distance between the LED and the receiver.

I_illum,total represents the total illuminance at the point (x,y) on the receiving surface, considering contributions from all n LEDs.

Table 3 presents the parameters used for calculating the illuminance pattern in the study. The table outlines the configurations for different numbers of LEDs, their luminous intensities, and the positions of the transmitters in the VLC system.

- *One LED Configuration*

Luminous Intensity: The luminous intensity for this single LED setup is 1200 candela (w/sr).

Transmitter Position: The LED is positioned centrally at coordinates [2.5, 2.5], which likely represents the center of the room or area being analyzed.

- *Four LED Configuration*

Luminous Intensity: In this configuration, the luminous intensity of each LED is 300 candela (w/sr).

Transmitter Positions: The LEDs are placed symmetrically at four positions: [1.25, 3.75], [3.75, 3.75], [1.25, 1.25], and [3.75, 1.25]. These coordinates suggest that the LEDs are positioned near the corners of the area, ensuring more uniform coverage across the entire space.

- *Five LED Configuration*

Luminous Intensity: Each LED in this setup has a luminous intensity of 240 candela (w/sr).

Transmitter Positions: The LEDs are positioned at [1.25, 3.75], [3.75, 3.75], [1.25, 1.25], [3.75, 1.25], and [2.5, 2.5]. This configuration combines the positions from the four LED setup with an additional central LED, which is located at [2.5, 2.5]. This setup is likely designed to provide even better coverage by filling in any potential gaps in illuminance that might occur with just four LEDs.

Table 3 Transmitter Value Forilluminance Pattern

Numbers of LED	Luminous intensity w/sr	Transmitter position
One	1200	[2.5,2.5]
Four	300	[1.25,3.75],[3.75,3.75],[1.25,1.25]&[3.75,1.25]
Five	240	[1.25,3.75],[3.75,3.75],[1.25,1.25],[3.75,1.25]&[2.5,2.5]

- *Receive Power*

The received power at the photodetector in a Visible Light Communication (VLC) system, particularly in a direct Line-of-Sight (LOS) scenario, is a critical factor in determining the efficiency and reliability of the communication link. This power is influenced by various factors including the characteristics of the LED source, the geometry of the system, and the properties of the photodetector and its associated components. Understanding this equation is critical for designing and optimizing VLC systems, as it allows engineers to predict the performance of the system under various conditions, such as changes in

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distance, angle, or environmental factors. By carefully selecting components and configuring the system parameters, the received power can be maximized, leading to more reliable and efficient communication. The received power at the photodetector from a single LED source in a direct Line-of-Sight (LOS) scenario is given by:

Prec = Pt . (((m + 1) * 〖cos〗^m (θ) * cos(φ)))/(2πR^2) rect(φ/φmax) * AR * Ts(φ) * g(φ) (13)

Where:

- ✓ Pt is the transmitted optical power from the LED.
- ✓ m is the order of Lambertian emission, which characterizes the LED beam spread.
- ✓ θ is the angle of emission from the LED.
- ✓ φ is the angle of incidence at the receiver.
- ✓ R is the distance between the LED and the receiver.
- ✓ φmax is the receiver's field of view (FOV).
- ✓ AR is the effective receiver area.
- ✓ Ts(φ) is the gain of the optical filter (if present).
- ✓ g(φ) is the concentrator gain.

This relationship between received power and illuminance is essential for designing efficient VLC systems. By understanding and controlling each of the factors in the equation, engineers can optimize the placement of LEDs and photodetectors, select appropriate photodetector characteristics, and manage the lighting environment to ensure reliable communication. The received power refers to the amount of optical power detected by a photodetector after light from an LED source has traveled through the environment and possibly undergone reflections, scattering, and attenuation. The received power is typically measured in watts (W). For example, in a scenario where path loss is significant (e.g., due to a large distance or obstructed line-of-sight), designers might choose a photodetector with higher responsivity or increase the LED's luminous output to maintain sufficient received power. Conversely, in well-lit environment with minimal path loss, a lower responsivityphotodetector might suffice-

Received power can be related to illuminance by –

$$R_p = 2 * E_r^2 * (\gamma A_r \alpha)^2 \quad (14)$$

Where,

[A/W] denotes the receiver responsivity

α =Path Loss

A_R =Receiver Area

- *Signal to Noise Ratio determination for Direct LOS Link*

The SNR in a VLC system is influenced by the received signal power, the photodiode's responsivity, and the noise introduced by ambient light. By modeling the system as a single source and virtual channel, we can use the equations mentioned below to predict and optimize the system's performance, ensuring reliable communication even in challenging noise environments.

For simulation results it is easier to regard it as one source, P_{chip} and one virtual channel, |H|, which is sum of all LOS gains.We define a reference signal-to-noise ratio as the total electrical signal power generated by the photodiode (containing the dc component) over the AWGN power in bandwidth (B=10 GHz)-

$$SNR_o = 2\gamma^2 P_R^2 / (N_0 B) = 2\gamma^2 P_{chip}^2 |H|^2 / N_0 B \quad (15)$$

In a typical VLC environment, the dominant noise contribution is often due to shot noise, which arises from the ambient light, such as sunlight entering through windows. Shot noise is a type of electronic noise that occurs due to the random arrival of photons at the photodiode. Noise power spectral density is, representing the power per unit bandwidth (W/Hz)-

$$N_0 = 2q \gamma P_{ambient} \quad (16)$$

q is the elementary charge of an electron, approximately 1.602 x 10^{-19} coulombs.

$P_{ambient}$ is the ambient optical power incident on the photodiode, primarily due to sunlight.

For worst-case noise scenarios, we consider bright sky irradiance, which could be as high as 5.8 W/(nm·m²) across the visible spectrum. This ambient light contributes significantly to the shot noise experienced by the photodiode

- *Signal to Noise Ratio determinationfor diffuse propagation (NLOS)*

We assume that all LEDs are driven by the same (electrical) signal. Then, in a flat channel, the received optical signal power is the sum of powers coming from all light emitting chips-

$$P_R = \sum_i |H_i(0)| P_{T,i} = P_{Chip} |H| \quad (17)$$

The illumination at any point of the receiving surface includes line of sight (LOS) from the LED chips as well as a contribution of reflections off the walls or objects in the room. To describe the illuminance at any point on a receiving surface in a visible light communication (VLC) system, it is important to consider both the Line-of-Sight (LOS) and reflective components of light, including those reflected by walls. The channel response for directed (LOS) light can be modeled using Dirac pulses, while the diffuse portion can be represented by an integrating-sphere model. The channel frequency response, in terms of optical power, can then be written as-

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$$H(f) = \sum_{i=1}^{n} \eta_{LOS,i} \exp(-j2\pi f \Delta\tau_{LOS,i}) + \eta_{DIFF} \frac{\exp(-j2\pi f \Delta\tau_{DIFF})}{1 + j(f / f_0)} \quad (18)$$

where η_{LOS} and η_{DIFF} represent the channel gain for the LOS and diffuse signal; respectively- $\Delta\tau_{LOS}$ [s] and $\Delta\tau_{DIFF}$ [s] are the corresponding signal delays and f_0 [Hz] the cut-off (3-db) frequency of the purely diffuse channel.The LOS gain from the i_{th} LED chip is given by-

$$\eta_{LOS,i} = A_R (m+1) \cos^m \phi_i \cos\psi_i / 2\pi r_i^2 \quad (19)$$

The Lambert index m depends on the radiation semi-angle ϕ as

$$m = -1/ \log_2 \cos\phi_{max} \quad (20)$$

Where, $A_R[m^2]$ is the effective receiver surface (together with filter and concentrator gain) and the other variables are introduced here

- ✓ r=distance between transmitter and receiver
- ✓ ϕ = angle of irradiance when light is emitted from transmitter
- ✓ ψ = angle of incidence when light is incident to receiver
- ✓ ρ =reflectivity of material=0.78(for white concrete)
- ✓ f =varying frequency
- ✓ f_0 =3-db frequency

η_{DIFF} is related to optical path loss by α = -10log(η_{DIFF}). Path loss can be calculated using this relation.

For diffuse link the law is-

$$\eta_{DIFF} = \frac{A_R}{A_{RooM}} \frac{p}{1-p} \quad (21)$$

In indoor VLC systems, light often undergoes multiple reflections off walls, ceilings, and other surfaces. The ratio $\frac{p}{1-p}$ can be relevant when considering the cumulative effect of these multiple reflections. For instance, when light is reflected multiple times within a room, the overall contribution of reflected light to the received signal can be estimated using this ratio. It helps in understanding how much light remains available for communication after successive reflections. It represents a situation where light is repeatedly reflected, and the ratio gives insight into how much light remains in the system versus how much is lost after each reflection.

- *Bit Error Rate in Optical On-Off Keying Modulation for VLC Systems*

In Optical On-Off Keying modulation for Visible Light Communication (VLC) systems, the Bit Error Rate (BER) can be expressed using the error function (erf), which accounts for the noise and signal-to-noise ratio (SNR) in the system. For OOK modulation, assuming additive white Gaussian noise (AWGN), the BER is given by:

$$\text{BER} = \frac{1}{2} \cdot \text{erfc}\left(\frac{\sqrt{SNR}}{\sqrt{2}}\right) \quad (22)$$

or equivalently using the error function:

$$\text{BER} = \frac{1}{2} \cdot \left(1 - \text{erfc}\left(\frac{\sqrt{SNR}}{2}\right)\right) \quad (23)$$

Where:

- ✓ erfc(x) = 1 - erf(x) is the complementary error function.
- ✓ SNR is the signal-to-noise ratio at the receiver.

In OOK, a higher SNR leads to a lower BER, improving the communication reliability.This equation provides a direct relationship between the BER and the SNR for OOK modulation in VLC systems under Gaussian noise conditions.

- *Bit Error Rate in Optical QAM Modulation for VLC Systems*

The Bit Error Rate is a critical performance metric in Visible Light Communication (VLC) systems, particularly when using Quadrature Amplitude Modulation (QAM) schemes. In optical QAM, the BER is influenced by factors such as signal-to-noise ratio (SNR), modulation order, and the characteristics of the transmission medium. The BER for a QAM system in VLC can be calculated using the following equation:

$$\text{BER} = 2 * (1 - 1/\sqrt{M}) * Q(\sqrt{(3 * \log2(M) * SNR / (M - 1))}) \quad (24)$$

➢ *Comparative Analysis*

This study conducts a comparative analysis of different transmitter configurations based on a comprehensive evaluation of key parameters, including illuminance distribution, received power, Signal-to-Noise Ratio, and Bit Error Rate. The analysis focuses on three specific configurations: a single transmitter, four transmitters, and five transmitters. Through this comparative analysis, the study examines how each configuration impacts the performance of the VLC system in terms of the evaluated parameters.

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IV. RESULTS AND DISCUSSION

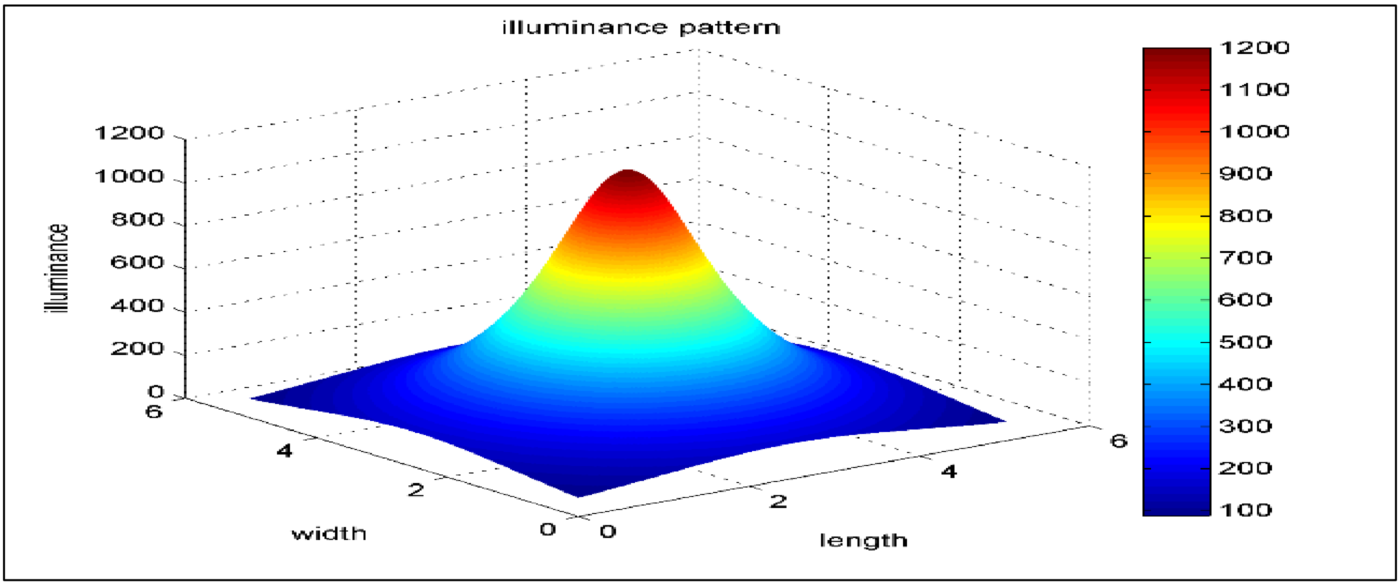
This section presents an evaluation and discussion of the results related to various key characteristics, including illuminance distribution, received power, Signal-to-Noise Ratio, and Bit Error Rate. The analysis is centered on three specific transmitter configurations: a single transmitter, four transmitters, and five transmitters. Each configuration is examined to understand its impact on the performance of the Visible Light Communication (VLC) system, providing insights into how different setups influence overall system efficiency and effectiveness. For the simulation of these results, this study utilized MATLAB 2020 software, which was instrumental in modeling and analyzing the different configurations and their respective performance metrics.

➢ *Performance Evaluation of Different Characteristics of VLC System*

This sub-section provides a performance evaluation of the various characteristics of the VLC system, including illuminance distribution, received power, Signal-to-Noise Ratio, and Bit Error Rate.

- *Illuminance Pattern*

The Figure 4 and Figure 5 shows the 3D and 2D plot of illuminance distribution across the entire working plane in relation to receiver positions. This visualization illustrates how the illuminance varies across the surface of the receiver. The color gradient displayed in the sidebar reflects the range of illuminance, from the minimum to the maximum value.



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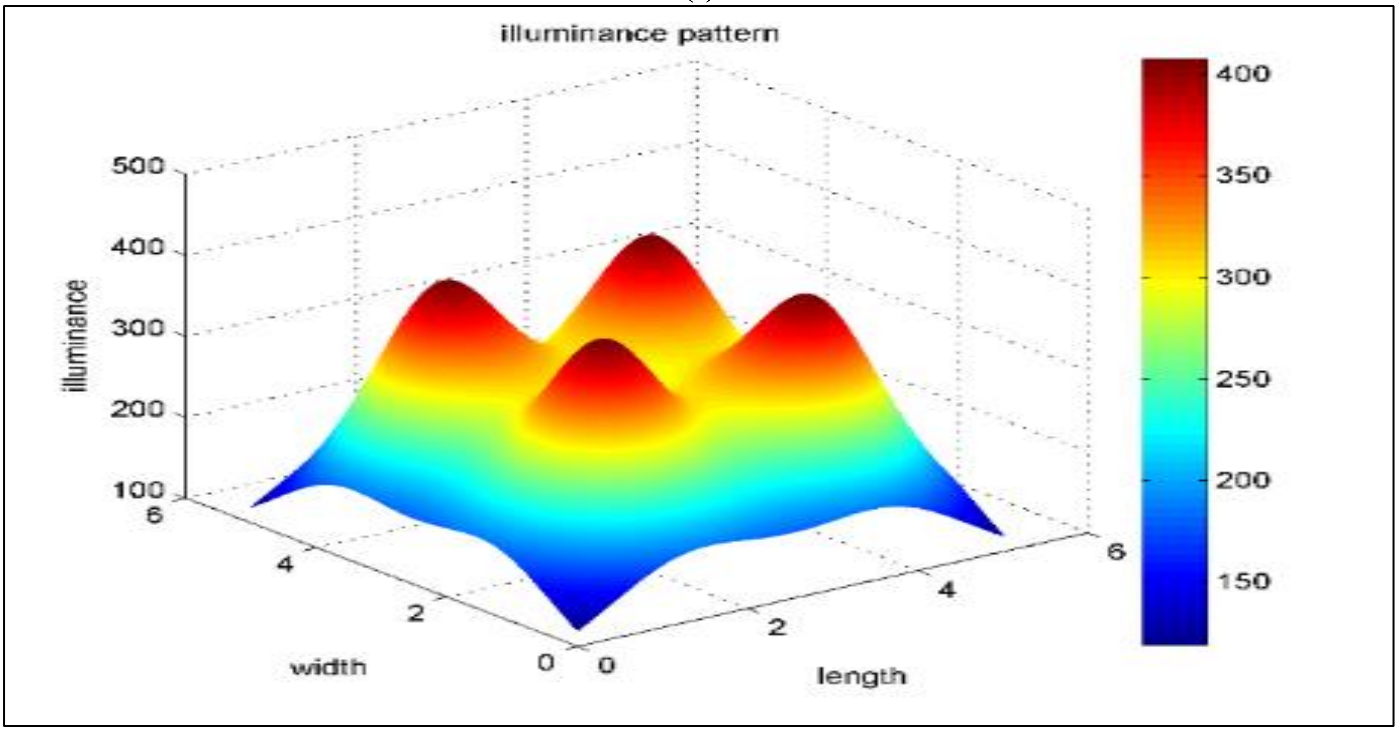

(b)

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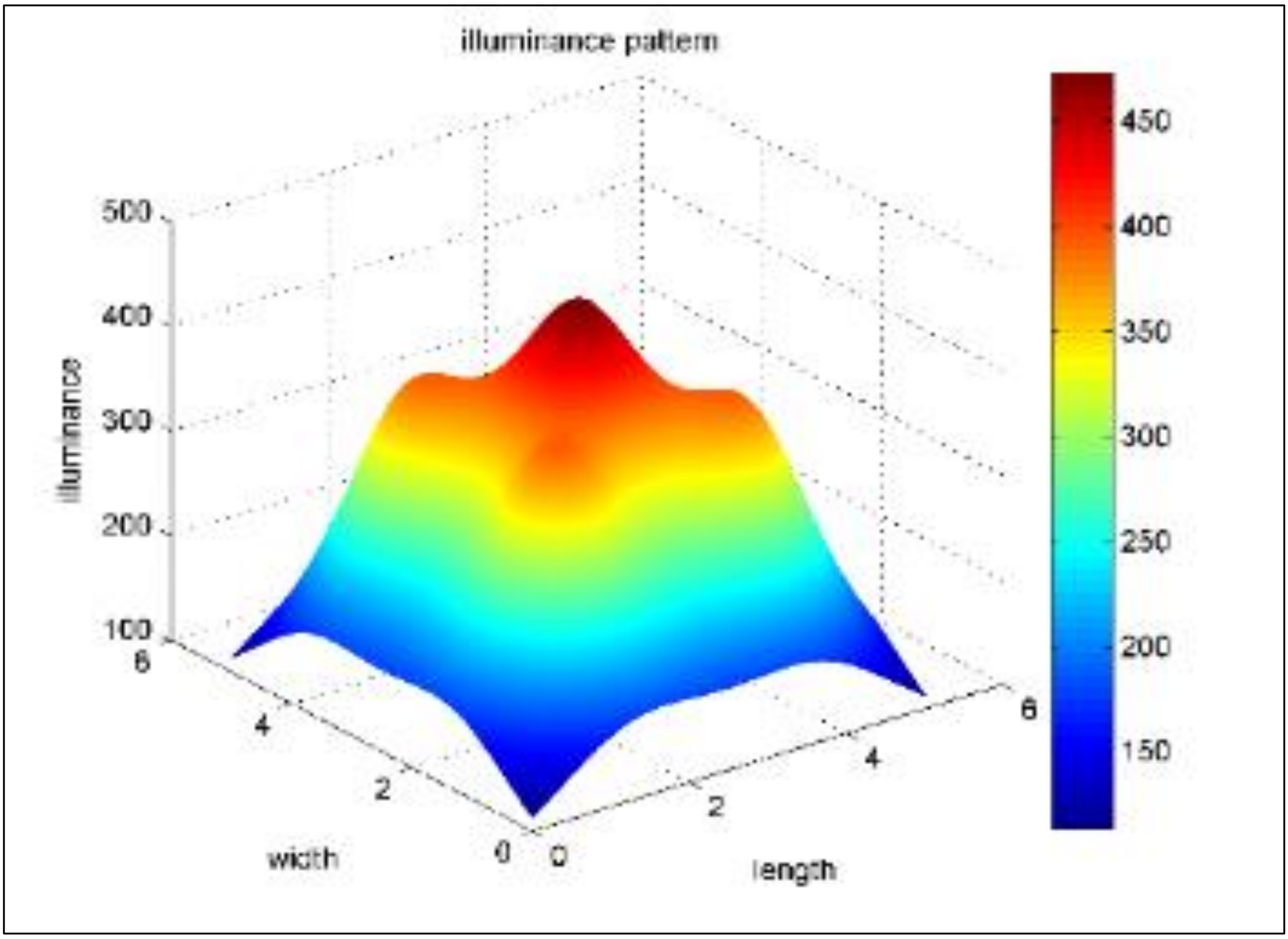

(c)
Fig 4 Illuminance pattern for (a) single (b) four (c) Five LED models (3D)

For 4(a) and 5(a) single LED model, the illuminance ranges from a minimum of 88.89 lux to a maximum of approximately 1200 lux, attributable to the use of an LED lamp with a luminous intensity of 1200 W/sr. In a system with four LEDs 4(b) and 5(b), where each LED has a luminous intensity of 300 W/sr, the illuminance varies between 150 lux and 400 lux. The increase in maximum illuminance to approximately 400 lux is due to the cumulative effect of light contributions from adjacent sources. In the case of a five-LED 4(c) and 5(c) system, with each LED having a luminous intensity of 240 W/sr, the illuminance ranges from 150 lux to 450 lux. The increase in maximum illuminance beyond 450 lux is attributed to the additional central LED, which enhances the overall light distribution. As the distance from the transmitter increases, the brightness level diminishes, leading to a noticeable decrease in illuminance towards the edges of the receiver plane. The corners, in particular, exhibit significantly lower illuminance levels compared to the areas directly aligned with the line-of-sight (LOS) link from the transmitter.

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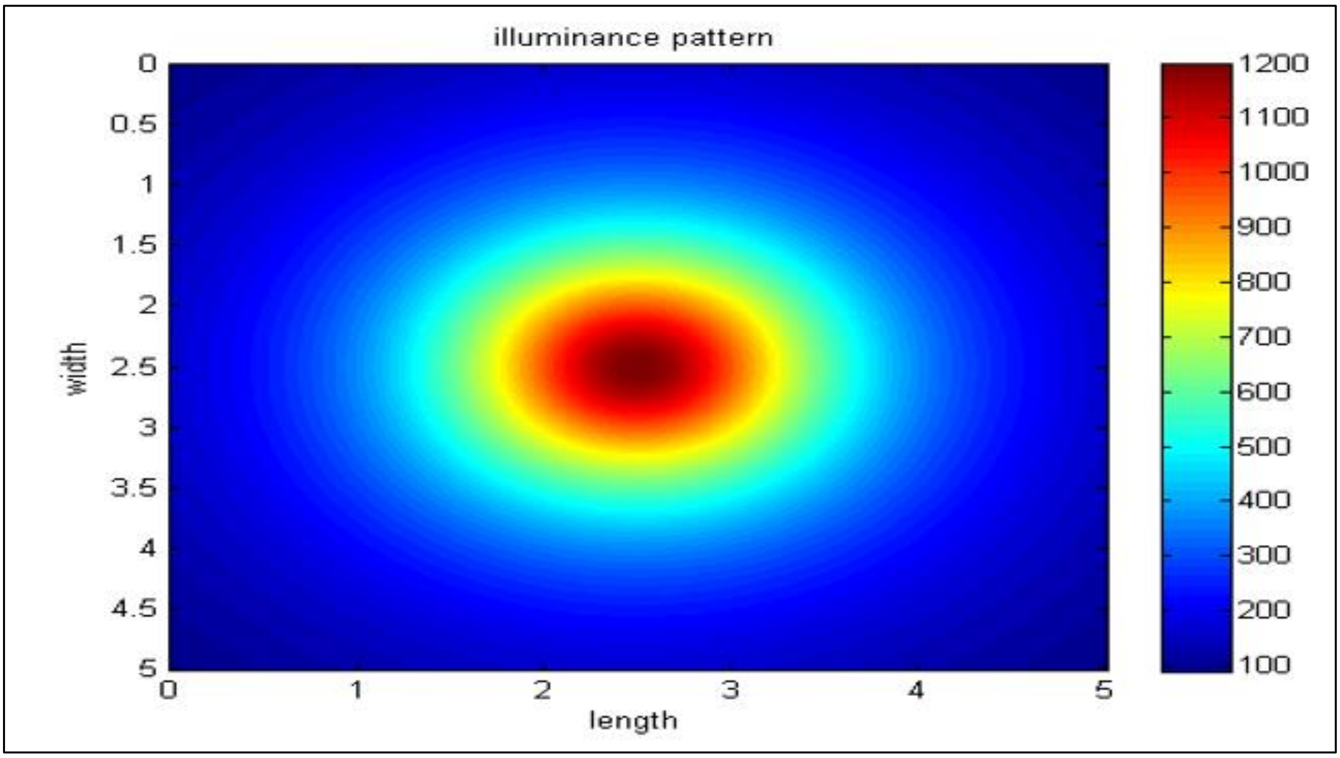
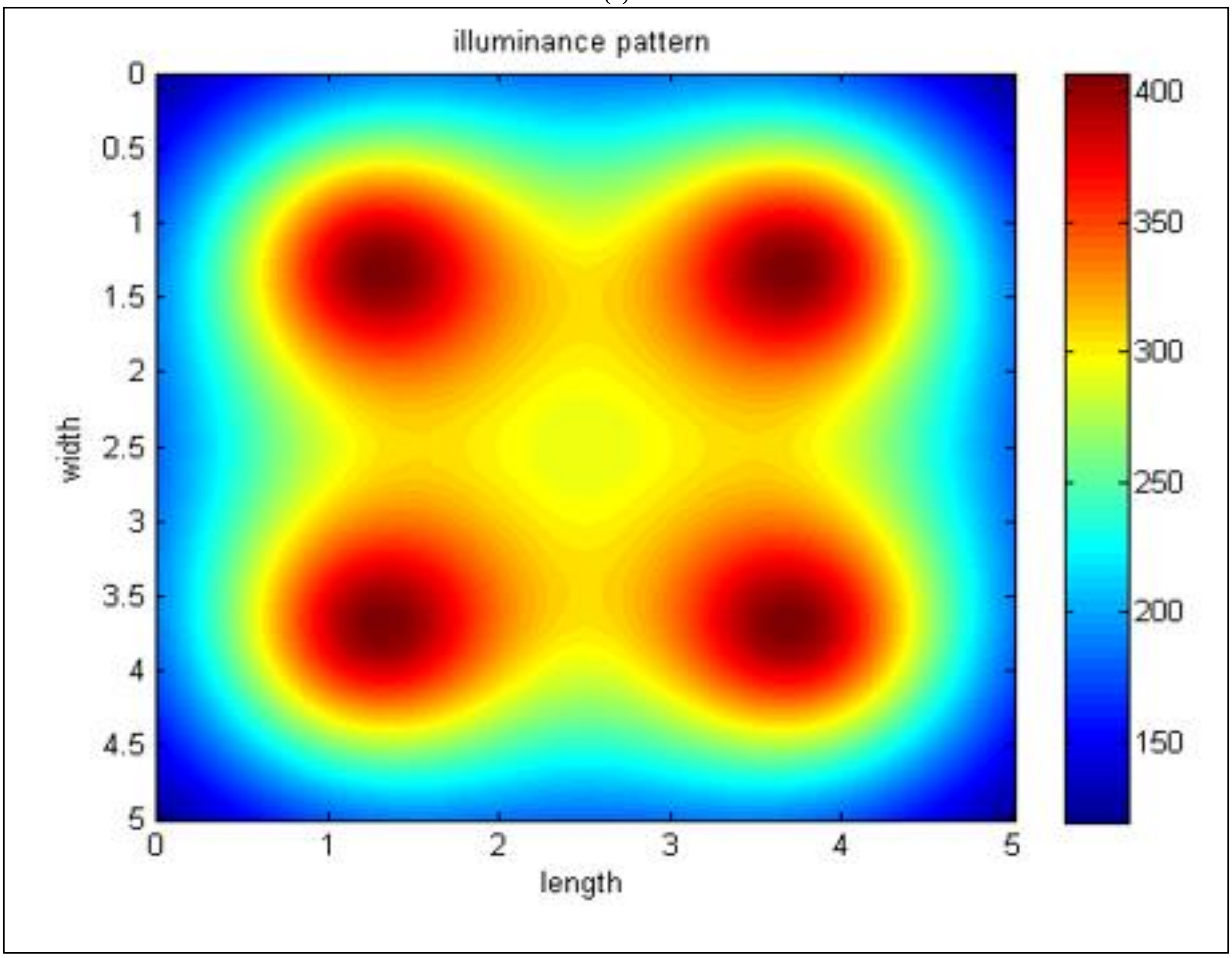


(a)



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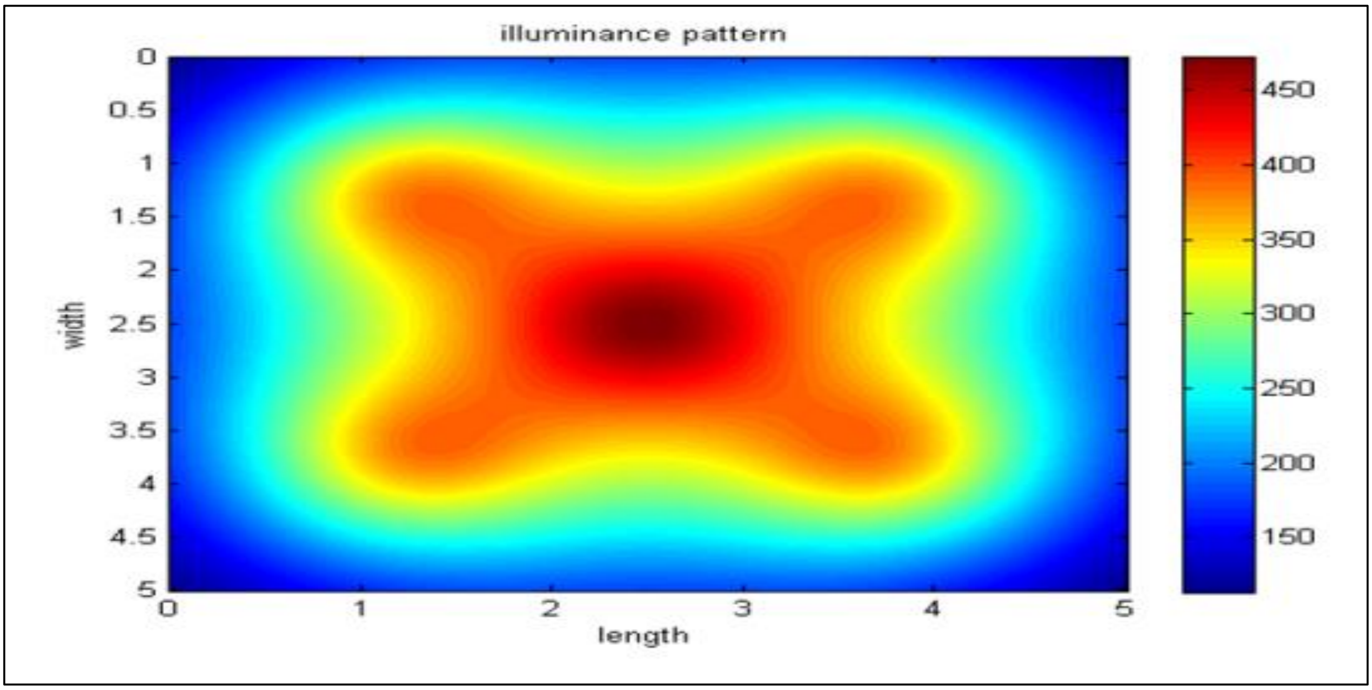
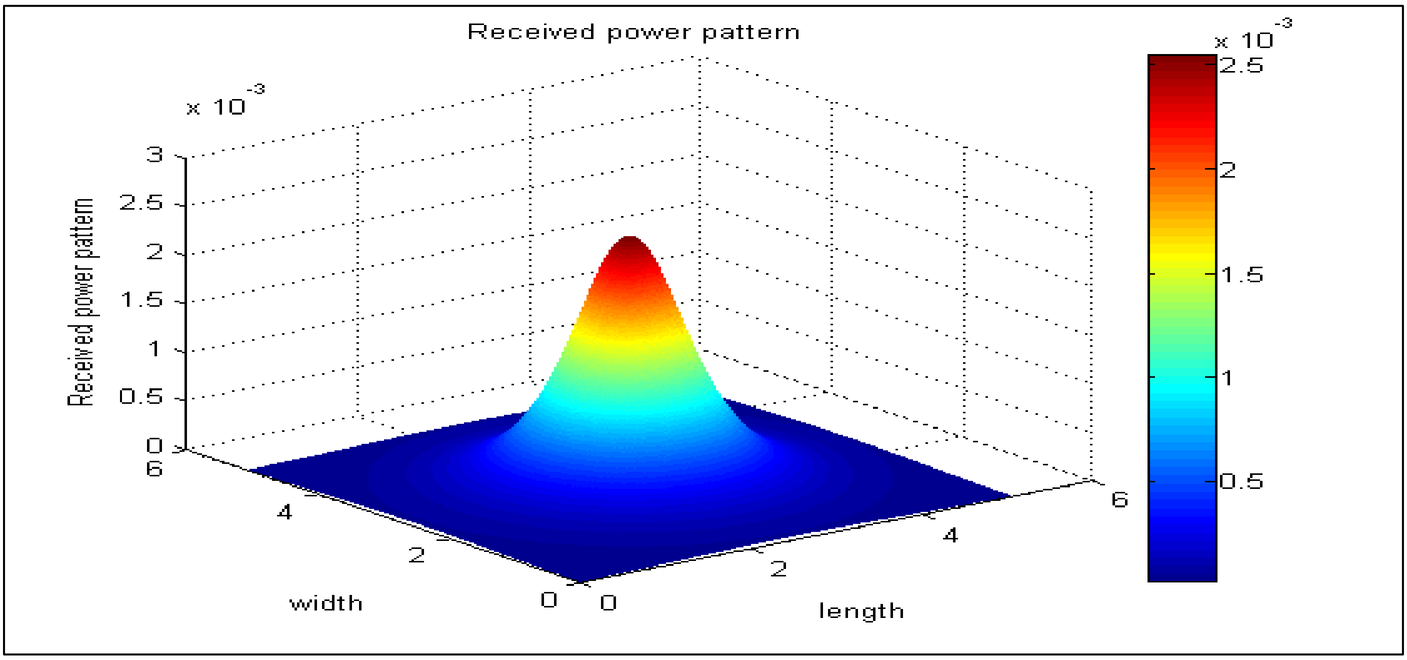


(c)

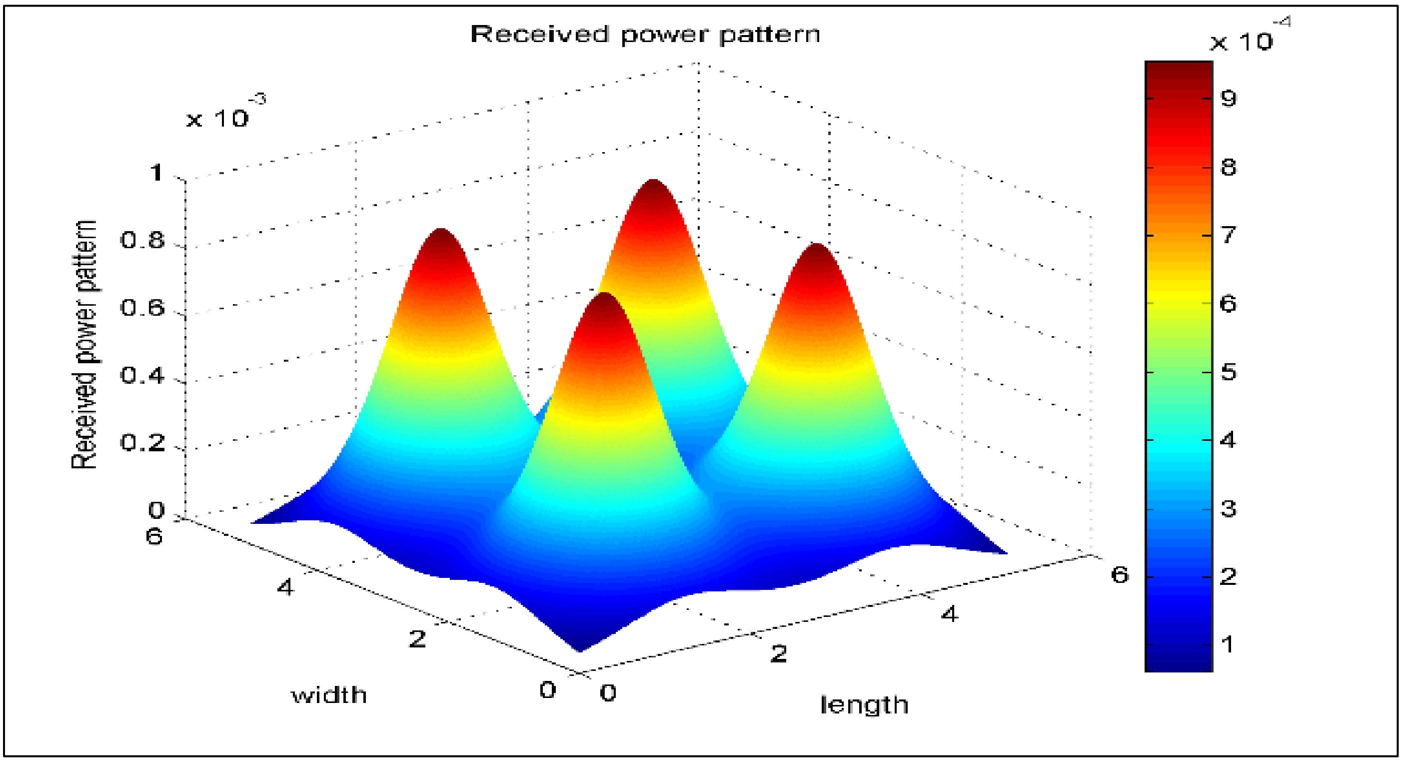
Fig 5 Illuminance pattern for (a) single (b) four (c) Five LED models (2D)

- *Received Power*

When designing visible light communication (VLC) systems, received power is a critical factor in determining the system's overall performance, particularly in terms of signal strength and data transmission reliability. The distribution of received power can vary significantly depending on the arrangement of LED transmitters and optocells within a given environment. Different configurations, such as single, multiple, or arrayed LED setups, influence how light is distributed and received across the communication area. Figure 6 and Figure 7 illustrates the received power for different LED configurations (3D and 2D). In the 6(a) and 7(a) model, the received power at the center point is above 2.5 mW, reaching its maximum value, while the minimum value is less than 0.5 mW. In contrast, the 6(b) and 7(b) model shows that the received power reaches a maximum of 0.9 mW at the line-of-sight (LOS) link of the four transmitters, but decreases to below 0.1 mW at the center of the receiver surface and the corner edges. This reduction is attributed to lower illuminance, resulting in a diminished amount of light received in these areas. For the 6(c) and 7(c) plot, the received power at the central position is approximately 1.1 mW, with the other transmitters showing received power ranging from 1 mW to 0.9 mW.



(a)



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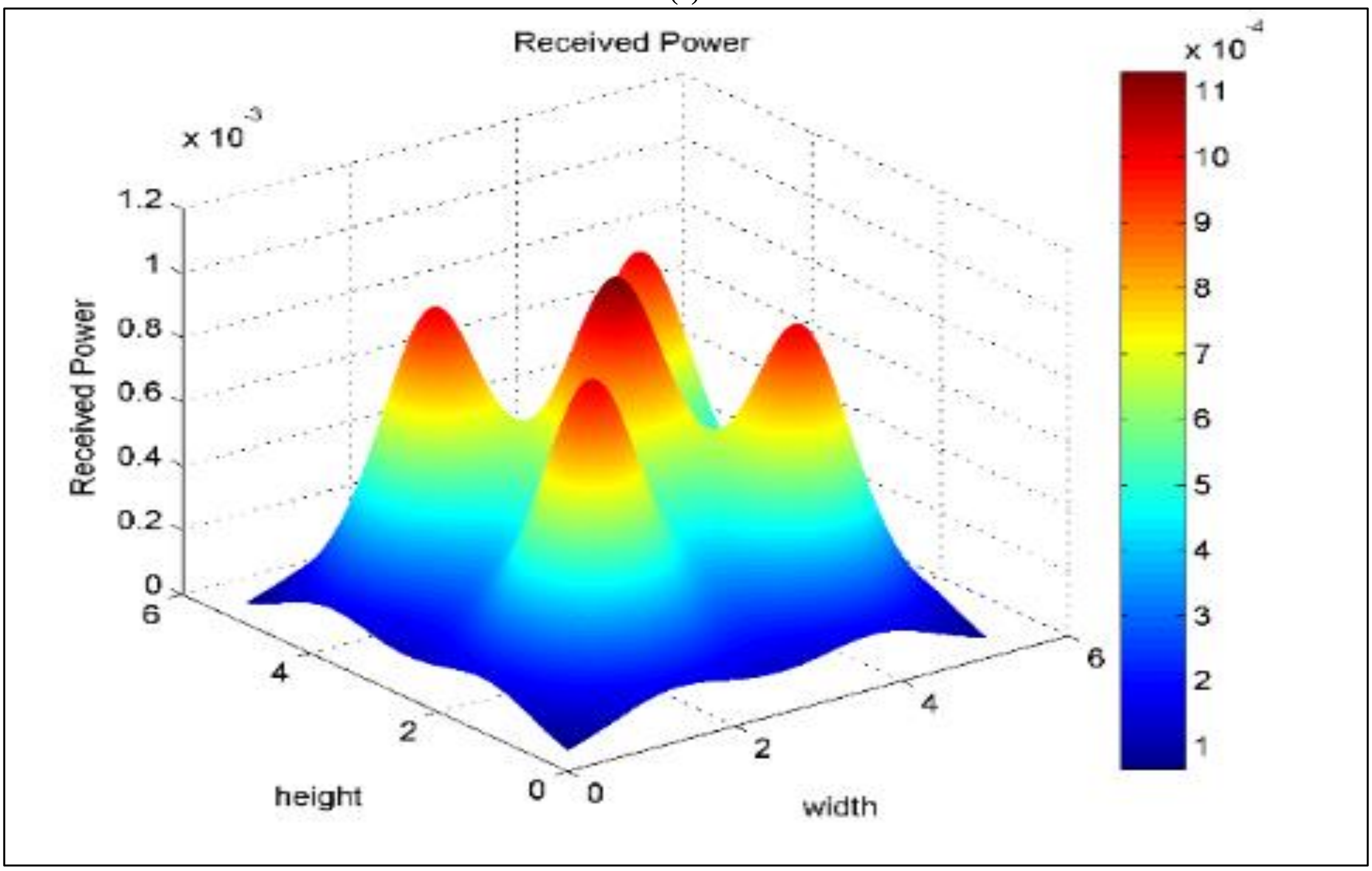

(c)

Fig 6 Received Power pattern for (a) single (b) four (c) Five LED models (3D)

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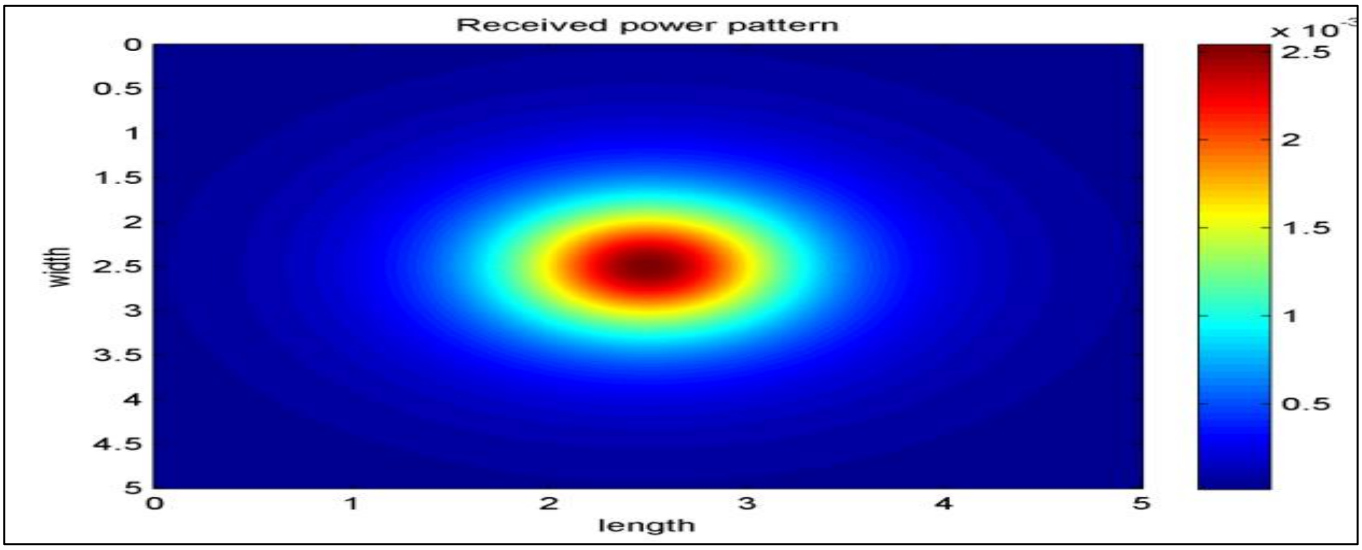
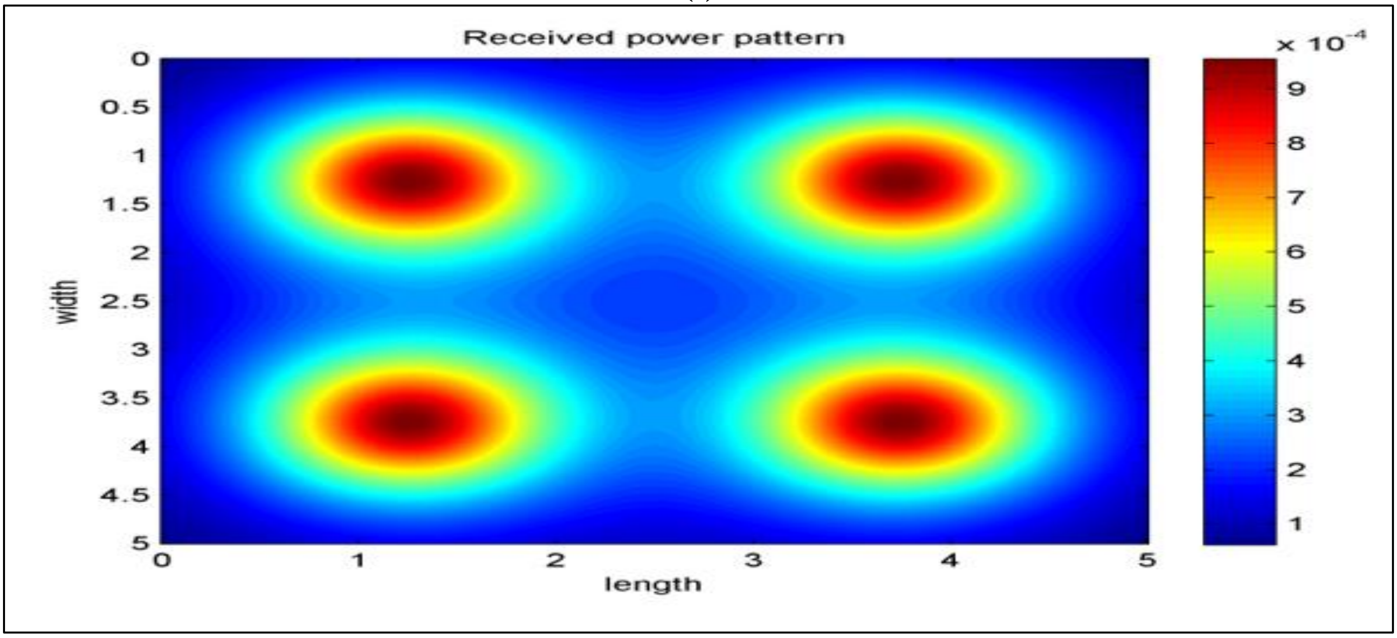


(a)



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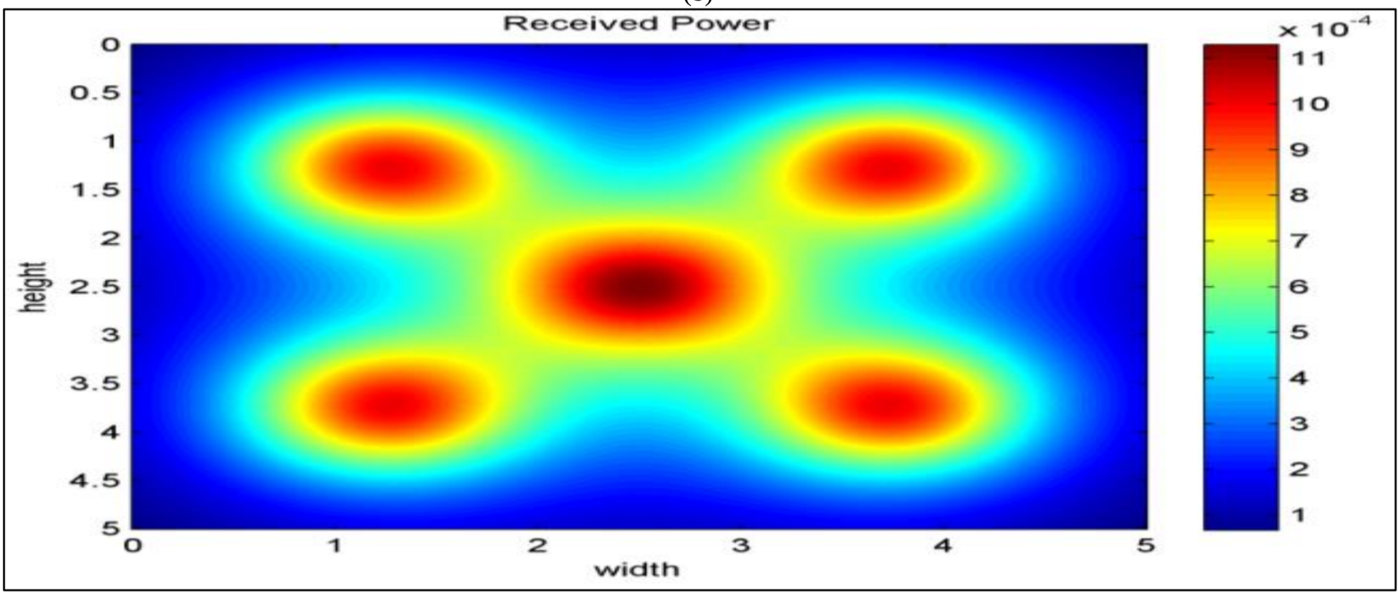

(c)

Fig 7 Received Power pattern for (a) single (b) four (c) Five LED models (2D)

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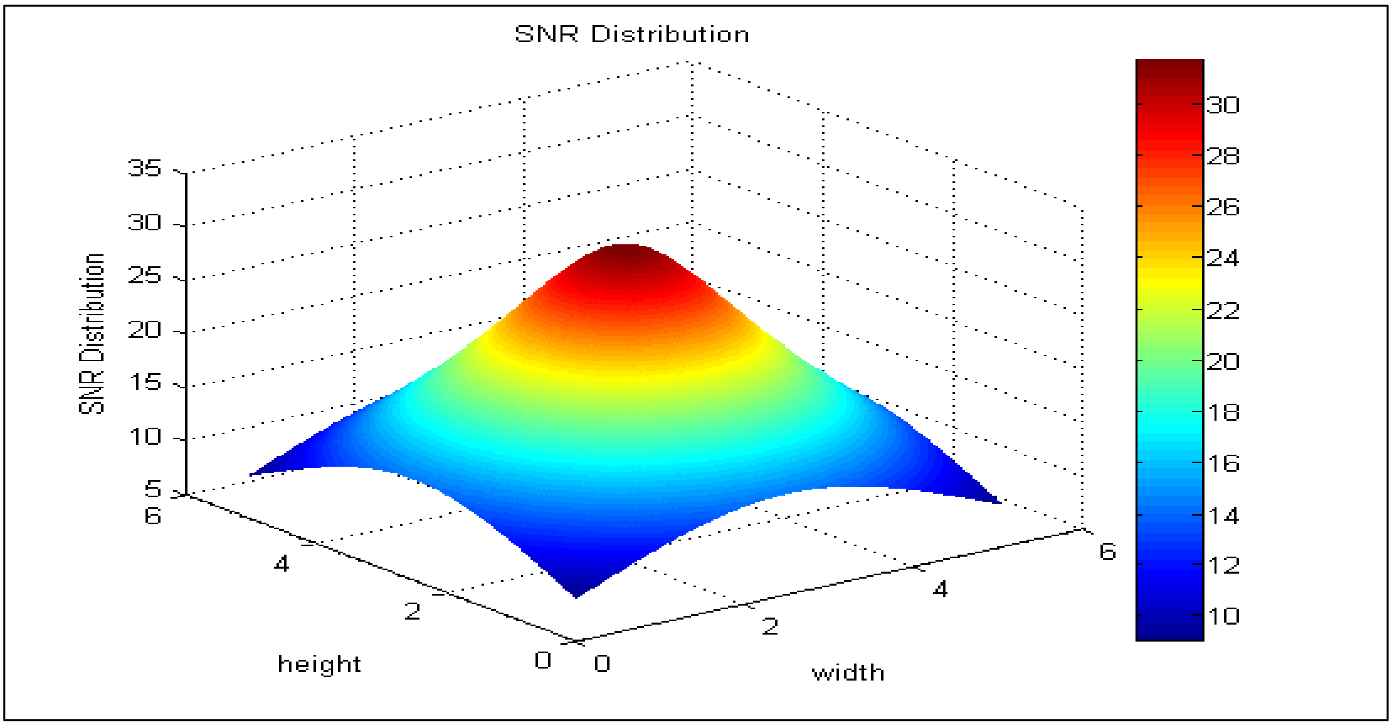
- *Signal to Noise Ratio determination for Direct LOS Link*

In Line-of-Sight (LOS) links, the Signal-to-Noise Ratio (SNR) tends to be higher because the signal travels directly from the transmitter (e.g., an LED) to the receiver (e.g., an optocell) without significant obstruction or reflection. This direct path minimizes signal degradation, resulting in stronger signal reception and, consequently, a higher SNR. Figure 8 and Figure 9 illustrates the distribution of SNR in LOS for different LED configurations (3D and 2D). In the single LED system depicted in Figure 8(a) and Figure 9(a), the SNR varies from 9.0510 dB to 31.6577 dB. For the four LED system shown in Figure 8(b) and Figure 9(b), the SNR ranges from -11.9584 dB to 29.2319 dB. In contrast, the five LED system in Figure 8(c) and Figure 9(c) display an SNR that spans from -24.6396 dB to 39.6514 dB. While the five LED system achieves a higher maximum SNR, indicating the potential for better performance at the same brightness level, it also exhibits a significantly lower minimum SNR compared to the single and four LED systems. Conversely, the single LED system maintains a higher minimum SNR than the other two systems, suggesting more consistent performance under conditions where the SNR is lower.



(a)

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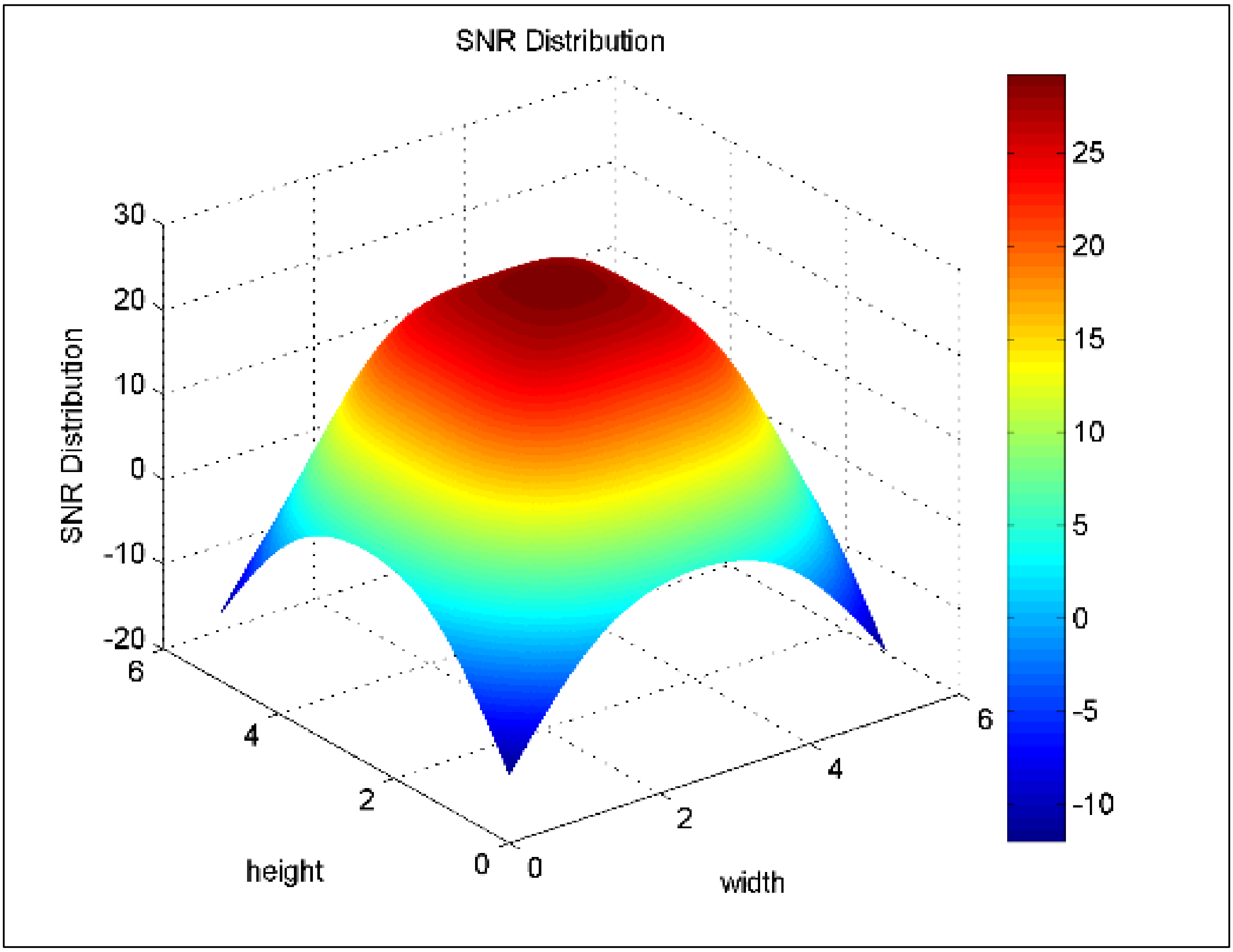
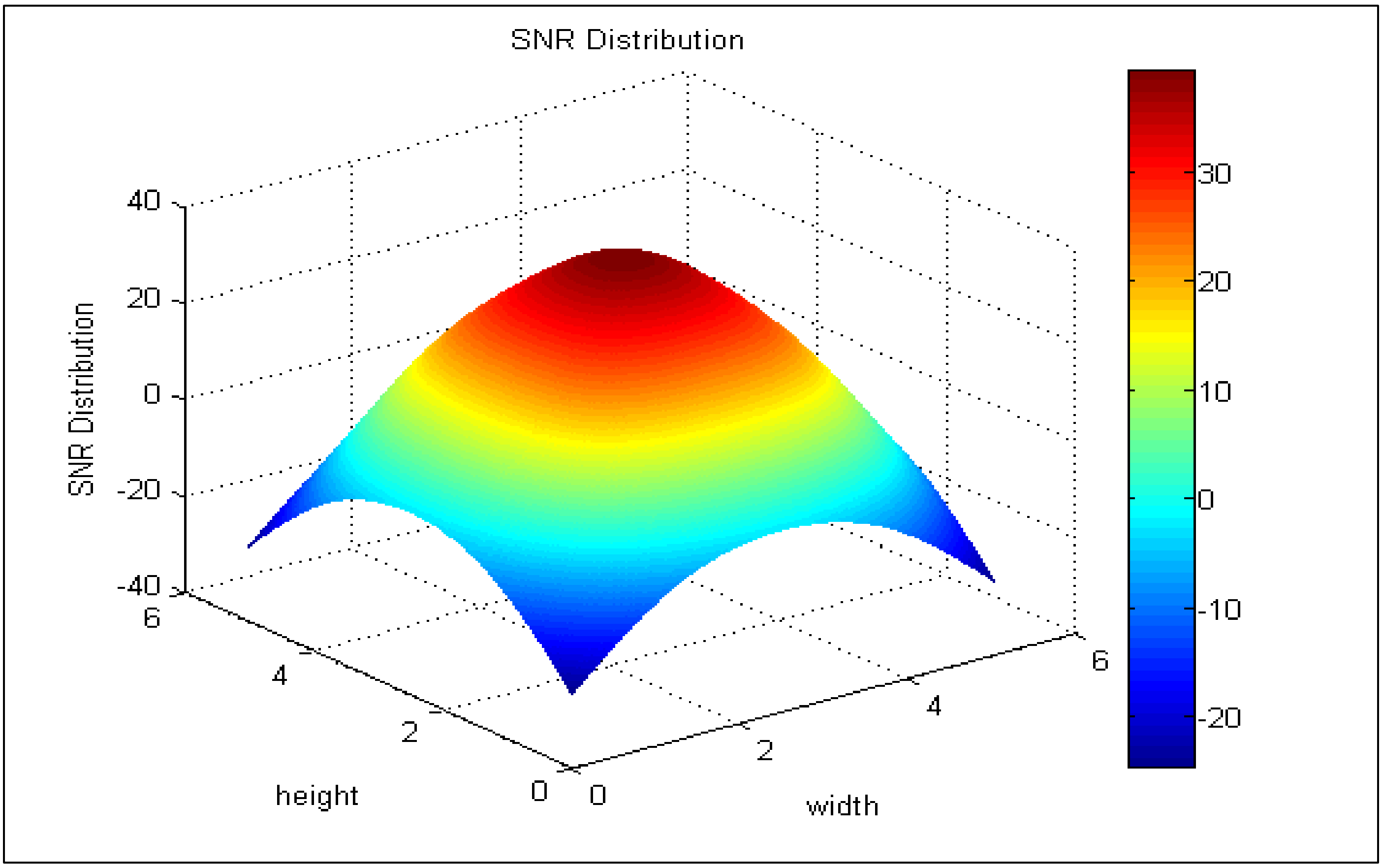
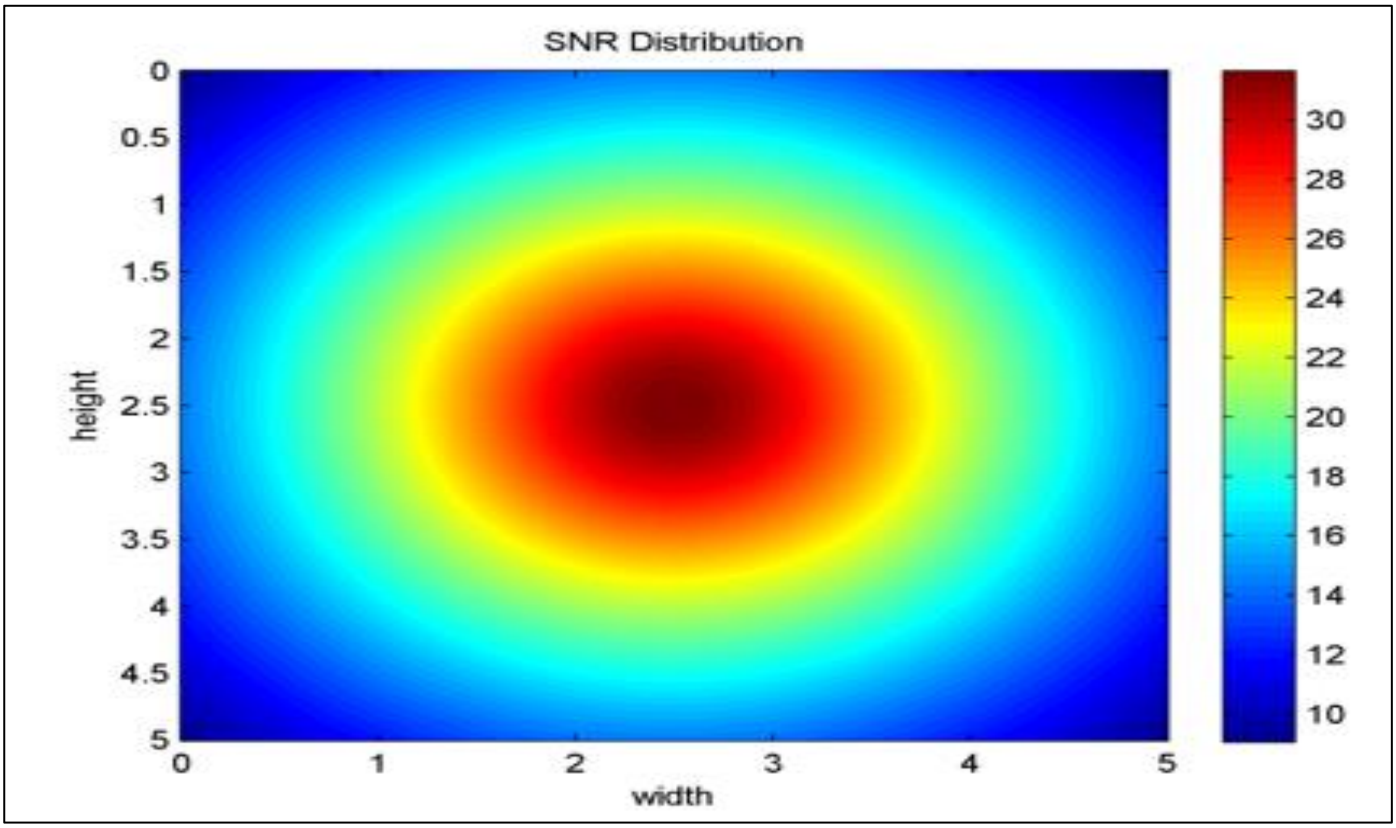


(b)


SNR Distribution
SNR Distribution
40
20
0
-20
-40
6
4
2
0
height
0
2
4
6
width
30
20
10
0
-10
-20

(c)


SNR Distribution
height
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
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width
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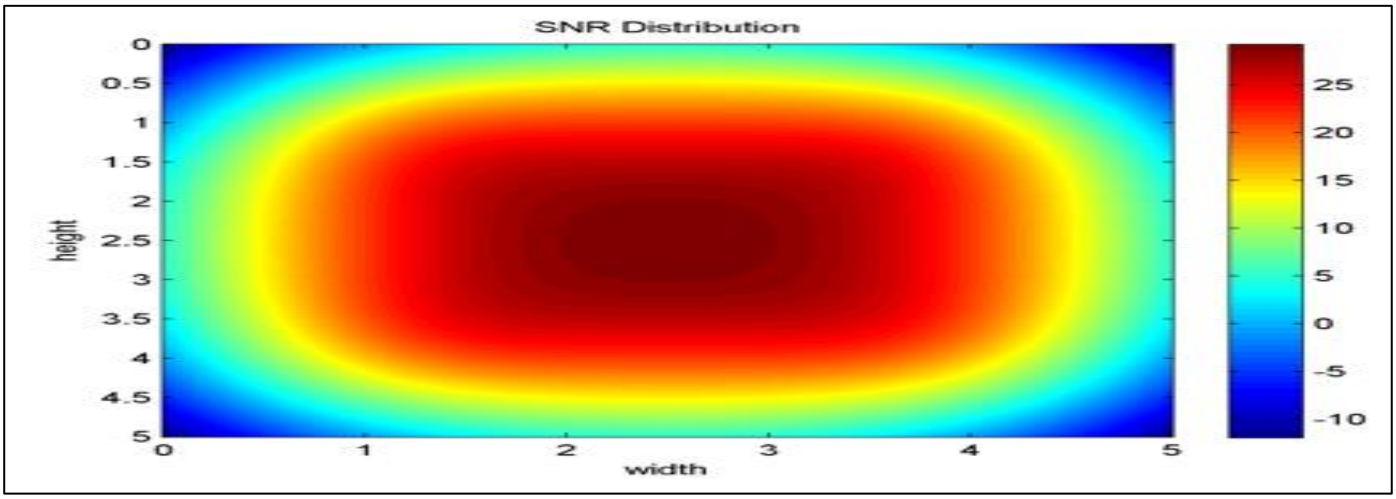
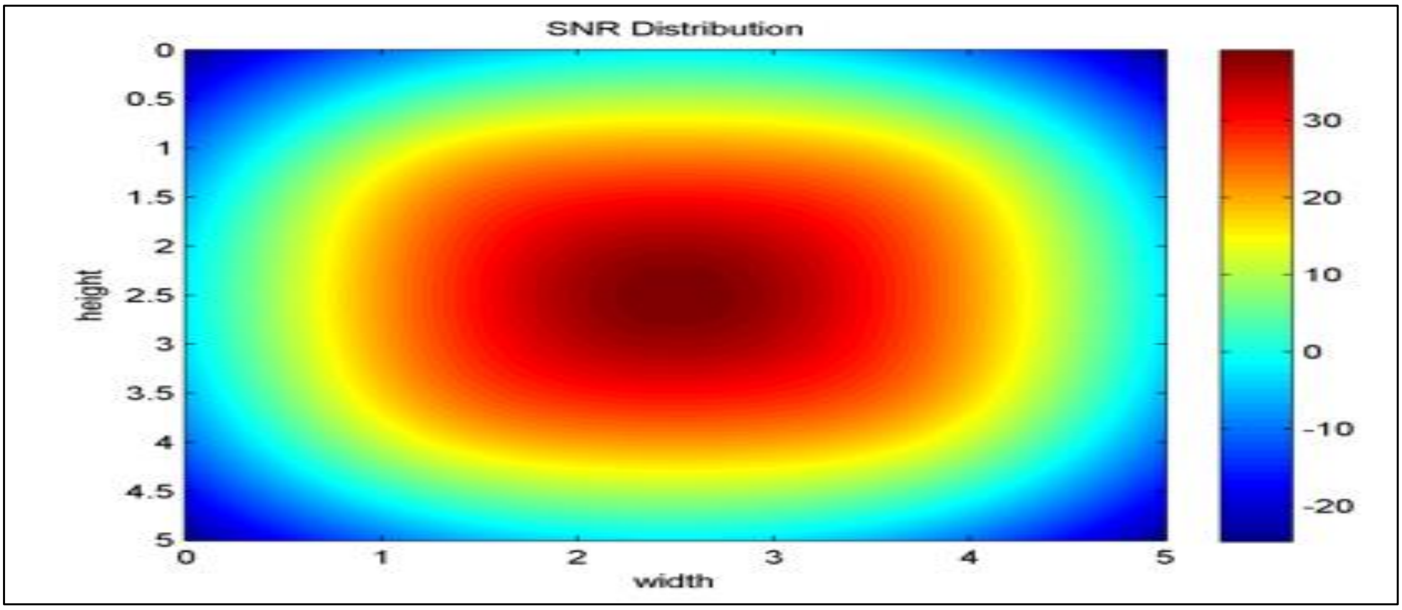
(a)



(b)



(c)

- *Signal to Noise Ratio determinationfor diffuse propagation (NLOS)*

In Visible Light Communication (VLC) systems, the Signal-to-Noise Ratio (SNR) in Non-Line-of-Sight (NLOS) links with diffuse propagation is a critical factor in assessing system performance, particularly when direct Line-of-Sight (LOS) paths are unavailable. Unlike LOS scenarios, where light travels directly from the transmitter to the receiver, NLOS links rely on light that is reflected or scattered off surfaces such as walls, ceilings, and other obstacles before reaching the receiver. This scattering process can significantly reduce signal strength, leading to a lower SNR compared to LOS links. In NLOS environments with diffuse propagation, the signal is typically weakened due to multiple reflections, which not only reduce signal strength but also introduce additional noise and interference. These factors contribute to a further decline in SNR, making it challenging to maintain strong and reliable communication.To achieve adequate SNR in these scenarios, it is essential to optimize the reflective properties of the environment, strategically place transmitters and receivers, and apply techniques that boost signal strength while minimizing noise. A careful balance between signal coverage and SNR is critical to ensure effective communication in NLOS VLC systems.

Figure 10 and Figure 11 illustrates the SNR in NLOS conditions for different transmitter configurations (3D and 2D). In these scenarios, the signal strength is typically highest directly beneath the LED chip, where both LOS and diffuse components significantly contribute to the signal. As the distance from the LED increases, the SNR decreases, indicating that signal coverage weakens towards the edges and corners of the room due to increased reliance on diffuse propagation and a reduced LOS component. In Figure 10(a) and Figure 11(a), the SNR reaches its peak value of approximately 170 dB near the center of the room, where the LOS component from the LED chip is strongest and most directly contributes to signal strength. Figure 10(b) and Figure 11(b) shows an SNR range from approximately 150 to 170 dB, with the highest values centered around 165 dB. The regions of peak SNR correspond to areas where LOS components from multiple LEDs constructively interfere, resulting in stronger signals. Conversely, the SNR decreases in areas dominated by diffuse propagation or where destructive interference between signals from different LEDs

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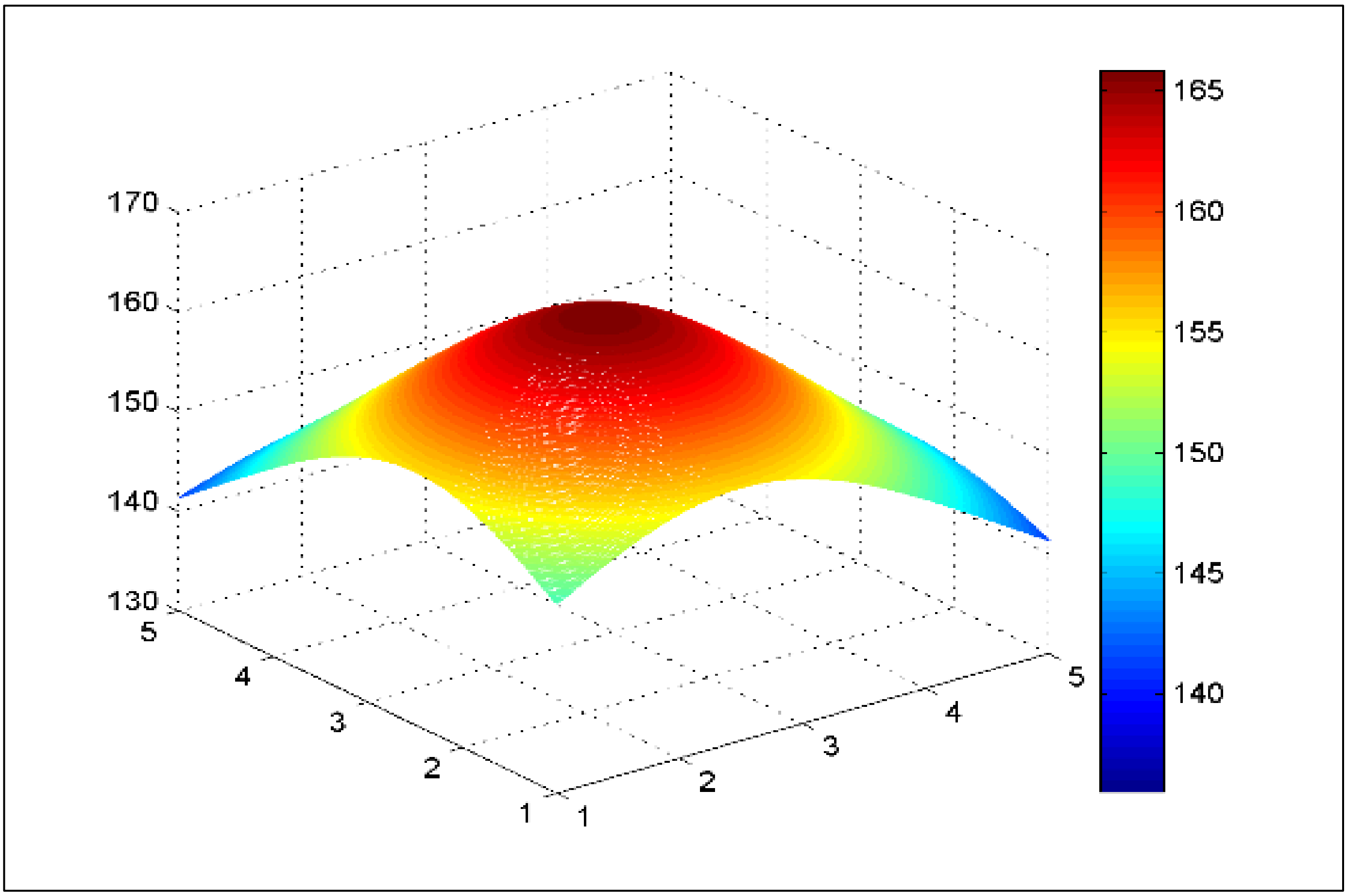
occurs. In Figure 10(c) and Figure 11(c), the use of five LED chips creates multiple regions of strong signal coverage, leading to a more evenly distributed SNR profile across the space. The presence of several peaks in SNR values indicates that the LEDs are contributing to robust signal strength in multiple regions, thereby enhancing overall coverage compared to the scenario with a single LED. This configuration effectively spreads signal strength throughout the room, improving communication reliability in NLOS settings.



(a)

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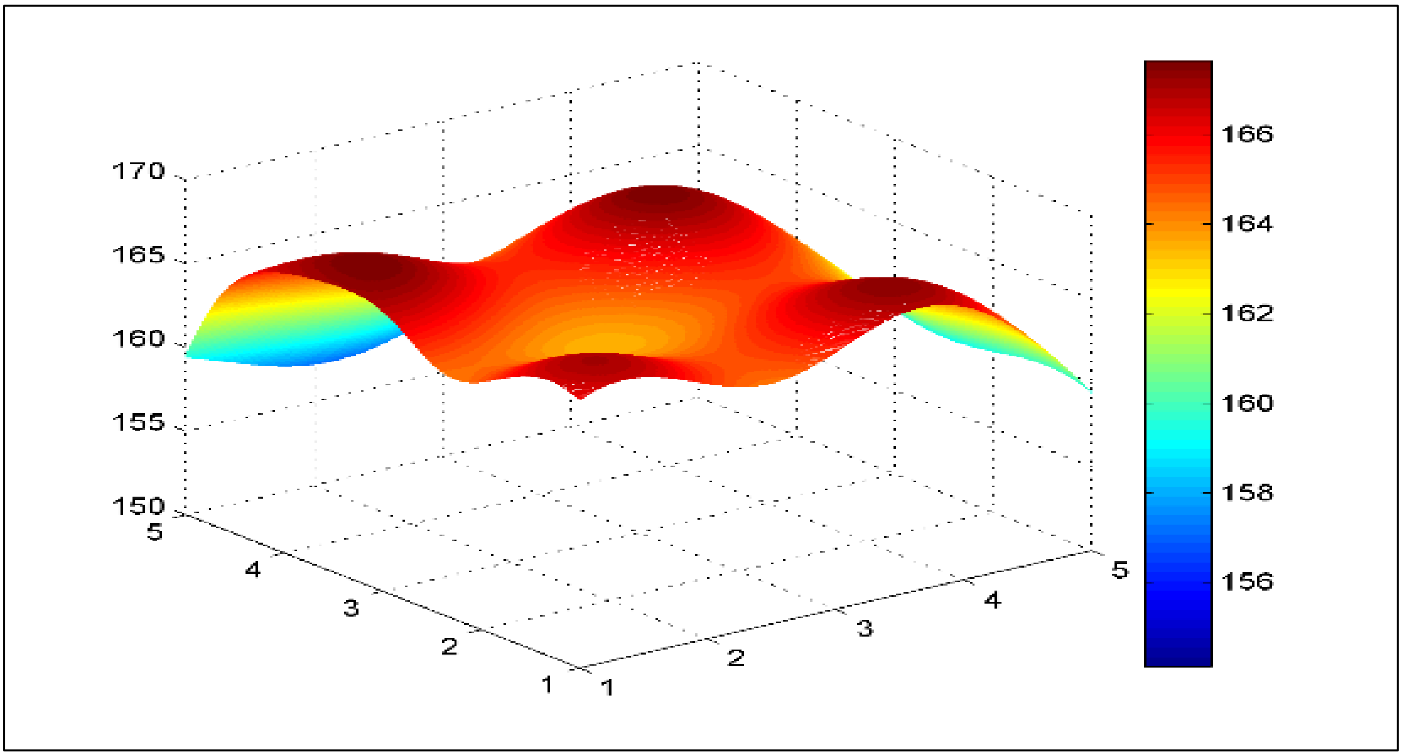

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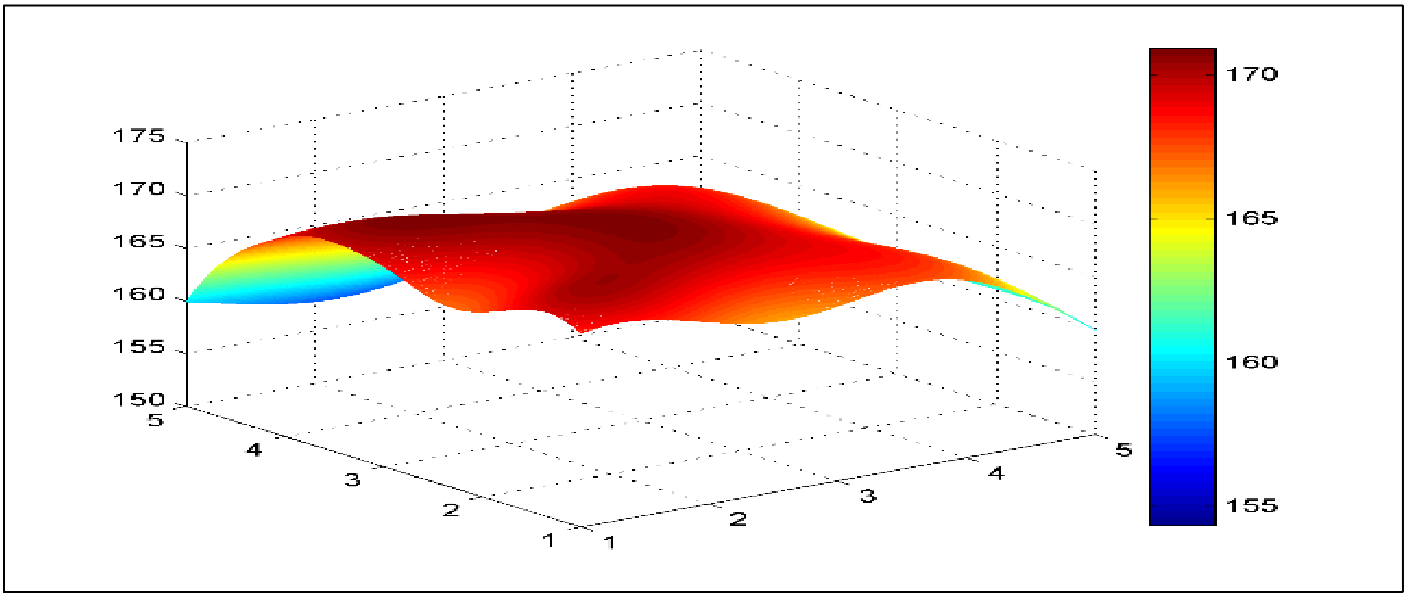

(c)

Fig 10 SNR pattern for (a) single (b) four (c) Five LED models in NLOS propagation (3D)

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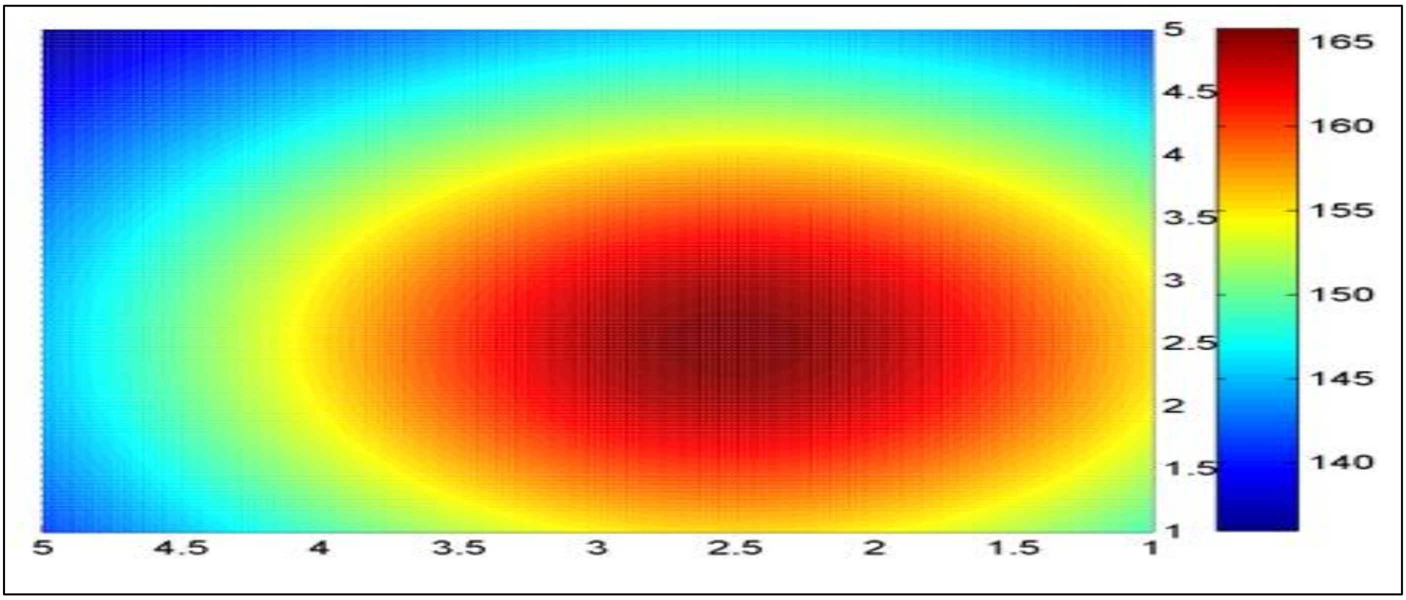
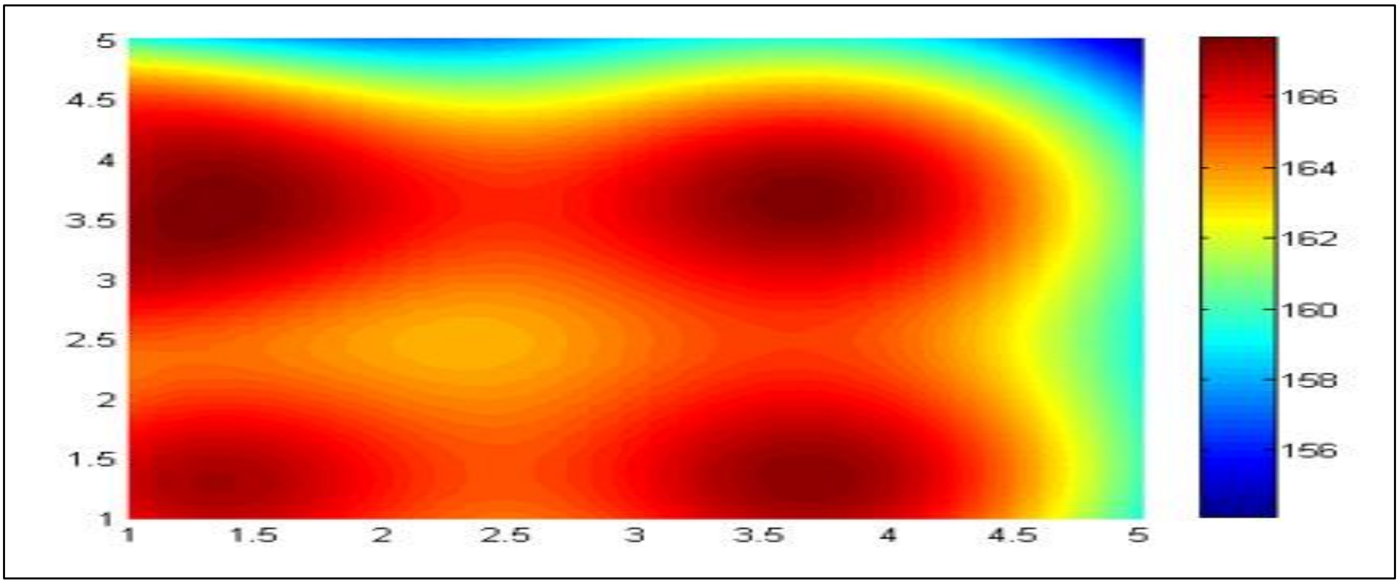


(a)



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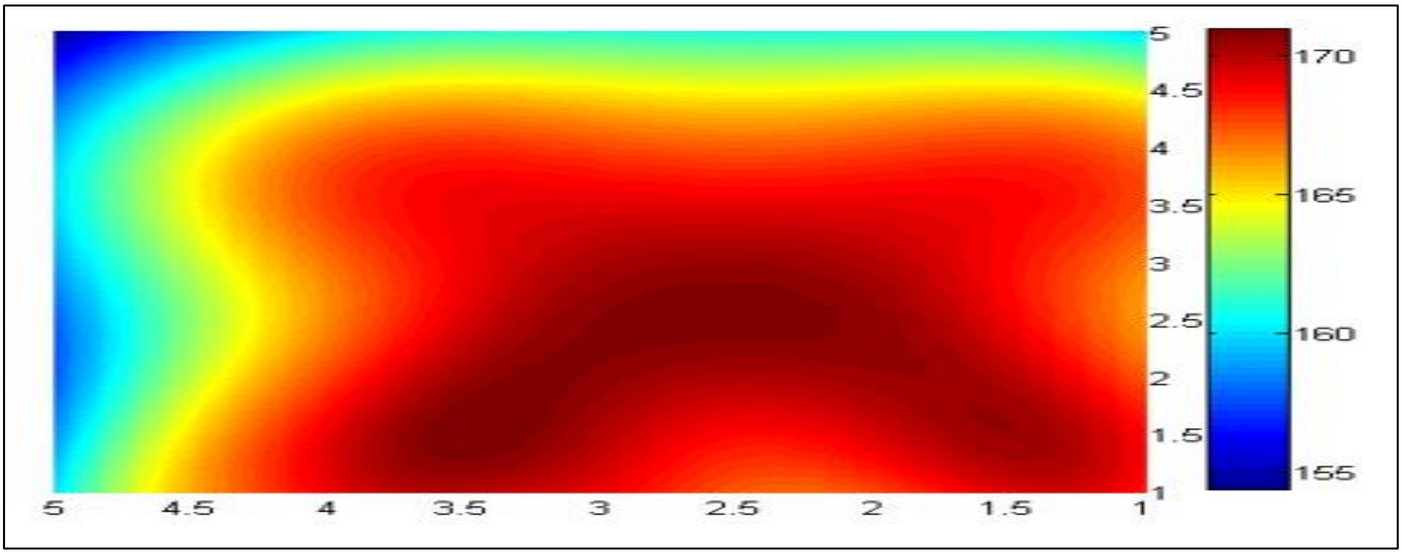

(c)

Fig 11 SNR pattern for (a) single (b) four (c) Five LED models in NLOS propagation (2D)

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- *Bit Error Rate in Optical On-Off Keying Modulation for VLC Systems*

Figure 12 presents the BER versus SNR curve for OOK (On-Off Keying) modulation, comparing the performance of a system using multiple LEDs with that of a single LED. The results demonstrate that the system with multiple LEDs outperforms the single-LED setup in terms of BER at any given SNR. This is attributed to several factors, including diversity benefits, stronger signal strength, and the potential use of spatial multiplexing in multi-LED systems. Multiple LEDs provide a more robust and consistent signal at the receiver, enhancing system performance. A stronger signal leads to a higher SNR, resulting in fewer bit errors. Moreover, spatial multiplexing, which allows different parts of the data to be transmitted simultaneously via multiple LEDs, further increases the data rate and improves overall performance. In contrast, the single-LED system lacks these capabilities, which leads to inferior BER performance. As the SNR reaches 0 dB, the BER reduces to 0.1 for all configurations. At higher SNR values, such as 10 dB and 20 dB, the BER continues to decrease. Interestingly, at these elevated SNR levels, the single-LED setup achieves the lowest error rates, while the four- and five-LED configurations exhibit slightly higher BERs.

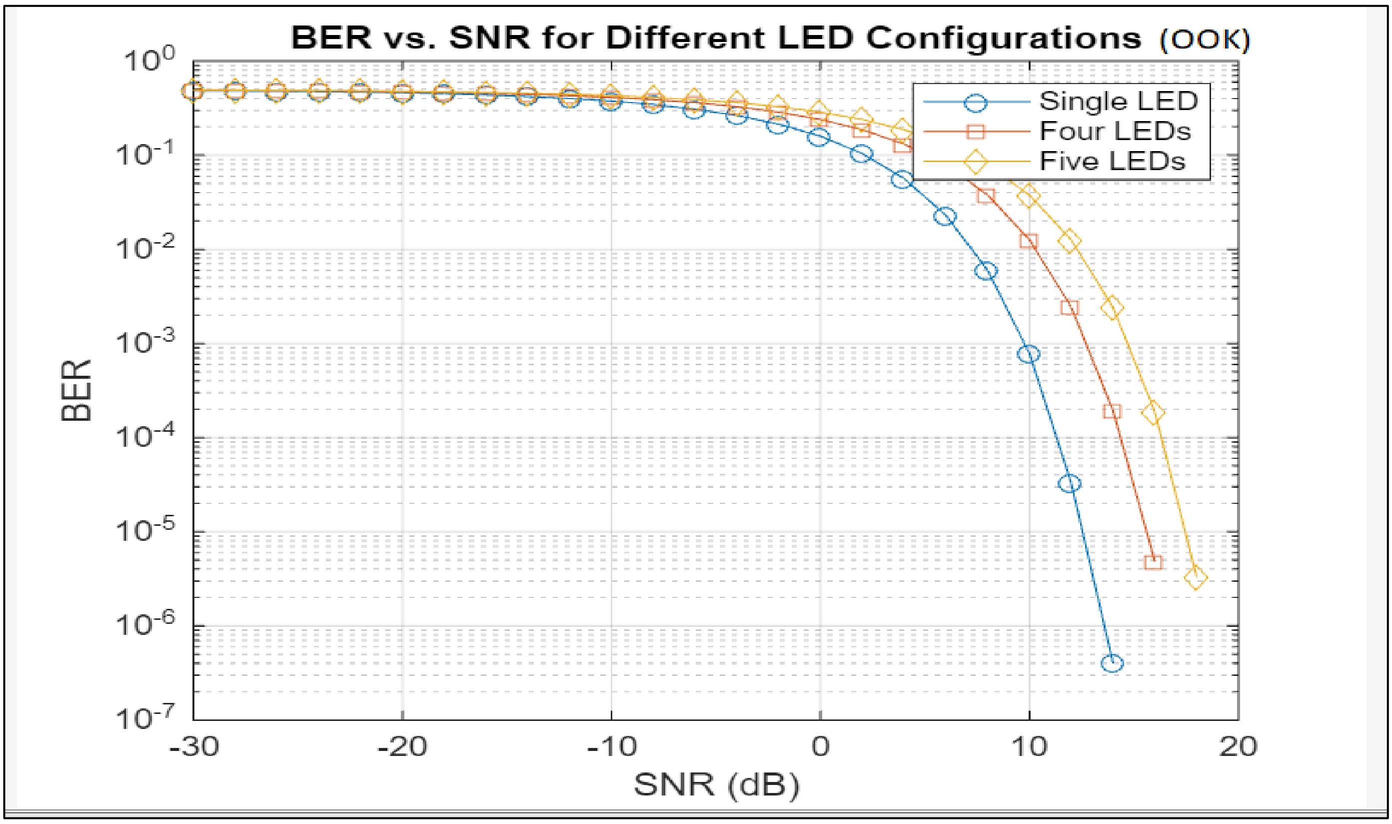

Fig 12 BER versus SNR Curve for OOK

- *Bit Error Rate in Optical QAM Modulation for VLC Systems*

Figure 13 illustrates the BER versus SNR performance for 16-bit QAM (Quadrature Amplitude Modulation), comparing single-LED and multi-LED (four and five LEDs) configurations. The graph reveals distinct trends at different SNR levels. At low SNR values (below 10 dB), the single-LED configuration outperforms the multi-LED setups by achieving a lower BER. This suggests that the four- and five-LED systems are more susceptible to noise at lower SNR levels, resulting in higher BERs compared to the single-LED system. As the SNR increases to medium and high levels (greater than 10 dB), the performance gap between the configurations narrows significantly. All three setups achieve similarly low BERs at higher SNRs, with the five-LED configuration eventually converging to the performance of the single-LED setup around 20 dB.Despite the single-LED setup demonstrating better performance at lower SNRs, the multi-LED configurations (four and five LEDs) offer enhanced system robustness and coverage overall. However, this increased robustness comes at the cost of requiring higher SNR to achieve comparable BER performance.

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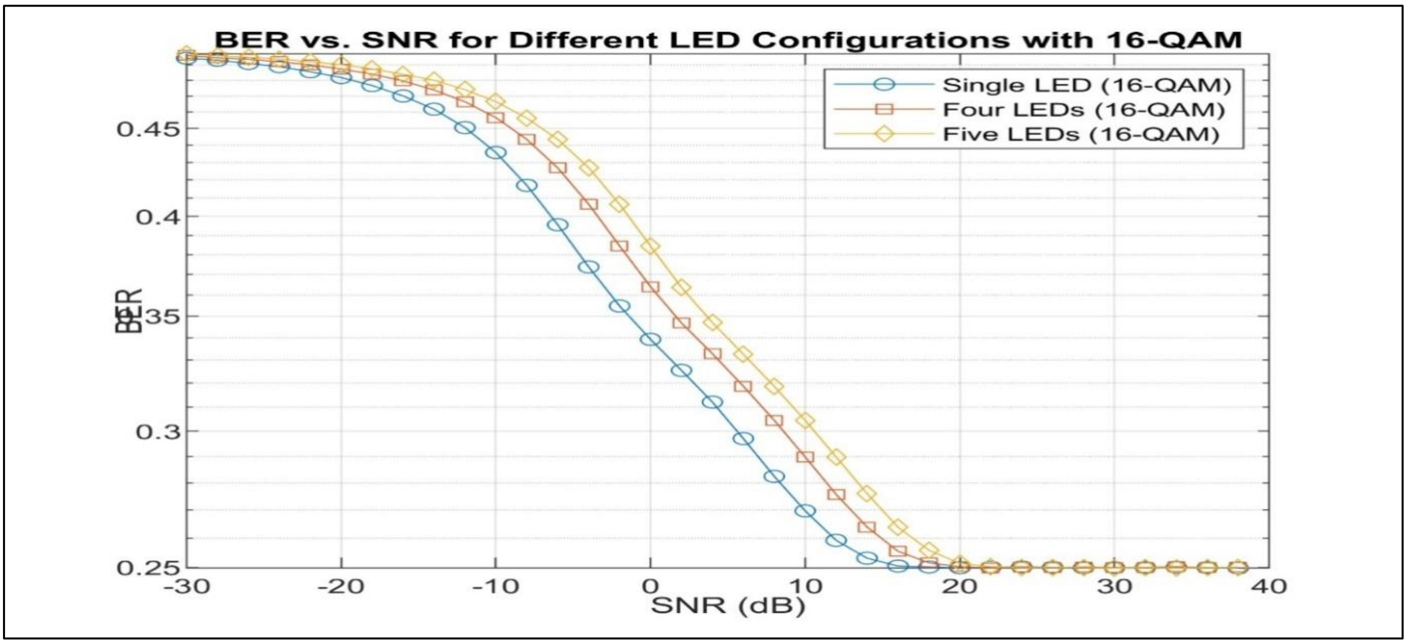

Fig 13 BER versus SNR performance for 16-bit QAM

➢ *Comparative Analysis*

Table 4 provides a comparative analysis of key performance characteristics across different LED configurations, including single, four, and five LEDs. The table evaluates factors such as illuminance patterns, received power, and SNR for both Line of Sight (LOS) and Non-Line of Sight (NLOS) conditions.

- *Illuminance Pattern:*

The single LED configuration demonstrates a wider range of illuminance, with values ranging from 88.89 lux to 1200 lux. In contrast, the multi-LED setups (four and five LEDs) exhibit more focused illuminance patterns, with minimum values of less than 150 lux and maximum values exceeding 400 lux and 450 lux, respectively. This suggests that multi-LED systems provide more concentrated lighting with slightly narrower illuminance coverage.

- *Received Power:*

For the single LED configuration, received power varies between 0.5 mW and 2.5 mW. In comparison, the multi-LED setups show less variation, with the four-LED configuration ranging from 0.9 mW to 1 mW and the five-LED configuration ranging from 0.9 mW to 1.1 mW. These results indicate that multi-LED systems provide more consistent power delivery, though with a narrower range than the single-LED setup.

- *SNR (LOS):*

In Line of Sight (LOS) conditions, the single LED setup exhibits an SNR range of 9.0510 to 31.6577. The four-LED setup shows an SNR range from -11.9584 to 29.2319, while the five-LED configuration ranges from -24.6396 to 39.1574. Notably, while the single LED setup generally performs better at lower SNR levels, the five-LED system demonstrates the highest maximum SNR, indicating stronger performance under favorable conditions.

- *SNR (NLOS):*

In Non-Line of Sight (NLOS) conditions, the SNR for the single LED ranges from 135.9570 dB to 165.8352 dB. The multi-LED setups, however, provide higher SNR values, with the four-LED configuration achieving an SNR range of 154.1244 dB to 167.6480 dB, and the five-LED setup reaching 154.3274 dB to 170.8975 dB. These results indicate that multi-LED configurations offer significantly improved SNR in NLOS scenarios, particularly at higher values.

- *BER (OOK):*

Multi-LED systems outperform single-LED setups in terms of BER due to diversity benefits, stronger signal strength, and spatial multiplexing. Multi-LED configurations provide a more robust and consistent signal, enhancing overall performance. However, at higher SNR levels, the single-LED setup achieves the lowest error rates, while the multi-LED systems exhibit slightly higher BERs. Despite this, multi-LED setups offer better system robustness and higher data rates.

- *BER (QAM):*

At low SNR values (below 10 dB), the single-LED configuration outperforms the four- and five-LED setups by achieving a lower BER, as the multi-LED systems are more susceptible to noise. As the SNR increases above 10 dB, the performance gap narrows, and all configurations achieve similarly low BERs, with the five-LED system converging to the performance of the single-LED setup around 20 dB. While the single-LED performs better at lower SNRs, the four- and five-LED setups offer greater system robustness and coverage, though they require higher SNR to match the single-LED's BER performance.

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Table 4 Comparative analysis of illuminance patterns, received power, and SNR for single-LED and multi-LED (four and five LEDs) configurations under Line of Sight (LOS) and Non-Line of Sight (NLOS) conditions

Characteristics	No. of LED	Minimum value	Maximum value
Illuminance pattern	Single LED	88.89 lux	1200 lux
	Four LED	<150 lux	>400 lux
	Five LED	<150 lux	>450 lux
Received Power	Single LED	0.5 mW	2.5 mW
	Four LED	0.9 mW	1 mW
	Five LED	0.9 mW	1.1 mW
SNR (LOS)	Single LED	9.0510	31.6577
	Four LED	-11.9584	29.2319
	Five LED	-24.6396	39.1574
SNR (NLOS)	Single LED	135.9570db	165.8352 db
	Four LED	154.1244 db	167.6480db
	Five LED	154.3274db	170.8975db

Each LED configuration presents unique advantages based on the specific performance metric:

- *Single LED:*

The single LED setup excels in providing a broader illuminance pattern and higher received power. It also shows strong SNR performance in Line of Sight (LOS) conditions, especially at lower SNR levels, making it suitable for applications where wider coverage and higher signal strength are required in direct transmission scenarios. In terms of BER performance, for both OOK and QAM modulations, the single-LED setup performs better at lower SNR levels (below 10 dB), achieving a lower BER compared to the four- and five-LED systems.

- *Four LEDs:*

The four-LED configuration offers more concentrated illuminance and consistent received power, though it performs slightly worse in LOS SNR compared to the single LED. However, it improves significantly in Non-Line of Sight (NLOS) conditions, making it a better choice in environments with potential signal obstructions or where indirect transmission paths are more common. For BER (OOK), the four-LED setup shows a higher BER at low SNR, but its performance converges closer to the single-LED system as SNR increases. In QAM modulation, the four-LED setup follows a similar trend, with higher BER at low SNR but narrowing the gap at medium and high SNR levels.

- *Five LEDs:*

The five-LED configuration demonstrates the best overall performance in terms of maximum SNR in both LOS and NLOS conditions, particularly at higher SNR levels. Although it lags behind the single LED at lower SNR levels, it outperforms both the single and four-LED setups in NLOS scenarios, making it ideal for environments that require high robustness and signal reliability. For BER (OOK), the five-LED system initially shows higher BER at low SNR values but outperforms the single LED as SNR rises. In QAM modulation, the five-LED system converges to the single-LED performance at around 20 dB SNR, offering better robustness at high SNR levels.

While the single LED performs well for general coverage and power, particularly at low SNR levels, the five-LED configuration offers the most robust and reliable performance, especially in challenging environments with NLOS conditions and higher SNR requirements. Therefore, the five-LED setup is the best option for applications prioritizing strong signal quality and consistency over a wide range of conditions.

➢ *Discussion*

The results of this study provide valuable insights into the performance of different LED configurations in Visible Light Communication systems. The use of multiple LEDs, particularly in the four- and five-LED configurations, proved to be effective in achieving a more uniform illuminance distribution across the receiver plane. This is particularly useful in environments where consistent lighting is critical for communication reliability, such as large indoor spaces with multiple users or devices. The spread of light in multi-LED setups ensures that even in non-line-of-sight conditions, sufficient light reaches the receiver, maintaining strong signal integrity. However, the increased illuminance in multi-LED setups comes at the cost of complexity, particularly in managing the Signal-to-Noise Ratio and Bit Error Rate. The results show that multi-LED configurations, while enhancing signal strength and reliability, are more susceptible to interference and noise, especially in lower SNR environments. This is evident in the BER performance, where single-LED configurations outperform multi-LED setups at higher SNR levels. In these scenarios, the single-LED system demonstrates a more consistent BER, suggesting that in simpler indoor environments with minimal interference, single-LED systems may be the optimal choice. When comparing modulation techniques, On-Off Keying shows clear advantages in terms of BER performance, particularly in single-LED setups. Its simplicity makes it more robust against noise, especially in high-SNR conditions. Quadrature Amplitude Modulation, while offering higher data rates, suffers from higher BER at lower SNR levels, particularly in diffuse propagation scenarios. This indicates that while QAM can be beneficial in systems where higher data throughput is required, it may not be suitable for environments with significant noise or where minimizing errors is critical. The comparison between line-of-sight (LOS) and non-line-of-sight (NLOS) conditions further highlights the strengths and

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weaknesses of each configuration. In LOS conditions, the direct transmission path allows for higher SNR values and lower BER, particularly in single-LED setups. However, in NLOS conditions, multi-LED configurations demonstrate their superiority by maintaining a higher SNR, even when signals are reflected or scattered. This makes multi-LED setups particularly useful in environments where direct light paths are frequently obstructed, such as in rooms with partitions or furniture.

This study illustrates that VLC performance is highly dependent on the specific indoor environment and communication requirements. Multi-LED setups offer the advantage of broader coverage and higher reliability in complex environments, but they require careful management of noise and interference. Single-LED configurations, on the other hand, are more suited for environments where maintaining low BER is more critical than coverage. These findings will be instrumental in guiding the design and optimization of future VLC systems, allowing them to be tailored to different use cases, from secure indoor communication networks to energy-efficient smart lighting systems.

V. CONCLUSION

This study explored the performance of Visible Light Communication (VLC) systems with different transmitter configurations and modulation techniques, focusing on key performance metrics such as illuminance distribution, received power, Signal-to-Noise Ratio (SNR), and Bit Error Rate (BER). The results demonstrate that multi-LED configurations, particularly those using four or five LEDs, offer significant advantages in terms of achieving uniform illuminance and higher SNR, making them ideal for environments where broader coverage and stronger signal reliability are essential. These setups excel in non-line-of-sight (NLOS) conditions where signals are likely to scatter due to reflections from surfaces like walls or furniture. However, the study also reveals that these benefits come with trade-offs, particularly in terms of BER. While multi-LED setups improve coverage and reliability, they are more prone to errors, especially at lower SNR levels. The single-LED configuration, though more limited in terms of coverage, consistently achieves lower BER at higher SNR levels, making it more suitable for simpler indoor environments where direct communication paths are prevalent, such as in line-of-sight (LOS) conditions. This suggests that for applications requiring low error rates and reliable data transmission, the single-LED system is still a strong contender, especially in controlled environments with minimal interference.

The comparison of modulation techniques further emphasizes the importance of selecting the right configuration for the specific application. On-Off Keying (OOK), due to its simplicity, is more resilient to noise and performs better in environments where minimizing errors is critical. On the other hand, Quadrature Amplitude Modulation (QAM), while offering higher data rates, is more sensitive to noise and requires higher SNR to achieve comparable performance, particularly in more complex multi-LED setups. This indicates that while QAM can provide increased data throughput, it is better suited for environments where higher SNR can be consistently maintained. Overall, the findings of this study highlight the need for a balanced approach when designing VLC systems. While multi-LED setups provide enhanced coverage and reliability, particularly in complex indoor environments, they also introduce challenges related to managing noise and maintaining low BER. Single-LED configurations, despite their limitations in coverage, offer a more stable performance in terms of BER, especially at higher SNR levels. These insights are critical for optimizing VLC systems based on the specific needs of the environment and application.

Future VLC systems will benefit from these findings by adopting hybrid approaches that combine the strengths of different configurations and modulation techniques. For instance, a system could use multi-LED setups in areas where broader coverage is needed and switch to single-LED configurations in environments where data integrity and low error rates are paramount. Additionally, improvements in modulation techniques and noise management strategies will further enhance VLC's potential as a viable alternative to traditional RF systems, especially in environments where security, energy efficiency, and minimal interference are prioritized. This study contributes to the growing body of research on VLC technology, offering a comprehensive evaluation of the trade-offs between different transmitter configurations and modulation schemes. The findings provide valuable guidance for optimizing VLC systems for specific use cases, whether for smart lighting systems, secure indoor communication networks, or high-speed data transmission in complex environments. By addressing the challenges related to BER and SNR, this research paves the way for the broader adoption of VLC technology in real-world applications.

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- *Conflict Interests*

The authors have no conflict of interest to disclose.

- *Ethics Approval*

This article does not involve any studies conducted with human participants or animals by the authors.

- *Data Availability*

The datasets generated during this study are available from the corresponding author upon reasonable request.

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