

Simulation Research on Channel Modeling and Light Source Layout Optimization for Visible Light Communication Systems

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Abstract

Indoor visible light communication (VLC) integrates illumination with broadband wireless data transmission and is regarded as a key enabling technology for next-generation wireless networks. In practical indoor environments, the spatial layout of light sources and the adopted channel model directly determine illumination uniformity, communication coverage, and link reliability. In this study, an indoor VLC channel model is established based on the Lambertian radiation model. Simulation frameworks are developed for both a single point-source LED and a multi-LED array, and MATLAB-based simulations are conducted to evaluate received optical power, illuminance, signal-to-noise ratio (SNR), and bit error rate (BER) over the receiving plane. The spatial communication performance of the single-source configuration is evaluated to characterize its limitations in coverage, illumination uniformity, and link stability. For the multi-LED configuration, light-source layout optimization is formulated by jointly minimizing illuminance standard deviation and mean BER, and the effects of LED spacing and array layout are systematically explored. The results demonstrate that an appropriate LED-array layout can substantially improve communication-link quality and system reliability while maintaining more uniform indoor illumination. The proposed modeling and simulation framework provides a theoretical basis and practical reference for light-source deployment and performance evaluation in indoor VLC systems.

Keywords: Visible Light Communication, Channel Modeling, Lambertian Radiation Model, LED Array Layout.

1. Introduction

With the rapid development of next-generation wireless communication technologies, conventional radio-frequency (RF) systems are increasingly challenged by spectrum scarcity, electromagnetic interference, and security concerns. Indoor visible light communication (VLC) exploits the high-speed modulation capability of white LEDs to provide data transmission while simultaneously delivering illumination. Owing to its abundant spectrum resources, absence of RF electromagnetic radiation, strong physical-layer confidentiality, and low deployment cost, VLC is widely regarded as an important technology for short-range, high-speed indoor wireless communications ^[1]. With advances in LED lighting and optoelectronic devices, VLC has also shown broad application prospects in indoor positioning, intelligent lighting, and high-speed data transmission ^[2].

In indoor VLC systems, light-source layout is a major factor governing overall system performance. The spatial distribution of emitters not only determines the illuminance distribution over the receiving plane but also affects the received optical power and, consequently, key communication metrics such as signal-to-noise ratio (SNR) and bit error rate (BER). An inappropriate layout may cause nonuniform illumination and insufficient communication coverage. Therefore, improving communication performance without compromising illumination uniformity has become an important design problem for indoor VLC systems. In recent years, extensive research has investigated VLC light-source layout optimization. For example, Ref. [3] proposed a light-source layout optimization method based on a genetic algorithm to improve indoor illuminance uniformity; Ref. [4] investigated a reconfigurable intelligent surface-assisted VLC light-source optimization strategy to improve channel propagation characteristics; and Ref. [5] proposed a random light-source layout method for large-scale indoor environments to enhance system coverage. However, most existing studies focus on optimizing either illumination or communication performance, while integrated optimization that jointly considers illumination uniformity and communication reliability remains comparatively limited [6]. In addition, the influence of different light-source layouts on received optical power, SNR, and BER distributions over typical indoor receiving planes requires further systematic investigation. It is therefore necessary to perform systematic simulation and performance evaluation of different layout schemes under a Lambertian radiation model to support indoor VLC system design.

A typical 4 m × 4 m indoor environment is considered in this study. Based on the Lambertian radiation model, an indoor VLC channel model is established [7], and an end-to-end simulation is performed for a single point-source LED to characterize the spatial distributions of received optical power, illuminance, SNR, and BER on the receiving plane. On this basis, multi-LED array configurations are designed, and the array layout parameters are optimized through exhaustive parameter sweeps with illumination uniformity and communication BER as the performance objectives. The resulting layout schemes provide a compromise between lighting and communication performance. The proposed simulation workflow and analysis method are implementable and can serve as a reference for light-source layout design and performance evaluation in indoor VLC systems.

2. Indoor Visible Light Communication System Channel Model

The classical line-of-sight (LoS) indoor VLC link model is adopted. Non-line-of-sight components caused by wall reflections are neglected, and the channel characteristics are determined by the Lambertian emission pattern of the LED. The model includes optical-power transmission, illuminance, SNR, and BER formulations, all of which are consistent with the simulation implementation.

2.1. Lambertian Radiation and Optical Power Transmission Model

An LED source is modeled as Lambertian, following the Lambertian cosine law. Its Lambertian order m is determined by the LED semi-angle at half power $\phi_{1/2}$ and is given by [8]:

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

A Lambertian order of $m = 1$ is used in the simulation, corresponding to a semi-angle at half power of $\phi_{1/2} = 60^\circ$.

For an arbitrary receiving position indoors, the received optical power is jointly determined by the

transmitted optical power, the separation distance, and the incidence angle. For the LoS link, the received optical power is expressed as [3]:

$$P_r = \frac{(m+1)AP_t \cos^{m+1}\theta}{2\pi d^{m+3}} \quad (2)$$

where P_t is the transmitted optical power of the LED, A is the effective photosensitive area of the photodetector (PD), d is the distance between the LED source and the receiver, and θ is the angle between the emitted optical ray and the normal to the receiving plane (i.e., the incidence angle).

The receiving plane is assumed to be horizontal, and the LED is mounted vertically downward. From the geometric relationship, $\cos \theta = z/d$, where z is the perpendicular separation between the LED and the receiving plane. Substitution into Eq. (2) yields the received-optical-power model used for system performance evaluation [9]:

$$P_r = \frac{(m+1)AP_t z^{m+1}}{2\pi d^{m+3}} \quad (3)$$

where d is the spatial distance, (x_0, y_0, z_0) denotes the spatial coordinates of the LED source, and (x, y) denotes the two-dimensional coordinates on the receiving plane.

2.2. Illuminance Calculation Model

The horizontal illuminance over the receiving plane is a key physical indicator of indoor lighting performance. Assuming a Lambertian LED source, the luminous intensity in an arbitrary emission direction ϕ is $I(\phi) = I \cos^m \phi$, where I denotes the normal luminous intensity of the source. The horizontal illuminance at a point on the receiving plane is jointly determined by the luminous intensity in the corresponding direction, the propagation distance, and the incidence angle, and its basic expression is given by:

$$E = \frac{I(\phi) \cos \theta}{d^2} \quad (4)$$

In a typical indoor VLC scenario, the transmitting and receiving planes are parallel. From the spatial geometry, $\cos \theta = z/d$, where z is the LED installation height and d is the line-of-sight distance. The resulting illuminance model over the receiving plane is therefore [10, 11]:

$$E = \frac{I \cos^{m+1} \theta}{d^2} = \frac{I z^{m+1}}{d^{m+3}} \quad (5)$$

where I denotes the normal luminous intensity of the LED source.

2.3. SNR and BER Calculation Model

The dominant receiver noise components in the VLC system are shot noise associated with the optical signal and thermal noise from the front-end amplifier [12, 13]. The total noise-power variance is expressed as follows:

$$\sigma^2 = \sigma_{shot}^2 + \sigma_{thermal}^2 = 2qRI_2 R_b (P_r + P_n) + i_a^2 B_a \quad (6)$$

where q is the elementary charge, R is the PD responsivity, I_2 is the noise-bandwidth factor, R_b is the system data rate, P_n is the ambient optical-noise power, i_a is the amplifier noise-current density, and

B_a is the amplifier bandwidth.

The electrical SNR is defined as the ratio of the received signal photocurrent power to the total noise-power variance:

$$SNR = \frac{(RP_r)^2}{\sigma^2} \quad (7)$$

SNR can be expressed either in linear form or in decibels (dB), with the conversion relationship:

$$SNR_{dB} = 10 \log_{10}(SNR) \quad (8)$$

For an on-off keying (OOK) VLC system operating over an additive white Gaussian noise (AWGN) channel, the theoretical BER is related to the linear SNR by the standard Q-function [14]:

$$P_e = Q(\sqrt{SNR}) \quad (9)$$

where $Q(x)$ is the complementary cumulative distribution function of the standard normal distribution, defined as:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp(-\frac{u^2}{2}) du \quad (10)$$

3. Simulation Experiment Design and Parameter Settings

The spatial coverage performance of the VLC system is evaluated in a typical 4 m × 4 m indoor communication environment. The receiving PD is located at floor level ($z = 0$), and the LED source is mounted vertically downward at a ceiling height of $z = 2.25$ m. To ensure reproducibility, the core simulation parameters are summarized in Table 1.

Table 1. Core parameters of the simulation system

Simulation Parameter	Symbol	Value
Room dimensions	—	4 m × 4 m
LED installation height	z	2.25 m
Optical power per LED	P_t	0.5 W
Lambertian order	m	1
Photodetector responsivity	R	0.35 A/W
Normal luminous intensity	I	21.5 cd
Ambient optical-noise power	P_n	2×10^{-4} W
Noise bandwidth factor	I_2	0.562
Amplifier noise-current density	i_a	5×10^{-9} A/ $\sqrt{\text{Hz}}$
Amplifier bandwidth	B_a	50 MHz
Data rate	R_b	10 Mbps

Single-source baseline analysis: A single LED source is placed at the center of the ceiling. Its

three-dimensional position is defined accordingly. The spatial distributions of received optical power, illuminance, SNR, and BER over the receiving plane are then evaluated to characterize the performance degradation near room boundaries.

Joint optimization of multi-LED layouts: To improve indoor illuminance uniformity and communication quality, two multi-source array configurations are designed, namely a 4×9 LED array and a hybrid configuration consisting of four 8-LED peripheral arrays plus a central 6×6 LED array. The array origin L and adjacent-source spacing d are selected as the main decision variables and exhaustively swept. The joint objective minimizes the global illuminance standard deviation and mean BER to obtain layout parameters that balance illumination and communication performance.

4. Performance Analysis of Single-Point Light Source System

4.1. Spatial Distribution of Received Optical Characteristics

Using the system parameters described above, the received optical-power distribution for the single-source case is simulated in three dimensions. As shown in Fig. 1, the received optical power exhibits pronounced central symmetry over the receiving plane. The global maximum, approximately 0.002 mW, occurs in the room center directly below the LED. As the physical distance from the center increases, the received optical power decreases sharply and nonlinearly. Near the room boundaries and corners, the received optical power falls below 0.002 mW, with the edge value reaching only about 10% of the central peak.

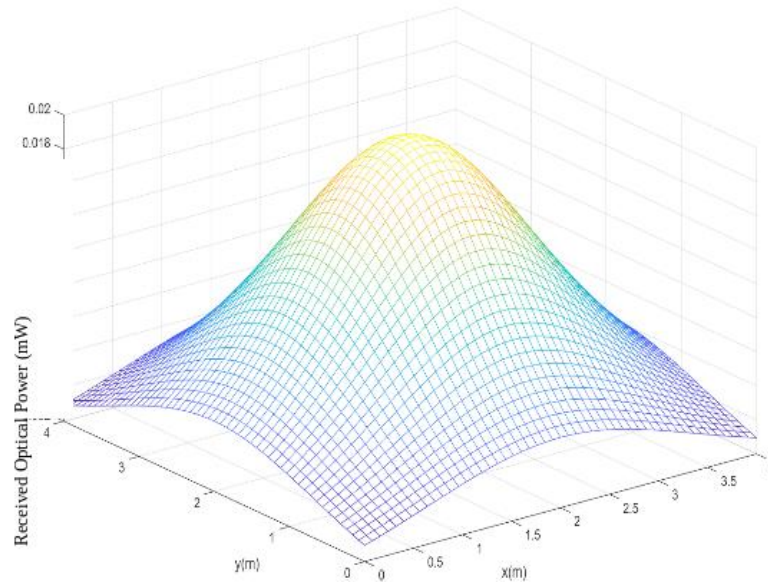


Fig. 1. Received optical power distribution on the receiving plane with a point light source.

This spatial distribution is consistent with the underlying physics of the Lambertian radiation model: as the receiving point moves away from the source center, the LoS propagation distance increases and the incidence angle becomes larger, resulting in severe spatial path loss. The results indicate a pronounced center-to-edge performance imbalance for the conventional single-source deployment, preventing uniform optical-power coverage across the indoor working area and degrading communication service quality near the boundaries. This limitation provides direct motivation for the subsequent optimization of multi-LED layouts.

4.2. Illuminance Distribution on the Receiving Plane

The spatial illuminance distribution of the single-source system is analyzed over the receiving plane, as shown in Fig. 2. The results show that its attenuation trend closely matches the three-dimensional distribution of received optical power. Directly beneath the source, i.e., at the center of the receiving plane, the shortest LoS path yields the peak illuminance of 4.24 lx. As the horizontal distance from the center increases, illuminance decreases markedly and nonlinearly. Specifically, the illuminance decreases to 2.18 lx and 1.19 lx at distances of 1.5 m and 2.5 m from the center, respectively.

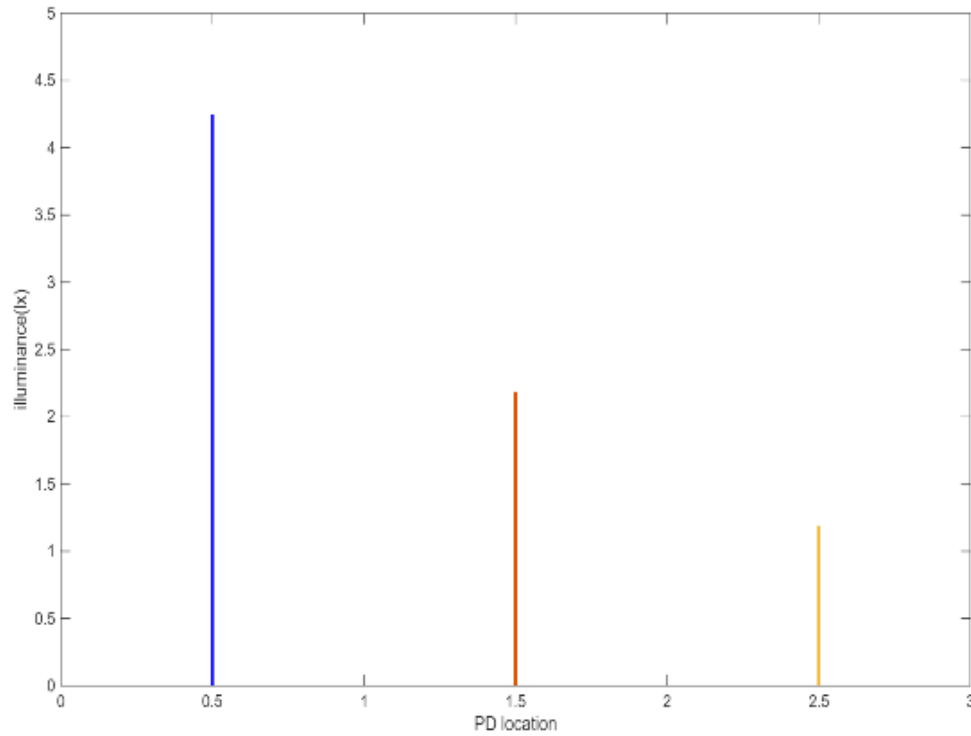


Fig. 2. Illuminance distribution at different PD positions.

The data indicate that the illuminance at the room edges and corners is less than 30% of the central peak. Because the single source has limited emitted power (0.5 W) and suffers substantial spatial path loss, large illumination blind zones arise. The resulting illuminance is far below the office-lighting requirement specified in the Architectural Lighting Design Standard (GB 50034-2013), which is typically not less than 300 lx, and the required illuminance uniformity cannot be satisfied. This optical limitation further motivates the introduction and layout optimization of multiple LED sources.

4.3. Spatial Distribution of SNR on the Receiving Plane

The SNR distribution over the receiving plane is simulated in three dimensions, as shown in Fig. 3. The spatial SNR distribution is highly positively correlated with the received optical power. At the geometric center of the room, directly below the single LED, path loss is minimized and the SNR reaches its global maximum of approximately -2.4 dB. As the receiver moves horizontally toward the room boundary, SNR decreases continuously and nonlinearly because of the rapid attenuation of the optical signal, falling to below -3.2 dB near the edges and corners.

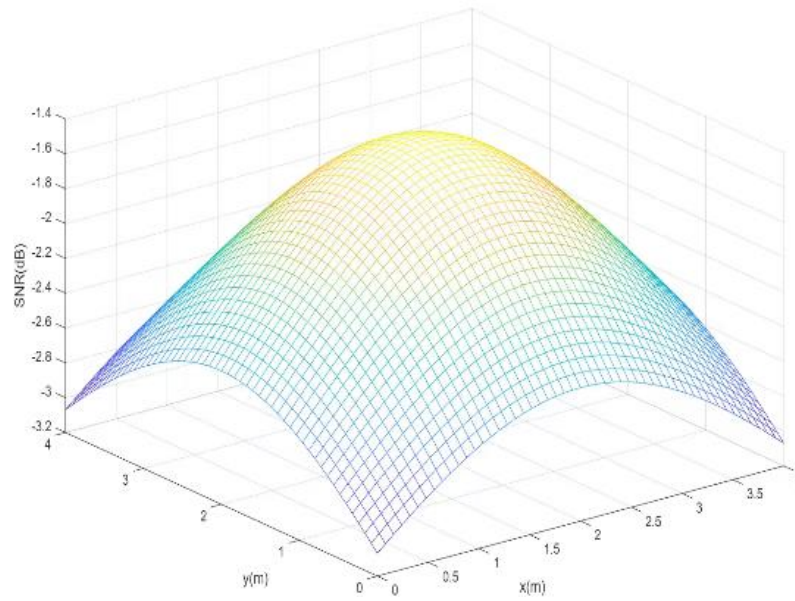


Fig. 3. Signal-to-noise ratio distribution on the receiving plane under point light source illumination.

This pronounced spatial fading induced by a single source causes substantial nonuniformity of the indoor communication link. The edge and corner regions remain under low-SNR channel conditions and cannot reliably support broadband VLC transmission.

4.4. BER Distribution on the Receiving Plane

The BER distribution over the receiving plane is simulated, as shown in Fig. 4. The spatial evolution of BER is strongly negatively correlated with SNR. At the geometric center directly beneath the source, the system achieves its local best communication quality; however, because the source power is limited, the BER remains high, at approximately 0.92. As the receiver moves toward the room boundaries and corners, increased signal attenuation causes the BER to rise sharply toward the deterioration limit of 1.

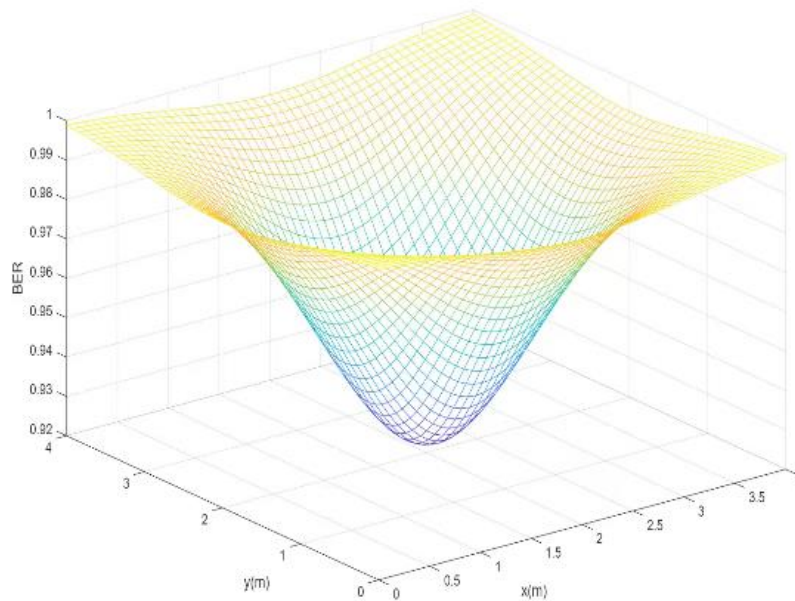


Fig. 4. Bit error rate distribution on the receiving plane with a point light source.

The results reveal the severe coverage limitations of a single point-source architecture for indoor broadband communication. Because of strong path loss and spatial nonuniformity, even the best receiving position cannot sustain a basic reliable communication link, while the edge regions are effectively disconnected. Therefore, a multi-LED array and joint optimization of its spatial layout parameters are required to reshape the optical-power distribution, improve the global SNR, and fundamentally reduce BER for practical high-speed VLC applications.

5. Joint Optimization of Multi-LED Array Layout

To address the severe performance degradation of the single-source scheme near the room boundaries, a multi-LED array topology is introduced. The array spatial parameters are jointly optimized to improve indoor illuminance uniformity and communication-link reliability. The primary optimization objectives are minimum illuminance standard deviation, representing lighting uniformity, and minimum global mean BER, representing communication performance. Two multi-array layouts are designed and evaluated in this section.

5.1. Optimization of 4×9 LED Array Layout

The proposed configuration symmetrically deploys four 9-LED subarrays in the four spatial quadrants of the ceiling. The array origin L and adjacent LED spacing d are selected as the principal decision variables. The global parameter search is performed over $L \in [0.10 \text{ m}, 1.0 \text{ m}]$ with a step of 0.05 m and $d \in [0.005 \text{ m}, 0.03 \text{ m}]$ with a step of 0.005 m . The illuminance standard deviation over the receiving plane is first used as the objective function, and the resulting three-dimensional response surface is shown in Fig. 5.

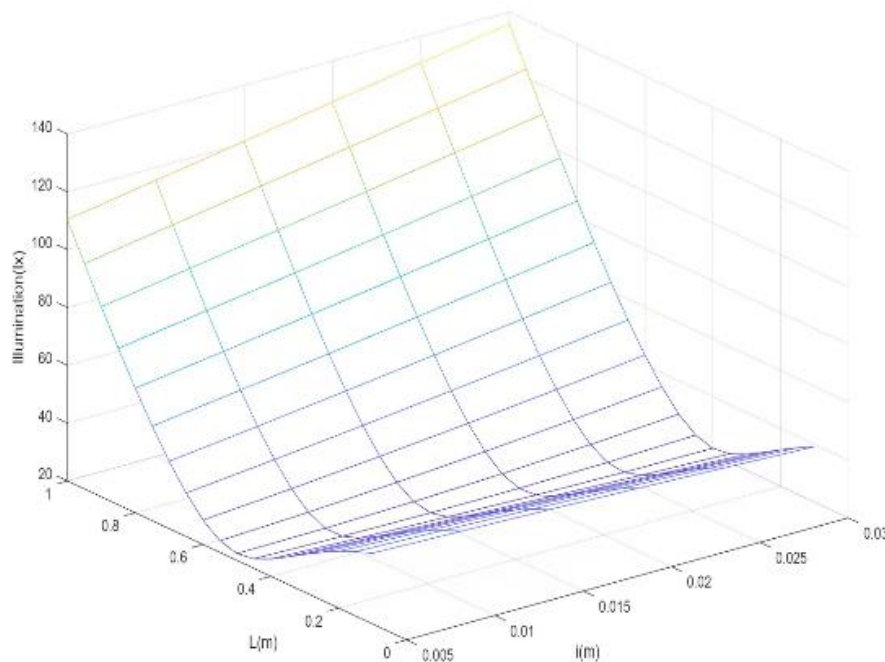


Fig. 5. Distribution of minimum illuminance on the receiving plane for $N = 9$.

The simulation results show that the illuminance standard deviation first decreases and then increases nonlinearly with increasing L and d , exhibiting a convex response. A two-dimensional parameter sweep

indicates that the global minimum is obtained at $L = 0.4$ m and $d = 0.03$ m. Under this optimal configuration, the spatial optical-power distribution over the receiving plane reaches its highest uniformity, with a global mean illuminance of approximately 400 lx and a minimum edge illuminance maintained above 300 lx. This optimization eliminates the blind-zone effect associated with a single light source and satisfies the standardized lighting requirements of a typical indoor office environment.

5.2. Optimization of Hybrid LED Array Layout

To simultaneously improve indoor illumination uniformity and communication-link reliability, a hybrid LED-array configuration is further designed. It consists of four peripheral 8-LED arrays distributed across the four room quadrants plus a central 6×6 LED array on the ceiling. During the two-dimensional parameter sweep, the search interval for L is [0.10 m, 1.0 m] with a step of 0.05 m, while the search interval for d is [0.01 m, 0.03 m] with a step of 0.005 m.

To evaluate the two physical objectives simultaneously, a joint optimization objective is constructed using the illuminance standard deviation σ_E and the mean BER BER_{avg} :

$$f(L, d) = \sigma_E + \omega \cdot BER_{avg} \quad (11)$$

where ω is a weighting penalty coefficient used to balance the difference in numerical scale between the two objectives ($\omega = 6 \times 10^7$). The objective function jointly represents the requirements for visual illumination and data-transmission quality; a lower value indicates better overall system performance.

The simulation results show that the joint objective reaches its global minimum at $L = 0.4$ m and $d = 0.01$ m. Under this optimal spatial topology, the illuminance standard deviation over the receiving plane is reduced to below 10 lx, indicating highly uniform illumination, while the mean spatial BER is reduced to the 10^{-7} order of magnitude. This optimization mitigates the edge attenuation of the single-source configuration, and the resulting system meets the requirements for high-speed, reliable indoor VLC.

6. Conclusions

This study established and evaluated indoor VLC system models based on a Lambertian radiation channel model for a typical 4 m $\times$ 4 m indoor environment. The effects of single point-source and multi-LED array layouts on illumination and communication performance were investigated. In the single-source configuration, received optical power, illuminance, and SNR exhibit pronounced central symmetry: performance is highest near the center and decays rapidly toward the room boundaries, resulting in an increased BER and preventing simultaneous satisfaction of indoor lighting and communication requirements. In contrast, multi-LED layouts improve the spatial uniformity of illuminance and SNR over the receiving plane. With appropriate parameters, the 9-LED array satisfies indoor lighting requirements, while the hybrid LED layout further reduces BER while maintaining high illuminance uniformity, thereby enabling coordinated optimization of illumination and communication performance. The optimal hybrid-layout parameters are $L = 0.4$ m and $d = 0.01$ m. The proposed channel model and layout-optimization approach can provide a useful reference for indoor VLC light-source deployment and performance evaluation, with potential engineering value for improving communication reliability and illumination uniformity.

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