Experimental validation of the appropriate channel model for an indoor Visible Light Communication system

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***Abstract*—This research is centered around the evaluation of existing channel models for planning the VLC network coverage within indoor environments. The primary focus of this study is to enforce three types of channel models, Line of Sight (LoS), Nakagawa's first reflection model, and the Spherical model through MATLAB simulations and obtain simulation results by varying the distance parameter. Furthermore, this research intends to implement a physical prototype representing a real-world scenario, and thereby determine the nearest channel model that aligns with the physical measurements obtained from the physical prototype.**

***Index Terms*—VLC - Visible Light Communication, LoS - Line of Sight, DC channel gain - Direct Current channel gain, PD - Photodiode, LED - Light Emitting Diode**

I. Introduction

Visible Light Communication (VLC) was developed and integrated by numerous research and industrial organizations as a result of the growth of LED technology. A channel model is a mathematical representation that describes how light signals propagate through a communication channel. Jupeng Ding et al. compared the performance of four VLC channel types [1]. This research was about the simulation used to assess the correctness of four distinct modeling approaches in VLC with scattered array sources. In a multiple reflections modeling approach, the results reveal that higher-order reflections have a considerable impact on the received optical power distribution, impulse response, and 3 dB bandwidth. In 2014, Zhou Zhou et al. developed a channel model for indoor VLC systems that included multiple reflections [2]. The impact of high-order light reflections on IOWC (Indoor Optical Wireless Communication) channel model inaccuracy is the subject of this study. The findings show that traditional channel models based on the first few, most usually three, orders of reflections are not accurate enough for high-speed IOWC transmission systems with data rates in the Mbps or Gbps range. In 2017 Farshad Miramirkhan et al. built a mobile VLC channel built on non-sequential ray tracing [3]. Wavelength dependency was specifically taken into consideration for realistic modeling, and several types of reflections, such as diffuse, specular, and mixed reflections, were taken into consideration. The simulations used CAD human models, a furnished interior space, and a commercially available measured light source. Oluwafemi Kolade et al. presented the indoor amplify-and-forward (AF) hybrid power-line communication (PLC) and visible light communication (VLC) channel model of a multicarrier in 2020 [4]. In this study, software-defined radios were used to get measurements from various locations between the VLC transmitter and receiver in an indoor testbed. A Fritchman channel state representation model assists in the derivation of channel models utilizing a semi-hidden Markov model (SHMM) based on the measurements that were obtained. The indoor visible light/radio frequency (RF) hybrid communication system that is capable of simultaneous light wave information and power transfer was examined by Kapila W. S. Palitharathna et al. in 2023 [5]. This study gives an overview to optimize the beamforming matrices and time allocation parameters and achieve an almost ideal uplink sum rate, this method can forecast human bottlenecks effectively. In 2023 Kapila W. S. Palitharathna et al. developed a system to discuss an intelligent reflective surface (IRS) supported indoor visible light communication system using simultaneous lightwave power transfer (SLIPT) [6]. The SLIVER system helps to improve performance under a variety of user mobility, receiver orientations, and blockage situations, according to the results.

It is evident from the preceding that the vast majority of literary works of different channel models have merely undergone theoretical analysis and simulations, but have not been physically implemented. The central objective of this study is to replicate and assess the user experience within VLC systems by selecting three of the existing channel models namely, the LoS channel model, Nakagawa's first reflection channel model, and Spherical channel model. The adoption of the three chosen channel models in this research was prompted by constraints in available resources, making it challenging to depict the complexities associated with newer and more advanced channel models. Furthermore, the chosen photodiode in this study, demonstrated inefficiency in detecting and receiving the minimal light produced by these contemporary channel

models, given the challenges posed by multiple reflections and diffused light signals reaching the receiver. Additionally, the absence of efficient equipment for converting faint light signals into electrical signals has hindered our ability to employ the latest and intricate channel models.
This study involves conducting MATLAB simulations for these channel models under specified conditions along with constructing a physical setup that mirrors a real-world room scenario, using an LED as the transmitter and a Photodiode (PD) as the receiver for unidirectional VLC communication. This setup facilitates the collection of data on received power at varying link distances between the LED and the PD. Finally, the project aims to compare the simulation outcomes with the physical measurements to identify the most suitable channel model for the physical results within the defined conditions.

II. MATLAB Simulation Analysis and Physical Implementation

A. Analysis of LoS Channel Model

LoS refers to the clear and uninterrupted path between the transmitter and the receiver, where the transmitter directs a focused light beam toward the receiver. In the MATLAB simulation, the LoS channel model is employed, utilizing the DC channel gain equation. In this simulation, the distance parameter is adjusted while keeping other parameters constant. This process allows us to calculate the channel gain and determine the coverage area based on the variation in the distance parameter.

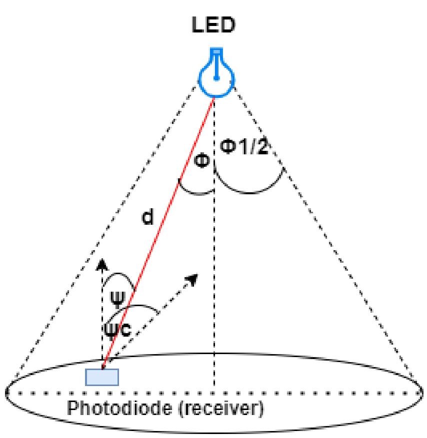

Fig. 1. LoS Channel Model.

In a Los link, the DC channel gain equation can be represented as [7]:

$$H_{LoS}(0) = \begin{cases} \frac{A_r(m+1)cos^m(\phi)}{2\pi d^2} \times T_s(\psi)g(\psi)cos(\psi), \\ \qquad 0 \leq \psi \leq \psi_c \\ \qquad 0, \\ \qquad \psi \geq \psi_c \end{cases} \tag{1}$$

The received power P_R can be obtained as follows:

$$P_R = P_E H_{LoS}(0) \tag{2}$$

TABLE I
Parameter Description Of LoS Equation

Parameter	
Ti	Transmitter
Ri	Receiver
$\phi1/2$	Semi-angle half power of the LED
ϕ	Irradiance angle
ψ	Incidence angle
ψ_c	Field of View of the Photodiode
m	Lambertian order of emission
d	Distance between LED and the photodiode
Ar	Active area of the photodiode
Ts(ψ)	Gain of an optical filter
g(ψ)	Gain of an optical concentrator
P_R	Received power
P_E	Transmit power
H_{LoS}	DC channel gain of Line of Sight propagation

The Lambertian order of emission can be represented as given by [8]:

$$m = \frac{-\ln 2}{\ln(cos(\phi_{1/2}))} \tag{3}$$

The optical gain of the optical concentrator can be represented as given by [7]:

$$g(\psi) = \begin{cases} \frac{n^2}{sin^2\psi_c} & ; 0 \leq \psi \leq \psi_c \\ 0 & ; \quad \psi \geq \psi_c \end{cases} \tag{4}$$

where n depicts the refractive index of the optical concentrator.

B. Analysis of Nakagawa's First Reflection Channel Model

Given that the transmission bandwidth of the channel is significantly impacted by the temporal dispersion brought on by reflections. Masao Nakagawa built the modeling approach on the LoS modeling strategy and included the first reflection from the room's surface. The channel DC gain on the first reflected path is employed in the MATLAB simulation.

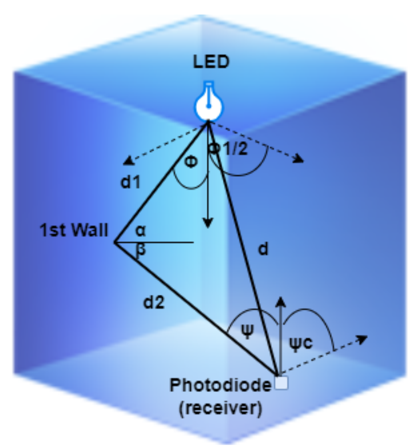

Fig. 2. Nakagawa's First Reflection Channel Model.

The DC channel gain equation of first reflection can be represented as [7]:

$$H_{ref}(0) = \begin{cases} \frac{A_{PD}(m+1)}{2\pi d_1^2 d_2^2} \times \rho dA_{wall} cos^m(\phi)cos(\alpha)cos(\beta) \\ \qquad T_s(\psi)g(\psi)cos(\psi), \\ \qquad 0 \leq \psi \leq \psi_c \\ \qquad 0, \\ \qquad \psi \geq \psi_c \end{cases} \quad (5)$$

TABLE II
PARAMETER DESCRIPTION OF NAKAGAWA EQUATION

Parameter	
Ti	Transmitter
Ri	Receiver
$\phi 1/2$	Semi-angle half power of the LED
ϕ	Irradiance angle
ψ	Incidence angle
FOV(ψ_c)	Field of View of the Photodiode
m	Lambertian order of emission
β	Angle of the irradiance from the reflective area of the wall
α	Angle of the irradiance to the wall
d1	Distance between LED and the wall
d2	Distance between the wall and the photodiode(receiver)
Apd	Active area of the photodiode
Awall	Reflective area
Ts(ψ)	Gain of an optical filter
g(ψ)	Gain of an optical concentrator
ρ	Reflection coefficient
P_R	Total received power
P_E	Transmit power
H_{LoS}	DC channel gain of Line of Sight propagation
H_{ref}	DC channel gain of multipath propagation

The total received power of the effect of reflections of all the walls and the effect of LoS in the room setting can be represented as [9]:

$$P_R = P_E H_{LoS}(0) + \int_{walls} P_E H_{ref}(0) \quad (6)$$

C. Analysis of Spherical Channel Model

The Spherical modeling technique offers a distinct modeling approach frequently utilized for assessing the diffuse area within a space. Its key characteristic, unlike the two other modeling methods mentioned earlier, is the consistent maintenance of diffuse (scattered) signal gain throughout the entire room. When determining the total received power for a space, this approach combines both the Line-of-Sight (LoS) component and the Diffused power signal component.

The DC channel gain equation of the diffused signal component can be represented as given by [7]:

$$H_{diff}(0) = \frac{A_r \rho}{A_{room}(1-\rho)} \quad (7)$$

where A_r is the effective receiver surface area, A_{room} is the room area and ρ is the reflective coefficient of the room.
Therefore, the total DC channel gain of the spherical model is the summation of the DC channel gain of the LoS link and the DC channel gain of the diffused signal component. Hence

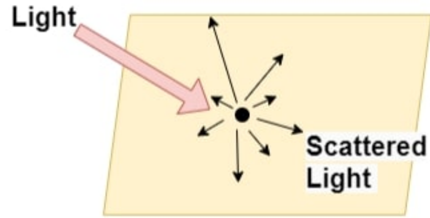

Fig. 3. Diffused signal representation

the total DC channel gain is the summation of Equation (1) and Equation (6).

$$H_{total} = H_{LoS}(0) + H_{diff}(0) \quad (8)$$

Therefore, the total received power can be represented as:

$$P_R = P_E H_{total} \quad (9)$$

D. Hardware Implementation

The actual received power is evaluated based on a physical prototype and it is assessed by varying the link distance between the LED and the Photodiode (PD). By measuring the photocurrent induced from the PD the actual received power is calculated by utilizing the responsivity parameter obtained from the Photodiode (PD) specifications. The responsivity of the PD employed in this study is 0.34 A/W [10].

$$PDResponsivity(A/W) = \frac{Photocurrent}{Receivedpower} \quad (10)$$

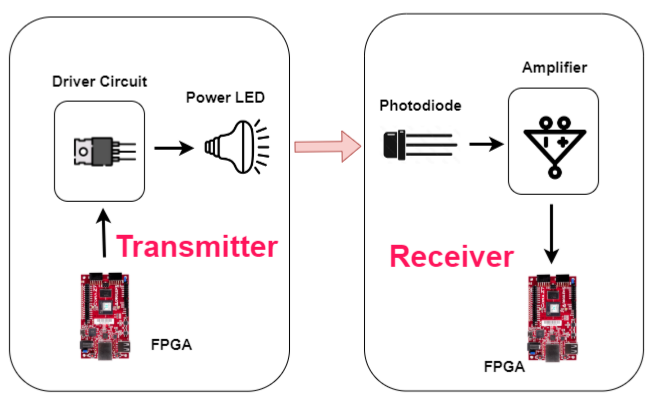

Fig. 4. Block Diagram - Hardware Components

White sheets were placed inside the cardboard box because white paper reflects more light than brown cardboard and does not absorb light, unlike brown cardboard. This is because materials with a high reflectance factor do not absorb light.
Moreover, three distinct boxes were employed in the experiment, each with varying dimensions to represent a real room setting, along with two different LED power levels.

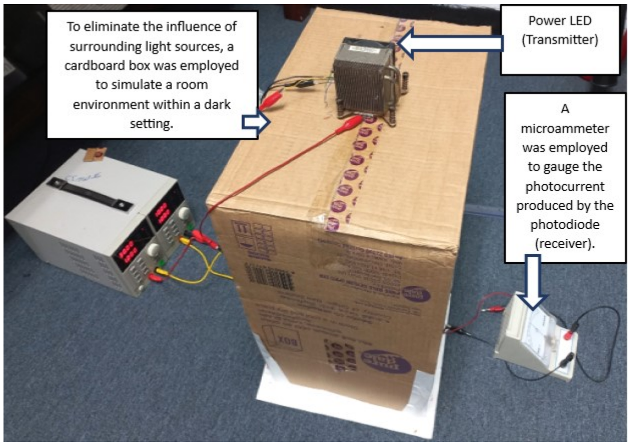

Fig. 5. Physical prototype

TABLE III
DIMENSIONS OF THE PROTOTYPES USED

Box No.	Dimensions		
	Height (cm)	***Width (cm)***	***Length (cm)***
1	26.5	23	30.5
2	50	29.5	45
3	24	22	58

III. RESULTS AND DISCUSSION

The MATLAB simulation results below are based on the following simulation input values. The received power is derived by altering the distance parameter while maintaining the other parameters at a constant value in the DC channel gain equation in all the 3 channel models (Equations (1), (5), and (7)). Additionally, the comparison between the physical and simulation results for each of the three Boxes according to the two types of LEDs are depicted below.

TABLE IV
TYPES OF LEDS USED AND OPERATING POWER

LED Types	Operating Parameters		
	Voltage(V)	***Current(A)***	***Power(W)***
50W	30	0.8	24
30W	30	0.175	5.25

TABLE V
SIMULATION INPUT VALUES

Parameter	Channel Model		
	LoS	***Nakagawa***	***Spherical***
ϕ	60°		
Ar	7.45E-6m^2		
Ts(ψ)	1		
g(ψ)	1		
ψ_c	55°		
Room dimensions	Depends on the type of Box based on Table III		
P_E	Depends on the type of Box based on Table II		
ρ	-	Reflectance factor of white paper=0.8	
A_{room}	-	-	0.07015m^2

The MATLAB simulation results of the 3 channel models based on the dimensions of Box number 1 utilizing 50W LED as the transmitter with an operating power of 24W according to Table IV are as follows:

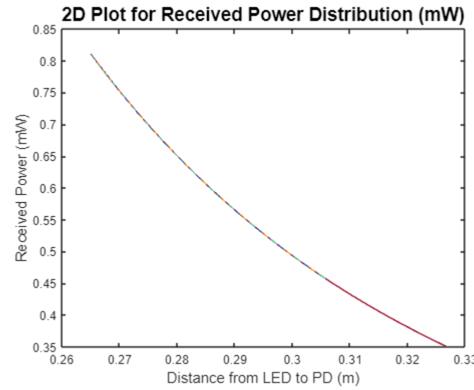

Fig. 6. Box1-50W LoS MATLAB Simulation for Received Power (mW)

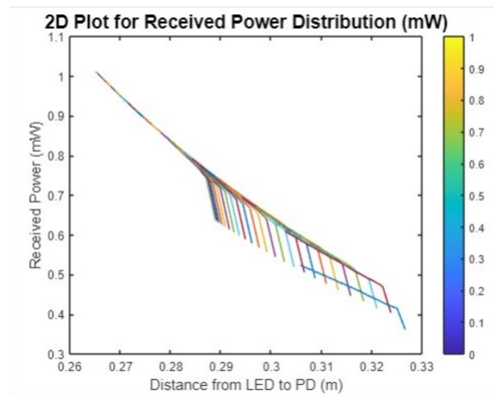

Fig. 7. Box1-50W Nakagawa MATLAB Simulation for Received Power (mW)

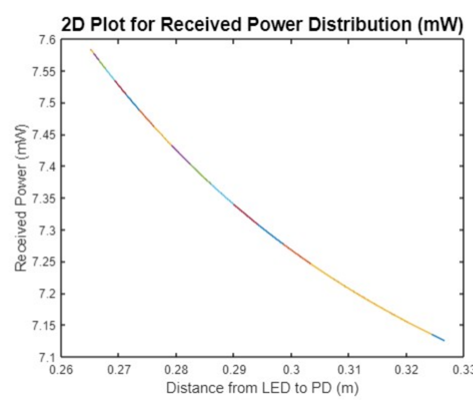

Fig. 8. Box1-50W Spherical MATLAB Simulation for Received Power (mW)

Likewise, MATLAB simulations were conducted using a 30W LED for Box1. Similarly, MATLAB simulations were also carried out for the remaining Boxes (Box no. 2 and 3)

using 50W and 30W LEDs.
The comparison between the physical and the simulation received power based on both 50W and 30W LEDs for Box number 1 are given in Fig 9 and Fig 10.

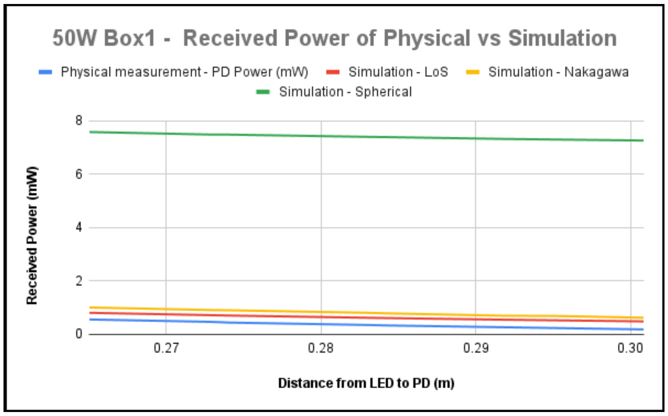

Fig. 9. Box1-50W Physical vs Simulation Received Power (mW)

Due to a significant disparity between the actual received power and the MATLAB simulation output for the Spherical model, and considering the minimal difference observed in received power between the physical and MATLAB simulation outputs for the LoS and Nakagawa models, the MATLAB output for the Spherical model can be disregarded. This pattern is consistent across all boxes utilizing both types of LEDs. Hence, the MATLAB simulation output for the Spherical model can be disregarded in subsequent comparisons between the physical and simulated received powers for all boxes employing the two types of LEDs.

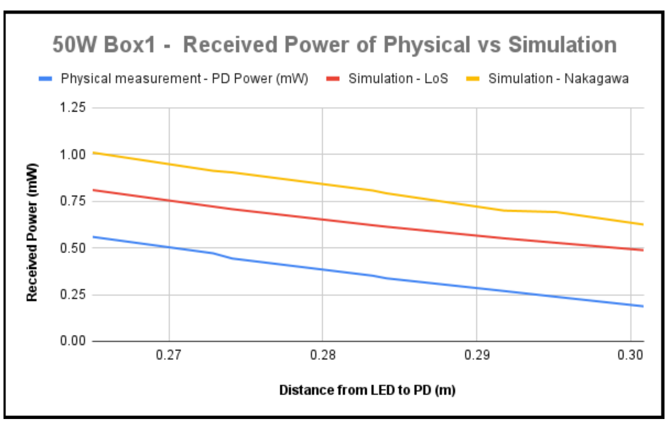

Fig. 10. Box1-50W Physical vs Simulation Received Power (mW) except Spherical Model

The comparison between the physical and the simulation received power based on both 50W and 30W LEDs for Box number 2 and 3 are as follows:

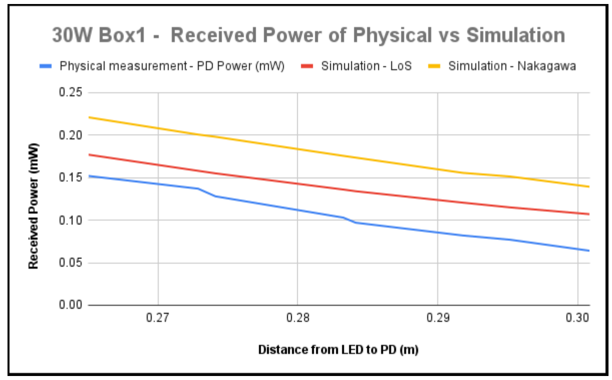

Fig. 11. Box1-30W Physical vs Simulation Received Power (mW) except Spherical Model

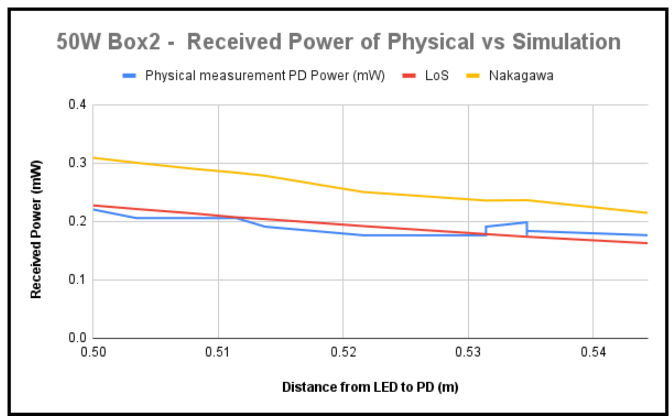

Fig. 12. Box2-50W Physical vs Simulation Received Power (mW) except Spherical Model

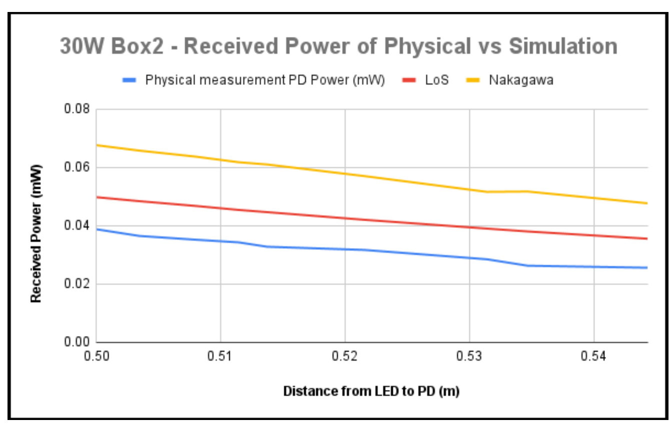

Fig. 13. Box2-30W Physical vs Simulation Received Power (mW) except Spherical Model

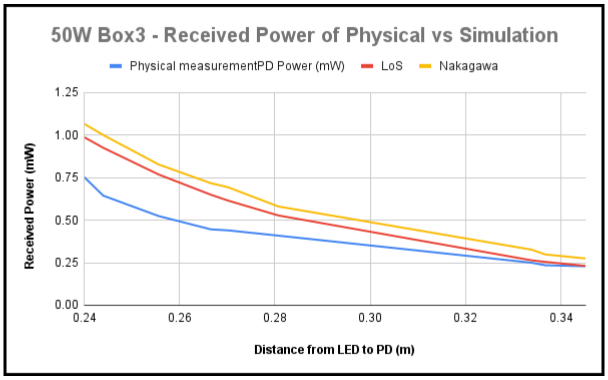

Fig. 14. Box3-50W Physical vs Simulation Received Power (mW) except Spherical Model

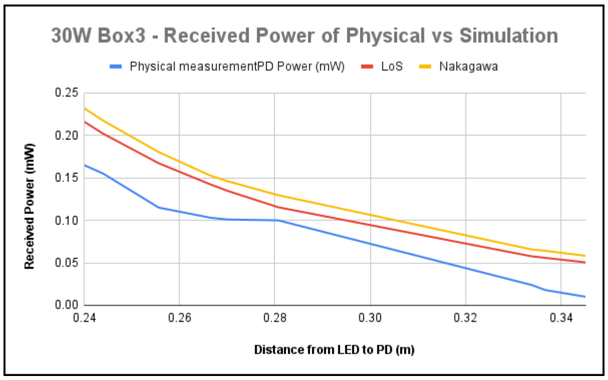

Fig. 15. Box3-30W Physical vs Simulation Received Power (mW) except Spherical Model

Based on the aforementioned results, it is clear that when the distance between the LED and the PD increases, the received power decreases. This observation aligns with the principles outlined in the DC channel gain equations for Line of Sight (LoS), Nakagawa, and Spherical channel models (Equations (1) and (5)). These equations establish that the distance between the LED and the PD is inversely proportional to the DC channel gain ($H_{LoS}(0)$, $H_{ref}(0)$). Consequently, an increase in DC channel gain leads to an increase in received power, and vice versa, as they are directly proportional to each other, as expressed in Equations (2), (6), and (9).
Furthermore, it is evident from the above graphical results, relative to the given conditions the most proximate channel model for the physical measurements is the LoS channel model. Thus, it can be concluded that based on the given room conditions, there is no effect from either reflections or diffused light signals for the actual received power.

IV. Conclusion

This research covers the evaluation of the proximate channel model to the real coverage area measured under specified conditions in an indoor environment. The MATLAB simulations conducted for the three chosen models contribute to our comprehension of the DC channel gain for each model, as well as the fixed and changing parameters associated with each model, and the resulting received power. The proposed setup and the prototype explain the aspects including the components used and the process of obtaining the physical measurements respectively. Furthermore, some notable progressions from the preceding decade have been incorporated, along with highlighting the significance of VLC (Visible Light Communication) and channel models incorporating practical experiments. The concluding part of this study discusses the outcomes observed under different prototype (room) dimensions and conditions and with varying transmission powers. By contrasting the results of MATLAB simulations with actual measurements, it is identified that the predominant channel model is the Line of Sight (LoS) channel model for all room conditions. This leads to the conclusion that reflections and scattered light signals are unaffected.

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