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RESEARCH

A Visible Light Communication Channel Model for Agronomic Environments

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Abstract

Currently, agriculture based on agronomic greenhouses is replacing traditional agriculture. This technique reduces dependence on rain on crops. It also generates a controlled internal environment making optimal use of land and water resources. However, this environment needs more care and attention compared to traditional agriculture. To overcome this limitation, various radio frequency (RF)-based technologies can be used. Nevertheless, studies show that the use of communications in RF bands degrades crops' growth and quality. Therefore, an efficient solution is to use the visible light spectrum for communication, the main technology of which is called visible light communication (VLC). Despite numerous studies for the application of VLC in indoor environments, specific VLC systems for agronomic greenhouse environments or their channel models are not yet investigated in depth. To collaborate on state of art on this topic, we present in this paper a novel channel model that incorporates specific factors that affect the quality of VLC systems in agronomic greenhouse environments. Factors such as the random position and orientation of the transmitters and external environmental agents such as atmospheric and different noise types are considered. These components are integrated into an analytical framework by developing the mathematical model of the VLC channel. Furthermore, the analytical expressions of the received power, the signal-to-noise-ratio (SNR), and the bit error rate (BER) are obtained. A VLC system applied to an agronomic greenhouse scenario is developed through computer simulations to validate the mathematical analysis. The results show that illuminance is adequate for the efficient operation of the greenhouse. Besides, the influence of atmospheric factors and noises on the magnitude and temporal dispersion of the channel impulse response is verified. Finally, the results show the system's performance in terms of SNR and BER, observing their differences compared to a traditional indoor VLC system.

Keywords: agronomic greenhouse; channel DC gain; channel impulse response; channel modeling; visible light communication

Introduction

It is mostly known that traditional agriculture is one of the most practiced occupations in developed and developing countries. However, their inherent work environment is harsh, and it depends mainly on the human factor. Besides, agriculture is highly dependent on the environment, which is not very controllable and is deteriorating more and more. In search of providing efficient agriculture, technological advances propose solutions to facilitate agricultural work and depend to a lesser extent on external factors [1]. Automating and implementing irrigation systems

such as sprinkler and drip on agricultural farms has gained much popularity [2]. However, these systems still do not address the problem of unpredictable environmental effects. Therefore, farmers are moving to a new environment for agriculture, called agronomic greenhouses. These environments provide controlled environmental conditions since they allow handling factors such as temperature, humidity, and adequate illuminance [3]. Agronomic greenhouses are apparently an effective solution to improve crops. However, controlling all the external variables that affect crops is a challenge that must be analyzed.

Based on agronomic greenhouses' characteristics and how they can modify an environment of communication and data transmission, one way to control the variables that affect crops is using communication technologies based on radio frequency (RF) [4]. There are several categories studied in greenhouse communications: radio-communication systems, carrier wired systems with current carriers, and the combination of some of these systems (hybrid systems). It is understood that the agricultural environment in greenhouses is delicate and highly susceptible to external factors. Therefore, several studies have shown that RF electromagnetism degrades the growth and quality of crops [5]. Although agronomic greenhouses, depending on the crop, need good lighting, this problem also requires special attention. All the aforementioned challenges are presented as opportunities for the scientific community to search for complementary communication systems that optimize both communication and lighting in greenhouses. It is here that the concept of Visible Light Communication (VLC) is introduced as a communication system for agronomic greenhouse environments.

Several benefits come with VLC systems, among which we mention: the use of unlicensed spectral bands ranging from 400 THz to 800 THz, transmitting and receiving elements with reasonable prices and easy to obtain, and that VLC is considered as a technology green that does not affect the environment or nature, which is the main characteristic to be implemented in greenhouses [6, 7]. Unfortunately, in this physically variable and difficult-to-control environment, communication channel modeling is generally more challenging than typical indoor VLC scenarios.

An agronomic greenhouse is composed of sheds and materials in its walls and roof whose characteristics do not appear in typical indoor environments. Factors such as aerosols, gases, and molecular constituents that cause scattering and absorption of light, an angular positioning and orientation of light-emitting diodes (LEDs) to provide better illuminance and light reception within the greenhouse, and temperature variations produced by rain, snow, fog, among others, are a challenge for the design of VLC systems in the agronomic greenhouse. Considering all these variables and modeling a realistic communication channel that includes them, the system's overall performance can improve.

According to our current knowledge, applied specifically to VLC systems for agronomic greenhouse environments, no channel model has been presented that considers external factors that affect it or basic characteristics. To design better communication systems applicable to agricultural environments, we present a novel VLC channel model that considers external factors and physical characteristics that affect greenhouses. We characterize and include in the VLC channel model for greenhouses the inclination and rotation of LEDs that impact the line of sight (LoS) of the optical link. We consider the reflections produced by the walls with their respective

coefficients of the materials. Furthermore, as a differential factor with other indoor environments, we include in the channel model attenuation and dispersion coefficients depend on the size of the molecules and aerosols inside the greenhouse, which vary depending on atmospheric factors. Finally, the different noise types that affect the optical link are characterized and included in the propagation model. The inclusion of the aforementioned parameters helps us understand the differences between a typically indoor VLC channel and the VLC channel for agronomic greenhouses. For channel modeling in a computational environment, we use the ray-tracing methodology, which allows a precise description of the interaction of the rays emitted by the LEDs to the photo-diodes (PDs) within a simulation scenario of a greenhouse with its main characteristics.

The main contributions of this paper are summarized as follows:

- 1 Adjusting and characterizing the effect of the LEDs' positioning and orientation on the scenario to adequately model the optical signal in the proposed VLC channel for agronomic greenhouses.
- 2 Proposing a VLC channel model applied to agronomic greenhouses based on ray tracing that includes the effects of absorption and dispersion phenomena due to aerosols and constituent molecules' presence due to atmospheric variations. The main types of noise that affect these environments, such as background light, bright skylight, direct sunlight, shot, and thermal, are included in the propagation model.
- 3 Developing a simulation framework based on an agronomic greenhouse scenario to verify the system's performance in terms of illuminance, channel impulse response, SNR, and bit error rate (BER).

The remainder of this manuscript is organized as follows. Section II provides an overview of work related to communication technologies applied to agricultural and crop environments. The analysis and mathematical characterization of the VLC channel model applied to agronomic greenhouse environments are explained in Section III. Section IV describes the agronomic greenhouse scenario where we evaluate the proposed VLC channel model, present our results, and discuss our findings. Finally, conclusions of our work are described in Section V.

Related Work

There are multiple works that present communication systems based on various technologies implemented in agriculture, specifically in greenhouses. In [8], a wireless monitoring system based on wireless sensor networks (WSN) is designed for greenhouse environments. The general structure of the system is introduced, which is based on ZigBee technology. The designs of the sensor and controller nodes are described. As a result, the system's comprehensive performance is better than the traditional greenhouse monitoring system. However, the work does not involve robust mathematical models of the system or channel, which could improve system applications' performance.

In [9], a monitoring and control system for greenhouses based on global system for mobile (GSM) (800-900 MHz)-WSN (IEEE 802.15.4) technology is presented. The proposed system includes the sensors, which communicate with the base by ZigBee, and the base station, which communicates with the user by short message service

(SMS). Despite presenting the block diagrams of the system elements, an analysis of signal propagation or performance of the system in terms of the physical layer is not carried out, which would help in the optimization of communication.

In [10], a smart lighting system prototype based on Narrowband-internet of things (IoT) is proposed. The communication system is designed to connect the back-end system and fields such as greenhouses. In the testbed, the dimming of the light is programmed and controlled and monitors the environmental temperature and humidity of the scenario. Experimental results are shown to verify usability and advantages. Although the work performs an illuminance control in the experimental setting, it does not use light as a communication system, nor does it present a rigorous study of the channel or the propagation model for Narrowband-IoT.

In [11], a study based on the intelligent control of parameters that govern adequate growth and crop health such as temperature, humidity, the water level is realized. This work's novelty is that the information from these parameters is shared with farmers using GSM technology. This study's main focus is to arrive at a cost, time, and energy-efficient transmit/receive module. However, no physical layer or propagation model analysis is performed, which limits the results.

In [12], a first research that does not involve a technology directly based on RF is presented. This paper develops a new electronic system for low bit rate infrared (IR) communication applications. This novel remote transmission system concept also features the use of pulse-width modulation (PWM) and ON/OFF encoding. The system is designed to process signals or data that change slowly with a low bit rate. Illuminance detection in agricultural environments represents a practical application of the proposed concept. However, this work's focus is more electronic, so an analysis of the channel or the propagation model is not executed.

In [13], a mobile greenhouse environmental monitoring system based on the IoT is designed. This work's novelty presents a four-layer system architecture with motion control using mobile acquisition instead of multiple detection nodes to perform the automatic collection of greenhouse environmental information. In this study, a Raspberry Pi and an Arduino chip are combined for environmental monitoring. As in the previous works that we mentioned, this article's focus is on the development of the control system, so they do not perform an analysis of the behavior of the signals with the propagation model to be used.

Finally, in [14], a recent research describes several questions and challenges for implementing green technologies based on wireless communication that are more energy efficient. The focus in this work for energy reduction is explored using a LoRa-based IoT pilot implementation in a greenhouse. This pilot study helps identify challenges and greenhouse IoT connectivity limitations. The authors theoretically discuss the possible research prospects to increase savings opportunities power and wireless data communication. However, the entire study focuses on IoT and RF technologies, relegating technologies such as VLC or mm-waves, which are also energy efficient.

As we can see in this literature review, all the works are focused on presenting solutions for monitoring and communication in greenhouses and agricultural environments. However, these solutions are based on technologies such as ZigBee, GSM, infrared (IR), and others based on RF. As we mentioned, it is proven that electromagnetism and RF negatively affect crops. Furthermore, as we explained, there is

no research related to green or complementary technologies to provide communication within an agronomic greenhouse environment. Therefore, we consider this research opportunity to present a novel communication approach based on VLC, from the point of view of the channel model's characterization.

VLC system model for agronomy environments

Typically, a traditional indoor VLC channel is modeled using a closed indoor environment composed of reflective objects, such as walls and ceiling. Optical wireless transmission is also considered to be specific to a down-link channel model. For our case, the down link transmission's geometric configuration is applied to an agronomic greenhouse scenario illustrated in Fig. 1, where all its variables and constants will be described in the following subsections. We will consider a section of the greenhouse for analysis. This section is equipped with LED transmitters, and to optimize the communication effect, the intensity of the light in the greenhouse should be distributed as evenly as possible. Therefore, multiple LEDs must be installed throughout the greenhouse. The dimensions, the location of the LEDs, and the key parameters of the VLC system applied to the proposed agronomic greenhouse are detailed in the Table 1, located in Section 0.1.

The VLC channel is the space between the LED and the PD, and to model it, three different components must be analyzed: LEDs (light sources) with the Orientation-Based LED Model, PDs (light detectors) with the Non-Imaging Photo-detector Model, and the optical propagation model.

Orientation-Based LED Model

To optimize and prioritize correct communication in agronomic greenhouses, we must efficiently distribute the light in the entire physical space. According to VLC systems for indoor environments, multiple LEDs are installed in the greenhouse to provide lighting and communication simultaneously. In typical indoor VLC environments, customers usually install the LEDs pointing vertically downward. However, in agronomic environments such as greenhouses, LEDs' ideal location is in the curved sections between the wall and the ceiling, as we can see in Fig. 1. This position is due to the easiness of installation and maintenance of the LEDs.

In order to mathematically model the orientation of the LED in the greenhouse, we define ϕ as the angle of radiation with respect to the normal vector \mathbf{n}_i of the LED position and the position of the LED in the greenhouse as (x_i, y_i, z_i) in the Cartesian coordinate system, where $i = 1, 2, \dots, I$ and I is the total number of LEDs.

As we mentioned, in greenhouses the LEDs do not point vertically downwards due to their orientation. Therefore, it must be described based on two separate angles. These angles are defined as the tilt angle with respect to the z-axis, which is represented by β and takes values in range of $[-90^\circ, 0^\circ)$ and the rotation angle with respect to the x-axis, which is denoted as α and defined in the interval $[0^\circ, 180^\circ)$. The ranges of values were adjusted to the real physical characteristics that the orientation of the LED can take in the greenhouse.

Assuming that each LED has the same generalized Lambertian radiation pattern, and since this model is widely used for the light emission distribution of the LEDs

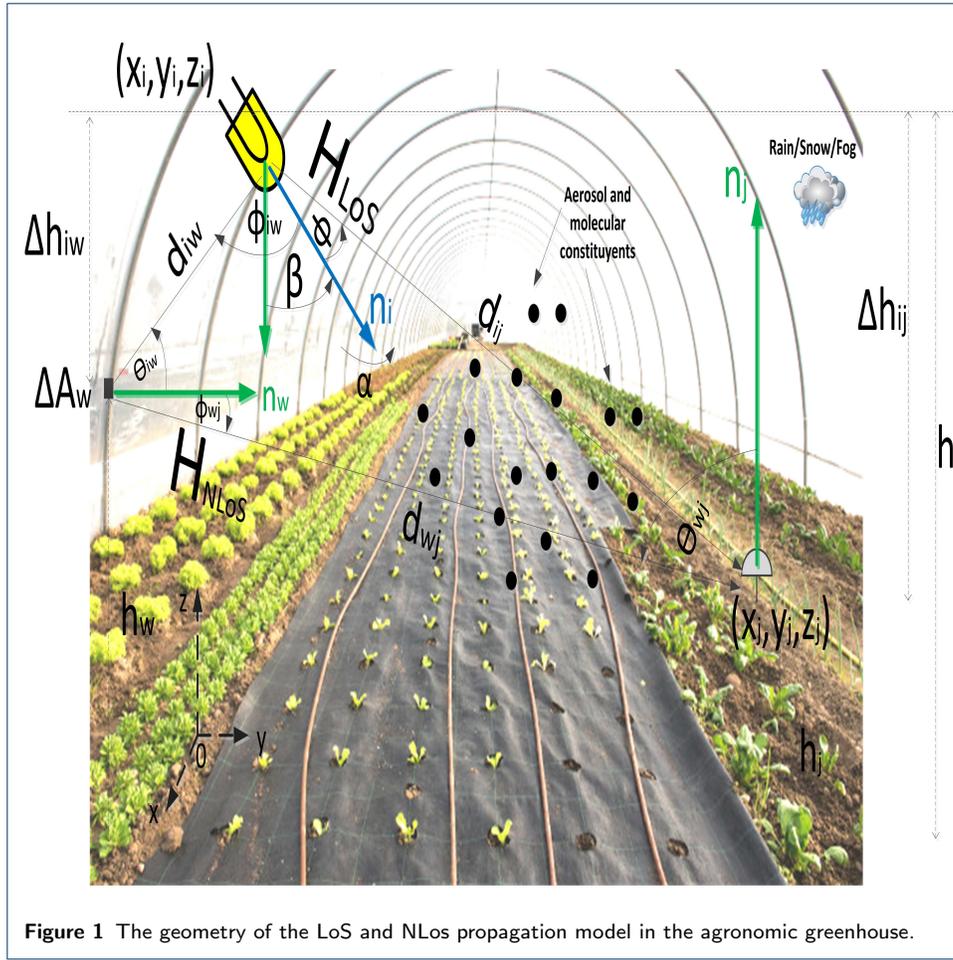


Figure 1 The geometry of the LoS and NLoS propagation model in the agronomic greenhouse.

[15, 16], the radiation intensity pattern $S(\phi)$ is given as [15, 16]

$$S(\phi) = \begin{cases} \frac{m+1}{2\pi} \cos^m(\phi) & \text{if } \phi \in [-\frac{\pi}{2}, \frac{\pi}{2}] \\ 0 & \text{otherwise} \end{cases}, \quad (1)$$

where m is the Lambertian mode number, which is a function of the half angle at half power $\Phi_{1/2}$ emitted by the LED; m acquire the form of [15, 16]

$$m = \frac{-\ln(2)}{\ln[\cos(\Phi_{1/2})]}. \quad (2)$$

It is evident that the orientation of the LED affects ϕ and is distinguished specifically in the term $\cos(\phi)$, which based on vector concepts is defined as follows:

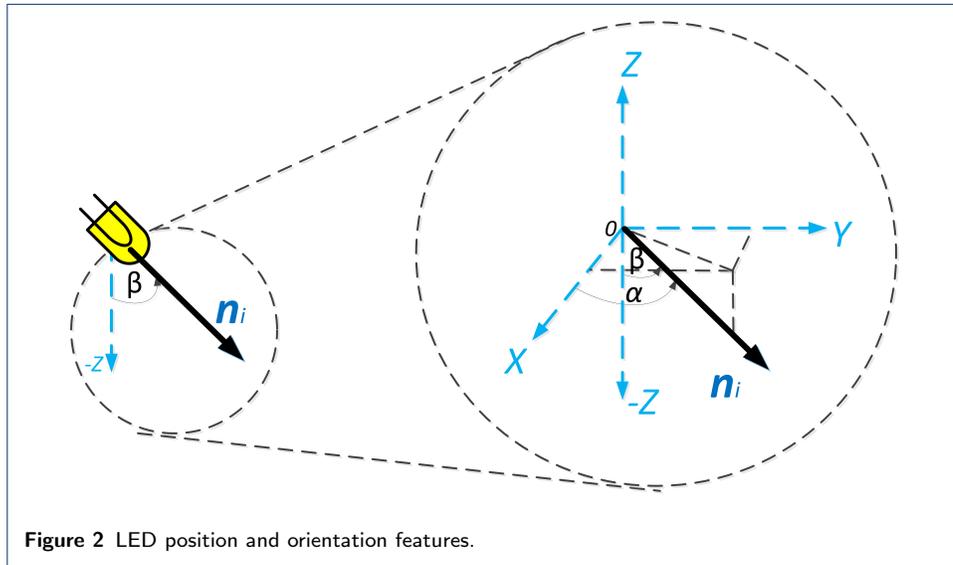
$$\cos(\phi) = \frac{V_{i-j} \cdot \mathbf{n}_i}{\|V_{i-j}\| \|\mathbf{n}_i\|}, \quad (3)$$

where the vector from a LED to a PD is denoted by V_{i-j} , the notation $\|\cdot\|$ denotes the 2-norm, and \cdot represents the product dot operation. Also, for vector concepts, $\|V_{i-j}\| = d_{ij}$, where d_{ij} is the Euclidean distance between the

LED and the PD, $\|\mathbf{n}_i\|=1$, and \mathbf{n}_i can be represented in terms of α and β as $\mathbf{n}_i = [\sin(\beta) \cos(\alpha), \sin(\beta) \sin(\alpha), -\cos(\beta)]$. Notice that the z-component of the \mathbf{n}_i is negative since the LED is pointing downwards. Furthermore, $V_{i-j} = [x_j - x_i, y_j - y_i, -\Delta h_{ij}]$, where the PD position is represented by (x_j, y_j, z_j) in the Cartesian coordinate system and assuming that Δh_{ij} is the difference height between the LED and the PD, that is $z_i - z_j = \Delta h_{ij}$. Consequently, the expression (3) can be rewritten in the following form:

$$\cos(\phi) = \frac{[x_j - x_i, y_j - y_i, -\Delta h_{ij}]}{d_{ij}} [\sin(\beta) \cos(\alpha), \sin(\beta) \sin(\alpha), -\cos(\beta)]. \quad (4)$$

The Cartesian position and the elementary angles that make up the orientation of the LED are represented in Fig. 2.



Non-Imaging Photo-detector Model

Typical indoor VLC systems use light detectors called PDs on the receiving side. A PD is composed of a non-imaging concentrator (lens) and a physical active area A_p . PDs collect the incident power produced by the light intensity of the LED.

For our agronomic greenhouse scenario, we easily assume that the PDs are installed in the soil above sensors that control the functions to be applied in the crops. Thus, PD are assumed as fixed and vertically oriented upwards, where its position is represented by (x_j, y_j, z_j) in the Cartesian coordinate system with $j = 1, 2, \dots, J$ and J is the total number of PDs.

The effective collection area of the PD acquires the form of [15, 16]

$$A_{eff}(\theta) = \begin{cases} A_p \cos(\theta) & \text{if } -\Theta/2 \leq \theta \leq \Theta/2 \\ 0 & \text{otherwise} \end{cases}, \quad (5)$$

where A_p is the physical active area of the PD, θ is the incidence angle with respect to the normal vector \mathbf{n}_j of the PD position and Θ is the PD field of view (FoV).

The optical concentrator gain can be written as $g(\theta) = \eta^2/\sin^2(\Theta)$, being η the internal refractive index of the concentrator.

0.1 Channel modeling for VLC in Agronomic Environments

In Sections and , the mathematical models for LEDs and PDs were presented, based on the characteristics of the VLC system for the agronomic greenhouse. These models are used as the basis for deriving the reference VLC channel model for our study.

In general, VLC channel models feature two main optical components: the LoS component and the non Line of sight (non-LoS) component. These components vary according to factors such as location of the PD in the greenhouse, distance between the LED and the PD, among others. In our manuscript, the LoS component directly results from the LED lighting falling on the PD. Therefore, the LoS link depends on LEDs and PDs parameters as seen above. The direct current (DC) gain of the LoS optical wireless channel is formulated by merging (1) and (5) as follows [15, 16]:

$$H_{LoS}(0) = \frac{(m+1)A_p}{2\pi d_{ij}^2} \cos^m(\phi) \cos(\theta) G(\theta) \text{rect}\left(\frac{\theta}{\Theta}\right), \quad (6)$$

where $\text{rect}\left(\frac{\theta}{\Theta}\right) = 1$ for $0 \leq \theta \leq \Theta$ and 0 otherwise and $G(\theta) = T_s(\theta) g(\theta)$ represents the combined gain of the optical filter and optical concentrator, respectively.

As explained in Section , we consider a variable and random LED orientation. Therefore, we can integrate expression (4) into the derived LoS channel component, obtaining the following expression:

$$H_{LoS}(0) = \frac{(m+1)A_p}{2\pi d_{ij}^{m+2}} \{[x_j - x_i, y_j - y_i, -\Delta h_{ij}] \cdot [\sin(\beta) \cos(\alpha), \sin(\beta) \sin(\alpha), -\cos(\beta)]\}^m \cos(\theta) G(\theta) \text{rect}\left(\frac{\theta}{\Theta}\right), \quad (7)$$

On the other hand, although there are fewer or no obstacles in a greenhouse, it is possible to create a diffuse optical component produced by reflecting light on the walls or ceiling. The sum of all the generated reflections arriving at the PD generates a non-LoS component of the VLC channel, described as H_{NLoS} . A common diffuse reflection pattern is Lambertian reflectance, where light is reflected with equal magnitude in all directions.

We consider only the first bounce of our model's reflections for practical purposes because it most affects the channel impulse response in magnitude and temporal dispersion. Therefore, the DC channel gain of the non-LoS component can be calculated by adding all the components that arrive at the PD after being reflected off a surface, as follows:

$$H_{NLoS}(0) = \frac{(m+1)A_p}{2\pi} \sum_{w=1}^W \frac{\Delta A_w \rho_w}{d_{iw}^2 d_{wj}^2} \cos^m(\phi_{iw}) \cos(\theta_{iw}) \cos(\phi_{wj}) \cos(\theta_{wj}) G(\theta_{wj}) \text{rect}\left(\frac{\theta_{wj}}{\Theta}\right), \quad (8)$$

where ΔA_w denotes the w^{th} area of the considered reflective element w , whose reflection coefficient and position are respectively represented by ρ_w and (x_w, y_w, z_w) .

W is the total number of reflective elements considered in the greenhouse. The incidence angle concerning the normal vector \mathbf{n}_w to the reflective element w and the radiance angle of the light component reaching the reflective element w are symbolized with θ_{iw} and ϕ_{iw} , respectively. The angles of incidence and radiance denoted by θ_{wj} and ϕ_{wj} respectively are measured concerning the light component reflected in the reflective element w and reaches the PD. Finally, the Euclidean distances between the LED and the reflective element w , and between the reflective element w and the PD are given by d_{iw} and d_{wj} , respectively.

As we have mentioned, to present a complete VLC channel model applicable to agronomic greenhouse environments, we must consider all the factors that affect these scenarios. These factors will be conceptualized in Section 0.1 that follows.

Atmospheric factors integrated into the VLC channel model for agronomic greenhouses.

The mechanisms and factors of losses in optical links due to environmental factors in an agronomic greenhouse are virtually identical to those of an RF channel (microwave and millimeter). However, in optical links, the fading is greater than in RF signals. The optical signal propagating through a free space channel is susceptible to atmospheric conditions such as fog, rain, sun, among others.

For optical radiation traveling through the VLC channel, the interaction between photons (light beam) and the molecular constituent of the atmosphere makes some of the photons extinguished while other photons are scattered. These events can be modeled by the Beer-Lambert's law (BLL). The BLL law describes a mathematical model to represent the absorption and scattering of light through the atmosphere. These factors, combined, reduce the PD's received power and must be included in the VLC channel model.

For our modeling purposes, we introduce the exponential BLL as a function of the distance between the LED and the PD, as follows:

$$\tau(d_{ij}) = e^{-\gamma(\lambda)d_{ij}}, \quad (9)$$

where $\gamma(\lambda)$ is the extinction coefficient per unit of length with wavelength .

As we explained, the optical signal's attenuation in the greenhouse environment is due to scattering and absorption introduced by gases and aerosols. The aerosol comprises small particles of various shapes ranging from spherical to irregular forms suspended in the atmosphere. In general, $\gamma(\lambda)$ can be expressed as

$$\gamma(\lambda) = \alpha_m(\lambda) + \alpha_a(\lambda) + \beta_m(\lambda) + \beta_a(\lambda), \quad (10)$$

where α_m and α_a are the absorption coefficient for the molecular and aerosol, respectively, and β_m and β_a are the scattering coefficients for the molecular and aerosol, respectively.

These coefficients can be varied and adapted according to the atmospheric factors that affect the agronomic greenhouse. The next step is to integrate them into the

VLC channel model, both for the LoS component (expression 11) and for the non-LoS component (expression 12), rewriting them as follows:

$$H_{LoS}(0) = \frac{(m+1)A_p}{2\pi d_{ij}^{m+2}} \{[x_j - x_i, y_j - y_i, -\Delta h_{ij}] \cdot [\sin(\beta) \cos(\alpha), \sin(\beta) \sin(\alpha), -\cos(\beta)]\}^m \cos(\theta) G(\theta) \\ \times \text{rect}\left(\frac{\theta}{\Theta}\right) \tau(d_{ij}), \quad (11)$$

$$H_{NLoS}(0) = \frac{(m+1)A_p}{2\pi} \sum_{w=1}^W \frac{\Delta A_w \rho_w}{d_{iw}^2 d_{wj}^2} \cos^m(\phi_{iw}) \cos(\theta_{iw}) \cos(\phi_{wj}) \cos(\theta_{wj}) G(\theta_{wj}) \text{rect}\left(\frac{\theta_{wj}}{\Theta}\right) \tau(d_{iw}) \tau(d_{wj}). \quad (12)$$

Finally, the total DC gain for the VLC channel applied to agronomic greenhouses is the sum of the LoS and NLoS components, namely,

$$H_{greenhouse}(0) = H_{LoS}(0) + H_{NLoS}(0). \quad (13)$$

Optical Propagation Model in Agronomic Environments

A VLC system applicable to agronomic greenhouses can be modeled as any wireless communication system, considering an input optical signal $X(t)$ and an output optical signal $Y(t)$. Furthermore, due to the lighting characteristics that greenhouses must have, multiple LEDs and PDs are distributed in the scenario. Therefore, the equivalent base-band model that we use to describe a VLC intensity modulation/direct detection (IM/DD) system for agronomic greenhouses is given as follows:

$$Y(t) = r\xi X(t) \otimes h_{greenhouse}(t) + N(t), \quad (14)$$

where r is the PD responsivity, ξ is the LED modulation index, $h_{greenhouse}(t)$ is the VLC channel impulse response of the greenhouse environment, and \otimes is the convolution operator. An important point to consider in our work is noise. Since VLC applications for agronomic greenhouses are susceptible to multiple external noise sources influencing the VLC channel, these must be considered in the full propagation model. We establish $N(t)$ as the additive noise in the PD, including the following types of noise: (1) The background light, which is the biggest source of noise in the greenhouse VLC system. The background light can come from artificial or natural sources. (2) The bright skylight and direct sunlight are the natural light sources that can saturate the PD and make it blind. (3) There are other background noise sources on the receiver side, such as the thermal noise, which is generated in the components of the receiver's electronic circuit, such as resistors and capacitors. To estimate the total noise on the receiver side, the total variance of the noise is roughly given by

$$\sigma_{total}^2 = 2qrP_r B_n + 2qP_a B_n + \frac{8\pi\kappa T_k}{G} \eta A_p I_2 B_n^2 + \frac{16\pi^2\kappa T_k \Gamma}{g_m} C_{pd}^2 A_p^2 I_3 B_n^3. \quad (15)$$

The first term corresponds to photon fluctuation noise or quantum noise, where q is the electric charge constant, and B_n is the bandwidth of the electrical filter that follows the PD. Here, P_r is the power received by the PD due to the light emitted by the LED P_t , which is expressed as

$$P_r = P_t H_{greenhouse}(0). \tag{16}$$

The second term of the expression (15) corresponds to the dark current and excess noise, where P_a is the ambient light power detected by the receiver expressed as

$$P_a = P_{bg} \lambda A_p I_2, \tag{17}$$

where P_{bg} is the background irradiance per unit bandwidth, $\Delta\lambda$ is the filter bandwidth, and I_2 is the noise bandwidth factor. Finally, The third and fourth terms of the expression (15) represent the feedback-resistor noise and field-effect transistor (FET) channel noise, respectively. Here, κ is Boltzmann’s constant, T_k is absolute temperature, G is the open-loop voltage gain, C_{pd} is the fixed capacitance of PD per unit area, Γ is the FET channel noise factor, g_m is the FET trans-conductance, and I_3 is the noise bandwidth factor.

The block diagram of the complete VLC system is shown in Fig. 3.

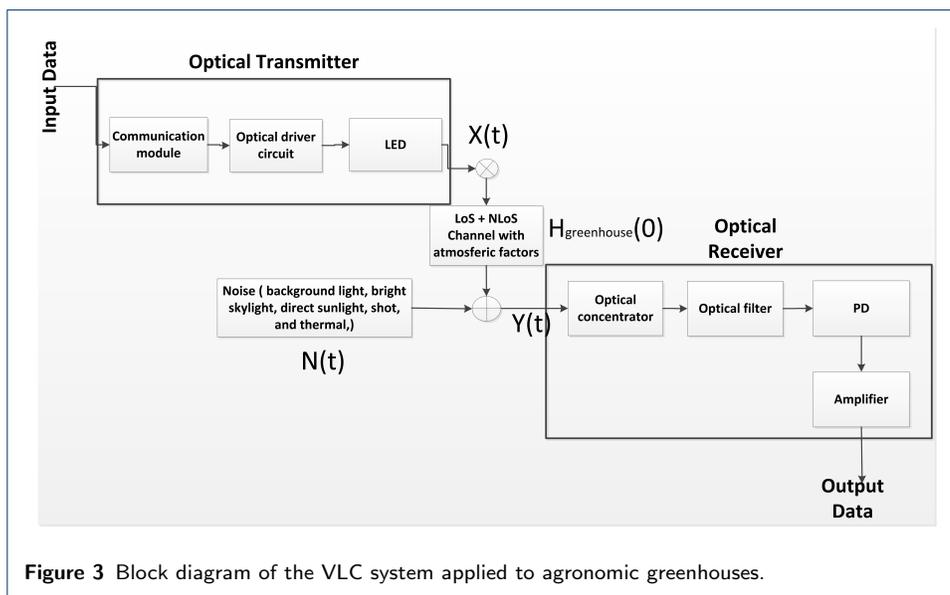


Figure 3 Block diagram of the VLC system applied to agronomic greenhouses.

As we mentioned, this work aims to study, characterize, and derive a mathematical model for the VLC channel in the environment of agronomic greenhouses. The analysis established in this Section allowed us to derive expression (13), complying with the initial premise. In the next section, we will focus on evaluating the obtained models and the verification of the system’s performance in terms of several common metrics in wireless communication systems.

Results and analysis

In this section, we focus on evaluating the VLC system’s performance applied to an agronomic greenhouse environment based on the channel derived in Section .

Table 1 Agronomic greenhouse VLC system simulation parameters.

System model parameters	Values	References
Greenhouse scenario		
Dimensions ($w \times l \times h$)	$(2 \times 5 \times 4)\text{m}$	
Coordinates of the LEDs (x, y, z)	$T_1 = (-0.5, -1.25, 3.7), T_2 = (0.5, 1.25, 3.7),$ $T_3 = (0.5, -1.25, 3.7), T_4 = (-0.5, 1.25, 3.7)$	
Other parameters		
Channel parameters		
Absolute temperature	295 K	[15, 16, 17]
Background dark current	10 nA	[15, 16, 17]
Boltzmann constant	$1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$	[15, 16, 17]
Capacitance	$112 \times 10^{-8} \text{ F/m}^2 (\text{s}^4 \text{ A}^2 \text{ m}^{-4} \text{ kg}^{-1})$	[15, 16, 17]
Electronic charge	$1.6 \times 10^{-19} \text{ C}$	[15, 16, 17]
FET channel noise factor	1.5	[15, 16, 17]
FET transconductance	$0.03 \text{ S} (\text{kg}^{-1} \text{ m}^{-2} \text{ s}^3 \text{ A}^2)$	[15, 16, 17]
Noise bandwidth	100 MHz	[15, 16, 17]
Noise bandwidth factor I_2	0.562	[15, 16, 17]
Noise bandwidth factor I_3	0.0868	[15, 16, 17]
VLC transceiver parameters		
Average output optical power	10 W	[15, 16, 17]
Band-pass filter of transmission	1	[15, 16, 17]
Gain of the optical filter	1	[15, 16, 17]
LED rotation angle	45°	[17]
LED tilt angle	45°	[17]
Modulation	OOK	[15, 16, 17]
Modulation bandwidth	50 MHz	[15, 16, 17]
Modulation index	0.3	[15, 16, 17]
Number of PDs	1	
Open-loop voltage gain	10	[15, 16, 17]
PD physical area	1 cm^2	[15, 16, 17]
Optical filter bandwidth	340 nm to 694.3 nm	[18]
Optical filter center wavelength	$340 \pm 2 \text{ nm}$	[18]
Optical filter full width half max	$10 \pm 2 \text{ nm}$	[18]
Refractive index	1.5	[15, 16, 17]
Reflection coefficient	0.8	[15, 16, 17]
Responsivity	0.53 A/W	[15, 16, 17]
Rx FoV	60°	[15, 16, 17]
Tx semi-angle at half power	60°	[15, 16, 17]

First, we analyze through simulations the illuminance conditions in the greenhouse scenario. Second, we analyze and simulate basic performance metrics for wireless communications systems in a greenhouse environment, such as channel impulse response (CIR), received power, BER, and SNR. For the simulation, we choose a greenhouse of dimensions $2\text{m} \times 5\text{m} \times 4\text{m}$. In our analysis, without losing the generality, we consider four LEDs, with fixed rotation and tilt angles for ease and a single PD. It should be emphasized that the LED positions are referential only to verify the proposed VLC channel model's feasibility. We have also considered the inclusion in the simulation of molecular constituents and aerosols produced by snow or rain in the environment to demonstrate the effect on the performance metrics to be evaluated. All the evaluations are numerical and created using simulations in Matlab software, applying the ray-tracing methodology for the optical links and Monte Carlo simulations to give it greater support and statistical rigor. The most relevant parameters used for the simulations development, with their respective values and references, can be seen in the Table 1.

Analysis of the illuminance in the greenhouse agronomic scenario

As we mentioned at the beginning of our work, in addition to providing a robust and effective communication system in agronomic greenhouses, VLC is also proposed to offer adequate lighting in these environments. Since LEDs are an artificial

source of direct light, we initially present a mathematical model to calculate LEDs' illuminance. Therefore, to calculate this parameter, we define the luminous flux Q as the optical power that the human eye can receive in the following expression [15, 16]:

$$Q = 683N_{T_x} \int_{380}^{720} S(\lambda)V(\lambda)d\lambda, \quad (18)$$

where $V(\lambda)$ is the sensitivity function of the human eye and $S(\lambda)$ is the distribution of the radiation spectrum. The relationship between Q and the illuminance $I(\phi)$ on the PD is given by [15, 16]

$$I(\phi) = \frac{\delta Q}{\delta A_p} = \sum_{j=1}^{N_{T_x}} jI_0 \cos^m(\phi), \quad (19)$$

where I_0 is the center of light intensity of T_x . This expression allows us to calculate the light intensity in the PD reception plane. However, we need baseline data on greenhouse illuminance to be compared with our analysis. Consequently, the results are contrasted with general rules established for illuminance in these scenarios. Among the minimum light intensity requirements for greenhouses are that they must comply with a minimum illuminance of [70-100] *lux* [19]. Considering these values, we obtain the illuminance in the agronomic greenhouse scenario, as shown in Fig. 4.

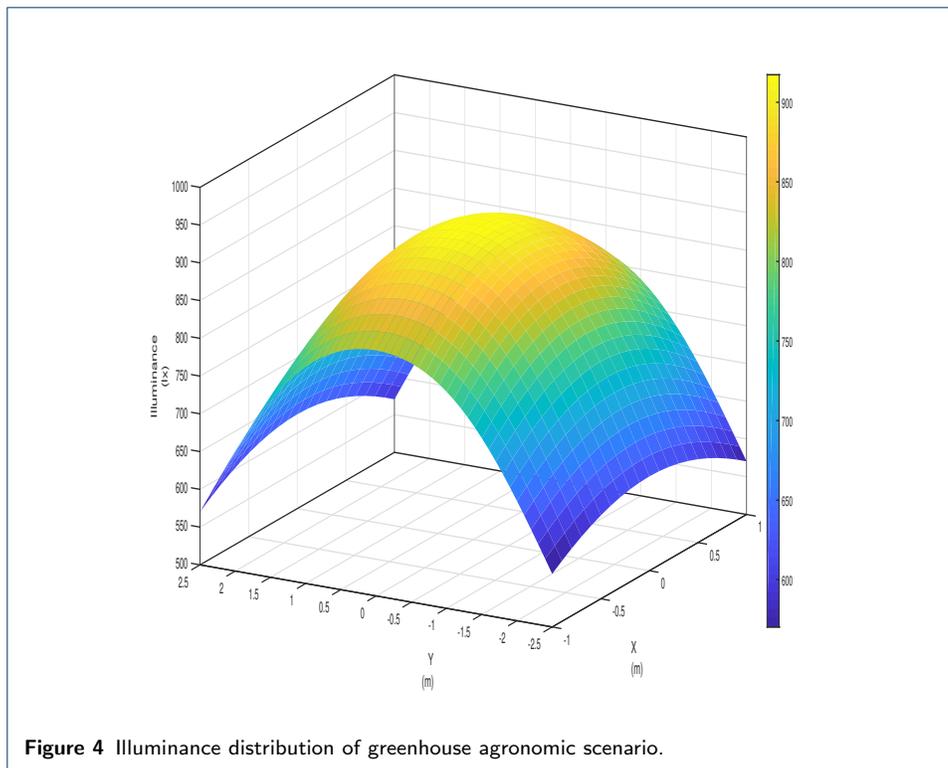
Based on Fig. 4, we can see that the illuminance values range from [600-900] *lux*. It is also observed that the highest illuminance values are found in the center of the greenhouse. This is due to the location of the LEDs on the scenario and their tilt and rotation. Precisely, the center of the greenhouse, where all the crops are located, must be the area with the greatest illuminance, first to keep the crops in an optimal condition and second to obtain the highest optical power that can reach the PD. Comparing our results with the minimum illuminance values in the standard, the illuminance standard for agronomic greenhouse environments is met.

Analysis of the greenhouse agronomic VLC channel impulse response

To evaluate the derived VLC channel model for agronomic greenhouse environments and verify our approach's features and precision, we presented the CIR at all points of the greenhouse. The CIR, which we represent as $h_{greenhouse}(t)$ is defined as the received optical intensity when the transmitted optical intensity is a Dirac delta function of unit area. Therefore, $h_{greenhouse}(t)$ can be obtained from the expression (13), adding the delta components $\delta(\cdot)$, which depends on the distance it travels the light beam, as follows:

$$h_{greenhouse}(t) = h_{LoS}(t)\delta\left(t - \frac{d_{ij}}{c}\right) + h_{NLoS}(t) \sum_{w=1}^W \delta\left(t - \frac{d_{iw} + d_{wj}}{c}\right). \quad (20)$$

Given a certain number of optical paths (rays), including the LoS and non-LoS components, we calculate the detected power and the path lengths from each of the

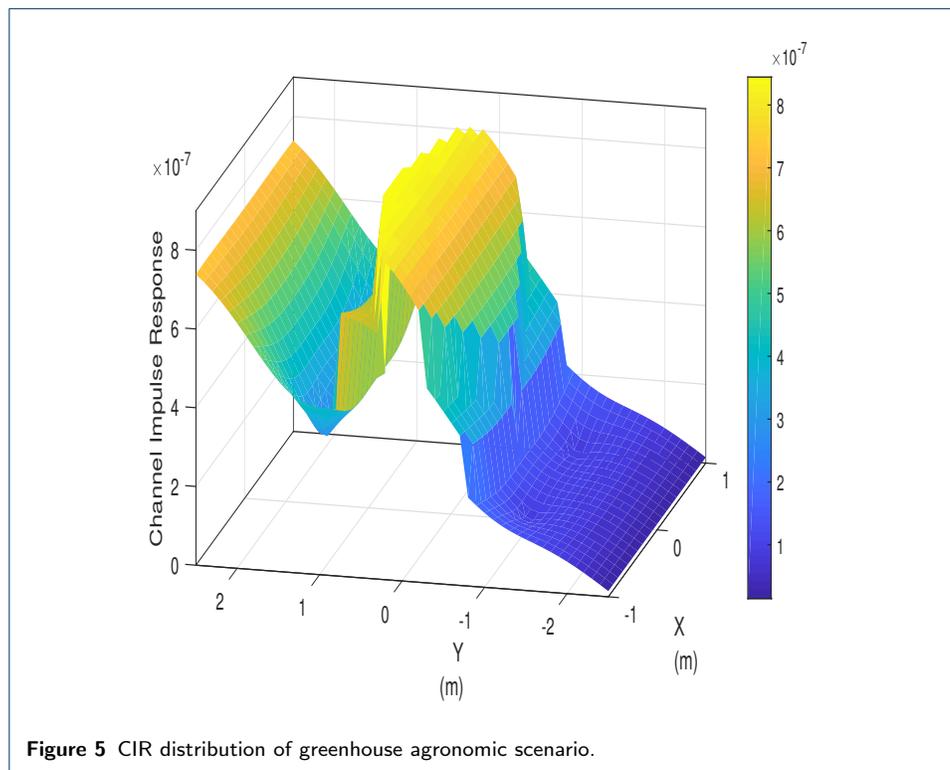


LEDs to the PD for each beam. This data is then processed to obtain the total CIR. To present realistic results and to be able to compare them with the CIR of other scenarios, it seems convenient to assume that the transmitted power is 10 W .

Fig. 5 shows the distribution of CIR throughout the simulated agronomic greenhouse environment. The number of partitions is set to 18 for X and Y, and 15 for Z. The spacial resolution is set to 0.33 m for X and Z, and 0.16 m for Y. The temporal resolution is set to 0.25 ns. In the graphic several interesting findings can be distinguished. Firstly, we can notice that the CIR in the complete scenario varies between a range of values of $[0.8 \times 10^{-7} - 8.1 \times 10^{-7}]$. Secondly, based on the theoretical aspect, as the distance between the LEDs and the PD increases, the CIR magnitude should decrease. However, this does not occur in the agronomic greenhouse scenario. If we observe the distribution of Fig. 5, we note that the CIR is not uniform, and its decrease is not inversely proportional to the distance between LEDs and PD. This effect is due to the position of the LEDs and their angles of inclination and rotation. This causes the largest magnitude values of the CIR to be in the center of the stage. We also observed a drop in CIR magnitudes in certain parts of the greenhouse. This is due to the higher concentration of constituent molecules and aerosols, which affects the optical paths since they absorb or reflect light, which produces a vertiginous decrease in CIR.

If we compare the CIR values obtained in our work with CIR values obtained in other environments, such as in [17], we may notice some differences. The CIR values obtained in the greenhouse are lower than those obtained for underground mines and obviously much lower than ideal indoor VLC environments. This comparison

gives us an idea that the greenhouse's external environment is difficult to control, and its atmospheric variables produce a harmful effect on the optical links.



Analysis of the power received

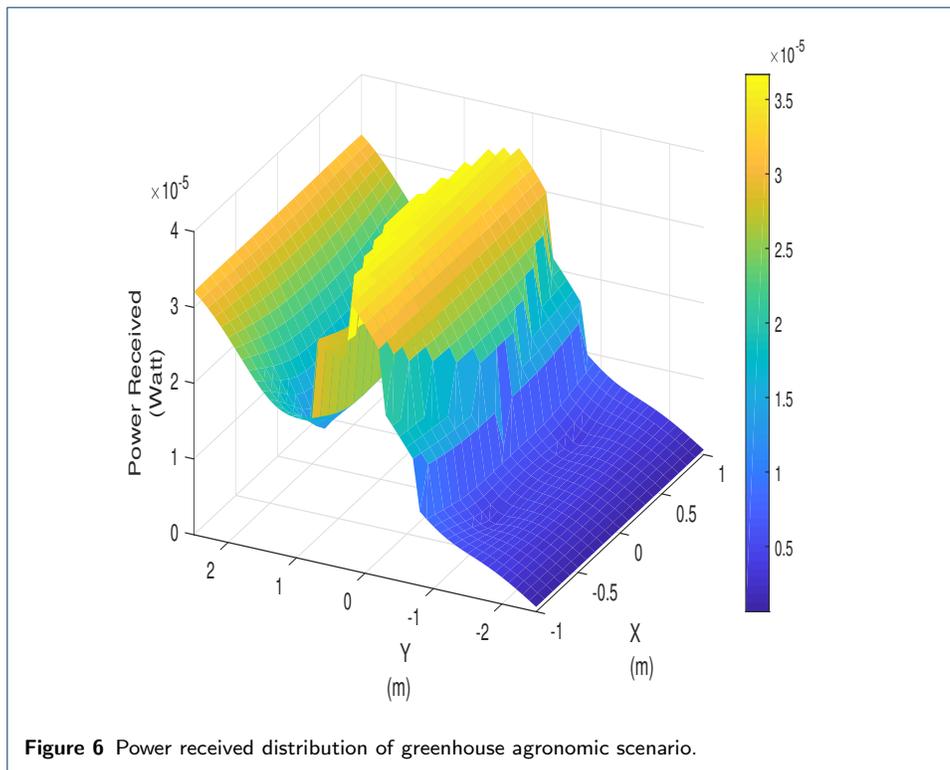
A fundamental metric in communication systems is the power received at the PD. This parameter allows us to verify and analyze the behavior of the derived optical channel. For our proposed agronomic greenhouse scenario, since we consider four LEDs along with a single PD, to obtain the power received by the PD due to the light emitted by the LEDs, we use the expression derived in (17).

Fig. 6 shows the graphical distribution of the power received in the evaluated agronomic greenhouse scenario. The power received in the complete scenario varies between a range of values of $[0.82 \times 10^{-5} - 3.8 \times 10^{-5}] W$. Let's compare these power values with underground mining VLC scenarios or ideal indoor VLC scenarios [17]. We can see that the powers received in the proposed greenhouse environment are lower. Furthermore, the obtained power distribution is not uniform and is not always directly proportional to the distance between the LEDs and the PD. Therefore, we observe that the effect of the rotation and tilt of the LEDs and the atmospheric factors of the environment that produce aerosol particles and constituent molecules influence the received optical power levels.

Finally, we can see that the received power distribution that we obtain follows the same pattern as the CIR, so we could deduce that our results are consistent.

Analysis of the of the SNR

In the proposed VLC system for agronomic greenhouses, it is necessary to use intensity modulations with direct detection (IM/DD). In these schemes, the intensity of



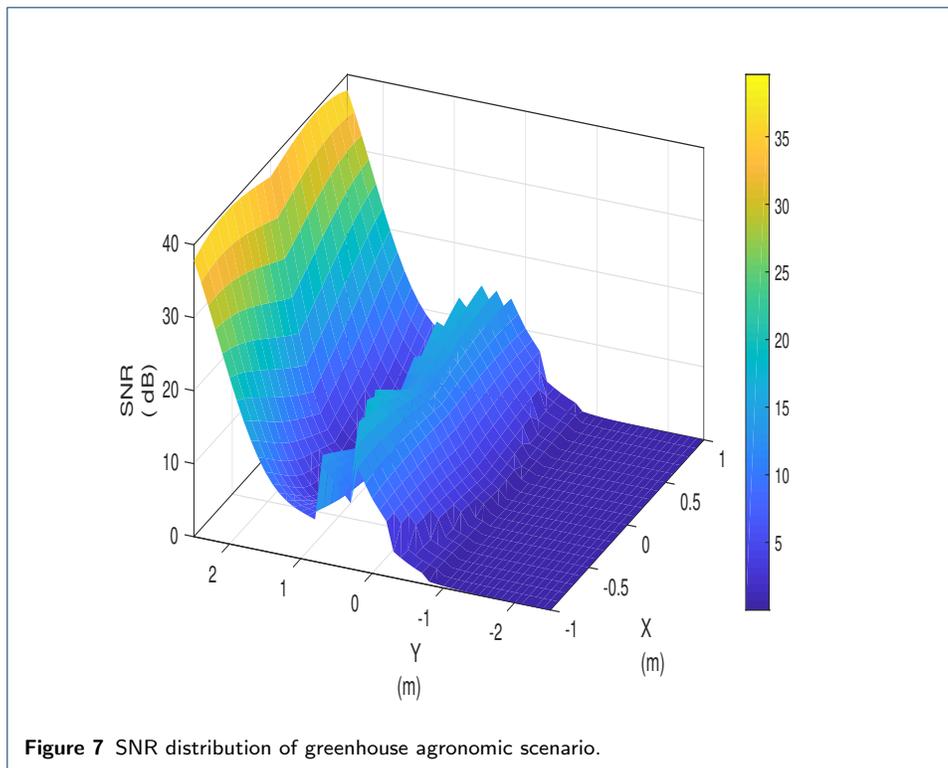
the LED is modulated by the input signal. Then, demodulation is achieved through direct detection, which produces a current proportional to the light received. Several modulations are considered in the literature depending on the applications. However, for our work, we use OOK modulation.

To achieve reliable communication is necessary to calculate the SNR with the aim of, in the next subsection, ensuring a good BER. The SNR in our work is calculated based on the following expression [15, 16]:

$$SNR = \frac{rP_r}{\sigma_{total}^2}. \tag{21}$$

Fig. 7 shows the SNR over the entire greenhouse coverage area under rainy weather, which produces aerosols and constituent molecules within the greenhouse. The SNR in the complete scenario varies between a range of values of [3.25-39.32] dB. As we can see in the graph, the SNR distribution in the greenhouse follows the same irregular trend of the CIR and the received power. However, a significant effect is evident; the highest SNR values are not found in the greenhouse center. This effect is mainly due to noise factors (thermal, shot, among others) found in greater magnitude in the greenhouse center. We can also note that the distributions of aerosols and constituent molecules are random in the greenhouse. This environment leads to shallow SNR values in certain areas when the weather effect is greater since more significant attenuation, absorption, and dispersion of the signal concerning noise.

Finally, we can observe that we have positive SNR values in the entire greenhouse scenario, so we could affirm that there is coverage of the optical signal throughout the analyzed environment.



Analysis of the bit error rate

As we mentioned in the previous section, the modulation used in our work is OOK, complying with the paradigm that VLC technology must use IM in transmission and DD in reception. In OOK modulation, given that the optical receiver analyzes employing a threshold which of the possible signals it handles is closer to the received signal, it is logical to think that there will be a lower probability of noise error. Consequently, it would be more efficient in BER than other more complex modulations applied to indoor VLC environments.

The BER was estimated via Monte Carlo simulations with the direct error counting method, i.e. 21 runs of 10^5 bits were performed to have a confidence interval of 95% with an uncertainty factor of two on the error rate scale [20, 15]. The simulated BER curves are shown in Fig. 8 for a typical indoor VLC scenario based on an ideal indoor channel model and for the proposed VLC scenario in conjunction with the VLC channel for agronomic greenhouse environments. In this last scenario, we have varied the PD's FoV values, considering typical commercial values to analyze their effect.

From the Fig. 8, we can see that the ideal indoor scenario presents the best performance in terms of BER. This result could be expected since this scenario does not consider the effects that we include in the channel for agronomic greenhouses, such as environmental characteristics and positioning and orientation of the LEDs. For example, for a BER of 10^{-2} , the E_b/N_0 obtained is approximately 17 dB. On the other hand, by increasing the FoV value in the PD, several findings are evidenced. First, by increasing the opening range of the FoV, the performance of the BER worsens. This is because despite being able to have a greater reception

area for the optical signal, we also have greater noise reception. Therefore, as it is a complicated scenario in handling external agents, it produces more errors in the received signal. Secondly, we observe that for FoV values of 60° and 70°, the curves are similar, which for a BER value of 10^{-2} , E_b/N_0 values of approximately 26 and 27 dB are obtained, respectively. Finally, for FoV values of 120° and 140°, the curves are also similar. However, their performance gets much worse. Therefore, the use of PDs with these FoVs in agronomic greenhouse environments would not be recommended.

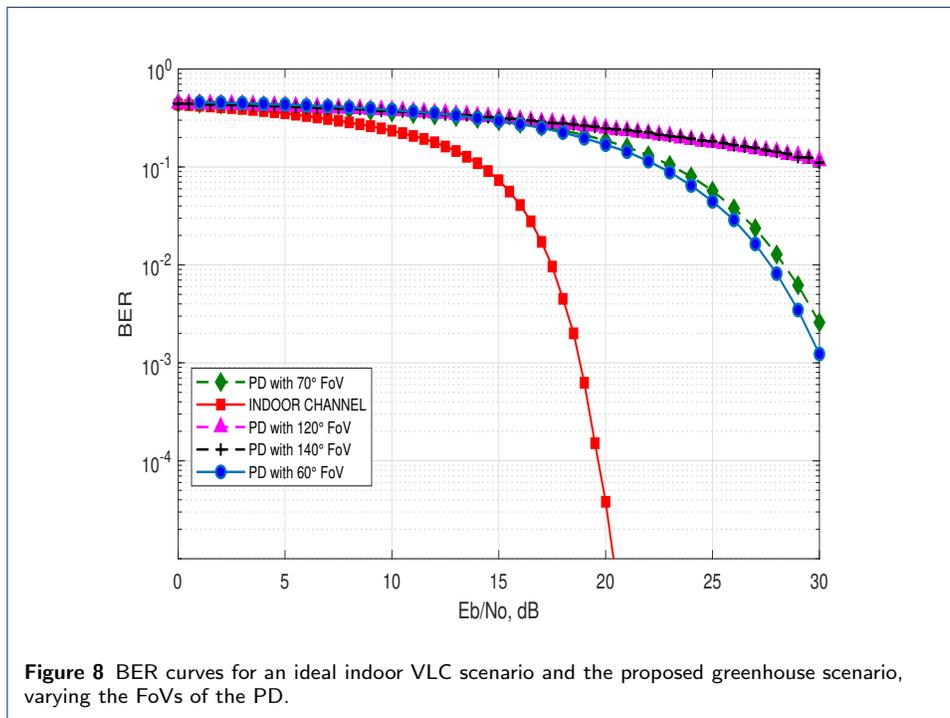


Figure 8 BER curves for an ideal indoor VLC scenario and the proposed greenhouse scenario, varying the FoVs of the PD.

Conclusion

In this article, we proposed a novel VLC channel model applicable to agronomic greenhouse environments. The derived model is different from traditional indoor VLC channel models due to the unique features found in greenhouses. These characteristics are the following: randomly rotated and tilt LEDs, the presence of aerosol particles and constituent molecules produced by atmospheric effects that could cause the dispersion, absorption, and attenuation of the optical signal, and the presence of various sources of noise that could create errors in the reception of the optical signal. To reasonably present the proposed VLC channel model, we derive the mathematical expressions of the DC channel gain, the CIR, and the power received. With these expressions, we verify the validity of the proposed model using numerical simulations inside a greenhouse. The simulated data were obtained using a Monte Carlo and ray tracing methodology. The results obtained demonstrate the VLC channel model’s characteristics for agronomic greenhouses proposed in terms of typical communications performance metrics. In the greenhouse evaluated, it is observed that the illuminance provided by the VLC system on scenario complies

with international standards for these environments. Regarding the CIR and power received obtained, we observe that their distributions are irregular, and their values are lower than other indoor scenarios. This is due to the orientation effects of the LEDs and environmental factors that generate attenuation, dispersion, and variability in the LoS and non-LoS components' magnitudes. Finally, the SNR and BER metrics were presented in the proposed greenhouse scenario, using the OOK modulation. An in-depth discussion of these parameters showed that the effects of different types of noise and the harshness of external atmospheric factors are evident in the magnitude of the SNR and the generation of errors. Besides, by varying the FoV of the PD, we note that the greater the opening has, the system's performance in terms of BER worsens.

To experimentally validate our proposal is necessary to develop real measurements in agronomic greenhouses. Furthermore, it is essential to present reception solutions that allow us to mitigate the received signal's errors and optimize the received power. These approaches will be addressed in future work.

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Abbreviations

BER Bit error rate; BLL Beer-Lambert's law; CIR Channel impulse response; DC Direct current; DD Direct detection; FET Field-effect transistor; FoV Field-of-view; GSM Global system for mobile; ICI Inter-cell interference; IM Intensity modulation; IoT Internet of things; IR Infrared; LED Light-emitting diode; LoS Line of sight; Non-LoS Non Line of sight; OOK On-off keying; PD Photo-diode; PWM Pulse-width modulation; RF Radio frequency; SMS Short message service; SNR Signal-to-noise-ratio; VLC Visible light communication; WSN Wireless sensor network.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Conceptualization, H.S. and P.P.; methodology, H.S. and P.P.; software, H.S. and P.P.; validation, F.A., M.R., S.L., and H.F.; formal analysis, H.S. and P.P.; investigation, H.S. and P.P.; resources, F.A., H.S., S.L., and H.F.; data curation, F.A., H.S., S.L., and H.F.; writing—original draft preparation, H.S. and P.P.; writing—review and editing, F.A., M.R., S.L., and H.F.; supervision, F.A., M.R., S.L., and H.F.; project administration, H.S. and P.P.; funding acquisition, F.A., H.S., S.L., and H.F..

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Figures

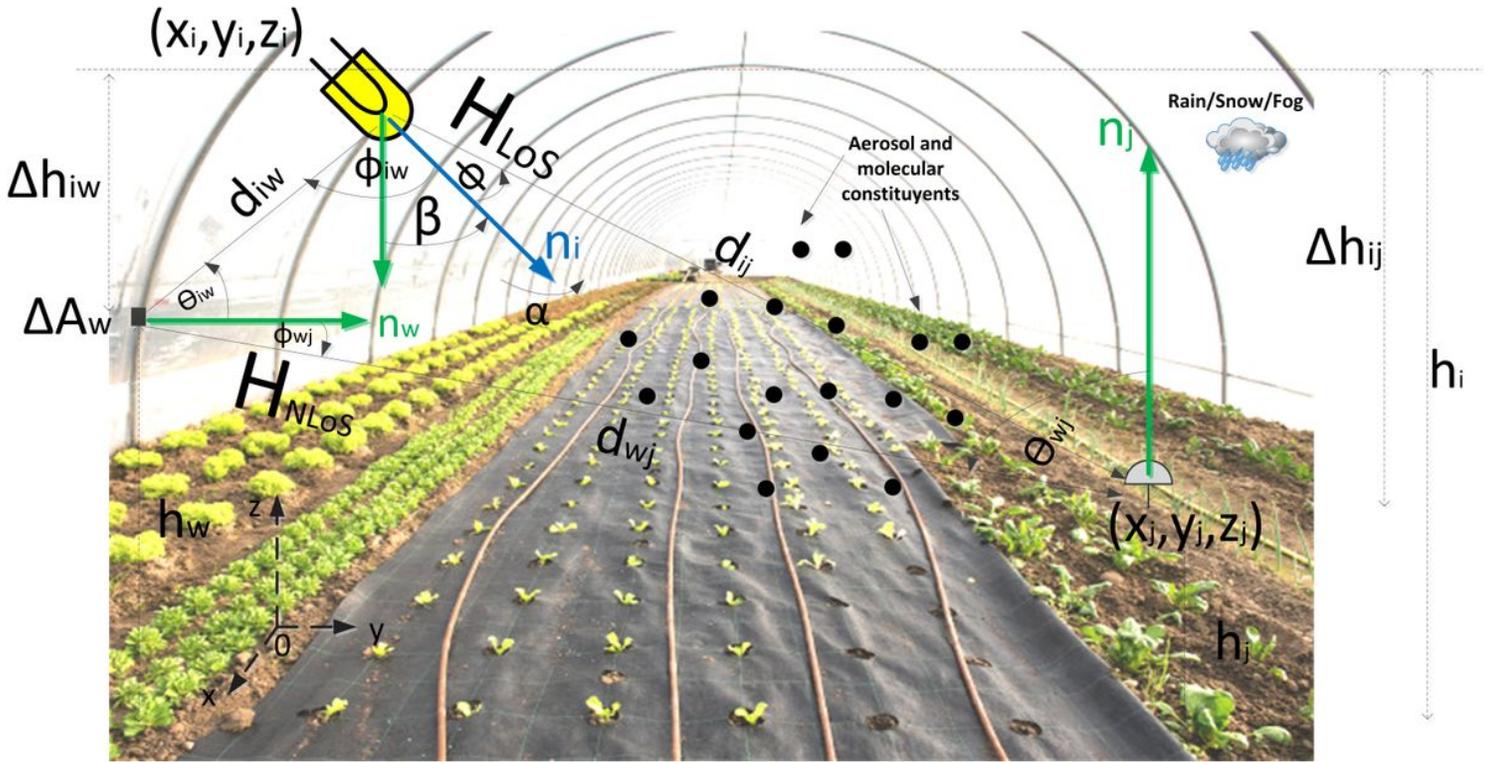


Figure 1

The geometry of the LoS and NLoS propagation model in the agronomic greenhouse.

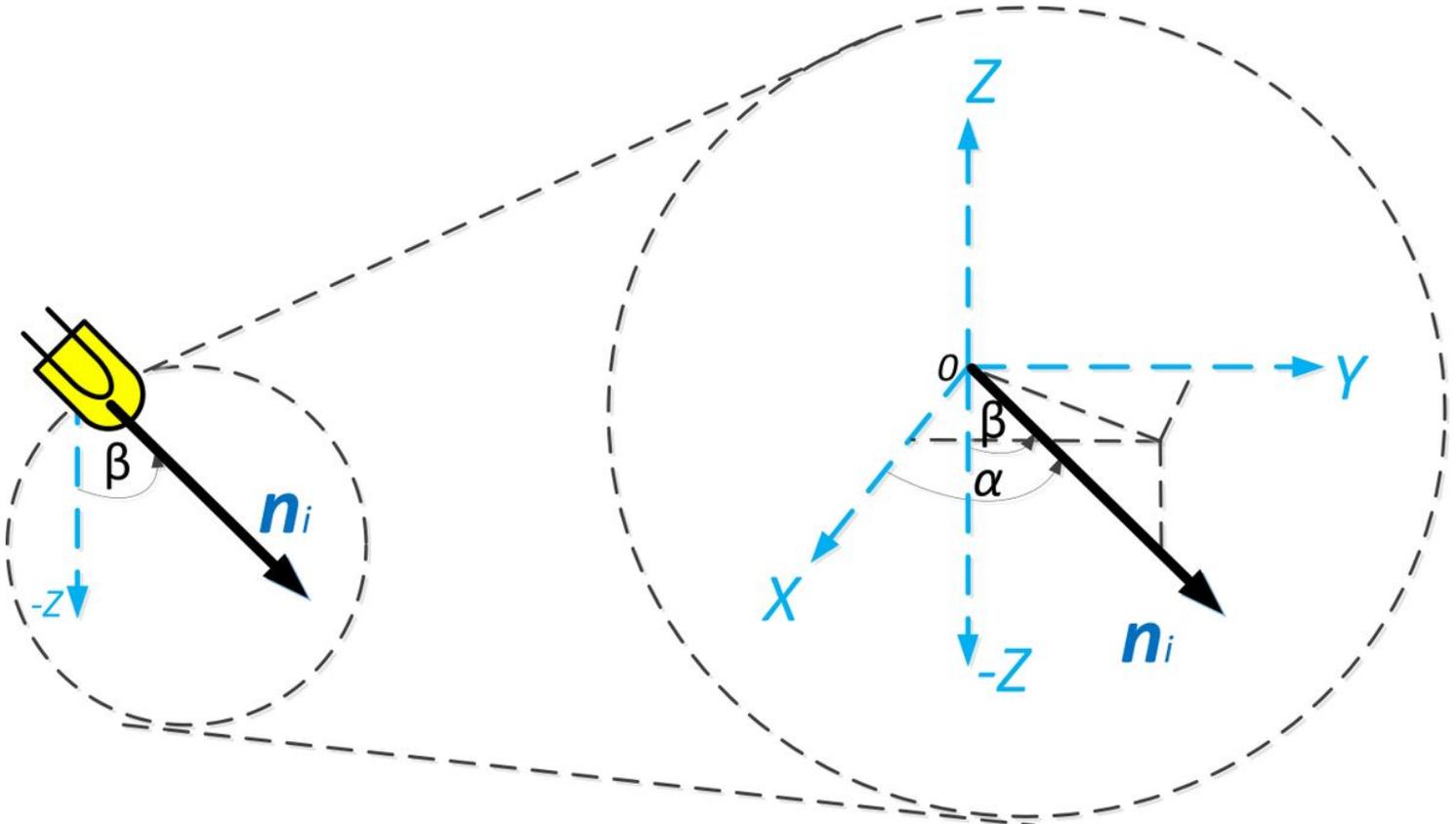


Figure 2

LED position and orientation features.

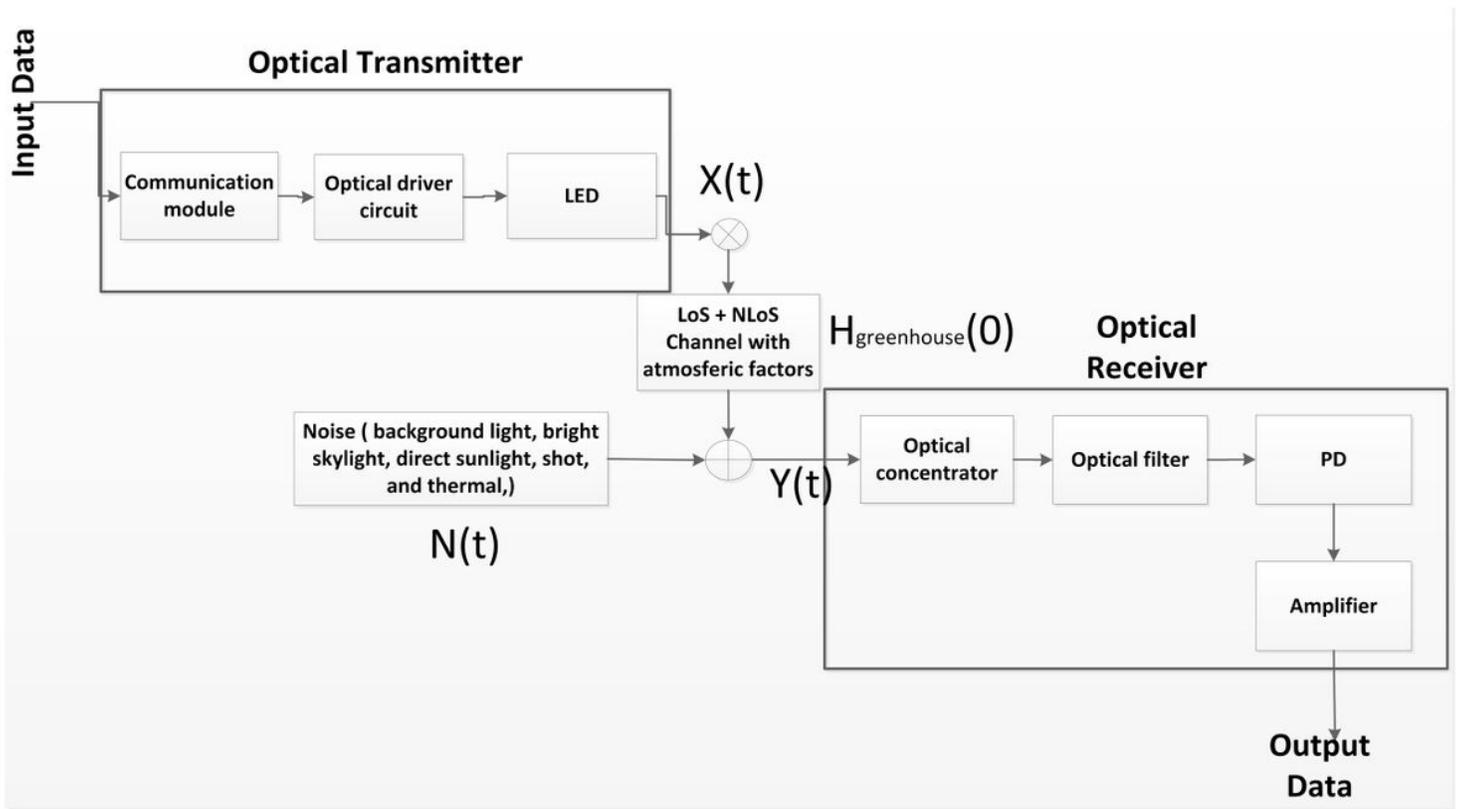


Figure 3

Block diagram of the VLC system applied to agronomic greenhouses.

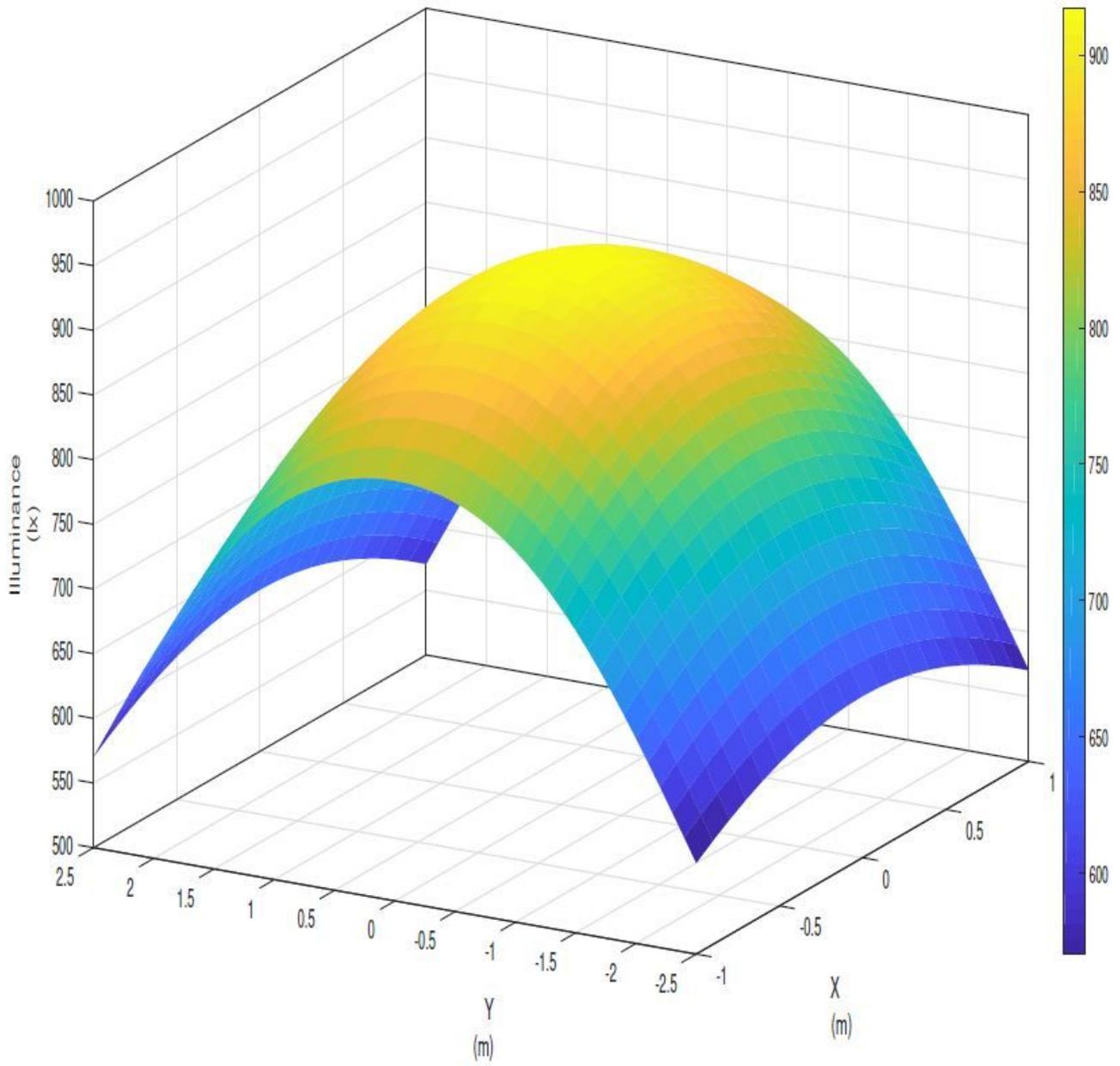


Figure 4

Illuminance distribution of greenhouse agronomic scenario.

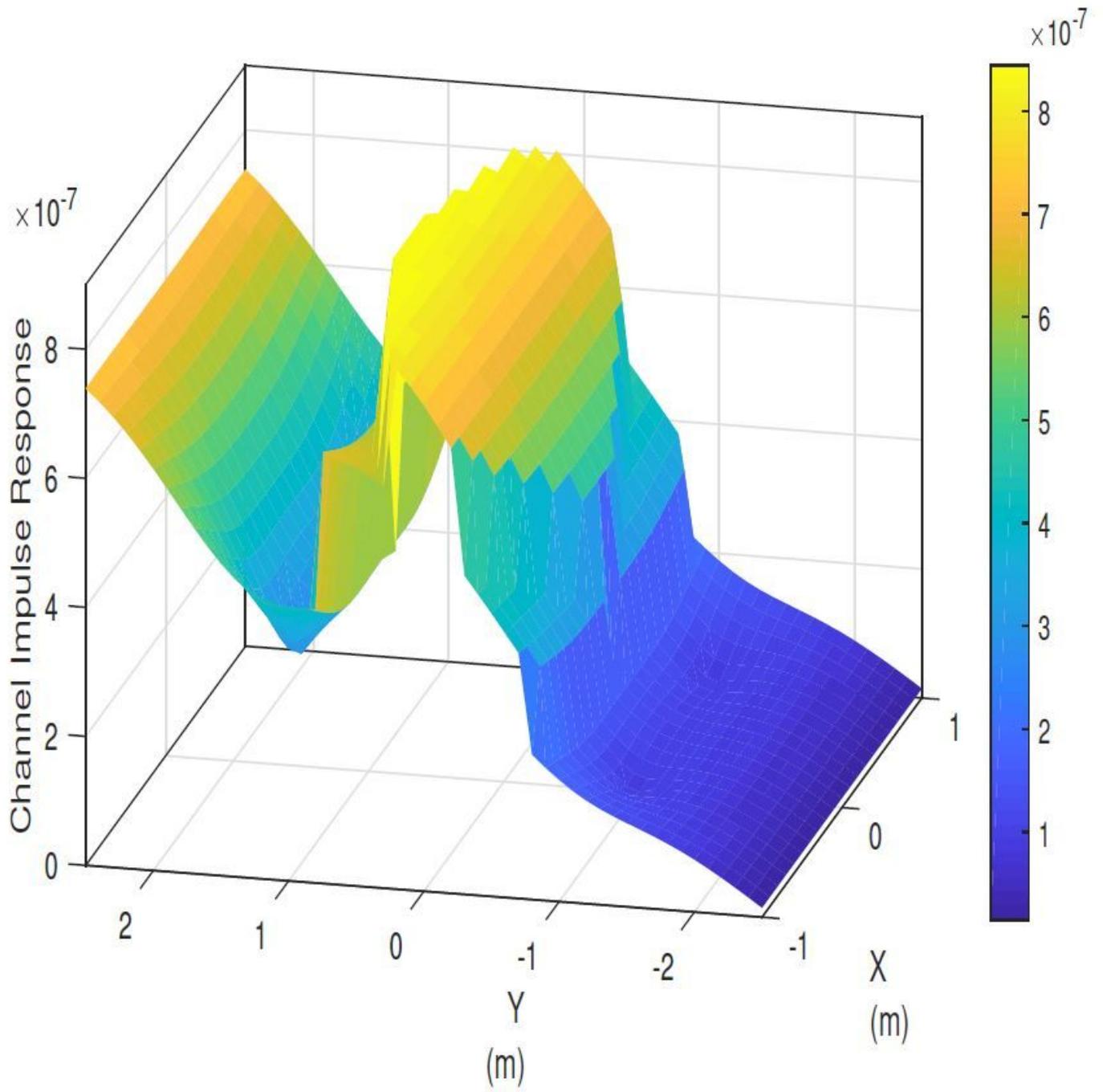


Figure 5

CIR distribution of greenhouse agronomic scenario.

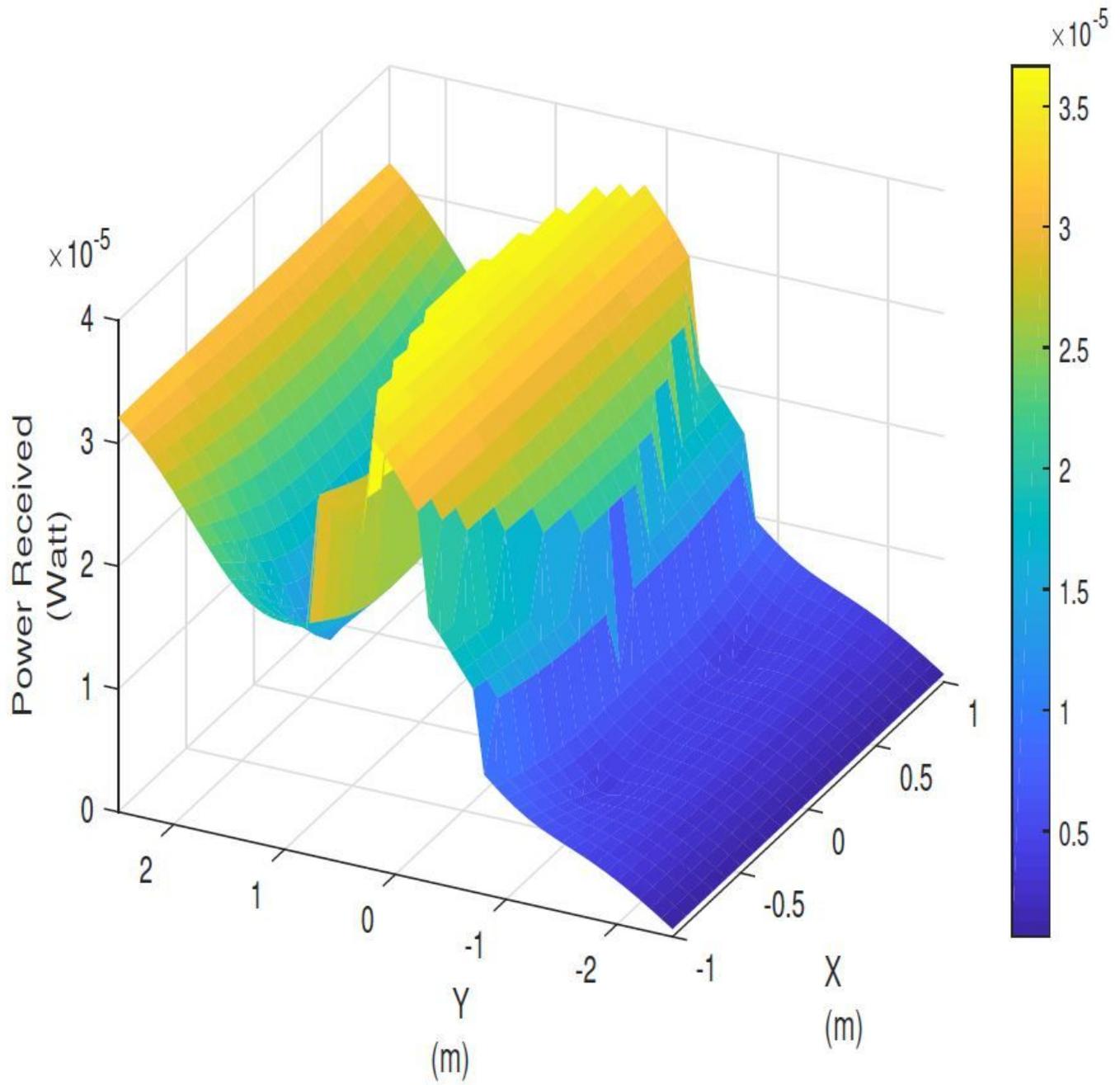


Figure 6

Power received distribution of greenhouse agronomic scenario.

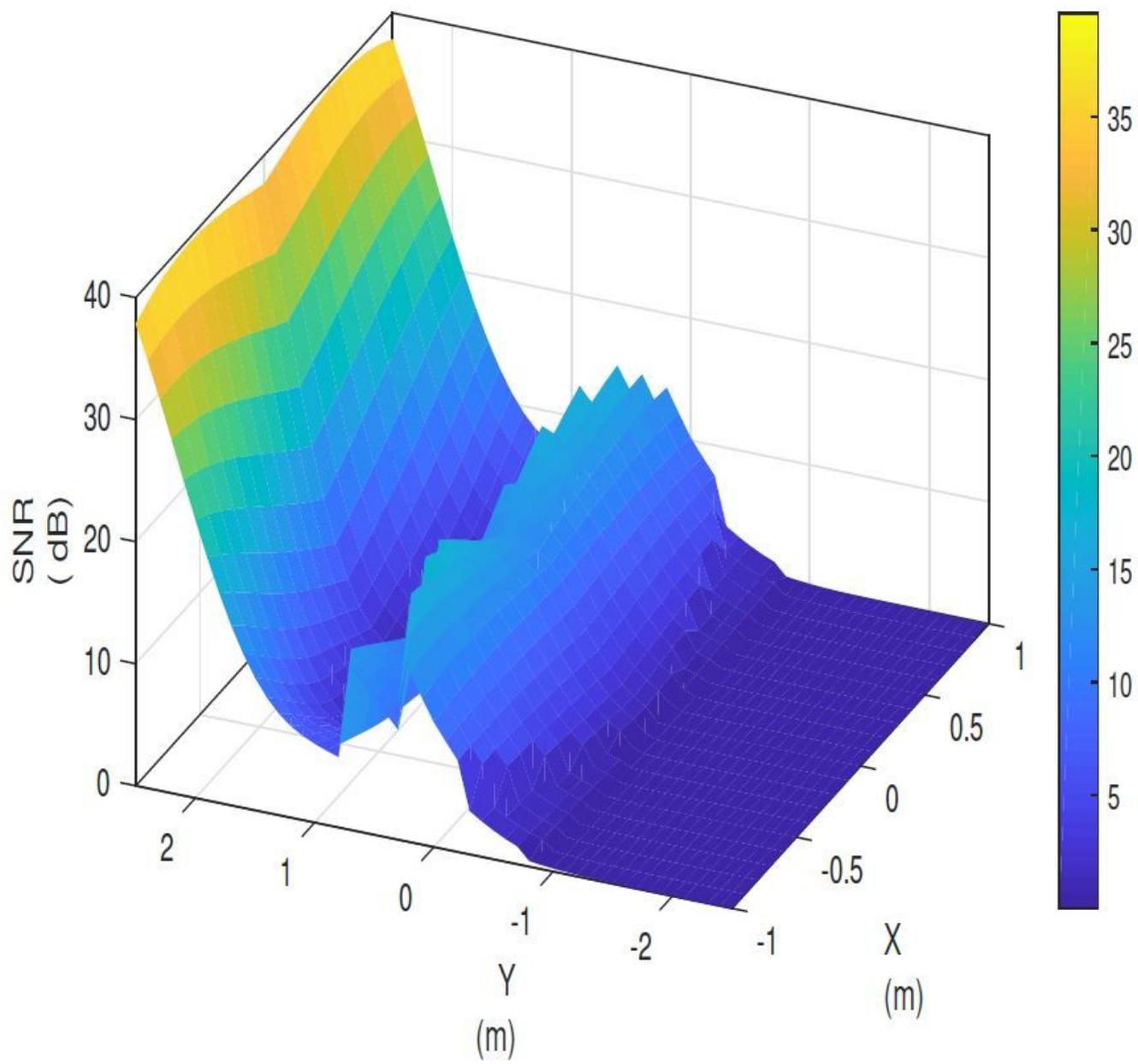


Figure 7

SNR distribution of greenhouse agronomic scenario.

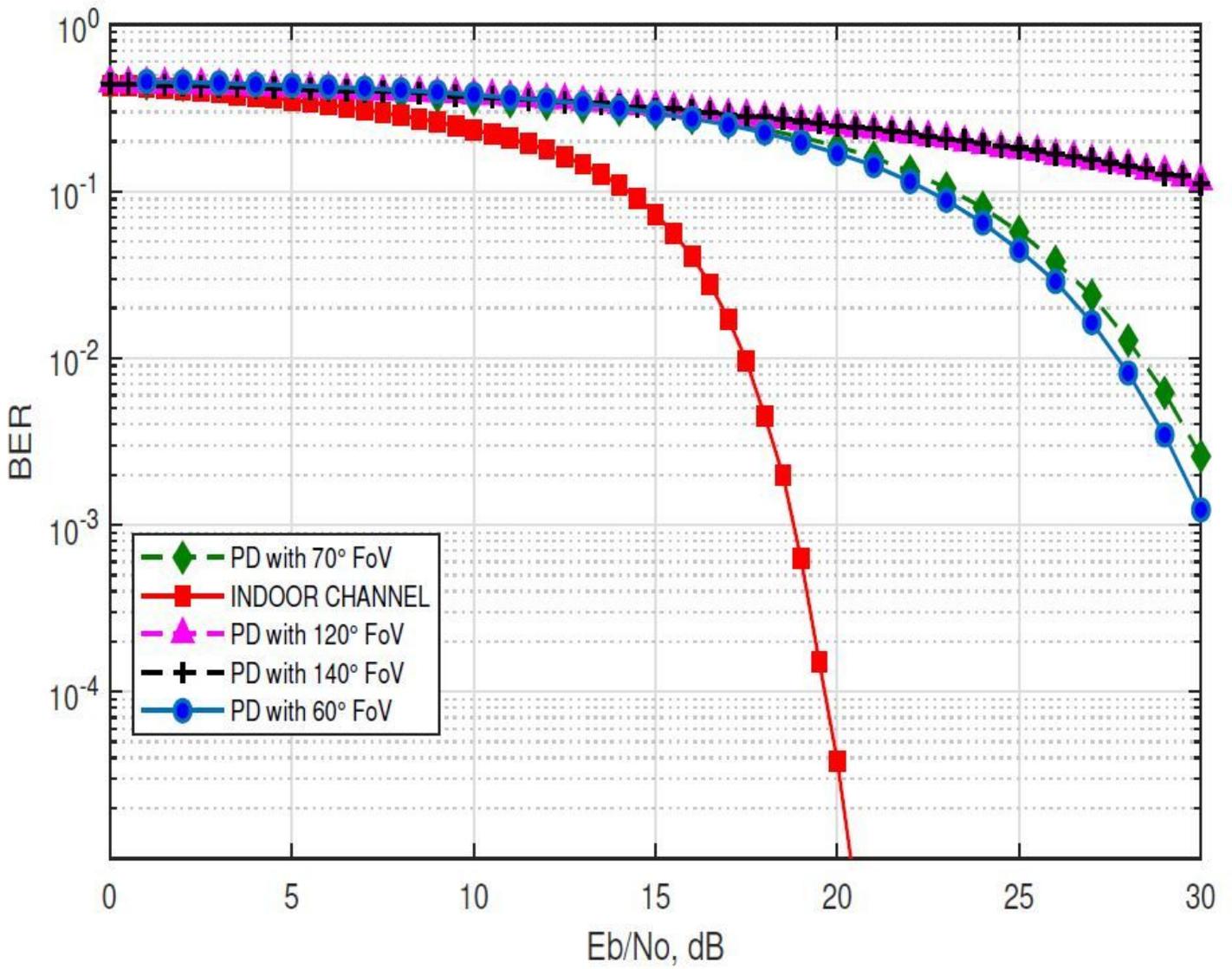


Figure 8

BER curves for an ideal indoor VLC scenario and the proposed greenhouse scenario, varying the FoVs of the PD.