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Simulation and Performance Analysis of a VLC-Based Greenhouse Farming System Under Different Atmospheric Conditions

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Abstract: This paper presents a simulation-based performance analysis of a visible light communication (VLC) system for wireless monitoring in greenhouse farming under different atmospheric conditions. The proposed system employs LED-based transmitters to simultaneously provide illumination and data communication for transmitting sensor information such as temperature, humidity, and soil moisture to a central controller. A MATLAB-based model is developed to evaluate the VLC link for a bit rate of 1 Mbps over transmission distances up to 40 m, considering attenuation coefficients ranging from 0.005 m^{-1} (clear condition) to 0.18 m^{-1} (dense fog). The impact of temperature variation (30–40 °C), humidity, dust, and fog on received optical power, bit-error rate (BER), and energy efficiency is analyzed using on–off keying (OOK) and OFDM modulation schemes. Simulation results show that received optical power decreases exponentially with distance and temperature, while BER increases significantly under severe scattering conditions. At 4 dB Eb/N0, OFDM achieves nearly 50% BER improvement compared to OOK and maintains higher energy efficiency in high-attenuation environments. The results demonstrate that atmospheric effects strongly influence VLC reliability, and OFDM-based VLC provides a robust and energy-efficient solution for precision greenhouse farming and smart agriculture applications.

Keywords: *Greenhouse, Agriculture, VLC.*

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I. INTRODUCTION

Currently, greenhouse-based farming plays an important role in agriculture. For the growth and development of plants in a greenhouse, a controlled greenhouse environment is required for smart and sustainable farming (SSF) [1]. Several methods are available for controlling greenhouse environments using wired radio frequency (RF)-controlled greenhouse systems. In the current study, we have considered Visible Light Communication (VLC) for a controlled greenhouse environment system. VLC has several advantages over RF and wired-based systems like high-data-rate services for communication, security, and power consumption, etc. [2].

Visible Light Communication (VLC) is an emerging wireless communication technology that uses visible light (wavelength range 380-780nm) to transmit data. Unlike the traditional radio frequency (RF) system, VLC relies on light Emitting Diodes (LED) as the source of data transmission. With the rapid global shift towards LED lighting for energy efficiency, VLC has gained significant attention as it can provide both illumination and high-speed wireless communication simultaneously. The fundamental principle of VLC is based on the rapid switching of LED light intensity at speed too fast for the human eye to detect. [3]

One of the key advantages of VLC is the availability of a large, unlicensed and interference-free spectrum. In contrast, the RF spectrum is heavily congested and regulated. VLC offers improved security because visible light cannot penetrate walls; therefore, data transmission remains confined within a closed environment, reducing risks of unauthorized access.

II. MOTIVATION

Recently, there is a need for reliable, high data rate and interference free wireless communication technologies for the growth of precision agriculture and smart farming. In agricultural scenario, radio frequency-based communication systems face significant challenges like electromagnetic interference, performance degradation in different atmospheric conditions, bandwidth limitations and adverse effect on plants. These challenges motivated us to explore other alternative options.

VLC came into the frame of wireless communication technology to replace RF technologies in agriculture. Visible light communication does not affect plants, and it is immune to Electromagnetic interference. There is spectrum limit in VLC. In greenhouse farming, vertical farming and indoor cultivation LEDs play significant role in growth of plant and power consumption because VLC based system gives light and transmission together. The motivation of our research is as follows:

- *Growing Demand of Precise and Smart Farming*

In greenhouse farming, there is a need for high-speed data communication. For monitoring the growth of plants, irrigation and watering in greenhouse by using sensors and cameras can enable smart, sustainable and precision farming in controlled VLC based system. There are lot of difficulties in greenhouse agriculture like reflection, strength and proper communication to need to improve, this need motivates us.

- *Increase Performance*

Any communication system has some advantages and some limitations. VLC also comes with some difficulties, in agricultural atmosphere conditions. These conditions (temperature, humidity, mist and fog) degrade the performance of system. For the improvement of the performance of VLC in real-world agricultural condition needs more research through data rate, SNR, and BER to help assess feasibility and optimization of system.

- *Enhanced Power Efficiency*

VLC emerges as the energy efficient alternative for greenhouse farming; LEDs can be used simultaneously as the light source and data transmission. Since LEDs are used for lighting in greenhouse farming, hence it gives unique advantage of no need of extra dedicated power source to transmission of data. For long-term deployment sensors and devices are essential to improve the technology, it motivates us to investigate and enhance the power efficient VLC system.

- *Line-of-Sight Enhancement*

Visible light travels in straight line, so visible light communication relies on the Line-of-Sight (LOS) path. Transmission between transmitter and receiver needs LOS for high data rate and reliable communication. In agricultural conditions of greenhouse, it is difficult to maintain LOS due to several dynamic factors like growth of plants, canopy density, and leaf movement. These factors degrade the performance of VLC by shadowing and blocking signals. In real-time monitoring, there is a need of improvement which motivate us for research.

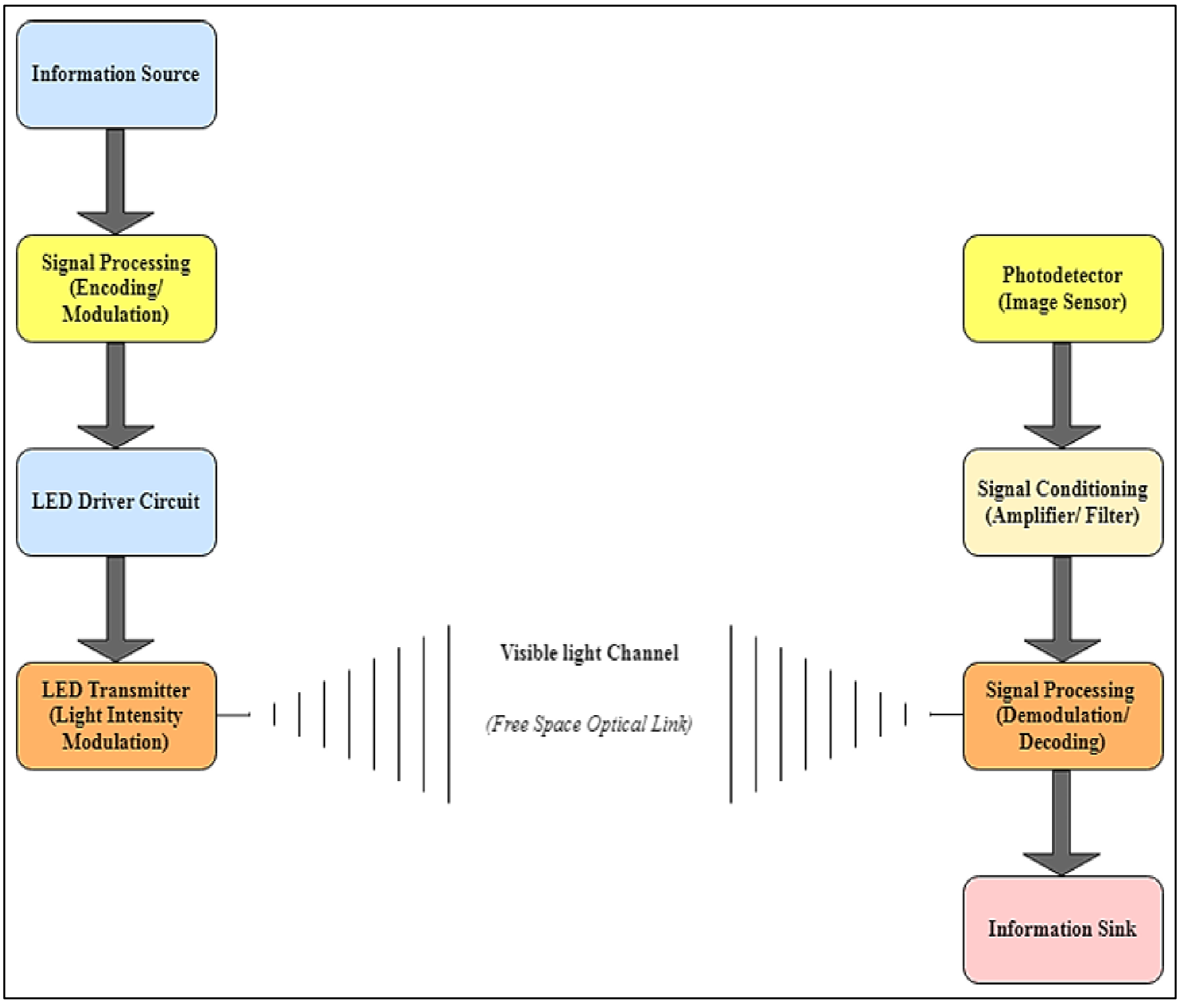

Fig 1 Transmission and Reception of Basic VLC System

III. IMPLEMENTATION OF VLC SYSTEMS IN GREENHOUSE FARMING SCENARIO

Many researchers have also done research in this field. Islim et al. (2018) provides a rigorous experimental investigation into the feasibility of visible light communication (VLC) as an alternative connectivity solution for smart and sustainable farming within greenhouse environments. Georlette et al. (2020) presents a detailed study on outdoor visible light communication (VLC) channel modeling under smoke conditions, with a comparative analysis to fog-induced optical attenuation. By empirically describing the effects of particulate matter on VLC signal transmission, with an emphasis on absorption and scattering mechanisms that reduce received optical power, the work provides a significant contribution. Hasnavi et al. and Georlette et al.'s parallel studies expand the use of VLC analysis to include unfavorable meteorological circumstances like smoke and fog. These studies demonstrate how aerosol-induced scattering and absorption results in significant optical attenuation, which lowers received power and raises BER. The implementation of Visible Light Communication (VLC) systems in a greenhouse farming scenario offers a promising and sustainable approach for enabling reliable wireless communication while simultaneously supporting plant growth. The transmission and reception process of basic VLC system is depicted in Fig.1. In this system, LED grow lights serve a dual purpose by providing the necessary illumination for photosynthesis and acting as optical transmitters that convey data through high-speed light intensity modulation, which is imperceptible to both plants and human observers.

VLC technology is particularly well suited for greenhouse environments due to its energy efficiency and immunity to electromagnetic interference, as it leverages the existing LED lighting infrastructure without introducing additional radio-frequency pollution. Furthermore, the inherent confinement of light within the greenhouse structure enhances data security, reducing the risk of external interference or unauthorized access. The greenhouse farming scenario is depicted in Fig.2 in which various environmental sensors are deployed within the greenhouse for continuous monitoring of critical parameters such as soil moisture, temperature, humidity, carbon dioxide concentration, and light intensity. The collected sensor data is transmitted via VLC to photodiode or image-sensor-based receivers, which decode the optical signals and forward the information to a central control unit or gateway. Based on real-time data analysis, automated decisions can be made to regulate irrigation schedules, ventilation systems, nutrient delivery, and lighting conditions, thereby ensuring optimal crop growth and resource utilization.

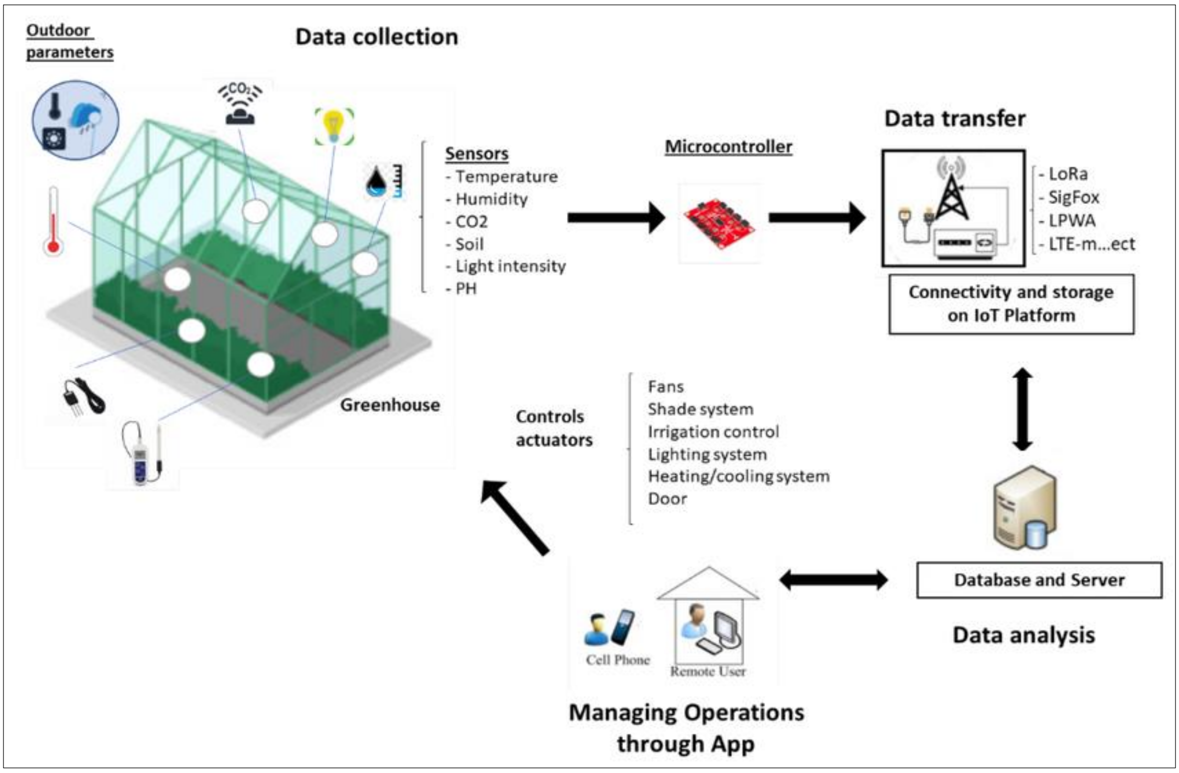

Fig 2 The Greenhouse Farming Scenario

The integration of VLC with greenhouse automation systems enables precise microclimate monitoring, adaptive lighting control based on crop growth stages, and efficient management of water and fertilizers. Despite its advantages, practical implementation requires careful consideration of line-of-sight constraints, signal attenuation caused by dense foliage or dust, and appropriate modulation techniques to avoid disturbing plant photosynthetic processes. Overall, the adoption of VLC in greenhouse farming contributes to improved crop yield and quality, reduced energy and resource consumption, and aligns strongly with the goals of smart agriculture and environmentally sustainable farming practices.

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IV. IMPACT OF ATMOSPHERIC CONDITIONS ON VLC SIGNAL PROPAGATION

This section provides the impact of different atmospheric conditions on VLC signal propagation in precision farming scenario. Atmospheric variability refers to the changes in environmental conditions that affect the propagation of visible light used in VLC systems. Since VLC relies on light traveling through free space, any change in the atmosphere can impact signal strength, quality, and reliability. The impact of different atmospheric conditions in VLC link is discussed below in detail.

- *Scattering*

Particles present in the air such as dust, smoke, fog, or pollution cause light scattering**.** In conditions like fog or heavy dust, the light beam spreads or weakens which reduces the received signal power and errors are increased . [13] [14]

- *Absorption*

Some atmospheric gases (water vapor, carbon dioxide, aerosols) partially absorb visible light. This absorption reduces the intensity of the transmitted light, especially in humid or polluted environments. [13]

- *Turbulence*

Temperature variations in the air cause optical turbulence, creating random fluctuations in the light path. This results in signal fading, twinkling, and instability in data transmission.

- *Weather Conditions*

Weather plays a significant role. Rain has minimal effect on visible light compared to fog. Fog and haze significantly attenuate light that can affect the VLC system. Humidity increases scattering and absorption that increases the SNR. [2] [13] [14]

- *Ambient Light Interference*

Sunlight and other strong light sources create background noise, reducing the signal-to-noise ratio (SNR) and affecting VLC performance. VLC has a significant advantage in indoors. In outdoor, VLC has difficulties in receiving signals due to ambient light. [9]

V. SIMULATION FRAMEWORK

To study the system performance, the MATLAB based simulation is employed to model the VLC transmitter, receiver, and optical channel under different weather conditions. The VLC simulation Flow diagram using OOK/OFDM under greenhouse farming conditions is represented in Fig.3. The impact of different atmospheric conditions such as humidity, fog, and temperature are considered to analyze the VLC system for precision agriculture. In our proposed work the performance is analyzed for two modulation schemes ie. OOK and OFDM to identify the most effective techniques for greenhouse farming conditions.

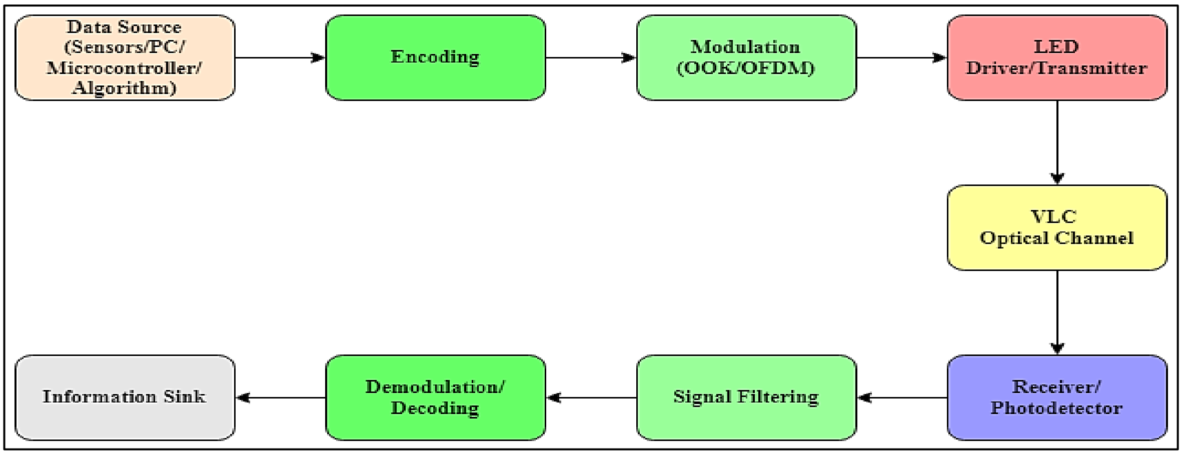

Fig 3 VLC Simulation Flow Diagram Using OOK/OFDM for Greenhouse Farming Conditions

- *Simulation Parameters*

The simulation parameters are given in Table 1

Table 1 Simulation Parameters

Parameter	**Value**
Transmitted Optical Power P_t	1 W (normalized)
Bit Rate ($R_{b)}$	1 Mbps
Distance Range (d)	1-40m
Reference Temperature (T_{ref})	30 °C
Simulated Temperatures	30, 35, 40 °C
Base Attenuation Coefficient ($\alpha_{ref)}$	$0.02\ m^{-1}$
Temperature Sensitivity (β)	0.02 per °C

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LED Efficiency (η_{LED})	0.3
Circuit Power (P_{cir})	0.5 W
Total Power (P_{tot})	$\eta_{LED}P_t+P_{circuit}$
Noise Term (Theory Model)	0.01
Modulation Schemes	OOK (IM/DD)

VI. RESULTS AND DISCUSSION

The simulation models different atmospheric conditions relevant to precision farming. A clear greenhouse environment is represented by an attenuation coefficient of 0.005 m⁻¹, while high humidity conditions typical of mushroom farming use 0.04 m⁻¹. Dust conditions caused by soil particles are modeled with 0.10 m⁻¹, and dense fog with 0.18 m⁻¹, indicating severe optical attenuation. System performance is evaluated over an E_b/N_0range of 0–30 dB to analyze BER and energy efficiency under varying signal conditions.

- *Temperature Dependance*

The optical power received as the usual exponential attenuation model is represented as:

$$P_r\,(d,T)=P_t e^{-\alpha(T)d} \tag{1}$$

Where $\alpha(T)$is the attenuation coefficient at temperature T. This is the free-space, scattering-dominated model:

$$\alpha(T)=\alpha_{ref}[1+\beta(T-T_{ref})] \tag{2}$$

$$P_r=P_t\,H_{greenhouse}\,(0)+N_t \tag{3}$$

The received optical power is evaluated as a function of distance at 30 °C temperatures using an exponential attenuation model depicted in Fig.4. From the simulation results, it is easier to understand from the graph that an increase in temperature results in a slight increase in the attenuation coefficient, which leads to reduced received power at larger distances. The received optical power is minimum at fog condition and maximum at clear weather condition. The simulated results were compared with the theoretical greenhouse model $P_r = P_t H_{greenhouse}(0) + N_t$, showing consistent decay trends and validating the adopted channel model for smart farming environments. Where $H_{greenhouse}(0)$denotes the baseline DC channel gain for greenhouse experimental conditions and $N_t$is a small noise term.

Absolute humidity (water vapor) typically increases with temperature and can increase light absorption and scattering in near-surface conditions; several remote-sensing studies demonstrate that atmospheric absorption depends on temperature & water vapor.

Received optical power vs distance at different temperatures is shown in Fig.5. It is clear from the graph that the received optical power shows a smooth exponential decay with distance, consistent with VLC propagation theory. At 30 °C, the received power is the highest, indicating minimal attenuation, while at 35 °C it decreases moderately. At 40 °C, the received power is the lowest due to increased temperature-induced absorption and scattering. The clear separation between the curves highlights the temperature-dependent behavior of the optical channel, and the theoretical reference curve closely follows the same decay trend, validating the simulation results for greenhouse precision-farming conditions.

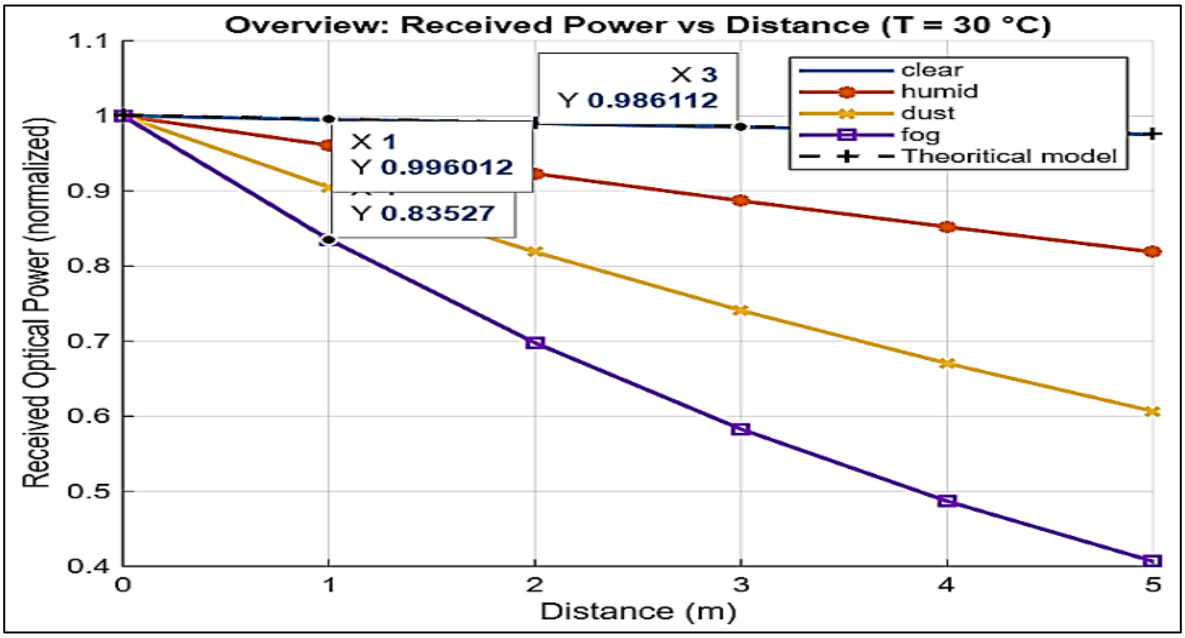

Fig 4 Received Optical Power vs Temperature Curve

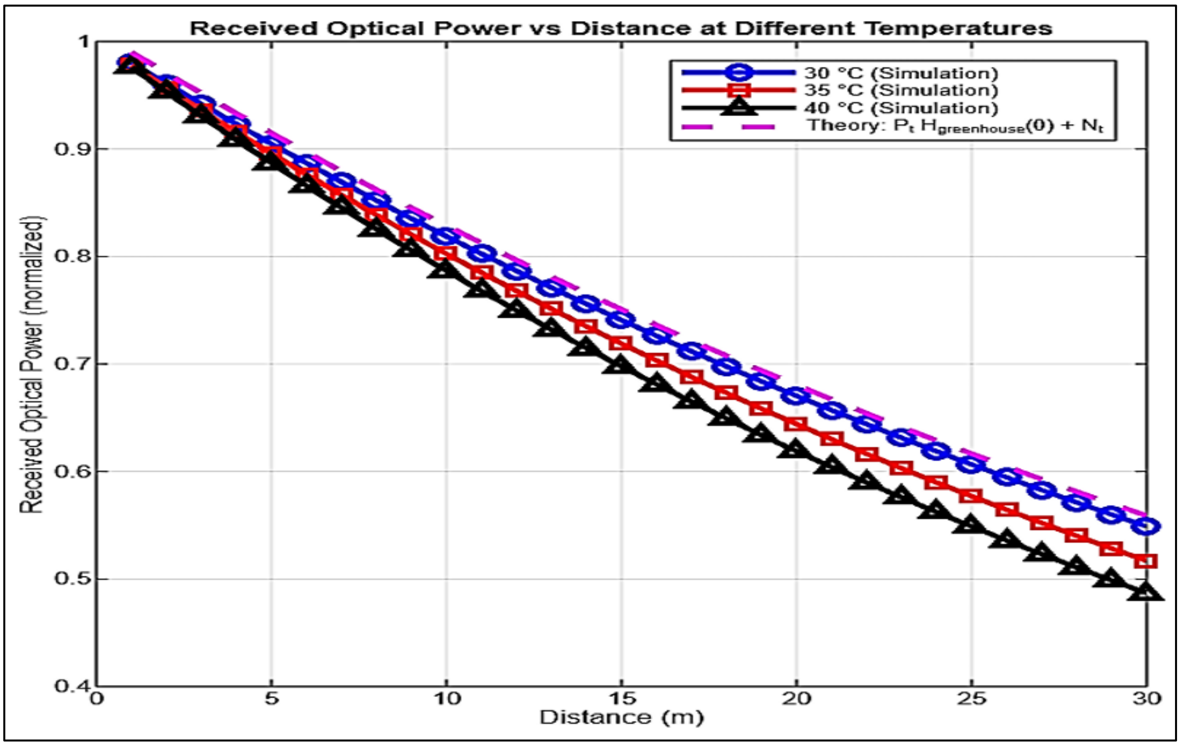

Fig 5 Received Optical Power vs Distance at Different Temperatures

- *Energy Efficiency vs E_b/N_0 Under Different Weather Conditions*

Energy efficiency is an important parameter to check the performance of Precision Farming. Lots of tiny sensors are spread over the farm to keep an eye on the soil, how hot it is, how much moisture there is, the health of the crops, and the irrigation. These sensors generally run on batteries or the sun, getting a lot of use from a little energy means they won't need batteries changed as often. This cuts down on how much it costs to maintain the system and is a benefit for farms in distant places that aren't easy to get to for regular maintenance. Using energy efficiently for sending information also helps with solar-powered farms, as they have only a certain amount of power to use., using energy wisely guarantees that data gets from the sensors to the controlling parts of the system reliably; good decisions in smart agriculture depend on this. With Precision Farming using so many points of data all at once, energy efficiency is essential for keeping costs down, the network going for a long time, and communication between devices consistent.

Energy efficiency (bits/Joule) of the VLC system represented by η is given as follows:

$$\eta = \frac{R_b(1-\mathrm{BER})}{P_{\mathrm{tot}}} \tag{4}$$

Where BER depends on atmospheric attenuation:

$$\left(\frac{E_b}{N_0}\right)_{\mathrm{eff}} = \left(\frac{E_b}{N_0}\right) \cdot e^{-2\alpha d} \tag{5}$$

The parameter R_b represents the bit rate of the VLC system (in bits per second). In a precision-farming scenario, R_b corresponds to the rate at which sensor data such as temperature, humidity, or soil moisture is transmitted. Since agricultural sensor data is typically low-rate, R_b is kept moderate to ensure reliable and energy-efficient communication.

The parameter P_{tot} denotes the total power consumption of the VLC transmitter. It includes both the optical power consumed by the LED and the electrical power consumed by the associated circuitry, such as the LED driver, signal processing unit, and sensor interface. It can be expressed as:

$$P_{\mathrm{tot}} = \frac{P_t}{\eta_{\mathrm{LED}}} + P_{\mathrm{circuit}}, \tag{6}$$

Where P_t is the transmitted optical power, η_{LED} is the electro-optical efficiency of the LED, and P_{circuit} accounts for non-optical power consumption.

Together, R_b and P_{tot} determine how efficiently useful information is delivered per unit energy, making them key parameters for evaluating VLC suitability in energy-constrained precision-farming applications.

Fig.6 and Fig.7 demonstrate the energy efficiency of the proposed system under different atmospheric conditions. The energy efficiency curves demonstrate that atmospheric attenuation significantly impacts the number of successfully transmitted bits per unit energy. Fog and dust conditions cause a substantial reduction in energy efficiency, whereas OFDM-based VLC consistently outperforms OOK due to its lower BER. These results confirm the suitability of OFDM-VLC for energy-constrained precision farming environments such as mushroom cultivation units.

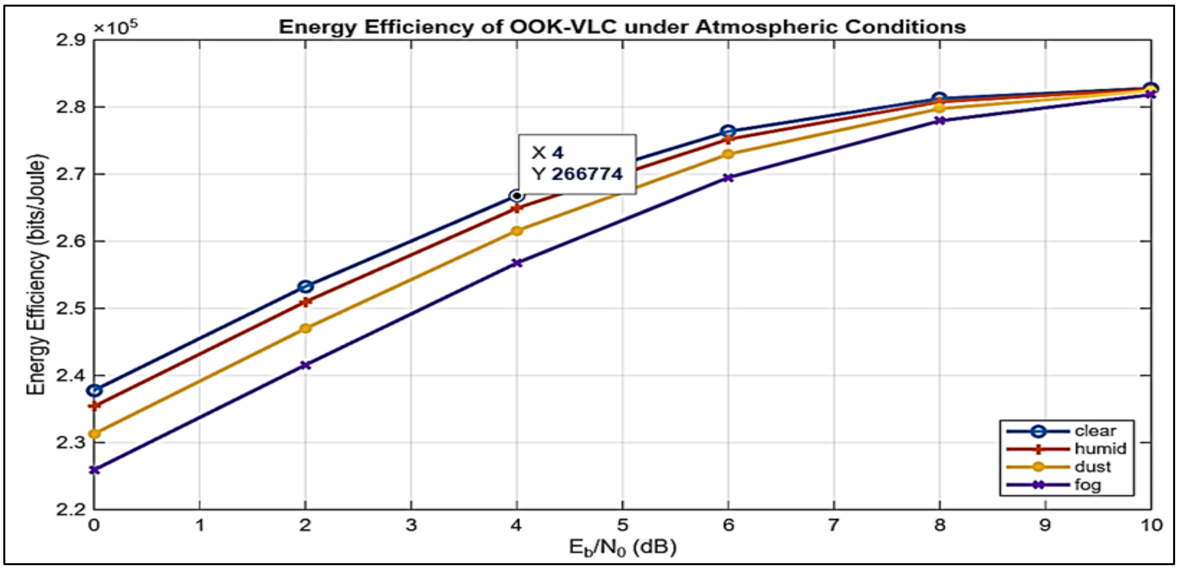

Fig 6 Energy Efficiency Graph of OOK-VLC Under Different Atmospheric Conditions

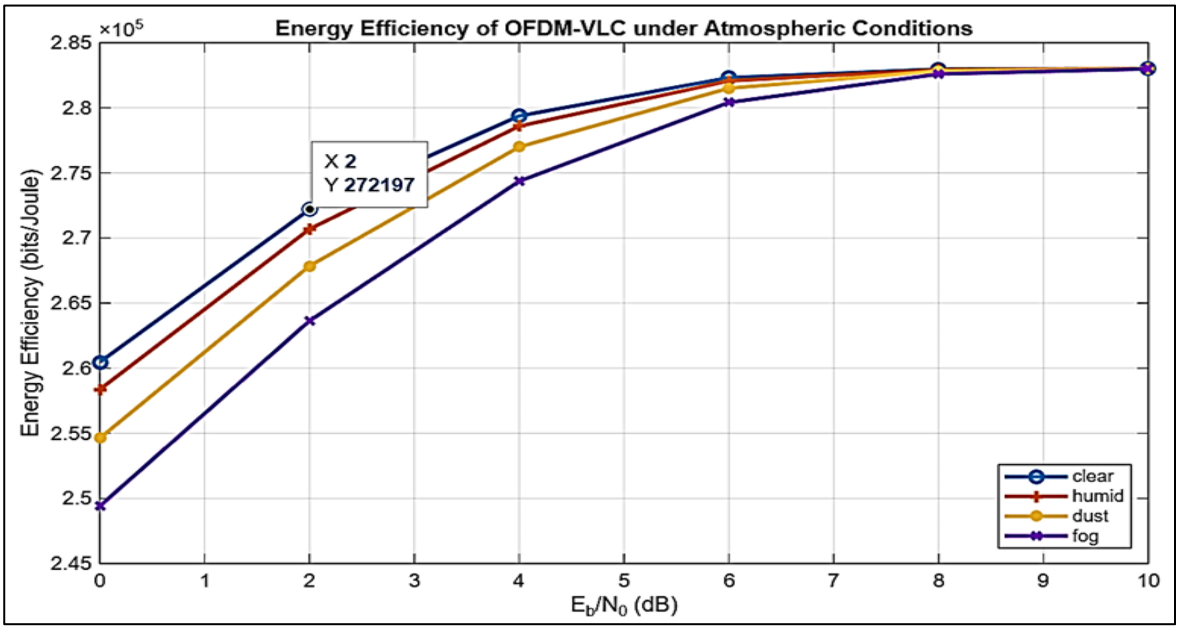

Fig 7 Energy Efficiency Graph of OFDM-VLC Under Different Atmospheric Conditions

➤ *Bit Error Rate Analysis*

Bit Error Rate (BER) represents the probability that a transmitted bit is received incorrectly due to noise, attenuation, or interference in the channel. Bit Error Rate analysis provides the performance of the communication link under different weather conditions.

- *OOK (IM/DD, AWGN Approximation)*

For VLC systems using on-off Keying with Intensity Modulation and Direct Detection (IM/DD) under AWGN approximation, the BER is given by:

$$\mathrm{BER}_{OOK} = Q\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{7}$$

Which shows that the error probability decreases as the ratio E_b/N_0increases. In more advanced VLC systems, BPSK-OFDM modulation is used to improve reliability, especially in outdoor precision farming where fog, rain, and dust affect the optical signal.

- *BPSK-OFDM (Per Subcarrier)*

For BPSK-OFDM per subcarrier, the BER is given by:

$$\mathrm{BER}_{OFDM} = Q\left(\sqrt{2\frac{E_b}{N_0}}\right) \tag{8}$$

A comparison of BER performance of OFDM based VLC system and OOK based VLC system under different weather conditions are depicted in Fig .8. It is clear from the results that OFDM provides better error performance compared to OOK for the same E_b/N_0. This means that OFDM-based VLC systems can achieve higher energy efficiency and more reliable communication in precision farming environments under different weather conditions.

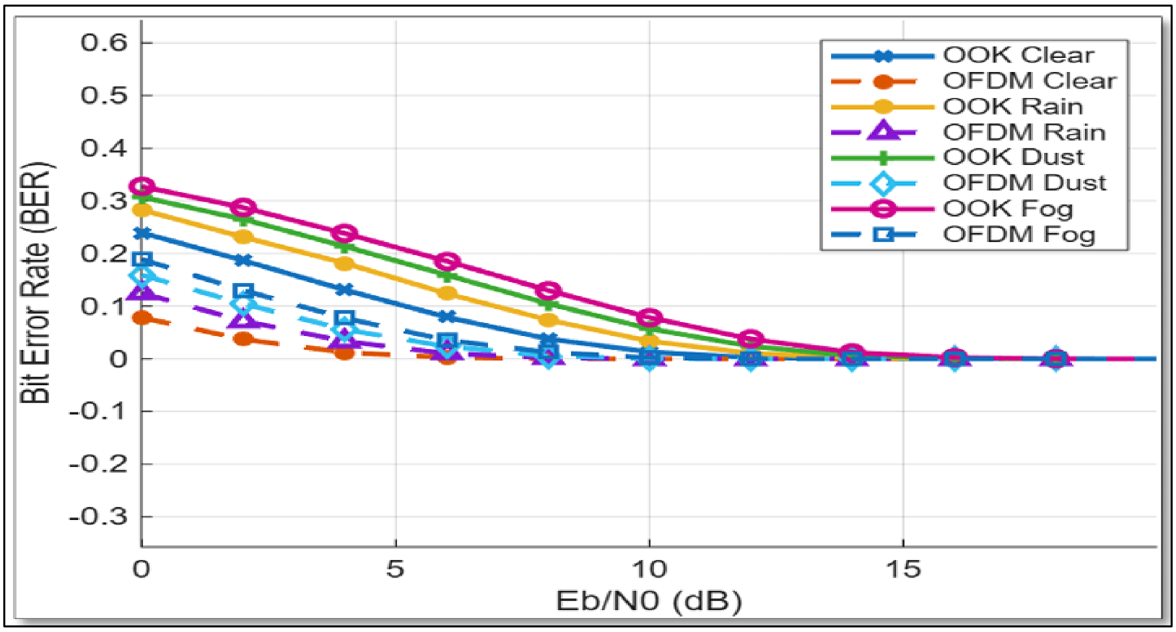

Fig 8 BER Comparison of VLC System for Precision Farming Under Different Weather Conditions

BER Comparison of OFDM and OOK based VLC system at 4dB and at 8dB Eb/N0 is represented in Table 1 and Table 2 respectively.

Table 2 BER Comparison of OFDM and OOK Based VLC at 4dB Eb/N0

Condition	OOK BER	OFDM BER	Improvement
Clear	0.14	0.07	0.07 (50%)
Rain	0.18	0.09	0.09 50%)
Dust	0.21	0.10	0.11 (52%)
Fog	0.24	0.12	0.12 (50%)

Table 3 BER Comparison of OFDM and OOK Based VLC at 12 dB Eb/N0

Condition	OOK BER	OFDM BER	Improvement
Clear	0.03	0.01	0.02
Rain	0.04	0.015	0.025
Dust	0.05	0.02	0.03
Fog	0.06	0.025	0.035

Obtained results reveals that The BER improvement of OFDM over OOK is smallest in clear atmospheric conditions because the channel attenuation is low and both modulation schemes perform well. In contrast, under fog conditions, severe scattering and attenuation degrade the OOK performance significantly, while OFDM maintains better robustness due to its multi-carrier structure, resulting in the largest BER improvement. This behavior confirms the expected theoretical performance of OFDM in highly attenuated optical wireless channels.

VII. CONCLUSION

This paper investigated the performance of a VLC-based wireless communication system for greenhouse farming under realistic atmospheric conditions using simulation analysis. The results confirm that temperature increase, humidity, fog, and dust introduce additional optical attenuation, which reduces received power and degrades BER performance with increasing distance. The study shows that the attenuation coefficient increases from 0.005 m^{-1} in clear conditions to 0.18 m^{-1} in fog, leading to significant performance degradation at longer ranges. Among the evaluated modulation schemes, OFDM consistently outperforms OOK, achieving nearly 50% BER improvement at 4 dB Eb/N0 and providing better energy efficiency in high-attenuation environments. The findings indicate that VLC can effectively support secure, interference-free, and energy-efficient communication in smart greenhouse systems by utilizing existing LED lighting infrastructure. However, reliable deployment requires careful consideration of line-of-sight constraints and atmospheric variability. Overall, VLC with OFDM modulation is a promising candidate for sustainable and precision agriculture applications.

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