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Abstract

This study evaluates the performance of different modulation techniques, such as On-Off Keying (OOK), Amplitude Shift Keying (ASK) and Orthogonal Frequency Division Multiplexing (OFDM) in an Indoor Visible Light Communication (VLC) system for image transmission using the Line of Sight (LOS) transmission channel. Metrics such as Bit Error Rate (BER), data transmission rate, and latency are investigated as the Signal-to-Noise Ratio (SNR) and transmission distance functions. The results indicate that OOK and ASK are suitable for transmitting less demanding images in noisy environments. At the same time, OFDM offers better performance with its high transmission rate and low latency, making it ideal for rapidly transferring High-Definition (HD) images.

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***Abstract*—This study evaluates the performance of different modulation techniques, such as On-Off Keying (OOK), Amplitude Shift Keying (ASK) and Orthogonal Frequency Division Multiplexing (OFDM) in an Indoor Visible Light Communication (VLC) system for image transmission using the Line of Sight (LOS) transmission channel. Metrics such as Bit Error Rate (BER), data transmission rate, and latency are investigated as the Signal-to-Noise Ratio (SNR) and transmission distance functions. The results indicate that OOK and ASK are suitable for transmitting less demanding images in noisy environments. At the same time, OFDM offers better performance with its high transmission rate and low latency, making it ideal for rapidly transferring High-Definition (HD) images.**

***Index Terms*—Visible Light Communication (VLC), On-Off Keying (OOK), Amplitude Shift Keying (ASK), Orthogonal Frequency Division Multiplexing (OFDM), Line of Sight (LOS) Channel, Bit Error Rate (BER).**

I. Introduction

Wireless communications have become one of the main interaction activities in society, leading to a continuous growth in the demand for mobile services and Internet access. This growing demand has caused a saturation of the Radio-Frequency (RF) spectrum, prompting the search for new alternatives to complement traditional wireless networks [1]. In the field of wireless communication, there are several established technologies.

For example, Bluetooth technology is widely known and used, but it has limitations in terms of range and data transfer speed. Bluetooth is ideal for short-range, low-power communications, such as portable devices and computer peripherals. However, its data transmission capacity is limited compared to other technologies [2]. On the other hand, Near Field Communication (NFC) technology facilitates contactless communication at very short distances, typically a few centimeters. NFC is commonly used in mobile payment systems and quick information transfer [3]. However, its extremely limited range restricts its applicability to long-distance transmission scenarios.

In the context of wireless communication, 5G networks represent the latest generation of mobile technology, offering high data speeds and low latency. 5G networks promise to revolutionize mobile connectivity and enable a wide range of new applications, from autonomous vehicles to the Internet of Things (IoT) [4]. Despite their advantages, the large-scale deployment of 5G is still ongoing and its geographic coverage can be variable, depending on the infrastructure and implementation policies in each region. In addition to the mentioned wireless technologies, it is common to send images through file-sharing applications that rely on Internet connections. These applications have a clear limitation: they require an Internet connection, which may not always be possible.

In search of solutions to the challenges presented previously, one of the emerging alternatives that could complement radiofrequency wireless networks is Visible Light Communication (VLC) [5], [6]. Unlike other wireless communications, VLC technology does not use the radiofrequency spectrum. Instead, it takes advantage of the visible light spectrum, ranging from 380 nm to 780 nm, to transmit data using LED light sources. This technique offers numerous advantages, including the large available bandwidth, low electromagnetic interference, high data security, and the possibility of integration with existing lighting infrastructure [7]. These characteristics make VLC an attractive option for various applications, including high-speed data transmission in urban and domestic environments.

Based on this premise, in this work we present research on the specific uses of VLC communications: the transmission of high-definition images between devices. Although image transmission has become a routine activity, there is still no completely efficient solution for carrying it out. Therefore, the objective of this study is to explore the potential of VLC communications to optimize image transmission, leveraging its unique characteristics and evaluating its performance.

In this study, different modulation techniques will be used.

Amplitude Shift Keying (ASK) is a technique in which the carrier amplitude varies based on transmitted data, allowing simple implementation, but with susceptibility to interference [8]. On-Off Keying (OOK) is a form of ASK that uses two amplitude levels, representing bits 1 and 0 through the presence or absence of the carrier [9]. On the other hand, Orthogonal Frequency Division Multiplexing (OFDM) will be employed due to its high spectral efficiency and resistance to Inter-symbol Interference (ISI) [10]. OFDM-QPSK divides the bandwidth into multiple sub-carriers, enabling more robust transmission in noisy channels. Furthermore, the VLC line of sight (LOS) component will be considered for transmission, which refers to direct transmission of light between the transmitter and receiver without obstructions. This channel component always requires that it encounters the least possible obstruction for VLC communications because of its low attenuation and high efficiency. However, signal quality can be affected by factors such as alignment and distance between devices.

The remainder of this manuscript is organized as follows. Section II presents related works that have addressed similar topics in the field of VLC communications. The analysis and mathematical characterization of the VLC system model and the modulation schemes are explained in Section III. Section IV describes the indoor scenario in which we evaluate the proposed VLC system model and modulation techniques, present the results, and discuss the findings. Finally, the conclusions of the work are described in Section V.

II. Related Works

In the context of related works that address image transmission in wireless communication systems, the authors of [11] investigate the transmission of compressed images in VLC systems using pre-coded OFDM over the LOS channel. It is based on the use of a Hadamard matrix and partial DCT measurement for block sampling. Performance is evaluated based on the BER and Peak Signal-to-Noise Ratio (PSNR) in the transmission of different images. The proposed system has the advantage of dividing the bits into blocks, which improves transmission efficiency and allows better data recovery. However, it lacks comparisons of the performance of the modulation used at different distances. In this sense, our study incorporates the evaluation of different modulation schemes such as OOK and ASK, providing a more comprehensive view of the performance of the VLC system in various transmission scenarios and enhancing the understanding of how different modulation techniques affect image transmission and recovery in LOS channels.

On the other hand, the work presented in [12] explores the use of OOK modulation for image transmission in cooperative VLC networks. It employs a Decode-and-Forward (DF) relay technique along with a Maximal Ratio Combining (MRC) scheme to improve the robustness, range, and reliability of the system. The study focuses on comparing the image data transmission in cooperative and non-cooperative VLC networks using parameters such as Mean Square Error (MSE), PSNR, Normalized Cross-Correlation (NCC), Normalized Absolute Error (NAE), and Laplacian Mean Square Error (LMSE). The research concludes that cooperative communication offers superior image reception compared to non-cooperative communication due to lower error rates and higher image quality under various SNR conditions. However, the study is limited to the evaluation of OOK in a cooperative and non-cooperative scenario without considering other modulation techniques that could offer a broader and more robust performance comparison. Furthermore, our study includes the evaluation of OFDM-QPSK and ASK modulation techniques, providing a more comprehensive view of transmission efficiency in terms of BER and transmission rate in different distance and image quality scenarios.

Finally, in [13], the authors investigate the BER performance for different Optical OFDM (O-OFDM) schemes in VLC systems. It focuses on how the non-linear characteristics of LEDs, the modulation constellation size, the O-OFDM schemes, and the type of channels impact the BER performance. It uses a convolutional encoder at the transmitter and the Viterbi algorithm at the receiver to improve BER. The research demonstrates improvements in SNR for various O-OFDM schemes in both LOS and Non-Light of Sight (NLOS) channels, highlighting the proposed system's ability to mitigate LED nonlinearity and reduce BER. This article is a good comparison with our work in terms of evaluation system performance. However, our study considers other modulations to compare their performance and also compares at different distances and how these affect these communications.

III. System Model

The system model implemented in this work is based on an indoor VLC system with the LOS channel component, where a transmitter and a photodetector (PD) transmit the image between them. The block diagram of the system is presented below, and each component will be explained in the next subsections.

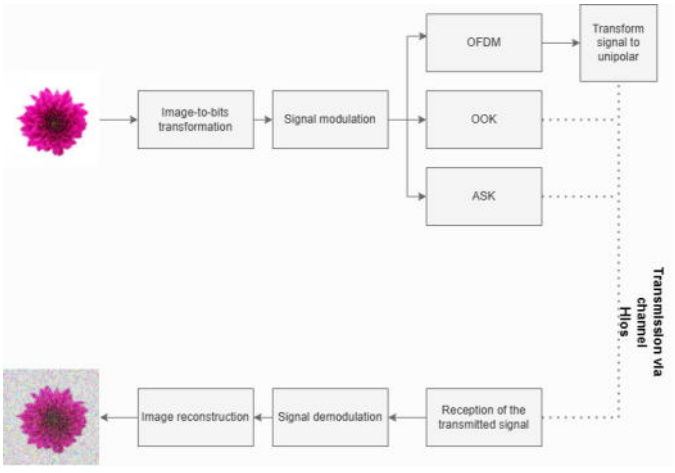

Fig. 1. VLC system block diagram.

A. LOS Channel

The objective of the scenario is to perform image transmission through the LOS channel. This channel provides a direct line of sight between the transmitter and the receiver, minimizing signal loss and allowing for a more accurate evaluation of the performance of the modulation techniques used. The LOS channel was preferred over the NLOS channel due to its lower attenuation and higher efficiency in data transmission. The NLOS channel, which involves non-line-of-sight propagation with potential reflections and scattering, introduces additional complexities and signal degradation that can obscure the evaluation of modulation performance. By using the LOS channel, we ensure a clearer assessment of the inherent capabilities of each modulation technique under ideal conditions.

The transmission is carried out using the Lambertian model to describe the propagation of light from LEDs, defined by:

$$h_{los}(t) = \frac{A_t(m_t+1)}{2\pi d^2}\cos^m(\phi)T_s(\psi)g(\psi)\cos(\psi)\delta\left(t-\frac{d}{c}\right), \tag{1}$$

where A_t is the physical area of the PD, m_t is the Lambertian order of the LED, d is the Euclidean distance between the transmitter and the receiver, ϕ is the light irradiance angle, $T_s(\psi)$ is the gain of the optical filter in the PD, $g(\psi)$ is the concentrator gain in the PD, ψ is the light incidence angle and c is the speed of light.

In our study, we use this mathematical expression to convolve it with the modulated signal to be sent (image signal) according to the following expression:

$$y(t) = Rx(t) \otimes h_{los}(t) + n(t), \tag{2}$$

where $x(t)$ represents the modulated signal which can take different expressions according to the modulation we use, which would be $p(t)$ in the OOK modulation, $s(t)$ in the ASK scheme, and $\tilde{x}_n^{(uni)}$ in the OFDM technique. Finally, $n(t)$ is the noise added in the simulation. The expressions (1) and (2) are described in detail in [14].

B. Modulations

In this work, we used three different modulation techniques to evaluate their performance in the indoor VLC system with LOS channel, which are mentioned below.

1) OOK Modulation: OOK modulation is a digital modulation technique in which the presence or absence of the carrier signal is used to represent the binary data to be transmitted. The modulated signal for a bit 1 can be expressed as:

$$p(t) = \begin{cases} 2P_t & \text{for } t \in [0, T_b] \\ 0 & \text{otherwise,} \end{cases} \tag{3}$$

where T_b is the bit period and P_t is the average power during transmission of bit 1. This expression corresponds to the Non-Return-to-Zero (NRZ) scheme, where a pulse of duration equal to the bit period is transmitted to represent a 1, while no pulse is transmitted for a 0 [14].

2) ASK Modulation: ASK modulation varies the amplitude of the carrier signal based on the binary data. The modulated signal for a bit 1 can be expressed as:

$$s(t) = A_1\cos(2\pi ft), \tag{4}$$

and for a bit 0:

$$s(t) = A_2\cos(2\pi ft), \tag{5}$$

where A_1 and A_2 are the amplitudes of the signal for bits 1 and 0, respectively, and f is the carrier frequency [15].

3) OFDM-QPSK Modulation: OFDM scheme combined with the Quadrature Phase Shift Keying (QPSK) modulation is performed in several stages. We first define the complex signal we need to be sent as:

$$s_i = \frac{1}{\sqrt{2}}\left((2b_{2i}-1) + j(2b_{2i+1}-1)\right), \tag{6}$$

where b_{2i} and b_{2i+1} are the input bits grouped in pairs and converted into QPSK symbols. Then, the Inverse Fast Fourier Transform (IFFT) is applied to convert the frequency data to time as follows:

$$x_n = \frac{1}{N}\sum_{k=0}^{N-1} S_k e^{j2\pi kn/N}, \tag{7}$$

where S_k is the k^{th} QPSK symbol and N is the number of subcarriers. To avoid ISI, a cyclic prefix is added, as shown in the following expression:

$$\tilde{x}_n = [x_{N-CP}, x_{N-CP+1}, \ldots, x_{N-1}, x_0, x_1, \ldots, x_{N-1}], \tag{8}$$

here CP is the length of the cyclic prefix.

Finally, due to the constraints of the VLC nature, the OFDM signal must be unipolar. A DC bias is added to the signal to ensure that all values are positive, such as:

$$\tilde{x}_n^{(uni)} = \tilde{x}_n + DC_{bias}. \tag{9}$$

The OFDM modulation process is detailed in [14].

C. Receiver

After the transmission process, the receiver captures the modulated signal through the LOS channel. The received signal first passes through a filter that removes noise and other possible interferences. Then, demodulation is performed using the method corresponding to the employed modulation.

For OOK and ASK, demodulation involves detecting the amplitude of the received signal and comparing it to a threshold to determine whether it corresponds to bit 1 or 0. In the case of OFDM-QPSK, the received signal is transformed back to the frequency domain using the Fast Fourier Transform (FFT), the cyclic prefix is removed, and then the QPSK symbols are decoded.

Finally, the recovered binary information is converted back into an image. This demodulation and decoding process ensures that the transmitted image can be accurately reconstructed, thus evaluating the performance of the modulation techniques in terms of BER and the quality of the recovered image.

IV. Simulation Results

This section begins with the analysis and presentation of the results obtained from the simulation of the constructed VLC system. This is a VLC system designed for the transmission of images in an indoor environment, which can be seen in the scenario presented in Fig. 2. The communication is performed through the LOS channel with the signal modulated using OFDM-QPSK, OOK, and ASK schemes.

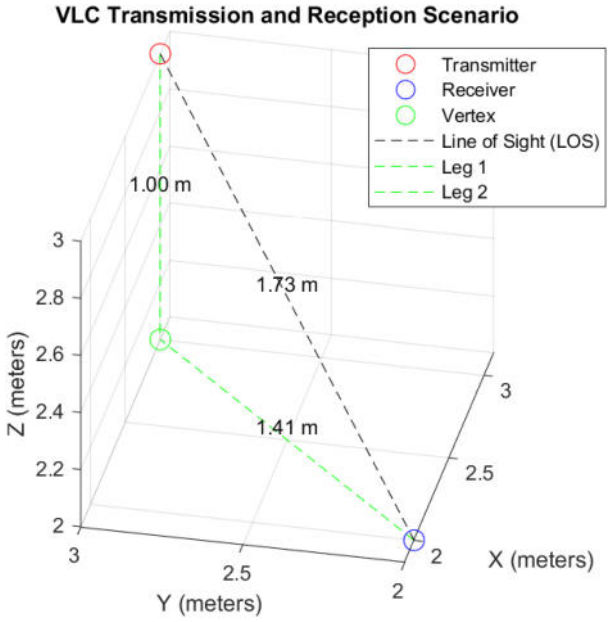

Fig. 2. Indoor VLC scenario simulation.

For the simulation results, eight scenarios were evaluated, which include the transmission of images with OFDM, OOK, and ASK modulations. The distances considered for transmission were 1.73 m. and 2.60 m. In addition, two additional cases were evaluated using OFDM modulation, but with a HD image at 2.60 m. This latter consideration was made because, as observed later in Fig. 6, the results with OOK and ASK modulations with HD images are excessively high in terms of latency. The relevant system parameters used in the simulation and their respective values are presented in Table I.

TABLE I
Simulation Parameters

System Model Parameters	
Scenario parameters	**Values**
Coordinate one of the Transmitter (x, y, z)	(3, 3, 3) for 1.73 m.
Coordinate two of the Transmitter (x, y, z)	(3.5, 3.5, 3.5) for 2.60 m.
Coordinates of the Receiver (x, y, z)	(2, 2, 2)
Image specifications	
Image	256 x 256 pixels
Image HD	1920 x 1080 pixels
Modulation parameters	
Carrier frequency	1 MHz
Sampling frequency	10 MHz
Block size (OOK/ASK)	1×10^6
Bit period (bp)	1×10^{-6} s
Amplitude (A1)	OOK: 1, ASK: 10
Amplitude (A0/A2)	0
Bits per symbol (OFDM-QPSK)	2
Number of subcarriers (OFDM-QPSK)	64
Cyclic prefix length (OFDM-QPSK)	16
SNR range	-10:2:60 dB
Packet size	1024 bits
LOS Channel Parameters	
Semi-angle of the LED (theta)	90°
Lambertian order (m)	$-log_{10}(2)/log_{10}(\cos(\theta))$
Field of View (FOV)	180°
Aperture area (Ap)	0.05

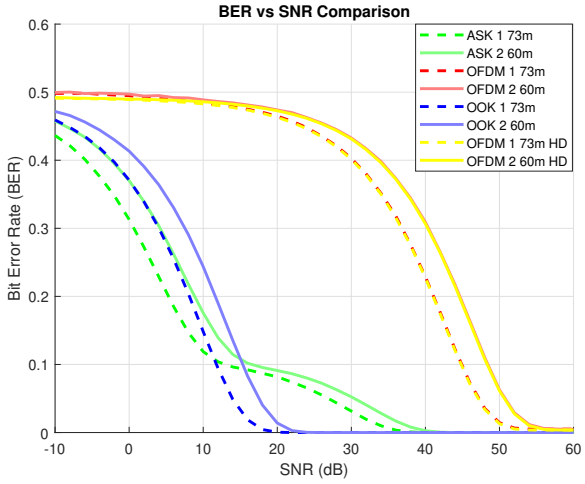

Fig. 3. BER vs SNR for different modulation schemes and Euclidean distances.

A. BER vs SNR

The first metric used to evaluate the system's performance is the BER as a function of the SNR. In the graph in Fig. 3, it can be observed that OOK and ASK modulations perform better than OFDM modulation. As distances increase, the results worsen for each case. Finally, it is observed that OOK tends to have better results at both short and long distances. On the other hand, it can be seen that OFDM's performance is the same for both low-resolution and HD images.

The superiority of OOK in terms of BER is due to its simplicity and robustness to noise, as it uses two clear amplitude levels to represent bits, facilitating precise demodulation. In contrast, OFDM, although spectrally efficient, is more susceptible to noise due to the complex nature of its signal, which is divided into multiple subcarriers. This susceptibility increases especially with longer distances, where signal dispersion and attenuation more significantly affect performance. Additionally, the similar performance of OFDM for images of different resolutions is explained by the high spectral efficiency and resistance to inter-symbol interference (ISI) that characterize this modulation.

B. Data Transmission Rate vs SNR

The second metric used to evaluate the system's performance is the data transmission rate as a function of the SNR. In the graph in Fig. 4, it can be observed that OFDM modulation has significantly better performance in terms of transmission

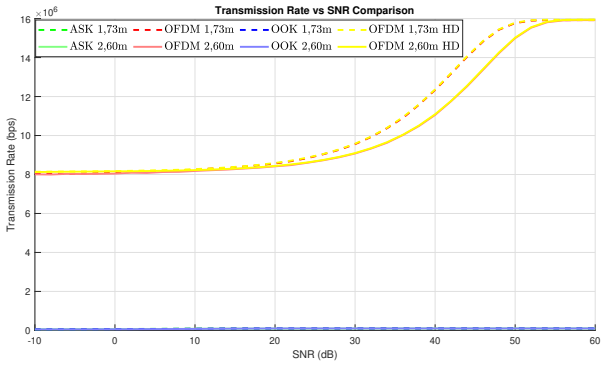

Fig. 4. Transmission Rate vs SNR for different modulation schemes and Euclidean distances.

rate compared to OOK and ASK. OFDM reaches values in the range of 8×10^6 to 16×10^6 bps, while, as shown in Fig. 5, OOK and ASK modulations remain in the order of 6×10^4 to 11×10^4 bps. The transmission rate of OFDM begins to increase significantly from approximately 30 dB for both distances (1.73 m. and 2.60 m.), reaching very high transmission rates. It is also observed that the transmission rates remain constant when handling a high-resolution image.

The superior performance of OFDM in terms of transmission rate is due to its ability to divide the bandwidth into multiple subcarriers, allowing parallel data transmission and, therefore, more efficient use of the spectrum. This results in a significantly higher transmission rate compared to OOK and ASK, especially at high SNR values. OFDM modulation is less affected by noise and ISI, contributing to its high spectral efficiency and ability to maintain high transmission rates even at longer distances.

To provide a more detailed analysis of the ASK and OOK modulations, which have much lower transmission rates, a second comparative graph is presented. In the graph in Fig. 5, it is observed that both ASK and OOK show an increase in transmission rate with increasing SNR. For shorter distances (1.73m), both modulations achieve a higher transmission rate

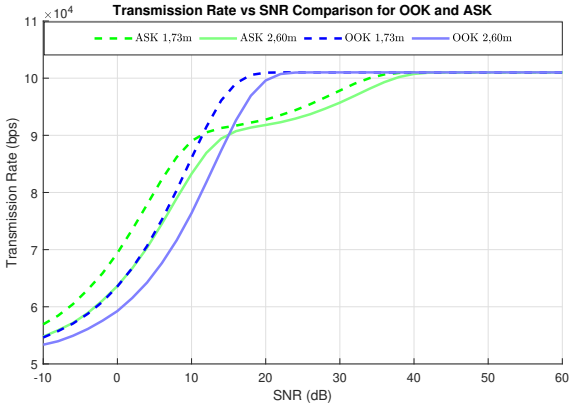

Fig. 5. Transmission Rate vs SNR for ASK and OOK modulation schemes.

compared to longer distances (2.60m).

OOK modulation shows a transmission rate slightly higher than the ASK modulation across all the SNR ranges evaluated. For SNRs above 20 dB, OOK tends to stabilize, while for ASK, stabilization occurs above 40 dB, reaching maximum rates close to 100,000 bps.

The difference in transmission rates between OOK and ASK is due to the simplicity of OOK, which allows faster transmission with less processing. However, both modulations are less efficient than OFDM due to their inability to handle multiple subcarriers simultaneously, limiting the amount of data that can be transmitted in a given period. The stability of OOK at lower SNR compared to ASK is due to its more robust design, albeit at the cost of lower spectral efficiency.

C. Latency vs SNR

The last metric used to evaluate the system's performance is latency as a function of the signal-to-noise ratio (SNR), where lower latency represents better performance. In the graph in

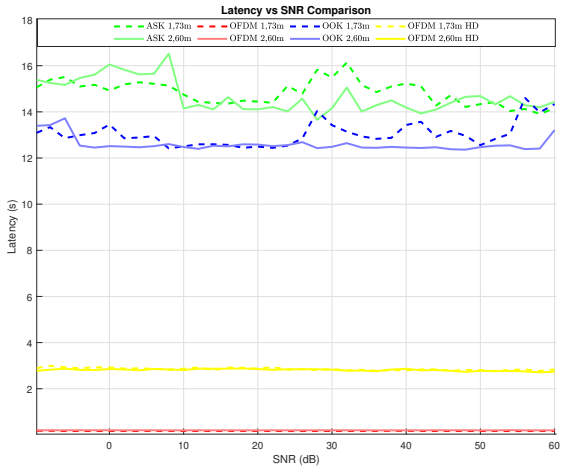

Fig. 6. Latency vs SNR for different modulation schemes and Euclidean distances.

Fig. 6, it is observed that OOK and ASK modulations have significantly higher latency compared to OFDM. In particular, the latency for OOK and ASK remains high and constant throughout the evaluated SNR range, with OOK showing slightly lower latency than ASK, ranging from 12-13 and 14-16 seconds, respectively.

OFDM modulation, on the other hand, shows an exceedingly lower latency, remaining almost constant and very low, with values very close to 0.2 s for the low-quality image. For this reason, simulations of HD image transmission with OOK and ASK modulations were not considered, as seen in Fig. 6, the difference between the modulation of the low-quality image with OFDM and the HD image shows a notable increase, since the simulation with the HD image shows a latency performance close to 3 seconds. In contrast, with the other modulations, the increase in latency would have been even greater, possibly near 200 seconds.

The speed and low latency of OFDM are due to its ability to transmit data across multiple subcarriers simultaneously, allowing for more efficient spectrum use and rapid data recovery. This makes OFDM especially suitable for HD image transmission, as it can handle large amounts of data efficiently, significantly reducing transmission time and ensuring fast and reliable delivery of high-quality images. OFDM's ability to maintain low latency even under variable SNR conditions highlights its suitability for image transmission applications where speed and efficiency are critical.

V. Conclusions

In this study, the performance of different modulation techniques (OOK, ASK, and OFDM) in a VLC system for image transmission has been evaluated. The results show that for the transmission of less demanding images, OOK and ASK modulations are suitable, especially in environments where noise can significantly affect signal quality. These modulations exhibit a lower bit error rate (BER) compared to OFDM under noisy conditions, making them more reliable in such scenarios.

However, when rapid image transfer is required, particularly for high-definition images, OFDM modulation stands out as the best option. OFDM offers a significantly higher transmission rate and considerably lower latency, which is crucial for applications demanding high speed and efficiency. Therefore, for applications that require the transmission of high-definition images and high transfer rates, OFDM provides superior performance, making this modulation technique the most suitable choice in these cases.

Future work in this line of research includes transmission scenarios not only with images but also with video in several formats, improving the performance metrics obtained in this work with artificial intelligence schemes in reception and including the analysis of the reflection components in the indoor environment.

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