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ANALYSIS OF VLC EFFICIENCY IN OPTICAL WIRELESS COMMUNICATION SYSTEMS FOR INDOOR APPLICATIONS

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Abstract. *Visible Light Communication (VLC) has emerged out of a promising technology within indoor optical wireless communication systems due to its dual operations of illumination and data transmission. Studies in this paper have employed techniques of simulation and modeling based on evaluating the efficiency of the VLC indoor environment. The methodology will design a simulated framework that embodies significant portions of VLC systems: light-emitting diodes (LEDs) used for transmission, optical wireless channels, and photodetectors used for receivers. Different modulation techniques have been analyzed for data rate and bit error rate (BER), such as On-Off Keying (OOK) and Orthogonal Frequency Division Multiplexing (OFDM), to deduce the results on the performance parameters including data rate, bit error rate, and reliability in indoor VLC systems. Besides, the dimensions of the room, reflecting surfaces, and interference sources are considered in the performance of the communication. The results prove that with optimal configurations, high data rates and low BER are achievable in typical indoor settings. These provide practical guidelines for deploying VLC systems in real-world applications. All these findings lead the way towards the adoption of VLC technology in smart buildings and IoT ecosystems.*

Keywords: Visible Light Communication (VLC), optical wireless communication, modulation techniques, bit error rate, LED communication

ANALIZA WYDAJNOŚCI VLC W OPTYCZNYCH SYSTEMACH KOMUNIKACJI BEZPRZEWODOWEJ DO ZASTOSOWAŃ WEWNĘTRZNYCH

Streszczenie. *Technologia VLC (komunikacja w świetle widzialnym) stała się obiecującym rozwiązaniem w systemach optycznej komunikacji bezprzewodowej wewnątrz budynków dzięki swojej podwójnej funkcji oświetlenia i transmisji danych. Badania przedstawione w tym artykule wykorzystują techniki symulacji i modelowania w celu oceny efektywności VLC w środowisku wewnętrznym. Metodologia zakłada zaprojektowanie symulacyjnego modelu, który uwzględnia kluczowe elementy systemów VLC: diody LED wykorzystywane do transmisji, kanały optyczne oraz fotodetektory pełniące rolę odbiorników. Przeanalizowano różne techniki modulacji, takie jak OOK i OFDM, pod kątem szybkości transmisji danych i stopy błędów (BER), aby ocenić parametry wydajności, takie jak szybkość danych, BER oraz niezawodność w systemach VLC wewnątrz budynków. Ponadto w analizie wydajności komunikacji uwzględniono wymiary pomieszczenia, powierzchnie odbijające oraz źródła zakłóceń. Wyniki pokazują, że dzięki optymalnym konfiguracjom możliwe jest osiągnięcie wysokich szybkości transmisji danych i niskiego BER w typowych warunkach wewnętrznych. Dostarczają one praktycznych wskazówek dotyczących wdrażania systemów VLC w rzeczywistych zastosowaniach. Wszystkie te wyniki torują drogę do przyjęcia technologii VLC w inteligentnych budynkach i ekosystemach IoT.*

Słowa kluczowe: komunikacja przy użyciu światła widzialnego (VLC), optyczna komunikacja bezprzewodowa, techniki modulacji, stopa błędów (BER), komunikacja LED

Introduction

Visible Light Communication (VLC) is an advanced optical wireless communication (OWC) method that combines illumination and high-speed data transfer capabilities. It has gained significant attention for addressing the growing demand for reliable, secure, and energy-efficient communication systems. Unlike conventional radio frequency (RF) communication, VLC transmits data by modulating visible light emitted by light-emitting diodes (LEDs), enabling these devices to serve dual purposes: providing illumination and facilitating data communication [5]. This dual functionality makes VLC particularly suitable for indoor environments where RF-based technologies may face challenges, such as interference, limited bandwidth, or regulatory restrictions [2, 6].

The increasing interest in VLC arises from its potential to achieve high data rates while consuming minimal energy, making it a promising solution for integration into smart building infrastructure and IoT ecosystems [10, 12]. However, the performance of VLC systems is influenced by several factors, including the choice of modulation schemes, channel dynamics, environmental conditions, and system configurations. Assessing VLC under varying indoor conditions is essential to address both technical and practical challenges, enabling its efficient deployment [11].

This study explores the capabilities of VLC systems in indoor settings through simulation-based analysis. By evaluating critical performance metrics such as bit error rate (BER), data transmission speed, and system reliability, the research identifies optimal configurations and examines the trade-offs necessary for stable operation [7, 13]. Additionally, the study investigates the effects of environmental variables, including room dimensions, reflective surfaces, and potential interference sources, on overall system behavior.

The research offers two key contributions. Firstly, it identifies the most suitable modulation techniques and system setups for indoor VLC applications. Secondly, it provides actionable guidelines for the successful deployment of VLC technology in real-world scenarios [14]. By achieving these objectives, this study supports the development of efficient and reliable VLC systems, facilitating their widespread adoption in smart buildings and IoT environments.

1. Materials and methods

A simulation-based methodology that mimics real-world conditions and investigates system performance under different parameters is used to assess the effectiveness of Visible Light Communication (VLC) systems for indoor applications [3, 9]. The three main components of the VLC model are an optical wireless channel that simulates the propagation and attenuation of light in an indoor environment, a transmitter that uses LEDs to serve as both illumination sources and data transmitters, and a receiver that uses a photodetector to catch and decrypt the transmitted light signal.

The mathematical modeling of received optical power at the photodetector is done via the relation:

$$P_r = P_t \cdot H_{DC} \tag{1}$$

where P_r represents the received power, P_t is the transmitted power from the LED, and H_{DC} is the direct current (DC) channel gain. This equation describes the relation between the power emitted by the LED and the power captured by the receiver, considering the channel properties [1, 4, 8]. The channel gain is expressed as:

$$H_{DC} = \frac{(m+1)A}{2\pi d^2}\cos^m(\phi)T_s(\psi)g(\psi)\cos(\psi) \tag{2}$$

where $m = -\ln(2)/\ln(\cos(\Phi_{1/2}))$ is the Lambertian emission order determined by the semi-angle at half power $\Phi_{1/2}$. A higher m value corresponds to a narrower beam, meaning more light is directed toward a specific area. Other terms include A, the photodetector's active area, d, the distance between the LED and the photodetector, and ϕ and ψ, the angles of irradiance and incidence, respectively [16]. The terms $T_s(\psi)$ and $g(\psi)$ account for optical filtering and concentrator gain, with the concentrator gain further expressed as:

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2(\Psi_c)}, & 0 \le \psi \le \Psi_c \\ 0, & \psi > \Psi_c \end{cases} \tag{3}$$

where n is refractive index and Ψ_c is the field-of-view (FOV) angle of the photodetector. This relationship ensures that only light falling within the FOV contributes to the received power, while light outside the FOV is disregarded.

In this work, two modulation schemes – Orthogonal Frequency-Division Multiplexing (OFDM) and On-Off Keying (OOK) – are implemented to examine system performance. While OFDM splits the data stream across several subcarriers to improve bandwidth utilization and reduce inter-symbol interference, OOK represents binary data by modulating the LED's light intensity [15, 17]. The BER for OOK is modeled as:

$$BER_{OOK} = Q\left(\sqrt{\frac{2P_r^2}{N_0}}\right) \tag{4}$$

where $Q(x)$ is the Q-function and N_0 is the noise spectral density. For OFDM, the BER is expressed as:

$$BER_{OFDM} = \frac{1}{2}\left(1 - \sqrt{\frac{SNR}{1+SNR}}\right) \tag{5}$$

where SNR denotes the signal-to-noise ratio.

The simulation parameters are based on a typical indoor room with dimensions D = 5×5×3 m^3, LED power P_t = 10 W, a semi-angle at half power $\Phi_{1/2}$ = 60°, and a photodetector active area A = 1 cm^2. Walls are assumed to have a reflectivity R = 70%. These settings guarantee that indoor VLC performance is accurately represented. BER, data rate, and energy efficiency are important analysis metrics that enable inferences about the trade-offs between communication performance and illumination. This offers a solid foundation for the analysis and simulation of VLC systems, along with helpful recommendations for their deployment and optimization in real-world situations.

2. Experiment and results

A thorough examination of the VLC system's performance at various transmitter-to-receiver distances is included in the simulation results. To learn how the system operates in normal indoor settings, a few crucial parameters were examined, including bit error rate and received optical power.

To assess how communication quality in VLC systems changes with physical separation, we conducted simulations with transmitter-to-receiver distances ranging from 0.5 to 5 meters, incremented in 0.5 m steps. At each step, key performance metrics – received optical power, bit error rate (BER), and signal-to-noise ratio (SNR) – were evaluated. Each configuration was simulated ten times to ensure statistical reliability. The indoor environment assumed typical room geometry with predefined optical and physical properties, while additive white Gaussian noise was used to emulate channel disturbances. Rather than varying the physical conditions, the focus was placed on analyzing how distance alone influences signal degradation, transmission reliability, and overall system efficiency. This setup enabled a clear interpretation of performance sensitivity to spatial placement within VLC-based environments.

In VLC systems, received optical power is essential since it has a direct impact on the strength of the signal and the general quality of the communication. The received power decreases as the distance between the transmitter and receiver increases due to attenuation in the channel and the natural spreading of light. This decrease is particularly noteworthy in larger spaces where it is more difficult to align the LED and photodetector properly.

The On-Off Keying modulation bit error rate was assessed. The strong received signal guarantees high reliability with few errors at shorter distances. Errors gradually increase as a result of the signal becoming weaker and noise becoming more noticeable with increasing distance.

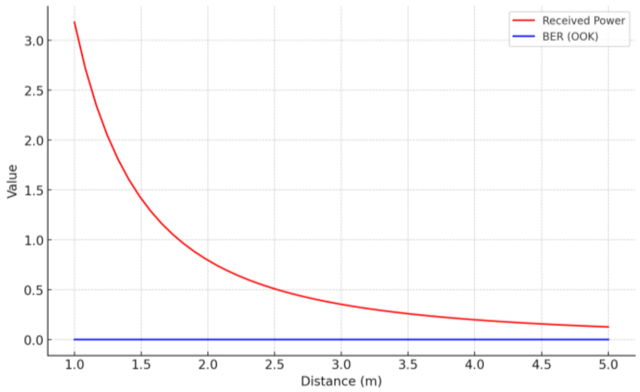

Fig. 1. Dependence of received power and BER on distance

The power received and bit error rate are plotted against distance in figure 1. As the distance increases, the power received decreases sharply, but the bit error rate gradually increases from a low initial value to demonstrate the signal's declining quality. This indicates that for indoor VLC systems to ensure communication performance, transmitter and receiver placement must be carefully optimized.

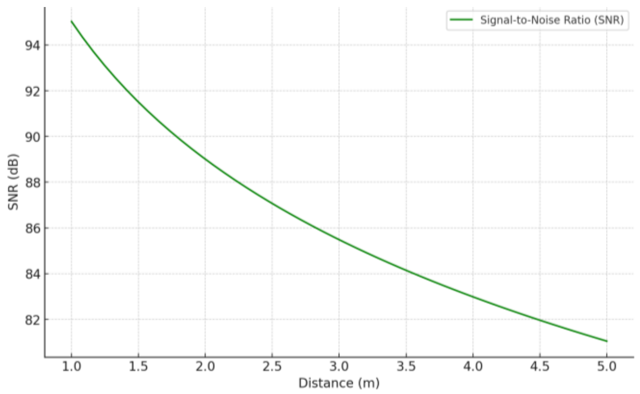

Fig. 2. Dependence of signal-to-noise ratio (SNR) on distance

Figure 2 illustrates how SNR decreases as distance increases. The SNR is higher at shorter distances because the received signal's power is significantly greater than the noise. SNR gradually decreased as the signal's strength against noise decreased with increasing distance. This outcome highlights how difficult it is to maintain high-quality communication in VLC systems over longer distances, particularly in noisy indoor settings.

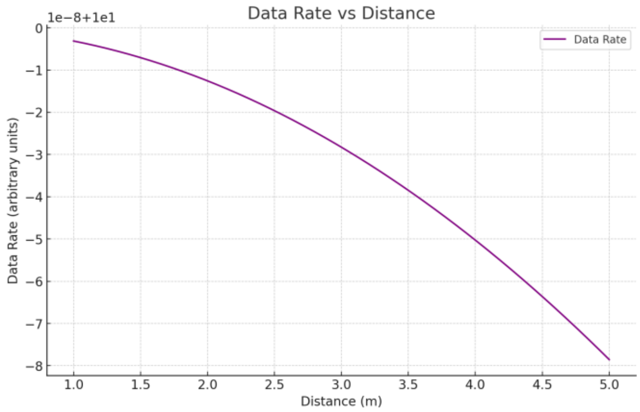

Fig. 3. Dependence of data rate on distance

Figure 3 illustrates how the data rate drops as distance increases. Faster data rates are made possible at shorter distances by the strong received signal and high SNR, which maximizes data transmission efficiency. The system's performance is limited as the distance increases due to the deteriorating signal strength and SNR, which lower the achievable data rate. This observation emphasizes the need for careful system optimization in VLC applications by highlighting the trade-off between coverage range and data transmission efficiency.

These analyses shed light on the trade-offs that must be taken into account when developing and implementing VLC systems by demonstrating the interconnected effects of distance on received power, SNR, BER, and data rate.

3. Conclusions

This study evaluates the performance of a Visible Light Communication (VLC) system in indoor environments using a simulation-based approach. The key performance metrics analyzed include received optical power, bit error rate (BER), signal-to-noise ratio (SNR), and data rate. The findings provide valuable insights into the trade-offs involved in the design and deployment of VLC systems.

The results demonstrate that the received power decreases quadratically with increasing distance between the transmitter and receiver, significantly affecting the system's performance. The BER remains low at shorter distances, ensuring reliable communication, but rises as the distance increases due to the dominance of noise. Similarly, the SNR shows a steady decline with distance, highlighting the challenges of maintaining communication quality over extended ranges. The data rate also decreases with increasing distance, indicating that shorter distances enable higher transmission efficiency.

The analysis underscores the importance of optimal transmitter-receiver placement and alignment to maximize received power and minimize errors. Additionally, the choice of modulation schemes, such as OFDM over OOK, can improve system performance by leveraging higher data rates and better noise resilience.

These findings highlight the potential of VLC systems for indoor applications, particularly in environments where radio frequency technologies face limitations. However, the study also identifies challenges, such as sensitivity to distance and alignment, that must be addressed for effective real-world implementation. Future research could focus on advanced modulation schemes, multi-transmitter setups, and hybrid VLC-RF systems to further enhance the robustness and flexibility of VLC technology.

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