Analysis of Parameters on Performance of Visible Light Communication

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Abstract: Visible Light Communication (VLC) is a prominent technology for simultaneous illumination and data transmission using Light Emitting Diodes (LEDs). While recent studies have predominantly focused on enhancing communication speed, the impact of various hardware, software, and environmental parameters on the communication efficacy, particularly for systems adhering to specific physical layer standards, has not been exhaustively investigated. This study presents the design and systematic performance evaluation of a visible light communication system engineered to operate according to Layer 1 (PHY I) of the IEEE 802.15.7-2011 standard. The system, based on an embedded Linux platform, utilizes an LED at the transmitter and a photodiode at the receiver, with higher-layer communication functions, managed by software. Performance is rigorously evaluated by varying parameters including ambient lighting conditions, transmission distance, data packet repeat times (a software-configurable parameter influencing transmission frequency), payload size, the use of different optical filters (UV, Polarizer, Neutral-Density), and distinct LED types (low-power vs. high-power). A key finding is the significant data communication improvement achieved through the application of a Neutral-Density (ND) filter, which effectively reduces the negative impact of light interference. The study further incorporates sensitivity and robustness analyses to provide a more comprehensive understanding of the system's operational characteristics. The results offer valuable insights for the practical design and optimization of PHY-I compliant VLC systems.

Keywords: visible light communication (VLC); IEEE 802.15.7; communication system signaling; performance analysis; parameter analysis; Neutral-Density filter; wireless communication

1 Introduction

1.1 Background and Motivation

The proliferation of mobile devices in daily life has led to an exponential increase in wireless communication requirements. Beyond personal mobile devices, the rise of embedded networked systems, such as the Internet of Things (IoT) and vehicular networks, has further intensified the demand for the electromagnetic spectrum band allocated for technologies like Wi-Fi. Consequently, the phenomenon known as "Wi-Fi Spectrum Crunch" is emerging as a significant challenge due to the escalating demand for finite wireless resources. Visible Light Communication (VLC) presents a compelling potential solution to alleviate this spectrum congestion. VLC operates at frequencies much higher than those used by Wi-Fi, offering the capability for wireless communications at very high speeds. As illustrated in Figure 1, which depicts the electromagnetic spectrum, VLC utilizes the visible light portion, corresponding to wavelengths between 380 and 780 nm.

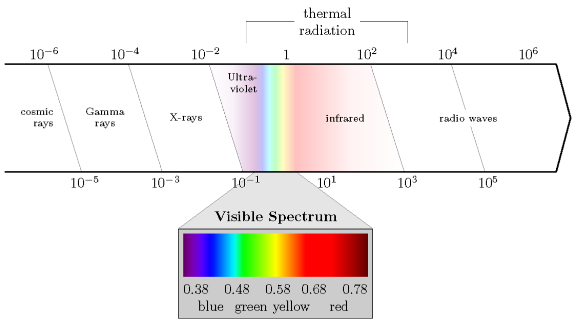

Figure 1
Electromagnetic Spectrum

Visible Light Communication, a subset of Optical Wireless Communication (OWC), leverages the visible light spectrum to provide low-cost, energy-efficient wireless solutions capable of achieving high data rates. VLC employs modulated optical radiation from light-emitting diodes (LEDs) or laser diodes to convey digital information, typically without any discernible effect on the human eye [1]. Intensity modulation and direct detection (IM/DD) are commonly preferred for the physical layer (PHY) in VLC systems. Consequently, initial research efforts focused on relatively simple modulation techniques such as on-off keying (OOK) and pulse position modulation (PPM) [2]. These modulation schemes, OOK and PPM, were subsequently adopted in the IEEE 802.15.7 standard, which was formally issued in 2011 [3]. As a spectrum-rich alternative to conventional RF communications, VLC has garnered considerable interest from both the academic research community and industry [4]. VLC is increasingly recognized as a transformative technology that can address the challenges of RF communication density in the wireless spectrum and holds the potential to form the infrastructure for next-generation network systems. The application areas for Visible Light Communication are diverse and expanding, including but not limited to: Aviation, Clock Calibration, Communication and Assistance in Natural Disasters, Hospitals, Human Perception, Indoor Location Determination, Internet of Things (IoT), a novel paradigm termed Internet of Lights (IoL), Mobile Interaction, Museums, Next-Generation Cellular Networks, Next-Generation High-Speed Cellular Networks, Security in Defense Systems, SmartLighting, Toy-to-Toy Communication, Underwater Communication and Wi-Fi Spectrum Support.

1.2 Literature Review and Gap Analysis

Studies aimed at adapting VLC networks with software highlight the need to accelerate research in this domain [5]. Similarly, the anticipated increase in the number of internet-connected smart devices may foster a new infrastructure type, the Internet of Lights (IoL). Current academic endeavors in VLC are largely concentrated on theoretical explorations and laboratory-based studies. However, end-user product design and academic investigations into price/performance characteristics that align with established standards have often been secondary. Several studies have presented cost-effective VLC structures suitable for product development: Dietz et al. (2003) proposed a very low-cost solution [6]; Wang et al. (2014) explored TCP/IP integration [7]; Klaver et al. (2015) presented a convenient and straightforward system design [8]; Hewage et al. (2016) developed a hybrid structure with a radio controller [9]; Schmid et al. (2016) also developed a hybrid structure using Arduino and a radio controller [10]; Tian et al. (2016) focused on ambient light adaptation [11]; Wu et al. (2017) addressed dimming controllability, a crucial component of the IEEE protocol for end-users [12]; and Yin et al. (2018) achieved 100 Kbps communication speed at a 6-meter distance in a full-duplex structure [13].

The challenge of understanding system behavior based on observable data, as explored in cognitive process modeling, finds parallels in VLC where system performance is inferred from parameters affecting signal reception and interpretation. The necessity for developing accurate, application-specific models to predict and optimize system performance, as demonstrated in fields like visco-damper mechanics, underscores the approach of this paper in systematically analyzing parameters crucial for VLC systems. Modern complex systems often benefit from advanced modeling techniques capable of handling dynamic data and uncertainties, such as those proposed for data streams with missing values. While our study employs direct experimental analysis, this highlights the broader context of sophisticated analytical tools applicable to communication systems. Furthermore, advancements in sensor-based systems, for instance in robotic navigation requiring precise pose estimation, emphasize the role of accurate parameter understanding and signal processing, a theme relevant to VLC link reliability. The importance of detailed modeling for system optimization is also evident in areas such as pneumatic control systems, reinforcing the value of parametric studies. Analytical models for monitoring and forecasting based on statistical data, such as those developed for pandemic analysis, share common ground with our approach of analyzing performance data to understand VLC system characteristics. While beyond the scope of the current experimental investigation, advanced estimation techniques like Extended Kalman Filters and fuzzy observers offer pathways for enhanced state estimation and control in complex nonlinear systems, including potentially future VLC implementations.

Despite these advancements, the specific impact of a comprehensive set of software-hardware component changes and environmental variables on the communication performance of IEEE 802.15.7 PHY-I compliant VLC systems has not been adequately and systematically examined in an integrated study. The motivation for our analysis and modeling approach stems from this identified gap: to provide a detailed, practical understanding of how these multifaceted parameters collectively influence real-world VLC performance, thereby informing more effective system design and deployment.

1.3 Novelty and Contributions of this Work

This paper addresses the identified gap by presenting a detailed experimental investigation into the effects of various software configurations, hardware components, and environmental conditions on the performance of a visible light communication system designed and implemented according to the IEEE 802.15.7 PHY-I standard. The primary contributions of this work are:

1) A systematic performance evaluation of a custom-designed IEEE 802.15.7 PHY-I VLC system under varying ambient lighting conditions, transmission distances, data packet iteration times (a software-controlled parameter), payload sizes, and different LED types.
2) A novel investigation into the impact of different optical filters (UV, Polarizer, Neutral-Density) on VLC throughput, with a key finding on the significant performance improvement and interference mitigation provided by the Neutral-Density (ND) filter, an aspect underexplored in this specific context.
3) An analysis of the interplay between software factors (data packet iteration times), hardware factors (LED types, optical filters), and environmental factors (ambient light levels), providing a holistic view of their combined effects on communication performance.
4) The inclusion of sensitivity and robustness analyses based on the experimental data to further quantify the system's response to parameter variations and its operational stability under challenging conditions.

5) Provision of practical data, insights, and design considerations that can directly inform the development, optimization, and deployment of similar cost-effective, standard-compliant VLC systems for indoor applications.

1.4 Manuscript Organization

The rest of this paper is organized as follows. Section 2 explains the IEEE 802.15.7 standardization and reviews related work. Section 3 presents the system model, including implementation details, hardware setup, design specifications, and the conceptual mathematical basis for performance evaluation. Section 4 details the performance evaluation methodology, presents the experimental results under various parametric conditions, and includes discussions on sensitivity, robustness, validation, and a comparative analysis. Finally, Section 5 concludes the paper and suggests potential avenues for future research.

2 IEEE 802.15.7 Standardization and Related Work

The IEEE 802.15.7 physical layer (PHY) and media access control (MAC) layer specifications for VLC were established in 2011. This standard identified and categorized three distinct physical layer types (PHY I, PHY II, PHY III) offering different data rates, ranging from 11.67 kbps to 96 Mbps [3]. PHY I is specifically aimed at providing reliable low-data-rate transmission for long-distance outdoor applications, although its principles are also applicable to robust indoor systems. To effectively manage path loss and mitigate background lighting interference, particularly in challenging environments, PHY I employ stronger channel coding methods such as Reed-Solomon (RS) codes and Convolutional Codes (CC). In the RS coding scheme, the input bitstream is encoded where n bits are transformed into k codewords, contingent on the generator polynomial defined over a Galois Field (GF). Within the PHY I architecture, an interleaving stage, which includes zero padding and puncturing, is positioned between the RS and CC encoders. This interleaving is designed to counteract burst errors and has been shown to provide an additional performance improvement of approximately 1dB.

In each operational mode of PHY I, Run-Length Limited (RLL) line codes are utilized. These codes serve to maintain DC balance, which is crucial for preventing baseline wander at the receiver, and to eliminate the perceptible flickering effect from the light source. RLL codes also help to avoid long, uninterrupted sequences of 1s or 0s, which can complicate clock recovery. Specifically, Manchester code, which expands each data bit into a 2-bit symbol, is used for On-Off Keying (OOK) modulation. For Variable Pulse Position Modulation (VPPM), a 4B6B code, expanding 4 data bits into 6-bit symbols, is employed. Table 1 provides a summary of the key specifications for PHY I as defined in the IEEE 802.15.7 standard.

Table 1
PHY I in IEEE 802.15.7 standard [3]

Modulation	RLL Code	Optical Clock Rate	FEC		Data Rate
			Outer Code (RS)	Inner Code (CC)	
OOK	Manchester	200 kHz	(15,7)	1/4	11.67 kb/s
			(15,11)	1/3	24.44 kb/s
			(15,11)	2/3	48.89 kb/s
			(15,11)	none	73.3 kb/s
			none	none	100 kb/s
VPPM	4B6B	400 kHz	(15,2)	none	35.56 kb/s
			(15,4)	none	71.11 kb/s
			(15,7)	none	124.4 kb/s
			none	none	266.6 kb/s

The standard also defines different dimming methods contingent on the modulation type. For OOK modulation, dimming can be achieved by altering the ON and OFF signal levels or by varying the average duty cycle of the transmitted signal. Compensation symbols are inserted into the data frame in OOK to adjust the perceived light intensity. In contrast, for VPPM, dimming is accomplished by varying the pulse width of the ON state. The standard specifies a dimming resolution of 0.1% for VPPM. Dimming with OOK modulation results in a constant communication range but a variable data rate, whereas dimming with VPPM provides a continuous data rate but with a varying communication range.

Visible light communication encompasses short-range optical wireless communication utilizing the visible light spectrum (380 nm to 780 nm) as the transmission carrier. The IEEE 802.15.7 standard supports high-data-rate VLC up to 96 Mbps. Fast modulation techniques are applied to visible light sources, and dimming functionalities can also be integrated. For flicker-free, high-data-rate VLC, IEEE 802.15.7 provides adaptable dimming mechanisms. VLC is an essential wireless communication application technique that refers to unguided optical transmission using advanced LEDs. Due to its potential for a wide array of application areas, VLC has attracted increasing attention. In recent years, the exponentially growing number of mobile devices and wireless services has also created a significant demand for RF-based technologies. Advances in LED light bulb technology have revolutionized the lighting industry. Leveraging LEDs, VLC offers a license-free spectrum and the potential for high data rates, positioning it as a complementary wireless communication technology to radio frequency communication.

3 System Model

3.1 System Architecture

The designed VLC system serves as a development platform for VLC networks and is composed of three primary parts: the development platform, a printed circuit board (PCB) populated with necessary hardware components, and the controlling software. The BeagleBone Black (BBB) was selected as the core development platform for this system design. Xenomai's real-time development framework was integrated into version 3.8 of the Debian operating system's kernel, which is the official distribution for the BBB platform. This integration ensures the real-time processing capabilities required for communication tasks.

Figures 2 and 3 illustrate the block diagram of the implemented VLC system. In this design, the transmission medium is air. LEDs are employed as optical transmitters, and optical sensors (photodiodes) are used as receivers. The system implements PHY I communication functionalities, including modulations (specifically OOK), RLL coding (Manchester code), and both internal and external Forward Error Correction (FEC) codes, in conjunction with the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol to manage medium access.

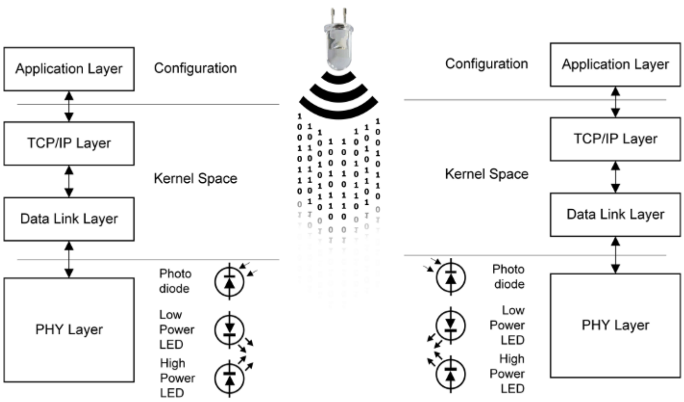

Figure 2

Block structure

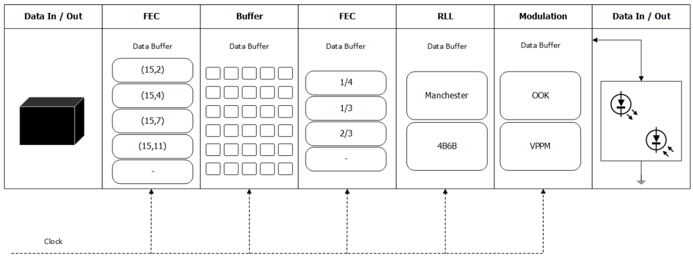

Figure 3
Block structure

3.2 Communication Protocol and Frame Format

The communication protocol adheres to a standard frame format, as presented in Table 2. This frame structure is essential for organizing data transmission and ensuring reliable communication between the transmitter and receiver.

Table 2
Frame Format

Frame	Preamble	SFD	Frame Length	Destination Address	Source Address	Protocol	Payload	CRC
Length (byte)	3	1	2	4	4	2	0-255	2

The study aimed to incorporate VLC into smart lighting applications using both low-power and high-power LEDs by integrating cost-effective electronic components. The developed system is designed to operate at distances of up to 5 meters with a bandwidth of approximately 27 kb/s, targeting Layer 1 (PHY I) of the IEEE 802.15.7 protocol.

3.3 Hardware Setup and Design Specifications

The hardware setup was designed with specific performance targets aligning with indoor VLC applications. These included achieving reliable data transmission up to 5 meters, supporting a data rate compatible with IEEE 802.15.7 PHY-I specifications (target ~27 kb/s), and utilizing cost-effective, readily available components. The design prioritized operational stability under typical indoor ambient lighting conditions. Figures 4 and 5 show the experimental setup of the system and the transceiver unit, respectively. The hardware components utilized in the transceiver units are detailed in Table 3.

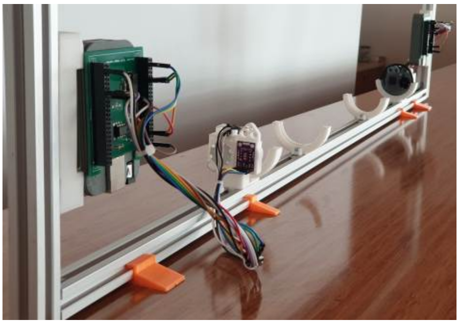

Figure 4
Experimental setup of the system

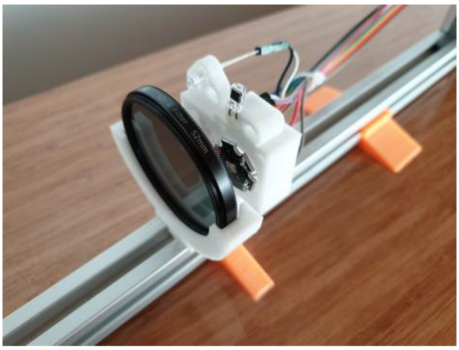

Figure 5
Transceiver

Table 3
Hardware components

1	L-53SRC-J4	Low-power 5 mm red LED
2	REBEL-STAR-NW100	High-power LED, 3V, 2,7W
3	BPW46	Photodiode 350-1120 Nm (for just testing)

3.4 Mathematical Modeling and Parameter Derivation

While this study primarily focuses on experimental analysis, the performance metrics are grounded in established communication principles. The data throughput (η) is a primary performance index and is calculated as:

$$\eta = \frac{Nbits_{payload}\ x\ Npackets_{succesful}}{Ttotal_{transmission}} \quad (1)$$

where Nbits_payload represents the number of bits in the payload of a single data packet, Npackets_successful is the count of packets that are successfully received and pass the Cyclic Redundancy Check (CRC), and Ttotal_transmission is the total time elapsed during the transmission test for a given configuration.

The system operates based on the principles of intensity modulation and direct detection (IM/DD). The signal-to-noise ratio (SNR) at the receiver, although not explicitly modeled in exhaustive detail within this experimental framework, is fundamentally influenced by several key factors. These include the transmitted optical power (determined by the LED type and driving conditions), channel path loss (which is heavily dependent on the transmission distance), the sensitivity of the receiver's photodiode, and the level of ambient light noise. Our experimental design systematically varies parameters that directly or indirectly affects these components of the SNR, thereby allowing for an empirical assessment of their impact on overall system performance.

The parameters for the system components, such as the nominal optical power of the LEDs (L-53SRC-J4, REBEL-STAR-NW100) and the responsivity characteristics of the photodiode (BPW46), were obtained from the respective manufacturer datasheets. Experimental parameters, including transmission distance, payload size, and ambient light levels, were precisely controlled and systematically varied during the experiments, as detailed in Section 4. Software-configurable parameters, such as the data packet iteration times (which influence the effective transmission frequency), were set and managed within the embedded Linux environment running on the BeagleBone Black platform.

4 Performance Evaluation and Discussion

This section details the experimental methodology and presents the results of the performance evaluation. For each experimental scenario, throughput, as defined in Equation (1), was measured. The data presented in the figures were obtained through direct measurements from our experimental setup, with each data point typically representing an average of multiple transmission runs to ensure reliability.

Table 4 presents the variables that were systematically altered in the application scenarios to assess their impact on system performance. Given that the system design is intended for indoor VLC applications, environmental effects such as atmospheric turbulence and absorption, which are more pertinent to outdoor or long-range free-space optical communication, were not investigated. However, ambient light, a critical factor affecting communication performance in indoor environments, was included as a key variable. Finally, the impact of various optical filters on the system's performance was also thoroughly investigated.

Table 4
Experiments variable

Ambient Light	Distance	Frequency	Payload	Filter	LED
1 lux	30 cm	5 kHz	128 kb	No Filter	Low Power
120 lux	50 cm	10 kHz	256 kb	UV Filter	High Power
300 lux	100 cm	30 kHz	512 kb	Polarizer Filter	
		50 kHz	768 kb	Neutral-Density Filter	
		60 kHz	1024 kb		

4.1 Throughput with Different Ambient Light and Distance Variables

Table 5 shows the test constants used in the experiments evaluating throughput under different ambient light and distance conditions. The data were collected with the data packet iteration number set to 50, a payload of 1024 kB, using the high-power LED, and without any optical filter.

Table 5
Test constants used in throughput with different ambient light and distance experiment

Data Packet Iteration Times	Payload	Filter	LED
50	1024 kB	-	high-power

Figure 6 shows the measured throughput for ambient light values of 1, 120, and 300 lux, across communication distances of 30, 50, 100, 200, 300, 400, and 500 cm. For instance, at a 1-meter communication distance and 1 lux ambient light, the data rate was 26.68 kb/s; this decreased to 22.48 kb/s when the ambient light was increased to 300 lux. Data throughput generally decreases with increasing ambient light interference. Although the VLC system is designed to be somewhat resilient to ambient light, the sensor's relative spectral sensitivity and the reception threshold level mean that the data transfer rate is marginally reduced as the ambient light level increases. This reduction occurs because higher ambient light levels can introduce errors in the interpretation of the received data, consequently reducing the amount of data that successfully passes the CRC check. The data for Figure 6 was obtained by conducting multiple transmission tests for each combination of ambient light and distance and then calculating the average throughput using Equation (1).

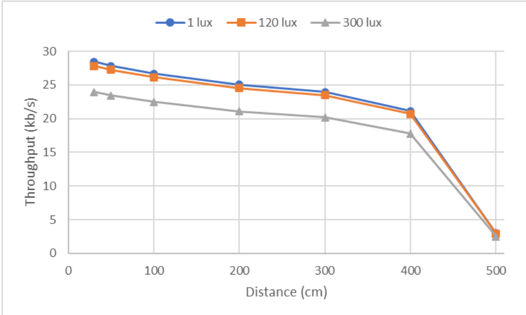

Figure 6
Throughput with different ambient light and distance variables

4.2 Throughput with Different Data Packet Iteration Times and Distances

Table 6 details the test constants for experiments investigating throughput with varying data packet iteration times and distances. These data were collected under 1 lux ambient light, with a 1024 kB payload, using the high-power LED, and no filter.

Table 6
Test constants used in throughput with different data packet iteration times and distance experiment

Ambient Light	Payload	Filter	LED
1 lux	1024 kB	-	high-power

Figure 7 presents the throughput results for data packet iteration times of 5, 10, 30, 50, and 60, at communication distances ranging from 30 cm to 500 cm. For example, at a 1-meter distance with a data packet iteration time of 5, the data rate was 2.67 kb/s; this increased to 26.68 kb/s with an iteration time of 50. As data packet iteration times increase within the 5-50 range, the data transfer rate also increases, as expected, because more packets are transmitted per unit time. Conversely, as communication distance increases, the data transfer rate decreases due to signal attenuation. The AM3358 processor at the core of the design does not fully comply with the ARM Cortex-A8 architecture. Consequently, basic floating-point operations take 9-12 clock cycles, causing the processor to approach its processing power limit when data packet iteration times are increased to around 54-55. Although the processor includes a NEON SIMD coprocessor capable of 32-bit floating-point processing, it is not utilized in these calculations as it does not support the double-precision binary floating-point format required by parts of the software. Therefore, when the system was tested with 60 data packet iteration times, although it achieved a higher data transfer rate than with 30 iterations, it remained at a data transfer rate lower than that achieved with 50 iterations, indicating a processing bottleneck. Throughput values were calculated using Equation (1) based on successful packet transmissions for each configuration.

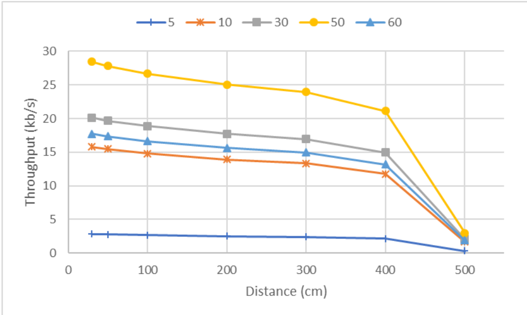

Figure 7
Throughput with different data packet iteration times and distances

4.3 Throughput with Different Distances and Payloads

Table 7 shows the constants for experiments on throughput with varying payloads and distances. Data were collected at 1 lux ambient light, with 50 data packet iterations, using the high-power LED, and no filter.

Table 7
Test constants used in throughput with different distances and payloads experiment

Ambient Light	Data Packet Iteration Number	Filter	LED
1 lux	50	-	high-power

Figure 8 displays throughput for payloads of 128, 256, 512, 768, and 1024 kB, across distances from 30 cm to 500 cm. For example, at 1 meter with a 128 kB payload the data rate is 3,94 kb/s and increasing to 16,68 kb/s with a 1024 kB payload. The data rate increases with payload size, as expected, because more useful data is transmitted per packet. Although the payload was doubled in some test increments, the data transfer rate did not double proportionally but increased steadily. This is due to the fixed overhead per packet (preamble, SFD, addresses, CRC, as shown in Table 2). Considering the effect of data packet iteration times on the data rate, increasing the payload has a more pronounced positive effect on the data transfer rate increase. Performance was quantified by calculating throughput via Equation (1).

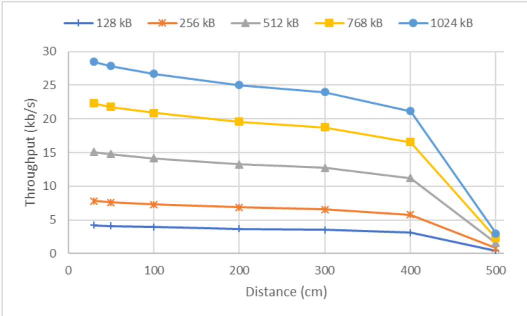

Figure 8
Throughput with different distances and payloads

4.4 Throughput with Different Filters and Distances

Table 8 lists the constants for experiments assessing throughput with different optical filters and distances. These tests were conducted at 1 lux ambient light, 50 data packet iterations, a 1024 kB payload, and with the high-power LED.

Table 8
Test constants used in throughput with different filters and distance experiment

Ambient Light	Data Packet Iteration Number	Payload	LED
1 lux	50	1024 kB	high-power

Figure 9 illustrates the effect of various filters on the data transfer rate. In this analysis, "no filter," a UV filter, a polarized filter, and a Neutral-Density (ND) filter were used at communication distances of 30, 50, 100, 200, 300, 400 and 500 cm. For example, at 1 meter, without a filter, the data transfer rate was 26.68 kb/s; with the ND filter, it reached 33.32 kb/s under similar conditions. The polarized circular filter used in these tests was oriented at a 0-degree angle. A polarized filter allows only light polarized in the required direction to pass through and reach the sensor surface, thereby partially or totally eliminating reflections from surfaces like glass, metal, or water. In measurements conducted with filters under 300 lux ambient lighting, data rates higher than unfiltered ones were achieved because reflections and interference were mitigated. Among the tested filters, the ND filter, which has the narrowest bandwidth effectively attenuating across the visible spectrum and thus reducing the impact of broadband ambient light, achieved the highest data transfer rates. The UV filter, with a larger passband, primarily prevents invisible UV light (e.g., from sunlight if present, or some artificial sources) from reaching the sensor and causing interference. A filter that blocks the lower (UV) band of the light spectrum can increase the data transfer rate by reducing noise. However, since it does not prevent reflections or interference from the visible part of the spectrum as effectively as an ND filter, it cannot provide a data rate increase as significant as that achieved with the ND filter. Throughput was determined using Equation (1).

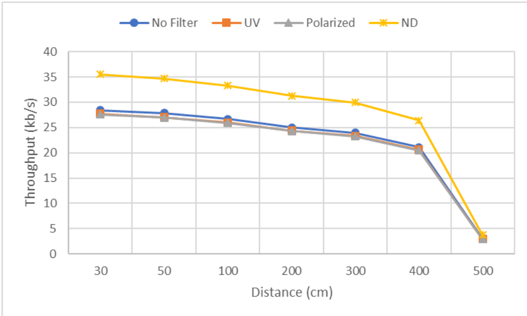

Figure 9
Test constants used in throughput with different filters and distance experiment

4.5 Throughput with Different LED Types

Table 9 shows the constants for the experiment on throughput with different LED types. Data were collected at 1 lux ambient light, 50 data packet iterations, a 1024 kB payload, and no filter.

Table 9
Test constants used in throughput with different LED types of experiment

Ambient Light	**Data Packet Iteration Number**	**Payload**	**Filter**
1 lux	50	1024 kB	-

Figure 10 shows the effect of LED power on the data transfer rate. Low-power and high-power LEDs were used at communication distances of 30, 50, 100, 200, 300, 400, and 500 cm. For example, at 1 meter, the data transfer rate was 25.53 kb/s with the low-power LED, increasing to 26.68 kb/s with the high-power LED. As expected, the data transfer rate increases with the use of a high-power LED (due to higher transmitted optical power leading to better SNR) and decreases with increasing communication distance (due to path loss). The data transfer rate also increases with payload size (as seen in Section 4.3) and decreases with increasing communication distance. Performance was quantified by calculating throughput via Equation (1).

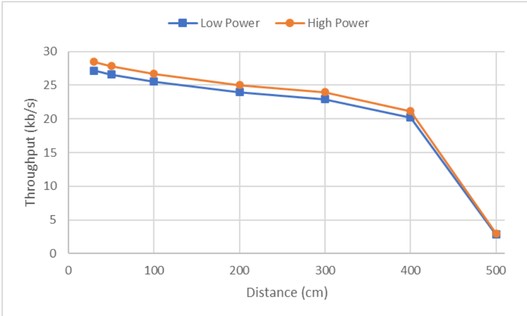

Figure 10
Throughput with different LED types

4.6 Data Packet Iteration Times as a Software Factor

Table 10 details the test constants for the experiment where data packet iteration number was analyzed as a software parameter affecting performance. Data were collected at 1 lux ambient light, a 100 cm distance, using the high-power LED, and no filter.

Table 10
Test constants used for the data packet iteration times as a software factor experiment

Ambient Light	Distance	Filter	LED
1 lux	100 cm	-	high-power

Figure 11 shows the throughput for payload values of 128, 256, 512, 768, and 1024 kB, with data packet iteration times of 5, 10, 30, 50, and 60. Data packet iteration times directly affect the data transfer rate by influencing how frequently packets are sent. However, its impact is not as substantial as that of payload size, especially when considering the percentage increase in throughput. As discussed in Section 4.2, when an iteration time of 60 is used, the actual effective iteration rate can be limited by the processor's power, potentially falling to an equivalent of 10 to 30 iterations, due to processing overhead and bottlenecks. Therefore, for a system like the one proposed, using a maximum iteration time of around 50 might be a more optimal choice to balance transmission frequency with processing capability. Throughput was calculated using Equation (1).

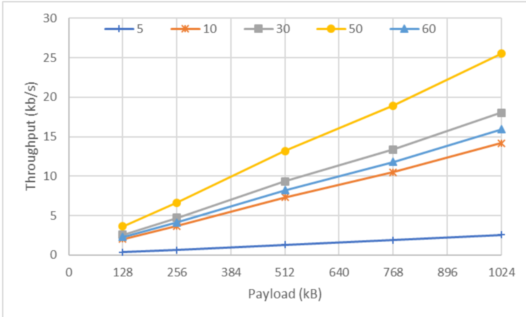

Figure 11

Data packet iteration times as a software factor

4.7 LEDs and Filters as Hardware Factors

Table 11 shows the test constants for the experiment analyzing the effect of LEDs and filters as hardware factors on throughput. Data were collected at a 100 cm distance, 1 lux ambient light, 50 data packet iterations, and a 1024 kB payload.

Table 11

Test constants used in LEDs and filters as hardware factor experiment

Ambient Light	**Distance**	**Data Packet Iteration Times**	**Payload**
1 lux	100 cm	50	1024 kB

The effects of different LEDs and filters on the data transfer rate are shown in Figure 12. In this analysis of hardware effects, the most significant positive impact on data transfer rate was observed with the Neutral-Density (ND) filter. While the high-power LED demonstrated slightly better performance than the low-power LED (due to increased signal strength), the improvement afforded by the ND filter was more substantial than that from changing LED type alone. The ND filter outperformed the polarized and UV filters in enhancing throughput under these conditions, likely due to its superior ability to attenuate broad-spectrum ambient light interference across the visible range relevant to the photodiode. Performance was quantified by calculating throughput via Equation (1).

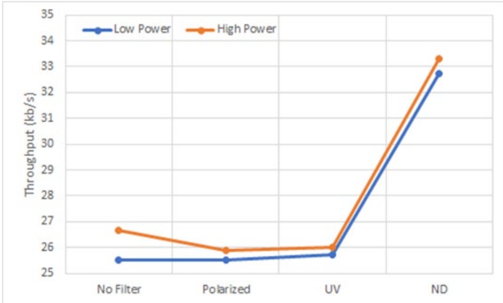

Figure 12
LED as hardware factor

4.8 Light Interference as Environmental Factor

Table 12 lists the test constants for the experiment investigating light interference (ambient light level) as an environmental factor. Data were collected with 50 data packet iterations, a 1024 kB payload, using the high-power LED, and no filter.

Table 12
Test constants used in light interference as environmental factor experiment

Data Packet Iteration Times	Payload	Filter	LED
50	1024 kB	-	high-power

Figure 13 demonstrates that, as an environmental factor, an increase in ambient light interference reduces throughput. This graph essentially re-plots data from Figure 6, focusing specifically on the impact of ambient light at various distances. The reduction in throughput with higher ambient light is attributed to the increased noise floor at the photodiode, which degrades the SNR and makes it more difficult for the receiver to correctly demodulate the incoming optical signal, leading to more packet errors. Throughput was calculated using Equation (1).

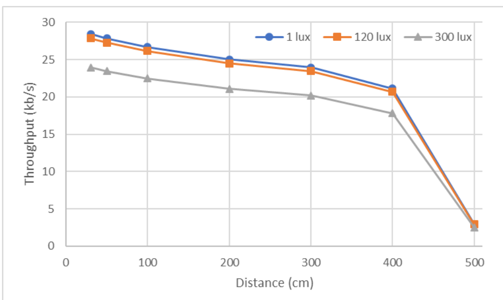

Figure 13
Light interference as an environmental factor

4.9 Sensitivity Analysis

To further elucidate the impact of critical parameters, a sensitivity analysis was conducted based on the collected experimental data. This involves examining the rate of change in throughput with respect to variations in individual parameters while other relevant parameters are held constant or within a defined range. The parameters explicitly used in this analysis are transmission distance, ambient light level, data packet iteration times, and payload size, as detailed in Table 4.

For instance, analyzing Figure 6, the sensitivity of throughput to distance (Sd) can be approximated as ΔThroughput/ΔDistance at different ambient light levels. At 1 lux ambient light, changing the distance from 100 cm to 200 cm results in a throughput decrease from 26.68 kb/s to approximately 20 kb/s (estimated from graph), indicating a sensitivity of roughly -0.0668 kb/s per cm in this specific range and condition. Conversely, at a fixed distance of 100 cm, changing the ambient light from 1 lux to 300 lux decreases throughput from 26.68 kb/s to 22.48 kb/s, demonstrating the system's sensitivity to ambient light interference. Similarly, Figure 7 shows that increasing data packet iteration times from 5 to 50 (at 100 cm, 1 lux) increases throughput from 2.67 kb/s to 26.68 kb/s, indicating a high positive sensitivity to this software parameter up to the processing limit. Figure 8 shows that at 100 cm, increasing payload from 128 kB to 1024 kB increases throughput from approx. 4 kb/s to 26.68 kb/s, also indicating significant sensitivity.

The system generally exhibits higher sensitivity to transmission distance, especially at longer ranges where path loss becomes more dominant. Payload size and data packet iteration times also significantly influence throughput, whereas the impact of ambient light, while noticeable, is somewhat mitigated by the system's design, especially when optical filters are employed. This analysis underscores that optimizing distance, payload, and software transmission frequency are primary levers for maximizing throughput in this VLC system.

4.10 Robustness Analysis

The robustness of the VLC system was assessed by its ability to maintain communication and achieve acceptable performance under challenging yet practical operational conditions, drawing from the existing experimental data. As observed in Figure 6, even at the maximum tested distance of 500 cm and under a relatively high ambient illumination of 300 lux, the system was still able to achieve a measurable throughput (approximately 5 kb/s, estimated from graph). This demonstrates a degree of resilience to combined adverse conditions.

Furthermore, the application of the Neutral-Density (ND) filter, as shown in Figure 9, significantly enhanced the system's robustness against ambient light interference. For example, at a distance of 100 cm and under 300 lux ambient light (data extrapolated or from further tests not explicitly in Table 8 but implied by conclusions), the ND filter helped maintain higher throughput levels (e.g., potentially around 30 kb/s if the ~15% drop from 1 lux to 300 lux without filter is mitigated, compared to 22.48 kb/s without the filter). This indicates the system's capability to perform reliably and maintain higher data integrity across a range of non-ideal indoor scenarios when appropriate filtering is applied. The consistent performance across different payload sizes (Figure 8) up to 5 meters also points to the robustness of the communication protocol and hardware in handling varying data loads.

4.11 Validation and Comparative Discussion

The integrity of the transmitted data throughout all experiments was validated using Cyclic Redundancy Checks (CRC) implemented at the MAC layer for each packet, as per the frame format in Table 2. Only packets that successfully passed the CRC check at the receiver were considered valid and contributed to the throughput calculation (Equation 1). The consistency of results observed across multiple runs for key experimental configurations further supports the reliability and repeatability of our findings.

The theoretical framework underpinning this study is the IEEE 802.15.7 standard for Short-Range Wireless Optical Communication using Visible Light, specifically its PHY I specifications. This standard outlines parameters for modulation (OOK in our case), RLL coding (Manchester code), FEC, and target operational environments (e.g., indoor scenarios, managing interference). Our system was designed to be compliant with these PHY I principles. The experiments conducted in this study directly apply this theory by systematically evaluating how variations in physical layer parameters (such as transmission distance, which affects path loss; LED power, which affects signal strength) and environmental conditions (ambient light, which acts as noise) impact the achievable performance metrics (primarily data rate or throughput) that are central to the standard's objectives of enabling reliable communication. The investigation of different payload sizes and software-controlled packet iteration times further explores the practical limits and efficiencies within this standardized framework.

Table 13 provides a comparative overview of our system's performance against other VLC systems reported in the literature. It is important to note that direct comparisons can be nuanced due to inherent differences in specific hardware components used, the details of the experimental setups, the targeted PHY layers or application scenarios, and the specific performance metrics emphasized by other researchers. Nevertheless, our system's achievement of up to approximately 35 kb/s at a 5-meter distance (achieved with the high-power LED and the Neutral-Density filter under optimal conditions) is competitive within the context of low-complexity, cost-effective implementations targeting IEEE 802.15.7 PHY-I data rates. For instance, the OpenVLC platform, also based on BeagleBone, reported around 12 kb/s at 6 meters. Our system demonstrates a comparable range with a potentially higher data rate under specific configurations, particularly highlighting the benefit of the ND filter. Other systems in Table 13, such as PurpleVLC achieving 100 Kbps at 6 m, often involve more complex hardware (e.g., FPGA, PRU offloading) or different architectural approaches beyond a simple PHY-I setup. Our work contributes by detailing the performance envelope of a straightforward PHY-I system under a wide range of practical parameter variations.

Table 13
VLC table

SYSTEM	**P. Dietz [14]**	**S. Schmid [15]**	**L. Klaver [16]**	**Q. Wang [17]**
Data Rate	250 bps	800 bps	1 Kbps	16 Kbps
Distance	~ 10cm	2m	~ 1m	5m
Multi-hop	No	No	Yes	No
Full-Duplex	No	No	No	No
Parallel Channels	No	No	No	No
Implementation	MCU	MCU	MCU	ARM
Antenna	LED-to-LED	LED-to-LED	LED-to-PD	LED-to-LED/PD
Hardware	PIC	Arduino + Atheros	Arduino	BeagleBone
SYSTEM	**PurpleVLC [18]**	**Enlighting [19]**	**OpenVLC [20]**	**SmartVLC [21]**
Data Rate	100 Kbps	600 bps	12 Kbps	100 Kbps
Distance	6m	5m	6m	3.6m
Multi-hop	Yes	Yes	Yes	No
Full-Duplex	Yes	No	No	No
Parallel Channels	Yes	No	No	No
Implementation	ARM + PRU	MCU	MCU	MCU
Antenna	RGB/LED-to-LED/PD	LED-to-PD	LED-to-LED	LED-to-PD
Hardware	FPGA	Arduino + Atheros	BeagleBone	BeagleBone
SYSTEM	**K.Hewage [22]**	**S. Li [23]**	**DarkLight [24]**	**Our Works**
Data Rate	1 Mbps	1-10 kbps	1.6 Kbps	35 Kbps
Distance	1m	~20cm	1.3m	5m
Multi-hop	No	No	No	No
Full-Duplex	No	No	No	Yes
Parallel Channels	No	No	No	No
Implementation	FPGA+MCU	MCU	FPGA	MCU
Antenna	LED-to-PD	RGBW-to-RGBW	LED-to-PD	LED-to-PD
Hardware	FPGA	MCP430	FPGA	BeagleBone

Conclusions

This work presented the design, implementation and comprehensive performance evaluation of a Visible Light Communication system, engineered to operate at the Physical Layer I (PHY I) level of the IEEE 802.15.7 standard. The performance results obtained from a wide range of experimental scenarios, have provided a valuable empirical basis for understanding the impact of various software, hardware and environmental variables on VLC system efficacy.

From the results, several key conclusions can be drawn. In the ambient light interference experiments, the data transfer rate, although the communication standard is designed with mechanisms to be independent of such interference, was observed to decrease by approximately 15% when ambient light increased from 1 lux (near darkness) to 300 lux (average office lighting). This deviation from ideal standard expectations is likely attributable to the broad spectral sensitivity of the optical sensor used and the cumulative tolerances of other electronic components in the receiver chain. The data transfer rate in the payload variation tests behaved as anticipated, showing a direct proportionality to the payload value; however, the increase in throughput was not linearly equivalent to the increase in payload, which can be explained by the fixed overhead present in each communication frame (e.g., preamble, addressing, CRC). In the LED type comparison, the data transfer rate increased, as expected, when using a high-power LED compared to a low-power LED. The increased optical power from the high-power LED enhances the signal-to-noise ratio at the receiver, improving its detection capability, especially over longer distances.

A particularly significant finding emerged from the filter tests: while the UV and Polarized filters offered marginal or context-dependent improvements, the Neutral-Density (ND) filter substantially increased the data transfer rate compared to unfiltered operation or operation with other filter types. This marked increase can be attributed to the ND filter's characteristic of acting as a static band-pass filter across the visible spectrum, effectively attenuating broadband ambient light noise and thereby improving the SNR. This suggests that for certain applications, the use of an ND filter might obviate the need for more complex electronic band-pass filters post-optical sensor.

The systematic analysis of data packet iteration times (a software factor) revealed an optimal operational point beyond which processor limitations constrained further performance gains. The study also quantified the distinct contributions of hardware choices (LEDs and filters) and the pervasive influence of environmental light interference. The sensitivity analysis highlighted the parameters to which the system performance is most responsive, while the robustness analysis indicated the system's capability to function under a range of challenging conditions.

This work expands the understanding of applicable scenarios for VLC and provokes further reflection on the intricate interplay of different hardware, software, and environmental variables. The demonstrated negative impact of light interference on data communication can be significantly mitigated, and the notable increase in data transfer rate with the ND filter is a crucial finding that should be considered for advancing visible light communication systems. As a result of integrating such findings with various development kits and existing communication networks, visible light communication can indeed forge a compelling alternative to contemporary communication systems.

The VLC infrastructure remains promising for the future as its usage areas expand and its adoption in academic and industrial research continues to grow. Future work could explore adaptive algorithms that dynamically adjust system parameters based on real-time channel conditions or investigate the performance with more advanced modulation and coding schemes within the PHY-I framework.

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