Lighting Efficiency: Using Visible Light Communications Technology for Enhanced Energy Management in Built Environment and Beyond

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***Abstract*— In the context in which human society is struggling to achieve carbon neutrality and to reduce energy waste, this work proposes a novel Visible Light Communications (VLC) prototype designed for emergency message transmission enhanced with energy management consumption capability. Thus, in order to be able to accommodate different lighting requirements, the VLC transmitter is able to work with variable duty cycles, while maintaining the data link active. Moreover, different from existing works, the VLC receiver integrates a light monitoring function and an infrared data transmission function, which can be further expanded into a Light Fidelity (Li-Fi) system. This way, based on the workspace's illumination level, the VLC transmitter can maximize energy efficiency through duty cycle adjustments. The proposed prototype has been implemented in a real working space and experimentally evaluated. The preliminary experimental results have confirmed the advantages of this concept, as the prototype demonstrated its ability to constantly adjust its illumination level while maintaining the active communication link. Additionally, the prototype is able of achieving a BER lower than 10^{-7} for duty cycles between 10% and 90%.**

Keywords*— energy efficiency, light dimming control, lighting management, lights-off visible light communications, visible light communications.

I. Introduction

In a modern society, lighting plays an important role, accompanying our everyday life, both indoor and outdoor. The complexity of lighting systems has increased, while additional lighting purposes have been integrated. Thus, illumination systems now have aesthetic, guiding, entertainment or signaling purposes, while various other uses are constantly brought to light [1]. As applications diversify, the share of energy consumption for lighting shows an increasing trend [2]. Therefore, lighting reached up to 15% of the total electric energy consumption [3], which calls for new methods to increase efficiency based on modern management of energy consumption. Therefore, traditional lighting solutions are on the way of being replaced by energy-efficient Solid-State Lighting (SSL) solutions such as LEDs, revolutionizing energy efficiency in lighting [4].

Apart from its already proven efficiency, LEDs offer other advantages, including longer lifespans and superior controllability. By utilizing these devices for both lighting and data transmission, buildings can connect multiple advantages, thereby enhancing versatility and cost-effectiveness. By transitioning to LED lighting and implementing smart lighting setups, building owners and operators can achieve better energy management solutions. Thus, the impact of lighting on energy consumption and versatility underlines the importance of integrating innovative technologies to achieve sustainability goals in the built environment.

In addition to aforementioned advantages, LEDs are also capable of rapid switching, enabling their use in Visible Light Communications (VLC) – an emerging technology which uses solid-state devices for simultaneous illumination and wireless data transfer [5]. In this context, it should be highlighted that VLC can be one of the most efficient wireless technologies, as the same light that is used for illumination is also used as a data carrier, not necessitating additional energy consumption for this purpose. Li-Fi, a subset of VLC technology that uses light to transmit data wirelessly, could see important advancements, including higher data transmission speeds, expanded compatibility with various devices and improved reliability [5], [6]. Also, Li-Fi could potentially complement the traditional Wi-Fi technology, especially in environments where radio frequency interference is a concern, such as hospitals, airports, or mining operations [7]. Nevertheless, the management of energy consumption remains one of the most important factors in achieving sustainability and reducing operational costs, but continued research and development efforts are necessary for advancing VLC technology and unlocking its full potential in diverse applications and use cases without sacrificing performance and reliability. Thus, although the IEEE 802.15.7 standard for wireless communications using visible light mentions that lighting systems enhanced with data transmission should prevent flickering and be capable of light intensity control [8], there are rather few experimental prototypes with such capabilities [9]-[12], whereas most of the works on this topic do not make the transition toward experimental investigations, pointing out that additional research efforts are required in this direction.

In this context, the present paper presents the preliminary experimental results for a VLC prototype designed for emergency message transmission and enhanced energy efficiency. To achieve this goal, the proposed indoor VLC system constantly adapts its duty cycle in accordance to the illuminance level within the room, based on some predefined settings. The experimental results confirmed that the prototype is able to maintain the active link while adjusting its duty cycle in the 10-90% range. From our best knowledge, this is the first work which provides an experimental VLC prototype where the duty cycle is constantly adapted in

This work is supported by the NetZeRoCities Competence Center, funded by European Union – NextGenerationEU and Romanian Government, under the National Recovery and Resilience Plan for Romania, contract no.760007/30.12.2022 with the Romanian Ministry of Research, Innovation and Digitalisation through the specific research project P2-Sustainable energy & environments.

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accordance to the necessary illuminance level, based on practical needs.

II. Design and Hardware Implementation of the Visible Light Communications Prototype

The diagram of the proposed indoor VLC system is provided in Fig. 1. The concept contains a lighting infrastructure VLC transceiver and a mobile VLC transceiver. The VLC transceiver is integrated as part of a standard luminaire using four 60 cm light tubes, which have been replaced by four 9W LED tubes. The four off-the-shelf LED tubes are modulated by a microcontroller board with an ARM Cortex M7 processor operating at 600 MHz through a custom made driver. To enable the data transfer, the microcontroller builds the data frame with a header that includes synchronization, duty cycle information and other characteristics, followed by the message to be sent. The frame is then encoded and modulated. To enable light intensity control, the VLC transceiver uses a modified Variable Pulse Position Modulation (VPPM). VPPM is a particular modulation format specially designed for VLC applications, which enables high precision light dimming, and a relatively simple data encoding mechanism [8], [13]. Thus, in a similar way as in Pulse Width Modulation (PWM), the light intensity can be adjusted by controlling the pulse width, whereas the data extraction is possible based on the principles used in Pulse Position Modulation (PPM). Moreover, the use of this approach ensures that 1 and 0 bits have the same light energy, preventing the light flickering phenomenon.

The main element of novelty associated with this concept comes from its ability to constantly and independently adjust the VLC transmission duty cycle, and in turn, of its illuminance level in accordance to the light intensity perceived at the work space level. For this purpose, the VLC infrastructure also englobes an optical receiver capable to receive data from the mobile VLC device's optical transmitter. Thus, feedback concerning the illuminance at the workspace level is available and used to adjust the VLC transmitter duty cycle. In terms of data rate, the system was tested for 100 kb/s, enough for sending emergency messages, but further increase of data rate is possible, paving the way to a real Li-Fi system.

On the other hand, the VLC mobile device consists of a standard VLC receiver, an ambient light monitoring unit, and an IR transmitter. The VLC receiver uses an optical detector to transform the incident modulated light into an electrical signal, which is converted with a transimpedance circuit, then is filtered, amplified, and transformed into a digital signal that contains the data from the VLC transmitter. Finally, the digital data is processed by a controller with an ARM Cortex M7 processor working at 1008 MHz. The data is obtained in real time based on a pulse width measurement algorithm. Additionally, to enable a quality of service analysis, the processor is also able to perform the evaluation of the received data packets, providing the Bit Error Ratio (BER) and the Packet Delivery Ratio (PDR) results. It should be emphasized here that the VLC receiver is able to work in current setup with variable duty cycles from 1% to 99%, and adjustable data rates ranging from 10 to 500 kb/s. To process these variable pulse width signals, the VLC receiver uses the information provided by the VLC transmitter in the data frame physical header. In addition to the VLC receiver, the mobile device also contains an ambient light sensor based on a photodiode connected in a voltage divider configuration, whose signal is then fed to a microcontroller board. This unit is able of making assessments relating to the illuminance level within the workspace area. The ambient light sensor captures the light coming from the VLC transmitter, the other sources of artificial light, and the natural light coming through the windows (see experimental setup in Fig. 2). Next, the microcontroller compares the values of the estimated illuminance with the optimal value set in its memory, and based on this comparison it transmits through the IR transmitter if the VLC transmitter's illuminance should be adapted. It should be mentioned here that the Illuminating Engineering Society of North America (IESNA) recommends for general office areas illuminance levels higher than 300 lx. Table I presents a summary of the prototype's features.

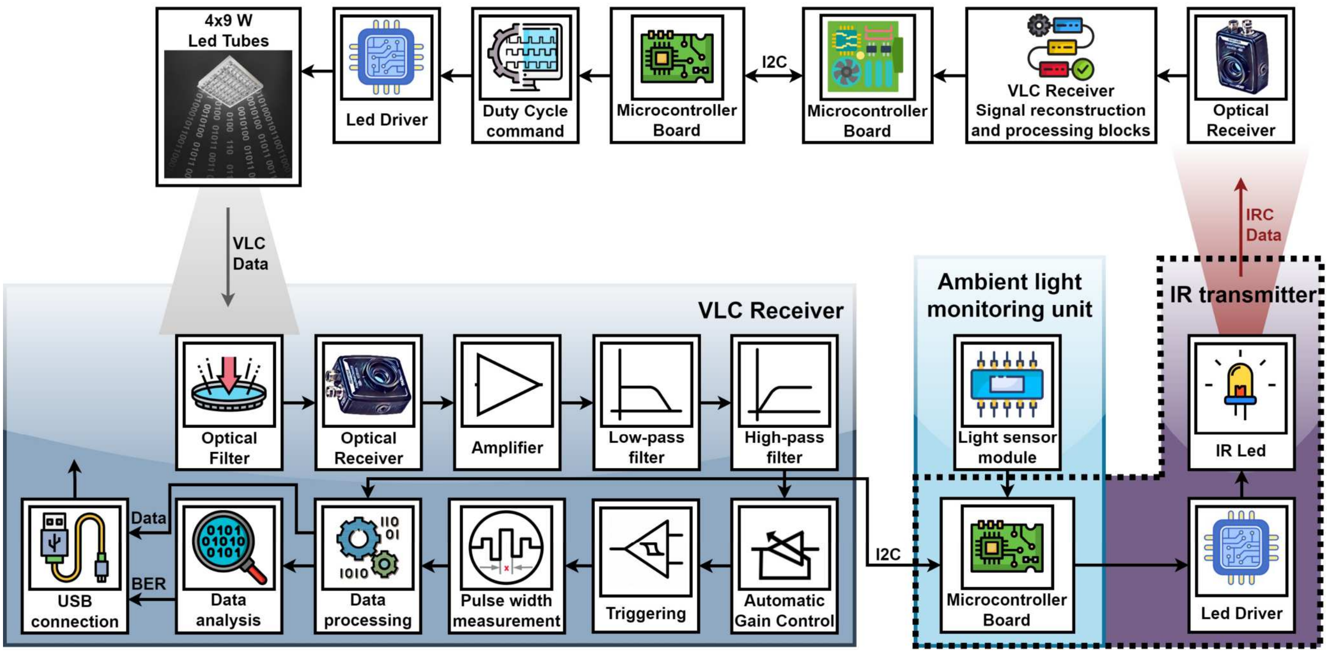

Fig. 1. Schematic design of the proposed VLC architecture.

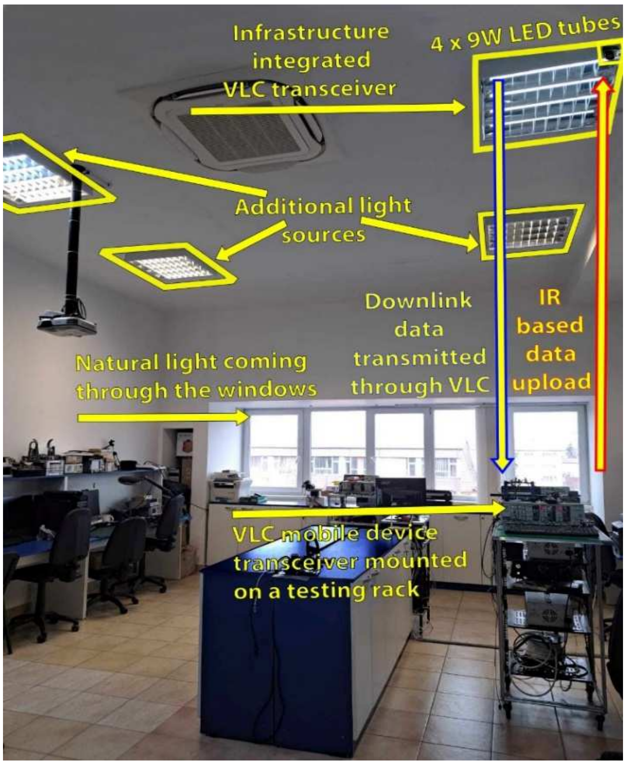

Fig. 2. Experimental testing setup showing the VLC transceiver implemented within the indoor lighting system and the VLC mobile device.

TABLE I. SUMMARY OF THE VLC PROTOTYPE PARAMETERS.

Characteristics of the VLC prototype	*Features*
Optical communication parameters	• Full duplex communication using visible light for download and infrared light for data upload; • Auto-adaptive light dimming functions based on the estimated light intensity measured at the VLC receiver level; • VPPM modulation employing adjustable duty cycle from 1% to 99% (10-90% in these tests); • 10-500 kb/s data rates (100 kb/s in these tests);
Lighting infrastructure VLC transceiver parameters	• VLC transmitter integrated within of the laboratory lighting system using a luminaire consisting of 4×9W 60 cm LED tubes; • Up to 188 lx optical emission at work space level (i.e. 2.7 m from the ceiling); • 4.7 meters radius coverage; • Optical receiver for data reception used for light level adaptation;
Mobile VLC transceiver parameters	• ±53˚ reception angle; • Adaptive gain for mobile applications; • Real-time data processing; • No error correcting codes; • Illuminance estimation function; • Data upload function using an IR transmitter;

III. TESTING PROCEDURE, EXPERIMENTAL RESULTS AND DEBATES

A. Experimental Testing Setup

The objective of these tests is to demonstrate a new function for indoor VLC systems – namely, the enhanced energy management. For these tests, the aim is to demonstrate that the prototype is able to: i). adapt the VLC messages duty cycle in order to improve user experience while optimizing the energy consumption and ii). maintain the wireless connection. As illustrated in Fig. 2, the prototype has been installed into a research laboratory, configured as an open space office, accommodating 6 users, each user with his own luminaire placed relatively above the workspace. The ceiling of the office is at a height of 3.5 meters, whereas the workspace is at a height of 80 cm. The prototype has been tested in daytime conditions, with natural light coming through the windows. In order to evaluate the system's ability to adapt to various conditions, the system has been tested on a partially cloudy day, at various moments of the day, and at different lighting intensities. Additionally, the system has been tested in conditions with limited natural light compensated by artificial light coming from the neighboring users. The purpose of these scenarios is to evaluate if the prototype is able to adequately adapt to variable ambient lighting conditions in order to keep slightly above 300 lx, to evaluate the VLC system communication performance and to investigate the system's energy efficiency capabilities.

B. Experimental Results

The summary of the experimental results is available in Table II, whereas Fig. 3 shows an oscilloscope capture illustrating the signal processing plan at the VLC receiver level. The results showed that the proposed prototype is able to evaluate the lighting conditions at the workspace level, to transmit this information using the optical channel, and to adapt the light intensity by modifying the VLC transmitter duty cycle. Additionally, the experimental results have confirmed that the VLC component is able to ensure reliable communication even in light dimming conditions, providing BER results lower than 10^{-7}, where the BER has been determined based on the transmission of three data sets, each comprising 10 million bits.

TABLE II. EXPERIMENTAL RESULTS SUMMARIZING THE VLC PROTOTYPE PERFORMANCE

Ambient light at the workspace level: natural /artificial [lux]	**VLC Duty Cycle**	**Power drawn per luminaire [W]**	**Total light intensity at the workspace level [lux]**	**VLC BER**
74 / 0	90%	28.7	245	$<10^{-7}$
158 / 0	90%	28.7	328	$<10^{-7}$
165 / 0	80%	25.5	312	$<10^{-7}$
198 / 0	70%	21.7	325	$<10^{-7}$
232 / 0	50%	14.9	318	$<10^{-7}$
263 / 0	30%	8.9	312	$<10^{-7}$
328 / 0	10%	2.6	345	$<10^{-7}$
373 / 0	10%	2.6	389	$<10^{-7}$
25 / 186	70%	21.7	313	$<10^{-7}$
48 / 220	50%	14.9	321	$<10^{-7}$

C. Discussions on the Experimental Results and Perspectives

The experimental results presented in Table II show that the proposed prototype is capable to constantly adapt its duty cycle in order to maintain the illuminance level at values above the imposed 300 lx limit. Nevertheless, in low lighting conditions, the limited power of the four LED tubes is not able to increase the illuminance level to the imposed value, pointing out that additional lighting sources are required. On the other hand, in conditions in which the natural light coming through the windows is sufficient to ensure an optimally illuminated workspace, the VLC prototype provides a

Fig. 3. Oscilloscope print-screen showing the VLC receiver signal processing mode for a 30% duty cycle modulated frame: Channel 1 illustrates the output of the transimpedance circuit; Channel 2 shows the amplified signal; Channel 3 represents the Schmitt trigger output signal used for data processing.

minimum duty cycle and in turn a minimum illuminance, necessary to provide the user with wireless data transmission. In such conditions, the energy consumption is reduced to minimum (i.e. in this case to 2.6 W). For comparison, a wireless router providing users' devices with wireless connectivity has an energy consumption of 30-50 W, which is significantly higher. Moreover, the duty cycle could be reduced even more, reaching values of 1% or even lower [11], [12]. In such conditions, the user perceives the lights as being off, whereas the energy consumption can be reduced proportionally.

On the other hand, the most important aspect pointed out by the experimental evaluation is related to the prototype's ability to maintain the active communication link and to provide a BER lower than 10^{-7}. The very low BER is the result of a high SNR level associated with the indoor scenario, and the effect of a very well-designed signal processing plan integrated within the VLC receiver. From this perspective, our previous experience has shown that a well-designed VLC receiver can ensure a BER lower than 10^{-6} even in extreme conditions [14], [15].

IV. Conclusions

In the context in which energy efficiency and wireless communications technologies represent major preoccupations for our society, this paper proposed a new indoor VLC prototype capable to ensure enhanced energy management. The proposed concept has been implemented and experimentally evaluated in laboratory conditions. The experimental results have shown that the newly developed prototype is able to ensure significant energy savings by integrating light management techniques, combined with a VLC transmitter capable to adjust its light intensity by dynamically modifying the duty cycle. Moreover, the experimental results also showed that the VLC prototype is able to ensure reliable data communication, providing a BER lower than 10^{-7} and covering the ranges required in indoor applications. As far as we know, this is the first work to report the experimental results for a VLC prototype capable to combine data transmission with dynamic light management, accomplished by light monitoring and duty cycle adjustment, based on a modified VPPM technique. Future work on this project will be focused on optimizing the hardware prototype and additional experimental investigation in complex daily activities testing scenarios.

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