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Experimental Evaluation of an Indoor Visible Light Communications System in Light Dimming Conditions

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Abstract— Visible Light Communications (VLC) are a new wireless communications technology that benefits from numerous advantages. Nevertheless, due to particular limitations, its deployment is still not in sight. A specific VLC challenge is establishing the link when the transmitter needs to provide light dimming function or even when it is in off-state. To achieve this goal, a new indoor VLC prototype was developed and experimentally evaluated. The VLC transmitter has been developed as part of the indoor lighting infrastructure, whereas the VLC receiver is being developed as part of a smart backpack for visually impaired persons' assistance. The prototype has been evaluated in light dimming conditions, going down to 1% duty cycle, which is perceived by the human eye as almost in an off-state. The experimental results demonstrate the feasibility of the concept, as a BER lower than 10^{-6} can be maintained while decreasing the light intensity down to the point where the light seems totally off.

Keywords—light dimming, lights-off visible light communications, visible light communications, visually impaired assistance.

I. INTRODUCTION

Visible Light Communications (VLC) have emerged several years ago as a technology that provides simultaneous illumination and data transmission in various purposes and applications [1], [2]. Its progress was pushed forward by the occurrence of a well-developed LED lighting infrastructure [3], [4], which can be used for data transmission as well. Furthermore, it has been demonstrated that in addition to the ability to support high data rates [5], [6], this technology can be used for high precision positioning and localization [7], [8], as well as for environment sensing applications [9] or in smart buildings development [10].

VLC assume the dual use of the visible light both for illumination and data transmission. Thus, different from any other wireless communication technology, in VLC the data carrier is visible for the human eye, which means that certain restrictions should be considered. As a result, the IEEE 802.15.7 standard for optical communications using visible light imposes that the lighting function should not be affected in any way by the data transmission function. Therefore, VLC should not influence the optical power, should not generate light flickering and should be compatible with light dimming if the lighting applications requires it [11].

In the current context in which the 2019 Paris Green Deal treaty imposes the society to reach carbon neutrality by 2050,

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whereas lighting represents a major electricity consumer sector, VLC light dimming features become very important. Thus, light dimming enables a lighting system to improve its energy efficiency by constantly adapting the lighting output in accordance with different factors such as user preference, user presence within an area, moment of the day, daylight intensity, user activity and so on [12]. Thus, the development and the optimization of VLC light dimming abilities represent an important research topic, whereas the transition from conceptual design to implementation and experimental evaluation are an imperative step toward the VLC deployment.

As part of our efforts in developing a functional system that provides Visually Impaired Persons (VIP) with assistance in indoor scenario [13], a new VLC system is proposed. Its purpose is to use the indoor lighting network in order to provide a VIP with personalized assistance based on a user location-aware protocol. Nevertheless, considering the fact that the system should maintain its initial lighting function, whereas in the current context, energy waste is a major concern, the proposed VLC system is aimed to be light dimming compatible as well. Thus, this paper is focused on the development and the experimental evaluation of an indoor VLC prototype in light dimming conditions. The experimental results indicate that the proposed system is able to provide a 3.4 meters radius range for each 65 x 65 cm luminaire, and can maintain its low Bit Error Ratio (BER) performance even in light dimming conditions. Thus, different from most of the existing works that are investigating light dimming VLC solutions [14]-[16], this work provides a VLC prototype implementation together with its experimental evaluation, demonstrating the VLC functionality in light dimming conditions down to a duty factor of 1%.

II. CONCEPT PRESENTATION AND HARDWARE DESIGN OF THE VISIBLE LIGHT COMMUNICATIONS PROTOTYPE

A. System Design Requirements

In addition to the VLC prerequisites, an additional set of requirements is imposed by this specific application. From this point of view, the system aims to be noise resilient, in order to maintain the established link even in daylight outdoor environment, when other applications can be used for sending various types of information, but specifically for VIP assistance, the system does not necessary need high data rates. Having this in mind, the first version of the prototype was designed to work with a minimum data rate of 10 kb/s, going up to 100 kb/s.

Another aspect that has been envisioned focuses on the system's ability to provide coverage in the indoor environment. Thus, the system should be able to cover different space configurations and should support user mobility. Therefore, the proposed prototype is envisioned based on the fact that each luminaire cone light covers a relatively wide floor area, while overlapping each other's range in order to ensure the coverage without leaving gap zones at the receiver's level. Additionally, the prototype is being developed while focusing on its ability to be as compatible as possible with the preexisting lighting infrastructure. Thus, standard luminaires and off-the-shelf LED tubes have been considered in the VLC transmitter's design.

B. Indoor Visible Light Communications System Design and Hardware Implementation

The schematic of the smart backpack VLC component is presented in Fig. 1. As one can see, the prototype consists in a VLC transmitter and a VLC receiver.

The VLC transmitter is implemented as part of the indoor lighting system in a luminaire located at 3.5 meters above the floor. Thus, it uses four 60 cm LED tubes, each having a 9W power, designed to be fitted in fluorescent tube sockets. The LED tubes are controlled, through a digital driver, by an ARM Cortex M7 processor working at 600 MHz. In order to enable light dimming, the VLC transmitter uses an adapted form of Variable Pulse Position Modulation (VPPM) [17]. VPPM is a specific modulation designed for light dimming VLC applications, which combines Pulse Width Modulation (PWM) with Pulse Position Modulation (PPM) coding ability. Thus, the information is stored based on the position of the pulse and it is not influenced by the pulse width, enabling precise light dimming without affecting the data transmission capability. Furthermore, as 0-bit and 1-bit have the same pulse width, light flickering is prevented. Based on this design, the VLC transmitter generates an optical intensity of 101 lux with a duty cycle of 50% measured at the workspace level (2.7

meters from the ceiling), whereas the light dimming function should enable the adjustment down to the point where the user perceives the light as being off, and up to the point where the light is almost to its maximum optical intensity, at 99%.

The VLC receiver is part of a smart backpack designed for visually impaired persons' assistance [13]. It consists of an optical collecting system, a signal processing part and a data processing component. The front-end contains an optical filter, which eliminates part of the unwanted spectral components and an optical receiver with a Field-of-View (FoV) of $\pm 53^\circ$, which transforms the incident light into an electrical signal. This block is followed by a signal processing component, which is responsible for signal band-pass filtering, signal amplification and signal reconstruction to its original shape. The final component of the receiver is a data processing unit, consisting of an ARM M7 Cortex processor running at 1008 MHz, which performs the real-time data decoding, data analysis and BER measurement. Table I summarizes the VLC prototype characteristics.

TABLE I. SUMMARY OF THE VLC PROTOTYPE PARAMETERS.

Parameters of the VLC system	Characteristic
Communication parameters	<ul style="list-style-type: none"> Asynchronous communication; Light dimming function between 1% and 99%; VPPM modulation with variable duty cycle between 1% and 99%; 10-100 kb/s data rates;
VLC transmitter parameters	<ul style="list-style-type: none"> VLC transmitter based on indoor lighting system component; 4x9W LED tubes mounted in a 65 x 65 cm luminaire; Up to 198 lux optical emission at work space level (i.e. 2.7 m from ceiling); 380-780 nm spectral emission; Intended data coverage at the floor level for one luminaire: at least 4.7 meters radius.
VLC receiver parameters	<ul style="list-style-type: none"> IR reject filter starting from 780 nm; $\pm 53^\circ$ FoV; Adaptive gain factor up to 5000; Real-time data processing; No Forward Error Correcting (FEC) protocols

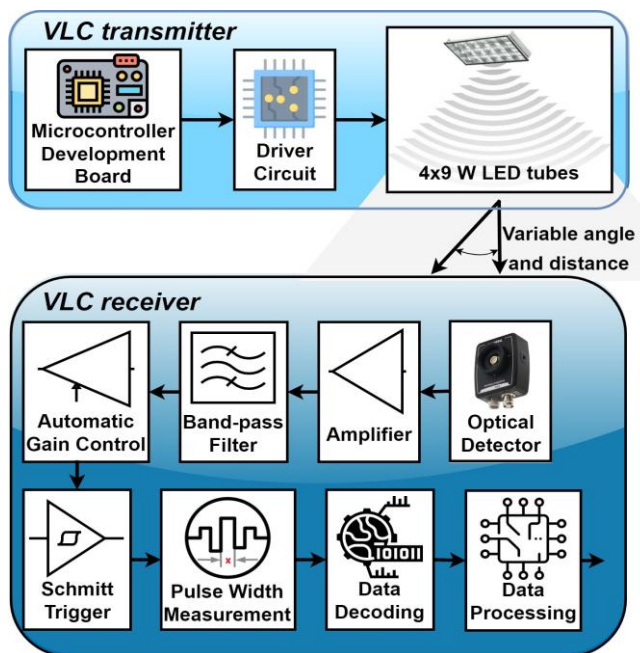


Fig. 1. Schematic design of the VLC system emphasizing the VLC transmitter and the VLC receiver.

III. EXPERIMENTAL TESTING AND RESULTS

This section provides the preliminary results for the experimental evaluation of the indoor VLC system light dimming performance, together with a short debate on results and perspectives.

A. Experimental Testing Setup

In order to prove the functionality of the VLC prototype, its performance has been evaluated in indoor conditions with natural light coming through the windows. The VLC receiver has been mounted on a mobile testing bench at a height of 100 cm from the floor, being 250 cm from the luminaire. In no light dimming conditions, the optical irradiance measured at the VLC receiver from the luminaire (i.e. at night, without the influence of any natural light) is of $67 \mu\text{W}/\text{cm}^2$. During the actual tests, the sunlight irradiance at the VLC receiver level ranged from 40 to $90 \mu\text{W}/\text{cm}^2$. In order to evaluate the prototype performance, the experiment was started from 50% dimming of the light intensity of transmitter, which has been gradually reduced by modifying the signal's duty cycle down to 10% in steps of 10%, going further from 9% to 1% in steps

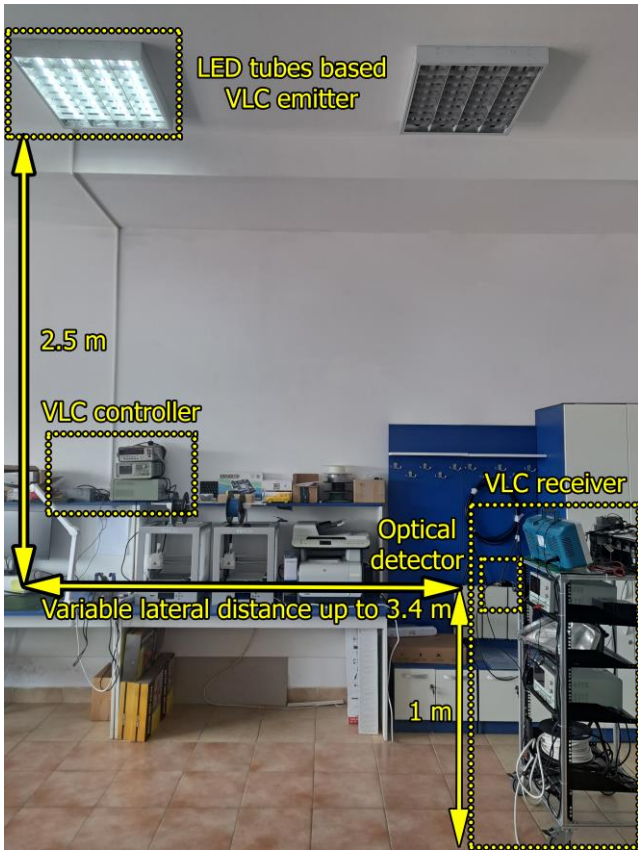


Fig. 2. Implementation of the VLC system within the laboratory and experimental setup during the experimental evaluation.

of 1%, while measuring the BER at each step. The BER determination procedure assumed the cyclic transmission of a predefined 80-bit message. At the VLC receiver level, the incident light is converted into an electrical signal which is processed until it regains its initial characteristics and it can be processed by the embedded data processing unit. Then, the data processing unit compares the received bits with the bits it is supposed to receive and performs the BER in real-time, without FEC usage. As part of the experimental testing procedure, the location of the VLC receiver with respect to VLC transmitter has been modified in order to determine the coverage of the luminaire (in addition to the modification of the duty cycle). Thus, the tests begun with the VLC receiver being placed exactly below the luminaire (0°) and continued by gradually increasing the lateral distance in 50 cm steps, while constantly monitoring the BER at each step. Figure 2 shows the indoor testing setup with the VLC transmitter and the VLC receiver test bench.

B. Experimental Results and Discussions

The first part of the experimental results, summarized in Table II, shows the correlation between the duty cycle on the one hand and the energy consumption and the luminous output on the other hand. Thus, these results confirm that the VLC transmitter is able to fulfill its lighting function and that the user has full control over the light intensity, despite the VLC integration. Additionally, the table presents the energy consumption associated with the different duty cycles, pointing out the potential energy saving.

The next part of the experimental results shows the performance of the VLC link. Figure 3 shows an oscilloscope screen exemplifying the signal processing at the VLC receiver

level for a 20% duty cycle. Next, Table III provides the summary of the VLC link experimental evaluation. The first remark regarding these experimental results is related to the very low BER achieved and maintained even in light dimming conditions. As one can see, the prototype is able to achieve a BER lower than 10^{-7} for a confidence level of 95%. Furthermore, the experimental results show that the VLC receiver is able to maintain the link active and the low BER even when the orientation with respect to the VLC transmitter is changing, and the light incidence angle increases from 0° to $\approx 53^\circ$ (a lateral distance of 3.4 m). Thus, a 3.4 meters radius can be covered by the prototype for the upper-described testing setup. Above this range, the VLC transmitter is no longer within the VLC receiver's Line of Sight (LoS) and the connection is lost. In that regard, the luminaires can be placed at a maximum distance of 6 m from each other at this height, in order to enable the user to be within the coverage of at least one lighting source. This condition is easily met in indoor spaces, meaning that the proposed solution is able to cover a wide area. On this topic, it needs to be mentioned that the irradiance of the received signal is dependent to the incident angle. Thus, as the incidence angle increases from 0 to 53° , the signal generated by the photosensitive element has a cosine dependency of the incidence angle, affecting in turn the SNR. In such conditions, the Automatic Gain Control (AGC) circuit is constantly adapting the gain, compensating the signal amplitude decrease and enabling the receiver to maintain the active link. On the downside, it should be mentioned that the light dimming control increases the complexity of the data generation function, and for this reason, for duty cycles below 10%, the data rate has been reduced from 100 to 10 kb/s in our tests.

TABLE II. EXPERIMENTAL RESULTS SHOWING THE VLC TRANSMITTER LIGHTING PERFORMANCE

Duty Cycle	Energy consumption per luminaire [W]	Light intensity at workspace level [lux]	Optical irradiance at VLC receiver level (0°) [$\mu\text{W}/\text{cm}^2$]
99%	34	198	71
50%	17	101	38.8
40%	13.6	80	31.2
30%	10.2	61	23.8
20%	6.8	39	15.1
10%	3.4	19.2	6.7
1%	0.34	2	0.5

TABLE III. SUMMARY OF EXPERIMENTAL RESULTS SHOWING THE VISIBLE LIGHT COMMUNICATIONS SYSTEM'S PERFORMANCE

Duty Cycle [%]	Lateral distance [cm]	Transmitter - Receiver Angle	Data Rate [kb/s]	BER at a 95% confidence level
10-50	0-340	$0-53^\circ$	100	$<10^{-7}$
1-9	0-340	$0-53^\circ$	10	$<10^{-6}$

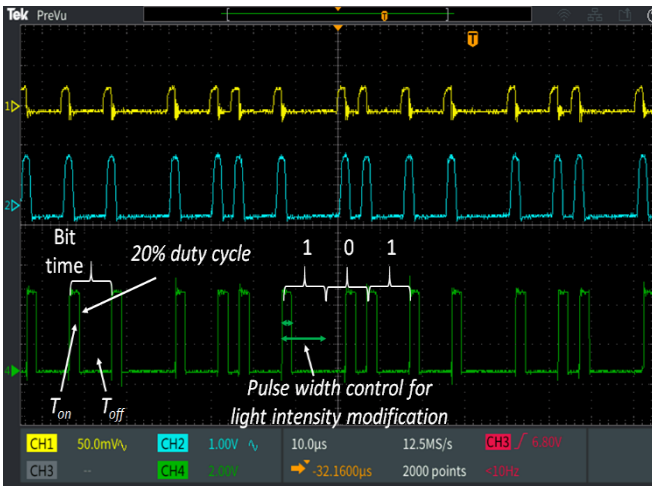


Fig. 3. Oscilloscope screen illustrating the VLC receiver signal processing plan for a 20% duty cycle: Channel 1 (Yellow) shows the output of the frontend; Channel 2 (Cyan) is the amplified signal; Channel 4 (Green) is the output of the Schmitt trigger circuit used in for data extraction.

Therefore, the experimental results confirm the viability of the proposed concept, pointing out that the VLC technology is compatible with light dimming and suitable for energy saving applications. Additionally, it has been demonstrated that the proposed prototype is able to provide data connectivity even with a 1% duty cycle which is close to being unperceived by the user, enabling VLC use even in situations where no lighting conditions are necessary. User mobility could hamper the communication at the edge of coverage area, because the angle between emitter and transmitter is already 53° and the user's body position could shadow other luminaries. Anyway, with further improvements, such as an automatic tracking mechanism for maximum signal power, for example, this issue can be avoided.

IV. CONCLUSIONS

As energy efficiency is becoming a major preoccupation of our society, whereas wireless communications represent an important component within our daily lives, this paper focused on the implementation and experimental testing of an indoor VLC system that has light dimming capability. The proposed prototype has been tested in laboratory conditions demonstrating its ability to maintain the VLC link even for duty cycles as low as 1%. Furthermore, it has been experimentally demonstrated that the system is compatible with user mobility as the prototype is able to adjust its gain in order to compensate the optical irradiance loss generated by the modification of the incidence angle. Thirdly, the viability of the proposed prototype it has been demonstrated by a BER lower than 10^{-6} , which was achieved without the help of FEC protocols. Thus, the most important contribution of this paper is represented by the experimental demonstration of an indoor VLC system compatible with light dimming. Ongoing work in this project is focused on the miniaturization of the prototype and on its further integration within a complete VLC-based visually impaired persons' assistance solution.

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