VLC Footprint maps for Positioning and Guidance

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***Abstract*— Visible Light Communication (VLC) is currently a research topic due to the possibility to handle the general, worldwide demanding need for communication. VLC uses Light Emitting Diodes (LED), operating in the visible part of the electromagnetic spectrum, as optical sources for optical wireless communication. The technology simultaneous lighting and communication, providing high data rates, reliability and a secure data transmission compared to other wireless technologies (such as Wi-Fi). This paper explores the use of VLC to establish different optical communication links for bidirectional communication between vehicles and infrastructures, using 2 links, namely Infrastructure-To-Vehicle (I2V) and Vehicle-To-Infrastructure (V2I) communication. The proposed application uses VLC to support autonomous navigation of mobile robots inside an automated warehouse, providing guidance and management services. Specific coding schemes are used in each optical link. In the I2V link, RGB white LEDs are used to allow simultaneous modulation of the emitters embedded in each LED, which enables wavelength division multiplexing of the transmitted optical signals. The detection is based on an a-SiC:H pin-pin photodetector with tunable sensitivity in the visible range. Different indoors communication scenarios are presented and bit error rate is discussed using a parity check bits for error control.**

Keywords- Visible Light Communication; Indoor guidance; White LEDs; Lambertian model; navigation cell.

I. INTRODUCTION

Indoor positioning can be addressed by several techniques, such as Wi-Fi, Assisted GPS (A-GPS), Infrared, Radio Frequency Identification (RFID), and many other technologies [1][2]. Visible Light communication (VLC) is also an alternative, enhanced accuracy technology. VLC operates with visible light extending from 400 nm up to 750 nm [3][4]. VLC systems use modulated LEDs to transmit information [5]. Due to its characteristics, LEDs [6] can be switched very fast to produce modulated light in high frequencies, allowing data transmission in high speed. For lighting purposes, energy saving demands the use of white LEDs [7][8], either based on blue emitter coated with a phosphor layer or based on polychromatic emitters. Phosphor-based LEDs usually consist of a blue LED chip covered in a yellow phosphor layer. Due to the long relaxation time of the phosphor, when this LED is used for VLC, the modulation bandwidth is limited, thereby limiting the transmission capacity. Using a blue filter before the receiver unit can increase the LED modulation bandwidth by eliminating the slow response of the yellow light component [9][10]. Although tri-chromatic LEDs are more expensive, they provide more bandwidth due to the independent modulation of each chip of a monolithic device.

The receiver unit of VLC systems usually include silicon based photodiodes, as these devices operate in the visible region of the spectrum, or CMOS image sensors [11][12]. In this paper we propose the use of a multilayered a:SiC:H [13] [14] device to perform the photodetection of the optical signals generated by white trichromatic RGB LEDs [15], [16]. The system was designed for positioning and guidance [17][18], and the transmitters of each white LED were specifically modulated at precise frequencies and coding bit sequences [19][20].

The proposed lighting and positioning/guidance system involves wireless communication, computer based algorithms, smart sensor and optical sources network, which constitutes a transdisciplinary approach framed in cyber-physical systems.

The paper is organized as follows. After the introduction (Section I), the general description of the system is presented in Section II. In Section III, the communication protocol and the encoding/decoding techniques are analyzed and discussed. At last, conclusions are addressed in Section IV.

II. VLC SYSTEM GENERAL DESCRIPTION

The VLC system is composed by the transmitter and the receiver modules, located at the infra-structure and at the mobile vehicle. Two optical links are established between the lamps and the vehicles, for I2V and V2I transmission. The optical source of the transmitter at infrastructure consists of four white RGB LEDs, while at a vehicle it is a multicolor LED or a single-color LED placed at the top. The sensor device used for the detection of the optical signals is a monolithic heterojunction composed of two pin structures [21]. As a result of its narrow thickness (200 nm) and higher bandgap (2.1 eV), the front pin a-SiC:H photodiode is responsible for the device's sensitivity to short wavelengths of the visible range (400 - 550 nm). The back pin a-Si:H structure operates in the complementary past of the visible range, collecting the long wavelengths (520 nm - 700 nm) [22]. The illumination window is established on the front

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photodiode. The use of steady state light as background light provides an enhancement of the electrical field of the front pin photodiode and the amplification of the generated photocurrent signal due to long wavelength light.

A. Transmitter configuration

For every channel of the I2V and V2I links, synchronous transmission based on a 64 bits data frame was used. In Figure 1, it is displayed the configuration of the LED lamp with four RGB white LEDs used in the I2V link. A uniform white light is provided in the indoor area by all three emitters (red, green, and blue). However, only specific emitters are modulated at a frequency imperceptible to the human eye. Each of these lamps illuminates an area with full radial coverage as shown in Figure 1.

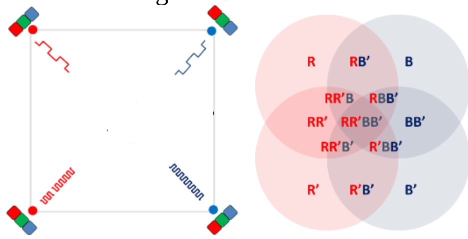

Figure 1. Configuration of the VLC emitter: a) 4 RGB white LEDs; b) coverage area of each modulated emitter.

The illuminated area corresponds to the coverage area of each lamp, defining a unit cell for the vehicle navigation along the space. The modulated emitters are the red junctions of the LEDs placed at the left side and the blue junctions of the LEDs at the right side.

B. Footprint map

In each unit navigation cell, any receiver will be able to identify the emission lamp and make a correspondence to the spatial position inside the warehouse. By modulating the red and blue emitters of each lamp, the optical pattern created within each navigation cell can enhance position accuracy. Inside the navigation cell, top emitters (labelled R and B) point north, bottom emitters (R' and B') point south, and left (R and R') and right (B and B') emitters point west and east, respectively. Based on this assumption, the RB' optical pattern corresponds to the north direction, R'B' to the south, RR' to the west and BB' to the east. The intercardinal directions inside the navigation cell correspond to RR'B (northwest), RBB' (northeast), RR'B' (southwest) and R'BB' (southeast).

Using adjacent LED lamps to light the indoor space, different navigation cells are enabled by each lamp. Every navigation cell contains 3 racks in each direction (forward and reverse) of the movement. The information transmitted by each set of four RGB LEDs includes the spatial location and information on the available items of the racks under their coverage area.

C. Coding

In Figure 2, it displayed the data frame structure the bi-directional communication I2V and V2I.

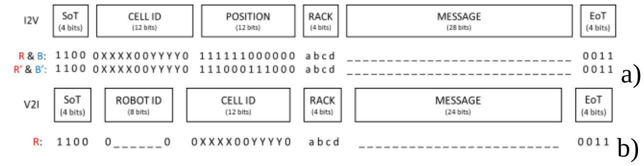

Figure 2. Data frame structure the communication: a) I2V and b) I2V channels.

Data frames are words of 64 bits composed each of six blocks. First and last blocks, labelled respectively as SoT and EoT are used to trigger synchronization of the transmitter and receptor in each link.

In the I2V link, there are also the blocks CELL ID, POSITION, RACK and MESSAGE. Identification of the unit cell is given by the block CELL ID. The format of the word code is 0XXXX00YYYY0, where XXXX addresses the line and YYYY the column of the unit navigation cell. Block POSITION provides information about which emitters are being detected by the mobile vehicle and thereby enables the vehicle to know its relative position within the navigation cell. The block RACK contains information about the stock stored inside the rack, addressing different sections. The MESSAGE block (32 bits) enables the possibility of transmitting a random message to the vehicle.

In the V2I link, a single LED is used to transmit information from the vehicle to the infrastructure, namely information about items being removed from the rack within the navigation cell to the shipping station. The code word contains the blocks ROBOT ID, CELL ID, RACK and MESSAGE, besides SoT and EoT blocks. The blocks ROBOT ID and CELL ID encode the identification of the transmitting vehicle and of the receiver infrastructure, The RACK block identifies the specific rack from where items are being removed and the MESSAGE block encodes the item and quantity being removed.

III. RESULTS AND DISCUSSION

In the V2I link, a single emitter is used to transmit information from the mobile robot to the LED infrastructure. In Figure 3, it is displayed the output signal due to the optical signal transmitted by the mobile robot after removing items from a specific rack. On the top it is displayed the optical signal with the transmitted bit sequence. As this V2I link uses a single emitter is used in this link, the photocurrent signal, when under line of sight condition, follows the pattern of the single transmitted optical signal. Thus, decoding is a simple process, limited only by the photodiode sensitivity at low illumination conditions.

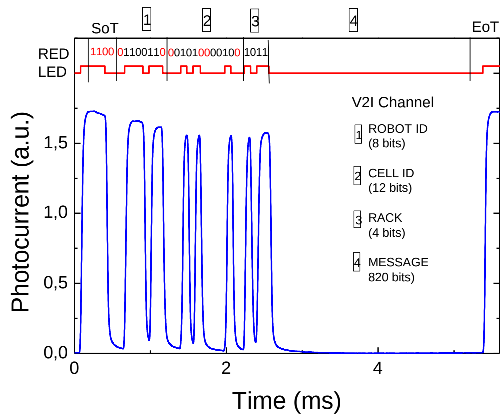

Figure 3. Output signal transmitted by the robot to the infrastructure after removal of items from the rack. On the top it displayed the transmitted optical signal.

As shown in the figure, bits in red color, either set to 1 or to 0, cannot be changed in this channel. Bits in black color are those that define the specific communication conditions. In this case, the blocks of the coded 64-bits word can be easily decoded. Bits of the ROBOT ID are 01100110, corresponding to the identification code 118 (decimal representation). The CELL ID provides for the decoded bits, the number 001010000100, which corresponds to line 5 and column 2. Bits of the RACK block are 1011, representing that items from the first and third racks were removed when the vehicle moved in the forward lane.

In the I2V link, the use of four emitters to transmit the coded information generates 16 photocurrents levels, assigned to 16 different optical excitations. These levels are dependent on the optical intensity at the reception end, however, its relative position is assumed to be constant. This, supports the use of a calibration curve to demultiplex the signal, decode the transmitted bits and enable identification of the input optical signals. In Figure 4, it is displayed the calibration curve, showing the 16 output levels assigned to each input optical state. The driving current of each LED emitter was adjusted to provide different levels of photo excitation.

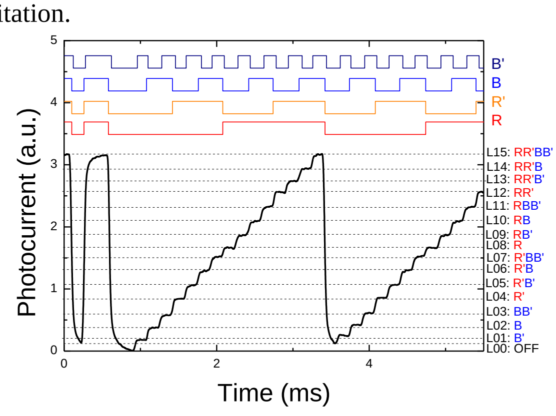

Figure 4. Calibration photocurrent signal using two red and two blue optical signals (on the top it is displayed the waveform of the emitters modulation state).

On the right side of the picture it is shown the label of the modulated emitters that correspond to each photocurrent level. The decoding methodology based on the calibration curve may result in some error mismatch when the photocurrent levels are too close. In order to increase the accuracy of the decoding task, bit error detection with parity check bits can be used. Parity bits (P1, P2, P3) assigned to the 4 transmission channels (R, R', B, B') are evaluated using a simple algorithm that sums up the bits transmitted by 3 of the channels:

$$P1 = R + R' + B'$$
$$P2 = R' + B + B' \quad (1)$$
$$P3 = R + B + B'$$

In Figure 5, it is displayed the parity check bits evaluated by equation (1) for the transmission of the bit sequences plotted in The parity check bits sequences (P1, P2 and P3) are transmitted, respectively, by the R, R' and B emitters.

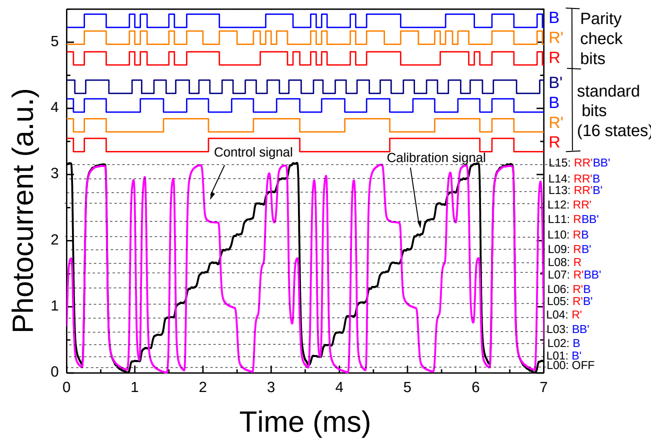

Figure 5. Calibration data and correspondent error control signal obtained by the transmission of the parity check bits.

Results show that the error control signal can be used to help on the decode process when photocurrent levels are very close. Under these circumstances, the use of parity check bits is able to detect and correct errors without the need to discard the transmitted data from the specific error bit and re-transmit it again.

In Figure 6, it is displayed the photocurrent signal acquired along the forward lane at positions under the coverage of RR'BB'. In superposition it is displayed the calibration grid. At the top it is displayed the input optical signals (R, R', B and B').

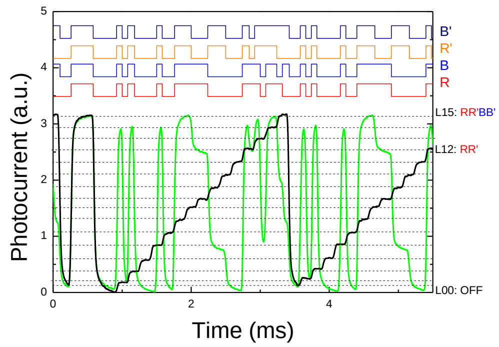

Figure 6. Photocurrent signal acquired along the forward path at cell central position under the coverage of RR'BB'.

The comparison of the output signal with the calibration curve allows the decode of the signal and identification of the receiver's position. Bit decoding of the multiplexed signal resulted for the CELL ID block the word 001010000100 (every 4 transmitters), corresponding to line 5 and column 2, for the POSITION block to the word 111111000000 from R and B transmitters and word 111000111000 from R' and B' transmitters, which indicates that the vehicle is at the center of the navigation cell. For the RACK block it is decoded the words 1110 from R and B transmitters and 1011 from R' and B' transmitters, which means that all racks of the cell are available with exception to the second rack in forward direction.

In Figure 7a), it is displayed the error control signal obtained with parity check bits of the transmitted signal of the I2V link shown in Figure 6.

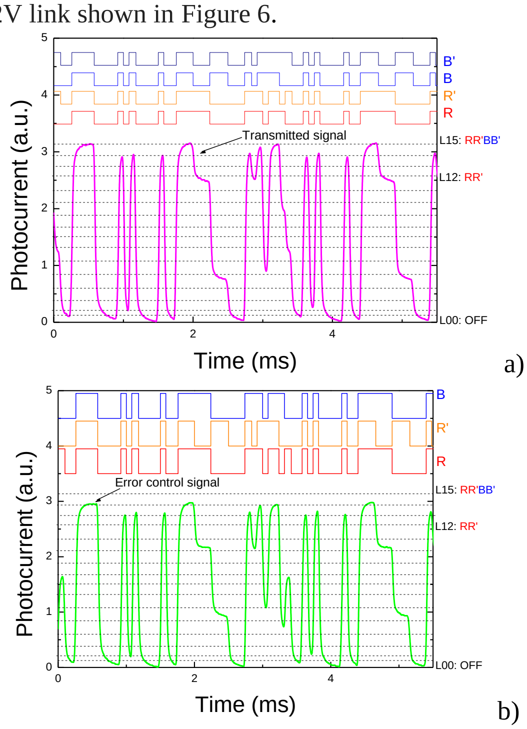

Figure 7. a) Transmitted signal by the I2V link and b) correspondent error control signal.

The use of the calibration curve for decoding the multiplexed signal, demands a periodic transmission of the 16 possible combination of the 4 optical signals to provide update of the calibration data and ensure correct output signal assignment. In this application, speed is not a critical issue, and this procedure does not overload the transmission efficiency. However, it can be discarded or done with less frequency, when the accuracy of the decoding is increased using parity check bits. The system is also feasible to be enhanced using feedback control for adjustment of the LED driving currents when the output photocurrent levels generated by the photodiode become too close. This procedure would minimize decoding errors due to parasitic effects such as optical intensity variations caused by to multiple reflections, light dispersion or other light sources.

IV. CONCLUSIONS

Bi-directional communication using VLC in both downlink and uplink channels has been addressed in a autonomous vehicle guidance system. The proposed indoors application deals with infrastructure to vehicle (I2V) and vehicle to infrastructure (V2I) communication in a warehouse. The vehicle moves autonomously through the warehouse transporting goods from the carts to the packaging station. The transmitted data is encoded in a 64 bits word, defined using specific data frames in communication channel. Codification of the optical signals ensured synchronization between frames. The code word of each channel was designed to ensure synchronization between frames, to transmit information of the transmitter identification and of spatial location. Experimental evaluation demonstrated that the decoding solution can provide robust communications, especially if automatic bit error control is implemented in the optical domain. This methodology will be used to support indoor positioning and guidance of autonomous guided vehicles operating in industrial environments, such as automated warehouses.

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