Propagation Model Using White LEDs in a Visible Light Communication Link

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***Abstract*—Nowadays, Global Positioning Systems (GPS) are used everywhere for positioning and navigation. However, its use is not suitable in indoor environment, due to the strong attenuation inside buildings. Therefore, indoors navigation takes advantage of other technologies to infer position. Recently, several Visible Light Positioning (VLP) systems have been reported. Among these technologies, Visible Light Communication (VLC) is one of the most promising, as its operation is based on the use of Light Emitting Diode (LED) light, currently widely used in the illumination solutions of most buildings. In this paper, we propose an indoor navigation system based on VLC in an industrial application for automated warehouses, where the navigation of Autonomous Guided Vehicles (AGV) is supported by VLC. The proposed VLC system establishes bi-directional communication between the infrastructure and the guided vehicles. LED transmitters at the warehouse ceiling support downlink data transmission from the Infrastructure to Vehicle (I2V). This channel provides positioning and navigation of the vehicles, as well as transmission of dedicated messages related to the requested tasks of the management warehouse system to the AVGs. The uplink channel from the Vehicle to the Infrastructure (V2I) is used to acknowledge the requested tasks and transmit updates on the concluded tasks. Optical transmitters are tri-chromatic white LEDs with a wide angle beam. The characterization of the optical transmitter system is done through MatLab simulations for path loss and VLC channel gain prediction using the Lambertian model for the LED light distribution. Dedicated receivers based on a-SiC:H/a-Si:H photodiodes with selective spectral sensitivity are used to record the transmitted signal. The decoding strategy is based on accurate calibration of the output signal.**

Keywords - visible light communication; RGB LED; photodiode; indoor navigation; optical sensor.

I. INTRODUCTION

Visible Light Communication (VLC) technology makes use of the visible part of the light spectrum to modulate specific wavelengths and encode and transmit information [1]. White LED lamps are the most adequate transmitters in this technology, as white LEDs are currently the most efficient lighting solution and can also be easily modulated, fulfilling the VLC requirements for signal transmission [2][3]. An attractive application of VLC technology is for indoor positioning and navigation services [4]. Its use can be extended from in-house navigation to guide users inside large buildings or underground spaces to the navigation of AVGs, safe communication at RF hazardous places (petrochemical industries, mining) [5] or RF undesirable locations (hospitals, aircrafts) [6][7].

Nowadays, retail market has several online and offline channels of sales and services like same day delivery or store pickups [8]. Thus, the trend for the conception of modern warehousing has provide efficiency in the delivery process [9]. Order picking is one of the most labor intensive and expensive activity in every warehouse. Thus, automation of this task through the use driverless vehicles, such as, mobile picking robots, self-driving forklifts, autonomous inventory robots or unmanned aerial vehicles [10] are an attractive solution. The vehicle movement inside the warehouse lays on indoor localization and indoor navigation techniques based on WiFi communication technology [11][12].

We propose a communication system operating in the visible range using four ultra-bright white RGB and photodetector device based on two stacked multilayered a-SiC:H/a-Si:H structures that act as optical filters in the visible range [13][14]. The system is designed to establish bidirectional communication between a static infrastructure and an AGV.

The LEDs enable four transmission optical channels supplied by the modulation of the internal red and blue chips of the white RGB LED [15][16]. The propagation model of the channel is analyzed to characterize the signal coverage.

The possibility of tuning the spectral device sensitivity is analyzed and discussed using several optical bias conditions that induce different modulations of the electrical field along both front and back heterostructures, amplifying or cutting specific wavelengths [17]. This enables the identification of the transmitted individual input channels allows the location identification of the photodetector. The correct assignment of the identified signal to the location is the basis of the position algorithm proposed in this work .

A decoding strategy based on the evaluation of the output photocurrent for the detection of different optical signals is presented and discussed [18][19].

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The rest of this paper is organized as follows. Section II describes the transmitter characterization. Section III describes the use of the receiver unit and the decoding strategy. Section IV addresses results and discussion. Section V goes into conclusions and presents guidelines for future work

II. TRANSMITTER UNIT

The proposed VLC system intends to establish bidirectional infrastructure-to-device communication in an industrial indoor space. The proposed application is an automated warehouse where AGV pick goods from the racks and carry them to the packaging station where they are labeled and shipped.

The LED lamps placed at the warehouse ceiling are used to illuminate the space, to transmit information that enable position and navigation services and to transmit instructions to the AGV. The AVG robots communicate with the ceiling lamps to transmit information on the items that are being removed, which enables the update of the database.

The proposed system is composed of transmitter and the receiver modules, located at the LED lamps at the ceiling and at the AVG. Downlink communication is established from the ceiling lamps to the AVGs and uplink communication from the AVG to the correspondent ceiling lamp. The optical source of the transmitter at the ceiling lamps is composed of four white RGB LEDs. At the AGV the optical source is single-color LEDs.

The configuration proposed for the LED ceiling lamp includes four white RGB LED placed at the corners of a square (Figure 1a)). Here the red emitter of LEDs A and D and the blue emitters of LED B and C are used for data transmission. Assuming a quasi-circular signal distribution from each LED, the predicted signal coverage of this setup is shown in Figure 1b).

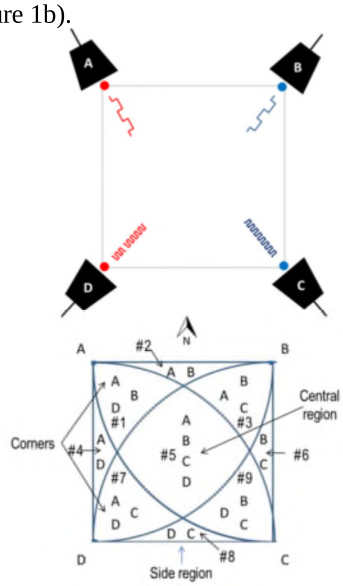

Figure 1. Configuration of the white LED lamp: a) modulated emitter of each LED ; b) signal coverage of the lamp.

It was assumed that each LED light contribution would overlap in the central region. In the lateral and corner parts this intersection would be partial due to the radiation patterns superposition of the closest two or three LEDs. The identification of the different signals is crucial for the identification of the position and thus for the indoor navigation.

The used RGB LEDs are commercial LEDs designed for general illumination providing therefore, high output power (550 mcd, 850 mcd and 320 mcd, for the red, green and blue emitters, respectively) and wide viewing angle. Analysis of the output light spectrum demonstrates the presence of three distinct gaussian peaks located in the blue (460 nm – 480 nm), green (520 nm – 540 nm) and red (619 nm – 624 nm) regions.

The light emitted by the LEDs is attenuated by the path distance to the receiver following the inverse of the square distance. Dependence on the wavelength is also stated using the propagation models (Friis equation).In Figure 2 it is shown the attenuation of the light signal dependence on the light wavelength for different distances between emitter and receiver units.

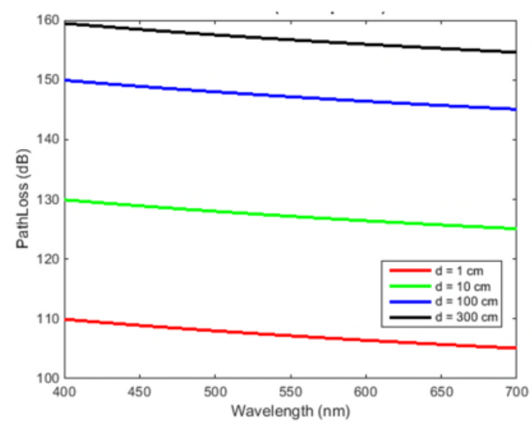

Figure 2. Attenuation of the light signal dependence on the light wavelength for different distances between emitter and receiver units sub-sections

The dependence on the wavelength is almost negligible, as the analyzed range (visible range) is very narrow. However, the dependence on the emitter-receiver distance is more evident, being very reduced at short distances and enlarging with wider distances.

III. RECEIVER UNIT

The receiver module includes a photodetector to transform the light signal into an electric signal that is later demodulated and decoded to extract the transmitted information. The photodetector used for the transduction of the optical signal is a monolithic heterojunction composed of two pin structures based on a-Si:H and a-SiC:H and built on a glass substrate between two transparent electrical contacts (Figure 3).

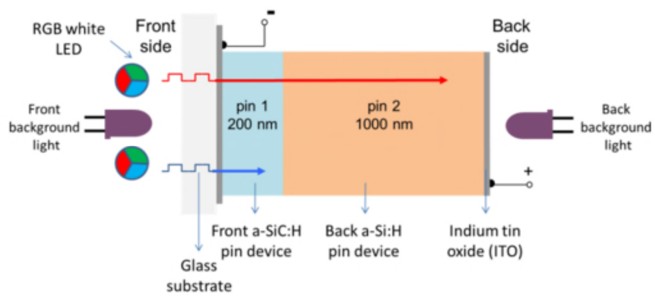

Figure 3. Simplified cross-section view of the photodetector.

The front pin a-SiC:H photodiode is responsible for the device sensitivity in the short wavelengths of the visible range (400 – 550 nm) due to its minor thickness (200 nm) and higher bandgap (2.1 eV). The back pin a-Si:H structure works in the complimentary past of the visible range, collecting the long wavelengths (520 nm – 700 nm). Selective absorption of long and short wavelengths can be achieved by adding steady state illumination of short wavelength (400 nm) to the photodetector. In Figure 4 it is displayed the output characteristics of the photodetector in transient mode measured without and under background light from both front and back sides.

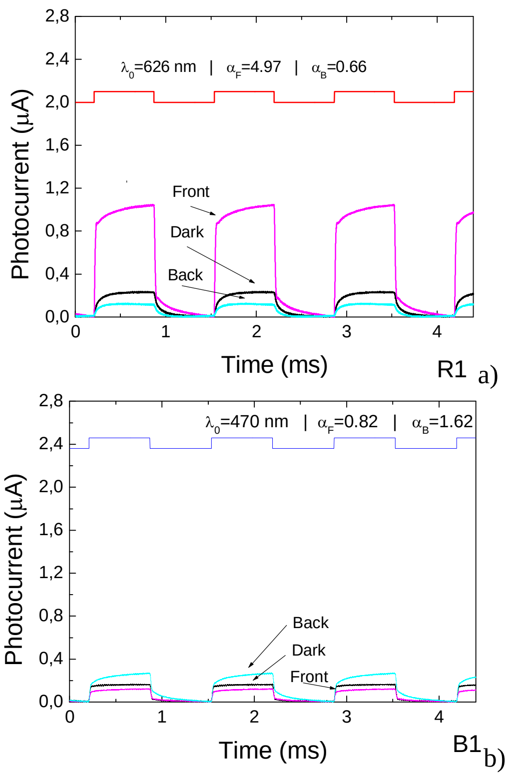

Figure 4. Transient photocurrent measured under pulsed illumination of the a) red and b) blue chips without optical bias and under front and back optical bias.

When this background light soaks the device, from the side of the a-SiC:H pin structure (front illumination), long wavelengths (red and green) provide amplification of the photocurrent, while short wavelengths (blue) attenuate the signal. Under background illumination, from the side of the a-Si:H pin structure (back illumination), the behavior is reversed. Signal amplification is obtained for shorter wavelengths and attenuation for longer wavelengths.

IV. RESULTS AND DISCUSSION

The frame used to transmit information related to the position and instructions to the AGV are coded in a word with a predefined size. The first and last blocks of the frame are used to ensure synchronism between the emitter and the receptor for correct demodulation of the transmitted signal. The second block is a word of 12 bits. In the fast and slow red and/or blue emitters, this word contains the information on the position within the navigation cell, which is assigned to the frequency. Slow emitters have a frequency half of the fast emitters. The green emitter is used to carry the identification of the unit cell. Its format was designed to ensure safe decode of the signals and prevent errors. It is a 12 bits word where the logic state of each bit never changes simultaneously with the other fast and slow red and blue emitters. The format of the word code is 0XXXX00YYYY0, where XXXX addresses the line and YYYY the column of the unit navigation cell. The third block of every emitter is a 12 bits word, reserved for the transmission of the information related to the available racks inside each navigation area. As the area covered by the navigation unit comprises nine cardinal sub-sections containing four quadrants each, it is necessary 9 x 4 = 36 bits to infer which of these spatial positions, i.e. racks, are available. Each of the channels (12 bits available) transmits information about 3 sub-sections, using 4 bits for each. The first bit is assigned to the first quadrant, the second to the second quadrant and so on. Slow emitters of each navigation cell transmit information about northwest, north and northeast directions, fast emitters at the bottom about southwest, south and southeast, and the green emitters about west, center and east positions.

When the AGV reaches the desired position defined by the route, it removes the rack and carries it to the packaging station. At the same time it provides information on this task, that is necessary for database update using the uplink channel. The establishment of this communication link demands the identification of both partners (lamp and robot). The uplink channel uses three wavelengths and the info is coded in a 3x32 bits word with a simple structure of four blocks: two synchronization blocks (2x4 bits) located at the beginning and at the end of the word and two informative blocks (2x12 bits) in the middle. The first 12 bits block contains the identification of the ceiling luminaire that is illuminating the AGV and the identification of the AGV responsible for picking the items from the rack.

The test case used to validate the proposed communication scheme is displayed in Figure 5, that shows the specific blocks of the 32 bits word of each emitter assigned to the lamps and to the mobile robot.

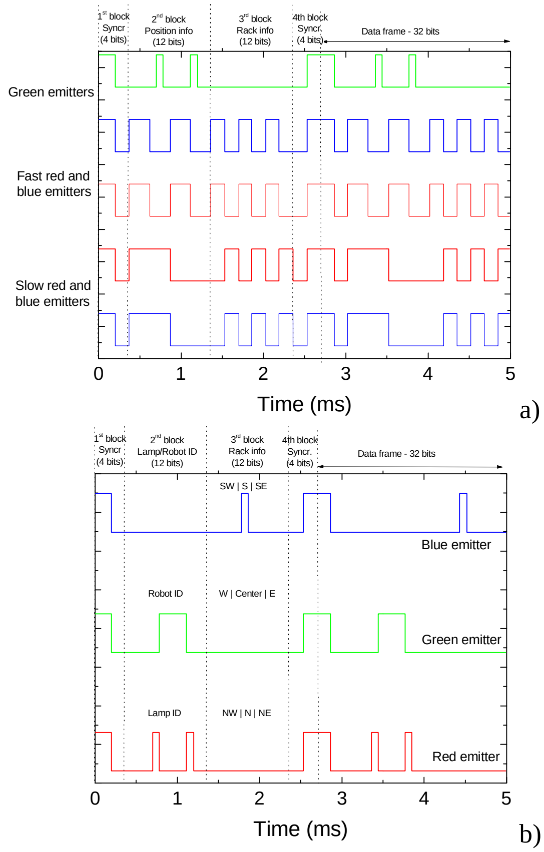

Figure 5. Codification of the optical signals transmitted by the: a) ceiling lamp; b) mobile picking robot.

In the code transmitted by the ceiling lamp (Figure 5a), the green transmitters send the code 1100 | 000010000100 | 0000 0000 0000 | 0011, which corresponds to the navigation cell with identification 1-2 (line 1: 0001, column 2: 0010) and to the information that there is no rack placed in the position west, center and east of the same cell. Slow emitters transmit the 1100 | 111111000000 | 0011 0011 0011 | 0011 code which identifies them as top emitters inside the navigation unit cell and states that in northwest, north and northeast sub-sections the third and fourth quadrants contain available racks that can be picked by the robot. In these quadrants, the 1st and 2nd quadrants are empty of available racks. Fast emitters transmit the code 1100 | 111000111000 | 1100 1100 1100 | 0011 which represents their position as bottom emitters in the navigation unit cell and informs that in the southwest, south and southeast sub-sections the 1st and 2nd quadrants contain available racks to be moved while the 3rd and 4th racks are not accessible as they are empty

In Figure 6, it is displayed the photocurrent signal measured by the mobile robot under variable conditions of optical bias (without and with front/back steady state background light). The signal was acquired in position (9) of the navigation cell 1-2, when the picking robot moves in the forward lane to remove a rack of the first quadrant of sub-section southwest (SE).

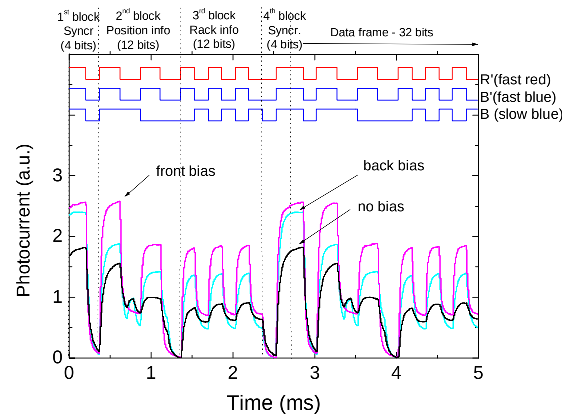

Figure 6. Photocurrent signal (measured without and with front/back steady state light) measured at position (9) of the navigation cell 1-2 after removing the contribution from the green emitters At the top it is displayed the optical signal of each emitter.

The signal was acquired in the central position (9) of the navigation cell 1-2, when the picking robot moves in the forward lane to remove a rack of the first quadrant of sub-section southwest (SE). At this position the optical excitation comes from the fast red and blue emitters and from the slow blue emitter. The displayed output signal has already been removed of the contribution due to the green optical excitation. In the graph, the trigger event allows easy synchronization and identification of each transmitted frame. This is noticeable by the highest peaks of the front photocurrent signal (represented in the graphs by the magenta line), as well as by the idle bits (all emitters are set to 1). This combination results in photocurrent amplification when the device is soaked by front steady state illumination. By opposition, the same signal under back background light is decreased.

Then, it is necessary to decode the next blocks of the data frame. It is assumed that in the front photocurrent the highest levels correspond to the presence of the red light, while the lowest ones to its absence, which allows the immediate recognition of the ON-OFF states for the red channel. The same reasoning can be used to analyze the back-photocurrent signal. Here the highest levels are assigned to the presence of the blue input signal and the lowest levels to its nonexistence, which allows the decoding of the blue channel. However, at the regions where there are two different signals transmitted by the same wavelength, this approach is not feasible, as it is necessary to infer which of these is channels is on or off. The approach used to decode each optical state was based on the use of a calibration curve. This was obtained by scaling all the possible signal output levels (Figure 7, solid black line) and measuring the photocurrent signal under front optical bias using two red and two blue optical signals. The driving current of each LED emitter was adjusted to provide different levels of photo excitation. On the right side of the picture in Figure 7, it is shown the label of the modulated emitters that correspond to each photocurrent level.

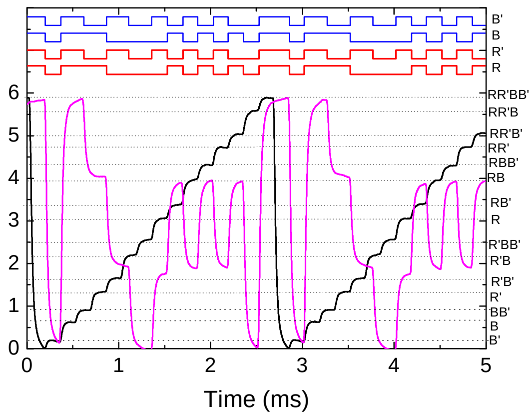

Figure 7. Front photocurrent signal measured along the forward path at the central position of the navigation cell. In superposition it is displayed the calibration grid.

In Figure 8, it is displayed the front photocurrent signal due to the optical signal transmitted by the AGV after concluding a specific task of items removal.

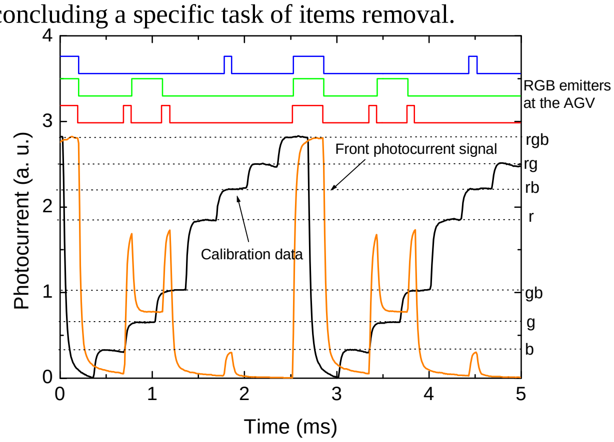

Figure 8. Front photocurrent signal transmitted by the robot when removing a rack. In superposition it is placed the calibration curve with 8 levels.

The calibration curve obtained with the 8 possible combinations is also displayed for decoding purposes.

V. Conclusion and Future Works

Simultaneous navigation and data transmission based on visible light communication were presented using bidirectional communication based on VLC between the infrastructure and AGV in an industrial application of an automated warehouse. The infrastructure is the ceiling LED lamp and the AVG a mobile warehouse picking robot. The transmitted data is encoded in a 32 bits word, defined using specific data frames in each communication channel. Codification of the optical signals ensured synchronization between frames and was also designed to make the decoding process more robust and prevent errors that might provide wrong identification of the correspondent spatial position.

Future work includes a more complete characterization of the channel gain and integration of the propagation model with the specific amplification features of the device under light bias.

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