Optical link for bidirectional communication based on visible light

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ABSTRACT

Visible Light Communication (VLC) is currently a research topic under severe development due to the possibility to provide high data rates and handle the general, worldwide demanding need for climbing bandwidth. VLC uses Light Emitting Diodes (LED), operating in the visible part of the electromagnetic spectrum, as optical sources for optical wireless communication. The technology provides dual functions of lighting and communication. Its main advantages are related to high data rates, higher bandwidth, 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 3 links, namely Infrastructure-To-Vehicle (I2V), Vehicle-To-Infrastructure and (V2I) communication. The proposed application uses VLC to support autonomous navigation of mobile robots inside a modern, automated warehouse, providing navigation and stock management services. Specific coding schemes are used in each optical link using On-OFF keying modulation. 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 a based a-SiC:H pin-pin photodetector with tunable sensitivity in the visible range. Different indoors communication scenarios are presented and the system performance on bit error rate is discussed using a bit parity error control methodology. Requirements related to synchronous transmission and flicker mitigation were addressed to enhance the system performance.

Keywords: Visible light communication, Vehicle-To-Infrastructure, Infrastructure-To-Vehicle, Vehicle-To-Vehicle, white LEDs, autonomous vehicle, indoor positioning, bit error control.

1. INTRODUCTION

White light-emitting diodes (LEDs) have in the last few years showed an increased performance concerning energy efficiency, delivered output power and color rendering. The combination of these features together with low driving voltage, low power consumption and long service life, gradually expanded its application fields from display to illumination. Actually, white LEDs established a breakthrough lighting technology when compared with the traditional optical sources based on filament or halogen light bulbs [1]. LED lamps are considered as energy saving and environmentally friendly lighting equipment, providing sustainable solutions for the lighting market. As LEDs are able to be modulated fast, they can be used for highspeed data communication. This, enabled Visible Light Communication (VLC) as a wireless optical communication technology with white LEDs playing a dual role for communication and illumination. The issue of data transmission using visible light demands fast modulation rates, impossible to achieve with other optical sources than LEDs. These have the ability to be switched on and off at very high rates, without being perceived by the human eye. Thus, data transmission using indoor illumination will not either disturb the lighting function either will be leaked to the outside, as radio wave communication does. This feature, enables higher security to the system and additionally, it can also be regarded as a communication technology able to be used in environments sensitive to RF signals, such as hospitals or oil plants [2, 3, 4, 5].

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Common applications of VLC include mainly indoor smart lighting systems, location-based services, robotics, and industrial applications. The use of VLC in outdoor applications is also feasible, however, quite challenging as different sources of light will add noise to the transmission channel.

Indoor navigation is an application of great interest for VLC as RF signals are absorbed by the walls of buildings, tunnels, and other structures, becoming then as inoperative technology indoors. Modern, automated warehouses work to deliver goods as fast as possible [6, 7]. Mobile robots are used to collect the selected goods of each parcel and carry them to the shipping station [8]. The autonomous vehicle movement inside the warehouse is supported by indoor localization and indoor navigation techniques based on wireless communication technologies, either Wi-Fi or VLC [9, 10]. VLC can be proposed for indoor communication to complement or replace RF-based communication. In an automated warehouse items are collected by mobile robots that carry them to the packaging station. Reliable, robust and secure bi-directional communication among vehicle and infrastructure (Infrastructure-To-Vehicle, I2V and Vehicle-To-Infrastructure, V2I) and among vehicles, (Vehicle-To-Vehicle, V2V) is required.

In this paper we propose bidirectional communication using VLC links for I2V and V2I data transmission. Indoor localization information and navigation services [11, 12] inside the warehouse and information on available stock are supplied by the I2V link. Cooperation services in the grabbing task of the mobile robots are provided by the V2I link, with the mobile robots informing the infrastructure (V2I) about the items of the rack that are being removed and carried to the packaging station.

White RGB LEDs are used as optical emitters and a p-in-p photodiode based on a-SiC:H/a-Si:H [13, 14, 15] as photodetector. This device operates in the visible/near infrared ranges and its sensitivity is enhanced using appropriate steady state light illumination to amplify the photocurrent signal [16, 17] due to long wavelengths. The decoding strategy of the multiplexed signals uses a calibration table of the output photocurrent level [18]. In order to prevent errors in the decoding task, optical bit error control was implemented.

The proposed lighting and positioning/navigation system involves wireless communication, computer-based algorithms, smart sensor and optical sources network, which constitutes a transdisciplinary approach framed in cyber-physical systems. The rest of the paper is organized as follows: Section 2 introduces the design of the proposed links in the VLC system. Section 3 discusses the obtained results under different experimental conditions, namely the decoding strategies and the parity bit error control methodology. Section 4 summarizes the paper and proposes further developments for future work.

2. VLC SYSTEM

The VLC system is composed by the transmitter and the receiver modules, located at the infra-structure and at the mobile robot. Propagation occurs in free space under line of sight condition using on-off keying modulation. Three optical links are established between the lamps and the mobile robots, for I2V and V2I transmission.

The optical source of the transmitter at infrastructure is composed by four white RGB LEDs, while at the robot it is a multicolor LED or single-color LEDs placed at the top of the robot.

The sensor device used for the detection of the optical signals is a monolithic heterojunction composed by two pin structures built on a glass substrate and sandwiched between two transparent electrical contacts [19]. The active area is 1 mm² and the operation region is the visible range. 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 narrow 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) [20]. The illumination window is established on the front 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. The device works also under reverse bias (-4 V) to enhance spectral responsivity.

2.2. Optical links

Specific coding schemes to enable the accurate identification of signal transmitters and receivers were defined to establish the I2V and V2I channels. For every channel, synchronous transmission based on a 64 bits data frame was used. In Figure 1 it is displayed the configuration of the LED lamp with the four RGB white LEDs. All emitters (red, green and blue) are switched on to provide uniform white lighting in the indoor area. 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. The illuminated area corresponds to the coverage area of each lamp, defining a unit cell for the robot 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. Inside each unit navigation cell any receiver will be able to obtain the identification of the emission lamp and make the correspondence to the spatial position inside the warehouse. Increased position accuracy within each navigation cell is obtained through the optical pattern established by the red and the blue modulated emitters of each lamp. Top emitters (labelled as R and B) are assigned to the north cardinal direction inside the navigation cell, while bottom emitters (R’ and B’) to the south, and left (R and R’) and right (B and B’) emitters, respectively, to the west and east directions. 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). Areas of a single optical pattern, such as, R, B, R’ or B’ cover a wider area inside the cell, providing reduced position accuracy.

Figure 1 - Coverage area of each RGB lamp composed by four RGB LEDs with red and blue modulated emitters (Red emitters at each left side: R and R’, and blue emitters at each right side: B and B’) and spatial organization of adjacent unit navigation cells.

Using adjacent LED lamps to light the indoor space, different navigation cells are enabled by each lamp, as shown at the right side of Figure 1. Every navigation cell contains 3 racks in each direction (forward and reverse) of the movement labelled a, b and c. 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.

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.](image)

Data frames of both links are words of 64 bits composed each by six blocks. The first and the last blocks, each with 4 bits, are used to trigger synchronization of the transmitter and receptor of the respective link. In the I2V link the blocks are SoT (4 bits), CELL ID (12 bits), POSITION (12 bits), RACK (4 bits), MESSAGE (28 bits) and EoT (4 bits). The block CELL ID gives the identification of the unit cell. The format of the word code is XXXXXXYYYYY, where XXXX addresses the row and YYYY the column of the unit navigation cell. The block POSITION is encoded with 6 bits set to 1 and 6 bits set to 0 in channels R and B, while, for the bottom emitters, R’ and B’, the sequence is composed by 3 bits set to 1, 3 bits set to 0, 3 bits set to 1 and 3 bits set to 0. This block provides then information on the emitters being detected by the mobile robot and gives information on its relative position inside the navigation cell. The block RACK has the first 3 bits (a, b, c)
reserved to inform if racks inside the cell are available to deliver products (1 if possible, 0 if not). The last bit labelled as d is a control bit (set to 1 for the R and B channels, and to 0 for the R’ and B’ channels). In the MESSAGE block (32 bits) the infrastructure can transmit a random message to the mobile robot.

In the V2I link a single LED is used to transmit information from the mobile robot 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 (8 bits), CELL ID (12 bits), RACK (4 bits) and MESSAGE (24 bits) sandwiched between the SoT (4 bits) and EoT blocks (4 bits). The blocks ROBOT ID and CELL ID encode the identification of the transmitting vehicle and of the reception 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.

3. 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 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, as summarized in Table 1.

<table>
<thead>
<tr>
<th>Block</th>
<th>Decoded bits</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROBOT ID</td>
<td>01100110</td>
<td>118_{10}</td>
</tr>
</tbody>
</table>
| CELL ID | 001010000100 | line 0101[2] (5|10)  
column 0010|2 (2|10). |
| RACK    | 1011         | Items from a and c racks were removed (forward lane)                        |
As 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.

In the I2V link, the use of four emitters to transmit the coded information generates 16 possible photocurrents levels, assigned each to 16 different optical excitations. These levels are dependent on the signal optical intensity at the reception end, however, the relative position of the levels is assumed to be constant. This, supports the use of the calibration curve to demultiplex the electrical signal and provide identification of the input optical signals assigned to each photocurrent level. In Figure 4 it is displayed the calibration curve, showing the 16 possible output levels assigned to each input optical state. The driving current of each LED emitter was adjusted to provide different levels of photo excitation. On the right side of the picture it is shown the label of the modulated emitters that correspond to each photocurrent level.

![Calibration photocurrent signal using two red and two blue optical signals modulated with multiple frequencies](image)

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

The assignment of the photocurrent levels to the optical excitation can be summarized in Table 2.

<table>
<thead>
<tr>
<th>Photocurrent level</th>
<th>Optical state</th>
</tr>
</thead>
<tbody>
<tr>
<td>L00</td>
<td>OFF</td>
</tr>
<tr>
<td>L01</td>
<td>B’</td>
</tr>
<tr>
<td>L02</td>
<td>B</td>
</tr>
<tr>
<td>L03</td>
<td>BB’</td>
</tr>
<tr>
<td>L04</td>
<td>R’</td>
</tr>
<tr>
<td>L05</td>
<td>R’B’</td>
</tr>
<tr>
<td>L06</td>
<td>R’B</td>
</tr>
<tr>
<td>L07</td>
<td>R’BB’</td>
</tr>
<tr>
<td>L08</td>
<td>R</td>
</tr>
<tr>
<td>L09</td>
<td>RB’</td>
</tr>
<tr>
<td>L10</td>
<td>RB</td>
</tr>
<tr>
<td>L11</td>
<td>RBB’</td>
</tr>
<tr>
<td>L12</td>
<td>RR’</td>
</tr>
<tr>
<td>L13</td>
<td>RR’B’</td>
</tr>
<tr>
<td>L14</td>
<td>RR’B’</td>
</tr>
<tr>
<td>L15</td>
<td>RR’BB’</td>
</tr>
</tbody>
</table>
This 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:

\[
P1 = R + R' + B' \\
P2 = R' + B + B' \\
P3 = R + B + B'
\]

(1)

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.

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’ together with the calibration curve.

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

Figure 6 – Photocurrent signal acquired along the forward path at cell central position 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’).
In Table 3 it is summarized the decoded information of transmitted data blocks of Figure 6.

<table>
<thead>
<tr>
<th>Block</th>
<th>Channels</th>
<th>Decoded bits</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELL ID</td>
<td>R, R', B, B'</td>
<td>001010000100</td>
<td>line 0101</td>
</tr>
<tr>
<td>POSITION</td>
<td>R, B</td>
<td>111110000000</td>
<td>Center of the navigation cell</td>
</tr>
<tr>
<td></td>
<td>R', B'</td>
<td>111000111000</td>
<td></td>
</tr>
<tr>
<td>RACK</td>
<td>R, B</td>
<td>1110</td>
<td>a, b, c racks available (reverse lane)</td>
</tr>
<tr>
<td></td>
<td>R', B'</td>
<td>1011</td>
<td>a, c racks available (forward lane)</td>
</tr>
</tbody>
</table>

The comparison of the output signal with the calibration curve allows the decode of the signal and identification of the receiver’s position. In the case of the magenta line shown in the plot, it corresponds the spatial region where the signals from the four emitters are ON, i.e., the center of the navigation cell located at line 5, column 2.

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.

![Transmitted signal](image)

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.

4. CONCLUSIONS

Bi-directional communication using VLC in both downlink and uplink channels has been addressed in a robot navigation system. The proposed indoors application deals with infrastructure to vehicle (I2V) and vehicle to infrastructure (V2I) communication in a warehouse. The vehicle is a robot, that moves autonomously inside the warehouse carrying 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. Flickering effects were addressed by proper control of the amount of transitions to zero. The experimental evaluation in small range indoor conditions also demonstrated that the decoding solution can provide robust communications, especially if automatic bit error control methodology is implemented in the optical domain. Future work comprises the analysis of the system under other illumination sources that may induce photodetector saturation or noise in the decoding algorithm.

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