Visible LED-Assisted Navigation System for Large Indoor Environments

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***Abstract*— This paper investigates the applicability of an intuitive advertising system for large indoor environments using Visible Light Communication (VLC). This VLC based positioning system includes the use of the visible light signal to light the space and to transmit the information for positioning of travelers and of advertising campaigns in the surroundings. An LED-assisted positioning and navigation VLC system is proposed. A VLC scenario for large environments is analyzed, the emitters and receivers are characterized and the communication protocol presented. Different layouts are investigated. Square and hexagonal meshes are tested and a 2D localization design, demonstrated by a prototype implementation, is presented. The key differences between both topologies are discussed. For both, the transmitted information, indoor position, path direction, as well as bidirectional communication are determined. The results showed that the LED-aided VLC navigation system makes possible to determine the position of a mobile target inside the network, to infer the travel direction as a function of time and to interact with the information received.**

Keywords- Visible Light Communication; Indoor positioning; Advertising, Optical sensors; Large indoor environments; SiC technology; Transmitter/receiver; Multiplexing/de-multiplexing techniques.

I. INTRODUCTION

Advertising is used to stimulate market demand. The purpose is to transmit the right message to the right receiver at the right time, as well as the collection, understanding and decoding of the message in a proper manner. Usually, advertisement signs are used to communicate, and they are placed in geographically identified areas in order to capture customers' attention. The most obvious method of using signs is through billboards located in high traffic areas. Indoor billboards are designed in order to attract the attention of those moving past the sign. Handheld devices make up the growing mobile device market. Such devices allow customers to stay informed, gather information and communicate with others without being tied to a physical location and offer significant opportunity for marketers to reach customers at anytime and anyplace. Also, with geographic positioning features included in newer mobile devices, the medium has the potential to provide marketers with the ability to target customers based on their geographic location.

Airports are among the largest shopping centres. They must satisfy high service requirements. Business travellers have all the information concerning their flight on their boarding pass. With a clearly arranged Web interface, they can see the most frequented areas inside an airport and can take action if certain areas become overcrowded, meaning that those places can be highlighted on an interactive map. Additionally, it is also an advantage if the shopping function is complemented by other features, for example, if the customer could be informed about the current waiting times or be given recommendations.

Nowadays, indoor positioning methods are mainly based on Wi-Fi [1], Bluetooth, Radio-Frequency Identification (RFID) [2] and Visible Light Communications (VLC) [3]. VLC is a data transmission technology [4] that can easily be employed in indoor environments since it can use the existing LED lighting infrastructure with simple modifications [5][6]. In this paper, we propose the use of modulated visible light, carried out by white polychromatic low cost LEDs. This means that the LEDs are useful twofold by providing illumination as well as communication. The use of white polychromatic LEDs offers the possibility of Wavelength Division Multiplexing (WDM), which enhances the transmission data rate. A WDM receiver based on tandem a-SiC:H/a-Si:H pin/pin light controlled filter can be used [7][8] to decode the received information. Here, when different visible signals are encoded in the same optical transmission path, the device multiplexes the different optical channels, performs different filtering processes (amplification, switching, and wavelength conversion) and finally decodes the encoded signals recovering the transmitted information.

Research is still necessary to design LED arrangements that can optimize communication performance while meeting the illumination constraints for a variety of large indoor layouts. The main idea is to divide the space into spatial beams originating from the different light sources, and identify each beam with a unique timed sequence of light signals. Fine-grained indoor localization can enable several applications in airports, supermarkets and shopping malls. Information on the exact location of products can greatly improve the customer's shopping experience and enable customer analytics and marketing [9].

In this paper, an LED-assisted positioning and navigation VLC system is proposed. The paper is organized as follows. After the introduction (Section I), in Section II, a VLC scenario for large environments is established, the emitters and receivers are characterized and the communication protocol is presented. In Section III, different layouts are analyzed. Square and hexagonal meshes are tested and a 2D localization design' demonstrated by a prototype implementation, is presented. The key differences between the two topologies are discussed. For both, the transmitted information, indoor position, path direction as well as bidirectional communication are determined. Finally, in Section IV, conclusions and future trends are addressed.

The proposed LED aided system involves wireless communication, smart sensors and optical sources network, building up a transdisciplinary approach framed in cyber-physical systems.

II. SYSTEM DESIGN

A. VLC Scenario

The indoor environment chosen is an airport and two topologies were considered: the square for the main hall and the hexagonal for the marketing zones. The reported plan and the proposed scenario are presented in Figure 1. Here, a user navigates from outdoor to indoor. The user sends a request message to find out what gate he/she is boarding at, and in the available time until boarding, he/she adds customized points of interest, routes from restaurants, shops, and halls within the airport. The requested information is sent by the emitters from the ceiling to the receiver. The traveler is equipped with a receiver. After the check-in at the main airport entrance, the user passes through airport security and, depending on the available time until boarding, he/she can go directly to the gate or shop, eat or rest. After registration, he/she sends to the central controller a message request in order to add, in the available time, customized points of interest, routes from restaurants, shops, gates, halls to boarding or the right track. On his path, the passenger is advised how to reach its destination and the possibility to use location based advertising (available selection of goods advice and restaurants).

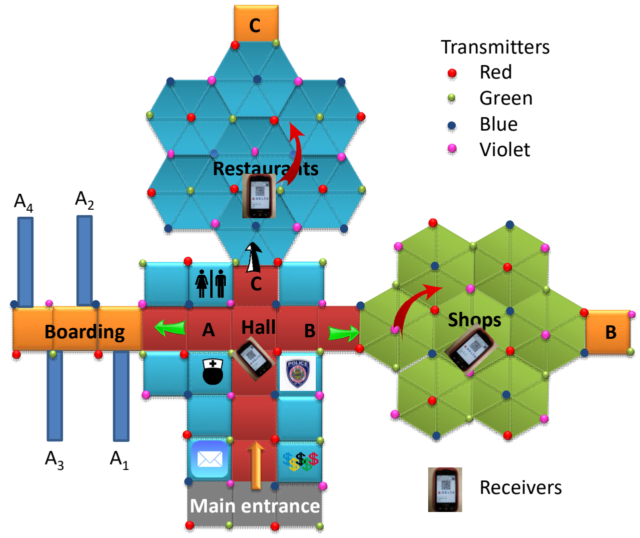

Figure 1. Optical infrastructure and indoor layout.

B. The Emitters for Large Environments

LED bulbs, at the nodes of the network, act as transmitters, broadcasting the information. An optical receiver extracts its location to perform positioning and, concomitantly, the transmitted data from each transmitter. To synchronize the signals from multiple LEDs, the transmitters use different IDs, allowing the signal to be reconstructed at the receiver.

Ceiling plans for the LED array layout are shown in Figure 2. Two topologies were set for the unit cell: the square, (Figure 2a) and the hexagonal (Figure 2b). Red (R; 626 nm), Green (G; 530 nm), Blue (B; 470 nm) and violet (V; 390 nm) LEDs, at the nodes of the network, are used [10][11]. In both topologies, each node, $X_{i,j}$, carries its own color, X, (RGBV) as well as its ID position in the network (i,j). In both, the grid sizes were chosen to avoid overlap in the receiver from adjacent grid points. To improve its practicality, the tested geometric scenario in the experimental results uses a grid in smaller size (with 2 cm between adjacent nodes).

For data transmission, commercially available polychromatic white LEDs were used. On each node, only one chip is modulated for data transmission. To receive the information from several transmitters, the receiver must be positioned where the irradiated circles from each transmitter overlap, producing at the receiver, a multiplexed (MUX) signal that, after demultiplexing, acts twofold as a positioning system and a data transmitter. The generated regions, defined onwards as footprints, are pointed out in Figure 2 and reported in Table I.

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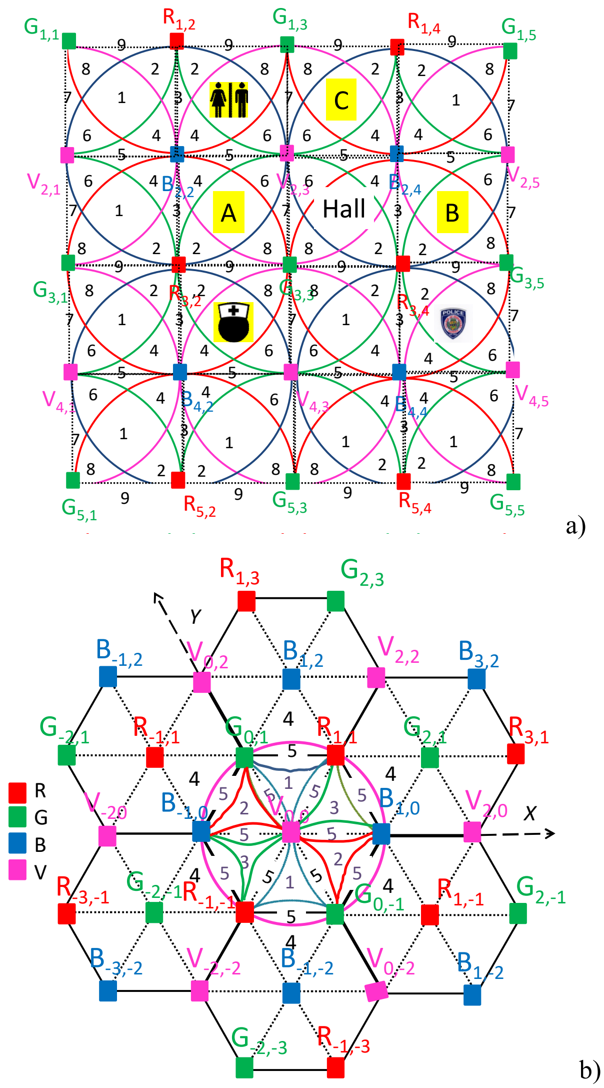

Figure 2. Optical infrastructure and storage model (LED array = RGBV color spots): a) Clusters of cells in orthogonal topology (square). b) Clusters of cell in hexagonal topology.

TABLE I. FINE-GRAINED TOPOLOGIES: FOOTPRINT REGIONS.

Footprint regions	Square topology	Hexagonal topology
#1	RGBV	RGV
#2	RGB	GBV
#3	RB	RBV
#4	RBV	RGB
#5	BV	RGBV
#6	GBV	-
#7	GV	-
#8	RGV	-
#9	RG	-

The device receives multiple signals (footprints), finds the centroid of the received coordinates and stores it as the reference point position.

C. *The receiver*

The VLC photosensitive receiver is a pinpin photodetector based on a multilayer hetero-structure, p-i'(a-SiC:H)-n/p-i(a-Si:H)-n sandwiched between two transparent contacts [8]. The device offers high sensitivity and linear response, generating a proportional electrical current. Its quick response enables the possibility of high speed communications. The device operates within the visible range using, for data transmission, the modulated light supplied by the RGBV LEDs transmitters. The generated photocurrent is processed using a trans-impedance circuit obtaining a proportional voltage. The voltage is then processed, by using signal conditioning techniques (adaptive bandpass filtering and amplification, triggering and demultiplexing), until the data signal is reconstructed at the data processing unit (digital conversion, decoding and decision) [12].

D. *The OOK Modulation Scheme*

An on-off keying modulation scheme was used. To create a communication protocol to ensure the required system performance and overcome the technology constraints, a 32 bits data frame was designed.

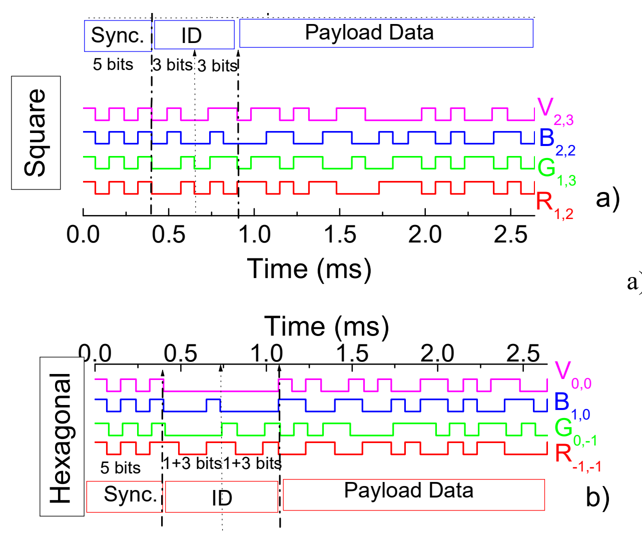

Figure 3. Data frame structure. Representation of one original encoded message, in a time slot: a) Square topology. b) Hexagonal topology.

Three control fields, one for synchronism (Sync.) and two for the identification of the cell (ID) begin each frame. This sequence is followed by a fourth block that is for the payload, as shown in Figure 3, for both topologies: a) Square topology; R_{12} ; $G_{1,3}$; $B_{2,2}$ and $V_{2,3}$ are the transmitted node packet from the array in the network. b) Hexagonal topology; $R_{-1,-1}$; $G_{0,-1}$; $B_{1,0}$ and $V_{0,0}$ are the transmitted node packet from the array in the network. A stop bit is used at the end of each frame. The first five bits are used for time synchronization. The same synchronization header [10101], in an *on-off* pattern, is imposed simultaneously to all emitters. Each colour signal (RGBV) carries its own ID-BIT, so, the next bits give the coordinates of the emitter inside the array ($X_{i,j}$). The cell's IDs are encoded using a binary representation for the decimal number. In the square topology (Figure 3a), six bits are used: the first three for the binary code of the line and the other three for the column. In the hexagonal topology, 60º Cartesian coordinates were applied (Figure 2b). An extra bit was added at the beginning of the binary code to represent the number's sign: setting that bit to *0* is for a positive number, and setting it to *1* is for a negative number. The remaining bits in the number indicate the absolute value. So, the next eight bits (ID) are assigned, respectively, to the *x* and *y* coordinates (*i,j*) of the emitter in the array (Figure 3b). For both, the last bits in the frame are reserved for the message sent by the X_{ij} node (payload data). With this information, the method will give an exact, unique answer, *i.e.*, the location of the receiver in the array ($X_{i,j}$).

Results show that, in the square network, $R_{1,2}$, $G_{1,3}$, $B_{2,2}$ and $V_{2,3}$ are the transmitted node packets, in a time slot, from the unit cell where the restrooms are located (Figure 2a). In the hexagonal network, the nodes $R_{-1,-1}$, $G_{0,-1}$, $B_{1,0}$ and $V_{0,0}$, located in the first ring of the restaurant zone (Figure 2b), are the transmitters.

III. SYSTEM EVALUATION

A. *Positioning*

In Figure 4, a MUX signal due to the joint transmission of four R, G, B and V optical signals, in a data frame, is displayed.

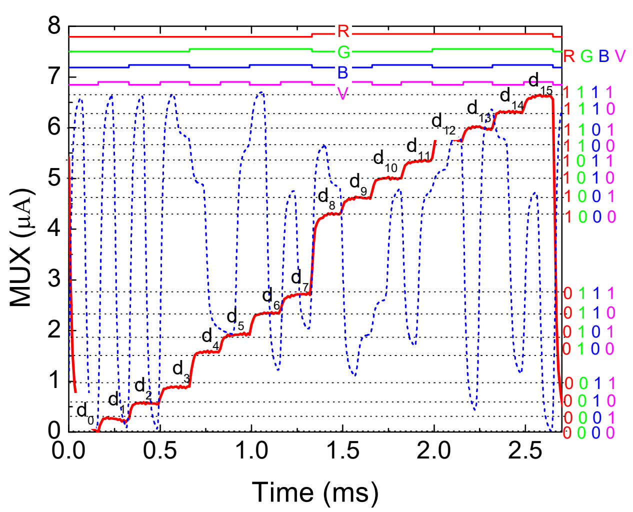

Figure 4. MUX signal of the calibrated cell. On the top the transmitted channels packets [R, G, B, V] are depicted. A received MUX signal is also superimposed to exemplify the decoding algorithm.

The data acquisition was obtained with the presence of environment light. The bit sequence (on the top of the figure) was chosen to allow all the sixteen possible *on/off* combinations of the four input channels (2^4).

Results show that the code signal presents as many separated levels as the *on/off* possible combinations of the input channels, allowing decoding the transmitted information [12]. All the ordered levels (d_0-d_{15}) are pointed out at the correspondent levels and are displayed as horizontal dotted lines. On the right hand side, the match between MUX levels and the 4 bits binary code assigned to each level is shown. For demonstration of the decoding technique, a signal received in the same time frame in #1, is also added (dotted curve). Comparing the calibrated levels (d_1-d_{15}) with the different assigned 4-digit binary code, the decoding is straightforward. Each decoded message also carries the transmitter's node address. So, the next block of six bits, in the square topology (or eight in the hexagonal one), gives de ID of the received node.

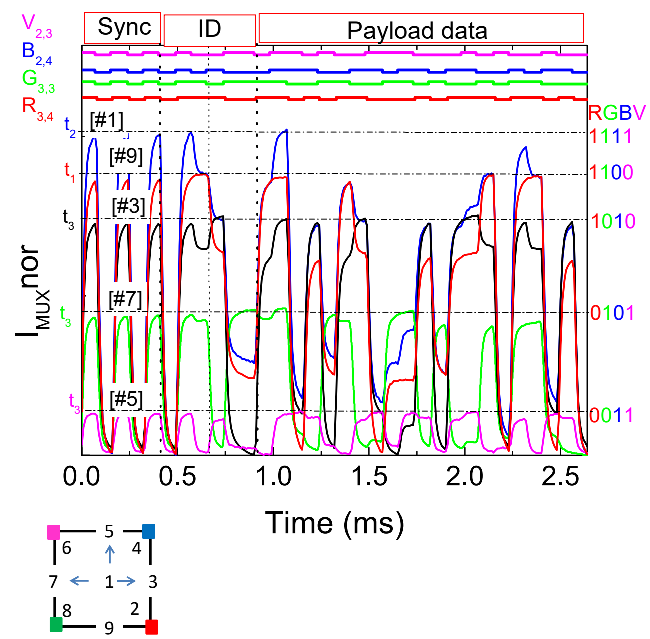

Figure 5. MUX/DEMUX signals at the main hall (#1, #3, #5, #7 and #9). On the top the transmitted channels packets [R, G, B, V] are decoded.

In Figure 5, the MUX signals acquired at the main hall in different positions (#1, #3, #5, #7 and #9) are displayed. On the top, the transmitted channels packets [R, G, B, V] are decoded. Here, in position #9 the network locations of the transmitters are $R_{3,4}$ [011;100] and $G_{3,3}$ [011;011] while in #1 the assigned transmitters are $R_{3,4}$, $G_{3,3}$, $B_{2,4}$ and $V_{2,3}$. The last block is reserved for the transmission of the advertising (payload data). The stop bit (0) is always used at the end of each frame.

B. Travel direction

To compute the point-to-point along a path, we need the data along the path. The input of the aided navigation system is the coded MUX signal, and the output is the system state decoded at each time step (*Δt*). As a proof of concept, in the lab, a navigation data bit transition was tested by moving the receiver along a known pattern path. In this example (Figure 5), at $t_{1,}$ the user enters the hall by line #9, goes to position #1 at t_2 and chooses the boarding terminal or the marketing zones at $t_{3,}$ being directed into one of the three indicated directions (A # 7; B # 3 or C # 5).

The results show that, as the receiver moves between generated point regions, the received information pattern changes. Between two consecutive data sets, there is a navigation data bit transition (channel is missing or added). We observe that, when the receiver moves from #9 to # 1 (Figure 5), two different ID channels are added ($B_{2,4}$ and $V_{2,3}$). Here, the 4-binary bit code has changed from [1100] to [1111].

In Figure 6, a path crossing the hexagonal topology is also tested. Here, the receiver enters the restaurants area (#4> #5> #3).

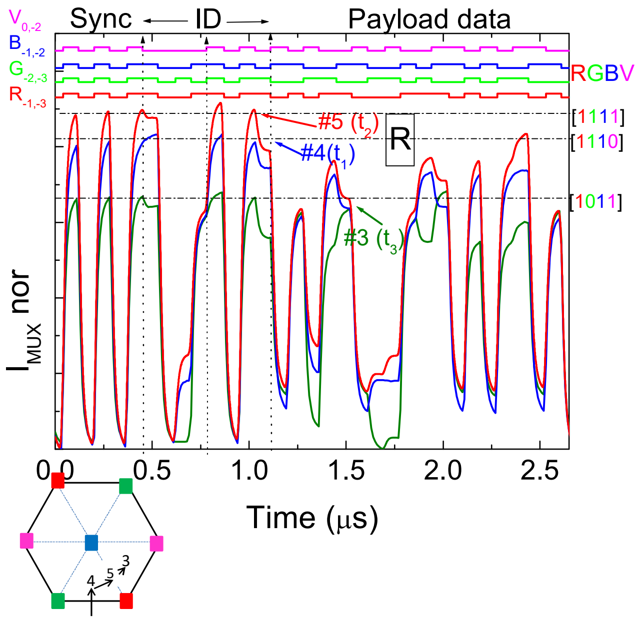

Figure 6. Fine-grained indoor localization and navigation in successive instants. Signal acquisition through the restaurants area (R). On the top the transmitted channels packets are decoded [R, G, B, V].

Taking into account Figure 2b and the frame structure (Figure 3b), results show that, at t_1, the receiver was located at #4 [1110]/ $R_{-1,-3}$ $G_{-2,-3}$ $B_{-1,-2}$. At t_2, it arrives at #5 [1111]/ $R_{-1,-3}$ $G_{-2,-3}$ $B_{-1,-2}$. $V_{0,-2}$, and then, at t_3, it moves towards #3, [1011]/ $G_{-2,-3}$ $B_{-1,-2}$. $V_{0,-2}$.

The main results from both topologies show that fine grained localization is achieved by detecting the wavelengths of the received channels in each region. The location and path of a mobile receiver was obtained based on the LED-based navigation system. In an orthogonal layout (hall), the square topology is the best. It allows crossroads and the client can walk easily in the horizontal, vertical, or both directions. In concentric layouts, to fill all the space with hexagons presents advantages (restaurants, and shops areas). Here, the client can move around and walk between the different rings toward the outside region.

C. Bidirectional communication

Bidirectional communication between VLC emitters and receivers in a handheld device can be established through a control manager linked to an indoor billboard. Each ceiling lamp broadcasts a message with its ID and advertising, which is received and processed by the receiver. Using a white polychromatic LED as transmitter, the receptor sends to the local controller a "request" message with its location (ID) and adds its needs for the available time (payload data). For route coordination, the local controller emitter sends the "response" message.

In Figure 7, the MUX signal assigned to a "request" and a "response" message are displayed. At the top, the decoded information is presented. On the right side, the match between the MUX signal and the 4-binary code is pointed out. Here, in a time slot, the traveler, in position #3 ($R_{3,2}$, $B_{2,2}$), sends to the central controller the message "request" in order to add the points of interest (boarding or the right track). After that, it is advised through a "response" message, that the request was received, how to reach the destination in time and how to use location based advertising.

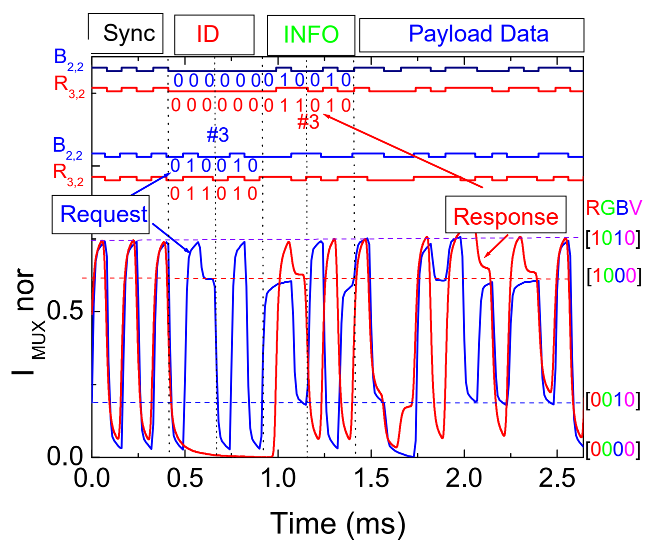

Figure 7. MUX/DEMUX signals assigned to a "request" and a "response" message. On the top the transmitted channels packets [$X_{i,j}$] are decoded.

Taking into account the frame structure (Figure 3), results show that the codification of both signals is synchronized (Sync). The "request" message includes the complete address of the traveler (Sync+ID) and the help need (payload data). In the "response" message, the block

(ID), in a pattern [000000], means that a response message, from the local manager, is being sent. The next block (6 bits) identifies the address (INFO) for which the message is intended and finally in the last block appears the requested information (payload data). Here, the emitter controller [000000] responds to a request of a passenger located in position # 3 ($R_{3,2}$, $B_{2,2}$) and sends back the requested information.

IV. Conclusions

An LED-assisted navigation system for large indoor environments was proposed. For lighting, data transmission and positioning, white LEDs were used. A SiC optical MUX/DEMUX mobile receiver decodes the data and based on the synchronism and ID of the joint transmitters it infers its path location, timing and user flows.

A VLC scenario for an airport was established and the communication protocol presented. The bi-directional communication between the infrastructure and the mobile receiver was analysed. Two cellular networks were tested and compared: square and hexagonal. The main results show that, for both topologies, the location of a mobile receiver, concomitant with data transmission is achieved. The LED-aided VLC navigation system makes possible to determine the position of a mobile target inside the network, to infer the travel direction as a function of the time and to interact with the received information.

Minding the benefits of VLC, it is expected that this type of communication will have an important role in positioning applications. Moving towards real implementation, the performances of such systems still need to improve. As a future goal, we plan to finalize the embedded application for experimenting in several network layouts. Effects such as synchronization, shadowing and ambient light noise will be minimized by distributing lighting sources (MIMO techniques) to optimize the coverage.

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