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Geolocation and Wayfinding Services Using Visible Light Communication

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Abstract: This paper investigates the applicability of an intuitive wayfinding system in complex buildings using Visible Light Communication (VLC). Typical scenarios include finding places. Data from the sender is encoded, modulated and converted into light signals emitted by the transmitters. Tetra-chromatic white sources are used providing a different data channel for each chip. At the receiver, the modulated light signal, containing the ID and the 3D geographical position of the transmitter and wayfinding information, is received by SiC photodetector with light filtering and demultiplexing properties. Each luminaire for downlink transmission become a single cell, in which the optical access point (AP) is located in the ceiling and the mobile users are scattered within the overlap discs of each cells underneath. The light signals emitted by the LEDs are interpreted directly by the receivers of the users underneath. The effect of the location of the APs is evaluated and a model for the cellular networks is analyzed using orthogonal topologies. A 3D localization design, demonstrated by a prototype implementation, is presented. Uplink transmission is also implemented and the 3D best route to navigate calculated. The results showed that the system allows to determine the position of a mobile target inside the network, to infer the travel direction along the time and to interact with information received optimizing the route towards the destination.

Keywords: Visible Light Communication, Indoor navigation, Bidirectional Communication, Wayfinding, Optical sensors, Transmitter/receiver, Multiplexing/demultiplexing techniques.

1. Introduction

Optical wireless communication has been widely studied during the last years in short-range applications. Therefore, communications within personal working/living spaces are highly demanded. Multi-device connectivity can tell users, from any device, where they are, where they need to be and what they need to do when they get there. In future accurate indoor positioning might not be viable by sole utilizing RF communications. Research has shown that compared to outdoors, people tend to lose orientation a lot easier within complex buildings [1, 2]. Fine-grained indoor localization can be useful enabling several applications [3, 4].

To support people's wayfinding activities in unfamiliar indoor environments, a method able to generate ceiling landmark route instructions using VLC is proposed. VLC is a data transmission technology [5, 6]. It can be easily used in indoor environments using the existing LED lighting infrastructure with few modifications [7, 8]. This means that the LEDs are twofold by providing illumination as well as communication. Research is still needed to design LED arrangements that can optimize communication performance while meeting the illumination constraints.

Each luminaire for downlink transmission become a single cell in which the optical access point (AP) is located in the ceiling. Data from the sender (the map information and the path messages necessary to wayfinding) is encoded, modulated and converted into light signals emitted by the transmitters. Tetra-chromatic white sources are used providing a different data channel for each chip. The use of white polychromatic LEDs in the ceiling offers also, the possibility of Wavelength Division Multiplexing (WDM) which enhances the transmission data rate. To receive the mapped information generated from the ceiling light in visual light form the users are equipped with a receiver module that displays this fabricated information in the mobile terminal. Receiver modules includes a photodetector based on a tandem a-SiC:H/a-Si:H pin/pin light controlled filter [9-11] that multiplexes the different optical channels, performs different filtering processes (amplification, switching, and wavelength conversion) and finally decodes the encoded signals, recovering the transmitted information. This kind of receiver has proved to be adequate when used in large indoor environments with a 2D building model [12]. However, vertical positioning is also important [13, 14]. 3D tracking is difficult by the need for additional coverage for passages between floors (*e.g.* stairs, elevators).

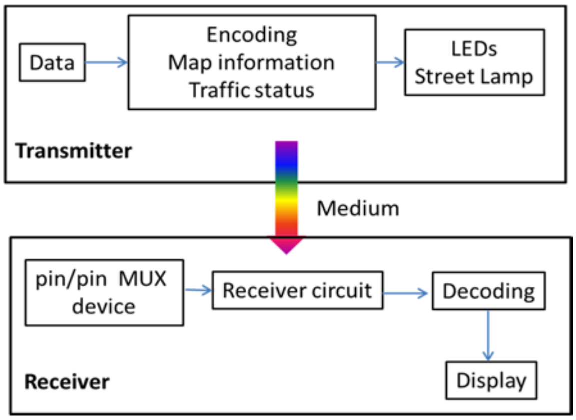
In this paper, a dynamic LED-assisted positioning and navigation VLC system is proposed. A 3D model for the building is established. The transmitted information, indoor position, motion direction as well as bi-directional communication are determined.

2. VLC Dynamic Navigation System

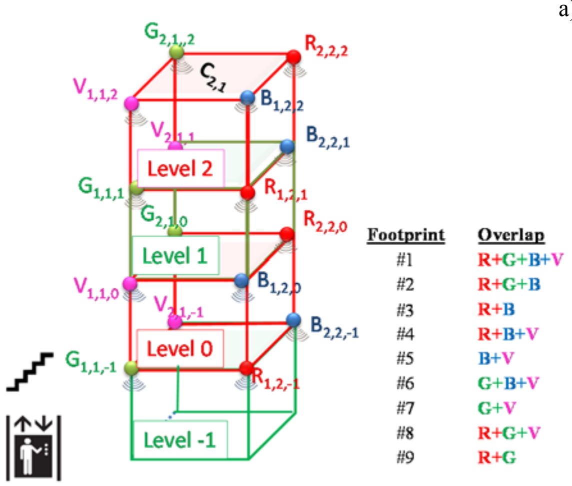
2.1. VLC Virtual Scenario

When we are looking for the shortest route to a place, we want to be guided on a direct, shortest path to our destination. A destination can be targeted by user request to the central manager (CM).

The dynamic navigation system is composed of several transmitters which send the map information and path messages required to wayfinding. Mobile optical receivers, using joint transmission, extracts theirs location to perform positioning and, concomitantly, the transmitted data from each transmitter. To synchronize the signals from multiple LEDs, the transmitters use different ID´s, such that the signal is constructively at the receiver. Bidirectional communication between the emitters and the receivers is available in strategic optical access point (Li-Fi zone). The block diagram of the VLC system is presented in Fig. 1a. The system is composed by the transmitter and the receiver modules located, respectively, at the infrastructures and at the mobile users.



a)



b)

Fig. 1. a) VLC block diagram; b) The 3D virtual floorplan.

The indoor environment chosen is a shopping center with several floors. The 3D virtual floorplan with the information about the number of floors and the nodes localization is draft in Fig. 1b. The ground floor is level 0, and the user can go both below and above from there. Each unit cell can be referred as $C_{i,j,k}$ were i, j, k are respectively the line, the row and the level of the top left node of each unit cell. To exemplify, Cell $C_{2,1}$ is depicted in the figure for levels -1, 0, 1 and 2. Therefore, each node, $X_{i,j,k}$ carries its own color, X, (RGBV) as well as its horizontal (line and row) and vertical (level) ID position in the network (i,j,k). For data transmission commercially available polychromatic white LEDs were used.

In Fig. 2 the ceiling plans for the LED array layout in a 3D building, for even and odd floors is shown (R,G,B,V are the modulated color spots for data transmission in each level). A multi-layer orthogonal geometry with lines and rows for each floor was considered for a square unit cell framed with four tetra-chromatic LEDs. Only one chip, in each node, is modulated, the Red (R; 626 nm), the Green (G; 530 nm), the Blue (B; 470 nm) and the Violet (V; 390 nm)], the other have a dc driving current for white perception [3, 15].

To receive the information from several transmitters, the receiver must be positioned where the circles from each transmitter overlaps, producing at the receiver, a multiplexed (MUX) signal that, after demultiplexing, acts twofold as a positioning system and a data transmitter.

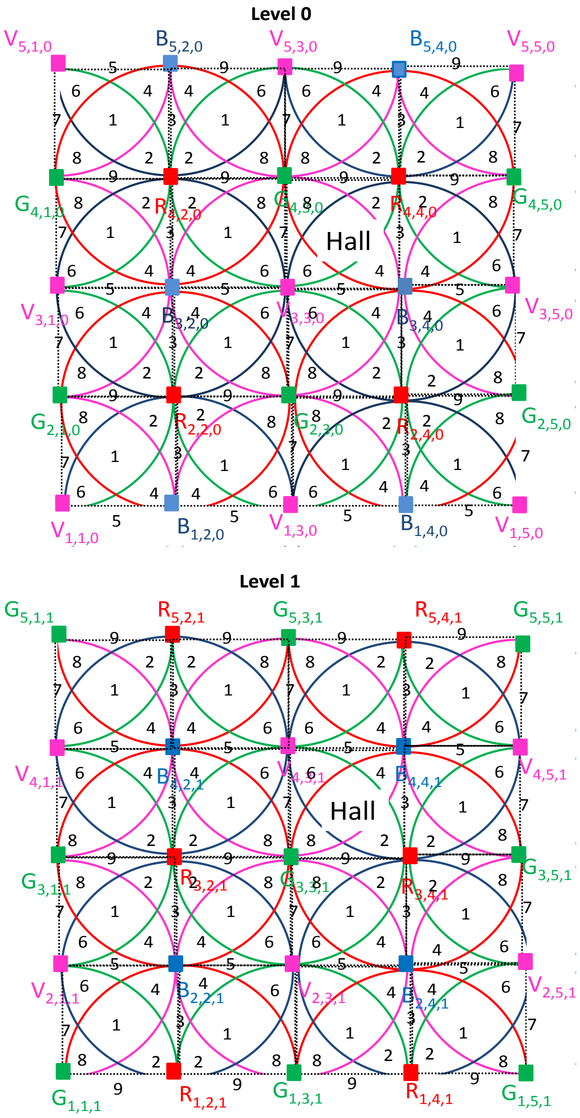


Fig. 2. Illustration of the proposed scenario. Ceiling plans for the LED array layout in a 3D building, for even and odd floors. The footprint regions assigned to the overlaps are pointed out in Fig. 1.

The overlap regions, the footprints, are also pointed out in Fig. 1. Nine reference points, for each unit cell, are identified and give a fine grained resolution in the localization of the mobile device across each cell.

The user positions is represented as $P\ (x,\ y,\ z)$ by providing the horizontal positions $(x,\ y)$ and the correct floor number z. By integrating floor number information into the previous 2D system [16], the overall performance of the system will not be significantly affected as this time the 2D positions are more important and the floor detection accuracy is high enough to handle automatic floor plan changes. Also, there needs to be stairs or an elevator to enable a connection between the floors.

The VLC photosensitive sensor, in the receiver module, is a double pin/pin photodetector based on a tandem heterostructure, p-i'(a -SiC:H)-n/p-i(a-Si:H)-n sandwiched between two transparent contacts [3]. The device is an active filter able to identify the wavelengths and intensities of the impinging optical signals. Its quick response enables the possibility of high speed communications [17]. Bi-directional communication between VLC emitters and receivers is available at a VLC ready handheld device through a control manager (CM) interconnected with a billboard receiver located in a Li-Fi zone.

Different users, are considered. Depending on the time available, they can find a friend, shop, have a meal or rest. When arriving, they notify the controller manager (CM) of their location (x,y,z), asking for help to find the best way for their needs. A code identifies each user. If a user wishes to find a friend both need previously to combine a common code for the schedule meeting. The first arriving initiates the alert notification to be triggered when the other is in his floor vicinity and generates a buddy list for the meeting. The buddy finder service uses the location information from the network's VLC location from both users to determine their proximity and sends a response message with the location and path of the meeting point.

2.2. Encoding Techniques: Communication Protocol

An on-off keying modulation scheme was used to code the information. To create a communication protocol and overcome the technology constraints, a 64 bits data frame was designed. In Fig. 3 it is displayed the representation of one original encoded message, in a time slot.

In Fig. 3a, the transmitted node packet ($R_{4,4,0}$; $G_{4,3,0}$; $B_{3,4,0}$; $V_{3,3,0}$) from cell $C_{4,3,0}$ (ground floor Hall; Fig. 2) are displayed and in Fig. 3b, an encoded message send by the CM transmitter, at cell $C_{2,3,-1}$, are shown in the same frame of time. Several control fields are used for the transmitted messages depending on the type of transmitter. The synchronism (Sync) is the first and the next are used for the identification of the ceiling (Fig. 3a) or CM (Fig. 3b) transmitters and wayfinding data. A stop bit is always used at the end of each frame. For the luminaires, the cell ID (x,y,z) begin the second block while for the CM transmitter a pattern [000] precedes this identification. Those sequences are followed by a new block (pin_1) with the password of the user if a request is needed, if not this block is set at zero and the user only receives its own location.

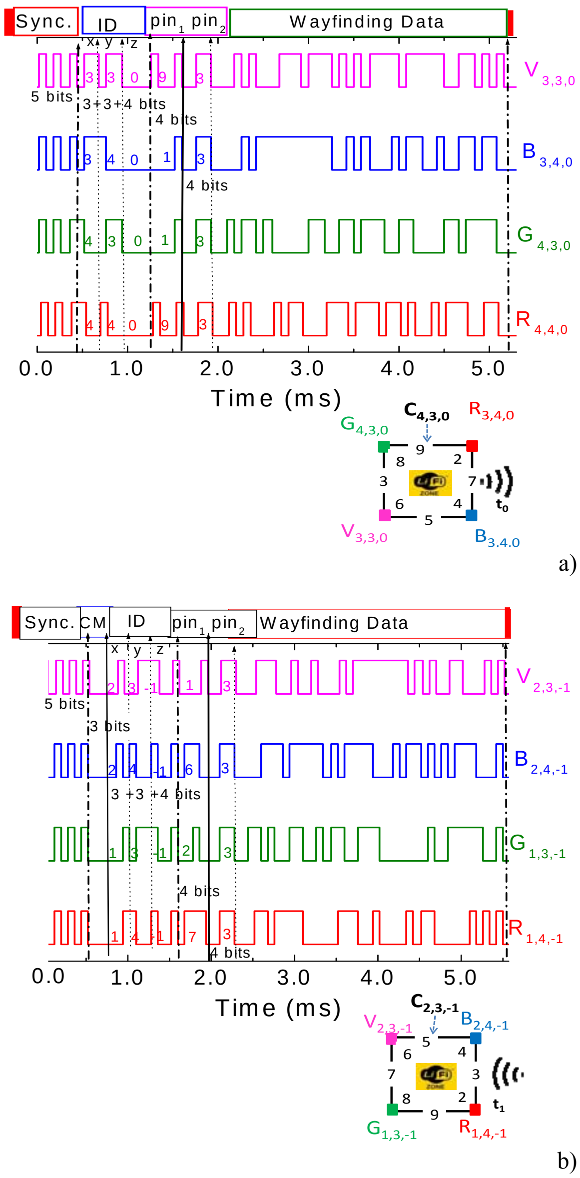


Fig. 3. Data frame structure. Representation of one original encoded message, in a time slot: a) $R_{4,4,0}$; $G_{4,3,0}$; $B_{3,4,0}$ and $V_{3,3,0}$ are the transmitted node packet from the unit cell $C_{4,3,0}$ in the network. b) $R_{1,4,-1}$; $G_{1,3,-1}$; $B_{2,4,-1}$ and $V_{2,3,-1}$ are a transmitted node packet from the CM at the unit cell $C_{2,3,1}$.

The last block is used to transmit the wayfinding message and may include, in the beginning, the code of the request meeting (pin_2). 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 10 bits (3+3+4) give the *x,y,z* coordinates of the emitter inside the array ($X_{i,j,k}$). Cell's IDs are encoded using a binary representation for the decimal number. Since positive and negative floors were considered, an extra bit was added at the beginning of the binary code of the *z* coordinate to represent the number's sign: setting that bit to *0* is for a positive number, and setting it to *1* for a negative number, the remaining 3 bits indicate the absolute value of the *z* coordinate. The last bits, in the frame, are reserved for the message send by the $X_{i,j,k}$ node (payload data). With this information, the method will give an exact, unique answer, *i.e.*, the location of the receiver in the array ($X_{i,,j,k}$). When bidirectional communication is required, the user has to register by choosing a user name with 4 decimal numbers, each one associated to a colour channel. Here, each channel (RGBV) needs a binary 4-digid code. The decimal numbers assigned to each ID block are pointed out in the Fig. 3. Results from Fig. 3a show that $R_{4,4,0}$, $G_{4,3,0}$, $B_{3,4,0}$ and $V_{3,3,0}$ are the transmitted node packets, in a time slot, from an AP ($C_{4,3,0}$) located in level 0. In this location, an identified user *9119* [1001, 0001, 0001, 1001] receives his response message [wayfinding needs] from the infrastructure. From Fig. 3b we notice that the a CM transmitter, located at cell $C_{2,3,-1}$, in the basement ($R_{1,4,-1}$; $G_{1,3,-1}$; $B_{2,4,-1}$; $V_{2,3-1}$), responds to a request from the user *7261* [0111, 0010, 0110, 0001]. Both identify users have previously arranged a meeting with the code 3 [0011].

3. Results

3.1. Travel Direction: Wayfinding Services

To compute the point-to-point along a path, we need the data along the path. As a PoC, in the lab, a navigation data bit transition was tested by moving the receiver along a known pattern path.

In Fig. 4, the MUX signal acquired by a user, as well as the decoded information, is displayed in different instants. The visualized cells, paths and the reference points are also shown. The user enters the floor 1 (see Fig. 2) by line #7 ($C_{4,1,1}$), it goes to position #1(t_0) being directed by the CM into the pretended directions ($C_{4,2,1}$ # 5) where he arrives at t_3 passing through footprints #3 (t_1) and #1(t_2) from the next cell.

Results show that the location and path of a mobile receiver was obtained based on the dynamic LED-based navigation system. As the receiver moves between generated point regions, the received information pattern changes. For instance, when the receiver moves in the reverse direction, from $C_{4,1,1}$ #3 to $C_{4,1,1}$ # 1 two different ID channels are added ($G_{3,1,1}$ and $V_{4,1,1}$). Here, the 4-bynary bit code has changed from [1010] to [1111]. In the forward direction ($C_{4,2,1}$) the added channels have the same colour but different ID ($G_{3,3,1}$ and $V_{4,3,1}$). So, just by tracking the path in successive instant the direction of the receiver is known. Going forward corresponds to crossing lines #3 and #7, turning left cross of line #5 and turning right to line #9.

3.2. Bi-directional Communication: Buddy Services

Bi-directional communication is available at ready handheld device through a control manager (CM) interconnected with a billboard receiver located at each unit cells in a Li-Fi zone (Ci,j,k, #1) [18]. In Fig. 5, the MUX synchronized signals from two identify users are displayed. In the right side, the match between the MUX signal and the 4-binary code is pointed out. On the top the decoded channels packets are shown [R, G, B, V].

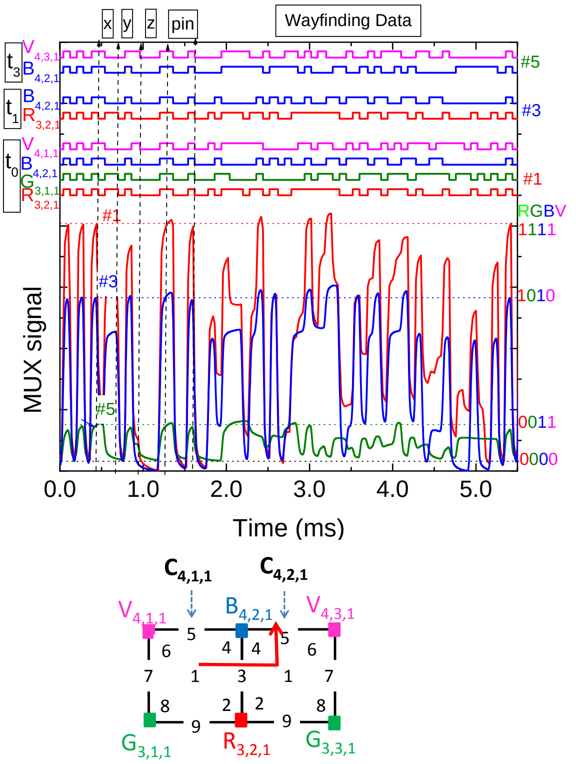


Fig. 4. Fine-grained indoor localization and navigation in successive instants. On the top the received channels packets are decoded at each time step [R, G, B, V].

The user sends to the CM a "request" message with his location (x,y,z), identification (pin_1) and also adds its needs (Wayfinding data). If a meeting between users is requested they need previously to combine a common code and insert it in the "request" (pin_2). The user password (pin_1) is a decimal number of one or four digits depending on the requested services. A 4-bynary code is used for each digit. If only wayfinding services are required one digit (0-9) is enough, and is the same for all the transmitted channels, if buddy services are needed a 4-decimal code has to be inserted to identify the user, followed by the meeting code.

Taking into account Fig. 2, results show that in a time slot, two identified users ("2015" and "7261"; pin_1) have successively (t_0, t_1) request to the buddy wayfinding services, the right track (wayfinding data) for their previously scheduled meeting, pin_2 [0011/3;]. At the right hand of the figure the scenario is illustrated. In the proposed scenario, user "2015" initiates the alert notification ($C_{4,1,1}$; t_0) to be triggered in his floor vicinity (level 1) and initializes the buddy list that includes all the users who have the same meeting code (pin_2:[0011]; 3). User "7261" arrives later ($C_{2,3,-1}$; t_1), identifies himself and uses the same code in the buddy wayfinding services to track the best way to the scheduled meeting. For route coordination the CM sends a personalized "response" message at the requested position ($C_{2,3-1}$). In this message the buddy finder service uses the location information from both to determine their proximity and sends a response message to user "7261" with the best route to the meeting.

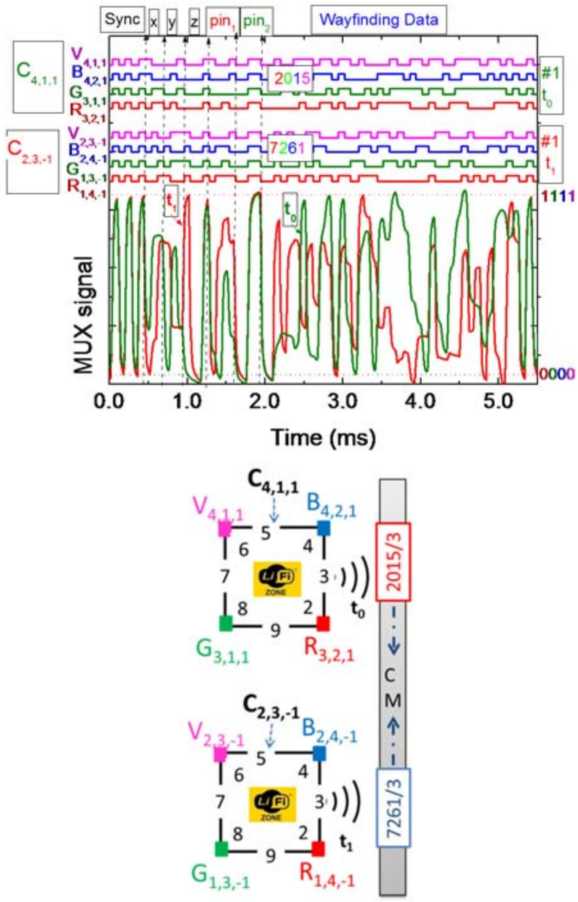


Fig. 5. MUX/DEMUX signals assigned to a "request". MUX signal received by the CM receiver from two users ("2015" and "7261") at different locations ($C_{4,1,1}$; #1 and $C_{2,3,-1}$; #1) in successive instants (t_0 and t_1). On the top the transmitted channels packets are decoded [$X_{i,j}$].

During both routes every time a user changes floors he has to notify the CM and a new alert is received to optimize the way. Fig. 6 shows the type of responses sent by the CM to user "7261" the moment he arrives for the scheduled meeting (t_1) and when he is in the vicinity of the chosen location (t_2). Here, the MUX signals assigned to each "response" and the decoded information, in the top of the figure, are shown. Below the figure the routes are illustrated.

In the "response", the block (CM), in a pattern [000], means that a response message, from the local manager (CM), is being sent. The next block (10+4 bits) identifies the cell address ($C_{i,j,k}$) and the user (pin_1) for which the message is intended and finally in the last block appears the requested information (meeting code+ wayfinding instructions). In Fig. 6, the emitter controller [000] responds to the successive requests (t_1, t_2) of an user ("7261") that has required the shortest path (Fig. 6) to have a meeting (pin_2/3) with a friend that was shopping in the same center when he arrives ($C_{2,3\text{-}1}$; t_1) and has asked for buddy wayfinding services before (t_0), from cell ($C_{4,4,1}$). Below Fig. 6, the required way to meet the friend is outlined in successive moments.

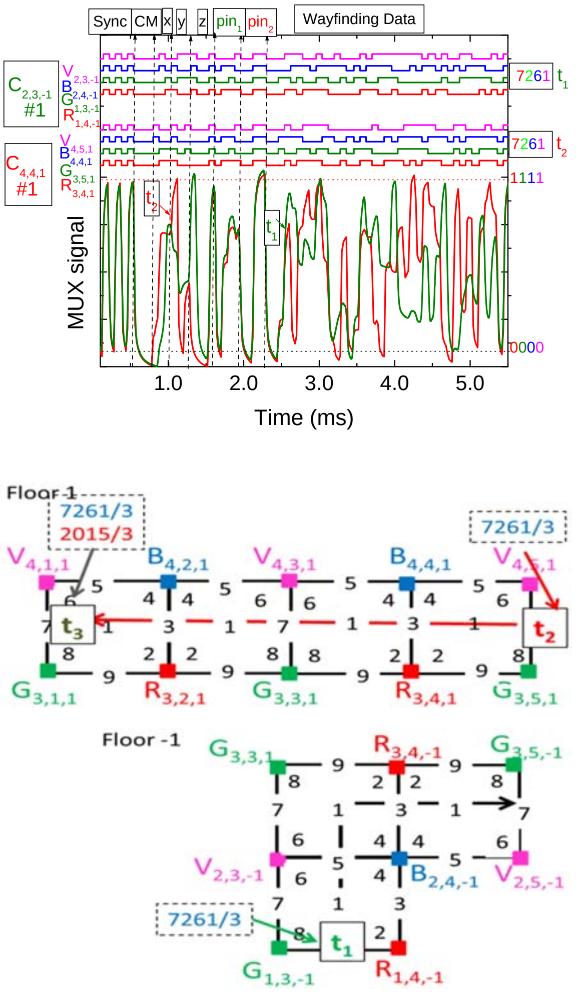


Fig. 6. MUX/DEMUX signals assigned to a "response". MUX signal received by user "7261", pin_1, during his path, beginning at t_1 from $C_{2,3,-1}$; #1, changing floor at t_2 in $C_{4,4,1}$; #1 and when arriving ($C_{4,1,1}$; #1) at t_3 for the arranged meeting ([0011]; pin_2). On the top the transmitted channels packets are decoded [$X_{i,j}$].

4. Bit Error Control

In a data frame, in Fig. 7a, a MUX signal (data) due to the joint transmission of four R, G, B and V optical signals is displayed. The data bit sequence (R G B V; on the top of the figure) was chosen to allow all the *on/off* sixteen possible combinations of the four input channels (2^4).

Results show that the code signal presents as much separated levels as the *on/off* possible combinations of the input channels, allowing decoding the transmitted information [10]. All the levels (d_0-d_{15}) are pointed out at the correspondent levels, and displayed as horizontal dotted lines. In the right hand side, the match between MUX levels and the 4 bits binary code assigned to each level is shown. Hence, the signal can be decoded by assigning each output level (d_0-d_{15}) to a 4- digit binary code [X_R, X_G, X_B, X_V], with X=1 if the channel is *on* and X=0 if it is *off*.

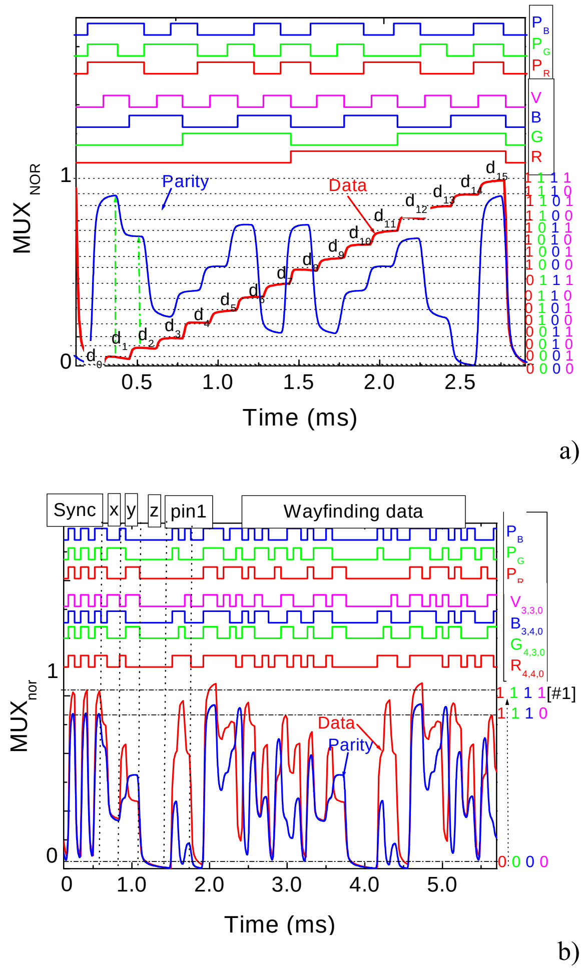


Fig. 7. Normalized MUX data signals The parity MUX signal is also superimposed to exemplify the bit error detection. On the top the transmitted channels packets [R, G, B, V] and parity bits [P_R, P_G, P_B] are depicted. a) Calibrated cell. b) Signals acquired by a receiver in positions #1, cell [$R_{4,4,0}$, $G_{4,3,0}$, $B_{3,4,0}$, $V_{3,3,0}$].

The proximity of the magnitude of consecutive levels can leads to errors in the decoded information that should be checked and corrected using the parity bit control [19]. Error detection codes (parity bits, P_R, P_G, P_B) are generated as a function of the bits (R, G, B, V) being transmitted. Such codes are appended to the data bits and transmitted. The receiver calculates the code based on the incoming bits and compares it with the incoming code to check for errors. For a four channel transmission, three parity channels are needed to define the parity bits generating channel *redundancy*. Thus, the encoder takes four input data bits [R G B V] and generates three additional parity bits to which corresponds one of the eight (2^3) allowed levels in the parity MUX signal (parity in Fig. 4a). The parity bits [P_R, P_G, P_B] are defined as [17]:

$$P_R = V \oplus R \oplus B$$
$$P_G = V \oplus R \oplus G$$
$$P_B = V \oplus G \oplus B$$

For parity check three red, green and blue channels were read in simultaneous with the data code [P_R, P_G, P_B]. The 7-bit word [R G B V; P_R, P_G, P_B] at the output of the encoder will be read in a format with the data and the parity bits separated. In Fig. 4a the received codeword that corresponds to ”0001;111” (see arrow in figure) are in the same time slot. Since d_1 is too near d_2 the message (0010:111) could be measured instead, which is impossible since the d_2 (0010) correspondent parity level is ”101”, is too far way). So, an error can be detected in the transmission and has to be corrected. In order to automate the process of decoding the original transmitted data an algorithm was developed and tested. The transmitted information is recovered by comparing, for the same time slot, both signals from the word and parity MUX levels as shown in Fig. 7b.

Here, the data MUX and the correspondent parity signals received by the user 7261, located bellow AP C4,3,0 in footprint #1, and the decoded information (in the top of the figure) are shown. Here, after decoding the MUX signals, and taking into account, the frame structure (Fig. 3), the position of the receiver and its ID in the network is revealed [17]. The footprint position comes directly from the synchronism block, where all the received channels are, simultaneously, on or off. In the received MUX signal, the maximum amplitude detected corresponds to the binary word [1111], meaning that it has received the overlap transmission from the red (R) green (G), blue (B) and the violet (V) channels (footprint #1). The next block of ten bits gives de ID of the received nodes. In footprint #1, the network location of the received signal are $R_{4,4,0}$ [100;100;0000], $G_{4,3,0}$ [100;010;0000] $B_{3,4,0}$ [011;100;0000] and $V_{3,3,0}$ [011;011;0000]. The next 4 bits identifies the user RGBV code 7261 [0111, 0010, 0110, 0001] and finally the last block is reserved for the transmission of the wayfinding message (Payload data). The stop bit (0) is used always at the end of each frame.

5. Conclusions

This paper proposes a generating method of ceiling landmark route instructions using VLC. 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 3D building model for large indoor environments was presented, and a VLC scenario in a three level building was established. The communication protocol was presented. Bi-directional communication between the infrastructure and the mobile receiver was analysed. Global results show that the location of a mobile receiver, concomitant with data transmission is achieved. The dynamic LED-aided VLC navigation system enables to determine the position of a mobile target inside the network, to infer the travel direction along the time and to interact with received information.

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