Light-Fidelity (Li-Fi)

Optical Sensing and Detection in Large Indoor Environements

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***Abstract*— In this work, a Light Emitting Diode (LED) assisted navigation system for large environments is presented. The LEDs are used both for room illumination purposes and as transmitters if modulated at high frequencies. The payload data together with the identifiers, IDs, assigned to the physical location of the transmitters are broadcast using an On-Off Keying (OOK) modulated scheme. The mobile receiver is a double p-i-n/pin SiC photodetector with light controlled filtering properties. Coded multiplexing techniques for supporting communications and navigation together on the same channel are analysed. A demonstration of fine-grained indoor localization is simulated. Different indoor layouts for the LEDs are considered. Square and hexagon mesh are tested, and a 2D localization design, demonstrated by a prototype implementation, is presented. The results showed that the LED-aided Visible Light Communication (VLC) navigation system makes possible not only to determine the position of a mobile target inside the unit cell but also in the network and concomitantly to infer the travel direction in time.**

Keywords- Visible Light Communication; Indoor positioning; Square and hexagonal topologies; SiC technology; optical sensor; transmitter; receiver; Multiplex/demultiplex techniques.

I. INTRODUCTION

With the rapid advancement of smart equipment, location based services that employ different kinds of communication and positioning technologies have started to develop. Although Global Positioning System (GPS) works extremely well in an open-air localization, it does not perform effectively in indoor environments, due to the inability of GPS signals to penetrate building materials. Nowadays, indoor positioning methods are mainly based on Wi-Fi, Bluetooth, Radio-frequency identification (RFID), Visible Light Communications (VLC) and inertia navigation [1]-[5]. Although many methods are available, they require dense coverage of WiFi access points or expensive sensors, like high-performance cameras, to guarantee the localization accuracy.

VLC is a data transmission technology [6]-[8]. VLC can easily be employed in indoor environments, such as offices, homes, hospitals, airplanes/airports and conference rooms. Compared with other positioning methods, indoor VLC based positioning has advantages, since it can use the existing LED lighting infrastructure with simple modifications.

In the following, we propose to use modulated visible light, carried out by white low cost LEDs, to provide globally consistent signal-patterns and engage indoor localization. The LEDs are capable of switching to different light intensity levels at a very fast rate. The switching rate is fast enough to be imperceptible by the human eye. This functionality can be used for communication where the data is encoded in the emitting light in different ways [9]. A photodetector can receive the modulated signals and decode the data. This means that the LEDs serve twofold for providing illumination as well as for communications.

Research is necessary to design LED arrangements that can optimize communication performance while meeting the illumination constraints for a variety of indoor layouts, using four-code assignment for the LEDs in an extended square or diamond mesh. 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. The receiver, equipped with an a-SiC:H pinpin photodiode, determines its physical position by detecting and decoding the light signals. The overlap of different light beams at the receiver is used as an advantage to increase the positioning accuracy. Fine-grained indoor localization can enable several applications; in supermarkets and shopping malls, exact location of products can greatly improve the customer's shopping experience and enable customer analytics and marketing [10][11].

The use of Red-Green-Blue (RGB) LEDs is a promising solution as they offer the possibility of Wavelength Division Multiplexing (WDM), which can enhance the transmission data rate. A WDM receiver has been developed [12][13]. The device is based on tandem a-SiC:H/a-Si:H pin/pin light controlled filter. 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.

In this paper, a LED-assisted indoor positioning and navigation VLC system, for large indoor environment is proposed. The paper is organized as follow. After the introduction (Section I), in Section II, the system configuration is presented. The principle of the positioning scheme and the algorithm to decode the information are described and experimental results are presented, in Section III. A 2D localization design, demonstrated by a prototype implementation is tested. Fine-grained indoor localization is demonstrated using square and hexagonal topologies. Finally, in Section IV, conclusions are addressed. The proposed, composed data transmission and indoor positioning, involves wireless communication, smart sensoring and optical sources network, building up a transdisciplinary approach framed in cyber-physical systems.

II. System Configuration

LED bulbs work as transmitters, broadcasting the information. An optical receiver extracts its location to perform positioning and, concomitantly, the transmitted data from each transmitter. Multiple LEDs can transmit simultaneously to the same receiver using joint transmission. To synchronize the signals from multiple LEDs, the transmitters use different ID´s, such that the signal is constructively at the receiver.

A. *Shapes and topologies*

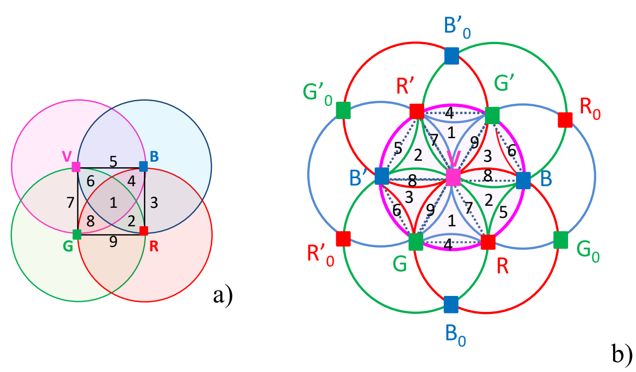

Figure 1. Top-down view of unit cells (LED array = RGBV color spots) having each one four modulated RGBV-LEDs located at the corners of the grid. a) Square cell. b) First hexagon ring.

The unit cells, for the analyzed topologies, are displayed in Figure 1. In Figure 1a, the proposed LED arrangement employs four modulated LEDs placed at the corners of a square grid. In Figure 1b, a cluster of three diamond cells sharing the violet node, fill the space with a hexagon, leading to the hexagonal topology.

The estimated distance from the ceiling lamp to the receiver is used to generate a circle around each transmitter on which the device must be located in order to receive the transmitted information (generated location and coded data).

Table 1. Fine-grained cell topology.

Footprints regions	Square topology	Hexgonal topology
P#1	RGBV	RGV R’G’V
P#2	RGB	RBV R’B’V
P#3	RG	G’BV GB’V
P#4	RBV	RGB$_0$V R’G’B’$_0$V
P#5	BV	RG$_0$BV R’ G’$_0$B’V
P#6	GBV	R$_0$G’BV R’$_0$GB’V
P#7	GV	RGBV R’G’B’V
P#8	RGV	RG’BV R’GB’V
P#9	RG	RGB’V R’GB’V

In all topologies, the grid sizes were chosen to avoid overlap in the receiver from adjacent grid points. To improve its practicality, the tested geometric scenario for the calculations, in both topologies, uses a grid in smaller size (2 cm between adjacent nodes). To receive the information from several transmitters, the receiver must be positioned where the circles from each transmitter overlap, producing at the receiver, a 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 1 and reported in Table 1. In the hexagonal topology, each node has six neighbors, so, eighteen footprints are possible. Twelve at the edges of the six equilateral triangles where four circles overlap (#P4 to #P9) and six at their centroids (#P1 to #P3), where only three channels are received. Taking into account the XY symmetry (Figure 1b), the R, G and B nodes and their symmetric (R’G’B’) must be considered. When the received channels come from outside the hexagon edges (first ring), the nodes are label with *0* (see Figure 1b). When the signal comes only from one LED, the coordinates of the LED are assigned to the device’s reference point. If the device receives multiple signals, *i.e.*, if it is in an overlapping region of two or more LEDs, it finds the centroid of the

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received coordinates and stores it as the reference point. This is the so called fine-graining of the unit cell.

For data transmission commercially available white RGB-LEDs and a violet (V: 400 nm) LED were used. The output spectrum of the white LED contains three peaks assigned to the colours red (R: 626 nm), green (G: 530 nm) and blue (B: 470 nm), that mixed together provide the white perception to the human eye. Each chip, in the trichromatic LED, can be switched *on* and *off* individually for a desired bit sequence. The luminous intensity is regulated by the driving current for white perception. They exhibit a wide divergence angle (2x60º), since they are also designed for general lighting and allow a wide delivery of the VLC signal around the surrounding area. The driving current of each emitter is controlled independently, suppling the respective coding sequence and frequency [14]. In both topologies, the driving current of the emitters having the same wavelength was always the same.

B. *Cellular topologies for large environments*

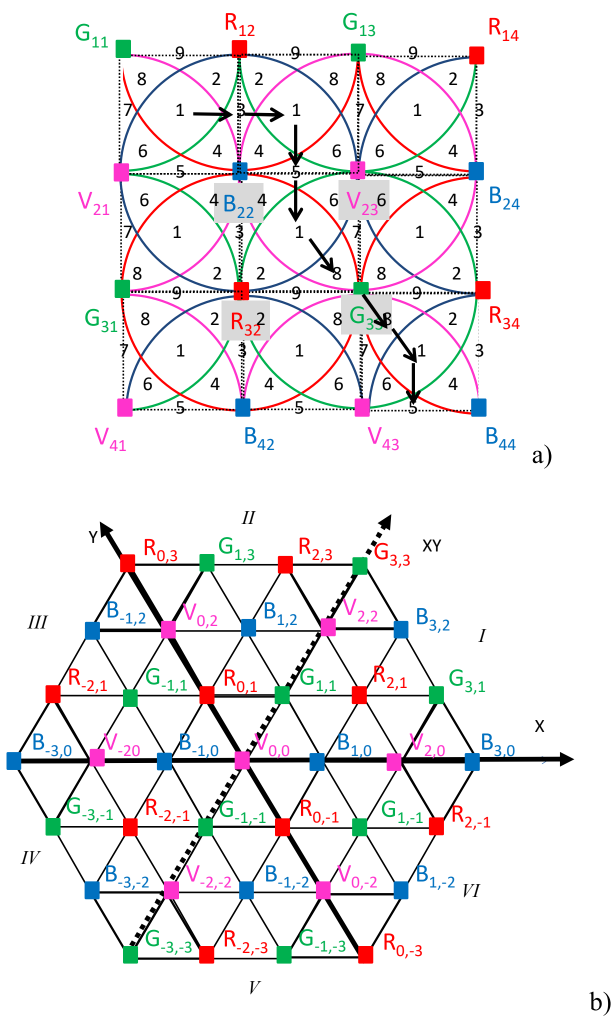

Figure. 2. Illustration of the proposed scenarios (LED array = RGBV color spots): a) Clusters of cells in orthogonal topology (square). b) Clusters of cell in hexagonal topology.

When the rooms are very large, such as in supermarkets or large shopping malls, the positioning technique (four-code assignment for the LEDs), is applied in the whole room [15]. Two topologies were set for the unit cell: the square, (Figure 2a) and the hexagon (Figure 2b). In the first, the proposed LED arrangement employs four modulated LEDs placed at the corners of a square grid. The unit cell $C_{i,j}$ is repeated in the horizontal and vertical directions in order to fill all the space. In the second topology (Figure 2b), the hexagon, the same LED array was used, but in a no-orthogonal system. We select a pair inclined at 120 degrees to be the axes, labelled as X and Y. We have readdressed the nodes, in the oblique Cartesian system. Consequently, 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).

C. *The OOK modulation scheme*

The modulation of the emitted light was done through the modulation of the driving electrical current of the semiconductor chips of each LED. An on-off keying modulation scheme was used. The frame structures are illustrated in Figure 3, for both topologies.

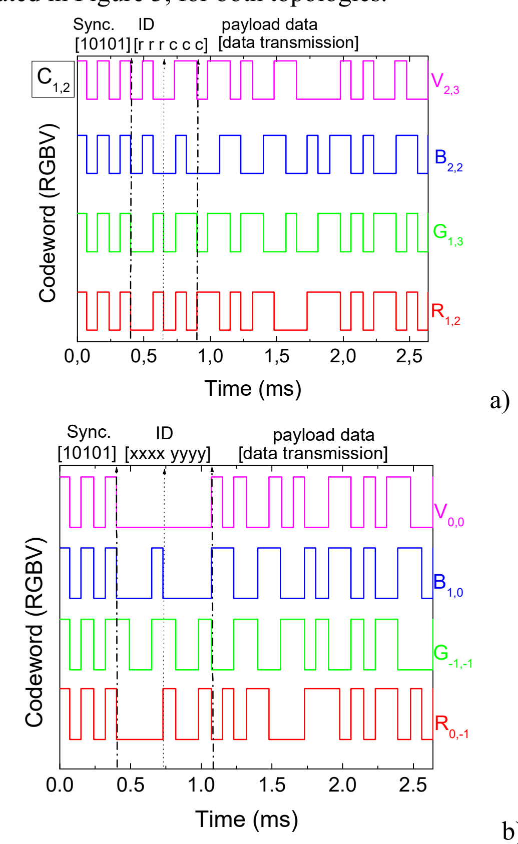

Figure 3. Frame structure. Representation of one original encoded message, in a time slot. a) Square topology; R_{12}; $G_{1,3}$; $B_{2,2}$ and $V_{2,3}$ are the transmitted node packet from the $C_{1,2}$ array in the network.. b) Hexagonal topology; $R_{0,-1}$; $G_{-1,-1}$; $B_{1,0}$ and $V_{0,0}$ are the transmitted node packet of the unit cell in the network.

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For both, the frame is built based on three separate blocks; the synchronism (Sync), the ID address of the transmitter (ID) and the message to transmit (payload data). The first five bits are used for time synchronization. The same synchronization header [10101], in an ON-OFF pattern, is imposed simultaneously to all the emitters. Each color signal (RGBV) carries, its own ID-BIT, so, the next bits give the coordinates of the emitter inside the array ($X_{i,j}$). 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 (Figure 1b to code the positive and the negative coordinates "sign and magnitude" representation was used, setting 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* coordinate (*i,j*) of the emitter in the array (Figure 3b). For instance, R_{12} emitter sends a six ID_BIT [001 010] in the square topology while in the hexagonal one the eight ID bits are [0001 0010]. For both, the last bits, in the frame, are reserved for the message send by the X_{ij} node (payload data).

D. The VLC receiver

The VLC receiver is a two terminal, p-i'(a-SiC:H)-n/p-i(a-Si:H)-n photodiode packed in two transparent conductive contacts (TCO). The deposition conditions, optoelectronic characterization and device optimization are described in [13]. The configuration and operation is illustrated in Figure 4.

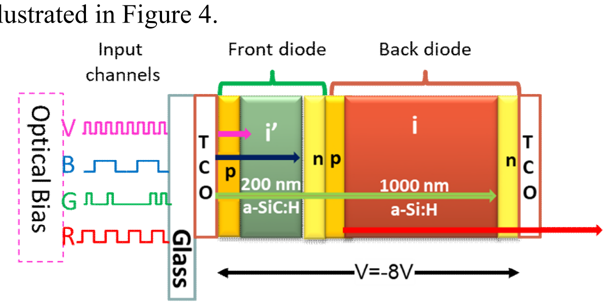

Figure 4. Double pi´n/pin configuration and device operation.

The device operates within the visible range using for data transmission the modulated low power light supplied simultaneously by the RGBV LEDs located at the nodes of the array. A mix of R, G, B, and V pulsed communication channels (input channels; transmitted data), each one with a specific bit sequence, impinges on the device and are absorbed accordingly to their wavelengths (see arrows in the figure). The combined optical signal (MUX signal; received data) is analyzed by reading out the generated photocurrent under negative applied voltage and violet background lighting, applied from the front side of the receiver [12] [16].

III. Experimental Results and Discussion

A. Coding/Decoding techniques

In Figure 5, the normalized received data due to the mixture of the four R, G, B, and V input channels, i.e., the MUX code signal in a stamp time, are displayed, for the square topology. In Figure 5a, the bit sequence was chosen to allow all the on/off sixteen (2^4) possible combinations of the four input channels. For three times slots (t_1, t_2, t_3), in Figure 5b, the MUX signal acquired by a receiving positions P#3, P#1, and P#5 (see Table 1), is displayed. The decoded packet of transmitted information is presented in the top of both figures.

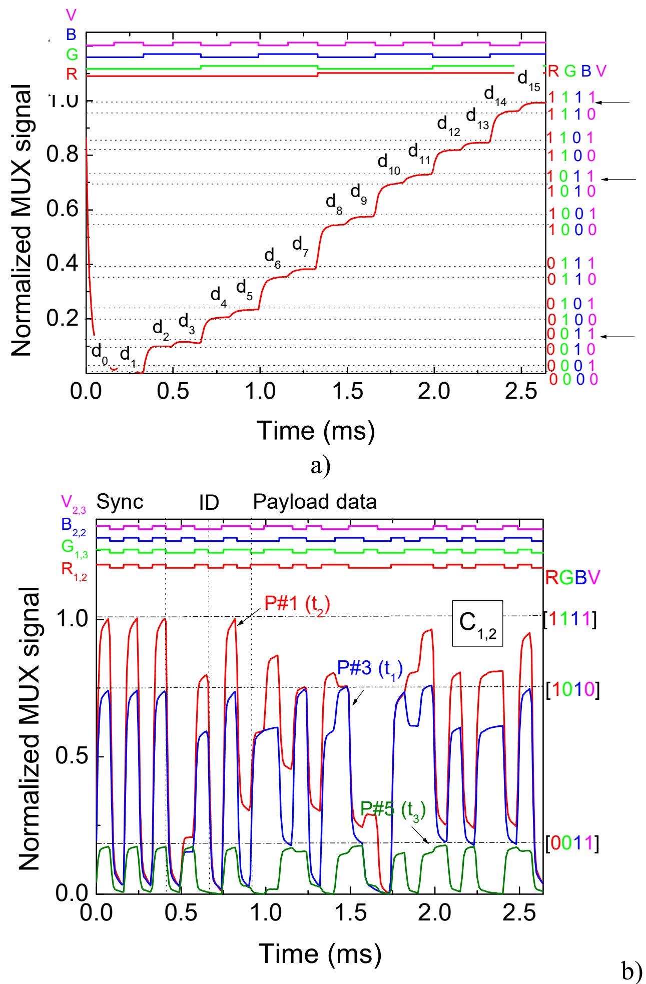

Figure 5. MUX/DEMUX signals under 390 nm front irradiation. On the top the transmitted channels packets [R, G, B, V] are decoded. a) Calibration cell. b) MUX signal in three successive instants (t_1, t_2, t_3).

The results from Figure 5a show that the MUX signal presents as many separated levels as the possible *on/off* combinations of the input channels, allowing to decode the transmitted information [17]. 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 of Figure 5a, the match between MUX levels and the 4 bits binary code assigned to each level is shown. Hence, by assigning each output level 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*, the signal can be decoded. The MUX signal presented in Figure 5a is used for calibration purposes. Comparing the calibrated levels with the different generated levels (Figure 5b), in the same frame of time, a simple algorithm [18] is used to decode the multiplex signals. After decoding the MUX signals, the localization of the receiver is straightforward. Taking into account, the frame structure (Figure 3), the position of the receiver inside the navigation cell and its ID in the network is revealed [19]. The ID position, in the unit cell, comes directly from the synchronism block, where all the received channels are, simultaneously, *on* or *off*. The 4-bit binary code ascribed to the higher level identifies the receiver position in the unit cell (Table 1). Those binary codes are displayed in the right hand of the Figure 5b. For instance, the level [1010] corresponds to the level d_{10} where the red and the blue channels are simultaneously *on* (see arrow in Figure 5a). The same happens to the other footprints (P#1 and P#5). Each decoded message carries, also, the node address of the transmitter. So, the next block of six bits, in the square topology or eight in the hexagonal one, gives de ID of the received node. In P#5 the location of the transmitters, in the network, are $B_{2,2}$ and $V_{2,3}$ while in P#1 the assigned transmitters are $R_{1,2}$, $G_{1,3}$, $B_{2,2}$ and $V_{2,3}$. The last block is reserved for the transmission of the message (payload data). A stop bit (0) is used always at the end of each frame.

B. *LED-aided navigation system*

The input of the aided navigation system is the MUX signal, and the output is the system state estimated at each time step (Δt). As a proof of concept, the suitability of the proposed navigation data bit transition was tested, in the lab [20]. The solution was to move the receiver along a known pattern path as described in Figure 2a, the arrows illustrate the simulated path in successive instants. The signal acquisition on the different generated locations was performed and the transition actions were correlated by calculating the ID position codes in the successive instants.

Taking into account Figure 5b, results show that, as the receiver moves between generated point regions, the received information pattern changes. Note that, between two consecutive data sets, there is one navigation data bit transition (a channel is missing or added). We observe that when the receiver initially moves from P#3 to P#1, the green, $G_{1,3}$ and the violet, $V_{2,3}$, channels are added and the 4-bynary bit code changes from [1010] to [1111].

In Figure 6a, the arrows illustrate the simulated path, in the hexagon topology, at six successive instants (t_1 to t_6). Figure 6b, displays the MUX signals acquired at t_1, t_2 and t_3. At the right hand of the figure, the 4-bit binary codes are pointed out at the correspondent levels.

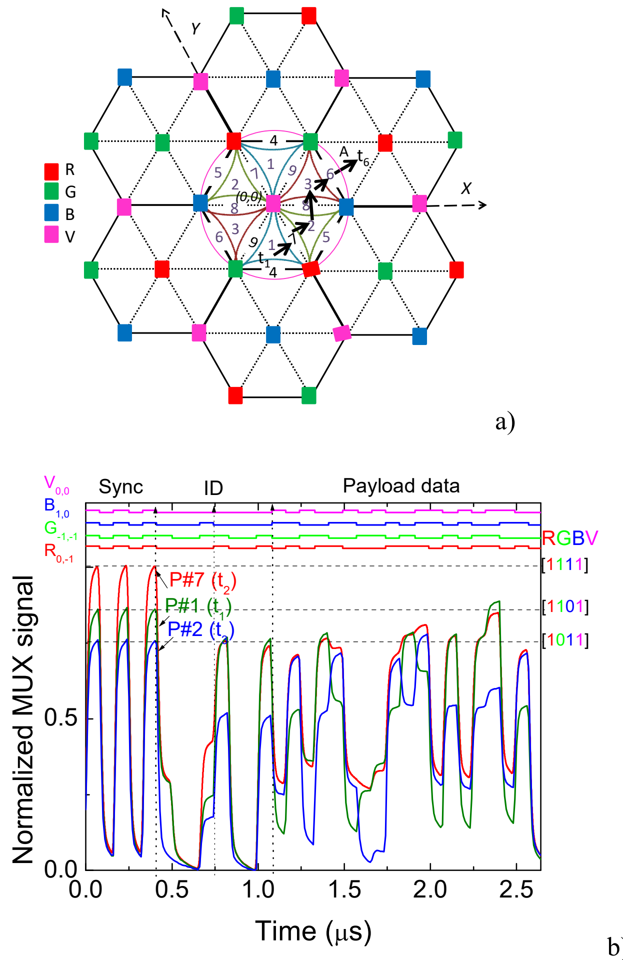

Figure 6. a) Fine-grained indoor localization and navigation, as illustrated by the arrows. b) Signal acquisition at t_1, t_2 and t_3. On the top the transmitted channels packets [R, G, B, V] are decoded

Results show that at t_1 the receiver was located at P#1 [1101]/ $R_{0,-1}\,G_{-1,-1}\,V_{0,0}$. At t_2, it arrives to P#7 [1111]/$R_{0,-1}\,G_{-1,-1}\,B_{1,0}V_{0,0}$, then, at t_3, moves towards P#2, [1011]/ $R_{0,-1}\,B_{1,0}V_{0,0}$.

The main results show that, for both topologies, the location of a mobile receiver is achieved based on the LED-based navigation system. At the client's end, positioning bits are decided by the received MUX signal (wavelengths and ID address of the received channels). Fine grained localization was achieved by detecting the wavelengths of the received channels in each cell (Table 1). Nine sub-regions fill each square cell while in the hexagonal, due to the existing XY symmetry, eighteen possible sub-regions can be designed. The use of the square, hexagonal or both topologies depends on the layout of the environment.

IV. CONCLUSIONS AND FUTURE TRENDS

We have proposed a VLC LED-assisted navigation system for large indoor environments. For illumination

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purposes, data transmission and positioning, white LEDs were used. An a-SiC:H/a-Si:H pin/pin 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. A four-code assignment for the LEDs was proposed. Two cellular networks were tested and compared: the square and the hexagon. The results show that, in large indoor environments, the use of VLC technology allows different cellular topologies, where both location and data transmission are achieved. The choice of one or both topologies depends mainly on the layout of the environment.

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