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Enhancing Building Guidance: A Visible Light Communication-Based Identifier (ID) System

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Abstract: This paper introduces an innovative approach employing Visible Light Communication (VLC) to generate landmark-based routes and alert instructions, enhancing support for individuals during wayfinding activities. The system utilizes ceiling luminaries as transmitters, broadcasting map information, alerts, and path messages. Through real-time data collection by optical receivers, users are provided with the most efficient routes to navigate around congestion. Tetrachromatic identifier white sources are employed for lighting, featuring various data channels. Data is encoded, modulated, and transformed into light signals, with mobile optical receivers capturing and interpreting this information, allowing users to interact bidirectionally. The system calculates optimal routes for static or dynamic destinations, including buddy wayfinding services. Results demonstrate the system's capability to enable self-location, deduce travel direction, and facilitate efficient navigation towards both static and dynamic locations.

Keywords: Visible Light Communication (VLC), Geolocation, Indoor navigation, Bidirectional communication, Wayfinding, Optical sensors, Transmitter/receiver.

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1. Introduction

In the realm of modern technology, visible light has emerged as an innovative and versatile tool for creating identification systems with a unique twist. The concept revolves around harnessing the power of light signals, carefully choreographed in timed sequences and divided into spatial beams, to serve as an Identifier (ID) system for building recognition. This groundbreaking approach leverages the capabilities of LED arrays, enabling bidirectional communication channels where light takes on the roles of both down-link and up-link channels.

The implications of this novel technology are vast and far-reaching. With its ability to encode information through modulated light signals, it finds applications in diverse domains such as positioning, navigation, security, and mission-critical services. This cutting-edge communication paradigm is known as Visible Light Communication (VLC), [1] a data transmission technology that seamlessly integrates into indoor environments, making use of existing LED lighting infrastructure with minimal modifications [2, 3]. VLC has become the development direction of the next generation communication network with its huge spectrum resources, high security, low cost, and so on [4, 5].

One of the standout features of this technology lies in its adaptability. By employing white polychromatic LEDs, a phenomenon known as Wavelength Division

Multiplexing (WDM) comes into play, enabling the simultaneous transmission of multiple data streams at different wavelengths. This ingenious approach effectively increases the data transmission rate, allowing for more information to be conveyed within a given timeframe.

A pivotal aspect of this innovative system is the development of a WDM receiver that capitalizes on light-controlled filters. This receiver is designed to decode the intricate information carried by the multiplexed signals. Through the process of multiplexing, filtering, and decoding, the encoded signals are meticulously unraveled, resulting in the accurate recovery of the transmitted information [6, 7].

In summary, the convergence of visible light, LED arrays, and sophisticated data transmission techniques has birthed a revolutionary approach to identification and communication within building environments. As we delve deeper into the intricacies of this technology, we uncover its transformative potential to reshape various industries and propel us into an era of more efficient, secure, and intelligent systems.

In this paper, a VLC based guidance system to be used by mobile users inside large buildings is proposed. After the Introduction, in Section 2, a model for the system is proposed and the communication system described. In Section 3, the main experimental results are presented, downlink and uplink transmission is implemented and the best route to navigate calculated. In Section 4, the conclusions are drawn.

2. VLC System Model

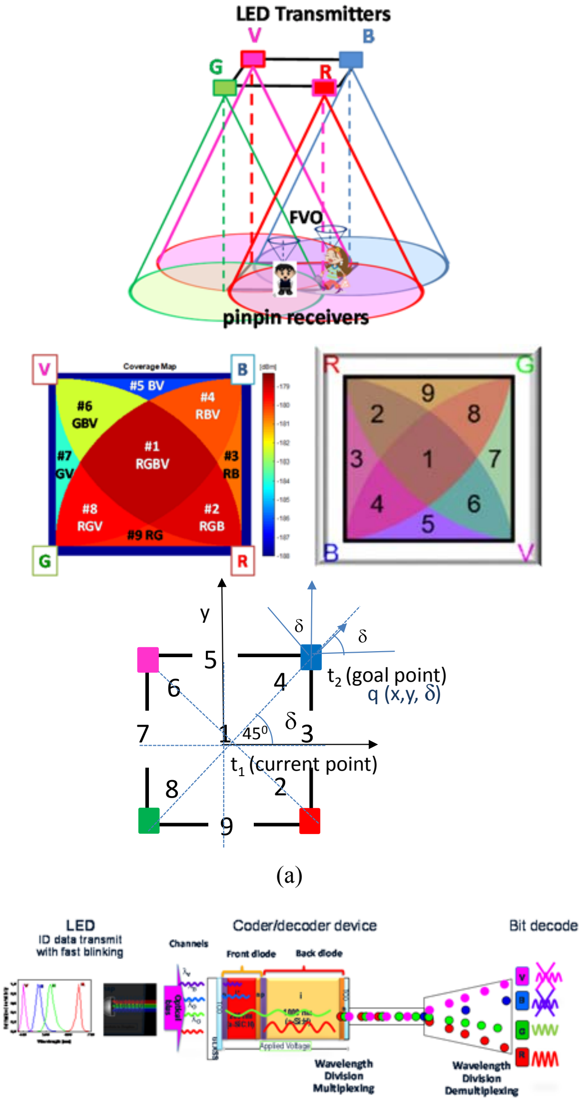
The main goal is to specify the system conceptual design and define a set of use cases for a VLC based guidance system to be used by mobile users inside large buildings.

2.1. VLC Emitter and Receiver Modules

The system model is structured around two primary modules: the transmitter and the receiver, illustrated in Fig. 1. The functionality of these modules is key to the successful operation of the technology.

The first of these modules, the transmitter, assumes the crucial role of transforming data from the sender into an intermediary representation in the form of bytes. These bytes serve as an intermediate step before they are translated into light signals by the transmitter.

In addition to robustness of electronic devices, modulation is imperative for the viability and performance of VLC systems. Data from the sender is converted into an intermediate data representation, byte format, and converted into light signals emitted by the transmitter module. The data bit stream is input to a modulator where an ON–OFF Keying (OOK) modulation is utilized. On the transmission side, a modulation and conversion from digital to analog data is done. The driver circuit will keep an average value (DC power level) for illumination, combining it with the analog data intended for communication. The visible light emitted by the LEDs passes through the transmission medium and is then received by the MUX device.



(a)

(b)

Fig. 1. a) Transmitters and receivers 3D relative positions, coverage map and footprints in the square topology; b) Configuration and operation of the pin/pin receiver.

To realize both the communication and the building illumination, white light tetra-chromatic sources (WLEDs) are used providing a different data channel for each chip. The transmitter and receiver relative positions are displayed in Fig. 1a. Each luminaire is composed of four polychromatic WLEDs framed at the corners of a square. At each node, only one chip is modulated for data transmission (see Fig. 1a), the Red (R: 626 nm, 25 μW/cm^2), the Green (G: 530 nm, 46 μW/cm^2), the Blue (B: 470 nm, 60 μW/cm^2) or the Violet (V, 400 nm, 150 μW/cm^2). A fundamental difference between VLC and regular radio frequency (RF) communication is that VLC does not allow amplitude or phase modulation, and it must encode information by varying emitted light intensity. The LED can be dimmed ("off") when transmitting data bit '0' and at its maximum brightness ("on") when transmitting data bit '1'. This way, digital data is represented by the presence or absence of a carrier wave.

The conversion process involves taking the original data bit stream and feeding it into a modulator. This modulator employs an ON-OFF Keying (OOK) modulation scheme, which is a fundamental modulation technique widely used in communication systems. The essence of the OOK modulation lies in its binary nature. In this scheme, the presence of light signifies a binary "1" and its absence signifies a binary "0." By using this straightforward approach, the modulator effectively encodes the data onto the light signals. As the data bit stream varies, the modulator toggles the light emission on and off accordingly, translating the information into a sequence of light pulses.

Through this process, the transmitter converts the sender's data into light signals that will traverse the transmission medium. This methodology serves as the foundation for the subsequent stages of the communication process, as outlined in the system model.

The signal is propagating through the optical channel, and a VLC receiver, at the reception end of the communication link, is responsible to extract the data from the modulated light beam. In the receiving system, a MUX photodetector acts as an active filter for the visible spectrum. The integrated filter consists of a p-i'(a-SiC:H)-n/p-i(a-Si:H)-n heterostructure with low conductivity doped layers [10] as displayed in Fig. 1b. It transforms the light signal into an electrical signal that is subsequently decoded to extract the transmitted information. The obtained 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) [8, 9]. At last, the message will be output to the users. In order to receive information from several transmitters, the receiver must position itself so that the circles corresponding to the range of each transmitter overlap. This results in a multiplexed (MUX) signal that acts both as a positioning system and as a data transmitter. The grid sizes were chosen to avoid overlap in the receiver from adjacent grid points. The nine possible overlaps (#1-#9), defined as fingerprint regions are also pointed out for the unit square cell, in Fig. 1a.

In this system model, there are a few assumptions that should be noted: The channel state information is available both at the receiver and the transmitter; compared with the direct light, the reflected light is much weaker in the indoor VLC systems; only the Line OF Sight (LOS) path is considered and the multipath influence is not considered in the proposed indoor VLC system.

The received channel can be expressed as:

$$y = \mu h x + n, \tag{1}$$

where y represents the received signal, x the transmitted signal, μ is the photoelectric conversion factor which can be normalized as $\mu = 1$, h is the channel gain and n is the additive white Gaussian noise of which the mean is 0.

The LEDs are modeled as Lambertian sources (Fig. 1b) where the luminance is distributed uniformly in all directions, whereas the luminous intensity is different in all directions. The luminous intensity for a Lambertian source is given by Eq. (2) [11]

$$I(\emptyset) = I_N \cos(\emptyset)^m \quad ; m = \frac{\ln(2)}{\ln(\cos(\phi_{1/2}))}, \tag{2}$$

I_N is the maximum luminous intensity in the axial direction, ϕ is the angle of irradiance and m is the order derived from a Lambertian pattern. For the proposed system, the commercial white LEDs were designed for illumination purposes, exhibiting a wide half intensity angle ($\phi_{1/2}$) of 60º. Thus, the Lambertian order m is 1. Friis' transmission equation is frequently used to calculate the maximum range by which a wireless link can operate. The coverage map is obtained by calculating the link budget from the Friis Transmission Equation [12]. The Friis transmission equation relates the received power (P_R) to the transmitted power (P_E), path loss distance (L_R), and gains from the emitter (G_E) and receiver (G_R) in a free-space communication link.

$$P_{R\,[dBm]} = P_{E\,[dBm]} + G_{E\,[dB]} + G_{R\,[dB]} - L_{R\,[dB]} \tag{3}$$

Taking into account Fig. 1b, the path loss distance and the emitter gain will be given by:

$$L_{R\,[dB]} = 22 + 20\ln\frac{d}{\lambda}, \tag{4}$$

$$G_{E\,[dB]} = \frac{(m+1)A}{2\pi d_{E-R}^2} I(\emptyset) \cos(\theta) \tag{5}$$

With A de area of the photodetector and d_{E_R} the distance between each transmitter and every point on the receiver plane. Due to their filtering properties of the receptors the gains are strongly dependent on the wavelength of the pulsed LEDs. Gains (G_R) of 5, 4, 1.7 and 0.8 were used, respectively, for the R, G, B and V LEDs. I_N of 730 mcd, 650 mcd, 800 mcd and 900 mcd were considered. Taking into account Equations 1-5, the coverage map for a square unit cell is displayed in Fig. 1a. All the values were converted to decibel (dB).

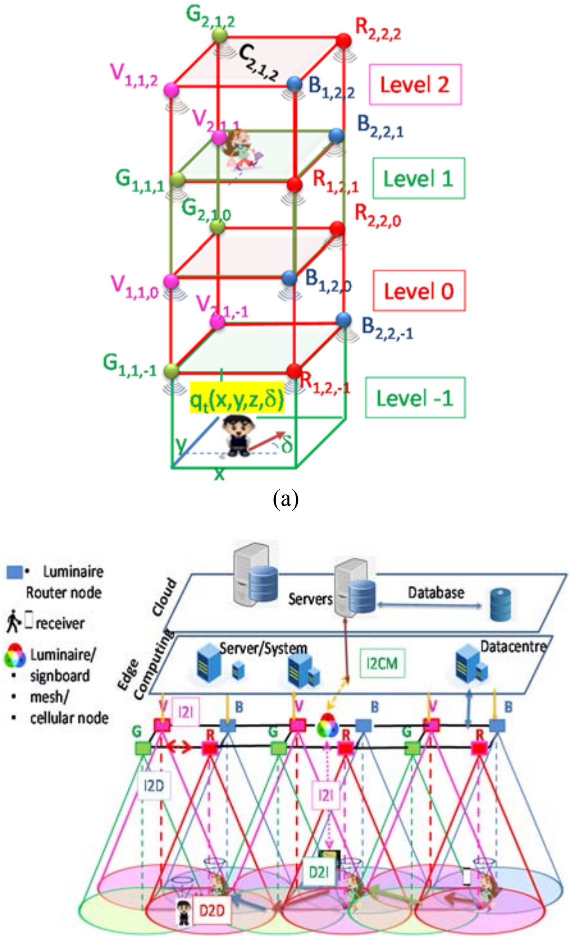
To gather information from multiple transmitters, the receiver must strategically position itself to ensure the overlapping of circles corresponding to the range of each transmitter. This configuration produces a multiplexed (MUX) signal serving both as a positioning system and a data transmitter. The selection of grid sizes is designed to prevent interference in the receiver from neighboring grid points. Figs. 1a highlight the nine potential overlaps (#1-#9), referred to as fingerprint regions, and various receiver orientations (2-9 steering angles; δ) within the unit square cell. The device captures multiple signals, computes the centroid of received coordinates, and establishes it as the reference point position. Nine reference points per unit cell offer a nuanced resolution in localizing the mobile device within each cell.

2.2. Lighting Plan layout Architecture and Geolocation

In VLC geotracking, geographic coordinates are generated, but the feature's usefulness is enhanced by using them to determine a meaningful location, to guide the user through an unfamiliar building, or to lead him to his desired meeting destination. To accomplish this, VLC uses cells for positioning and a CM (Central Manager) to keep track of everything and generate the optimal route.

Building a geometry model of buildings' interiors is complex. Indoor VLC cell design is especially important since, being man-made, buildings such as these commonly follow basic shapes (squares, equilateral triangles/regular hexagons). A square lattice topology was considered for each level. A user navigates from outdoor to indoor. This topology is represented using x, y and z axes to simplify both the figure comprehension and the distance between any pair of nodes. Each room/crossing/exit represents a node, and a path as the links between nodes. In Fig. 2a the 3D building model is depicted. The user positions can be represented as P (x, y, z) by providing the horizontal positions (x, y) and the correct floor number z. The ground floor is level 0 and the user can go both below (z<0) and above (z>0) from there. In this study, the 3D model generation is based on footprints of a multi-level building that are collected from available sources (luminaires), and are displayed on the user receiver for user orientation. It is a requirement that the destination can be targeted by user request to the CM and that floor changes are notified. Each unit cell can be referred as $C_{i,j,k}$ were i, j, k are the x, y position in the square unit cell of the top left node.

In VLC geotracking, geographic coordinates are generated to provide location information. However, the usefulness of this feature is further enhanced by using these coordinates to determine meaningful locations within a building and guide users through unfamiliar spaces or towards specific destinations, such as meeting rooms. To facilitate this process, VLC employs cells for positioning and a Central Manager (CM) that oversees and manages the entire system, including generating optimal routes. Introducing a paradigm-shifting concept, a mesh cellular hybrid structure is unveiled, offering an approach to network architecture. This groundbreaking framework takes shape in the form of Fig. 2b, where the components and their interactions are vividly portrayed.



(a)

(b)

Fig. 2. a) Lighting plan; b) Mesh and cellular hybrid architecture.

In addition to the establishment of secure pathways, the mesh network excels at enabling peer-to-peer communication, commonly known as I2I interactions. This architecture is designed to foster direct information exchange among devices, a process that assumes significance in a data-driven environment. The heart of this operation lies in the ability of each WLED (White Light Emitting Diode) to emit a unique Visible Light Communication (VLC) signal, essentially acting as a beacon of identification. Employing this beacon, the optical receiver adeptly calculates the user's trajectory, employing a specialized position algorithm. This calculated indoor route, denoted as q(x, y, z, δ, t), encapsulates critical spatial and temporal information, offering users insight into their movement within the indoor environment. A user moves from outdoor to indoor and requests assistance in finding the right track (D2I). They can customize their points of interest for wayfinding services. The requested information (I2D) is sent by the emitters, at the ceiling, to its receiver.

This architecture serves two purposes: enabling edge computing and device-to-cloud communication, and enabling peer-to-peer communication for information exchange. The culmination of this intricate network architecture is marked by the role of ceiling luminaires, which assume the mantle of routers or mesh/cellular nodes. Functioning as central hubs within this ecosystem, they engage in the vital task of disseminating messages (I2D) that encapsulate the calculated indoor route. Through their orchestrated efforts, users are provided with a tangible representation of their indoor trajectory, a testament to the architecture's capability to transform data into actionable insights.

3. Cooperative Guidance System

3.1. Communication Protocol, Coding and Decoding Techniques

In the process of encoding the information, a modulation scheme known as On-Off Keying (OOK) was employed. This approach involves the toggling of the signal between two distinct states, representing binary values. Furthermore, the transmission was executed synchronously, adhering to a 64-bit data frame structure. This frame is partitioned into three primary segments: Sync, Navigation Data, and Payload. This breakdown is visually represented at the upper section of Fig. 4, and its essence is succinctly captured in the summarized form presented in Table 1.

Table 1. Frame structure.

Header	**Navigation Data**						**Payload**
Synch	x	y	z	pin$_1$	pin$_2$	δ	Wayfinding data
5 bits (10101)	24 bits (4 bits per field)						34 bits (…….)

Frame length = 64 bits

The header block stands as a synchronization mechanism, encompassing the bit sequence [10101]. This initial segment holds high importance, as it serves as a consistent marker repeated within each data frame. This repetition enables the receiver to accurately pinpoint the commencement of every frame. To achieve this, a standardized header bit sequence, specifically [10101], is concurrently applied to all emitters. This sequence is enacted in an alternating fashion between "on" and "off" states [10101].

Moving on to the second block, it accommodates the Identification (ID) data. This ID comprises 4+4+4 bits and conveys the geolocation information (x, y, z coordinates) of the emitters within the array. To encode these IDs, a 4-bit binary representation is adopted for decimal numbers. Notably, the z coordinate accounts for the floor number, which can be either positive or negative. To address this, the initial bit is employed to signify the sign of the floor number ("0" for positive, "1" for negative), with the remaining three bits encapsulating the numerical value of the coordinate.

In scenarios requiring bidirectional communication, user registration is necessitated. This process involves selecting a username (pin1) comprising four decimal numbers, with each number correspondingly linked to an RGBV channel. Additionally, should buddy friend services be sought, a 4-binary code for the meeting (pin2) must be provided.

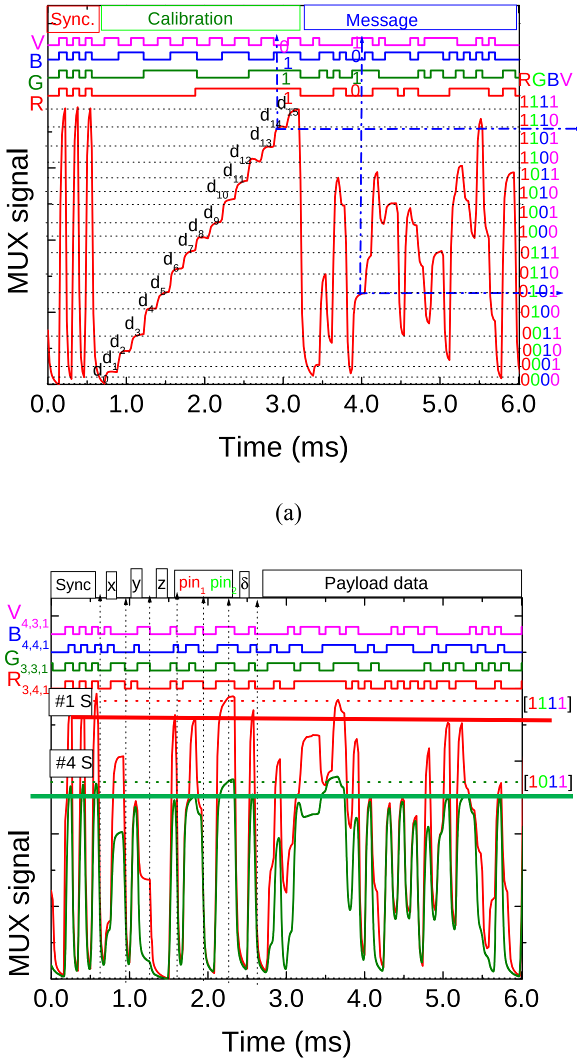
The last segment, termed the δ block (steering angle δ), constitutes a 4-bit sequence. This component completes the user's pose within the time frame q(x, y, δ, t). This pose is augmented with steering angle information, encompassing eight possible angles along the cardinal points. The significance of these angles, guiding the trajectory from a start point to the subsequent destination.

The codes assigned to both pin$_2$ and δ remain consistent across all channels. In scenarios where wayfinding services are unnecessary, these final three blocks assume a value of zero, thus furnishing the user solely with their own location information.

The third and concluding block is aptly labeled the "payload." This segment pertains to a sequence of bits that doesn't directly contribute to the navigation service. It encompasses miscellaneous data and concludes with a stop bit. To decode the information received via the photocurrent signal as captured by the photodetector, a crucial step is undertaken. This process relies on a calibration curve that has been pre-established to facilitate this mapping [10]. The calibration curve represents a sequence of bits meticulously designed to correspond to each conceivable decoding level. In essence, this calibration curve serves as a guide, aiding in the establishment of associations between photocurrent thresholds and specific bit sequences. In Fig. 3 a MUX/DEMUX signals of the calibrated cell is presented. In the same frame of time a random signal (Payload) is superimposed.

This calibration curve leverages 16 distinct photocurrent thresholds. These thresholds correspond to bit sequences meticulously engineered to cover all sixteen permutations achievable from the four RGBV input channels (24 combinations). The brilliance of this approach lies in its simplicity: by juxtaposing the calibrated levels (d$_0$-d$_{15}$) with the assigned four-digit binary codes for each level, the decoding process becomes transparent and straightforward. This direct comparison illuminates the decoding pathway, rendering the message intelligible.

At the receiver end of the communication link, decoding occurs to separate and retrieve the encoded data coming from the emitters, which is crucial to determine the location and pose of the receiver relative to the lighting/communication infrastructure. In Fig. 3b two MUX signals received by user "7261" are displayed. On the top the decoded signals are shown.



(a)

(b)

Fig. 3. a) MUX/DEMUX signals of the calibrated cell. In the same frame of time a random signal (Message) is superimposed. b) MUX signals. On the top the transmitted channels packets are decoded [R, G, B, V].

In Fig. 4 the MUX received signal and the decoding information that allows the VLC geotracking and navigation in successive instants (t_0, t_1, t_2) from user "7261" guiding him along his track is exemplified. The visualized cells, paths and the reference points (footprints) are also shown as inserts.

Here, the MUX received signal and the decoding information that allows the VLC geotracking and guidance in successive instants (t_0, t_1, t_2) from user "7261" guiding him along his track is exemplified. The visualized cells, paths, and the footprints are also shown as inserts. Data shows that at t_0 the network location of the received signals is $R_{3,2,1}$, $G_{3,1,1}$, $B_{4,2,1}$ and $V_{4,1,1}$, at t_1 the user receives the signal only from the $R_{3,2,1}$, $B_{4,2,1}$ node and at t_2 he was moved to the next cell since the node $G_{3,1,1}$ was added at the receiver. Hence, the mobile user "7261" begins his route into position #1 (t_0) and wants to be directed to his goal position, in the next cell (# 9). During the route the navigator is guided to E (code 3) and, at t_1, steers to SE (code 2), cross footprint #2 (t_3) and arrives to #9. The ceiling lamps (landmarks) spread over all the building and act as edge/fog nodes in the network, providing well-structured paths that maintain a navigator's orientation with respect to both the next landmark along the path and the distance to the eventual destination.

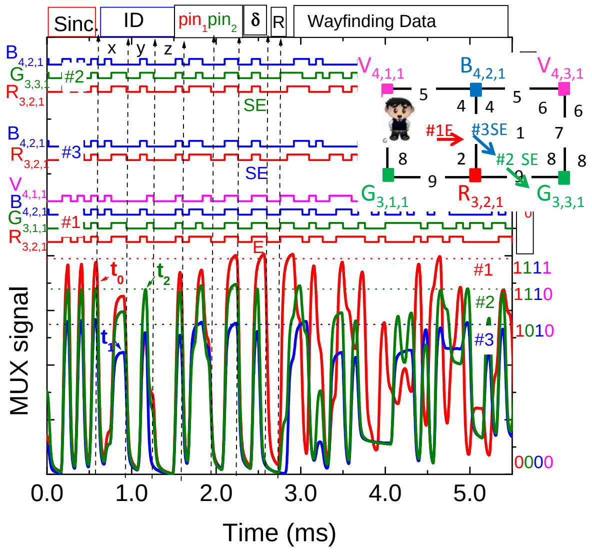


Fig. 4. Fine-grained indoor localization and navigation in successive instants. On the top the transmitted channels packets are decoded [R, G, B, V].

3.2. Multi-person Cooperative Localization and Guidance Services

In Fig. 5 the MUX synchronized signals received by two users that have requested guidance services, at different times, are displayed. In the top of the figure, the decoded information is shown and the simulated scenario is inserted to guide the eyes. At the right hand the request/response information is inserted.

We have assumed that a user located at $C_{2,3,-1}$, arrived first (t_1), auto-identified as ($q_i (t_1), i =$ "7261",) and informed the controller of his intention to find a friend for a previously scheduled meeting (code 3). A buddy list is then generated and will include all the users who have the same meeting code. User "3009" arrives later (q_j (t_3), sends the alert notification ($C_{4,4,1}$; t_3) to be triggered when his friend is in his floor vicinity, level 1, identifies himself ("3009") and uses the same code (code 3), to track the best way to his meeting. The "request" message includes, beyond synchronism, the identification of the user ("3009"), its address and orientation, $q_i(t)$, ($C_{4,4,1}$, #1W) and the help requested (Wayfinding Data). Since a meet-up between users is expected, its code was inserted before the right track request. Upon receiving this request (t_3), the buddy finder service uses the location information from both devices to determine the proximity of their owners (q_{ij} (t_3)) and provides the best route to the meeting, avoiding crowded areas. In the "response", the block CM identifies the CM [0000] and the next blocks the cell address ($C_{4,4,1}$), the user (3009) for which the message is intended and finally the requested information: meeting code 3, orientation NE (code 4) and wayfinding instructions.

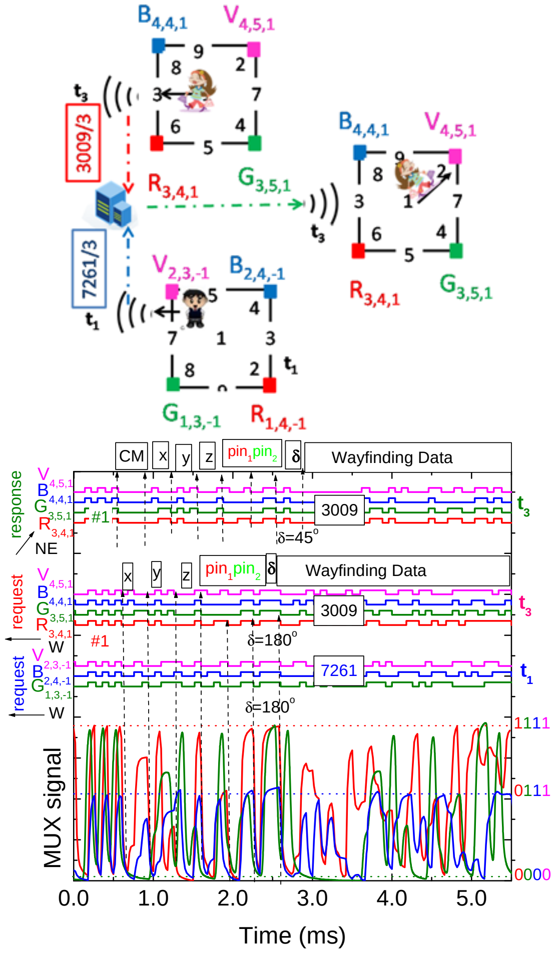


Fig. 5. MUX/DEMUX signals assigned requests from two users (“3009” and “7261”) at different poses ($C_{4,4,1}$; #1W and $C_{2,3,-1}$; #6 W) and in successive instants (t_1 and t_3).

The outcomes of our study underscore the remarkable capabilities of VLC's dynamic LED-enhanced guidance system. This system not only furnishes users with precise and dependable route guidance but also empowers them to navigate effectively and engage in geotracking activities. As users traverse large building complexes, VLC technology offers a groundbreaking solution that steers them towards optimal routes while delivering continuous guidance throughout their journey.

The bidirectional communication prowess embedded within the system introduces a realm of possibilities for diverse services. Mission-critical applications can harness the inherent reliability and low-latency communication offered by the ID system. This reliability is particularly pertinent in scenarios requiring swift and trustworthy data exchange. Beyond this, the system's bidirectional communication capacities pave the way for an array of consumer-centric services. For instance, location-based advertisements can be intelligently deployed, personalized information can be seamlessly delivered, and indoor wayfinding functionalities can be fine-tuned to heighten user experiences within the building environment.

In essence, our research not only highlights the technical capabilities of the VLC-enabled guidance system but also envisions the transformative potential it holds for users within expansive indoor spaces [13]. The system's dual nature, combining navigation and communication sets the stage for improved efficiency, enhanced experiences, and novel applications that redefine how individuals interact with and navigate through complex building structures.

4. Conclusions

This paper embarks on an exploration of the potential for Visible Light Communication (VLC) to revolutionize indoor navigation within vast building complexes. Tailored to the needs of mobile users, it introduces a novel guidance system that leverages the capabilities of VLC technology. Central to this system is a hybrid mesh cellular architecture, complemented by the establishment of an encompassing communication protocol tailored to multi-level scenarios.

The system acts as a steadfast navigational companion, seamlessly providing precise route guidance within complex indoor environments. The spectrum of functionalities includes navigation assistance, real-time route tracking, and reliable guidance for users in motion. The culmination of our experimental endeavors is reflected in global results, where the successful localization of mobile receivers coincides with the simultaneous transmission of data.

A distinctive hallmark emerges in the form of a cooperative localization mechanism. As regions within the environment become densely populated, this mechanism adeptly adapts by autonomously rescheduling localization tasks. This dynamic feature orchestrates the dissemination of guidance information and issues alerts, ensuring a responsive approach to dynamic environmental conditions.

Acknowledgements

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