Self-location, Routing and Navigation Through Visible Light Communication

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***Abstract*— The paper describes an approach that utilizes Visible Light Communication (VLC) to generate landmark route and alert instructions for supporting people's wayfinding activities. The system consists of multiple transmitters, which are ceiling luminaries that transmit map information, alerts, and path messages necessary for wayfinding. Optical receivers are used to collect this information. The system operates in real time, providing users with the most optimal route to their destination, thereby helping them avoid congested areas. The transmitters employ tetrachromatic identifier white sources, which serve the dual purpose of providing lighting and different data channels for each chip. The data is encoded, modulated, and converted into light signals. By employing joint transmission, mobile optical receivers can capture data at high frame rates, determine their own location, and simultaneously read transmitted data from each transmitter. The communication is bidirectional, allowing users to interact with the received information. The system calculates the best route through the venue, taking into account static or dynamic destinations. Additionally, the paper mentions the consideration of buddy wayfinding services. According to the results presented, the system not only enables self-location but also deduces the travel direction and interacts with the received information. This optimization process helps users navigate efficiently towards their desired destination, whether it is a static or dynamic location.**

Index Terms*— Visible Light Communication; Geolocation; Indoor navigation; Bidirectional Communication; Wayfinding; Optical sensors; Transmitter/Receiver.

I. INTRODUCTION

Navigation systems have traditionally relied on Global Positioning System (GPS) for outdoor positioning, providing users with direct and shortest routes based on their current location and intended destination. However, when it comes to indoor navigation, GPS is not suitable due to the difficulty of satellite signals penetrating buildings' roofs, tunnels, or floors. This limitation has led to the development of alternative indoor positioning systems based on various radio technologies.

One commonly used technology for indoor positioning is Wi-Fi. Wi-Fi signals can be utilized to estimate a user's location within a building by measuring signal strengths from multiple access points. By comparing these measurements, the system can determine the user's position. Bluetooth is another technology used for indoor positioning. Bluetooth beacons or tags placed strategically within a building emit signals that can be detected by users' devices. The strength and proximity of these signals allow the system to calculate the user's position. Radio-Frequency Identification (RFID) [1][2] is also employed in some indoor positioning systems. RFID tags attached to objects or worn by users emit radio signals that can be detected and used for determining location. Visible Light Communication (VLC) [3] is a relatively newer technology used for indoor positioning. As mentioned, VLC can be utilized to transmit data, including map information and path messages, to aid in wayfinding activities. VLC systems use light signals emitted by transmitters and collected by optical receivers to determine the user's location and provide navigation instructions. These radio-based technologies provide alternatives to GPS for indoor positioning and have been employed in various indoor navigation systems. Each technology has its own advantages and limitations, and the choice of technology depends on factors such as the specific use case, accuracy requirements, and infrastructure availability. In order to solve the contradiction between the explosive growth of data and the consumption of spectrum resources, 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].

Visible light can be used as an Identifier (ID) system and can be employed for identifying the building itself. The main idea is to divide the service area into spatial beams originating from the different ID light sources and identify each beam with a unique timed sequence of light signals. The signboards, based on arrays of LEDs, positioned in strategic directions [6], can be modulated acting as down- and up-link channels in the bidirectional communication. For the consumer services, the applications are enormous. Positioning, navigation, security and even mission critical services are possible use cases that should be implemented. VLC is a data transmission technology that can easily be employed in indoor environments since it can use the existing LED lighting infrastructure with simple modifications [7] [8]. 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 [9] [10] 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.

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.

II. 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.

A. *Background Theory*

The system model consists of two main modules: the transmitter and the receiver, as depicted in Figure 1.

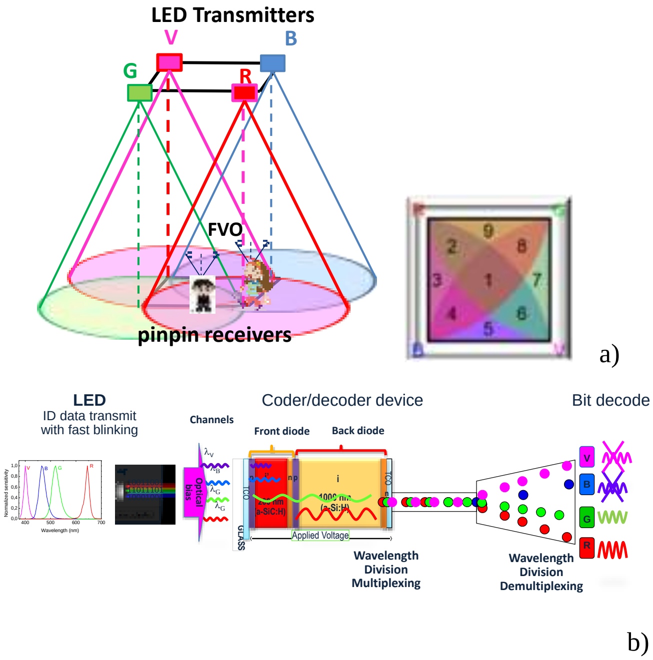

Fig. 1. a) Transmitters and receivers 3D relative positions and footprints in the square topology. b) Configuration and operation of the pin/pin receiver.

The transmitter module is responsible for converting data from the sender into an intermediate data representation in byte format. This byte-format data is then converted into light signals emitted by the transmitter. To achieve this, the data bit stream is input to a modulator, which utilizes an ON-OFF Keying (OOK) modulation scheme. The OOK modulation modulates the light signal to represent the digital data being transmitted. On the transmission side, the digital data is converted into analog data, and a modulation process takes place. 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.

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 Figure 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 Figure 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 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 Figure 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) [11] [12]. 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 Figure 1a.

B. *Lighting Plan layout and Building model*

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. In Figure 2 the 3D building model is depicted.

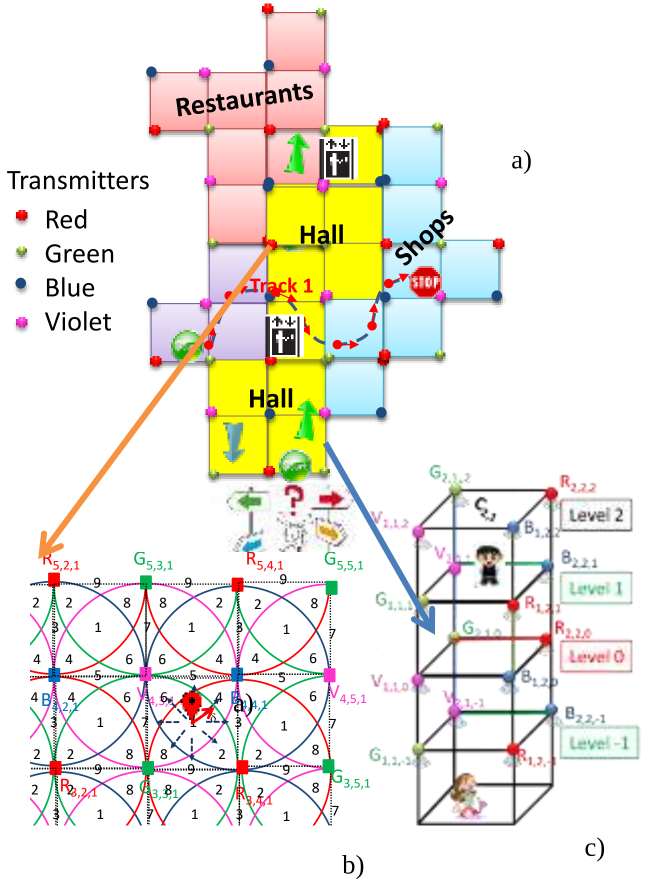

Fig. 2. a) Indoor layout and proposed scenario. b) Clusters of cells in square topology. c) 3D optical scenario (RGBV).

Building a geometry model of buildings' interiors is complex. A square lattice topology was considered for each level [13]. A user navigates from outdoor to indoor (Figure 2a). This topology is represented using x, y and z axes to simplify the distance between any pair of nodes. Each room/crossing/exit represents a node, and a path as the links between nodes. 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. Lighting in large environments is designed to illuminate the entire space in a uniform way. Ceiling plans for the LED array layout, in floor 1 is shown in Figure 2b. Each node emits light all around it and up to a certain range, which allows each cell to be divided into nine footprints depending on which LEDs are covering any given space (Figure 2b), thus allowing the system to determine the position of a user or device in any given cell, $q(x,y,z,\delta)$. δ is one of the eight possible steering angles (arrows along the cardinal points in Figure 2b) and guides the user across his path. 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 and k the floor level.

C. Architecture and Geolocation

Fog/Edge computing is a paradigm that brings computing capabilities closer to IoT devices by utilizing network nodes in the proximity of these devices. It enables tasks such as computing, storage, networking, and data management to be performed on these nodes, thereby reducing latency and bandwidth usage by offloading processing from the cloud.

A mesh cellular hybrid structure is proposed and displayed in Figure 3. This architecture consists of VLC-ready access equipment, that provides the computing resources, end devices, and a controller that is in charge of receiving service requests and distributing tasks to fog nodes.

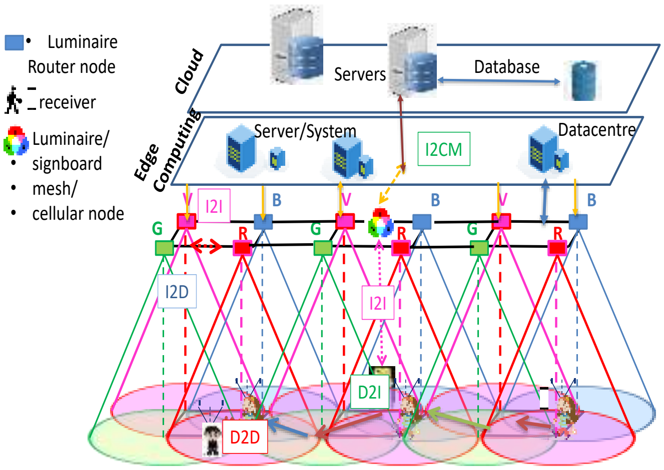

Fig. 3. Mesh and cellular hybrid architecture.

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.

Under this architecture, the short-range mesh network purpose is twofold: enable edge computing and device-to-cloud communication, by ensuring a secure communication from a luminaire controller to the edge computer or datacenter (I2CM), through a neighbor luminaire/signboard controller with an active cellular connection; and enable peer-to-peer communication (I2I), to exchange information.

Each WLED emits a unique VLC signal for identification, and the optical receiver calculates the user's track using this information and a position algorithm The indoor route (track; $q(x, y, z, \delta, t)$) is presented to the user via messages (I2D) transmitted by the ceiling luminaires acting as routers or mesh/cellular nodes.

III. COOPERATIVE GUIDANCE SYSTEM

Cooperative guidance systems enhance navigation accuracy by integrating data from multiple sources for seamless and reliable guidance.

A. Communication protocol, coding/decoding techniques

To code the information, an OOK modulation scheme was used, and it was considered a synchronous transmission based on a 64- bits data frame. The frame is divided into three main blocks (Sync, Navigation data and Payload) as displayed in the top of Figure 4 where a received MUX signal is displayed and decoded.

TABLE 1. FRAME STRUCTURE

Header	**Navigation Data**						**Payload**	
Synch	x	y	z	pin_1	pin_2	δ	Wayfinding data	Stop bit
5 bits (10101)	24 bits (4 bits per field)						34 bits (…….)	1 bit (0)
Frame length = 64 bits								

The header block is the synchronization block [10101]. This first block refers to the starting bit sequence that is repeated in every data frame and allows the receiver to determine from an array of incoming bits where each frame begins. For this purpose, the same header bit sequence is imposed simultaneously to all emitters, in this case in an alternating "on"- "off" pattern [10101]. The second block contains the ID, 4+4+4 bits, gives the geolocation (x,y,z coordinates) of the emitters inside the array ($X_{i,j,k}$). These IDs were encoded using a 4-bit binary representation for the decimal number. The z coordinate refers to the floor number, which can be negative thus the first bit is used to represent the floor number's sign ('0' when a positive number, '1' when a negative number) and the remaining three bits indicating the coordinate's value. When bidirectional communication is required, the user must register by choosing a username (pin_1) with 4 decimal numbers, each one associated to a RGBV channel. If buddy friend services are required a 4-binary code of the meeting (pin_2) must be inserted. The δ block (steering angle (δ)), a 4-bit sequence, completes the user's pose in a frame time q(x,y, δ, t). Eight steering angles along the cardinal points are possible from a start point to the next goal as pointed out as dotted arrows in Figure 2. The codes assigned to the pin_2 and to δ are the same in all the channels. If no wayfinding services are required these last three blocks are set at zero and the user only receives its own location. The third and final block is named the payload and refers to sequence of bits that is not necessary for the navigation service. It is made up of miscellaneous data and followed by a stop bit. Using the photocurrent signal measured by the photodetector, it is necessary to decode the received information. A calibration curve is previously defined to establish this assignment [14].The calibration curve refers to a sequence of bits that, when received, is purposefully meant to reach each of the possible decoding levels. calibration curve (MUX signal) make use of 16 distinct photocurrent thresholds which correspond to a bit sequence that allows all the sixteen combinations of the four RGBV input channels (2^4). If the calibrated levels (d_0-d_{15}) are compared to the different four-digit binary codes assigned to each level, then the decoding is obvious, and the message may be read [14].

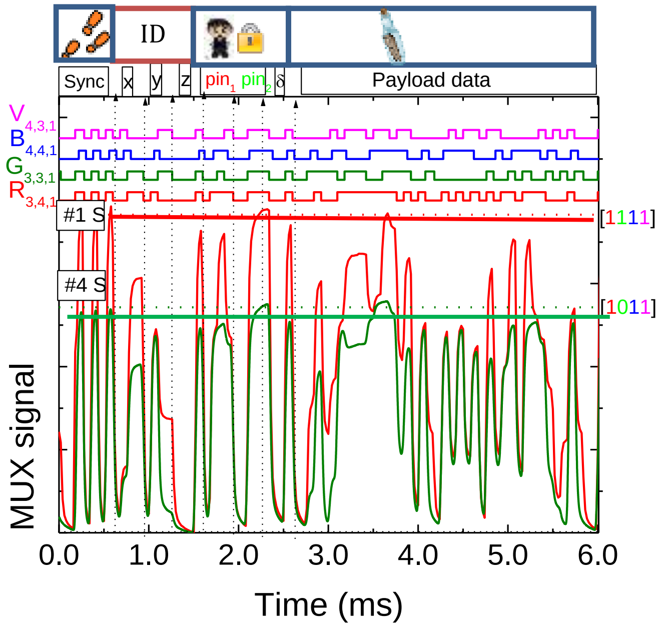

Fig. 4. MUX signals. On the top the transmitted channels packets are decoded [R, G, B, V].

The footprint position comes directly from the synchronism block, where all the received channels are, simultaneously, *on* or *off*. The binary code from the higher amplitude (horizontal lines in Figure 4) gives the received channel. So, two different signals were received by user "7261" at footprints #1 [1111] and # 4 [1011]. The next block of 12 bits gives de ID of the received nodes $R_{3,4,1}$, $G_{33,1}$, $B_{44,1}$ and $V_{4,3,1}$ (#1) or $R_{3,4,1}$, $B_{44,1}$ and $V_{4,3,1}$ in #4. Then the user code (pin1/"7261") and the meeting code (pin2/"3") as well as the steering angle (δ/S) are decoded . The last block is reserved for the transmission of the wayfinding message.

B. Fine-grained indoor localization, navigation and route control

In Figure 5, 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

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him along his track is exemplified. The visualized cells, paths, and the footprints are also shown as inserts.

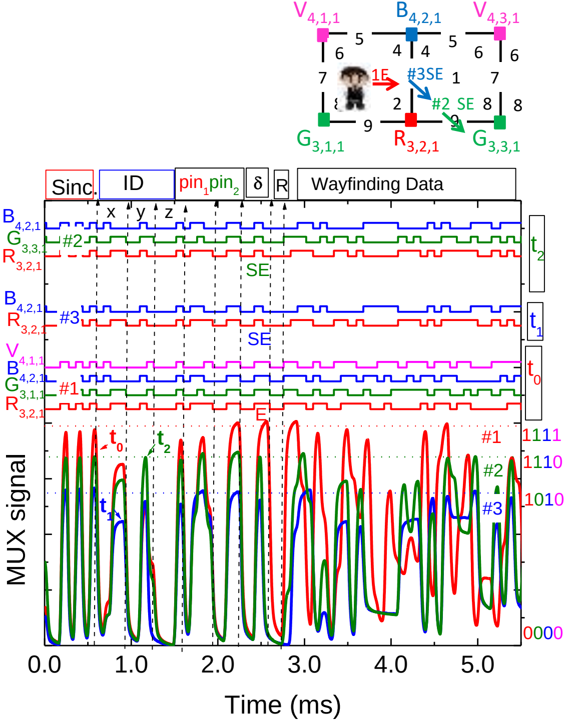

Fig. 5. Fine-grained indoor localization and navigation in successive instants. On the top the transmitted channels packets are decoded [R, G, B, V].

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 $R_{3,2,1}$, $B_{4,2,1}$ nodes 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.

Also, the VLC dynamic system enables cooperative and oppositional geolocation. In some cases, it is in the user’s interest to be accurately located, so that they can be offered information relevant to their location and orientation (pin $_1$, pin$_2$ and δ blocks). In other cases, users prefer not to disclose their location for privacy, in this case these last three blocks are set at zero and the user only receives its own location.

C. *Multi-person cooperative localization and guidance services*

In Figure 6, 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.

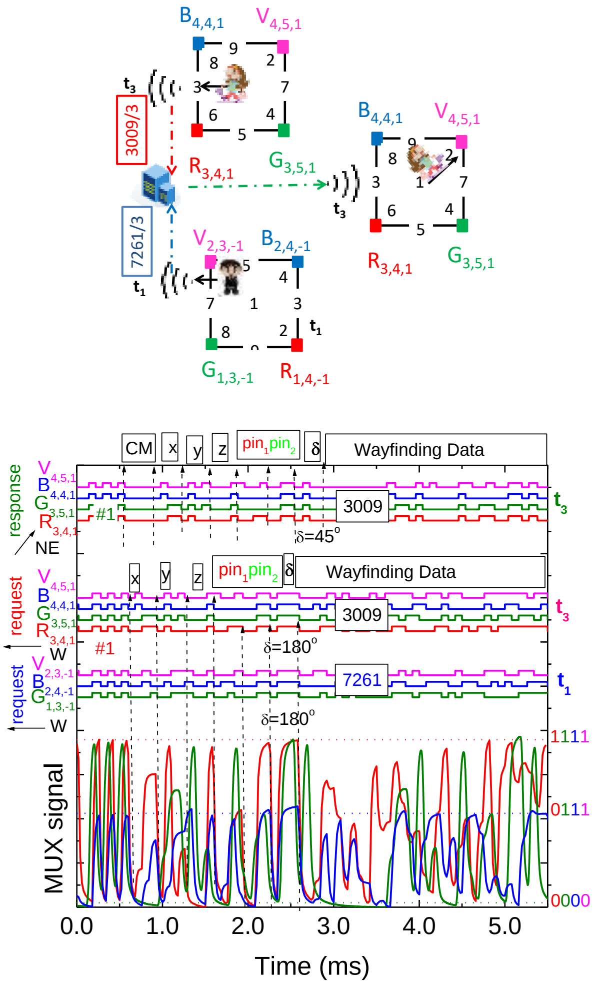

Fig. 6. MUX/DEMUX signals assigned requests from two users (“3009” and “7261”) at different poses ($C_{4,4,,1}$; #1W and $C_{2,3,-1}$; #6 W) and in successive instants (t_1 and t_3).

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.

Results show that, with VLC's dynamic LED-aided guidance system, users can get accurate route guidance and perform navigation and geotracking. Users of VLC in large buildings will be able to find the shortest route to their destination, providing directions as they go.

Moreover, the bidirectional communication capabilities of the system open up possibilities for various services. For example, mission-critical services can utilize the reliable and low-latency communication provided by the ID system. Furthermore, consumer-oriented services such as location-based advertisements, personalized information delivery, and indoor wayfinding can be implemented to enhance user experiences within the building.

IV. CONCLUSIONS

We have proposed and characterized a VLC-based guidance system for mobile users inside large buildings. A mesh cellular hybrid structure was chosen as the architecture, and the communication protocol was defined for a multi-level building scenario. An analysis of bidirectional communication between the infrastructure and the mobile receiver was conducted.

According to global results, the location of a mobile receiver is found in conjunction with data transmission. The dynamic LED-aided guidance system provides accurate route guidance, allows navigation, and keeps track of the route. Localization tasks are automatically rescheduled in crowded regions by the cooperative localization system, which provides guidance information and alerts the user to reschedule.

Additionally, the ID system based on visible light can enhance security within the building. The unique identification of spatial beams enables the implementation of access control systems, ensuring that only authorized individuals can access specific areas. Overall, the utilization of visible light as an ID system offers significant potential for a wide range of applications, including positioning, navigation, security, and various consumer services.

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