Using Visible Light Communication to Guide Mobile Users Inside Large Buildings

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Abstract— **The main goal of this paper is a Visible Light Communication (VLC) based guidance system to be used by mobile users inside large buildings. This system is composed of several transmitters (ceiling luminaries), which transmit map information and path guidance messages. Mobile devices, with VLC support, decode the information. A mesh cellular hybrid structure is proposed. The luminaires, via VLC, deliver their geographic position and specific information to the users, making them available for whatever use they request. The communication protocol, coding/decoding techniques, and error control are examined. Bidirectional communication is implemented and the best route to navigate through venue calculated. We propose several guidance services and multi-person cooperative localization. By analyzing the results, it became clear that the system not only provides self-location, but also the capability to determine the direction of travel and to interact with information received in order to optimize the route towards a static or dynamic destination.**

Keywords- Visible Light Communication; Assisted indoor navigation; Bidirectional Communication; Optical sensors; Transmitter/Receiver; Edge-Fog architecture.

I. INTRODUCTION

This paper is an extended and polished version of the paper presented in SENSORDEVICES 2022 conference [1]. 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. The most obvious method of using guidance signs is through billboards located in high traffic areas. Handheld devices allow customers to stay informed, gather information and communicate with others without being tied to a physical location.

With the rapid increase in wireless mobile devices, the continuous increase of wireless data traffic has brought challenges to the continuous reduction of radio frequency (RF) spectrum, which has also driven the demand for alternative technologies [2][3]. 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].

With the increasing shortage of radio frequency spectrum and the development of Light-Emitting Diodes (LEDs), VLC has attracted extensive attention. Compared to conventional wireless communications, VLC has higher rates, lower power consumption, and less electromagnetic interferences. 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 [6][7]. 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 [8][9] 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.

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 [10], are 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.

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

II. SYSTEM MODEL

The system model of the proposed system will be presented in this section.

A. *Communication system*

The system model is composed by two modules: the transmitter and the receiver. The block diagram is presented in Figure 1. Both communication modules are software defined, where modulation/demodulation can be programed.

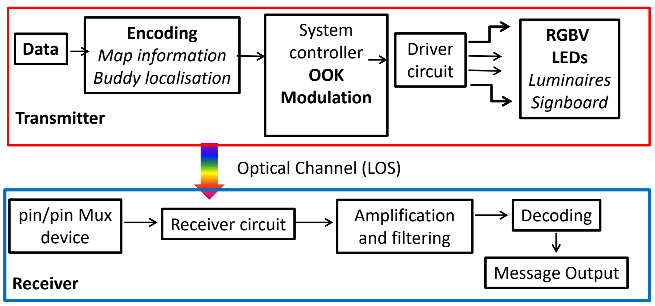


Figure 1. Block diagram. System model of the proposed control scheme applied to OOK modulation.

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.

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 2a. Each luminaire is composed of four polichromatic WLEDs framed at the corners of a square. At each node, only one chip is modulated for data transmission (see Figure 2b), 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). Data is encoded, modulated and converted into light signals emitted by the transmitters. Modulation and digital-to-analog conversion of the information bits is done using signal processing techniques. An OOK modulation scheme was used to code the information. 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. 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.

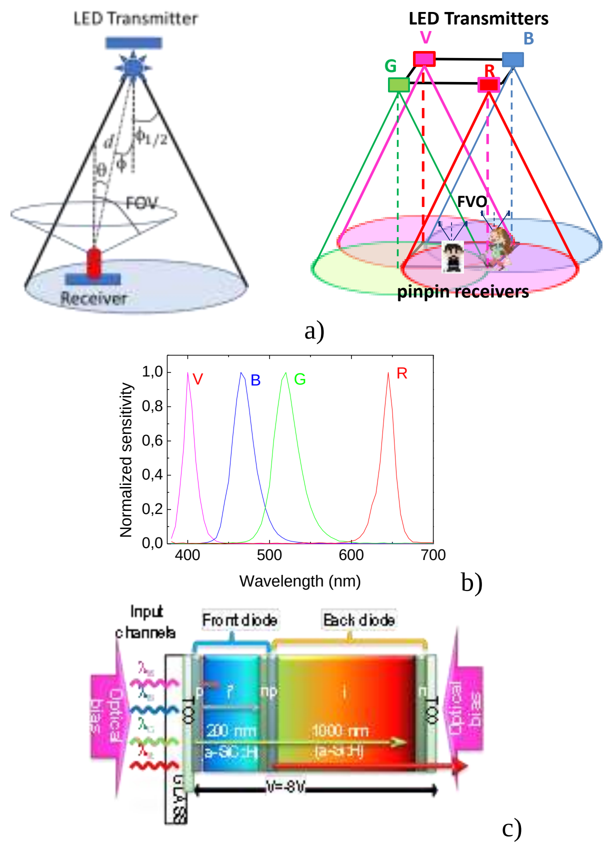


Figure 2. a)3D relative positions of the transmitters and receivers. b) Spectra of the input channels. c)Configuration and operation of the pin/pin Mux device

On the receiving side, a MUX photodetector acts as an active filter for the visible region of the light 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 [7] as displayed in Figure 2c. Independent tuning of each channel is performed by steady state violet optical bias (λ_{bias}= 2300 μW/cm^2) superimposed from the front side of the device and the generated photocurrent measured at -8V. The generated photocurrent is processed using a transimpedance circuit obtaining a proportional voltage. Since the photodetector response is insensitive to the frequency, phase, or polarization of the carriers, this kind of receiver is useful for intensity-modulated signals. After receiving the signal, it is in turn filtered, amplified, and converted back to digital format for demodulation. The system controller consists of a set of programmable modules.

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 expresssed as:

$$y=\mu hx+n \qquad (1)$$

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 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 Equation (2) [13]:

$$I(\emptyset)=I_N \cos \emptyset^m \,;\; m=\frac{ln(2)}{ln\left(\cos \emptyset_{1/2}\right)} \qquad (2)$$

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 [14].

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.

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

Taking into account Figure 2a, the path loss distance and the emitter gain will be given by:

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

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

With A the 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. The coverage map, for a square unit cell, is shown in Figure 5.

B. Building model and Architecture

Lighting in large environments is designed to illuminate the entire space in a uniform way. The proposed scenario is a multi-level building. Ceiling plans for the LED array layout, in floor level is shown in Figure 3. A square lattice topology was considered for each level.

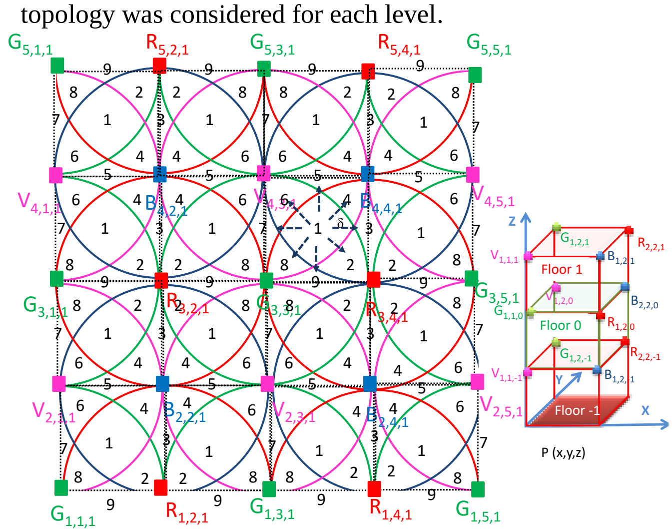


Figure 3. Clusters of cells in square topology. Illustration of the optical scenario. (RGBV =modulated LEDs spots).

In fog /edge computing, computing, storage, networking, and data management services are provided on nodes within close proximity to IoT devices, bridging the gap between the cloud and end devices.

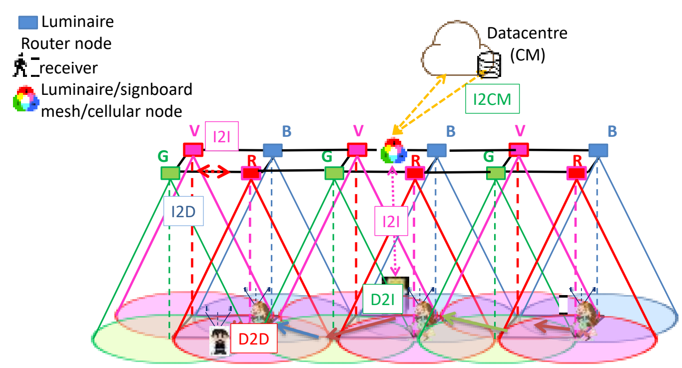


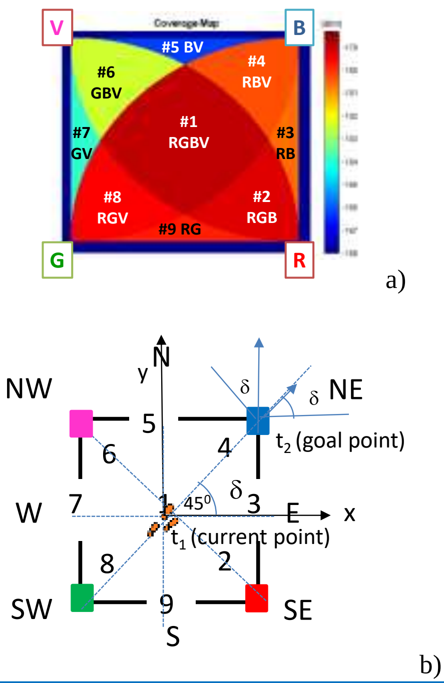
Figure 4. Mesh and cellular hybrid architecture.

In Figure 4, the proposed architecture is illustrated. 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.

A user navigates from outdoor to indoor. It sends a request message (D2I) to find the right track and, in the available time, he adds customized points of interest (guidance services). The requested information (I2D) is sent by the emitters at the ceiling to its receiver.

In this architecture, the polychromatic WLEDs are placed on the ceiling in a square lattice topology (see Figure 3), but only one, chip is modulated (R, G, B, V). The principle is that each WLED transmits a VLC signal with a unique identifier. The optical receiver uses this information and a position algorithm, based on the received joint transmission, calculates the track of the user.

To receive the I2D information from several transmitters, the receiver must be located at the overlap of the circles that set the transmission range (radial) of each transmitter.



Steering angle code	1	2	3	4	5	6	7	8	9
Square topology (δ)	-	(SE)°	(E)	(NE)	(N)	(NW)	(W)	(SW)	(S)

Figure 5. Illustration of the coverage map in the unit cell: a) Footprint regions (#1-#9). b) Steering angle codes (2-9).

Taking into account (1)-(5), the coverage map for a square unit cell is displayed in Figure 5. All the values were converted to decibel (dB). The nine possible overlaps (#1-#9), defined as fingerprint regions, as well as receiver orientations (2-9 steering angles; δ) are also pointed out for the unit square cell, in Figure 5. The input of the aided navigation system is the coded signal sent by the transmitters to an identified user (I2D), and includes its position in the network *P(x, y, z)*, inside the unit cell and the steering angle, δ, that guides the user across his path at a given time, *t*. The device receives multiple signals, finds the centroid of the received coordinates, and stores it as the reference point position. Nine reference points, for each unit cell, are identified giving a fine-grained resolution in the localization of the mobile device across each cell.

The indoor route throughout the building (track; *q(x, y, z, δ, t)*) is presented to the user by a responding message (I2D) transmitted by the ceiling luminaires that work also either as router or mesh/cellular nodes.

Two-way communication (D2I-I2D) between users and the infrastructure is carried out through a neighbor luminaire/signboard controller with an active cellular connection (I2CM). With this request/response concept, the generated landmark-based instructions help the user to unambiguously identify the correct decision point where a change of direction (pose) is needed, as well as offer information for the user to confirm that he/she is on the right way.

C. *Communication protocol, coding/decoding techniques and error control*

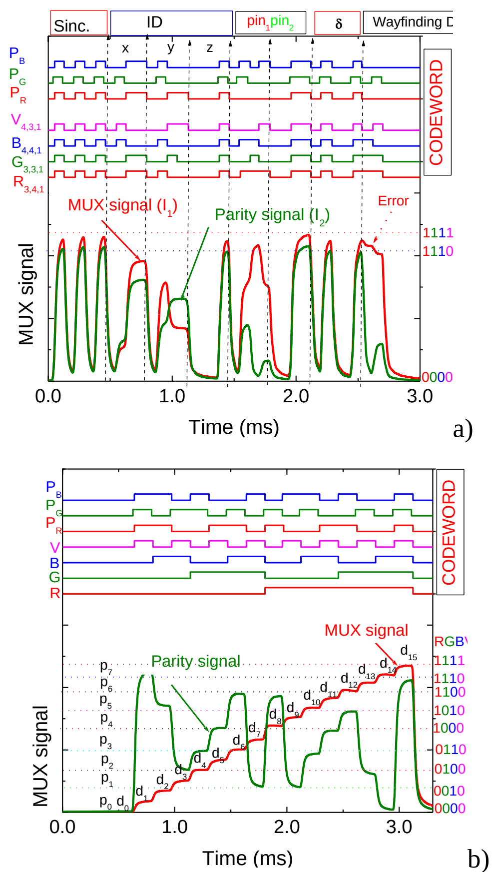


Figure 6. Code and parity MUX/DEMUX signals. On the top the transmitted channels [R G B V : P_R P_G P_B] are shown. a) Calibrated cell. b) Error control assigned to a request from user “7261” at $C_{4,3,1}$; #1 N.

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 [15]. As displayed in Figure 6b, calibration curves 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]. Due to the proximity of successive levels (see Figure 6a) occasional errors occur in the decoded information. A parity check is performed after the word has been read [16]. The parity bits are the SUM bits of the three-bit additions of violet pulsed signal with two additional RGB bits and defined as:

$$P_R = V x\ R\ x\ B;\ P_G = V x\ R\ x\ G;\ P_B = V\ x\ G\ x\ B \quad (6)$$

In Figure 6b, the MUX signal that arises from the transmission of the four calibrated RGBV wavelength channels and the MUX signal that results from the generation of the synchronized parity MUX are displayed. On the top the seven bit word [R,G,B,V, P_R, P_G, P_B] of the transmitted inputs guides the eyes. The colours red, green, blue and violet were assigned respectively to P_R, P_G , P_B and P_V. For simplicity the received data (d_{0-15} levels) is marked in the correspondent MUX slots as well as the parity levels marked as horizontal lines. On the top the decoded 7-bit coded word is exhibited. In the right side 4-bit binary codes assigned to the eight parity sublevels are inserted**.**

In Figure 6a we illustrate how error control is achieved using check parity bits. A request from user "7261" is shown at $C_{4,3,1}$; #1 N, along with the matching parity signal. To automate the process of recovering the original transmitted data, an algorithm was developed. The transmitted data is decoded by comparing the code MUX signal with the parity MUX levels. The decoding algorithm is based on a proximity search [17].

For each time slot, the data are translated into a vector in multidimensional space, which is determined by the signal currents I_1 and I_2, where I_1 is the d level and I_2 is the p level for the 4-bit codeword (RGBV). The corresponding parity levels, [P_R, P_G P_B] in the respective time slot are also obtained and are assumed to be correct. The result is then compared with all vectors resulting from the calibration sequence (Figure 6a) where each code level, d (0-31) is assigned the corresponding parity level, p (0-15). Euclidean metrics are used to calculate distances.

The tests were done with a variety of random sequences, and we were able to recover the original colour bits. Figure 7 illustrates the encoding/decoding process with and without check parity error. In Figure. 7a, the encoded optical signals (codewords) and the experimental received signals are depicted. After encoding, Figure 7b shows how information can be recovered with and without error control. The encoded signals transmitted by the LEDs are determined through the interpolation of the signals received by the photodiode, (MUX and Parity, Figure 6a), with the calibration curves (Figure 6b).

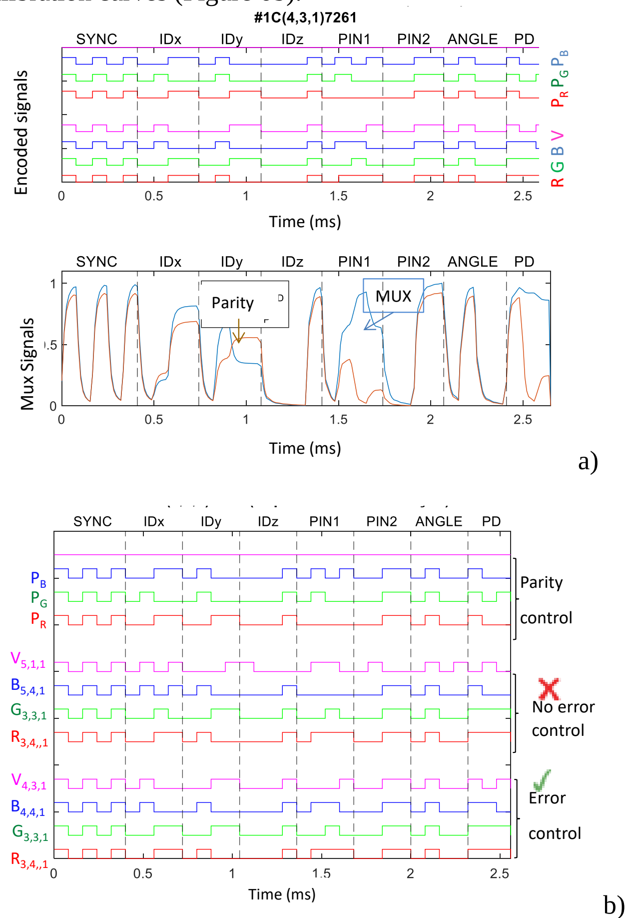


Figure 7. Encoding/decoding process with and without check parity error. a) Transmitted code signals [R G B V : P_R P_G P_B] and received MUX and Parity signals. b) Decoded information with and without error control assigned to a request from user "7261" at cell $C_{4,3,1}$ #1 NE.

Results show that without check parity bits, decoding was difficult primarily when levels were close together (dotted arrow). Based on the results for the analysed cases, the BER is high (4.6% without error correction) whereas it is negligible with error correction.

III. Cooperative Self-localization and Guidance Services

Concepts of self-localization and route control will be present in this section.

A. *Self-localization*

Self-localization is a fundamental issue since the person must be able to estimate its position and orientation (pose) within a map of the environment it is navigating. We consider the path to be a geometric representation of a plan to move from a start pose to a goal pose (Figure 5). Let us consider a person navigating in a 2D environment. Its non-omnidirectional configuration is defined by position (x, y) and orientation angle δ, with respect to the coordinate axes. q(t) = [$x(t)$, $y(t)$, $\delta(t)$] denote its pose at time t, in a global reference frame. In cooperative positioning systems, persons are divided into two groups, the stationary persons and the moving persons. Let us consider that $q_i(t,t')$ represents the pose of person i at time t' relative to the pose of the same person at time t and $q_{ij}(t)$ denotes the pose of person j relative to the pose of person i at time t. $q_i(t,t')$ is null for people standing still and non-zero if they move. These three types of information $q_i(t)$, $q_i(t,t')$and $q_{ij}(t)$ compose the basic elements of a pose graph for multi-person cooperative localization.

We consider that the risk of catching a disease exists if $q_{ij}(t)$ is less than 2 m. The system will alert the users to stay away from those regions and to plan the better route to the desired wayfinding services. To estimate each person track the pure pursuit approach [18][19] is used. The principle takes into account the curvature required for the mobile receiver to steer from its current position (t_1) to its intended position (t_2). By specifying a look-ahead distance, it defines the radius of an imaginary circle. Finally, a control algorithm chooses a steering angle in relation to this circle. This then allows to iteratively construct the intermediate arcs between itself and its goal position as it moved, thus, obtaining the required trajectory for it to reach its objective position. To avoid the risk of transmission, in the same frame of time and in known crowded regions, $q_{ij}(t)$ is estimated and the steering angle readjusted [20].

B. Geotracking, Navigation and Route Control

VLC geotracking is the process of identification or estimation of the geographic position of a device through visible light. It involves the generation of a set of geographic coordinates but its usefulness is enhanced by the use of these coordinates to determine a meaningful location, to help the user navigation through an unfamiliar building or, to guide him to an intended destination or planned meeting.

In Figure 8, 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. In the right side, the match between the MUX signals and the 4-binary codes are pointed out (horizontal dotted lines) to facilitate the decoding process. On the top, the decoded channels packets are shown [R, G, B, V]. The visualized cells, paths and the reference points (footprints) are also shown as inserts.

After decoding the MUX signals, and taking into account the frame structure, the ID of the receiver in the network (footprint and 3D coordinates), wayfinding services required (pin_1, pin_2) orientation (δ) and wayfinding data are revealed.

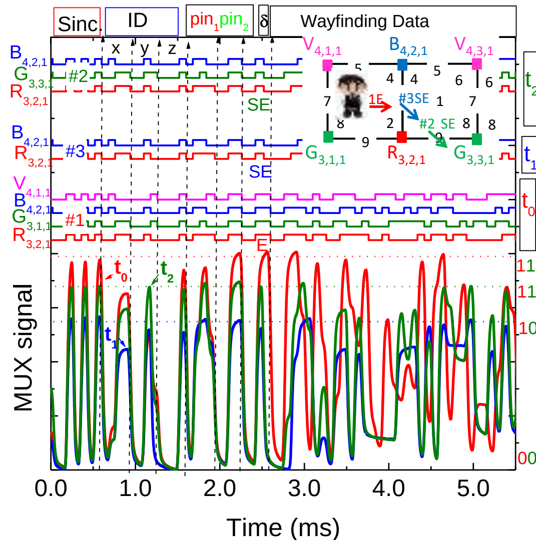


Figure 8. Fine-grained indoor localization and navigation in successive instants. On the top the transmitted channels packets are decoded [R, G, B, V]

Data shows that as a receiver moves between generated point regions, the received information pattern changes. Between two consecutive data sets, there is always a navigation data bit transition (channels are missing or added). At t_0, a maximum in the synchronism amplitude was detected and corresponds to the binary word [1111], meaning that the user has received the overlap transmission from all the four channels, footprint #1, while at t_1 the green and violet channels were missing, indicating footprint #3, and at t_3 the green channel from an adjacent cell was added, footprint #2. The transmitter's node address comes directly from the ID bits. At t_0 the network location of the received signals are $R_{3,2,1}$, $G_{3,1,1}$, $B_{4,2,1}$ 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. The next 12 bits identify the user code (pin_1, "7621"), the meeting code, (pin_2, 3) and the steering angles (δ) required for the mobile receiver to steer from its current position (#1) to its intended position (#9). Finally, the last block is reserved for the transmission of the wayfinding message (Payload data). 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 proposed VLC dynamic geolocation system gives every location a unique perceptual identity, so that the navigator can associate their immediate surroundings (unit cell) with a location in the larger space (building network). This is one of the main principles of wayfinding. The ceiling lamps (landmarks) are spread over all the building and can act as edge/fog nodes in the network (see Figure 4), 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). Since geolocation software can get the information of user location, companies using geomarketing may provide web content or products that are famous or useful in that specific location. In other cases, users prefer not to disclose their location for privacy, in this case these last three blocks are set to zero and the user only receives its own location. This architecture also allows that advertisements and content on a website that uses geolocation software may be tailored to provide the information that a certain user wants.

IV. MULTI-PERSON COOPERATIVE LOCALIZATION AND GUIDANCE SERVICES

A VLC system consists of two entities, infrastructure and device (I and D), which establish bidirectional communication through cellular edge nodes. Bi-directional communication between VLC emitters and receivers is available at a VLC ready handheld device, through the control manager interconnected with a signboard receiver located at each unit cells (#1). Via the control manager, a handheld device with VLC connectivity communicates bidirectionally with a signboard receiver in each unit cell (#1). Each user (D2I) uplinks to the local controller a "request" message with the pose, $q_i(t)$, (x, y, z, δ), user code (pin_1) and also adds its needs (code meeting and wayfinding data). For route coordination the CM, using the information of the network's VLC location capability, downlinks a personalized "response" message to each client at the requested pose with his wayfinding needs (I2D).

These communication channels constitute the uplink (D2I) and downlink channels (I2D) as exemplified in Figure 9a. Each user (D2I) sends to the local controller a "request" message with the pose, $q_i(t)$, (x,y,z, δ), user code (pin_1) and also adds its needs (code meeting and wayfinding data). For route coordination the CM, using the information of the network's VLC location capability, sends a personalized "response" message to each client at the requested pose with his wayfinding needs.

In Figure 9b, the MUX synchronized signals received by two users that have requested guidance services, at different times, are displayed. We have assumed that a user located at $C_{2,3,-1}$, arrived first (t_1), auto-identified as ("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 (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.

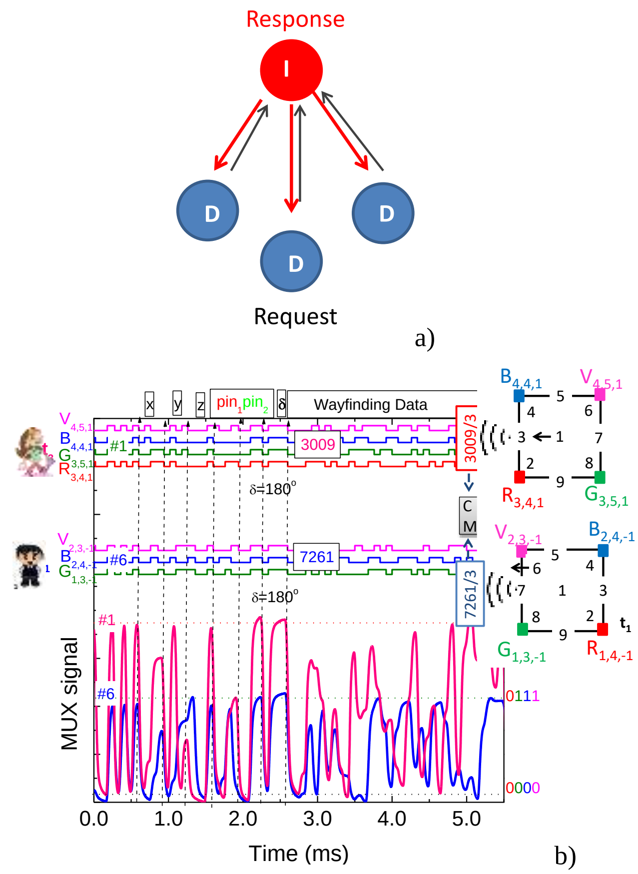


Figure 9. a) Communication channels established between the infrastructure and the vehicles for geolocation and navigation. b) MUX/DEMUX signals assigned requests from two users ("3009" and "7261") at different poses (C4,4,,1; #1W and C2,3,-1; #6 W) and in successive instants (t1 and t3).

Upon receiving this request (t_3), the buddy finder service uses the location information from both devices to determine the proximity of their owners ($q_{ij}(t)$) and provides the best route to the meeting, avoiding crowded areas.

An example of the MUX signals assigned to a request/response received by user "3009" during his path to reach user "7261" is displayed in Figure 10. In the top of the figure, the decoded information is shown and the simulated scenario is inserted to guide the eyes.

The "request" message includes, beyond synchronism, the identification of the user ("3009"), its address and orientation ($C_{4,4,1}$, #1W) and the help requested (Wayfinding Data). Since a meet-up between users is expected, its code was inserted before the right track request. In the "response", the block CM identifies the sender [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.

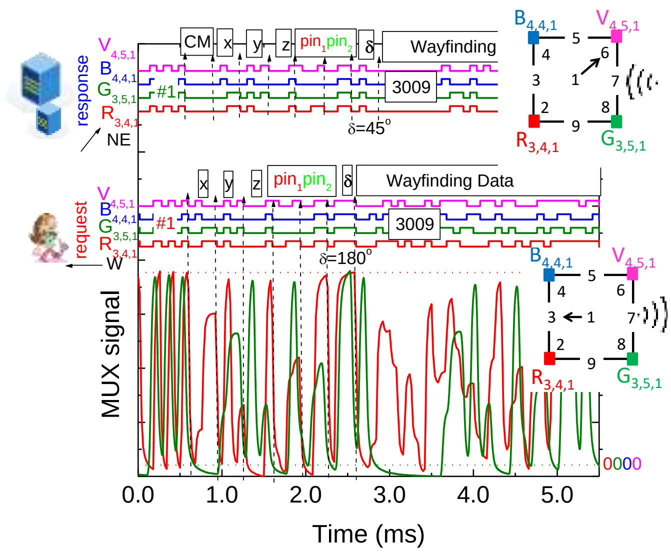


Figure 10. Request from user "3009" and response from the CM to him. On the top the transmitted channels packets are decoded [Xi,j,k].

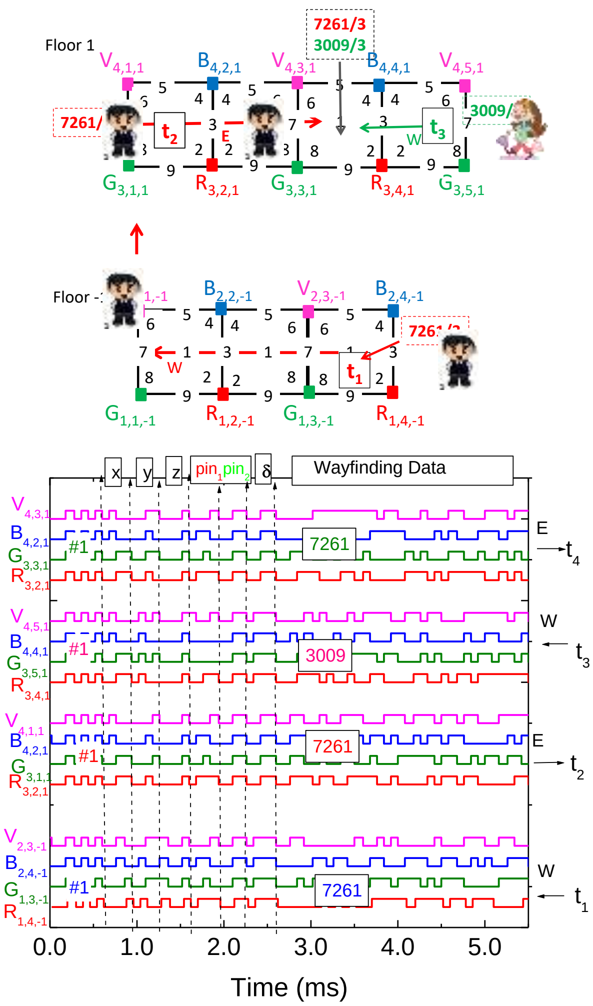


Figure 11. Decoded messages from the two users as they travel to a pre-scheduled meeting.

In response to the estimated relative pose position, $q_{i,j}(t)$, between the users with the same meeting code, the CM sends a new alert that takes into account the occupancy of the service areas along the paths, $q_i\ (x,y,z,\ \delta,\ t)$, which optimizes the path without crowding the users. This allows the CM to recalculate, in real time, the best route for the users, $q_i\ (t,t')$, that request wayfinding services avoiding crowded regions.

In Figure 11, the decoded messages from the two users as they travel to the pre-scheduled meeting is displayed.

Decoded data shows that user "7621" starts (t_1) his journey on floor -1, $C_{2,3,-1}$; #1W, goes up to floor 1 in $C_{2,1,-1}$ and at t_2 he arrives at $C_{4,1,1}$ heading for E. During his journey, user "3009" from $C_{4,4,1}$ #1 asks the CM (t_3) to forward him to the scheduled meeting and follows course to W. At t_4 both friends join in $C_{4,3,1}$.

The pedestrian movement along the path can be thought as a queue, where the pedestrians arrive at a path, wait if the path is congested and then move once the congestion reduces. In Figure 12, a graphical representation of the simultaneous localization and mapping problem using connectivity as a function of node density, mobility and transmission range is illustrated.

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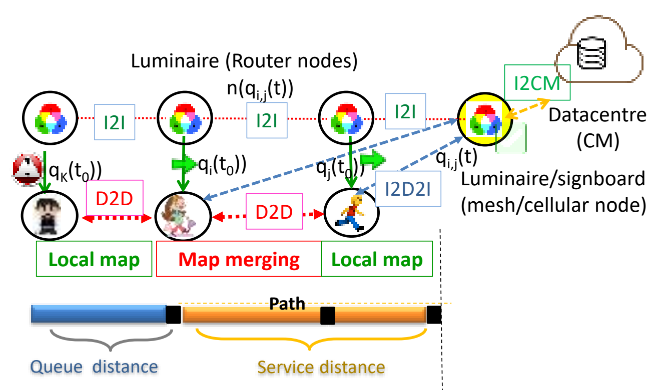

Figure 12. Graphical representation of the simultaneous localization and mapping problem using connectivity as a function of node density, mobility and transmission range.

The following parameters are therefore needed to model the queuing system: The initial arrival time (t_0) and the path, defined as the time when the pedestrian leaves the previous path and the actual movement along the path, $q_i\,(t,\ t')$. Here, the service time is calculated using walking speed and distance of the path. The number of service units or resources is determined by the capacity of the pathway, $n(q_i\ (x,y,z,\ \delta,\ t))$ and walking speed which depends on the number of request services, and on the direction of movement along the pathway $q_i\,(x,y,z,\ \delta,\ t)$. The pedestrians are served as soon as the request message is appended by the CM (response message) as displayed in Figure 12.

If the number of pedestrians exceeds the path capacity, a backlog is automatically formed until the starting node. The hybrid controller integrates the number of requests and individual positions received during the same time interval. Once the individual positions are known, $q_i(t)$, the relative positions are calculated, $q_{ij}(t)$. If the relative position is less than a threshold distance, a crowded region locally exists, and an alert message is sent for the users. This alert allows the CM to recalculate, in real time, the best route for the users, $q_i(t,t')$, that request wayfinding services avoiding crowded regions.

V. CONCLUSIONS

A VLC based guidance system to be used by mobile users inside large buildings was proposed and characterized. According to global results, the location of a mobile receiver is found in conjunction with data transmission. VLC's dynamic LED-aided guidance system is designed to give users accurate route guidance and enable navigation and geotracking. The multi-person cooperative localization system detects crowded regions and alerts the user to reschedule meetups, as well as provides guidance information. With those alerts, the CM can recalculate, in real time, the best route for users requesting wayfinding services, avoiding crowded areas. Further research activities are still necessary to optimize the coverage, namely the effects of synchronization, shadowing and ambient light. Also, the LED design and positioning has to be improved in the future, in order to optimize the communication performance while meeting the illumination constraints.

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