Indoor Guidance Services through Visible Light Communication

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Abstract— Communications within personal working/living spaces are highly demanded. To support people's wayfinding activities, we propose a Visible Light Communication (VLC) cooperative system that supports guidance services and uses an edge/fog-based architecture for wayfinding services. A mesh cellular hybrid structure is proposed. The dynamic navigation system is composed of several transmitters (ceiling luminaries), which send the map information and path messages required to wayfinding. The luminaires are equipped with one of two types of nodes: a "mesh" controller that connects with other nodes in its vicinity and can forward messages to other devices in the mesh, effectively acting like routers nodes in the network and a "mesh/cellular" hybrid controller, that is also equipped with a modem providing IP base connectivity to the central manager services. These nodes act as border-router and can be used for edge computing. Mobile optical receivers, using joint transmission, collect the data at high frame rates, extracts their location to perform positioning and, concomitantly, the transmitted data from each transmitter. Each luminaire, through VLC, reports its geographic position and specific information to the users, making it available for whatever use. Bidirectional communication is implemented and the best route to navigate through venue calculated. The results show that the system makes possible not only the self-localization, but also to infer the travel direction and to interact with information received optimizing the route towards a static or dynamic destination.
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Keywords- Visible Light Communication; Indoor navigation; Bidirectional Communication; Wayfinding, Optical sensors; Indoor multi-level environments; Transmitter/Receiver.

I. INTRODUCTION

Nowadays, wireless networks have seen a demand for increased data rate requirements. For a realistic coverage with the data rate requirements, a large bandwidth is needed which remains a limiting factor when compared with the RF communication technologies. Consequently, research has started exploring alternate wireless transmission technologies to meet the ever-increasing demand. In this context, the huge bandwidth available in the unlicensed electromagnetic spectrum in the optical domain is seen as a promising solution to the spectrum crunch.

Visible Light Communication (VLC) makes use of the higher frequencies in the visual band and extends the capabilities of data transmission using general light sources. VLC has been regarded as an additional communication technology [1] [2] to fulfill the high data rate demands and as a new affiliate in the beyond fifth generation (5G) heterogeneous networks. It can be easily used in indoor environments using the existing LED lighting infrastructure with few modifications [3] [4]. Research has shown that compared to outdoors, people tend to lose orientation a lot easier within complex buildings [5] [6]. Fine-grained indoor localization can be useful, enabling several applications [7] [8].

This work focuses on the use of VLC as a support for the transmission of information, providing advertising services and specific information to users. The goal is a cooperative system that supports guidance services and uses an edge/fog based architecture for wayfinding services. Here, the luminaire, through VLC, reports its geographical positions and specific information to the users since its infrastructure can also be reused to embed the fog nodes in them. The system is composed of several transmitters (LEDs luminaries), which send the map information and path messages required to wayfinding. Data is encoded, modulated and converted into light signals emitted by the transmitters. Every mobile terminal is equipped with a receiver module for receiving the mapped information generated from the ceiling light and displays this information in the mobile terminal. The receiver module includes a photodetector based on a tandem a-SiC:H/a-Si:H pin/pin light-controlled filter [9] [10].

Visible light can be used as an ID system and can be employed for identifying the room number and 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 to broadcast the

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information [11], are modulated acting as down- and up-link channels in the bidirectional communication. For the consumer services, the applications are enormous. The objective is to allow the implementation of new services in these areas using data from the VLC System, for indoor and outdoor. Positioning, navigation, security and even mission critical services are possible use cases that should be implemented.

In this paper, a LED-supported guidance VLC system is proposed. After the Introduction, in Section II, the communication system is described. In Section III, the main experimental results are presented, downlink and uplink transmission is implemented and the best route to navigate calculated. In Section IV, the conclusions are drawn.

II. COMMUNICATION SYSTEM, DESIGN AND ARCHITECTURE

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. *Communication system and cooperative localization*

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

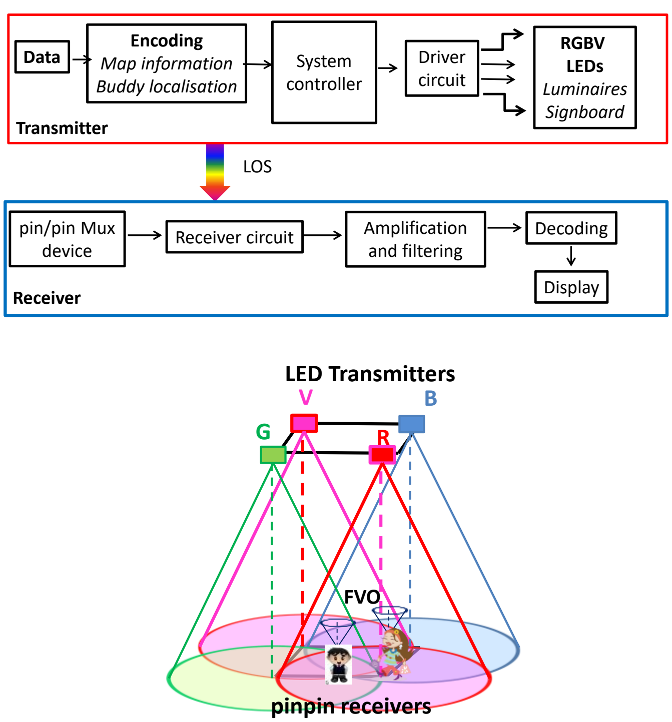

Figure 1. Block diagram and transmitters and receivers 3D relative positions.

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 are used providing a different data channel for each chip. Each luminaire is composed of four white LEDs framed at the corners of a square. At each node, only one chip of the LED is modulated for data transmission, the Red (R: 626 nm), the Green (G: 530 nm), the Blue (B: 470 nm) or the Violet (V). 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. 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.

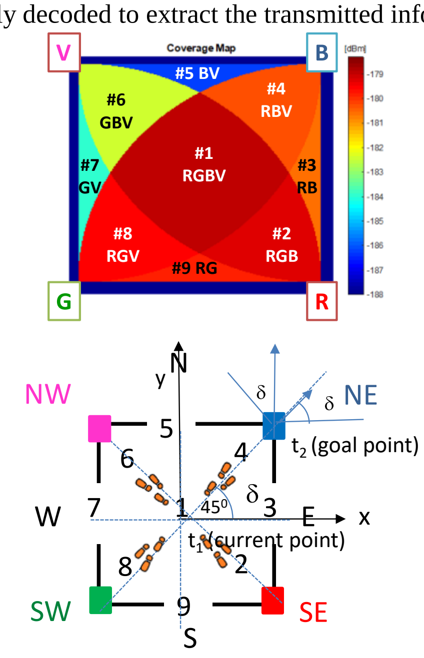

Figure 2. Illustration of the coverage map in the unit cell: footprint regions (#1-#9) and steering angle codes (2-9).

On the receiving side, this is first done by a silicon carbide (SiC) pinpin MUX device that acts as an active filter for the visible region of the light spectrum. 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. To receive the I2V information from several transmitters, the receiver must be located at the overlap of the circles that set the transmission range (radial) of each transmitter. The coverage map for a square unit cell is displayed in Figure 2. 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 [12]. 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 2. The input of the aided navigation system is the coded signal sent by the transmitters to an identify user, 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. 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 VLC photosensitive receiver is a double pin/pin photodetector based on a tandem heterostructure, p-i'-n/p-i-n sandwiched between two conductive transparent contacts. Exposed to light, the device offers high sensitivity and linear response, generating a proportional electrical current. Its quick response enables the possibility of high-speed communications. 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. The generated photocurrent is processed using a transimpedance circuit obtaining a proportional voltage. 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 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) [13] [14].

B. Architecture and Multi-person Cooperative Localization

Fog/Edge computing bridges the gap between the cloud and end devices by enabling computing, storage, networking, and data management on network nodes within the close vicinity of IoT devices. A mesh network is a good fit since it dynamically reconfigures itself and grows with the size of any installation. In Figure 3, 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. It performs much of the processing on embedded computing platforms, directly interfacing to sensors and controllers. It supports geo-distribution, local decision making, and real-time load-balancing. Moreover, it depends on the collaboration of near-located end-user devices, instead of relying on the remote servers, which reduces the deployment costs and delay.

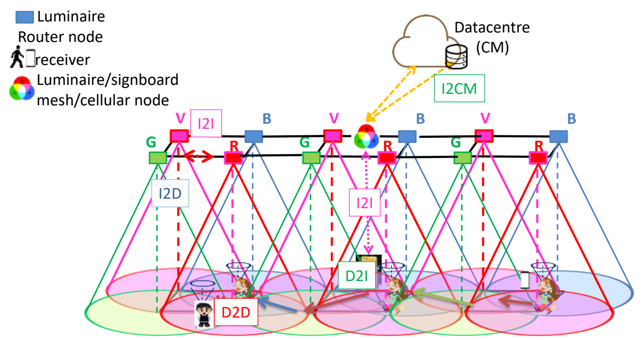

Figure 3. Mesh and cellular hybrid architecture.

C. Scenario and building model

Building a geometry model of buildings' interiors is complex. In the proposed architecture each room/crossing/exit represents a node, and a path as the links between nodes. The proposed scenario is a multi-level building. Lighting in large environments is designed to illuminate the entire space in a uniform way. Ceiling plans for the LED array layout, in floor level is shown in Figure 4.

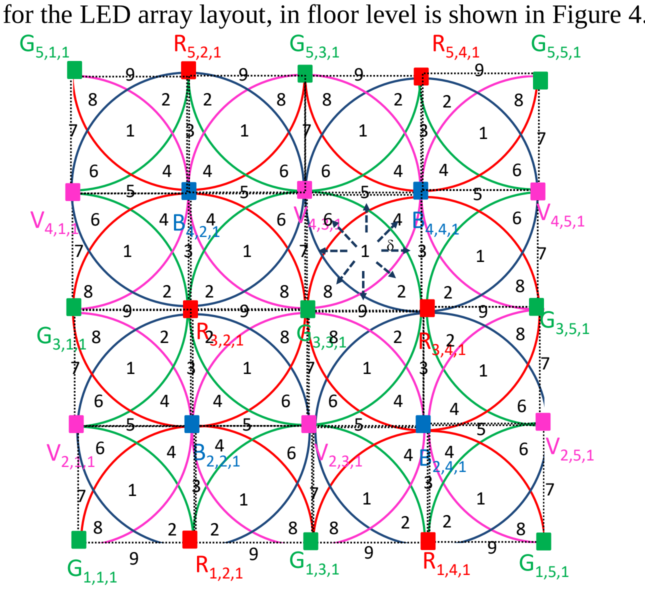

Figure 4. Illustration of the optical scenarios (RGBV =modulated LEDs spots). Clusters of cells in square topology.

A square lattice topology was considered for each level. A user navigates from outdoor to indoor. It sends a request message to find the right track (D2I, in Figure 3) and, in the available time, he adds customized points of interest (wayfinding services). The requested information (I2D) is sent by the emitters at the ceiling to its receiver.

The indoor route throughout the building (track) is presented to the user by a responding message transmitted by the ceiling luminaires that work also either as router or mesh/cellular nodes. 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.

III. Geotracking, Navigation and Route Control

Bi-directional communication between the infrastructure and the mobile receiver is analyzed.

A. *Communication protocol and coding/decoding techniques*

To code the information, an On-Off Keying (OOK) modulation scheme was used, and it was considered a synchronous transmission based on a 64- bits data frame.

The frame is divided into six blocks (Sync, ID, pin1/pin2, Angle δ, Request/Response and Wayfinding Data). The first block is the synchronization block [10101], the last is the payload data (wayfinding message) and a stop bit ends the frame. The second block, the ID block, 4+4+4 bits, gives the geolocation (*x,y,z* coordinates) of the emitters inside the array ($X_{i,j,k}$). Cell's IDs are encoded using a 4 bits binary representation for the decimal number. 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)) completes the 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 4. 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 last block is used to transmit the wayfinding message.

When bidirectional communication is required, the user must register by choosing a username (pin_1) with 4 decimal numbers, each one associated to a colour channel. So, to compose the decimal code each digit (0-9) has its own colour, codified in a 4-binary bit code. If buddy friend services are required a 4-binary code of the meeting (pin_2) must be inserted. The δ block (steering angle (δ)) completes the pose in a frame time q(x,y, δ, t). Eight steering angles along the cardinal points and coded with the same number of the footprints in the unit cell (Figure 2) are possible from a start point to the next goal. If no wayfinding services are required these last three blocks are set at zero and the user only receives its own location. The last block is used to transmit the wayfinding message. A stop bit is used at the end of each frame.

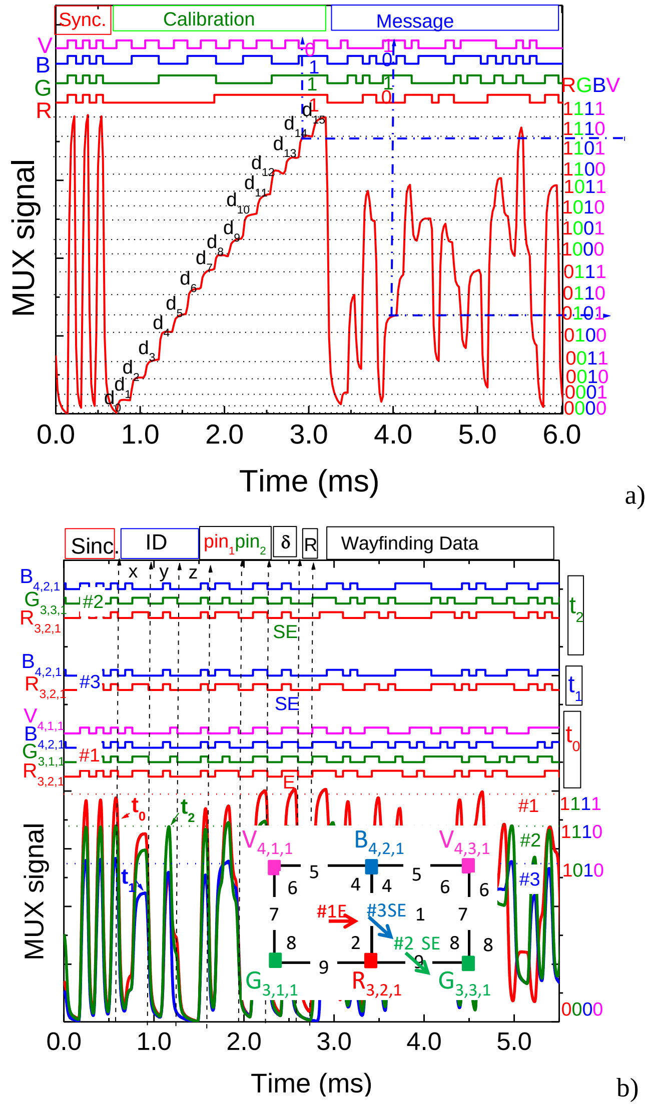

Figure 5. a) MUX/DEMUX signals of the calibrated cell. In the same frame of time a random signal (Message) is superimposed. b) Fine-grained indoor localization and navigation in successive instants. On the top the transmitted channels packets are decoded [R, G, B, V].

Based on the measured photocurrent signal by the photodetector, it is necessary to decode the information received. A calibration curve is previously defined to establish this assignment. In Figure 5a, it is plotted the calibration curve that uses 16 distinct photocurrent thresholds resultant from the combination of the RGBV modulated signals from VLC emitter. The correspondence between each 4-binary code and the photocurrent level is highlighted on the right side. Here, the MUX signal obtained at the receiver as well as the coded transmitted optical signals is displayed. The message, in the frame, start with the header labelled as Sync, a block of 5 bits. The same synchronization header [10101] is imposed simultaneously to all emitters. In the second block, labelled as calibration, the bit sequence was chosen to allow all the *on/off* sixteen possible combinations of the four RGBV input channels (2^4). Finally, a random message was transmitted [15]. Comparing the calibrated levels (d_0-d_{15}) with the different assigned 4-digit binary [RGBV] codes, ascribed to each level, the decoding is straightforward, and the message decoded [16].

In Figure 5b, 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 reference points (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 $R_{3,2,1}$, $B_{4,2,1}$ 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.

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

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). These communications channels constitute the uplink (D2I) and downlink channels (I2D). 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 6, the MUX synchronized signals received by two users that have requested wayfinding 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.

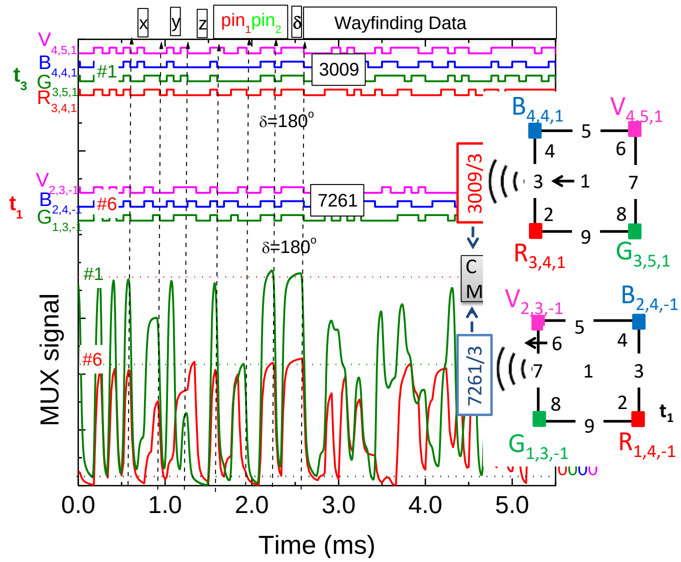

Figure 6. MUX/DEMUX signals assigned requests from two users ("3009" and "7261") at different poses ($C_{4,4,,1}$; #1W and $C_{2,3,-1}$; #6 W) and in successive instants (t_1 and t_3).

After this request (t_3), the buddy finder service uses the location information from both user' devices to determine the proximity of their owners ($q_{ij}(t)$) and sends a response message with the best route to the meeting.

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.

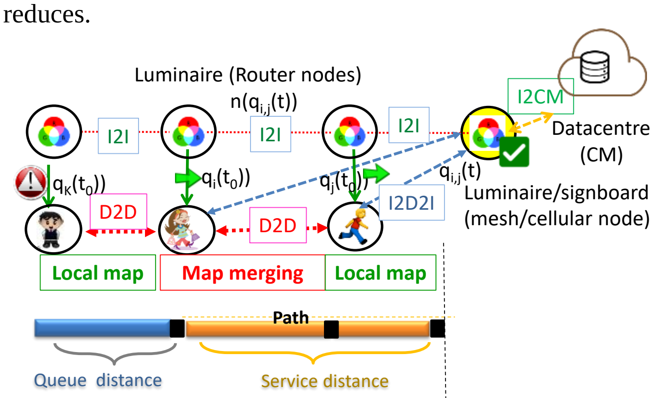

Figure 7 Graphical representation of the simultaneous localization and mapping problem using connectivity as a function of node density, mobility and transmission range.

In Figure 7, a graphical representation of the simultaneous localization and mapping problem using connectivity as a function of node density, mobility and transmission range is illustrated. The following parameters are therefore needed to model the queuing system: The initial arrival time (t_0) and the path, respectively, 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 from the capacity of the path, $n(q_i\,(x,y,z,\, \delta,\, t))$ and walking speed that depends on the number of request services, and on the direction of movement along the path $q_i\,(x,y,z,\, \delta,\, t)$. Since the number of service units is same as the capacity of the path, the queue size is theoretically zero. Once appended by the CM (request message), the pedestrians are served immediately (response message). 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.

IV. Conclusions

A cooperative indoor VLC localization and navigation system is proposed. In a multi-level building scenario, the architecture of the system and the protocol of communication were defined. Bi-directional communication between the infrastructure and the mobile receiver was analyzed. According to global results, the location of a mobile receiver is found in conjunction with data transmission. VLC's dynamic LED-aided navigation 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.

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