VLC Based Guidance System to Be Used by 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

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 [1][2]. 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 [3][4].

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 [5] [6]. 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 [7] [8] 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 [9], 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, 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.

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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.

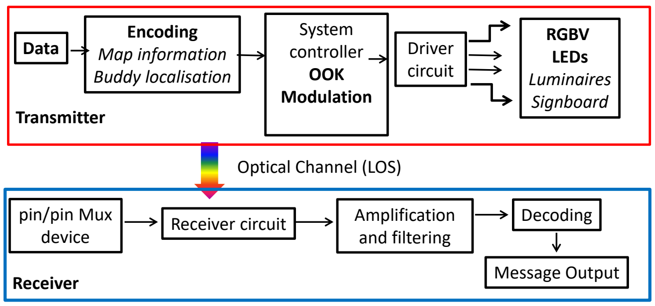

Figure 1. Block diagram. System model of the proposed control scheme applied to OOK modulation.

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 $\mu W/cm^2$), the Green (G: 530 nm, 46 $\mu W/cm^2$), the Blue (B: 470 nm, 60 $\mu W/cm^2$) or the Violet (V, 400 nm, 150 $\mu W/cm^2$). 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) [10] [11]. At last, the message will be output to the users.

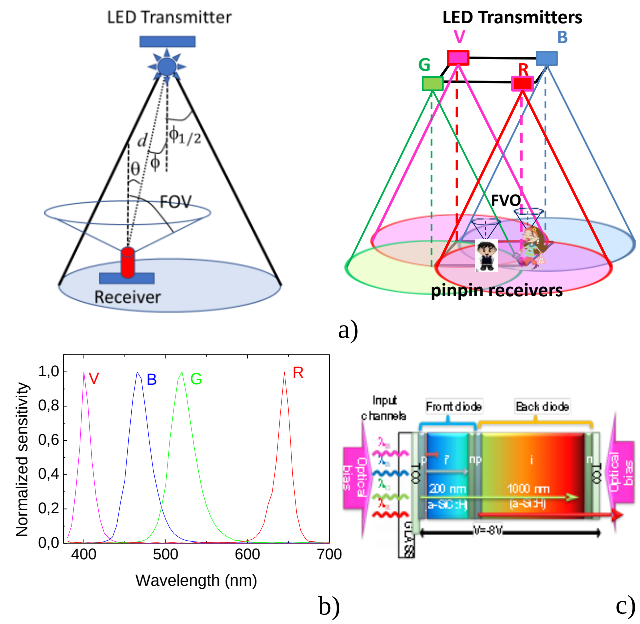

Figure 2. a)3D relative positions of the transmitters and receivers. b) Spectra of the input channels. c)Configuration and operation of the pin/pin Mux device

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 $\mu W/cm^2$) 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.

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The received channel can be expresssed as:

$$y=\mu hx+n \tag{1}$$

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 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) [12]:

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

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 [13].

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 Figure 2a, 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. The coverage map, for a square unit cell, (see 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.

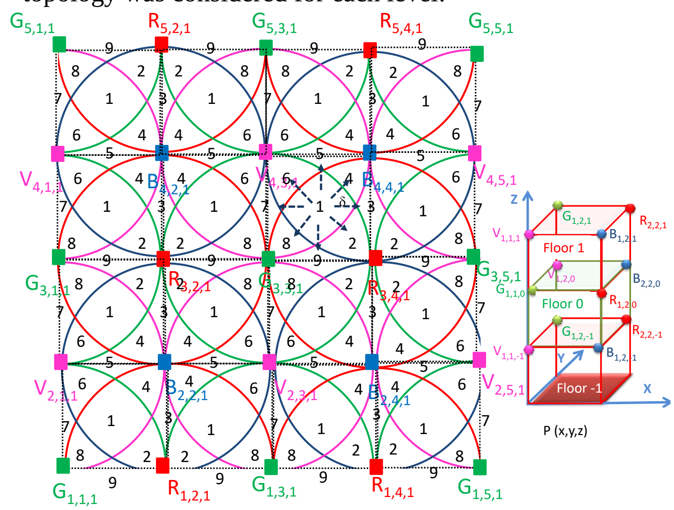

Figure 3. Clusters of cells in square topology. Illustration of the optical scenario. (RGBV =modulated LEDs spots).

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. 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.

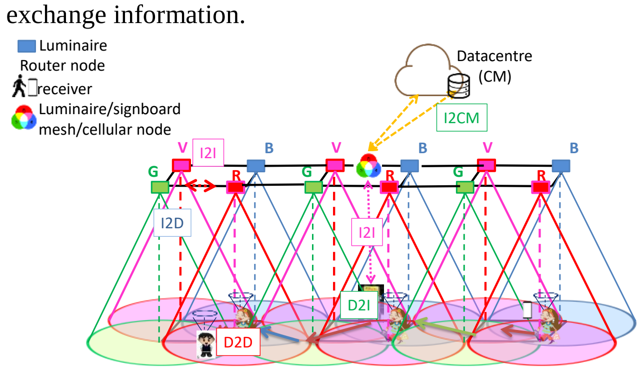

Figure 4. Mesh and cellular hybrid architecture.

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.

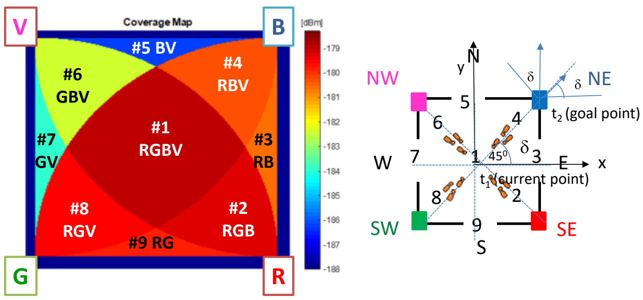

Figure 5. Illustration of the coverage map in the unit cell: footprint regions (#1-#9) and steering angle codes (2-9).

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 identify 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

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 coded transmitted signals are shown in Figure 6 along with their respective MUX signals.

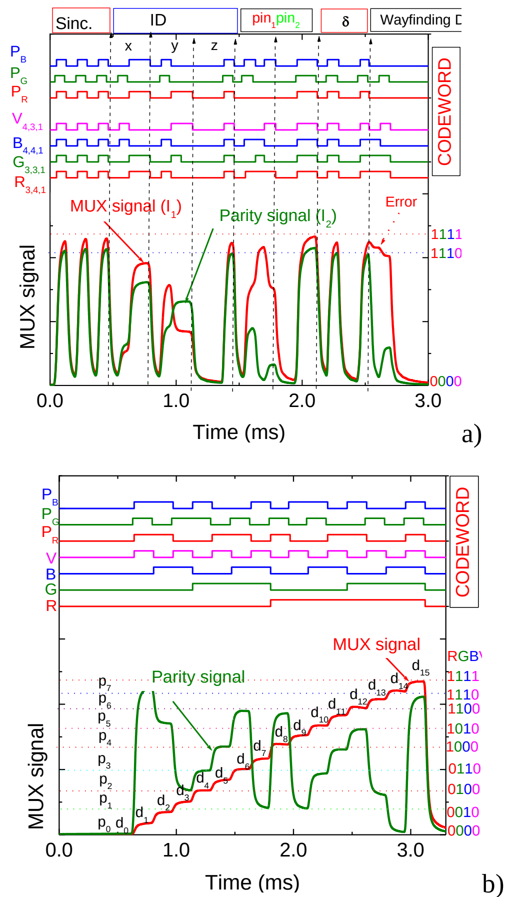

Figure 6. Code and parity MUX/DEMUX signals. On the top the transmitted channels [R G B V : P_R P_G P_B] are shown. a) Calibrated cell. b) Error control assigned to a request from user "7261" at $C_{4,3,1}$; #1 N.

All messages, in a frame, start with the header labelled as Sync, a block of 5 bits. The same synchronization header [10101], in an ON-OFF pattern, is imposed simultaneously to all emitters. The next block (ID) 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. So, the next 12 (4+4+4) bits in are assigned, respectively, to the *x*, *y* and *z* coordinates (*i, j, k*) of the emitter in the array. If the message is diffused by the CM transmitter, a pattern [0000] precedes this identification. When bidirectional communication is required, the user has to register by choosing a user name (pin_1) with 4 decimal numbers, each one associated to a color channel. So, to compose the decimal code each digit (0-9) has its own color, codified in a 4-binary bit code. Whenever buddy friend

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services are required, the 4-binary code of the meeting (pin_2) must be entered. In a frame time, The δ block (steering angle (δ)) completes the pose, $q(x, y, \delta, t)$. Eight steering angles along the cardinal points and coded with the same number of the footprints in the unit cell (Figure 5) are possible from a start point to the next goal. The codes assigned to the pin_2 and to δ are the same in all the channels. In the absence of wayfinding services these last three blocks are set to zero and the user receives only its own location. The last block is used to transmit the wayfinding message. A stop bit is used at the end of each frame.

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]. 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 [15]. The parity bits are the SUM bits of the three-bit additions of violet pulsed signal with two additional RGB bits and defined as:

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

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. 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. MULTI-PERSON COOPERATIVE LOCALIZATION AND GUIDANCE SERVICES

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).

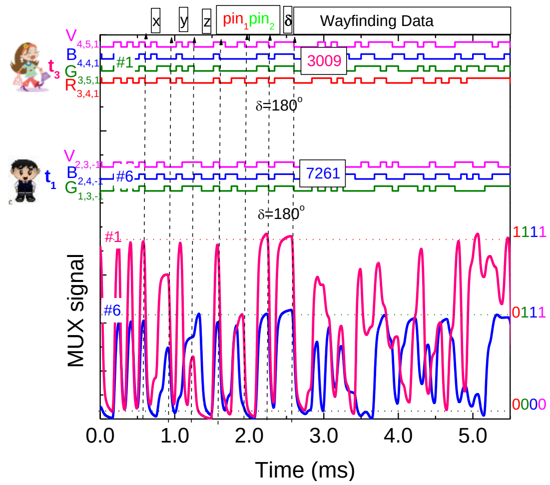

Figure 7. MUX/DEMUX signals assigned requests from two users ("3009" and "7261") at different poses ($C_{4,4,1}$; #1W and $C_{2,3,-1}$; #6 W) and in successive instants (t_1 and t_3).

In Figure 7, 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.

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.

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 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, 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 8.

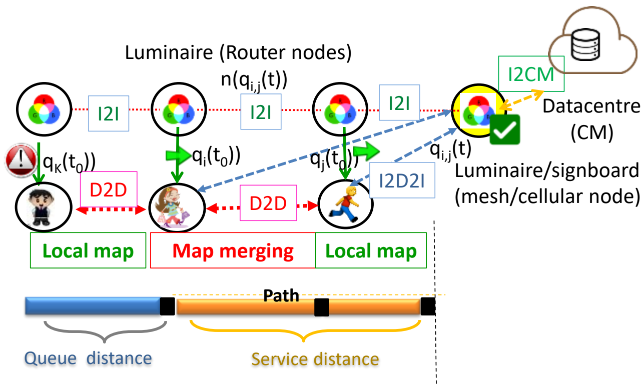

Figure 8 Graphical representation of the simultaneous localization and mapping problem using connectivity as a function of node density, mobility and transmission range.

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 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.

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