Indoor Self-localization and Wayfinding Services using Visible Light Communication: A model

Manuela Vieira, Manuel Augusto Vieira, Paula Louro,
DEETC/ISEL/IPL,
R. Conselheiro Emídio Navarro, 1959-007
Lisboa, Portugal
CTS-UNINOVA
Quinta da Torre, Monte da Caparica, 2829-516,
Caparica, Portugal

e-mail: mv@isel.ipl.pt, mv@isel.pt, plouro@deetc.isel.pt,

João Rodrigues, Pedro Vieira
ADETC/ISEL/IPL,
R. Conselheiro Emídio Navarro, 1959-007
Lisboa, Portugal
Instituto das Telecomunicações
Instituto Superior Técnico, 1049-001,
Lisboa, Portugal
e-mail: A42101@alunos.isel.pt, pvieira@isel.pt

***Abstract*— Visible Light Communication (VLC) is a promising technology that can jointly be used to accomplish the typical lighting functionalities of the Light-Emitting Diodes (LEDs) and data transmission, where light intensity can be modulated on a high rate that cannot be noticed by the human eye. A VLC cooperative system that supports guidance services and uses an edge/fog based architecture for wayfinding services is presented. The dynamic navigation system is composed of several transmitters (luminaries) which send the map information and path messages required to wayfinding. Each luminaire for downlink transmission is equipped with one two type of controllers: mesh controller and cellular controllers to forward messages to other devices in the vicinity or to the central manager services. Data from the luminaires is encoded, modulated and converted into light signals emitted by the transmitters. Tetra-chromatic white sources, located in ceiling landmarks, are used providing a different data channel for each chip. Mobile optical receivers, collect the data, extracts theirs location to perform positioning and, concomitantly, the transmitted data from each transmitter. Uplink transmission is implemented and the best route to navigate through venue calculated. The results show that the system allows determining the position of a mobile target inside the network, to infer the travel direction along the time and to interact with information received optimizing the route towards the destination.**

Keywords- Visible Light Communication; Indoor navigation; Bidirectional Communication; Wayfinding services; Optical sensors; Multiplexing/demultiplexing techniques.

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. The advancement in data streaming and multimedia quality has an adverse effect on the available radio spectrum, which is soon set to hit a roadblock. 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 [1][2]. It transmits data by high-speed switching or flickering at a rate that is not perceivable to the naked eye. VLC has been regarded as an additional communication technology 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]. This means that the LEDs are twofold by providing illumination as well as communication. Therefore, communications within personal working/living spaces are highly demanded. Multi-device connectivity can tell users, from any device, where they are, where they need to be and what they need to do when they get there. 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].

To support people's wayfinding activities this paper proposes a method able to generate ceiling landmark route instructions using VLC. Tetra-chromatic white sources are used providing a different data channel for each chip and offers the possibility of Wavelength Division Multiplexing (WDM), which enhances the transmission data rate. 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 modules

 ISBN: 978-1-61208-918-8

includes a photodetector based on a tandem a-SiC:H/a-Si:H pin/pin light controlled filter that multiplexes the different optical channels, performs different filtering processes and finally decodes the encoded signals, recovering the transmitted information [9] [10] [11]. This kind of receiver has proved to be adequate when used in large indoor environments with a 2D building model [12]. The proposed LED aided system involves wireless communication, smart sensoring and optical sources network, building up a transdisciplinary approach framed in cyber-physical systems.

The paper is organized as follows. After the introduction (Section I), in Section II, a VLC scenario, architecture and building model are established and the dynamic navigation system explained. In Section III, models for the VLC link are presented and in Section IV, the communication protocol and the encoding/decoding techniques are analyzed and the wayfinding evaluation discussed. Finally, in Section V, conclusions are addressed.

II. Scenario, Architecture and Building model

A. *Scenario*

When we are looking for the shortest route to a place, we want to be guided on a direct, shortest path to our destination. A destination can be targeted by user request to a Central Manager (CM).

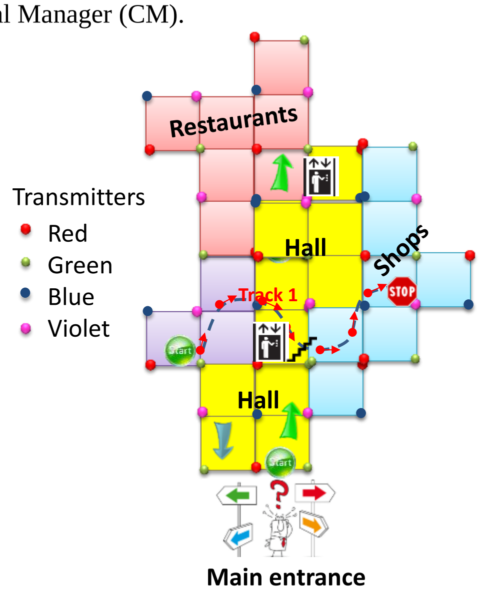


Figure 1. Optical infrastructure and indoor layout. Proposed scenario: a user navigates from outdoor to indoor. It sends a request message to find the right track and, in the available time, he adds customized points of interest (wayfinding services). The requested information is sent by the emitters at the ceiling to its receiver.

So, 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.

The scenario simulated is a 3D complex building. Different users are considered (Figure 1). Depending on the time available, they can find a friend, shop, have a meal or rest. When arriving, they notify the CM of their localization (x, y, z), asking for help to find the right track for their needs (wayfinding services). A code identifies each user. If a user wishes to find a friend both need previously to combine a common code for the schedule meeting. The first arriving initiates the alert notification to be triggered when the other is in his floor vicinity and generates a buddy list for the meeting. The buddy finder service uses the location information from the network's VLC location from both users to determine their proximity and sends a response message with the location and path of the meeting point avoiding crowded regions and minimizing the path.

We consider the path to be a geometric representation of a plan to move from a start pose to a goal pose. Let us we consider a person navigating in a 2D environment (Figure 1). Its non-omnidirectional configuration is defined by position (x, y, z) and orientation angle, δ, with respect to the coordinate axes. q(t) = [x(t), y(t), z(t), δ(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's 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.

B. *Mesh cellular hybrid structure*

In Figure 2, the proposed architecture is illustrated. A mesh cellular hybrid structure to create a gateway-less system is proposed. This network configuration is wireless and ad-hoc. It spans all devices, is wire free, demonstrate resiliency to physical obstructions and adapt to changes in the transmission medium. A mesh network is a good fit because it dynamically reconfigures itself and grows to the size of any installation [13]. As illustrated in Figure 2, the luminaires, in this architecture, are equipped with one of two types of nodes: A "mesh" controller that connects with other nodes in its vicinity. These controllers can forward messages to other devices (I2D) in the mesh, effectively acting like routers nodes in the network. A "mesh/cellular" hybrid controller, that is also equipped with a modem providing IP base connectivity to the central manager services (CM). These nodes act as border-router and can be used for edge computing. 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 controller with an active cellular connection; and enable peer-to-peer communication ($I2I_{IP}$), to exchange information between smart devices.

 ISBN: 978-1-61208-918-8

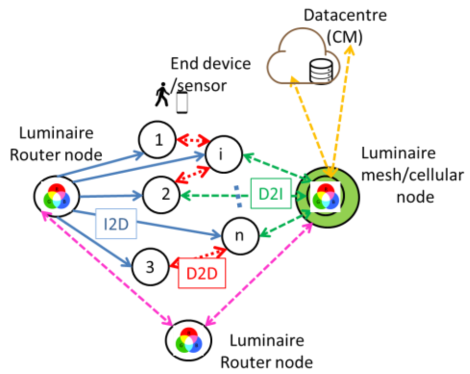


Figure 2. Mesh and cellular hybrid architecture.

To estimate each person track the pure pursuit approach [14] [15] is used. The principle took into account the curvature required for the mobile receiver to steer from its current position to its intended position. By specifying a look-ahead distance, it defines the radius of an imaginary circle. This 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 (see Figure 1).

C. Building model

Building a geometry model of interiors of buildings is complex since the interior structure has to be seen as an aggregation of several different types of objects (rooms, stairs, etc.) with different shapes. In the proposed architecture the logical model is easier since represents each room/crossing/exit with a node (Figure 1), and a path as the links between nodes. By integrating floor number information into the previous 2D system, the overall performance of the system will not be significantly affected. The user positions can be represented as P (x, y, z) by providing the horizontal positions (x, y) and the correct floor number z. The ground floor is level 0 and the user can go both below (z<0) and above (z>0) from there. In this study, the 3D model generation is based on footprints of a multi-level building that are collected from available sources (luminaires) and are displayed on the user receiver for user orientation. It is a requirement that the destination can be targeted by user request to the CM and that floor changes are notified. The indoor route throughout the building is presented to the user by a responding message transmitted by the ceiling luminaires that work also either as router or mesk/celular nodes (Figure 2). 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. VLC LINK MODELS

The principal components of the VLC system are the LEDs which act as the communication sources and the SiC WDM devices that serve as receiving elements as pointed out in Figure 3. 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. Here, a bit one is represented by an optical pulse that occupies the entire bit duration, while a bit zero is represented by the absence of an optical pulse.

LEDs are modeled as Lambertian source 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 1. [16]:

$$\mathrm{I}(\emptyset) = \mathrm{I}_N(\cos\emptyset)^m \quad (1)$$

Where m is the order derived from a Lambertian pattern, I_N is the maximum luminous intensity in the axial direction and , ϕ is the angle of irradiance. The Lambertian order m is given by:

$$\mathrm{m} = -\frac{\ln(2)}{\ln\,\cos(\emptyset_{1/2})} \quad (2)$$

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.

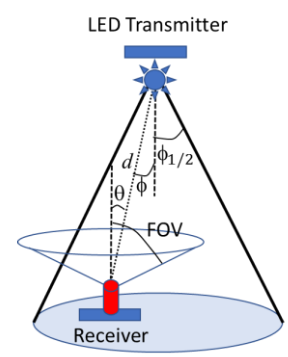
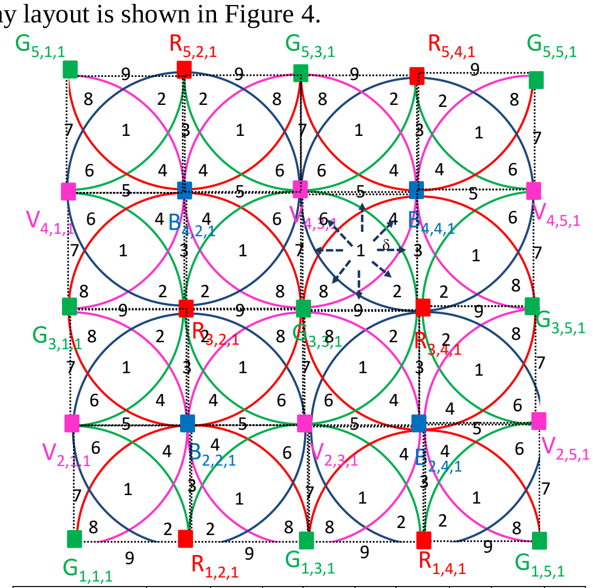


Figure 3. – Geometry of the relative position of the transmitter and receiver units.

The light signal is received by the WDM photodetector that detects the on/off states of the LEDs, generates a binary sequence of the received signals and convert data into the original format. For simplicity, we will consider a line of sight (LoS) connection for both VLC links, which corresponds to the existence of straight visibility between the transmitter and the receiver. In Figure , it is plotted the geometry of the transmitter and receiver relative position, with emphasis to the main parameters used for characterization of the LED source and the photodiode receiver (angles of irradiance and illumination, transmitter's semi-angle at half-power and field of view). The Lambertian model is used for LED light distribution and MatLab simulations are used to infer the signal coverage of the LED in the illuminated indoors space [17] [18].

Lighting in large environments is designed to illuminate the entire space in a uniform way. Ceiling plans for the LED array layout is shown in Figure 4.



Footprint regions	#1	#2	#3	#4	#5	#6	#7	#8	#9
Square topology	RGBV	RGB	RB	RBV	BV	GBV	GV	RGV	RG

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

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

A square lattice topology was considered. Here, cells have squares shapes to form an orthogonal shaped constellation with the modulated RGBV LEDs at the nodes.

The LEDs emit light when the energy levels change in the semiconductor diode. The wavelength depends on the semiconductor material used to form the LED chip. For data transmission, commercially available polychromatic white LEDs were used at the nodes of the network. On each node only one chip is modulated for data transmission and carries useful information while the others are only supplied with DC to maintain white color illumination. Red (R; 626 nm), Green (G; 530 nm), Blue (B; 470 nm) and violet (V; 390 nm) LEDs, are used [19] [20].

Since lighting and wireless data communication is combined, each luminaire for downlink transmission become a single cell, in which the optical access point (AP) is located in the ceiling and the mobile users are scattered within the overlap discs of each cells underneath. So, each node, $X_{i,j}$, carries its own color, X, (RGBV) as well as its ID position in the network (i,j). The grid sizes were chosen to avoid overlap in the receiver from adjacent grid points. To receive the information from several transmitters, the receiver must be positioned where the circles from each transmitter overlaps, producing at the receiver, a multiplexed (MUX) signal that, after demultiplexing, acts twofold as a positioning system and a data transmitter. 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 overlap regions (footprints) are pointed out in Figure 4.

Planning the route to follow from the current position to a goal point is achieved with the help of a CM linked to the ceiling landmarks (Figure 2). To compute the point-to-point along a path, we need the data along the path. 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. In Figure 4, the steering angles are pointed out as dotted arrows and the associated codes displayed.

IV. COMMUNICATION PROTOCOL AND DECODING TECHNIQUE

In Figure 5, the MUX/DEMUX signals from two users, that have request wayfinding services, are displayed.

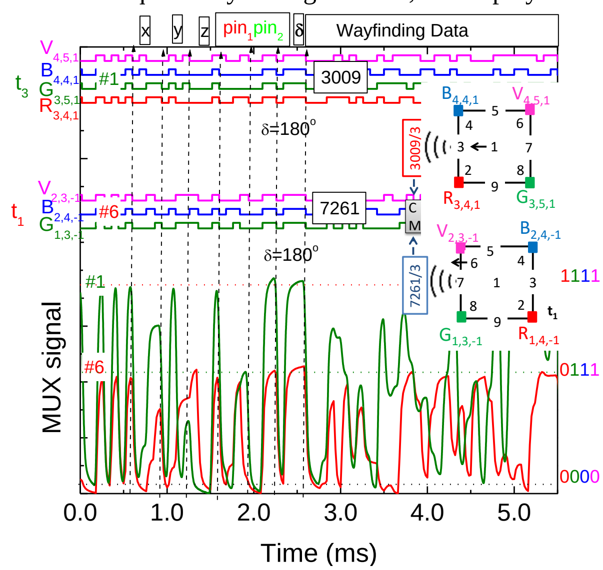


Figure 5. MUX/DEMUX signals assigned requests from two users ("3009" and "7261") at different poses ($C_{4,4,1}$; #1W and $C_{2,3,-1}$; #6 W) and in successive instants (t_0 and t_1).

In the right side, the match between the MUX signals and the 4-binary codes are pointed out (horizontal dotted lines). 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.

The data was coded using an On-Off keying (OOK) modulation in a 64-bits word, divided into five blocks. 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. The first bit represents the number's sign: setting that bit to *0* is for a positive number, and setting it to *1* for a negative number, the remaining 3 bits indicate the absolute value of the coordinate. 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.

In the proposed architecture, bi-directional communication is available through the mesh/cellular nodes. Each user sends to the local controller a "request" message with his pose (x,y,z, δ), user code (pin_1) and also adds its needs (code meeting and wayfinding data). 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 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) has to be inserted. The coded steering angle (δ) completes the pose in a frame time (Table 2). The codes assigned to the pin_2 and to δ be 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. A stop bit is used at the end of each frame.

The calibration of the receiver supplies an additional tool to enhance the decoding task and includes the simultaneous modulation of the four RGBV emitters in the cell [21]. The resultant optical signal is a combination of the all the possible optical excitation (2^4), which results in 16 possible photocurrent levels at the photodetector. Under these conditions, when all possible signal output levels are well distinct, it is possible to infer the corresponding input optical states.

Taking into account the frame structure, results from Figure 5, show that the user located at $C_{2,3,-1}$, arrived first (t_1), identified himself ("7261") and has informed the controller of his intention to find a friend for a scheduled meeting ([0011]; 3). Then, a buddy list was generated and includes all the users who have the same meeting codes. User "3009" arrives later sends the alert notification ($C_{4,4,1}$; t_3) to be triggered when his friend is in his floor vicinity, identifies himself ("3009") and uses the same code, in the buddy wayfinding services (code 3), to track the best way to his meeting. After this second request, the buddy finder service uses the location information from both user devices to determine the proximity of their owners and sends a response message with the best route to the meeting.

Figure 6, shows the decoded messages from the two users as they travel to the pre-scheduled meeting. The trajectory followed (poses) is shown on the right side of the figure. At the top the figure the simulated scenario is illustrated.

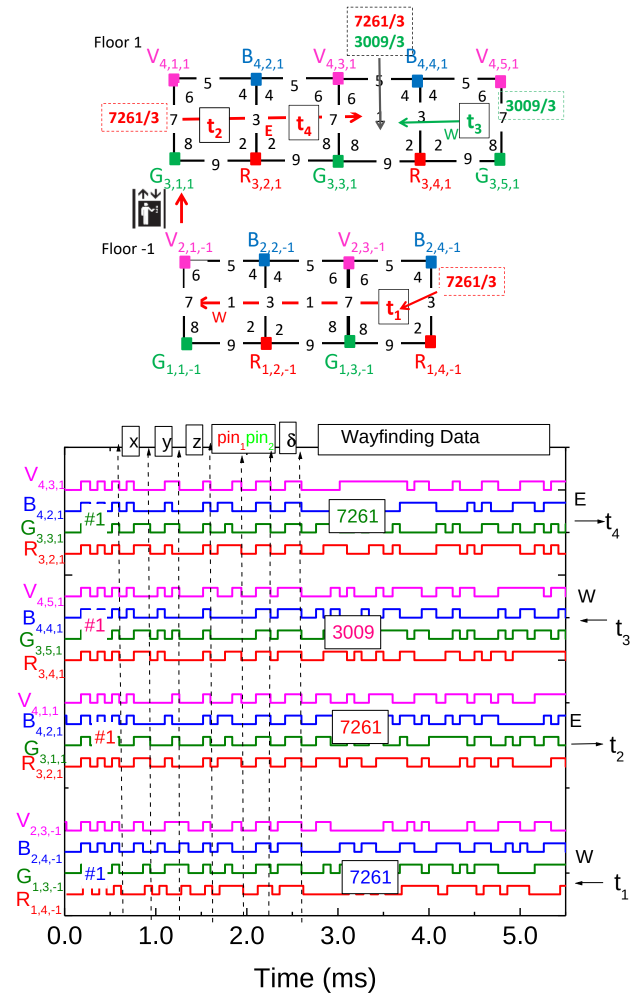


Figure 6. Decoded messages from the two users as they travel to a pre-scheduled meeting.

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 existence of congested zones can be locally detected by the "mesh / cellular" hybrid controller (Figure 1a), which is also equipped with a modem providing IP base connectivity to the central manager. The hybrid controller integrates the number of requests and individual poses, q_i *(t)*, received during the same time interval. Once the individual poses are known, the relative poses, q_{ij} *(t)* are calculated. An alert notifies the user of the best route.

V. CONCLUSIONS

A VLC multi-person cooperative localization dynamic LED-assisted positioning and navigation system was proposed based on ceiling landmark route instructions using VLC. A 3D building model for large indoor environments was presented, and a VLC scenario in a multilevel building was established. The communication protocol was presented. Bi-directional communication between the infrastructure and the mobile receiver was analyzed. Global results show that the location of a mobile receiver, concomitant with data transmission is achieved. The dynamic LED-aided VLC navigation system enables to determine the position of a mobile target inside the network, to infer the travel direction along the time and to interact with received information.

The VLC system, when applied to large building, can help to find the shortest path to a place, guiding the users on a direct, shortest path to their destinations.

ACKNOWLEDGEMENTS

This work was sponsored by FCT – Fundação para a Ciência e a Tecnologia, within the Research Unit CTS – Center of Technology and Systems, reference UIDB/00066/2020. The project IPL/IDI&CA/2020/Geo-Loc/ISEL, is also acknowledge.

REFERENCES

[1] E.Ozgur, E. Dinc, and O. B. Akan, “Communicate to illuminate: State-of-the-art and research challenges for visible light communications,” Physical Communication 17 pp. 72–85, (2015).

[2] C. Yang and H. R. Shao, “WiFi-based indoor positioning,” IEEE Commun. Mag., vol. 53, no. 3, pp. 150–157 (Mar. 2015).

[3] D. Tsonev, et al. “A 3-Gb/s single-LED OFDM-based wireless VLC link using a Gallium Nitride μLED,” IEEE Photon. Technol. Lett. 26 (7), pp.637–640 (2014).

[4] D. O’Brien et al. “Indoor visible light communications: challenges and prospects,” Proc. SPIE 7091, 709106 (2008).

[5] H.-H. Liu and Y.-N. Yang,”WiFi-based indoor positioning for multi-floor environment,” Proceedings of the IEEE Region 10 Conference on Trends and Development in Converging Technology Towards (TENCON '11)November 2011Bali,Indonesia59760110.1109/TENCON.2011.61291752-s2.0-84863014825 (2011).

[6] Y. Wang, H. Li, X. Luo, Q. Sun, and J. Liu, “A 3D Fingerprinting Positioning Method Based on Cellular Networks,” International Journal of Distributed Sensor Networks, (2014).

[7] M. Vieira, M. A. Vieira, P. Louro, P. Vieira, and A. Fantoni, “Fine-grained indoor localization: optical sensing and detection,” Proc. SPIE 10680, Optical Sensing and Detection V, 106800H (9 May 2018).

[8] A. Jovicic, J. Li, and T. Richardson, “Visible light communication: opportunities, challenges and the path to market,” Communications Magazine, IEEE, vol. 51, no. 12, pp. 26–32 (2013).

[9] M. A. Vieira, M. Vieira, P. Louro, V. Silva, P. Vieira, "Optical signal processing for indoor positioning using a-SiCH technology," Opt. Eng. 55 (10), 107105 (2016), doi: 10.1117/1.OE.55.10.107105 (2016).

[10] M. A. Vieira, M. Vieira, P. Vieira, P. Louro, “Optical signal processing for a smart vehicle lighting system using a-SiCH technology,” Proc. SPIE 10231, Optical Sensors 2017, 102311L (2017);

[11] M. Vieira, M.A. Vieira, P. Louro, A. Fantoni, and Steiger-A. Garção, “Light-activated amplification in Si-C tandem devices: A capacitive active filter model,” IEEE sensor journal, 12, NO. 6, 1755-1762 (2012).

[12] M. A. Vieira, M. Vieira, P. Louro, V. Silva, P. Vieira, "Optical signal processing for indoor positioning using a-SiCH technology," Opt. Eng. 55 (10), 107105 (2016), doi: 10.1117/1.OE.55.10.107105 (2016).

[13] A. Yousefpour et al.“All one needs to know about fog computing and related edge computing paradigms: A complete survey”, Journal of Systems Architecture,Volume 98, pp. 289-330 (2019).

[14] R. Rajamani “Dynamic Vehicle and control” Mechanical Engineering Series, ISBN 978-1-4614-1433-9 (2012).

[15] J. Ackermann, J. Guldner, W. Sienel, R. Steinhauser, and V. Utkin, “Linear and Nonlinear Controller Design for Robust Automatic Steering” IEEE Transactions on Control Systems Technology (Volume: 3, Issue: 1, Mar 1995), pp. 132 – 143, DOI: 10.1109/87.370719 (1995).

[16] Y. Zhu, W. Liang, J. Zhang, and Y. Zhang, “Space-Collaborative Constellation Designs for MIMO Indoor Visible Light Communications,” IEEE Photonics Technology Letters, vol. 27, no. 15, pp. 1667–1670, (2015).

[17] Y. Qiu, H. Chen and W. Meng, “Channel modeling for visible light communications—a survey”, Wirel. Commun. Mob. Comput. 2016; 16:2016–2034,(2016)

[18] S. Raza, et al. ”Optical Wireless Channel Characterization For Indoor Visible Light Communications”, Indian Journal of Science and Technology, Vol 8 (22), DOI: 10.17485/ijst/2015/v8i22/70605, 2015

[19] M. Vieira, M. A. Vieira., P. Louro., P. Vieira, A. Fantoni, “Fine-grained indoor localization: optical sensing and detection,” Proc. SPIE 10680, Optical Sensing and Detection V, 106800H (9 May 2018).

[20] M. Vieira, M. A. Vieira., P. Louro., P. Vieira, A. Fantoni, “Light-emitting diodes aided indoor localization using visible light communication technology,” Opt. Eng. 57(8), 087105 (2018).

[21] M. Vieira, M. A. Vieira, P. Louro, A. Fantoni, and P. Vieira "Location and wayfinding services through visible light in crowded buildings", Proc. SPIE 11772, Optical Sensors 2021, 117721V (2021).