Indoor Guidance in Multi-Terminal Airports through Visible Light Communication

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Abstract**—— This study introduces an innovative method for guiding navigation in busy airports using Visible Light Communication (VLC) technology. By utilizing existing lighting fixtures to transmit encoded messages via light signals, users can receive location-specific guidance. The system employs tetrachromatic Light Emitting Diodes (LEDs) and VLC capabilities to efficiently transmit data, supported by a mesh cellular hybrid structure that enhances flexibility without the need for traditional gateways. Integrating VLC into Edge/Fog architecture maximizes its benefits, such as wireless connectivity and secure communication while leveraging existing infrastructure. This integration allows for distributed data processing, storage, and communication at the network edge, improving system performance. The study develops a detailed airport model and analyzes navigation for pedestrians and luggage/passenger carriers. Users equipped with PINPIN optical sensors interpret light signals for localization and positioning, supported by a tailored communication protocol and coding techniques for reliable transmission.**

Keywords-Visible Light Communication (VLC); Wayfinding; Indoor Navigation; User Behavior; Agent-Based simulator; Edge/Fog Architecture.

I. INTRODUCTION

VLC is a data transmission technology [1]-[3] that can easily be employed in indoor environments since it can use the existing LED lighting infrastructure with simple modifications [4]-[6]. In the sequence, we propose to use modulated visible light, carried out by white low-cost LEDs. LEDs are capable of switching to different light intensity levels at a very fast rate, imperceptible to the human eye. This functionality can be used for communication where the data is encoded in the emitting light. A mobile receiver is used to demodulate and decode the electrical signal generated at a photodetector. This means that the LEDs are twofold by providing illumination as well as communication. Multicolored LEDs based luminaires can provide further possibilities for signal modulation and detection in VLC systems [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 was used [8][9]. 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.

Fine-grained indoor localization technology presents various applications, particularly beneficial in complex environments like airports. By implementing VLC technology, the indoor navigation can be significantly improved, offering users precise location information and enhancing their overall experience in crowded indoor environments [10][11]. Passengers can receive precise directions to boarding gates, check-in counters, baggage claim areas, lounges, and other amenities, reducing confusion and enhancing their overall experience. Additionally, it enables real-time tracking and management of assets such as luggage carts and maintenance equipment, optimizing their deployment and utilization throughout the airport. For airport retailers, indoor localization facilitates personalized promotions, wayfinding assistance, and location-based services, leading to increased sales and customer satisfaction. Ultimately, this technology streamlines operations, improves passenger experience, and enhances safety and security

ISBN: 978-1-68558-208-1

measures, contributing to a more efficient and enjoyable air travel experience for all stakeholders.

This paper is organized as follows: In the Introduction, the challenges faced in navigating multi-terminal airports are presented, the existing literature is reviewed, and the concept of utilizing VLC for indoor navigation is justified. Section 2 describes the approach used for supporting wayfinding activities in multi-terminal airports using VLC technology. In Section 3, the methodology for generating the airport model is presented, and the analysis of two types of users (pedestrians and luggage/passenger carriers) is described. Section 4 describes the agent-based simulator used to control traffic for both user categories and presents and discusses the results on users halting and average speeds and different geometric scenarios. Finally, in Section 5, the conclusions summarize the key findings of the study and suggest future research directions to further enhance indoor navigation systems using VLC technology.

II. METHODOLOGY

A. VLC background

The system model is structured around two primary modules: the transmitter and the receiver (Figure 1).

The transmitter module plays a crucial role in converting sender data into byte format before transmitting it as light signals. White light tetra-chromatic sources (WLEDs) with four polychromatic LEDs are utilized, each representing a data channel. Each luminaire is composed of four polychromatic WLEDs framed at the corners of a square. The setup, shown in Figure 1a. At each node, only one chip is modulated for data transmission (Figure 1a), the Red (R: 626 nm¸ 25 μW/cm^2), the Green (G: 530 nm, 46 μW/cm^2), the Blue (B: 470 nm, 60 μW/cm^2) or the Violet (V, 400 nm, 150 μW/cm^2) and the intensities of the other is controlled to give the white light perception.

The ON-OFF Keying (OOK) modulation scheme is used, where light presence signifies a binary "1" and absence a binary "0." The signal is transmitted through the optical channel and received by a VLC receiver, which extracts the data using a MUX photodetector acting as an active filter. The integrated filter consists of a p-i'(a-SiCH)-n/p-i(a-Si:H)-n amorphous heterostructure with low conductivity doped layers as displayed in Figure 1b. It transforms the light signal into an electrical signal that is subsequently decoded to extract the transmitted information. The obtained voltage is then processed, by using signal conditioning techniques (adaptive bandpass filtering and amplification, triggering, and demultiplexing), until the data signal is reconstructed at the data processing unit (digital conversion, decoding, and decision) [12].

The receiver needs to be positioned to overlap the range circles of multiple transmitters, resulting in a multiplexed (MUX) signal for both positioning and data transmission. The grid sizes prevent overlapping from adjacent grid points, defining nine fingerprint regions per unit square cell. The device computes the centroid of received coordinates, establishing it as the reference point position, offering nuanced resolution in localizing the mobile device within each cell.

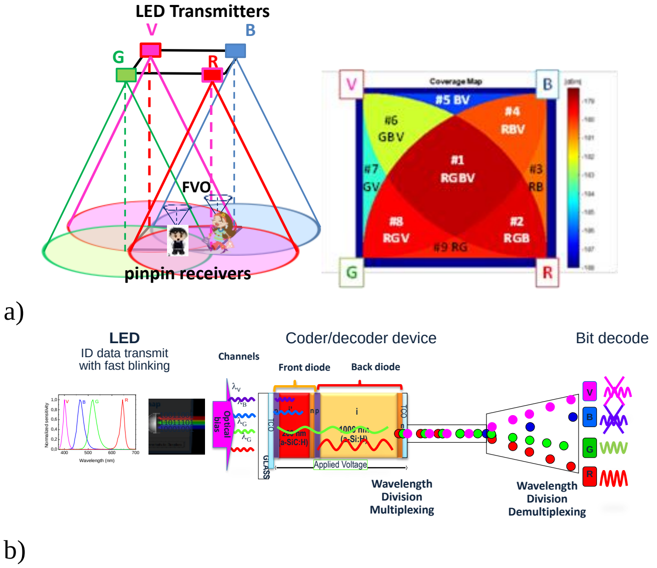

Figure 1. a) Transmitters and receivers 3D relative positions, footprints and coverage map in the square topology. b) Configuration and operation of the PINPIN receiver.

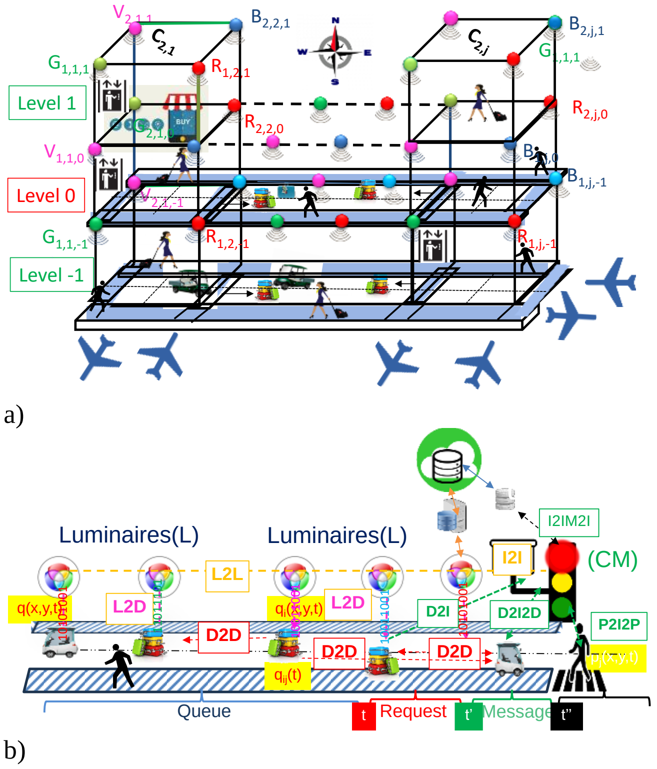

Figure 2. a) lighting plan. b) One lane draft of the Edge/Frog hybrid architecture.

B. *Lighting Plan Layout, Architecture and Geolocation*

Building a geometry model of buildings' interiors is complex. Indoor VLC cell design is especially important since, being man-made; buildings, such as these commonly follow basic shapes. A square lattice topology for the luminaires was considered for each level, as illustrated in Figure 2a.

This topology is represented using the *x*, *y*, and *z* axes to simplify both the figure comprehension and the distance between any pair of nodes. Each room/crossing/exit represents a node, and a path is the link between nodes. Figure 2a the 3D building model is draft. The user positions can be represented as $q\ (x,\ y,\ z,\ t)$ 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. Each unit cell can be identified as $C_{i,j,k}$ where i, j, k are the x, y, z position in the square unit cell of the top left node.

In VLC tracking, geographical coordinates are used to guide users through buildings and towards specific destinations. This is facilitated by employing cells for positioning and a Central Manager (CM) to manage the system and generate optimal routes. A mesh cellular hybrid structure is introduced to enhance network architecture, enabling direct device-to-device communication and secure pathways. Each WLED emits a unique VLC signal, serving as an identification beacon, allowing precise user trajectory determination. The indoor route, containing spatial and temporal data, provides valuable insights into user movements. Users personalize their points of interest for wayfinding services, and average speeds are assigned based on the device type. Information is transmitted to the appropriate receivers by emitters within the infrastructure, such as Light Traffic controllers or signboards, positioned at crosswalks. In Figure 2b, the edge/fog architecture and the request communications between the Devices (D2D), the Devices and the Infrastructures (D2I) or the responses from the Infrastructure to the Devices /pedestrians (I2D/P) is draft. The user positions can be represented as q (x, y, z, t) by providing the horizontal positions $(x,\ y)$ [13].

C. *Communication protocol, coding, and decoding techniques*

Data transmission in the VLC system follows a synchronous approach using a 64-bit data frame structure. Information is encoded using OOK modulation, with each luminaire containing WLEDs (RGBV), enabling simultaneous transmission of four signals. A PIN-PIN demultiplexer decodes the message based on calibrated amplitudes of RGBV signals. The communication protocol includes components like Start of Frame (SoF) for synchronization, Identification Blocks encoding communication type (COM) and localization (position, time), and other ID Blocks for additional identifiers, Traffic Message containing vehicle information, and End of Frame (EoF) indicating the end of transmission. This structured protocol ensures efficient encoding and decoding of critical movement information, maintaining synchronization and data integrity in the VLC system. In Table 1, the communication protocol is depicted. Decoding the information received from the photocurrent signal captured by the photodetector involves a critical step reliant on a pre-established calibration curve [14].

TABLE I. COMMUNICATION PROTOCOL.

	SoF	COM	Position		ID (device)		Time				payload				EoF
L2D	Sync	1	x	y	0 bits		END	Hour	Min	Sec					EOF
D2D	Sync	2	x	y	Lane (0–7)	Device. (nr)	END	Hour	Min	Sec	Device IDx	DeviceI Dy	nr behind		EOF
D2I	Sync	3	x	y	TL (0–15)	Device (nr).	END	Hour	Min	Sec	Device IDx	DeviceI Dy	nr behind		EOF
I2D	Sync	4	x	y	TL (0–15)	ID Device	END	Hour	Min	Sec	Device IDx	DeviceI Dy	nr behind		EOF
P2I	Sync	5	x	y	TL (0–15)	N,S, E,W	END	Hour	Min	Sec					EOF
I2P	Sync	6	x	y	TL (0–15)	Phase	END	Hour	Min	Sec					EOF

This curve meticulously maps each conceivable decoding level to a sequence of bits. Essentially, the calibration curve serves as a guide, facilitating the establishment of associations between photocurrent thresholds and specific bit sequences.

III. AIRPORT MODEL

The capacity of an airport is closely tied to its gateways, boarding areas, and aircraft door layouts. Assigning these areas involves a coordinated process, tailored to specific objectives and criteria for each scenario. Objectives may include enhancing customer service by minimizing travel distances for pedestrians or passenger/luggage carriers during landing, transit, baggage claim, terminal changes, or shopping.

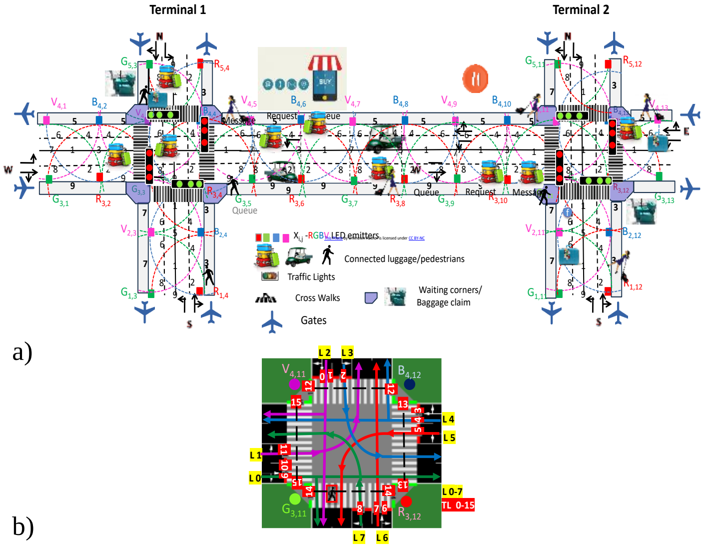

Figure 3. a) Simulated scenario and environment with the optical infrastructure (Xij), the generated footprints (1-9) and the connected luggage and pedestrians' flow. b) Schematic diagram of Terminal 2 with coded lanes (L/0-7) and traffic lights (TL/0-15)

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Airports are assessed based on factors like walking distances between terminal facilities and accessibility to ground transportation and parking. This research enhances our understanding of pedestrian behavior within terminal corridors, informing better decisions in terminal facility design. The airport model is generated using footprints of a multi-level airport collected from available sources and displayed on user receivers for orientation [15]. The simulated scenario includes two terminal intersections with four-way arms and moving lanes, along with sidewalks and areas for shopping, dining, or resting. Traffic management involves directing carriers along cardinal points using road request and response segments, exclusive passenger lanes, waiting areas, and crosswalks. Central traffic light systems controlled by a Central Manager regulate carrier flow and prevent collisions. Pedestrians on sidewalks have the freedom to move in both directions. It's a prerequisite that destinations can be targeted by user requests to the CM within a specific request distance (D/P2I) and any floor changes notified if applicable. The indoor route throughout the airport is communicated to the user via a responding message (message distance range; I2D/P) transmitted by the traffic signals, which also function as routers or mesh/cellular nodes (refer to Figure 2).

This request/response framework provides landmark-based instructions to help carriers identify decision points where a change of direction is necessary (action). Furthermore, it offers information to users to confirm that they are on the correct path. The Simulated scenario and environment with the optical infrastructure (X_{ij}), the generated footprints (1-9) and the connected luggage and pedestrians' flow are displayed in Figure 3a. In Figure 3b the schematic diagram of Terminal 2 with coded lanes (L/0-7) and traffic lights (TL/0-15) is draft.

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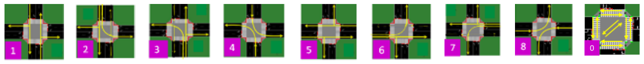
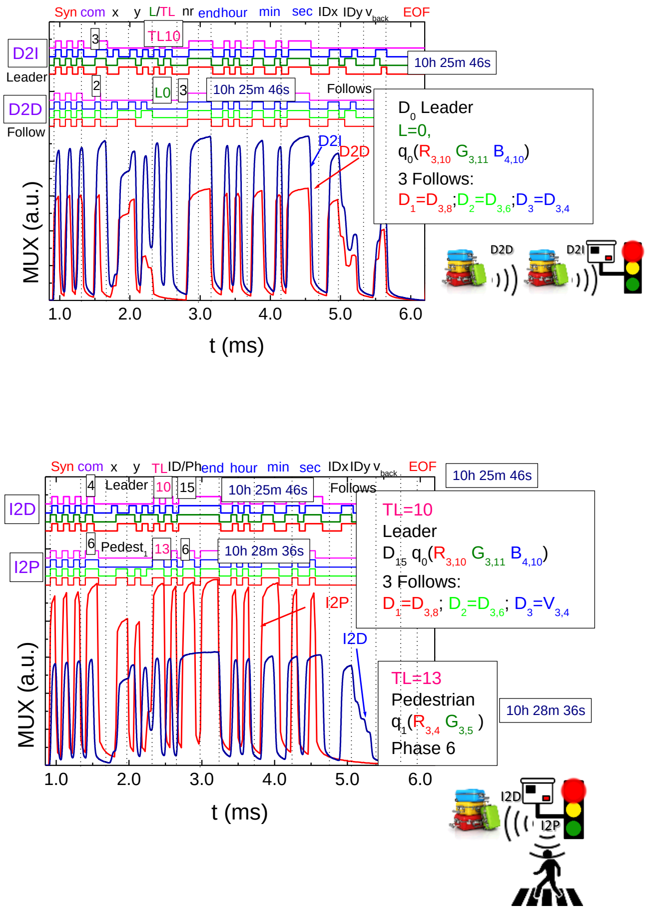


Figure 4. Schematic of a one cycle phase diagram with eight moving walkway phases and an exclusive pedestrian phase.

Figure 4 visually outlines intersection phase progressions (actions) within a structured cycle length, comprising eight AGV carrier phases in the lanes and an exclusive pedestrian phase for the walking passengers. Each phase is subdivided into discrete time sequences, providing a comprehensive temporal framework.

IV. RESULTS

In this section, the algorithms developed for guiding users through indoor spaces are described. Explanation of turn-by-turn directions, landmark highlighting, alerts, and alternate route suggestions are given. Figure 5a displays the decoded optical signals (at the top of the figures) and the signals received (MUX) by the receivers in a D2D (COM 2) and D2I (COM 3) communication scenario involving a leader device in the moving walkway at position ($R_{3,10}$, $G_{3,11}$, $B_{4,10,}$). This device is communicating with the CM at the second terminal (T2) on lane L0 (direction E) at 10:25:46 and is followed by three other devices (nr) D_1, D_2, and D_3 with the same direction, located at positions (IDx,y) $R_{3,8}$, $G_{3,6}$ and $R_{3,4}$, respectively.



a)

b)

Figure 5. MUX signal request (a) and responses (b) assigned to different types of V-VLC communication. On the top the decoded messages are displayed.

In Figure 5b, the responses (I2D and I2P) from two traffic lights (TL10 and TL13) to the crossing request from the preceding carrier d_o ($R_{3,10}$, $G_{3,11}$, $B_{4,10,}$) and a pedestrian q_1 located in the "waiting corner" of the first terminal ($R_{3,4}$, $G_{3,5}$) are exemplified. The timestamps "10:25:46" and "10:28:36" represent the times at which the two responses were sent respectively for the pedestrian (COM 6) and for the Passenger/luggage carrier (COM 4) and provide a reference point for when each response was generated.

Assessing the effectiveness of the proposed V-VLC system in multi-terminal airports utilizes the Simulation of Urban MObility (SUMO), employing agent-based simulations. SUMO serves as a powerful tool for optimizing traffic operations within airports, enhancing efficiency, safety, and passenger experience.

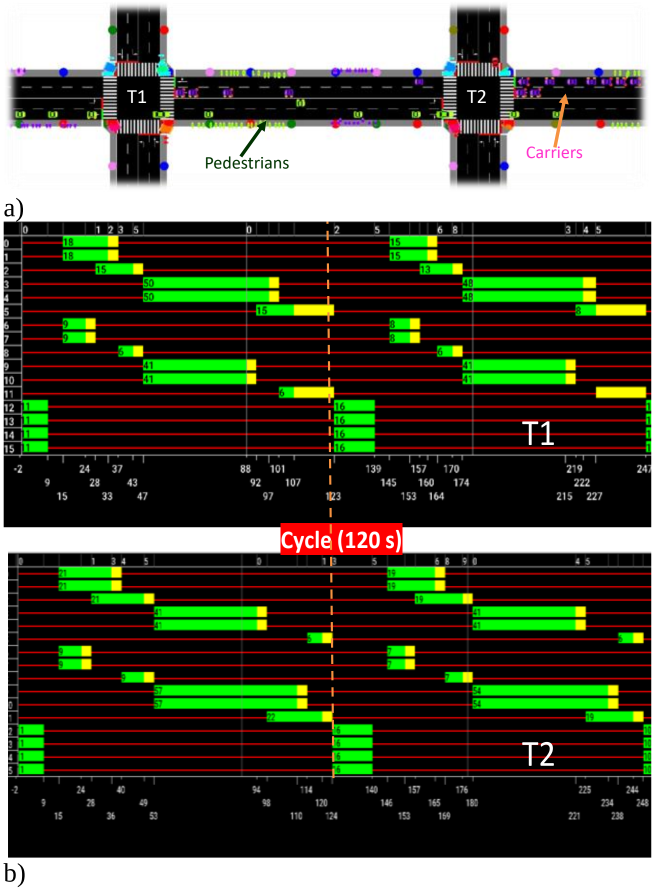


Figure 6. a) SUMO environment. b) State phasing diagram.

SUMO simulates vehicles, pedestrians, and entities in the airport environment, adjusting parameters like traffic density and road layouts. It tests traffic control algorithms, manages intersections, and oversees pedestrian crossings, mirroring real-world airport conditions.

Moreover, SUMO’s API supports interaction with external programs, enabling the extraction of diverse traffic flow statistics. State and phase diagrams within SUMO offer insights into traffic signal dynamics and movements within the terminals. The simulation operates on an agent-based system, where agents accumulate experience to navigate traffic situations effectively. They control Traffic Lights (TL) based on decisions aimed at optimizing traffic flow, whether in walkway lanes or sidewalks [16][17].

For data analysis, SUMO collects and analyzes simulation data, including vehicle trajectories, travel times, congestion levels, and pedestrian movements. Visualization capabilities aid in analysis and decision-making, while SUMO's API supports interaction with external programs for diverse traffic flow statistics. Gate assignment approaches for aircraft movement are outlined, aiming to minimize pedestrian walking distances or maximize passenger throughput. Traffic scenarios with varying cycle durations and carrier flows were considered, integrating pedestrian flows to reflect realistic scenarios.

Two potential approaches to gate assignment for aircraft movement, including landings and takeoffs, are outlined: The first approach involves a low carrier flow, accommodating 1800 carriers per hour. Assumptions include a carrier velocity of 9 km/h, primarily moving from east and west directions. The primary objective is to minimize the total pedestrian walking distance inside the terminal. The second approach adopts a high carrier flow, accommodating 2300 carriers per hour at the same velocity. Here, the aim is to maximize the number of passengers served by gates. Both scenarios maintain a consistent pedestrian flow of 11200 per hour. Within these flows, it is expected that 20% of passengers/luggage carriers will turn (remain in the same terminal), while 75% will continue straight (change terminal).

In the airport context, two traffic scenarios were evaluated. The first scenario, termed the High traffic scenario, has cycle duration of 120 seconds and is capable of dispatching 2300 carriers per hour. The second scenario, with a cycle duration of 88 seconds, dispatches 1800 carriers per hour. In Figure 6 the high traffic scenario State phasing diagram. illustrated.

For each terminal, pedestrian flows were simulated with 7200 pedestrians at Terminal T1 and 4000 pedestrians at Terminal T2. Pedestrians were introduced exclusively on the N and S roads in both directions, starting at various distances from the intersection. This setup aims to replicate a more realistic scenario where pedestrians originate from different points, reflecting varied starting positions and paths within the airport environment.

These diagrams offer insights into the dynamic behavior of traffic light signals and carrier/pedestrian movements within the simulated terminals. As can be observed in the diagrams, it is possible to distinguish the different cycles that occur during the simulation. It always begins with a pedestrian phase (Phase 0), during which some individuals can cross the crosswalk, turning red for pedestrians starting from 11 seconds. Then, phases dedicated to carriers (Phases 1-8) take place until it concludes at 123 seconds. At this moment, the second cycle begins, with the pedestrian phase becoming active again. The same process repeats until 247 seconds, marking the end of this second cycle and the initiation of a third cycle. These diagrams align with the analysis conducted for pedestrians.

V. CONCLUSIONS AND FUTURE WORK

Utilizing VLC signals offers a promising solution for enhancing indoor navigation in multi-terminal airports. Integrating VLC with existing lighting infrastructure and traffic control algorithms significantly improves pedestrian and carrier traffic management. By optimizing traffic flow, minimizing pedestrian walking distances, and providing real-time guidance, VLC-based systems enhance accessibility and efficiency in airport environments.

This study developed a two-terminal airport model based on Edge/Fog architecture, established communication protocols, and tested VLC algorithms. These algorithms effectively transmit encoded messages, enabling accurate localization and positioning, and reliable communication between traffic signals and user devices. Real-time guidance provides turn-by-turn directions, highlights landmarks, and suggests alternate routes, thus improving traffic flow management and operational efficiency.

SUMO simulations offer valuable insights into pedestrian behavior and traffic dynamics, revealing the impact of traffic flow, road length, and cycle durations on pedestrian movement. This comprehensive analysis underscores the potential of VLC-based systems in optimizing airport navigation and enhancing overall user experience.

While this study has demonstrated the potential of VLC-based systems for improving indoor navigation and traffic management in multi-terminal airports, several areas warrant further investigation and development:

- Future research should focus on scaling the VLC system to accommodate larger and more complex airport environments. This includes adapting the system to varying architectural designs and passenger volumes to ensure consistent performance.
- Investigating the integration of VLC with other emerging technologies such as 5G, IoT devices, and advanced AI algorithms could further enhance the system’s capabilities. Combining these technologies could improve data processing speeds, accuracy, and overall system intelligence.

By addressing these areas, future work can build on the current findings to develop more robust, efficient, and user-friendly VLC-based navigation and traffic management systems for airports.

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 and by IPL project reference IPL/IDI&CA2024/NUTRAMISEL.

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] K. Panta and J. Armstrong, “Indoor localisation using white LEDs,” Electron. Lett. 48(4), pp. 228–230, 2012.

[3] T. Komiyama, K. Kobayashi, K. Watanabe, T. Ohkubo, and Y. Kurihara, “Study of visible light communication system using RGB LED lights,” in Proceedings of SICE Annual Conference, IEEE, pp. 1926–1928, 2011.

[4] Y. Wang, N. Chi, J. Yu, and H. Shang, “Demonstration of 575-Mb/s downlink and 225-Mb/s uplink bi-directional SCM-WDM visible light communication using RGB LED and phosphor-based LED,” Opt. Express 21(1), pp.1203–1208, 2013.

[5] 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.

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

[7] E. Monteiro and S. Hranilovic, “Constellation design for color-shift keying using interior point methods,” in Proc. IEEE Globecom Workshops, Dec., pp.1224–1228, 2012.

[8] M. Vieira et al., “Three Transducers Embedded into One Single SiC Photodetector: LSP Direct Image Sensor, Optical Amplifier and Demux Device” Advances in Photodiodes in Tech, Chap.19, pp. 403-425, 2011.

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

[10] 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.

[11] S T. Komine and M. Nakagawa, “Fundamental analysis for visible-light communication system using led lights,” Consumer Electronics, IEEE Transactions on, vol. 50, no. 1, pp. 100–107, 2004.

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

[13] M. A. Vieira, G. Galvão, M. Vieira, P. Louro, M. Vestias, P. Vieira, “Enhancing Urban Intersection Efficiency: Visible Light Communication and Learning-Based Control for Traffic Signal Optimization and Vehicle Management.” Symmetry 2024, 16, 240. https://doi.org/10.3390/ sym16020240.

[14] M. Vieira, M. A. Vieira, P. Louro, A. Fantoni, P. Vieira, "Dynamic VLC navigation system in Crowded Buildings", International Journal on Advances in Software, vol. 14 no. 3&4, pp. pp. 141-150, 2021.

[15] M. Vieira, M. A. Vieira, P. Vieira, and P. Louro “Enhancing Building Guidance: A Visible Light Communication-based Identifier (ID) System,” Sensors & Transducers Journal, vol. 263, issue 4, pp. 74-81, December 2023.

[16] M. Vieira, M. A. Vieira, P. Louro, A. Fantoni, and P. Vieira, “A System for Indoor Guidance Using Visible Light Communication” International Journal on Advances in Networks and Services, vol. 15 no. 3 & 4, year 2022, ISSN: 1942-2644, pp.35-45, December 31, 2022.

[17] M. Vieira, M. A. Vieira, G. Galvão, P. Louro, P. Vieira, and A. Fantoni, "Enhancing Indoor Navigation in Multi-Terminal Airports through Visible Light Communication Signals," Proc. SPIE 12999, Optical Sensing and Detection VIII, 129991N, June 2024.