Mobility of Autonomous Guided Vehicles Supported by Visible Light Communication

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***Abstract*— This paper explores Autonomous Guided Vehicles (AGV) mobility in dense industrial environments, utilizing Visible Light Communication (VLC) technology for data transmission between infrastructures and vehicles, establishing X2X links. Tetrachromatic white Light Emitting Diodes (LEDs) and dedicated pinpin photodiodes facilitate simultaneous lighting and data transmission, while VLC-based indoor positioning enables guidance services with tailored coding schemes for each link. By analyzing AGV flow regulation within warehouse lanes similar to urban traffic flow, an urban mobility simulator generates movement data. A dynamic model integrating VLC queuing/request/response behaviors, efficiently schedules routes, ensuring optimal travel and avoiding congestion. The proof-of-concept is demonstrated through evaluations of travel time and traffic flows.**

Keywords- Visible Light Communication; positioning; guidance system; mobility; autonomous guided vehicle.

I. INTRODUCTION

Autonomous Guided Vehicles (AGVs) are driverless carts widely utilized in industrial and distribution settings for material movement [1]. AGVs streamline operations across various industries, enhancing inventory management, production flexibility, and staff efficiency. They facilitate data-driven analytics, predictive maintenance, and reliability improvement. Originally used in manufacturing, AGVs now serve diverse industrial applications including warehouse logistics and container terminal operations [2]. Some AGVs feature robotic arms or serve as collaborative robots (cobots), extending their functionality to tasks like picking and assembly AGVs are prominent in automotive, logistics, e-commerce, food, pharmaceuticals, and more [3].

The rapid adoption of Autonomous Guided Vehicles (AGVs) in industrial environments has increased the need for efficient and reliable communication systems. While traditional wireless technologies such as Wi-Fi and Radio Frequency (RF) are widely used, they face challenges in dense industrial settings due to signal interference, limited bandwidth, and security vulnerabilities. Visible Light Communication (VLC) presents a promising alternative, offering high-speed data transmission with minimal interference and enhanced security [4]. However, there is limited research on integrating VLC into AGV systems, particularly in highly congested environments where signal reliability and uninterrupted communication are crucial for operational efficiency. This research aims to address this gap by exploring the potential of VLC to optimize AGV mobility and coordination in dense industrial environments, providing a novel approach to improving communication reliability and overall system performance [5].

VLC technology [6] enhances AGV collaboration in dense industrial environments by providing accurate indoor positioning and mapping. LED light sources are modulated to encode data, offering advantages like high-speed transmission, immunity to electromagnetic interference, and enhanced security. The dense deployment of VLC transmitters makes it ideal for indoor localization and navigation [6][7].

This paper discusses the integrated movement of AGVs performing tasks in indoor environments. AGV fleet management treats their movements similar to vehicular traffic, controlled by intelligent agents based on congestion conditions [8][9]. Vehicular communication relies on visible links, facilitating Lamp-to-Vehicle (L2V), Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Infrastructure-to-Vehicle (I2V) channels [10].

In this work, VLC technology is employed to create an indoor positioning system with additional communication capabilities. The system includes a pinpin heterostructure a:SiC:H device for photodetection of optical signals emitted by white trichromatic RGB LEDs. The photodetector [11][12], which is based on a-SiC:H/a-Si:H heterostructures, operates in the visible spectrum. It features active filtering and amplification properties, as well as selective sensitivity, designed to be wavelength-sensitive [14][15]. When different visible signals are encoded along the same optical transmission path, the device multiplexes these optical channels, performs various filtering processes (such as amplification, switching, and wavelength conversion), and outputs a multiplexed signal. Decoding this signal allows for the recovery of the modulated signal transmitted by each emitter [13].

The proposed system is modelled using the Simulation of Urban Mobility (SUMO) [14], with a dynamic algorithm effectively scheduling AGV routes [15][16]. Simulation experiments validate the method's efficiency in travel and congestion avoidance, as demonstrated in [15], that uses a similar methodology to optimize urban intersections by integrating VLC localization services with learning-based traffic signal control.

The indoor localization system combines optical wireless communication, computer algorithms, smart sensors, and an optical sources network, constituting a collaborative cyber-physical system approach.

The paper is organized as follows. Section I includes the paper introduction with related work. Section II outlines the VLC system specifications, including details on the transmitter and receiver, indoor positioning and guidance-based services and VLC protocols. In Section III, the experimental scenarios are described, along with a presentation and discussion of the obtained results. Finally, Section IV concludes the paper and offers guidelines for future work.

II. ARCHITECTURE OF THE VLC SYSTEM

The communication network uses four different VLC Channels ensuring communication Lamp-to-Vehicle (L2V), Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Infrastructure-to-Vehicle (I2V), as illustrated in Figure 1.

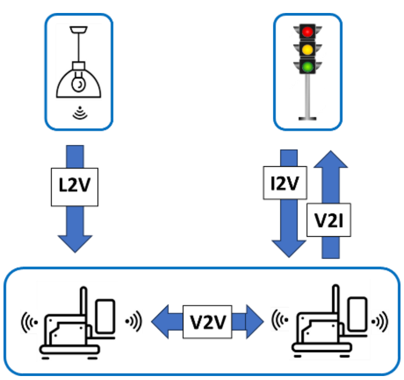

Figure 1. Communication channels established using visible signals.

A. VLC Transmitter and Receiver

The VLC system utilizes tetra-chromatic white LEDs, with each LED containing independently controllable red, green, and blue emitters. This configuration enables the creation of distinct data transmission channels by controlling each emitter separately. A single L2V transmitter comprises four LEDs arranged in a square formation, with only one emitter from each LED utilized for transmission. In V2V and V2I communication, only a single LED emitter is used. These tetra-chromatic LEDs emit distinct wavelengths in the red (620 nm), green (530 nm), blue (470 nm), and violet (405 nm) bands. These LEDs meet illumination standards, making them suitable for lighting and communication. Their effective channel separation and wide coverage area make them ideal for communication applications.

The VLC receiver features pinpin photodiodes with a-SiC:H/a-Si:H heterostructures, optimized for modulated wavelengths from RGB LEDs in the visible range. Its sensitivity is influenced by external optical bias, favoring short wavelengths under back violet background illumination and longer wavelengths under front illumination. The device acts as both a short-pass filter for back illumination and a long-pass filter for front illumination, with tuning options for short, medium, and long spectral regions. Front illumination enhances the red spectrum, while back illumination boosts the blue signal.

B. Indoor positioning and guidance based services

Indoor positioning with VLC uses L2V communication, where LEDs in ceiling lamps are arranged in a square configuration, defining unit navigation cells. Each cell is divided into footprints, assigned to different optical excitations. Figure 2 depicts the L2V transmitter configuration, unit navigation cell, and corresponding footprints. Footprint regions (#1, #2, ..., #9) correspond to optical excitations shown in Figure 2. Matrix notation identifies each emitter in the VLC transmitter network, transmitting data to determine navigation cell positions.

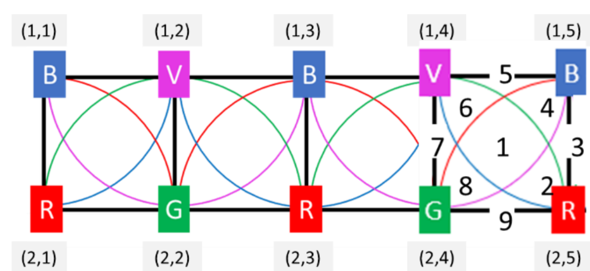

Figure 2. Square configuration of VLC transmitters of the L2V link showing the unit navigation cell and footprints inside the unit navigation cell.

Each L2V VLC transmitter uniquely identifies its position within the indoor space, defining navigation cells. Within each cell, resolution is enhanced by measuring optical patterns, resulting in 9 distinct regions. Vehicle guidance along lanes and directional changes are facilitated by transmitting respective directions via the I2V link.

C. VLC Protocols

Data transmission requires a specific modulation scheme. We use On-Off Keying (OOK), valued for its simplicity in VLC systems. In OOK modulation, the presence of a signal is represented by one level (usually the "on" state), while the absence of a signal is represented by another level (usually

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the "off" state). In other words, the carrier signal is switched on and off to represent digital data.

The communication protocol, outlined in Table I, controls information exchange, including synchronization, identification, and payload sections within each transmitted frame. The frame structure is systematic and standardized, with variations based on the type of communication (1-4: 1-L2V, 2-V2V, 3-V2I, 4-I2V). Each frame is 64 bits long, featuring specific blocks at the beginning and end to support synchronization of successive data frames.

TABLE I - CODIFICATION PROTOCOLS.

L2V	SYNC	1	x	y	END	h	m	s	Payload							EOF
V2V	SYNC	2	x	y	Lane (0-7)	#AVG	END	h	m	s	x'	y'	#N	Payload		EOF
V2I	SYNC	3	x	y	TL (0-15)	#AVG	END	h	m	s	x'	y'	#N	Payload		EOF
I2V	SYNC	4	x	y	TL (0-15)	ID-AVG	END	h	m	s	x'	y'	#N	phase	Payload	EOF

The data frame consists of modular blocks, each comprising 4 bits, except for SYNC and timeline-related blocks (h-hour, m-minute, s-second), which use 5 bits each. Each VLC link's coding begins and ends with SoH and EOF blocks ([10101] and [0000], respectively), ensuring synchronization. The transmitter's position is coded as x and y in matrixial notation, while timeline details are coded as {END, h, m, s} ([111] for END). Other codes include Lane, TL, #AGV, x' and y', ID-AVG, and #N, facilitating effective encoding and decoding of AGV movement information. This protocol guarantees synchronization and data integrity in VLC communication.

At the receiver, the photodetector generates a multiplexed signal based on input optical signals. With the VLC transmitter's 4 independent emitters, the output signals can combine one to four optical excitations, yielding 16 photocurrent levels. Bit decoding corresponds to assigning each photocurrent level to the respective optical excitation, achieved through previous system calibration to adjust photocurrent levels.

III. RESULTS AND DISCUSSION

A. AGV Traffic Scenario

Inside the warehouse, AGVs navigate corridors to pick up goods from predefined aisles. AGV flow is determined by assigned routes and stop times for aisle operations. AGVs adhere to right-hand traffic rules, using right lanes for forward and right turns, and left lanes exclusively for left turns. Tasks begin at the charging station, with AGVs following their routes until reaching the packaging station. AGVs can start operations from the packaging station while charging, upon receiving new collection instructions. The simulated scenario, depicted in Figure 3, comprises multi-intersections with two 4-way intersections having 2 lanes per arm.

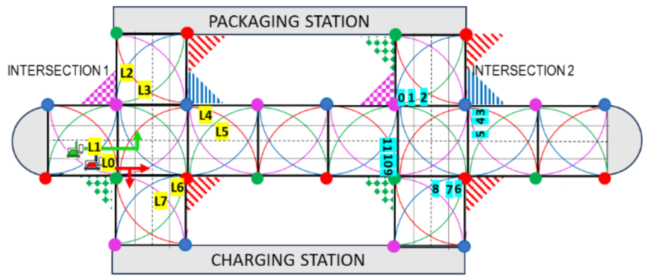

Figure 3. Lanes and aisles inside the warehouse.

Central traffic light systems, managed by Central Managers (CMs), control traffic flow. Four traffic flows along cardinal points are considered, with binary choices (turn left/straight or turn right) in road request and response segments. In intersection 1, even lanes (L0, L2, L4, L6) enable right turns or forward movements, while odd lanes allow left turns. Unit navigation cells defined by optical transmitters in the L2V channel are depicted along corridors, along with respective footprints. Each intersection has three traffic lights for possible movements (forward, turn left/right) in the convergent lane, totalling 12 traffic lights per intersection (TL0, TL1, …, TL11). Intersection 2 displays corresponding traffic lights, regulating flows from north to south (TL0, TL1, TL2), east to west (TL3, TL4, TL5), south to north (TL6, TL7, TL8), and west to east (TL9, TL10, TL11). Traffic lights are ordered by turns, with lower orders for right turns (TL0, TL3, TL6, TL9), higher for left turns (TL2, TL5, TL8, TL11), and intermediate for forward movements (TL1, TL4, TL7, TL10).

B. VLC signals

Using the described spatial layout, optical communication was simulated with multiple AGVs moving eastward along lane L0, as depicted in Figure 4. The foremost AGV in the lane, located at position $R_{3,10}$ (x and y in matrix notation), communicates with the intersection agent via V2I communication. It transmits a request for forward movement at the intersection and communicates the number and positions of trailing AGVs (AVG1, AVG2, and AVG3), occupying positions $R_{3,8}$, $R_{3,6}$, and $R_{3,4}$ simultaneously.

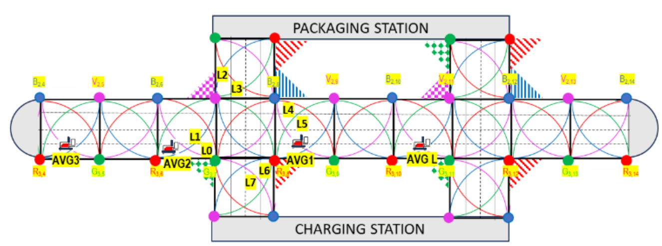

Figure 4. Simulation scenario.

Using the communication protocol defined in Table I, the VLC system was configured to establish data transmission from each link. The optical signals measured at the receivers of links V2I and V2V are displayed in Figure 5. The transmitted optical signals from each transmitter are represented on the top of the figure.

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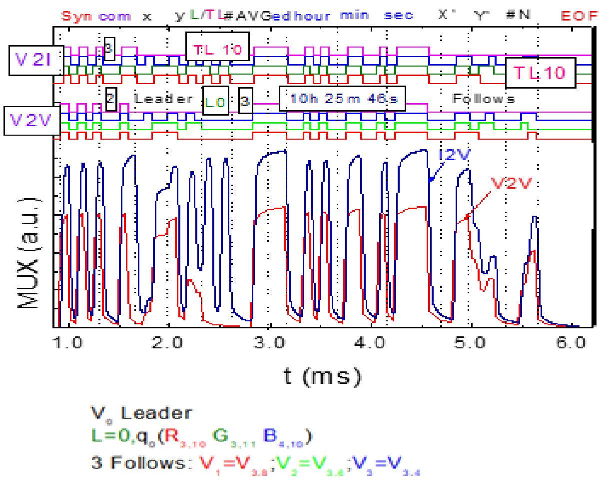

Figure 5. Experimental data acquired by the receiver of the V2V and V2I VLC links.

In the I2V link, the leading AGV transmits a bit sequence following the protocol in Table I. The receiver detects different signal levels, each corresponding to a specific input combination. Decoding these levels using appropriate calibration signals allows recovery of the input optical signals. The frame begins with synchronization bits, followed by communication type (3 for V2I), position ($R_{3,10}$, $G_{3,11}$,$B_{4,10}$), intersection movement request (TL = 10 for forward movement), communication time (10:25:46), number of AGVs behind in the lane (3), and their coordinates: (3,8) for AVG1, (3,6) for AVG2, and (3,4) for AVG3, transmitted by red, green, and blue transmitters. In the V2V link, the leading AGV transmits synchronization bits, communication type (2 for V2V), position ($R_{3,10}$, $G_{3,11}$,$B_{4,10}$),movement lane (L = 0 for forward or right turn), communication time (10:25:46), number of AGVs behind in the same lane (3), and their coordinates: (3,8) for AVG1, (3,6) for AVG2, and (3,4) for AVG3.

Figure 6 displays the optical signals acquired by the receiver of the I2V VLC link at the second intersection. The transmitted optical signals from each transmitter are represented on the top of the figure.

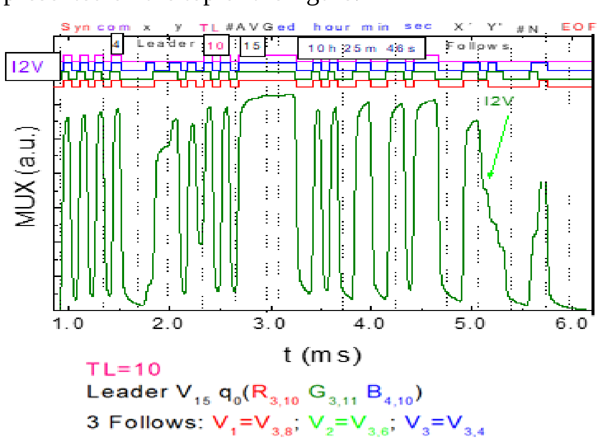

Figure 6. Experimental data acquired by the receiver of the I2V VLC link located at intersection #2.

In this communication, the block after the synchronization bits, define an I2V communication (ID=4), followed by the identification of the corresponding traffic light (TL=10), the identification of the leading AGV (15 in this case), the communication time and the number of leading AGV's followers (3), and respective coordinates: (3,8), (3,6) and (3,4). This is in accordance with the information transmitted by the AVG L.

C. Dynamic Traffic Model

AGV flow dynamics were assessed using SUMO, an open-source traffic simulation package for large networks. The simulation configured the scenario previously described and evaluated average speed and halting over a fixed period (one hour). Figure 7 and Figure 8 compare the average speeds and halting trends over time for low and high traffic AGV scenarios, assuming flows of 1800 and 2300 AGVs per hour, respectively.

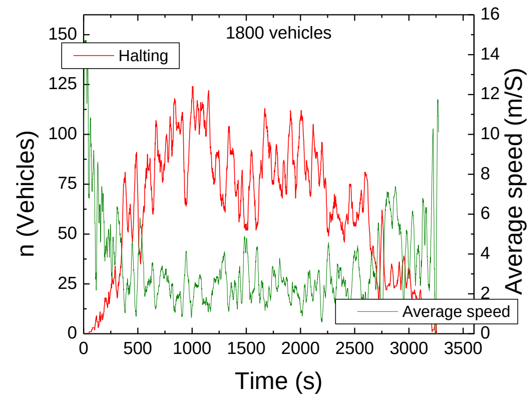

Figure 7. Average speed and halting in low traffic AGV scenario, 1800 AGV/hour.

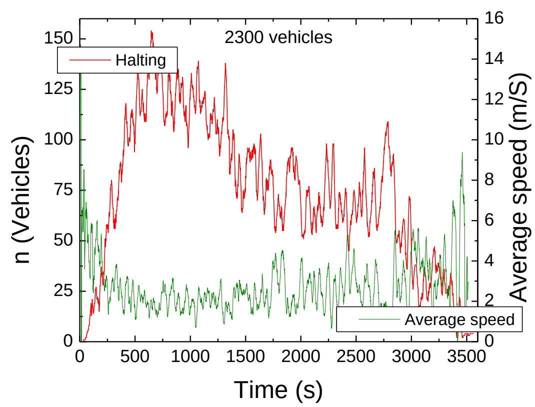

Figure 8. Average speed and halting in high traffic AGV scenario, 2300 AGV/hour.

Data from Figure 7 and Figure 8 show an initial spike in speed at the start of halting simulations, gradually decreasing as the simulation progresses. This acceleration is due to fewer AGVs at intersections, allowing faster movement. However, as more AGVs enter the system, average speed notably drops until the end of the simulation. As AGVs empty out, remaining ones have more space, leading to increased speed due to reduced congestion. Higher waiting AGV volumes correspond to decreased speed, while lower volumes result in increased speed, aligning with traffic dynamics expectations. The proof-of-concept evaluations demonstrated the feasibility of the approach using key metrics like travel time and traffic flow. However, these preliminary results were not tested for statistical significance. Future work will include larger-scale experiments to ensure statistical validation.

IV. CONCLUSIONS

The proposed application monitors and manages AGV movement in an optimized warehouse for material collection and transport. VLC links facilitate AGV flow, reducing congestion and waiting times. Various coding protocols were defined for VLC links, with experimental data obtained for V2V, V2I, and I2V links. Using the SUMO simulator, the same scenario was analyzed as urban traffic flow, considering low and high flows to simulate average speed and halting trends over a period. Results can predict traffic actions, prevent congestion, and reduce travel time, enhancing collection and transportation efficiency.

The paper presents a proof-of-concept of the use of Visible Light Communication (VLC) in combination with AGV (Automated Guided Vehicle) mobility The practical implementation of such a system in a real industrial environment might pose significant challenges, which must be addressed in future work, namely, scalability, cost, and potential obstacles to real-world deployment.

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