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Automated Guidance Vehicles Controlled by Visible Light Communication

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Abstract: The advent of devices with wireless communication capabilities has generated increased interest in indoor navigation. Several wireless technologies have been proposed for indoor location, as the traditional Global Positioning System has a poor performance in a closed space. This research proposes the use of an indoor localization system based on Visible Light Communication (VLC) to support guidance and operational tasks of Autonomous Guided Vehicles (AVG). The research is focused on the development of the guidance VLC system, transmission of control data information and decoding techniques. Trichromatic white LEDs are used as transmitters and photodiodes with selective spectral sensitivity are used as receivers. The downlink channel establishes an infrastructure-to-vehicle link (I2V) and provides position information to the vehicle. The decoding strategy is based on accurate calibration of the output signal. Characterization of the transmitters and receivers, description of the coding schemes and the use of different modulations will be discussed.

Keywords: Visible light communication, Autonomous guides vehicle, Indoor positioning, Guidance, On Off keying, Manchester.

1. Introduction

Automated guidance vehicles (AGV) are mobile robots powered by electricity that operate independently [1]. The navigation of the AGV can follow a fixed route or a free ranging route. AGVs are now found in all types of industries, with the only restrictions on their use mainly resulting from the dimensions of the goods to be transported or spatial considerations [2].

Several technologies can be used to provide guidance to the AGVs, ranging from magnetic, optical or radio-based technologies. Visible Light Communication (VLC) is an optical wireless communication technology operating in the visible range of the spectrum, that provides several advantages, such as, license-free spectrum, high-speed, immunity to electromagnetic radiation and security, among others [3, 4].

VLC can be implemented using phosphor coated blue LEDs and red-green-blue (RGB) LEDs. RGB LEDs provide higher speed, as their operation is not dependent on the slow decay of the phosphor. Besides, they allow the use of the three wavelengths to transmit different data streams simultaneously. VLC provides several applications ranging from short (a few meters) to medium range (few meters to few kilometers) distances, which includes data transmission for Short range IoT, Smart Homes, Light Fidelity, Under Water communication, Vehicular Networking, among others [5].

As it can be used in localization applications, in this paper we propose the use of an AGV guidance system based on Visible Light Communication (VLC) able to provide information on the current position of the vehicle and enable it to navigate autonomously. VLC [6].

This system uses white tetrachromatic LEDs operating as optical signal transmitters and a-SiC:H pinpin heterostructure as receivers [7-9]. These photodetector devices exhibit active filtering, amplification, and selective sensitivity [10, 11] in the visible range. Different visible wavelength signals are encoded in the same optical transmission path, so the device multiplexes the different optical channels, performs filtering processes (amplification, switching, and wavelength conversion), and outputs a multiplexed signal [12, 13] The modulated signal transmitted by each emitter can be recovered by decoding this signal [14, 15]. For a reliable calibration curve, each photocurrent level must be accurately regulated [16, 17]. To decode the multiplexed signal, we will use On-Off keying modulation and Manchester codes [18]. This system is intended for indoor positioning and guidance of autonomous guided vehicles (AGV) used to transfer materials from pickup places to drop off places [19] inside an automated warehouse. The system attends bidirectional communication with links Infrastructure-to-Vehicle (I2V) and Vehicle-to-Infrastructure (V2I). The link I2V provides an indoor localization information inside the warehouse enabling navigation services [20]. Operational information for operation inside the warehouse is also transmitted to the AGVs. The links V2I and V2V provide cooperation services to enhance system performance [21-23].

The indoor localization system involves optical wireless communication, computer-based algorithms, smart sensors, and optical sources network, which constitutes a transdisciplinary approach framed in cyber-physical systems.

This paper is an extension of work originally presented in the 9th International Conference on Sensors and Electronic Instrumentation Advances (SEIA' 2023) [24] that provided preliminary results of AGV guidance supported by VLC.

2. VLC System Description

This work describes the use of VLC for positioning and guidance in indoors environments based on VLC to be used for navigation of AGVs in automated warehouses. Based on VLC technology, the AGV and the infrastructure can establish bidirectional communication using two separate channels (Fig. 1), the uplink (vehicle to infrastructure or V2I) and the downlink (infrastructure to vehicle or I2V). Additional links can be established among the vehicles (vehicle to vehicle or V2V). This paper deals with the I2V channel.

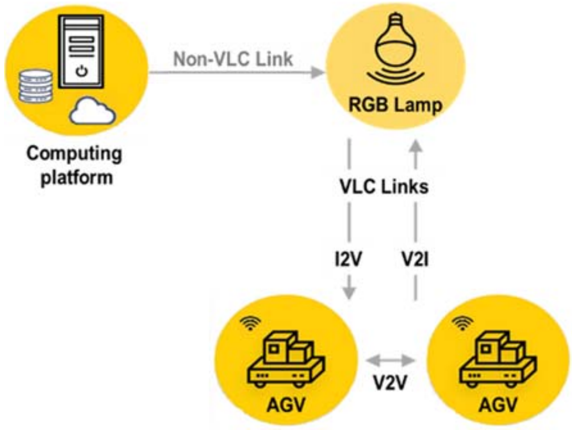


Fig. 1. Communication channels.

Lighting and communication are provided simultaneously by the infrastructure through optical emitters based on tetra-chromatic LED white lamps at the warehouse ceiling.

2.1. VLC Transmitter

The VLC transmitter uses commercial RGB LEDs provide three different wavelengths, centered on the red, green, and blue bands (620 nm, 530 nm and 470 nm) with standard linewidths (ranging from 24 nm to 38 nm), high luminous intensity (in the range from 340 mcd up to 980 mcd) and wide half intensity angle (120 º). Along the indoors space, LED bulbs provide simultaneous lighting and communication, defining navigation cells (Fig. 2).

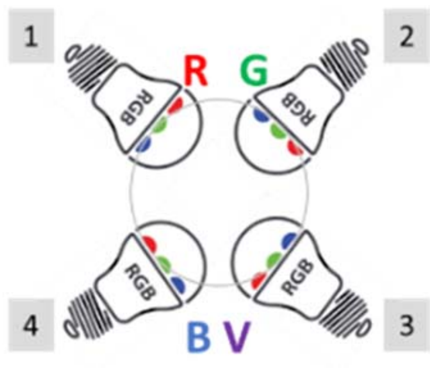


Fig. 2. VLC transmitters.

Each VLC transmitter defines a unit navigation cell containing the optical signals transmitted by each communication channel.

2.2. VLC Channel

The VLC channel was modeled using Lambertian beam distributions for each LED assuming line-of-sight conditions. Fig. 3 illustrates a 2D representation of the coverage signal due to four transmitters positioned in squares. The map representation is normalized to the maximum intensity at the center, after evaluating the delivered optical power in dBm. There is a strong signal at the center of the region because all four emitters contribute to it. Only three emitters contribute to the signal at the corners, while only two emitters contribute to the signal at the sides. As a result, the received signals inside the unit navigation cell determine the spatial coverage of the VLC transmitter, which allows for more accurate positioning within this delimited area. Each of these regions constitute the footprints of the cell and are labelled from #1 to #9 as indicated in Fig. 3.

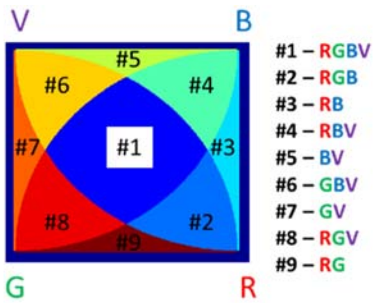


Fig. 3. Coverage produced by the VLC transmitter and footprints enabled by each emitter's signals.

2.3. VLC Photodetector

The VLC receiver used in the VLC system is a photodiode composed of a pinpin heterostructure based on a-SiC:H/a-Si:H. In the receiver unit, the photodetector is a pin-pin heterostructure based on a-SiC:H/a-Si:H [25] Since its design was tailored to address a wavelength sensitive device in the visible spectrum, it exhibits active filtering and amplification properties as well as selective sensitivity. In this photodiode, two a-Si:H pins are mounted on top of one a-SiC:H pin, which allows the device to be used over the full visible spectrum. The device is operated under reverse bias to improve collection efficiency. Steady state optical bias using short visible wavelength (400 nm) is used to improve amplification of the longer wavelengths and attenuation of the short ones.

The spectral sensitivity of the sensing photodiode shows that under back violet background illumination the gain is high at short wavelengths (blue light) and decreases for longer wavelengths (green and red). The device behaves as a short-pass filter. Under front violet background light, the device works as a long-pass filter for wavelengths above 500 nm, blocking the shorter wavelengths. The shift of the irradiation device side (front/back) allows tuning the short- and long-spectral regions, while the medium region (475 nm – 530 nm) can only be tuned by using both active filters. Under front illumination the red part of the spectrum is enhanced while under back illumination the main enhancement occurs for the blue signal (Fig. 4).

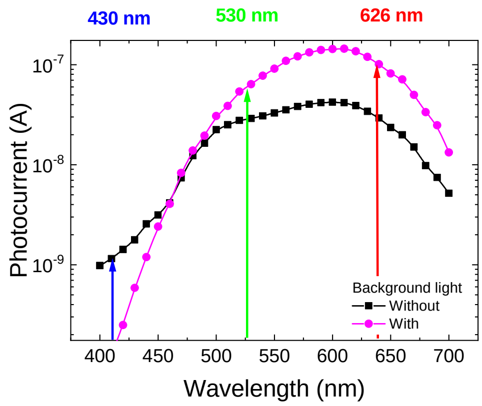


Fig. 4. Spectral sensitivity of the VLC receiver.

In this photodiode, two a-Si:H pins are mounted on top of one a-SiC:H pin, which allows the device to be used over the full visible spectrum. The device is operated under reverse bias to improve collection efficiency. Steady state optical bias using short visible wavelength (400 nm) is used to improve amplification of the longer wavelengths and attenuation of the short ones.

2.4. VLC Data Coding

Specific data codes are needed to define the communication link and the type of message to be transmitted. In every channel, it was used synchronous transmission based on a data frame of fixed length.

Synchronization of the frames can be enabled using different approaches. The SoT is placed at the beginning of the frame and the EoT at the end. Then a TYPE block with 4 bits is used to define the type of message (0000 in request/acknowledge mode, 0011 in standard/update mode). The complete structure of the data frame has the format displayed in Fig. 5.

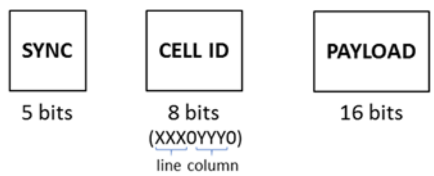


Fig. 5. Data frame structure of the VLC communication channel.

The block labelled GEO-LOCATION (16 bits) identifies the cell and footprint. The cell identification is coded as XXX0YYY0, where XXX addresses the line and YYY the column of the cell. The footprint is produced by coding the R and B emitters with four bits set to 1 and four bits set to 0, while the R' and B' emitters are coded with two bits set to 1 and two bits set to 0, and then two bits set to 1 and two bits set to 0. The 36 bits MESSAGE block addresses specific instructions transmitted to the user and dependent on the type of communication mode.

2.5. VLC Data Modulation

Data transmission demands the use of a specific modulation scheme. Here we will use both OOK and Manchester. While OOK is a valuable modulation scheme in VLC due to its low complexity and ease of implementation, it still severely limits data rates, which is further strengthened by systems that use different dimming levels.

An evaluation of OOK and Manchester coding VLC modulation techniques with differing levels of complexity is presented in this paper. OOK assigns different levels of amplitude to each of the data bits we wish to modulate, with a bit time duration of bit. Manchester assigns both levels to each bit, one per bit time duration bit, but it is the transitions from on to off ("on-off") or off to on ("off-on") that distinguish between '0' and '1' data bits.

In this paper the Manchester codes use the convention of considering "off-on" transitions as '0's and "on-off" transitions as '1's. The representation under OOK and Manchester modulations is shown in Fig. 6.

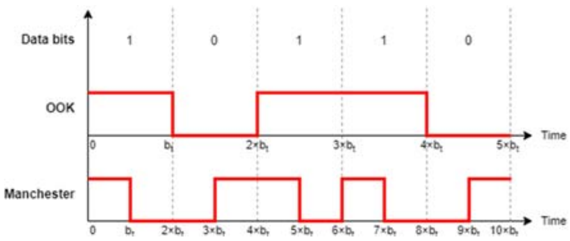


Fig. 6. Time domain representation of data bits in OOK and Manchester.

Data transmission in Manchester is halved since it takes twice as long to transmit the "on" or "off" pulses that encode the same information as in OOK. In contrast, Manchester forces at least one level transition per bit of data, leading to lower levels permanence, even in long sequences of the same bit.

2.6. Decoding approach of the VLC signal

With each optical emitter data transmission, a multiplexed signal is produced at the photodetector. Due to the VLC transmitter's four independent emitters, the out-put optical signals can combine one, two, three, or four optical excitations. If the driving currents for each emitter are adjusted correctly, this can produce 16 different optical combinations and therefore 16 different photocurrent levels.

The bit decoding of the multiplexed signal corresponds to the correct assignment of each photo-current level to the respective optical excitation. This is provided using a previous system calibration, by adjusting the photocurrent levels of the multiplexed signal.

The on-off states of the calibration signal and respective label of each photocurrent level are summarized in Table 1.

Table 1. On-off states of the calibration signal and respective levels.

	R	G	B	V
d0	Off	Off	Off	Off
d1	Off	Off	Off	On
d2	Off	Off	On	Off
d3	Off	Off	On	On
d4	Off	On	Off	Off
d5	Off	On	Off	On
d6	Off	On	On	Off
d7	Off	On	On	On
d8	On	Off	Off	Off
d9	On	Off	Off	On
d10	On	Off	On	Off
d11	On	Off	On	On
d12	On	On	Off	Off
d13	On	On	Off	On
d14	On	On	On	Off
d15	On	On	On	On

The coding of the calibration signal using either OOK or Manchester is summarized, respectively, in Table 2 and Table 3, where the '0' state for the off states and '1' for the on states of the LED. In the Manchester coding each on or off state is represented using two bits.

Table 2. Decoding levels in OOK calibration curves.

	R	G	B	V
d0	0	0	0	0
d1	0	0	0	1
d2	0	0	1	0
d3	0	0	1	1
d4	0	1	0	0
d5	0	1	0	1
d6	0	1	1	0
d7	0	1	1	1
d8	1	0	0	0
d9	1	0	0	1
d10	1	0	1	0
d11	1	0	1	1
d12	1	1	0	0
d13	1	1	0	1
d14	1	1	1	0
d15	1	1	1	1

Since Manchester codes demand the double of the bits to encode the same information, each 'on' or 'off' state of the LED produces two adjacent photocurrent levels.

Table 3. Decoding levels in Manchester calibration curves.

		R	G	B	V
d0	d15	01	01	01	01
d1	d14	01	01	01	10
d2	d13	01	01	10	01
d3	d12	01	01	10	10
d4	d11	01	10	01	01
d5	d10	01	10	01	10
d6	d9	01	10	10	01
d7	d8	01	10	10	10
d8	d7	10	01	01	01
d9	d6	10	01	01	10
d10	d5	10	01	10	01
d11	d4	10	01	10	10
d12	d3	10	10	01	01
d13	d2	10	10	01	10
d14	d1	10	10	10	01
d15	d0	10	10	10	10

Fig. 7 shows the calibration signal with 16 levels assigned to each input optical state. The optical signal transmitted by each emitter is displayed on top of the picture. The multiplexed signal is shown under OOK and Manchester modulations.

In OOK modulation (Fig. 7(a), the set of 16 distinct calibration levels produce a staircase-like shape in the MUX signal, each associated with a particular optical excitation type. The left side of Fig. 7(a) indicates the correspondence of the optical state RGBV and the level label (d_i, i = 0, 1, …, 15) using binary notation. When using Manchester codes (Fig. 7b), the same data bit sequence takes twice as long as OOK, which halves the data rate. The calibration curve takes on a very different shape. This occurs because of how Manchester uses 2 bits to represent each data bit, leading to the calibration curve having a shape of two alternating OOK calibration curves with one rising branch and the other falling branch.

3. Results and Discussion

An illustration of the proposed study involving the comparison of both modulations and the results obtained using the described methodology is included in this section.

3.1. Case Study

The case study used in this work the AGVs can move in a linear warehouse configuration with racks on either side of the aisle for picking up materials, as displayed in Fig. 8. A matrix notation that specifies the row and column of the navigation cells is used to number the cells. The AGV at the initial position (position 1) is directed to move to an intermediate position (position 2) and then to the destination (position 3).

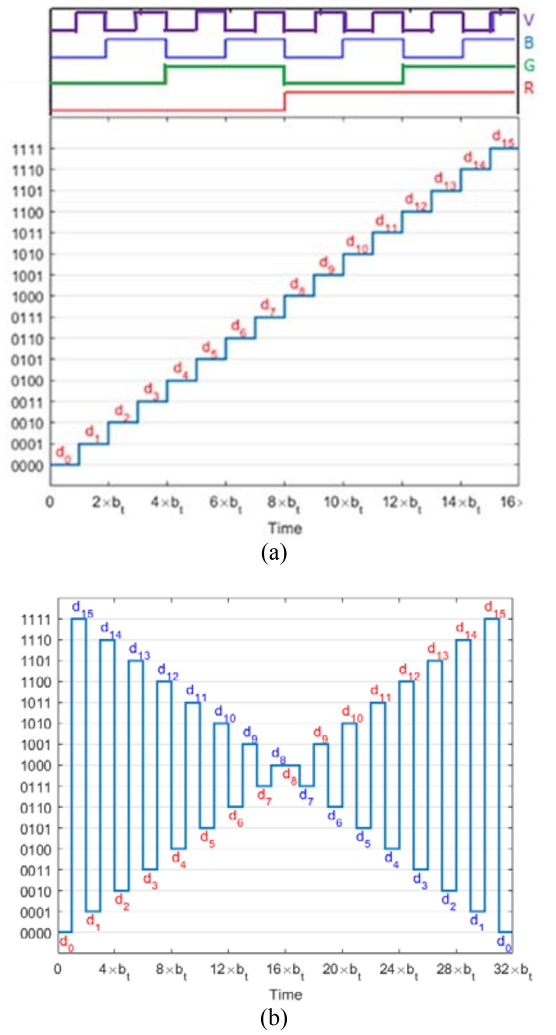


Fig. 7. Layout of the warehouse space including VLC transmitters and AGV successive positions (initial, intermediate and destination).

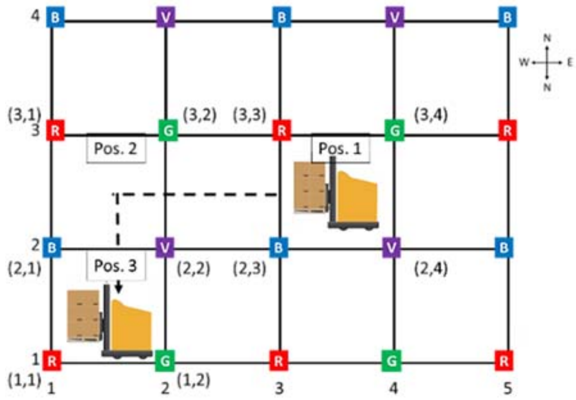
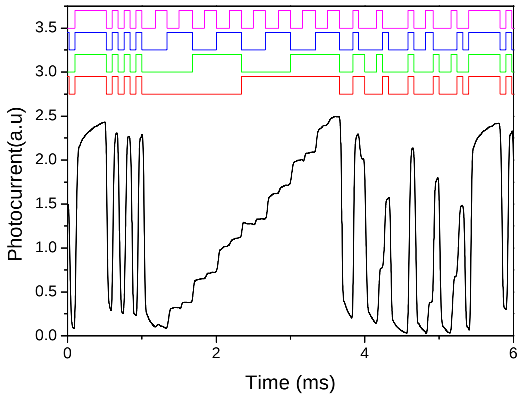


Fig. 8. Layout of the warehouse space including VLC transmitters and AGV successive positions (initial, intermediate and destination).

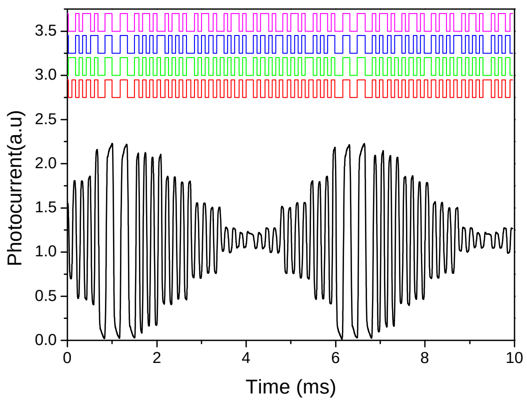
As the AGV moves, it establishes V2I communication. Even so, this paper will not address it, since its focus is on the analysis of the I2V multiplexed signal.

3.2. VLC Signal

In Fig. 9 it is displayed the photocurrent signal measured inside footprint #1 (region covered by the four optical signals RGBV) at position 1 using the OOK and Manchester modulations. The blocks SoH and EoT provide the necessary synchronization between frames.



(a)



(b)

Fig. 9. Transmitted data message at the intermediate position (2) using the modulation: a) OOK; b) Manchester.

Both measurements show that the presence of these blocks leads to maximum values of the photocurrent, since all emitters are on simultaneously. According to the photocurrent levels obtained in each signal, the optical excitation level is dependent on the footprint region, which hosts the AGV, as well as the bit sequence transmitted by the active emitters.

The output resultant signal acquired by the receiver device shows different levels of photocurrent that can be assigned to the correspondent optical excitation. As the device exhibits capacitive effects, the photocurrent level exhibits a rising or falling slope, dependent whether the transition occurs from a lower to an upper level, or vice-versa. Consequently, this effect becomes more evident when two or more adjacent bits have the same state.

In OOK modulation as the bit states are simply represented by '0's or '1's, it is possible that the signal contains many similar adjacent symbols ('1s' or '0s'), which reinforce this effect. It is clear from Fig. 9(a) that, for example, the upper levels achieved by every single 'on' bit are lower than those obtained by two adjacent 'on' bits. This may induce errors in the bit decoding process.

When using Manchester coding, Fig. 9(b) each state is represented with a transition between different states. Therefore, no more of two similar bits occur during the transmission and the limitations imposed by the capacitive effects of the sensing device are attenuated.

On the other hand, frame synchronization that is established by the heading block transmitted in the beginning of each frame is crucial to ensure correct data transmission. As this block is composed of a sequence of 5 specific states (‘on’-‘off’-‘on’-‘off’-‘on’) followed by the identification labels of the transmitting cells, the correct identification of the block among the transmitted frames is not a hard issue to complete successfully.

Nevertheless, under Manchester coding a level transition is less likely to coincide with the start of a frame due to the halved data rate, or even with the start of a data bit since a transition is forced to occur in the middle of each data bit.

The decoding strategy involves direct comparison of the signal levels with the calibration signal is achieved by assigning the bit level to the level closest to the calibration signal. Bits represented by close values may be improperly decoded. This is especially important when using OOK modulation, since capacitive effects can mislead the decoded level, whereas Manchester modulation minimizes this problem. Parity check bits are a possible solution to reduce the bit error decoding.

4. Conclusions

The proposed application focuses on the use of VLC based system to support the guidance of AGV. The physical layer of the communication system was fully characterized, from transmitters and receivers to the propagation channel modelling and data coding. Two modulation techniques, OOK and Manchester, were used to infer bit decoding performance. As the multiplexed signal results from multiple optical channels, its waveform is complex. It is necessary to use decoding techniques to determine the correct bits transmitted by each optical channel. Improvements to the decoding technique include parity check error control.

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