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Ph.D. THESIS SUMMARY

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COMUNICAŢII OPTICE ÎN SPECTRUL VIZIBIL

OPTICAL COMMUNICATIONS IN THE VISIBLE SPECTRUM

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Chapter 1

Introduction

1.1 Presentation of the field of the doctoral thesis

More and more wireless optical communication systems (OWC) [5] have been proposed in the literature in recent years. These systems are based on the optical spectrum, using visible light, infrared or ultraviolet light as the transmission medium. The reader can find more information in the scientific paper [23].

The technologies that are part of OWC are Visible Light Communication (VLC), Optical Camera Communications (OCC), Free Space Optical Communication (FSOC), Light Detection and Ranging (LiDAR) and Light Fidelity (LiFi).

The VLC technology uses LEDs as transmitters and photodetectors or image sensors [33, 2, 10] as receivers [6]. The data is transferred by changing the light intensity of the LEDs fast enough so that the human eye does not perceive their flicker. The advantages of this type of communication include the use of energy more efficiently, it is not harmful to the environment and the human body, has a wide bandwidth and is more secure. The disadvantage is that it requires a line-of-sight clearance and field-of-view alignment between the receiver and the transmitter. The VLC can be used in aviation, where media services can be provided to passengers, besides illumination, in hospitals, where the radio waves [9] cannot be used due to the interference that may occur with the medical equipment, in indoor localization systems [14, 30], where a moving object can be localized in real-time [28, 13] using an LED signal and an up-facing camera, in smart displays, where the various timetables can be displayed, in public places where advertisement light panels can be used to provide information to the user's smartphone via video camera [4], in museums, where the light used for exhibits can also transmit identifying information to be scanned by visitors' smartphones.

An important field in which the VLC has a rapid and important development is the automotive field, being integrated into the applications of the intelligent transport system (ITS) [3]. The ITS is divided into vehicle-to-vehicle (V2V) [31] and vehicle-to-infrastructure (V2I) systems. In V2V, the vehicle's taillights and headlights can transmit various information to other vehicles and transmit positioning signals [7], thus increasing safety, giving the car more environmental data than it would have only through its architecture's sensors/video cameras. In the V2I scenario, road traffic safety can be enhanced through the communication between the car and the traffic signalling system. As a widespread application of the two systems, in case of traffic congestion, the ITS system can adapt the traffic lights to ease the traffic.

The VLC is a technology that is easy to integrate with the transmission system but is complicated to be developed for the general public due to specialized receivers (photodetectors) or high-performance receivers (video recording cameras that capture many frames/s) [26]. In newer applications, there is a tendency to replace photodetectors with image sensors, which have the advantage of simultaneously receiving data from multiple LEDs. The available solutions use as receivers video cameras with a high number of frames/s, which operate at 1000 frames/s [11, 27], being very expensive. A cost-effective solution is to use a camera with a low number of frames/s, but current solutions require synchronization between transmitter and receiver [12].

1.2 Scope of the doctoral thesis

The purpose of the doctoral thesis is meant to contribute to increase the performance of optical communication systems by optimizing them using communication codes appropriate to the particularities of the transmission channel. It also investigates the use of recording cameras with a low number of frames/s, the degradation of the received signal in a visible spectrum communication, the key elements of infrastructure-vehicle communication, and presents the preliminary results of the use of visible spectrum communication for communication with road signalling infrastructure, together with the performance analysis of a varied set of low-cost video cameras that can guarantee a stable communication.

1.3 Content of the doctoral thesis

The thesis is structured as follows: Chapter 2 presents the procedure used to find the most appropriate measurement method for determining with high accuracy the photometric parameters for a white LED and investigates the degradation of the received signal in VLC communication. Chapter 3 studies the optical communication systems in the visible spectrum, discusses their limitations, followed by the personal contributions made in the field. The thesis ends with Chapter 4, which presents the general conclusions, the concrete personal contributions brought to the field, and finally, perspectives for the future.

Chapter 2

Optoelectronic devices and components usable in VLC

2.1 Transmitters

In optoelectronics, the signal carrying the information is a photon beam. The optoelectronic emitting devices convert the electricity into light radiation.

2.1.1 LED structure and application types

The semiconductor materials are the basis of electronic components and circuits. In terms of structure, the $p-n$ junction has two adjacent regions, n and p. The border or the imaginary line between the two regions is called a metallurgical junction [8]. Under thermal equilibrium conditions, the electron concentration is high in the n region and low in the p region. The hole concentration has an opposite profile in the two adjacent regions. The regions where the charge carriers recombine will be emptied of electrons and holes on both sides of the metallurgical junction. Thus, an area with a positive charge will appear on the n side of the metallurgical junction. Similarly, it happens on the p side of the metallurgical junction, where a negative area appears [1].

An LED, on the other hand, is a semiconductor diode. It consists of a chip of semiconductor material treated to create a structure called a $p-n$ junction, electrical contacts and a case. When the LED is connected to a power source, current flows from the p side or anode to the n side or cathode, but not in the reverse direction. When the minority charge carriers recombine radiatively with majority charge carriers, photons are emitted. This is the basic process of generating light in semiconductors. Depending on the semiconductor material used in the light-emitting layer, the wavelength of the emitted light can be anywhere in the range from visible to infrared. LEDs composed of a combination of InGaAsP and InP cover wavelengths from the band 1300 to 1550 nm and are those used in fiber optic communication systems [34].

2.1.2 Modulation types used in VLC

The most notable difference between the VLC system and the radio frequency (RF) system is that in VLC, the data cannot be encoded in the phase or amplitude of the light signal. This means that phase and amplitude modulation techniques cannot be applied in VLC [25]. The main methods that can be used to modulate data in the visible light spectrum are: On-Off Keying (OOK), Pulse Width Modulation (PWM), Pulse Position Modulation (PPM), Variable Pulse Position Modulation (VPPM), Color Shift Keying (CSK) and Orthogonal Frequency Division Multiplex (OFDM).

In OOK modulation, data bits "1" and "0" are transmitted by repeatedly turning the LED off and on. In PWM modulation, the encoded information is transmitted in the duration of a pulse. For PPM modulation, data is encoded using the pulse position in a frame. The VPPM modulation is a hybrid between PPM modulation and PWM modulation. The bits are encoded by choosing a different pulse position, as in the case of PPM modulation, and the pulse width can also be changed as needed. The CSK modulation can be used if the lighting system uses RGB LEDs. By combining different colors of light, the output data can be carried by the same color, and thus the output intensity can be constant. The OFDM modulation uses a set of sub-carriers, each at different frequencies but harmoniously related [25, 9, 32].

2.2 Receivers

The optoelectronic receiving devices are electronic devices based on the absorption of light radiation, converting it into an electrical signal.

2.2.1 Photodiode

Photodiodes are optical radiation sensors and are made based on semiconductors. Photodiodes generate current or voltage when the $p-n$ semiconductor junction is irradiated. Unlike the usual p-n junctions, the photodiode junctions have a very thin upper $p-layer$. Its thickness is imposed by the wavelength of the radiation to be detected. Usually, the $p-layer$ of the Si photodiode is formed by the selective diffusion of boron to a thickness of about 1 μm or less. By controlling the thickness of the $p-layer$, the $n-type$ substrate and the $n+$ lower layer, and the doping concentration, the spectral response and the response rate can be controlled.

2.2.2 Image sensor

Image sensors, although present in a wide range, perform a common function, namely, the conversion of the flow of light that enters through the lens into an electrical signal. In terms of structure, the image sensor consists of a microlens, color filter, photodiode and an analog-to-digital converter. These components allow us to further classify the sensors in several ways, such as the type of structure, the type of shutter, or by resolution, frame rate, pixel size or sensor format.

Core technologies

A first classification is their type, where CCD ("Charged Coupled Devices") and CMOS ("Complementary Metal-Oxide Semiconductor") are the most used sensors. CMOS is used mainly in cameras made on an industrial scale (mobile terminals, cameras, etc.) and CCD in analog cameras. The *CCD* sensor is an image transducer made in the form of a rectangular surface, organized in the form of an array, containing cells that can store electrical charges proportional to the intensity and duration of light radiation. The *CMOS* sensor is a widespread transducer that features general-purpose technology. In the case of this sensor, the circuit of a pixel also contains transistors for reading/amplification, besides the photodiode.

Image sensor format

Image sensors come in different types of formats and packages. The resolution and size of the pixels dictate the total size of a sensor, where larger sensors have higher resolutions or larger pixel sizes than smaller sensors.

The CMOS sensor is of particular interest in VLC because the time to capture a frame starts when the first row is reset and ends when the last row is read. During this period, the LED light turns on and off, leading to the appearance of light and dark bands that can be used to represent bits 0 and 1 on the image.

2.3 Contributions to determine the photometric parameters for a white LED

The following section presents the experiments performed to determine the most suitable measurement mode to increase the accuracy of determining the photometric parameters for a white LED using a light meter with multiple measurement modes for different classic light sources such as tungsten (incandescent), fluorescent, mercury (mercury) and sodium (sodium) based. The reader can find more information in the scientific paper [18].

Light meters are used to measure illuminance, which is a photometric parameter. Nowadays, many light meters can contain multiple calibration curves for typical light sources, but not for LEDs, especially for white ones. The starting point for the experiment is the investigation of the emission spectra for the sources that most light meters can accurately measure. Thus, we developed a test assembly to study the white LEDs, consisting of the investigated LED, a darkroom and a Lutron YK-2005LX light meter. OSRAM produces all the LEDs that were analyzed, LED1 being OSLON SSL 1503, LED2 LCW CR7P.EC, LED3 LCW CRDP.EC and LED4 LCW CRDP.PC.

Two measurements were made, one using the Coherent LabMax-Top Laser Power and Energy Meter and another using the already mentioned light meter. The purpose of this experiment was to determine the emission spectrum for each LED. The LCW CRDP.PC LED can be considered a "cold" white LED because the power ratio between the peak value for blue and the peak value for orange–red is greater than or almost equal to 1, while for LCW CR7P.EC and CRDP.EC same ratio is less than 1, which means that the last LEDs can be considered "warm" white. SSL 150 has the characteristics of a "neutral" white LED. By comparing the measured emission spectra of the tested LEDs with the emission spectra of the four classic light sources, it can be observed that the "cold" white LEDs are most similar to a sodium-based source and the "warm" white LEDs have properties of radiation similar to that of incandescent sources. The comparison was made by evaluating the measured values using the light meter in which the four predetermined measurement modes associated with the classical light sources were selected in turn. The decision regarding the recommended measurement mode for a white LED was made based on the experimental values. It can be concluded that the most suitable measurement mode for investigating "cold" white LEDs is the one corresponding to a sodium source, while "warm" white LEDs should be studied using the tungsten preset.

2.4 Contributions to the response time and bandwidth of the LED

Current research topics include the study of available bandwidth for VLC, with increased importance in determining the signal transfer rate and user multiplexing. Currently, there is no standard method for determining the bandwidth in VLC applications, such as developing an infrastructure-vehicle communications system. In this type of scenario, the transmitted waveform consists of a series of rectangular current pulses. Of interest is the observation of possible waveform distortions due to the LEDs and the receiver.

Next, we study the bandwidth that could be used for VLC by determining the rise time by measuring the response time of four different types of LEDs: white, infrared, red and green. The reader can find more information in the scientific paper [17]. The LED driver circuit was specially designed for this application due to the need for a very fast start-up time. Of great importance is investigating the received signal's rise time compared to the rise time of the current applied to the LEDs.

We developed a test bench that simulates a small-scale VLC communication system to simultaneously visualize the sent and received signals. The test bench consists of one of the power LEDs produced by Led Engin (LZ4-00G108 for the green LED, LZ4-00R308 for the red LED, LZ4-00R708 for the infrared LED and LZ9- 00CW00 for white LED), an adjustable power supply, a relay, a set of resistors, a button, a high-speed InGaAs detector (DET410) and an oscilloscope (Rigol DS1074Z Plus).

The measurement operation is performed as follows: the LED for testing is selected and connected to the electrical circuit. Then the voltage source is set to zero or the lowest possible value. The relay is switched on, and the voltage is adjusted until the desired current value is obtained. After this setting, the relay is turned off, and the oscilloscope is set to acquire a single sequence. The relay is switched on immediately. This will result in the acquisition of two waveforms: one for the current pulse and the second for the received pulse. Thus, their rise time can be directly compared.

The four LEDs were investigated at four different pulse currents: 300 mA, 400 mA, 600 mA and 800 mA. Measurements were made for all four LEDs, one for each value of the current pulse. Ten measurements of the rise time were performed under the same conditions and then mediated to obtain the result for a single current value. The obtained results are graphically illustrated for easier comparison in Figure 2.19.

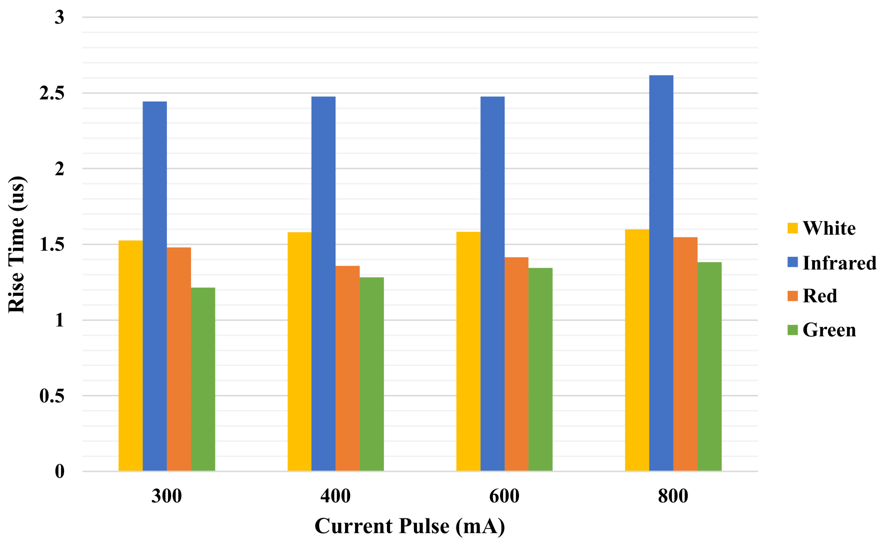


Fig. 2.19 The rise time of the received signal as a function of the current pulse applied to the transmitter LED [17].

The bandwidth was subsequently calculated using the relation $f_{BW} = 0,35/t_{RT}$, where f_{BW} is the bandwidth and t_{RT} is measured rise time. The highest available bandwidth was determined for the green LED, while the lowest was for the infrared LED. It has been observed that applications targeting car traffic control systems have a slight advantage over ambient lighting systems, as the bandwidth determined for the red and green LEDs was higher than for the white LED.

2.5 Conclusions

Optoelectronics is the field of science and technology in which photon beams are used to process information. The optoelectronic emitting devices convert the electricity into light radiation. The optoelectronic receiving devices are electronic devices based on the absorption of light radiation, converting it into an electrical signal.

Most modern light meters have several measurement modes designed for each of the four classic light sources, but none for LEDs, especially white ones. This section describes the procedure used to determine the most appropriate measurement method for determining the illumination of a white LED, depending on its type. For the "cold" and "neutral" white LEDs, the sodium preset is suitable for use, while for the "warm" white LEDs, the tungsten mode is recommended.

The VLC communication system consists of a transmitter (LED) and a receiver (photoreceptor). In this architecture, one of the key elements is the bandwidth of the communication, its study having increased importance for determining the signal transfer speed and the multiplexing of the users. In the case of a scenario in which the transmitted waveform consists of a series of rectangular current pulses, it is interesting to observe possible waveform distortions due to the LED and the receiver. For their determination, the bandwidth of the LEDs and their response time was studied.

Chapter 3

Optical communications systems in the visible spectrum

A VLC system consists of a transmitter and a receiver. An essential design requirement for the VLC system is that the lighting is not affected by communication [25].

3.1 Problems of optical communication systems

Although VLC has some advantages, as the visible light spectrum is not regulated and the use of LED is easier to implement in current lighting solutions, is more energy-efficient, and does not create electromagnetic interference, the communication faces many challenges [24].

Affordability is essential when designing VLC communication for regular use. Thus, a balance must be found between performance and cost. Line of sight is also a challenge for VLC systems - inside, the user is assumed to be within line of sight of the transmitter, so the illumination will often be provided by the reflection or refraction from the lampshades or from other objects that reflect light. A significant challenge in VLC is flickering, which is any fluctuation in brightness perceptible to humans, creating discomfort and health risks. For this reason, changes in light intensity must occur at a faster rate than the human eye can perceive. While light dimming control is an essential feature in many places for comfort or energy-saving, it can affect the communication range and the data communication range. Synchronization is a challenge that needs to be addressed in the code. The receiver should automatically synchronize with the transmitter at any moment in time by receiving only the communication code. The ISO noise (light sensitivity) is also a challenge for VLC, as it is one of the most common types of image noise, manifesting itself as a random variation in brightness.

3.2 The proposed optical receiver system

Technological progress allows autonomous vehicles to benefit from wireless connections between cars or between cars and infrastructure. The VLC technology can use existing headlights and taillights in cars. This chapter investigates the key elements of infrastructure-vehicle communication and presents preliminary results of the use of VLC communication in the implementation of an infrastructure-vehicle system for communication with the road signalling infrastructure. The reader can find more information in the scientific paper [19].

3.2.1 The description of the communication system

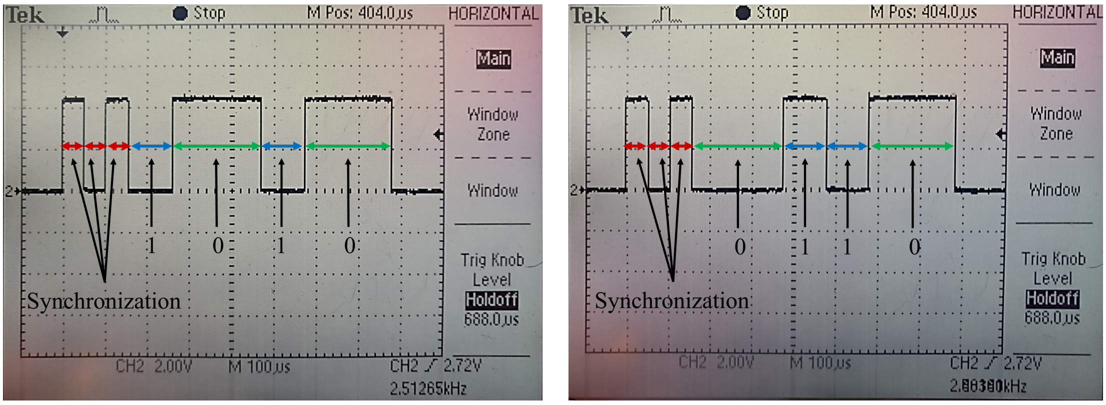
The infrastructure-vehicle system made by replacing the optical sources with LEDs in the same spectral range as the initial sources

The role of the proposed system is to obtain automatic braking if the traffic light is red and an audio warning inside the vehicle in the case of yellow. The communication system can be implemented by completely replacing the lamp-based traffic light system with an integral LED-based system. This approach is advantageous due to the low maintenance.

The proposed communication system consists of two modules, namely the transmitting and the receiving system, respectively. The emission module is mounted on the traffic light and transmits one code for the red light and another code for the yellow light. The transmission is made by modulating the voltage applied to the radiant element (LED). The code is chosen to prevent flickering. The second module, the receiving module, is mounted on the vehicle and is used to receive and decode the code sent by the transmission module using an optical receiver. It is checked if the received message corresponds to one of the codes, and if it corresponds to the code for the red color, the vehicle will brake automatically, while for the yellow color, an audio warning will alert the driver that the traffic light will turn red. If neither of these two codes is received, then no action is taken.

The code consists of synchronization pulses, pulses for logic "0", pulses for logic "1". Thus, a code word consists of three synchronization pulses and four other pulses, representing the four bits that carry the information about the light that is currently on. The three synchronization pulses were chosen for accurate synchronization, with a low probability that all three synchronization pulses could be obtained accidentally. Four pulses corresponding to the bits were chosen to end the code in logic "0".

The code is based on the duration between consecutive edges, as illustrated in Figure 3.2. The duration between two consecutive edges is, in the case of the synchronization pulse of 50 μs, in the case of the pulse for the logic "0" of 200 μs, and in the case of the pulse for the logic "1" of 100 μs. On emission, the module consists of a development board that transmits the code "1010" by modulating the red light and the



(a) (b)

Fig. 3.2 The waveform of the codes: (a) ”1010” (red), (b) ”0110” (yellow) [19].

code "0110" by modulating the yellow light. The duration of each word of code is 750 µs, and the maximum duration of the code, when sending the word "0000", is 950 µs. The receiving module consists of an optical receiver that captures the light from the traffic lights, converts it into voltage and, depending on the decoded code, sends the car’s brake command or the transmission of an audio warning.

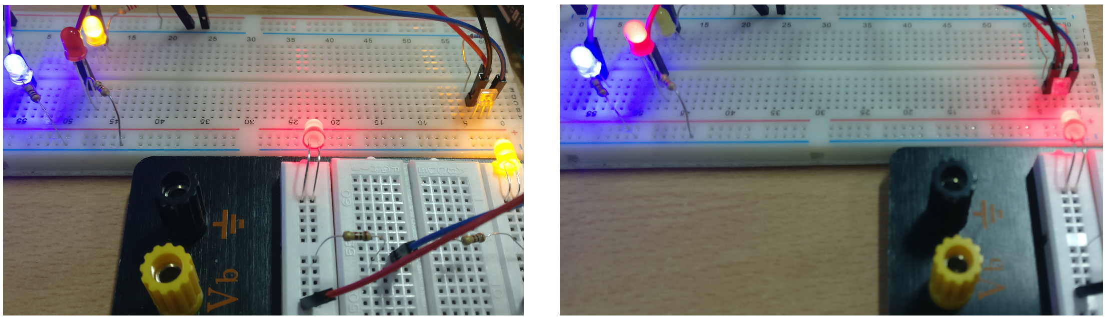
The system made by adding an optical transmitter equipped with an infrared LED for the transmission of information

In a secondary, incremental approach, the communication system can be implemented by adapting current lamp-based systems by adding an additional element of radiation. This approach does not require high costs, and only one element needs to be added to the emission module. Thus, the traffic light system will have a fourth element consisting of an infrared transmitter used to send either the code for red or the code for yellow, depending on the active color of the traffic light. The reception module remains unchanged (see Section 3.2.1).

3.2.2 The experimental system, results and discussions

The infrastructure-vehicle system made by replacing the optical sources with LEDs in the same spectral range as the initial sources

In terms of implementation, the communication system was developed as a prototype on a test board. The emission module consists of a red LED, a yellow LED, and a microcontroller, while the receiving module consists of an optical receiver (TSL14S), a red LED, a yellow LED, a blue LED and a microcontroller. The signal from the output of the optical receiver is applied to the microcontroller on a pin configured as a digital input pin for which an interrupt has been set to trigger the signal logic level change. Thus, the microcontroller measures the time elapsed between two consecutive interrupts corresponding to the signal's two consecutive logic level changes. After each measurement, the duration is compared with a set of stored values representing the duration of the emission pulses at which tolerance was taken into account.



(a) (b)

Fig. 3.4 Mode of operation of the system: (a) the yellow light code ("0110") is transmitted, (b) the red light code ("1010") is transmitted [19].

In Figure 3.4a, the microcontroller modulates the voltage applied to the yellow LED with the waveform for the code "0110", and the optical receiver receives the code from the light emitted by the LED, and if the message has been decoded correctly and corresponds to the code used for the yellow light, the yellow LED who plays the role of the audio warning lights up. A supplementary blue LED is used to determine if the receiving module is powered. In Figure 3.4b, the procedure is repeated for the red LED, using the code "1010". In real situations, the receiver could be blinded by ambient light during the day or by flashlights at night. These situations were investigated under small scale conditions. An optical filter is placed in front of the receiver to solve this problem. All experiments were performed using low power LEDs to highlight only the principles.

The system made by adding an optical transmitter equipped with an infrared LED for the transmission of information

In the case of the second approach, the emission module consists of an infrared LED and a microcontroller, while the reception module consists of an optical receiver (TSL14S), a red LED, a yellow LED, and a blue LED and a microcontroller. The signal from the optical receiver output is applied similarly to the first approach (see Section 3.2.2). The microcontroller modulates the voltage applied to infrared LED with the waveform for the code "0110", which corresponds to the code for the yellow light of the traffic light system, and the optical receiver receives the code from the light emitted by the LED, and if the message has been decoded correctly and corresponds to the code used for the yellow light, the yellow LED lights up. Similarly, the microcontroller transmits the code "1010", and if the optical receiver has received the code corresponding to the red light, the red LED lights up.

3.3 The proposed system for video cameras with 120 FPS

The current solutions for video-based VLC use cameras with a high number of frames/s. The advantage of these cameras is that they allow the detection of high-speed switches of the intensity level of the LED (on-off). However, the cost of these cameras makes them an impractical solution for large-scale use. The main challenge is to design a VLC system based on the video camera that allows the use of cameras with a low number of frames/s so that they are accessible to the general public. The reader can find more information in scientific papers [20], [16], [29].

3.3.1 The description of the communication system

The communication code plays a vital role in this system. The lack of synchronization between the transmitter and the receiver means that the sampling moments can be anywhere in the symbol period. A code must be invariant to the sampling moments to be able to be used in such conditions. In addition, the code should not produce flicker perceptible by the human visual system and should allow robust detection when sampled at low sample rates. The code symbols are made of specific sequences of frames.

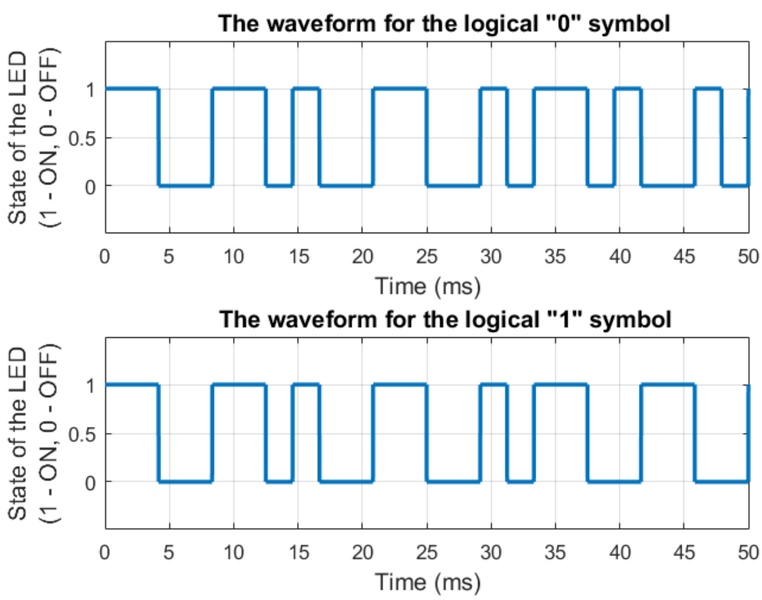


Fig. 3.10 The waveforms representing the two symbols of the communication code [16].

Thereby, we implemented a code consisting of two symbols, which consist of two parts: a common preamble and the symbol identifier. The preamble has the role of a synchronization sequence to signal the receiver that a new symbol starts. Their waveforms are illustrated in Figure 3.10 and indicate the LED's state variation in time ("1" means the LED is on, and "0" means the LED is off).

It can be observed that the waveforms consist of a series of long and short pulses. The duration of the long pulses is 1/240 seconds and of the short ones 1/480 seconds. The duration of the waveform corresponding to one code symbol is equal to 50 milliseconds. Since the code is used to transmit one bit per symbol, the maximum bit rate obtained is 20 bits per second.

A camera with a frame rate of 120 frames/s will capture an image every 1/120 seconds. In every frame, the LED will be captured lit or not, depending on its state when the frame is captured. Since the code consists of two symbols, four cases can be identified in the communication: the symbol for "0" followed by the symbol for "0", the symbol for "1" followed by the symbol for "0", the symbol for "0" followed by the symbol for "1", and the symbol for "1" followed by the symbol for "1". Two of these cases are illustrated in Figure 3.11. Because the time when the camera is turned on and when the LED is on is not synchronized, there is no information about where the sampling points will be placed on the waveforms. The sampling points corresponding to a possible acquisition are marked using the same type of bullet and are spaced at 1/120 seconds because of the camera's frame rate.

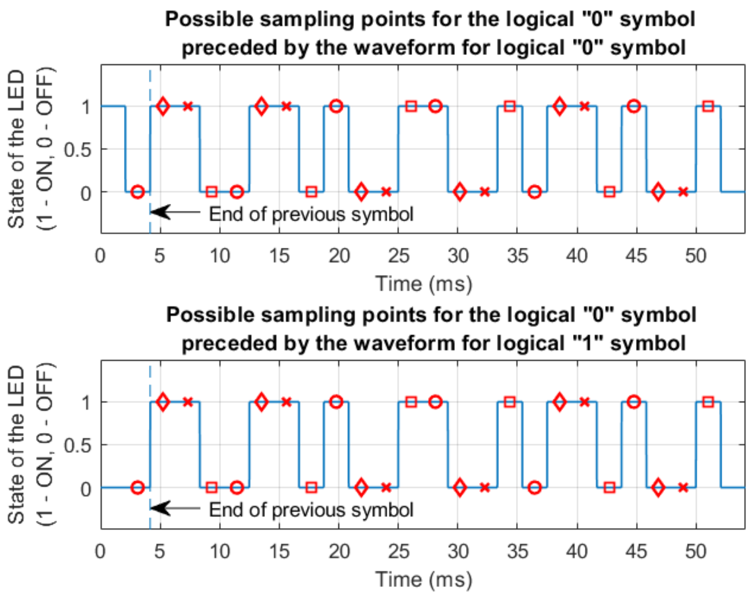


Fig. 3.11 The possible sampling points for the logical "0" symbol when preceded by both logical "0" and "1" symbols [16].

It was noticed that the LED status in each frame does not matter, but only the relation of the states of the LED in six consecutive frames. Given the state of the LED in the first frame, if the states that are identified in the next five frames are in the following sequence: same, different, different, same, different from the state found in the first frame, then the logical "0" symbol is identified. The other symbol is identified in a similar way, the difference being the desired states of the LED in the following five frames, compared to the state detected in the first frame: same, different, different, same,

same. This property of the code allows the correct extraction of the sent symbols without having synchronization between the transmitter and the receiver.

Detection problems can occur if the signal is sampled exactly on edge due to the uncertainty of the state of the LED in the captured frame (if the LED is captured while being turned on or off). To increase the robustness of the detection, the transmitter was improved by using two LEDs instead of one. One LED is controlled by the signal described above, and the other LED by a slightly delayed replica of the first signal. The optimal delay between the two signals is 1/960 seconds, as this will keep the edge of one signal as far away from the edges of the other signal as possible.The VLC system proposed in this paper can be used with cameras which work at a frame rate of 120 fps.

3.3.2 The experimental system, results and discussions

The proposed VLC system uses cameras operating at 120 frames/s ("Frames Per Second" - FPS). We implemented the system prototype using an Atmel-based development board, which is equipped with the components needed to successfully play the role of the transmitter (a microcontroller and an LED) and an uEye UI-1485LE-M-GL camera used as a receiver. The resolution of 100×100 pixels was sufficient for the experiment. The camera's shutter speed was configured to the lowest value available. The luminance of each captured frame is then analyzed to determine if the LED was on or off. The computation was done using MATLAB.

Figure 3.16 shows a captured video sequence, and code extraction is exemplified. The video sequence was captured by holding the camera in hand. The image's overall brightness was computed in MATLAB, and the decision regarding dark and bright frame occurrence was made by comparing the brightness of the frame with a threshold calculated adaptively by averaging the brightness of 120 frames.

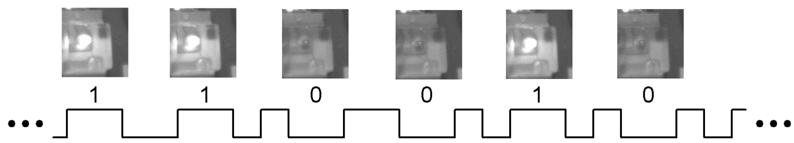


Fig. 3.16 The recorded video sequence corresponding to the first symbol of the communication code [20].

To increase the robustness of the detection, the VLC system has been improved by adding a second LED to the emission system. For each frame, the luminance of the image area where each LED is placed is compared with a threshold value. This value is determined by averaging the luminance of the same area over the whole recording. In this way, the state of the LEDs in each frame can be extracted. An example sequence of captured frames is shown in Figure 3.19, top row. Due to the very short exposure time, the camera automatically underexposed the background of the images, resulting in very dark overall pictures. In the same figure, the bottom row shows the brightness of a line (called the "Probe line") of each frame, the line that crosses the position of both LEDs (the horizontal position of LED 1 in the frame was marked with a red dotted line, and the horizontal position of LED 2 was marked with a magenta dotted line), so that the state of each LED can be extracted from each frame by comparing the brightness of the position of each LED with the threshold. A value equal to 0 means a completely dark area, and a value equal to 255 means a fully bright area. The brightness threshold is also illustrated. Because the decoding algorithm runs separately for each LED, it is sufficient for one decoder to correctly extract the transmitter signal to obtain a correct transmission.

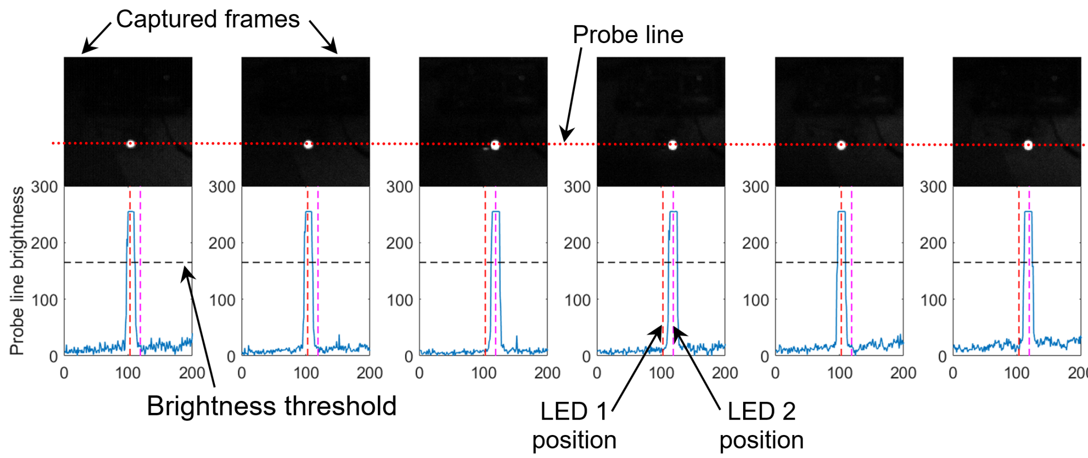


Fig. 3.19 Example of captured sequence of frames (top row) and the brightness on the probe line that crosses the LEDs forming the VLC transmitter (bottom row) [16].

Discussions about how the system could work in actual conditions

Noise can be caused by using a high ISO value (increased image sensor sensitivity to light). This could affect the proposed VLC if the LEDs' fingerprints (surfaces) on the image is very small, on the order of pixels. This is an extreme case caused by a very long distance between the transmitter and the receiver or by using a very low-resolution camera as the receiver.

Determining the minimum distance between the centers of the LEDs to separate them in the captured frames

To properly process the captured frames, the two LEDs must be separable in the images. Next, we performed experiments to determine the minimum distance between the centers of the LEDs that would allow their proper separation in the captured frames, depending on the distance between the LEDs and the camera. Thus, a Nikon D7200 camera with a Nikon 18-105mm f1:3.5-5.6 lens was used. The video resolution was set to 1080×720 pixels, the shutter speed was set to 1/8000 seconds, and the focal length was kept at 18 mm in all experiments. The LEDs to camera distance was varied from 15 cm to

150 cm with a 15 cm step. The distance between their centers was varied between 0.3 inches and 1.7 inches, with a step equal to 0.1 inches. The experiments showed that the minimum distance between the edges of the LEDs facing one another, which allows a correct detection, is 15 pixels.

3.4 The proposed system for video cameras with 60 FPS

Next, we present the VLC solution that uses a 60 frame/s camera and does not require synchronization between transmitter and receiver. The reader can find more information in scientific papers [15], [21].

3.4.1 The description of the communication system

We implemented a communication code consisting of two symbols: logical "1" and logical "0". Each of these symbols is physically represented by an on-off switching sequence of the transmitting LEDs. The sequences for the two code symbols are shown in Figure 3.23 as waveforms. It can be observed that both symbols have a total duration of 100 milliseconds. This leads to a maximum bit rate of 10 bits/s. Long and short pulses make the symbols. The long pulses have a duration equal to 1/240 seconds, and the short ones have 1/480 seconds.

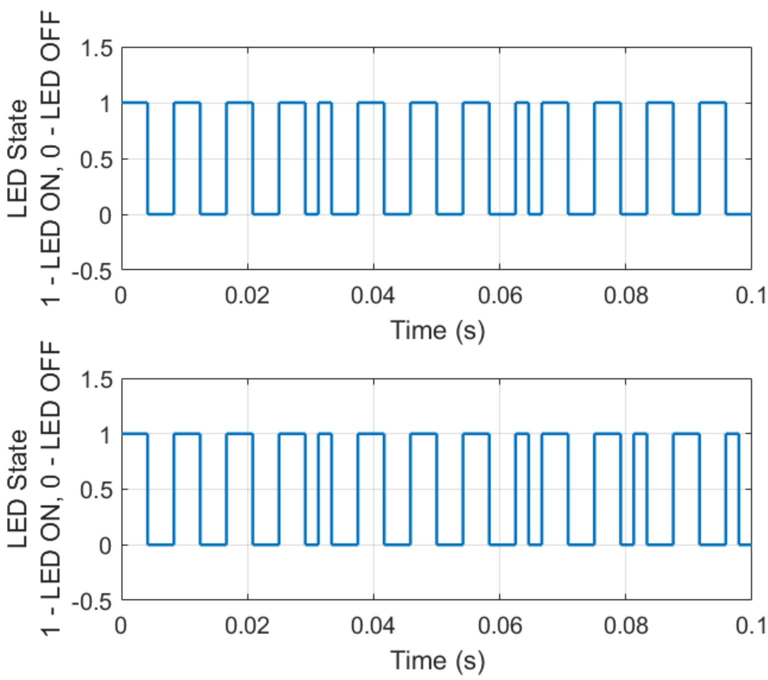


Fig. 3.23 The waveforms of the two symbols that form the communication code: top plot for logical "0" and bottom for logical "1" [15].

The transmitter and receiver can be started at any moment in time. This determines eight possible sampling positions on the waveforms, each having six sampling points.

Following the same symbol marking a sampling point on a waveform, four cases can be identified: "110010" or, the negated value, "001101" on a logical "1" waveform, regardless of the previous symbol, and "110011" or "001100" on a logical "0" waveform. After one frame is captured, only two patterns are detected with respect to the first captured frame, same-different-different-same-different for "1" symbol or same-different-different-same-same for "0" symbol. In this way, the system can differentiate between the two code symbols without any synchronization available. Problems could occur in determining the state of the LED if the sampling point is exactly on the edge of the waveform when LED turns on or off. To counteract this, two LEDs are used, and the waveform that controls the second LED is obtained by delaying the main waveform by 1/960 seconds (half of a short pulse). In this way, one of the two LEDs will always be sampled correctly.

3.4.2 The experimental system, results and discussions

The experimental system and the results

We implemented the system's prototype using a microcontroller development board that controls two LEDs (transmitter) and a uEye UI-1485LE-M-GL camera (receiver). Figure 3.26 illustrates the captured frames and the brightness along the probe line containing the LEDs. The camera was set to record 60 FPS. The resolution of the captured frames was 296 × 296 pixels. The camera's shutter speed was configured to the lowest value available. The two LEDs were identified in frames, and their brightness was extracted, compared to a threshold (illustrated with thin black lines in Figure 3.26), to obtain the LED status. The threshold is computed as the mean between the minimum and the maximum brightness recorded on the probe line in 12 consecutive frames during system initialization. The identified sequence is "110010" for both LEDs in the presented case, so the decoded symbol is a logical "1".

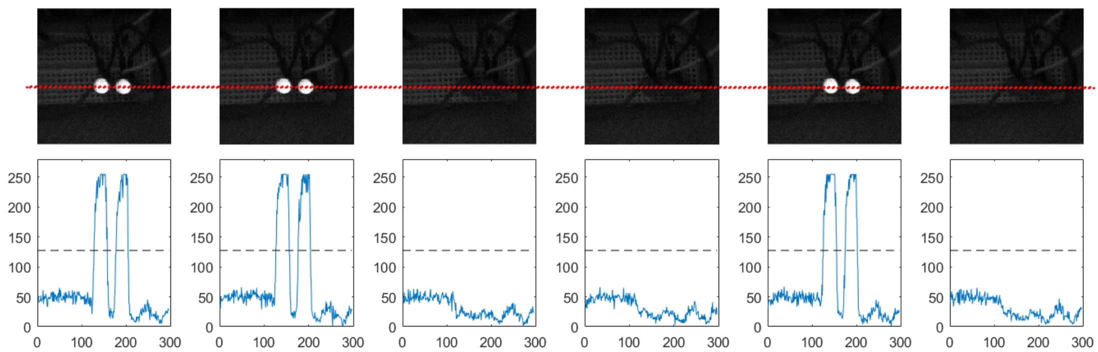


Fig. 3.26 The captured frames and the brightness on the probe line (red thick dashed line) in each frame (brightness of each pixel: 0 – black, 255 – white). The brightness threshold is illustrated with black thin dashed lines [15].

Discussions about how the system could work in actual conditions

The results presented were obtained in laboratory conditions, but the situation does not differ very much from a regular real-world functioning. The communication code only works if the receiver captures video at 60 FPS. There is one necessary lighting condition: the light emitted by the emitter's LEDs should be much brighter than the ambient light. Thanks to the average performed in the first 12 consecutive frames, the system can be automatically calibrated to conditions.

Investigation on the performances of VLC communication using low frame rate cameras

In this section, we investigated the performance of VLC communication using the system consisting of a microcontroller development board and two green LEDs, representing the transmitter, and a uEye UI-1485LE-M-GL camera for the first version of the experimental setup, a camera Nikon D7200 for the second version and a GoPro Hero 7 Black Edition camera for the third version, representing the receiver. In all three cases, the camera's frame rate was set to 60 FPS. In the first case, the resolution of the uEye UI-1485LE-M-GL camera is 512×384 pixels. In the second case, the resolution of the Nikon D7200 camera is 1280×720 pixels, and in the last case, the resolution of the GoPro Hero 7 camera is 1920×1440 pixels. The camera's shutter speed was set to 1/3200 seconds for the uEye UI-1485LE-M-GL, 1/8000 seconds for the Nikon D7200, and 1/960 seconds for the GoPro Hero 7. The pixel luminance was extracted from the LED positions and compared to a threshold. If the luminance value was above the threshold, the LED was determined to be on, otherwise off. As a performance criterion, the bit error rate (BER) was investigated for each of the three cameras used. It has been established that the BER decreases with the decrease of the shutter speed.

3.5 The proposed system for video cameras with 30 FPS

Next, we present the OCC solution that uses a camera that acquires 30 frames/s, as a receiver, does not produce flickering at the transmitter and, in addition, offers the possibility to turn on the transmitter and receiver at any time, as they will synchronize automatically. The reader can find more information in the scientific paper [22].

3.5.1 The description of the communication system

We implemented a communication code that provides waveforms for two symbols: logical "1" and logical "0". Each symbol is represented by an on-off switching of the transmitter LEDs, presented in Figure 3.28. The long pulse duration is equal to 1/240 seconds, while the duration of the short ones is equal to 1/480 seconds. Consequently, each symbol has a duration of 200 milliseconds, resulting in a bit rate of 5 bits per second.

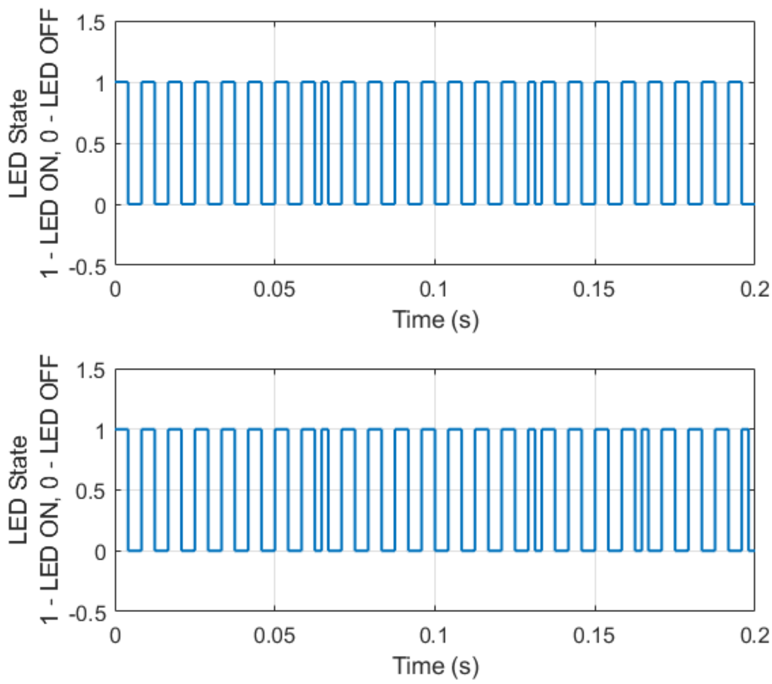


Fig. 3.28 The waveforms of the two symbols that form the communication code: top plot for logical "0" and bottom for logical "1" [22].

The transmitter and receiver can be started independently at any moment. Considering the waveforms of the symbols and the receiver camera frame rate, 16 possible combinations of sampling positions can be identified, each with six sampling points. A six-bit code can be identified on each waveform by following the same letter that marks a sampling point. On the waveform for the logical "0", regardless of the letter followed, the result is either "110011" or the negated value "001100". On the waveform for logical "1", similarly, only "110010" or the negated value "001101" can be found.

This means that the detector must only search for two patterns regarding the state of the LED captured in the first frame: same-different-different-same-same for "0" and same-different-different-same-different for "1", facilitating the differentiation between the two symbols. One of the most important properties of the code is that there are no six consecutive positions on the waveform, spaced at 1/30 seconds (the sampling rate) that give one of the searched patterns, other than the cases when the symbols are correctly decoded. This property is essential for automatic resynchronization between transmitter and receiver, without additional information, as the other solutions in the literature use.

3.5.2 The experimental system, results and discussions

The experimental system and the results

The transmitter is represented by a microcontroller development board and two LEDs. The receiver is represented by a Nikon D7200 camera with a Nikon 18-105mm f/3.5-5.6 lens, set to record video sequences. The camera's shutter speed was set to 1/8000 seconds. The video resolution was set to 1920×1080 pixels.

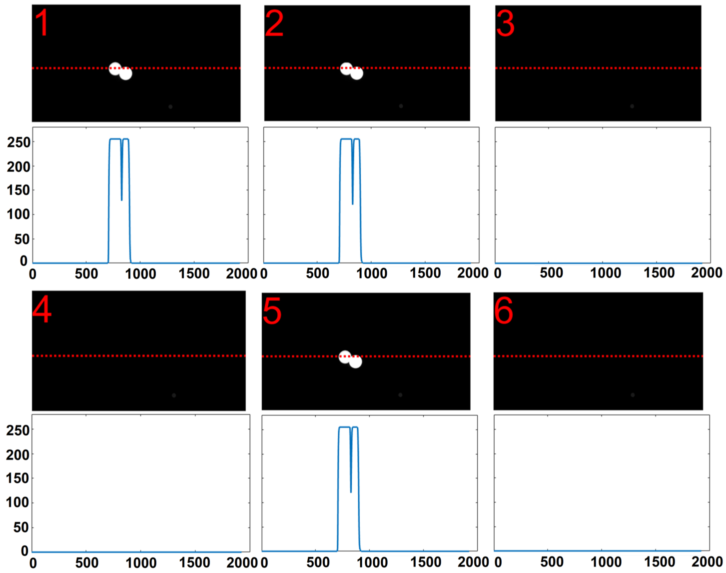


Fig. 3.32 The captured frames and the brightness on the probe line (red dotted line) in each frame (brightness of each pixel: 0 – black, 255 – white). The brightness threshold is illustrated with black dashed line [22].

After capturing, the video sequence was processed frame by frame using MATLAB. Each frame was converted into grayscale, then the luminance was extracted on a probe line (red dotted line in Figure 3.32), and the state of each LED was identified. The state of an LED is determined by comparing the luminance in the corresponding position in the frame with a threshold value, computed as the average between the minimum and maximum brightness recorded on the probe line in 12 consecutive frames. The threshold is illustrated with a black dashed line in Figure 3.32. In the presented case, the decoded sequence is "110010", therefore the logical "1" symbol has been decoded.

Discussions about applications and functioning in actual conditions

As an effect to satisfy the two harsh conditions, the compatibility with cameras that record 30 FPS and avoiding flickering, the bit rate is reduced to 5 bits per second. The proposed solution has been tested in laboratory conditions, but thanks to the adaptive threshold in the detector, it should give promising results in any situation, with the condition that the light emitted by the LEDs when they are turned on is much more intense than the ambient light.

3.6 Conclusions and original contributions

The proposed optical receiver system

The proposed communication system consists of two modules: a transmission system used to transmit communication codes and a reception system used to receive and decode them. The first module, the transmission, is mounted on the road signalling infrastructure. The second module, the reception, is mounted on the vehicle. It is checked if the decoded message corresponds to one of the transmitted codes, and if it corresponds to the code for the red color, the vehicle will brake automatically, while for the yellow color, an audio warning will alert the driver that the traffic light will turn red. The communication code consists of synchronization pulses, pulses for logic "0", pulses for logic "1". The code is based on the duration between consecutive edges, so the duration of each code is 750 µs.

The proposed system for video cameras with 120 FPS

We implemented a code consisting of two symbols, which consist of two parts: a common preamble and the symbol identifier. Their waveforms consist of long and short pulses, the duration of long pulses being 1/240 seconds and short ones of 1/480 seconds. The duration of the waveform corresponding to a one code symbol is equal to 50 milliseconds, resulting in a maximum bit rate of 20 bits/s.

The prototype of the VLC system was implemented using a development board equipped with a microcontroller and a LED as the transmitter and a uEye UI-1485LE-M-GL camera as the receiver. The camera's shutter speed was configured to the lowest value available. The luminance of each captured frame is then analyzed to determine if the LED was on or off. The image's overall brightness was computed in MATLAB, and the decision regarding dark and bright frame occurrence was made by comparing the frame's brightness with a threshold calculated adaptively by averaging the brightness of 120 frames. To increase the robustness of the detection, the VLC system has been improved by adding a second LED to the emission system.

Next, we performed experiments to determine the minimum distance between the centers of the LEDs that would allow their proper separation in the captured frames, depending on the distance between the LEDs and the camera. The experiments showed that the minimum distance between the edges of the LEDs facing one another, which allows a correct detection, is 15 pixels.

The proposed system for video cameras with 60 FPS

The implemented communication code consists of two symbols: logical "1" and logical "0". The symbols are made by long and short pulses, having a duration equal to 1/240 seconds in the case of long pulses and equal to 1/480 seconds in the case of short pulses. The total duration is 100 milliseconds, resulting in a maximum bit rate of 10 bits/s.

The proposed system was validated using a microcontroller development board that controls two LEDs (transmitter) and an uEye UI-1485LE-M-GL camera (receiver). The camera's shutter speed was configured to the lowest value available. The luminance of the LEDs was extracted from each video frame, and comparing the resulting value with a threshold, the status of each LED was determined. The threshold is computed as the mean between the minimum and the maximum brightness recorded on the probe line in 12 consecutive frames during system initialization.

We investigated the performance of VLC communication using a system consisting of a microcontroller development board and two green LEDs (transmitter), and uEye UI-1485LE-M-GL cameras, Nikon D7200 and GoPro Hero 7 Black Edition (receiver). The camera's shutter speed was set to 1/3200 seconds for the uEye UI-1485LE-M-GL, 1/8000 seconds for the Nikon D7200, and 1/960 seconds for the GoPro Hero 7. As a performance criterion, the bit error rate (BER) was investigated, and it was established that it decreases with the decrease of the shutter speed.

The proposed system for video cameras with 30 FPS

We proposed a camera-based VLC system that uses LEDs as a transmitter and a 30 FPS camera as a receiver. The implemented communication code consists of two symbols: logical "1" and logical "0". Each symbol has a duration of 200 milliseconds, resulting in a bit rate of 5 bits per second.

To validate the communication code, we used a VLC system consisting of a microcontroller development board and two LEDs representing the transmitter, and a Nikon D7200 camera, representing the receiver. The camera's shutter speed was set to 1/8000 seconds. Each frame was converted into grayscale, then the luminance was extracted on a probe line, and the state of each LED was identified. The state of an LED is determined by comparing the luminance in the corresponding position in the frame with a threshold value, computed as the average between the minimum and maximum brightness recorded on the probe line in 12 consecutive frames.

Chapter 4

Conclusions

4.1 Obtained results

Chapter 2 presented, in Section 2.3, the procedure used to find the most suitable measurement mode to determine with high accuracy the photometric parameters for a white LED using a light meter with multiple measurement modes. It was determined that for the "cold" and "neutral" white LEDs, the sodium preset is suitable for use, while for the "warm" white LEDs, the tungsten mode is recommended. In Section 2.4, the degradation of the received signal in the VLC communication was investigated, and the available bandwidth was determined. The LED driver circuit has been designed for this application due to the need for a very fast start-up time. It was observed that the rising time of the received signal is much longer than that of the waveform that represents the current passing through the LED with the role of the transmitter. The highest available bandwidth was determined for the green LED, while the lowest was for the infrared LED.

Chapter 3 studies the optical communication systems in the visible spectrum, discusses their limitations in Section 3.1, followed by personal contributions to the field, namely: i) optical receiver system in Section 3.2. The proposed communication system consists of two modules: a transmission system used to transmit communication codes and a reception system used to receive and decode them. The first module, the transmission, is mounted on the road signalling infrastructure. The second module, the reception, is mounted on the vehicle. It is checked if the decoded message corresponds to one of the transmitted codes, and if it corresponds to the code for the red color, the vehicle will brake automatically, while for the yellow color, an audio warning will alert the driver that the traffic light will turn red. A secondary, incremental solution was developed by adapting current lamp-based systems by adding an additional radiation element. The additional light-emitting element consists of an infrared emitter used to transmit codes depending on the active color of the traffic light, ii) system for video cameras with 120 FPS with a maximum bit rate of 20 bits/s in Section 3.3. A code consisting of two symbols has been implemented, consisting of a common preamble and the symbol identifier. The duration of the waveform corresponding to a one code symbol is equal to 50 milliseconds. In each frame, the LED will be captured on or off, depending on its state when the frame is recorded. To increase the robustness of the detection, the VLC system has been improved by adding a second LED to the emission system. Experiments were performed to determine the minimum distance between the centers of the LEDs that would allow their proper separation in the captured frames, depending on the distance between the LEDs and the camera. The experiments showed that the minimum distance between the edges of the LEDs facing one another, which allows a correct detection, is 15 pixels, iii) system for video cameras with 60 FPS with a maximum bit rate of 10 bits/s in Section 3.4. A camera-based VLC system has been proposed, which uses LEDs as a transmitter and a 60 FPS camera as a receiver. The implemented communication code consists of two symbols: logical "1" and logical "0". Both symbols have a total duration of 100 milliseconds. To avoid detection errors caused by capturing frames exactly when an LED turns on or off, two LEDs are used: one is controlled directly and the other by a delayed replica of the transmitted code, and iv) system for video cameras with 30 FPS with a maximum bit rate of 5 bits/s in Section 3.5. A camera-based VLC system has been proposed, which uses LEDs as a transmitter and a 30 FPS camera as a receiver. The implemented communication code consists of two symbols: logical "1" and logical "0". Each symbol has a duration of 200 milliseconds. Two LEDs are used in the transmitter, one being controlled by the primary waveform and the other by a delayed replica of the primary waveform to avoid possible detection errors caused by capturing the frames when the LED is on or off.

4.2 Original contributions

- In [C21], I performed experiments to find the most suitable measurement mode in order to determine with high accuracy the photometric parameters of a white LED using a light meter with multiple measurements modes (incandescent, fluorescent, on sodium-based, mercury-based). The comparison was made by evaluating the measured values using the light meter in which the four predetermined measurement modes associated with the classical light sources were selected in turn. The decision regarding the recommended measurement mode for a white LED was made based on the experimental values.

- In [C20] I proposed an optical communication system used for transmitting messages between the vehicle and the road signalling infrastructure with improvements to ambient light filtering resulting in correct decoding of the message in order to obtain automatic braking in case of red traffic light and playing an audible warning inside the vehicle in the event of yellow light.

- In [C14], I measured the response time of the power LEDs and determined the available bandwidth. We investigated the degradation of the rising time of the received signal compared to the rising time of the waveform corresponding to the current applied to the LEDs. The result of the investigation is helping the user in choosing the most suitable LED to obtain the desired communication. Another contribution is the development of the LED driver circuit to obtain a very fast start-up time.

- In [C15], I proposed a VLC communication system that uses an LED as a transmitter and a video camera with a frame acquisition system of 120 frames/s as a receiver. Another contribution is implementing a communication code that guarantees robust decoding, does not produce flicker, and does not need synchronization between transmitter and receiver. The proposed decoding solution uses an adaptive threshold calculated by averaging the luminance values obtained for the 120 frames.

- In [R1] I made improvements to the VLC communication system in [C15] by using two LEDs, where the first LED transmits the communication code and the second LED transmits a delayed replica to minimize losses due to LED state uncertainty. Another proposed improvement is the decoding system that uses a threshold calculated by averaging the luminance of each area of interest in each frame of the recording.

- In [C9], I made improvements to the systems [C15, R1], by implementing a communication code on 60 frames/s, a drastic improvement over the "state-of-the-art". The proposed decoding solution uses a threshold calculated based on the average between the minimums and maximums of the luminance values recorded in 12 consecutive frames during the system initialization.

- In [C13], I investigated the performance of a varied set of video cameras with a low frame/s acquisition system that can guarantee stable communication. As a performance criterion, the bit error rate (BER) was investigated, and it was established that it decreases with the decrease of the shutter speed.

- In [C6], I implemented a communication code in the visible spectrum that works on 30 frames/s, aiming to eliminate the flickering effect. We also improved the decoding time by processing the data acquired by the video camera in grayscale without affecting the robustness of the decoding.

- In [C6], I made a review of literature in the field of wireless optical communications.

- In [C4], I made measurements that highlight possible attacks in VLC and OCC networks.

4.3 List of original publications

Books:

B1: R. A. Dobre, **A. E. Marcu**: Culegere de probleme rezolvate: instrumentație electronica de măsură. Editura Politehnica Press, Bucuresti, ISBN: 978-606-515-871-9, 2019.

B2: N. Codreanu, C. Ionescu, M. Pantazică, **A. Marcu**: Tehnici CAD de realizare a modulelor electronice: suport de curs și laborator. Editura Cavallioti, București, Editura PIM, Iași, ISBN: 978-606-551-092-0, 978-606-13-4164-1, 2017.

Journals:

R1: **A. E. Marcu**, R. A. Dobre, R. O. Preda, P. Șchiopu: Flicker Free VLC System with Enhanced Transmitter and Low Frame Rate Camera. University Politehnica Of Bucharest Scientific Bulletin Series C - Electrical Engineering And Computer Science, vol. 81, pp. 133-144, ISSN 2286-3540, WOS: 000502008300011, 2019.

R2: M. Vlădescu, **A. E. Marcu**, A. Bărar: E-learning Approaches in Optoelectronics Education. International Journal of Advances in Science, Engineering and Technology (IJASEAT), vol. 7, nr. 4, pp. 52-54, 2019.

Conferences:

C1: **A. E. Marcu**, R. A. Dobre, M. Vlădescu: Visible light communications: current challenges and prospects. Advanced Topics in Optoelectronics, Microelectronics and Nanotechnologies X, vol. 11718, pp. 117182F, International Society for Optics and Photonics, DOI: 10.1117/12.2572074, WOS: 000641147900086, 2020, ISI indexed.

C2: D. A. Vlădescu, **A. E. Marcu**: LED lighting system with gradual control of light intensity through capacitive sensing. Advanced Topics in Optoelectronics, Microelectronics and Nanotechnologies X, vol. 11718, pp. 117182S, International Society for Optics and Photonics, DOI: 10.1117/12.2572105, WOS: 000641147900099, 2020, ISI indexed.

C3: M. Vlădescu, P. Şchiopu, A. Crăciun, **A. E. Marcu**, A. Bărar, V. Damian, A. Tulbure: Contributions to the analysis of substances with time-domain terahertz spectroscopy. Advanced Topics in Optoelectronics, Microelectronics and Nanotechnologies X, vol. 11718, pp. 1171829, International Society for Optics and Photonics, DOI: 10.1117/12.2571746, WOS: 000641147900080, 2020, ISI indexed.

C4: S. Riurean, R. A. Dobre, **A. E. Marcu**: Security and propagation issues and challenges in VLC and OCC systems. Advanced Topics in Optoelectronics, Microelectronics and Nanotechnologies X, vol. 11718, pp. 117182B, International Society for Optics and Photonic, DOI: 10.1117/12.2572029, WOS: 000641147900082, 2020, ISI indexed.

C5: D. G. Bălan, A. Drumea, **A. E. Marcu**: Embedded System for Smart Controlling Electronic Devices. 2020 IEEE 26th International Symposium for Design and Technology in Electronic Packaging (SIITME), pp. 192-195, IEEE, WOS: 000651085100039, 2020, ISI indexed.

C6: **A. E. Marcu**, R. A. Dobre, M. Vlădescu: Flicker Free Optical Camera Communication for Cameras Capturing 30 Frames per Second, 2020 43rd International Conference on Telecommunications and Signal Processing (TSP), pp. 166-169, IEEE, WOS: 000577106400036, 2020, ISI indexed.

C7: R. A. Dobre, R. O. Preda, **A. E. Marcu**: TIC-TAC Based Live Acoustic Watermarking With Improved Forgery Detection Performances. 2019 IEEE 25th International Symposium for Design and Technology in Electronic Packaging (SIITME), pp. 408-412, IEEE, 2019, WOS: 000564733700089, ISI indexed.

C8: R. A. Dobre, **A. E. Marcu**, M. Stanciu, M. Vlădescu: Spectroscopic investigation of transparent polylactic acid. EUROINVENT International Conference on Innovative Research (ICIR), pp. 012015, IOP Publishing, 2019, Scopus indexed.

C9: **A. E. Marcu**, R. A. Dobre, O. Datcu, G. Suciu, J. Oh: Flicker Free VLC System with Automatic Code Resynchronization using Low Frame Rate Camera. 2019 42nd International Conference on Telecommunications and Signal Processing (TSP), pp. 402-405, IEEE, WOS: 000493442800087, 2019, ISI indexed.

C10: **A. E. Marcu**, G. Suciu, E. Olteanu, D. Miu, A. Drosu, I. Marcu: IoT system for forest monitoring. 2019 42nd International Conference on Telecommunications and Signal Processing (TSP), pp. 629-632, IEEE, WOS: 000493442800138, 2019, ISI indexed.

C11: A. Bărar, **A. E. Marcu**, P. Şchiopu, M. Vlădescu: Design of an LED-based solar spectrum simulator for porphyrin dye-sensitized solar cell characterization. 2019 11th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), pp. 1-4, IEEE, WOS: 000569985400113, 2019, ISI indexed.

C12: F. V. Anghel, **A. E. Marcu**, R. A. Dobre, A. M. C. Drăgulinescu: Improved Remote Control System for Analog Audio Mixers Featuring Internet of Things Elements. International Conference on Future Access Enablers of Ubiquitous and

Intelligent Infrastructures (FABULOUS), pp. 138-145, Springer, Cham, WOS: 000552334400014, 2019, ISI indexed.

C13: **A. E. Marcu**, R. A. Dobre, M. Vlădescu: Investigation on The Performances of Visible Light Communication Using Low Frame Rate Camera. International Multidisciplinary Scientific GeoConference: SGEM, pp. 377 - 382, International Multidisciplinary Scientific Geoconference, 2019, Scopus indexed.

C14: **A. E Marcu**, R. A. Dobre, A. Vintea, M. Vlădescu: Investigation of power LEDs response time in visible light communications. Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies IX, vol. 10977, pp. 1097719, International Society for Optics and Photonics, WOS: 000458717900044, 2018, ISI indexed.

C15: **A. E. Marcu**, R. A. Dobre, M. Vlădescu: Flicker Free Visible Light Communication Using Low Frame Rate Camera. 2018 International Symposium on Fundamentals of Electrical Engineering (ISFEE), pp. 1-4, IEEE, WOS: 000480396400041, 2018, ISI indexed.

C16: R. A. Dobre, R. O. Preda, **A. E. Marcu**: Improved Active Method for Image Forgery Detection and Localization on Mobile Devices. 2018 IEEE 24th International Symposium for Design and Technology in Electronic Packaging (SIITME), pp. 255-260, IEEE, WOS: 000466960400054, 2018, ISI indexed.

C17: **A. E. Marcu**, R. A. Dobre, M. Vlădescu: Cost Effective Remote Control System for Analog Audio Mixers. 2018 IEEE 24th International Symposium for Design and Technology in Electronic Packaging (SIITME), pp. 280-283, IEEE, WOS: 000466960400059, 2018, ISI indexed.

C18: R. A. Dobre, **A. E. Marcu**: Practical Method for Emergency Intervention in Smart Cities. 2018 IEEE 24th International Symposium for Design and Technology in Electronic Packaging (SIITME), pp. 243-246, IEEE, WOS: 000466960400051, 2018, ISI indexed.

C19: R. A. Dobre, **A. E. Marcu**, A. Drumea, M. Vlădescu: Thermal and Electrical Investigation of Conductive Polylactic Acid Based Filaments. EUROINVENT International Conference on Innovative Research (ICIR), pp. 012005, IOP Publishing, WOS: 000446775900005, 2018, ISI indexed.

C20: **A. E. Marcu**, R. A. Dobre, M. Vlădescu: Key Aspects of Infrastructure-to-Vehicle Signaling Using Visible Light Communications. International Conference on Future Access Enablers of Ubiquitous and Intelligent Infrastructures (FABULOUS), pp. 212-217, Springer, Cham, WOS: 000481658200031, 2017, ISI indexed.

C21: **A. E. Marcu**, R. A. Dobre, M. Vlădescu: Study on determining the photometric parameters for a white LED using a light meter. Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies VIII, pp. 1001018, International Society for Optics and Photonics, WOS: 000391359600044, 2016, ISI indexed.

C22: A. Drumea, **A. E. Marcu**, I. Plotog: The influence of vibrations on time reference signals generated using quartz crystals. Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies VIII, pp.100101B, International Society for Optics and Photonics, WOS: 000391359600047, 2016, ISI indexed.

C23: **A. E. Marcu**, R. A. Dobre, M. Vlădescu: Investigation on available bandwidth in visible-light communications. 2016 IEEE 22nd International Symposium for Design and Technology in Electronic Packaging (SIITME), pp. 244-247, IEEE, WOS: 000390557400052, 2016, ISI indexed.

C24: **A. E. Marcu**, N. D. Codreanu, D. Ţarălungă: Bio-signals investigation platform for academic research and education laboratories. 2015 IEEE 21st International Symposium for Design and Technology in Electronic Packaging (SIITME), pp. 151-155, IEEE, WOS: 000377765500027, 2015, ISI indexed.

Research projects:

P1: 2018-2021: research assistant, ENI project. "Eco-nanotechnologies and intelligent equipment for soil properties mapping and evaluating the dynamics of the plant in order to improve agricultural production and environmental protection", partner Politehnica University of Bucharest, grant PN-III-P1-1.2-PCCDI-2017-0560.

P2: 2020-2022: researcher, SmartDelta project. "Increasing the innovative competitiveness of SC Ad Net Market Media through initial innovation investments in order to achieve a SmartDelta technological platform, within a newly established unit for the realization of CD activities in effective collaboration", partner Politehnica University of Bucharest, grant POC SMIS 121884.

4.4 Perspectives for further developments

Future perspectives include: (i) the development of an automated testing system for the investigation of the available bandwidth in VLC communications, (ii) increasing the bit rate using an LED array as the transmitter, where each LED represents a separate communication channel. This involves locating the LED in the frame. Due to the low resolution, in this case, the LED fills almost the entire frame, and it is not necessary to identify its position. If higher resolution cameras are used, the position of the LED in the frame could be determined by subtracting consecutive frames, (iii) the evaluation of the performance of the proposed system at different distances between transmitter and receiver and the evaluation of the benefits of using error correction codes. After determining the maximum working distance, a multiple transmitter scenario will be studied to determine the possibility of increasing the transmission rate, (iv) the use of RGB LEDs. The waveform of the main code could be added in one color channel, and the delayed waveform in one of the other two color channels.

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