FLICKER FREE VLC SYSTEM WITH ENHANCED TRANSMITTER AND LOW FRAME RATE CAMERA

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With the rapid and continuous development of the LEDs, the conventional lighting solutions are intended to be replaced. The advantages of using LED lighting systems led to the development of Visible Light Communications (VLC). The transmitter in these systems is made using LEDs and the receiver can be a photodetector or, in recent solutions, an image sensor. The current solutions use expensive cameras with high frame rate as receivers. The paper proposes a system that uses generic cameras with common frame rate and can work without an auxiliary synchronization between the transmitter and the receiver. The proposed system can make VLC available to the general public.

Keywords: visible light communication, camera receiver, low frame rate camera

1. Introduction

In the recent years, more and more optical wireless communications (OWC) [1], [2] began to appear. This communication is based on the optical spectrum. Some examples of OWC technologies are: VLC [3], [4], which uses the visible light spectrum, proving both illumination and communication, light fidelity (LiFi), which can provide illumination and high-speed communication, being a complementary technology to wireless fidelity (WiFi) and it uses in the downlink communication the visible light, and in the uplink communication the infrared [5], ultraviolet or visible light, free space optical communication (FSOC), which uses the near-infrared, visible light and ultraviolet spectrum and can provide high-data-rate communication over large distances and light detection and ranging (LiDAR), which uses the near-infrared and visible light spectrum and it is able to find information about distant target, as well as the range. In the future, the

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OWC technologies will be able to be paired with the 5G communication for internet-of-things (IoT) applications.

The VLC technology uses LEDs [6] transmitters, and photodetectors [7] or image sensors [8] – [12] as receivers [13]. The data is transferred by changing the light intensity of the LEDs fast enough so the human eye will not perceive the flickering of the light. The advantages of this type of communication are: the energy is used more efficient, it is not harmful to the environment and the human body, has a wide bandwidth and it is more secure. The disadvantage is that is requiring 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 [14] cannot be used due to the interferences that may occur with the medical equipment, in indoor localization systems, where an moving object can be localized in real-time [15], [16], in smart displaying signboards, where the various timetables can be displayed, and in museums or public places where advertisement light panels can be mounted and using the smartphone camera the information provided by the panels, such as the author of a painting or product details, can be read [17]. An important field in which the VLC has a rapid and important development is the automotive field, in Intelligent Transport System (ITS) [18] applications. The ITS is divided in vehicle-to-vehicle (V2V) [19] and vehicle-to-infrastructure (V2I) systems. In the first system, V2V, the taillights and the headlights of the vehicle can be used to transmit various information to other vehicles [20] and to transmit positioning signals [21]. Another example is that the system, in case of the hard braking of a car, can signal it to the surrounding vehicles. In the V2I scenario, the road traffic safety can be increased through the communication between the car and the traffic signaling system. As an overall application of the two systems, in case of traffic congestion, the ITS can adjust the traffic lights in order to ease the traffic. Another example can be given in case of an accident or a medical emergency in which the traffic lights can be turned green in order to provide the emergency vehicles ease of access. 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 the specialized receivers (photodetectors) or the high-performance receivers (cameras capturing many frames per second) [22]. The available solutions use as receivers high frame rate cameras, who work at 1000 frames per second [23] and are very expensive. An alternative has been found that uses low frame rate cameras, but this system has the disadvantage that it requires synchronization between the transmitter and the receiver [24]. The paper proposes a VLC system that can use as a receiver generic, widely available cameras, capturing 120 frames per second.

Besides this introduction, the paper contains three sections as follows: Section 2 describes the communication code used for a frame rate of 120 frames per seconds, Section 3 describes the experimental setup, shows the results, and discusses some possible noise sources. Section 4 concludes the paper and presents the future work.

2. The communication code

Usually, the information in VLC systems is transmitted using OOK (On/Off Keying) modulation [25], [26]. This means that the transmitter (usually an LED) is switched on and off according to the sequences that represent the transmitted code symbols. The current solutions for video-based VLC use high frame rate cameras. In this way, the luminous signal can be oversampled, and the signal processing operations implemented further in the detector (i.e., receiver) are much easier to design. However, the cost of these cameras makes them an impractical solution for large scale use. The main challenge that this paper addresses is designing a camera-based VLC system that would allow the usage of lower frame rate cameras so the large public could afford them.

A key role in this system is played by the communication code. One version of such code consists of two symbols that are used to send binary data: one symbol for logical “1” and another for logical “0”. It is very important to choose the symbols in such way that the receiver would be able to correctly decode them without needing any transmitter-receiver synchronization information (i.e., the system should work correctly no matter when the receiver or the transmitter are started and there are no other means of exchanging information between them). In addition, the code, when used for switching an LED on and off, should not produce flicker perceptible by the human visual system and should allow robust detection when sampled at low sample rates. Typical cameras used in vehicles to record what is happening on the road capture video at 120 frames per second. Moreover, the new smartphones include a slow-motion video recording function which captures video at 120 frames per second. Designing a communication code that would have the aforementioned properties and would allow correct detection when it is sampled 120 times per second is a clear improvement over the state-of-the-art similar solutions and could bring camera-based VLC available to the large public.

The proposed code consists of two symbols. Their waveforms are illustrated in Fig. 1 and they 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, and both have the same DC component. The duration of the long pulses is 1/240 seconds and the short pulses last 1/480 seconds, so the code will not produce flicker to the human visual system. 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 that can be obtained is 20 bits per second. It is demonstrated further that this code presents very useful properties that makes it usable in flicker free VLC using a low frame rate camera as a receiver.

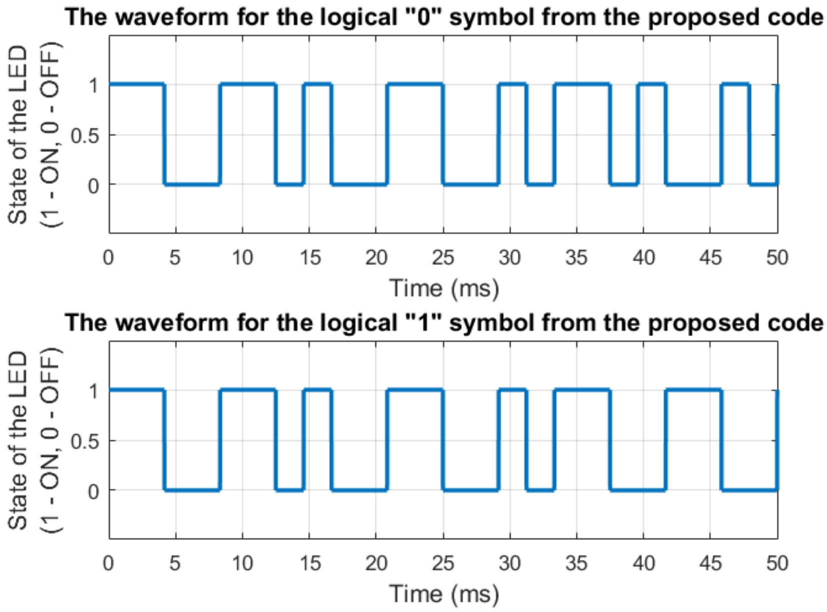

Fig. 1. The waveforms representing the two symbols of the proposed communication code.

A camera having a frame rate of 120 frames per second will capture an image every 1/120 seconds. In every frame, the LED will be captured lit or not, depending on its state in the moment the frame is captured. The frames can be marked depending on the captured state of the LED using two values, generically denoted with “A” (the led was captured lit) and “B” (the led was captured while it was off). 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”. Those cases are illustrated in Fig. 2 and Fig. 3. Because the start of the camera and the start of the LED are not synchronized, there is no information where the sampling points will be placed on the waveforms. Taking this situation into account, the possible sampling points are marked on each waveform using different types of red bullets. 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 frame rate of the camera.

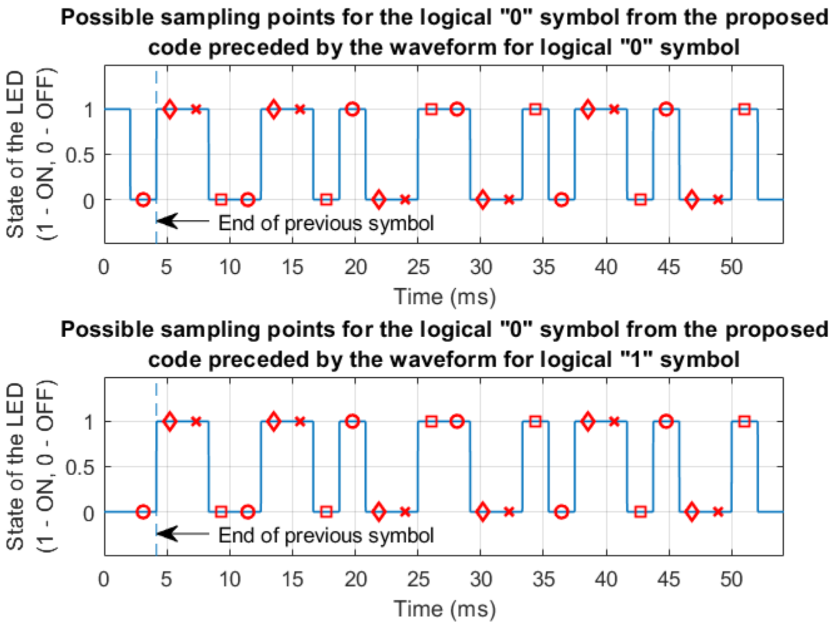

Fig. 2. The possible sampling points for the logical “0” symbol when preceded by both logical “0” and “1” symbols.

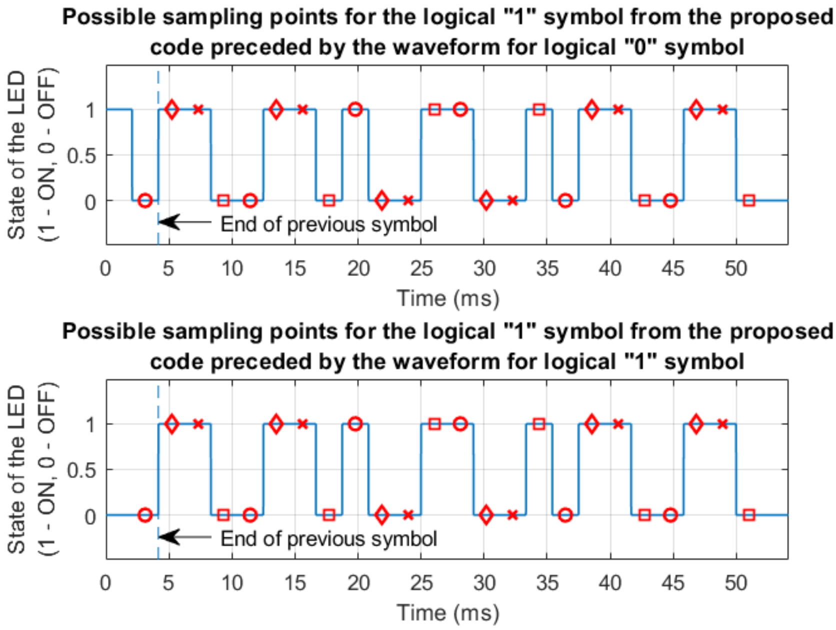

Fig. 3. The possible sampling points for the logical “1” symbol when preceded by both logical “0” and “1” symbols.

The sequences that can be identified by considering the possible sampling points on the four waveforms that were illustrated in Fig. 2 and Fig. 3 are summarized in Table 1. It can be observed that if the logical "0" symbol is preceded by the symbol for either "0" or "1", the extracted sequence is BBAABA or AABBAB (which is the negated version of BBAABA). Also, in the other case, no matter what symbol precedes the logical "1" symbol, the extracted sequence is BBAABB or AABBAA (which is the negated version of BBAABB).

Table 1

Sequences extracted according to each sampling point

Sampling points	Case	Extracted sequence
○	"0" before "0" "1" before "0" "0" before "1" "1" before "1"	BBAABA BBAABA BBAABB BBAABB
◇	"0" before "0" "1" before "0" "0" before "1" "1" before "1"	AABBAB AABBAB AABBAA AABBAA
×	"0" before "0" "1" before "0" "0" before "1" "1" before "1"	AABBAB AABBAB AABBAA AABBAA
□	"0" before "0" "1" before "0" "0" before "1" "1" before "1"	BBAABA BBAABA BBAABB BBAABB

It is shown that it does not matter the state of the LED in each frame, but only the relation of the states of the LED in six consecutive frames leading to only two cases for these relations. Given the state of the LED in the first frame, if the states that are identified in the next five frames are found in the following sequence: same, different, different, same, different with respect to the state found in the first frame, then the logical "0" symbol is identified. The other symbol is identified in a similar manner, the difference being the desired states of the LED in the following five frames, with respect 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 any synchronization between the transmitter and the receiver. If the camera is started in the middle of the transmission of a symbol, that symbol will not be decoded, but the receiver will be able to automatically synchronize with the next symbol and correctly decode it. The symbols that follow will also be correctly decoded.

Detection problems can occur if the signal is sampled exactly on the edges because of the uncertainty of the state of the LED in the captured frame (if the LED is captured while being turned on or off). The probability of this situation is very low, given the very short LED on or off switching time [27] compared to the duration of the shortest pulse contained in the code (1/480 seconds). To increase the robustness of the detection, an enhanced transmitter can be built using two LEDs instead of only one. One LED will be controlled by the signal described above, and the other LED by a slightly delayed replica of the first signal. The optimum delay between the two signals is 1/960 seconds as this will make the edge of one signal to be as far as possible from the edges of the other signal, as shown in the example in Fig. 4.

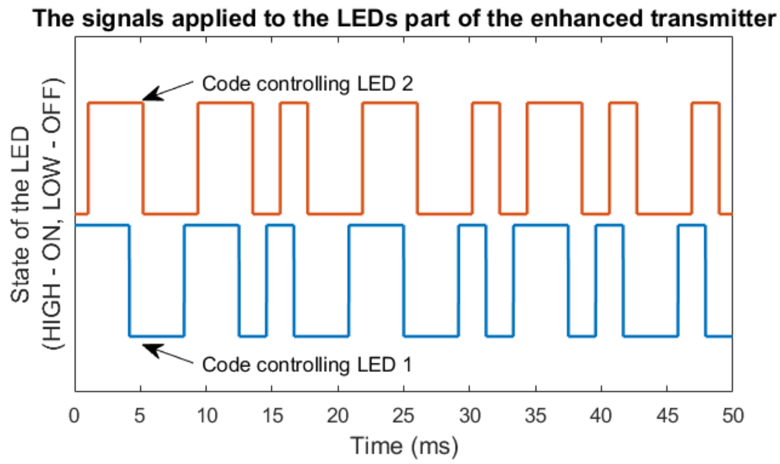

Fig. 4. The signals controlling the two LEDs that form the enhanced transmitter.

The algorithm for the receiver is presented as a flow chart in Fig. 5. It uses a shift register having six cells that is used to store the state of the LED extracted from consecutive frames. When the receiver is started, the register is empty. With each captured frame, a new state is added into the register, depending on the state of the LED in the frame. This process goes on until a pattern that matches one of the two symbols is identified. Then, the corresponding symbol is decoded, and the register is reset. The register can get full without identifying a symbol, if the receiver was started after the transmission of a symbol has begun. If this happens, the register behaves like a queue (first in, first out) until a symbol is identified which, thanks to the automatic resynchronization property of the code, will be the immediately following symbol. The decoding algorithm is run in parallel for the two LEDs. In this way, even if one decoder fails to extract the transmitted signal because uncertain state of one LED (e.g., caused by edge sampling), the other decoder will be able to correctly extract the code.

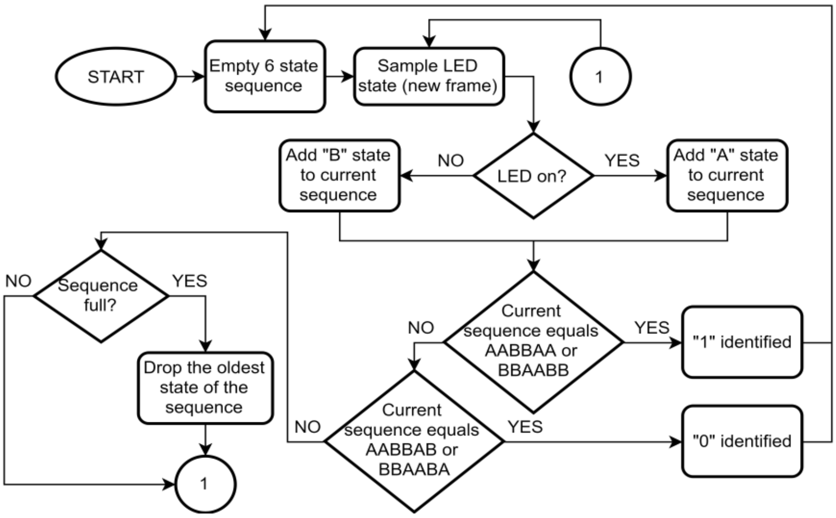

Fig. 5. The flow chart of the algorithm for decoding the received symbols (monitoring one LED).

3. Experimental setup, results, and discussion

The camera-based VLC system presented in this paper was implemented using a microcontroller development board and two general purpose green LEDs as the transmitter, and a uEye UI-1485LE-M-GL as the receiver. The frame rate of the camera was set to 120 frames per second, then 10 seconds of video recording were captured to be further processed using Matlab. The experimental setup is illustrated in Fig. 6. 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. The further processing is done like it was shown in Fig. 5. An example sequence of captured frames is shown in Fig. 7, top row. Due to direct exposure to the LEDs, the camera automatically underexposed the background of the images, resulting very dark overall pictures. This way of functioning is normal. On the same figure, in the bottom row is illustrated the brightness of one line (named “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 red dotted line, and the horizontal position of LED 2 was marked with magenta dotted line), so the state of each LED can be extracted from each frame by comparing the brightness on the position of each LED with the threshold. The brightness is represented using 8 bits. A value equal to 0 means totally dark area and a value equal to 255 means a fully bright area. The brightness threshold is also illustrated. In the given example, it can be observed that the states of LED 1 follow the AABBAB pattern, and the states of

LED 2 match the BBAABA pattern resulting that both LEDs decode the same symbol: “0”. Since the decoding algorithm runs separately for each LED, it is enough for one decoder to correctly extract the transmitter signal to obtain a correct transmission.

Fig. 6. The experimental setup for testing the proposed camera-based VLC system.

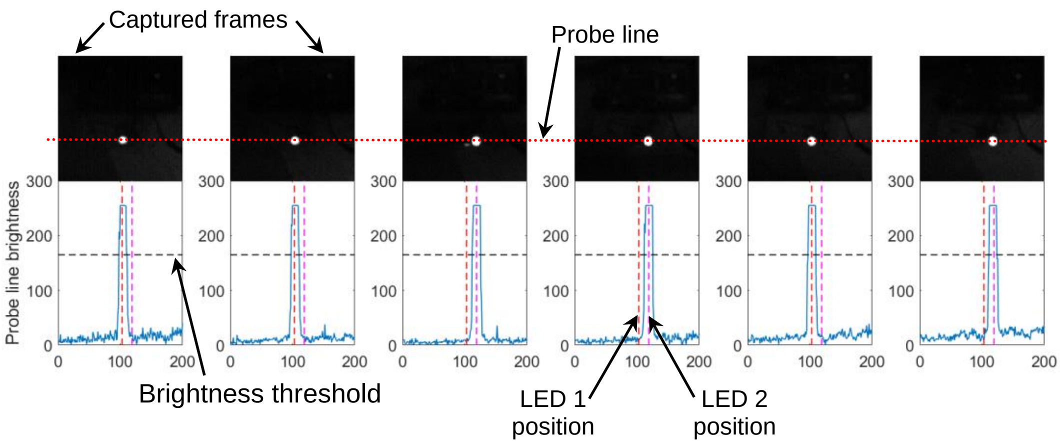

Fig. 7. Example of captured sequence of frames (top row) and the brightness on the probe line that crosses the LEDs forming the VLC transmitter (bottom row).

Noise can be caused by using a high ISO value (an increased image sensor’s sensitivity to light). This manifests as a random variation of brightness and it is one of the most common types of noise in images. This could affect the proposed VLC if the LEDs’ fingerprints (surfaces) on the image is very small, in the order of pixels. This is an extreme case caused by very long transmitter to receiver distance or by using a very low-resolution camera as the receiver. It can be countered by applying a blur effect on the captured images. Another noise source can be considered the movement of the camera, if the images are captured by holding the camera in the hand. This can be solved by using an image recognition algorithm that could identify and track position of the LEDs in the received images.

There are many commercial applications of the proposed system. One innovative system can be represented by advertisement light panels, for example in a museum. The light that is used to illuminate the exhibits can carry an index information using the communication proposed in this work. This index can be used to open a certain web page containing information about the exhibit. In this way, the visitors could get more information about the exhibits by scanning the light that illuminates them with their smartphone, if it can capture video at 120 frames per second, like Apple iPhone X, Google Pixel 2 XL etc. In the future, the proposed communication could become a more elaborate replacement for QR codes.

4. Conclusions

In this paper, the authors designed a camera-based VLC system using cameras that capture images at lower frame rates than similar state of the art solutions. The challenge was to design a system that would work regardless the time when the transmitter or the receiver has been started. The code has the property of allowing the correct decoding of the received symbols without the need of any synchronization between the main components of the system (the transmitter and the receiver). The communication code consists of two symbols: one symbol for logical “1” and one symbol for logical “0”, and the maximum bit rate is 20 bits per second. When controlled by the proposed code, the light sources involved in the system (LEDs) would not produce flicker to the human visual system. The current solutions use cameras with a frame rate of around 1000 frames per second or cameras with lower frame rate, but with the need of a synchronization method between the transmitter and the receiver.

The proposed VLC system was implemented using a microcontroller development board, two standard green LEDs, used as the transmitter, and a uEye UI-1485LE-M-GL camera, used as the receiver. The frame rate of the camera was set at 120 frames per second. The state of the LEDs in each frame was determined by comparing the luminance of the image area occupied by each LED with a threshold value. The experiments validated the functioning of the system.

In a future work, the authors aim to develop a code that will work on low frame rate cameras with 60 frames per second and 30 frames per second.

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