Signal processing scheme for error control in visible light communication data transmission system

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Abstract. We developed wireless visible light simplex data transmission channel and error correction algorithm for the receiver. The system was design specially for using modern smartphone device as a receiver and a conventional domestic LED illuminator as transmitter. We calculated highest probable data transfer speed in our communication channel, fabricated the transmitter modulator and developed the client application for an android smartphone equipped with stock camera module, perform a series of data speed measurements and conducted the analysis of both analog and digital signals. The system allowed to transmit data with rates up to 8 kbps on distance up to 1.5 meters.

1. Introduction

In recent years, technologies that allow to combine advanced functionality in conventional things are emerging [1]. This trend has not bypassed the illumination systems, an important task of which became the wireless communication through modulation luminous flux. Thus, arose VLC technology, using LED as an optical signal transmitter and a photodetector as a receiver [1]. The main signal transmission principle by such a system is based on the light emission modulation with a frequency of the order of several kHz and higher. The human eye is not able to perceive the frequency of flicker above 100 Hz, which allows you to make data transfer using VLC technology imperceptible to a user. A conventional modulation of LED illumination On-Off Keying is based on changes of luminous flux intensity. On-Off Keying is the modulation principle that the developing modulator designed to integrate into existing systems of urban, industrial and domestic lighting without the need to create special systems for matching and integrating additional photodetectors into existing lamps, and thereby expanding the functionality of such systems, providing the opportunity for creating wireless data transfer over the luminous flux. However, a very important functionality degree indicator of VLC technology-based systems is their bandwidth, increasing which, apart from everything else, allows to raise the transmitted data protection level, maintaining channel data transfer speed [1]. Using a mobile device as a receiver in such data transmission systems allows you to make information accessible to a large number of users, due to the absence of the need to have a special separate client module acting as a receiver, however, a mobile device camera module shooting frame rate is often limited to 120-240 Hz, due to the lack of a camera matrix possession ability, which makes it necessary to apply special processing methods of shots. The target of this work was the development of the algorithm that allows to use the maximum of channel capacity by special methods of working with camera frames.
2. System description
A prototype of an office-standard luminaire was used as a signal source. The emitting module consisted of white phosphors LEDs with a modulator was developed by the authors. Luminaire luminous flux was measured amounted to 1680 lm. In order to maintain the intensity of the luminous flux PWM modulation was used. LED luminaire was modulated with 50% duty ratio squarewave signal, the maximum received signal value was set for «1» and the minimum for «0», respectively. The Modulator had a maximum modulation frequency of 1 MHz and was designed to work with a up to 43 Watts LED luminaires. The CMOS censor of the mobile device camera module was used for signal receiving and the mobile device itself for the processing and visualizing transferred data. Mobile device equipped 1/2,6-inch size 12 megapixel resolution sensor and 1/1.8 aperture size camera module was used. The highest frame rate supported by the mobile device was 240 frames/sec. A software package was developed that includes part decoding signal shot by camera and an application designed for a mobile device having a user-friendly interface for reading received data. In order to obtain oscillograph of received signal photoreceiving module was used. The module was developed by the authors and used 4 THORLABS FDS100 Si photodiodes with the 350-1100nm wavelength and rise/fall time of 10 ns. The figure 1 is illustrating the experimental setup, which was used to perform series of algorithm tests.

![Figure 1. Experimental setup of the developing system.](image)

At the first stage, the authors created an algorithm that uses the "rolling shutter" effect. This effect is described in detail by N. Rajagopal et al. in [2]. The developed algorithm allowed to process data at speeds up to 2.5 kbps when shooting at 15 frames / sec. We used modulation frequencies from 1 to 7 kHz. However, a significant disadvantage of this algorithm was the loss of at least of 2/3 transmitted data. Only 1/3 of data transmitted was processed, as depicted in figure 2 (a), that can be explained by the fact that the process of exposing the CMOS matrix and the processing of the received signal are performed sequentially. At the second stage. We developed algorithm, so that the processes described above took place in parallel, thus it made possible to minimize the loss of transmitted information, as shown in Figure 2 (b,c). The figure 2 (c) illustrated the main principal of rolling shutter effect and the implementation of this effect into developed parallel algorithm.
Figure 2 (a, b, c). Schematic representation of the work of the processes of exposure and image processing. (a) sequentially, (b) in parallel, (c) sequential (top diagram) and parallel (bottom diagram) algorithm with the rolling shutter effect implementation, where blue lines are the group of camera module matrix rows that were exposed sequentially, according to the rolling shutter effect, and pink lines depict the time periods needed to process each of the matrix rows group.

3. Results & discussion
Throughout the experiment, all the devices were in a dark room. First, we estimated the channel capacity and measured the data transmission speed in the system. Bandwidth achieved with the use of developed algorithm can be calculated using equation (1), and maximum possible data transmission can be calculated by the equation (2).

\[ B = mNt^{-1}, \]  

where \( B \) is bandwidth, \( m \) is the number of separate exposed censor lines, \( N \) is the number of frames processed, \( t \) is the processing time.

And the maximum possible data transmission can be calculated as follows (2):

\[ B_{max} = s^{-1}, \]  

where \( B_{max} \) is the maximum available bandwidth and \( s \) is the camera module shutter speed of a mobile device.

According to the (2) the highest theoretical bandwidth with our setup using the developed algorithm was 24 kbps, as the shutter speed of a mobile device used during the experiments was 1/24000 sec, while the highest frame rate supported by smartphone was 240 frames / sec. Then we modulated the luminous flux from LED luminaire with 0&1 sequence by squarewave signal. The modulation frequency was from 1 kHz to up to 7.5 kHz. We perform the experiment for 3 different distances to the mobile device. We also use the oscilloscope and photoreceiving module in order to
analyze the optical analog signal we receive by the camera module of the mobile device. The results are shown in the figure 3.

![Figure 3](image)

**Figure 3.** Amount of processed data per second to the modulation frequency at different distances with the first version of the algorithm. The mobile device had 15 frames per second during the experiment.

From the figure 3 it can be seen that the blue and red line, illustrating the dependences at 0.4m and 1.006m, respectively, increase linearly in the modulation section from 1 to 7.5 kHz. The loss of 2/3 of data transferred can be observed at all distances. However, as the distance increases (the green curve), the graph becomes non-linear, which can be explained by a decrease in the received optical power by the matrix of the mobile device, as shown in Figure 4 (a), which causes individual light lines to “merge” into one wider line, as shown in the Figure 4 (b), and as a result, part of the data is lost. The authors also observed a similar problem with a modulation frequency of more than 10 kHz at a distance of more than a meter.

![Figure 4](image)

**Figure 4 (a, b).** (a) Waveform of an optical signal received by a photoreceiving module on a distance of 1.006m and 1.566m displayed by the yellow and blue curve, respectively, the waveform is not a squarewave signal, due to the design of the module (b) screenshots of the “white” and “black” lines received by a mobile device (left — 4 kHz, right — 11 kHz).
During the experiment we ascertain three main speed determining parameters are: sensor exposure time — a function that determines the duration of each pixel exposure, ISO sensitivity — a measure of the camera's ability to capture light and fps. The first two parameters define the contrast of the white and black lines. The results of series of experiments performed by the authors show that the minimal exposure time and maximum ISO value should be used in order to obtain the highest contrast. ISO — 3200 and exposure time — 56311 ns for the mobile device we used during the experiment.

In the second stage we conducted a series of experiments with the optimized algorithm so that the processes of exposure and image processing were parallel. As can be seen from the figure 5, the number of processed bits of information with the optimized algorithm is significantly higher than in the previous experiment, illustrated by the green line in the Figure 5. Moreover, the use of the parallel algorithm allowed us to increase the FPS, which also led to the increase of speed in channel. In addition, we also carried out real dataset transmitting measurements. We used Manchester coding for real dataset experiment. This type of coding allowed us to minimize strobe effect and determine the headline of a code definitely. The results are shown in Figure 5. The drop in the number of processed bits of information on 4.5 kHz can be explained by the fact that using real dataset, causes the sequences of bits contains combinations of several light (or dark) lines in a row, and with the modulation frequency increase, these line rows “merge” into one line, in the same way as shown in Figure 4 (b). The dataset was a pseudo random binary sequence (PRBS).

![Figure 5. Dependence of amount of processed data per second on the modulation; green curve — non-rebuilt algorithm; red curve — rebuild algorithm, blue curve — rebuilt algorithm, using Manchester coded OOK PRBS](image)

**4. Conclusion**

In this work we demonstrated the data transmission via LEDs and mobile device camera and developed the processing algorithm for camera capable to decode signals with modulation frequencies up to 9 kHz with the 0&1 PRBS and up to 4 kHz with the real Manchester coded OOK PRBS data. The future plan is the increasing of data transmission speed due to the introduction of special correction factors in the data processing algorithm, which makes camera better solve sequences with the same repeated symbols. Changing the design of the luminaire can also increase the speed of data transmission. For instance, an additional special-form diffuser will increase the uniformity of the light spot of the luminaire, which, in turn, will increase the uniformity of the light lines, thereby preventing them from merging. We are also
planning to add the ability to detect the brightest zones during the direct exposure to our algorithm. That will allow us to increase the possible speed in the channel by adding the correction index. In addition, we assume that the signal receiving in such a system will often occur from the reflected illumination, which also allows to increase the uniformity of light spot, and, as a result, reduce losses.

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