Errors in simplex data transmission channel based on visible light communication

A I Borodkin¹, I A Krasavtsev¹, E Z Gareev¹, I S Polukhin¹,², O A Kozyreva¹, S A Shcheglov¹, D S Shiryayev¹, M A Odnoblyudov² and V E Bougrov¹

¹ITMO University, Kronverksky Pr. 49, Saint Petersburg 197101, Russia
²Peter the Great St. Petersburg Polytechnic University, Polytechnicheskaya 29, Saint Petersburg, 195251, Russia

E-mail: borodkin.ai@itmo.ru

Abstract. We analyze the wireless visible light simplex data transmission channel based on visible light communication (VLC) technology and determine 2 main types of errors that occur while using a modern smartphone as a receiver. We have calculated highest probable data transfer speed in our communication channel, and have developed a cyclical data transmission system with bandwidths of up to 4 kbits at a distance of 1 m, using a conventional domestic LED illuminator equipped with a modulator as a transmitter and a developed client application for an Android smartphone with a standard camera module as a receiver.

1. Introduction

In recent years, the functionality of data transmission systems is increasing, which not only allows us to obtain advanced new features, but also significantly reduces the cost the complex new systems in general [1]. Following this trend, the use of optical communications systems for various purposes has increased significantly [2]. And the use of VLC technology based systems makes it possible not only to transfer data via modulation luminous flux, but also allows to use such systems for illumination purposes. LiFi systems are already capable of providing bandwidth up to several Mbps [3], while maintaining the functionality of the domestic LED illuminator, however, such systems require the use of a special client photoreceiving module and equipping a mobile device, such as a smartphone, with separate external module is extremely inconvenient and leads to a number of specific limitations. However, a smartphone camera can be utilized as a receiver in VLC systems, which greatly simplifies the use of such a system requiring no special skills, and, as a result, allows more people to use such a system. But in all data transmission systems there is always a bottleneck that significantly affects the bandwidth [4]. A camera module of a mobile device is the bottleneck in the system, due to the low frame rate which is usually limited to 120-240 frames per second (fps). Transmitting a signal with such a low modulation frequency nullifies all the convenience of using the smartphone camera due to the considerable waiting time necessary to transmit even the small data batch. In order to increase the bandwidth and reduce the bit error rate (BER) complex modulation schemes are used in wireless data transmission systems [5]. However, such modulation schemes are not applicable with the camera module of a smartphone. Therefore, the purpose of this work was to develop an algorithm that will significantly increase the receiving and processing data speed while using the camera module of a mobile device in VLC systems as a receiver, as well as to conduct a series of studies and analyze the
errors occurring in such communication channel in order minimize them and increase the bandwidth as a result.

2. System description

In order to perform a series of experiments a data transmission system was created that is capable of providing simplex data transfer with the 4 kHz frequency on-off keying modulation. The modulator, designed to work with an up to 60 Watts LED luminaires, capable 50% duty ratio squarewave signal up to 1 MHz modulations, and a 48 W power 4620 lm luminous flux model of a commercial LED luminary were developed and fabricated in order to use them as a transmitter. 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, 1/1.8 aperture size camera module and 240 fps highest possible frame rate was used. A software package, including camera shot signal decoding algorithm and the mobile device application with user friendly interface for reading and receiving data was developed. In order to obtain oscillograph of received signal 4 THORLABS FDS100 Si photodiodes with the 350-1100nm wavelength and rise/fall time of 10 ns photorecieving module was developed.

2.1 Algorithm description.

The used mobile device does not allow to process an optical signal, the modulation frequency of which is higher than 240 Hz, according to the 240 fps limit. Therefore, to increase the frequency of the processed optical signal, the algorithm that allows using a mobile device to receive and process a signal with a modulation frequency of up to 9 kHz with a shooting frequency of only 30 frames per second was developed. The theoretically maximum obtained bandwidth by utilizing the developed algorithm can be calculated as follows:

$$B_{\text{max}} = \frac{s}{s-1},$$ (1)

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

The algorithm is based on the “rolling shutter” effect, described in more detail by N. Rajagopal et al in [6]. The use of this effect became possible due to the CMOS matrix structure peculiarities. The figure 1 shows the work in general of the developed algorithm, which allows signals whose frequency is several orders of magnitude higher than the mobile device fps being received and processed.
Figure 1. The illustration of the based on rolling shutter effect algorithm; a green line illustrates the bit sequences, transferred with the modulation frequency higher than the fps, red areas determines 1 separately processed exposure area of a smartphone matrix as well as illustrates the time of the one exposure, the blue area depicts no processing between the frames; (a) an example of conventional exposure method when the exposure time $>>$ reciprocity value of modulation frequency ($mf^{1/3}$), (b) the illustration of exposure method used in the algorithm when the separately processed exposure $<$ $mf^{1/3}$.

3. Results & discussion

All experiments were conducted in a dark room to minimize the impact of external sources of illumination. During the first series of experiments a data batch consisted of “ITMO” ASCII alphabetic characters was transmitted using 4 kHz modulation frequency Manchester coding at a distance of 1 m from the illuminated surface to the smartphone lens. One experiment consisted of 100 data batch transfer cycles. Each experiment was conducted 10 times for three different configurations of the LED luminare: a module with a direct luminous flux, a module with the diffuser and the module with the reflective area. A schematic representation setup during the experiments is shown in the figure 2.

Figure 2. (a) A Setup for the experiments, (b) three different configurations of the LED luminaire.
As a result of the experiments, average values of the data batches processing were obtained. The results are shown in the table 1.

**Table 1. Processed data batch with different LED luminaire design.**

| LED luminaire design     | Transferred batches (%) |
|--------------------------|-------------------------|
| Direct luminous flux     | 67                      |
| With diffuser            | 74                      |
| Reflective area          | 87                      |

In this experiment the “processed batch” was considered to be a fully correct transmission of the “ITMO” alphabetic characters with no bit error in whole batch. One bit error was enough to consider the transmitted packet as completely erroneous. The results shown in the table 1 illustrate, the LED luminaire design with the reflective surface is the most effective one with the developed data transmission system. However, despite the fact that repeated cyclical data transmission allows to compensate errors by the number of transmission cycles, the number of erroneous bits received during the first series of experiments will significantly affect the communication channel bandwidth.

In order to identify the most common error appear points of the transferred data batch and to classify the errors the second experiment series were performed. During this experiment 100 batches were cyclically transferred under the same conditions the first experiment was performed. However, in order to identify the errors exactly all the bits of the data batches, except the bits of the batches with no “00001” headline determined were registered. Not all received bits of no-headline batch are incorrect, yet the information decoding in such a batch is of immense complexity. The figure 3 visualize the error bits.

![Figure 3](image)

**Figure 3.** The error bit map where each vertical line means 1 data batch; green lines illustrate correctly transferred batch, while blue lines stand for error headline batch and bit errors are depicted by the red segments of the map.

All the data transferred were received and processed by the developed photoreceiving module and the oscilloscope. By analyzing the oscillograph and the decoded bits the points of errors were definitely determined. The images consisting of light and dark lines exposed and processed by the smartphone were also taken. By analyzing the width and the order of the lines the error bits were detected. In the figure 4 the oscillograph as well as shot images for different segments of the data batch are presented.
Figure 4. (a) A screenshot of an image of the lines that were processed with no errors shot by the smartphone, (b) oscilloscope of the modulated illumination flux, the non-squarewave form on the oscillograph can be explained by the design of the photoreceiving module — the changes between 1 and 0 are registered by the voltage amplitude spike and the length of the only zeros or ones sequence is depicted by the distance between 2 nearest spikes, (c) a screenshot of a no headline registered data batch image, colored in blue data was not processed, (d) a screenshot of an image that was processed as “ITML” rather than “ITMO” due to the the last light line in the sequence was shot and processed shorter than in should be.

The analysis of all data taken allowed to classify the acquiring error to two main different types: the length of a data batch errors, appeared in case of the absence of the headline of a data batch, the dark lines width error, appeared when the algorithm failed to correctly determine the number of 0 bits transferred in a row. By introducing self-learning algorithm there is a possibility to approximate the similar parts of cyclically transferred small amount of data which will allow to decode the most part of a bit sequence in a data batch without received headline, thus the first type of errors will be minimized. The appearance of this type of errors mostly can be explained by the existence of a small delay between the taken by the camera module shots. By the improving the algorithm of parallel exposing-processing the shots this type of errors can also be minimized. The second type of errors can be reduced both hardware re-design introducing the construction of LED luminary with high uniformity level of illumination flux and software optimization by supplementing correction factors to the lines width.

4. Conclusion
In the framework of the study a simplex VLC technology based system capable of up to 4 kbits data transmission in a Manchester mode with a conventional LED luminary under normal conditions as a transmitter and using a standard mobile device camera as a receiver was demonstrated. Two types of errors appear in demonstrated transmission channel were classified and the errors minimization methods were proposed. The future plan is to implement software and hardware error reductions methods as well as perform series of experiments in order to analyze BER with the different modulation frequencies up to 10 kHz and variety of cyclic types of data transfer.
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