Performance Analysis of Software-Defined PHY-I Visible Light Communication System

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Received: date / Accepted: date

Abstract Visible Light Communication (VLC) is an up-to-date issue where Light Emitting Diode (LED) is used for lighting and data transmission. Although interest in Visible Light Communication has increased in current academic studies, the devices ready for commercial use are still lacking. In this study, the system design of semi-software-based visible light communication which is designed to work in Layer 1 of the IEEE 802.15.7-2011 standard is presented and its performance under different conditions is investigated.

Designed on an embedded Linux platform, where LED lights are used as transmitter and photodiode as a receiver, the system can supply the workload of the current standard at basic speeds with a basic physical layer, media access principles, and protocol support. In the structure, software and hardware are designed, which include basic principles such as signal sampling, symbol detection, encoding/decoding in the Physical layer of the OSI network model (PHY), and Medium Access Control (MAC).

Low and high power LEDs as transmitters and photodiodes as receivers are built on BeagleBone Black (BBB), a System on a Chip (SoC) platform. For performance measurements, the measurement results of variables such as ambient brightness, communication distance, ultraviolet (UV) - Polarizer - Neutral Density (ND) filters, and data load are presented.

Keywords Visible Light Communication · LED · PHY Implementation

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1 Introduction

Optical data communication can be realized, for example, by the fire used by the Ancient Greeks and Romans in 800 BC, by the smoke used by the Indians in 150 BC, or by the glass fiber as described in Kao and Hockham’s work in 1966 [12].

The first optical communication was made by Alexander Graham Bell with a photophone experiment in 1880 [5]. In the experiment, sound signals were modulated with sunlight on the transmitter with lenses and transmitted 213 meters through the atmosphere. In the receiver, the modulated light that carries the sound signal was obtained again with the selenium at the focal point [6]. In the research carried out in the MIT Lincoln Laboratory in 1962, the transmission of television signals was carried out at a distance of 50 kilometers using gallium-arsenic light-emitting diodes [23]. This experiment is considered to be the first major success of wireless optical communication. Similarly, in the United States in 1963, the helium-neon laser modulated sound signal was transmitted at a distance of 190 kilometers between Panamint Hill and San Gabrial Mountain. Goodwin published the studies in 1970 [10]. In 1970, Nippon Electric Company (NEC) realized the first laser connection to carry commercial traffic in Japan, at a distance of 14 kilometers, in a full-duplex. Since any infiltration to the wireless optical communication system after 1970 can be detected directly on the receiver side, it has continued to be investigated especially for military purposes.

Optical data to be used in communication is transported by modulating the intensity, phase, or frequency of the light. Direct viewing between the transmitter and receiver is a necessity for successful communication.

As the communication needs are increasing, fiber optic has been the structure that pioneered the development of communication technology. The communication provided by the transceivers on both sides of the light-carrying cables works efficiently as it is isolated from the external environment. One of the most important problems encountered is the cable that must reach every location where communication is needed.

The first optical wireless communication (OWS) systems designed to overcome this problem are realized with the communication devices placed at two points facing each other using a laser beam. The structures provide data communication between two points facing each other using a laser beam between 800 nm and 1550 nm wavelengths. The challenging part of the solution is the variability of the air, which is the communication medium. The atmosphere used as a communication medium has negative impacts on the scatter of light such as;

− Meteorological events such as fog, snow, rain, where smoke or various particles exist,
− Molecule absorption with open-air effects (Rayleigh Scattering)[28]),
− Turbulence effects.

In transceivers that have to see each other directly, the use of sensitive optical elements, precise settings, and angle adjustments, as well as the disruptive effects of the communication environment are considered as the difficulties of the structure.

Another structure that emerged with the development of technology has been the direct or indirect connection of devices that operate with low energy needs, called the Internet of Things (IoT). Wireless sensor networks and visible light communication solutions, which are accepted with their low bandwidth requirements
and wireless communication capabilities, have become prominent subjects in the academic field.

VLC, one of the optical wireless communication systems (OWS), is a new communication technology that will support communication in today’s radio frequency band. In communication, the transfer of information between two or more points is realized using transmitters between 370 nm and 780 nm wavelengths, which is the light band visible. Due to its structure, LED lamp technology from the solid-state lighting group is used and it has distinctive features such as long-lasting use, low power consumption, fast switching, and low cost.

VLC is not only a design that will support radio frequency communication but also offers a new option to wireless communication with the provision of communication with lighting. In the structure known as the visible light communication in the literature, the goal is to provide the lighting and communication together. Therefore, in the current situation, there is an advantage in providing communication for places to be lightened. Visible light communication infrastructure has advantages/superiorities such as; no magnetic propagation (unlike the radio frequency communication), not being affected by magnetic propagation, and enabling lightening and communication with a receiver/transmitter source. On the other hand, there are also disadvantages such as the fact that it is still in the development stage, the protocols designed for communication are slower than radio communication, and lighting is a must for communication.

In IEEE 802.15.7 standard, necessary suggestions are presented to provide an effective medium access protocol, which is the important problem of optical communication and to eliminate the flickering effect of light specific to this standard. The lighting requirement of today’s working environments plays a big role in the proposal of the structure. The communication capability, which is the unique value of visible light communication, comes to the fore in office environments that cannot be lightened with natural light, and in places where lighting is required.

Visible light communication 802.15.7 standards are suitable for creating acceptable systems within the framework of basic needs, although data communication speeds in Layer 1 are lower than today’s communication speeds (between 11-266kb/s). With Layer 1, the structure can be thought of as supportive to existing communication infrastructures. Subtypes of Layer 2 and 3, which can reach a speed of 96 Mb/s, suggest performance values that rival today’s communication infrastructures. In Table 1, the VLC layers are given.

Studies on communication with visible light started in 2003 with the Visible Light Communication Consortium (VLCC) established among Japanese companies [1]. The Visible Light ID System Standard published in 2007 and the Visible Light Communication System Standard published in 2008 are national standards [14]. The Japanese Electronics and Information Technology Industry Partnership (JEITA) has adopted these standards as JEITA CP-1221 and JEITA CP-1222. In 2011, visible light communication physical and medium access layers were standardized by the IEEE 802.15.7 VLC Task Force (IEEE, 2012). This standard, defining the properties of the MAC and PHY layers, has been a milestone in promoting visible light communication in short-range Wireless Personal Area Network Transmission (WPAN).

In the design presented in block structure in Figure 1, a structure is presented in which the transmission medium is air in which LEDs can be preferred as transmitters and optical sensors or LEDs as receivers [8].
### Table 1 VLC PHY Operating Modes

#### PHY I Operating Modes

| Modulation | RLL Code | Optical Clock Rate | FEC  | Outer Code (RS) | Inner Code (CC) | Data Rate  |
|------------|----------|--------------------|------|-----------------|-----------------|------------|
| OOK        | Manchester | 200 kHz           |      | (15,7)          | 1/4             | 11.67 kb/s |
| VPPM       | 4B6B     | 400 kHz            |      | (15,2)          | none            | 35.56 kb/s |
|            |          |                    |      | (15,4)          | none            | 71.11 kb/s |
|            |          |                    |      | (15,7)          | none            | 124.4 kb/s |
|            |          |                    |      | none            | none            | 266.6 kb/s |

#### PHY II Operating Modes

| Modulation | RLL Code | Optical Clock Rate | FEC  | Data Rate  |
|------------|----------|--------------------|------|------------|
| VPPM       | 4B6B     | 3.75 MHz           |      | 1.25 Mb/s  |
|            |          | 7.5 MHz            |      | 2.5 Mb/s   |
|            |          | 15 MHz             |      | 6 Mb/s     |
|            |          | 30 MHz             |      | 9.6 Mb/s   |
|            |          | 60 MHz             |      | 12 Mb/s    |
| OOK        | 8B10B    | 3.75 MHz           |      | 24 Mb/s    |
|            |          | 7.5 MHz            |      | 38.4 Mb/s  |
|            |          | 15 MHz             |      | 48 Mb/s    |
|            |          | 30 MHz             |      | 76.8 Mb/s  |
|            |          | 60 MHz             |      | 96 Mb/s    |

#### PHY III Operating Modes

| Modulation | Optical Clock Rate | FEC  | Data Rate  |
|------------|--------------------|------|------------|
| 4-CSK      | 12 MHz             | RS(64,32) | 12 Mb/s  |
| 8-CSK      |                    | RS(64,32) | 18 Mb/s  |
| 4-CSK      |                    | RS(64,32) | 24 Mb/s  |
| 8-CSK      |                    | RS(64,32) | 36 Mb/s  |
| 16-CSK     | 24 MHz             | RS(64,32) | 48 Mb/s  |
| 8-CSK      |                    | none    | 72 Mb/s   |
| 16-CSK     |                    | none    | 96 Mb/s   |

![Fig. 1 Block diagram of transceiver](image-url)
As a spectrum-rich alternative to RF communications, VLC is of interest to both researchers and industry [17][20]. VLC has been shown as a driving technology that solves the problem of RF communication density in the wireless spectrum and it has the potential to create the infrastructure of next-generation network systems.

The following options can be offered as areas where Visible Light Communication can be used:

- Museums,
- Indoor Location Determination [13][9][30][11] başta olmak üzere Konum Saptaması,
- Clock Calibration [19],
- Internet of Things (IoT), [9][27][26][16],
- Internet of Things with Light (IOL) as a New Structure,
- Next-Generation High-Speed Cellular Networks [25],
- Toy to Toy Communication [24],
- Human Perception [18],
- Mobile Interaction [29],
- Smart Lighting,
- Communication and Assistance in Natural Disasters,
- Security in Defense Systems,
- Hospitals,
- Wi-Fi Spectrum Support,
- Aviation,
- Underwater Communication,
- New Generation Cellular Networks [24][3].

Studies conducted for the adaptation of VLC networks with software show the need to accelerate research in this area [27][4][22]. Similarly, the increase in the number of devices that will become smart by connecting to the Internet may lead to a new type of infrastructure, the Internet of Lights (IoL), in the future.

The rest of the article is organized as follows.

Section II introduces the system structure and its design. Section III presents the study results, and Section IV provides discussions and conclusions.

2 Semi Software Define Design

The design structure is a development platform for VLC networks consisting mainly three parts:

- BeagleBone Black (BBB) board [2] is a low-cost development platform running on Linux operating system, equipped with BeagleBoneBlack, AM335x 1GHz CPU, two microcontrollers, and 65 GPIO for rapid prototyping,
- The printed circuit board, which can be attached directly to the BBB, and contains the transceiver and other hardware parts,
- The driver forms the software part of the structure.

As a System on Chip (SoC) Linux platform, BeagleBone Black (BBB) development board was preferred due to its low cost, flexible input-output ports, and real-time kernel extension installation. The BBB Debian Linux operating system
Wheezy version was run on kernel version 3.8 and Xenomai real-time development framework. On-Off-Keying modulation can be applied in the PHY layer with Manchester code and Reed-Solomon error correction code. To provide channel access between nodes and reduce transmission conflicts, the Carrier Sense Multiple Access with Collision Avoidance (CSMA / CA) MAC protocol type is implemented.

With the real-time kernel plug-in preference, standard Linux network diagnostic tools "iperf" and "ping" commands can be used. Thus, with a UDP connection, one can ping from one node to another and the transmission speed data can be viewed with "iperf". The general view of the driver is shown in Figure 2.

The standard framework used as the communication protocol is presented in Table 2.

With the study, it was aimed to include VLC in smart lighting with low and high power LEDs by integrating cost-effective electronic components. In its basic form, the structure operates at distances of up to 5 meters with a bandwidth of 27 kb/s for Layer 1 of the IEEE 802.15.7 protocol. Figure 3 shows a transceiver unit. Hardware components of the units are presented in Table 3.

3 Performance Evaluation

The variables used in the application scenarios are presented in Table 4. The values of 1, 120, and 300 lux were taken as reference to ambient light. 30, 50, and
Table 3 Hardware Components

|   | Component Description                          |
|---|-----------------------------------------------|
| 1 | L-53SRC-J4 Low-power 5 mm red LED             |
| 2 | REBEL-STAR-NW100 High-power LED, 3V, 2.7W     |
| 3 | OPT101 Photodiode together with an amplifier   |
| 4 | BPW46 Photodiode 350-1120 nm (for just testing) |
| 5 | PCB Communication with BeagleBone             |

Fig. 3 Transceiver

Table 4 Experiments Variable

| Ambient Light | Distance | Frequency | Payload | Filter             | LED                |
|---------------|----------|-----------|---------|--------------------|--------------------|
| 1 lux         | 30 cm    | 5 kHz     | 128 kb  | No Filter          | Low Power          |
| 120 lux       | 50 cm    | 10 kHz    | 256 kb  | UV Filter          | High Power         |
| 300 lux       | 100 cm   | 30 kHz    | 512 kb  | Polarizer Filter  |                    |
|               |          | 50 kHz    | 768 kb  | Neutral-Density Filter |                |
|               |          | 60 kHz    | 1024 kb |                    |                    |

100 cm values were chosen as the distance variables. 5, 10, 30, 50, 60 kHz values were determined as the transport frequency. 128, 256, 512, 768, and 1024 kb were selected as load size variables of the transported measurement data. Filter-free communication, ultraviolet filter, polarized filter, and ND filter (Neutral Density Filter) were used as filter variables.

In Figure 4, the effect of distance and payload size on the throughput is presented. As expected in the structure, as the data load increased, the data transfer
rate increased and decreased with the increase of the communication distance.

In Figure 5, the effect of ambient light and distance on the throughput is presented. Although the VLC structure has been presented with a design that will not be affected by ambient light interference, the data transfer rate decreases slightly in high artificial lighting conditions due to the sensor saturation of the hardware components used.
Figure 6 shows the effect of carrier frequency and distance on the throughput. When the communication transport frequency is increased in the range of 5 kHz to 50 kHz, the data transfer rate increases as expected, and the transfer rate decreases if the communication distance increases. The reason is since the AM3358 processor, located in the center of the structure, adopts the ARM Cortex-A8 design, the basic floating-point operations take 9-12 cycles, and the processing power limit is reached when the transport frequency is 54-55 kHz. There is a NEON™ SIMD coprocessor in the processor and although the processor can perform 32-bit floating-point operations in 1 to 2 cycles since it does not support ”double-precision binary floating-point format”, no coprocessor is used in the communication calculation. For this reason, in scenarios where the transmission frequency is tested with 60 kHz, although the average data transfer rates are more than 30 kHz, they remain below 50 kHz.

In Figure 7, the effect of filter type and distance on the throughput is presented. Among the filters used in filter tests, the circularly polarized filter vanishing point is positioned as zero degrees. Due to its structure, the polarizing filter ensures that only the light reflected in the desired direction reaches the sensor surface. Thus, reflections seen on surfaces such as glass, metal, or puddles can be partially or eliminated. The reason why the measurements realized by filters with the brightness value of 300 lux reach higher data transfer rates compared to the unfiltered ones is the effect of preventing the interferences and reflections from reaching the sensor surface. The ND filter, which has the narrowest light transmission band among the tested filters and close to the limits that the eye can perceive, reaches the highest data transfer rate. The UV filter, which has a wider working range, basically prevents the bursts of light that occur when the UV light hits the sensor, apart from blocking the UV lights coming from the sun and in the invisible area. Although the data transfer rate increases with the filter that prevents the lower band of the spectrum, it cannot provide as much speed as the ND filter because it does not prevent reflections in the visible part of the spectrum.
The effect of LED types on the throughput is presented in Figure 8. As expected, with the use of high power LED, the data transfer rate increases, and the transfer speed decreases with the increase in the communication distance.

4 Conclusions and Future Work

This article presents the design, implementation, and performance evaluation of a platform designed to enable VLC exploration in the field of network-based em-
bedded systems at Layer 1 level communication. The structure in the study has shown that it can be sufficient as a starter kit for VLC research. Going forward, the structure can simply be expanded and various functions can be added. Similarly, with the development of the network protocol, it can be used to support the use of existing networks.

Among similar studies, although the Transceiver designed by Pornchanok Namonta et al. for Layer 1 can reach performance values of 100 kb/s at 2.5 meters (5.9 meters by using repeater), the structure requires complicated ready-made parts and computer connection for processing power [21]. The main difference of our study is that it is cost-effective and self-operating.

More efficient and faster-LED drivers can be suggested for the improvement suggestions of the study. A more efficient structure for high power LED can be created by referring to the LED driver recommendations submitted by Fengyu Che et al. [7] in 2016 and by Yu-Chen Lee et al. [15] in 2016. Similarly, it is possible to replace the BBB circuit that forms the system infrastructure with a more powerful, new generation SoC.

Funding

Not applicable

Conflict of interest

The authors declare that they have no conflict of interest.

Availability of data and material

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

Code availability

Not applicable

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