Embedded Visible Light Communication: Link Measurements and Interpretation

Milad Heydariaan
Department of Computer Science
University of Houston, USA
milad@cs.uh.edu

Shengrong Yin
Department of Computer Science
University of Houston, USA
syin@cs.uh.edu

Omprakash Gnawali
Department of Computer Science
University of Houston, USA
gnawali@cs.uh.edu

Daniele Puccinelli
ISIN
University of Applied Sciences of
Southern Switzerland (SUPSI)
daniele.puccinelli@supsi.ch

Domenico Giustiniano
IMDEA Networks Institute
Madrid, Spain
domenico.giustiniano@imdea.org

Abstract

Embedded visible light communication (VLC) systems built with low-cost commodity hardware are starting to attract the interest of the embedded systems community, but are yet unexplored in many aspects. The performance of VLC channels is not comprehensively studied under different communication settings and scenarios. In this paper we present an experimental characterization of the performance of low-end VLC channels and investigate the impact of various transmitter/receiver settings, protocol-level parameters and deployment aspects using both low-power and high-power LEDs. Our goal is to discover the strengths, weaknesses and limitations of embedded VLC systems.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless Communication*

General Terms

Design, Measurement, Performance, Reliability

Keywords

Visible Light Communication, Data Rate, Packet Reception Ratio, VLC Channels, Performance, Reliability

1 Introduction

In Visible Light Communication (VLC) systems, information is transmitted using visible light with intensity modulation at the transmitter and direct detection at the receiver. A rich body of research exists in the high-end VLC space, where sophisticated physical layer schemes have been devised to achieve throughputs in the Gb/s range. At the other end of the design space, low-end Visible Light Communication (VLC) systems built with cheap commodity hardware have started to attract the interest of the embedded systems community.

Many factors may affect the performance of embedded VLC channels. The specific transmitter/receiver configuration certainly plays a major role, as many different kinds of LEDs may be used for transmission, while reception may be achieved with photodiodes or LEDs. As is the case with RF as well as wired links, the performance of embedded VLC is also sensitive to protocol-level parameters, such as symbol rate and frame payload size. Ambient light level and transceiver positioning settings such as internode distance and alignment also affect the performance.

The specified parameters that affect the performance of VLC, form a performance hypersurface. To characterize the impact of various defined parameters on the performance of VLC and find the "best" settings for each scenario, defined by local minima on the hypersurface, we need a comprehensive study of each parameter which requires exhaustive testing of all possible combinations of affecting parameters.

The goal of this paper is to carry out an initial characterization of the performance of embedded VLC channels across a wide variety of scenarios. Our work is based on the OpenVLC 1.0 platform, a notable example of embedded VLC aiming to bring VLC to the embedded systems community, and offers a complement to the study presented in [17], which to date is the only investigation of embedded VLC channels to be found in the literature.

We present a detailed study for each scenario with different settings for transmitter and receiver to identify strengths, weaknesses and limitations of VLC with different settings under different scenarios. We use various possible transceivers settings to measure the communication performance in terms of data rate and reliability. We employ various combinations of transceiver pairs for each scenario (different LED transmitters, LED and photodiode receivers). We characterize individual scenarios based on the internode distance, the transmitter/receiver pair, the ambient light level, the communication frequency and the frame payload size.

Our main contributions are:

- We evaluate the communication performance of VLC in application level with different settings under different scenarios.
- We characterize the impact of platform and protocol parameters, transceiver positioning and ambient light by exhaustive testing of combinations of different parameters.

2 Related Work

The idea of networking using LED-to-LED communication can be seen in many papers such as Giustiniano et al. [8], Schmid et al. [14], Chun et al. [7], Langer et al. [11] and O'Brien et al. [12] as they described how it is possible to use LED as both light emitter and detector and transmit data using OOK method. Also Vuvcic et al. [15] talked about possibilities of high speed network over VLC up to 1Gbit/s. However, the problem with these implementation needs complicated modulation scheme to achieve throughput above Gbit/s, and it is not easy to replicate their design in a scalable manner that can foster the research in VLC community.

Alternatively, to build low cost VLC platforms, Klaver et al. designed a novel embedded VLC platform in [10] that mounted 22 LEDs in two dimensional area that can receive and transmit light in every direction of a two dimensional space. The design is creative since it can solve the problem about uni-directionality for using one LED. However, the platform can not be connected to the Internet directly compared to our platform. Stefan et al. designed a linux bulb that integrate commercial wireless chipset with light bulb so that a normal light bulb will be functioned as both communication and illumination in [13]. They connected the light bulb to the Internet by running OpenWRT on the wireless chipset.

More recently, OpenVLC [5], is described in Wang et al. [18, 16]. They built the network stack, with some feature of PHY provided by IEEE 802.15.7, mainly developed in Linux driver. They also provide MAC layer implementation and interface to IP stack but the platform could only support LL-to-LL. They further improved their platform by constructing multiple communication links with different types of LED in [17]. In this paper, we adopt the OpenVLC1.0 platform in [20] to understand the performance of the platform with different experiment settings.

3 Experimental Settings

In this section, we describe the experimental settings for the evaluation. We adopt the OpenVLC1.0 platform that can be mounted on a BeagleBone Black board running a Debian Linux, since it is low cost, open source and easy to prototype.

3.1 OpenVLC

Our experiment platform OpenVLC [5, 17] consists of a BeagleBone Black [3] device and a printed circuit board (called cape) that can be easily attached to BBB, as shown in Figure 1. The equipped device can be connected to a computer using a USB cable and used as a network interface. Then we can connect to the device through SSH, setup the cape and do the experiments. We used the low-power and

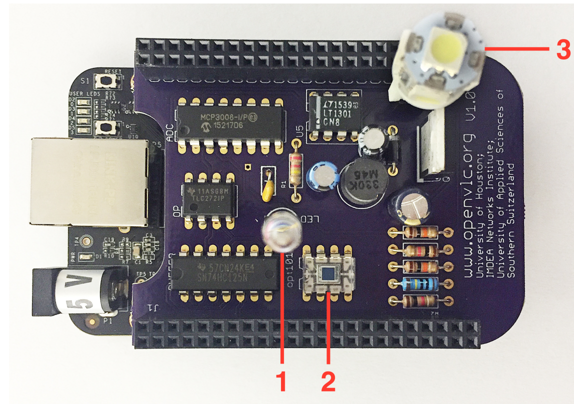


Figure 1: The OpenVLC1.0 platform. The cape is attached to BBB, the optical transceivers are shown: (1) Low-power LED, (2) Photodiode and (3) High-power LED

high-power LED circuitries presented in [17, 18, 19] and [9], respectively, in order to support different communication channels in a single board but we slightly improved the cape design to make the photodiode non-detachable and to make the GPIO pins accessible when the cape is connected to BBB.

BeagleBone Black: BeagleBone Black is a low-cost development platform that runs the Debian Linux operating system, offering full control over the GPIO pins and supporting the deployment of a cape on top of the device easily, which makes our platform small and easily usable.

BeagleBone Black Cape Design: The cape supports both low-power and high-power LEDs as well as a photodiode in one board which we can configure the driver using software-defined commands to use each of these three components as a transceiver.

Low-power LED: A low-power LED can be used both as TX and RX with our current modulation, on- off keying. We used TLCR5800-ND, a red LED in both nodes as our low-power LED.

High-power LED: A high-power LED can only be used as TX in our platform. We used EV-WEDGE-1W as our high-power LED.

Photodiode: A photodiode can only be used as RX in our platform. We used OPT101 photodiode as the receiver component.

3.2 Deployment and Measurement Tools

Ambient Light Setup: We use a combination of a dimmer switch and a few lamps to create and control the ambient light with help of a light sensor, TSL2561 [1], connected to an Arduino Uno [2] to to measure the light intensity.

Measurement Tools: For our measurements, we used iperf 2 [4], a network measurement tool. To avoid the need to receive ACK packets and to measure PRR correctly without retransmission, we exclusively employed UDP packets.

3.3 Metrics

To evaluate the communication performance in the dimensions of data rate and reliability, we used two metrics, throughput and PRR. Unlike the previous work [17] which

TX	RX	Distance	Ambient Light	Frequency	Packet Size	Alignment
LL	LL	50 cm	1 lx	5 kHz	0.1 kB	0°
HL	PD	100 cm	120 lx	10 kHz	0.2 kB	90°
		200 cm	300 lx	30 kHz	0.5 kB	180°
		300 cm		50 kHz	0.8 kB	
		400 cm		60 kHz	1.0 kB	
		500 cm			1.2 kB	

Table 1: Possible experiments for exhaustive testing

TX	RX
Low-power LED (LL)	Low-power LED (LL)
Low-power LED (LL)	Photodiode (PD)
High-power LED (HL)	Low-power LED (LL)
High-power LED (HL)	Photodiode (PD)

Table 2: Possible combinations of transceivers with current experiment platform

TX	Distance	Ambient Light	Packet Size	Alignment
LL	100 cm	1, 120, 300 lx	0.8 kB	180°
HL	30 cm	1, 120, 300 lx	0.8 kB	180°

Table 3: Experiment settings for impact of modulation frequency on the performance of VLC

TX	Distance	Ambient Light	Frequency	Alignment
LL	100 cm	1, 120 lx	30, 50, 60 kHz	180°
HL	30 cm	1, 120 lx	30, 50, 60 kHz	180°

Table 4: Experiment settings for impact of packet size on the performance of VLC

measured the MAC layer performance, we measure the metrics of communication performance in using UDP packets to represent the application layer performance of VLC. Theoretically, UDP throughput is lower than MAC throughput because of the overhead added by two additional layers but using UDP makes the development of VLC applications easier and it is more applicable.

3.3.1 Throughput

We measure UDP data rate using iperf to represent the application level throughput of the communication channels. In this paper we use data rate referring to throughput.

3.3.2 Reliability - PRR

We measure communication reliability in terms of packet reception ratio. Iperf measures the percentage of dropped packets in each time interval. We utilized this measurement to calculate the packet reception ratio using UDP packets.

3.4 Experiments

There are various parameters that affect the communication performance. In Table 1, we show the range in which each specified parameter can vary to form a new set of experiments.

However, we observed from experiment results and from previous work [17], that conducting all the possible experiments would result in almost the same patterns and redundant results in many cases. Hence we tried to choose the best set of experiments to represent the critical regions for each parameter with respect to communication performance.

4 Measurement Results

We categorize the different parameters impacting the system performance into three groups of the communication setup, including the transmitter/receiver configuration as well as protocol-level parameters, transceiver positioning and the ambient light level.

4.1 Platform and Protocol Parameters

Platform parameter means different transceiver components while protocol parameters refer to software-defined configurations such as symbol rate and frame payload size.

4.1.1 Transmitter/Receiver Components

Our experiment platform is capable of switching between sets of transceivers by using software level commands. Since only low-power LED can be used as both TX and RX, we can form the four combination of transceivers as shown in Table 2.

This capability of the platform allows communication over four channels by selecting each pair of transceivers. Difference in performance of each channel is a result of structural differences of pairs transmitter/receiver. A low-power LED has a very small FOV of 8°and more light intensity compared to the omnidirectional 180°high-power LED that we used in our experiments. However, a low-power LED has a very low sensitivity compared to a photodiode and cannot distinguish between ambient light and a low intensity light.

4.1.2 Symbol Rate

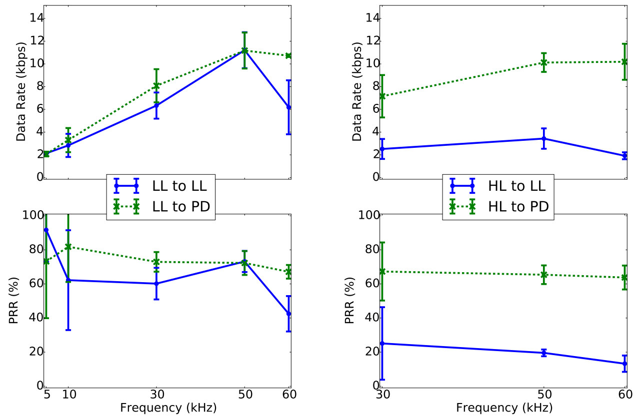
We can also define VLC channels in term of symbol period, which upper-bounds the communication frequency. We show our experiment settings in Table 3.

As we show in Figure 3 throughput is decreased as ambient light level goes higher. However, we observe similar trends for different ambient light levels. Hence we summarize the results in Figure 2. We can send more bits every second by increasing the symbol rate, but the data rate becomes unstable over 50kHz. By increasing modulation frequency to over 50kHz, we increase the chance of any momentary interference to degrade the performance.

4.1.3 Frame Payload Size

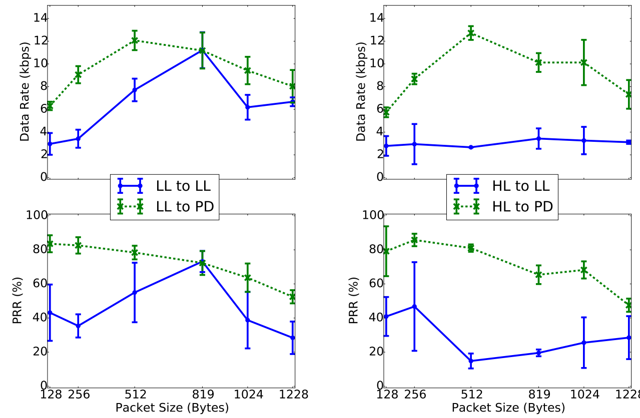
Our measurements are based on sending UDP packets with different sizes, therefore we refer to frame payload size as UDP packet size. In this section, we explain how packet size affects the performance of VLC channels. Our experimental settings are shown in Table 4.

From Figure 5 we observe that the higher data rate is achieved with 50kHz and 512B. We can send more bits in each transmission by increasing the packet size, but sending larger packets increase the chance of error because any small error makes the whole packet erroneous as PRR plots in Figure 4 verify this fact. The trends are similar for different combinations of Table 4. Hence we summarize the results



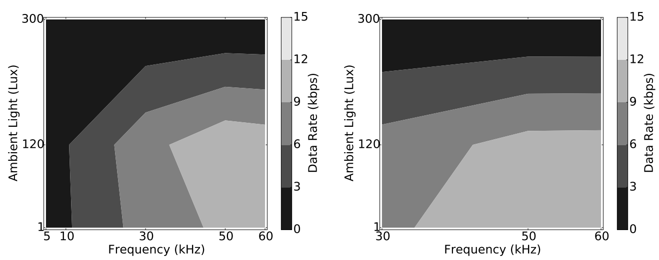
(a) Low-power LED as TX **(b)** High-power LED as TX

Figure 2: Impact of modulation frequency on throughput and packet reception ratio. We only show the results for ambient light intensity of 120 lx. Increasing modulation frequency results in a higher throughput but less reliable channel.



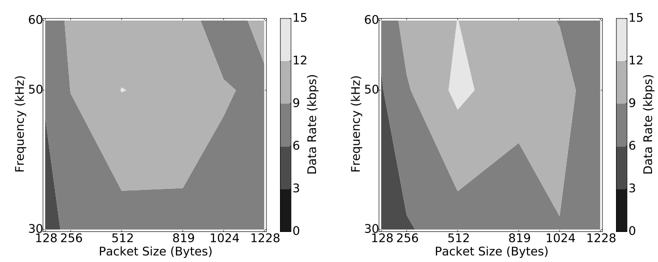
(a) Low-power LED as TX **(b)** High-power LED as TX

Figure 4: Impact of packet size on data rate and packet reception ratio. We only show the results for ambient light intensity of 120 lx and frequency of 50 kHz. Increasing packet size increases the throughput but also increases the chance of error.



(a) LL-to-PD **(b)** HL-to-PD

Figure 3: Data rate contours comparing different modulation frequencies and ambient light levels. Less ambient light and higher modulation frequency results in higher data rate.



(a) LL-to-PD **(b)** HL-to-PD

Figure 5: Contour plots comparing data rate with different packet sizes and different modulation frequencies. More data rate observed in 50kHz and 512B.

in the same figure. For LL as TX, the best performance is achieved in 0.8kB. HL to LL has a poor performance but less affected by the packet size.

4.2 Transceiver Positioning

Deployment scenario constraints the transceiver positioning which has a huge impact on communication performance. We observe the results of our measurements by changing two important positioning factors of internode distance and alignment.

4.2.1 Distance

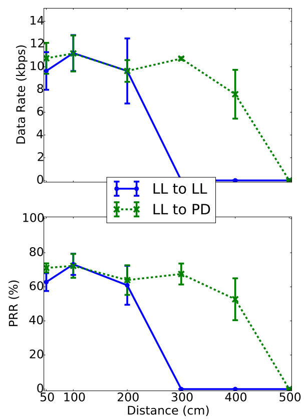
The internode distance has a major impact on VLC performance. Longer internode distance decreases the light intensity and increases the interferences. With our experiment platform and the transceivers, we couldn't achieve the same distances for high-power LED measured in [17] because the high- power LED used in our work has a more FOV compared to that work and the light intensity decreases quickly

TX	Ambient Light	Frequency	Packet Size	Alignment
LL	1, 120 lx	30, 50, 60 kHz	0.8 kB	180°

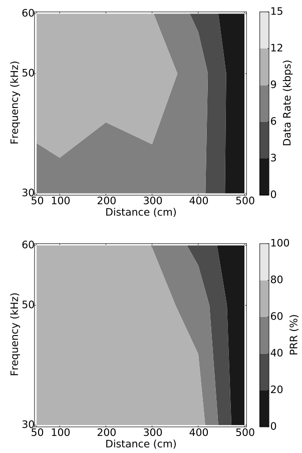
Table 5: Experiment settings for impact of internode distance on the performance of VLC

even in short distances. Since the maximum distance with high- power LED as transmitter was less than 50 centimeters, we omitted the results of HL as TX. Our experiment settings are shown in Table 5.

As shown in Figure 7 we could achieve the distance up to 5 meters with a photodiode as receiver and up to 3 meters with a low-power LED as receiver. Photodiode is more sensitive and can receive from longer distance compared to low-power LED which can only sense high intensity light.



(a) Low-power LED as TX



(b) LL-to-PD contours comparing data rate and packet reception ratio with different distances and different communication frequencies.

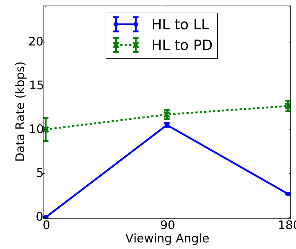
Figure 6: Impact of distance between transceivers on data rate and packet reception ratio when ambient light is 120 lx. Data rate decreases as the light intensity of transmitter decreases by increasing the distance.

TX	Distance	Ambient Light	Frequency	Packet Size
HL	30 cm	120 lx	50 kHz	0.1 kB, 0.2 kB 0.5 kB, 0.8 kB 1.0 kB, 1.2 kB

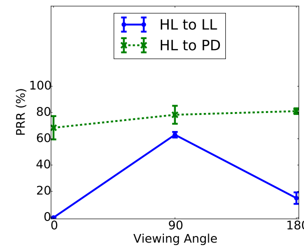
Table 6: Experiment settings for impact of internode alignment on the performance of VLC

4.2.2 *Alignment*

The direction of the LED has a significant influence towards on the point-to- point performance. We evaluated the performance of VLC under different internode alignments. We configure high-power LED as the transmitter and employ both the low-power LED and the photodiode as the receiver. Our experiment settings are shown in Table 6. Figure 7a shows the impact of the viewing angle between the TX and RX on the throughput. As we see in the figure, from 0°to 180°, the throughput is stable for PD compared to LL as the receiver. We also note that LL cannot receive any packets with a viewing angle of 0°while PD still can. This is because the photodiode we are using is able to receive light from a wide range of angles. Figure 7b shows the impact of the viewing angle between the TX and RX on the PRR. Using a low power LED as a receiver has lower PRR compared to the HL to PD link. Also, with different packet sizes, the PRR exhibits large variations even with respect to the same link. For example, with a packet size of 128 bytes, the HL to PD link can achieve a PRR of 80%, while the HL to LL link only achieves 60%.



(a) Data Rate



(b) PRR

Figure 7: Impact of viewing angle on data rate and packet reception ratio. We only plot the results only for packet size of 512B. By positioning TX and RX with different viewing angle, the throughput change and PRR change can be observed.

TX	Distance	Frequency	Packet Size	Alignment
LL	100 cm	30, 50, 60 kHz	0.8 kB	180°
HL	30 cm	30, 50, 60 kHz	0.8 kB	180°

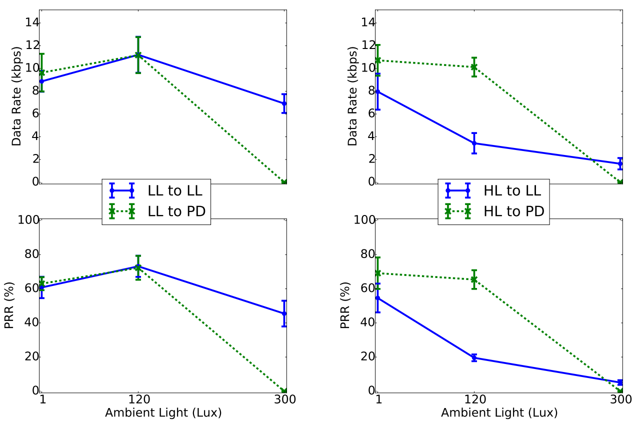
Table 7: Experiment settings for impact of ambient light level on the performance of VLC

4.3 Ambient Light

We designed a set of experiments to observe the impact of indoor lighting on the performance of VLC. We conducted the indoor experiments in a windowless office where ambient light could be controlled by adjusting the dimming level. We show our experiment settings in Table 7. Figure 8 shows the performance results when we adjust the ambient light level in typical indoor scenarios. One interesting result can be observed in Figure 8a which in a complete dark room (1 lx), the VLC performance is less than the regular office lighting scenario (120 lx). The reason for this behavior is the spectral responsivity of the receiver component (LL and PD [6]). In a complete dark room, the red low-power LED we used cannot saturate the receiver enough to output a considerable amount of voltage. But the white high-power LED can easily saturate the receiver as the results in Figure 8b suggest. When comparing LL and HL as TX in the dark room, we observe that the VLC performance for HL is better than LL and even better than typical office lighting.

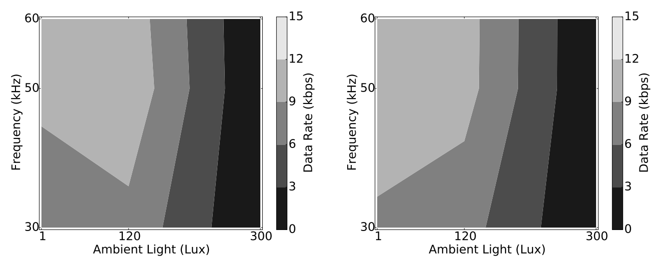
5 Conclusions

We have investigated the performance of embedded VLC channels in various scenarios, focusing on the key performance metrics such as throughput and packet reception ratio. After investigating various setups, we have ascertained that no single setup can guarantee an adequate performance across different scenarios. Going forward, we believe that embedded VLC efforts should keep all options open. For instance, LEDs deserve to be considered as receivers beside photodiodes and high-power LEDs can be attractive for omnidirectional communication. The impact of ambient light is significant, and the use of cheap front-end optics to lessen it should be considered.



(a) Low-power LED as TX **(b)** High-power LED as TX

Figure 8: Impact of ambient light level on data rate and packet reception ratio. We only show results for 50kHz in this figure.



(a) LL-to-PD **(b)** HL-to-PD

Figure 9: Contour plots comparing data rate with different ambient light level and different modulation frequencies. More data rate observed in higher communication frequency and less ambient light.

Acknowledgments

We are grateful to Qing Wang for sharing the VLC electronics schematics and codes used in [17, 18, 9] and therein, and for fruitful discussions.

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