Low-Cost, Flexible and Open Platform for Visible Light Communication Networks

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ABSTRACT

Built around a cost-effective embedded Linux system, OpenVLC1.0 is an open source, flexible, software-defined, and low-cost platform for research in Visible Light Communication (VLC) Networks. OpenVLC1.0 consists of simple electronic hardware for optical transmission and reception, and of software implementation that runs the MAC layer, part of the PHY layer, and offers an interface to Internet protocols. We have designed and developed a printed circuit board (OpenVLC1.0 cape) that implements a flexible optical front-end. Researchers can plug the cape into the main Beaglebone board and swiftly build and prototype innovative PHY and MAC protocols using the software implementation (OpenVLC1.0 driver). In this work, we provide preliminary measurement results that demonstrate the flexibility of the platform in a few but yet representative scenarios.

Categories and Subject Descriptors

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

1. INTRODUCTION

Visible Light Communication (VLC) is emerging as a complementary technology to traditional Radio Frequency (RF) technologies. VLC is believed to be a candidate for the next-generation cellular networks [18, 3], indoor localization [11, 2] and the Internet of Things [9, 22, 13]. Recent attempts for "softwarization" of VLC networks [22, 16, 6] show the need to speed up the research progress in this new field.

In this paper, we present OpenVLC1.0, a low-cost, flexible and open-source platform for rapid prototyping of VLC systems. To ease the exploration of the optical front-ends, we design and implement a printed circuit board (OpenVLC1.0 cape) that includes an optical front-end consisting of a high-power LED (HL), a low-power LED (LL), a Photodiode (PD) and simple circuitry that can be easily attached to a cost-effective and powerful embedded board. This plug-and-play approach allows researchers to focus on the software design of communication network protocols and the evaluation of how communication differs with different optical front-ends, without the hassle of wiring the optical components and the electronics in a breadboard. The cape is controlled using the OpenVLC1.0 driver, that implements key primitives at MAC and PHY layers such as signal sampling, symbol detection, coding/decoding, channel contention, carrier sensing and Internet protocol interoperability as well as a set of MAC protocols. Among its many benefits, OpenVLC1.0 provides the basic tools to implement various protocols and prototype them in real-world VLC network setups.

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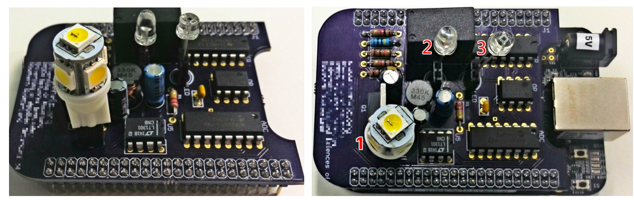


(a) The OpenVLC1.0 cape (b) Cape plugged into the board

Figure 1: The OpenVLC1.0 platform. The embedded board runs a Debian Linux and the OpenVLC1.0 driver to interface the OpenVLC1.0 cape to the Internet. The optical components are: (1) high-power LED; (2) low-power LED; (3) Photodiode (PD).

We provide a proof-of-concept of the capability of the board with a few key experiments with various optical front-end as well as environmental conditions. The results of this preliminary evaluation provide significant insights for the design of adaptive VLC protocols, moving towards reliable VLC networks. The driver and the cape presented in this contribution will be made available to the community.

2. SYSTEM DESIGN

OpenVLC is a research platform for embedded VLC networks. It mainly consists of three parts:

- **BeagleBone Black (BBB) board** [1], a low-cost development platform equipped with a AM335x 1GHz CPU, two microcontrollers, and 65 GPIOs for quick prototyping that runs Linux OS.
- **OpenVLC1.0 cape**, a front-end transceiver that can be attached directly to the BBB,
- **OpenVLC1.0 driver**, that implements the software solutions for VLC networking.

2.1 The Cape

The flexible front-end transceiver adopts the HL, LL and PD to transmit and receive light signals. The transceiver

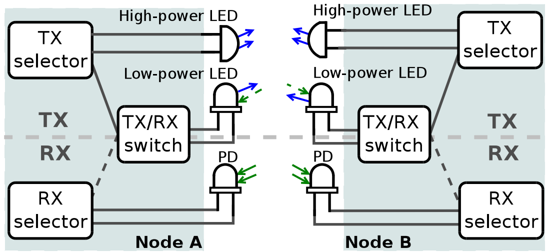


Figure 2: Block diagram of the OpenVLC1.0 cape.

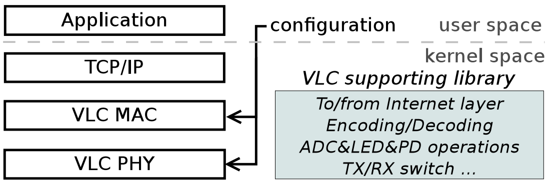


Figure 3: OpenVLC1.0 driver implementation in the software stack of an embedded Linux system.

is designed as a standard BBB cape, that can be easily attached to the BBB board. The prototype is represented in Fig. 1 and a simplified block diagram of the transceiver is shown in Fig. 2. Not shown in the figure, the cape has a DC/DC converter (5V to 12V) to supply the HL. The transceiver can choose a receiver (RX) between the LL and PD through the software-defined RX selector. Similarly, a transmitter (TX) can be chosen between the HL and LL through the software-defined TX selector. The HL can consume a power in the order of $0.1 - 10W$ and uses all the visible spectrum, while the LL has a consumption smaller than 50 mW and transmits using a narrower optical spectrum. Each TX&RX configuration comes with its own unique features in terms of channel propagation, RX sensitivity, Field of View (FoV), transmission coverage, etc. The choice of the optical front-end depends on the application and the ambient environment. For instance, the HL can be used to emulate the scenarios of communication under typical indoor illumination from the ceiling, while the LL can be adopted for applications where the primary goal is communication and the illumination is used as visual feedback. Communication links supported by the cape include:

LL/HL-to-PD communication: LL-to-PD can be used in scenarios where a directional communication, e.g., secure communication, is preferred; while a HL can act as an access point to serve a number of nodes.

LL-to-LL communication: in our platform, a software-defined TX/RX switch allows to control the operation mode of the LL between being a TX and RX [7, 9, 20].

HL-to-LL communication: a pair of HL as TX and PD as RX can form a transceiver that acts as an access point with wide FoV; while a single LL acts as a transceiver residing into embedded size-limited nodes.

2.2 The Driver

A high-level overview of the driver is represented in Fig. 3. Key primitives are implemented at MAC and PHY layers such as signal sampling, symbol detection, coding/decoding, channel contention, carrier sensing and Internet protocol interoperability. At PHY layer, we implement On-Off-Keying with Manchester run-length line code and Reed-Solomon correction code as part of PHY layer of the OpenVLC1.0 driver. We implement three contention-based MAC protocols, among which CSMA/CA for any configuration of the transceiver. In case of LL-to-LL communication, we can further run the CSMA/CD [9] and CSMA/CD-HA protocols [20].

Flexible protocols can be designed to dynamically choose the most desired configuration based on the application. Some motivating tests are conducted in the next section.

3. PRELIMINARY MEASUREMENT

In this section, we characterize OpenVLC in representative experiments. The cape adopts off-the-shelf electronic devices, which are listed in Table 1. Unless otherwise specified, each node uses a symbol period of $T = 20$ μs.

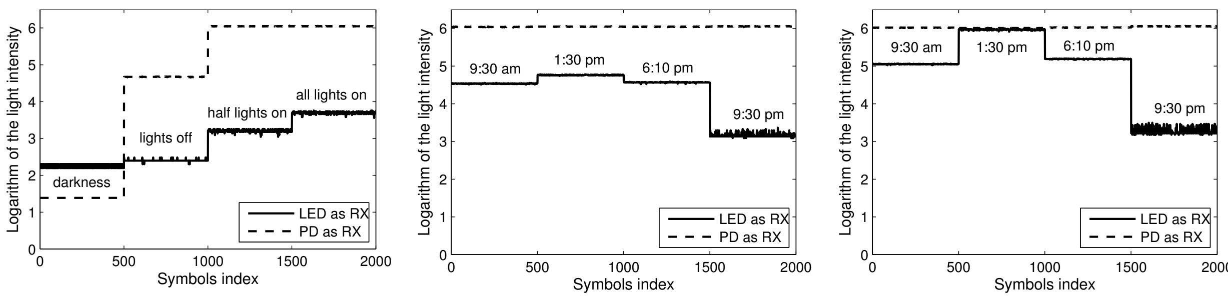
3.1 Optical Transceiver

As presented in Sec. 2, our front-end transceiver can select the optical RX between LL and PD through the software-defined RX selector. To compare their sensitivity, we measure the ambient light noise sensed by LL and PD under three scenarios: indoor, outdoor in the shadow, and outdoor in the sun. There is no data communication during these tests. The measured noises are shown in Fig. 4. For the indoor scenario, we carry out the measurements during daytime with four different settings: darkness (turn off all interfering bulbs and cover the LL and PD with obstructing materials), lights off (only turn off the interfering light bulbs), half lights on (turn on half of the interfering light bulbs), and all lights on (turn on all the interfering light bulbs). In each setting, we read 500 symbols continuously from either the LL or the PD. We observe from Fig. 4(a) that the PD is very sensitive to light changes, and when half or all interfering bulbs are turned on, the PD reaches its saturation state. The LL, however, is less sensitive to the lights emitted by interfering bulbs. Although the light intensity sensed by the LL increases consistently with ambient light noise, the LL is still unsaturated when all the interfering bulbs are on. These experiments show that using LL as a RX is more robust to ambient light interference. As shown in the optical tests conducted in [10, 5], the reason is that the LL is an optical pass-band filter whose receiving bandwidth almost matches the one as LED transmitter (and thus in the order of $625 - 640$ nm in wavelengths for LL) while the PD is a wide-band receiver that collects most of the light from the optical frequencies emitted by the sun.

We then measure the light noise sensed by the LL and PD in outdoor scenarios. Here we place the transceiver first in the shadow and then in the sun, and measure the light noise during different time slots of a day. In each time slot, we also read 500 symbols and the results are shown in Fig. 4(b)-(c). We observe that the PD is saturated during all the time in both the scenarios. The light noise received by the LL

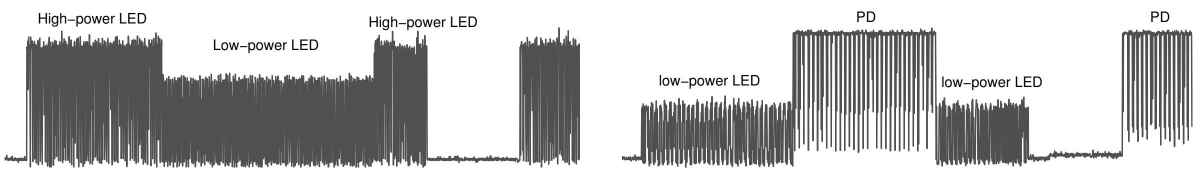
Table 1: Electronic devices used in the platform.

Model	Description
HLMP-EG08-YZ000	Low-power 5 mm red LED
EV-WEDGE-1W	High-power LED, 12V, 1W
OPT101	Photodiode together with an amplifier
74HCT244N	8-bit buffer with tri-state outputs
LM358N	Transimpedance amplifier
MCP3008	10-bit analog-to-digital converter



(a) Indoor (b) Outdoor, in the shadow (c) Outdoor, in the sun

Figure 4: Measurements of the ambient noise under different scenarios through the LL and PD. The outdoor experiments were carried out on a sunny day, with sunrise at 6:47 am and sunset at 9:38 pm.



(a) Switch the TX between the LL and HL during the transmission of a frame (the PD is selected as the RX).

(b) Switch the RX between the LL and PD during the reception of a frame (the HL is selected as the TX).

Figure 5: Change the optical transceiver on the fly during the frame transmissions.

changes with time and the LL is also saturated when exposed to the sun at noon. To conclude, using a single PD as RX under outdoor environment can hardly work for the entire day. It must be combined with additional light filters. Single LL as a RX can work outdoor in the shadow. When exposed to the sun, it also requires light filters to cancel ambient noise when the sunshine is strong. This would however come at an increased cost of the hardware, which is undesired. Dynamic resistance can be added to the RX's circuit to adjust the sensitive the PD. This would help to reduce the exposure of the PD to high ambient light interference. However, this will also shorten the communication distance.

Flexibility: our front-end transceiver is designed with flexibility as primary requirement. Through the software-defined selectors, the transceiver's TX and RX can be changed on the fly. This is illustrated in Fig. 5. The signals captured by an oscilloscope are those received at the RX during frame transmissions. In Fig. 5(a), the TX is switched from HL to LL, then to HL, within the transmission of a single frame. In Fig. 5(b), within the reception a frame, the RX is changed to LL, PD, and then to LL. This feature allows to design protocols that provide reliable performance under mobility, where the interfering light conditions may rapidly change.

Coverage: with different TX and RX, a transceiver's coverage in terms of the angle between a pair of TX and RX varies greatly. From our experiments, we observe that with LL as a RX, the communication link is very directional; while with PD as a RX, the system can work well with a maximum angle of 160 degrees, independent of the setting that either LL or HL is selected as a TX. Multiple LLs should be used to provide similar overall directionality as one single PD.

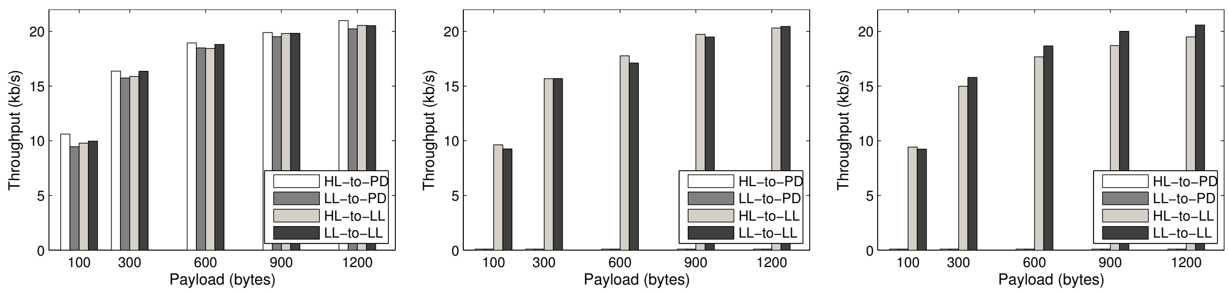
3.2 MAC layer

The saturation MAC layer throughput under a two-node scenario is measured, where the nodes are placed within the transmission range of each other. The saturation throughput is achieved under the setting that one node always has data to transmit to the other. Experiments are carried out for all the visible light links and under three indoor settings: lights off, half lights on, and all lights on. Throughput versus payload of each frame is presented in Fig. 6 using the CSMA/CA protocol. In Fig. 6(a) where all the interfering bulbs are turned off, we observe that the throughputs under all the links increase as the payload increases, e.g., the throughputs are around 9 kb/s when the payload is 100 bytes; while the throughputs can achieve about 20 kb/s for a payload of 1200 bytes. With the settings where interfering bulbs are turned on, the communication links where PD is used as RX can not work, resulting in a throughput of zero as shown in Fig. 6(b)-(c). In contrast, the links with LED as the RX can achieve similar performance as under the setting that all the interfering bulbs are turned off. This is because LL is less sensitive to ambient light interference than PD, and it is still unsaturated when all the interfering bulbs are on.

The achieved saturation throughput versus distance is shown in Fig. 7 under the indoor scenario where all the interfering bulbs are turned off. Here the per-frame payload is fixed to 600 bytes. We observe that the links LL-to-LL and LL-to-PD can work well at distances up to 4.5 m and 5.5m, respectively. The communication distance with the link HL-to-PD is around 4 m, while the link HL-to-LL can only work well at a distance up to 1.5 m.

3.3 Application Layer

The software of OpenVLC1.0 is implemented as a Linux driver connecting to the TCP/IP layers. Thus we can measure the platform's performance using various traditional network measurement tools. Here we present the measured performance under a two-node scenario using the well-know `iperf`. The IP addresses of the nodes are set to 192.168.0.1



(a) Lights off (b) Half lights on (c) All lights on

Figure 6: MAC layer throughput of different links under indoor environment.

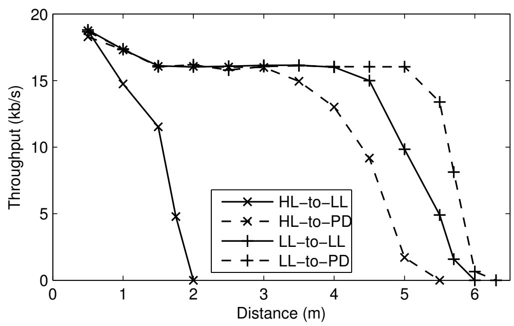


Figure 7: MAC layer throughput versus distance under different links (indoor scenario with lights off).

and 192.168.0.2, respectively. We run each experiment with UDP traffic for 300 seconds. The payload of each UDP packet is fixed to 1000 bytes. We set the `iperf` to report the throughput every 5 seconds. The results under the indoor scenario with lights off are shown in Fig. 8. We can observe that with both the four optical links, the `iperf` performs stable with an average throughput around 12 kb/s.

3.4 Dynamic Environment

In this subsection, we measure the performance of our platform under dynamic environments. The environment is changed by turning on/off the interfering bulbs. From Fig. 9(a)-(b), we observe that the LL as a RX is less sensitive to the light changes, while PD as a RX can not work when the interfering bulbs are turned on.

Based on the flexibility of our platform, we implement a mechanism to dynamically switch the RX between LL and PD. If the mechanism detects the PD is in saturated state, it switches to use the LL as the RX. Similarly, if it detects the LL is out of coverage (recall that the communication link with the LL as a RX is very directional), it switches the RX to PD. We measure the performance of the mechanism under a two-node scenario where the LLs of the two nodes point directly to each other during time slots 80s-150s and 240s-300s, and not during other time slots. From the results shown in Fig. 9(c), we can observe that the `iperf` works stable for most of the time. The dynamic switching of the RX between the PD and LL is shown in Fig. 9(d) and the result is as expected.

4. RELATED WORK

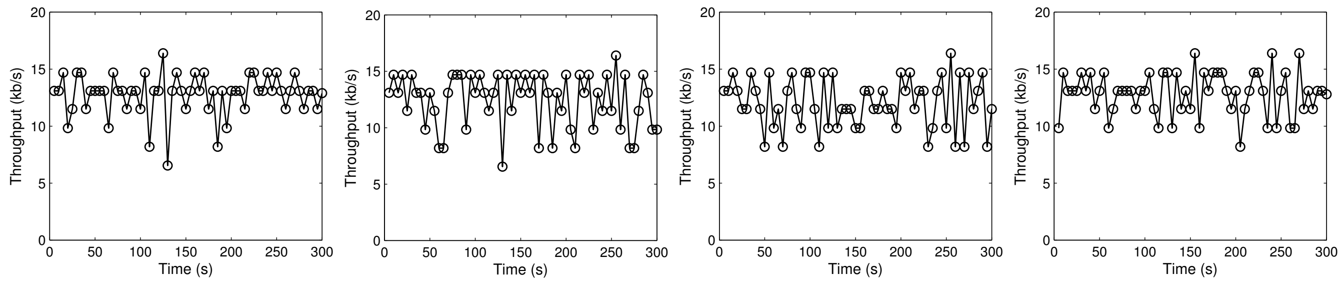
During the past decade, VLC has received strong attentions from both academic and industrial areas. Researchers have investigated VLC for next generation cellular networks [17, 23], indoor localization [12], vehicle-to-vehicle communication [15, 24], screen-to-camera communications [19, 14], etc. The IEEE has developed the 802.15.7 standard [4] for short-range communication with visible light. This standard specifies three PHY layers, which support data rate from 11.67 kb/s to 96 Mb/s. The standard is currently under amendment.

Most of current VLC implementations are based on resource-rich platforms. The work in [8] shows an implementation of 802.15.7 protocol in a software-defined radio platform from Ettus Research. Similar implementations can be found in [25, 16]. These works target at achieving high data rate networks, and their implementation cost is much higher than our target platform. Connecting these works with networking protocols is also not straightforward.

Another category on VLC implementations is based on low-cost solutions, such as [9, 21, 22]. The authors in [9] adopt microcontrollers to build low-power LED-to-LED networks. They study the fundamental research problems of low-cost embedded VLC, and propose a collision detection MAC protocol. Due to the lack of an amplifier for sensed currents, their design is sensitive to ambient noise. An open-source platform is proposed in [21, 22] for the LED-to-LED communication. They adopt one LED at each transceiver and implement the software as a Linux driver. By connecting their work with networking protocols, they can easily evaluate the platform's performance through common networking diagnostic tools. In our OpenVLC1.0, we adopt the same methodology and design a more flexible front-end transceiver that is implemented as a cape attached directly to the main board.

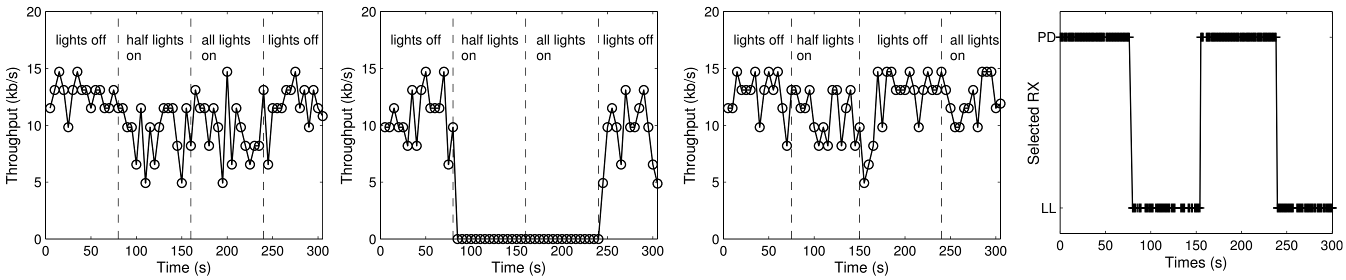
5. CONCLUSION

In this paper, we presented the design, implementation, and preliminary measurements of OpenVLC1.0, a low-cost, flexible, and open platform for networked VLC research. Preliminary measurements have shown that our platform can be adopted as a starter kit for low-cost VLC research, especially for embedded networks with a high-power LED, a low-power LED, and a PD to offer a total of four optical links, and that the design of a reliable, stable communication networks must take into account the unique properties of the visible communication channels and the sensitivity of optical front-ends to interfering sources. The achieved throughput can enable various IoT applications, indoor localization, etc. The driver and the cape presented in this contribution will be made available to the research community.



(a) LL to LL. (b) LL to PD. (c) HL to LL. (d) HL to PD.

Figure 8: Evaluation results of the UDP throughput using the `iperf` (indoor with lights off; evaluation results under other scenarios are omitted due to space limitation).



(a) LL is fixed as a RX. (b) PD is fixed as a RX. (c) Dynamically select the RX. (d) Selected RX at different time.

Figure 9: Evaluation results of the UDP throughput under dynamic environments (LL is selected as TX).

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