

modBulb: A Modular Light Bulb for Visible Light Communication

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ABSTRACT

Due to several interesting properties such as large bandwidth and immunity against radio interference, Visible Light Communication (VLC) has caught the attention of the research community. Current efforts are, however, hampered by the lack of open source platforms. We present modBulb, an open, modular light bulb. modBulb is a VLC transmitter that can be customized to the application's requirements. modBulb enables modulation and other processing through an MCU for flexibility and ease of programming or an FPGA for applications that require higher efficiency. Furthermore, modBulb supports several driving circuits to balance the trade-off between energy efficiency and switching noise. Last but not least, the light source itself can be selected according to the application's requirements. We present experiments that demonstrate modBulb's salient properties.

CCS Concepts

•**Computer systems organization** → *Embedded hardware; Embedded software*; •**Hardware** → *Networking hardware*;

Keywords

Visible Light Communication, VLC transmitters

1. INTRODUCTION

Visible Light Communication (VLC) is emerging as a viable medium for wireless communication. VLC offers numerous advantages over conventional radio frequency (RF) communication, for example, large and unlicensed spectrum, immunity against cross-technology interference and security against through-the-wall sniffing attacks. VLC has predominantly been researched as an alternative to technologies like WiFi, supporting high bitrates of the orders of GBit/s [13]. Recent efforts leverage VLC for sensing [4, 5] or communication with embedded devices [11, 12].

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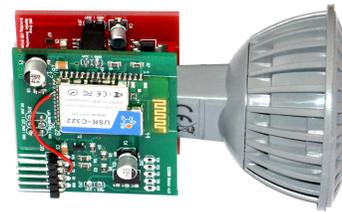


Figure 1: modBulb prototype. *modBulb is easy to customize to an application's needs.*

VLC being an emerging area of research is impaired by the unavailability of open source receivers and transmitters. Consequently, the existing research efforts spend significant resources composing transmitters and receivers using off-the-shelf components [1, 2, 4, 5, 6, 7, 11]. This is complex, time-consuming and makes it difficult to replicate research efforts. Using off-the-shelf components presents three major challenges: First, many systems use multiple deployed LEDs, with each LED controlled by a dedicated low power microcontroller (MCU). Applications using such an approach include indoor localization [4], gesture detection [5, 6] and semantic localization [7]. In VLC applications, LEDs are often located on the ceiling and hence difficult to access. This, together with MCUs lacking network connectivity makes even simple tasks challenging. For example, reprogramming the firmware requires extensive cabling to network the transmitters. Second, the use of low-power MCUs is detrimental to the performance as they often operate at a low clock frequency, thus limiting the achievable throughput. Finally, the transmitters are often designed to support specific applications which makes it difficult to support applications with different requirements.

In this paper, we take a step to ameliorate the problem of the unavailability of tools for VLC research. We design an open-source VLC transmitter. We begin with the question: *Can a transmitter be designed to enable a wide spectrum of VLC applications, yet be simple to operate?* We envision that such a transmitter would be widely usable. For example, in smart homes, it would enable over-the-air (OTA) upgrade of embedded devices while facilitating the control of ambient lights and appliances using gestures [5], or conserve household power by tracking inhabitants [4] and proactively

power cycling appliances. While supporting a range of applications, such a transmitter could be plugged into existing infrastructures and could be controlled wirelessly. To support diverse applications, the following requirements emerge:

1. *Flexible baseband generator*: Applications have contrasting requirements for baseband signals: for example, OTA upgrades require high throughput, while localization schemes transmit beacons at low throughput.
2. *Wireless connectivity*: Deployments should not require additional wiring to network transmitters.
3. *Exchangeable light source*: LEDs support different intensities, colors and wavelengths. For example, communication in the dark requires infrared LEDs, while communication together with illumination requires visible light LEDs.

Designing such a transmitter, however, is challenging owing to the diversity of requirements at stake.

Contributions. To support diverse VLC applications, we design modBulb¹. At the core of modBulb is the modular design which enables seamless adaptation to the requirements at hand. Supporting new functionality is as simple as adding a new module. For example, to support high throughput, an FPGA could be interfaced, or to support network connectivity an additional WiFi radio could be interfaced. More specifically, we demonstrate that modBulb allows:

1. Flexible generation of digital baseband signals on an MCU, an FPGA or a hybrid architecture.
2. Ease of deployment with the ability to wirelessly upgrade the bulb’s firmware over WiFi.
3. Efficient driving of the LEDs, with the flexibility to change LEDs according to applications needs.

The paper proceeds as follows. We first discuss existing VLC systems and how modBulb relates to them. In Section 3, we present a generic VLC transmitter architecture focusing on the different design choices available at each stage. We next describe the instantiations of these stages. Before concluding, we evaluate the overall system.

2. RELATED WORK

The recent interest in VLC has led to a number of VLC-based sensing and communication systems. Tian et al. describe a system that allows communication under extremely low illumination levels using extremely short light pulses [11]. To achieve very short light pulses they control LEDs using an FPGA and a MOSFET driver. Epsilon is a localization system that enables high accuracy indoor localization using light beacons received by an embedded receiver [4]. The authors acknowledge the lack of available off-the-shelf VLC tools. Li et al. describe a system that uses an array of photodiodes to track users’ gestures by detecting their shadow cast [5, 6]. Rajagopal et al. demonstrate the feasibility of communication between LEDs and smartphone cameras to build a semantic localization system [7] while Kuo et al. describe a localization system that uses a smartphone camera

¹modBulb is available at: <https://github.com/modbulb>

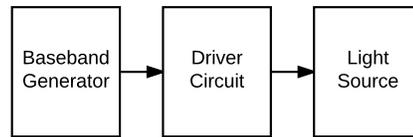


Figure 2: Abstract architecture. *modBulb* features a multistage architecture. Different applications can be supported by an appropriate selection of the components.

as a receiver and achieves sub-meter accuracy [2]. Hao et al. use rateless codes to improve communication between LEDs and smartphones [1]. Lee et al. tackle the problem of heterogeneous sampling rates of cameras and unsynchronized light-to-camera communication [3]. All of these systems design their own transmitters using off-the-shelf available commercial LEDs controlled using either an MCU or an FPGA. modBulb tackles the problem of supporting diverse applications and hence is complementary to all these efforts.

Schmid et al. design a VLC transmitter that uses consumer LEDs and demonstrate a throughput of 1 kb/s [9]. Their system uses an 8-bit microcontroller as baseband generator. They further improve their system by integrating a System-on-chip (SoC) to achieve a hybrid architecture which enables Internet Protocol (IP) connectivity [8]. Our work is related, but differs in two important ways: First, modBulb features a modular design which enables a wide spectrum of applications and abilities including IP connectivity. Second, we design an FPGA-based baseband generator together with an efficient LED driving circuitry which allows orders of magnitude higher throughput.

Zhang et al. develop a mechanism called DLit that adapts the bitrate under link dynamics using properties of VLC links [14]. They acknowledge the lack of off-the-shelf platforms for their work and develop custom transmitters and receivers. They drive consumer LEDs using analog modulation with the baseband signals synthesised by an FPGA. Our work is complementary as it provides an open-source VLC platform. We are, however, limited to only digital modulation in the present prototype and would include support for analog modulation in future versions.

Wang et al.’s OpenVLC [12] is similar to our effort in that it is an open-source VLC platform. OpenVLC’s focus is on the software for Linux-based systems. We complement their efforts by designing a modular transmitter that can be reprogrammed via RF and supports a wide range of applications including those that require high bandwidth.

3. DESIGN

3.1 Architecture

A VLC transmitter transforms information to modulated changes in light intensity through a multistage architecture. We base the design of modBulb on the architecture shown in Figure 2.

The architecture consists of three major components: Baseband generator (BG), driver circuitry and light source. We next describe these stages.

Baseband generator. The baseband generator transforms the information to modulated signals. The baseband generator can be realized either on an FPGA or an MCU. The

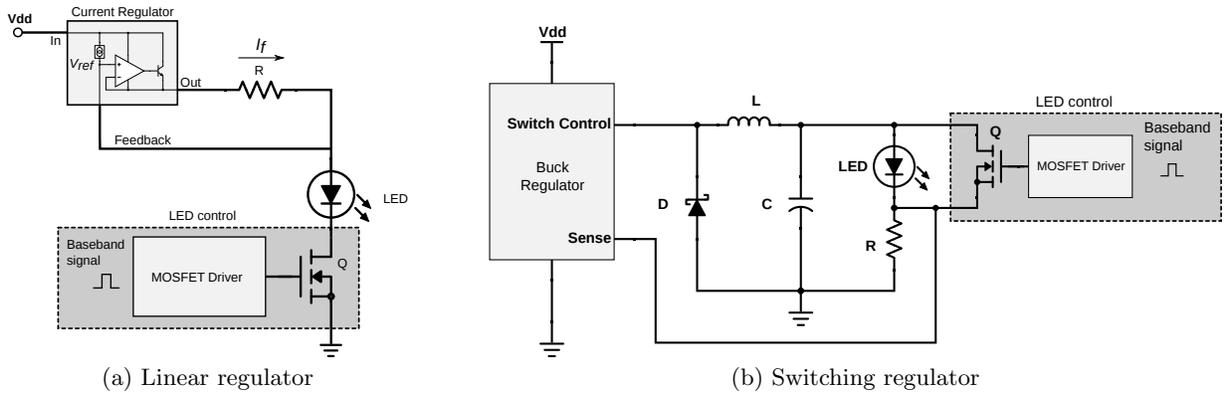


Figure 3: Schematic of driver circuits. The resistor R helps the regulator control the current flow. The MOSFET is driven by the baseband generator and controls the illuminance of the LEDs.

choice is dictated by the desired application goals.

A baseband generator realized on an MCU is the most widely used approach in VLC systems [3, 4, 5, 6, 7, 8, 9]. The MCU provides ease of programming and use, but is constrained by the clock frequency. As a minimum number of instructions needs to be executed at the transmission of each bit, this affects the achievable bitrate. On an MCU, it is also difficult to precisely control the baseband signal [11].

On the other hand, an FPGA allows precise control of the baseband signal, and can operate at much higher clock frequencies. This makes FPGAs suitable for generating baseband signals as is done in some VLC works [11, 14]. FPGAs are, however, significantly more complex to program. It is also often non-trivial to support higher layer functionality such as networking or OTA upgrades which are often intertwined with logic to generate baseband signals.

Driver circuit. The driver circuit tries to achieve the optimal current flow without inflicting damage to the LEDs. Furthermore, the driver circuit converts the baseband signals to electrical fluctuations necessary for the modulation process.

The light intensity of the LEDs is proportional to the forward current flow, and hence LEDs should be driven to the largest supported current to achieve maximum brightness. This is, however, difficult to achieve. The commonly used method to achieve a constant current flow across an LED is to serially connect an LED with a current limiting resistor. This approach, however, is suboptimal for LEDs that draw a current in the order of a few hundred mA . Such LEDs are commonly used in indoor localization systems. The sub-optimality stems from the non-linear relationship between the forward-current (I_f) and the forward voltage (V_f) of the LED. Consequently, a small increase in the forward voltage could significantly increase the current possibly damaging the LED, or conversely a small dip in the voltage could significantly decrease the brightness.

Driver circuits based on switching or linear regulators are commonly used methods to drive LEDs efficiently [10]. The regulators maintain a constant current flow by proactively sensing current across the LEDs. The choice of the regulator affects the energy efficiency and introduced noise in the circuit. Linear regulators draw a high current inducing energy wastage as heat, whereas switching regulators introduce noise which is often hard to filter at the transmitter.

Figure 3(a) and Figure 3(b) present the schematics of our driver circuits that are based on these regulators.

Light source. On a VLC transmitter, the light source is usually one or more LEDs. LEDs are diverse and exhibit varied characteristics. For example, infrared LEDs emit radiation invisible to the human eye. On the other hand, visible light LEDs allow both illumination and communication at the same time. Application requirements dictate the choice of LEDs.

3.2 Implementation

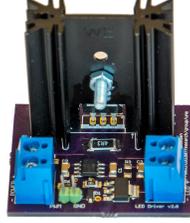
Baseband generator. We implement two different instances of the baseband generator, one using the FPGA and the other using an MCU. These instances can be used alone or together to achieve a hybrid architecture enabling additional processing. The MCU based instantiation uses a Texas Instruments CC3200 System on Chip (SoC). The CC3200 supports a maximum clock frequency of 80 MHz . It also includes an integrated WiFi radio allowing modBulb to be wirelessly networked. On the FPGA based instantiation, we use a Microsemi AGLN250. We operate the FPGA at a clock frequency of 20 MHz , sufficient to support high throughput. On both the instantiations, we support the commonly used digital modulation schemes On-off Keying (OOK), Binary Frequency-Shift Keying (BFSK) and Pulse Position Modulation (PPM). Figure 4(a) shows the CC3200 based instantiation of the baseband generator.

Driver circuit. We instantiate two different driver circuits. In the first instance we use a linear regulator (LR), while the second uses a switching regulator (SR). In both instances, we use DMN6068SE as the switching MOSFET, and MIC4429 the MOSFET driver. The linear regulator based driver circuit uses an LM350 regulator, and on the switching regulator based design we use an LM3406 regulator. Due to inefficiencies of the linear regulator, we add an external heat-sink to dissipate additional heat. Figure 4(b) and Figure 4(c) show our prototypes.

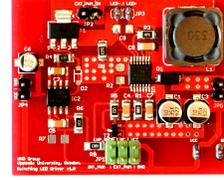
Light source. We have optimised our LED drivers to supply a constant current of 500 mA . The parameters can be optimised to the requirements of the LEDs by changing the current sensing resistor R in the driver circuit. In this paper, we use a commercial LED purchased from a local electronic store. The particular LED is used for indoor lighting, and is rated at a maximum light intensity of 320 lm . The LED



(a) Microcontroller BG



(b) Linear regulator



(c) Switching regulator

Figure 4: modBulb modules. Figure 4(a) shows the MCU based baseband generator which uses a CC3200 system-on-chip. Figure 4(b) and 4(c) show the driver circuit using a linear and switching regulator respectively. The linear regulator is equipped with an external heat sink to dissipate generated heat caused by inefficiencies of the regulator.

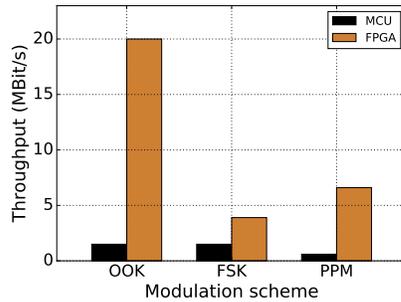


Figure 5: Achievable throughput. The FPGA based BG allows higher throughput at the expense of ease of use.

produces warm white light.

Multiple light sources. The driver circuit allows us to operate multiple LEDs at the same time, as needed by many VLC applications [4, 6]. The maximum number of LEDs that can be operated for a particular driver circuit is given by Eq. 1 for LR based, and Eq. 2 for SR based driver circuits.

$$n = \frac{V_{in} - V_{drop} - V_{sense}}{V_f} \quad (1)$$

$$n = \frac{V_{in} (1 - t_{off} \times f_{sw}) - V_{sense}}{V_f} \quad (2)$$

In the above equations, n denotes the maximum number of LEDs supported, V_{in} the input voltage to the regulator, V_{drop} the internal voltage drop of the regulator, V_{sense} the reference voltage at the feedback terminal, V_f the forward voltage of an LED, t_{off} the minimum off time of the regulator and f_{sw} the switching frequency.

In our implementation, we optimize for the operation of a single LED. Multiple LEDs can be operated by appropriately changing these parameters. The parameters in our implementation are: $V_{in} = 12\text{ V}$, $V_{drop} \approx 3\text{ V}$, $V_{sense} = 1.25\text{ V}$ for LM350 and $V_{sense} = 0.2\text{ V}$ for LM3406, $t_{off} \approx 280\text{ ns}$, $f_{sw} \approx 1\text{ MHz}$ and $V_f \approx 6\text{ V}$.

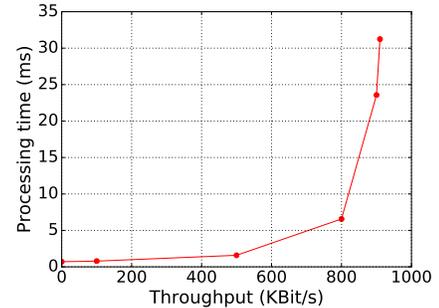


Figure 6: Modulation overhead. The modulation affects the ability of the BG to perform additional processing.

4. EVALUATION

In this section, we evaluate the modBulb’s performance. We first evaluate the individual modules, and finally evaluate the entire system. As a performance metric, we measure the throughput and energy consumption.

Experiment setup. We perform all the experiments conducted in this paper in our offices. We capture the output using a logic analyzer. In order to calculate the energy consumption, we measure the current flow at the input terminals by connecting a multimeter in series. To evaluate the complete system, we design a light receiver with a SLD-70BG photodiode from Silonex. This particular photodiode is most sensitive to a wavelength of 550 nm , which falls in the visible light spectrum. The output is amplified using the LTC6268 transimpedance amplifier from Linear Technology. We further digitize the output using a comparator. Any VLC receiver operating at the same bitrate and modulation could be used, for example, OpenVLC [12].

Baseband generator. We first evaluate the maximum achievable throughput of the baseband generator. We program the FPGA and MCU based baseband generators to modulate at the highest possible throughput and observe the output using a logic analyzer. Figure 5 demonstrates the result of the experiment. As expected, the FPGA based design significantly outperforms the MCU based design. The figure also shows that the choice of the modulation scheme impacts the throughput, as the number of bits encoded per symbol depends on the modulation scheme.

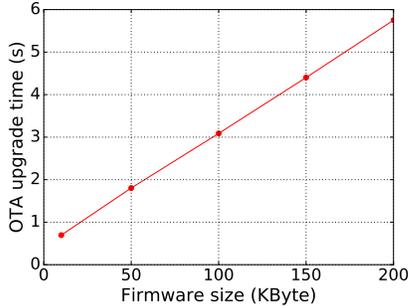


Figure 7: OTA upgrade time. Updating the firmware on an MCU based BG over WiFi only takes a few seconds.

LED driver	LED current (A)	Input power (W)	Output power (W)	Efficiency (%)
Linear	0.566	6.79	3.47	51.10
Switching	0.508	3.48	3.04	87.36

Table 1: Efficiency of the driver circuits. The linear regulator based driver is less efficient than the switching regulator based driver circuit.

We perform the next experiment to assess the impact of the modulation on the processing abilities of the microcontroller. We program the baseband generator to modulate at different throughputs using OOK as modulation scheme. Meanwhile, we transmit a randomly generated packet of length 500 bytes over WiFi to the microcontroller. We perform a 16-bit Cyclic Redundancy Check (CRC-16) on the payload as an illustrative operation. We measure the time it takes to perform the processing operation. Figure 6 shows the result of the experiment. The figure shows that the modulation significantly affects the ability of the microcontroller to perform processing especially at higher throughput.

modBulb enables applications with requirements to perform processing by supporting a hybrid architecture which leverages both the MCU and FPGA. The hybrid architecture enables one of the controllers to perform the modulation process, leaving the other to perform processing. For example, the FPGA can be programmed to generate the baseband signal while the MCU performs the network operations.

We next measure the energy consumption of the two different instances of the baseband generator. According to our measurements, the MCU based baseband generator consumes 93 mW, while the FPGA based module consumes 124 mW.

Driver circuit. The achievable throughput of the driver circuit is dependent on the switching frequency of the MOSFET driver and the regulator. In the present prototype, we are limited by the slow transient response of the regulator, and can achieve a throughput of 1 MBit/s with OOK as modulation scheme. We are working to improve this. The MOSFET driver can operate at much higher frequencies.

We next evaluate the driver circuit together with the LED, as the current draw is also dependent on the LED. Table 1 demonstrates the power consumption and efficiency of the driver circuits. The driver circuit using the linear regulator dissipates almost half of the energy mainly as heat, while

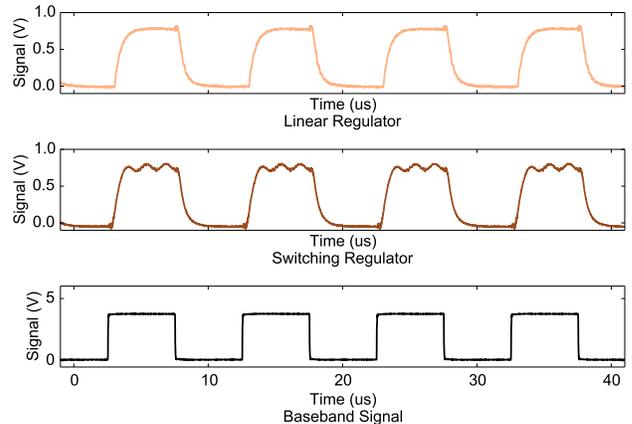


Figure 8: Noise comparison. Ripples in the output is the noise introduced by the regulator. The switching regulator introduces noise at the benefit of power efficiency.

the switching regulator based driver circuit dissipates only 13% of the total energy in switching and as heat. The increased efficiency comes at the cost of introducing noise in the modulating signal, as we see in the received waveform in Figure 8. The noise can be filtered using signal processing techniques at the cost of increased complexity.

modBulb allows the driver circuit to be easily interchanged. For example, on capable receivers the switching noise could be filtered, and the switching regulator based driver circuit could be used. On the other hand, the receivers used in embedded devices might be incapable to filter out the noise, and hence the driver circuit using linear regulators could be used.

OTA upgrade. modBulb enables OTA upgrades of both the MCU and the FPGA baseband generator. As the FPGA lacks access to the WiFi radio, firmware upgrades of the FPGA require a hybrid architecture. The upgrade process works as follows: First, modBulb connects to a WiFi access point. Next, it waits for an update request from the upgrade server on a designated UDP port. Once an update request is received, modBulb opens a TCP connection to the upgrade server, transfers the firmware image from the server, and verifies the signature to confirm integrity. Finally, the upgrade is performed on either the MCU or the FPGA.

First, we evaluate the OTA process on the MCU. We configure the radio to operate at 54 MBit/s bitrate, and connect the MCU to an access point running the upgrade server. We measure the time it takes to perform the upgrade process for different firmware sizes. Figure 7 demonstrates the result of the experiment. The upgrade time increases linearly with the firmware size. Still, it takes only a few seconds to perform the entire process. Finally, we evaluate the OTA upgrade on the FPGA. On the FPGA, the size of the firmware is fixed and it takes approximately 42 seconds to complete the OTA upgrade process.

Exchangeable light source. To meet applications requirements, modBulb allows the exchange or addition of LEDs. In this experiment, we demonstrate the reconfigurable nature of modBulb. We interface additional LEDs to improve the signal levels. In the experiment, we place a light sensor TSL2561 approximately 1.8 m away from modBulb.

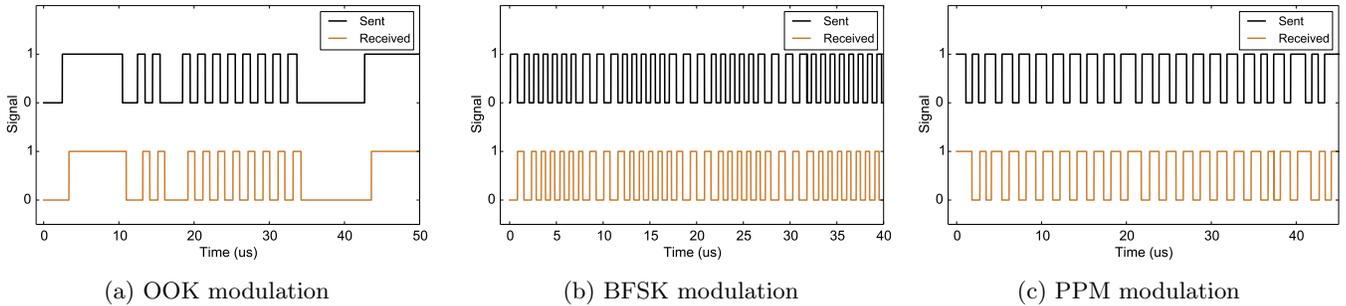


Figure 9: Received waveforms. We receive signals identical to the modulating signal. We send at a maximum throughput of 1 MBit/s, 500 KBit/s and 200 KBit/s with OOK, PPM and BFSK as modulation scheme.

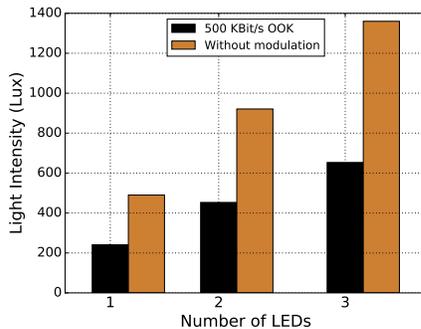


Figure 10: Exchangeable light source. *modBulb* allows additional LEDs to be added to increase the light intensity.

Further, we drive 1,2, and 3 LEDs at a bitrate of 500 KBit/s using OOK as modulation scheme. Figure 10 demonstrates that *modBulb* allows additional LEDs to be driven easily, as the light intensity levels increase as we add more LEDs. The light intensity of the modulated carrier is lower than that of the unmodulated carrier due to the duty-cycled operation of the former.

modBulb. Finally, we evaluate the performance of the complete system. We generate a baseband signal at frequency of 500 KHz resulting in throughput of 1 MBit/s, 200 KBit/s and 500 KBit/s for OOK, BFSK and PPM correspondingly, the three supported modulation scheme. We position the VLC receiver one meter away from the transmitter, and capture the received waveform using a logic analyzer. We compare the sent and the received waveform to evaluate the system. Figure 9 shows the result of the experiment. For brevity, we only demonstrate results from the FPGA based BG and switching regulator driver circuit. The figure shows that the sent and received waveforms are identical demonstrating the complete system. We also perform a long term experiment, where we sent 300 KB of data and receive all data successfully under ambient light conditions.

5. CONCLUSIONS

In this paper we have presented *modBulb*, a generic transmitter for visible light communication. *modBulb* is a modular light bulb that depending on the application needs can perform the processing tasks using either an MCU for flexibility and ease of programming or an FPGA for higher per-

formance. *modBulb* also allows the choice of driving circuits and light source. Our experimental evaluation has demonstrated that, for example, using the FPGA, *modBulb* supports data rates in the order Mbit/s. *modBulb* is available as open source for the research community.

6. REFERENCES

- [1] HAO ET AL. Ceilingcast: Energy efficient and location-bound broadcast through led-camera communication. In *IEEE INFOCOM 2016*.
- [2] KUO ET AL. Luxapose: Indoor Positioning with Mobile Phones and Visible Light. In *MobiCom 2014*.
- [3] LEE ET AL. RollingLight: Enabling Line-of-Sight Light-to-Camera Communications. In *MobiSys 2015*.
- [4] LI ET AL. Epsilon: A Visible Light Based Positioning System. In *NSDI 2014*.
- [5] LI ET AL. Human Sensing Using Visible Light Communication. In *MobiCom 2015*.
- [6] LI ET AL. Practical Human Sensing in the Light. In *MobiSys 2016*.
- [7] RAJAGOPAL ET AL. Visual Light Landmarks for Mobile Devices. In *IPSN 2014*.
- [8] SCHMID ET AL. Linux Light Bulbs: Enabling Internet Protocol Connectivity for Light Bulb Networks. In *VLCS 2015*.
- [9] SCHMID ET AL. Using Consumer LED Light Bulbs for Low-cost Visible Light Communication Systems. In *VLCS 2014*.
- [10] TEXAS INSTRUMENTS INC. LED Drivers for High-Brightness Lighting. <http://www.ti.com.cn/cn/lit/sl/snvy001/snvy001.pdf>. Visited 2016-05-10.
- [11] TIAN ET AL. The DarkLight Rises: Visible Light Communication in the Dark. In *MobiCom 2016*.
- [12] WANG ET AL. Low-Cost, Flexible and Open Platform for Visible Light Communication Networks. In *HotWireless 2015*.
- [13] WU ET AL. 1.1-Gb/s White-LED-Based Visible Light Communication Employing Carrier-Less Amplitude and Phase Modulation. *IEEE Photonics Technology Letters* 24, 19 (Oct 2012).
- [14] ZHANG ET AL. Dancing with light: Predictive In-frame Rate Selection for Visible Light Networks. In *IEEE INFOCOM 2015*.