Using Consumer LED Light Bulbs for Low-Cost Visible Light Communication Systems

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ABSTRACT

LED-to-LED Visible Light Communication (VLC) based on Light Emitting Diodes (LEDs) and microcontrollers provide a foundation for networking using visible light as communication medium. We describe a low-complexity smart LED light bulb prototype that is based on existing consumer light bulbs and hence can be replicated without effort. The protocol software employed for these smart light bulbs is consistent with earlier VLC protocols originally developed for communication between single LEDs. Using VLC with consumer light bulbs leads to improvements in communication range, field of view, and throughput compared to existing VLC communication systems based on single LEDs. VLC-enabled light bulbs are an important contribution to the vision of all-optical networks, i.e., a multi-hop network of light bulbs in which light bulbs deployed inside buildings and communicate with each other using free space optics only.

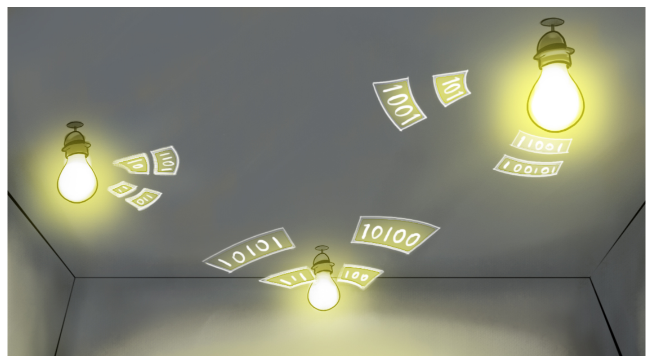

Figure 1: Concept art (© Disney): VLC with smart light bulbs. Light bulbs in line-of-sight communicate with each other (and with toys or mobile devices in the room) using free space optics.

1. INTRODUCTION

Visible Light Communication (VLC) combines illumination and communication. Light Emitting Diodes (LEDs) are an attractive light source for VLC as they are readily available, energy efficient, and subject to industry standardization [1]. Recent efforts to build VLC systems use LEDs both as receivers and transmitters [2] and have focused on low-power single LEDs controlled by a simple off-the-shelf microcontroller [3]. Such VLC systems are appropriate, e.g., for toy-to-toy networks but the limited range imposes restrictions. The illumination of larger spaces demands brighter light sources, e.g., as provided by LED light bulbs, which share many of the attractive features of single LEDs (wide availability, low cost, can be switched rapidly) but impose additional challenges if we want to use simple controllers.

This paper describes a prototype integration of a communicating light bulb based on integrating off-the-shelf consumer light bulbs and low-cost microcontrollers. The prototype light bulb can transmit and receive data using free-space optical communication. The communication protocol stack used for the prototype is based on a solution for single LEDs: A software-based VLC Physical (PHY) layer and a listen-before-talk VLC Medium Access Control (MAC) protocol with contention executed on a simple microcontroller [3, 4].

The LEDs in light bulbs can be switched on and off at high rates (kHz. . . MHz), a feature that allows LED-based lighting to be used for wireless communication by modulating the intensity of the emitted light. Our vision is to build interactive light bulbs that are indistinguishable from consumer light bulbs even while communicating over visible light. Bidirectional communication is possible thanks to the VLC protocol that uses a special coding scheme that ensures no flickering perceivable to the human eye [5].

Smart LED light bulbs can bridge larger distances than VLC devices based on single low-power LEDs. Since many buildings already provide light bulb sockets, no additional resources or interface is needed to power the smart LED light bulbs. Further, such bulbs cannot run out of power as they are supplied by the grid. There are many applications for smart LED light bulbs: They can act as VLC repeaters, amplifying messages and broadcasting them over a network of light bulbs to the intended destination. The light bulbs can also serve as access points to connect to other wide-area networks, or as stationary points to assist indoor positioning [6].

Section 2 gives an introduction to software- and LED-based light sensing and discusses hight power LEDs. Further we present the following contributions:

- Design and implementation of additional electronic circuitry to convert a consumer light bulb to a VLC system (Section 3.3).
- A tutorial how to disassemble and reassemble the light bulb with the help of 3D-printed parts to fit all the electronics in a flexible way (Section 3.4).
- Oscilloscope measurements to show the working system based on the software-based approach described in Section 2.1 (Section 3.5).

2. SOFTWARE-BASED VLC

The VLC system described in this paper is software-based and is hosted on a low-cost microcontroller. The PHY and MAC layers are implemented in software [3]. This setup enables a low-complexity system that is flexible and can be ported to different hardware platforms without effort. Further, the circuitry to modulate the light intensity is straightforward, consisting in only few hardware parts.

The light bulbs described later are equipped with an Atmel 8-bit AVR RISC microcontrollers [7] (ATmega328P). The microcontroller provides the basic features such as analog-to-digital converters (ADC) and timers needed to run a software-based communication system and also delivers reasonable computational performance to run the protocols. The Arduino [8] development boards, available in many different form factors, are also based on this microcontroller and can be used as starting point for development and testing.

2.1 LED-based Light Sensing

A light emitting diode emits light if positive voltage is applied from the anode to the cathode. The pn-junction is forward biased and electron-hole recombination in the junction region occur which result in light generation.

In addition to the light generation ability, an LED is also a photodiode that is sensitive to light at and above the wavelengths it emits [2]. Applying a negative voltage from the anode to the cathode reverse biases the pn-junction. In that case, the n-type section is positive with respect to the p-type section. As a consequence, holes in the p-type region and electrons in the n-type region are drawn away from the junction. Electrons in the p-type region move towards the n-type region and holes in the n-type region are filled. This setup results in a junction that is depleted of charge carriers and no current can flow.

An LED can receive light (with the aid of a microcontroller) by performing two steps in which the anode is always set to ground in output mode: First, the cathode is set to output mode driven high. The LED is reverse biased and its capacitance is being charged. Next, the cathode is set to input mode. At this point the capacitance of the LED is discharged. By timing the duration until the capacitance is discharged, we get an estimate of the photo current passing through the LED, which is proportional to the intensity of the incoming light. The timing measurement is done by measuring the duration until the drop in voltage reaches zero, that is, the digital input threshold. A different method to measure the incident light is to use the microcontroller's ADC to calculate the remaining voltage after a fixed time period. The measured voltage is then reverse proportional to the light intensity.

2.2 White High-Power LEDs

Most types of white LEDs are based on phosphor. The LEDs of commerical LED light bulbs are blue LEDs made of Indium Gallium Nitride (InGaN) and are coated with phosphors of different colors to emit white light. When emitting light, a fraction of this light undergoes a Stokes shift [9] and is transformed from shorter to longer wavelengths. With several phosphor layers of distinct colors, this leads to an increase in the Color Rendering Index (CRI) value of a given LED (spectrum is broadened). These layers block incoming photons and reduce the generated photo current and therefore also the light detection sensitivity. The LEDs are still able to receive but only at a close distance in the order of centimeters.

It is also possible to use RGB LEDs to generate white light by combining all three colors. An RGB LED is based on three separate LEDs with a common cathode or anode. Since the red LED has the shortest wavelength, it will be the most sensitive and can be used as a receiver. While emitting light, all three embedded LEDs can be enabled to generate white light. Unfortunately the three colors are still visible as separate beams and therefore cannot be used for proper illumination.

Further, LED light bulbs employ high power LEDs which need to be driven by higher currents. Often several LEDs are connected in series and demand a higher voltage in the order of 40 V to 90 V, depending on the number of LEDs. In such devices, it is not possible to drive the LEDs directly with the limited current and voltage from a microcontroller output pin.

To build a light bulb that can still be used to illuminate a room but at the same time is able to transmit and receive messages, we decided to use LEDs (reuse the ones already built into the consumer light bulb) and a phototransistor. To operate the phototransistor no changes in the circuit and microcontroller firmware are needed in respect of a system based on only LEDs. Using the phototransistor increases also the reception distance. Unlike the LED, the phototransistor's radiation pattern is more omnidirectional, thus, receiving light within larger opening angles. The light can still be modulated by the microcontroller using an output pin and a driver module (e.g, MOSFET) connected to the operation voltage.

3. SMART LED LIGHT BULB

We present the design and construction of a smart LED light bulb that is based on a consumer LED light bulb. The design reuses electronic parts, such as the power supply and the LEDs, that are already included in the off-the-shelf device. However, the light bulb is extended, using parts produced by a commercial 3D-printer, to make room for additional components. The size and the shape of the VLC light bulb case remain very similar to the original one.

3.1 Safety Precautions

The power supply modules of LED light bulbs are inexpensive and not galvanically isolated, hence, the hazard of an electric shock exists. Working with the power grid requires safety precautions. To reduce the possible hazards an isolation transformer can be employed to isolate the circuitry from the power source. The power transformer is 1:1 and it is used solely for the purpose of safety. It ensures that there is no conductive connection between earth and the transformer secondary. This way, live wires of the circuit are not at a hazardous voltage relative to grounded objects (e.g., the radiator or the computer casing), making it possible to touch ground and a live wire.

As an additional safety measure the isolation transformer may be connected in series with a Residual Current Device (RCD). An RCD is a safety device that switches off the electricity whenever it detects that the current is not balanced between the return neutral conductor and the energized conductor. That is, it detects if there is a fault and electricity flows down an unintended path, e.g., a person.

3.2 Consumer LED light bulbs

Unlike mobile devices an LED light bulb is not battery powered but receives alternate current from the grid. The LEDs, however, are usually powered with direct current. Thus, most consumer LED light bulbs include an integrated AC/DC converter.

We decided to reuse parts of a consumer LED light bulb, including its AC/DC converter, although another AC/DC converter might have more desirable properties. However, finding an AC/DC converter that fits into the case of the light bulb is difficult (esp. when looking for a low-cost solution).

We consider three different consumer LED light bulbs based on their AC/DC converter characteristics and LEDs (Figure 2, Table 1). Light bulb no. 1 is selected for the following reasons: First, it shows the highest luminosity at comparatively low power consumption (most lumen per watt). Second, the AC/DC converter's high output current can be used to power the additional electronics. Further, the light bulb cap is not dimmed like the cap of light bulb no. 2 (in the middle of Figure 2) and its beam angle is not artificially reduced with inbuilt optical lenses as found in light bulb no. 3 (cf. Figure 3) and it provides enough space inside the ceramic setting to fit additional electronics.

3.3 Control Circuitry

Unlike battery powered LED devices for VLC [3] studied previously, the smart LED light bulb relies not only on a microcontroller, but also needs additional circuitry to modulate the light intensity.

The (off-the-shelf) included power supply converts the power grid voltage and outputs a DC voltage of around 60 V to power the 16 LEDs in series. This power supply can also be used to power the additional electronics. The microcontroller needs an operating voltage of 3.3 V or 5 V. Therefore, a DC/DC step-down converter is required for down-converting the output voltage of 60 V of the AC/DC converter. Since the microcontroller cannot switch large voltages directly, a MOS-

[1] http://www.ikea.com/ch/de/catalog/products/10266693/
[2] http://www.ikea.com/ch/de/catalog/products/70255291/
[3] http://www.ikea.com/ch/de/catalog/products/50255292/

Table 1: Characteristic of the three consumer LED light bulbs.

Consumer light bulb no. 1
IKEA LEDARE LED1221G7[1] 400 lm, 6.3 W 230 V AC → 61 V DC 16 LEDs
Consumer light bulb no. 2
IKEA LEDARE LED1012G5[2] 200 lm, 3.5 W 230 V AC → 13.0 V DC 9 LEDs
Consumer light bulb no. 3
IKEA LEDARE LED1205G8[3] 400 lm, 7 W 230 V AC → 30.6 V DC 21 LEDs

Figure 2: Consumer LED light bulbs, no. 1 to 3 from left to right.

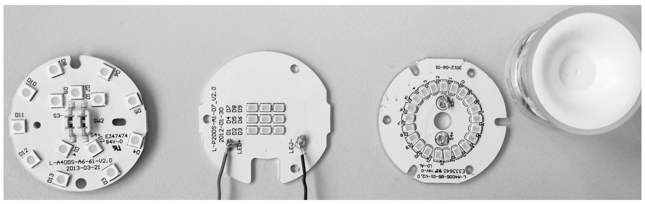

Figure 3: LED boards of the three consumer LED light bulbs, no. 1 to 3 from left to right.

FET needs to be employed to switch on and off the current flow through the LEDs to modulate a signal.

A clean solution to organize and connect all the additional electronics is to create a printed circuit board (PCB). Figure 4 shows the schematics of the dedicated PCB handling voltage conversion and switching of the current through the LEDs. The size of the board is kept small to still fit into the consumer light bulb's setting together with the power supply already in place. The following electronic parts are used (not mentioning the capacitors and resistors needed to stabilize the circuitry):

(1) DC/DC power converter from Tracopower (TMR1-4811)

(2) Voltage regulator, 3.3 V (ADP121-AUJZ33R7)

(3) N-channel MOSFET (BSP372)

The DC/DC converter module takes the 60 V from the power supply and transforms it down to the 5 V needed to run the microcontroller. To also support 3.3 V, a voltage regulator is connected to the output voltage of the DC/DC power converter. Further the N-channel MOSFET's source is connected to ground. Through pads on the PCB, the LEDs cathode can connect to the MOSFET's drain and the microcontroller's output pin in charge of modulating the light to the gate. When driving the gate high, current can flow through the LEDs and the MOSFET to ground (LEDs emit light) and when driving the gate low, the LEDs cathode are separated from ground and no current flow is possible (LEDs off).

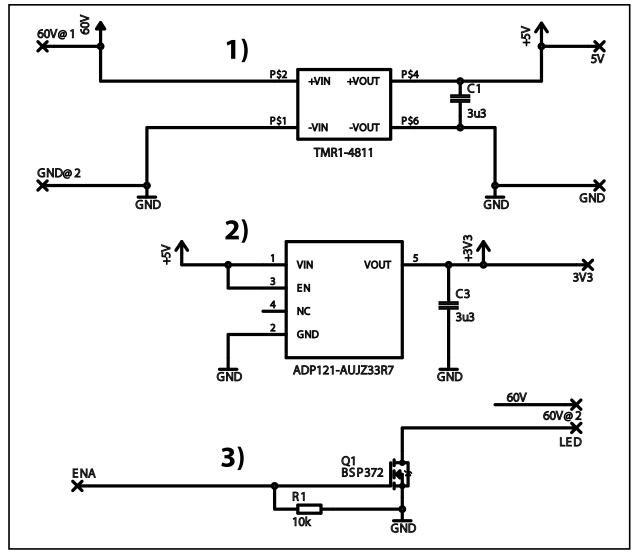

Figure 4: Schematics of the dedicated power module PCB. 1) DC/DC power converter, 2) 3.3 V regulator, 3) N-channel MOSFET.

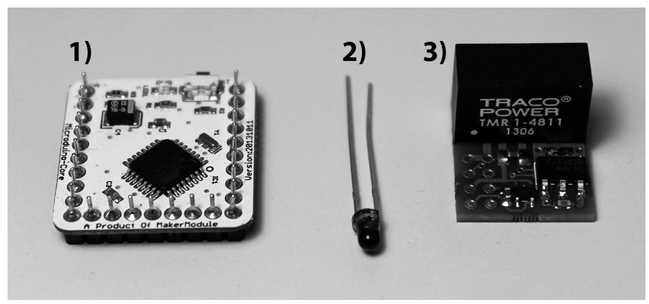

Figure 5: Additional electronics added to the consumer LED light bulb. 1) microcontroller board, 2) phototransistor, 3) custom designed power conversion PCB.

Figure 5 shows the PCB (on the right) together with the microcontroller board [10] used to run the communication protocols and the phototransistor from Mulitcomp (round, 3 mm) for light detection. The phototransistor connects directly to the microcontroller's pin as specified in the firmware. Further, the microcontroller connects to the power conversion PCB for power and to the MOSFET as mentioned above.

3.4 Assembly

The process of physically building smart LED light bulbs and any additional part needed to fit everything into the small constrained space is described in the following.

The plastic cap can be removed without breaking it by using a saw and cutting it just above the end of the light bulb ceramic setting. Now, the electronics is accessible. There are two screws that fix the metal plate with the LEDs to the ceramic case; removing the screws gives access to the bulb's power supply. The custom built power conversion board can now be connected to the original power supply. The connected power conversion board can than be lowered in to the bulb setting side-by-side with the power supply since there is still enough space. Cables connected to the conversion board will then later be connected to the LEDs and the microcontroller.

To create additional space for the microcontroller, the LED board is not directly connected to the bulb's setting anymore; it is suspended 1 cm above by a mounting. The mounting is shown in Figure 6 on the left. The part was modeled in a computer aided design (CAD) software and 3D-printed with an affordable printer from Ultimaker[4]. The mounting is modeled to fit on top of the light bulb's setting and can be attached to it using screws and the already existing holes used to fix the plate with LEDs. The bottom of the mounting provides slits to connect wires from the conversion board to the microcontroller and LEDs. The top of the mount includes a socket for the LEDs and screw holes. The microcontroller fits in the newly created space between the setting and the LED board.

Since the plastic cap was sawed off, it cannot be reattached without an additional holding mechanism. The cap needs to be attached in a secure way to allow the light bulb to be screwed into a light bulb socket without falling off to protect the user against the power grid voltage. Gluing is not an option, because it should be possible to remove the cap again for reprogramming the microcontroller or changing circuitry. The right side of Figure 6 shows the adopted solution: A 3D-printed ring with a thread on the inside that is glued to the plastic cap. The two small ridges absorb the force while screwing the light bulb and therefore do not strain the glued area. The mounting described in the previous paragraph also provides an external thread. This thread allows now to screw the ring attached to the plastic cap back to the light bulb setting and close the bulb in convenient and secure way. The ring inclusive thread is also 3D-printed using the same printer.

Before modifying the light bulb, the LED board was connected directly to the ceramic setting, which was used to absorb the heat produced by the 16 LEDs while on. Since the 3D-printed plastic mounting now holds the LEDs above the ceramic setting, it is not possible anymore to transfer the heat back to the setting. Instead of the setting, the 3D-printed mounting is now absorbing the heat. The material of the plastic is Polylactic Acid (PLA) and can withstand up to 150 degrees Celsius[5]. A convenient aspect of the the VLC protocols is that the LEDs are disabled 50 percent of the time. This setup reduces the generated heat (and the brightness). In practice, the mounting and the plastic cap get

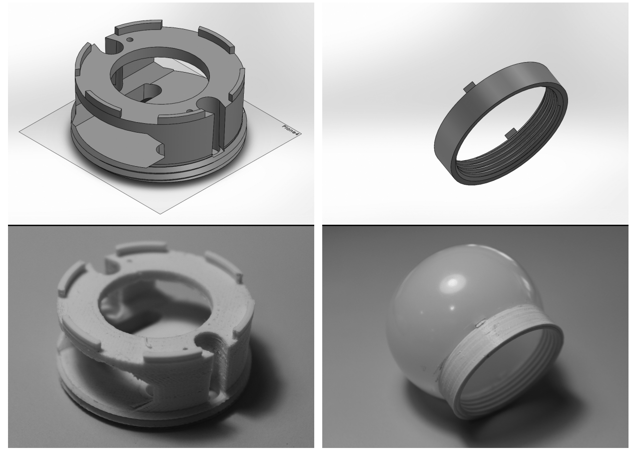

Figure 6: 3D-model and 3D-printed additional light bulb parts. Left: mounting to create additional room for the microcontroller, right: ring with internal thread attached to the plastic cap to securely close the light bulb again.

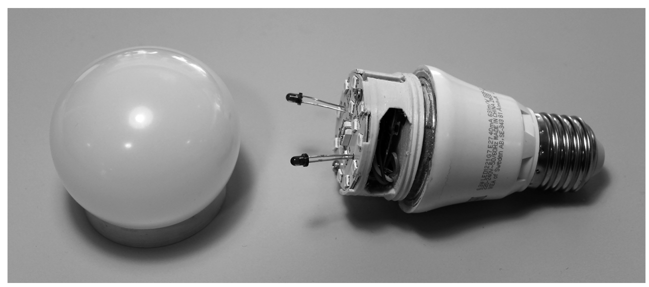

Figure 7: Assembled smart LED light bulb with unscrewed cap and connected phototransistors.

hot (after running for several hours) but the 3D-printed material does not melt. The modified light bulb, shown in Figure 7, may not meet all requirements of a consumer product, but it fulfills its purpose as a research vehicle.

3.5 Operation

To demonstrate that the modified light bulb is now able to emit light with an encapsulated signal, the following measurements are reported. To show the modulated light, a photodiode is connected to an oscilloscope to measure the light intensity over time. Figure 8 shows the behavior of an unmodified light bulb. The oscilloscope shows a small periodic change of intensity. This change is due to the internal power supply converting AC current to DC and in this process charging a capacitor while the LEDs draw current and discharge it again. To the human eye, the fluctuations are not visible and the LED seems to provide constant brightness. Figure 9 shows the light pattern detected from a modified light bulb. The LEDs are duty-cycled at

[4]Ultimaker (Original), https://www.ultimaker.com/
[5]PLA, http://reprap.org/wiki/PLA

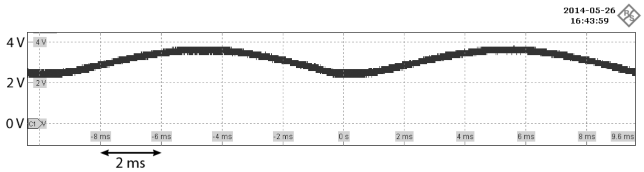

Figure 8: Oscilloscope snapshot of the light intensity output of an unmodified light bulb. The figure shows the typical pattern of an AC/DC power supply.

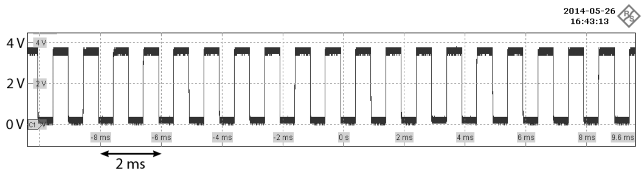

Figure 9: Oscilloscope snapshot of light intensity output of a modified light bulb in idle mode, the light is duty-cycled at 50 %.

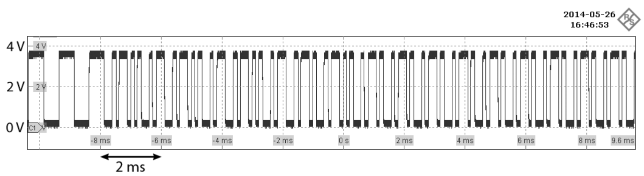

Figure 10: Oscilloscope snapshot of light intensity output of a modified light bulb while transmitting data.

50 % and at frequency of 1 kHz. This setup provides the basic requirements for the communication protocols. Figure 10 shows a modified light bulb transmitting a message. The light is modulated to encapsulate bit patterns. Since the overall light output per microsecond stays the same, namely 50 percent light, a human eye still sees constant light without any flickering but less bright than the original light bulb.

4. CONCLUSIONS

This project is motivated by the vision of multi-hop networks of smart LED light bulbs in which the light bulbs communicate with each other using VLC. Such a light bulb network can serve mobile devices (toys, phones, etc.) for services like indoor positioning or entertainment. The network throughput of a light bulb to light bulb network as tested here can reach up to 1 kb/s and scales with the number of communicating devices without noticeable detriment of throughput for larger networks. Multiple smart light bulbs on a ceiling of a room might observe the hidden station problem as they might only reach their direct neighbors. This remains a research challenge to be addressed with protocol modification. Using more sensitive photodetectors instead of white LEDs as receivers increases the communication range of the light bulb prototype and allows communication inside rooms in residences and offices.

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