Demonstration Abstract: How many lights do you see?

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***Abstract*—We demonstrate a Visual Light Communication (VLC) system [1] that enables LED lighting luminaires to communicate with cameras on mobile devices. Each LED pulses at a frequency above the humanly perceivable flicker threshold where cameras and photodiodes can still detect changes in light intensity. Our modulation scheme supports multiple light sources in a single collision domain, and works for both, line-of-sight (LOS) operation as well as from reflected surfaces like those found in architectural lighting. The spatial confinement of light makes this system ideal for use as localization landmarks. Our demonstration includes four LED ambient lights acting as location landmarks transmitting modulated data. A mobile device receiving and processing the signal displays the ID and RSSI of the closest landmark. Interacting with the system will allow users to see the practical effects of multiple-access, frequency of operation, distance from the lights, camera parameters and camera motion.**

I. Motivation

Inside buildings, light bulbs are pervasive, have ample access to power and are frequently ideally positioned for sensing applications. We demonstrate a system which transmits data from solid-state luminaries, used for interior ambient lighting, to mobile devices like smartphones in a manner that is imperceptible to occupants. One compelling application of this approach is the ability to transform lighting sources into landmark beacons that can be used for indoor localization. If each luminaire could uniquely identify itself to nearby mobile devices, it would be possible to distinguish between rooms and areas within a room that are illuminated by different lights. Since visual light is completely blocked by solid obstructions like walls, this approach is well suited for semantic localization (location, rather than geographical), which remains a challenge for many existing ranging or localization systems.

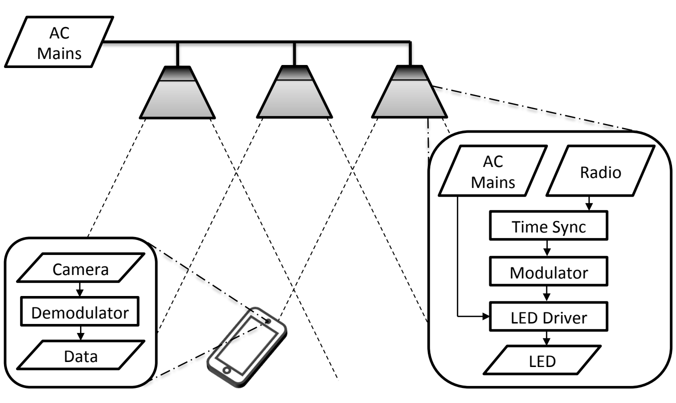

Fig. 1. System Architecture

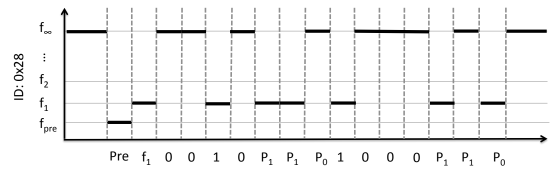

Fig. 2. Packet Structure

II. System Description

Figure 1 shows our system architecture with a stationary VLC transmission infrastructure and a mobile receiving device. We use a Binary Frequency Shift Keying scheme to modulate the bit sequence (or ID) onto the PWM signal driving the light. Figure 2 shows the frame format for a single transmission. A preamble indicates the start of each data packet, while the pilot which is identical to a transmitters *on* symbol, allows the receivers to measure the noise floor of each transmission. Multiple transmitters co-exist by using Frequency Division Multiple Access, where each is allocated a unique frequency for transmitting its *on* symbol.

The receiver is a common CMOS rolling shutter camera that captures the signal either through direct LOS or reflected from surfaces. Rolling shutter sensors expose and read out individual rows of pixels in a pipelined fashion. Figure 3 shows an LED pulsing at a period less than the the frame duration, producing light and dark bands coinciding with rows exposed during the LED *on*-time and *off*-time respectively. The frequency of bands in the image is proportional to the LED's frequency. Figure 4(b) shows the 1-D Fourier Transform (FT) of Figure 4(a) which was captured by the simultaneous blinking of two LED sources, one at 2kHz and the other at 3kHz.

After a sequence of image frames are acquired, the spatial variation of the frequency components over the images is used to estimate the input PWM frequency of the lights. The demodulation and decoding is performed in software (running locally or off-board if raw video can be streamed) to detect the received IDs. Each ID can be mapped to the transmitters location using a previously acquired lookup table, and the mobile device can identify its nearby transmitter landmarks.

III. Demonstration

A. Lighting infrastructure

Figure 6 shows a photograph of our demonstration setup. The ingrained image shows our prototype light, built with a commercially available 9.5W Cree warm white (2700K) LED

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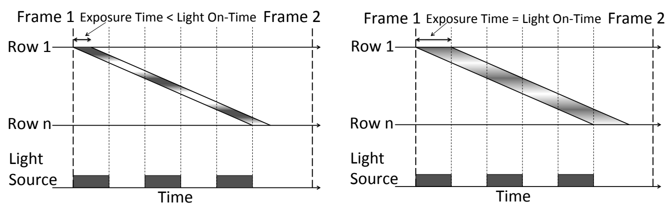
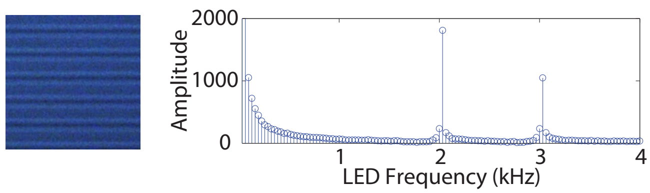


(a) (b)

Fig. 3. Capturing a time varying light signal as a spatially varying image (a) Short and (b) Long exposure



(a) (b)

Fig. 4. (a) 2kHz and 3kHz from two different sources (b) FFT of mixed signal

bulb. It features 80 white phosphorescent SMD LEDS driven in series, that are arranged in a radial pattern inside the soft white bulb. We replaced the bulb's power electronics with a simple MOSFET driver circuit, which is controlled from an external wireless micro-controller board based on the ATmega128rfa1 processor with integrated 802.15.4 radio. Figure 7 shows our 8-channel VLC driver board. Each light is programmed to transmit a unique code.

B. *Mobile Device Application*

We developed an iOS app to capture and process the VLC data. The user can hold an iPhone or an iPad loaded with our application, and point the camera anywhere in the vicinity of the lights. The app will capture one second of uncompressed 720p frames at 30fps. The app tunes the exposure and focus of the camera to achieve a higher SNR. Figure 5 shows a screen-

Fig. 5. iOS-based application for VLC

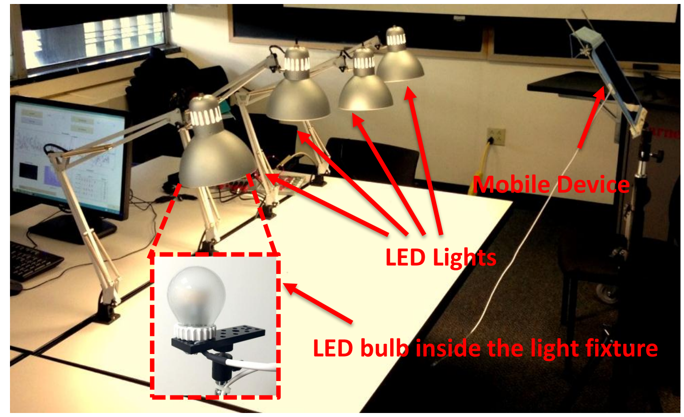


Fig. 6. Demonstration setup

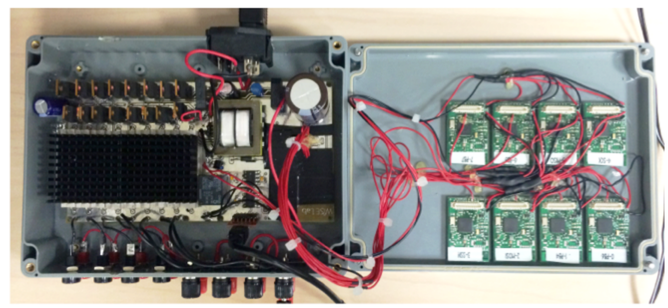


Fig. 7. 8-channel VLC Driver

shot of our application. The users can trigger the receiver with the *Record* button on the screen.

C. *Interactive user interface*

A Matlab-based visualization tool shown in Figure 8, will walk through the demodulation of the signal and decoding of the IDs of the lights. The interface loads live images captured directly from the iOS app. The users can switch on and off the lights, move the camera around, change camera parameters and through our interactive user interface, directly observe how these effect the system's performance.

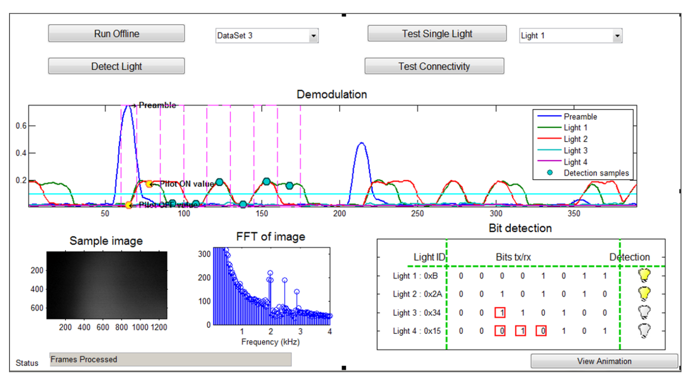


Fig. 8. Visualization Tool

References

[1] N. Rajagopal, P. Lazik and A. Rowe. Visual Light Landmarks for Mobile Devices. In *Proceedings of the 13th ACM/IEEE Conference on Information Processing on Sensor Networks*, 2014.