VLCR: Detecting Battery-free Users with Visible Lights

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Abstract. This paper presents the design and implementation of VLCR (visible light cognitive radio), a cognitive radio system where the base station can detect and communicate with users in a battery-free manner on the visible light band. Contrary to previous systems, VLCR works at visible light frequencies, which makes detecting users much harder because of the broad bandwidth and the low power constraint it incurs. We solve the power constraint problem by using a retro-reflector that can effectively focus optical energy, returning all the energy back to the base station passively, and an liquid-crystal display (LCD) that can modulate visible light signals efficiently. We have prototyped VLCR and showed that VLCR saves 2-3 orders of magnitude more power than previous cognitive radio systems, and supports concurrent operations among multiple users in the office environment.

Introduction

Visible light communication (VLC) has recently attracted a lot of interests in the ubiquitous computing and communication research community due to the ubiquitous availability of illumination devices and the fact that people are able to modulate and embed information bits on visible light beams. However, to be able to make VLC more attractive to general public as are Wi-Fi and cellular radios, there are still two challenges to solve. First and foremost is energy efficiency of VLC. As visible lights span electromagnetic frequencies from 4THz to 8THz, modulating and encoding such signals is extremely hard. Compared to Wi-Fi, this is often times 2 to 3 orders of magnitude more energy consuming. Second, it would not be very useful if a communication system cannot allow multiple users to communicate at the same time. However, enabling concurrent transmissions among multiple users is difficult in that the interference is immersing the space around the transceiver.

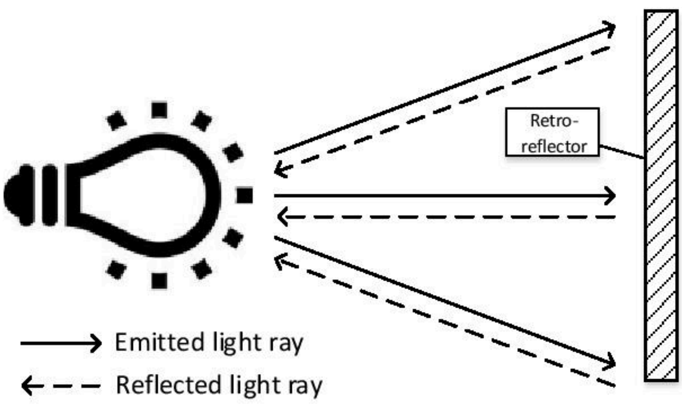

Fig. 1. VLCR architecture

VLCR solves these two problems by taking the advantage of LCDs and retro-reflectors, such that it totally avoids actively sending packets on the user side, who only needs to passively reflects and modulates the incoming signals from the base station. Also, the base station recognizes users not by the distinct spectrum element a user occupies as in conventional cases. Instead, the base station identifies users by their spacial information made possible by the highly concentrated signals reflected by the retro-reflectors. Fig. 1 shows the high level architecture of the VLCR system on a single link. At a high level, the system consists of a base station, and multiple users. A single user contains a transceiver that includes a retro-reflector and an LCD. A retro-reflector is put on the user side as the communication transmitter. Covered on the retro-reflector is an LCD that modulates the reflection; the LCD is controlled by the voltage that's added on it. The light bulb serves as the base station. It constantly emits lights, just as a normal light-emitting diode (LED), while modulating signals on the lights. In the following sections, we describe the system design in more detail, and explain how the base station recognize users from interference, and how users operate in a completely battery free manner.

System Design

1. Overview. Fig. 2 shows a link diagram of the VLCR system. On the downlink. the base station, i.e., the light bulb, sends out information bits modulated with Manchester codes, and encoded with on-off keying (OOK). The user captures the downlink signal with a light sensor on its top, as shown in Fig. 2. Upon receiving the signal, the user circuit will be waken up, activating the LCD that sits on top of the retro-reflector.

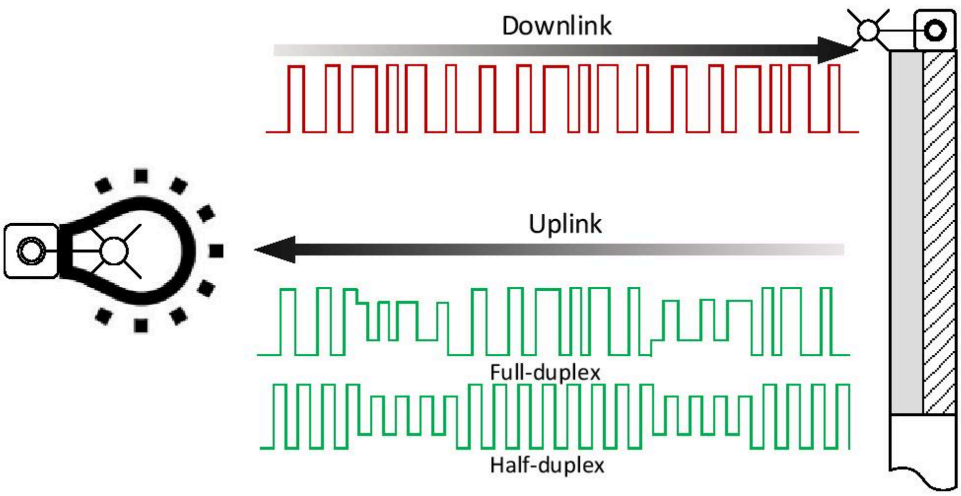

Fig. 2. VLCR link

2. Retro-reflector. The retro-reflector works as follows. A retro-reflector consists numerous small corners that are depicted in Fig. 3. One such corner consists of three perpendicular walls that can reflect incoming signals like a mirror. With three walls in a 3-D space, any signals that hit one of such corners will be perfectly bounced back along the direction it comes in along. At a high level, a retro-reflector can reflect back incoming signals back to the transmitter no matter what directions the incoming signals travels along. This implies a huge amount of energy that can be saved with the adoption of this material without any system optimization. In addition to energy conservation, this design also help focus the light so that when a user wants to access the base station, the base station easily recognizes the user by the direction the user's signal comes along at.

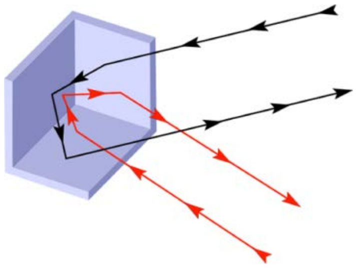

Fig. 3. The working principle of a retro-reflector

3. LCD. The retro-reflector combined with the LCD serves as the modulator of a user. The LCD works as follows. When there is a high voltage added to it, signals can pass through the LCD, as the polarization inside the LCD directs the light path all the way through. Alternatively, when the voltage added to the LCD is low, signals will be blocked, such that the bit being transmitted will be a zero. This way, the user just modulates the incoming signal and the reflected signal using this single mechanism. The principle of the LCD is illustrated in Fig. 4.

In terms of energy consumption, the LCD in total costs 200uA under 2V voltage. And the power that drives the LCD is supplied totally by solar cells, which makes the user battery-free. In later sections, we will describe how the circuit design benefits the user system with an energy recycling module in sections that follow.

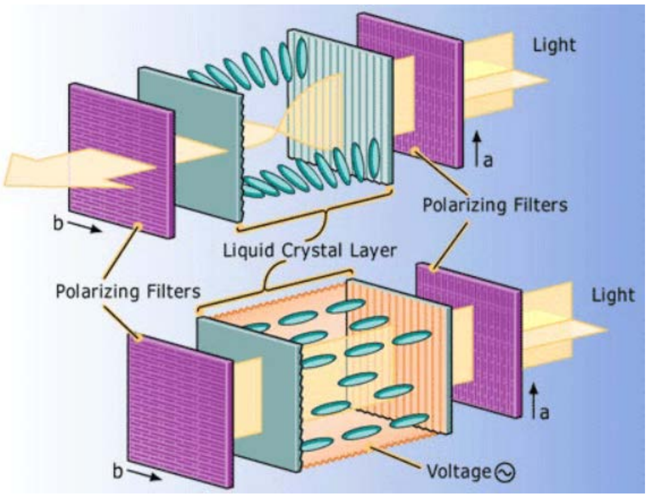

Fig. 4. The working principle of an LCD

We should note that one can also design the transmitter with an active LED, such that the base station can detect users by the light they send. However, we prove that passively transmitting signals is more energy efficient than actively sending signals using an LED. The following is the sketch of the proof.

Our goal is to prove that using the combination of an LCD and a retro-reflector as a passive emitter is more energy-efficient than using an LED as an active emitter when both systems have the same base station whose transmitter has power P_0 bit rate $1/\delta t$, user to base station distance r, energy used for transmitting per bit E_{tx} and receiving per bit E_{rx} , and noise power. We compare the SNRs of the base stations for the two methods. Further, since the noise power in the two scenarios are the same, we need only compare the quantities of the signal energy per bit E_{s1} and E_{s2} . We note that the system with the larger one has a better energy efficiency.

First, for the LCD tag with a retro-reflector, all the energy it transmits is received by the base station receiver, assuming the LED on the base station is at the same location with the light sensor. Also, the signal the user receives is modulated and bounced back. Therefore,

$$E_{s1} = \eta_1 P_0 / 4\pi r^2 \delta S_{user}$$

where η_1 stands for the energy dissipation caused by the absorption of the retro-reflector and the direct reflection of the LCD, and S_{user} denotes the equivalent reflective area on the tag.

Second, for the LED tag that actively transmits on the user side, within a bit period, we have

$$E_{s2}=\eta_1 P_0/4\pi r^2 \delta S_{base}$$

where η_2 is the efficiency of the LED tag hardware, and S_{base} denotes the light sensor area on the base station.

Finally, as we have assumed that the power supplies for both systems are identical, and for the LCD tag, $E_{tx}=kCV^2$, where k captures the efficiency of the energy reuse module and CV^2 denotes the energy cost per LCD capacitor period that corresponds to transmitting one bit, we have

$$E_{s1}/E_{s2}=\eta_1 P_0 \delta t\, \delta S_{user}/\eta_2 kCV^2 \delta S_{base}$$

Typically, V = 5V, C = 2000pF, k = 0.4, $\eta_1=10^{-2}$, $\eta_2=0.8$, $P_0=8W$, $\delta S_{base}=2*10^{-5}$ and $\delta S_{user}=10^{-3}$, so $E_{s1}/E_{s2}=10^9 \delta t$. This result shows that if the data rate $1/\delta t$ is smaller than $10^9 bps(1Gbps)$, then an LCD plus retro-reflector equipped user always enables higher energy per bit at the base station receiver than an LED equipped user. In typical office environment setting, LEDs are primarily used lighting, and the upper bound of its flickering rate is orders of magnitude smaller than 1GHz. That is to say, our method is always more energy-efficient than the alternative LED user in cognitive radio.

Literature References

With the ubiquity of light infrastructures and the increasing need for spectral resources, our VLCR system has the promise of enhancing present cognitive systems substantially, especially in indoor environments, whereas TV signal backscattering [1][2] systems are limited to areas close to TV towers, and Wi-Fi backscattering [3] further limits the communication range to the proximity of access points and can only work intermittently due to Wi-Fi signals' bursty nature. The TV-based cognitive systems aim at enabling communication among devices, instead of communicating back to the base station.

Users in RFID systems [4][5][6] typically hold a passive tag, too. However, RFID systems require a second-order modulation on the user end to eliminate the base band noise, while VLCR uplink does not have any second-order modulation, solely relying on the base station who conducts demodulation and decoding algorithms that extract useful information. In addition, RFID readers are not ubiquitous as LEDs, and readers are not readily networked like LEDs. In terms of capability, visible lights can transmit farther in the line-of-sight scenario in comparison with NFC RFID systems [7].

Finally, these cognitive systems tend to expose their transmissions to a wide area, because of the scattering nature in general. This potentially gives side attackers a chance to overhear the information being transmitted [8][9]. By contrast, VLCR relies on visible light to detect users, which implies overhearing is easily discernible. The use of retro-reflectors further retains the uplink transmission along the same incoming path. As a result, our system comes with a good security-preserving property inherently while other cognitive systems have to enhance their security with extra efforts [8][9].

Summary

In this paper, we present VLCR, a cognitive radio system that can identify users working on the visible light band without user equipped with any battery. The system features the use of retro-reflectors and LCDs on the user end that passively modulate and transmit signals to the base station. Also, retro-reflectors help focus the uplink beams and distinguishes a user from interfering with others in the space. Also, VLCR is better than Wi-Fi and TV based cognitive radio systems in terms of security preserving. We have implemented the system in indoor environment and showed it's promise in practice. As a final note, we are developing larger scale cognitive radio systems that scale up to maritime uses. The work presented in this paper can be seen as our first attempt towards an energy efficient and secure solution to the maritime cognitive radio problem.

Acknowledgement

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