VL-mac: Enabling Multiple Battery-free Users in Visible Light Cognitive Radio Systems

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Abstract

This paper introduces VL-mac, a media access control (MAC) protocol for visible light communication (VLC)-based cognitive radio systems. VL-mac provides a full stack of access control primitives for users that operate at visible light frequencies to access the base station and for the base station to assign resources intelligently to accessing users, such that the spatial resource is maximized. Specifically, VL-mac supports users that are located in different places in space to communicate with the base station without interference even at the same frequency, saving frequency resources substantially. VL-mac also makes sure that users are running in a completely battery-free manner, which essentially makes system deployment in a wide range of scenarios possible, including office environment, street environment, and even maritime communication.

Keywords: Cognitive Radio, spatial multiplexing, visible light communication.

1 Introduction

Visible lights have been exploited as a wireless carrier for data communication. Existing designs of VLC systems, however, consume significant power and only achieve one single user to base station communication, limiting the adoption of visible light band into the framework of cognitive radios, where resources are scheduled for multiple users to access at the same time. This situation is very unfortunate because visible light frequencies are resourceful, allowing for a much bigger capacity of users than conventional Wi-Fi or cellular bands.

In this paper, we introduce the design of the first cognitive radio system that runs on visible light frequencies. We call our system VL-mac which stands for the mac protocol for the visible light cognitive system. Specifically, we employ battery-free material in building the user transceiver, and design hardware and software components for users that handle both physical and mac layer complications. We use retro-reflectors and liquid crystal displays (LCD) to build our modulator, as discussed in [1], and shown in Fig. 1. We also demodulate and decode signals against noise and severe interference on the base station side, boosting the signal by 130dB. Finally, we design media access mechanisms to allow users to talk to the base station in a spatial multiplexing manner.

The mechanisms scale up the system with multiple users, and enable the system to be operated in a number of practical scenarios. We illustrate the communication facility on a typical user in Fig. 2.

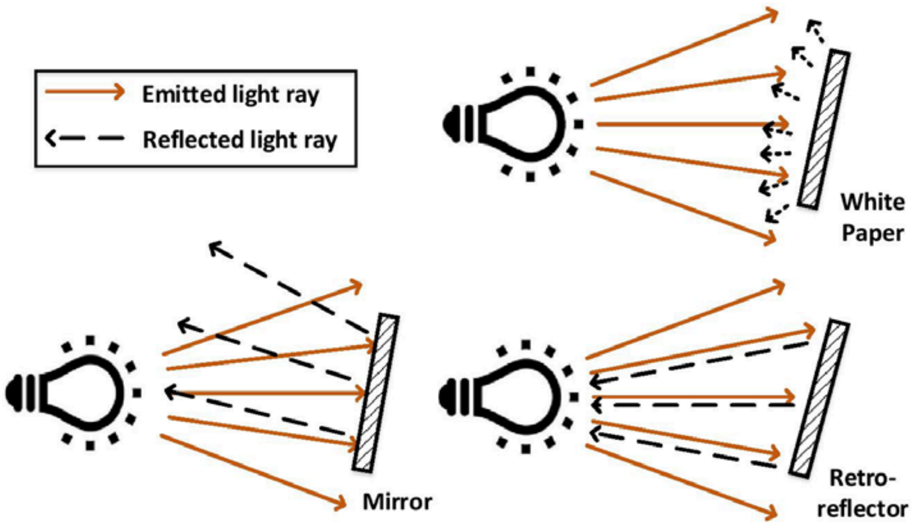


Fig. 1. The working principle of a retro-reflector with comparison to using a white paper and a mirror

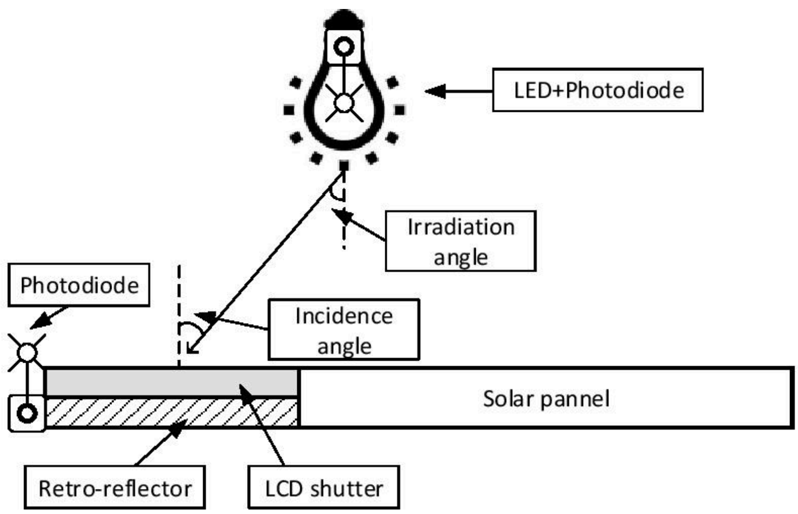


Fig. 2. Illustration of a single link and the architecture of the communication facility on a typical user

2 VL-mac system design

The discussion so far has focused on the communication aspects of a single base station-user pair. However, when many of these devices are in range of each other, we need mechanisms to arbitrate the channel between them. Unlike traditional RFID, the communication uplink from a user to the base station is highly directional because of the retro-reflectors. In addition, as a system with multiple access points that connect to the Internet, which is also different form RFID systems, a user needs a mechanism that provides roaming support. In this following sections, we explore the Media Access Control (MAC) design for users and base stations in four different scenarios. The scenarios are:

- one base station to multiple users
- multiple users to one base station
- multiple base stations to one user, and
- one user to multiple base stations.

3 One base station to multiple users

One of the problems building a cognitive radio system is faced with is how a base station identifies a user with a specific serial number out of a number of other users in range. This problem is critical because if multiple users respond simultaneously to a query from the base station, and the system has no frequency multiplexing mechanisms, then all the users will together jam the traffic. In VL-mac, we set all the users to a passive state, waiting for polling requests sent by the base station. When the serial number of a user is called, the user with this serial number responds within an assigned time slot. The rest of the users will ignore the payload that follows the serial number in the query, as they would notice that the serial number do not align with their own. For the requested user to respond, it only needs to modulate the LCD and directionally sends information bits back to the base station that initiated the conversation. Other users and base stations nearby will not hear anything from the requested user because of the directionality of the retro-reflectors equipped with the communication facility on every user.

4 Multiple users to one base station

When multiple users would like to talk to one base station simultaneously, every user has to wait for it's own time slot scheduled by the base station to transmit. All the base stations in range should have a consensus on the time slot scheduled for every single user so that there will not be overlaps between two time slots scheduled for the same user by two different base stations. This is for the case where every base station is standing by and every user is idle. However, when there is traffic going on, the need for roaming arises, which leads to the solution in the next section.

5 Multiple base stations to one user

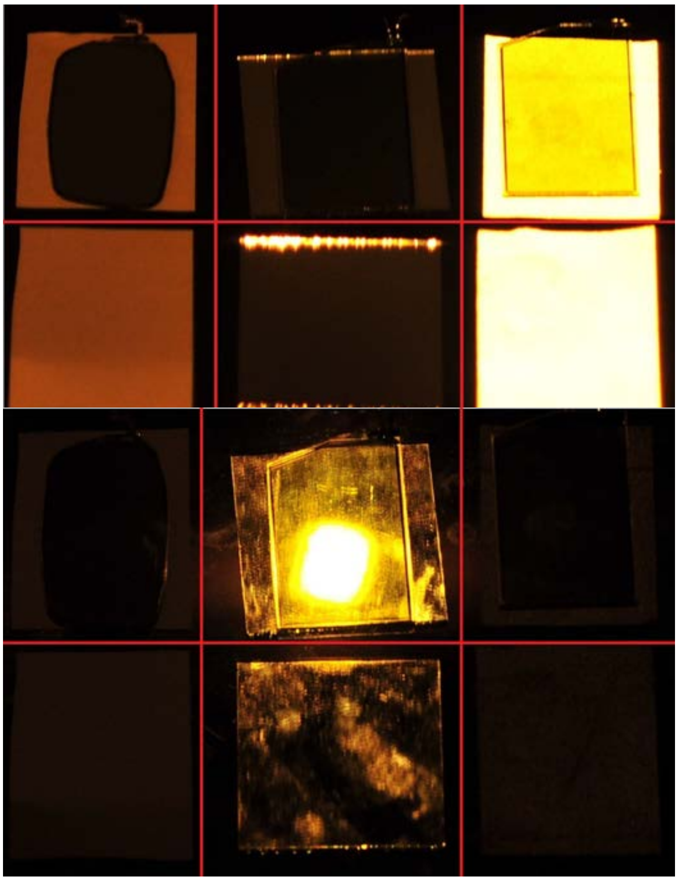
One of the problems for roaming is when multiple base stations would like to talk to one user, how to arbitrate the media. To solve this problem, base stations run ALOHA [2] with carrier sensing. Specifically, if a base station has data to send, then it sends the data. If the base station senses data transmission from another base station while transmitting its own data, the base station will declare a message collision, in which case all involved base stations back off for an arbitrary period of time before retrying. Unlike users, base stations do not usually have a tight energy budget, and so carrying out consistent carrier sensing on them is possible [3].

6 One user to multiple base stations

The reverse problem, and the key problem, in roaming, is when a user would like to talk to a base station, how it will prevent other base stations in range from being interrupted. In principle, a user is supposed to respond to the polling request sent by the base station that has the strongest illumination on the user, so as to get the best communication performance. However, detecting light strength is too energy consuming for a battery-free user that only harvests energy with a small patch of solar cell. On the other hand, base stations do not have a tight energy constraint and can asses the strength as well, of the signal backscattered by users, which is negatively correlated with the distance from a user to a base station. To provide users in the network with the best connection, base stations estimate the accessibility of every user in range using the feedback signal from every user in each of their time slot assigned by each of the base stations. Specifically, the network of base stations works out a mapping between best service-provisioning base stations and every user in range (one could exploit the link-state routing protocol to achieve consensus on such a mapping across base stations), and keeps this information in each base station's “user strength table”. Now, as every base station knows which set of users to serve such that the set of users could get the best performance, it will send polling requests only the on the instantaneous “user strength table” .

7 Putting things together

The discussion so far brings together the physical layer [1] and the MAC layer of the VL-mac cognitive radio system. The physical layer protocol deals with point-to-point communications on the downlink (from the base station to the user) and the uplink (from the user to the base station) as well as user duty-cycling, user wake-up, and error-correction. The VL-lac introduced in this paper addresses the multi-base station to multi-user problem in a way different from existing RFID or WLAN or other radio systems with cognition because of the different constraints and the different multiplexing mechanism used. With the four protocols introduced in VL-mac, the networked system of users can provide services like Internet connection to battery-free users in home-area sensor network scenario, identification service in traditional RFID scenarios with better security guarantees [1], all the way to inter-ship communications in maritime settings. We showcase the prototype we build for the RFID scenario in Fig. 3.



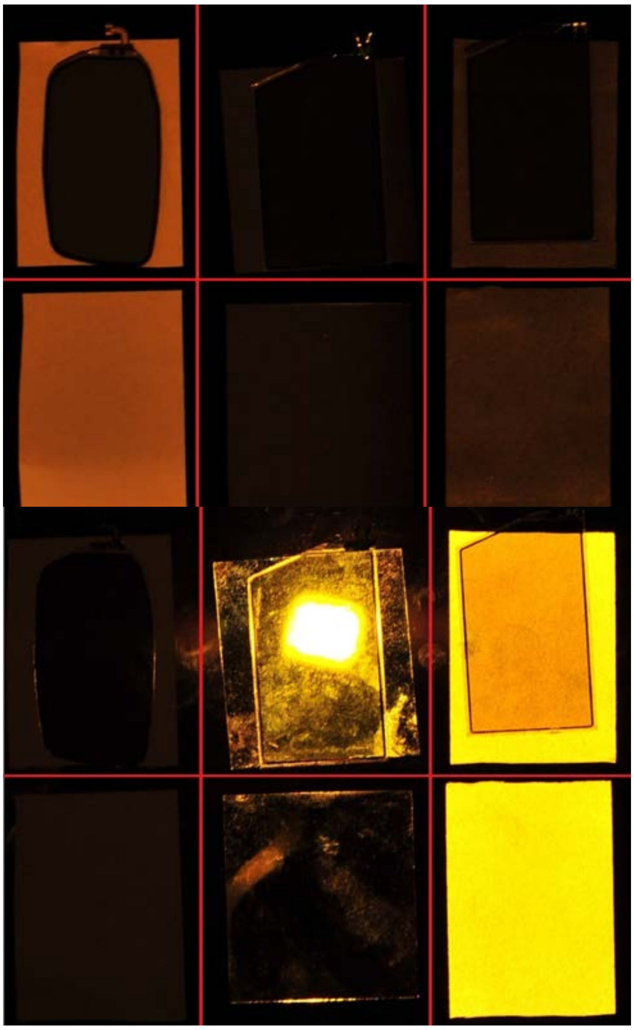


Fig. 3. Illustration of how VL-mac works in the office environment. Upper left: the right hand side user are selected in conversation with the base station (a light bulb that sends information embedded in visible lights). Upper right: the user in the middle is talking to the base station as the major user. Bottom left: none of the users is talking to the base station. Bottom right: the user on the right is talking to the base station as the major user, and the user in the middle is also talking to the base station from a different spatial angle, which won't conflict

with the user on the right who is also transmitting.

8 Literature References

At TV frequencies, a recent work on full-duplex backscatter system [4][5] uses different frequencies for the uplink and downlink, respectively, on the signal envelope. However, it lacks scalability and is not resource-efficient. VL-mac, as mentioned earlier and in [1], has focused uplink transmissions and does not differentiate carrier frequencies between the uplink and downlink, easily scalable to a network with multiple base stations and multiple users, essential to building a cognitive radio system on the visible light band.

9 Summary

This paper presents a MAC protocol design intended for enhancing cognition in radio systems running on the visible light band accessible by battery-free users. We introduce the protocol details of VL-mac, in four typical scenarios, and evaluate the system in the office environment. We believe this first work on cognitive radio systems that work on the visible light band connecting battery-free users paves the way towards highly scalable, energy efficient and secure cognitive radio systems.

Acknowledgement

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