Solving Node Synchronization, Indoor Localization, and Low-Power Communication with a Single VLC Bullet

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The Vision: Smart LED lights providing synchronization, communication, and localization for indoor sensor networks.

The Proposal: We propose to enable this vision by instrumenting the smart building with IPv6 over powerline communications. Our smart bulbs will leverage this back haul with support from the visual channel to automatically self-orient and synchronize wireless sensor nodes. We believe that decoupling synchronization from communication will enable nodes to run at lower energy levels and enable a new class of energy harvesting nodes to form full mesh networks.

1 Introduction

Node synchronization is the fundamental problem limiting the node size and network lifetime of the next tier of the Internet [5, 7, 12]. We claim that *decoupling synchronization from communication* holds the key to scaling node size and network lifetime. We propose to leverage emerging solid-state lighting technologies as a high precision optical synchronization channel while retaining bi-directional low power wireless communications for data transfer. This allows us to nearly eliminate the long guard times in today's duty cycled systems that needlessly burn power while waiting for a packet to arrive (or not). As we drive the power and energy budgets of wireless nodes down further to tens of microwatts, the impact of poor synchronization becomes the limiting factor. Recent efforts to build a completely battery-less battery-quality sensor node were stymied by the synchronization challenge, and compromised with a battery-backed RTC [12].

With a visual-light synchronization primitive, current assumptions can be turned on their head. Wireless nodes can schedule precise radio wakeups with confidence that messages will be heard. Nodes can remove power-hungry, expensive real-time clocks, offloading wakeup to the visual light system. Hardwired programming systems can rescue and reprogram buggy nodes. Room level localization is achieved trivially, with further refinement allowing the potential for greater localization precision.

This infrastructure enabled by visual-light is the foundation for realizing the smart building. We are particularly motivated in this area because buildings in the United States consume 41% of the nation's energy [1]. Monitoring and actuating offices, commercial buildings, and factories is essential for wrangling our nation's energy usage.

2 Smart Bulb Building Blocks

There are two building blocks that our smart bulb vision requires. The first – a powerline backbone – is largely solved, while the second – self-orientation – needs a little more support.

2.1 The Powerline Backbone

Networking over the existing powerline infrastructure was first explored in the 1960s. While initially deemed too noisy and too challenging to get high fidelity with good propagation, recent advancement in technology has seen a renewed interest [9, 10].

Standards such as HomePlug allow for high-speed (10s to 100s of MB/s) powerline communication, but they are challenging to implement, expensive, and currently there are no commercial modem ICs available for purchase. Recent exploratory research – both in our lab [11] and elsewhere [4] – have begun to explore the viability of applying protocols from the well-studied 802.15.4 arena over simpler powerline modems. As an example, a commercial device is available today that enables 30 kpbs (PHY) powerline access for less than $5 per node [2]. These modems couple elegantly to the power rectification hardware already present in current LED bulbs, making networking a natural extension of next-generation light bulbs.

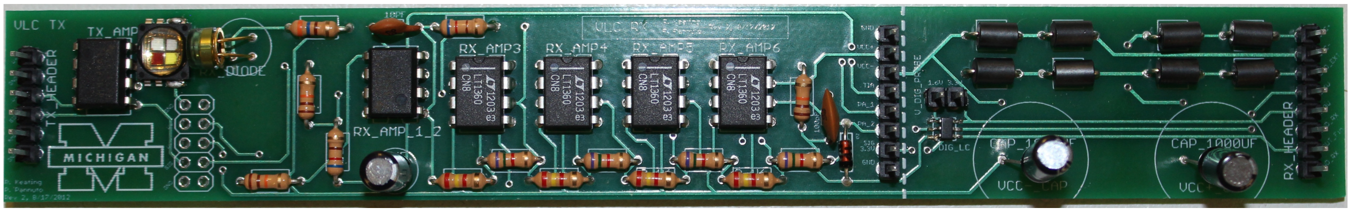

Figure 2: A first look at VLC communications. The leftmost inch is the TX component, with commercial LED driver and 5 W LED. The remainder of the board is a severable RX component that amplifies the recovered signal.

2.2 Self-Orientation

Modern static sensor deployment largely still requires manual notation of sensor IDs and sensor locations. In a commercial building, exploiting the visual channel vastly simplifies room-level localization. Room walls act to block the visual channel, isolating rooms from one another. By containing not only an LED but also a photodiode, each smart bulb can build up a set of all of its neighbors in the same physical room. Periodic exposure to other bulb beacons via doors opening and closing allow rooms to determine their connectivity to hallways. The powerline back haul allows all of these sets to be centralized, allowing for a full-building view of bulbs and their locations. The algorithms devised in the Smart Blueprints work [8] coupled with this higher fidelity data can create a system where indoor localization is as easy as screwing in a light bulb.

3 Visual Light Building Blocks

The two building blocks for any channel are the transmitter and receiver. The transmitter in our system is an LED that we intend to multi-task to also light the room. On the receiver side, we will use a low power wakeup circuit to receive data from the LED.

3.1 Transmit

Our initial work has shown the viability of adding a high frequency signal to a room illuminating LED. Our first prototype platform to explore this area is shown in Figure 2. This separable TX/RX board has a commercial 5 W LED and an off-the-shelf photodiode as a receiver. By varying the frequency at which we flash the LED, we found that we can transmit data that is imperceptible to the eye, but easily recoverable.

3.2 Receive

We have a reference design for a particular optical wakeup receiver. As part of the Michigan Micro Mote initiative [3], designers have built the FLOW (*Free*-space *Low*-power *Optical Wake*-up) receiver. FLOW, shown in Figure 1, is an always-on 695 *pico*watt optical receiver. FLOW has four programmable comparison registers allowing for system-global, room-local, and individual node addressing. The FLOW receiver is capable of simply interrupting an MCU to wake it or issuing I2C messages, enabling technologies such as DMA over visual light to recover nodes with corrupted programming. However, this receiver is a custom fabricated chip not ready for wide use. We intend to evolve FLOW to an off-the-shelf solution that can be integrated with existing sensor nodes.

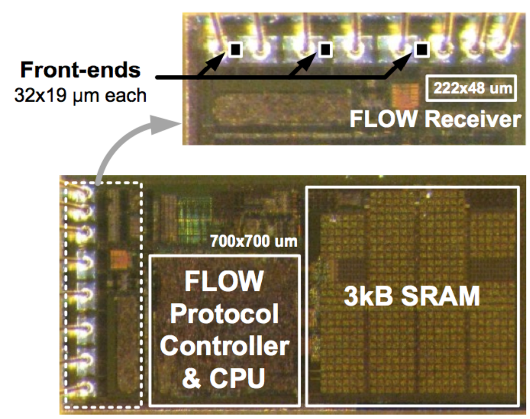

Figure 1: A 695 pW (standby) optical receiver circuit [6]. The receiver has four programmable registers allowing for system-global, room-local, and device-specific wakeup signals. Once awake, the receiver consumes only 140 pJ per bit and is capable of receiving data at 91 bps. The receiver is capable of issuing arbitrary I2C messages and DMA transactions, enabling node reprogramming and recovery.

4 Sensor Node Synchronization

We, and the larger research community, have begun to explore wireless sensor networks involving energy harvesting nodes. These nodes are extremely power constrained and can only operate after they have collected enough energy to power themselves for a short period of time. This eliminates RTCs, putting significant strain on the synchronization techniques developed to facilitate battery powered WSNs. When accurate time is not kept and large radio guard times cannot be maintained, current MAC and communication protocols fail to provide a stable network. We argue that by *decoupling synchronization from communication*, the visible light medium can provide the necessary synchronization primitive to enable WSNs comprised of energy harvesting sensor nodes.

It is currently possible to build a wakeup circuit that triggers an interrupt when it receives light modulated at a certain frequency. Because the light source is an always-powered LED light bulb, we can provide the illusion of a synchronized clock on the sensor node using the light bulb's clock and this light based wakeup primitive. Light-assisted synchronization, enables a truly battery-less sensor network that is fully capable of communicating and inter-operating with more traditional WSNs.

This decoupling also benefits more traditional RF mesh networks. With synchronization maintained and well defined, we can simplify wireless MAC protocols and reduce the time an RF transceiver must be powered. This larger power budget increases the number of battery-less energy harvesting nodes that the WSN can support [12] as well as the overall WSN efficiency and lifetime. We envision a network of these energy scavenging devices, which enables large scale battery-less monitoring and control platforms suitable for myriad applications in the smart building.

5 Indoor Localization

With a location-aware smart bulb, room-level localization becomes a solved problem. The nature of the visible channel confines smart bulb beacons within a room. While this solves the problem for a *node* knowing its own location, it does not on its own allow the *network* to know the location of each node. We argue, however, that this is simply an extension of synchronization/communication separation. Knowing ones own location is now as fundamental a primitive as knowing current time. Relaying the location information into the network is left to the communication layer, as such information is highly application-dependent.

6 Timeline and Personnel

Custom IC design, fabrication, and debugging can take on the order of six months. This fact promotes the characterization of the current FLOW receiver, its performance with a diverse array of commercial light sources, its reliability as a wake-up source, and an evaluation of the human perceptibility of its communication sequence, to the top priority. For characterization and refinement, Pannuto can leverage his strong working relationship with the hardware team of the Michigan Micro Mote project who designed the original FLOW receiver. In parallel, Campbell – who built the networking stack for the battery-less node [12] – will develop the first of the building blocks, adapting 6LoWPAN, a small-MCU friendly IPv6 translation layer, and IPv6 to powerline networks.

During months three through six, existing testbed motes (TelosB's) will be augmented with high-power optical links (such as Figure 2) allowing for the development of the second building block: self-orientation. Around this time, we begin to anticipate the arrival of the next-generation FLOW hardware. Anticipating challenges, the goals for the remaining six months include phasing out the high-power testbed motes in favor of the targeted low-power and energy harvesting platform. This includes replacing the optical receiver circuitry on the more-reliable testbed mote, and subsequently migrating the whole system to the truly battery-less node. In parallel with the introduction of the new hardware, we wish to further explore indoor localization. In particular, we aim to investigate the potential for sub-room level localization using information from multiple bulbs. We are also curious to explore the dynamics of the powerline network in greater depth, building more on preliminary work of Pannuto's [11].

7 Conclusion

Visual light as a communications medium has been overlooked in the wireless sensor community. It is *ubiquitous*, *room-level*, and extraordinarily *low-power*. Leveraging the visual channel, we are able to solve the node synchronization problem, enable truly battery-less sensor nodes, and achieve room-level indoor localization.

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