MIT 6.829: Computer Networks Fall 2017

Lecture 13: Visible Light Communications

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1 Overview

This lecture is on the use of visible light for sensing and communication. In particular, we discussed DarkLight, a technology for communication using light pulses too short for the human eye to detect[1], and StarLight, a system for detecting a user's location and skeleton posture without putting any sensors on the user[2].

2 Light Communication

Light communication involves using light, instead of radio frequency ($\approx 500\,Mhz - 100\,Ghz$) for communication. In this lecture, we focus on visible light communication which operates at $\approx 10^{15}\,Hz$. Visible light has about $400\,THz$ of unrestricted bandwidth that is entirely unregulated and does not have interference from existing communication systems. Light sources are ubiquitous that currently only serve to enable human sight. It is possible to augment/replace existing infrastructure to modulate light to transmit data without disturbing their illuminating properties. Since light, unlike radio, does not penetrate opaque walls, it is secure, since it is not possible to sniff data from afar. This is convenient, since boundaries across which light communication cannot be sniffed are also the boundaries that humans intuitively associate to be private. The common devices of choice for light transmitters and receivers are LEDs and photodiodes respectively. The use of lasers is explored in work on free-space light communication in controlled environments such as the datacenter. Optical fibers are a form of light communication devices that are already in very widespread use.

Summary
Basic idea: encode using intensity changed in light emitting diodes (LEDs), detect using semiconductor-based photodiodes. Can only detect intensity, not phase. Need to modulate light or flash LED at at least 1kHz to avoid hurting human eyes.

2.1 Ideas for VLC modulation schemes

- use intensity (amplitude) to encode data
- color shift
- on-off keying
- frequency shift keying
- spatial keying

- polarization
- pulse amplitude/width/position

2.2 Inherent challenges

- blockage (solve with spatial diversity, reflection)
- distance (solve with density of lights)
- uplink
- lights not always on

2.3 Challenges

While light communication provides several opportunities, it also has several challenges that prevent us from directly adopting many of the techniques developed for radio communication. Some of the challenges and possible solutions. are as follows.

1. Light is easily blocked by everyday objects. To make matters worse, due to its shorter wavelength, light diffracts much less than radio. A saving grace is that diffuse light can be sufficient for communication. This means that as long as the photodiode is illuminated by the transmitter's light, communicaiton is possible. This illumination can be diffuse reflections off other objects and does not need to be line-of-sight. To lessen the impact of blockage further, we can have greater spatial diversity, by having more LEDs/photodiodes to increase the probability that the receiver will be illuminated.
2. Light has a much higher frequency than radio. This means that it is very difficult to detect the phase of an incident signal. While possible, this requires expensive hardware, hence we cannot use modulation schemes like QPSK or OFDM with standard hardware. We discuss the alternate schemes in the next subsection.
3. Bitrate is often bottlenecked by how fast we can switch the LEDs and how quickly the photodiode responds to changing illumination. This is compounded by the fact that commodity devices are not designed to operate at high frequencies. In fact, commercially available white LEDs have a phosphor coating that, in addition to making the light white, increases the response
4. Because of the above problem and the other issues, it is not really possible to achieve the full theoretical Shannon capacity predicted by the $400\,THz$ bandwidth available. Nevertheless, under favorable conditions, it is possible to achieve 10Gbits/s with specialized LEDs.
5. Light is tightly coupled with illumination for humans. Hence we need to design our schemes, such that the modulation does not cause discomfort to the humans in the room. This means that there should be no flickering. Transmitters on mobile devices need to be imperceptible to humans to avoid creating an irritating glow everytime the device wants to transmit. This can be achieved by using infrared light or by using a system like DarkLight (this can be unsafe

however, as noted in §2.3). Transmitting data when the lights are "switched off" by humans is also a challenge, since any illumination used for communication needs to be imperceptible. This is that challenge that DarkLight addresses.

6. Uplink from a mobile device is challenging for two reasons. First, flashing an LED consumes a lot of power, leading to limited battery life. Second, light on a mobile device may be disturbing to humans. People have explored the use of retro-reflectors for this purpose. Retro-reflectors reflect incident light back to the source. Hence, if we can modulate on top of the retro-reflective surface (say, using an LCD), that controls whether or not the surface reflects, the reflected light can be modulated. Since this goes back to the light source, a photodiode placed near it can decode the modulated signal. This is similar to how RFIDs communicate using backscatter.

7. The presence of sunlight/background illumination is a challenge, since they can saturate the photodiode, making it harder to detect the modulated signals intended for communication. Thus even looking at derivative of intensity (not the absolute value), may fail to remove ambient light and resolve the data.

8. Light communication works best when coupled with existing illumination infrastructure. This has a deployment overhead however.

2.4 Modulation and Multiplexing

Although phase-based modulation is infeasible in light communication, a number of other modulation and multiplexing schemes are possible. The simplest is to use on/off keying, which is a form of intensity modulation. We can also exploit color (i.e. frequency) of the transmitted signal. This can be used for multiplexing, where the color denotes the transmitter. Alternately, we can use colors for frequency shift keying, where the color encodes which symbol is transmitted. Spatial keying is also possiblem, where each LED transmits a separate stream of data. Information can be encoded in the polarization of the transmitted light. The polarization of transmitte light can be conviniently controlled using LCD techniques. The receiver can simply use polaroid screens oriented in different directions to decode the transmitted symbols. OFDM schemes have also been implemented. The key to using OFDM is to transmit only real numbers. Such schemes have involved mechanisms, ACO-OFDM and DCO-OFDM are examples of such schemes. Pulse position modulation is another alternative, that we discus in detail in the next section, in the context of DarkLight.

Other, more esoteric, techniques have also been proposed to multiplex transmitters. One is to use the inherent flickering patterns in the driving circuits of commercial light sources to distinguish between. The disadvantage is that there are only a small number of distinct patterns, and light sources from the same manufacturer tend to have the same pattern. People have also experimented with transmitting from an LED to a camera, an LCD screen to a photodiode and from an LCD screen to a camera. The advantage with screens and cameras is their greater spatial resolution. The disadvantage is the lower temporal resolution. Both these devices are widely deployed however, making adoption easier.

2.5 DarkLight

The goal of the DarkLight paper is to enable visible light communication even when the humans instruct the sources of illumination to be turned off. The challenge is to enable communication without the transmitted light being perceptible to humans. One approach to this problem is to use infrared light. While infrared is imperceptible to humans and is widely deployed in some communication systems such as TV remote controllers, having high intensity infrared sources can burn the retina. This is because, since we cannot detect infrared, the eye cannot adjust to protect itself against high intensity light. Far infrared does not suffer from this problem, since its wavelength is sufficiently different from visible light that it doesn't focus on the retina. However, hot objects also tend to radiate in that range, making it harder to distinguish between communication and background radiation.

The key idea behind DarkLight is to use a mechanism that has a very low duty-cycle. That is, the transmitting LED is turned on only for a very small fraction of the time. To this end, it uses pulse-position modulation (PPM). PPM divides the time for each symbol into N parts. The LED is turned on for exactly one of these time-periods, creating a one-hot encoding of data. This is used by the receiver to decode which symbol was transmitted. PPM is used for its extremely small duty cycle ($1/N$).

Summary:

- basic idea: communicate via VL without it being visible to humans
- How? Very short pulses, below the threshold detected by the human eye
- Why not IR? It's not already in phones and it can be dangerous (thermal damage to retina)
- Challenges: generating short pulses, data encoding/decoding, and multiple transmitters

Generating short pulses

- MOSFET in circuit
- Transimpedance amplifier at receiver

Data encoding/decoding

- Use position of pulse (sparse in time)

Multiple transmitters

- Look at derivative of intensity, not absolute, to filter out ambient light
- Resolve collisions by identifying peaks and comparing their offset to the starting position of each transmission

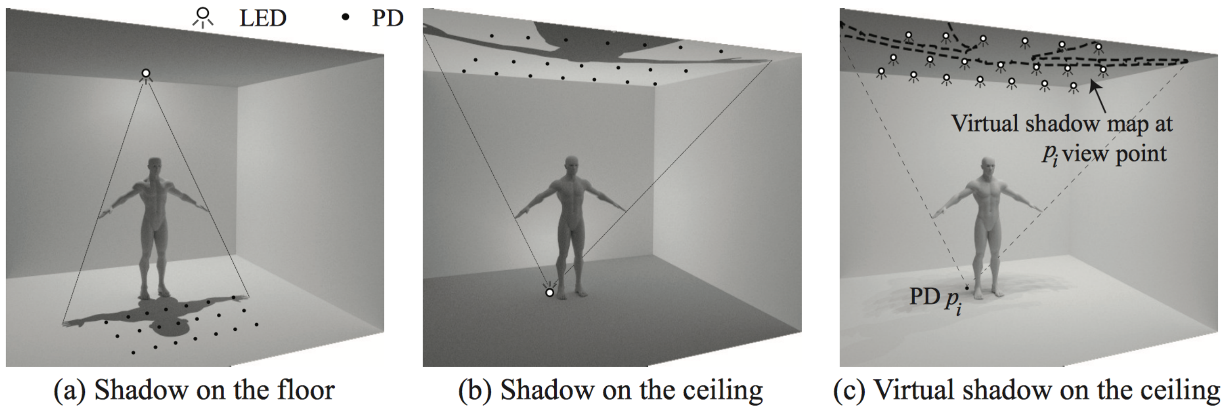

Figure 1: Comparison of the sensing architecture. Prior design relies on few LEDs and many photodiodes (PDs) to collect shadow information on the floor (a). To minimize the photodiode deployment overhead, the new sensing architecture aims to recover the shadow projected on the ceiling (b), by reusing arrays of LED chips realized as LED panels on the ceiling (c). Figure and caption was taken from the StarLight paper

Remaining challenges

- Limit of existing LED luminaries. Not designed for communication; tradeoff between modulation bandwith and efficiency.
- Coexistance of other media (WiFi, etc.)
- Power consumption of RX design
- Applications

3 Localization - StarLight

In addition to communication, visible light communication techniques can also be used for localization. Since visible artificial light is ubiquitous, this is a compelling application. Further, since light has a much smaller wavelength, it is possible to achieve greater spatial resolution more easily with visible light than with radio.

One approach to localization is to extend approaches used in radio communication to localization with light. For instance, we could try using triangulation with respect to multiple sources to obtain the position. However, measuring distances using light is non-trivial. Phase-based approaches are non-trivial due to light's high frequency. Intensity based approaches do not give sufficient spatial resolution. Further, this only tracks one point at a time.

StarLight seeks to track the precise pose and position of a person standing in the room. StarLight evolves from a prior system that placed a small number of light sources on the ceiling and a large number of photodiodes on the floor. The photodiodes capture the shadow cast by the person on the floor. The photodiodes distinguish between the shadow cast due to each of the light sources.

Hence the system knows that the person stands in the intersection of the shadow cones cast by each of the light sources on the photodiodes. The system then finds the best human-pose that explains the shadows. This provides the pose accurate to a few degrees.

This prior work only handles a person standing in a known location. StarLight seeks to remove this restriction while also making the system more deployable. The restriction that the person be standing in a known location is removed by a better real-time algorithm for pose-fitting. The prior work is less deployable because it requires a large number of photodiodes, which is not found in most rooms. However, a large number of light sources are common. Hence, StarLight flips the setup. It consists of a large number of LEDs placed on the ceiling and a small number of photo-diodes placed at optimized locations on the floor. The photodiodes can sense the intensity of light incident on it from each LED (the photodiodes distinguish between light incident from different LEDs as discussed in the next section). This creates several 'virtual shadow cones' for each photodiode. They are 'virtual shadows' because, instead of a shadow being cast by an LED on multiple photodiodes, this is a shadow 'cast' by a photodiode on the LEDs (look at the figure for reference). Assuming that a photodiode cannot sense the light from exactly those LEDs which are not blocked by the person, we can reconstruct the location and pose of the person. The method is similar to prior wok, except that additional processing is added to enable the estimation of position as well as pose. Note that, in typical indoor environments, light can also be blocked by objects other than the user. Hence the system needs to be calibrated to account for them. Photodiodes need to be placed at optimized locations to minimize said blocking and to cover a large spatial area for accuracy.

3.1 Multiplexing in StarLight

Now we discuss techniques that can be used at the receiver to determine which LED is transmitting a given signal. One approach is to use the color of the LED. However, color is perceptible to humans and could be distracting. Another approach is to flicker the LEDs at known patterns. The photodiode can detect which LED is transmitting by looking at this pattern. It is hence possible to distinguish between a small number of LEDs that are all transmitting simultaneously. One way to control the flickering pattern is to have each of them flash at a different frequency. An FFT can be performed at the receiver to determine which frequencies (and hence which LEDs) are present in the received signal. LEDs can also be time-division multiplexed, with different LEDs transmitting at pre-defined time-slots.

StarLight uses a combination of the last two approaches to distinguish between the large number of LEDs in the system. That is, time-division multiplexing is used to distinguish among groups of LEDs. To distinguish between LEDs within each group, their flickering pattern is used.

Summary

Indoor localization

- RSS-based, 0.4m
- Pattern-based, 0.1m
- Use light polarization to separate signals and triangulate.

- Exploiting inherent features: use ”flickering” frequency as a fingerprint for light fixtures. Problem: can differentiate between manufacturers, can’t reliably do so within manufacturers.

Skeleton pose estimation

- Minimalist sensing; replace cameras with low-end, distributed photodiodes.
- How to reconstruct user’s position from multiple sources and 2D binary shadow?
- Use different frequencies so you know which LEDs are blocked from each photodiode.
- Solve as optimization problem - match pose to shadow.

Challenges

- Too many lights? Use existing ones, they just need to be separable. 1 light per frequency per time.
- Sparse photodiodes? Treat as maximum set coverage problem and place using greedy algorithm.
- User mobility? Calculate user’s location at waist level.

3.2 Open Challenges

- Deployment overhead, low-power sensing
- Deployment in reasonable scale
- Fusion with other sensing modalities
- Applications: security, privacy in health...

References

[1] Tian, Zhao, Kevin Wright, and Xia Zhou. ”The DarkLight rises: Visible light communication in the dark.” MobiCom. 2016.

[2] Li, Tianxing, Qiang Liu, and Xia Zhou. ”Practical human sensing in the light.” Proceedings of the 14th Annual International Conference on Mobile Systems, Applications, and Services. ACM, 2016. APA