The DarkLight Rises: Visible Light Communication in the Dark

Tian, Wright, Zhou, ACM MobiCom '16

Motivation/Introduction

- Most VLC systems involve bright light, easily visible
- **Goal:** Low-rate, low-power, human *imperceptible* VLC
    - Suitable for mobile devices' limited battery capacity
    - Avoids safety issues with IR, avoids illluminating environment with VLC if this is not desired
- **Main Idea:** Encode information into light pulses that are short (and probably faint) enough to be imperceptible to the human eye, yet long enough to communicate data reliably
    - Human eye response time: 10 ms for cones (color, high light requirement), 100 ms for rods (B&W, low light requirement)
- Authors get credit for building a working system
- Transmitter side (LED)
    - Need rise time **less than** pulse duration so that LED reaches peak intensity
        - Figure 1(b): High-power LEDs have a rise time of about 1-2 μs, low power LEDs about 500-800 ns
- Receiver side (photodiode)
    - Needs to respond in time to not miss the short pulse
    - Figure 2(b): Shows two alternatives, they choose the **SD5421** for data, which responds in about 200 ns but takes > 1.4 μs to reach peak response, and has a low gain (so short distance for communication)
        - Missing out on full response to their short data pulses, perhaps? (Their pulse width, as we'll see later, is 500 ns)
- The issue of ambient light **interference**

- Switching off/on other lights, sun, reflections etc. are the sources of interference
- Figure 3: Their short pulsed data appears as the short pulses atop the slower interference
- Don’t have phase information from photodiodes, so no spatial separation techniques

DarkLight Design (§3)

- Figure 4: They reduce the rise time (marginally) with amplified imput voltage
- They increase the photodiode receiver gain (significantly) using an amplifier (no numbers, though)
- **Modulation (§3.2)**
  - Time divided into *symbols*, symbol time divided into 2^M *slots*, each of length L seconds
    - Overlapped Pulse Position Modulation (OPPM): encode bits as which slot the pulse starts in. The slots' durations overlap (so only rising edge position matters).
- **Demodulation:** Look for the rising edge, so take derivative
  - Issue: Derivative amplifies noise
    - Solution: Smooth the received signal first (Gaussian filter), then take derivative
  - Issue: Need to acquire packet timing
    - Solution: Preamble with three pulses in the first slot of each symbol

Ambient Light Adaptation (§3.3)

- Transmitter has another photodiode for sensing ambient light level, alongside the LED
- When ambient light is brighter, they use fewer slots per symbol
- Data rate is $M/(2^M \cdot L)$ bits per second
- Duty cycle $d = t_{ON}/(2^M \cdot L)$ and ambient light levels determine visibility
  - So data rate is also equal to $M \cdot d/t_{ON}$
- In brighter ambient light, they decrease M, increasing d and data rate (look at the first data rate equation above, and look ahead at **Table 1**)

DarkLight Networks (§4)

- Light is directional, but overlap will occur. *Many DarkLight links operating at the same time and interfering within overlap?*
- **Goal:** Receive multiple simultaenous streams

- Receiver-side ADC sampling drift causes variation in rise time offset around 100-200 ns (Figure 6)
- They remember the slot alignments for each data *stream* (light source) and allocate new streams when they see unaligned slots
    - Misses “colliding” streams (*slot collisions*)

Prototype Implementation (§5)

- Parameters: $t_{ON} = 500$ ns, $L = 3.2$ μs, $t_{symbol} = 6.55$ ms, which implies $M = 11$, but that’s not shown in Table 11 (?)
- Hardware:
    - Transmitter-side LED *for data transmission*: **Cree CXA 2520**
    - Transmitter-side photodiode *for ambient light adaptation*: **OPT101**
    - Receiver-side photodiode *for data reception*: **SD5421**

Experiments (§6)

User Perception Study (§6.1)

- Setup DarkLight LED on ceiling with a lampshade, measure human perception: ask people to look directly at the LED and indirectly at objects in the room (evidently people know LED is present)
    - Indirect viewing: Indistinguishable in bright ambient light, distinguishable in low ambient light
    - Directly looking at LED: More distinguishable, down to 65% in bright light

Single-link Performance (§6.2)

- Test link over a distance of **1.3 meters**, varying L (timeslot length), results in up to 1.8 Kbit/second throughput (Figure 10a)
- Increasing pulse width allows the LED to hit max brightness (Figure 10b) – is this optimized fully, then?
- Viewing angle is about 15 degrees (Figure 10c)
- The adaptation loop takes 5 seconds to converge (Figure 11b)
- Power consumption
    - Table 5: Transmitter side, FPGA dominates (can move to ASIC)
    - Receiver side, amplifier dominates
    - Appears that transmitter can be made quite low power, receiver perhaps not

Multi-link Performance (§6.3)

- Figure 13: To maximize throughput, need to increase the slot width from 3.2 μs to 32 μs – slowing down by an order of magnitude!

- When LEDs are synchronized, can space out the slots, otherwise they’ll collide
- Good match with their analytical model for collision frequency