CSE 291: Wireless and Communication in the Internet of Things

Non-RF stuff

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Today’s Goals

- Talk about other fun ways embedded stuff communicates
Outline

• Infrared

• Visible Light Communications

• Ultrasonic

• Vibratory
The Infrared Spectrum

- 300 GHz (1 mm) to 430 THz (700 nm)
  - Lower bound moving? Microwave up to 3 THz (0.1 mm)?
- Several meaningful subdivisions
  - Near-infrared (NIR) - Night vision, imager support
  - Short-Wavelength (SWIR) - Fiber optics
  - Mid-Wavelength (MWIR) - Thermal (~most heat xfer)
  - Long-Wavelength (LWIR) - Thermal imaging
  - Far Infrared (FIR) - PIR, towards Microwave/RF
The point: not all “IR” created equal

- Pay attention to the actual wavelengths when sourcing LEDs, photodiodes
- Also to the selectivity & response
- For communication, usually want narrow to minimize interference
The IR communications everyone has probably used: TV Remote Control

- Simple on-off keying
- Two “big” protocols: Phillips RC-5 and NEC
  - Though manufacturers of course have variations
  - RC-5 is 36 kHz carrier, Manchester encoded with 1.8 ms bit period, 1 start bit, 2 header bits (toggle, field), 5-bit address, 6-7 bit commands [why carrier?]

TV remotes usually use a NIR wavelength (850~950 nm)

• Many imagers ‘see’ into NIR spectrum, e.g. a smartphone video of a remote:

• Tip if trying yourself: Newer phones add IR filters (better for taking photos of naturally brightly lit [sunny] scenes), might block remote signals
  – However, at least on my iPhone8, only added to the rear camera, front facing camera still works great 😊
Newer remotes are switching to wireless technology

- Why: IR requires line-of-sight
  - ...ish... reflects well, including off semi-gloss paint (ever point remote at ceiling?)
- Cool new emerging trend: ‘battery-free’ remotes!
  - Envelope Math:
    - RC-5: $0.9 \text{ ms} \times 14 \text{ bits} \times 100 \text{ mW} \approx 1.2 \text{ mJ}$
    - BLE Advertisement: ~100 uJ [optimized DA14581]
    - Average button presses per day: 100?
    - **State-of-art-WiFi harvesting**: 50 uW (@ 2.5cm)
      - At 2.5 cm distance..., so let’s say more like 0.22 nW @ 5m
    - 100 uJ / 0.22 nW \approx 5.26 \text{ days
This will be cool, eventually, but today is probably still just a marketing gimmick [indoor photovoltaic ~30 µW/cm²]

Like the previous Eco Remote, this one can be charged with solar energy, but Samsung has also added RF harvesting capabilities that let the remote preserve its charge by “collecting routers’ radio waves and converting them to energy.” Neat. You don’t see this in many gadgets — mostly because it’s really only practical for low-power devices. But remotes certainly fall into that category.

Aside from the new RF harvesting option, the Eco Remote can be charged from both outdoor and indoor light or (for the fastest results) over USB-C. Samsung says it’s introducing a white model of the remote this year, which the company says is meant to better complement its “lifestyle” TVs like The Frame, Serif, and Sero.
Other popular uses of IR: Localization
Why use IR instead of RF?

• “I’m here to pick up fish”

• Walls are very contextually important, but difficult for localization systems to detect
IR localization systems semi-ubiquitous in healthcare settings

• General model is mixed-mode:
  – Anchor infrastructure in rooms beacon unique code for each room [LoS?]
  – Receivers (ID badges, patient trackers, asset tags...) use RF to beacon receiver ID + the IR code; central infrastructure then can track ~everything
  – Beacons mix wide angle emitters and tight lenses
    • E.g. for handwash detection
• Some tags also include passive RFID as extra redundancy
  – Takeaway: Different technologies suit sub-needs for applications

- Integrates with RTLS and Security Solutions platforms
- Gen2IR™ Technology for Clinical-Grade Locating™
- Low frequency sensor to trigger door and elevator locking response
- Small size, lightweight
- Alerts when band is loose, tampered, slipping off, or removed from a patient
- Waterproof
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VLC vs IR

• “next up” in the spectrum: ~380nm – 750nm
  – Very narrow compared to IR
• Interesting as its own topic because we build many visible light systems
• Generally single channel or tri-/quad-channel
  – White (brightness), RGB, RGBW
  – Of course, could be finer-grained...
• Very different interference model
  – Lots of visible light around...
You’ve been using VLC a lot lately
[at least, under the broad definition that some VLC researchers like to claim for the area]

• VLC endpoints are usually highly capable or very simple
  – Transmitters: Screen (large, 2D array of pixels); point source LED (1–small $n$)
  – Receivers: Imager(s) (large, 2D array of pixels); photodiodes (1–small $n$)
• Arguably, imager communicating from a still is VLC too
  – Usually, people are talking about digital / flexible at both endpoint; but blurry
VLC (and IR really) offer many dimensions for high-bandwidth data transmission

- Spatial diversity of transmitter, receiver elements
- Frequency diversity (spectrum / color)
- Intensity (brightness)
- Time (high frequency control, decode much easier than RF)
- Mechanical support
Most common VLC modulation schemes

- OOK (On-Off Keying)
- Variable PPM (VPPM)
- Color Shift Keying (CSK)
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• Frequency diversity (spectrum / color)
• Intensity (brightness)
• Time (high frequency control, decode much easier than RF)
• Mechanical support
  – Lenses / optics for beamforming — note: same fundamental concept as waveguides / directional antennas in RF, just much easier to manipulate shorter wavelengths
FSPL vs. FSO
Free Space Path Loss [RF] vs. Free Space Optical Communication [VLC / laser]

• Recall that RF falls off aggressively with distance
  – This is partially because we assumed isotropic radiators; non-iso RF is hard

https://www.urbe.edu/info-consultas/web-profesor/12697883/articulos/Free%20Space%20Optics%20FSO/Physics-of-FSO.pdf
Now let’s toss backscatter principles in the mix, and build something really wild, in the late 1990s[!]

- For 50 µW, VLC can communicate data for miles
  - Literally, they sent data across the SF Bay

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=895117

**Challenge:**
How to line up sender and receiver?
Modern Smart Dust does mixed mode: VLC for inbound data and RF for outbound data
More conventional systems also use VLC communication

- The Electric Imp uses VLC to load WiFi credentials
  - As do many other IoT devices — Cheap answer to “credentials no keyboard?”
The solid state lighting revolution should not be a simple substitute good

\[ \sim 10^{-4} \text{ Hz} \quad \neq \quad 00010100 \rightarrow \quad \sim 10^4 \text{ Hz} \]
Digital lighting creates application potential for smart spaces beyond baseline illumination

- Illumination
- Entertainment
- Communications
- Device Configuration
- Time Synchronization
- Indoor Positioning
VLCP: visible light communications and positioning

- **LED luminaires**
  - Slightly-modified
  - Transmit beacons
  - Identities or coordinates

- **Smart phones**
  - Run background mobile app
  - Take images periodically
  - Perform local processing
  - Offload to cloud/cloudlet

- **Cloud/cloudlet server**
  - Do photogrammetry
  - Do AoA Localization
  - Estimate location
  - Estimate orientation
  - Provide location-based services

Indoor localization using VLCP

Image processing extracts beacon locations and frequencies.
One vision: Software Defined Lighting

Multiplex all these services on same infrastructure
Real-world study: Illumination + Localization + Sensor Communication
With sufficient synchronization, transmitted signals can ‘constructively interfere’ (coherently combine)
VLC as a sensing channel

- Transmitter does not have to intentionally send a data signal...
  - Active research by our own Alex: Inferring grid and bulb information!
VLC as an attack channel

• From simple, ‘static’ modifications...

• ...rolling shutter to create ‘invisible’ attacks!

Kevin Eykholt, Ivan Evtimov, Earlene Fernandes, Bo Li, Amir Rahmati, Chaowei Xiao, Atul Prakash, Tadayoshi Kohno, Dawn Song. Robust physical-world attacks on deep learning visual classification. CVPR’18.

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Moving from the EM spectrum to the acoustic spectrum

• Many of the same principles apply
  – Recall the discussion on symmetry in waves earlier

• Note / Resources:
  – Lifted ultrasonic primer slides from https://www.teachengineering.org/content/mis_/lessons/mis-2227-ultrasonics/mis-2227-ultrasound-technology-lesson-ppt.pptx
  – I have no idea who made these slides, which is silly :/
    • Likely someone affiliated with CU Boulder?
    • TeachEngineering is a CU Boulder K12 outreach program...
The **wavelength** represents variation in air pressure and is the distance over which the wave’s shape repeats.

An **oscillation** of a wave is defined how long it takes for a wave to move from starting position, one position to the next and back to the start.

**Amplitude** refers to the intensity or power of the sound wave, and relates to volume.

The **frequency** of a wave is defined as number of oscillations the wave completes in a certain amount of time (usually seconds).

The unit of measurement for sound is a **hertz (Hz)**, and it is based on how many oscillations occur per second.
Can humans hear *all* types of sounds?

No, *audible* frequencies are what we can detect.
Acoustic spectrum does not have as many divisions as EM

• Possibly a statement of opportunity / underutilization for communication
Ultrasonic applications

Infrasound: 20Hz
Audible frequencies: 20kHz
Ultrasound: 2MHz, 200MHz
Measuring distance with sound

Ultrasonic waves can be used to accurately measure distances with special sensors.

In air, sound travels at a constant speed, which means we can measure distance by seeing how long it takes for a sound to hit an object and bounce back to the sensor.
Practical communications with Ultrasound?

- Not much that does *data* on the UL channel
- Acoustic often useful for data on otherwise difficult spaces
  - Recent paper on UL transmit *through solid media* gets 12.5 kbps

- In most sensor network work, UL used *with* other technologies
  - Primarily for ranging, easy to measure acoustic time-of-flight (b/c slow)
  - Not never data: ALPS labels chirps to distinguish transmitters
  - But very little, second generation ALPS is hybrid BLE + UL
Neat tricks with UL: Near-zero energy wakeup

- Opo is UL + RF ranging platform with 60 μW “UL wakeup radio”
Opo’s (and others’) actual ranging operation is simple —
Time Difference of Arrival (TDoA) ... $3 \times 10^8 \text{ m/s vs } 343 \text{ m/s}$
Pros and Cons of UL for embedded applications

- **Directional**
  - Can be problematic or useful
  - Middle point between optical and RF in shape options

- **Physically larger transducers**
  - Need to move a membrane that moves air; not that small

- **Propagation**
  - Generally does not cross physical media well
    - Stays in a room; but can also travel along a wall if transducers on wall...
  - “Echo-y”: Can take 50-200 ms for UL energy to die off in a room
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Premise: Exploit physical linkage for communication channel that has physical world implications

- Following slides shameless stolen from conference presentations for Ripple and Ving
Physical vibration:
a new mode of communication

Vibration Motor

Accelerometer
Applications

Touch activated smart-lock

Communication through bone conduction

P2P money transfer
Applications

Vibrations do not **tether**

Vibrations do not **broadcast**

Vibratory communication
Ripple: vibratory communication

Application

Vibratory Radio
- Morse-code
- Single-Carrier
- Multi-Carrier
- Spatial channels
- Phy-Security

6 bps 80 bps 200 bps 400 bps +secured

Hardware
Basic insight: Can do reasonably complex modulation schemes on this channel to get decent bandwidth using microphone to RX

The receiver:

- **Accelerometer**
  - Vibration

- **Microphone**
  - Vibration
  - Sound

Graphs:
- **OFDM**
  - Amplitude vs. Frequency
  - Frequency range: 1K to 15K Hz

- **1K 5K 10K 15K**
Decent data rates nowadays

Evaluation

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<th>Bandwidth</th>
<th>Modu.</th>
<th>Code</th>
<th>Tput: Kbps</th>
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<tbody>
<tr>
<td>Stylus</td>
<td>12 KHz</td>
<td>16 QAM</td>
<td>2/3</td>
<td>29.19</td>
</tr>
<tr>
<td>Phone</td>
<td>12 KHz</td>
<td>16 QAM</td>
<td>2/3</td>
<td>26.13</td>
</tr>
</tbody>
</table>

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</tr>
</thead>
<tbody>
<tr>
<td>Ring</td>
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<td>QPSK</td>
<td>1/2</td>
<td>7.41</td>
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<tr>
<td>Watch</td>
<td>3 KHz</td>
<td>QPSK</td>
<td>1/2</td>
<td>2.23</td>
</tr>
</tbody>
</table>
Ving argument: Mixed-mode again, use RF for high-bandwidth, but vibratory channel for wakeup [lower power] and security
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- Is there more?
  - So much more
Next time: There is no next time! :/