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

Light comparison[8]

Name	Wavelength	Frequency (Hz)
Gamma ray	less than 0.01 nm	more than 30 EHz
X-ray	0.01 nm – 10 nm	30 PHz – 30 EHz
Ultraviolet	10 nm – 400 nm	750 THz – 30 PHz
Visible	400 nm – 700 nm	430 THz – 750 THz
Infrared	700 nm – 1 mm	300 GHz – 430 THz
Microwave	1 mm – 1 meter	300 MHz – 300 GHz
Radio	1 meter and more	300 MHz and below

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

Wavelength

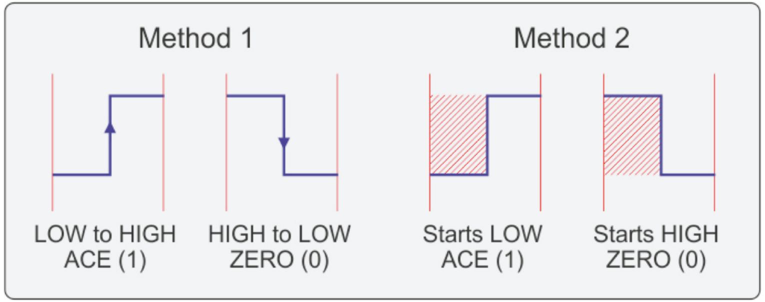
685nm
690nm
700nm
720nm
730nm (720nm ~ 740nm)
730nm
735nm
740nm
755nm
760nm

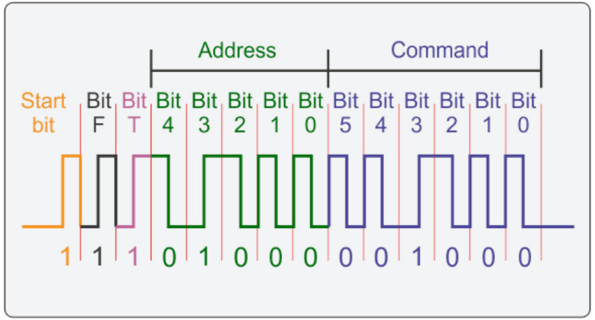
Spectral Range

760nm ~ 1000nm
760nm ~ 1100nm
770nm ~ 1000nm
780nm ~ 1050nm
780nm ~ 1100nm
780nm ~ 870nm
790nm ~ 1050nm
790nm ~ 980nm
800nm ~ 1000nm
800nm ~ 1050nm

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?]





Graphics from & more details on Phillips RC-5: http://www.pcbheaven.com/userpages/The_Philips_RC5_Protocol/

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 ms * 14 bits * 100 mW ~= 1.2 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 ~= 5.26 days

https://www.theverge.com/2022/1/2/22860390/samsung-eco-remote-2022-solar-rf-harvesting-charging

This will be cool, eventually, but today is probably still just a marketing gimmick [indoor photovoltaic ~30 μW/cm^2]

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?

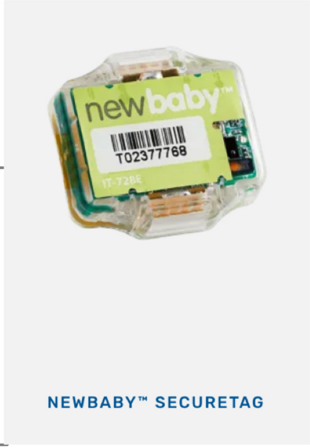
- "I'm here to pick up fish"

- 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

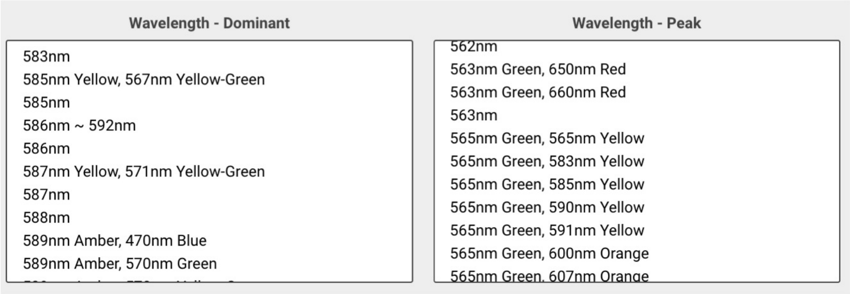


Outline

- Infrared
- **Visible Light Communications**
- Ultrasonic
- Vibratory

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

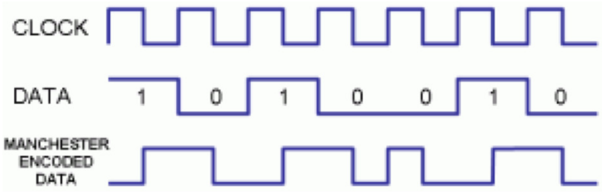
[at least, under the broad definition that some VLC researchers like to claim for the area]

- 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

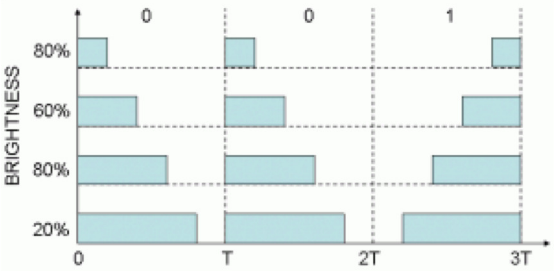
VLC (and IR really) offer many dimensions for high-bandwidth data transmission

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

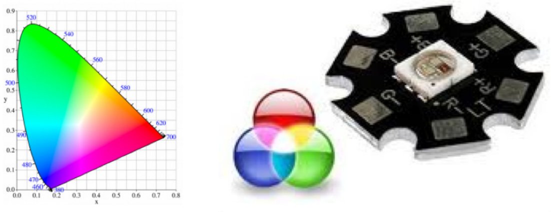
Most common VLC modulation schemes



- OOK (On-Off Keying)



- Variable PPM (VPPM)



- Color Shift Keying (CSK)

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
  - 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*

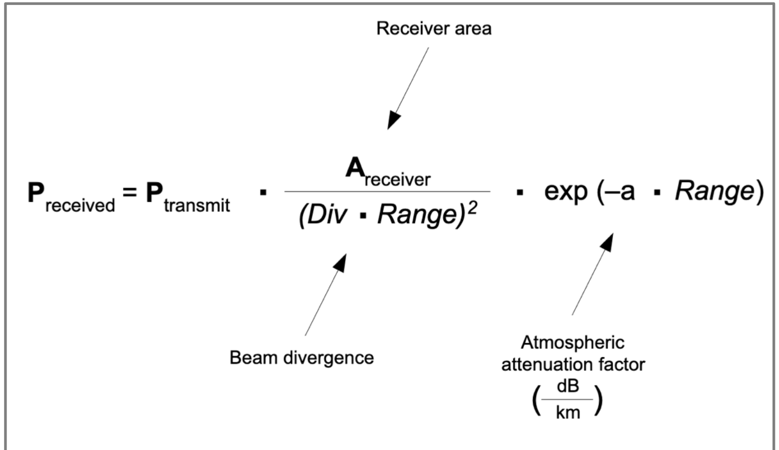


Figure 2. Basic FSO Link Equation

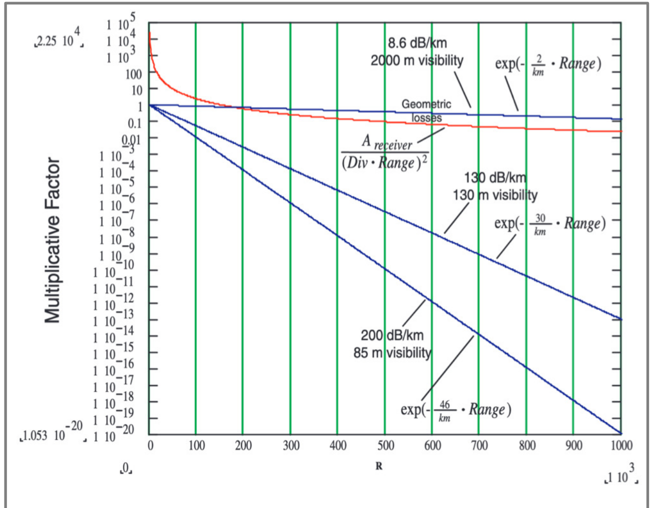
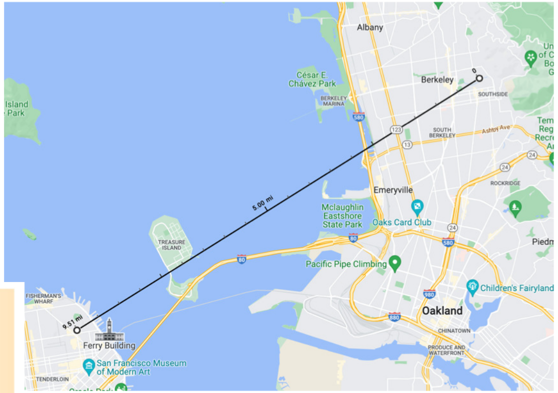


Figure 3. Geometric and Atmospheric Loss Components

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



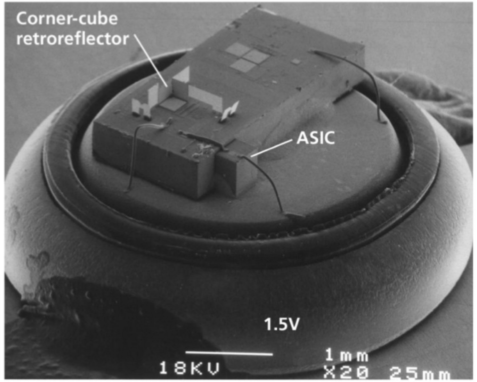


Figure 3. Autonomous bidirectional communication mote with a MEMS optics chip containing a corner-cube retroreflector on the large die, a CMOS application-specific integrated circuit (ASIC) for control on the 300 × 360 micron die, and a hearing aid battery for power. The total volume is 63 mm³.

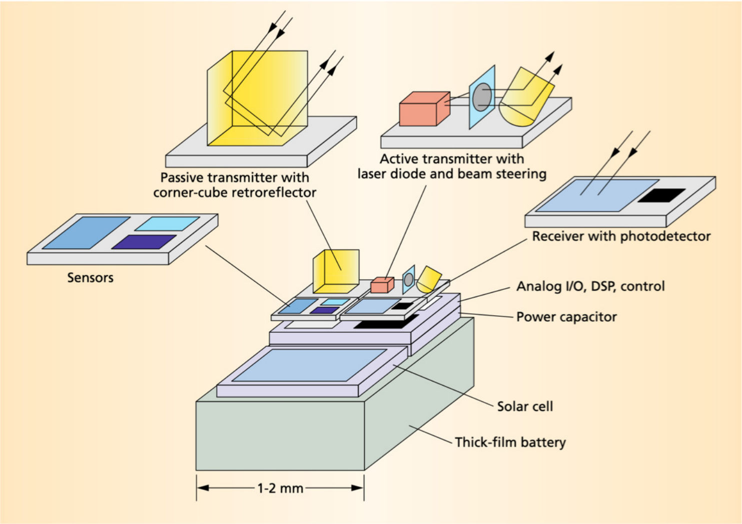
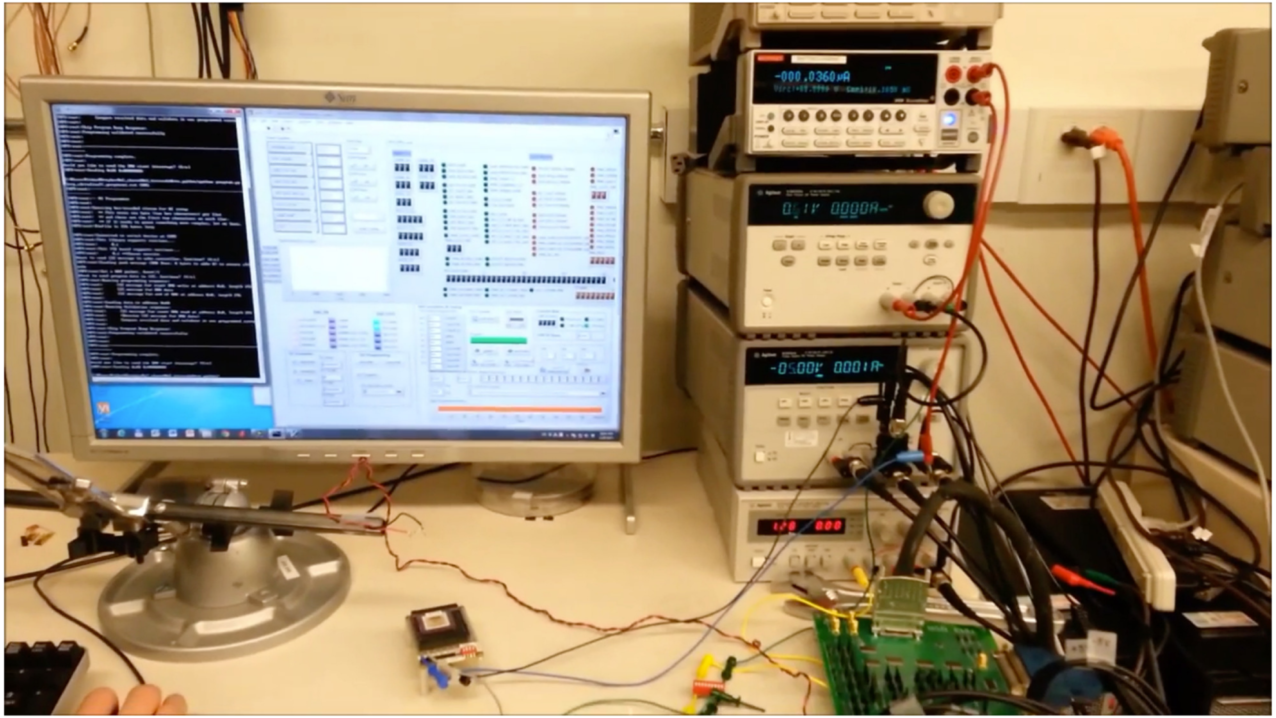


Figure 1. Conceptual diagram showing a Smart Dust mote's major components: a power system, sensors, an optical transceiver, and an integrated circuit.

Challenge:
How to line up sender and receiver?

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

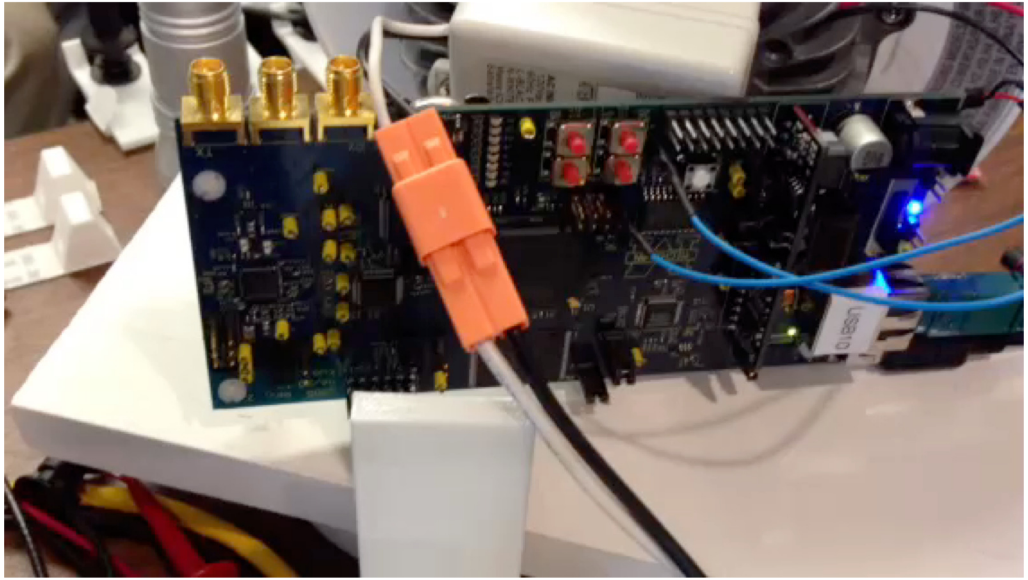
Modern Smart Dust does mixed mode: VLC for inbound data and RF for outbound data



A Millimeter-Scale Wireless Imaging System with Continuous Motion Detection and Energy Harvesting
Gyouho Kim, ZhiYoong Foo, **Pat Pannuto**, Ye-Sheng Kuo, Benjamin Kempke, Mohammad Hassan Ghaed, Suyoung Bang, Inhee Lee, Yejoong Kim, Seokhyeon Jeong, Prabal Dutta, Dennis Sylvester, and David Blaauw
2014 Symposium on VLSI Circuits (VLSIC)

More conventional systems also use VLC communication

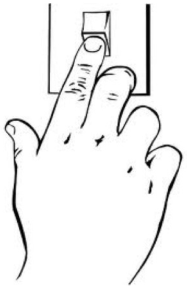
- The Electric Imp uses VLC to load WiFi credentials
  - As do many other IoT devices — Cheap answer to "credentials no keyboard?"



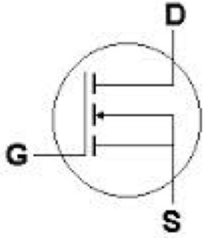
The solid state lighting revolution should not be a simple substitute good

≠

$\sim 10^{-4}$ Hz



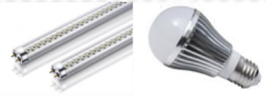
00010100 → G



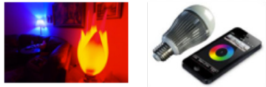
$\sim 10^{4}$ Hz

Digital lighting creates application potential for smart spaces beyond baseline illumination

Illumination



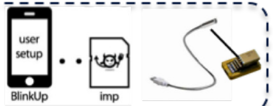
Entertainment



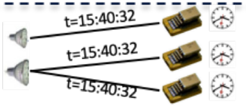
Communications

01100101000

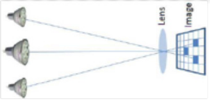
Device Configuration



Time Synchronization

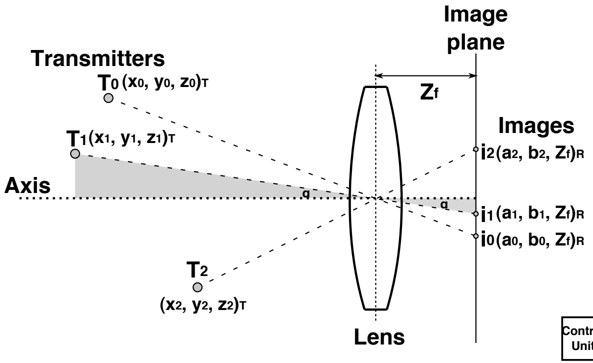


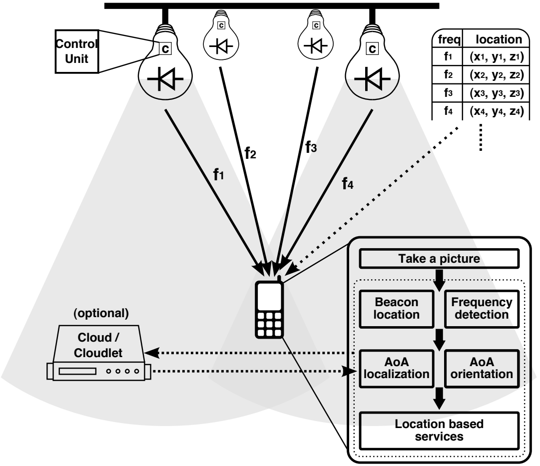
Indoor Positioning



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





Ye-Sheng Kuo, Pat Pannuto, Ko-Jen Hsiao, and Prabal Dutta, "Luxapose: Indoor Positioning with Mobile Phones and Visible Light," In Proceedings of the 20th Annual International Conference on Mobile Computing and Networking (MobiCom'14), Maui, HI, Sep. 7-11, 2014.

Indoor localization using VLCP

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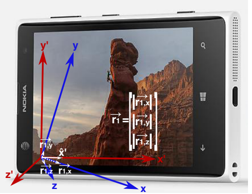
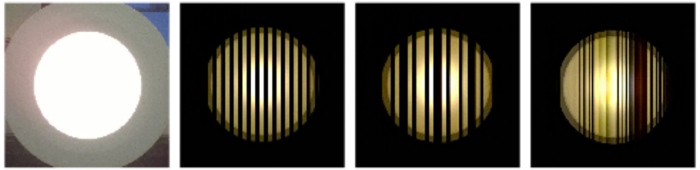
LED Luminaire

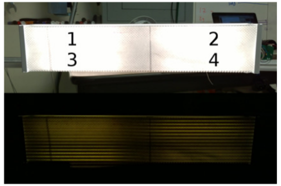


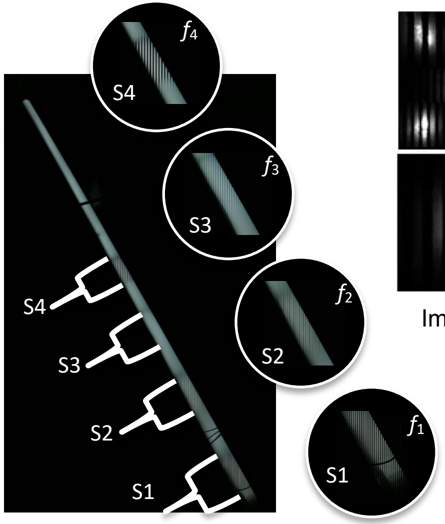
Smart Phone



Illuminate | Idle | TX <66> | TX packet

Captured using a rolling shutter





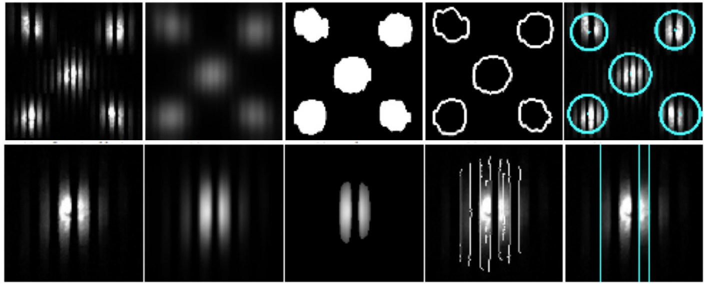


Image processing extracts beacon locations and frequencies

$$d_{0,1}^2 = (u_0 - u_1)^2 + (v_0 - v_1)^2 + (w_0 - w_1)^2$$
$$= (K_0 a_0 - K_1 a_1)^2 + (K_0 b_0 - K_1 b_1)^2 + Z_f^2 (K_0 - K_1)^2$$
$$= K_0^2 \left|\overrightarrow{Oi_0}\right|^2 + K_1^2 \left|\overrightarrow{Oi_1}\right|^2 - 2K_0K_1(\overrightarrow{Oi_0} \cdot \overrightarrow{Oi_1})$$
$$= (x_0 - x_1)^2 + (y_0 - y_1)^2 + (z_0 - z_1)^2,$$

Compute

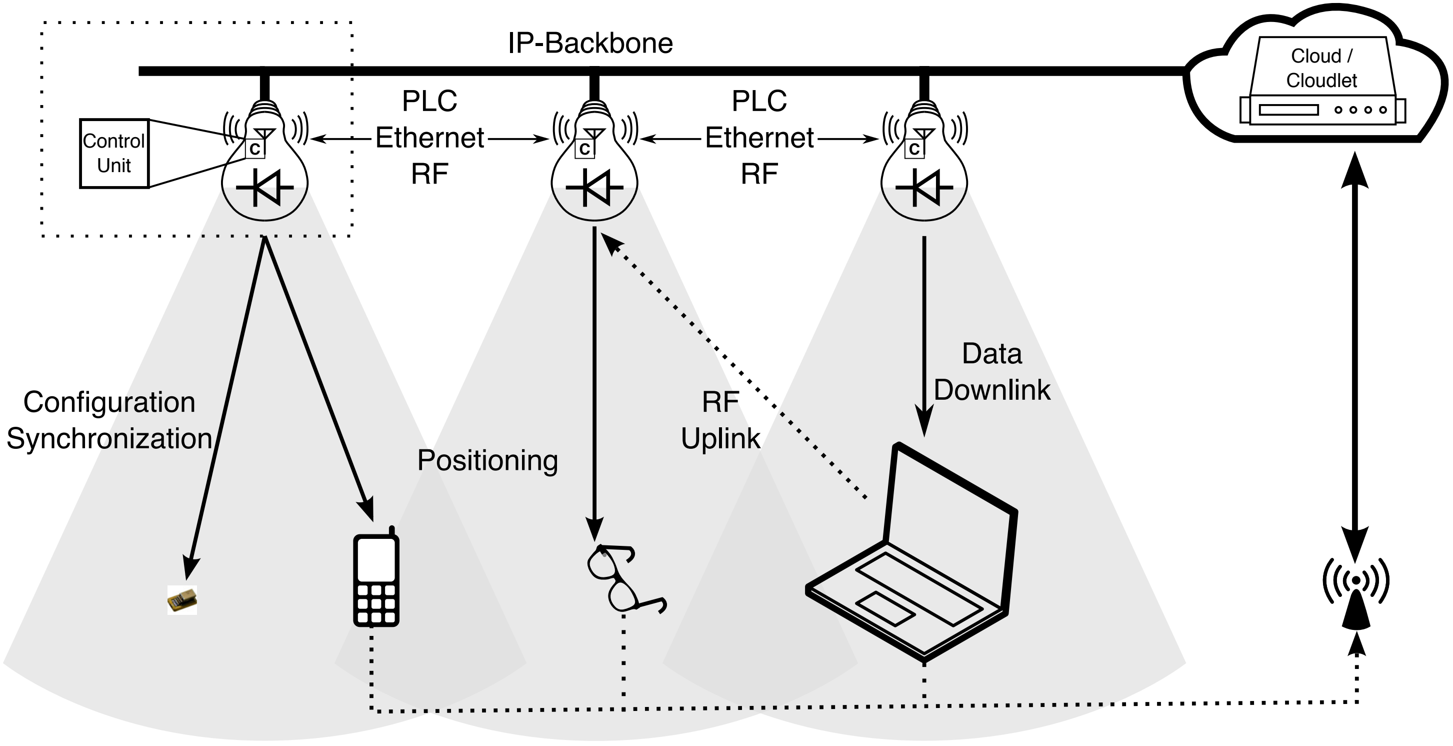
$$\sum_{m=1}^{N} ((T_x - x_m)^2 + (T_y - y_m)^2 + (T_z - z_m)^2 - K_m^2(a_m^2 + b_m^2 + Z_f^2))^2$$

Minimize

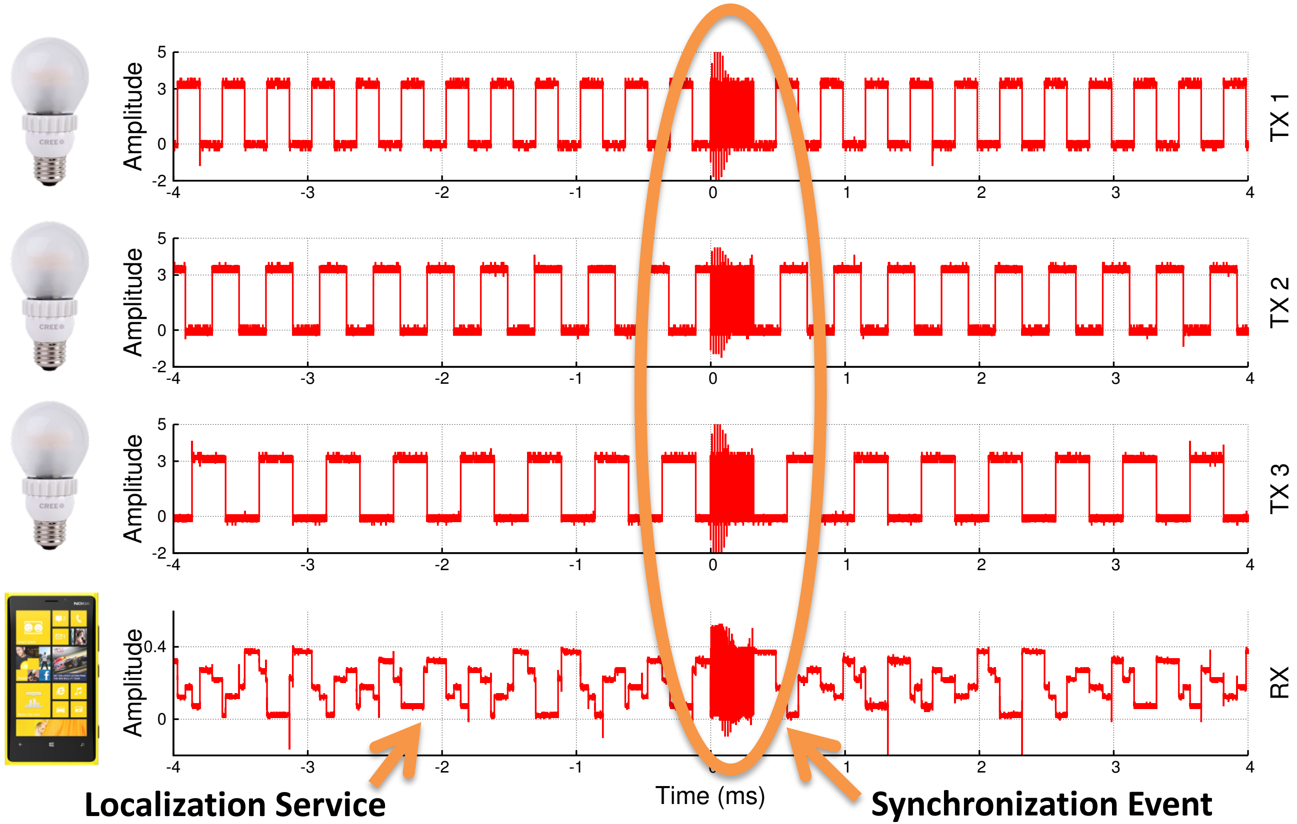
Ye-Sheng Kuo, Pat Pannuto, Ko-Jen Hsiao, and Prabal Dutta, "Luxapose: Indoor Positioning with Mobile Phones and Visible Light," In Proceedings of the 20th Annual International Conference on Mobile Computing and Networking (MobiCom'14), Maui, HI, Sep. 7-11, 2014.

One vision: Software Defined Lighting

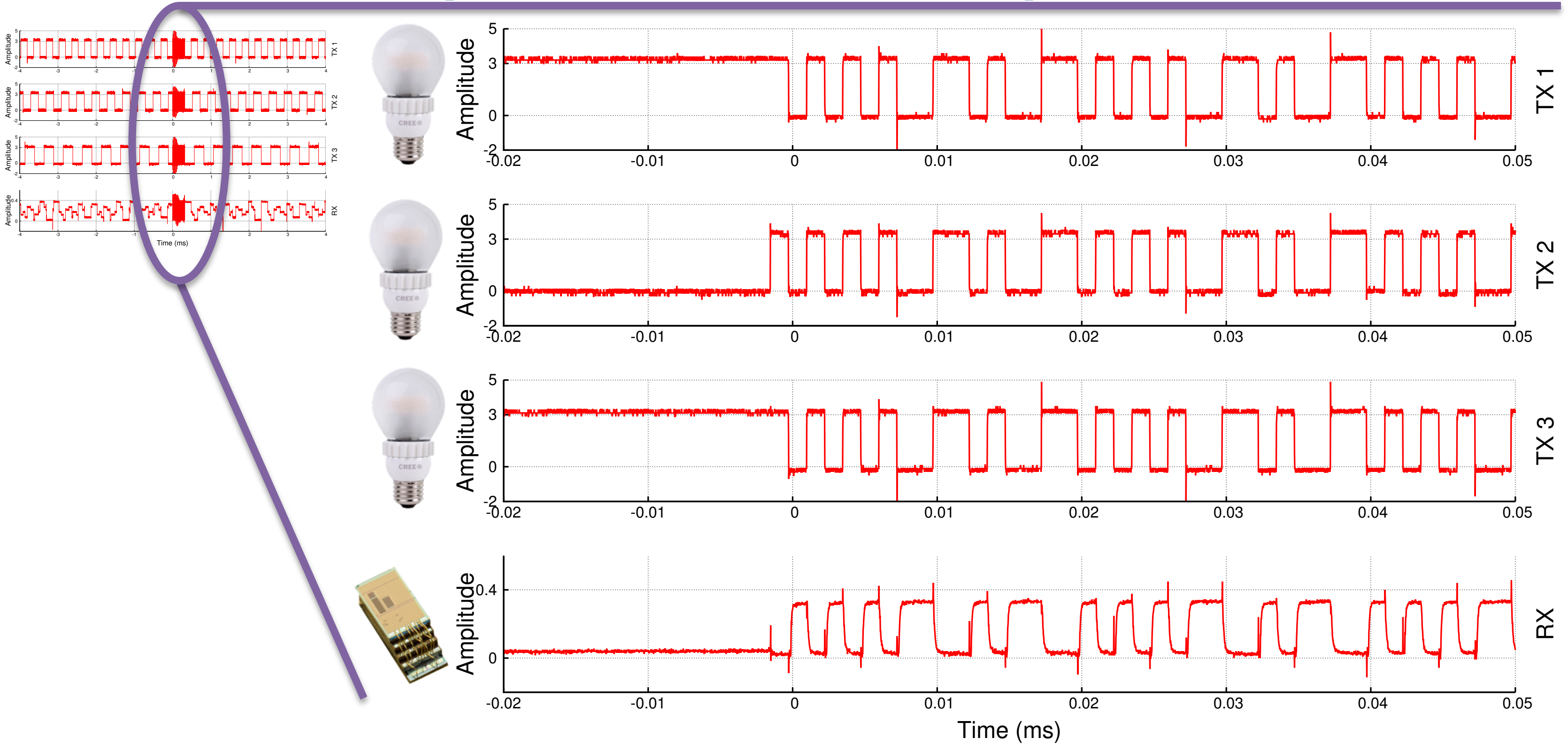
Multiplex all these services on same infrastructure



Real-world study: Illumination + Localization + Sensor Communication

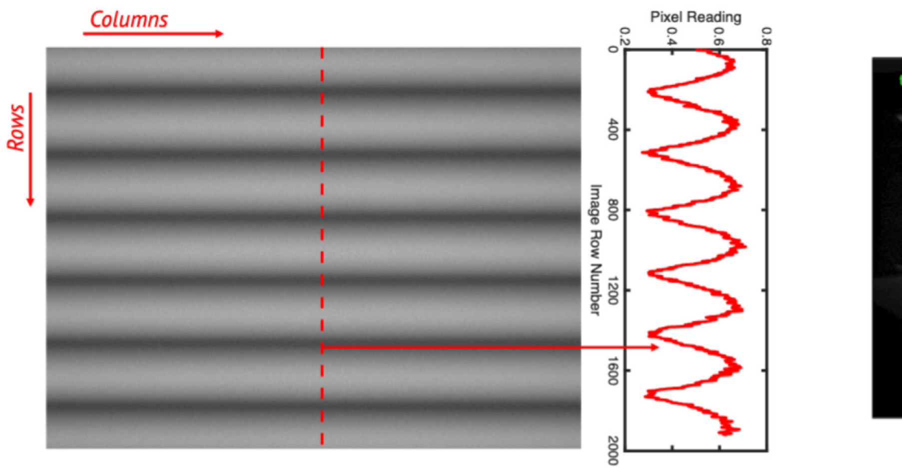


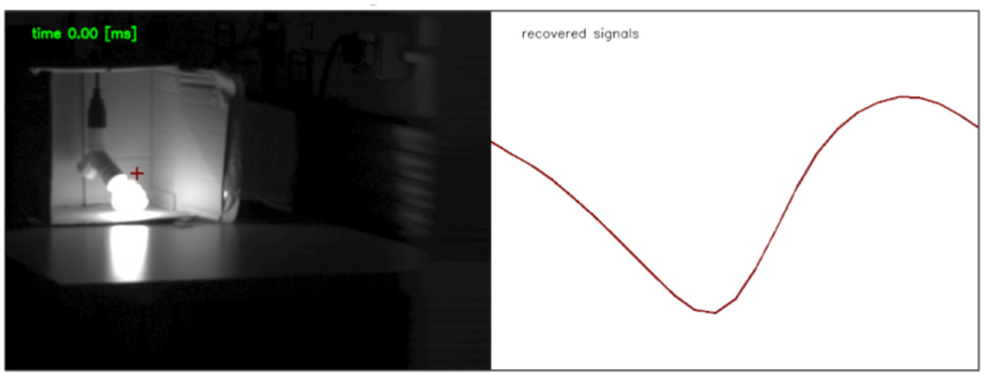
With sufficient synchronization, transmitted signals can ‘constructively interfere’ (coherently combine)



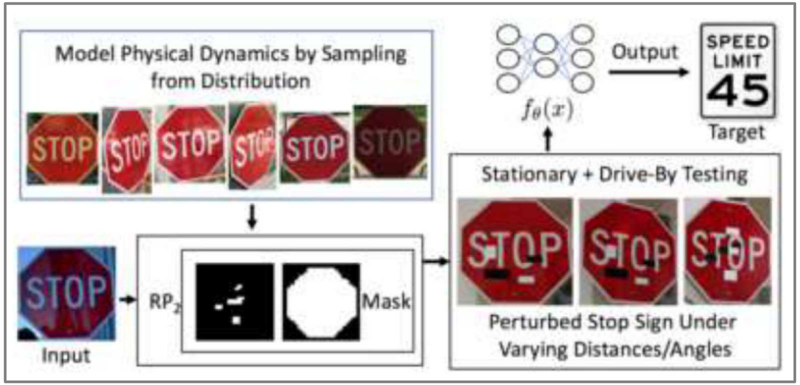
VLC as a sensing channel

- Transmitter does not have to intentionally send a data signal…
  - Active research by our own Alex: Inferring grid and bulb information!



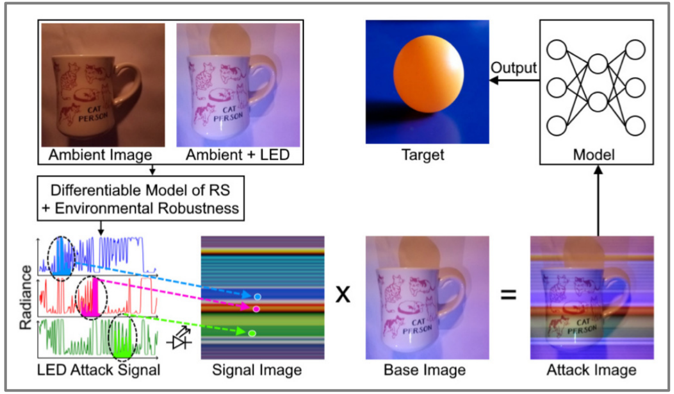


VLC as an attack channel



- From simple, 'static' modifications…

- …rolling shutter to create 'invisible' attacks!



Kevin Eykholt, Ivan Evtimov, Earlence Fernandes, Bo Li, Amir Rahmati, Chaowei Xiao, Atul Prakash, Tadayoshi Kohno, Dawn Song. *Robust physical-world attacks on deep learning visual classification.* CVPR'18.
Athena Sayles, Ashish Hooda, Mohit Gupta, Rahul Chatterjee, Earlence Fernandes. *Invisible perturbations: Physical adversarial examples exploiting the rolling shutter effect.* CVPR'21.

Outline

- Infrared
- Visible Light Communications
- **Ultrasonic**
- Vibratory

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...

Vocabulary

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.

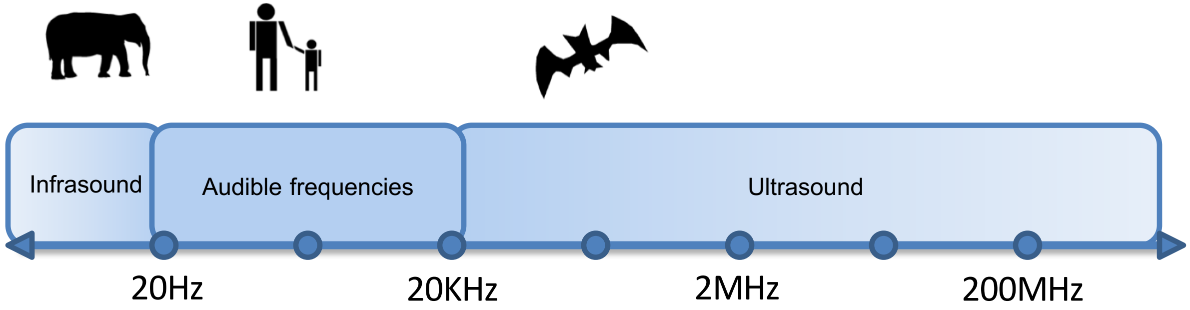
Amplitude refers to the intensity or power of the sound wave, and relates to volume.

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.

Sound comes in many frequencies

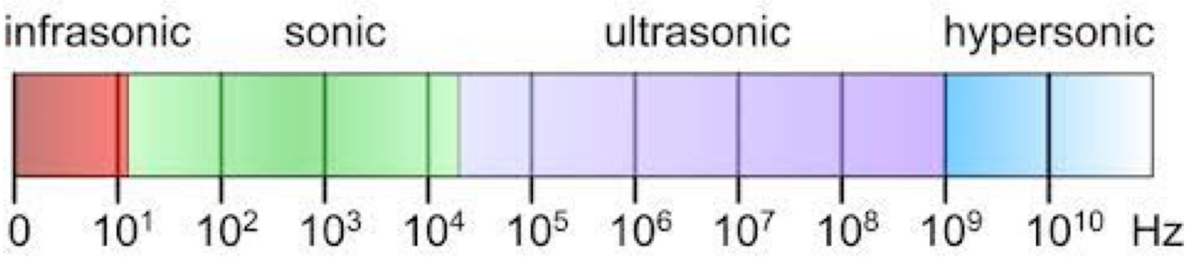
Can humans hear *all* types of sounds?



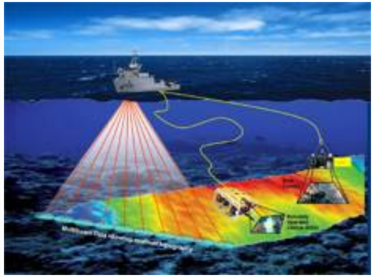
No, *audible* frequencies are what we can detect.

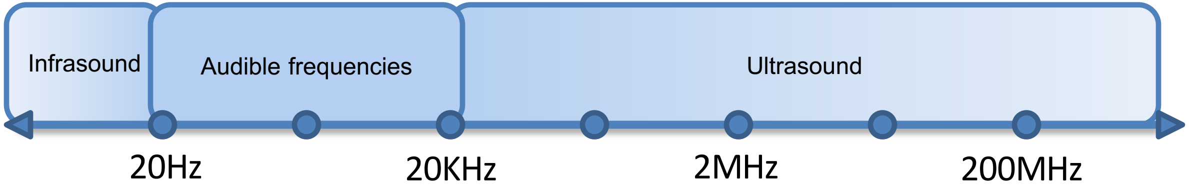
Acoustic spectrum does not have as many divisions as EM

- Possibly a statement of opportunity / underutilization for communication



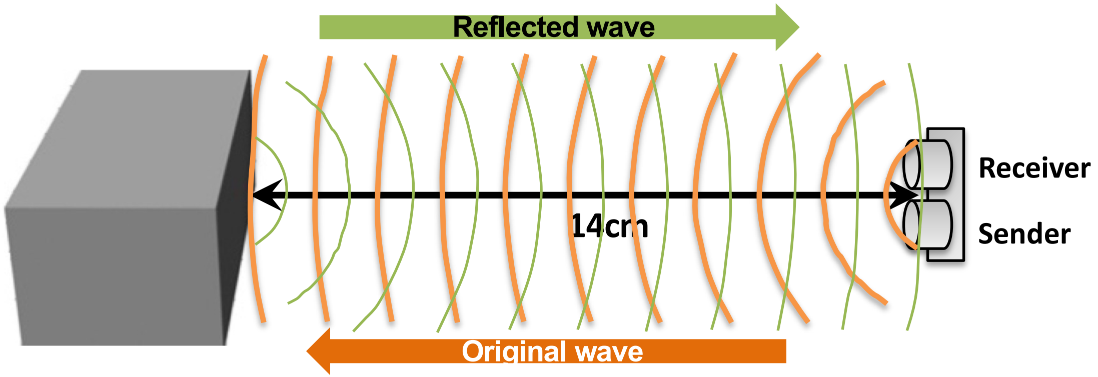
Ultrasonic applications





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 and object and bounce back to the sensor.

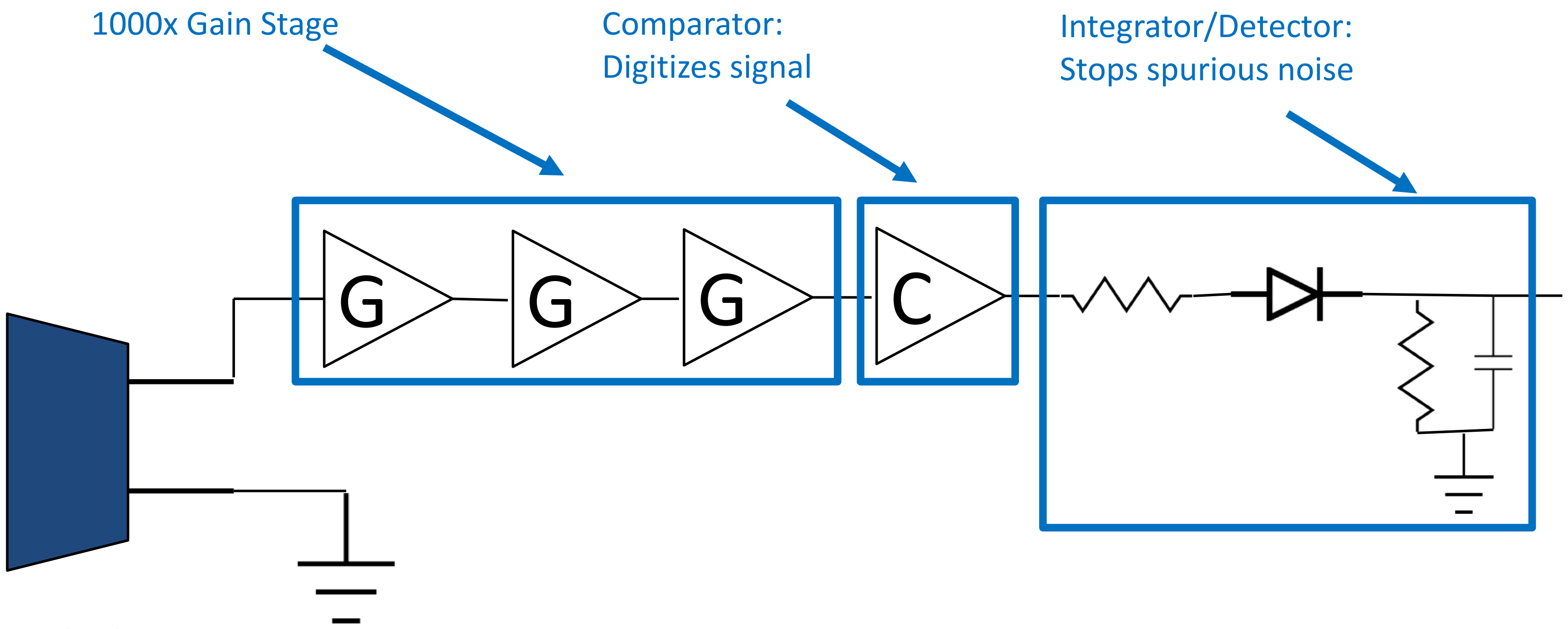
Practical communications with Ultrasound?

- 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

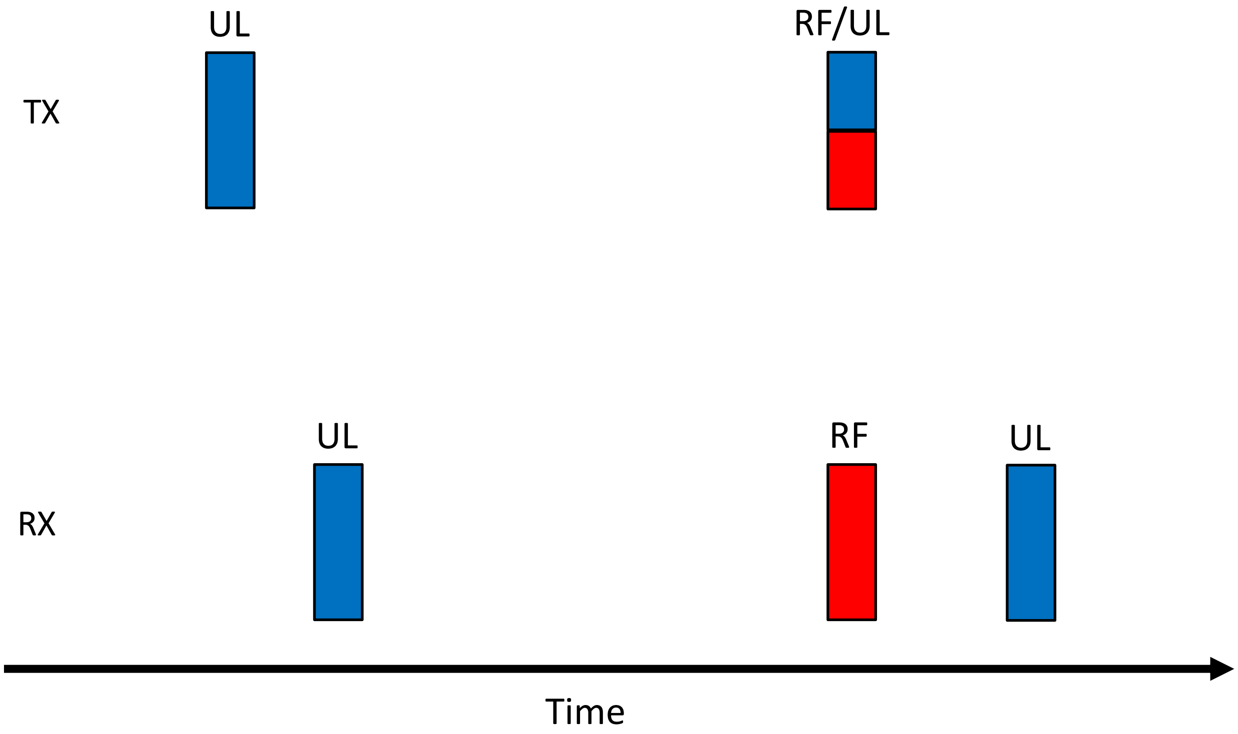
Neat tricks with UL: Near-zero energy wakeup

- Opo is UL + RF ranging platform with 60 µW "UL wakeup radio"

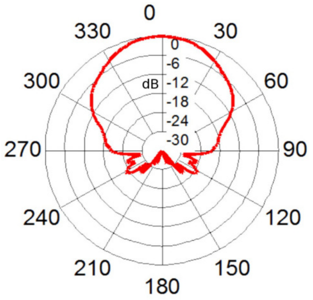


Opo's (and others') actual ranging operation is simple —

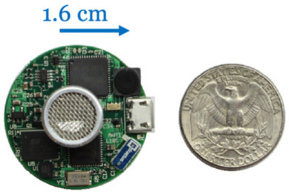
Time Difference of Arrival (TDoA) … $3*10^8$ m/s vs 343 m/s



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



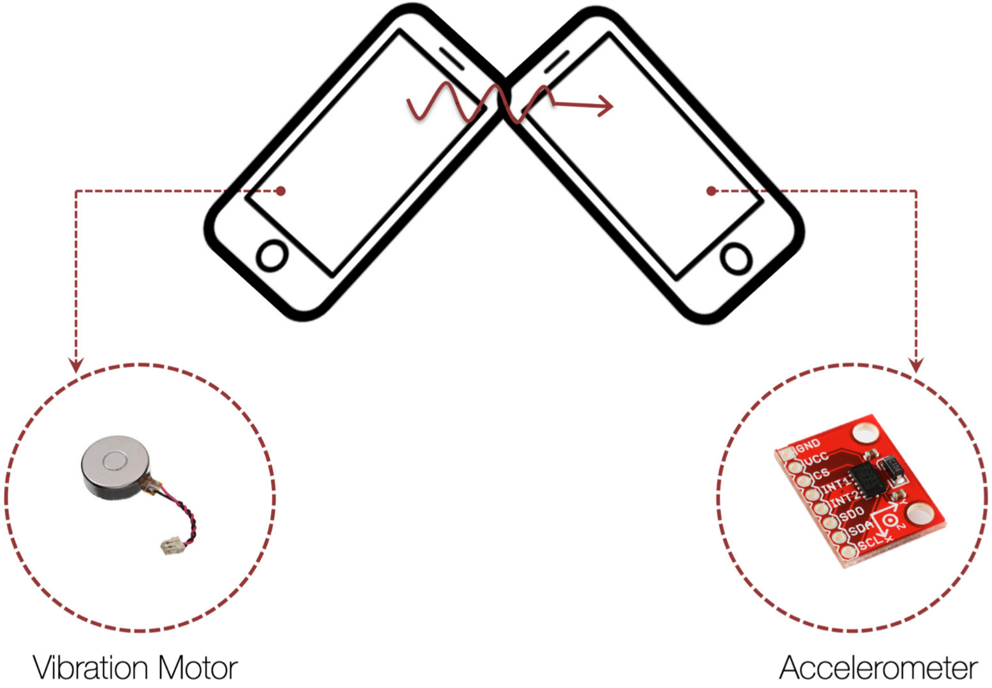
Outline

- Infrared
- Visible Light Communications
- Ultrasonic
- **Vibratory**

Premise: Exploit physical linkage for communication channel that has physical world implications

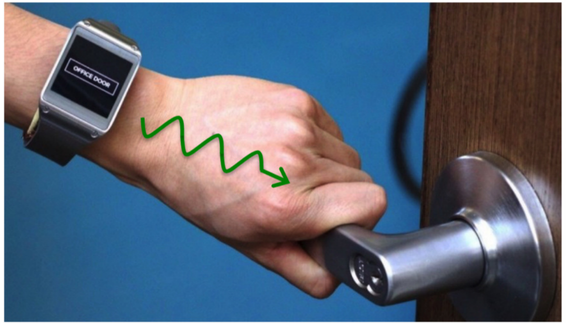
- Following slides shameless stolen from conference presentations for Ripple and Ving

Physical vibration:
a new mode of communicatio



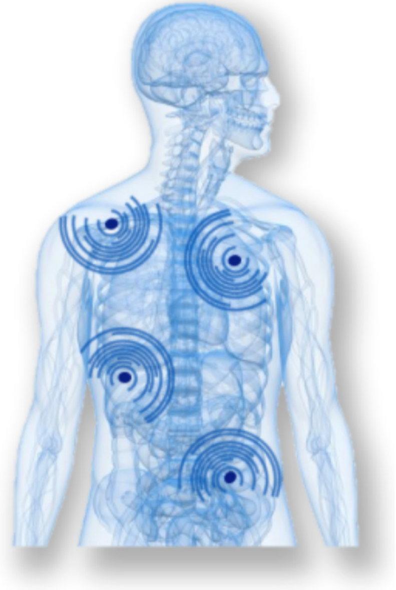
Applications

Touch activated smart-lock

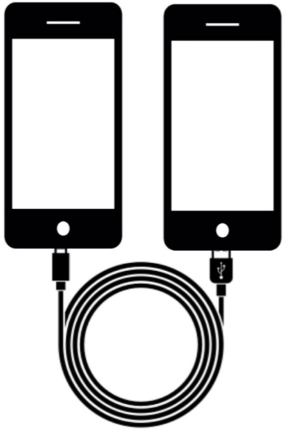


P2P money transfer

Communication through bone conduction



Applications

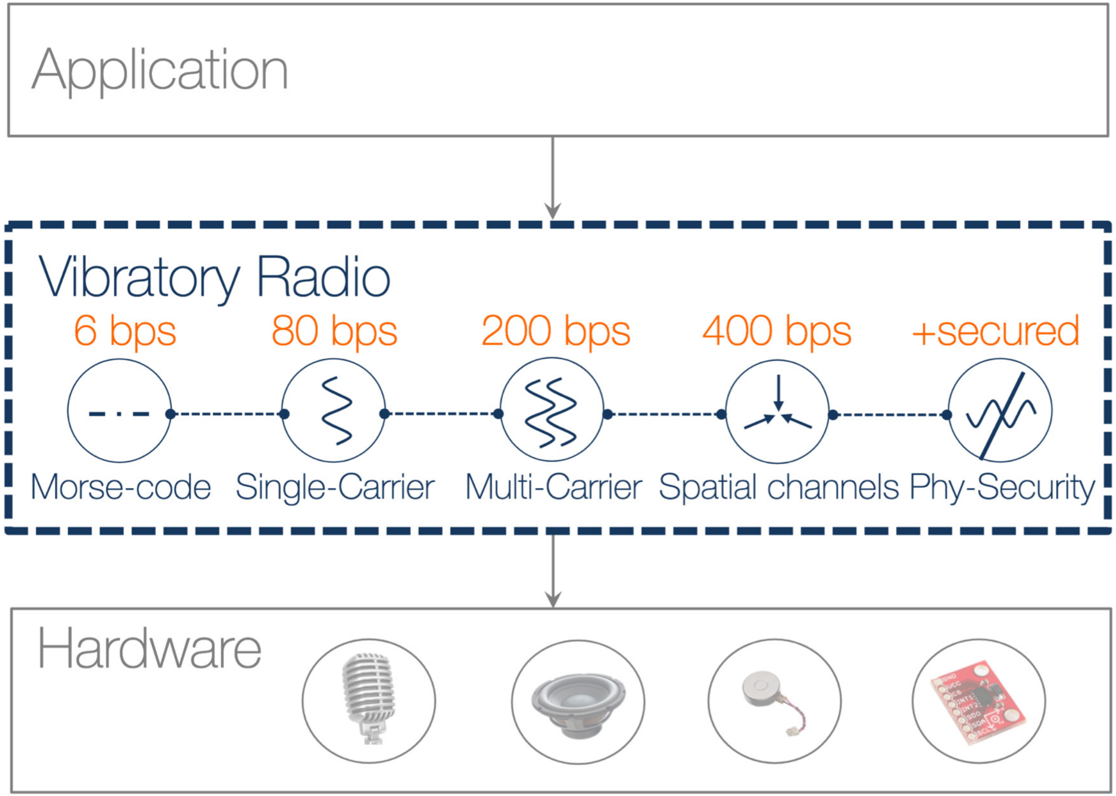


Vibrations do not **tether**

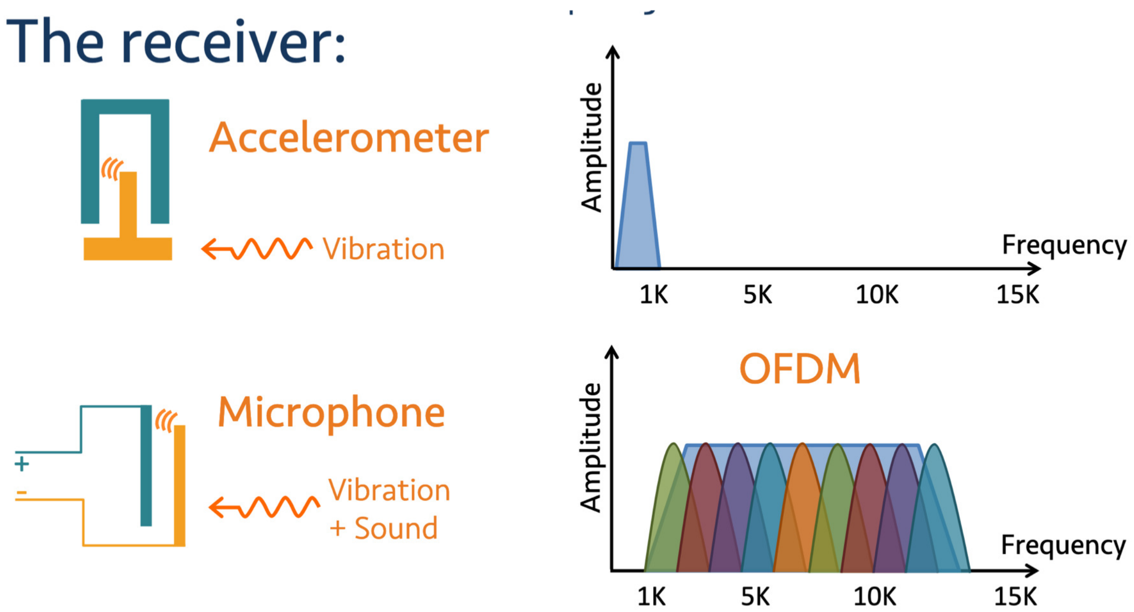
Vibrations do not **broadcast**

Vibratory communication

Ripple: vibratory communication

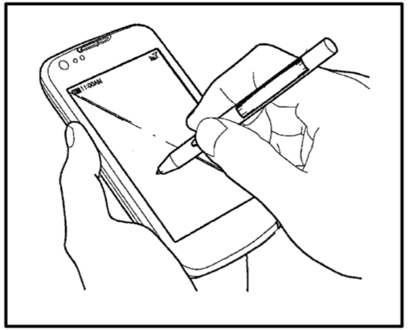


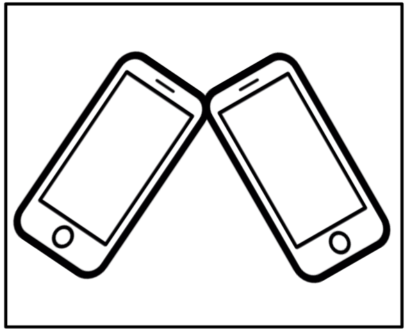
Basic insight: Can do reasonably complex modulation schemes on this channel to get decent bandwidth using microphone to RX



Decent data rates nowadays

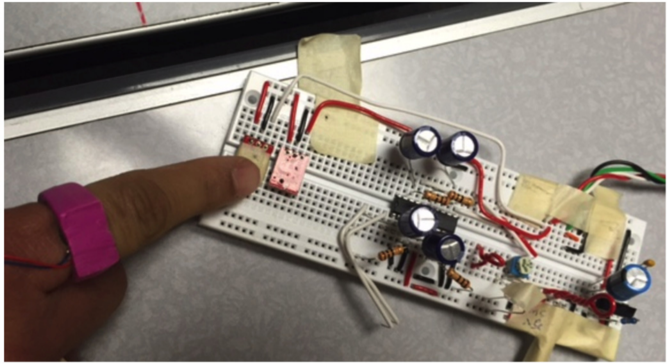
Evaluation





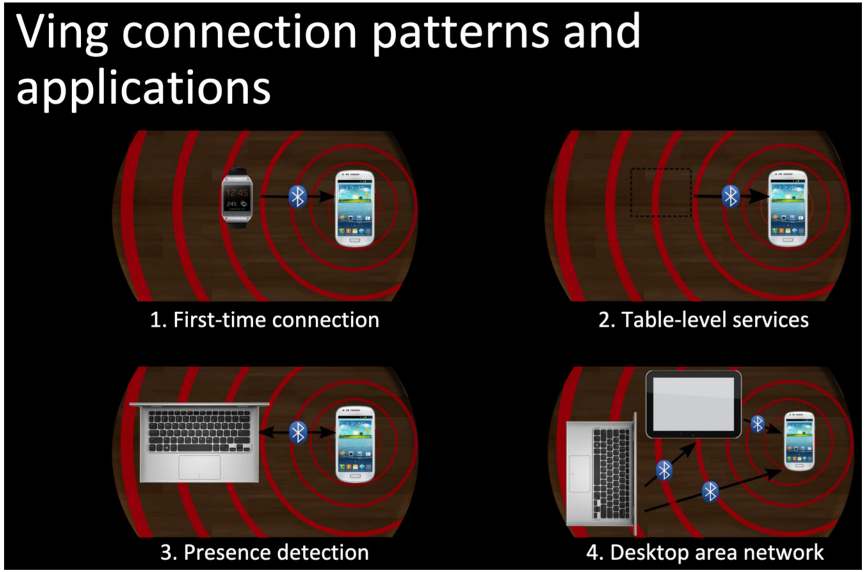
	Bandwidth	Modu.	Code	Tput:Kbps
Stylus	12 KHz	16 QAM	2/3	29.19
Phone	12 KHz	16 QAM	2/3	26.13

Evaluation



	Bandwidth	Modu.	Code	Tput:Kbps
Ring	8 KHz	QPSK	1/2	7.41
Watch	3 KHz	QPSK	1/2	2.23

Ving argument: Mixed-mode again, use RF for high-bandwidth, but vibratory channel for wakeup [lower power] and security



Outline

- Infrared
- Visible Light Communications
- Ultrasonic
- Vibratory

- Is there more?
  - So much more

Next time: There is no next time! :/