CSE 291: Wireless and Communication in the Internet of Things

Other RF: Backscatter & Wake Up Radios

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Today's Goals

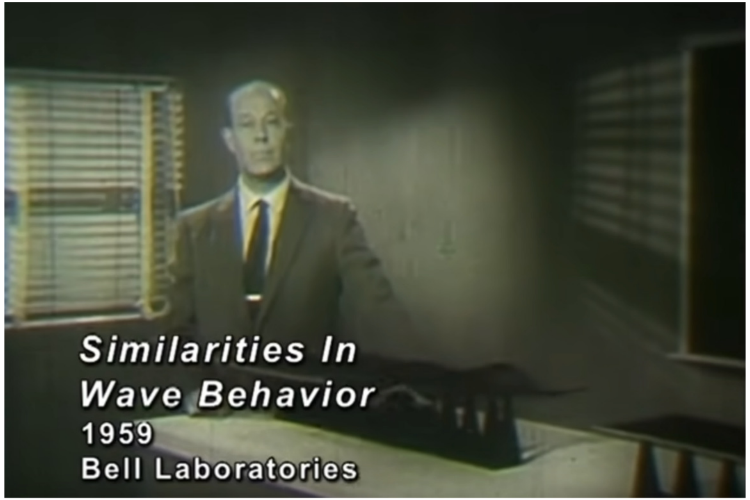
- Talk about some non-traditional RF designs
- Catch up on some of what's happening in modern RF-for-IoT Research
  - More advertisements / pointers-to-content

Outline

- Backscatter
  - Antenna & Wave Primer
  - History
  - Modern Uses
- Wakeup Radios
- Intermittent MACs

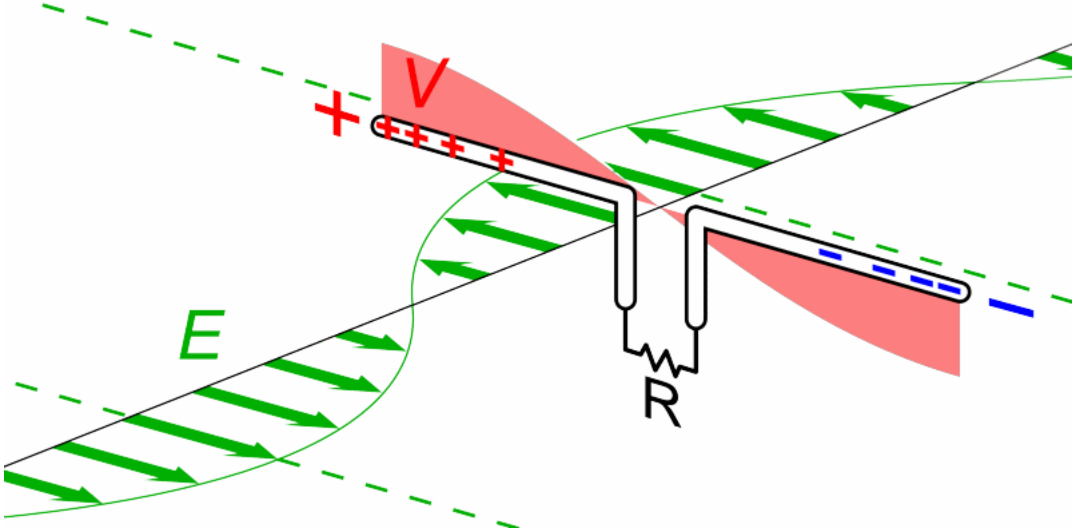
Resources

- This Bell Labs instructional video from 1959 is *excellent* background:
  - https://www.youtube.com/watch?v=DovunOxlY1k



What does an antenna *do?*

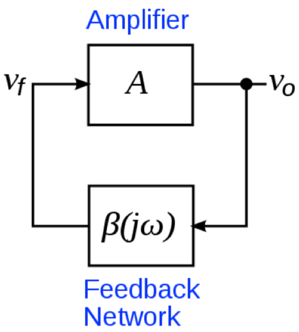
- Loosely: Converts between electric and magnetic waves



Animation by Chetvorno - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=40789783

What generates ~~electric~~ waves?

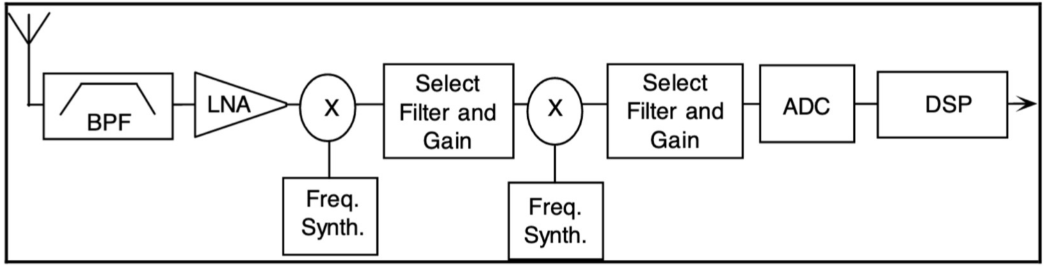
- Lots of stuff nowadays…
- Most commonly a frequency-selective resonator into an amplifier
  - i.e.



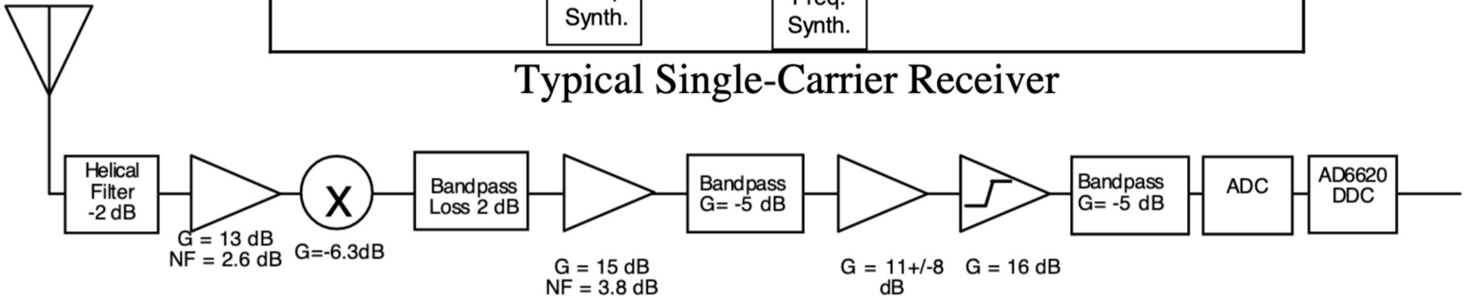
- Modern systems use physical structures to tune (e.g. SAW is e^- <> audio)
- Also can be done with high-speed digital components (e.g. fast DACs)

What receives electric waves?

- Again, lots of stuff nowadays…
  - Could be a high-speed ADC, more often with analog pieces in front:

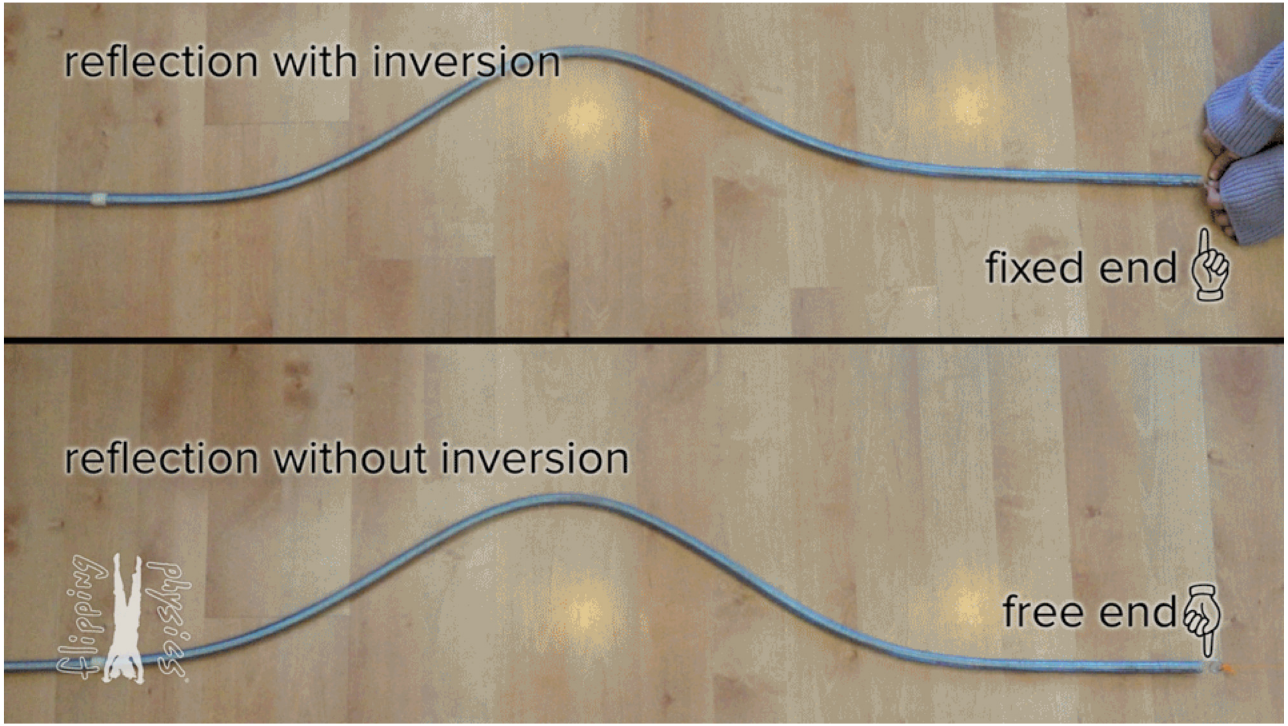


Typical Single-Carrier Receiver



Graphics from Analog Devices whitepaper: https://www.analog.com/media/en/technical-documentation/tech-articles/480501640radio101.pdf — significantly more detail here

What happens if nothing ‘receives’ the wave?



From: https://www.flippingphysics.com/standing-waves.html

"Fixed end" and "Free end" in electronic transmission

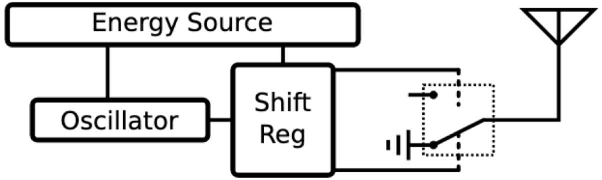
Short Circuit = "Free End"
- Reflects wave

Open Circuit = "Fixed End"
- Inverts wave

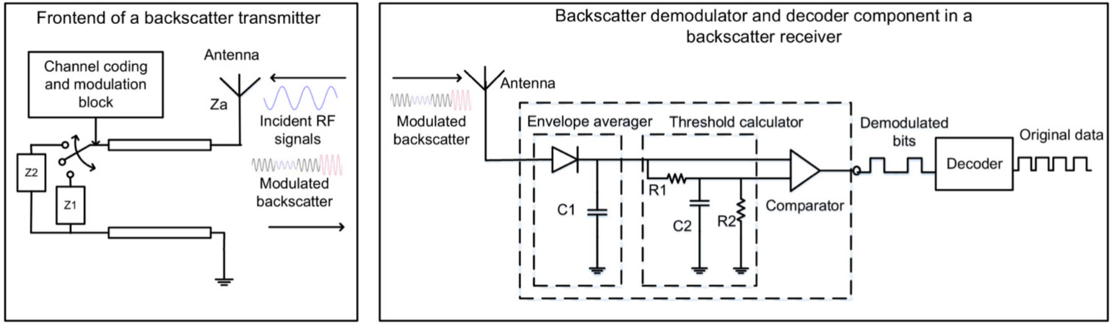
Matched Load
- Absorbs wave (no reflection)

Backscatter systems *reflect* waves rather than *generate* waves — significant (10,000x or more) power savings

- Simple versions just 'reflect or don't reflect'



- Modern designs can do more advanced modulation as well



(a) (b)

https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8368232

Backscatter is an *old* idea — history in spycraft!

- 1945: Leon Theremin* creates “The Thing” (aka Great Seal Bug)
  - *Yes, same guy who invented the instrument

RFID is *everywhere* nowadays

- Fundamental design principle is *asymmetry*
  - Extremely simple, cheap tags
  - Complex readers

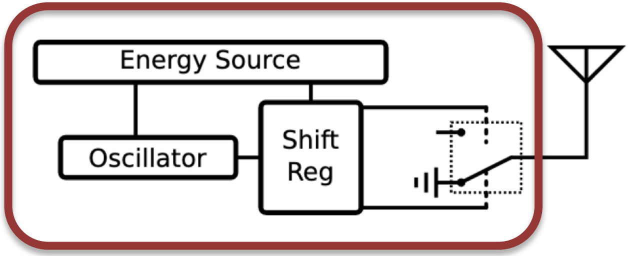
A brief digression to be precise in terminology

- RFID = Radio Frequency Identification = "a" communication standard
  - A *ton* through ~early 90's; "EPC" ~= UPC, standardized; most now EPC Gen2
- There are actually three types of "RFID" device
  - Passive Tags - harvest power from reader & reflect
  - Semi-Passive Tags - on-board power, but reflect data
  - Active Tags - on-board power that transmit data

These are "backscatter" — which describes any communication via reflected RF

The meaningful difference is in how the tag devices power themselves

- Even on simple designs, need some power:
- Let's look at FasTrak again:



Let's look at RFID standards to get a sense of the numbers

- Low Frequency (~300 kHz) — mostly legacy
  - ~10cm read range
- High Frequency (3~30 MHz; often 13.56 MHz)
  - Passive: 4~7 m max
  - Semi-Passive: 10~30 m max
  - Active: 30+ m
- Ultra-High Frequency (300 MHz ~ 3 GHz)
  - Passive: Up to 12 m
  - Active: Up to 100 m

Sidebar: What's NFC?

- Near Field Communications [both an RF term, and a standard, *sigh*] is a subset of the RFID protocol
  - 10-20cm range (usually <10)
  - Inductively coupled loop antennas
    - Communicates via local *magnetic field* rather than *electromagnetic waves*
      - This is the "near-field" part
    - (Basically a transformer)
  - N.b. does still emit RF, just weakly (i.e. can be eavesdropped on from afar)

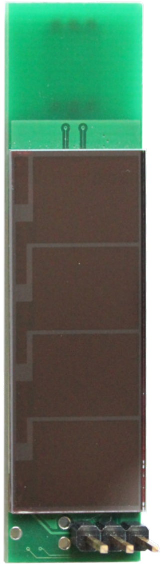
So how does RFID, Backscatter, etc map back to the IoT?

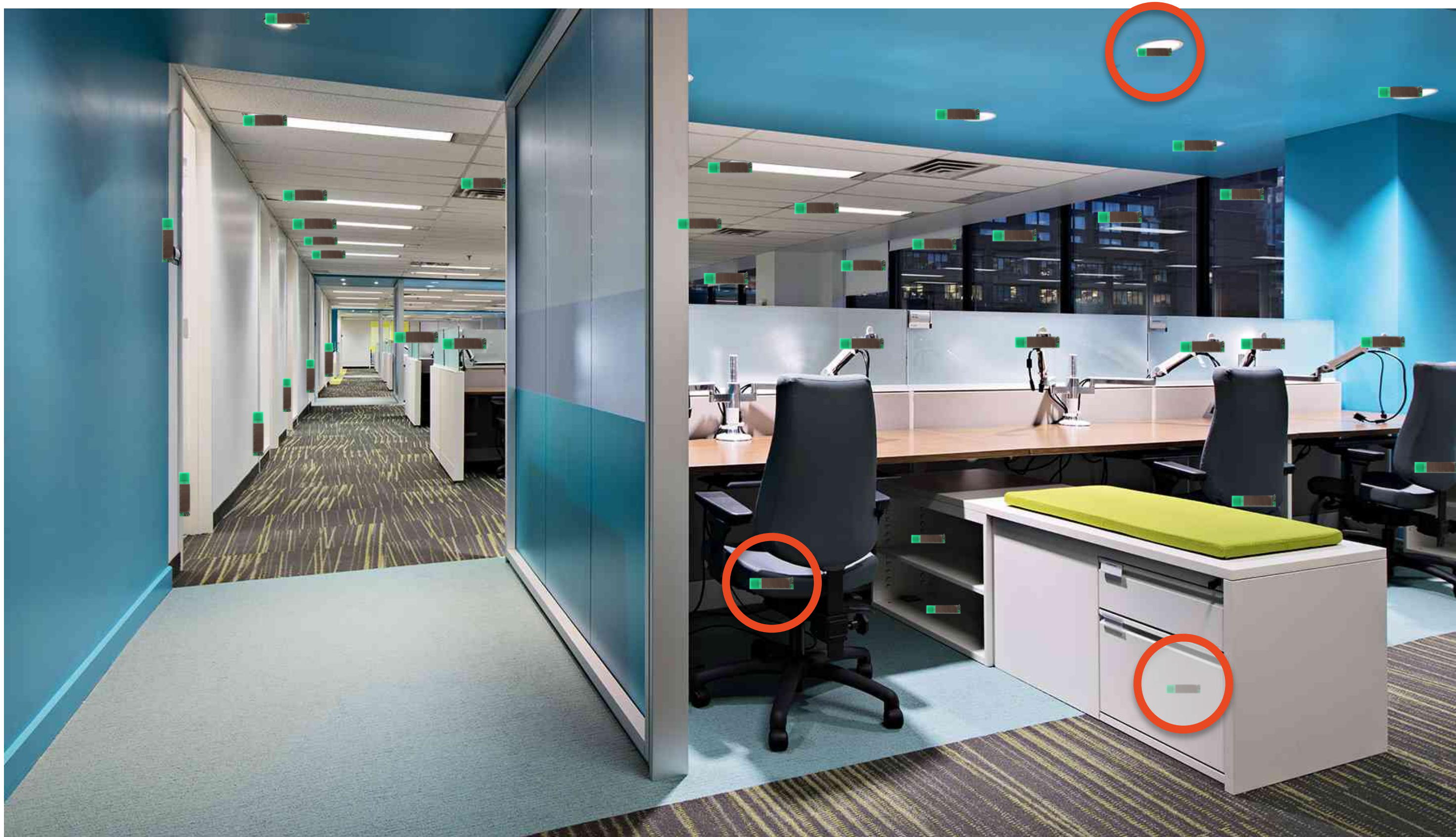
- Well, as always, "Power and Communication are the hard part"
  - RFID works, but only in the presence of an RFID reader
  - Recent research looks at eliminating that latter clause
- Power: RF Harvesting for general purpose computation
  - WISP
  - Moo
- Communication: Repurposing extant RF signals for other uses
  - Ambient Backscatter
  - Inter-Technology Backscatter

Backscatter can be used for more than just communication

- Can also use backscatter for *localization*

Slocalization: Ultra wideband backscatter localization

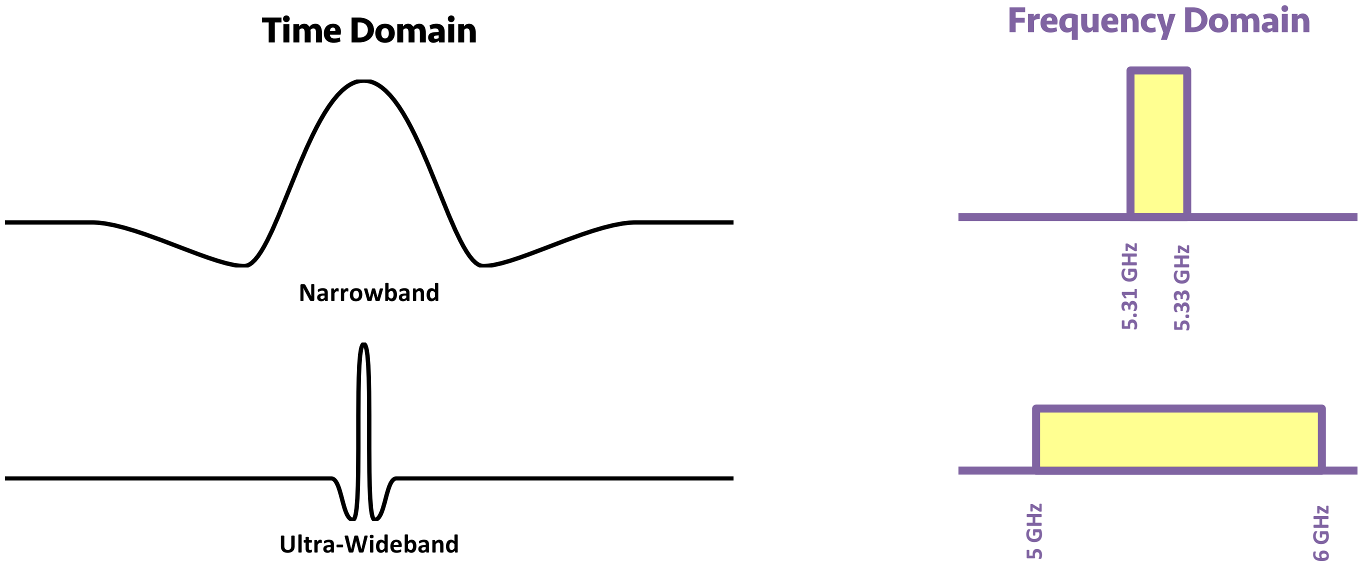




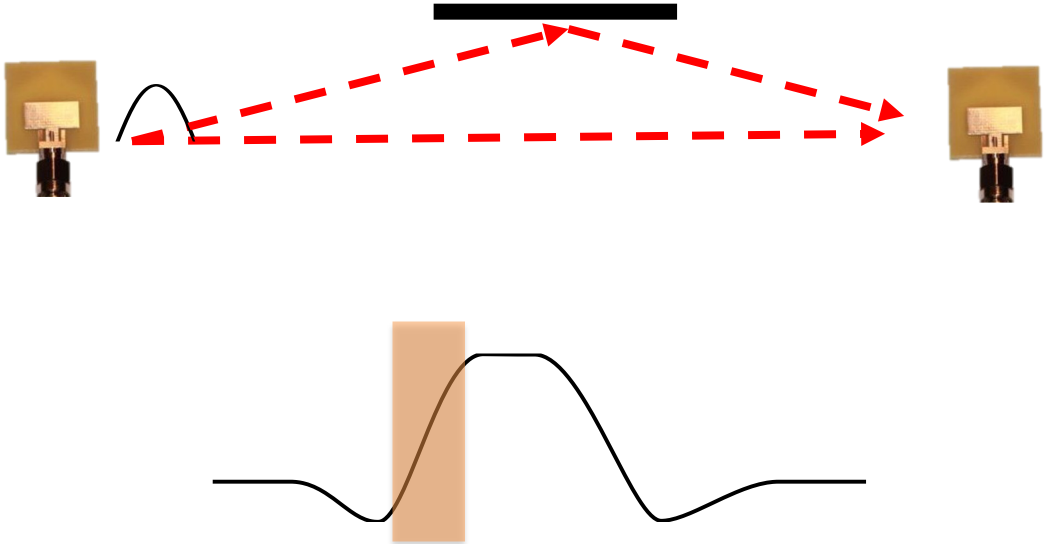
Why RF, why ultra wideband, why backscatter for ubiquitous localization?

Mautz, Rainer. "Indoor positioning technologies." (2012).

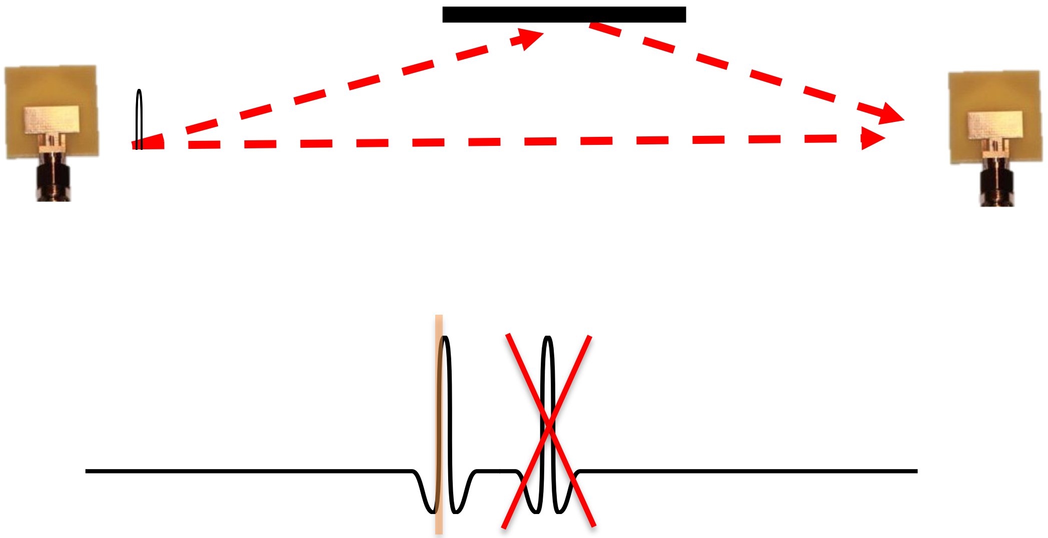
Why RF, why ultra wideband, why backscatter for ubiquitous localization?



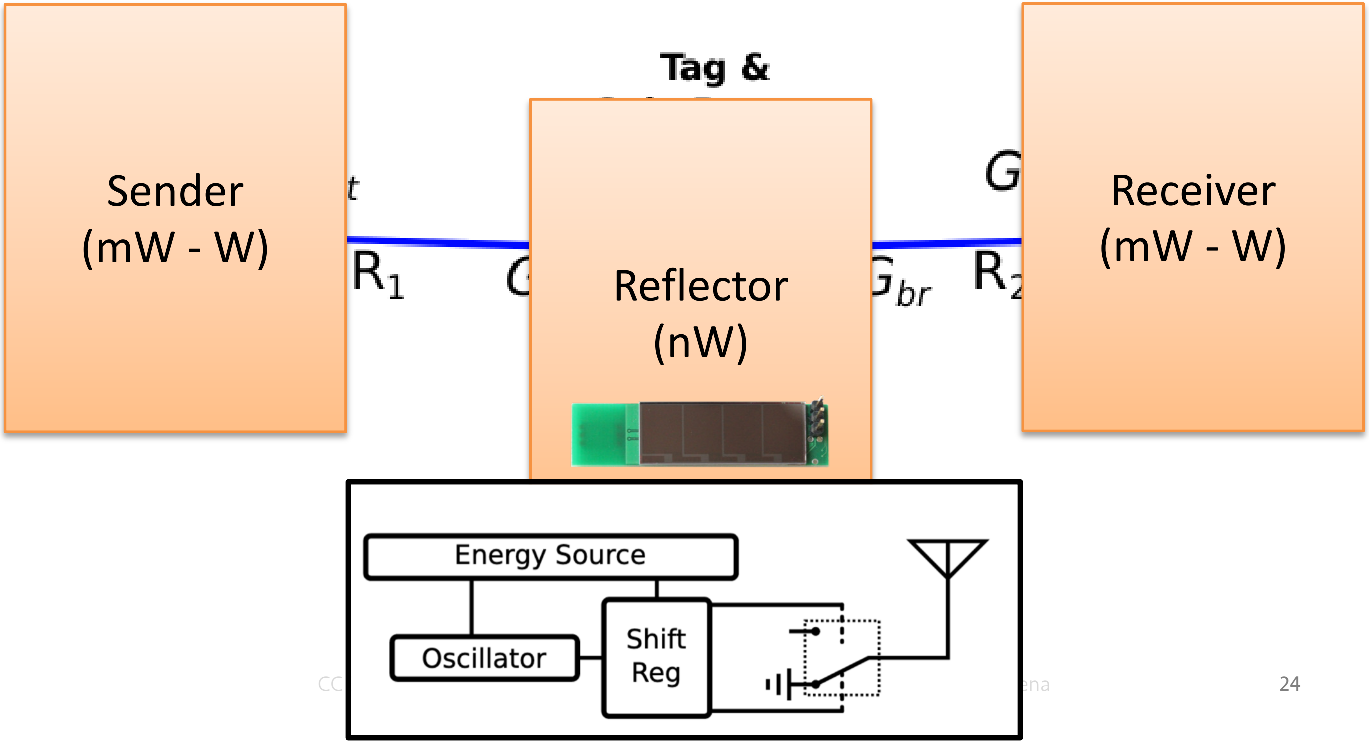
Reflections make time-of-flight estimation difficult and inaccurate



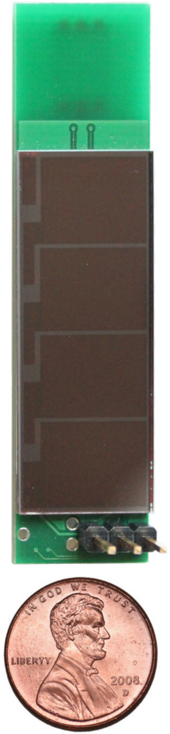
Ultra wideband can better disambiguate multipath and identify signal arrival time



Why RF, why ultra wideband, why backscatter for ubiquitous localization?



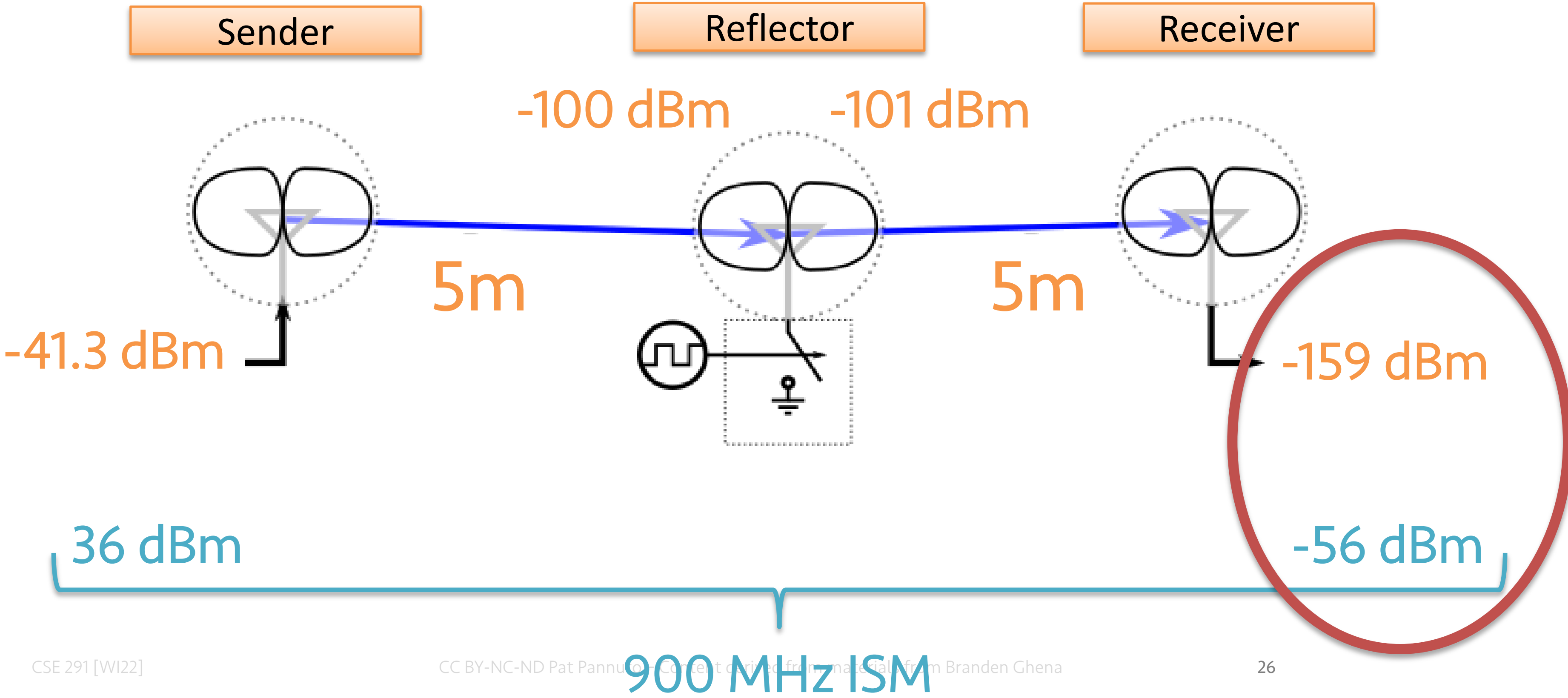
There is a new tradeoff to introduce to enable wide-area ultra-low power, high-quality localization



- Covers areas 30m+
  - "through walls"
- Decimeter accurate
- <1 μW tag
  - (COTS, can do order of magnitude or more better with VLSI)
- (Nearly) unlimited number of concurrent tags
- 1-15+ minutes per location fix
  - A latency/energy tradeoff for localization

Slocalization: Sub-μW Ultra Wideband Backscatter Localization
Pat Pannuto, Kempke, Benjamin, and Prabal Dutta
Proceedings of the 17th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN'18). **Best Paper Finalist.**

UWB Backscatter is passive reflection of a lot less energy than traditional communications



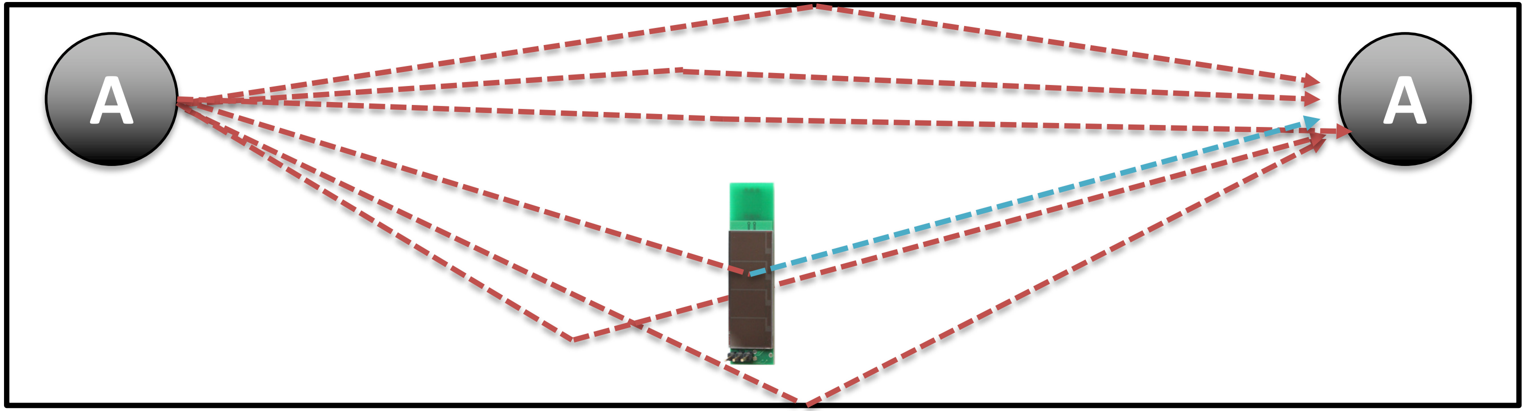
UWB Backscatter is passive reflection of a lot less energy

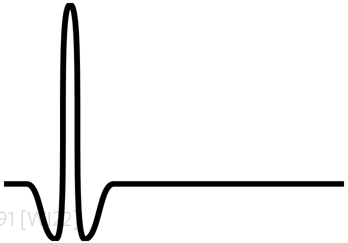
Packet Error Rate	Data Rate	Typical Receiver Sensitivity	Units
1%	110 kbps	-106	dBm/500 MHz
10%	110 kbps	-107	dBm/500 MHz
	[illegible] kbps	[illegible]	dBm/500 MHz
1%	850 kbps	-101	dBm/500 MHz
	6.8 Mbps	-93 (*-97)	dBm/500 MHz
10%	110 kbps	-106	dBm/500 MHz
	850 kbps	-102	dBm/500 MHz
	6.8 Mbps	-94 (*-98)	dBm/500 MHz

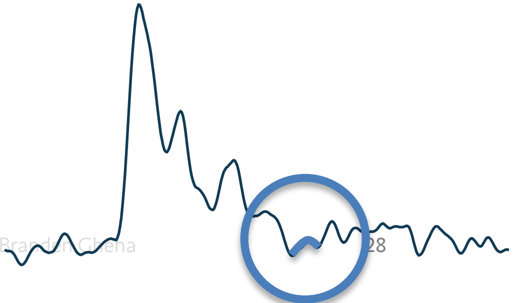
Typical receiver sensitivity ranges from -94 to -106

How do we recover a signal that is way below the noise floor?

- Exploit tag stationarity and environmental stability







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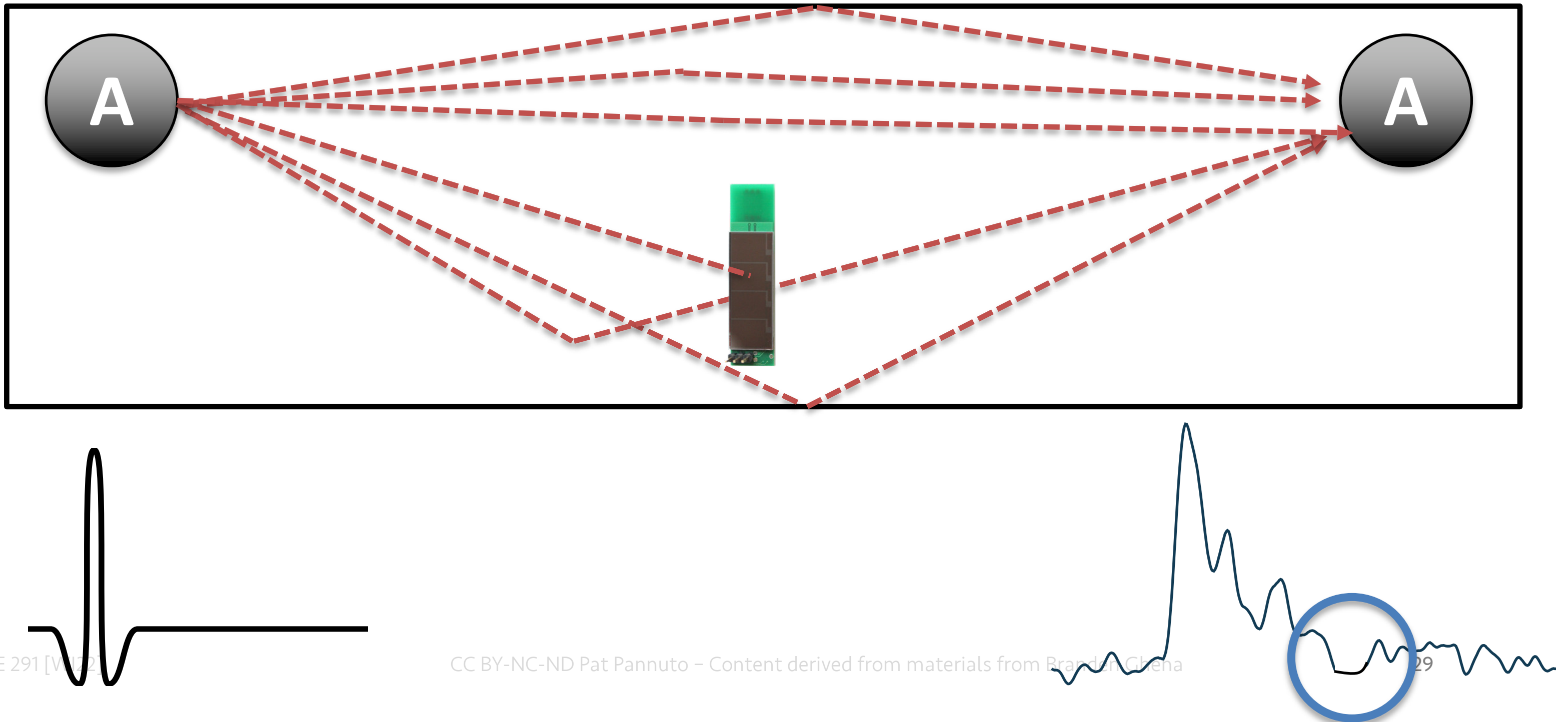
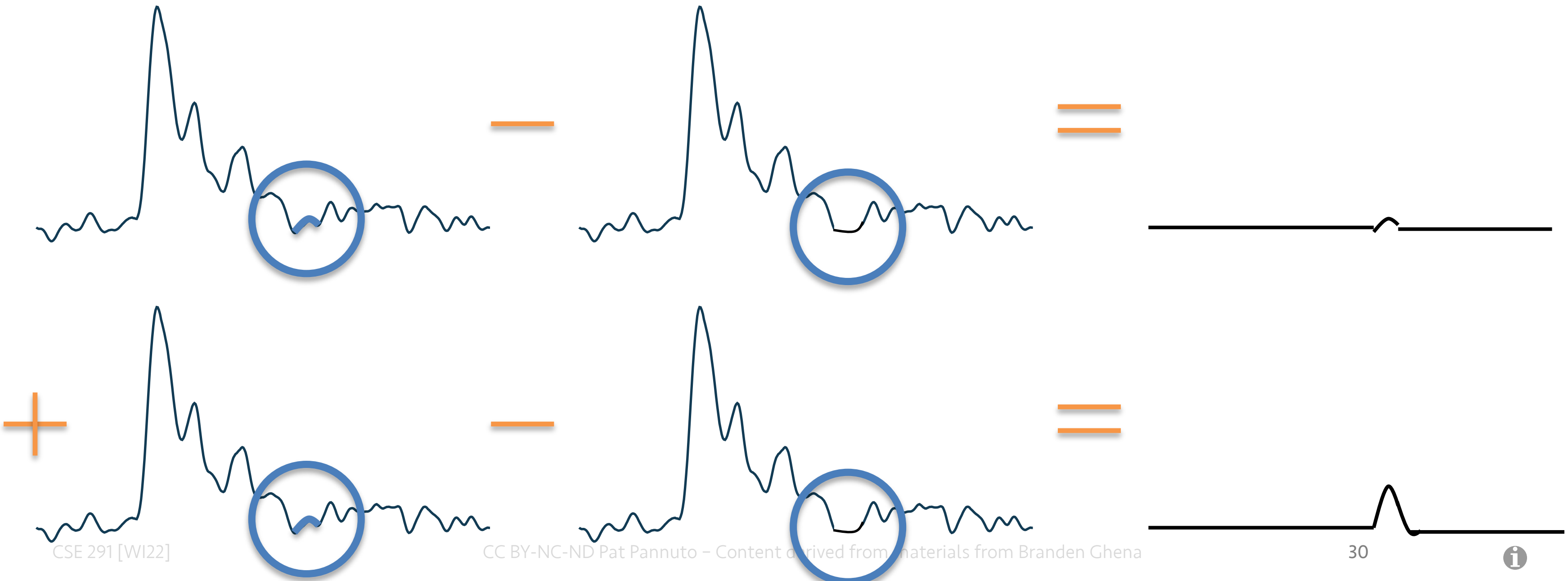
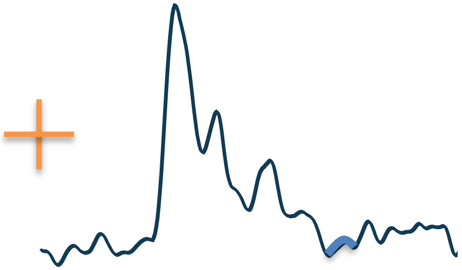


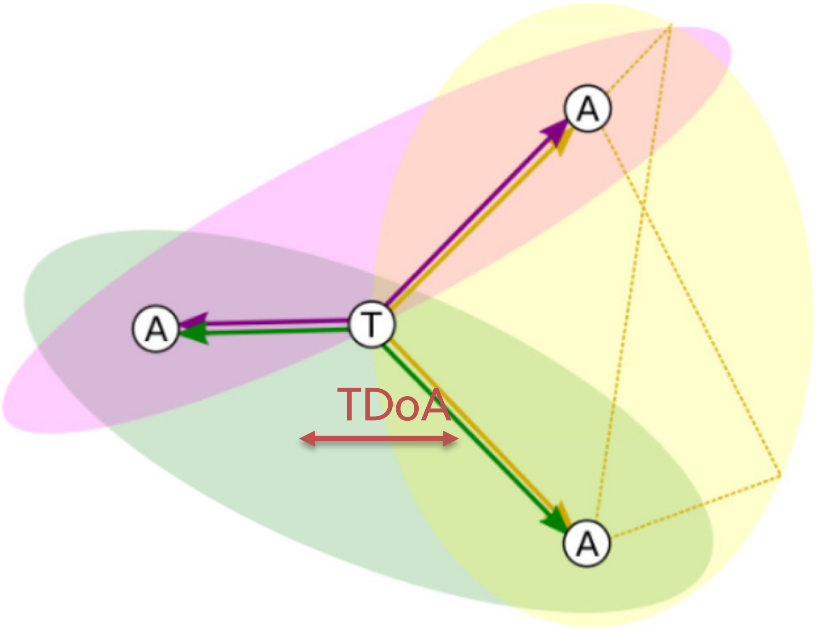
Ideally, the only change in the channel impulse response is the tag reflection

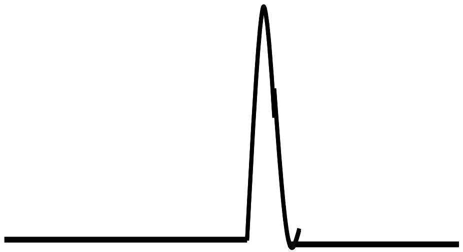
- Subtracting the environment finds the tag



The goal is to estimate the time difference of arrival (TDoA) and laterate



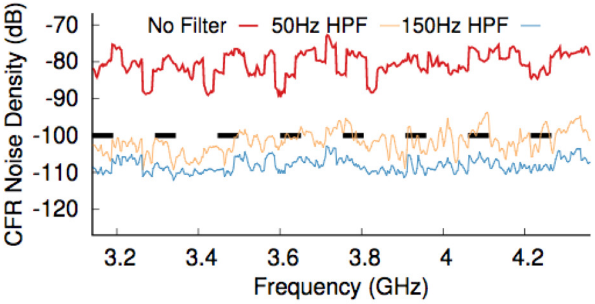




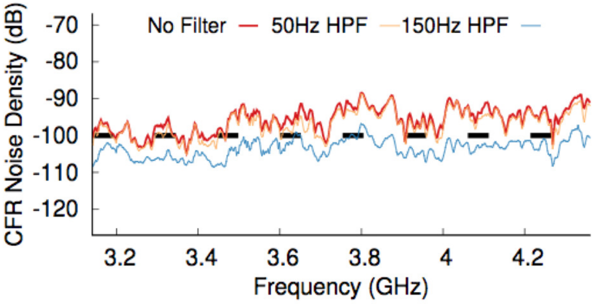
- First peak is anchor—anchor path, then anchor—tag—anchor

Extracting the tag signal in the real world has a few additional challenges

- The environment is not actually static
  - But noise is largely white & Gaussian
  - And we can filter out the rest (sets floor for tag frequency, active power)



(b) CFR Noise Walking



(c) CFR Noise Fluorescents

- Finding tag phase offset currently requires brute force search

Directly generating and recovering UWB signals is challenging (especially circa 2014-2018… changing fast!)

RTLS Systems are black box

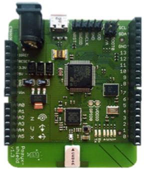
Time Domain P440
(now Humatics)

Ubisense Research Package
(now Investcorp Technology Partners)

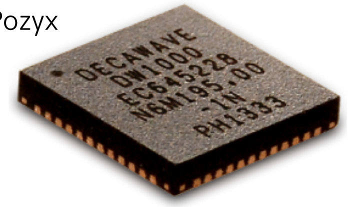
802.15.4a has protocol expectations & overhead

Pixie

Ciholas DWUSB

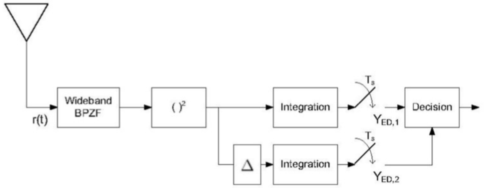


Pozyx

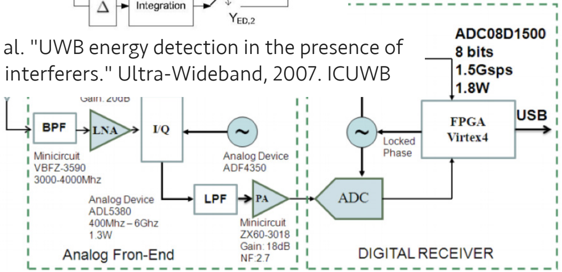


DecaWave DW1000

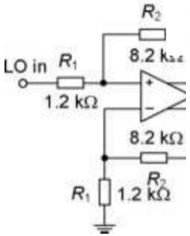
Research receivers: expensive, noisy, or niche



Rabbachin, Alberto, et al. "UWB energy detection in the presence of multiple narrowband interferers." Ultra-Wideband, 2007. ICUWB



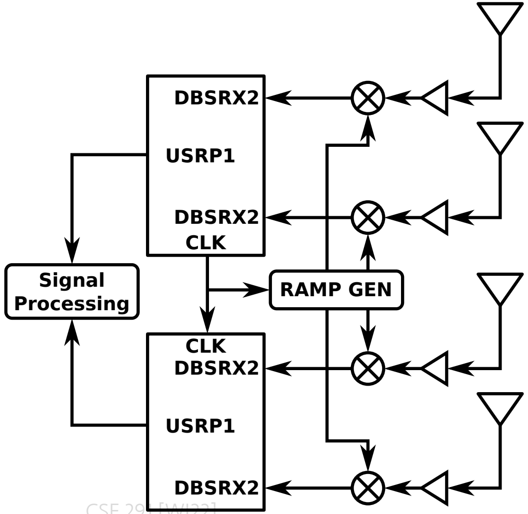
Segura, Marcelo, et al. "Experimental demonstration of self-localized ultra wideband indoor mobile robot navigation system." Indoor Positioning and Indoor Navigation (IPIN), 2010 International Conference on. IEEE, 2010.

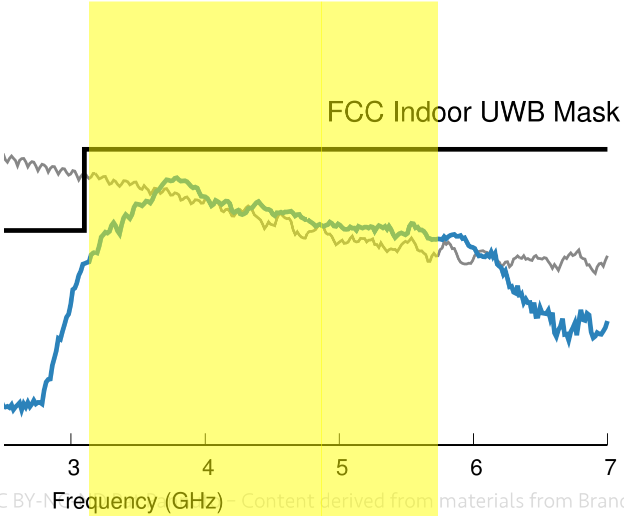


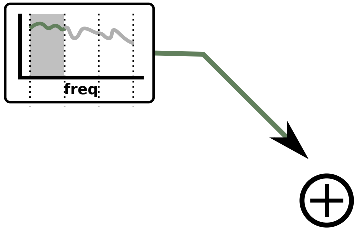
Hantscher, Sebastian, et al. "Hardware concepts for the sequential sampling of repetitive pulse radar echoes in cost-efficient ultra-wideband transceivers."Microwave and Optical Technology Letters 52.3 (2010): 585-591.

Directly generating and recovering UWB signals is challenging (especially circa 2014-2018… changing fast!)

- Developed bandstitched UWB transceiver architecture
  - Generic narrowband SDR (USRP)
  - Measure Channel Frequency Response in 20~25 MHz chunks







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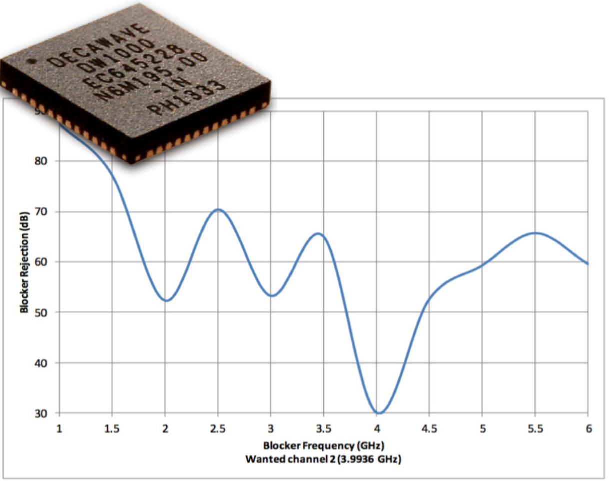
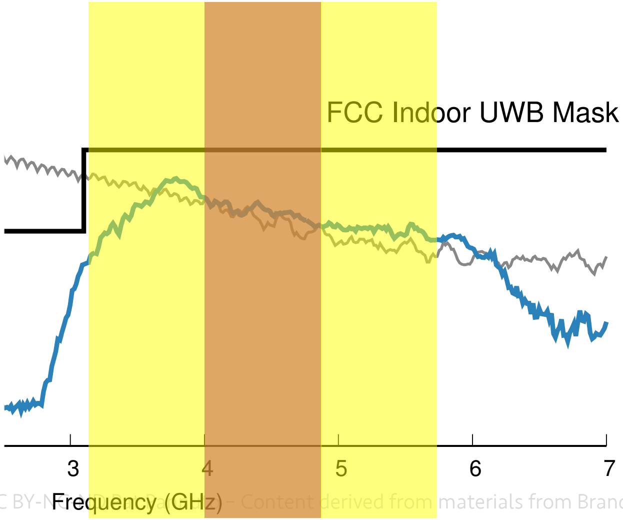
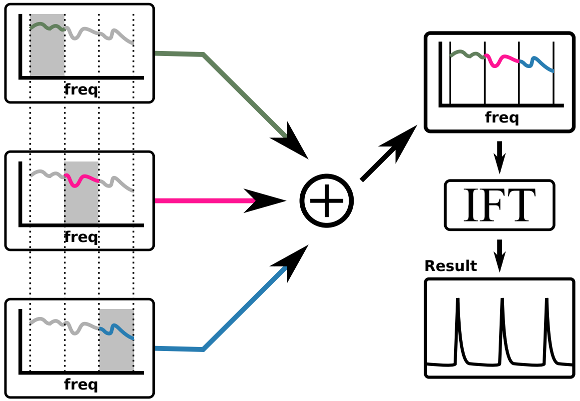


Figure 3 : RX Interferer Immunity on Channel 2

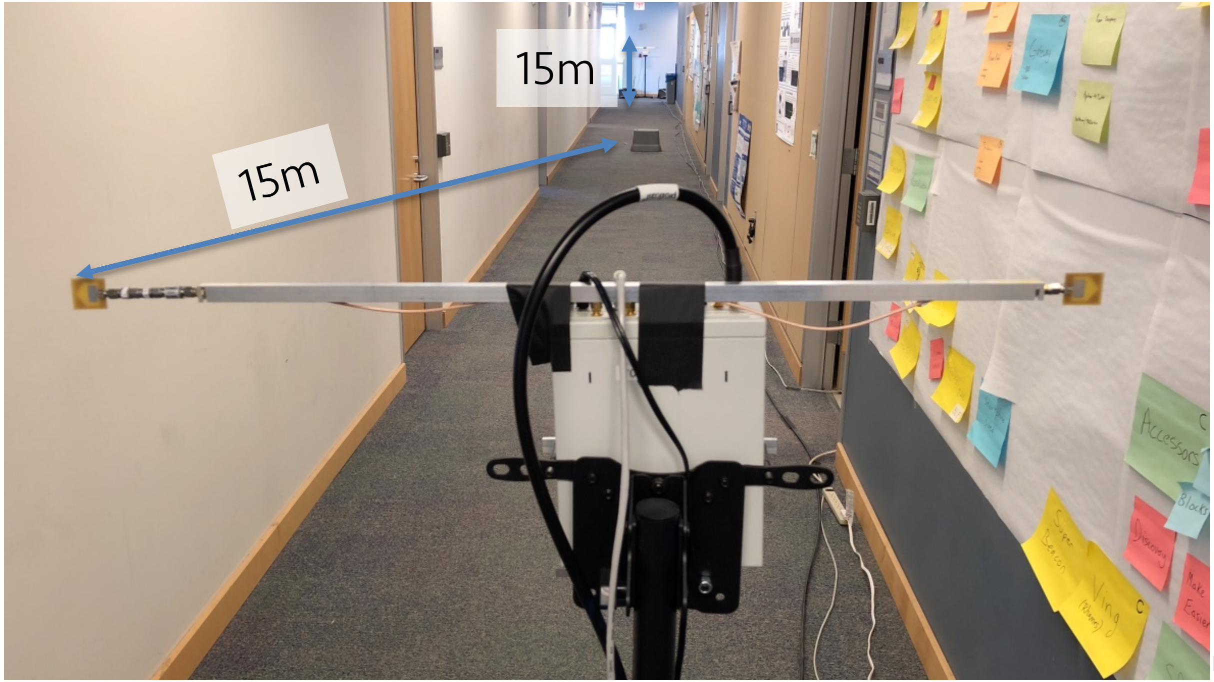
DW1000 Datasheet



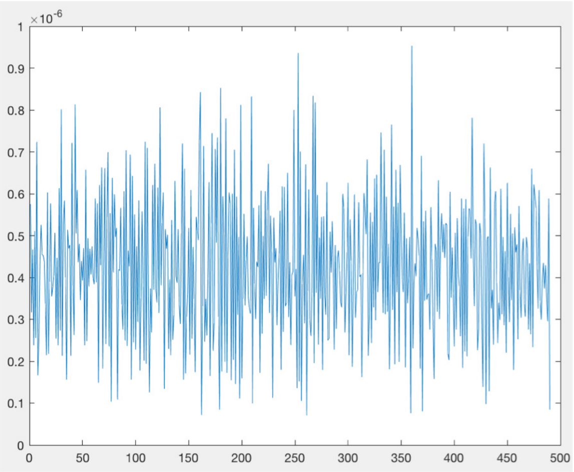


Does it really work?

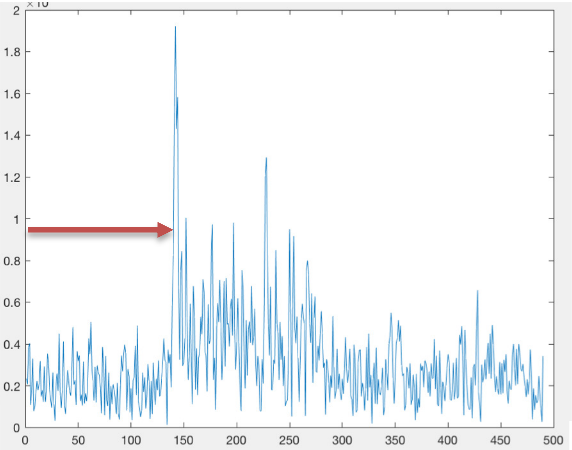
- 15 minutes can cover 30 meters
- 7 cm error (3D Euclidean distance)



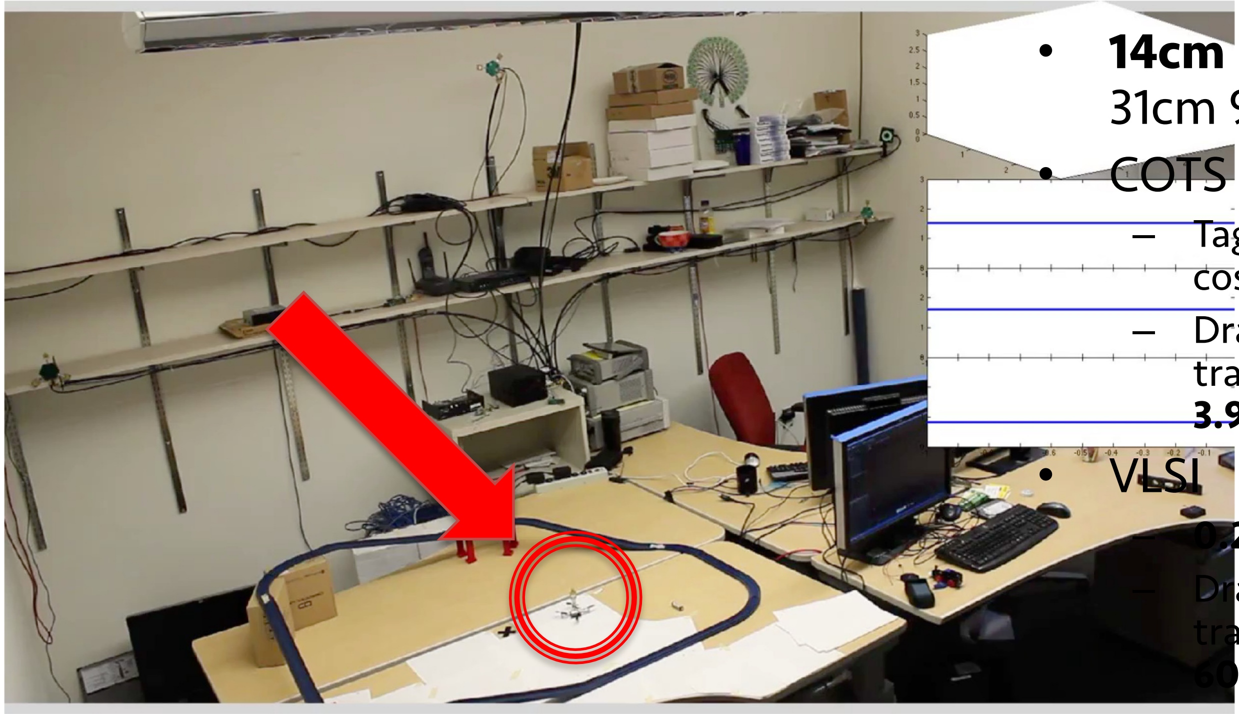
After a few seconds



After a few minutes



The same infrastructure can track moving devices on-demand, enabling adaptivity



- **14cm median**
  31cm 90%ile
- COTS
  - Tag weighs **3g** and costs **~$4.50**
  - Draws **75mW** transmitting, **3.9mJ / fix**
- VLSI
  - **0.2 mm²** IC
  - Draws **1mW** transmitting, **60µJ / fix**

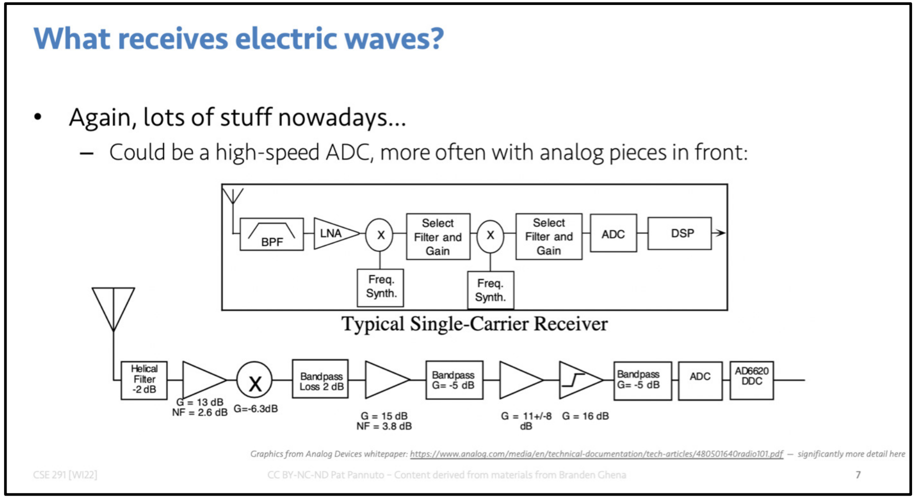
Harmonia: Wideband Spreading for Accurate Indoor RF Localization (HotWireless'14)
Harmonium: Asymmetric, Bandstitched UWB for Fast, Accurate, and Robust Indoor Localization (IPSN'16)
Harmonium: Ultra Wideband Pulse Generation with Bandstitched Recovery for Fast, Accurate, and Robust Indoor Localization (TOSN'18)

Outline

- Backscatter
  - Antenna & Wave Primer
  - History
  - Modern Uses
- **Wakeup Radios**
- Intermittent MACs

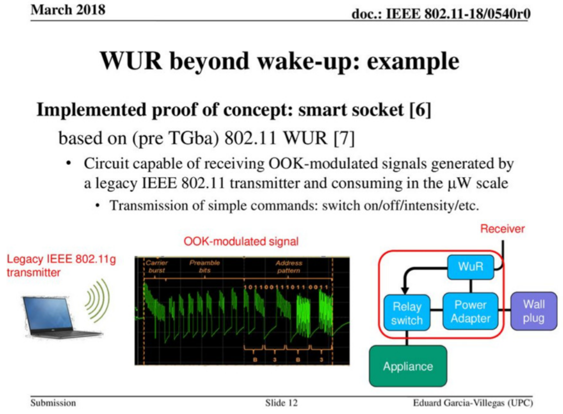
Wakeup radios are another form of “RF-lite”

- The problem: Pretty much all of this stuff is energy-expensive
  - Aka: “The idle listening problem”



Concept: Can we design something (much?) lower power that can't do general purpose data, but can signal wakeup?

- Energy detectors
  - Simple, but prone to false wakeups
- Extremely simple signaling?
  - Very often some form of on-off-keying (OOK)
  - Seeing new life
    - In mainstream networks, e.g. 802.11ba
    - In sensor network research, e.g. Zippy
    - Tuned energy harvesting frontends
    - Manipulated standards for lower-BW signals


March 2018 doc.: IEEE 802.11-18/0540r0

WUR beyond wake-up: example

Implemented proof of concept: smart socket [6]

based on (pre TGba) 802.11 WUR [7]

- Circuit capable of receiving OOK-modulated signals generated by a legacy IEEE 802.11 transmitter and consuming in the µW scale
  - Transmission of simple commands: switch on/off/intensity/etc.

Submission Slide 12 Eduard Garcia-Villegas (UPC)

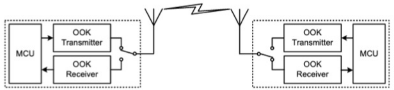


Figure 1: Proposed mote architecture with a micro-controller (MCU), OOK transmitter, and always-on ultra-low power OOK receiver.

Figure 2: Example OOK signal at the input to the receiver and its corresponding demodulated output.

(Re)-emerging new ideas in wakeup design

- Decoupling synchronization from communication
- External synchronization sources?
  - Ambient 60 Hz wave
  - Sudden change in room lighting, or a noise
  - Provide it efficiently?
- Synchronization and time-keeping burden is shifted to infrastructure

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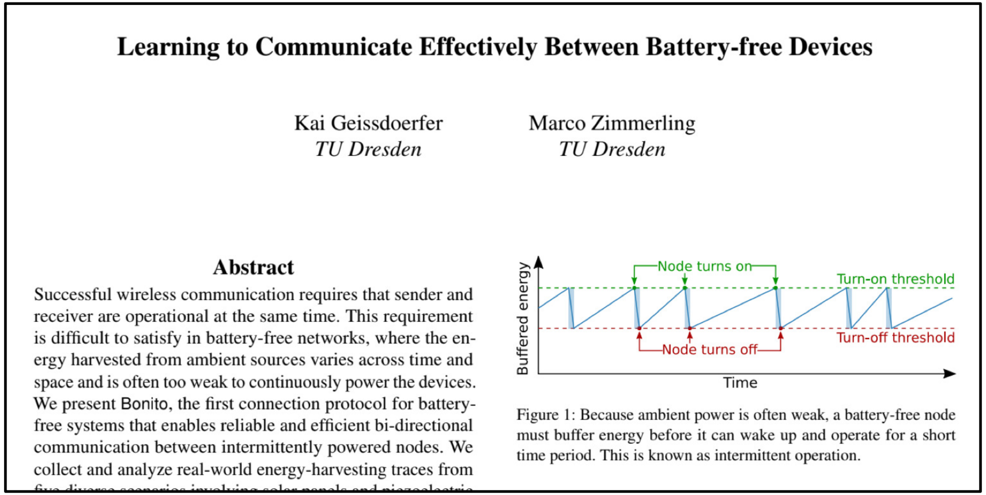
- Wakeup Radios
- ~~Intermittent MACs~~ – Actually, advertisements ☺

Do you like this kind of stuff, think it's interesting, want to keep learning more about it?

- Join the embedded seminar series!
  - https://sites.google.com/eng.ucsd.edu/embeddedlunch/
  - Spring Quarter: `CSE 290 – H00` with Ryan Kastner [but really all of us]
- Good way to stay abreast of modern research in greater IoT sphere
  - Our class has been largely about how existing stuff works; not new research
- Did Pat mean to advertise this at the beginning of the term and forget?
  - Yes, and Pat is very sorry about that :/

April 14th: Kai Geissdoerfer visit and live demo!

- Presenting their NSDI'22 paper and demoing system



Learning to Communicate Effectively Between Battery-free Devices

Kai Geissdoerfer, *TU Dresden*
Marco Zimmerling, *TU Dresden*

Abstract

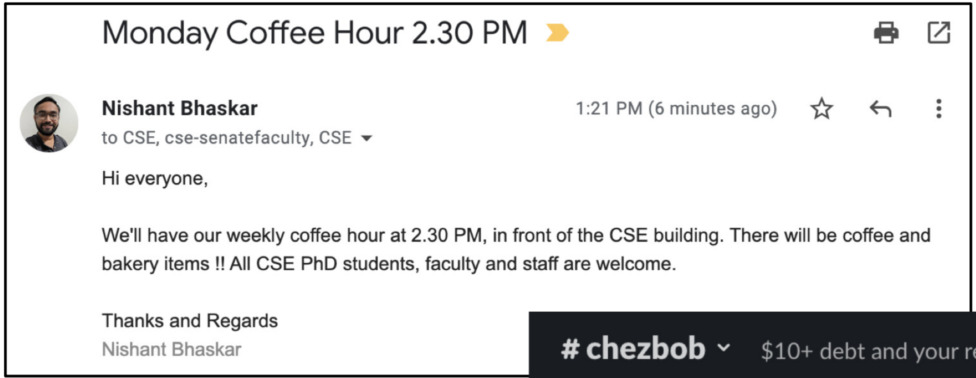
Successful wireless communication requires that sender and receiver are operational at the same time. This requirement is difficult to satisfy in battery-free networks, where the energy harvested from ambient sources varies across time and space and is often too weak to continuously power the devices. We present Bonito, the first connection protocol for battery-free systems that enables reliable and efficient bi-directional communication between intermittently powered nodes. We collect and analyze real-world energy-harvesting traces from

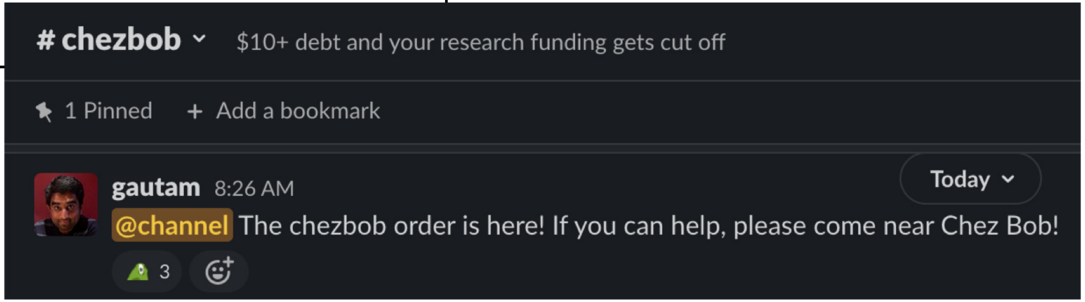
Figure 1: Because ambient power is often weak, a battery-free node must buffer energy before it can wake up and operate for a short time period. This is known as intermittent operation.

- Come see what next-generation systems might look like!

While I'm advertising things…

- A return to 'life as normal'





Next time: Non-RF stuff