CS7351 传感系统原理与设计
Principles and Design of Sensing Systems

Energy Harvesting (能量获取)

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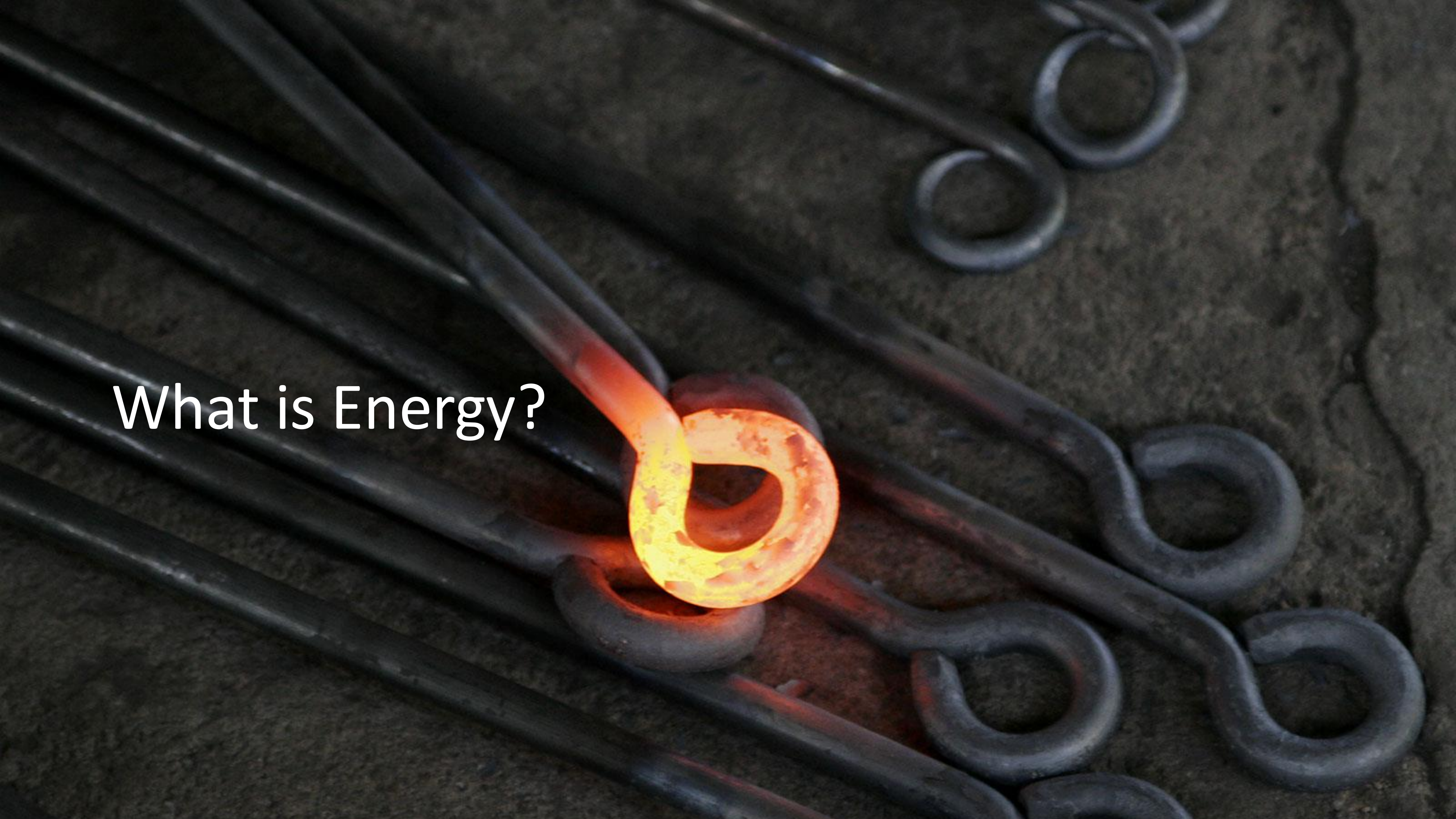
2025年秋季

About our Course Projects

1. Finalize your proposal
2. Set a meeting time with me if you haven’t done so
3. Confirm your topic

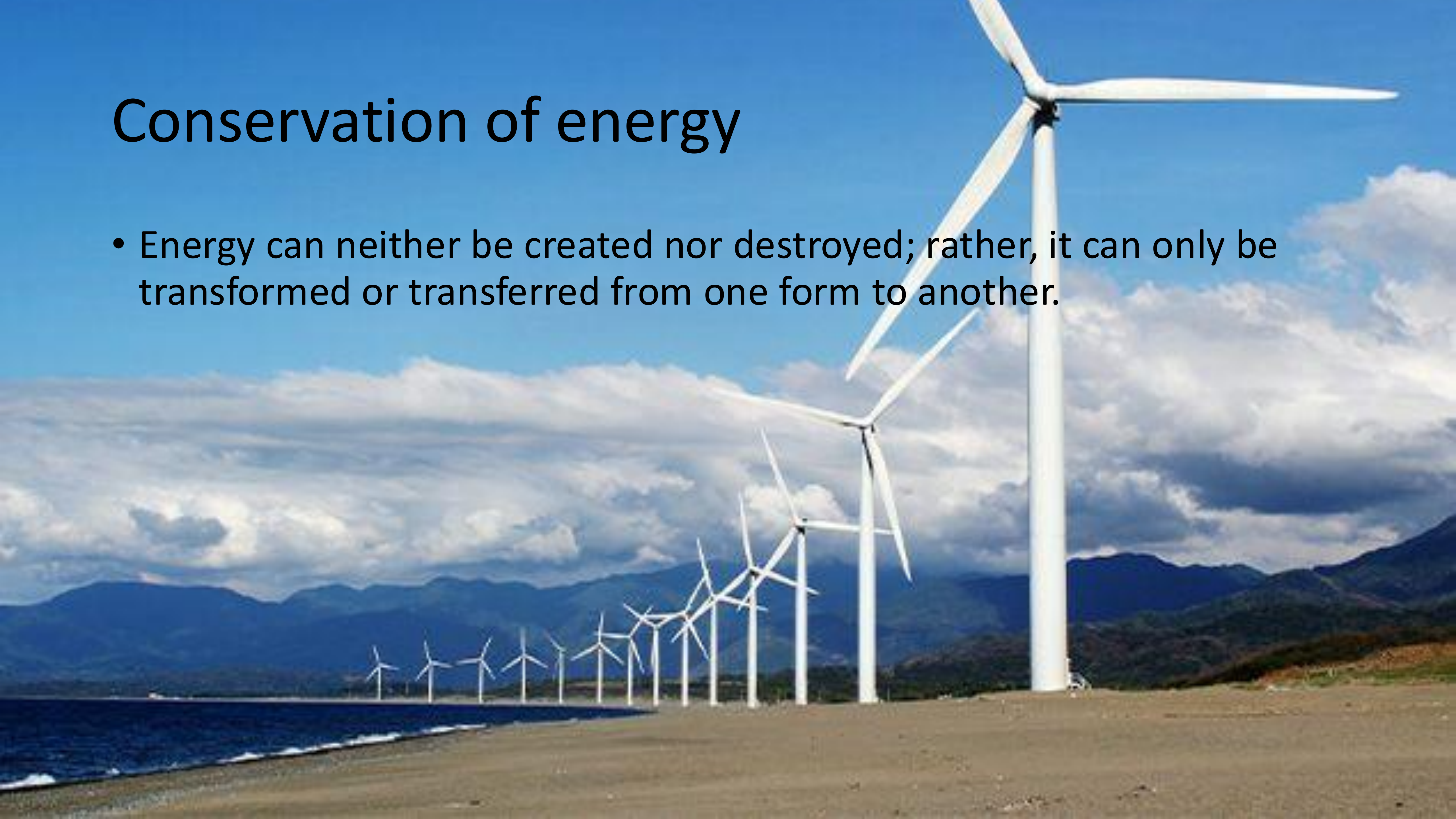
What is Energy?



What is Energy?

Conservation of energy

- Energy can neither be created nor destroyed; rather, it can only be transformed or transferred from one form to another.



What about for Mobile Devices?

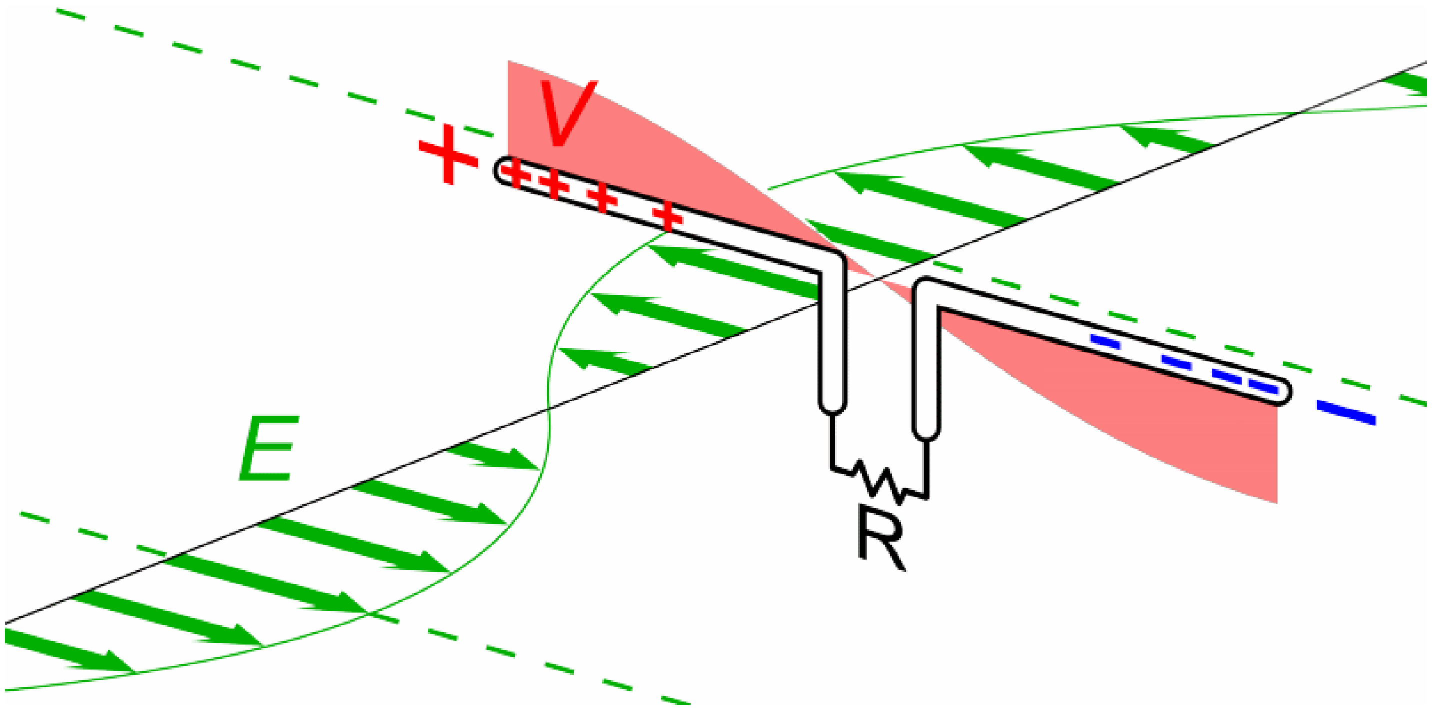
- They usually have **compact** form factor
- There are two major approaches:
  - Reflecting or harvesting existing energy

Outline

- Energy Reflection
  - Antenna
- Energy harvesting
  - RFID
  - WiFi
  - Backscatter

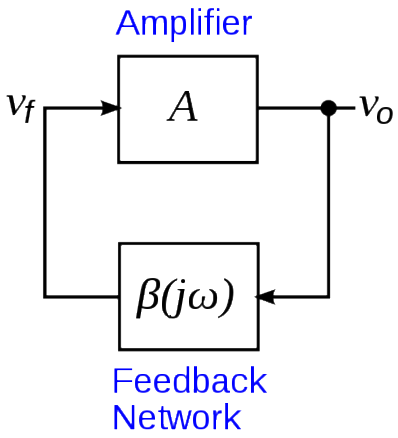
What does an antenna *do*?

- Converts between electric and magnetic waves



What generates electric waves?

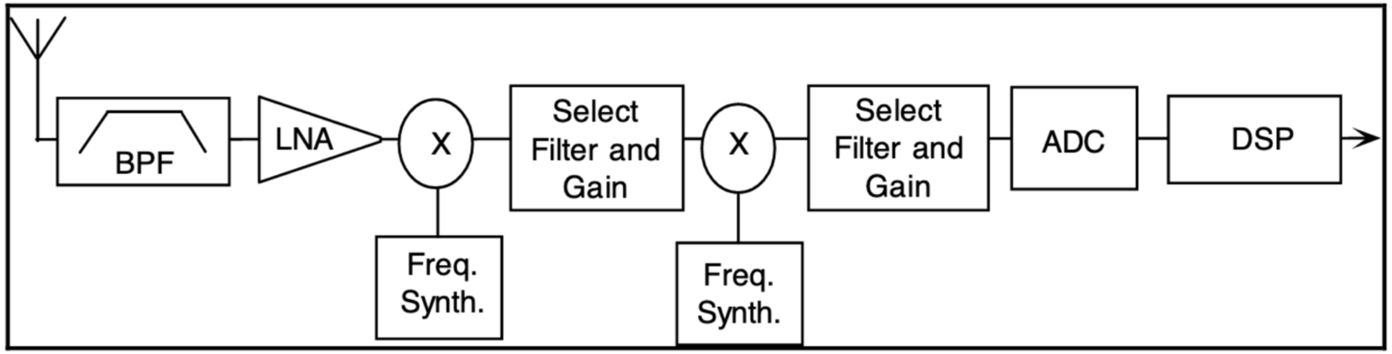
- Most commonly a frequency-selective resonator into an amplifier
  - i.e.



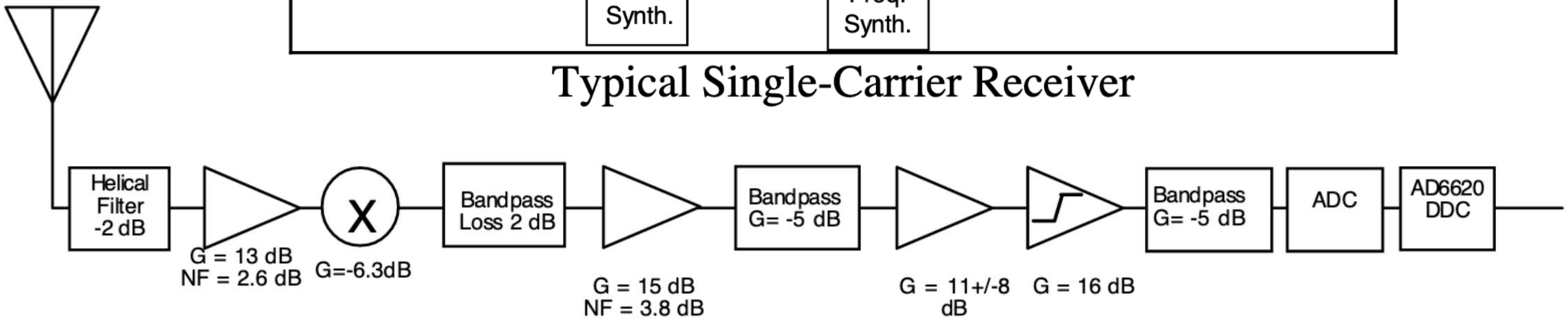
- Modern systems use physical structures to tune
- Also can be done with high-speed digital components (e.g. fast DACs)

What receives electric waves?

- A high-speed ADC, more often with analog component in front:

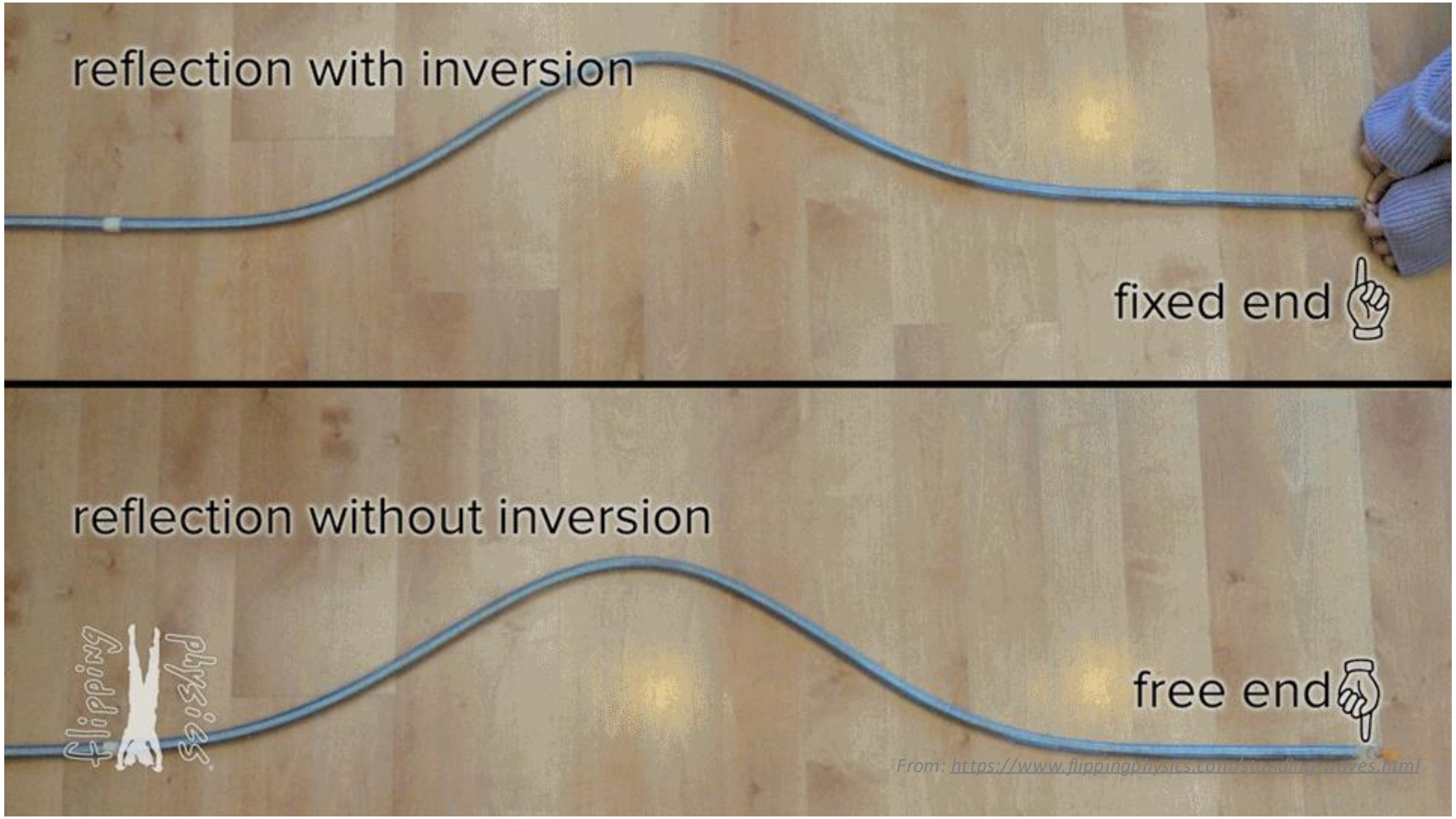


Typical Single-Carrier Receiver



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 ‘absorb’ the wave?

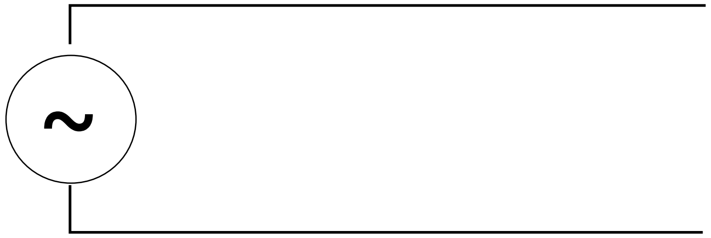


From: https://www.flippingphysics.com/standing-waves.html

”Fixed end” and “Free end” in electronic transmission

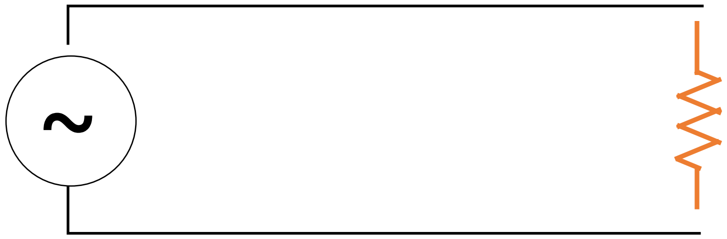
Short Circuit = “Free End”

- Reflects wave



Open Circuit = “Fixed End”

- Inverts wave

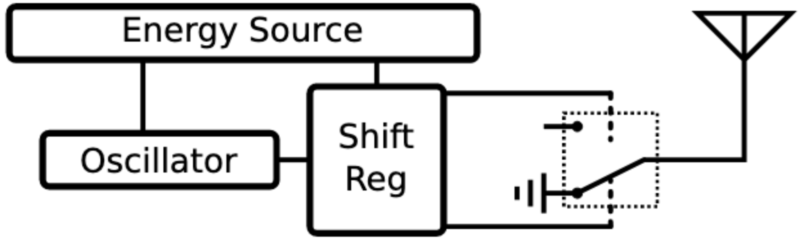


Matched Load （阻抗匹配）

- Absorbs wave (no reflection)

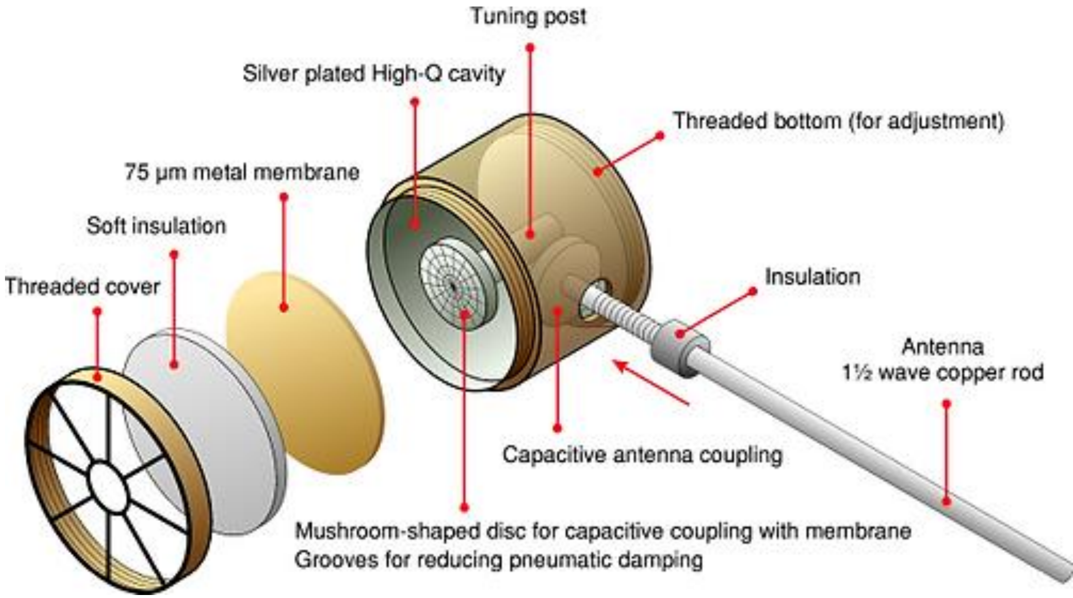
Backscatter systems *reflect* waves rather than *generate* waves

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



Backscatter (reflector) is not a new Idea

- 1945: “The Thing” (aka Great Seal Bug)

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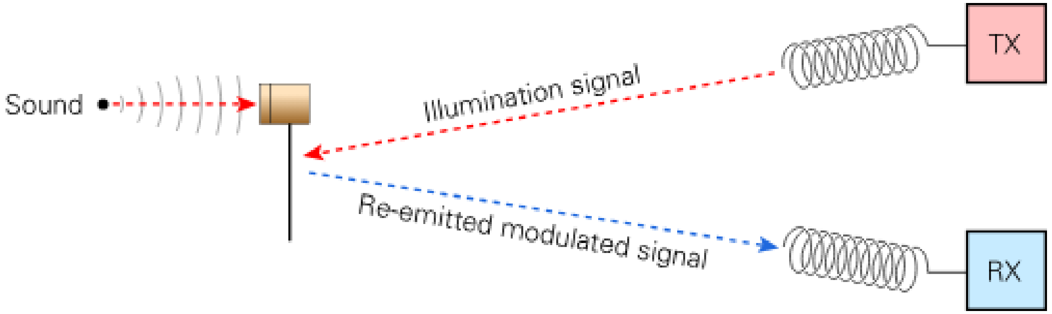


Outline

- **Signal Reflection**
  - **Antenna & Wave Primer**
  - **History**
- **Energy harvesting in**
  - **RFID**
  - **WiFi**
  - **Backscatter**

RFID is *everywhere* nowadays

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

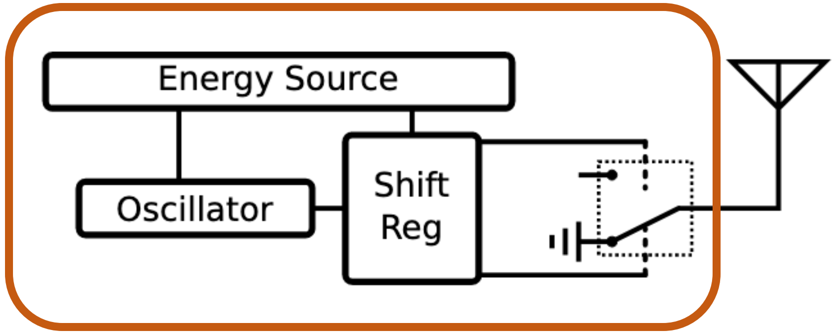
RFID

- RFID = Radio Frequency Identification

- There are 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

The meaningful difference is in how the tag devices power themselves

- Even on simple designs, need some power:
- FasTrak



RFID Standards

- Low Frequency (~300 kHz)
  - ~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

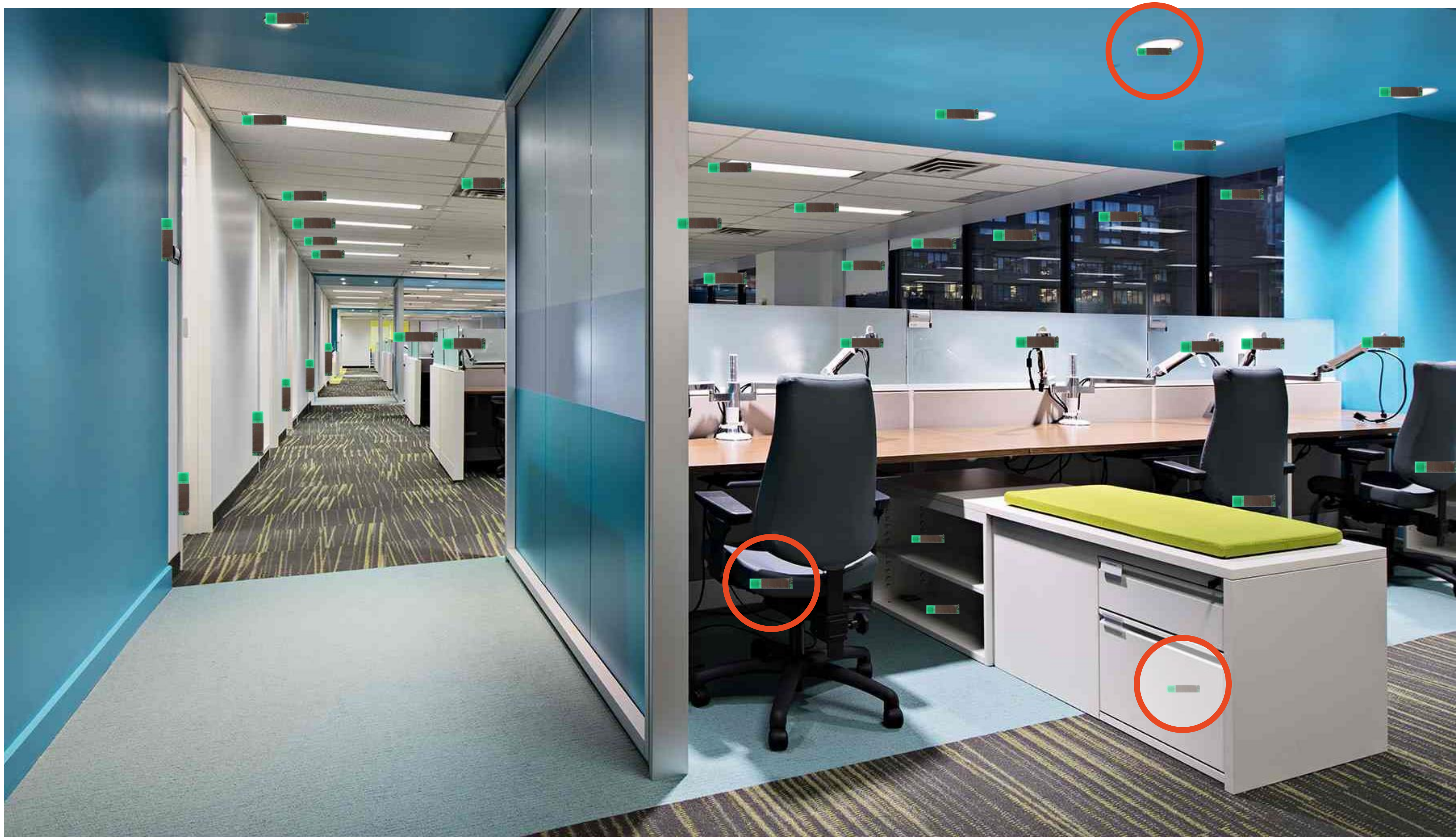
NFC

- Near Field Communications is a subset of the RFID protocol
  - 10-20 cm range (usually <10cm)
  - Inductively coupled loop antennas
    - Communicates via local *magnetic field* rather than *electromagnetic waves*

So how does RFID, Backscatter, Helps IoT

- “Power and Communication are the hard part”
  - RFID works, **but only in the presence of an RFID reader**
- Power: RF Harvesting for general purpose computation
- Communication: **Repurposing** RF signals for other uses

Localization: Ultra wideband backscatter localization



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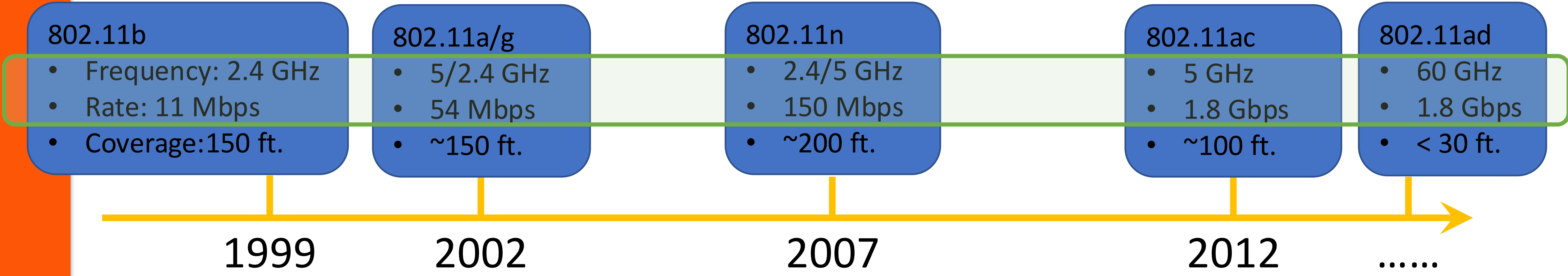
  - **WiFi Reflector**
  - **Backscatter**

WiFi Connection is Essential!

- It is important to guarantee both connectivity and speed

Evolution of WiFi



- Higher frequency enables faster data rate
  - Enables more complex modulation scheme and wider bandwidth

Evolution of WiFi

802.11b
- Frequency: 2.4 GHz
- Rate: 11 Mbps
- Coverage:150 ft.

802.11a/g
- 5/2.4 GHz
- 54 Mbps
- ~150 ft.

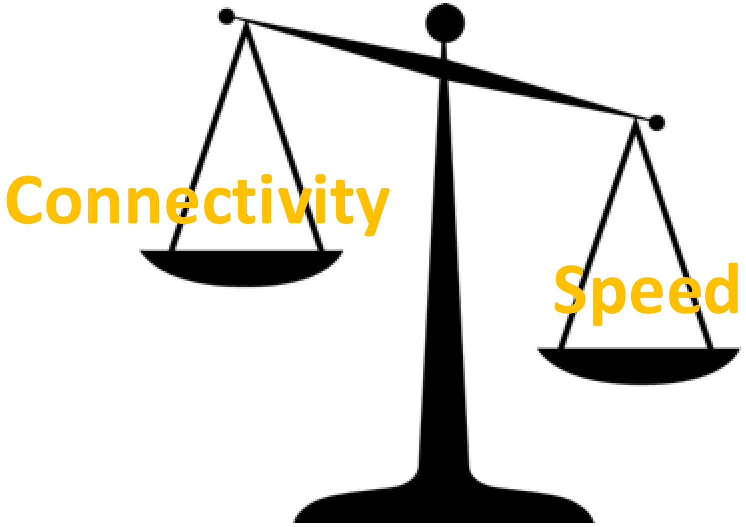
802.11n
- 2.4/5 GHz
- 150 Mbps
- ~200 ft.

802.11ac
- 5 GHz
- 1.8 Gbps
- ~100 ft.

802.11ad
- 60 GHz
- 1.8 Gbps
- < 30 ft.

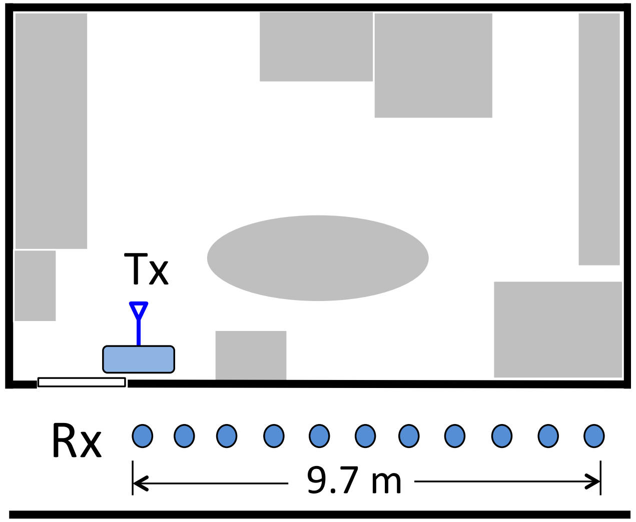
1999 2002 2007 2012 ……

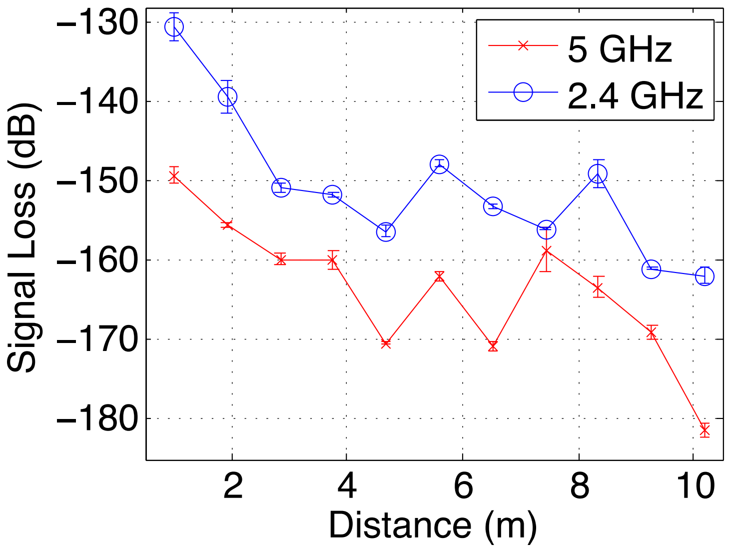
- Higher frequency enables faster data rate
- Coverage does not increase dramatically
  - High signal frequency loses connectivity



WiFi Signal Degradation

- WiFi signal is essentially electromagnetic waves
  - *Diffraction* is the main reason for its penetration feature
  - Considerable amount of energy is absorbed by obstacles during penetration
- A quick example: higher frequency → higher signal loss





Efforts in Building Better WiFi

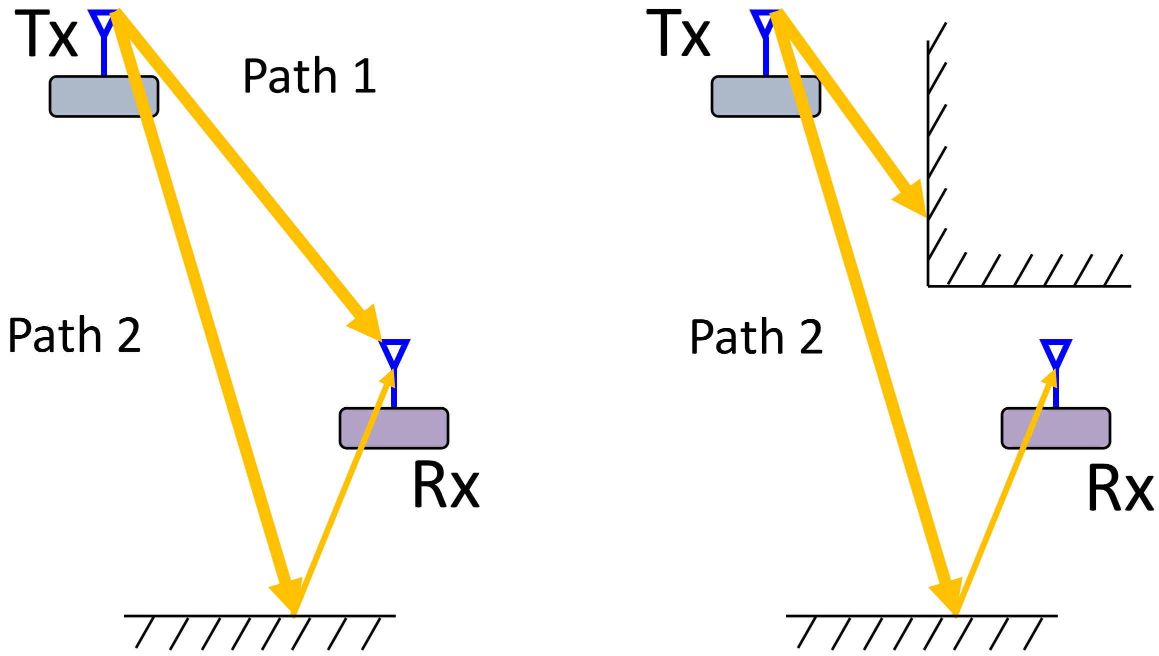
At transmitter (Tx) side
1. Adding more Txs
2. Increasing transmission power
3. Directional antenna
4. Advanced modulation scheme

What about in the propagation path?

At receiver (Rx) side
1. Increasing sample rate
2. Add more antennas
3. Advanced demodulation scheme

Who Stole my WiFi?

- Multipath: signal traverses through different paths before reaching the Rx
- A simplified example
  - Path 1: line-of-sight (LOS) transmission, Path 2: Non-line-of-sight (NLOS) transmission



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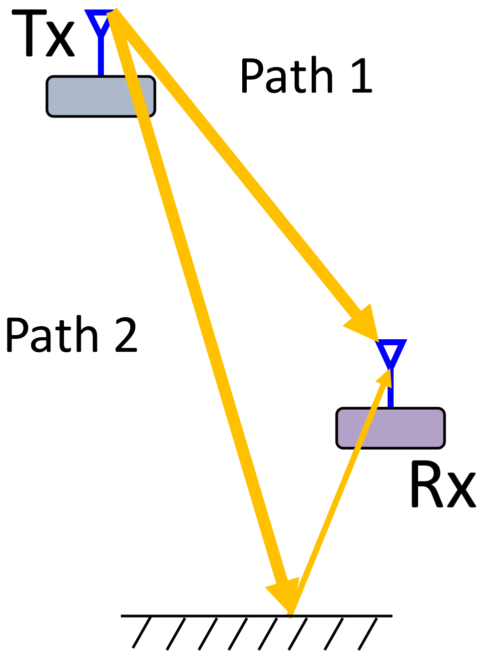
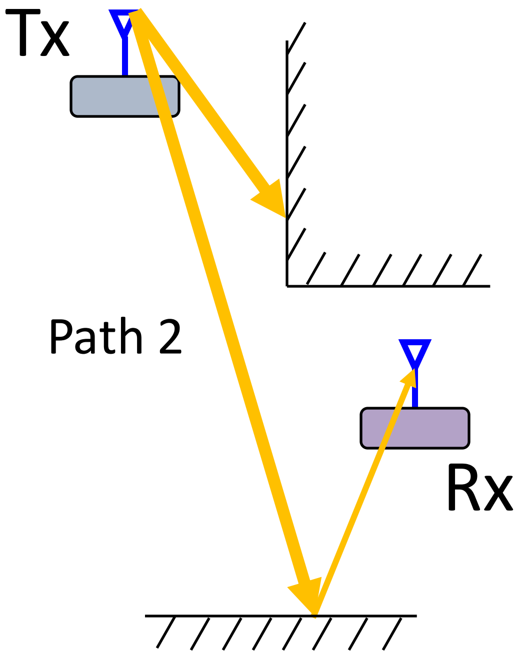




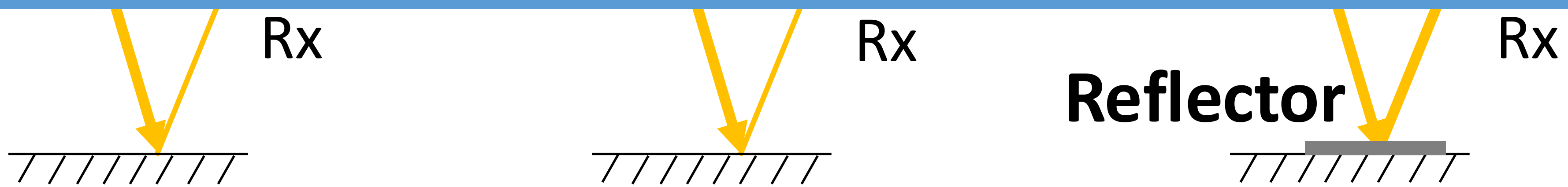
What can we do to amplify the weak reflection signal?

Key Idea: Utilize Reflection Path

- Multipath: signal traverses through different paths before reaching Rx
- A simplified example
  - Path 1: line-of-sight (LOS) transmission, Path 2: Non-line-of-sight (NLOS) transmission

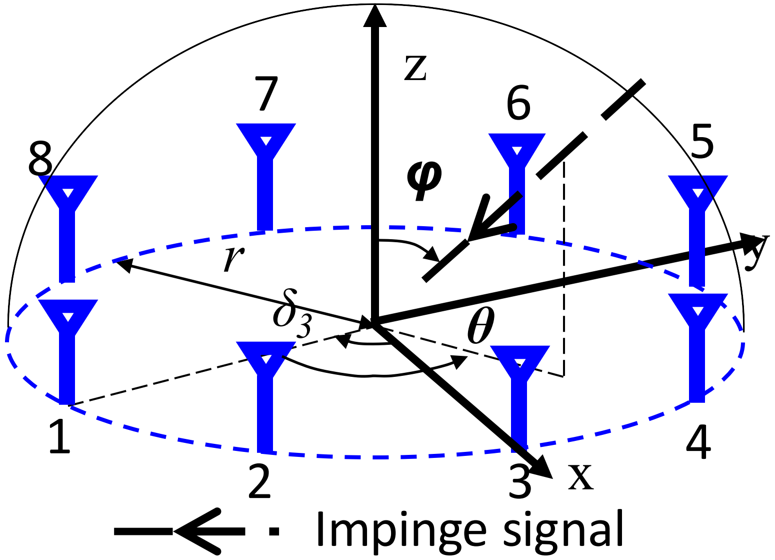
Goals

1. How WiFi signal propagation in real-life scenario looks like?
2. Would an ideal reflector be really helpful for enhancing WiFi signal?



Measuring WiFi Multipath: Terminology

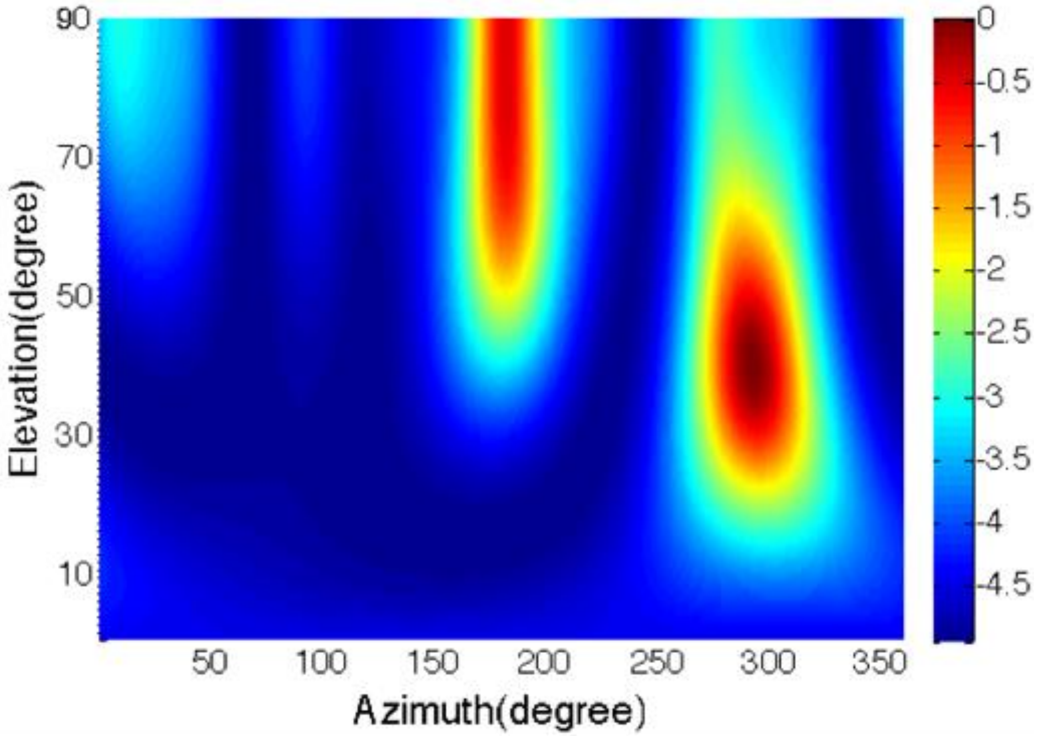
- Angle of Arrival (AoA)
  - Direction of signal incident on an antenna array
    - ($\boldsymbol{\theta}$, ϕ) pair
  - Determined by measuring the time difference of arrival at individual elements of array
- Phase shift at N[th] antenna
  - $\frac{2\pi r}{\lambda} cos(\theta - \delta_N) sin\phi$
- Steering matrix $\mathbf{A}$
  - For L different signal paths:
    $\mathbf{A} = [\mathbf{a}(\theta_1, \phi_1), \cdots, \mathbf{a}(\theta_L, \phi_L)]$



$$\mathbf{a}(\theta, \phi) = \exp\left(\begin{bmatrix} (j\frac{2\pi r}{\lambda} cos(\theta - \delta_1) sin\phi) \\ (j\frac{2\pi r}{\lambda} cos(\theta - \delta_2) sin\phi) \\ \vdots \\ (j\frac{2\pi r}{\lambda} cos(\theta - \delta_N) sin\phi) \end{bmatrix}\right)$$

Measuring WiFi Multipath: Algorithm

- MUSIC algorithm estimates AoA of incoming signal $\mathbf{y}$
  - $\mathbf{y} = \mathbf{A}\mathbf{x} + \mathbf{w}$
  - Compute the steering vectors that orthogonal to the eigenvectors.
- Impinge signal shows a peak in a AoA spectrum heatmap



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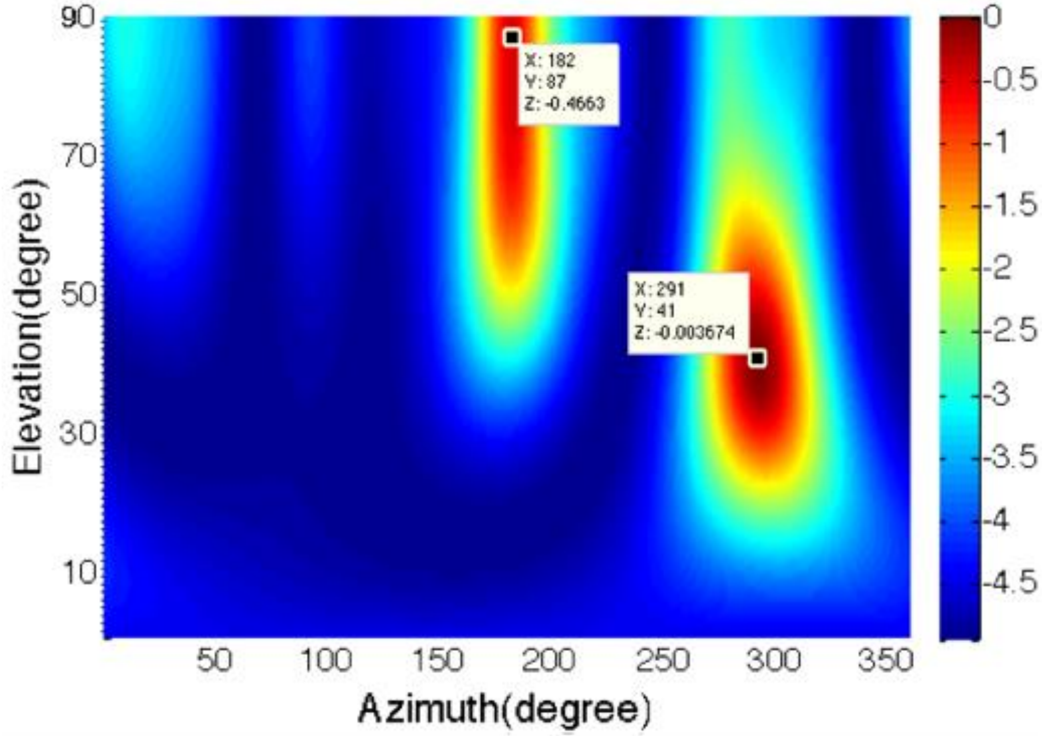
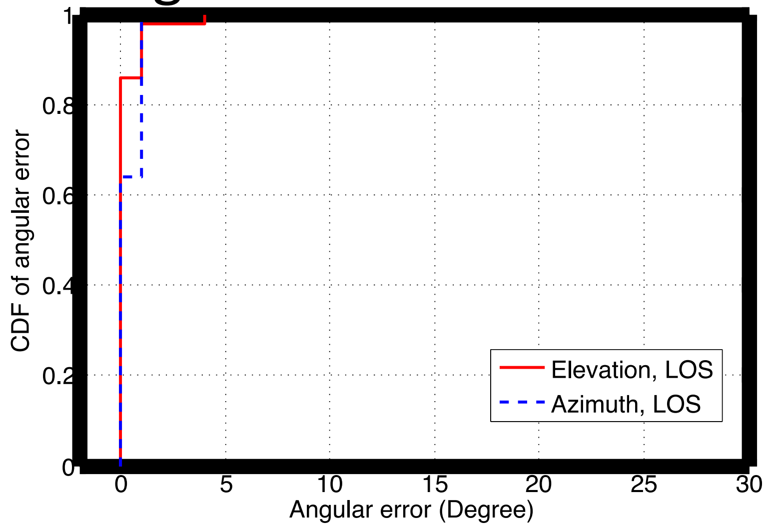
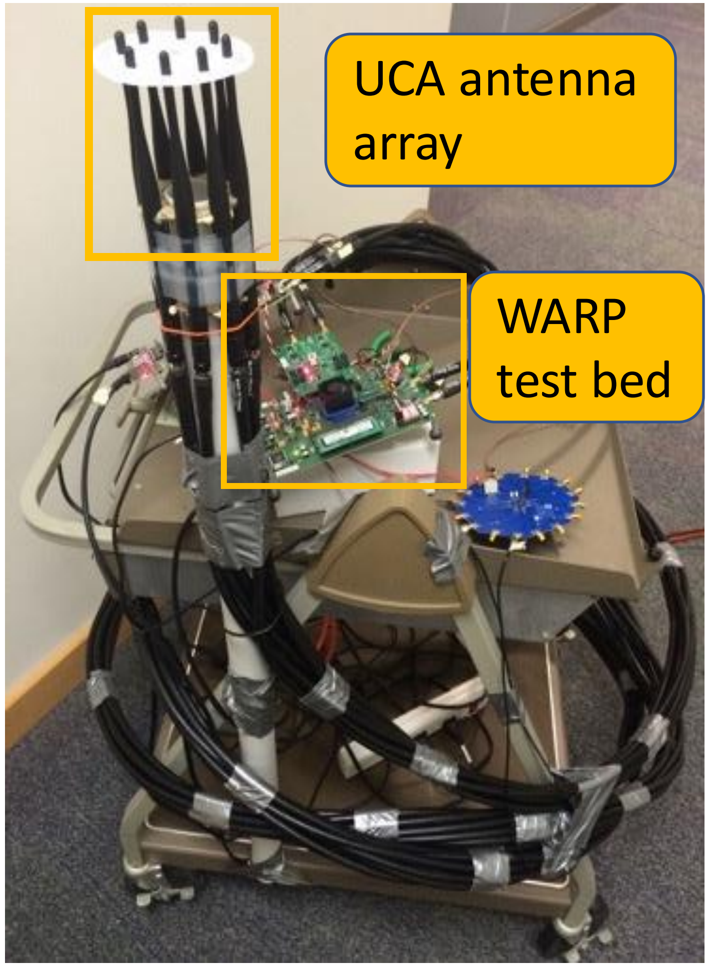
  - $\mathbf{y} = \mathbf{A}\mathbf{x} + \mathbf{w}$
  - Compute the steering vectors that orthogonal to the eigenvectors.
- Impinge signal shows a peak in a AoA spectrum heatmap
  - Strongest signal:
    $\Theta = 291^o$, $\phi = 41^o$
  - 2nd strongest signal
    $\Theta = 182^o$, $\phi = 87^o$



Measuring WiFi Multipath: Platform

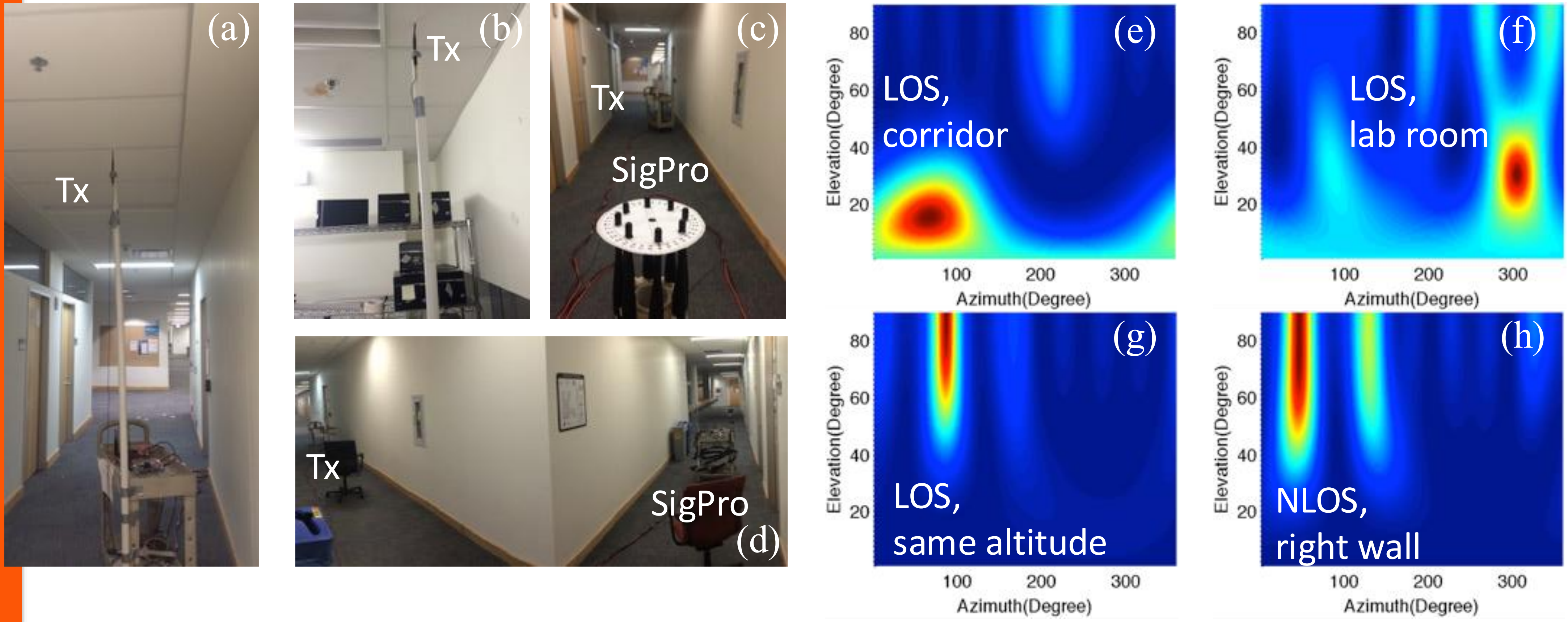
- Indoor WiFi signal multipath profiler (SigPro)
  - 8 X antenna
  - 2 X WARP software defined radio boards
- Performance of SigPro
  - The ground truth is measured by laser pointer





Measuring WiFi Multipath: Results

- WiFi signal shows interesting reflection patterns in indoor scenario



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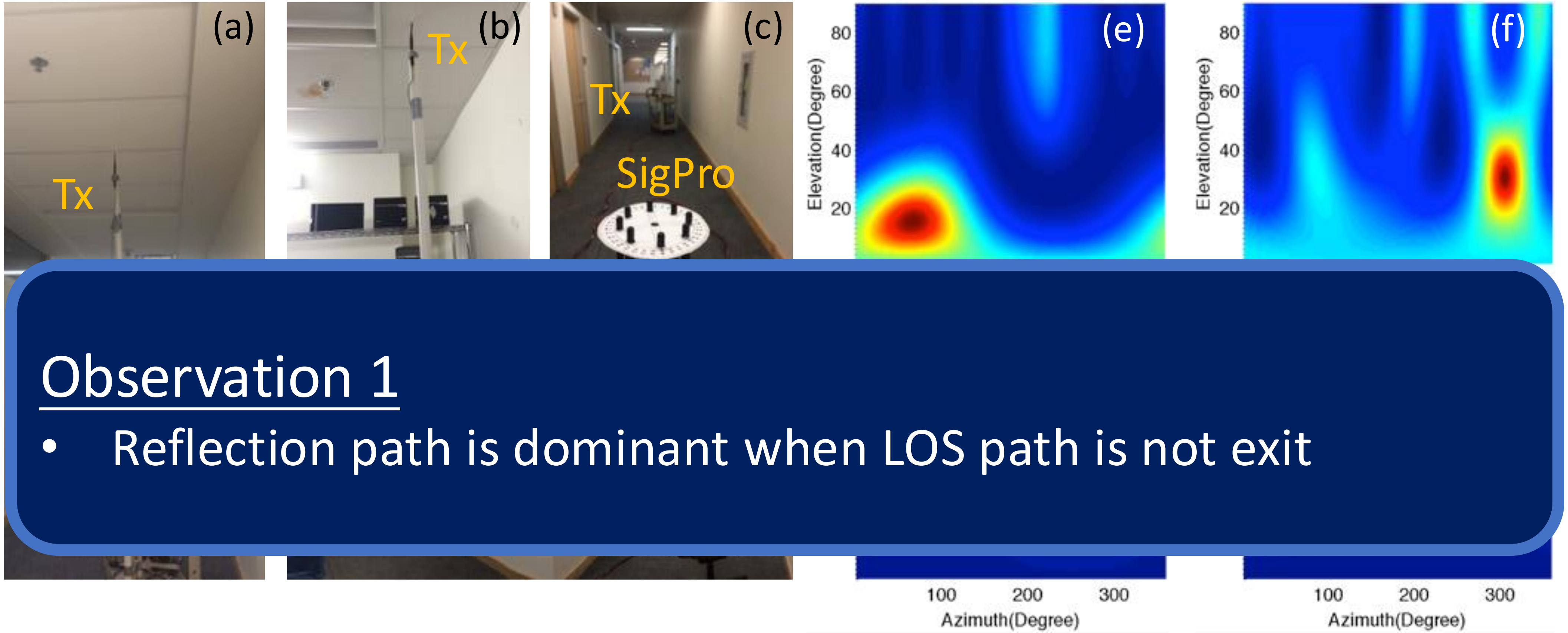
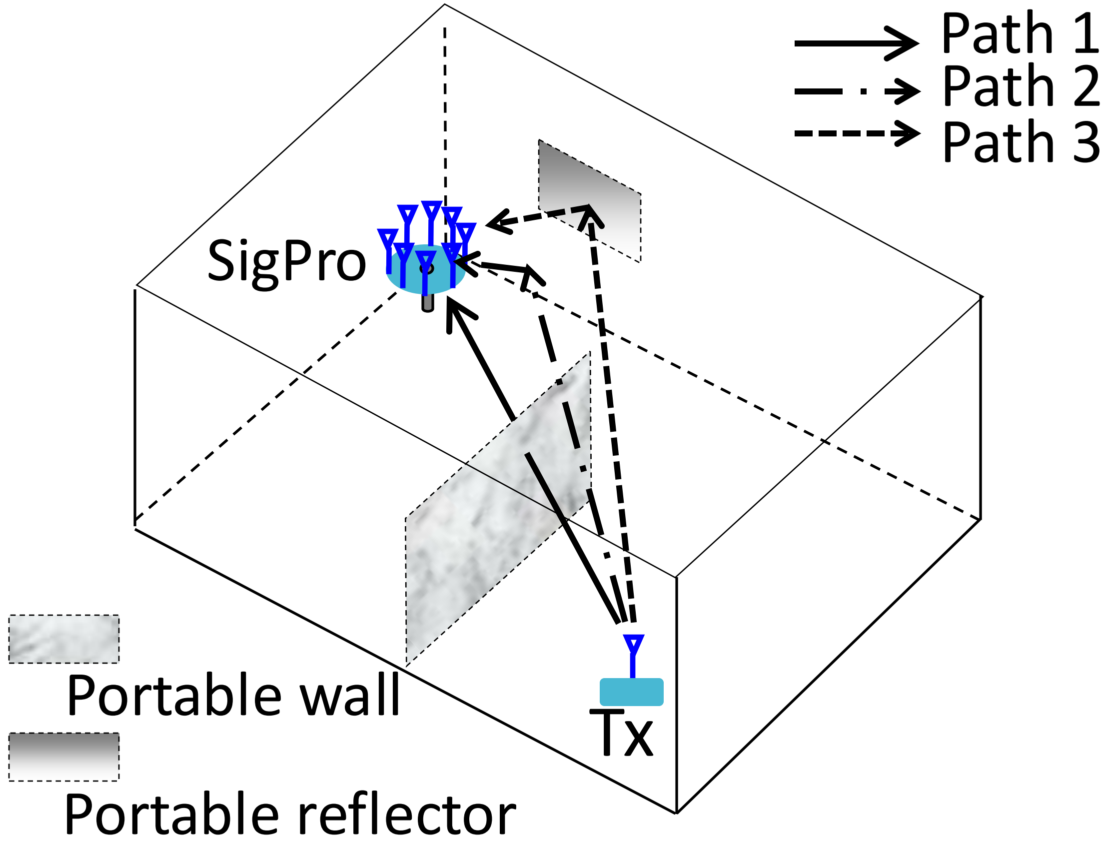


Observation 1

- Reflection path is dominant when LOS path is not exit

Investigate Reflectors' Performance

- Measurement of reflectiveness of different textures



Investigate Reflectors' Performance

- Measurement of reflectiveness of different textures

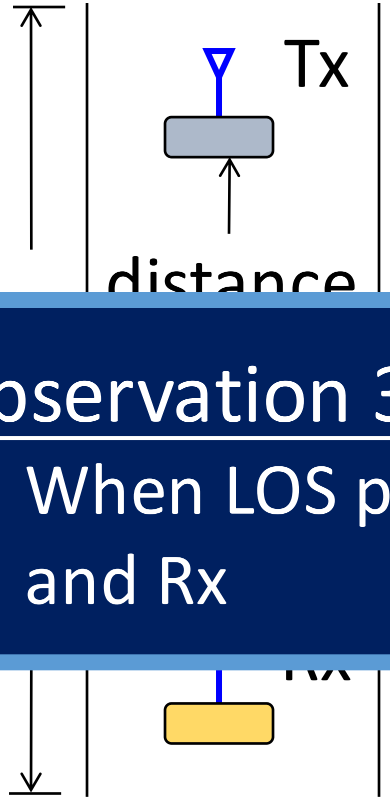
Observation 2

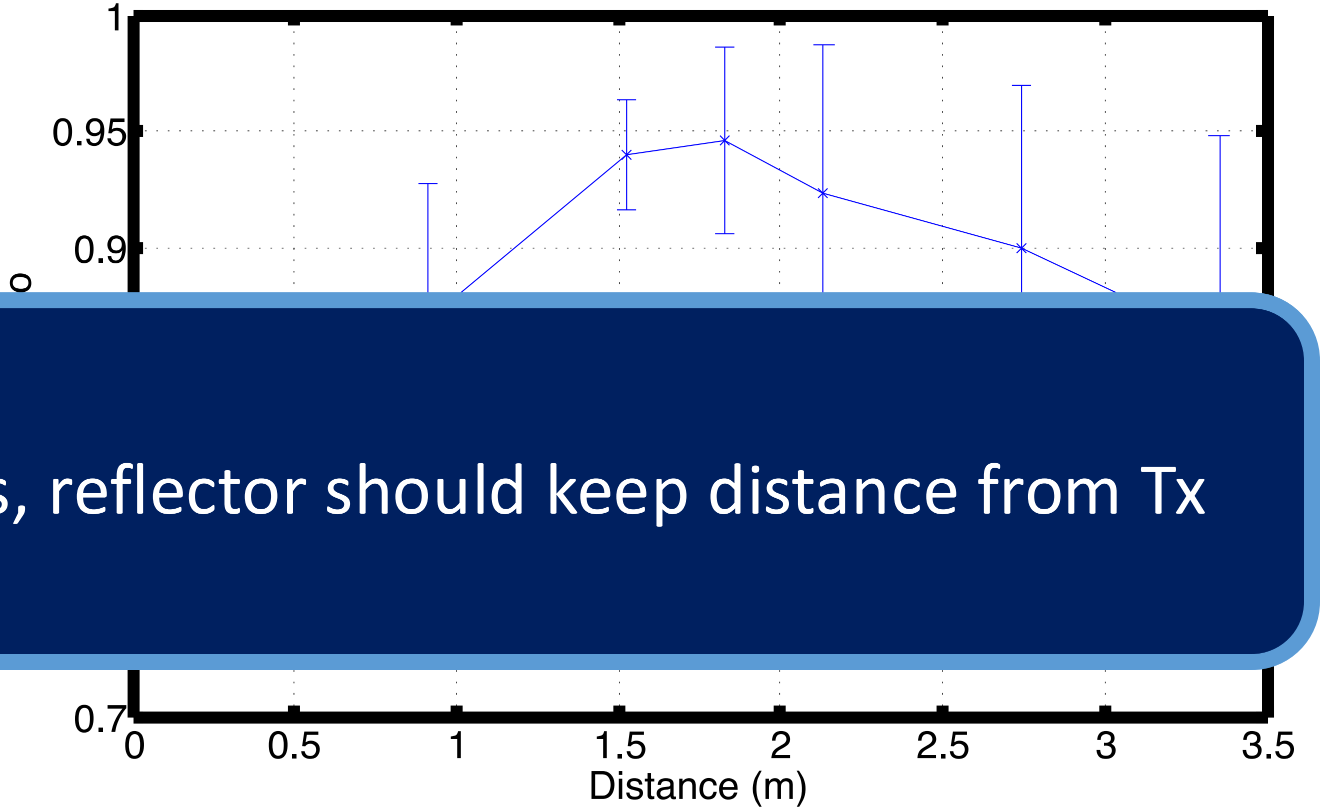
- Reflection patterns of WiFi signal on high-reflective surface follow the rule of speculation reflection
- Metallic material with smooth surface reflect WiFi signal well

(e) AoA spectrum of plain wall (f) AoA spectrum of (b) (g) AoA spectrum of (c) (h) AoA spectrum of (d)

Side Effect: Shadowing Effect

- WiFi signal can be blocked by reflector



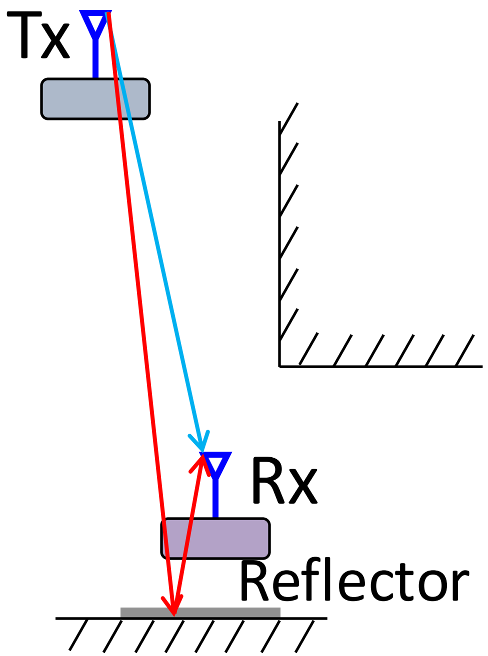


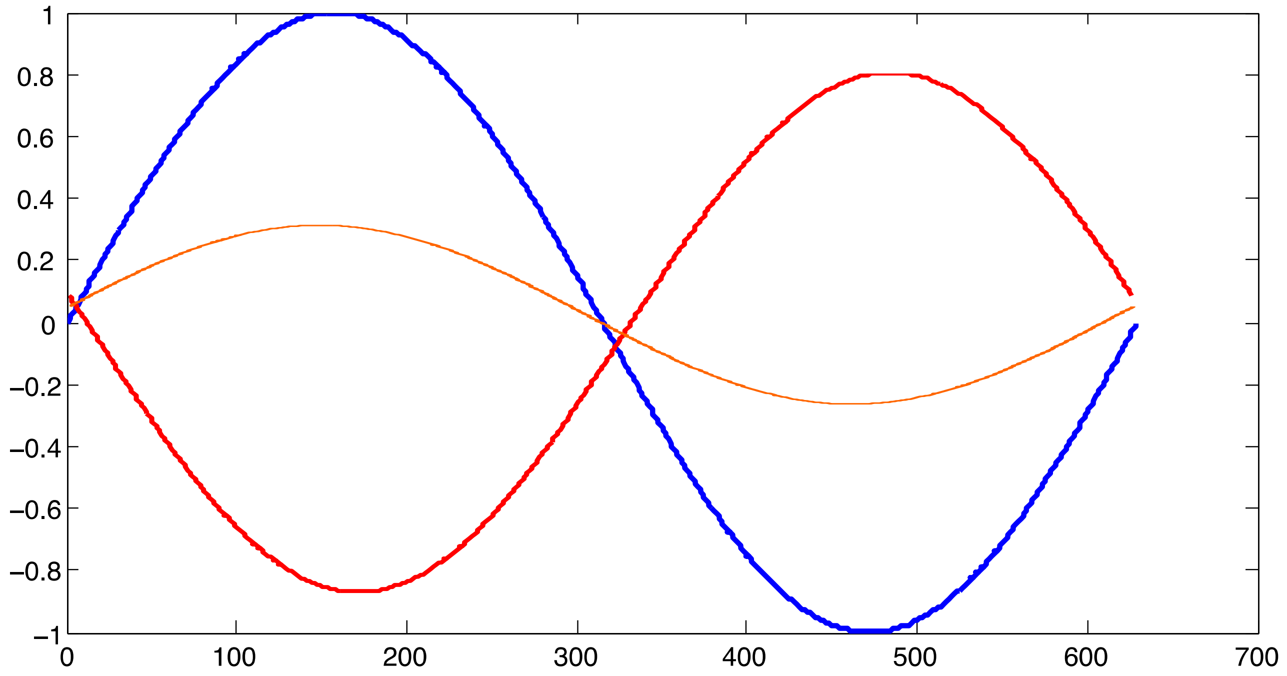
Observation 3

- When LOS path exists, reflector should keep distance from Tx and Rx

Side Effect: Signal Cancellation

- Signal cancellation
  - When Rx is very close (<0.5 m) to the reflector, reflected and LOS signals will add up destructively





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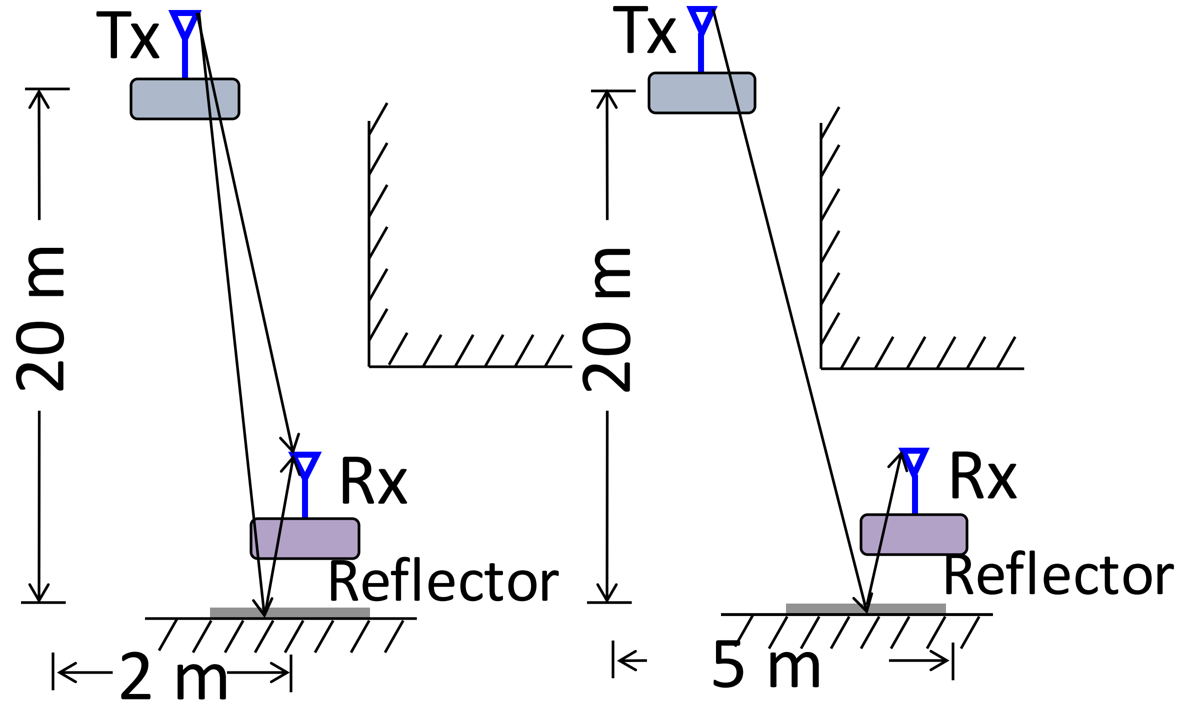

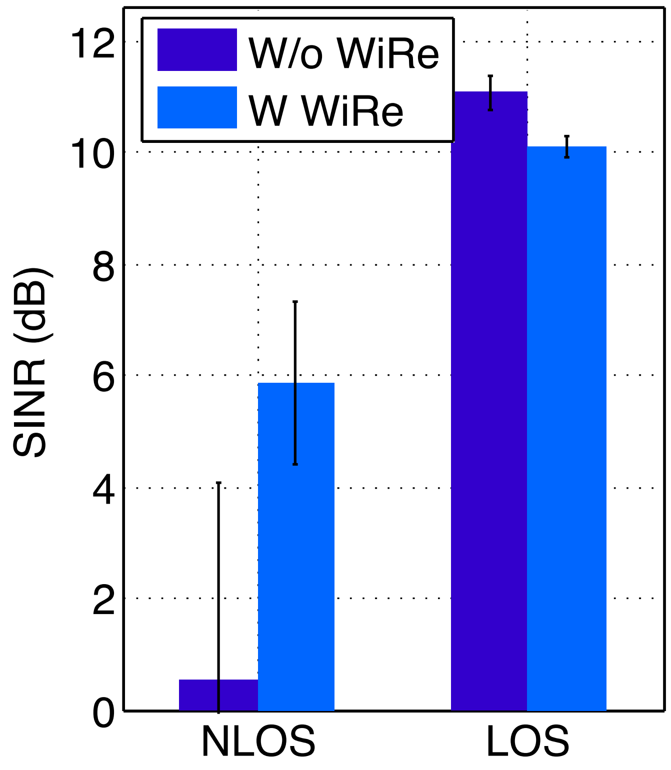

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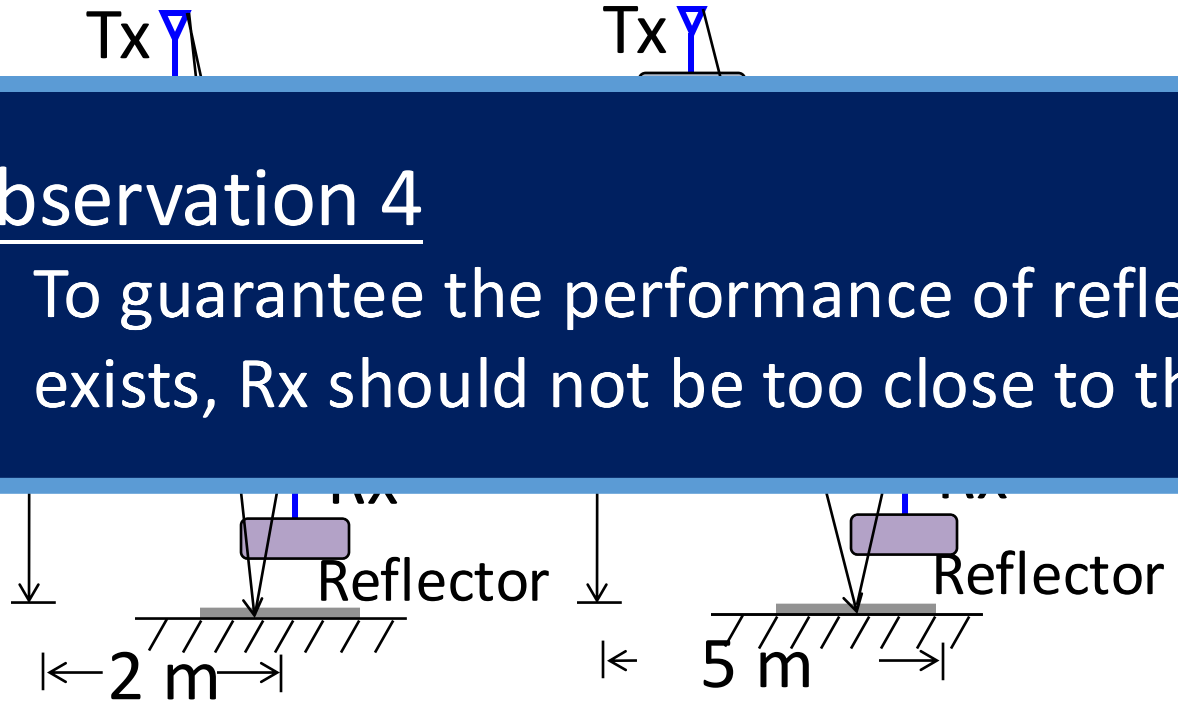
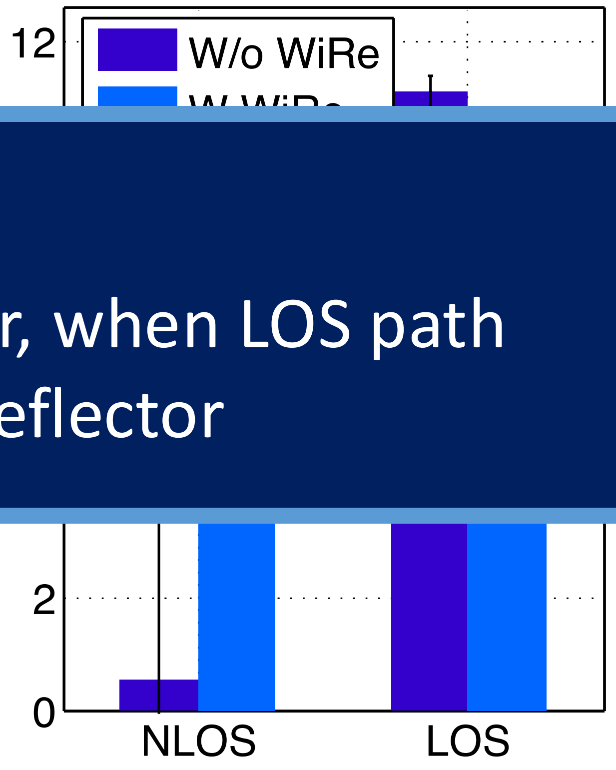




Observation 4

- To guarantee the performance of reflector, when LOS path exists, Rx should not be too close to the reflector

Design of WiFi Reflector (WiRe)

- Material: aluminum plate covered by plastic membrane
- Size: 0.6 X 1.2 m^2

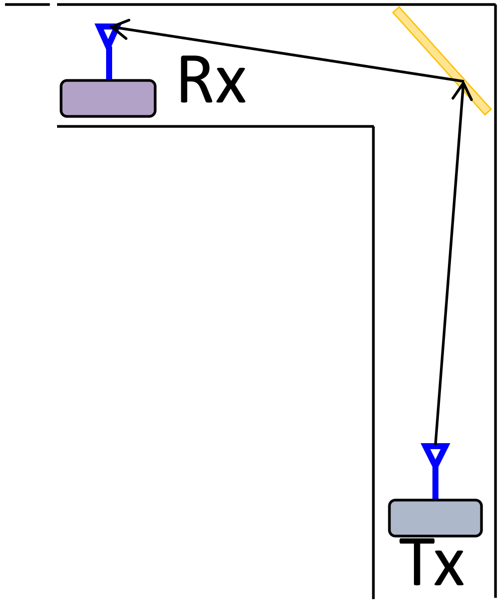
Problem

- How to determine placement for signal enhancement?

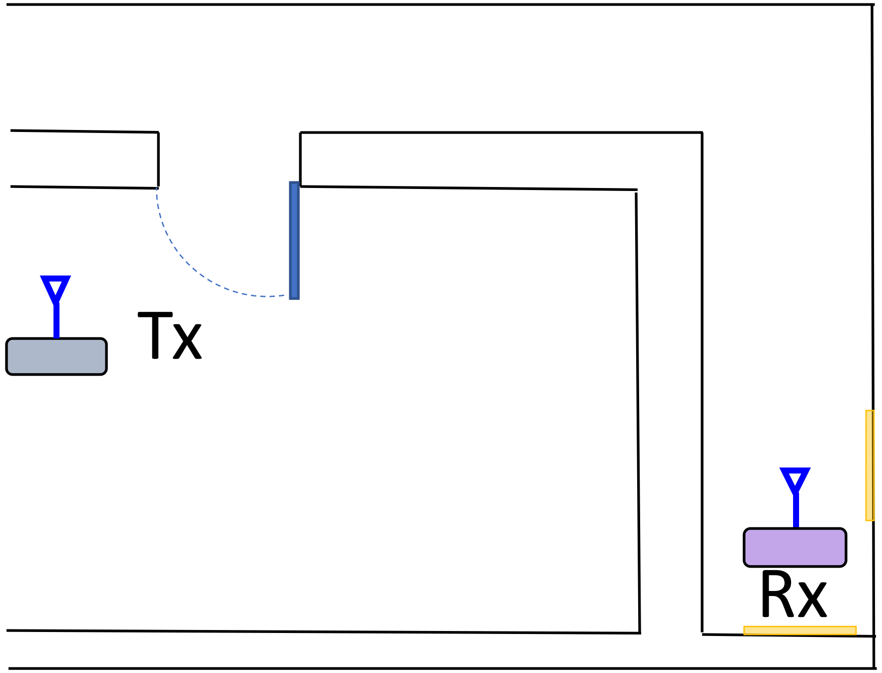
- No energy consumption and easy to use

Reflector Placement

- Mirror mode
  - When Rx is in “indirect” LOS path
  - Reflects WiFi signal to “light up” Rx

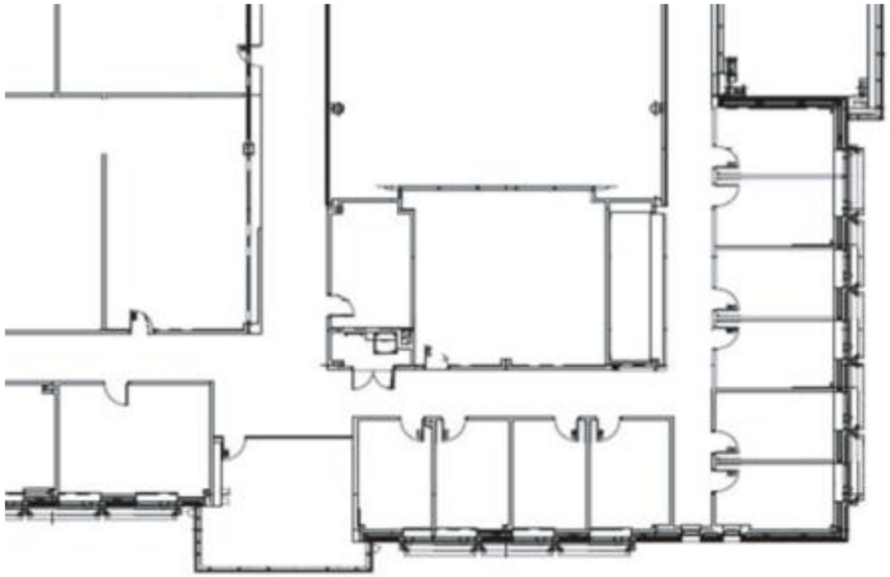


- Recycler mode
  - When Rx is in NLOS path
  - Bounces WiFi signal back from the wall



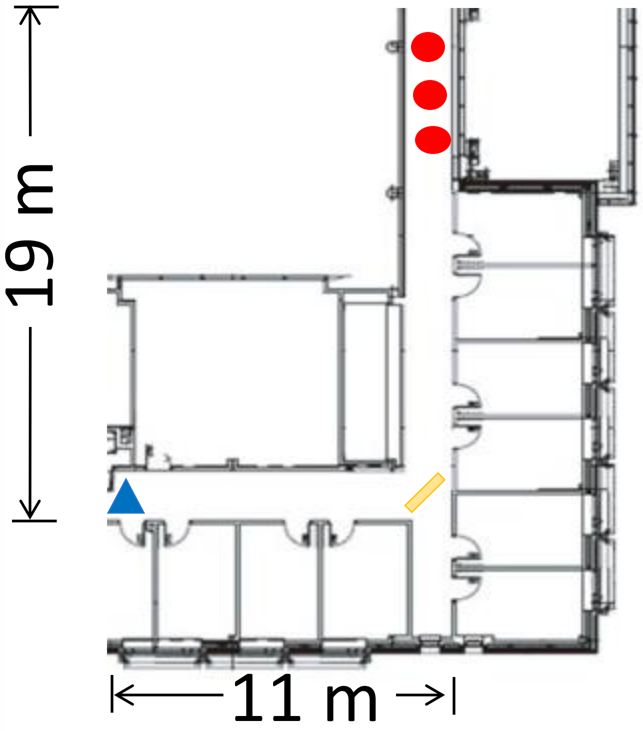
Evaluations

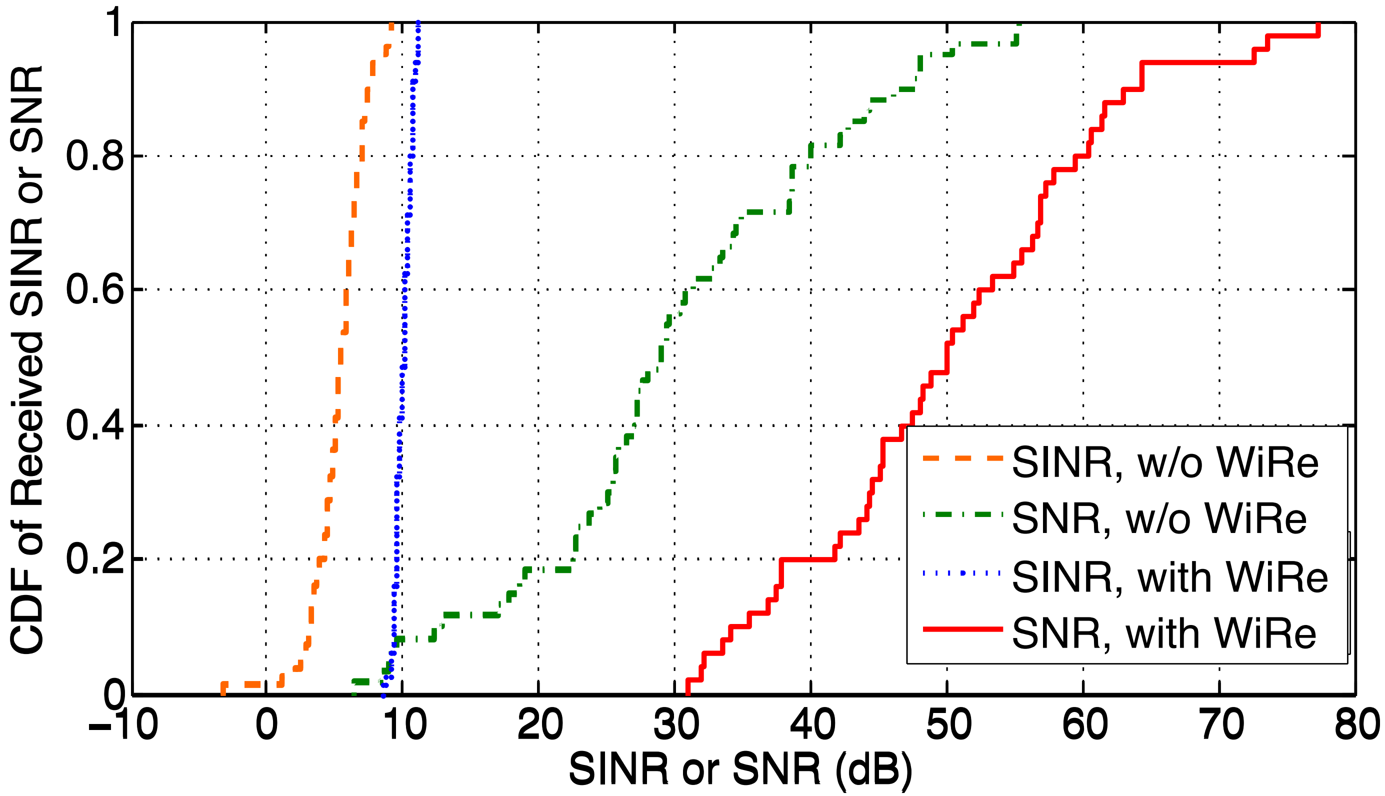
- Platform
  - We use 5 X WARP boards
  - Implement 802.11a reference design
  - Tested 5 GHz signal
- Environment
  - 38 X 25 m^2
  - Including corridor, office, and meeting rooms



Evaluation: Mirror Mode

- Tx and Rx are in two side of a corridor





Evaluation: Mirror Mode

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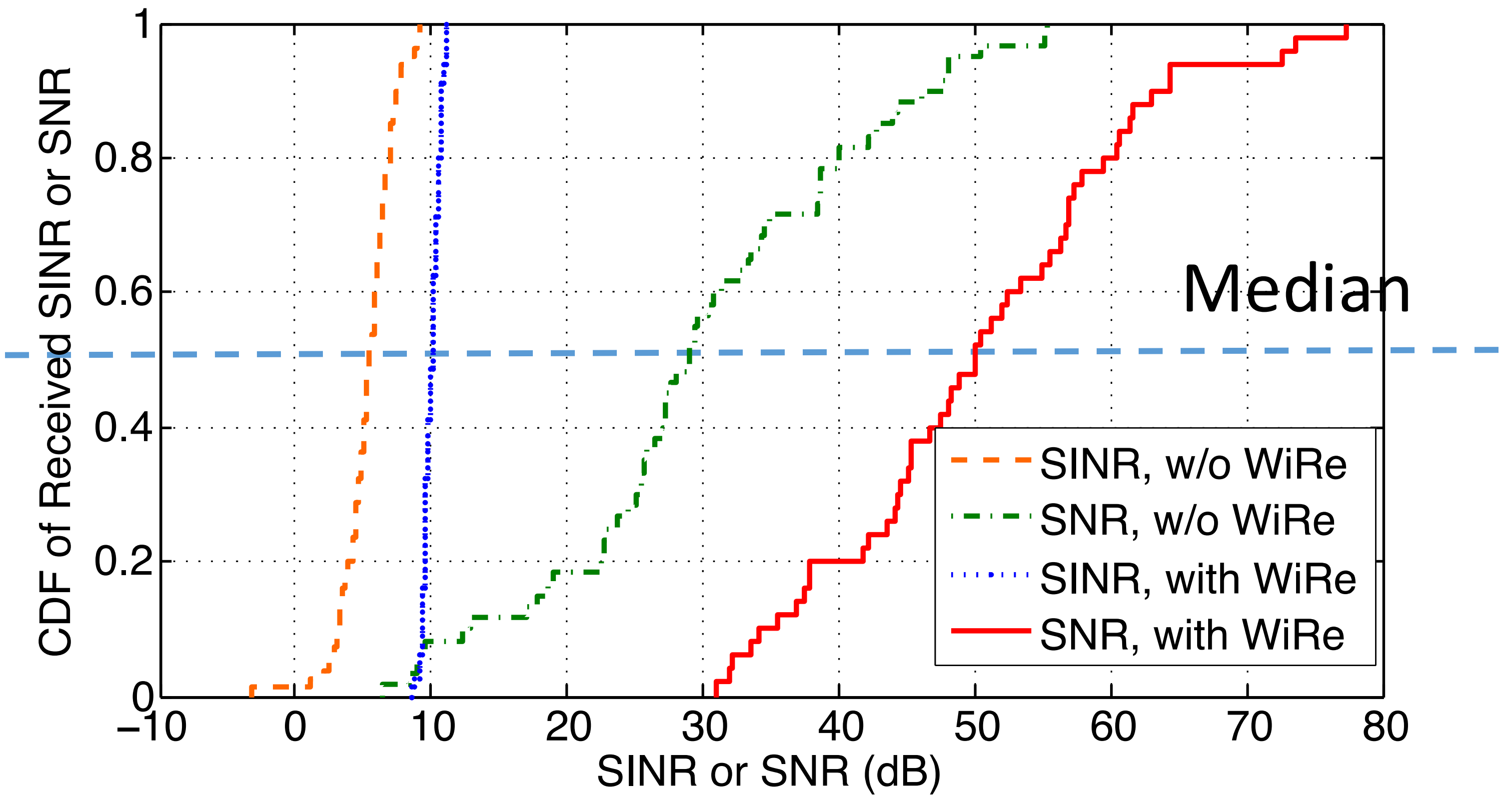
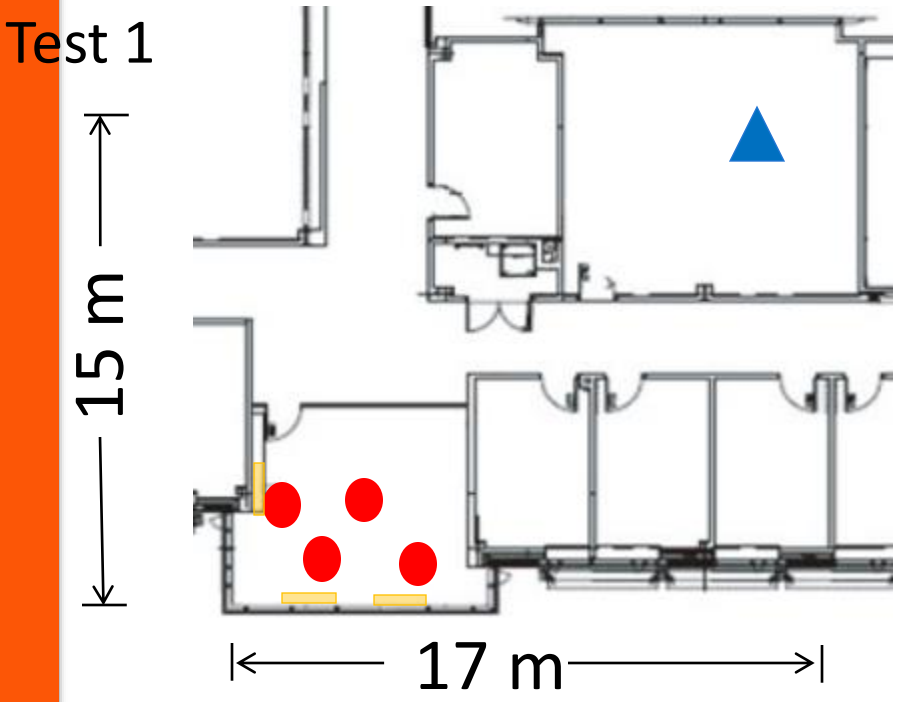
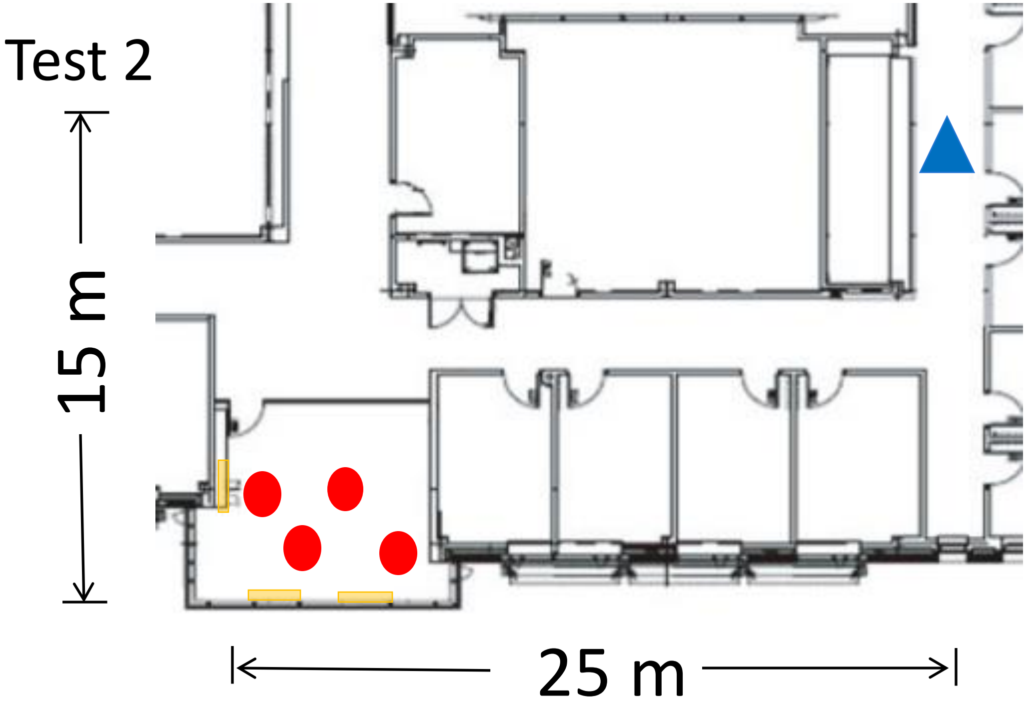
	SINR (dB)	SNR (dB)
w/o WiRe	5.2	27.2
w/ WiRe	10.0	50.1



Evaluation: Recycler Mode

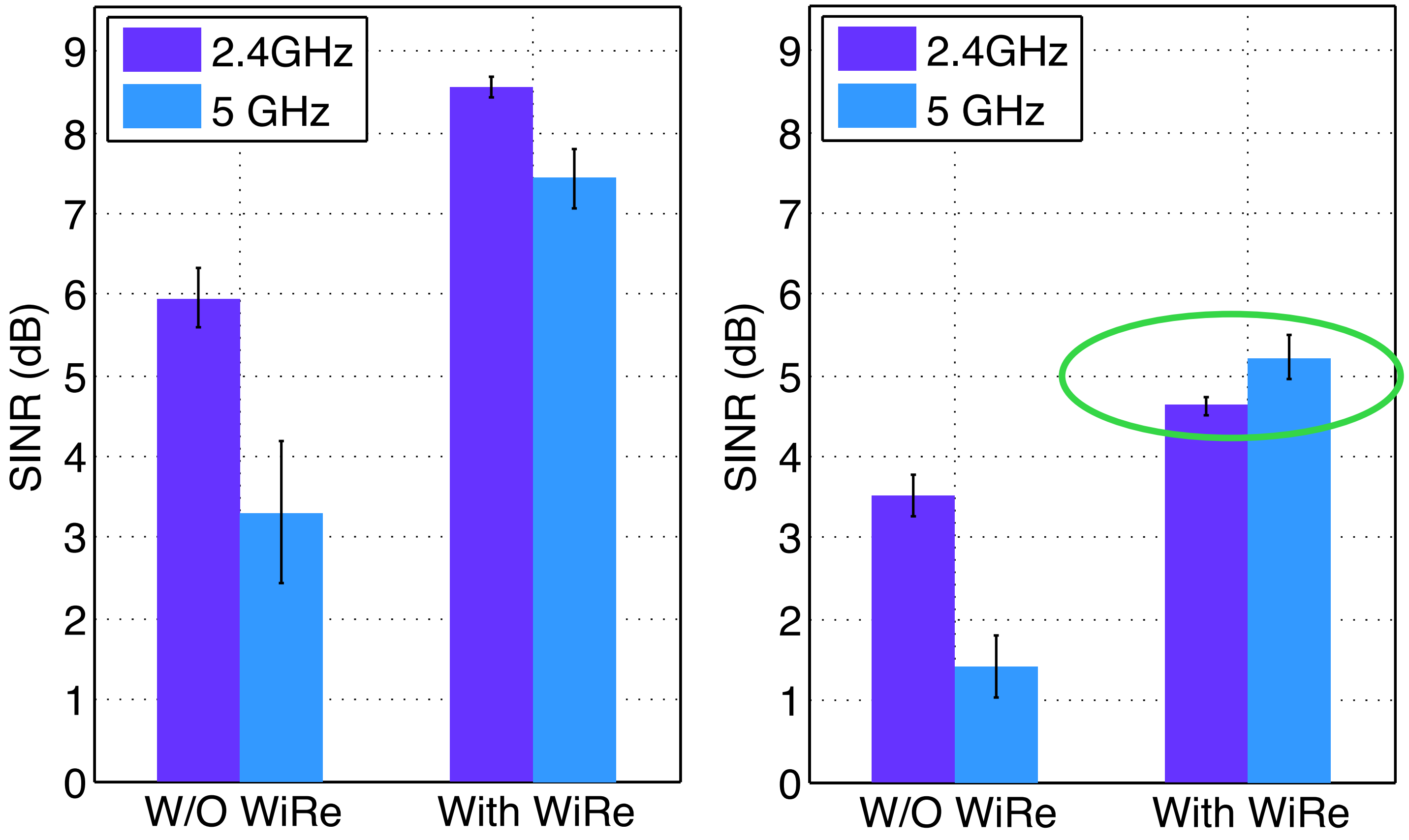
- Tx in lab room and corridor, Rxs in meeting room





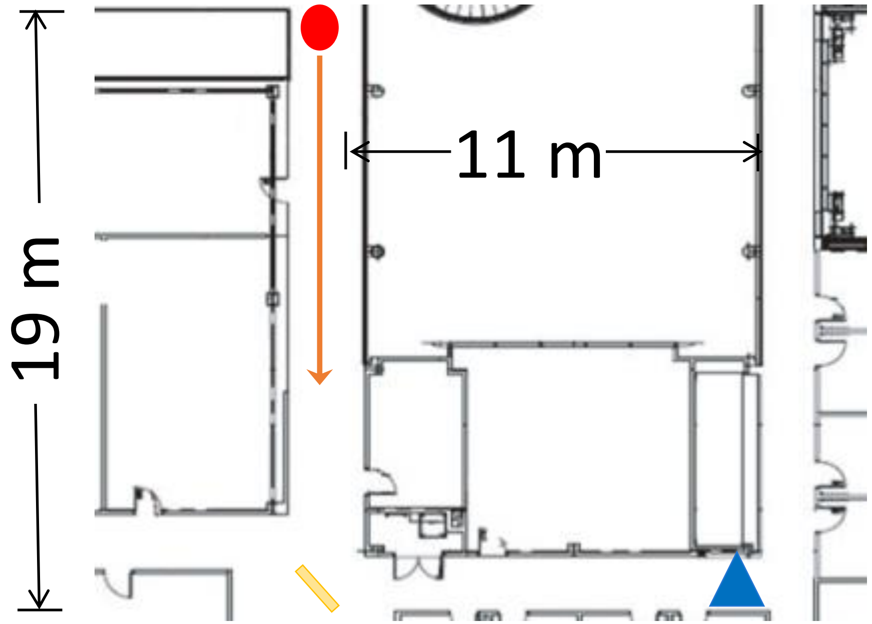
Evaluation: Recycler Mode

- Tx in lab room and corridor, Rxs in meeting room
  - Test 1
    - 2.4 GHz: ⬆ 41.7 %
    - 5 GHz: ⬆ 1.3 x
  - Test 2
    - 2.4 GHz: ⬆ 16.1 %
    - 5 GHz: ⬆ 2.5 x
- 5 GHz signal is even <u>stronger</u> than 2.4 GHz signal!



Evaluations: Mobile User Scenario

- Tx and Rx are in two side of a corridor
  - Rx moves at walking speed (1.3 m/s)



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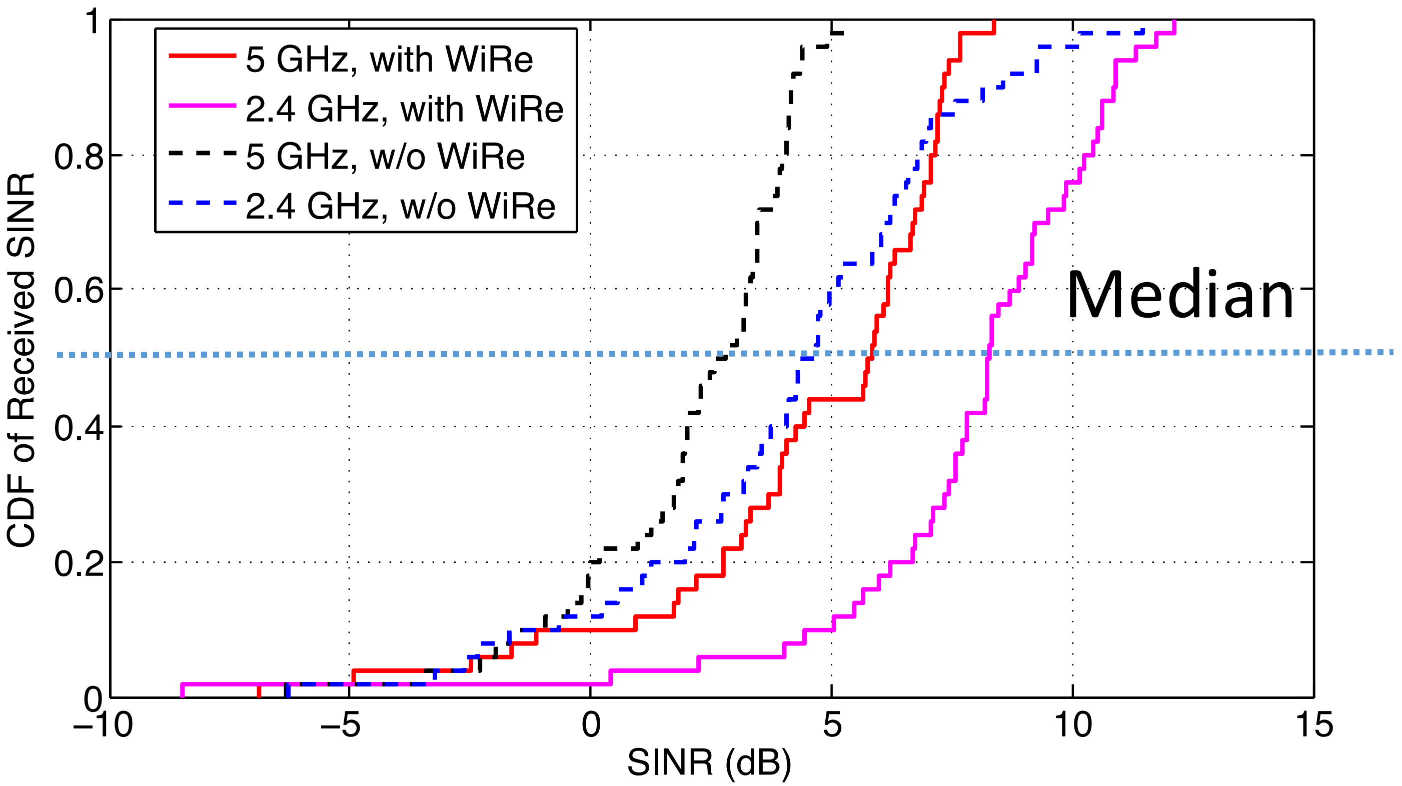
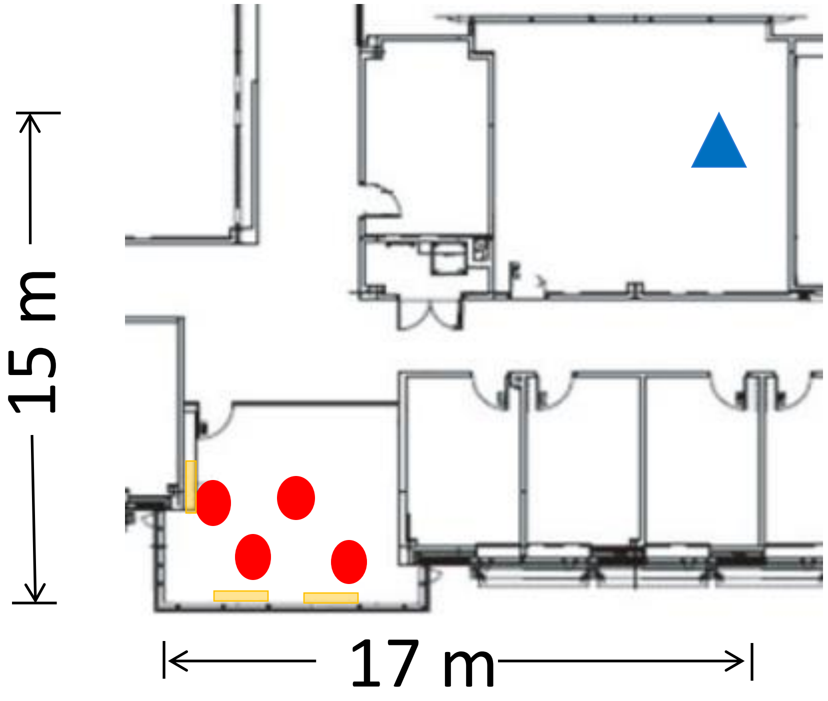
- Tx and Rx are in two side of a corridor
  - Rx moves at walking speed (1.3 m/s)

	5 GHz	2.4 GHz
W/o WiRe	2.5	5.0
W WiRe	5.8	8.0



Evaluation: Real User Case

- Data transmission
  - Transmitting picture (6 KB) from lab room to office room
- Recycler mode
  - Same experiment environment
- Constellation map
  - Shows the signal degradation



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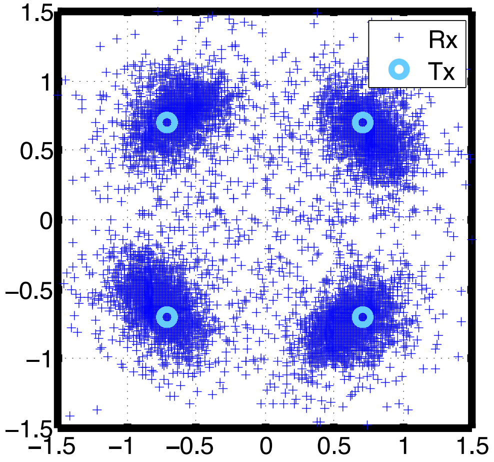
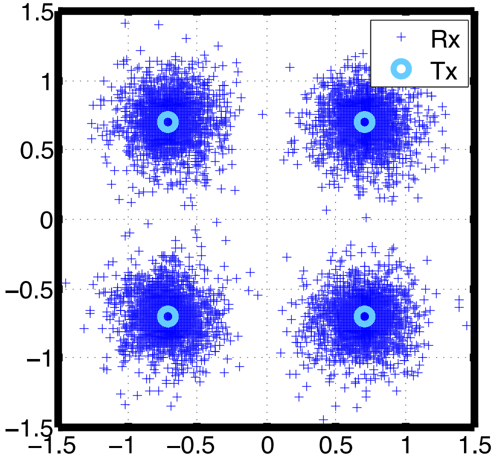




Conclusion

- Comprehensive indoor WiFi signal multipath profiling
  - Determine signal reflection patterns
  - Profile metallic reflector’s performance on reflecting WiFi signal
- Design WiFi Reflector (WiRe)
  - Determine physical features of reflector
  - Design placement scheme of reflector

Appendix: MUSIC algorithm

- Received signal is parameterized by steering matrix: $\mathbf{y} = \mathbf{A}\mathbf{x} + \mathbf{w}$
- Compute covariance matrix: $\mathbf{S} = E[\mathbf{y}\mathbf{y}^H]$
- Eigenvector decomposition of $\mathbf{S}$: $\mathbf{S} = \mathbf{E}\Lambda\mathbf{E}^{-1}, \quad \mathbf{E} = [\mathbf{E}_N | \mathbf{E}_S],$
- Computer AoA spectrum:

$$P(\theta, \phi) = \frac{1}{\mathbf{a}^H(\theta, \phi) E_N E_N^H \mathbf{a}(\theta, \phi)}$$

Appendix: Optimization of MUSIC for UCA

- UCA-RB-MUSIC:
  - $\mathbf{a}_e(\theta,\phi) = \mathbf{F}_e^H \mathbf{a}(\theta,\phi)$, $\mathbf{F}_e$ is beamformer matrix
- Phase-offset compensation

Algorithm 1 Phase-offset compensation

1: **Inputs:**
   Uncompensated received sinusoid wave
2: Calculate the phase difference $\Delta\gamma_i$ between reference antenna and each antenna i, $i \in [2,N]$;
3: Generate the phase compensation matrix: $\mathbf{C} = diag[e^{\Delta\gamma_2},\cdots,e^{\Delta\gamma_8}]$;
4: Premultiply the I/Q data of received signal with $\mathbf{C}$.

Outline

- Signal Reflection
  - Antenna & Wave Primer
  - History
- Energy harvesting in
  - RFID
  - WiFi
  - Backscatter

Magnetoelectric Backscatter

- *“Magnetoelectric backscatter communication for millimeter-sized wireless biomedical implants”* (ACM MobiCom’22)
  - Use one Magnetoelectric (ME) film for both power and uplink backscatter to minimize implant size; prior ME works lacked a near-zero-power uplink path

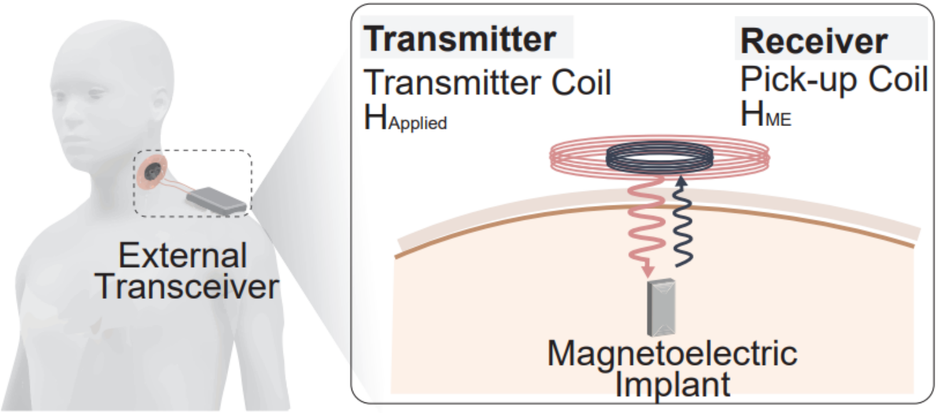


Figure 1: Overview of the proposed magnetoelectric wireless bio-implant platform. It achieves wireless power and bidirectional communication using a single magnetoelectric transducer.

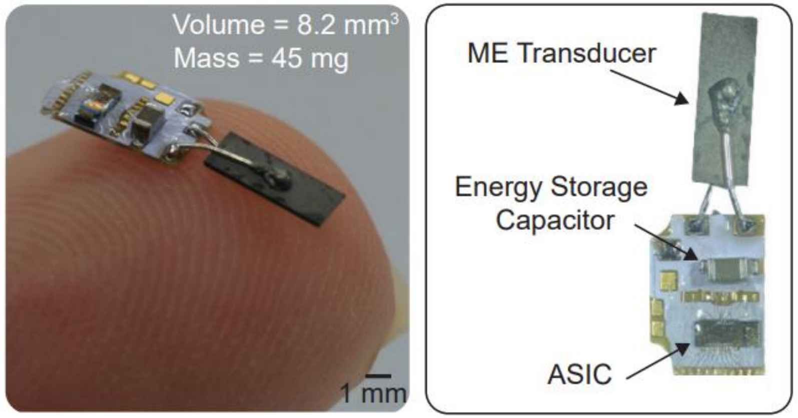


Figure 2: The prototyped magnetoelectric (ME) implant. The implant is shown on a fingertip to illustrate its miniaturized form factor. It integrates an ASIC chip, a ME transducer, and an energy storage capacitor onto the board with an 8.2-mm^3 volume and a 45-mg weight.

Magnetoelectric Backscatter

- *“Omnidirectional Wireless Power Transfer for Millimetric Magnetoelectric Biomedical Implants”* (JSSC 2024)
- What’s new vs. MobiCom’22 (ME backscatter)
  - 2022 showed single ME transducer = power + near-zero-power uplink (mm-scale implant) but no omnidirectional wireless power transfer (WPT); this work adds closed-loop, omnidirectional powering via implant-assisted sensing and multi-coil steering.

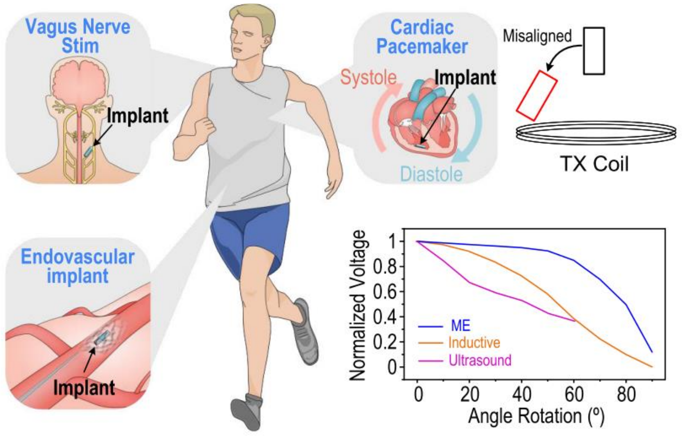


Fig. 1. Selected applications of wirelessly powered bioimplants and the sensitivity to angular rotations of various WPT modalities [10], [23], [27].

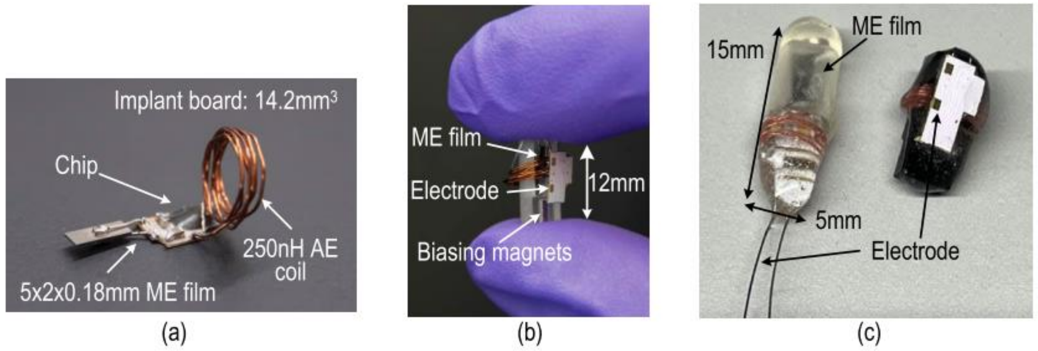
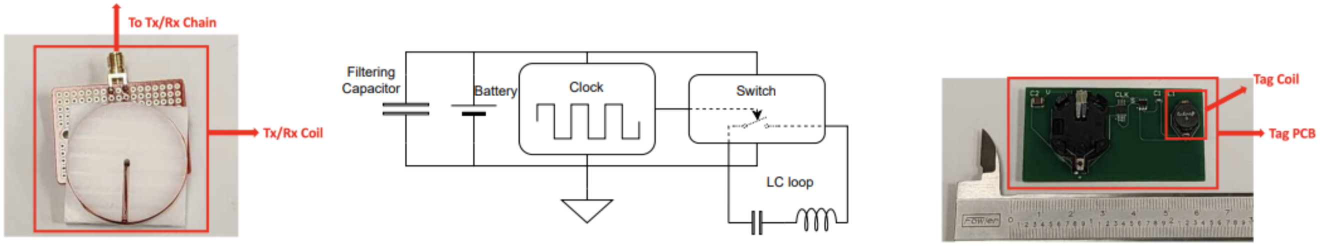


Fig. 5. Prototypes of implant: (a) Unfolded implant board with storage cap, ME film, and AE coil assembled. (b) Implant with an mm-scale plastic package and aligned ME film and AE coil. (c) Implant encapsulated with medical epoxy for cardiac pacing and neurostimulation.

Magnetic Backscatter

- *“Magnetic Backscatter for In-body Communication and Localization”* (*ACM MobiCom’23*)
- Motivation
  - RF in tissue suffers strong attenuation and interface reflections; Need a low-power, physics-based method that yields mm-level accuracy without per-environment retraining
- System overview
  - A few external coils transmit a low-frequency magnetic field; the in-body tag passively backscatters it
  - Frequency-multiplexed transmitters plus a small RX array yield ~N^2 RSSI measurements for data + 3D localization; a low-impedance series-LC driver boosts coil current for deeper reach



(a) InnerCompass’s Transceiver Coils. (b) InnerCompass circuit diagram. (c) InnerCompass tag PCB.

Figure 6: InnerCompass Hardware Implementation (a-c): (a) Photo of InnerCompass’s coils for the reader. (b) Circuit diagram for the tag in InnerCompass. (c) InnerCompass Tag PCB size measured with calipers.

RF Backscatter

- *“Enabling Native WiFi Connectivity for Ambient Backscatter” (MobiSys’23 and TON’24)*
- Motivation: Remove custom readers: make tags that a commodity Wi-Fi AP/phone can decode natively.
- Idea: Backscatter native 802.11 frames using productive (uncontrolled) Wi-Fi as carriers—no helper waveform changes
- Core design: Tag synthesizes 802.11-compliant preamble/header via reflection-coefficient control; receiver treats packets as normal Wi-Fi.

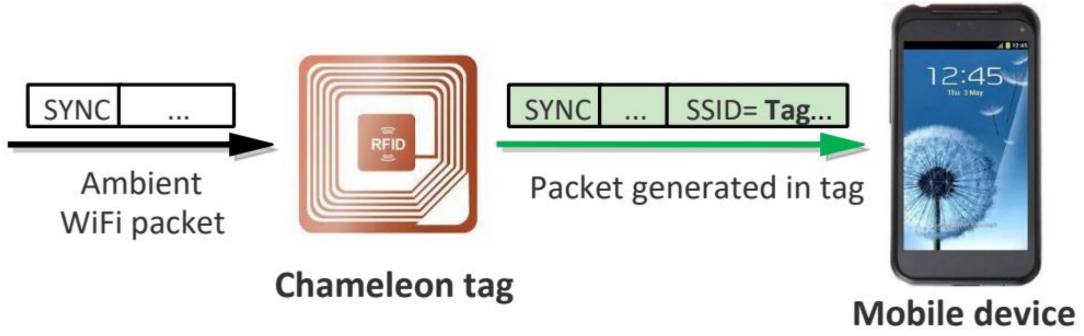
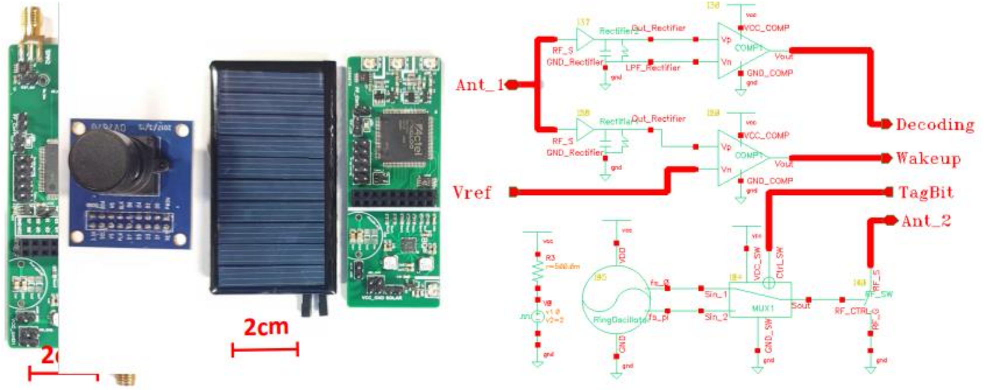


Figure 1: Conceptual design of Chameleon that generates native WiFi packets out of uncontrolled ambient 802.11b signals, ensuring 100% compatibility with COTS WiFi devices.



(a) Tag-1. (b) Tag-2. (c) Tag-3.

Figure 18: Tag-1: verification prototype; Tag-2: battery-free prototype; Tag-3: IC simulation.

RF Backscatter

- *REHSense — Battery-Free Wireless Sensing via RF Energy Harvesting (MobiHoc'24)*
- Motivation: Wi-Fi CSI sensing is accurate but power-hungry and often needs NIC/firmware tweaks → hard to deploy at scale.
- Goal: make sensing battery-free by turning the RF harvester itself into the sensor front-end.
- System: Replace the Wi-Fi receiver with a COTS RF energy harvester and use its harvested voltage waveform (DC + ripples) as the sensing signal; process it with a lightweight pipeline (noise cancellation, segmentation/normalization, counting for respiration; CNNs for activity & gestures)

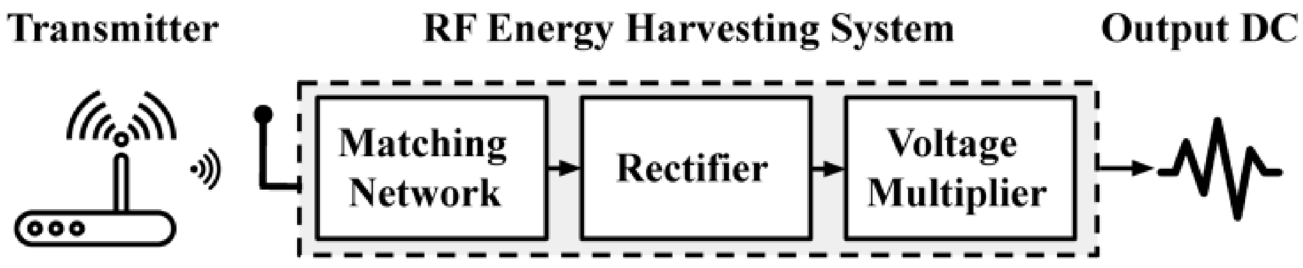


Figure 2: Workflow of RF energy harvesting.

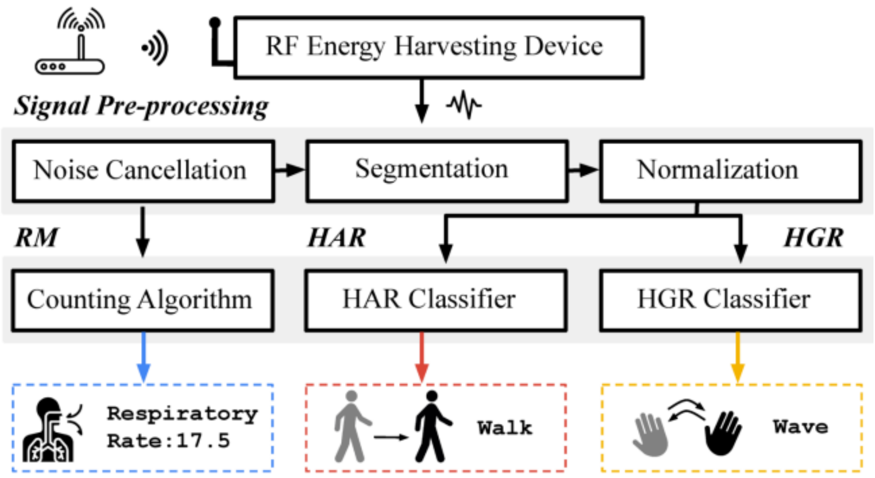
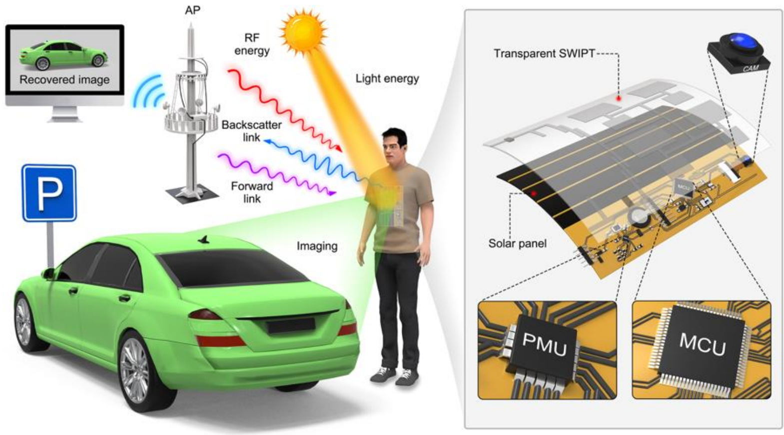


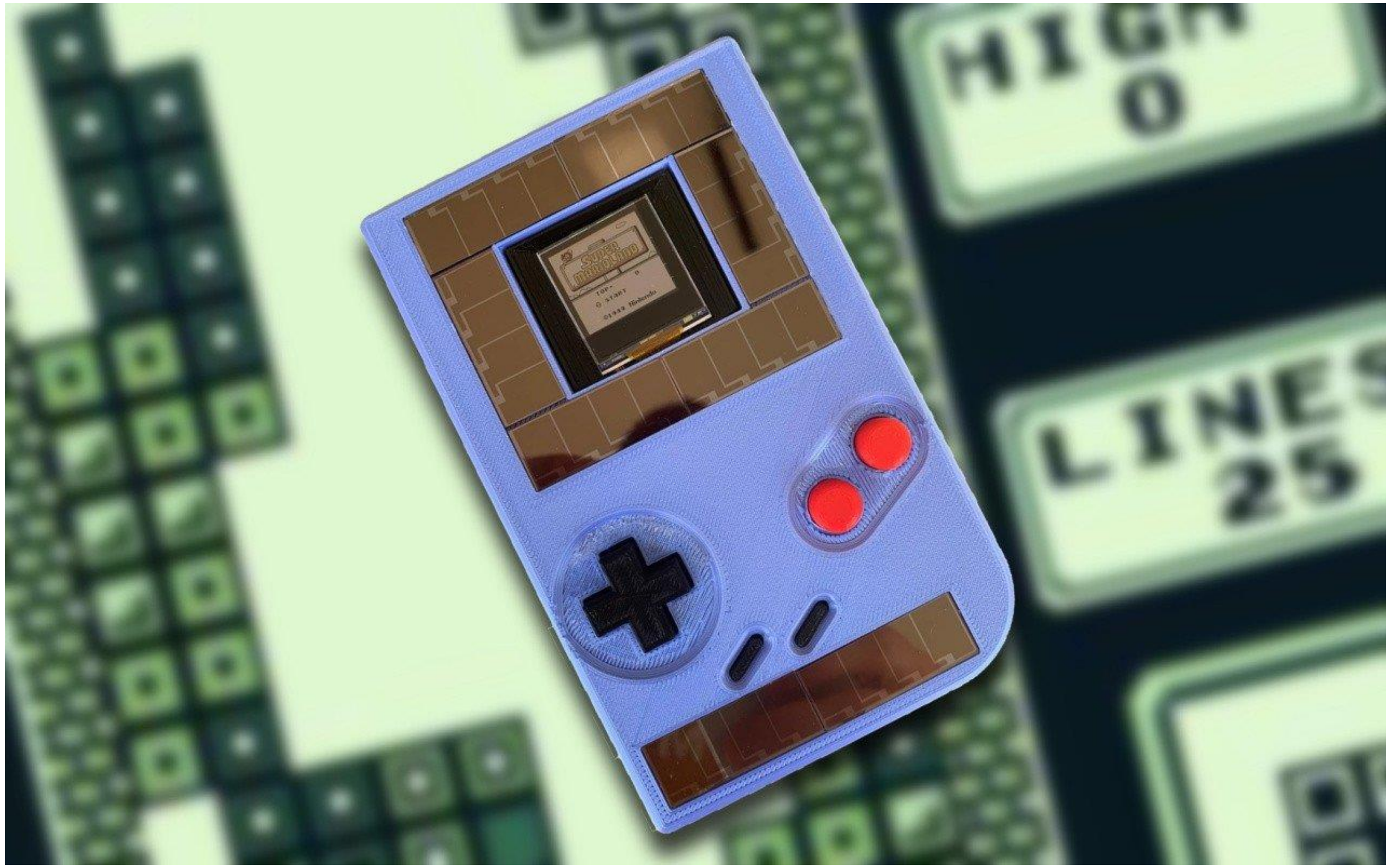
Figure 5: Overview of REHSense.

RF Backscatter

- Flexible and wearable battery-free backscatter wireless communication system for colour imaging (*Nat. Commun.'24*)
- A flexible, wearable, battery-free wireless system that captures colour images and transmits them via backscatter communication using a compact conformal device on the body.
- Energy harvesting
  - Uses a hybrid RF-solar energy harvest (EH) array: harvests energy from ambient RF + visible light to power the imaging, logic and backscatter radio.
  - Employs a shared-aperture antenna array designed for simultaneous wireless information & power transfer (SWIPT), enabling compact EH + backscatter integration.
  - Without efficient EH from RF & light, the "battery-free colour imaging + backscatter" goal couldn't be achieved.



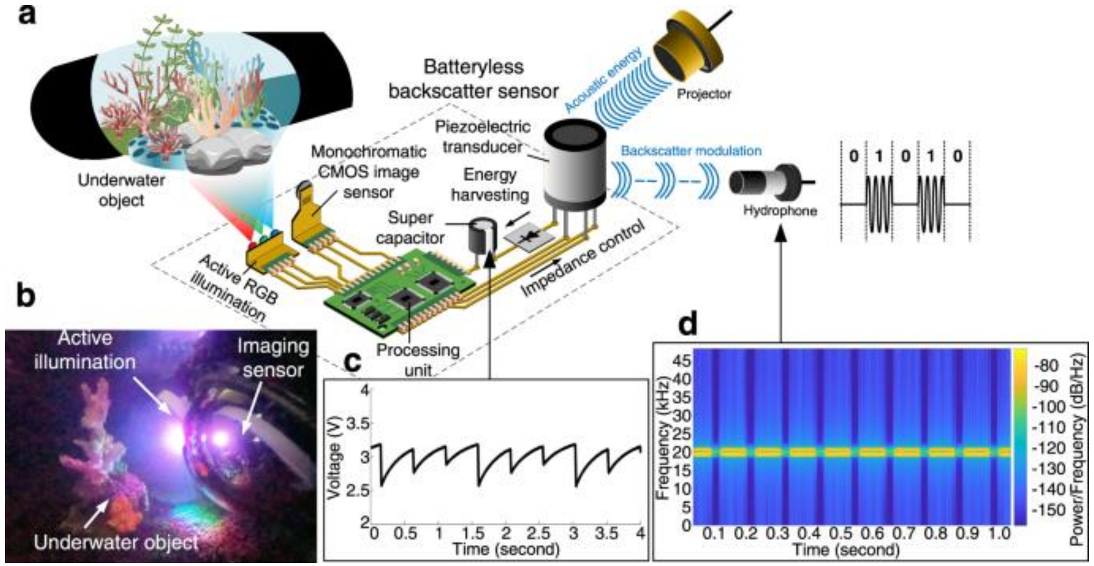
Battery-free Gameboy



Team: Jasper de Winkel, Vito Kortbeek, Josiah Hester, Przemysław Pawełczak
Paper: https://doi.org/10.1145/3411839
Venue: ACM IMWUT / UbiComp 2020
Code: https://github.com/tudssl/engage

Acoustic Backscatter

- *"Battery-free wireless imaging of underwater environments"* (*Nat. Commun.'22*)
- Motivation: Long-term, scalable underwater imaging without tethers or battery swaps; harvest acoustic energy
- System (energy & imaging)
  - Downlink: remote acoustic projector → piezoelectric harvester → rectifier → supercapacitor;
  - Camera: ultra-low-power monochrome CMOS + RGB LED active illumination; receiver reconstructs color from three mono exposures
  - Uplink: piezo-acoustic backscatter (load-switching modulates transducer reflectivity)



Related works: Survey of mmWave Backscatter

- A Survey of mmWave Backscatter: Applications, Platforms, and Technologies (ACM Computing Surveys)