6.1820/MAS.453: Mobile and Sensor Computing

aka IoT Systems

https://6mobile.github.io/

Lecture 4:
Seeing Through Walls & Device-Free Localization

Course Staff

Lecturers

Fadel Adib (fadel@mit.edu)

Tara Boroushaki (tarab@mit.edu)

TAs

Waleed Akbar (wakbar@mit.edu)

Jack Rademacher (jradema@mit.edu)

Announcements

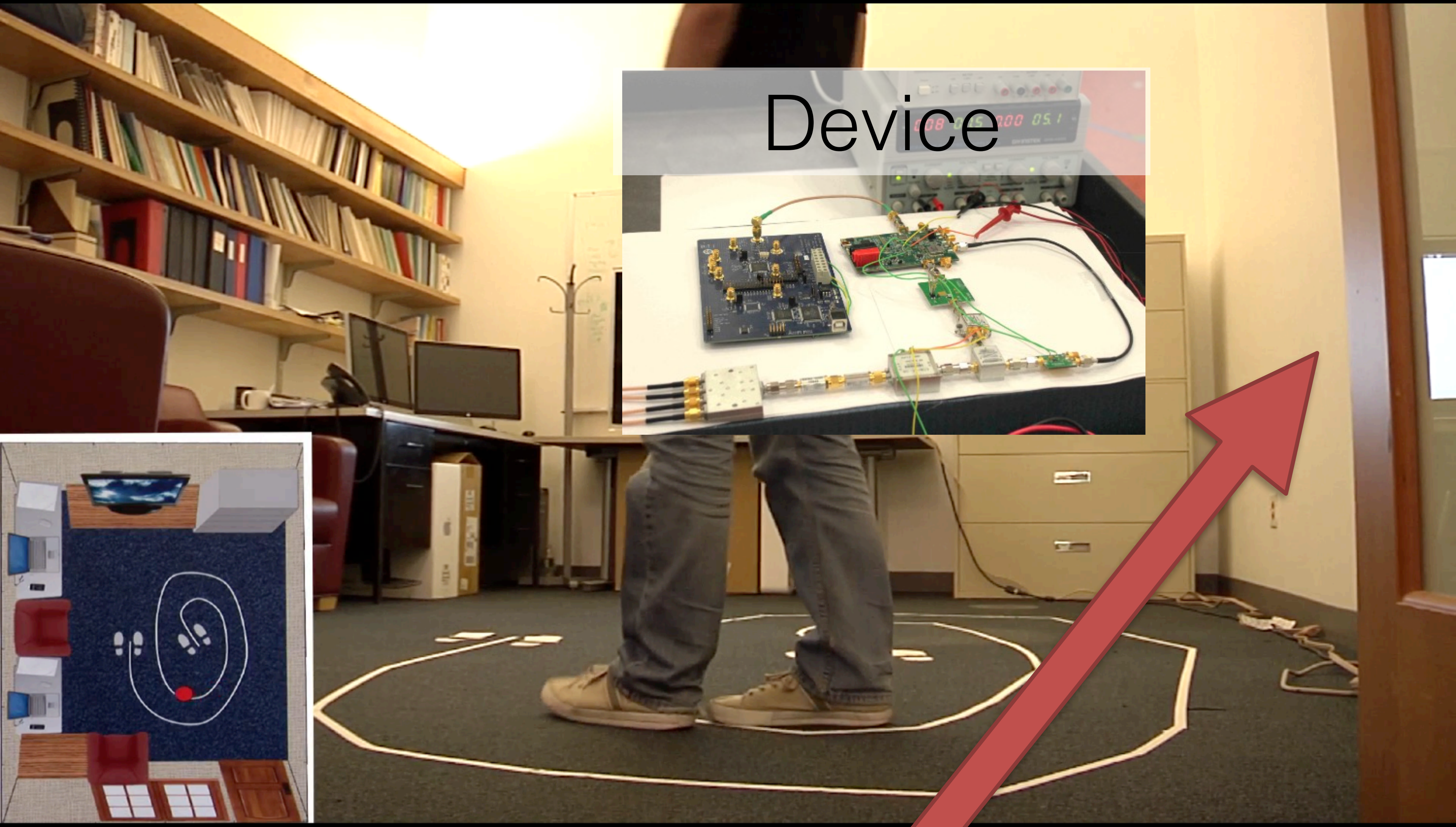
1- Did you join Slack & introduce yourself?

2- Answer the survey

2- Lab 0 due Today (i.e., checkoff in OH within 1wk)

3- Lab 1 due next week

4- #teamformation channel



Device in another room

Applications

Smart Homes

Energy Saving

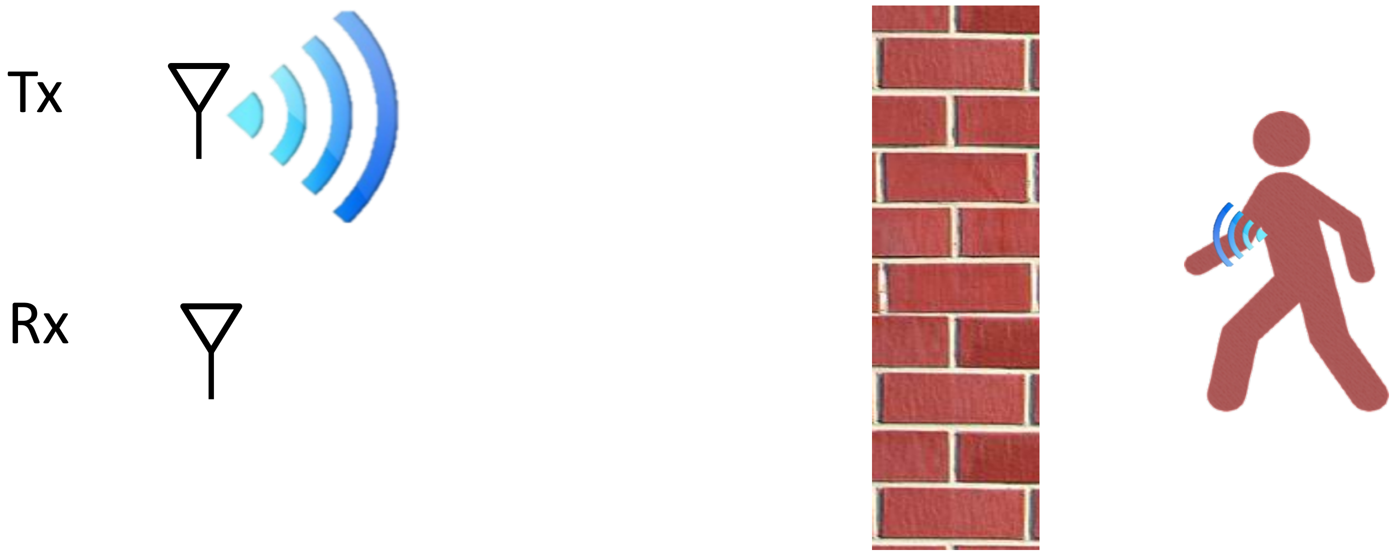
Gaming & Virtual Reality

What are we learning today?

Learn the fundamentals, applications, and implications of
wireless sensing

1. What is Frequency-modulated continuous-wave?
2. How can we obtain centimeter-scale localization from wireless reflections?
3. What are static and dynamic multi-path? How do they affect wireless sensing? how can we deal with them?

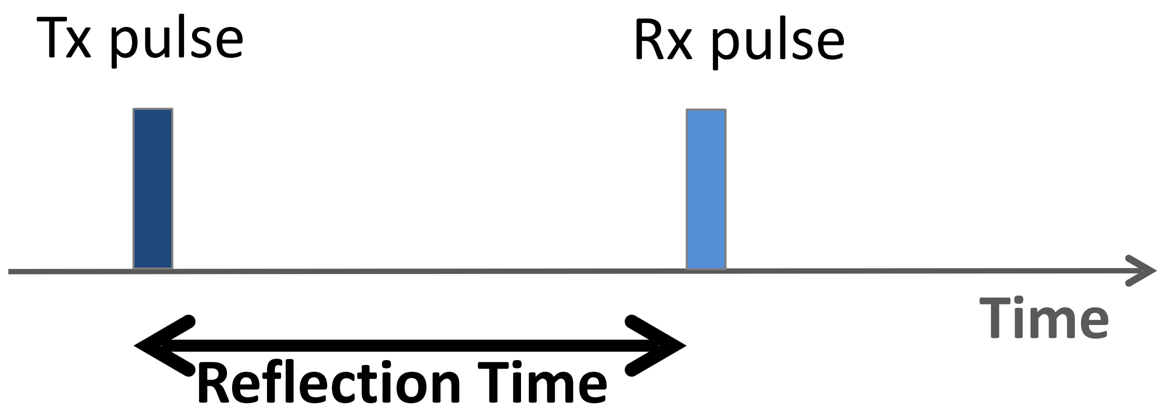
Measuring Distances



Distance = Reflection time x speed of light

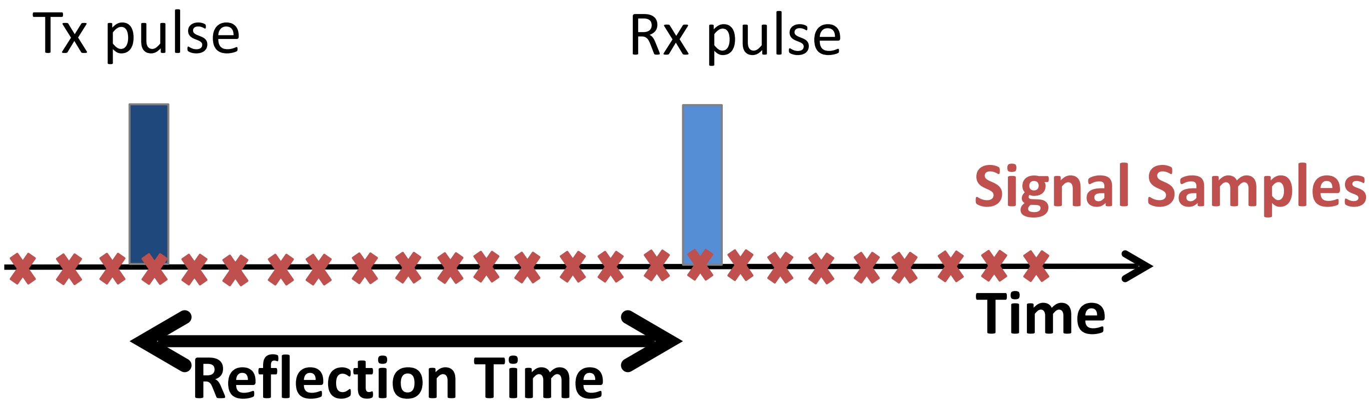
Measuring Reflection Time

Option1: Transmit short pulse and listen for echo



Measuring Reflection Time

Option1: Transmit short pulse and listen for echo



Capturing the pulse needs sub-nanosecond sampling

Why?

and why was this not a problem for Cricket?

Capturing the pulse needs sub-nanosecond sampling

Why?

Distance = time x speed

"smallest distance resolution"

"smallest time"

$$10cm = \Delta t \times (3 \times 10^8)$$

$$\Delta t = 0.3ns$$

0.3ns period => how many samples per second?

$$SamplingRate = \frac{1}{\Delta t}$$

3GSps! >> MSps for WiFi, LTE…

Multi-GHz samplers are expensive, have high noise, and create large I/O problem

---

Why was this not a problem for Cricket?

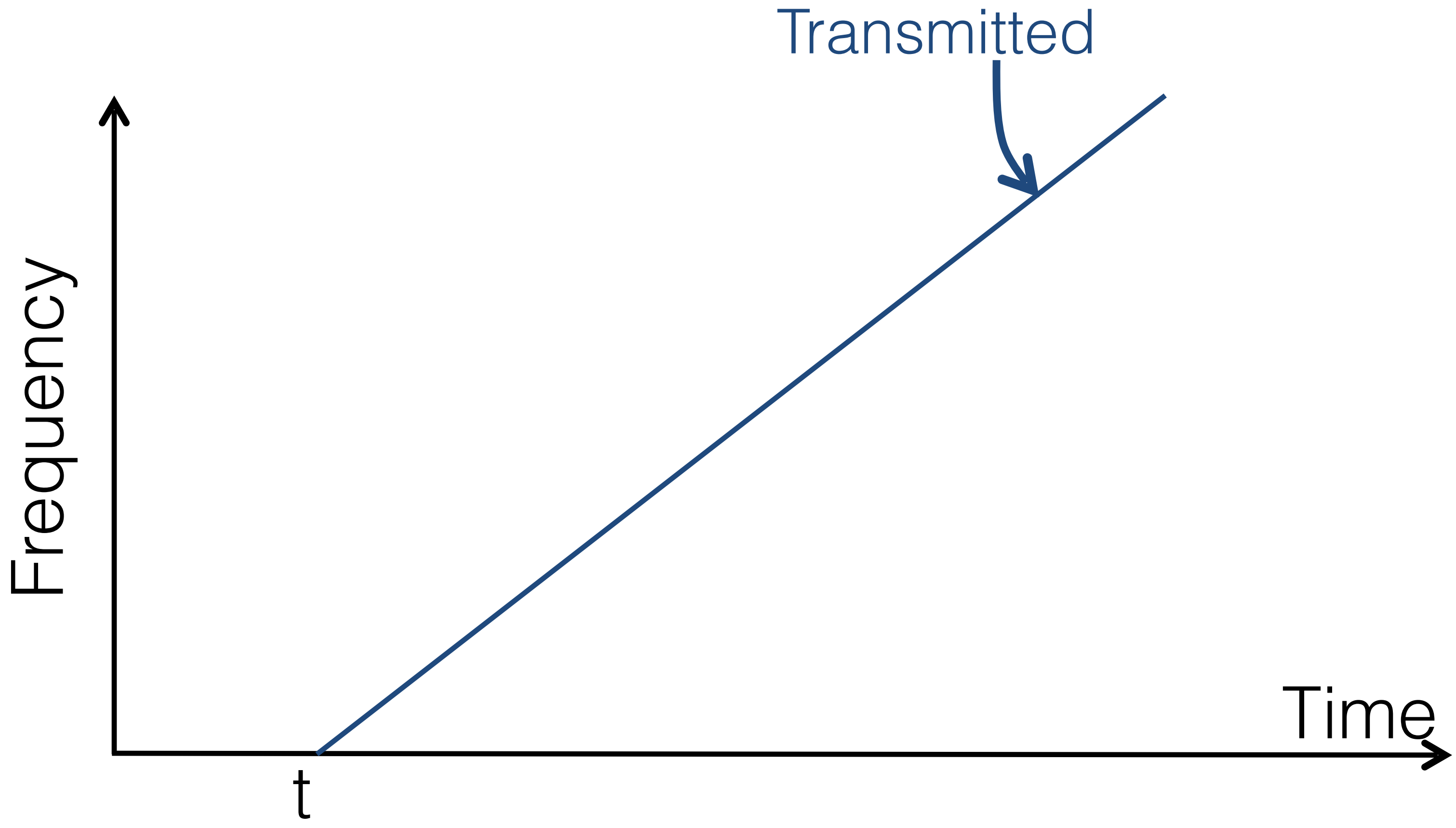
because speed of ultrasound

$$10cm = \Delta t \times 345$$

$$SamplingRate = \frac{1}{\Delta t} \approx 3kbps$$

Basics of Fourier Transform

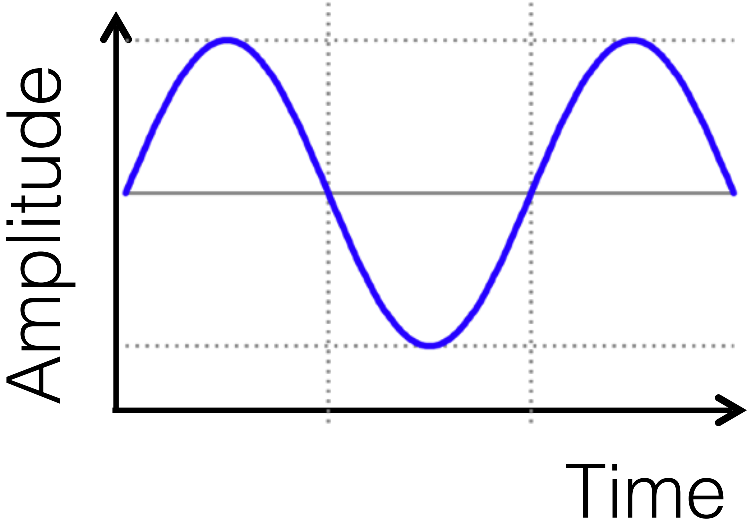
FMCW: Measure time by measuring frequency

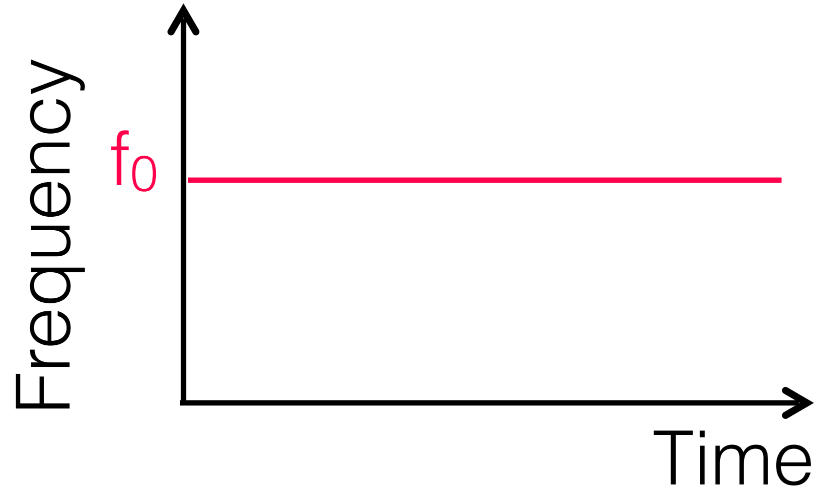


How does it look in time domain?
(and in comparison to single frequency)

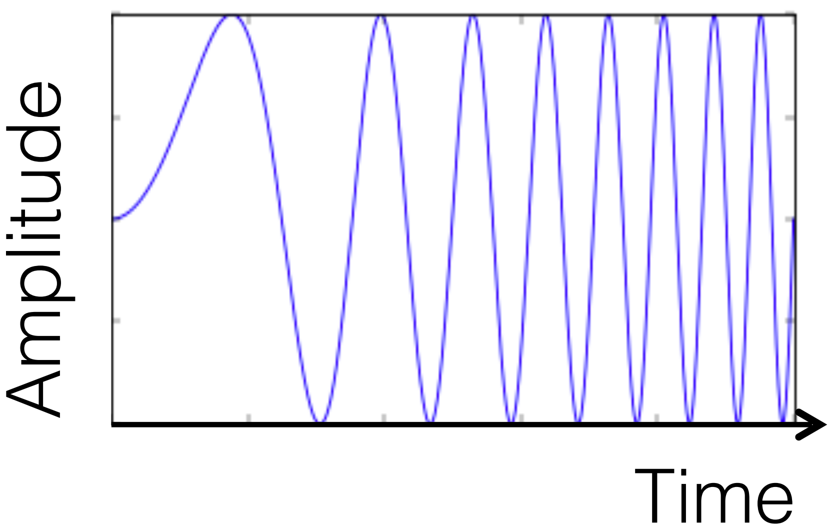
More intuitive understanding of FMCW

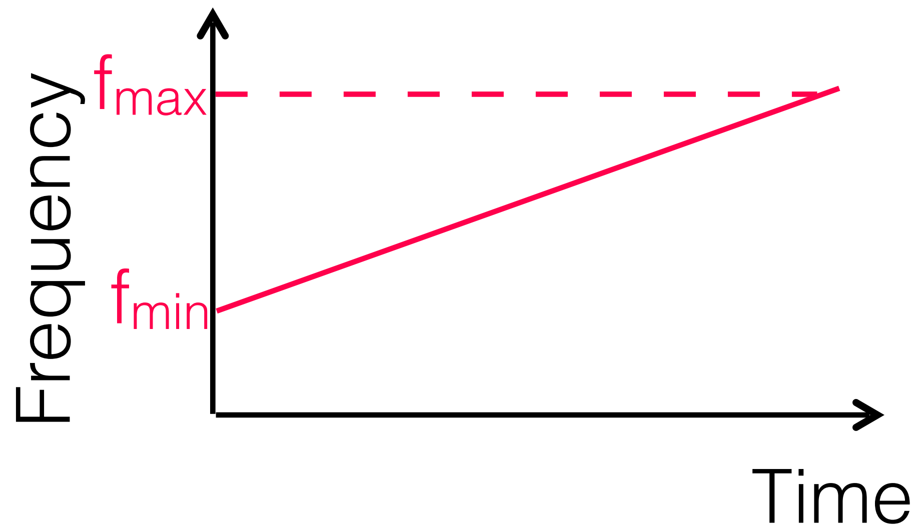
Wireless Signal at frequency f_0



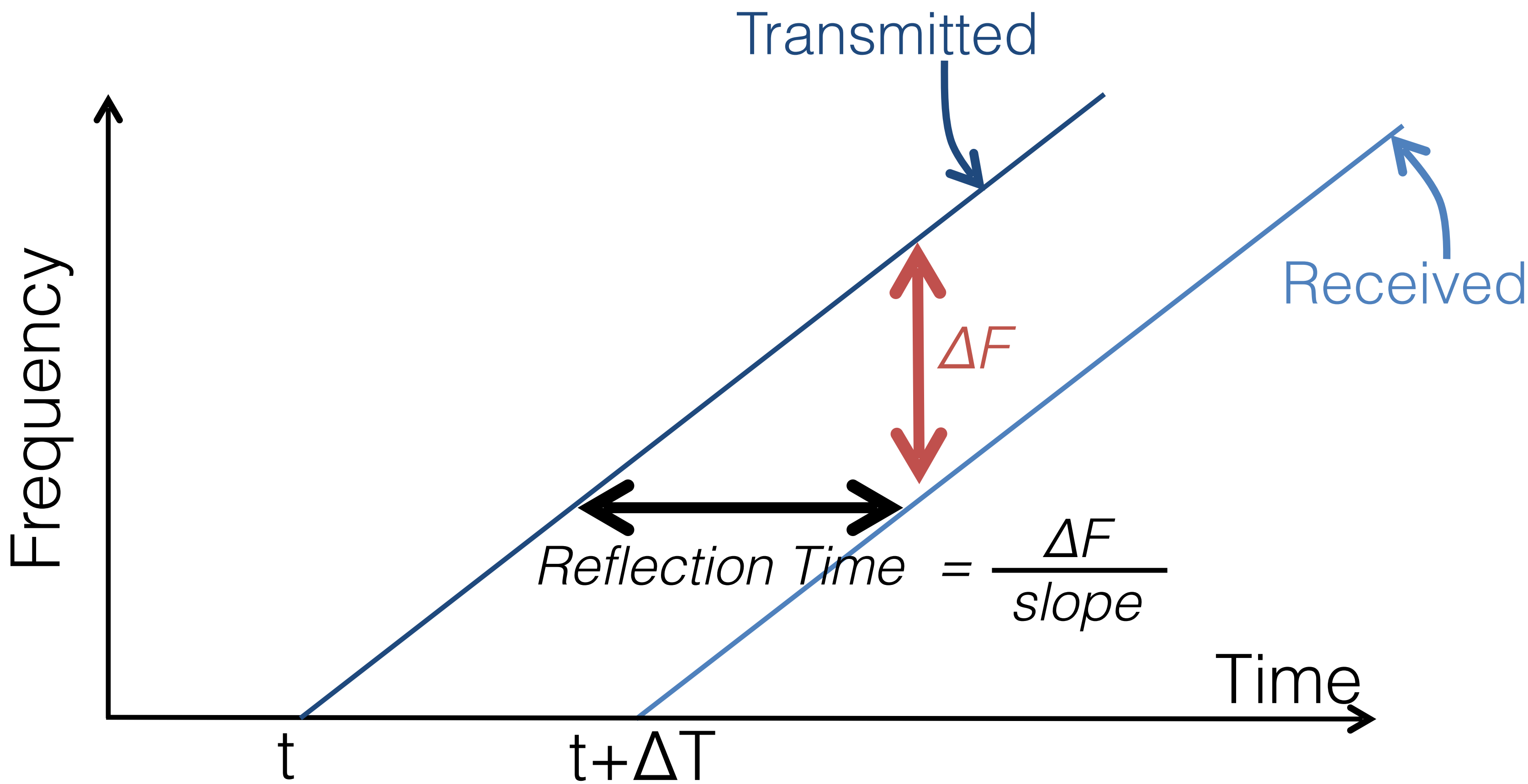


FMCW signal



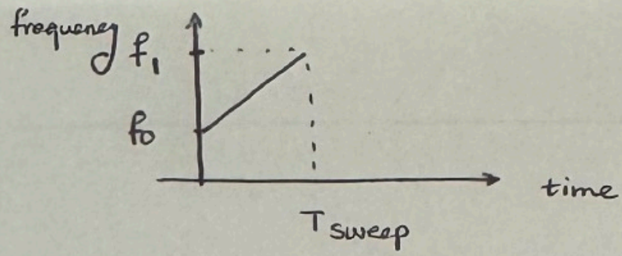


FMCW: Measure time by measuring frequency



How do we measure ΔF?

FMCW



$$f(t) = f_0 + \frac{K}{2} t \qquad K = \frac{f_1 - f_0}{T_{sweep}} \leftarrow \text{frequency sweep rate}$$

$$S_{TX} = \cos(2\pi f(t)\, t) = \cos(2\pi f_0 t + \pi K t^2)$$

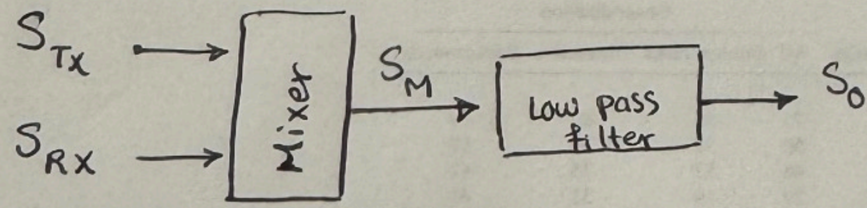
Signal transmitted by TX

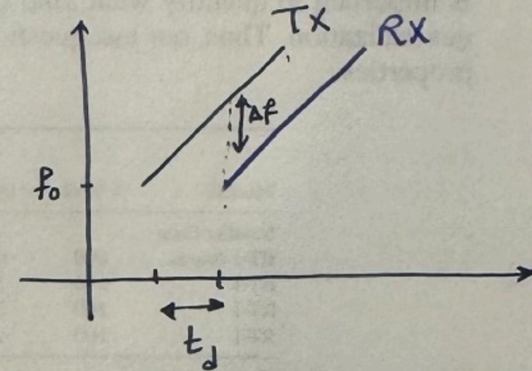
$$S_{RX} = \cos(2\pi f(t-t_d)\,(t-t_d)) = \cos(2\pi (f_0 + \frac{K}{2}(t-t_0))(t-t_d))$$

Signal Received by RX

$$= \cos(2\pi f_0 t + \pi K(t^2 + t_d^2) - 2\pi K t t_d)$$

{ the TOF is t_d }





$$S_M = S_{Tx} \cdot S_{RX} = \frac{1}{2}\left[\cos\left(\pi k t_d^2 - 2\pi k t t_d\right) + \cos\left(4\pi f_0 t + 2\pi k t^2 - 2\pi k t t_d + \pi k t_d^2\right)\right]$$

↑ low frequency ↑ high frequency

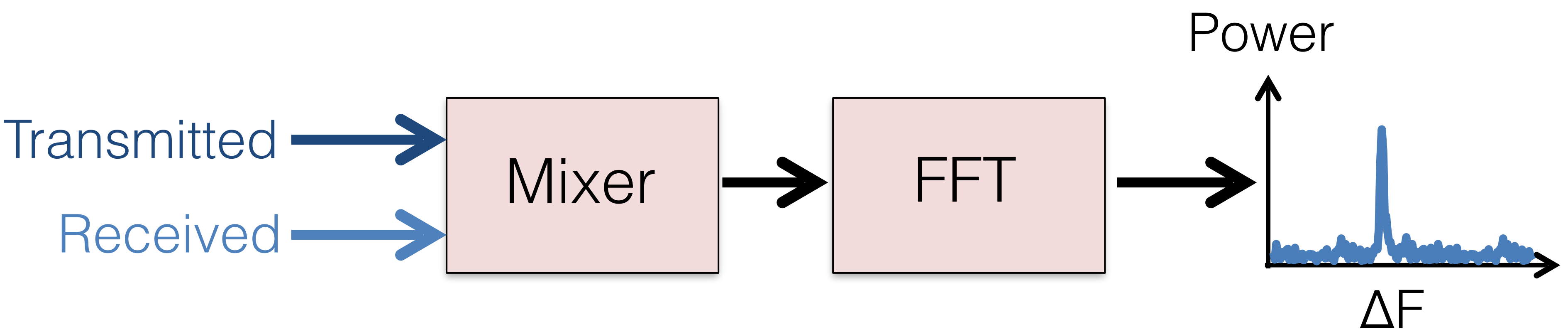
$$S_o = \cos\left(\pi k t_d^2 - 2\pi k t_d t\right)$$

the frequency of S_o is $\Delta f = \frac{2\pi k t_d}{2\pi} = k t_d$

$\Delta f = k t_d \rightarrow t_d = \frac{\Delta f}{k} \longrightarrow$ Round trip distance $= \frac{\Delta f}{k} \times c$

Measuring ΔF

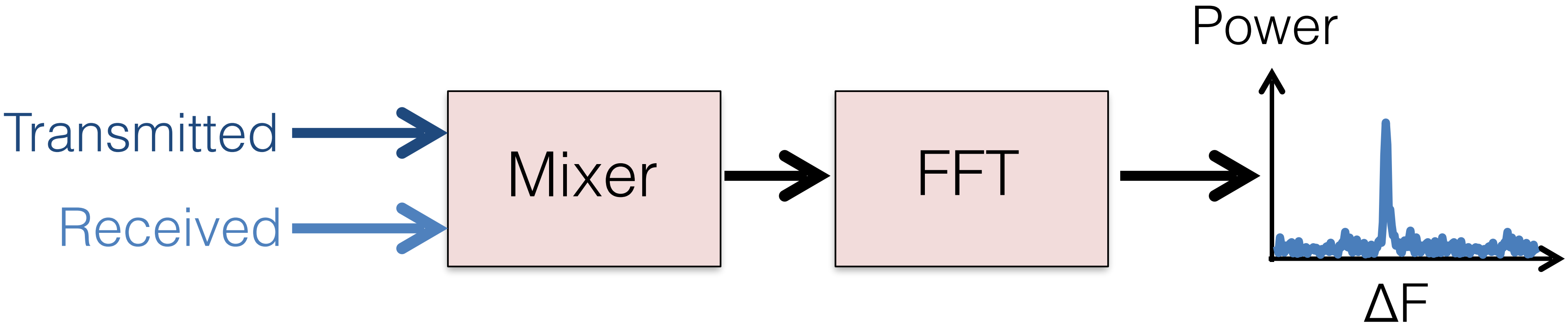
- Subtracting frequencies is easy (e.g., removing carrier in WiFi)
- Done using a mixer (low-power; cheap)



Signal whose frequency is ΔF

Measuring ΔF

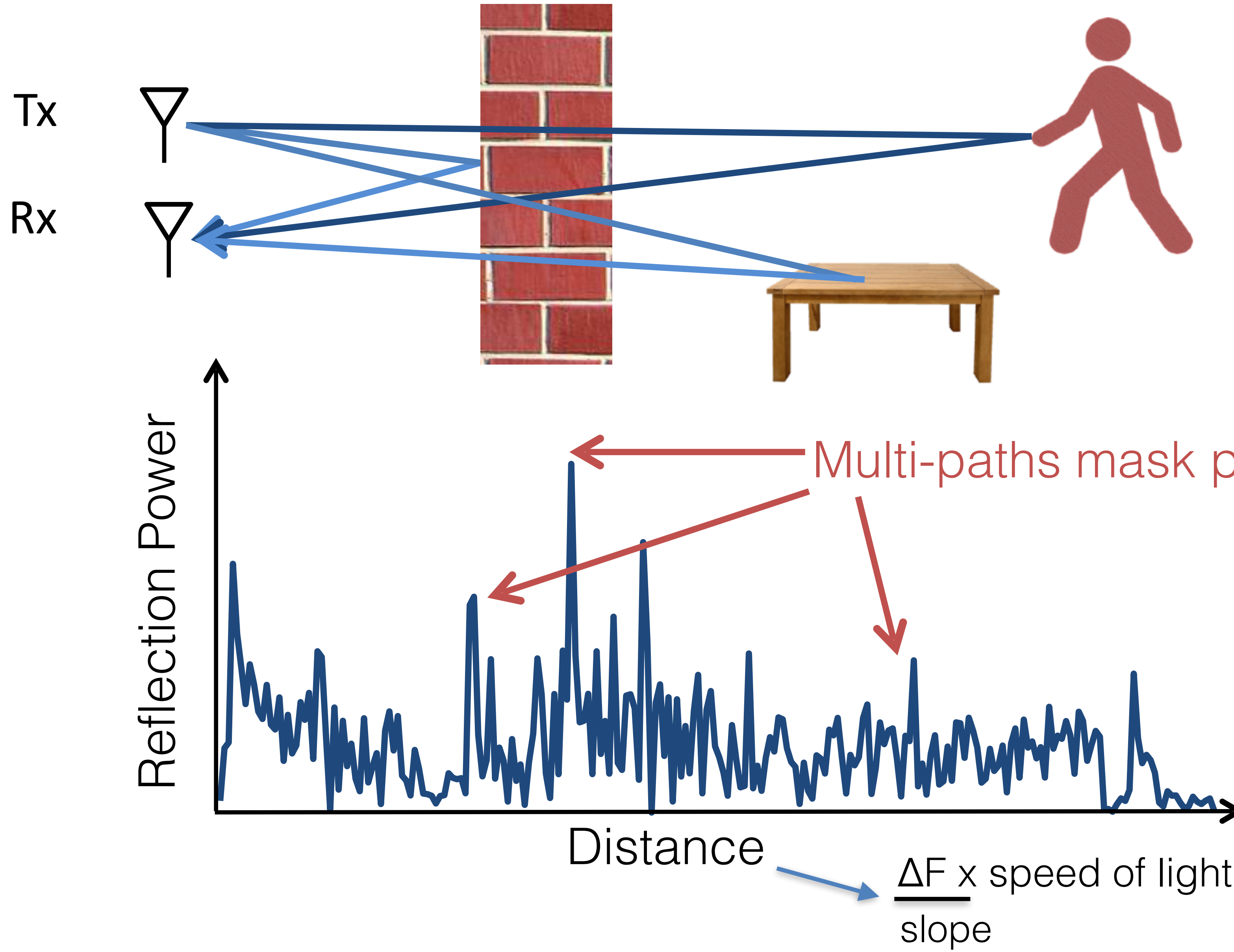
- Subtracting frequencies is easy (e.g., removing carrier in WiFi)
- Done using a mixer (low-power; cheap)



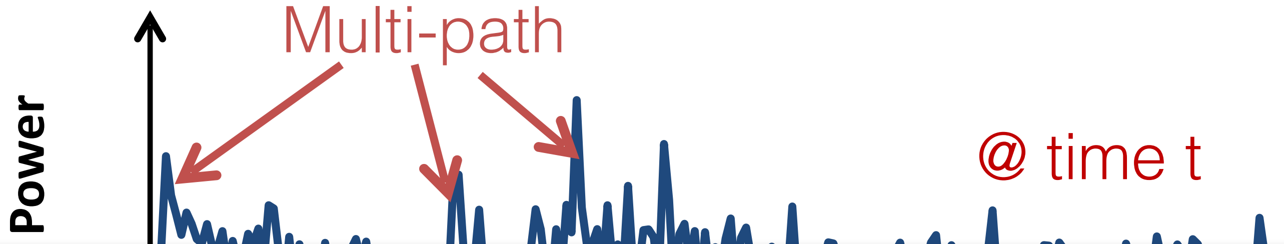
Signal whose frequency is ΔF

ΔF →Reflection Time → Distance

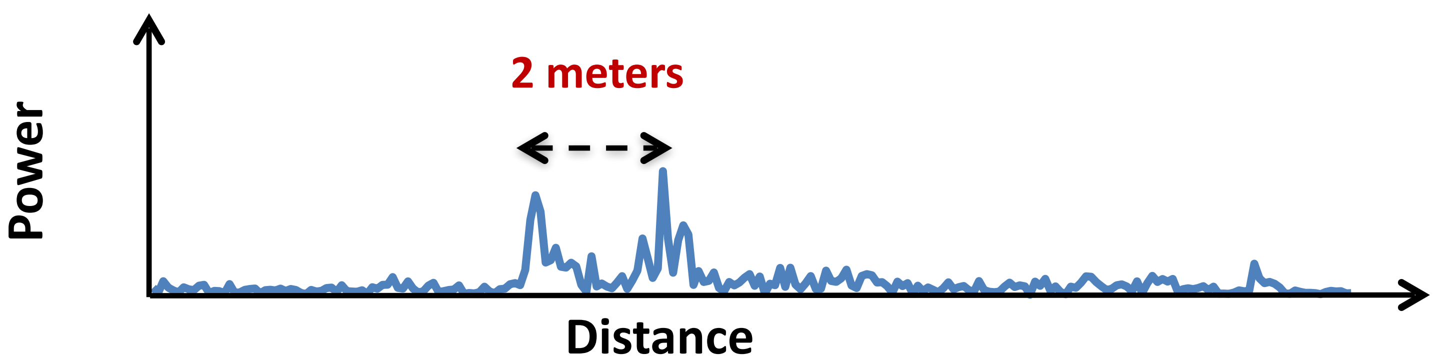
Challenge: Multipath → Many Reflections



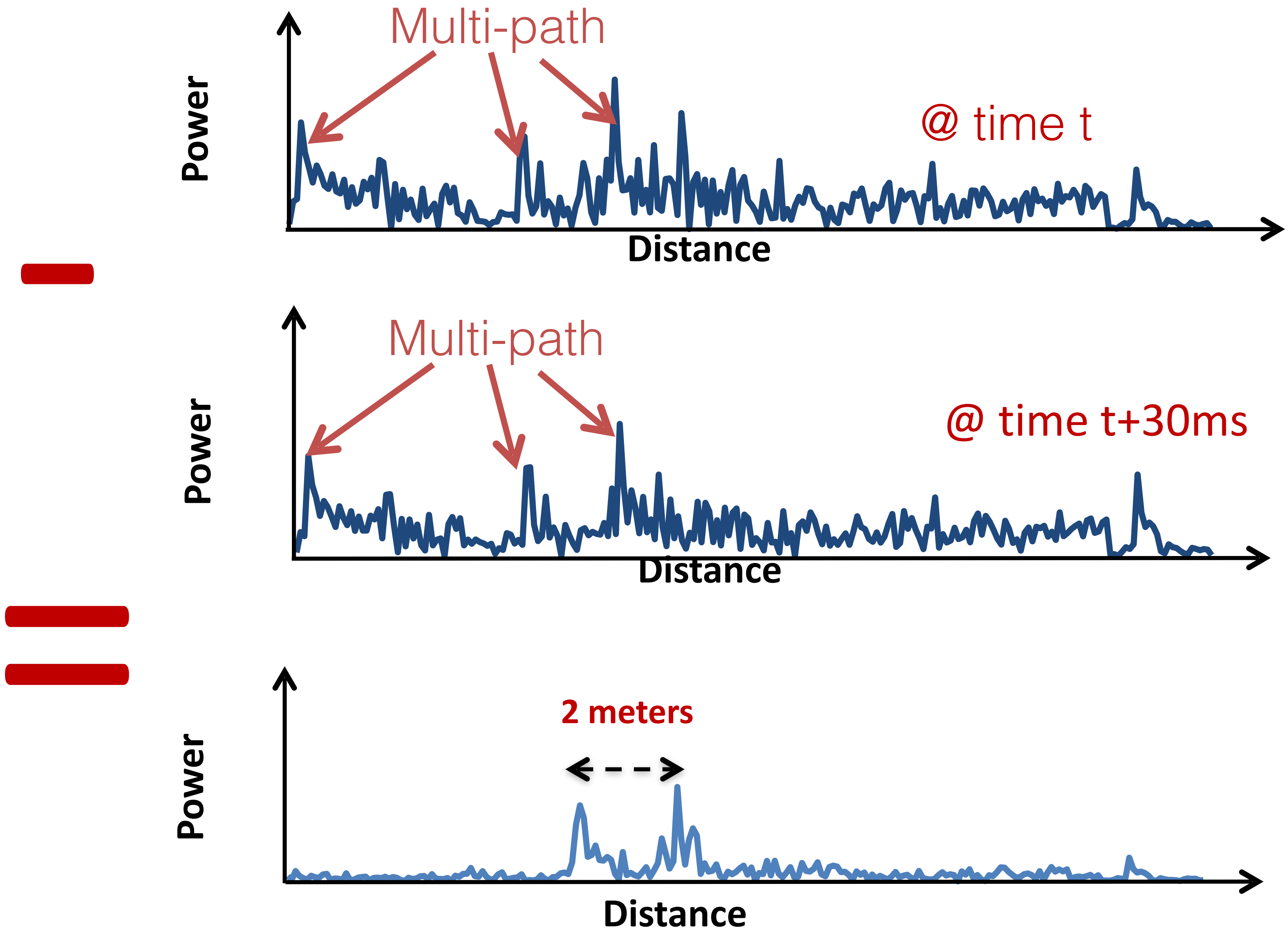
Static objects don't move
→ Eliminate by subtracting consecutive measurements



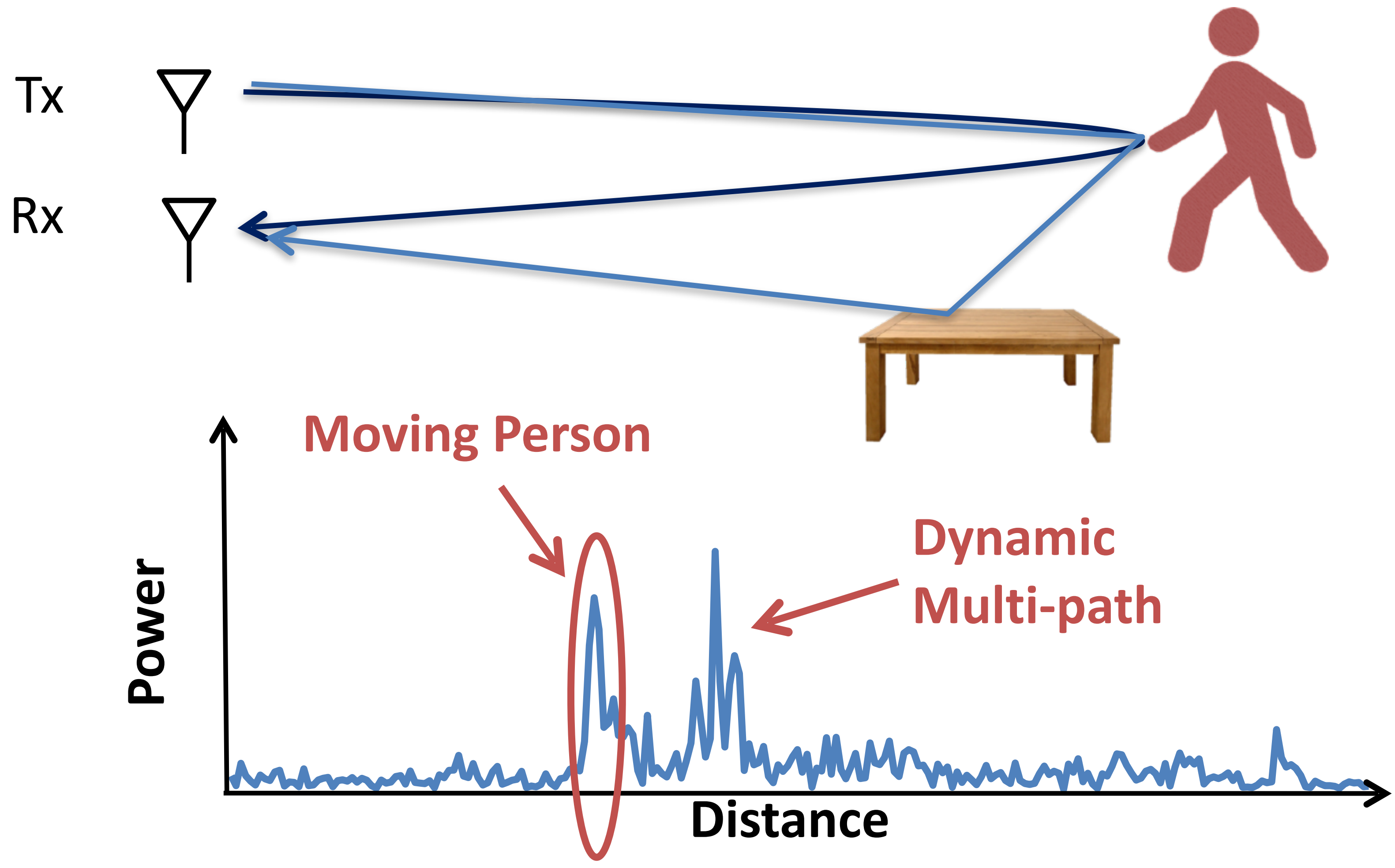
Why 2 peaks when we only have one moving person?



Static objects don't move
➔ Eliminate by subtracting consecutive measurements

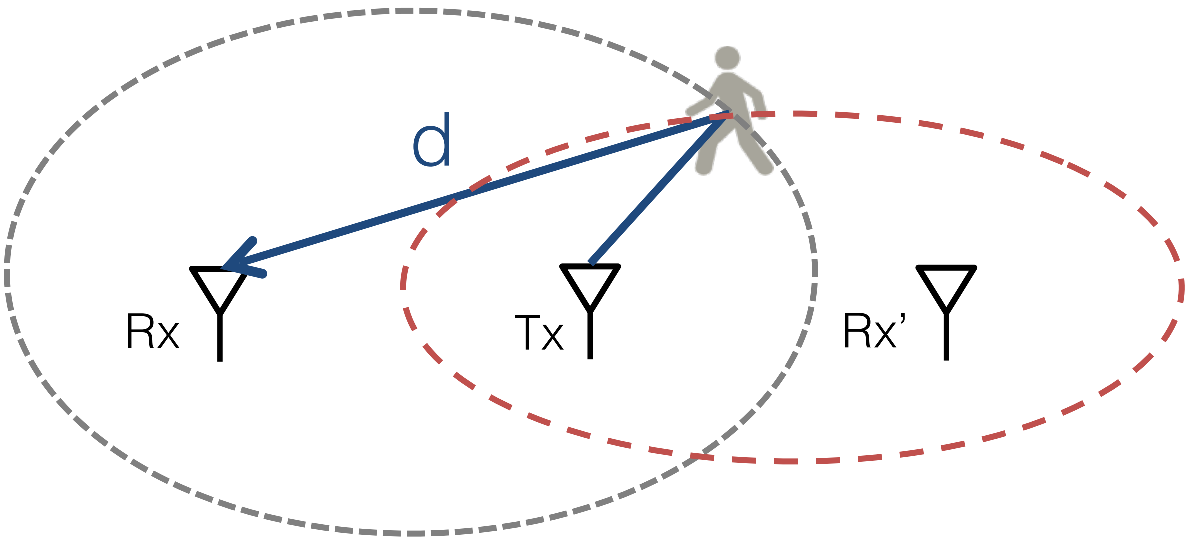


The direct reflection arrives before dynamic multipath!



Mapping Distance to Location

Person can be anywhere on an ellipse whose foci are (Tx,Rx)



By adding another antenna and intersecting the ellipses, we can localize the person

From Location to tracking (over time)

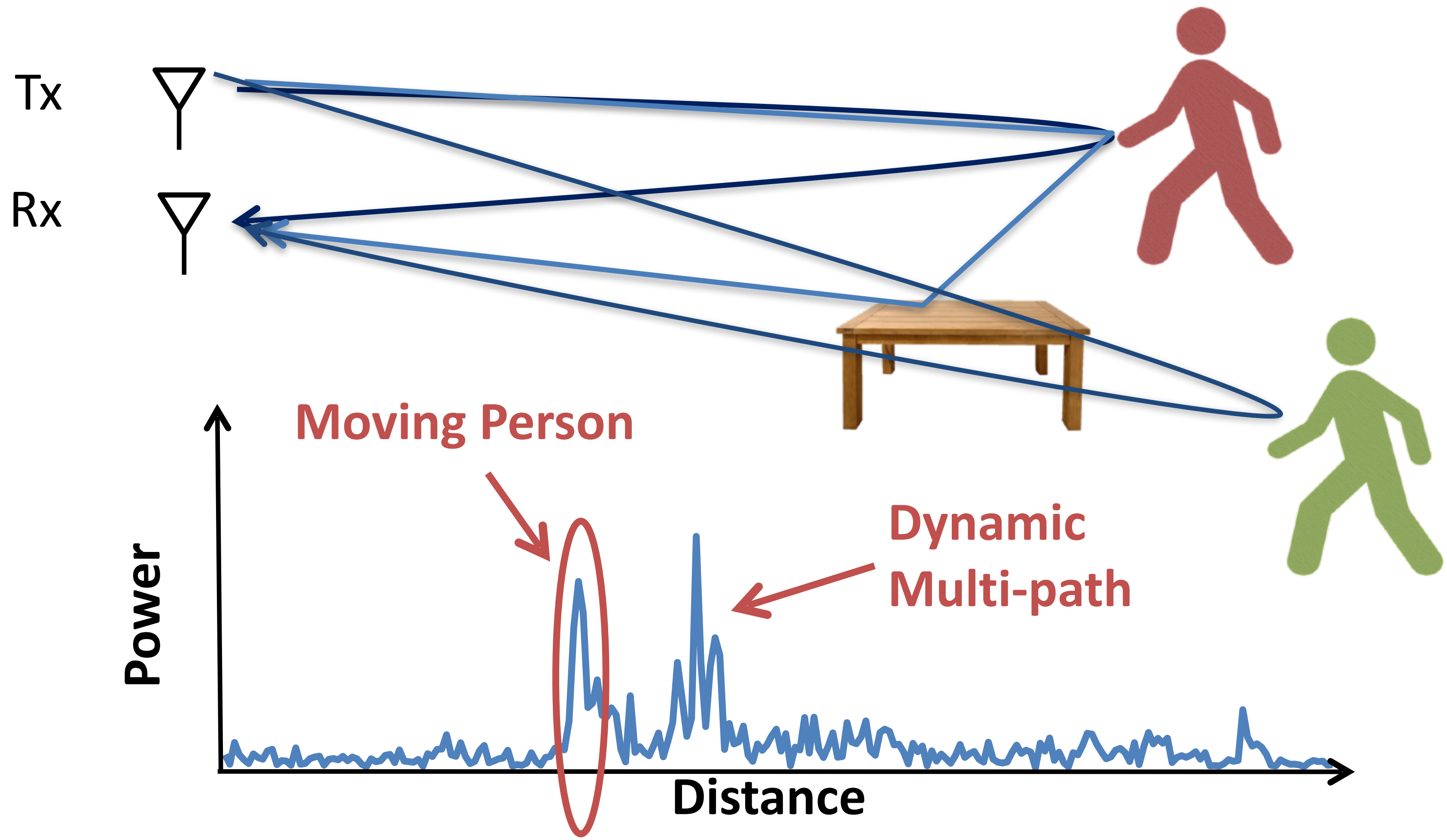
What are some challenges for WiTrack?

How would you overcome these challenges?

What are some challenges for WiTrack?

How would you overcome these challenges?

Fails for multiple people in the environment, and we need a more comprehensive solution



How can we deal with multi-path reflections when there are multiple persons in the environment?

How can we deal with multi-path reflections when there are multiple persons in the environment?

Discuss in groups of 3-5 student for 5 minutes

You will share your solution with the class

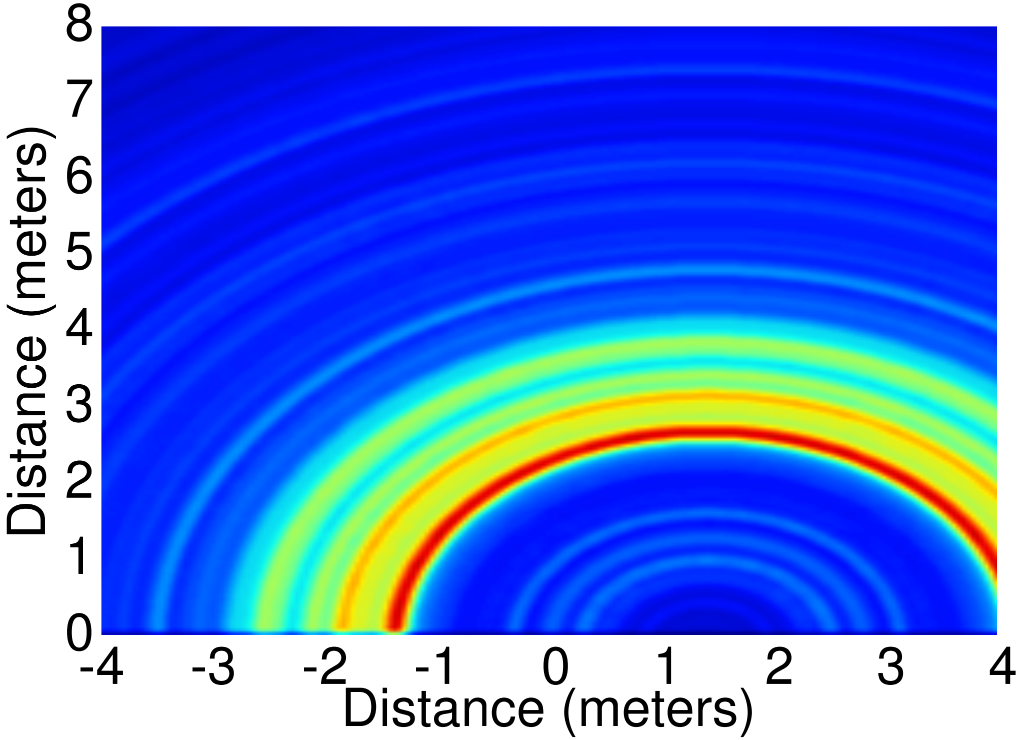
Idea: Person is consistent across different vantage points while multi-path is different from different vantage points

Combining across Multiple Vantage Points

Experiment: Two users walking

Setup

Single Vantage Point



Mathematically: each round-trip distance can be mapped to an ellipse whose foci are the transmitter and the receiver

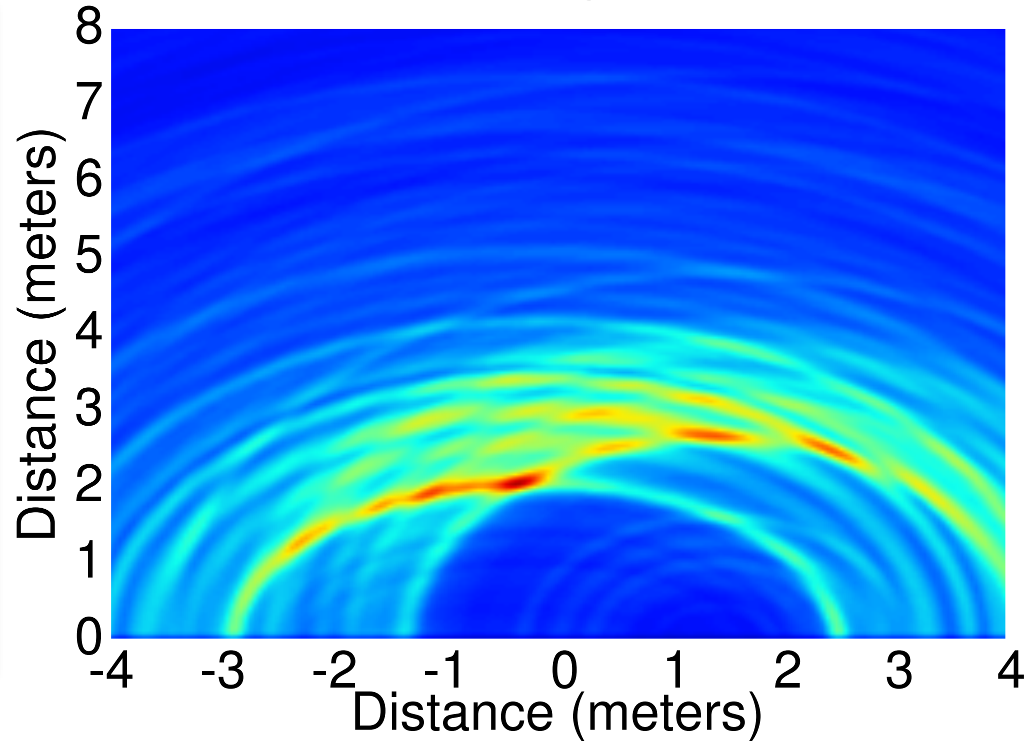
Mapping 1D to 2D heatmap

Combining across Multiple Vantage Points

Experiment: Two users walking

Setup

Two Vantage Points

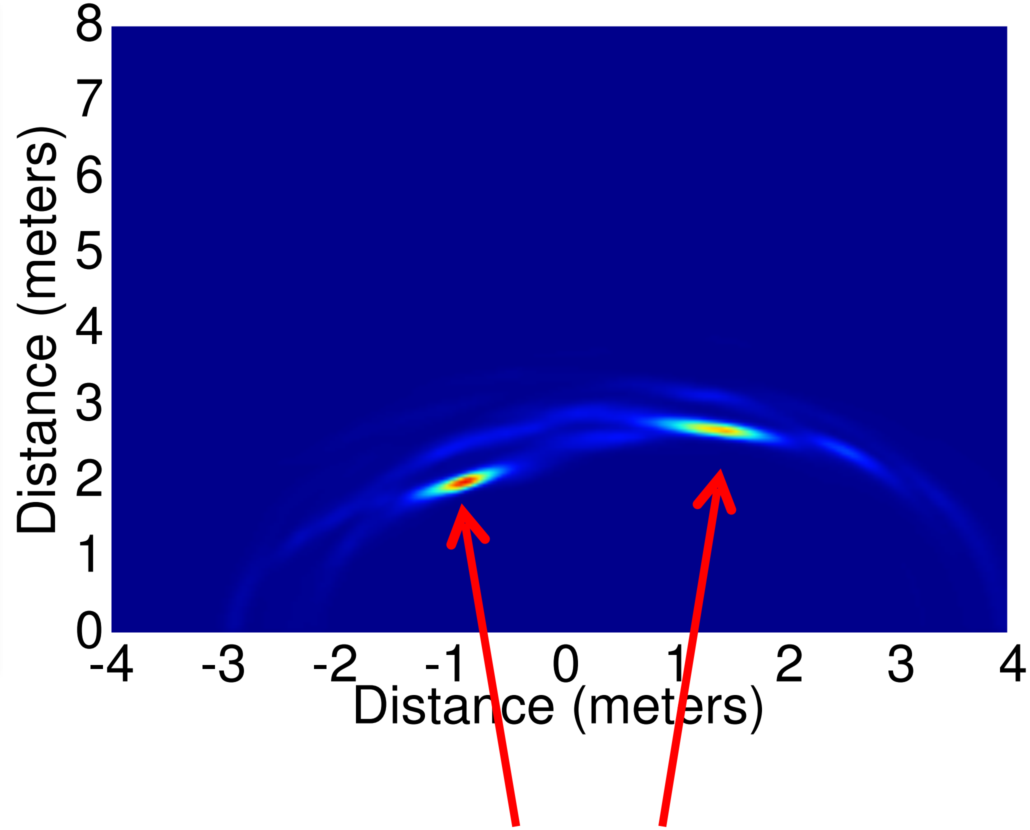


Combining across Multiple Vantage Points

<u>Experiment:</u> Two users walking

Setup

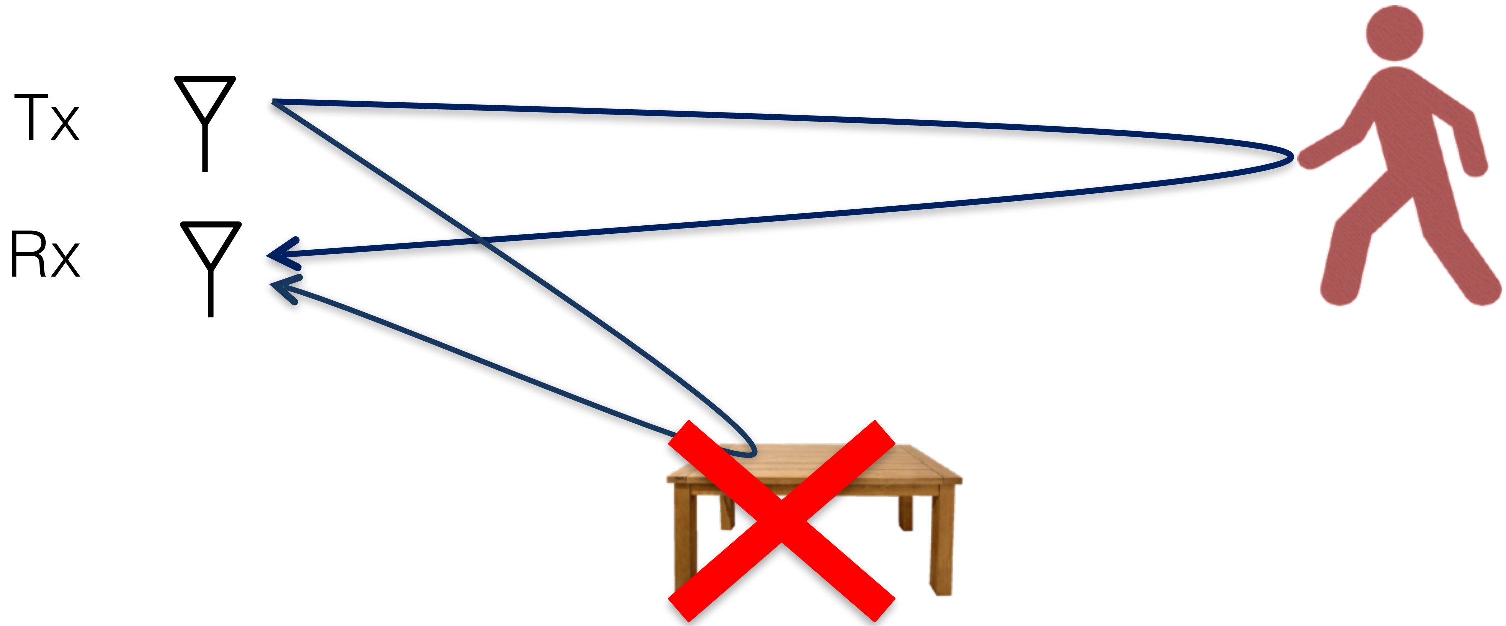
16 Vantage Points



Localize the two users

How can we localize static users?

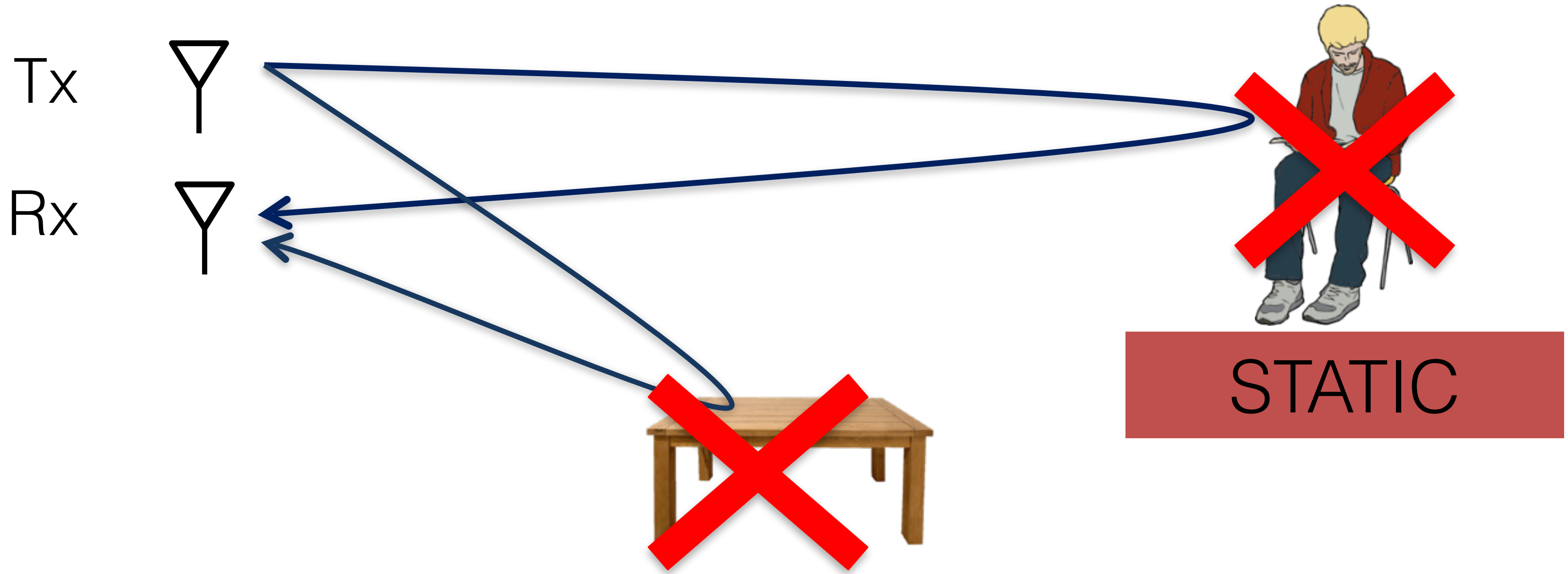
Dealing with multi-path when there is one moving user



We eliminated direct table reflections by subtracting consecutive measurements

Needs User to Move

Dealing with multi-path when there is one moving user



We eliminated direct table reflections by subtracting consecutive measurements

Needs User to Move

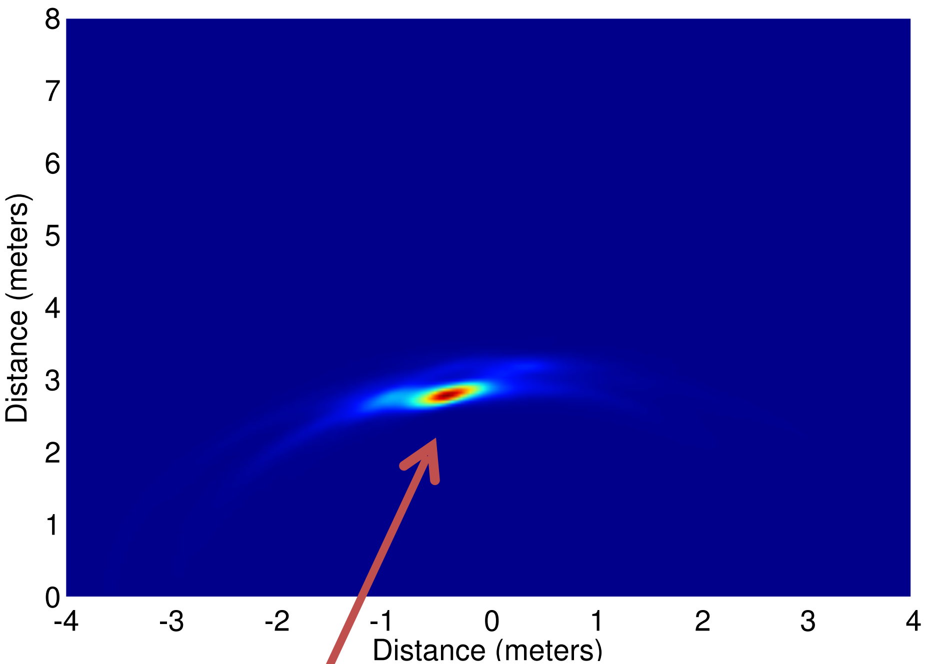
Exploit breathing motion for localize static users

- Breathing and walking happen at different time scales
  - A user that is pacing moves at 1m/s
  - When you breathe, chest moves by few mm/s

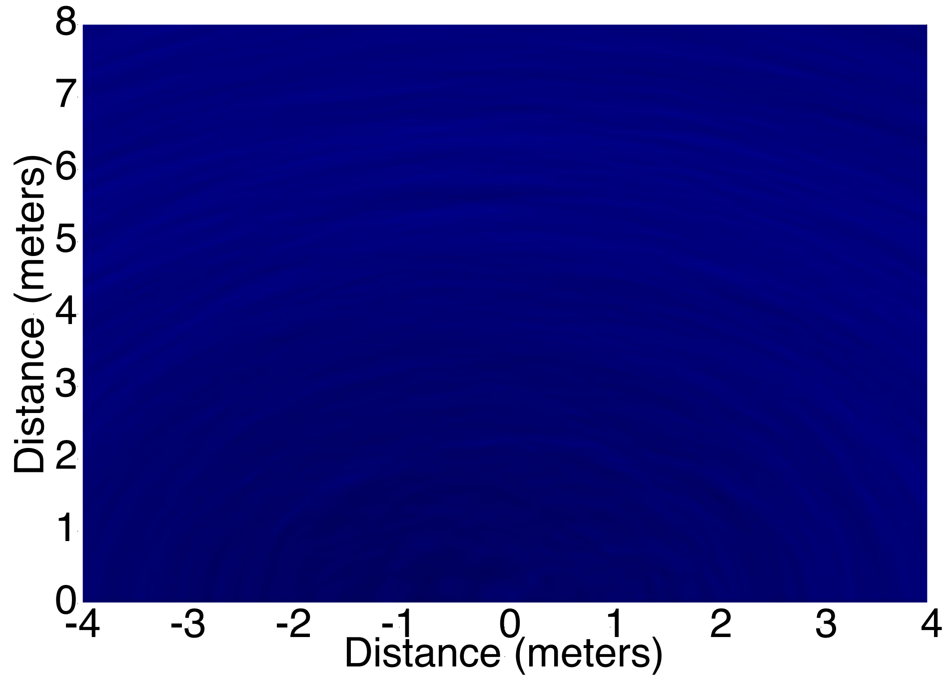
- Cannot use the same subtraction window to eliminate multi-path

30ms subtraction window

User walking @ 1m/s



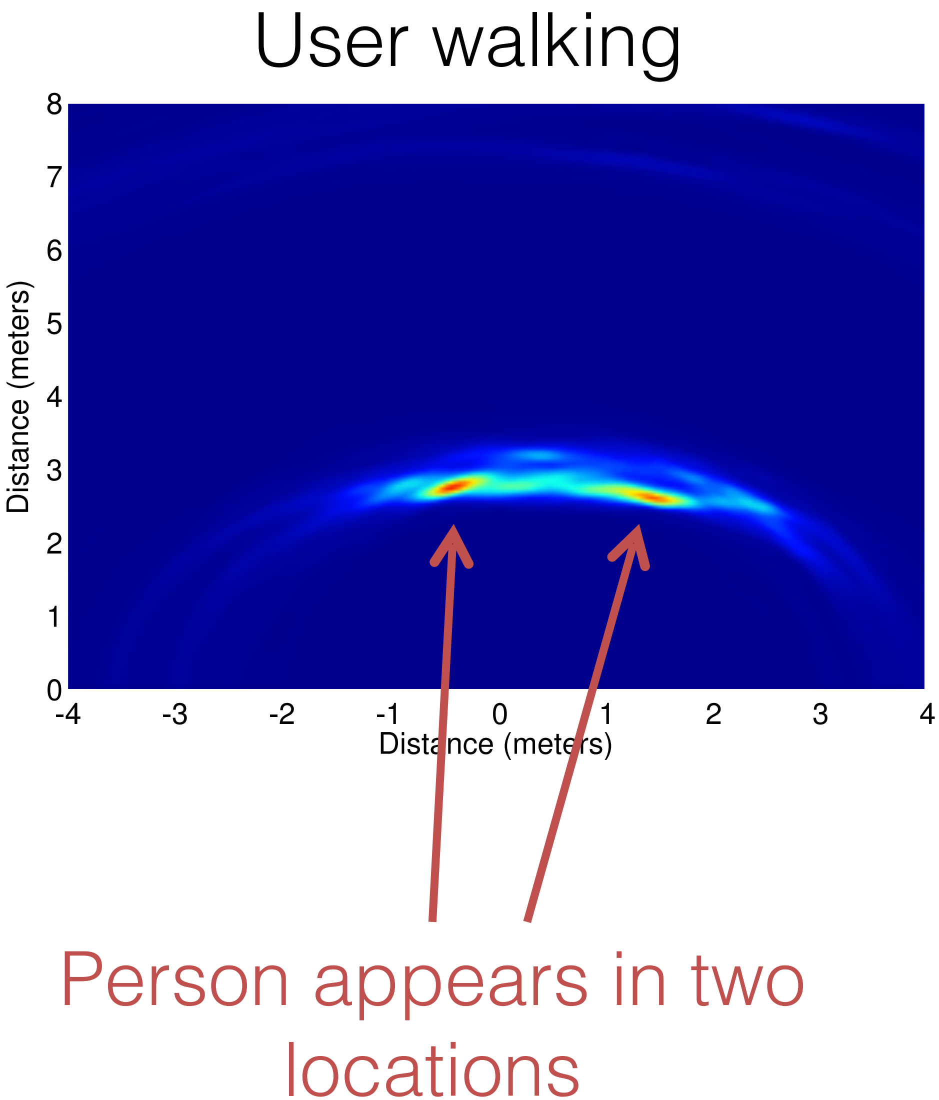
User Still (Breathing)

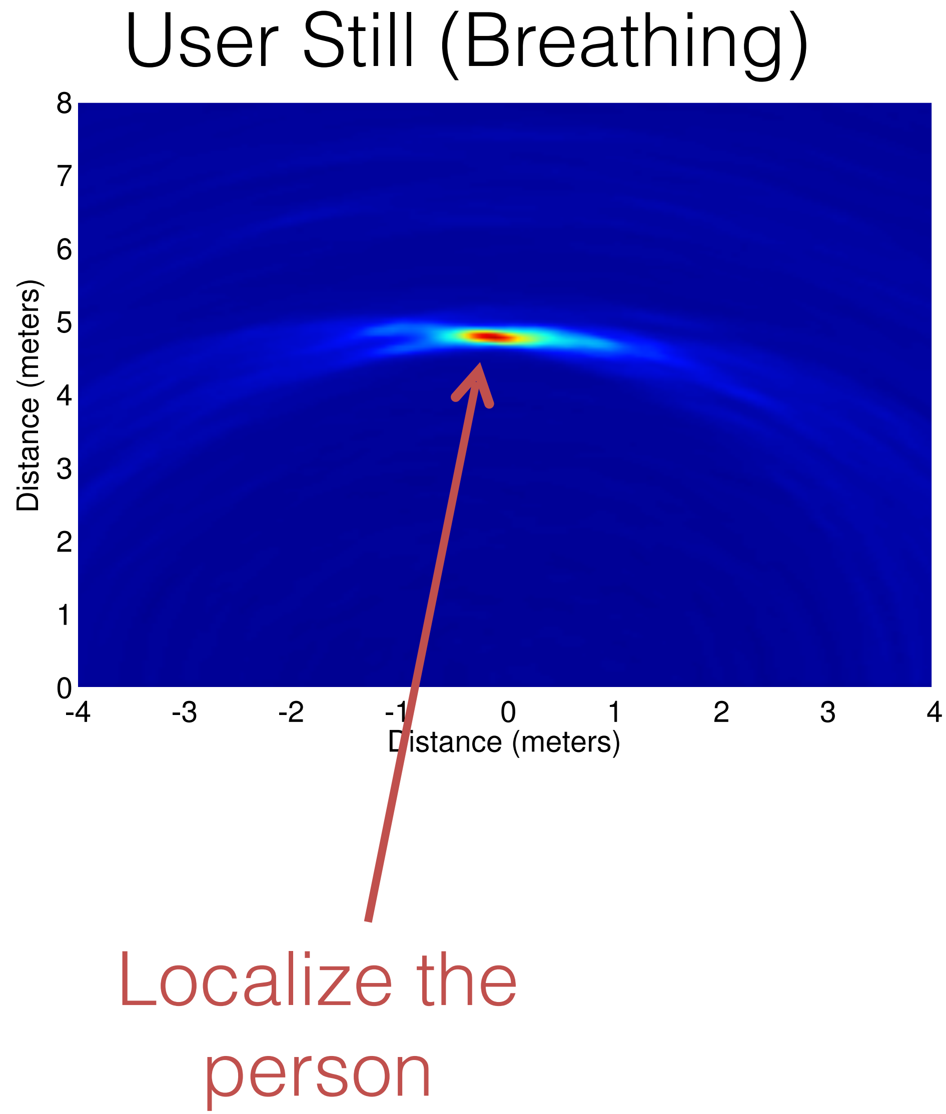


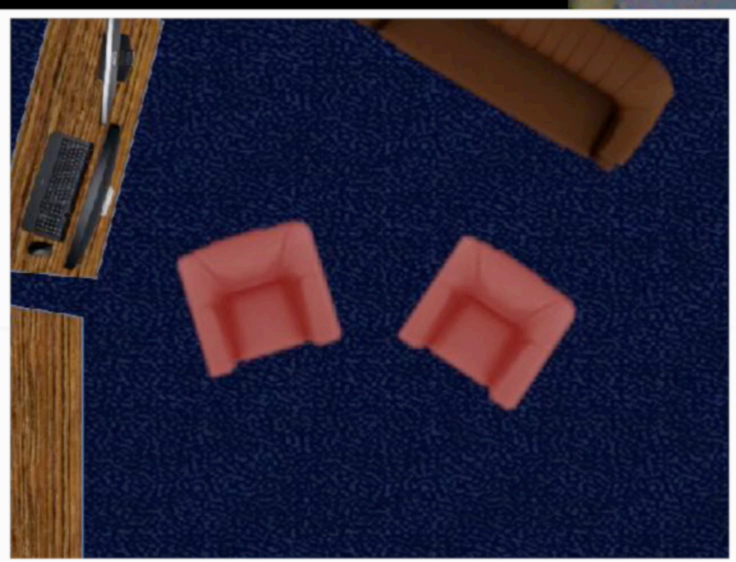
Cannot localize

Localize the person

3s subtraction window







Where is Wireless Sensing today?

1. **Research-wise:**
    - Sensitivity: close to ECG in measuring micro-cardiac events (2020)
    - Reconstruction: can recover 3D human skeleton + meshes (2020)
    - Can monitor new affective metrics: stress levels (2021)
    - Technologies: WiFi, millimeter wave, etc.
2. **Real-world Uses:**
    - Multiple startups in the space
    - Medical use in monitoring 1,000s of patients with Alzheimer's, Parkinson's, COVID-19, Multiple Sclerosis, etc.
    - Influenced the design of sensors like Google Soli and others
3. **Standards:**
    - WiFi standard (802.11bf)
    - Planning for 6G

Objectives of this Lecture

Learn the fundamentals, applications, and implications of **wireless sensing**

1. What is Frequency-modulated continuous-wave? ✓
2. How can we obtain centimeter-scale localization from wireless reflections? ✓
3. What are static and dynamic multi-path? How do they affect wireless sensing? how can we deal with them? ✓

TODO:

1- Lab 0 checkoff this week

2- Survey

3- Lab 1 due on Feb 20

4- PSet 1 due March 6

Start thinking about your projects