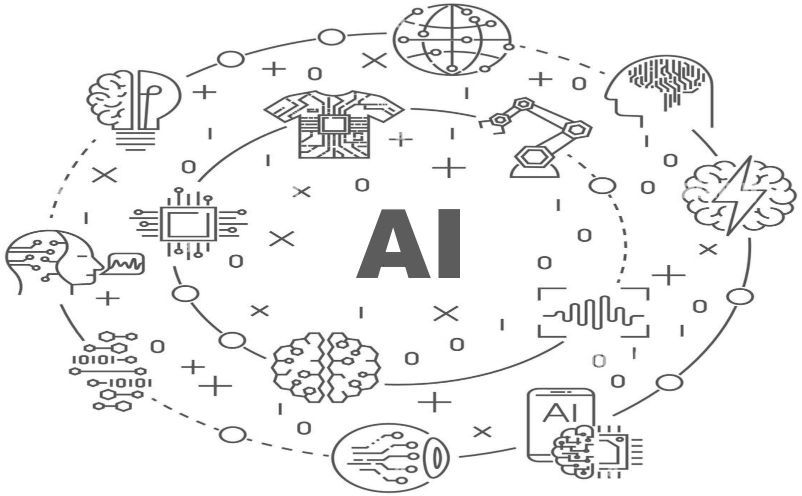
CIS 7000-008: Special Topics on Wireless and Mobile Sensing

Mingmin Zhao (mingminz@cis.upenn.edu)

Lecture 3

Wireless Localization: RFID



Penn
UNIVERSITY of PENNSYLVANIA

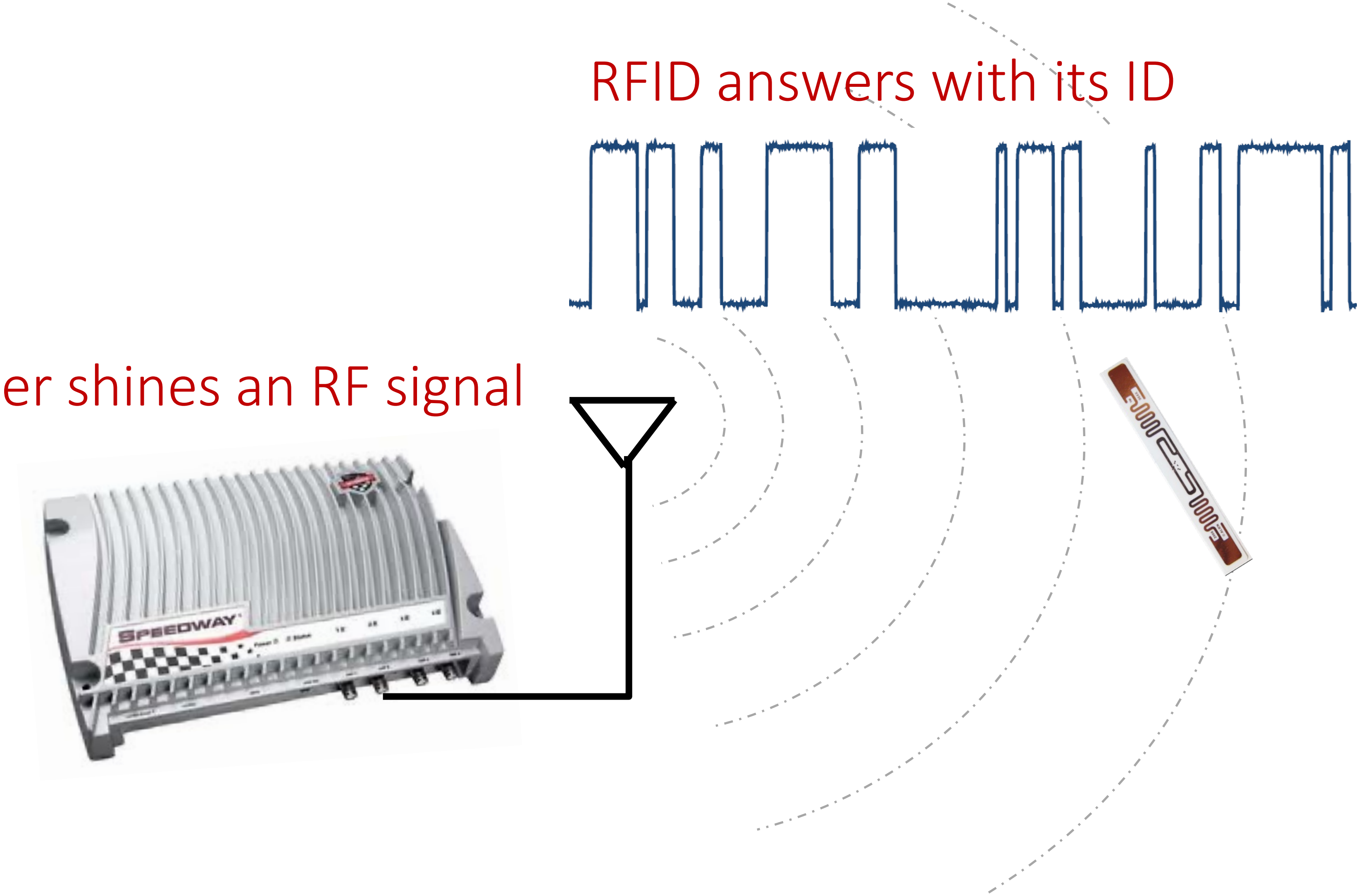
*Some of the slides in this lecture are courtesy of Jue Wang, Deepak Vasisht, Yunfei Ma & Haitham Hassanieh

Wireless Localization / Positioning

Last Lecture: WiFi	This Lecture: RFID
Method 1: Identity **Method 2: RSSI** (Trilateration, Fingerprinting) **Method 3: Phase** (Angle of Arrival, Triangulation) **Method 4: AoA** (Angle of Arrival, Triangulation) **Method 5: ToF** (Time of Flight) **Method 6: TDoA** (Time Difference of Arrival)	Ultra-low power localization! **System 1: PinIt** **Method:** Multipath Profile with SAR & DTW **System 2: RFIDraw** **Method:** Multi-Resolution Arrays **System 3: RFind** **Method:** Bandwidth Stitching

RFID: Radio Frequency IDentification

Battery-free RF stickers with unique IDs

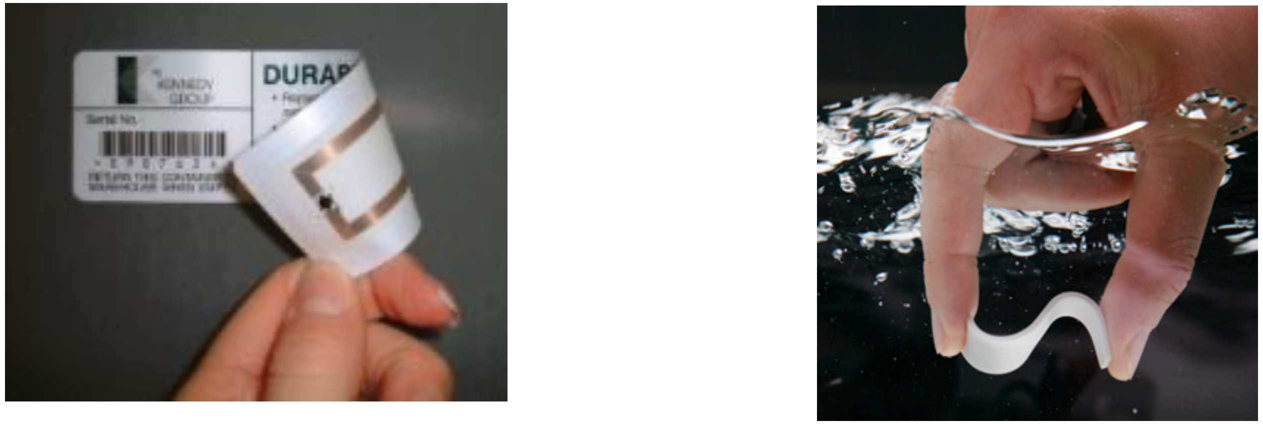


RFID answers with its ID

Reader shines an RF signal

RFID: Radio Frequency IDentification

Imagine you can localize RFIDs to within 10 to 15 cm!



5-cent stickers to tag any and every object

Reader’s range is ~15m

If we can locate RFID to within 10 to 15cm

No more customer checkout lines

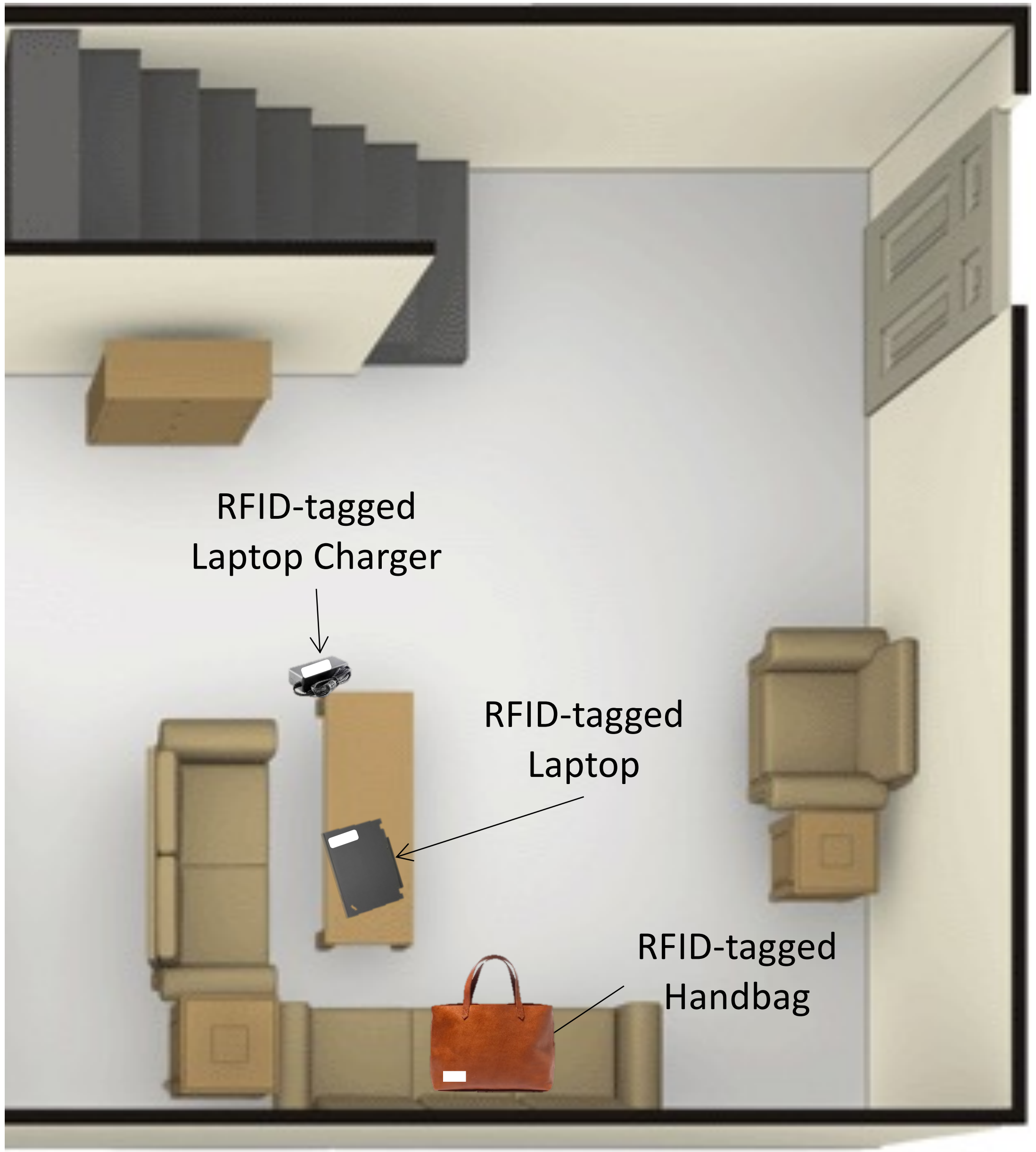
If we can locate RFID to within 10 to 15cm

No more customer checkout lines

RFIDs on Basket

If we can locate RFID to within 10 to 15cm

Smart Homes and Smart Objects



If we can locate RFID to within 10 to 15cm

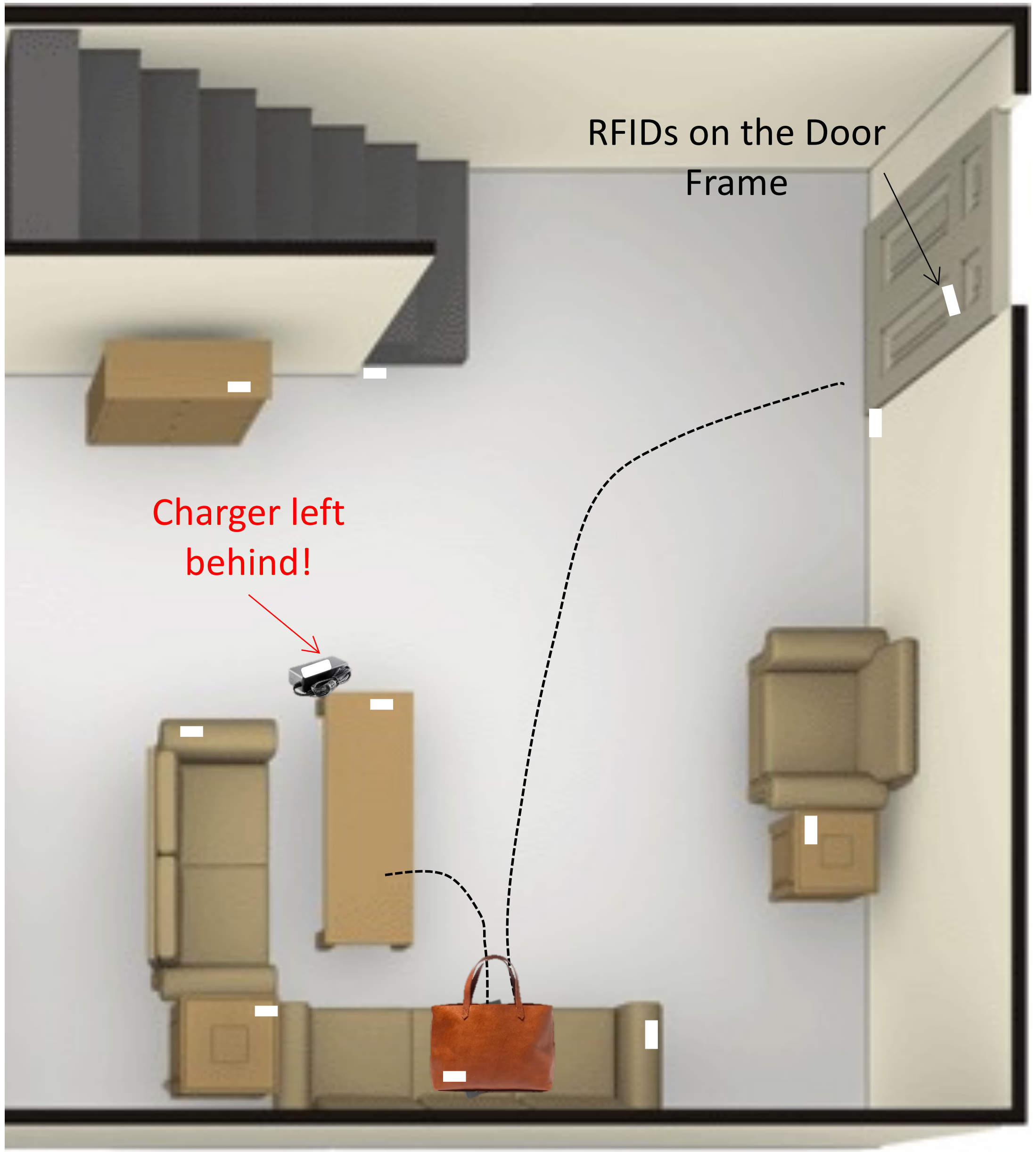
Smart Homes and Smart Objects

If we can locate RFID to within 10 to 15cm

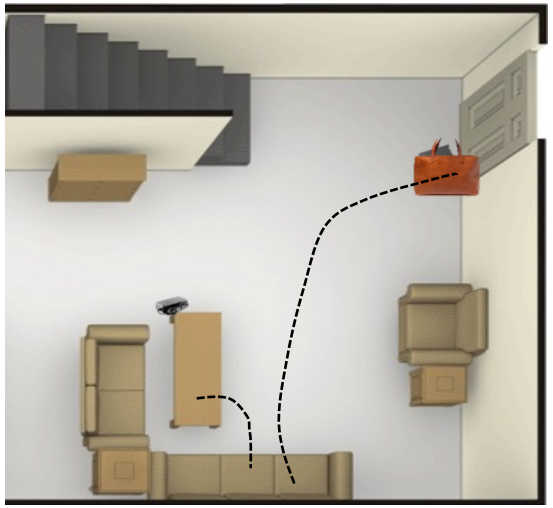
Smart Homes and Smart Objects

If we can locate RFID to within 10 to 15cm

Smart Homes and Smart Objects



Many applications can be enabled by 10-15 cm RFID localization



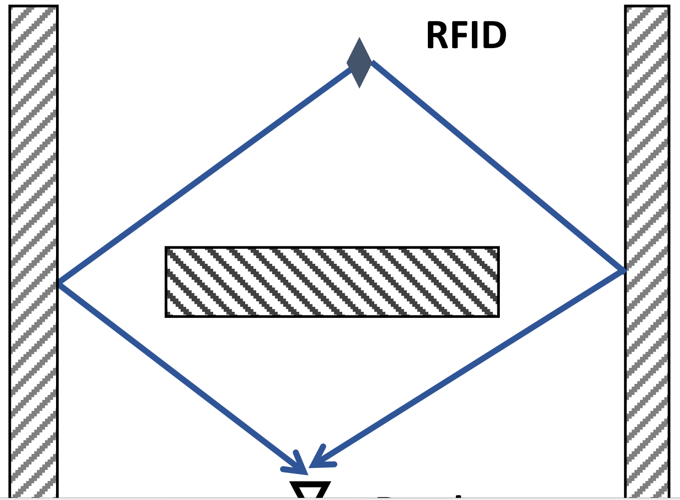
Why don’t we have accurate RFID localization?

Technologies in 2023

The Challenge: Multipath Effect

Localization uses **RSSI** or **Angle-of-Arrival (AoA)**

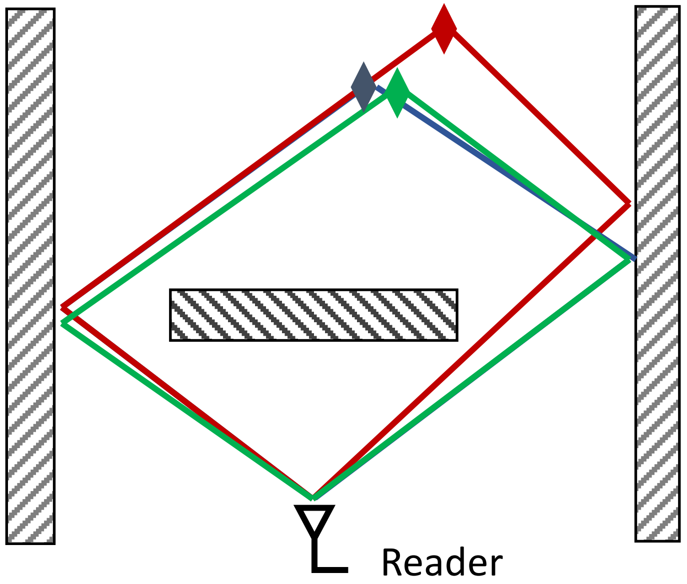
But, signal bounces off objects in the environment



Multipath propagation limits the accuracy of RFID localizations

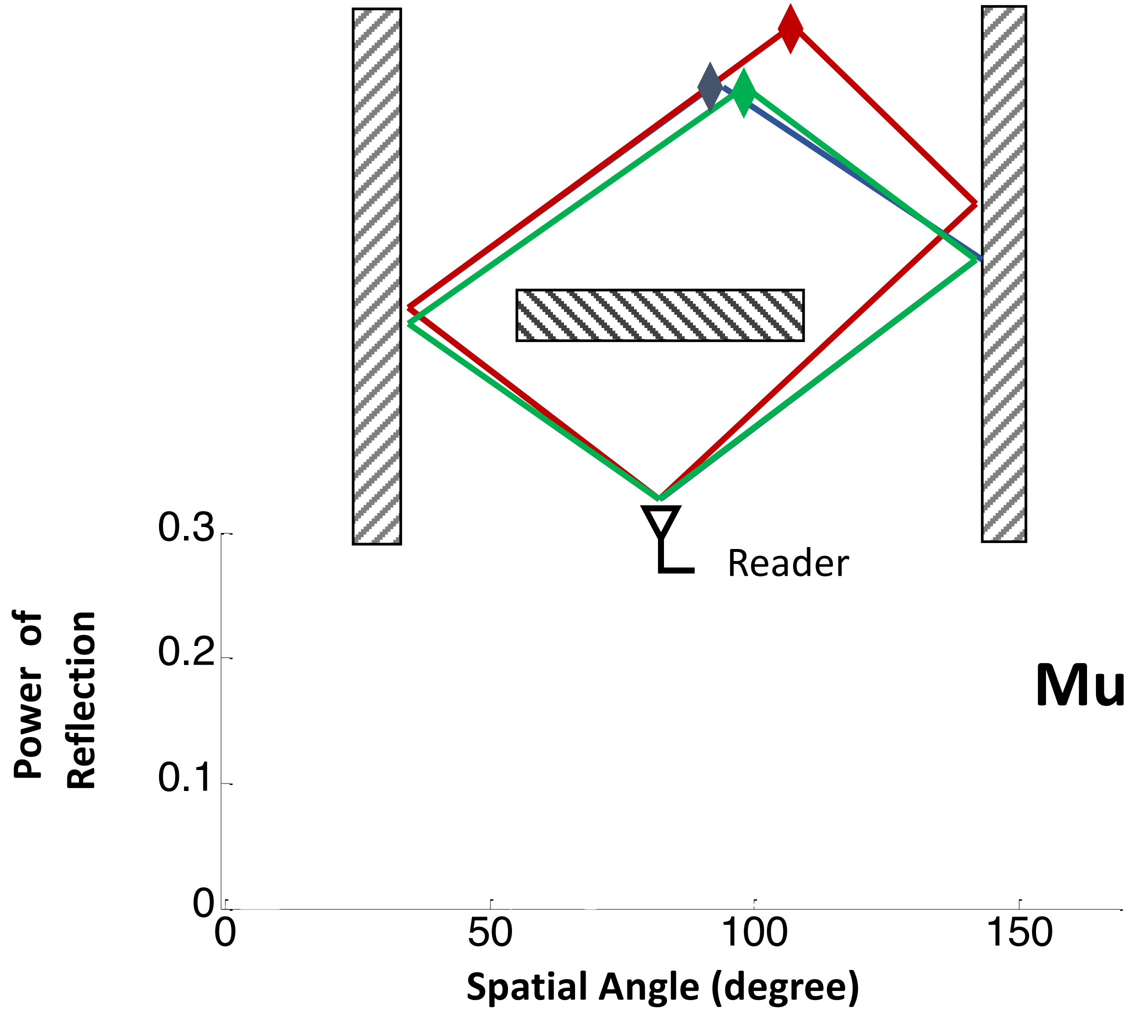
PinIt Exploits Multipath

Signals from nearby RFIDs propagate along closer paths and experience similar reflections



PinIt Exploits Multipath

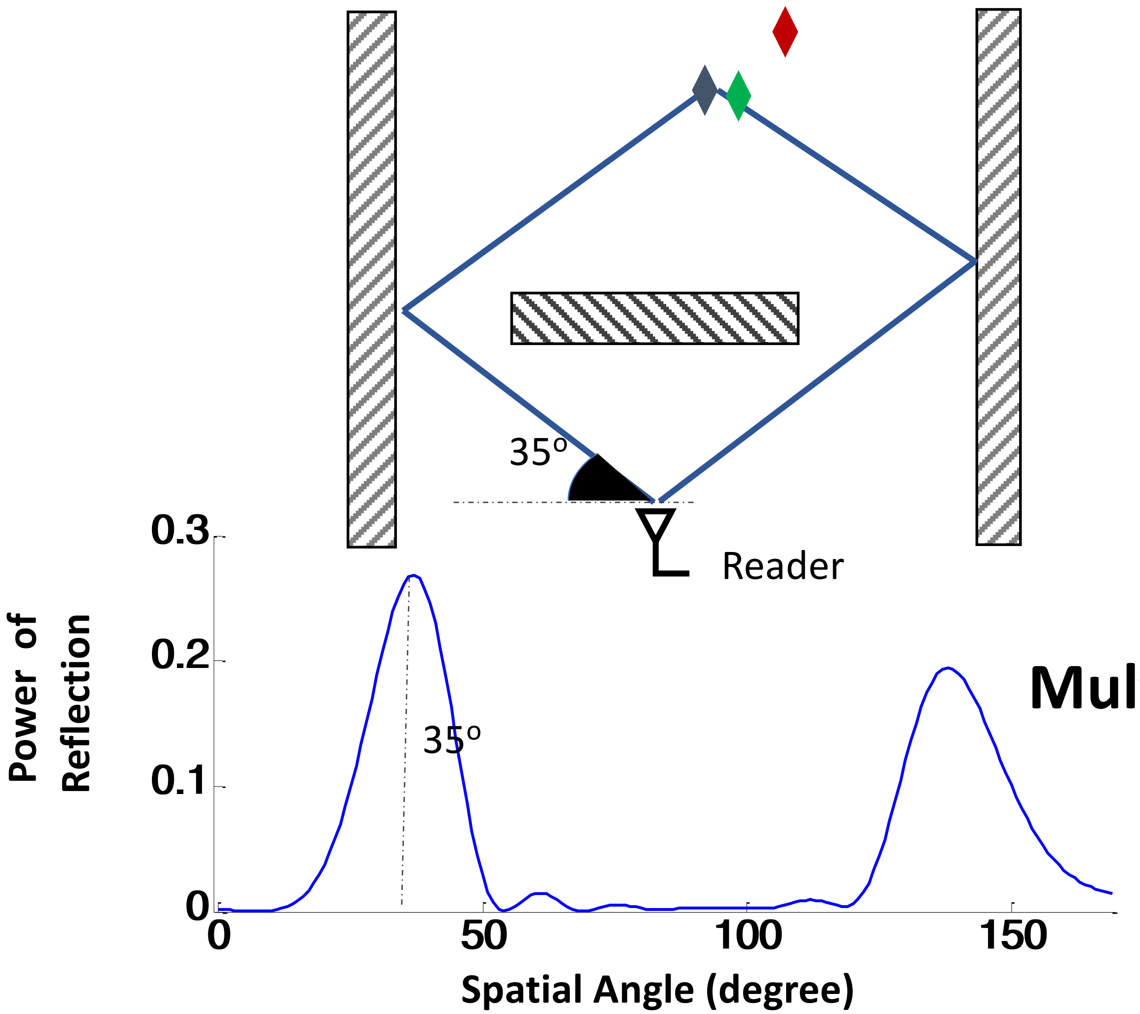
Signals from nearby RFIDs propagate along closer paths and experience similar reflections



Multipath Profiles

PinIt Exploits Multipath

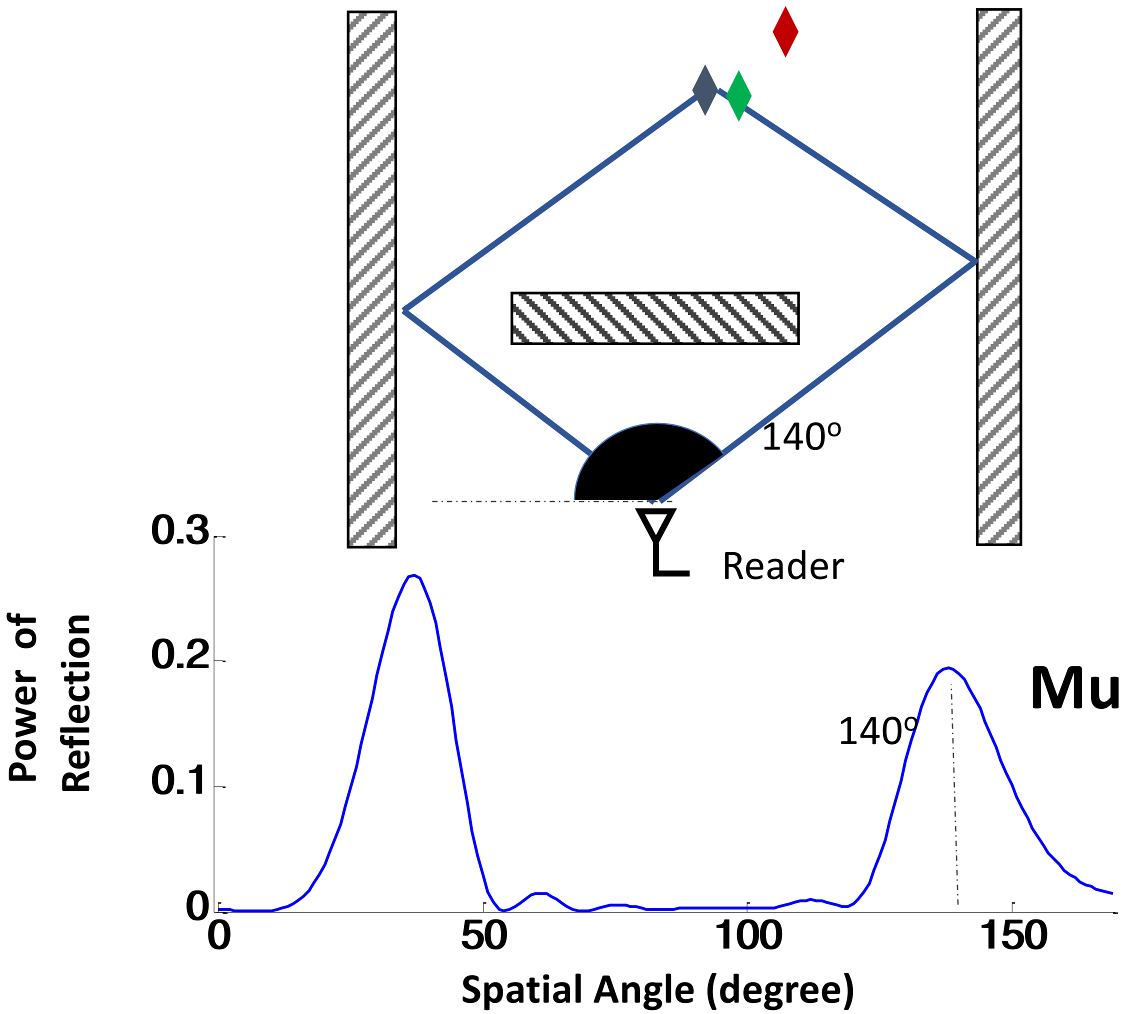
Signals from nearby RFIDs propagate along closer paths and experience similar reflections



Multipath Profiles

PinIt Exploits Multipath

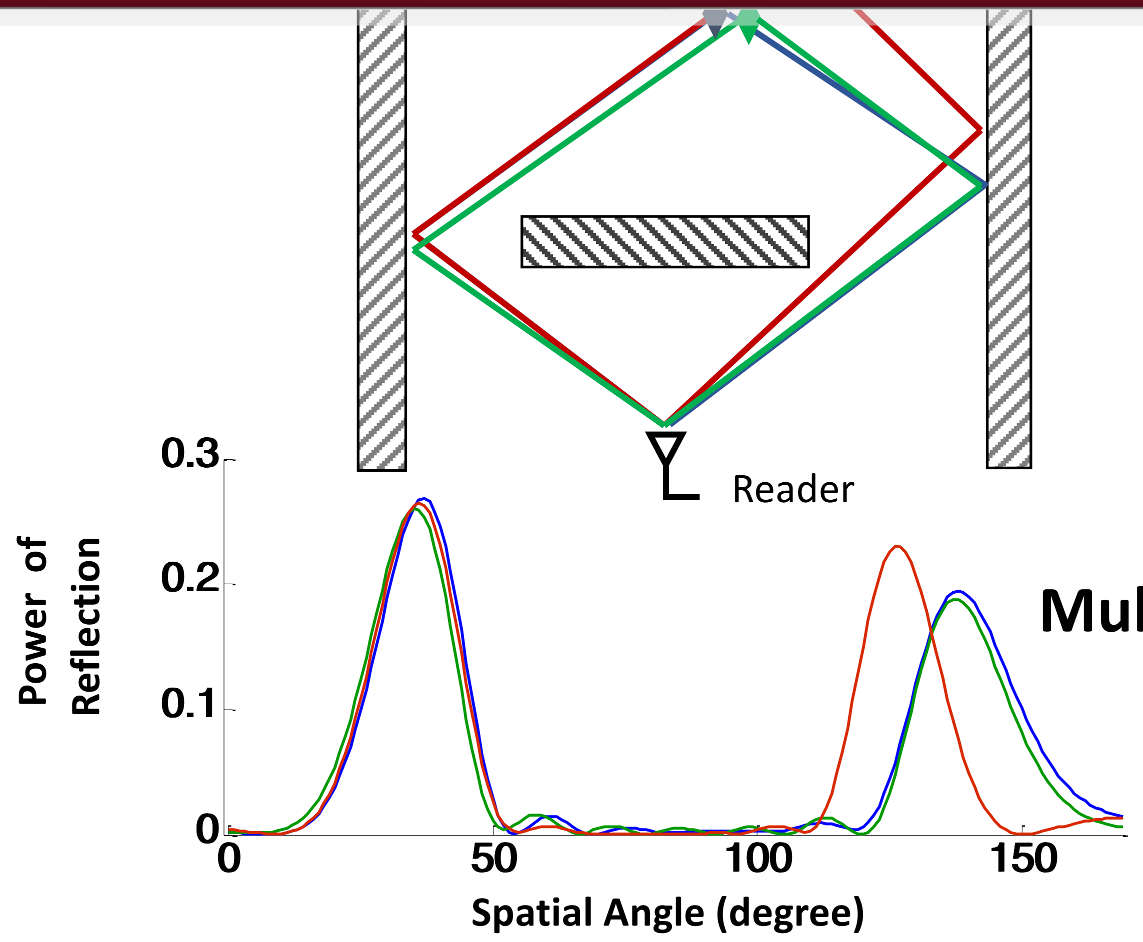
Signals from nearby RFIDs propagate along closer paths and experience similar reflections



Multipath Profiles

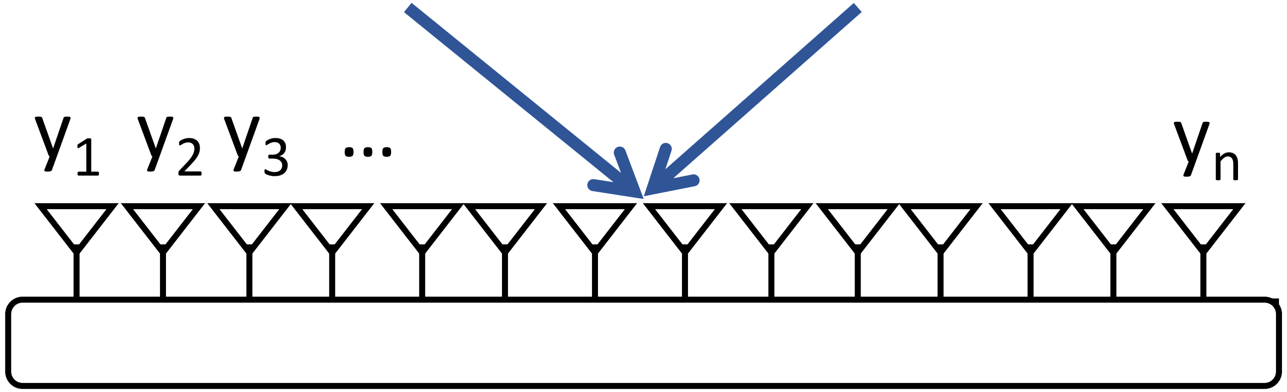
PinIt Exploits Multipath

Nearby RFIDs have similar profiles with smaller shifts in the peaks

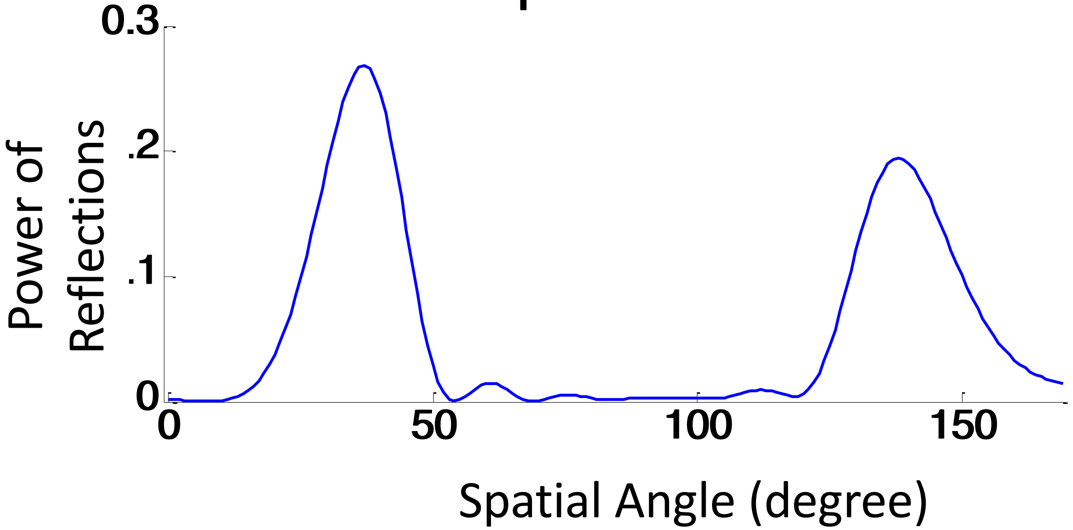


Multipath Profiles

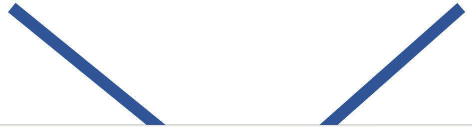
Capturing Multipath Profiles with an Antenna Array



Last lecture we showed how to obtain the multipath profile



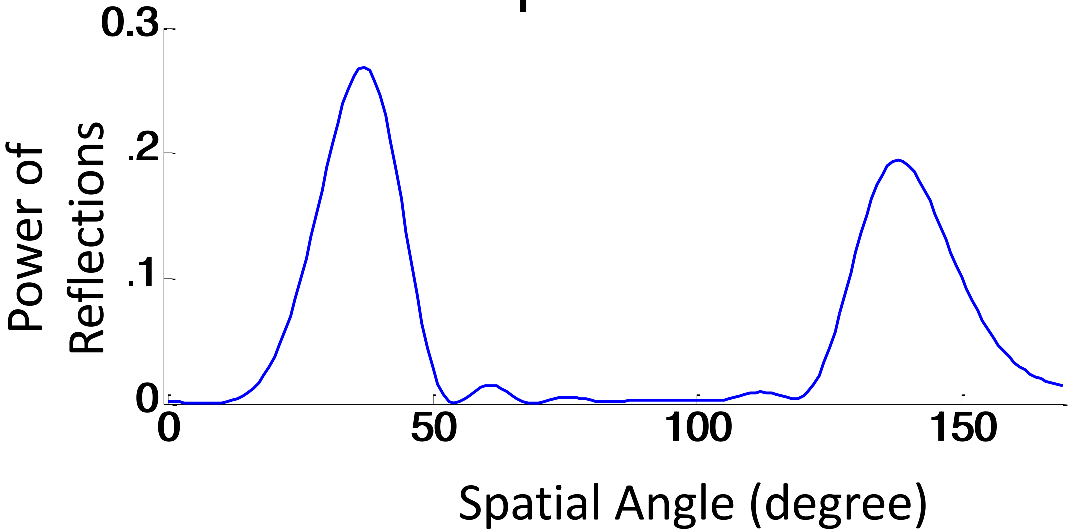
Capturing Multipath Profiles with an Antenna Array



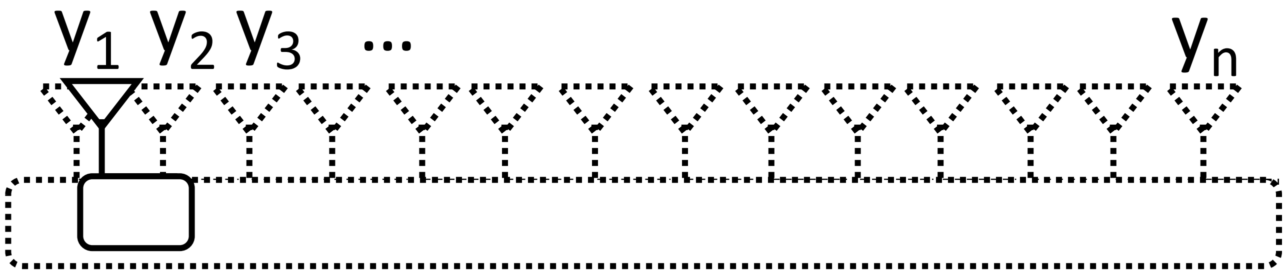
Accurate multipath profiles require many antennas in the array

→ Array is bulky and expensive

profile



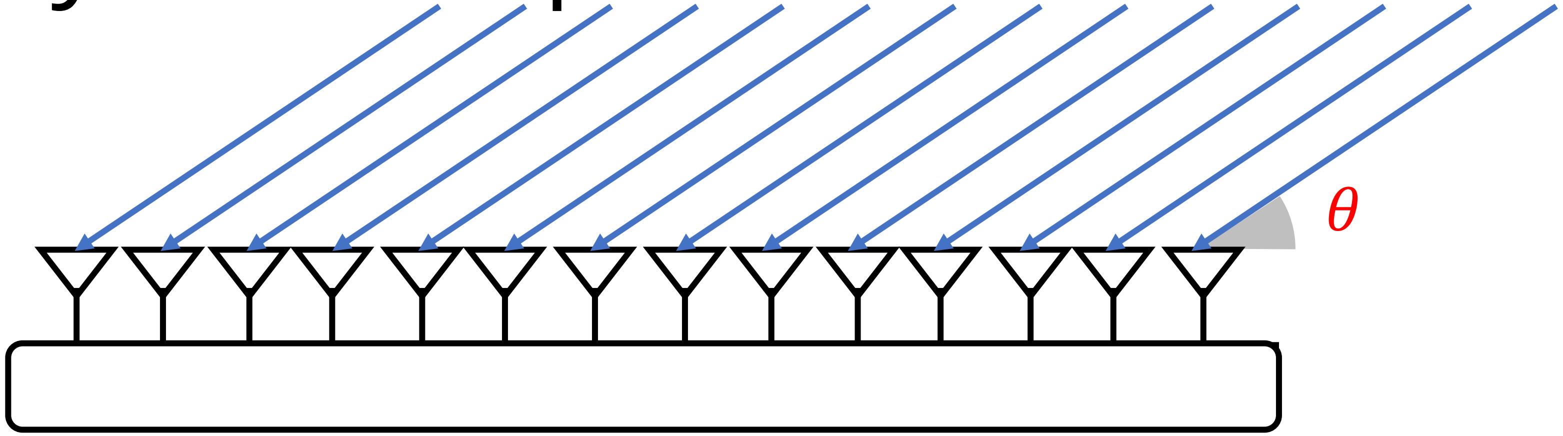
Capturing Multipath with a Sliding Antenna



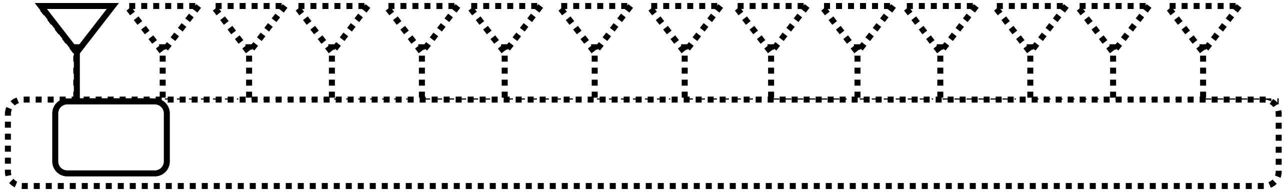
SAR: Synthetic Aperture Radar

Can capture very accurate multipath profiles with a single sliding antenna

Synthetic Aperture Radar



$$h_k = \alpha e^{-j2\pi \frac{d - k\ s \cos\theta}{\lambda}}$$



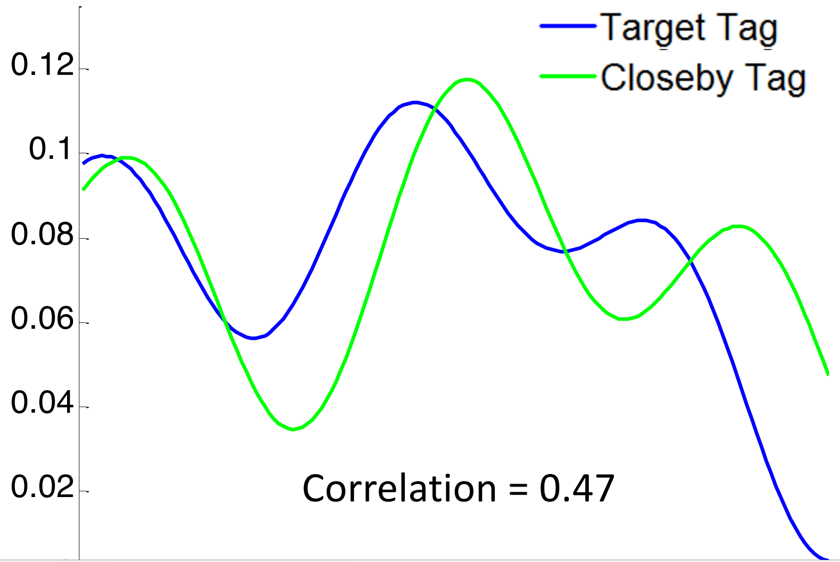
$$h_t = \alpha e^{-j2\pi \frac{d - vt \cos\theta}{\lambda}}$$

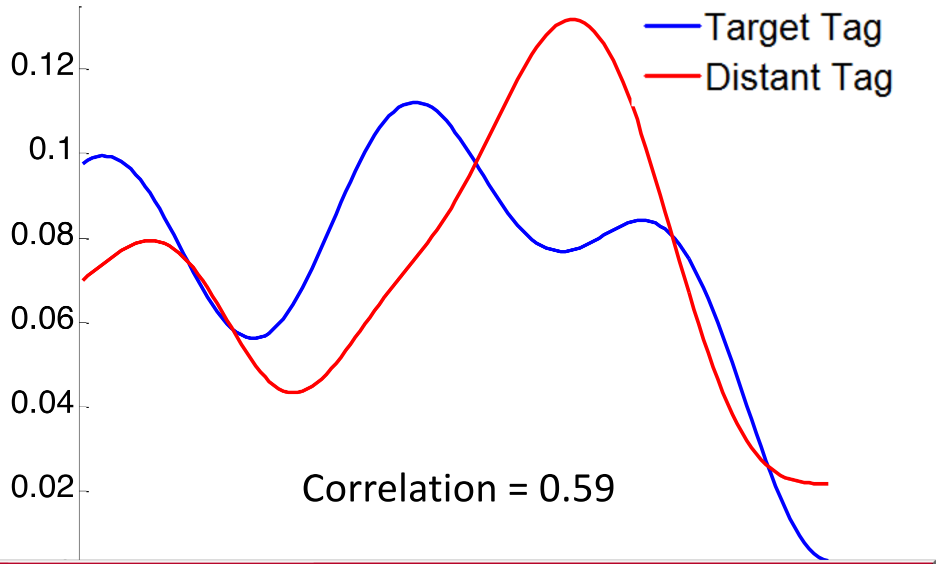
$\frac{v \cos\theta}{\lambda}$: *Doppler Shift*

SAR emulates a very large antenna array with single moving antenna.

How do we detect proximity from multipath profiles?

Naïve approach: correlate profiles!



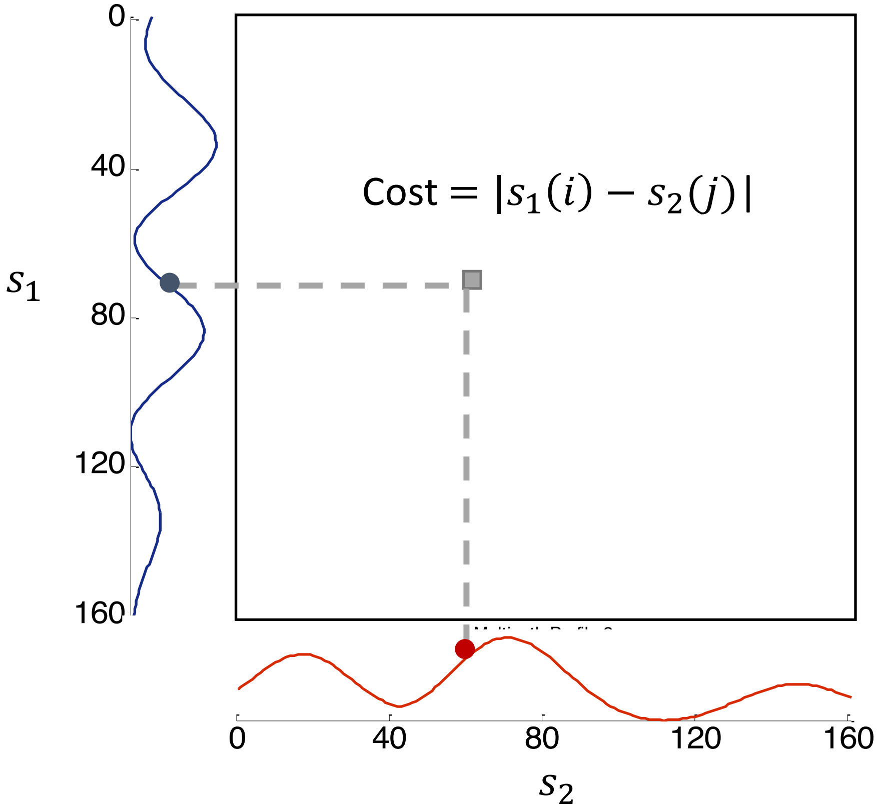


Correlation cannot capture peak shifts

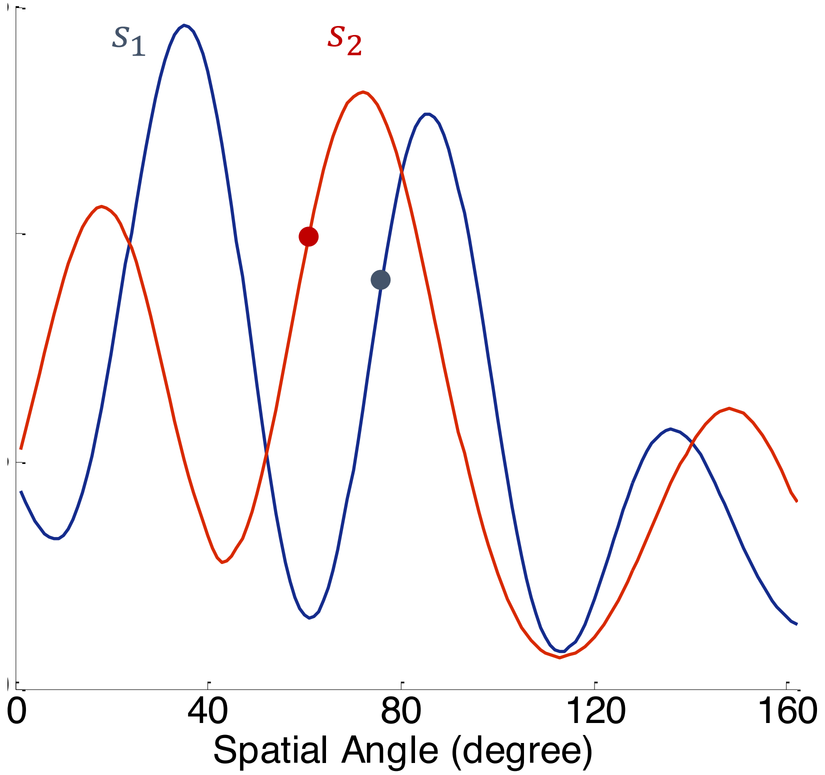
Dynamic Time Warping (DTW)

Dynamic Time Warping (DTW)

Computes the total warping to obtain s_1 from s_2

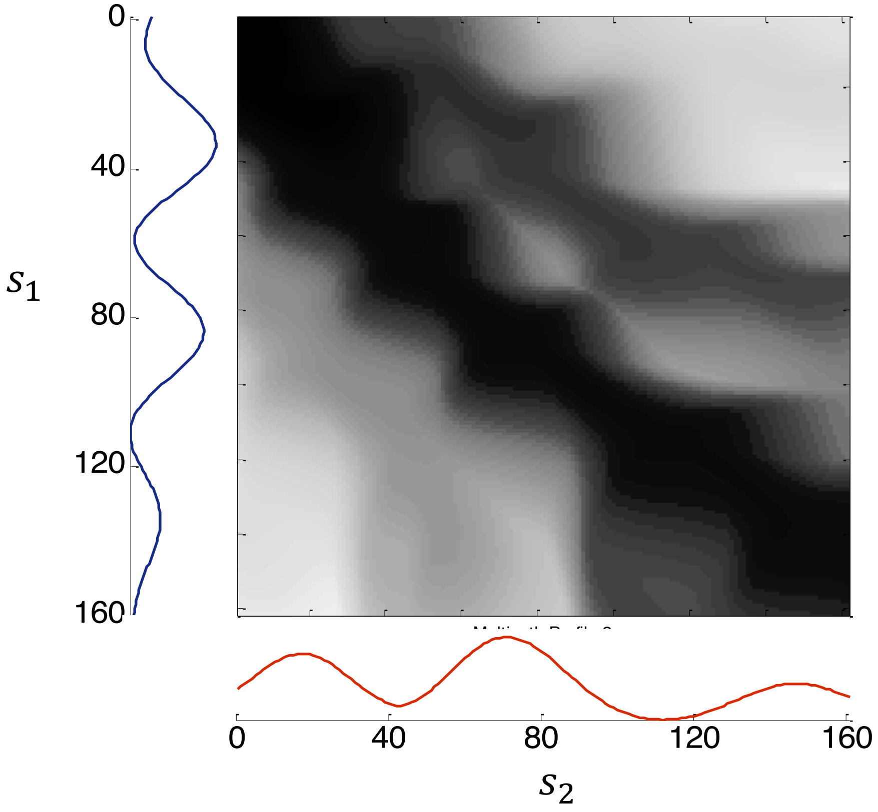


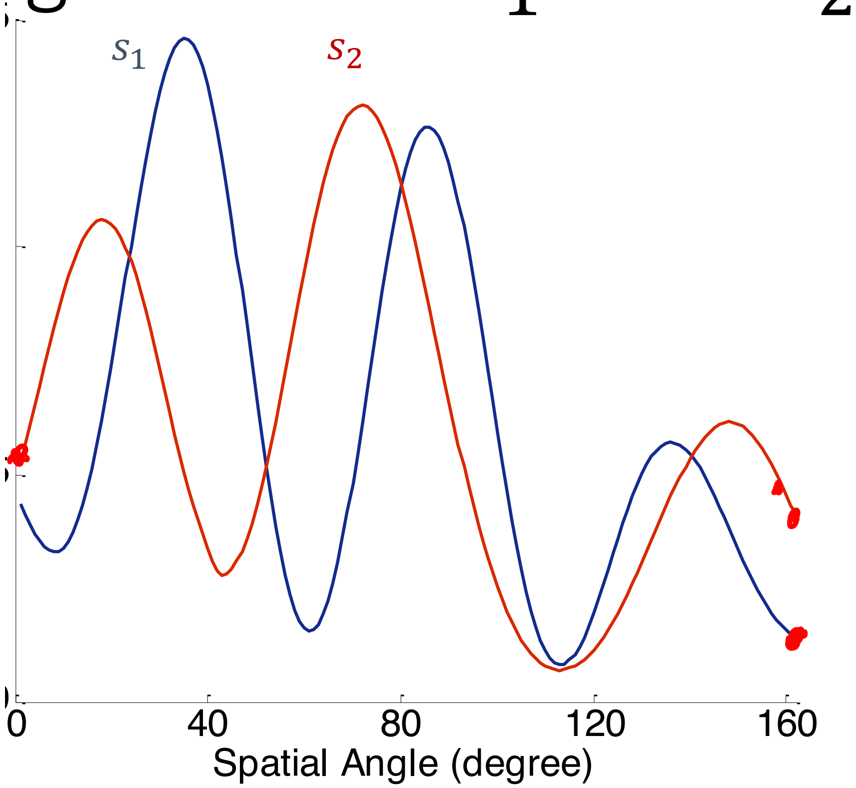
$\text{Cost} = |s_1(i) - s_2(j)|$



Dynamic Time Warping (DTW)

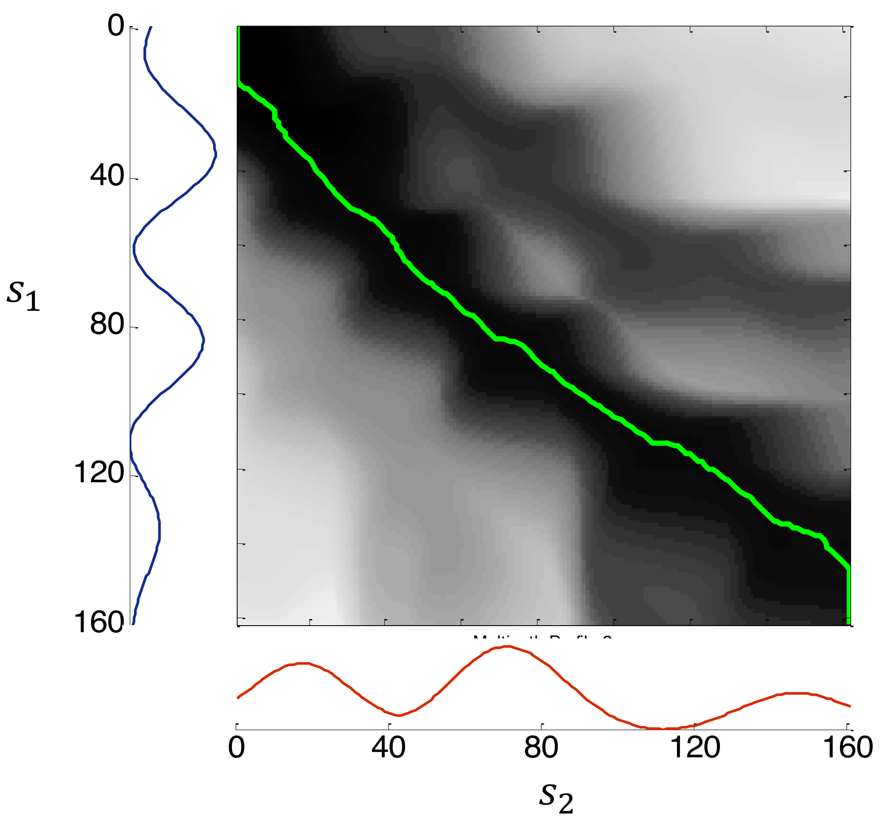
Computes the total warping to obtain s_1 from s_2

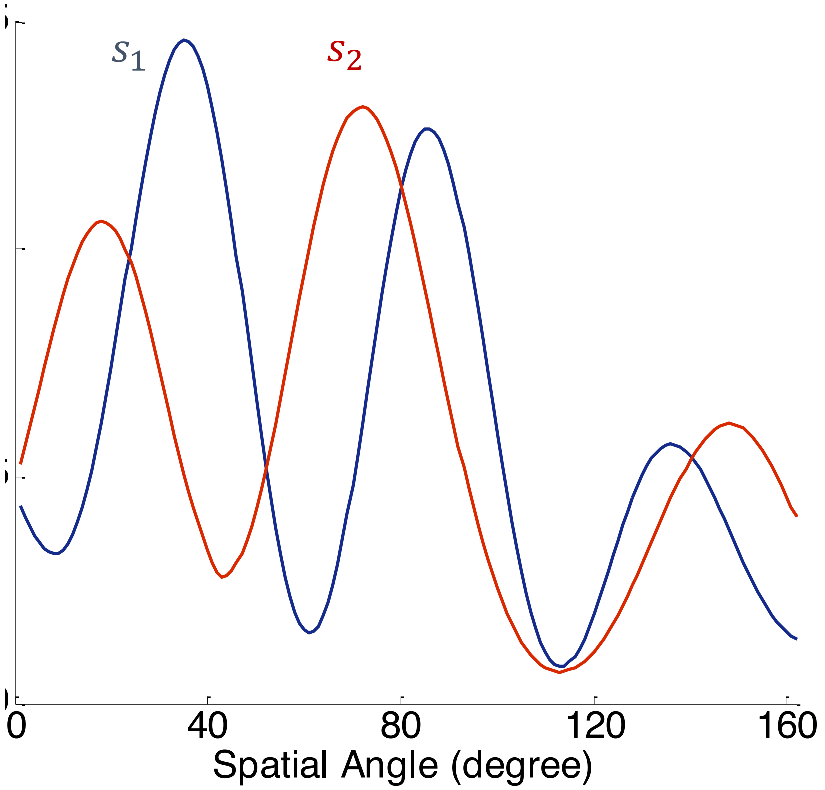




Dynamic Time Warping (DTW)

Computes the total warping to obtain s_1 from s_2

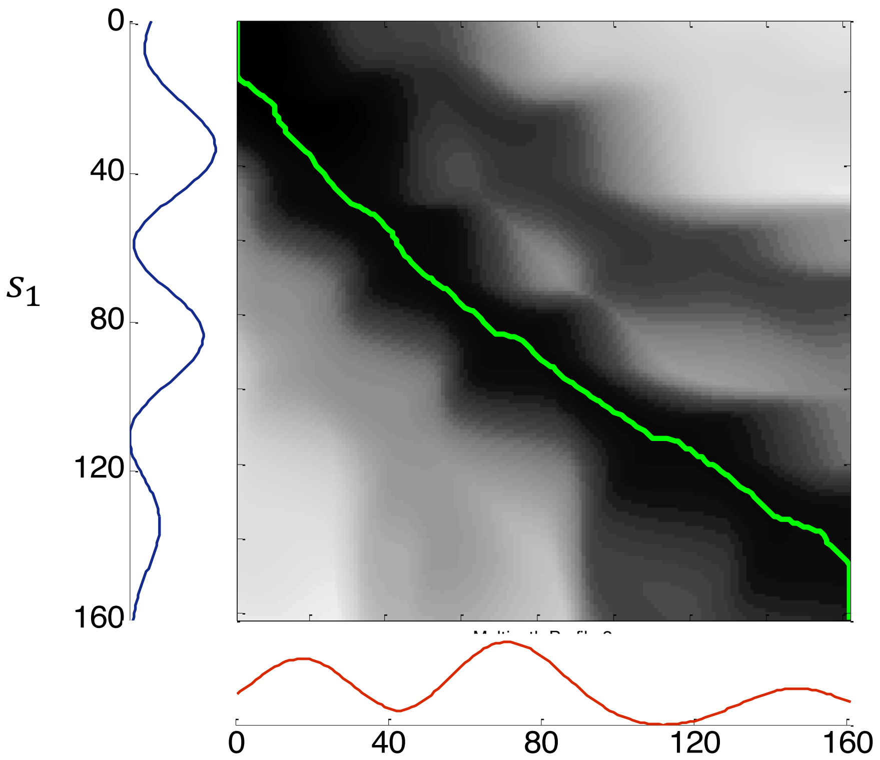


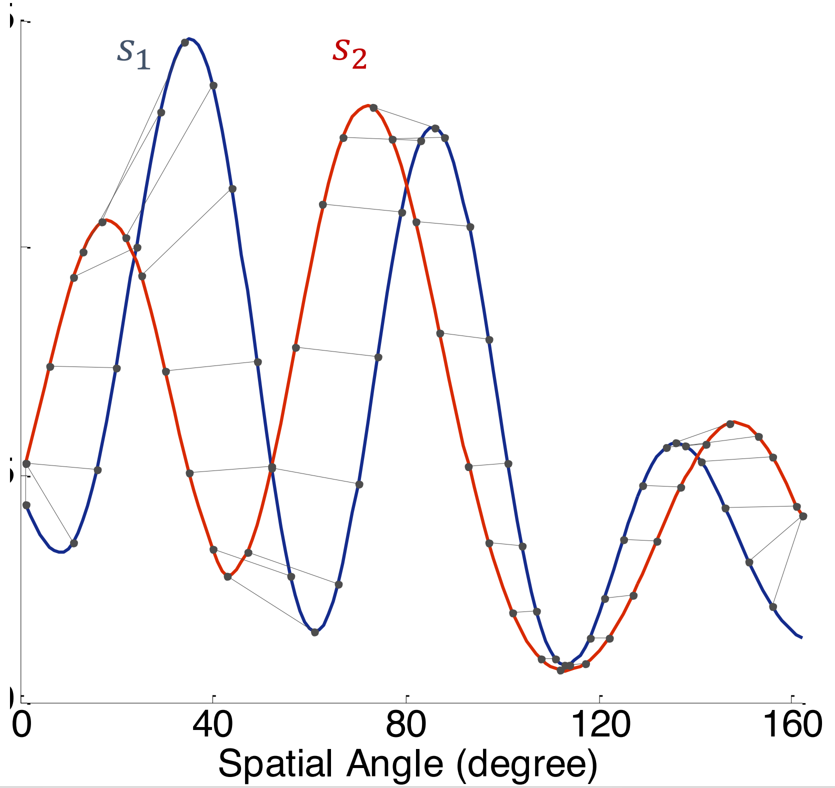


Compute DTW by finding the route with lowest total cost

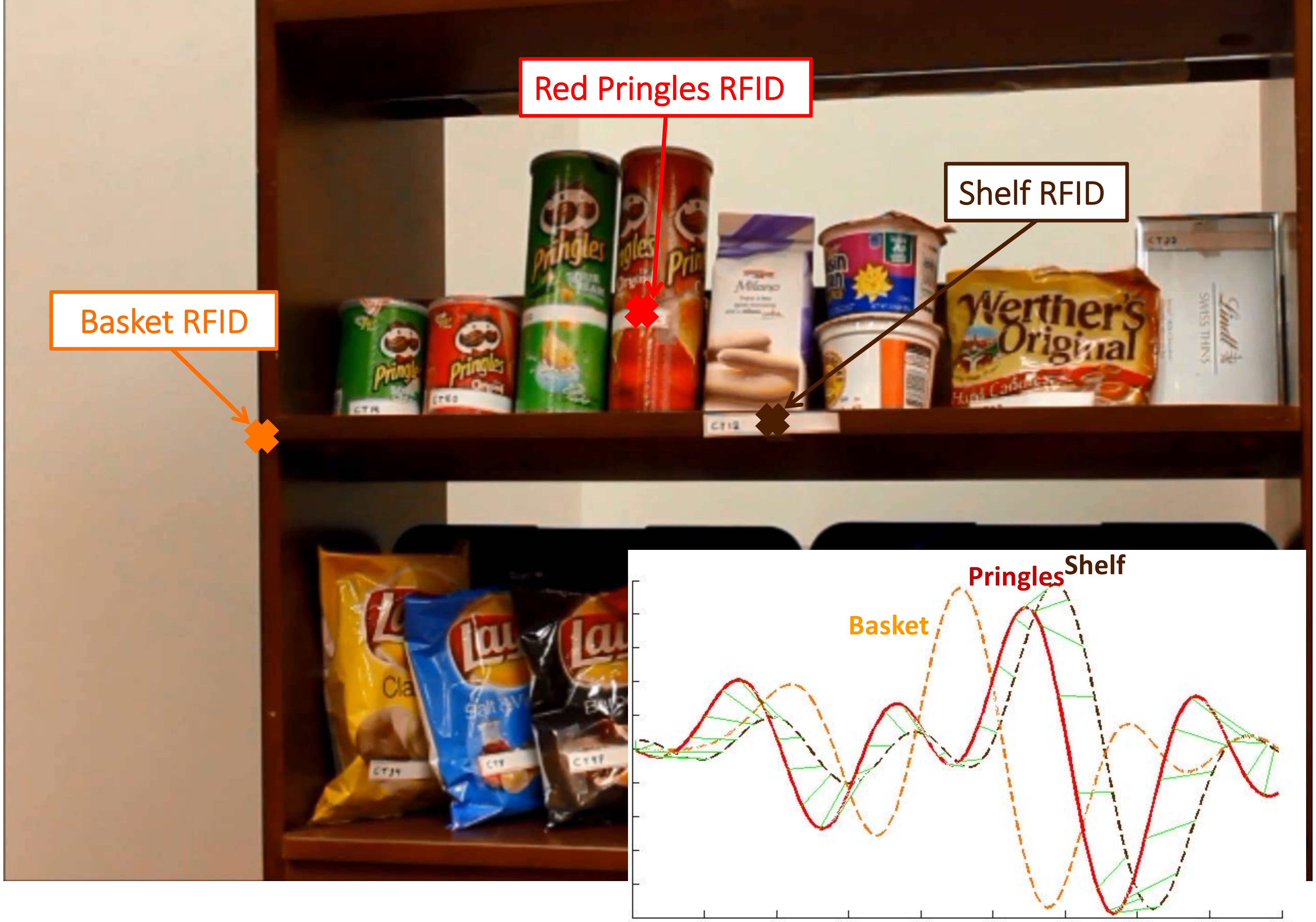
Dynamic Time Warping (DTW)

Computes the total warping to obtain s_1 from s_2





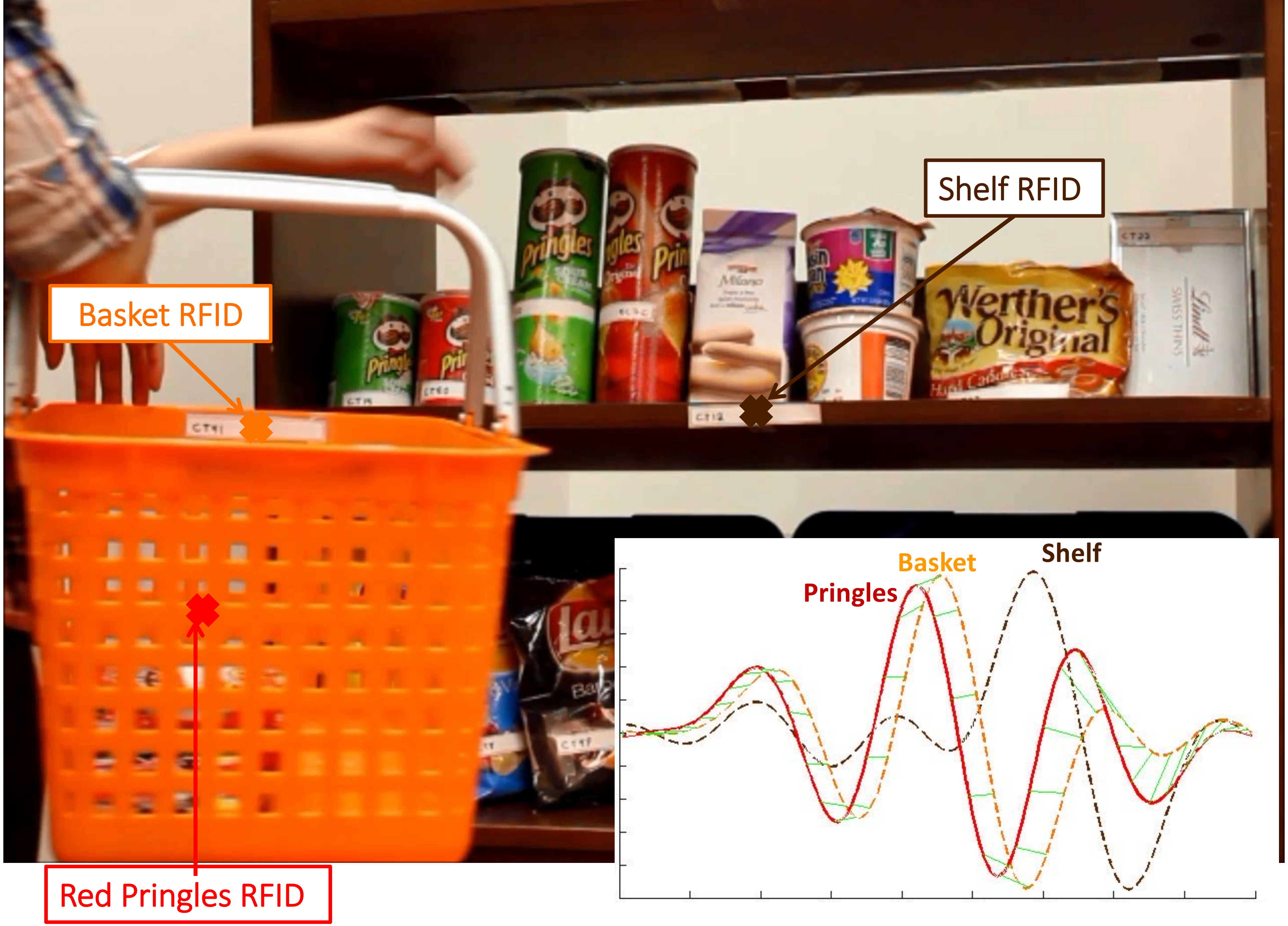
DTW captures proximity from multipath profiles



Red Pringles RFID

Shelf RFID

Basket RFID


Shelf RFID
Basket RFID
Red Pringles RFID
Basket
Shelf
Pringles


Pringles
Milano
Werther's Original
Lay's
Wavy
Ruffles
Cheddar & Sour Cream
Fritos
Classic

PinIt RFID Localization

Pros:

- Accurate RFID localization (10 to 15cm).
- Works with multipath and non-line-of-sight settings.
- Novel way to implement large antenna arrays & to localize using DTW

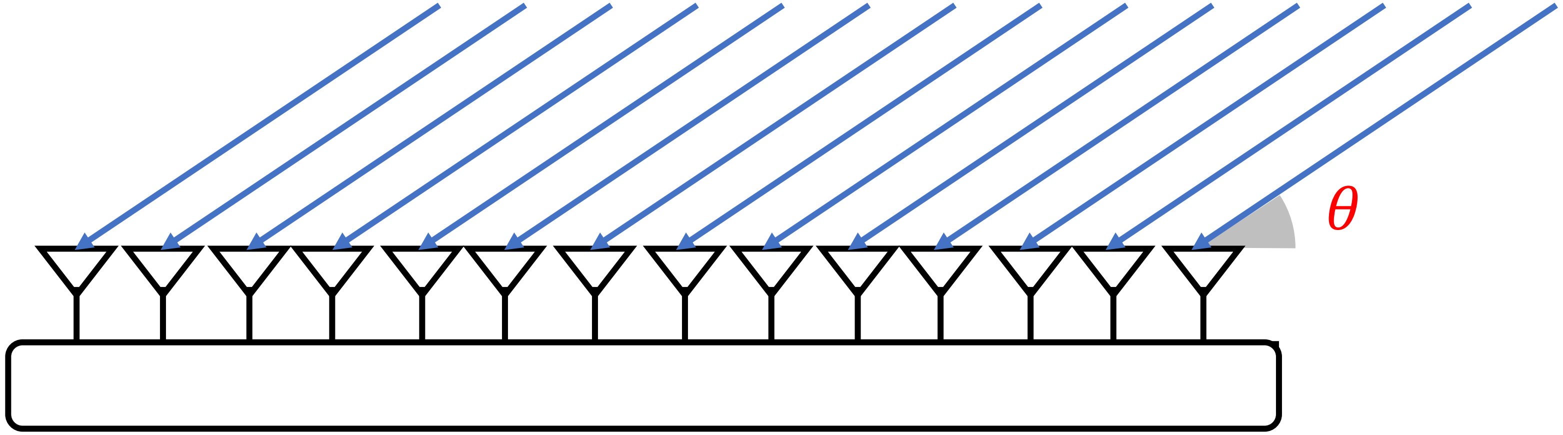
Cons:

- Reader Mobility
- Deploying the Environment with tags of known positions.
- Accuracy limited to deployment density of tags

Can we use SAR for WiFi?

Not as simple

Antenna Arrays in WiFi



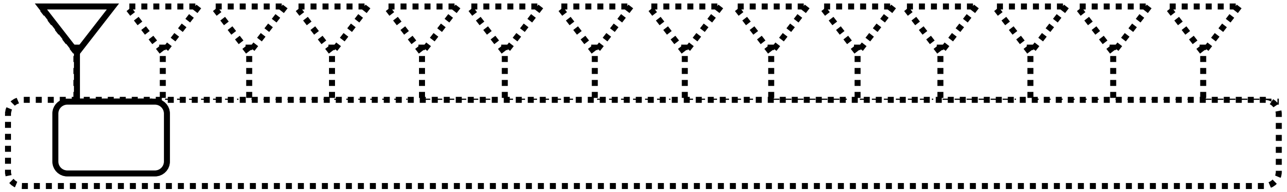
$$h_k = \alpha e^{-j2\pi\frac{d-k\ s\cos\theta}{\lambda}-j2\pi\Delta f_c t} = \alpha e^{-j2\pi\frac{d-k\ s\cos\theta}{\lambda}-j\phi(t)}$$

So far, we ignored CFO!

In antenna arrays: all antennas are synchronized!
→ All antennas see the same CFO relative to transmitter

Phase created by CFO is same on all antenna!
→ CFO is not a problem.

Synthetic Aperture Radar in WiFi



$$h_t = \alpha e^{-j2\pi \frac{d - vt\cos\theta}{\lambda} - j2\pi \Delta f_c t}$$

Channel at each location measured at different times

→Phase created by CFO is different for different antenna locations

In RFIDs,

Tags simply reflect reader's signal → No CFO

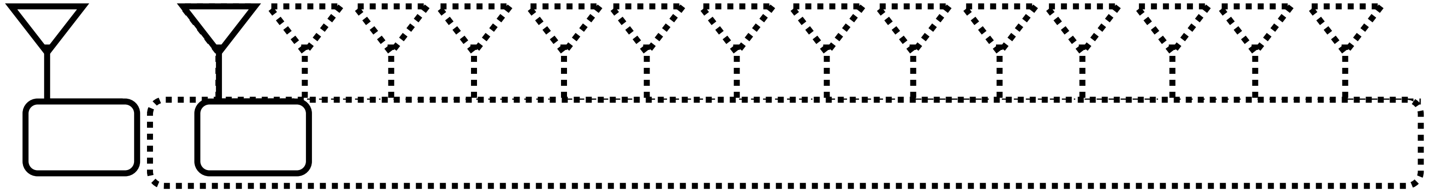
In WiFi,

Transmitter generates his own signal → CFO

CFO is a problem for using SAR in WiFi!

Synthetic Aperture Radar in WiFi

How to use enable SAR for WiFi?



Use 2 antennas that are synched:

- 1 Moving antenna $h_{1t} = \alpha e^{-j2\pi\frac{d_1 - vt\cos\theta}{\lambda} - j2\pi\Delta f_c t}$
- 1 Static antenna $h_{2t} = \alpha e^{-j2\pi\frac{d_2}{\lambda} - j2\pi\Delta f_c t}$

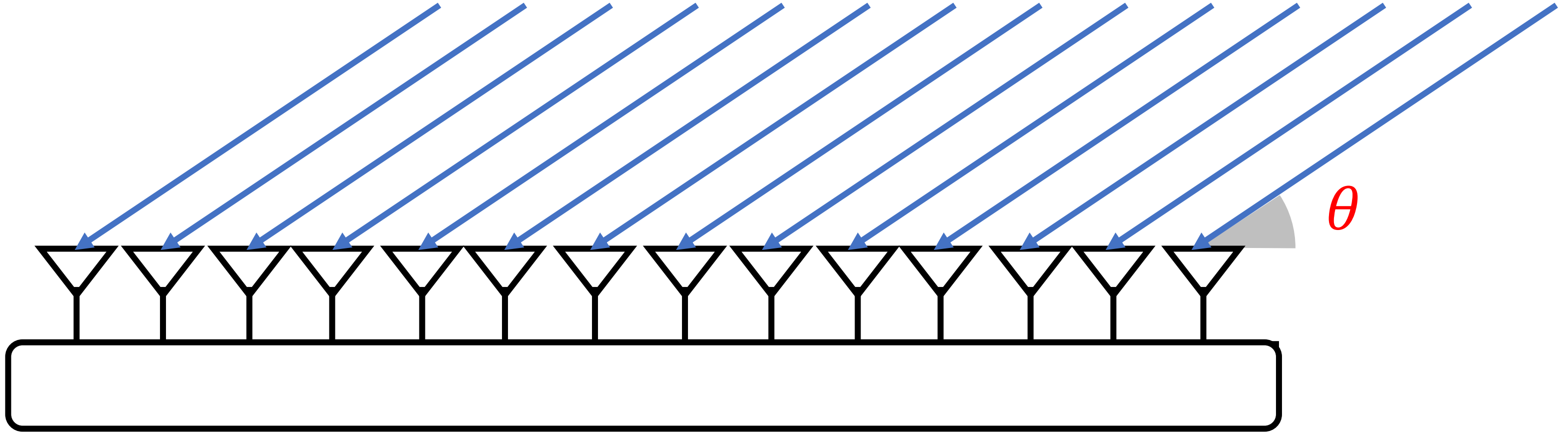
Taking ratio eliminates CFO: $\frac{h_{1t}}{h_{2t}} = e^{-j2\pi\frac{d_1 + d_2 - vt\cos\theta}{\lambda}}$

Enable SAR with WiFi but … limited mobility
→ Emulate small arrays

Why do we care about large antenna arrays?

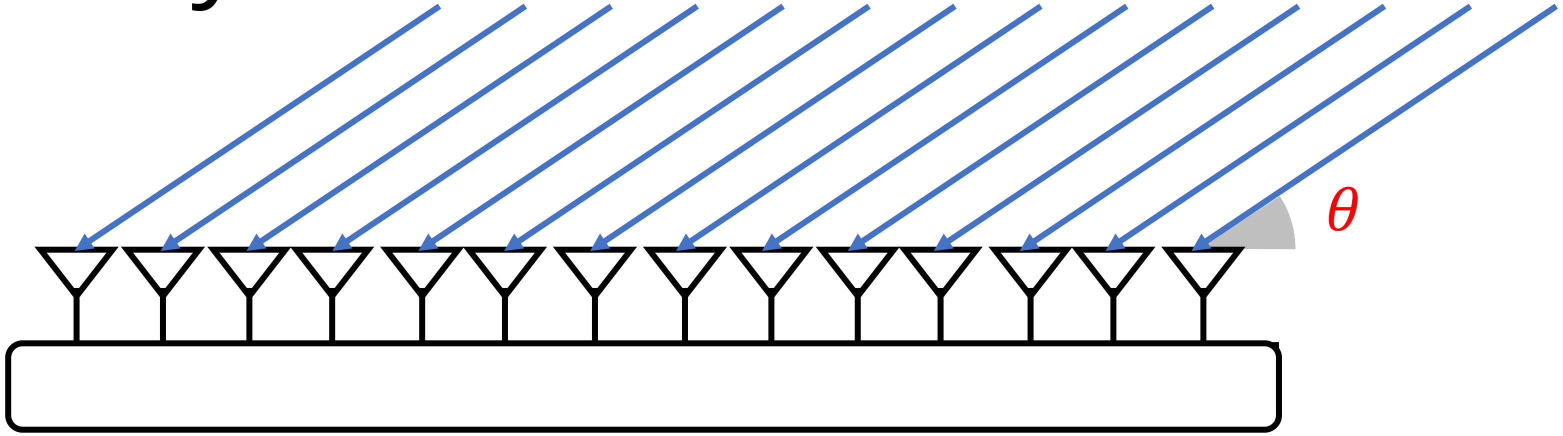
Larger antenna array
→ Higher AoA resolution

Antenna Arrays



$$h_k = \alpha_1 e^{-j2\pi\frac{d_1 - k\ s\cos\theta_1}{\lambda}}$$

Antenna Arrays



$$h_k = \sum_{l=1}^{L} \alpha_l e^{-j\phi_l} e^{j2\pi \frac{ks \cos\theta_l}{\lambda}}$$

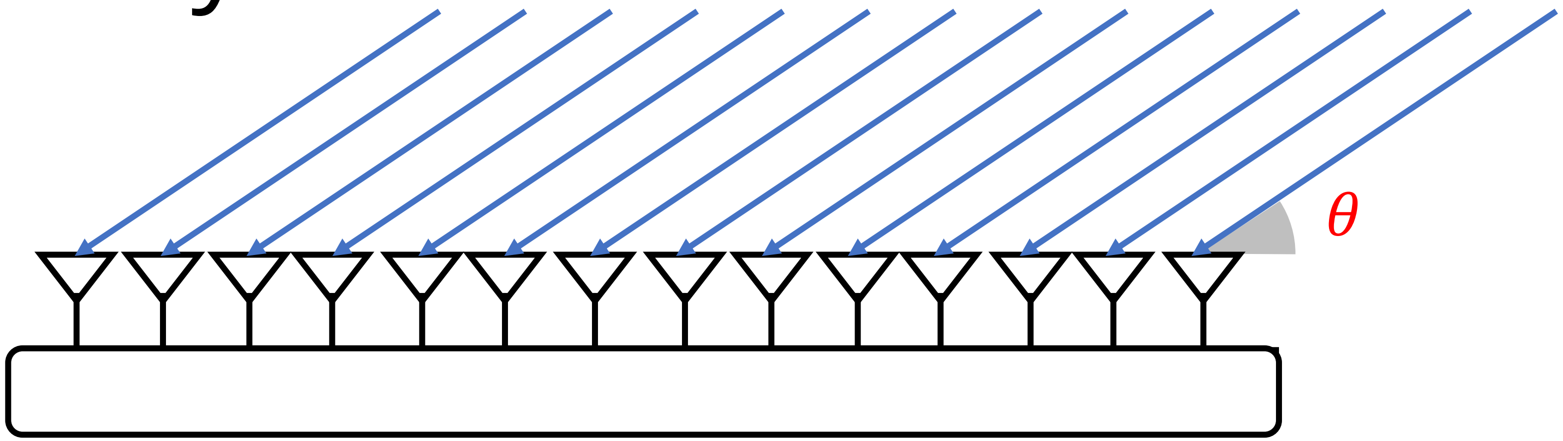
Let: $f = \cos\theta\,, t = ks/\lambda\,,$
$P_{\cos\theta} = \alpha_l e^{-j\phi_l}$

$$\Downarrow$$

$$h_t = \sum_f P_f e^{j2\pi f t} \quad \Leftrightarrow \quad x(t) = \sum_f X(f) e^{j2\pi f t}$$

Antenna Arrays are a Fourier Transform

Antenna Arrays as Fourier Transforms



$$h_k = \sum_{l=1}^{L} \alpha_l e^{-j\phi_l} e^{j2\pi \frac{ks\cos\theta_l}{\lambda}} \Longleftrightarrow x(t) = \sum_{f} X(f) e^{j2\pi f t}$$

Antennas ⟺ Time Samples

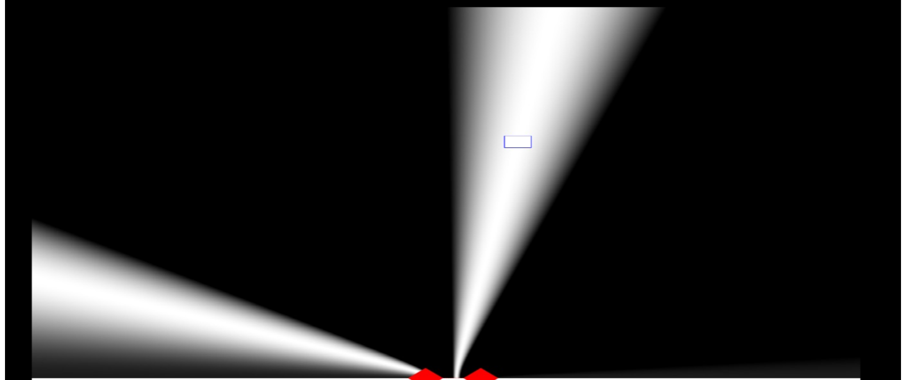
FFT ↓ FFT ↓

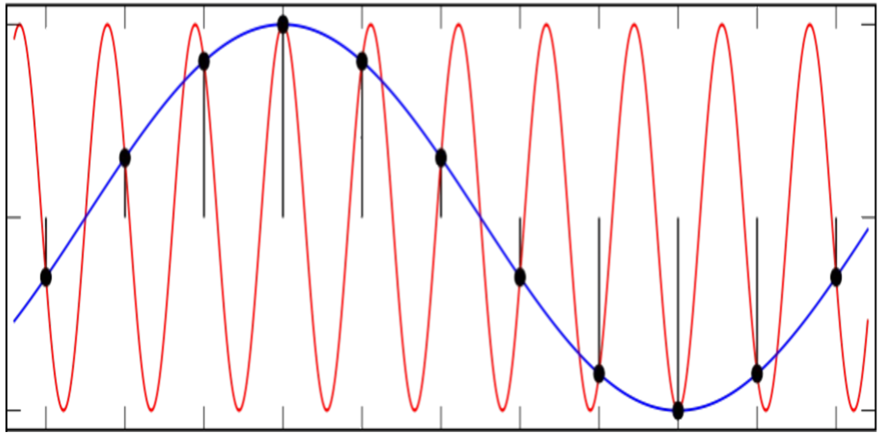
AoA Directions ⟺ Frequencies

Antenna Arrays ⟷ Fourier Transforms

Antenna Arrays		Fourier Transforms
Antennas	⟷	Time Samples
FFT		FFT
AoA Directions	⟷	Frequencies
Sample at Nyquist rate $\lambda/2$ otherwise you get AoA ambiguity	⟷	Sample at Nyquist rate $1/(2B)$ otherwise you get aliasing or frequency ambiguity

$$\frac{2\pi k s\cos\theta_1}{\lambda} = \frac{2\pi k s\cos\theta_2}{\lambda} \bmod 2\pi$$





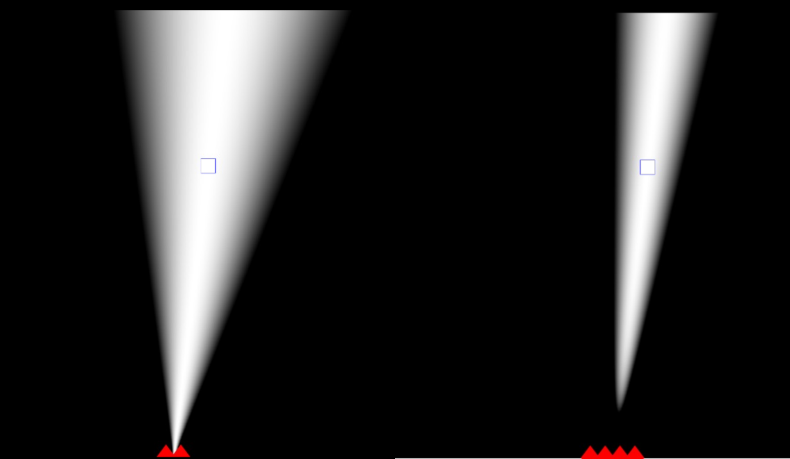
Antenna Arrays ⟺ Fourier Transforms

Antennas ⟺ Time Samples

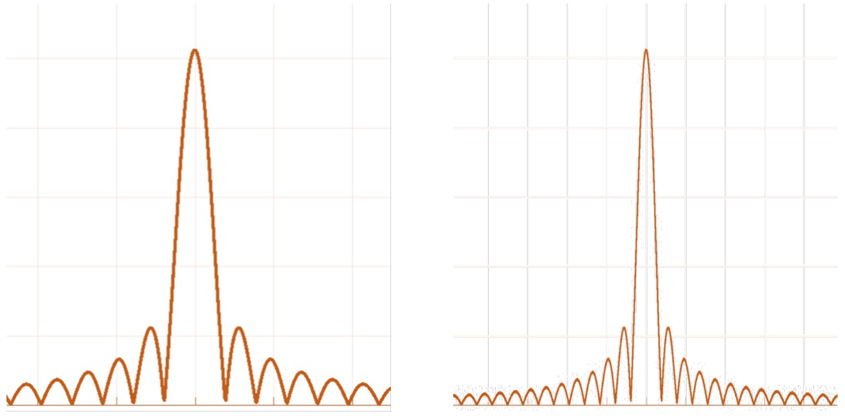
FFT

AoA Directions ⟺ Frequencies

AoA Resolution is inversely proportional to array length ⟺ Resolution in Frequency is inversely proportional to time window

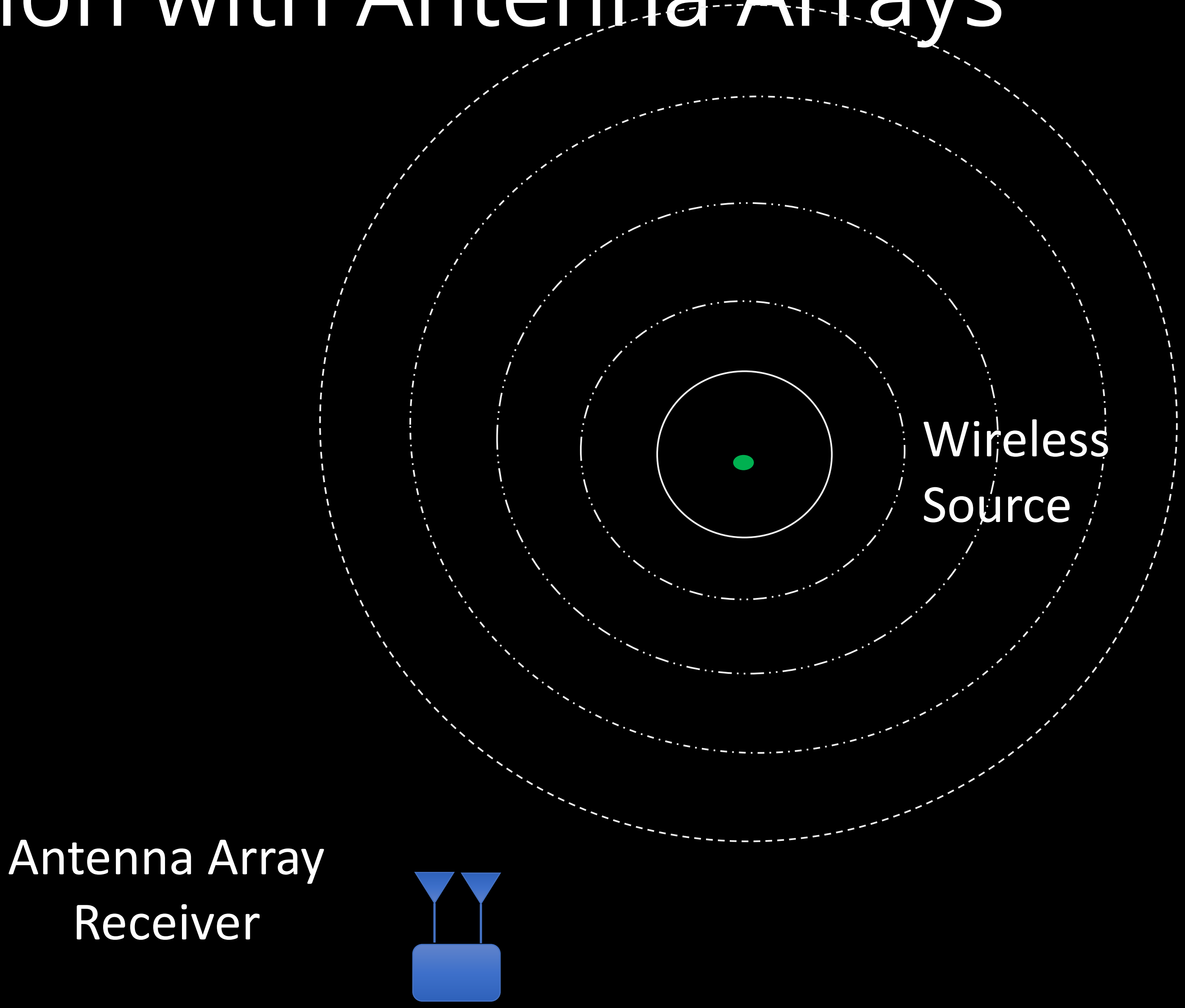

2 Antenna Array

4 Antenna Array

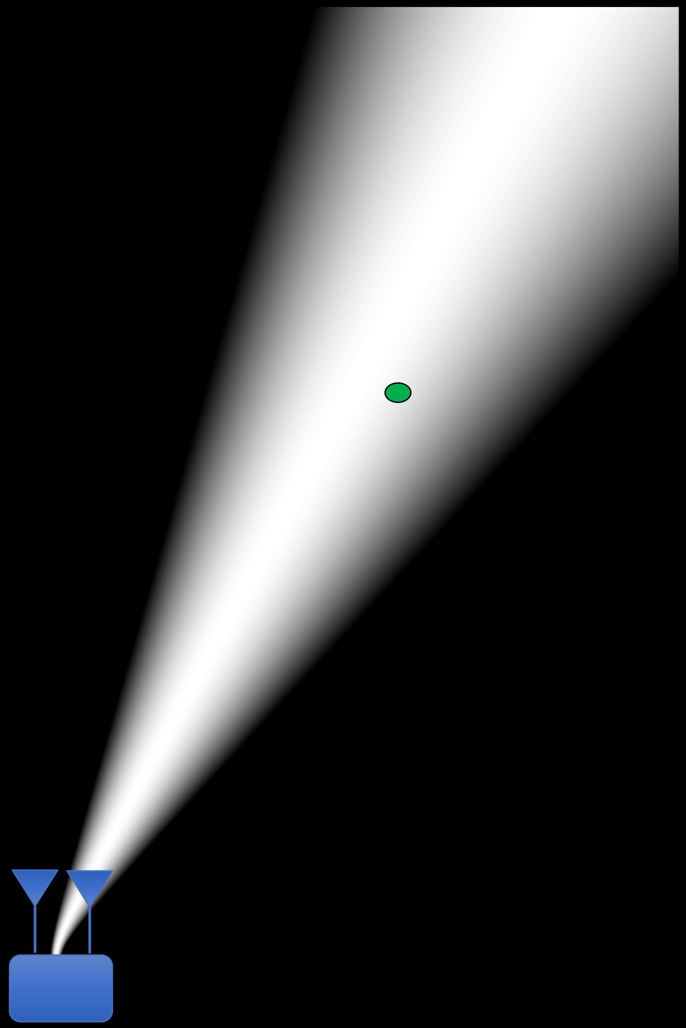

2ms Time Window

4ms Time Window

Localization with Antenna Arrays



Localization with Antenna Arrays

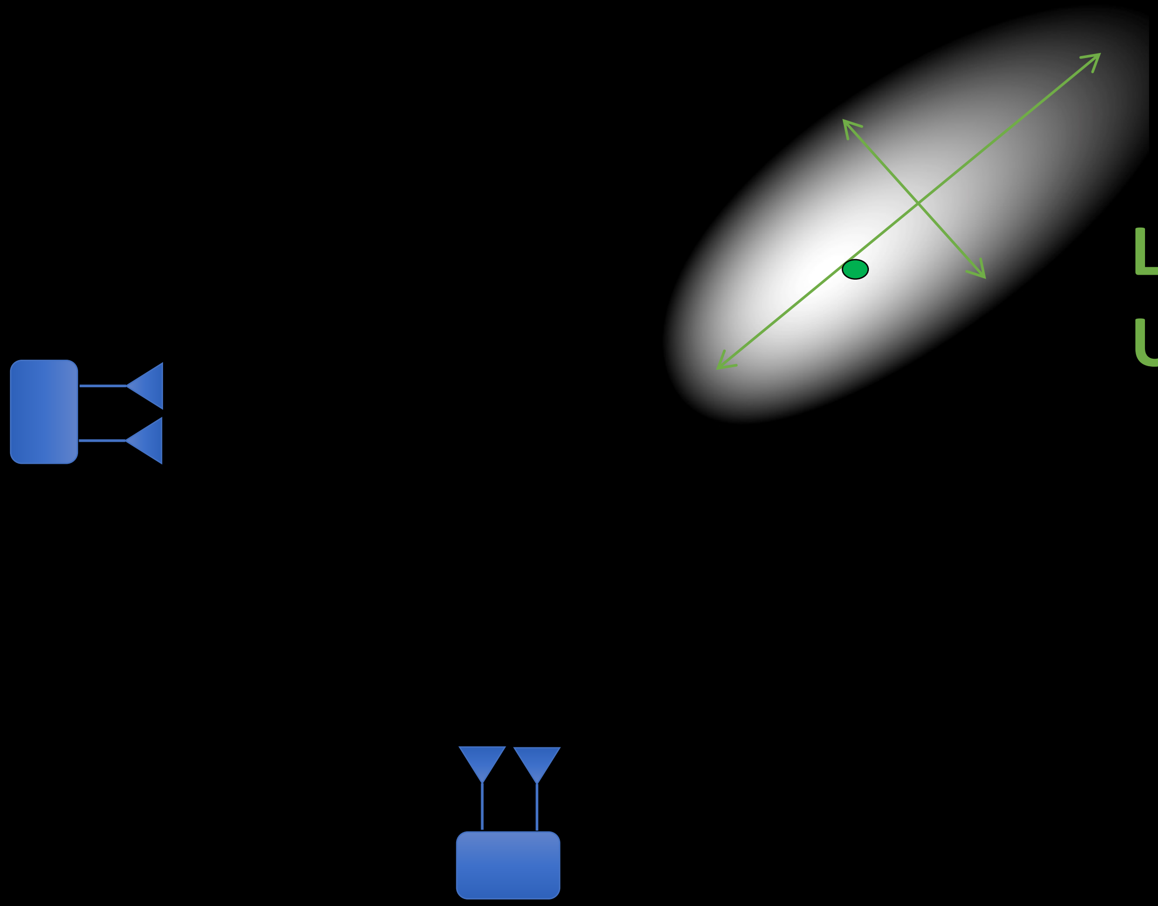


Array's beam points to source

Antenna Array Receiver

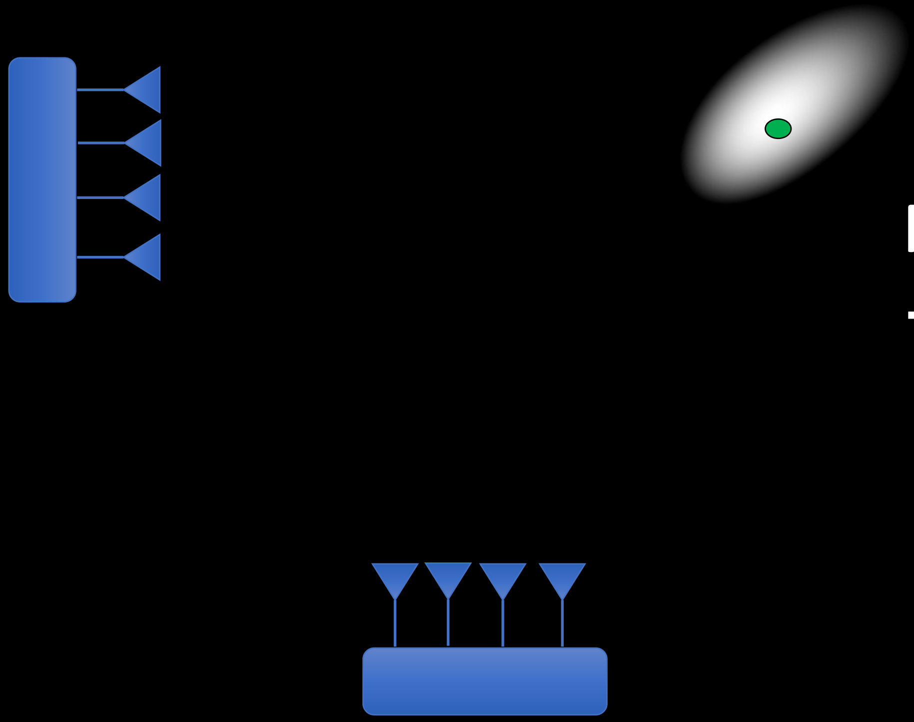
Localization with Antenna Arrays

Localization with Antenna Arrays



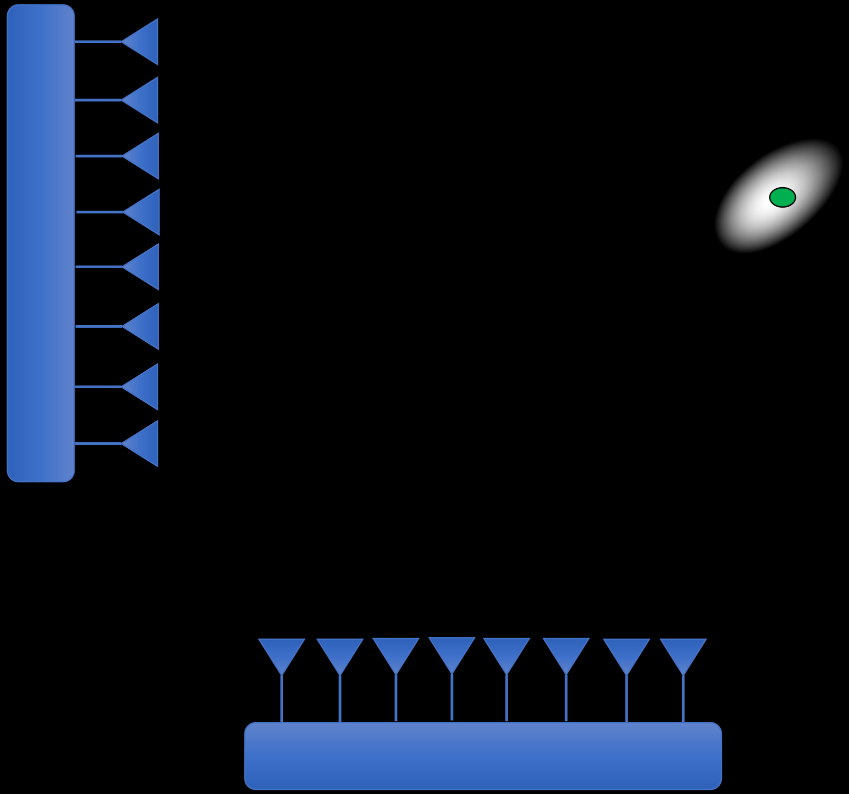
Location Uncertainty

Localization with Antenna Arrays

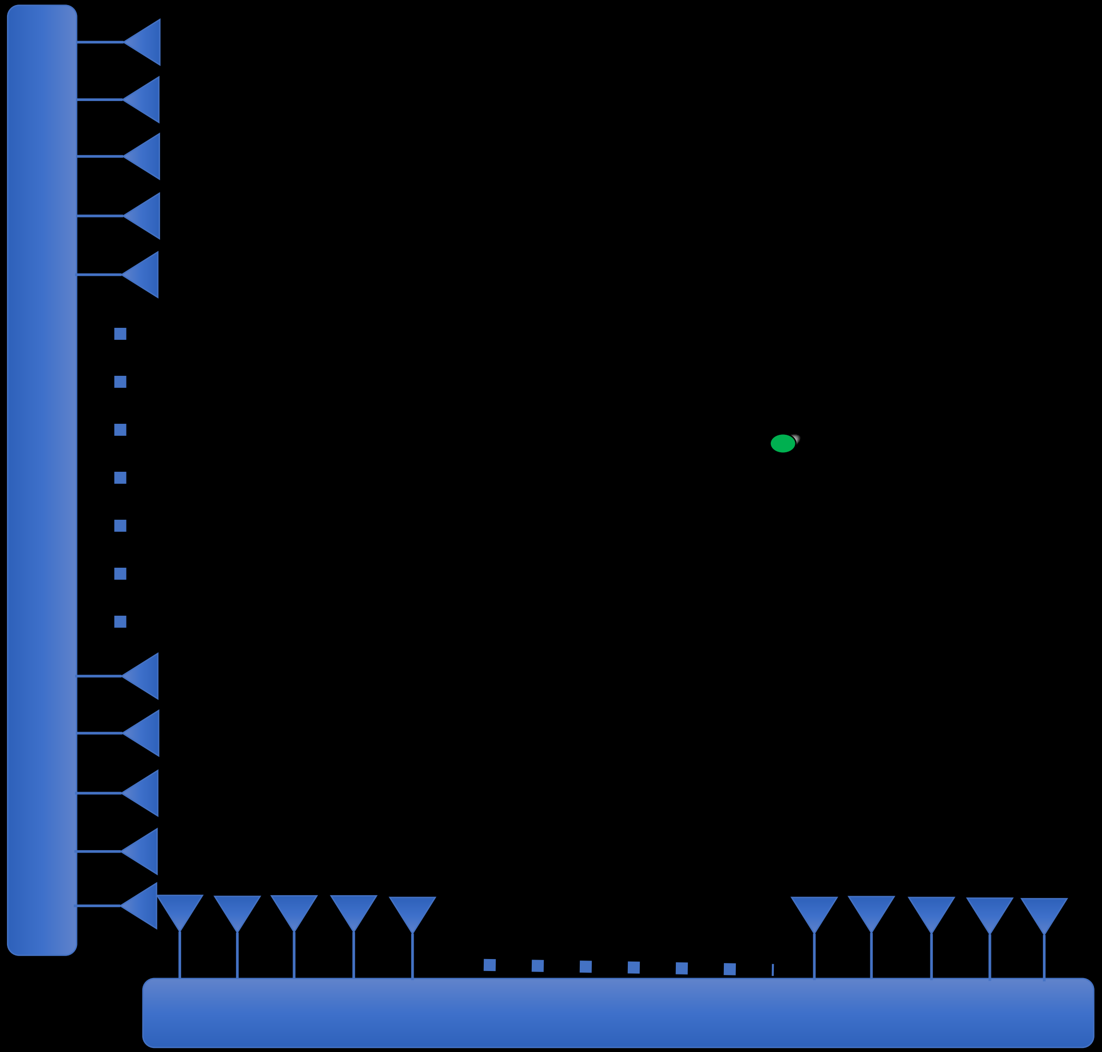


More Antennas
→ Less uncertainty

Localization with Antenna Arrays

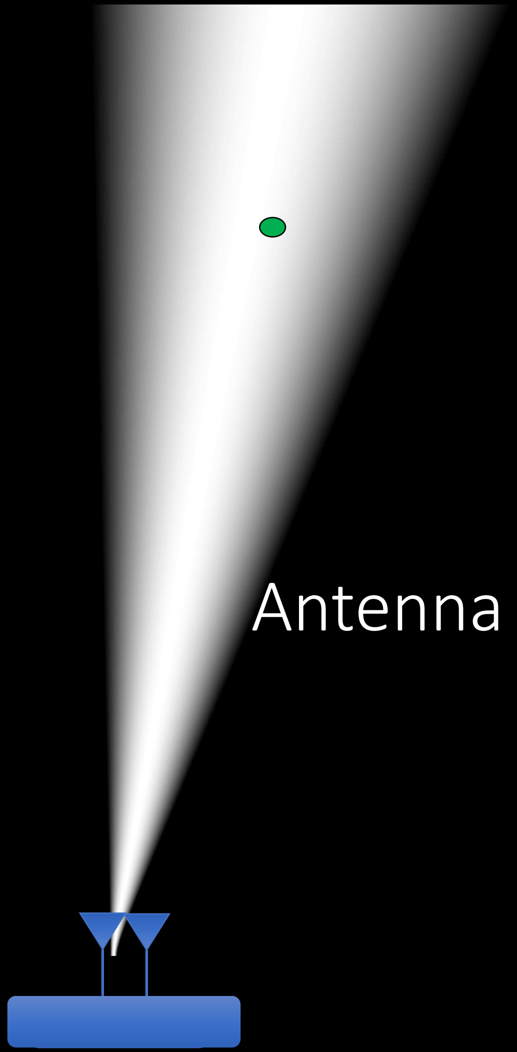


Not practical!



Ambiguity-Resolution Tradeoff

Ambiguity-Resolution Tradeoff

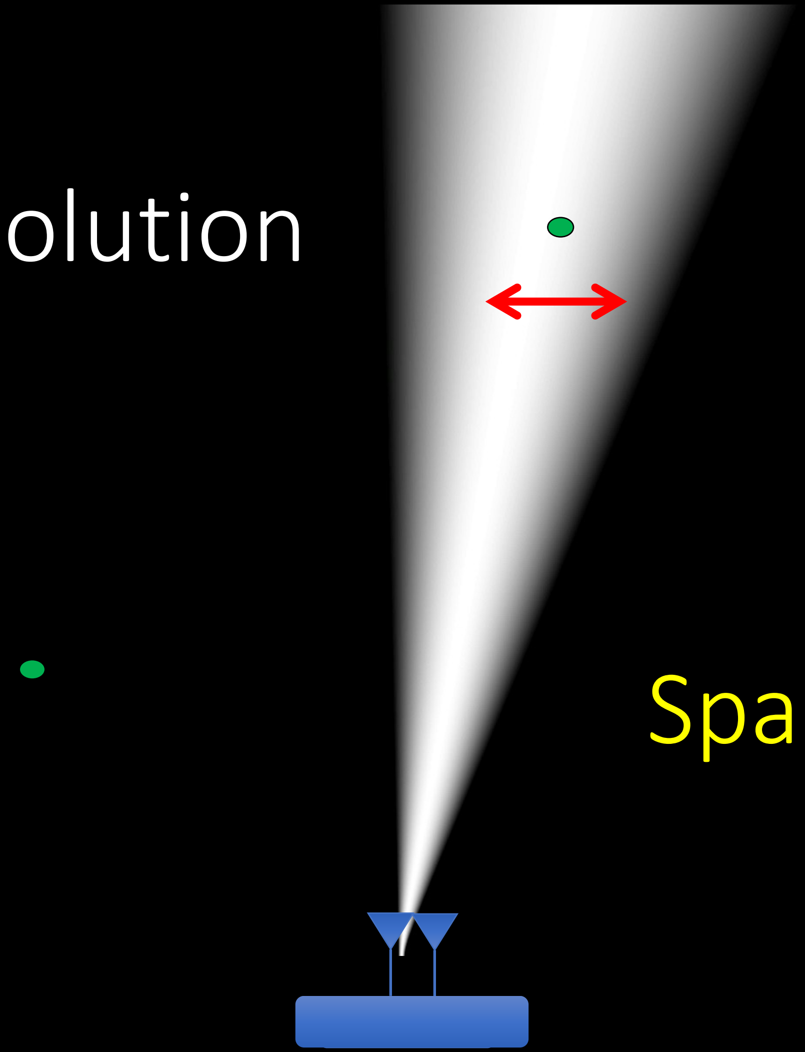


Antenna spacing is $\lambda/2$

Ambiguity-Resolution Tradeoff

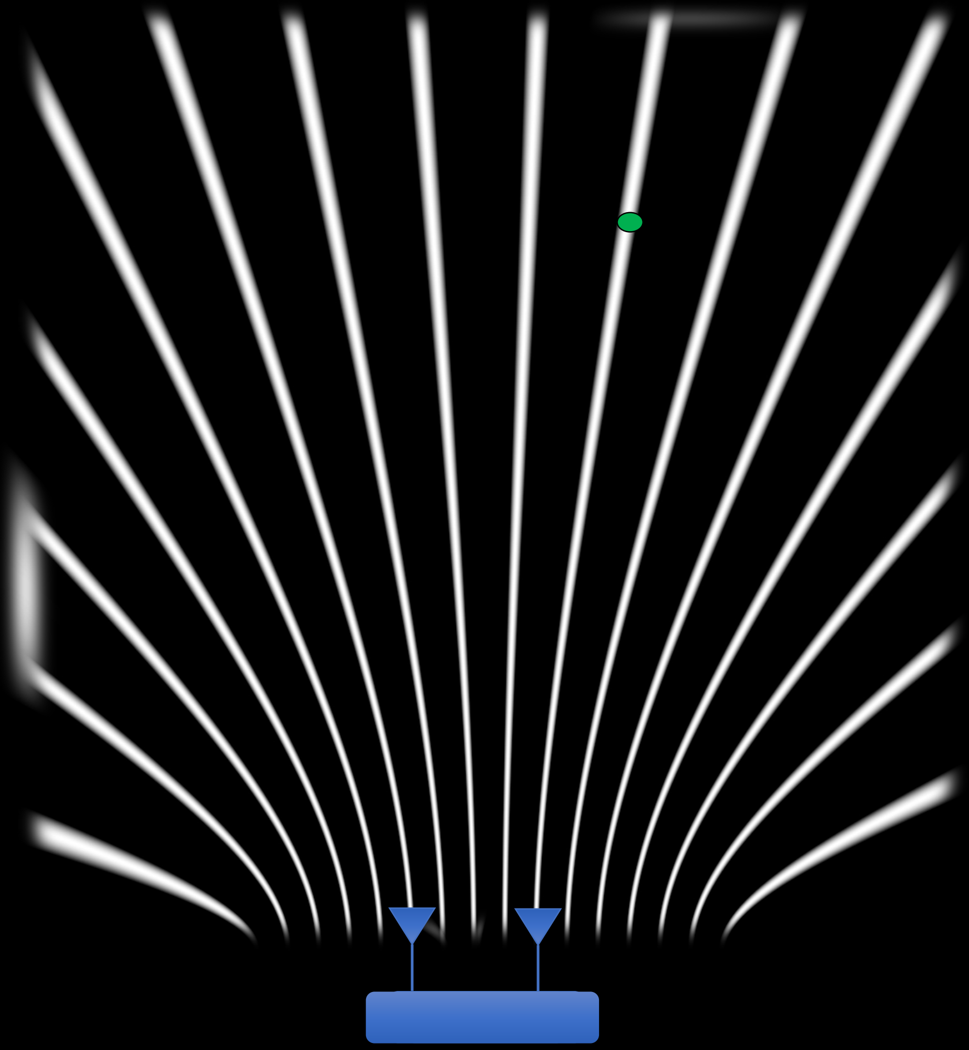
Ambiguity

Higher resolution



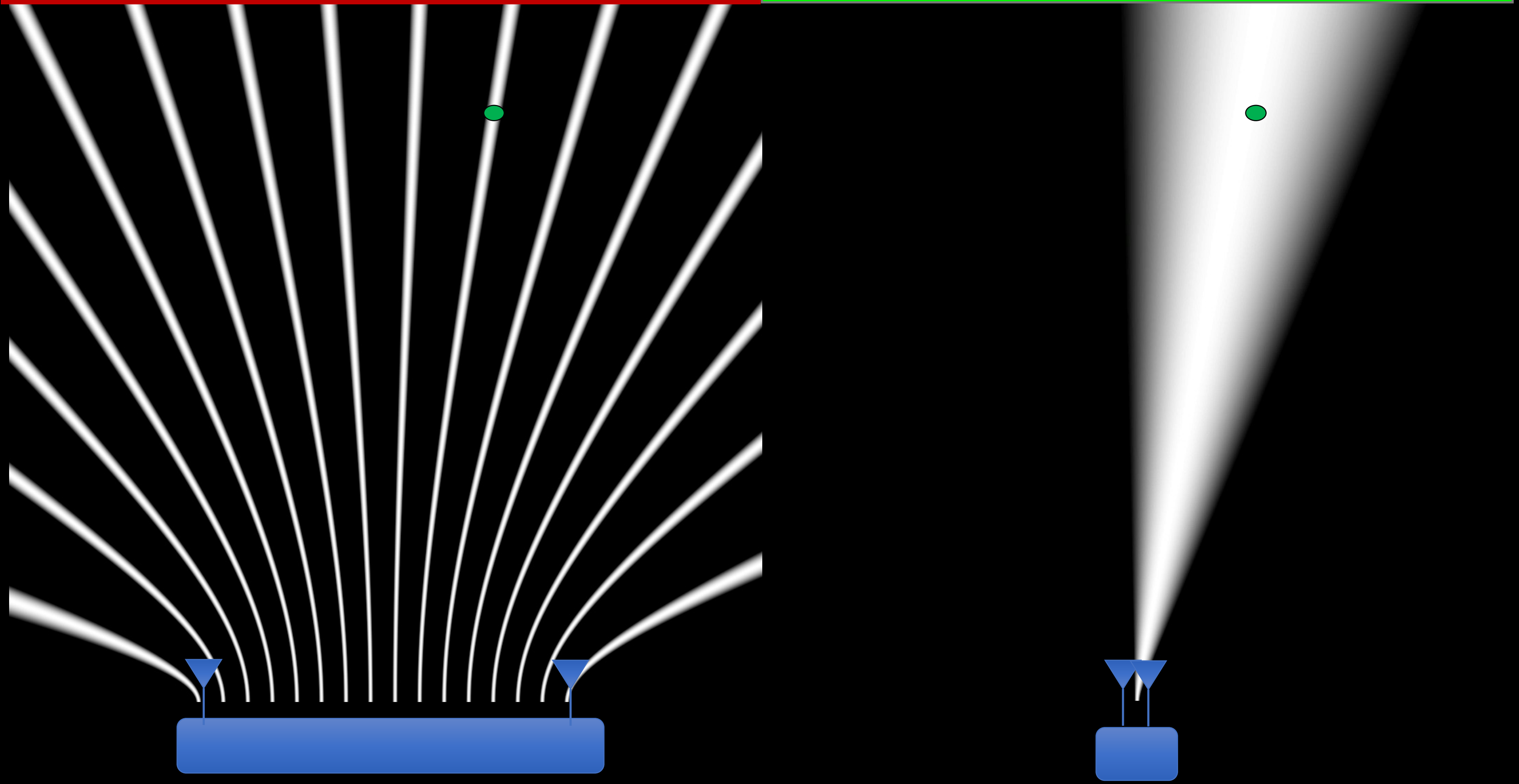
Spacing is λ

Ambiguity-Resolution Tradeoff



8 λ

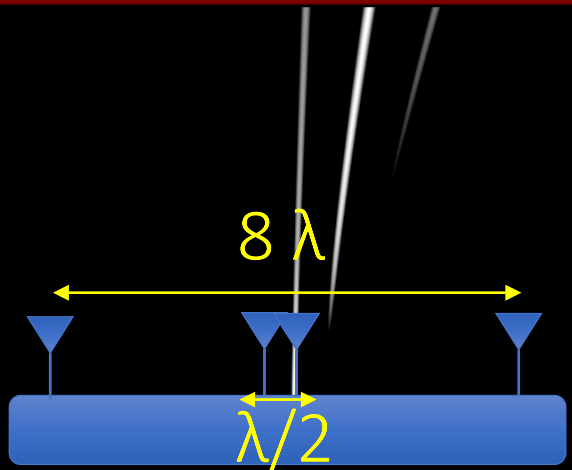
High resolution	Low resolution
Ambiguity in direction	No ambiguity



RF-IDraw: Multi-Resolution Array

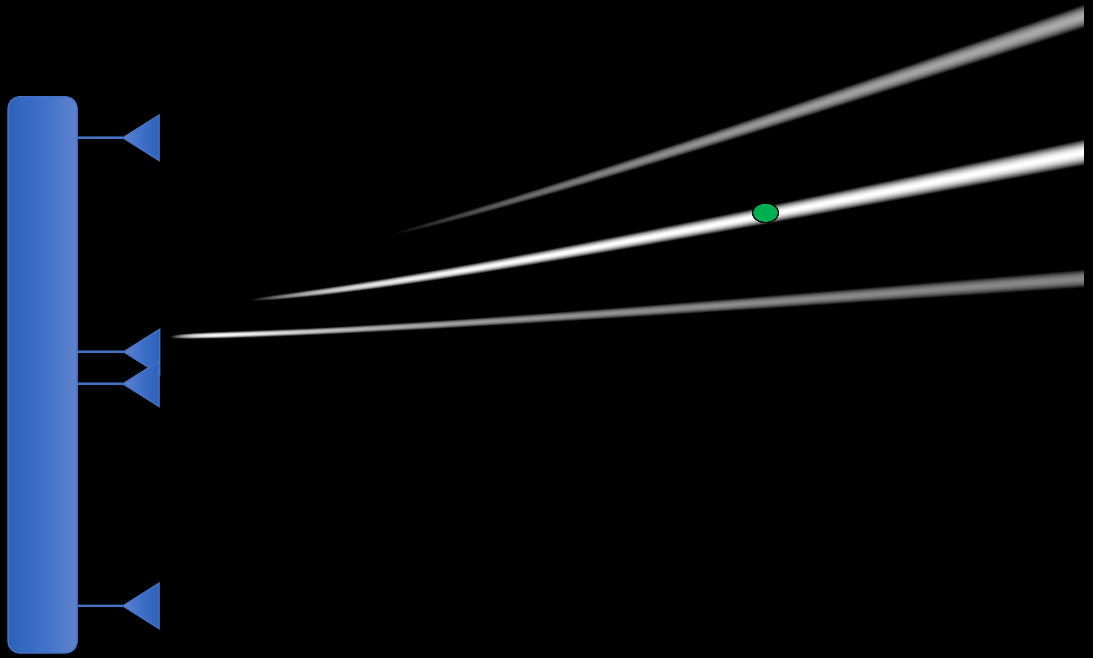
Narrowly spaced and widely spaced antennas create an overlay of multi-resolution beams.

Use fewer antennas, but place them smartly

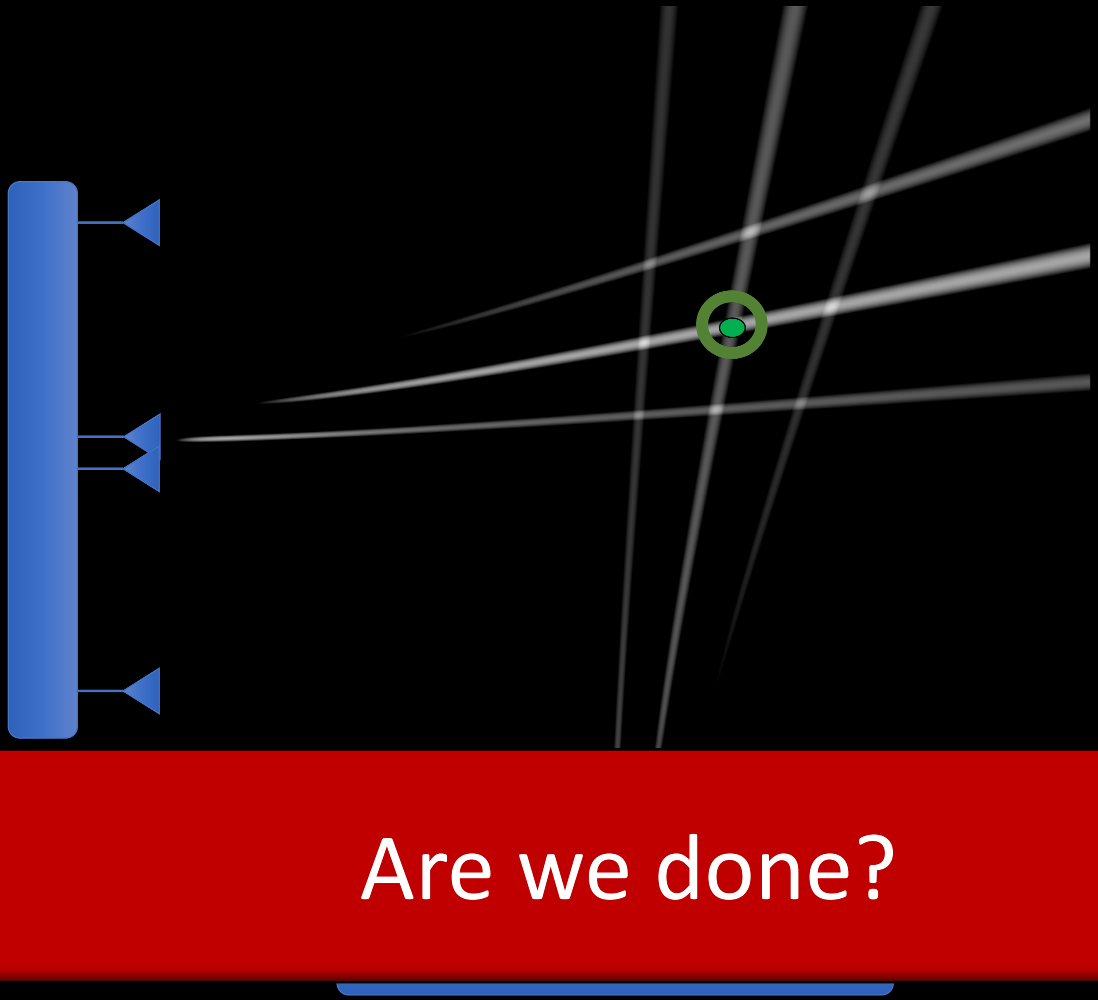


RF-IDraw: Virtual Touch Screen in the Air Using RF Signals. Jue Wang, Deepak Vasisht, and Dina Katabi

RF-IDraw Localization

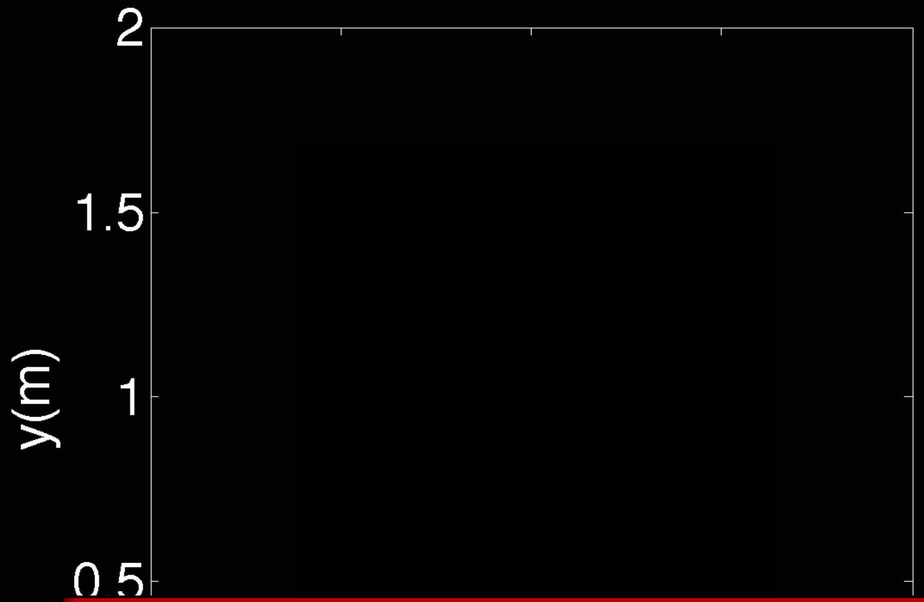


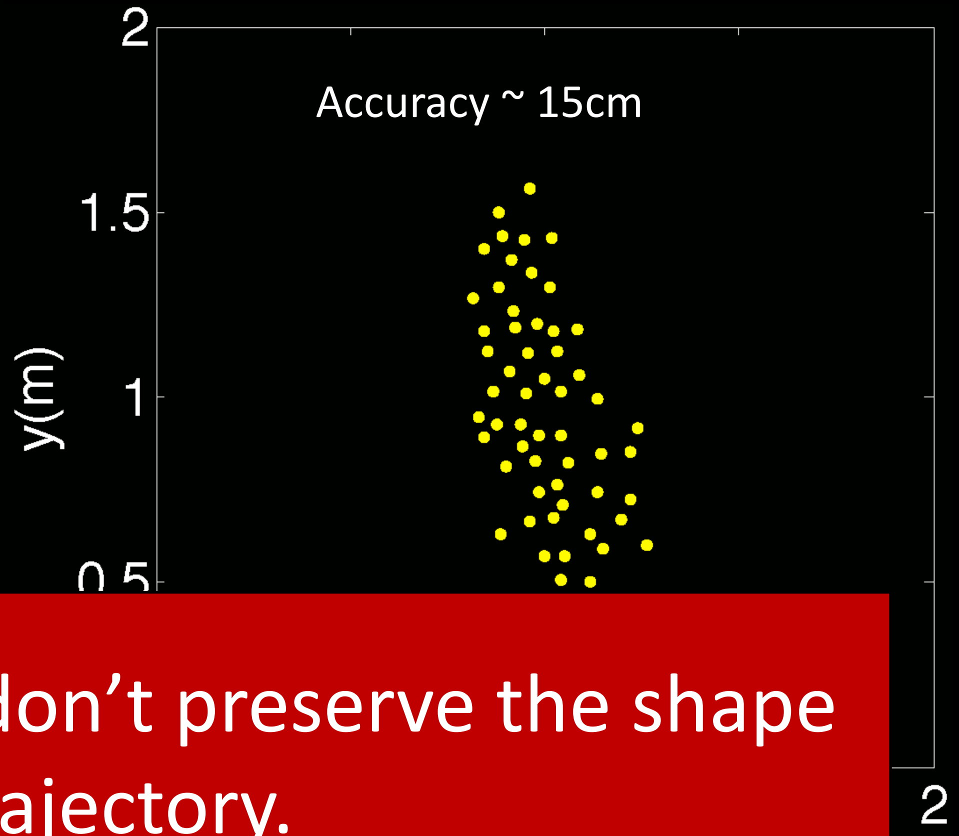
RF-IDraw Localization



Are we done?

Let’s Try

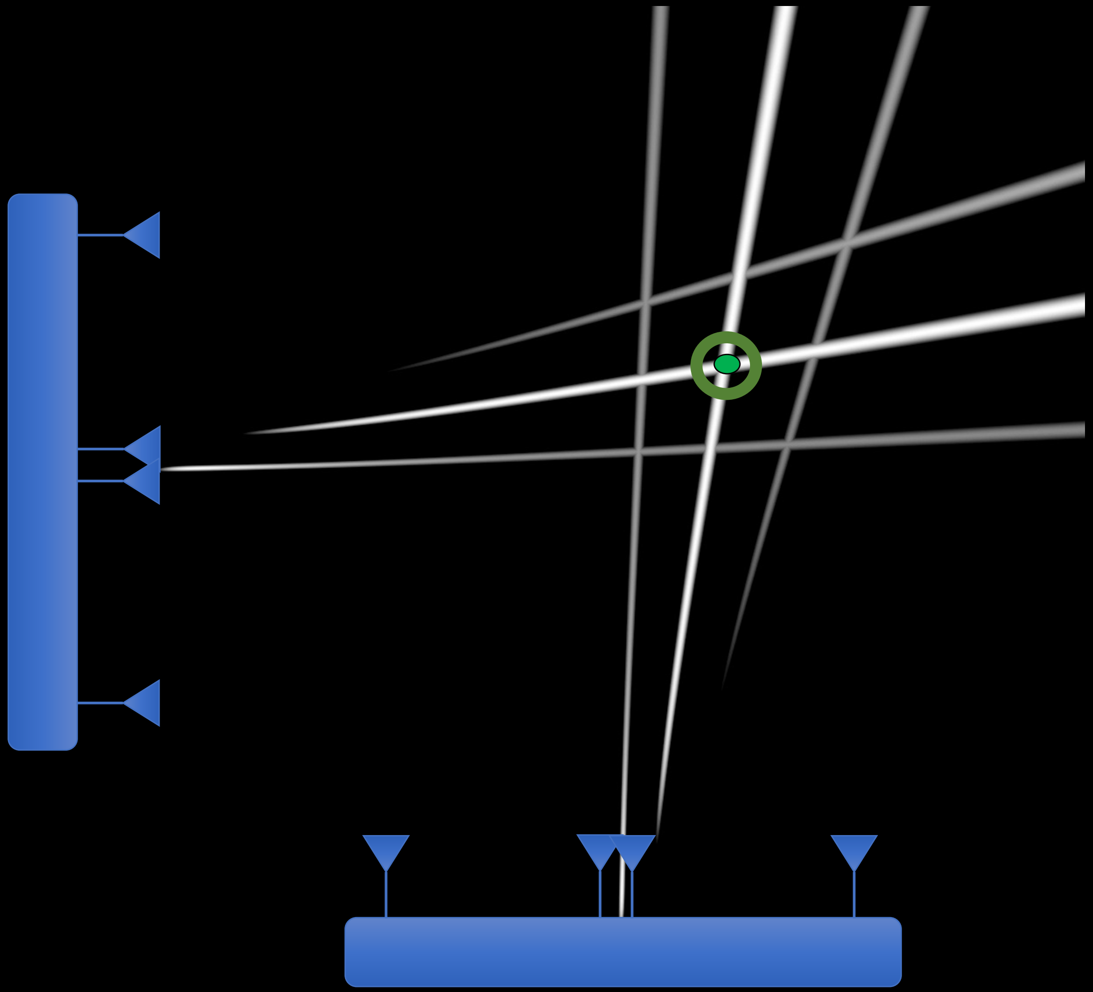




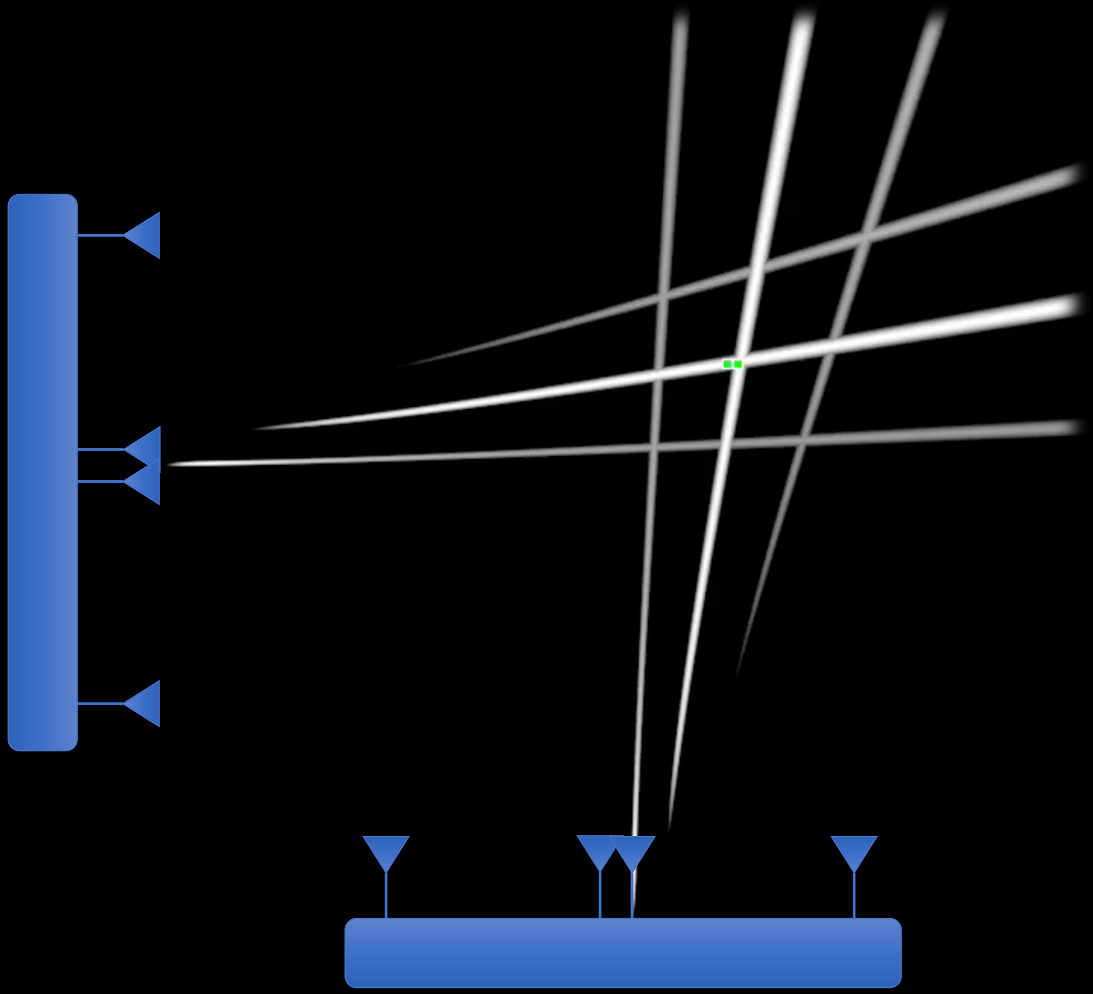
Accuracy ~ 15cm

Errors are random and don’t preserve the shape of the trajectory.

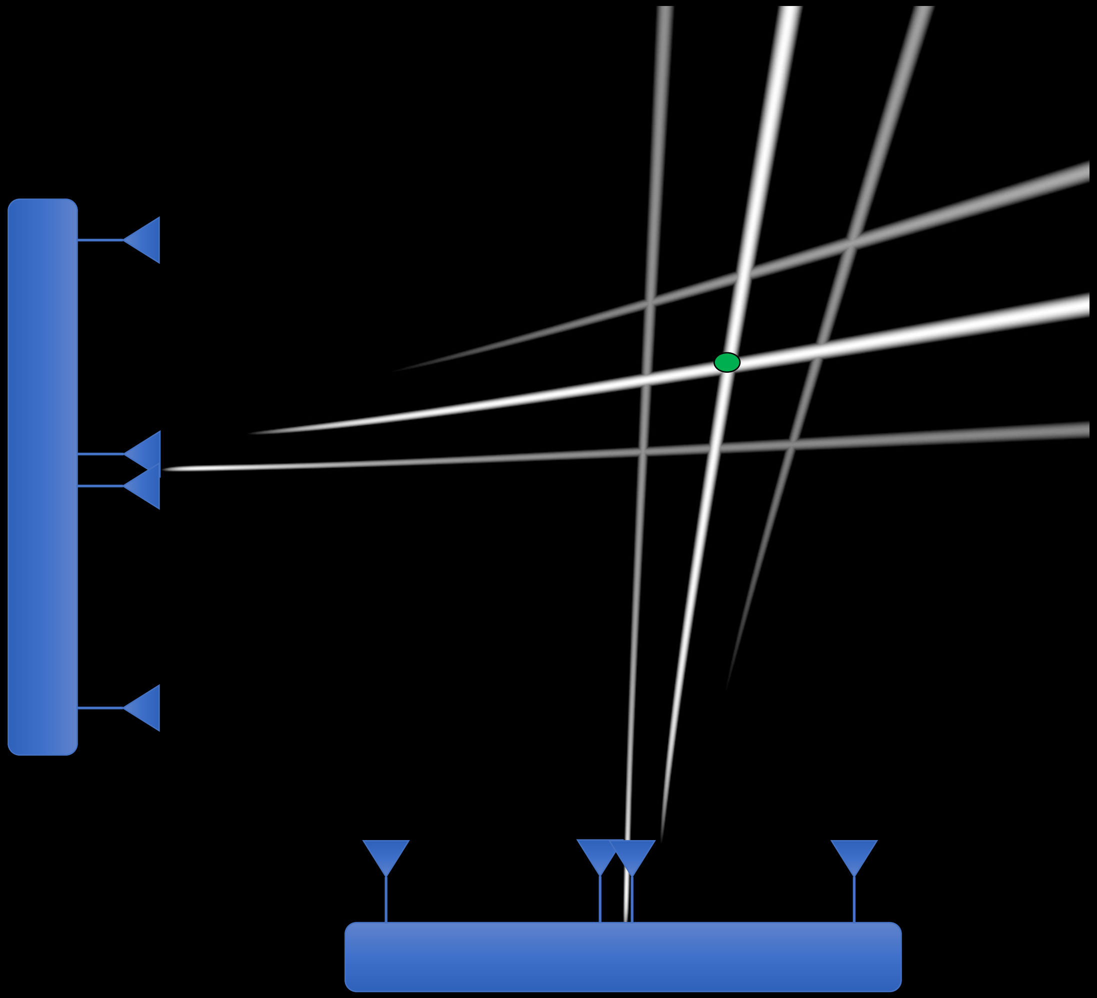
Noiseless Scenario



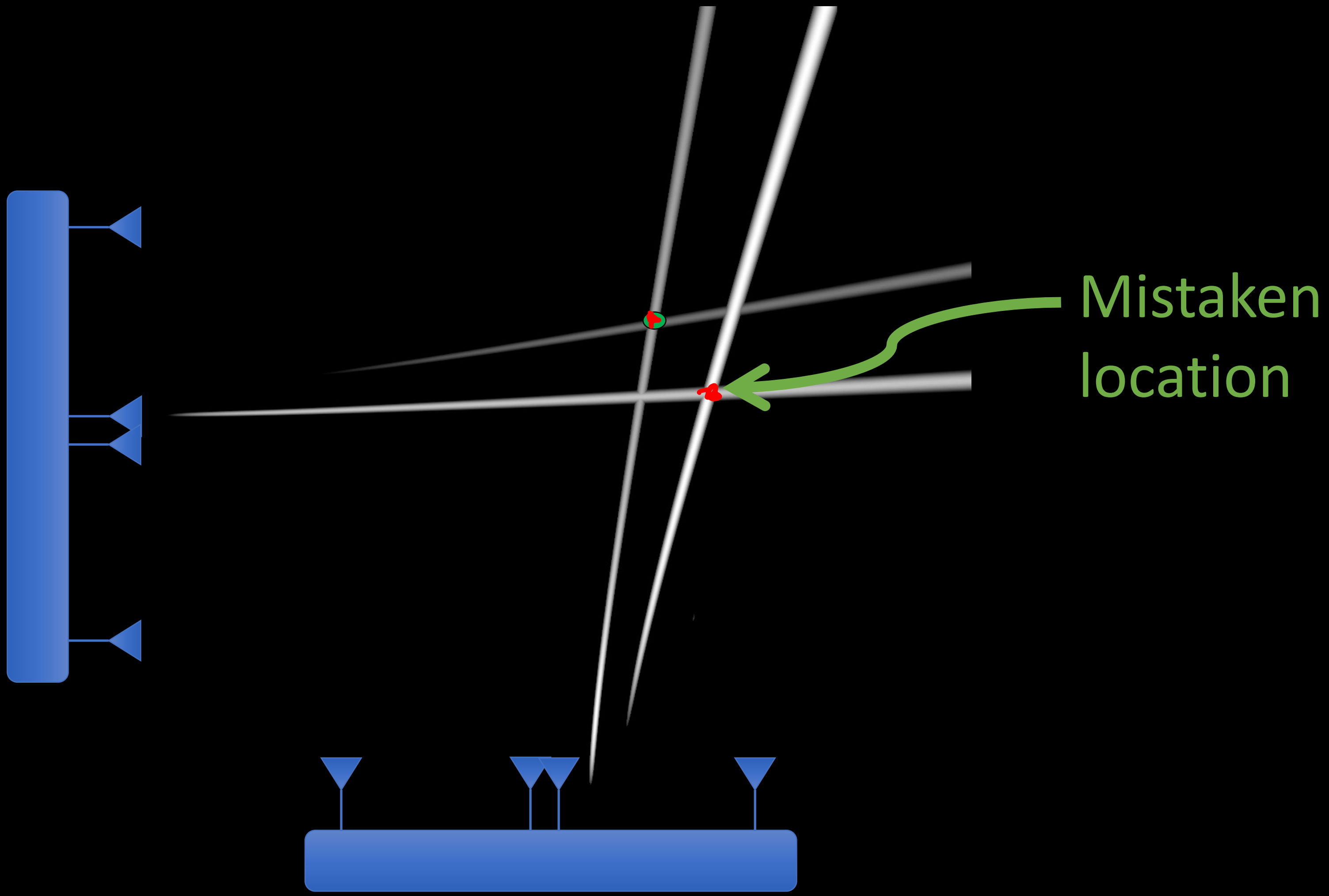
Noiseless Scenario



Noiseless Scenario

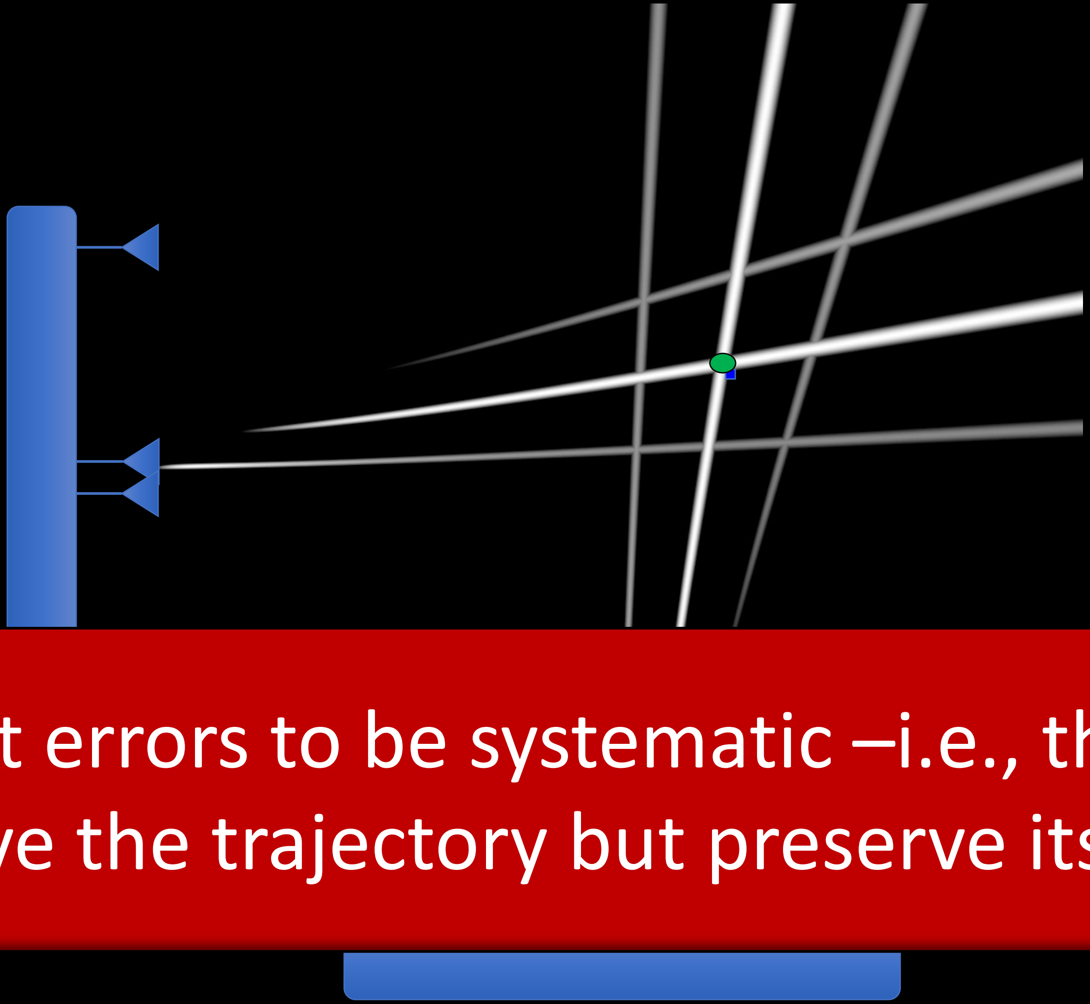


Impact of Noise



Mistaken location

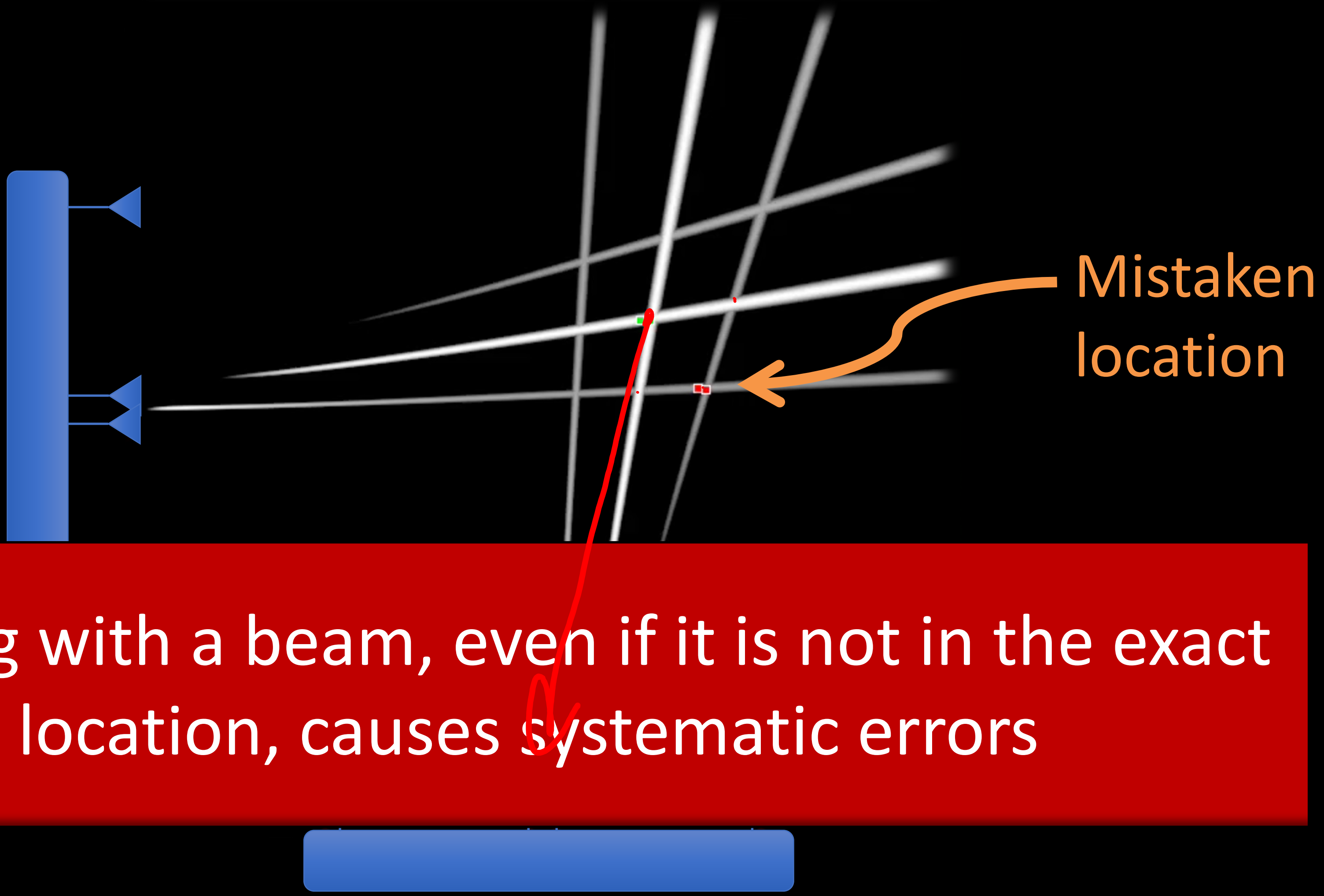
Impact of Noise



Want errors to be systematic –i.e., they may move the trajectory but preserve its shape

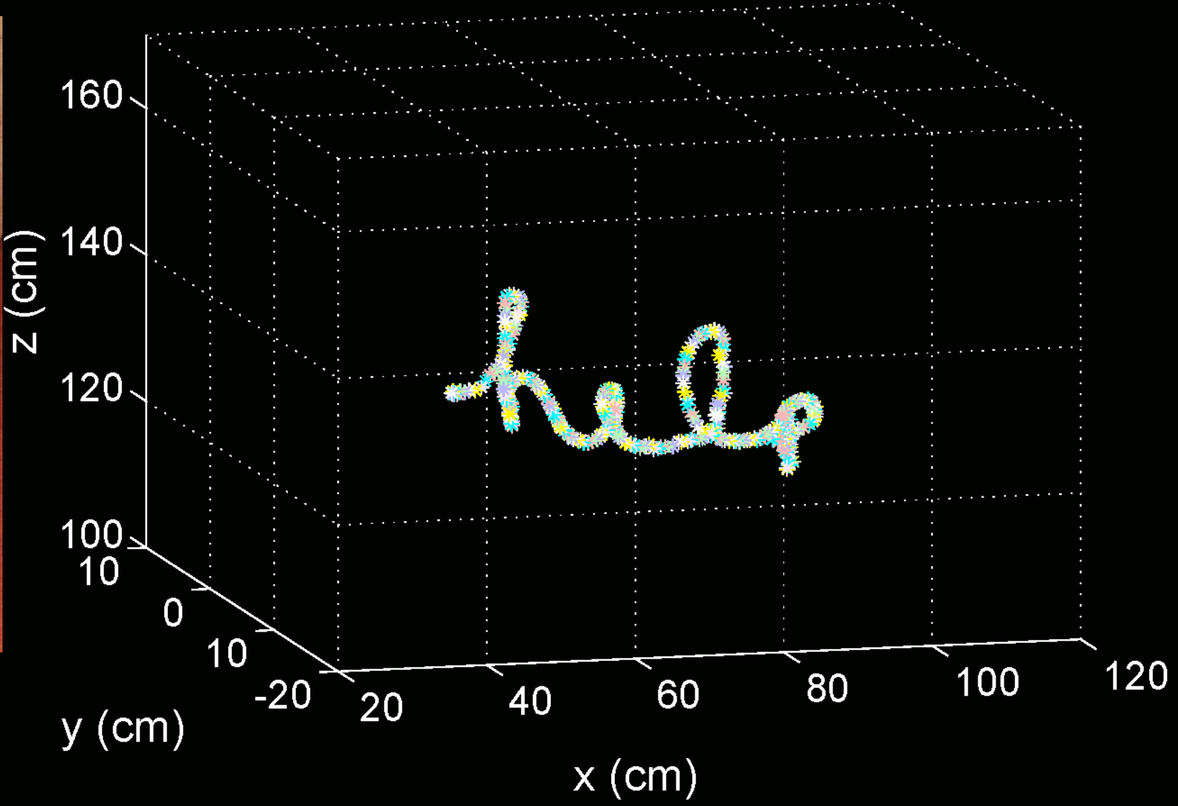
Idea: Stick with your choices

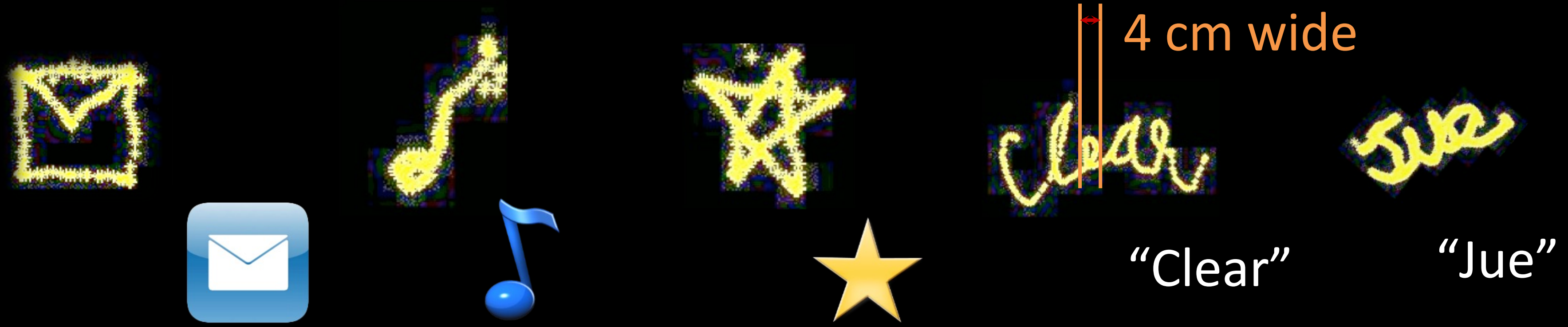
Idea: Stick with your choices



Sticking with a beam, even if it is not in the exact location, causes systematic errors

Enabling Virtual Touch Screens in the Air





RFIDraw Localization

Pros:

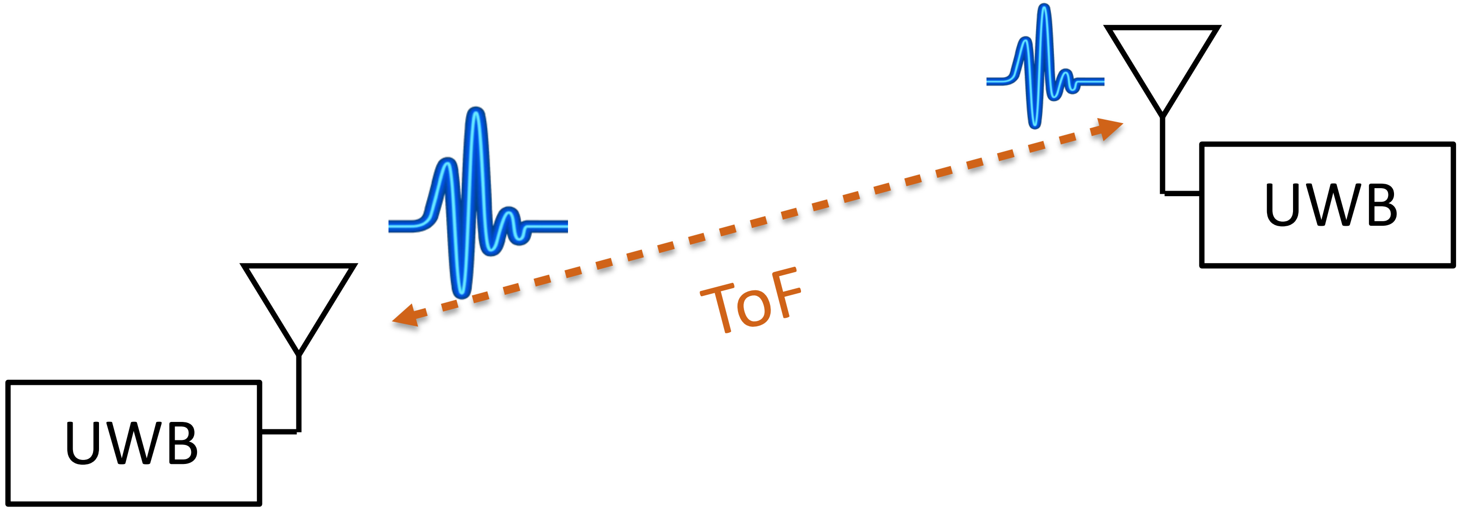
- Accurate RFID Tracking (4cm).
- Multi-Resolution Array→ Use few number of antennas
- No mobility or tagging environment

Cons:

- Accurate Tracking but not Localization
- Problematic in Multi-Path

How can we achieve cm RFID Localization?

UWB: Ultra-Wide Band

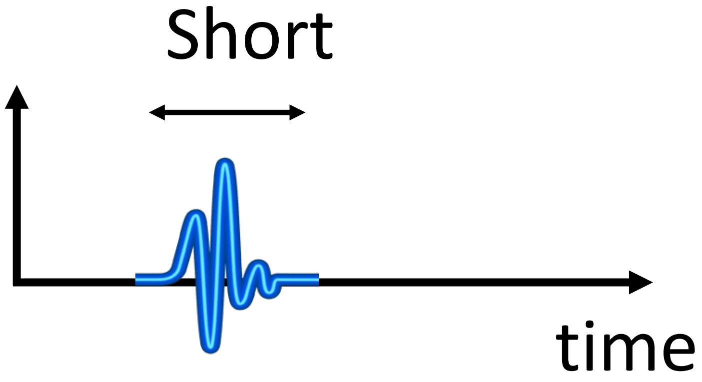


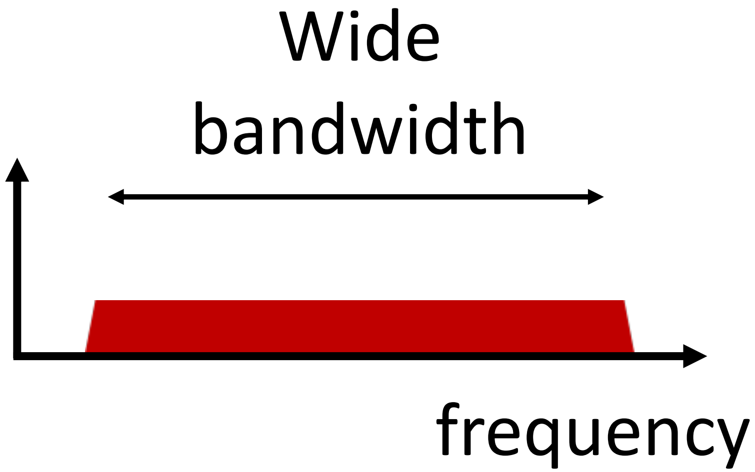
Localize by measuring the Time-of-flight

Distance = Time-of-flight × speed of light

UWB: Ultra-Wide Band

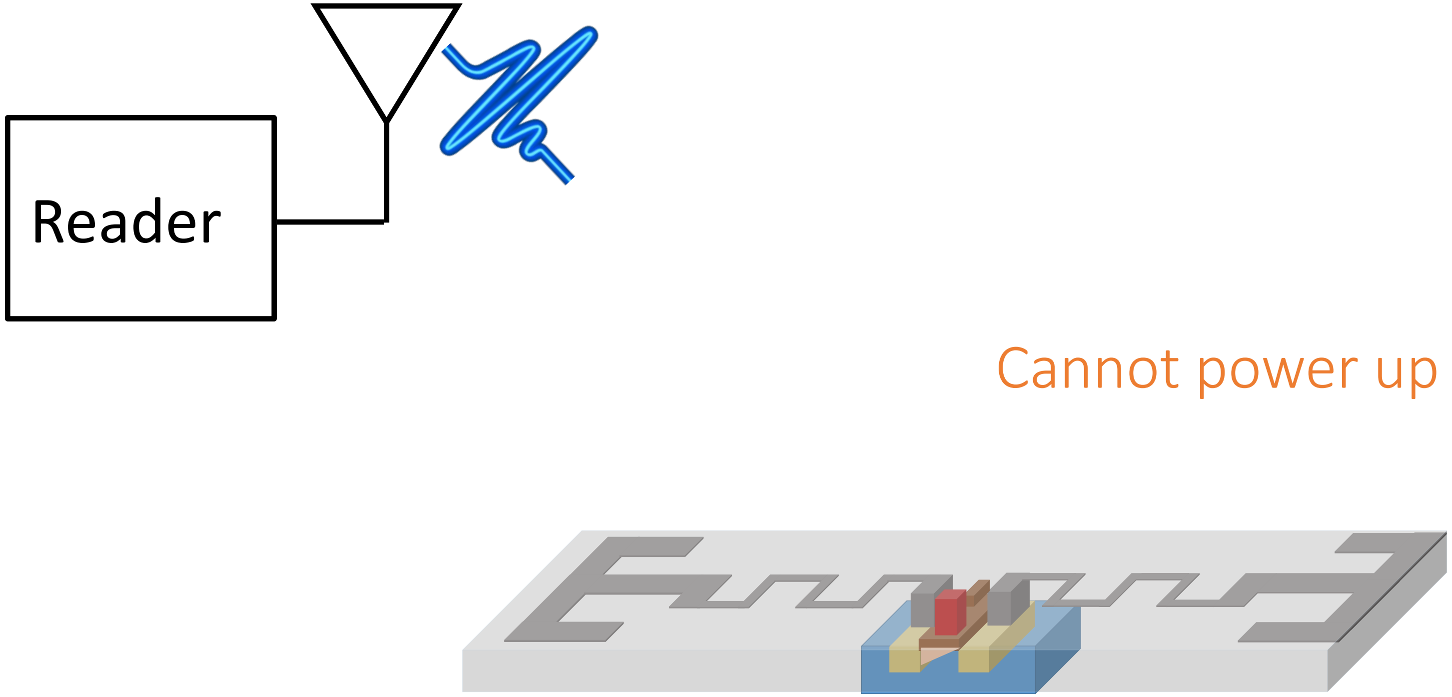
Short pulse allows measuring time at very fine granularity





Can we achieve wide bandwidth on battery-free off-the-shelf RFIDs?

How about we just transmit a very short pulse?

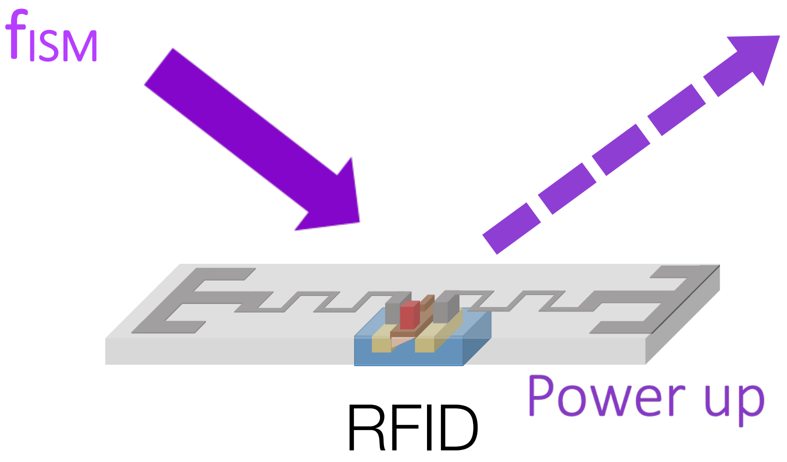


Cannot power up RFID

RFID

Problem: RFIDs cannot power up from a very short pulse

Problem: Battery-free RFIDs are designed to respond to a very narrowband signal



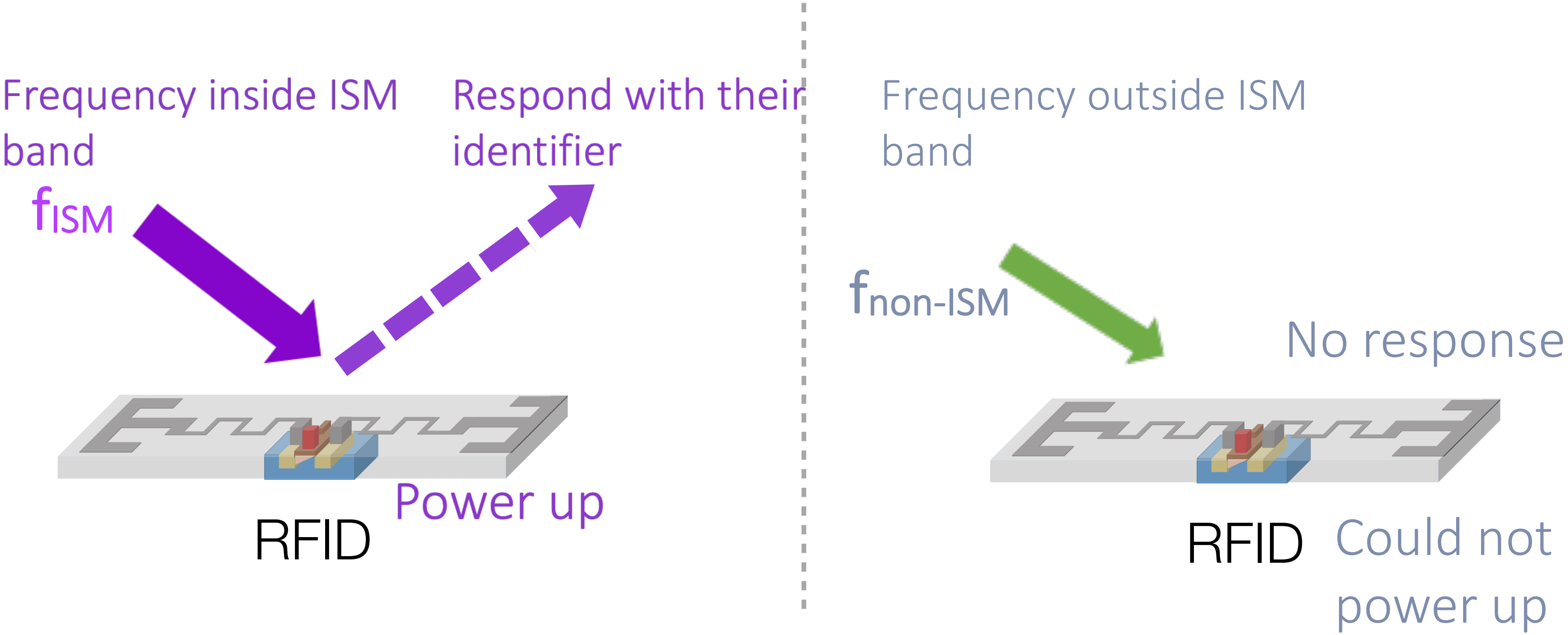
Frequency inside ISM band

f_{ISM}

Respond with their identifier

Power up

Problem: Battery-free RFIDs are designed to respond to a very narrowband signal



Frequency inside ISM band

f_{ISM}

Respond with their identifier

Power up

RFID

Frequency outside ISM band

$f_{non\text{-}ISM}$

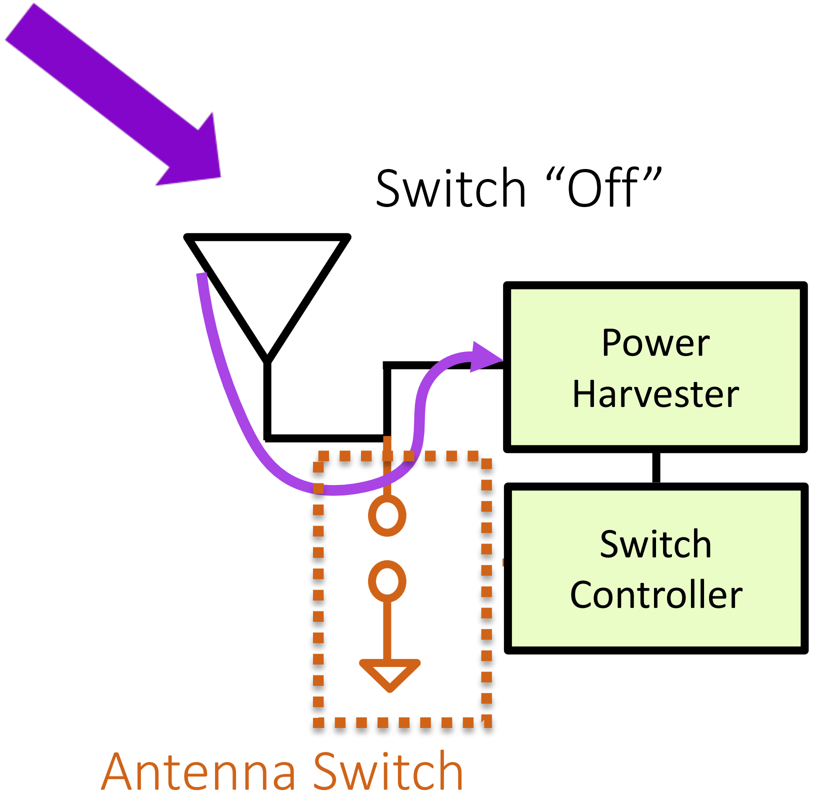
No response

RFID

Could not power up

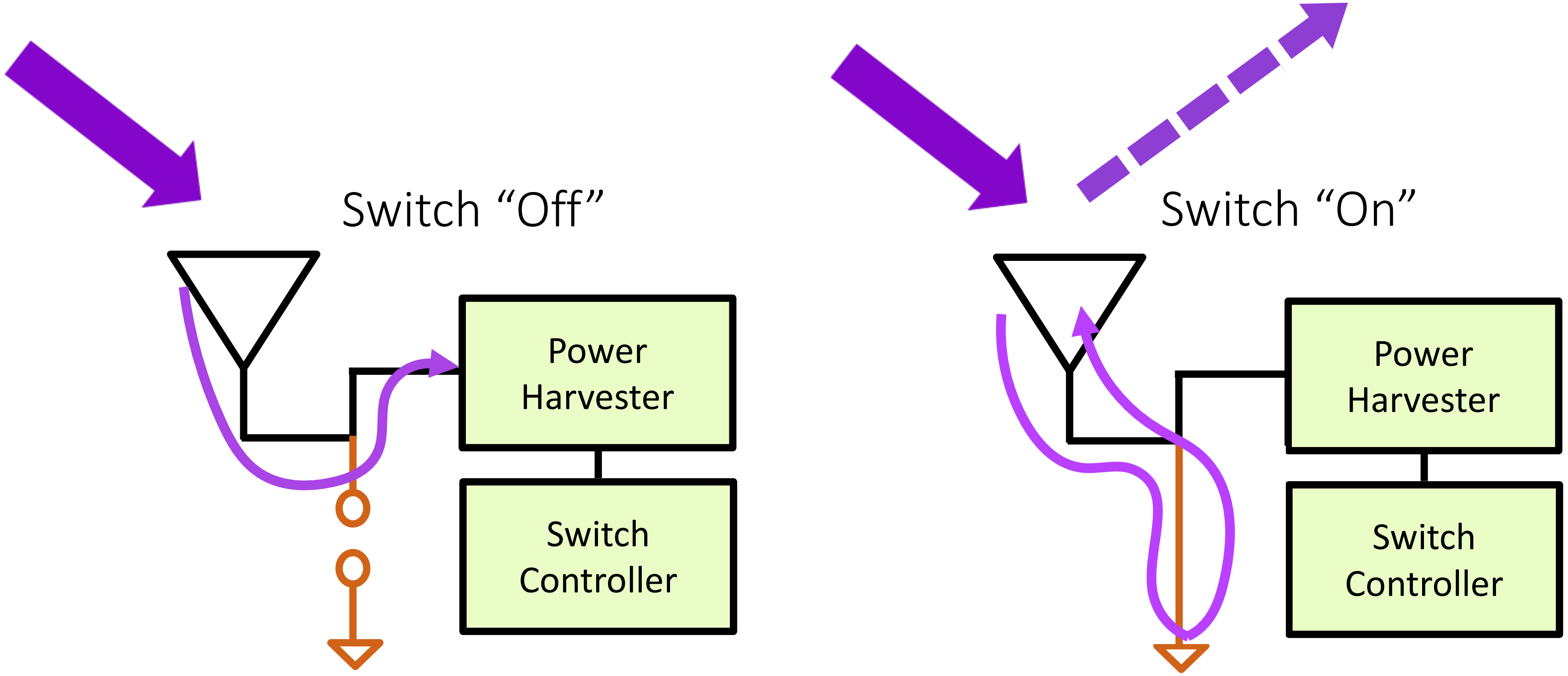
Battery-Free RFIDs are optimized to harness power from signals within the UHF ISM band (very narrow for time-of-flight estimation)

<u>RFind Key Idea:</u>
RFID Modulation is Frequency Agnostic



Simplified RFID schematic

Key Realization:
RFID Modulation is Frequency Agnostic



Switch “Off”

Switch “On”

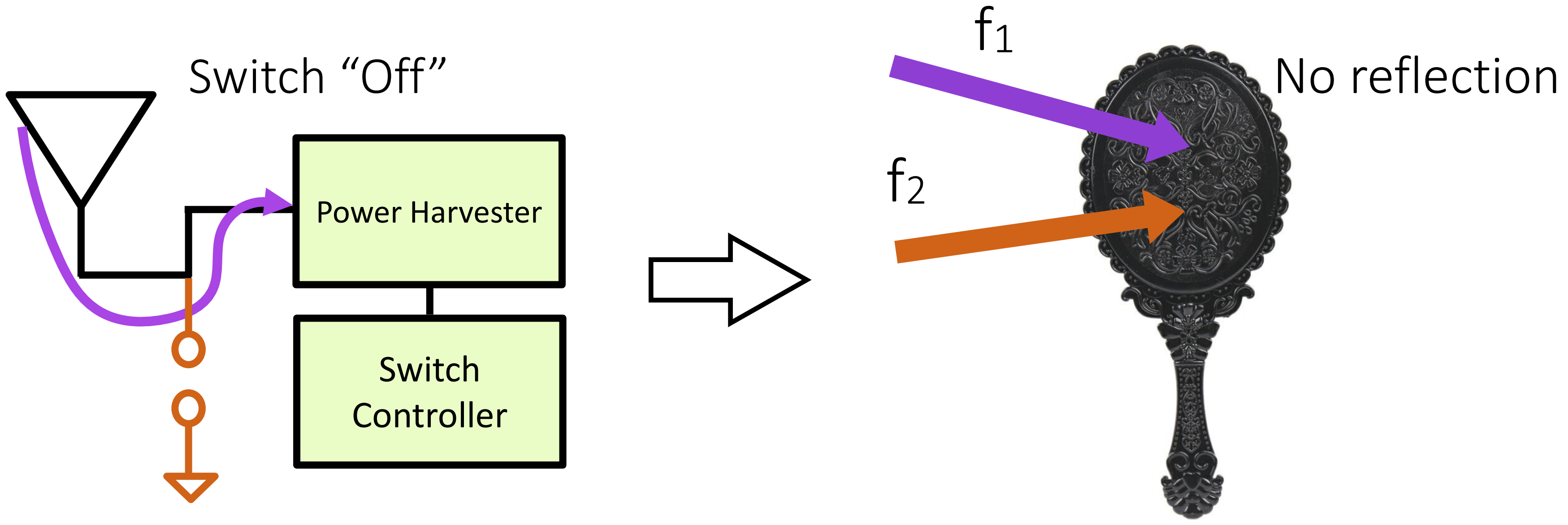
Power Harvester

Switch Controller

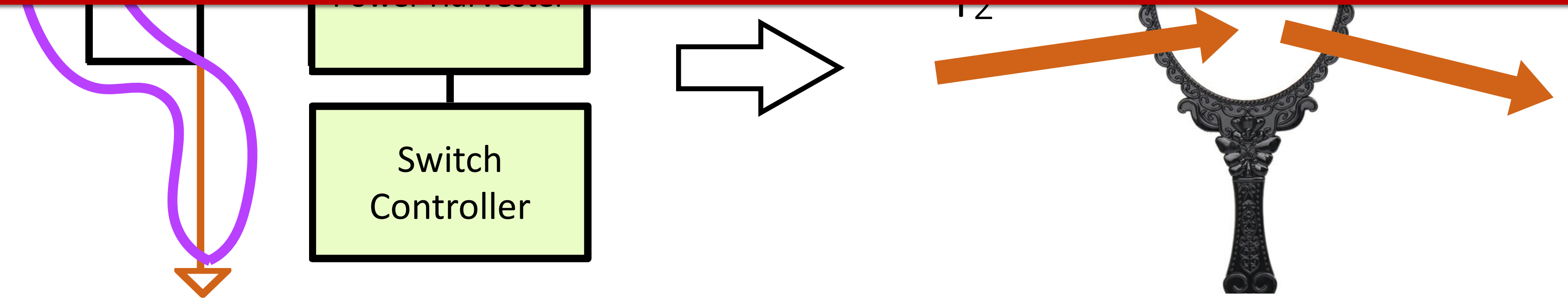
Power Harvester

Switch Controller

Key Realization:
RFID Modulation is Frequency Agnostic



But we need to power up RFID in the first place

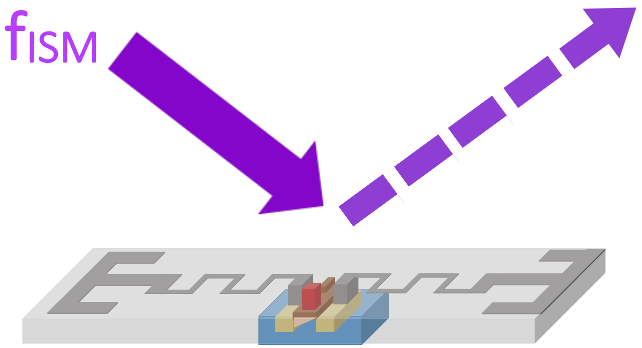


Dual-Frequency Excitation

A technique that decouples powering up from sensing in RFID localization

Dual-Frequency Excitation

Battery-Free RFIDs are optimized to harness power from signals within the UHF ISM band (very narrow for localization)



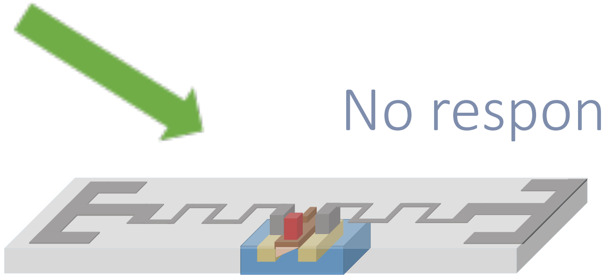
Frequency inside ISM band

Respond

f_{ISM}

Power up

RFID



Frequency outside ISM band

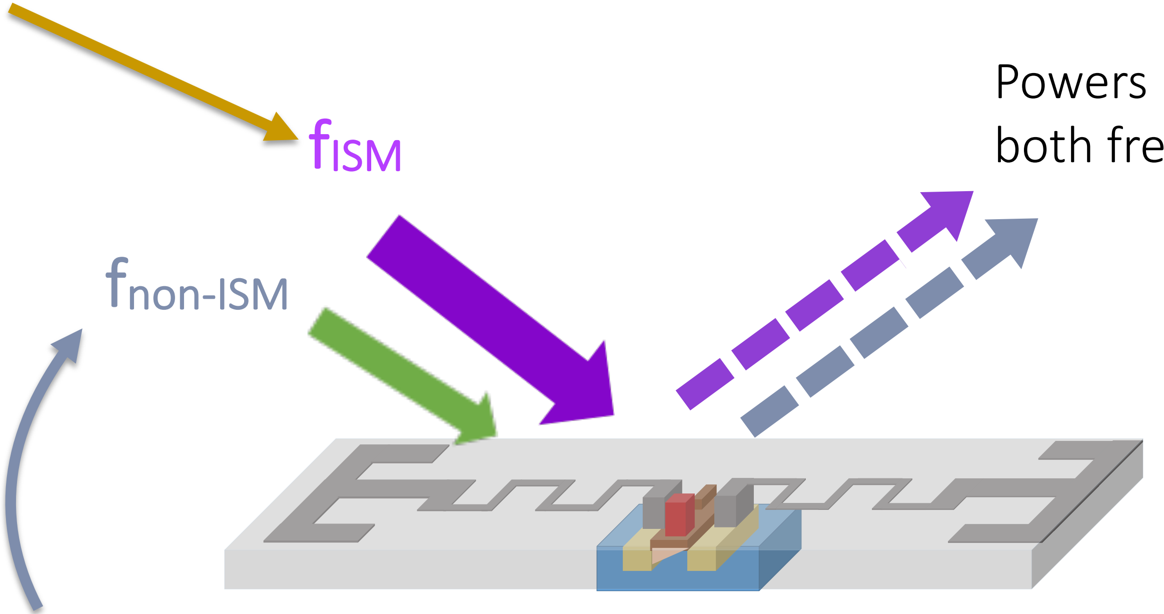
$f_{non\text{-}ISM}$

No response

RFID

Could not power up

Dual-Frequency Excitation



To power up and communicate with RFID

f_{ISM}

$f_{non\text{-}ISM}$

Powers up and modulates both frequencies

Power up

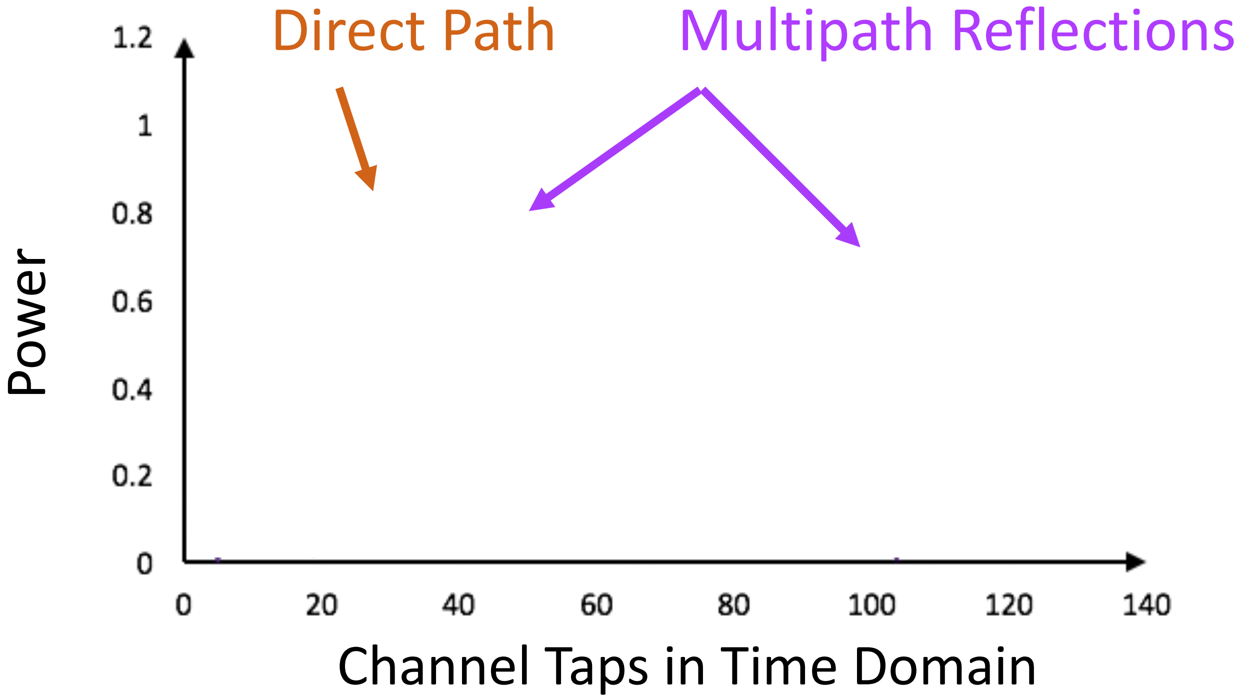
Vary the sensing frequency over a wide bandwidth

Wide Bandwidth → Time-of-flight → Accurate Localization

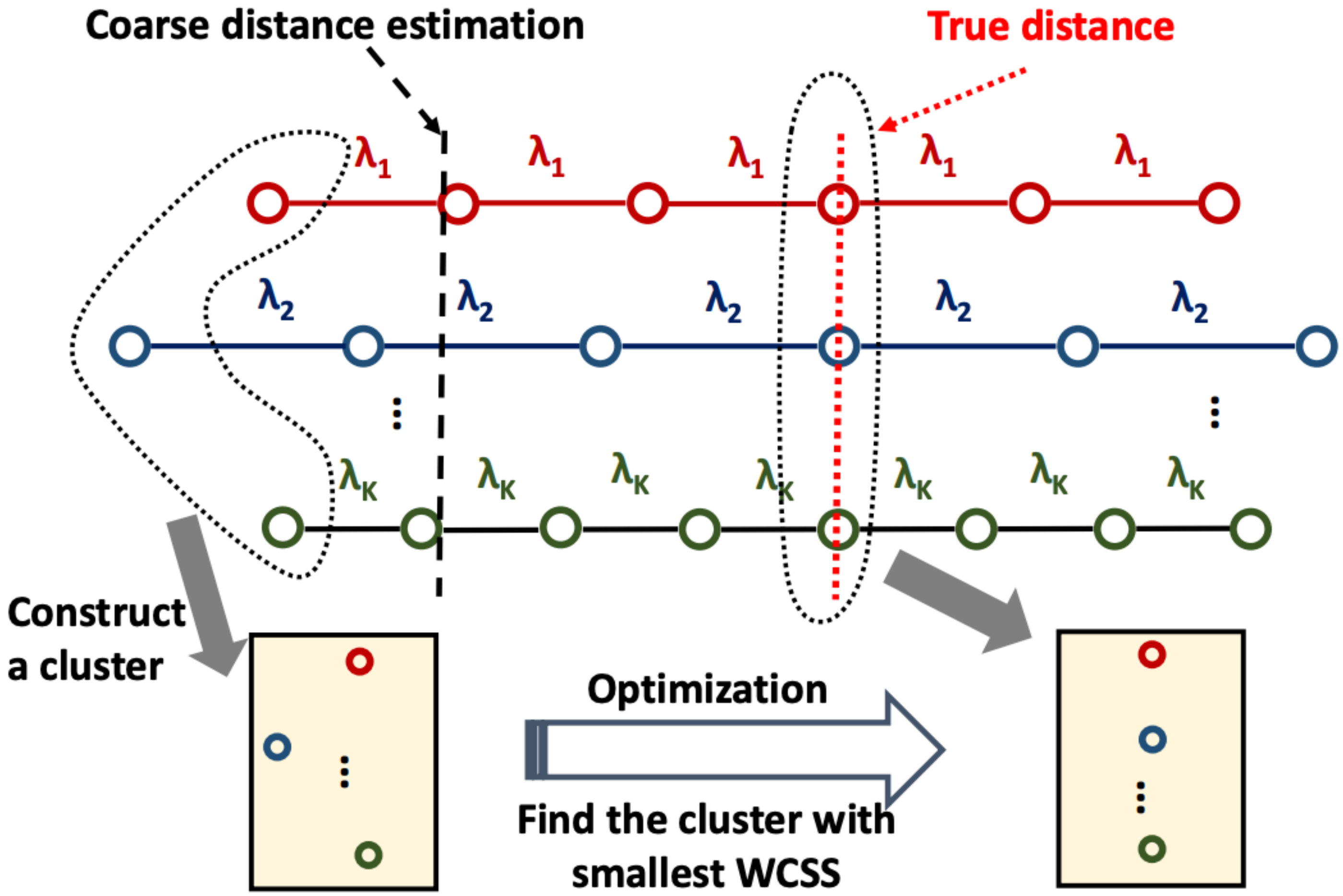
From Wide Bandwidth to Accurate Time-of-Flight Estimation

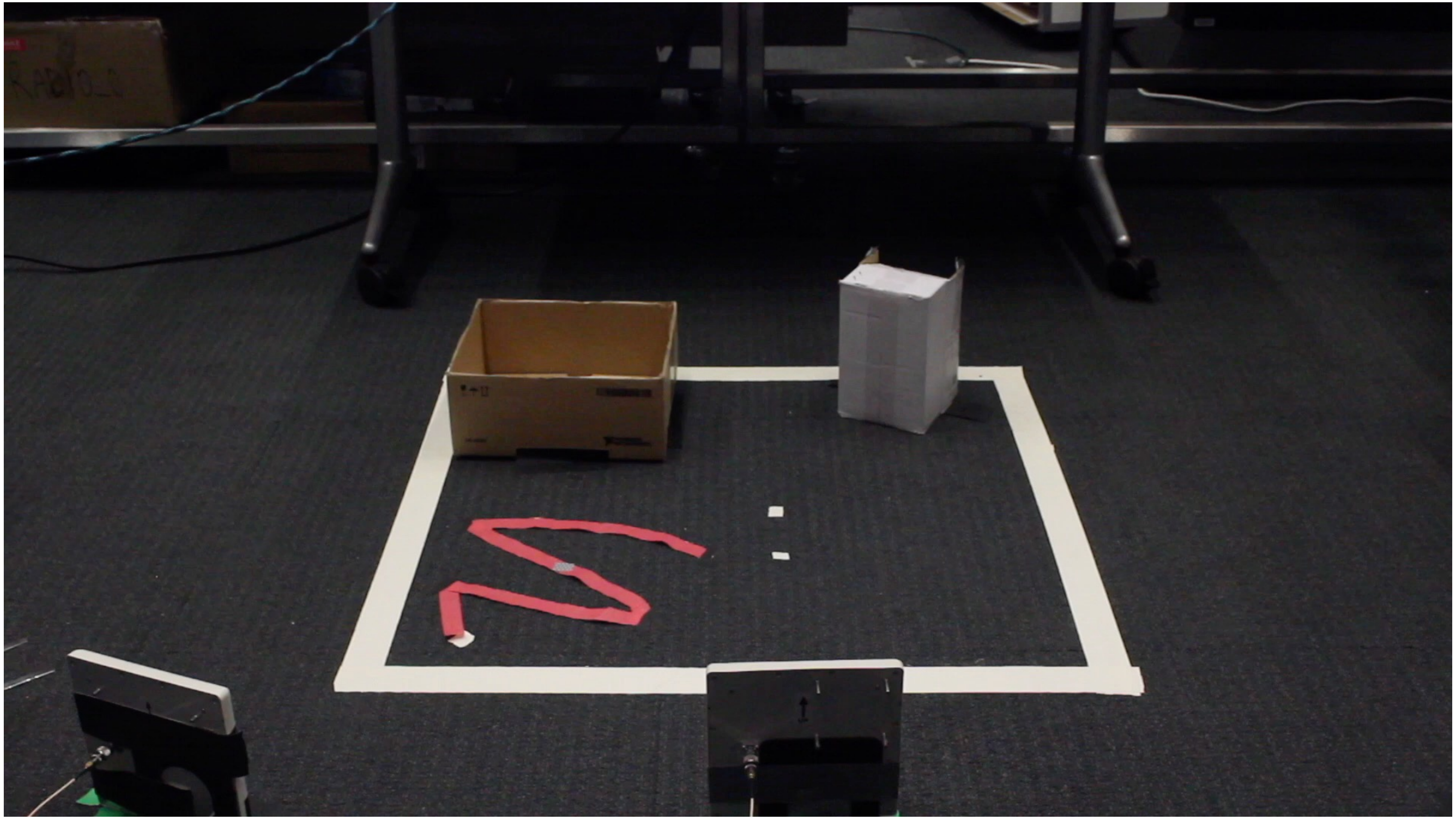
Estimating the Time-of-Flight

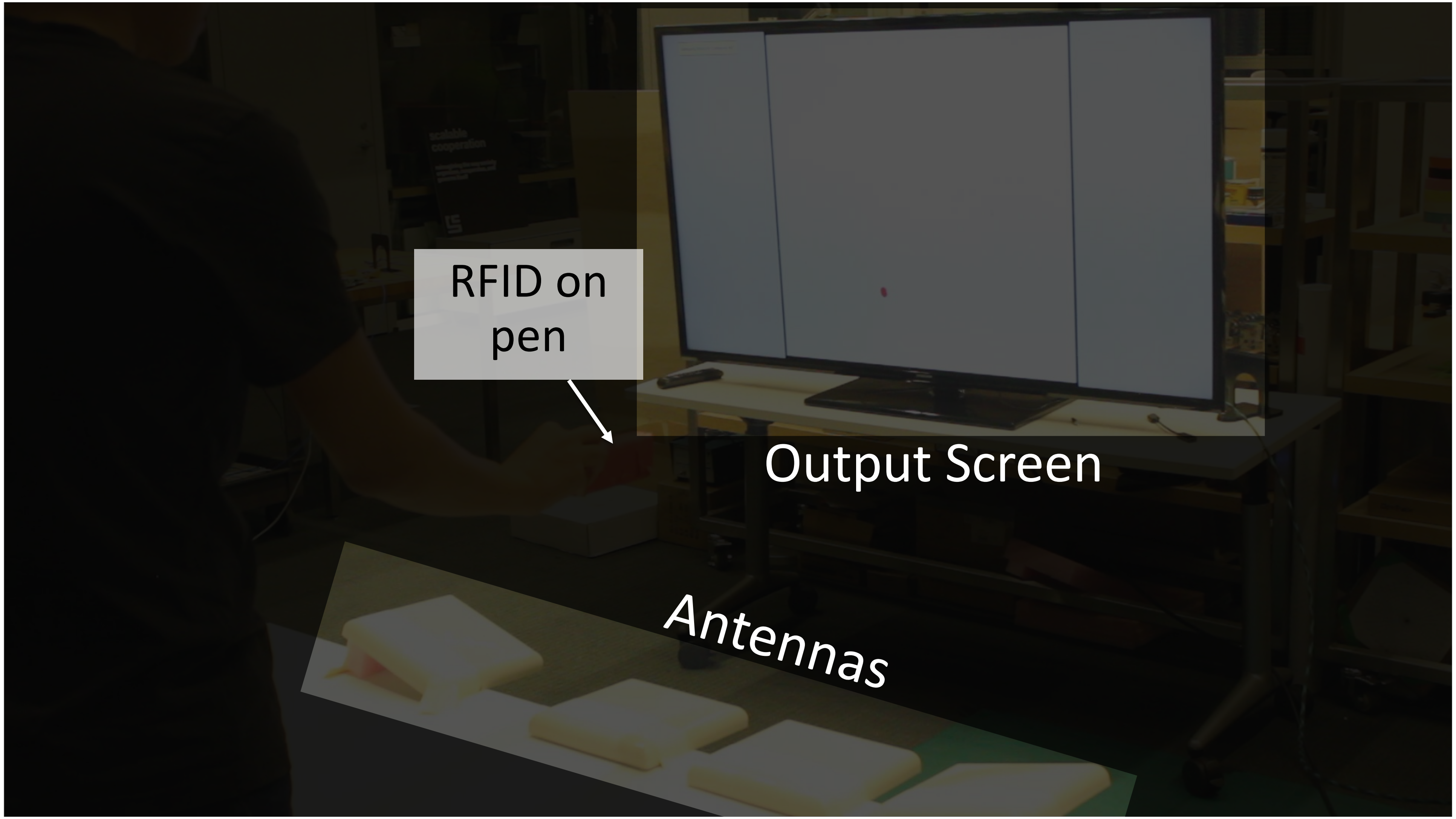
- Wide bandwidth can be used to estimate the channel taps in the time domain
  - Perform Inverse Fourier Transform



Range Estimation







RFID on pen

Output Screen

Antennas

Wireless Localization / Positioning

Last Lecture: WiFi	This Lecture: RFID
Method 1: Identity **Method 2: RSSI** (Trilateration, Fingerprinting) **Method 3: Phase** (Angle of Arrival, Triangulation) **Method 4: AoA** (Angle of Arrival, Triangulation) **Method 5: ToF** (Time of Flight) **Method 6: TDoA** (Time Difference of Arrival)	Ultra-low power localization! **System 1: PinIt** **Method:** Multipath Profile with SAR & DTW **System 2: RFIDraw** **Method:** Multi-Resolution Arrays **System 3: RFind** **Method:** Bandwidth Stitching

Next class

- Wed Jan 25th
- Wireless Localization
  - ✓ WiFi
  - ✓ RFID
  - Device-free Human Localization