ECE 598HH: Advanced Wireless Networks and Sensing Systems

Lecture 11: Localization Part 2

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

Wireless Localization / Positioning

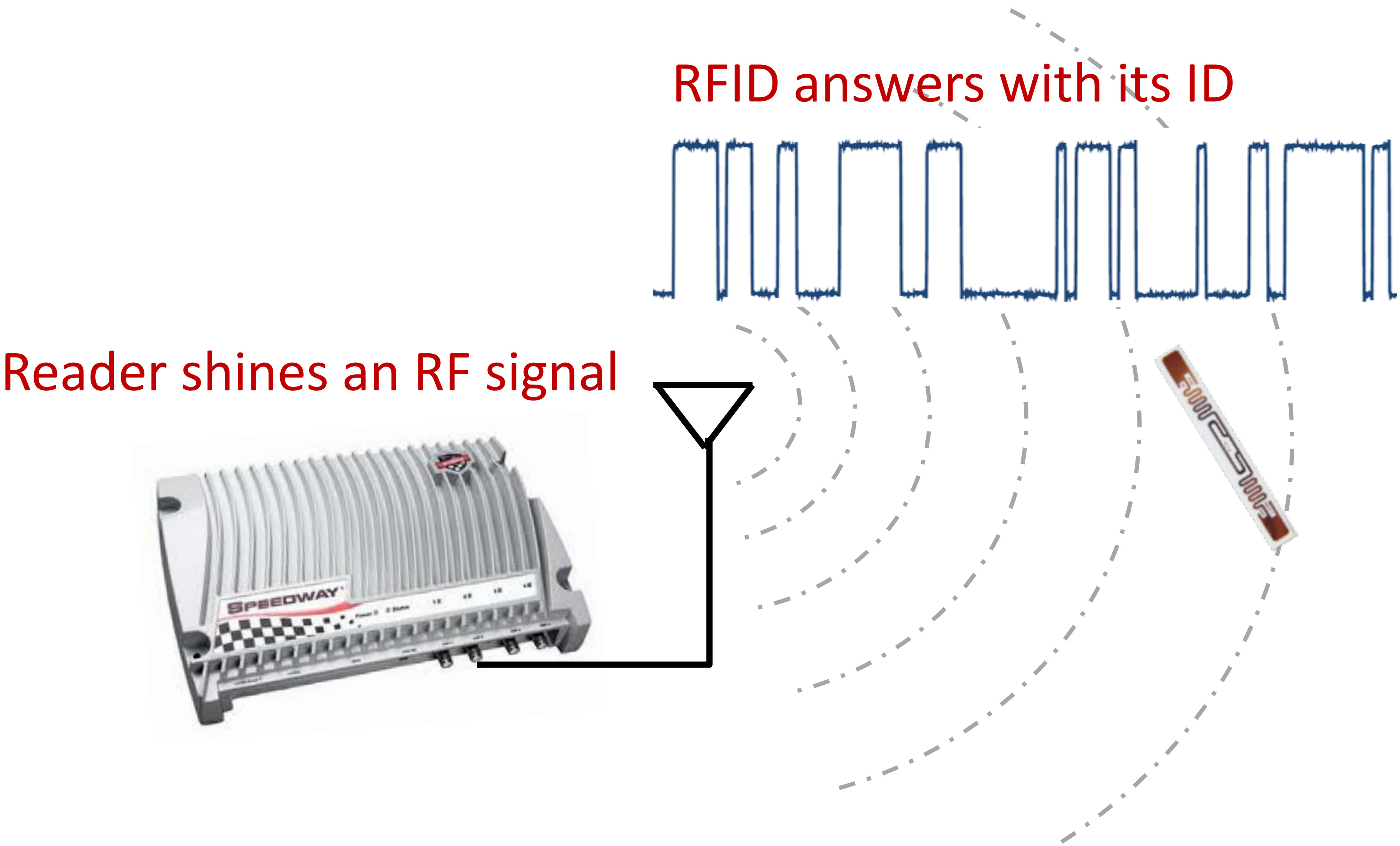
Last Lecture: WiFi	This Lecture: RFID
Method 1: RSSI (Trilateration, Fingerprinting)	Ultra-low power localization!
Method 2: AoA (Angle of Arrival, Triangulation)	**System 1: PinIt** **Method:** Multipath Profile with SAR & DTW
Method 3: Antenna Arrays (Multipath Profile)	**System 2: RFIDraw** **Method:**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

RFID: Radio Frequency IDentification

Battery-free RF stickers with unique IDs

RFID: Radio Frequency IDentification

Battery-free RF stickers with unique IDs



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

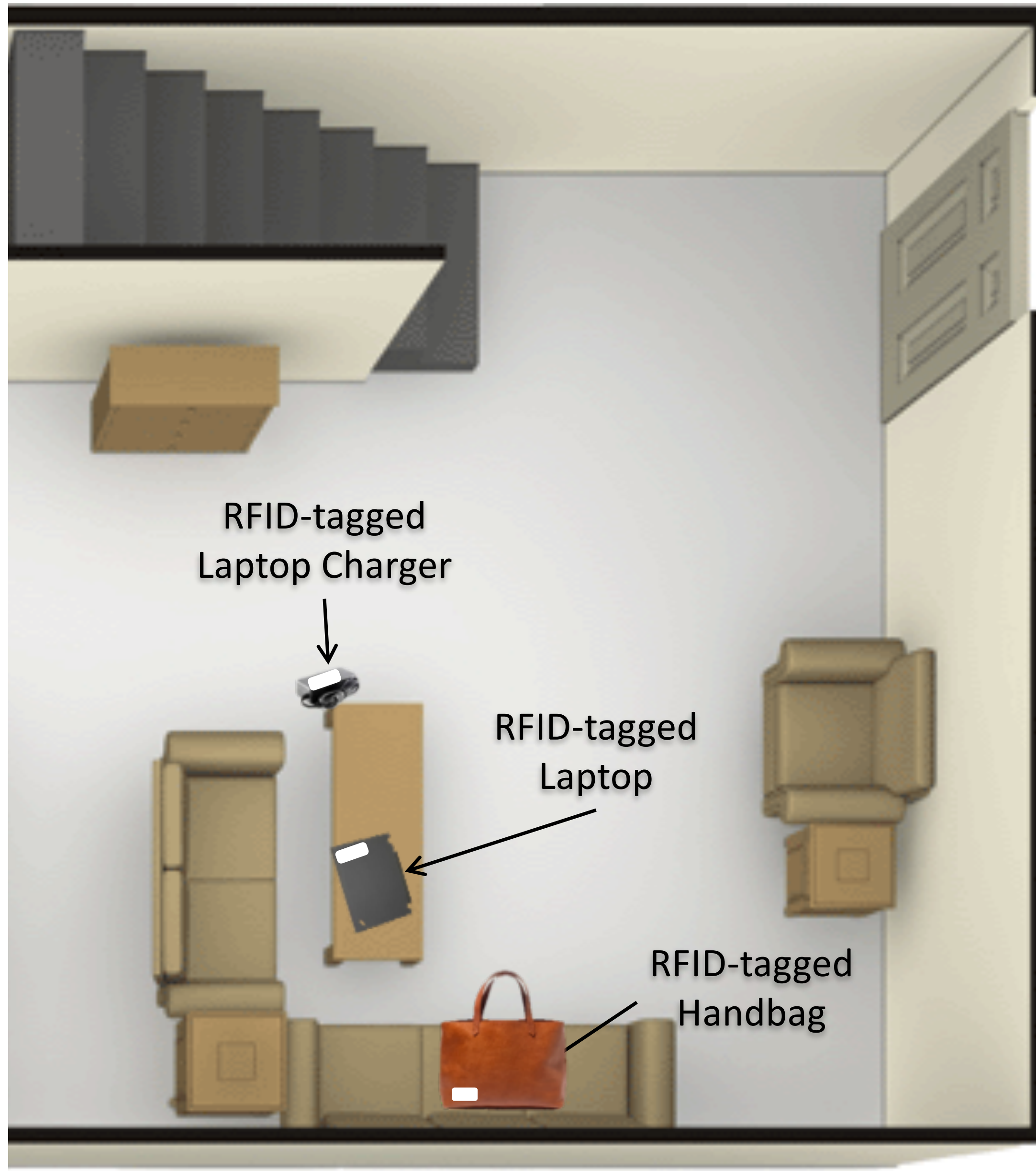
No more customer checkout lines

If we can locate RFID to within 10 to 15cm

No more customer checkout lines

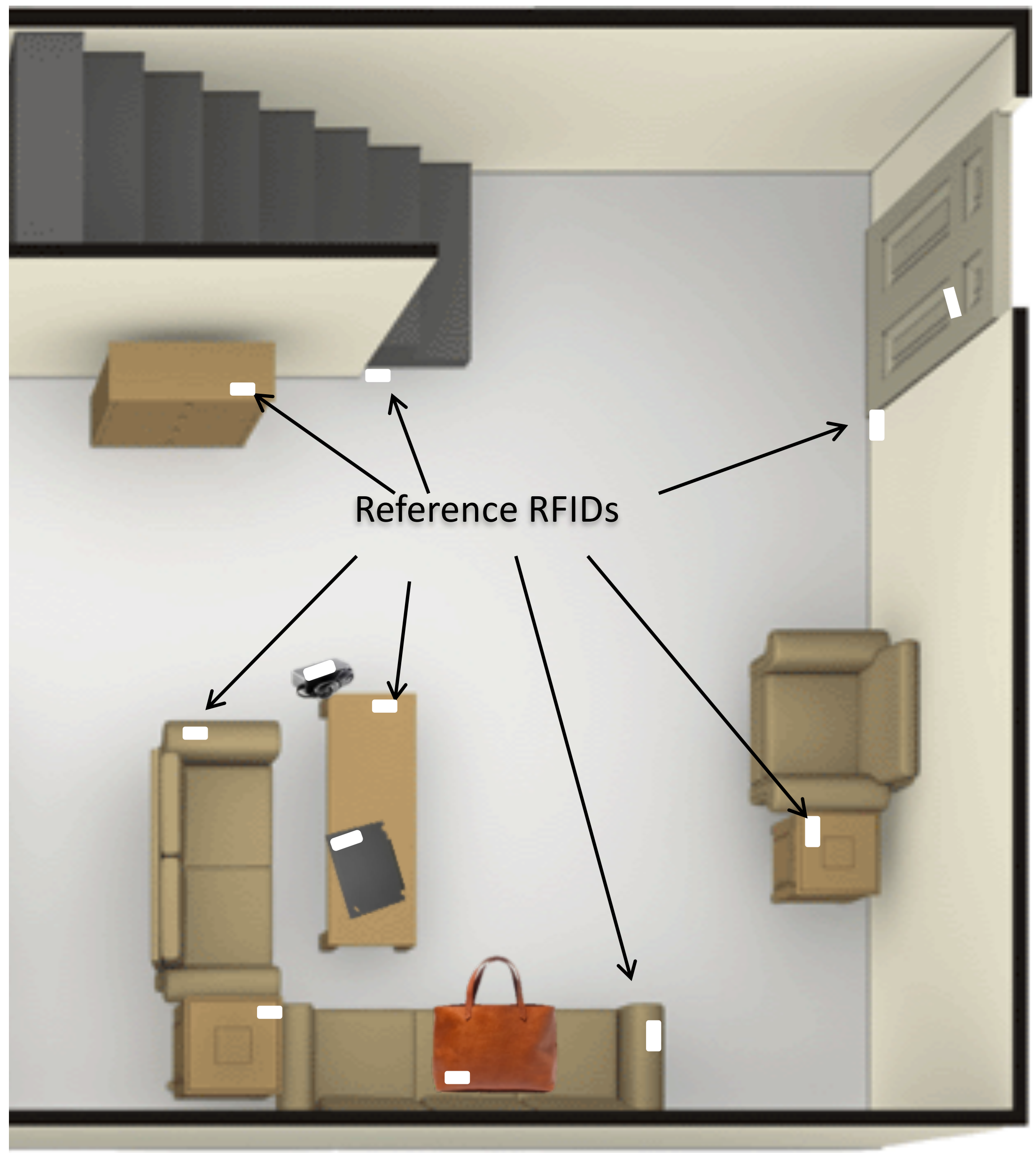
If we can locate RFID to within 10 to 15cm

Smart Homes and Smart Objects



If we can locate RFID to within 10 to 15cm

Smart Homes and Smart Objects

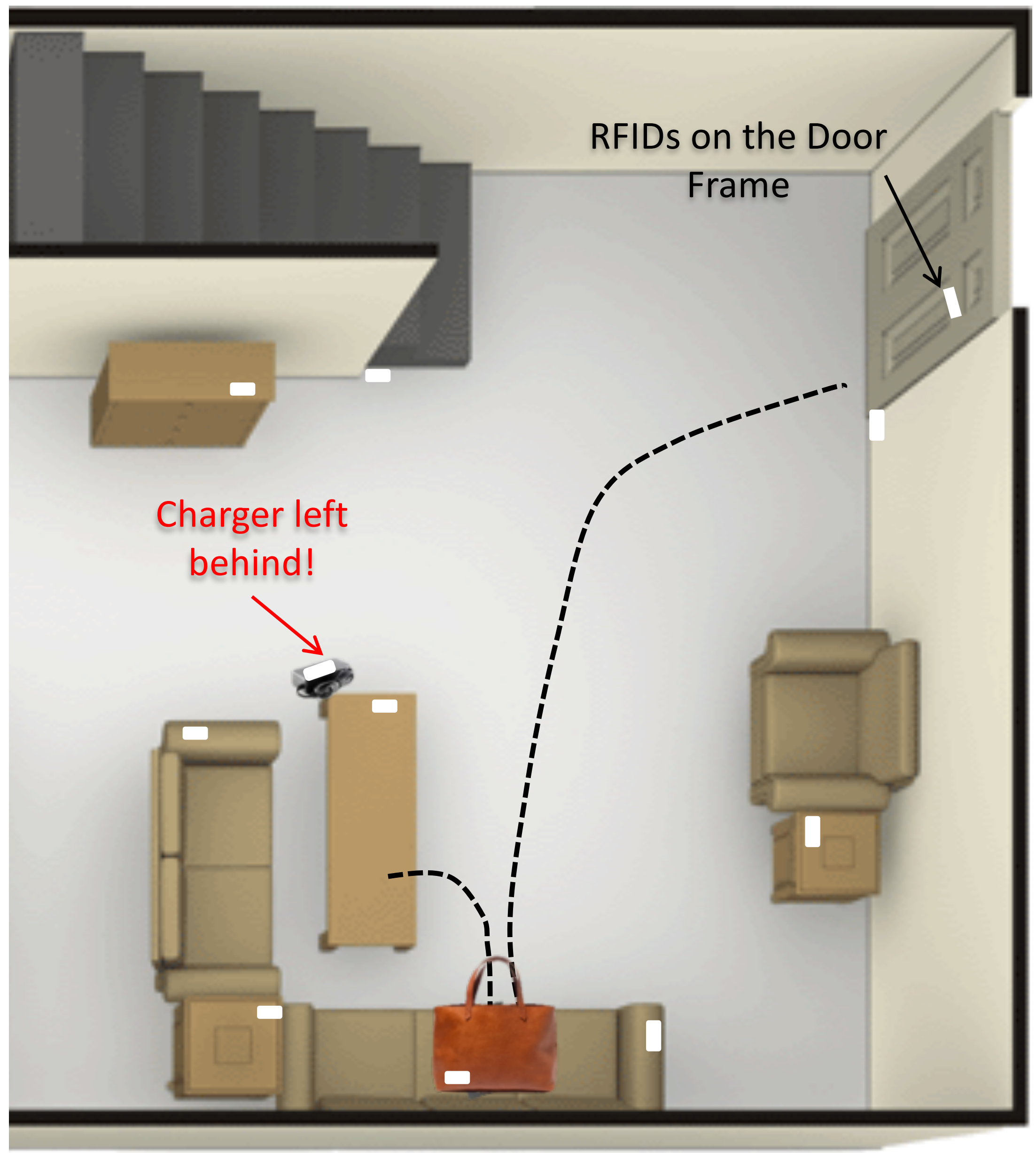


If we can locate RFID to within 10 to 15cm

Smart Homes and Smart Objects

If we can locate RFID to within 10 to 15cm

Smart Homes and Smart Objects



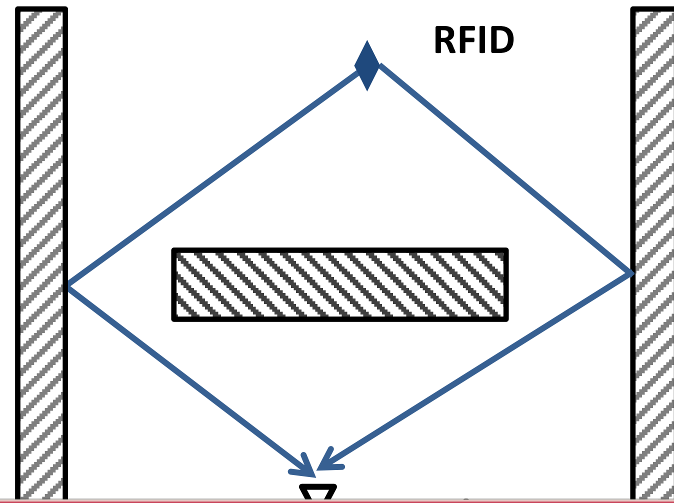
Many applications can be enabled by 10-15 cm RFID localization

Why don’t we have accurate RFID localization?

The Challenge: Multipath Effect

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

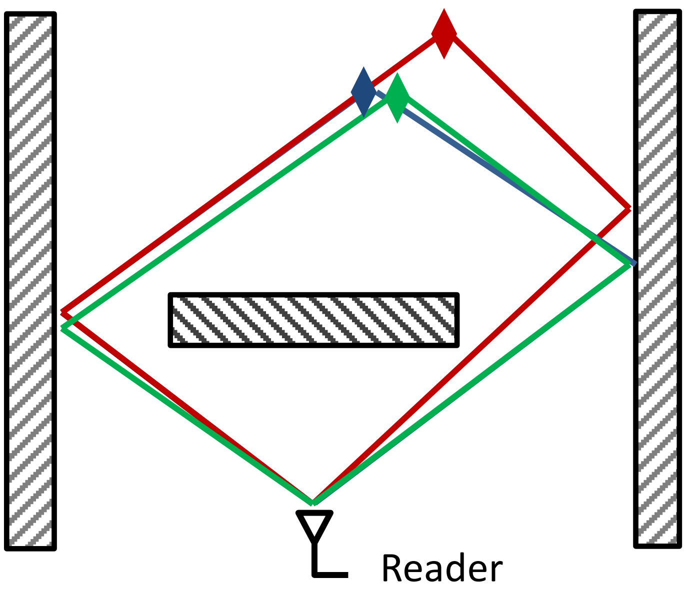
But, signal bounces off objects in the environment



Multipath propagation limits the accuracy of RFID localizations

PinIt Exploits Multipath

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



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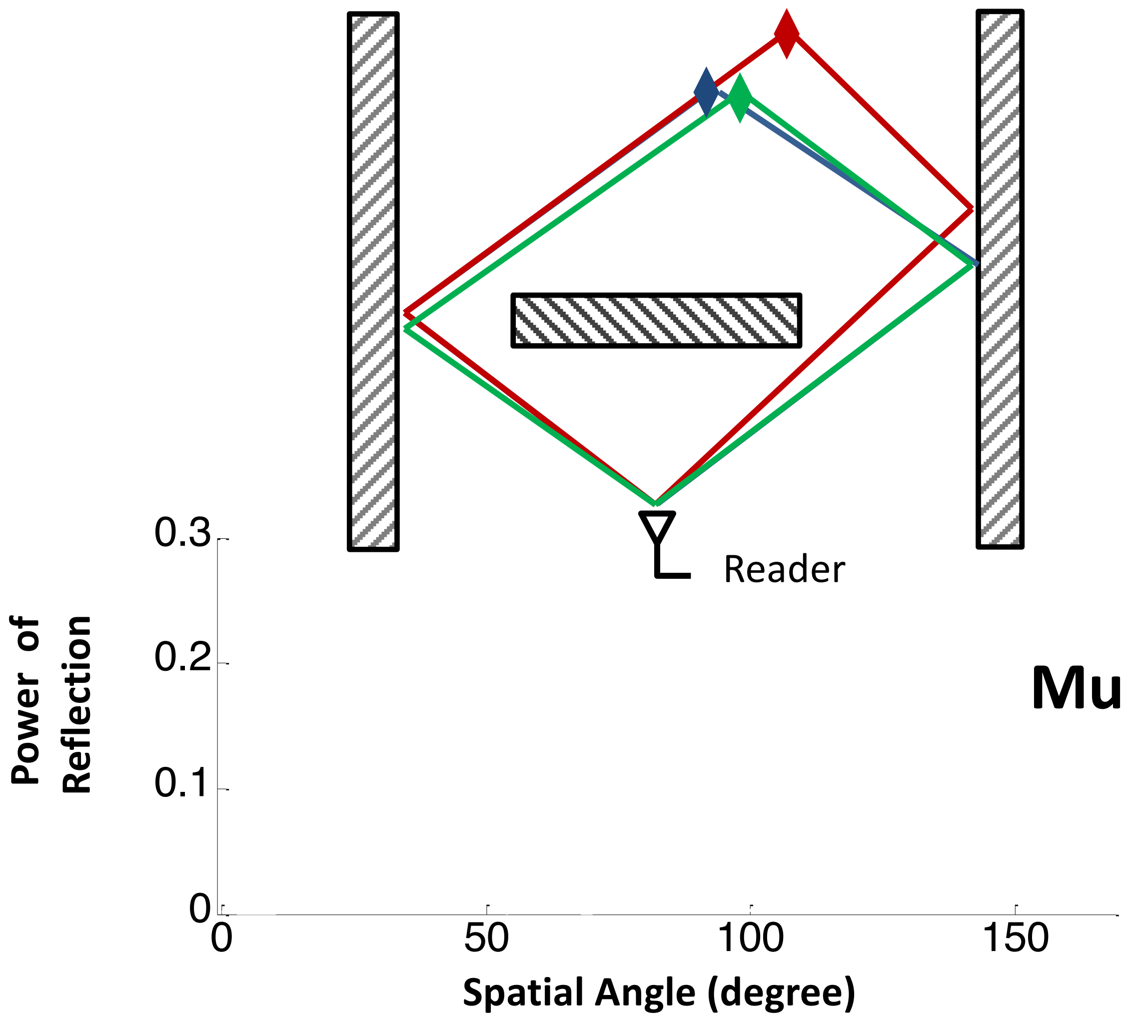
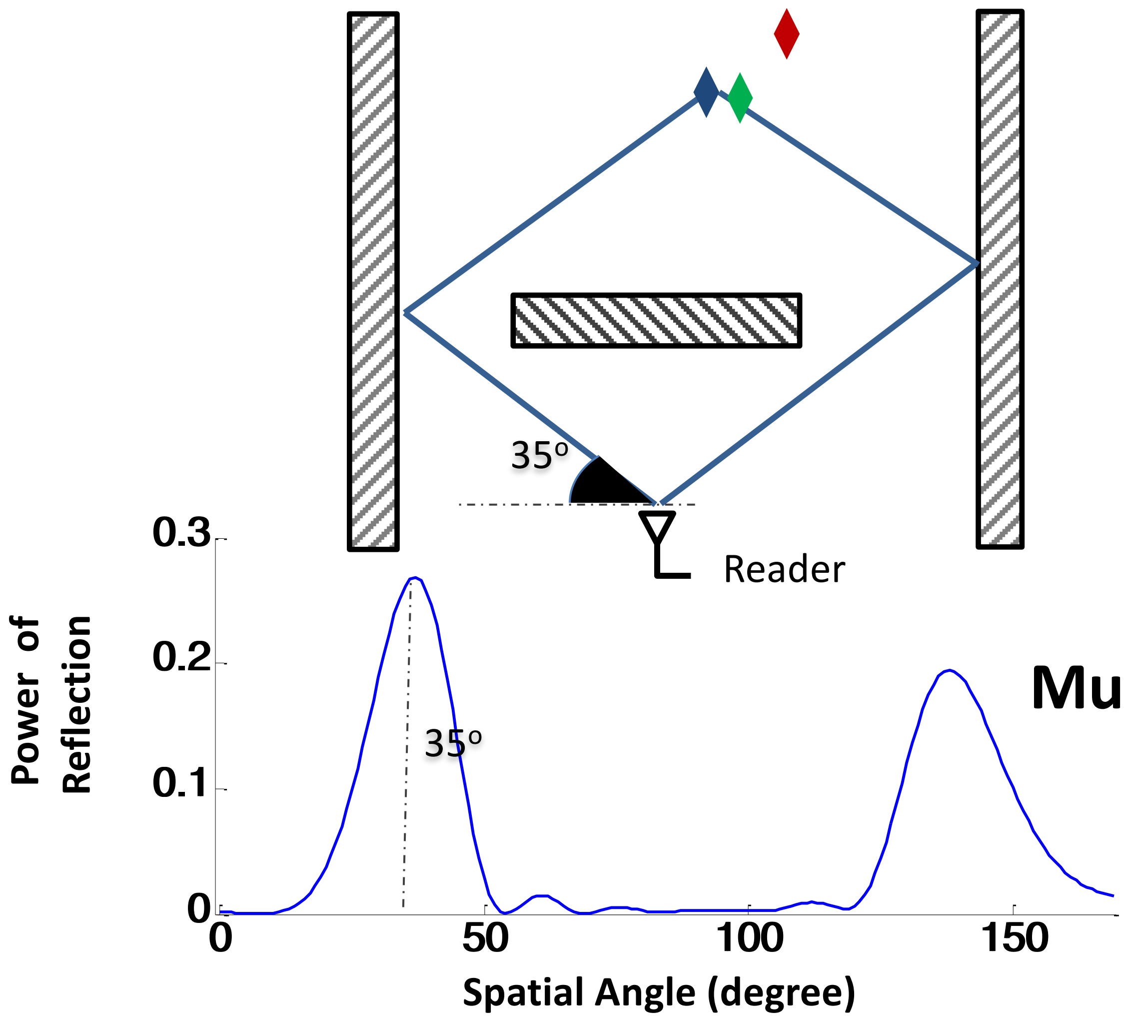


Multipath Profiles

PinIt Exploits Multipath

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



Multipath Profiles

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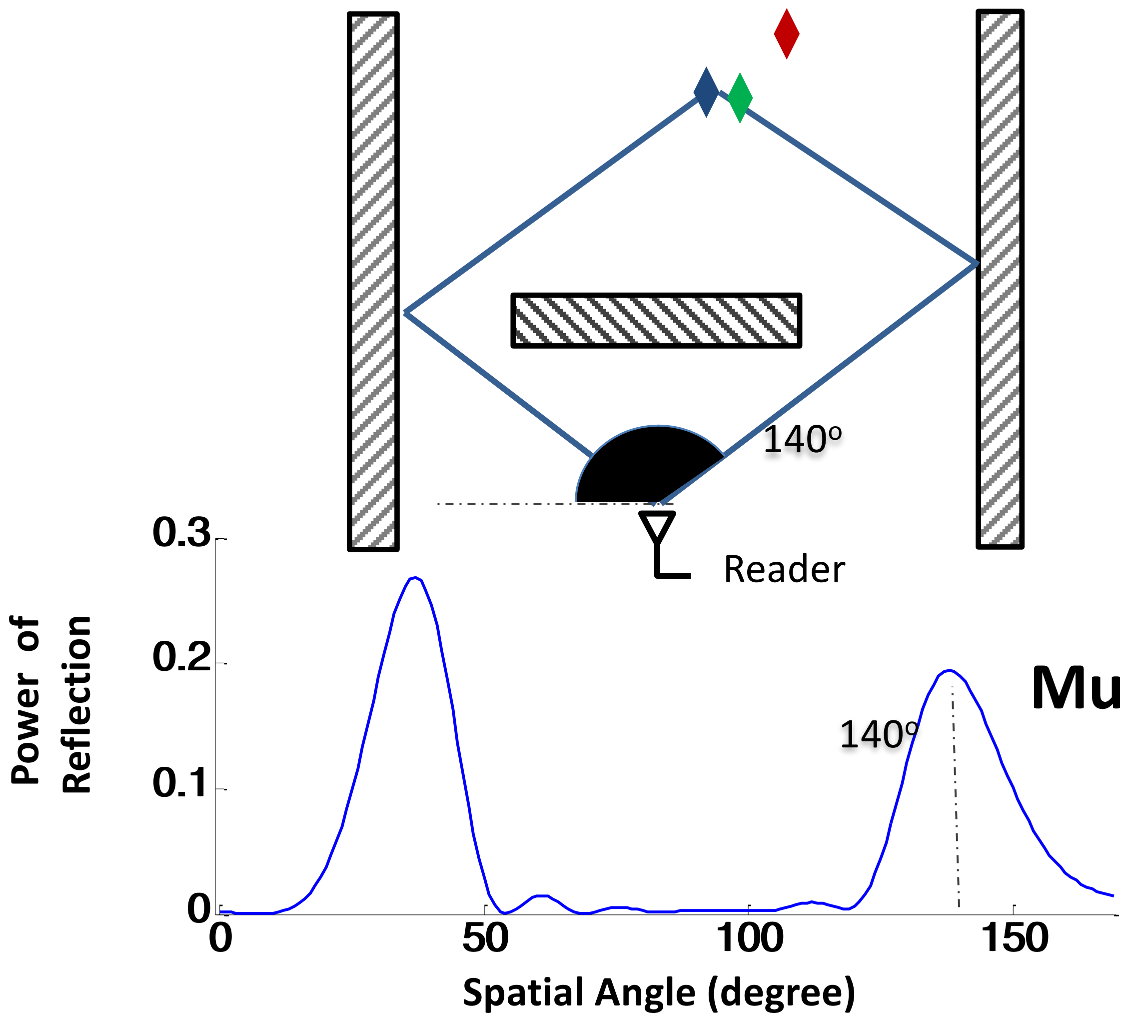
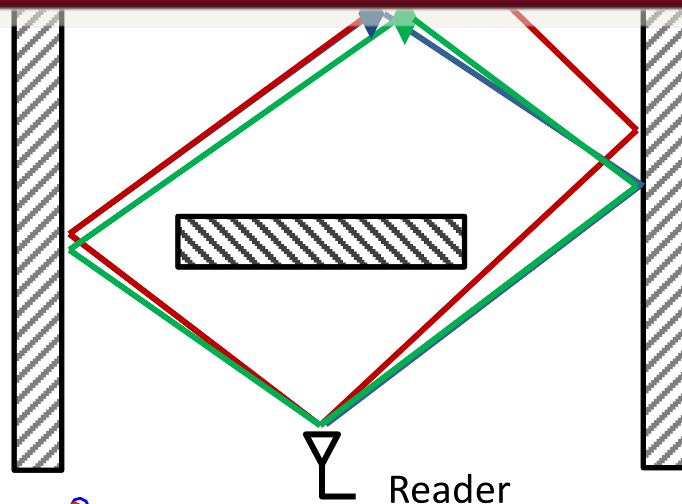
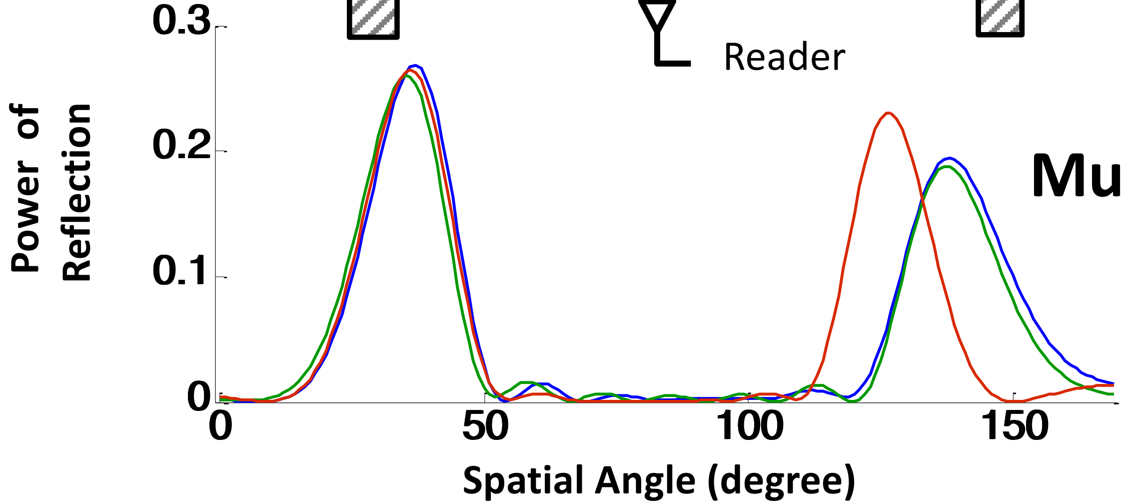


Multipath Profiles

PinIt Exploits Multipath

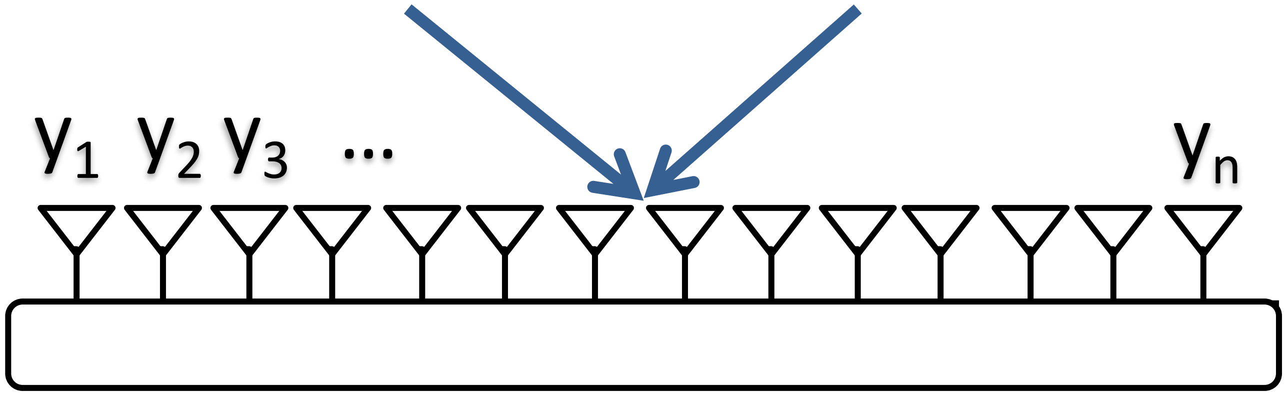
Nearby RFIDs have similar profiles with smaller shifts in the peaks



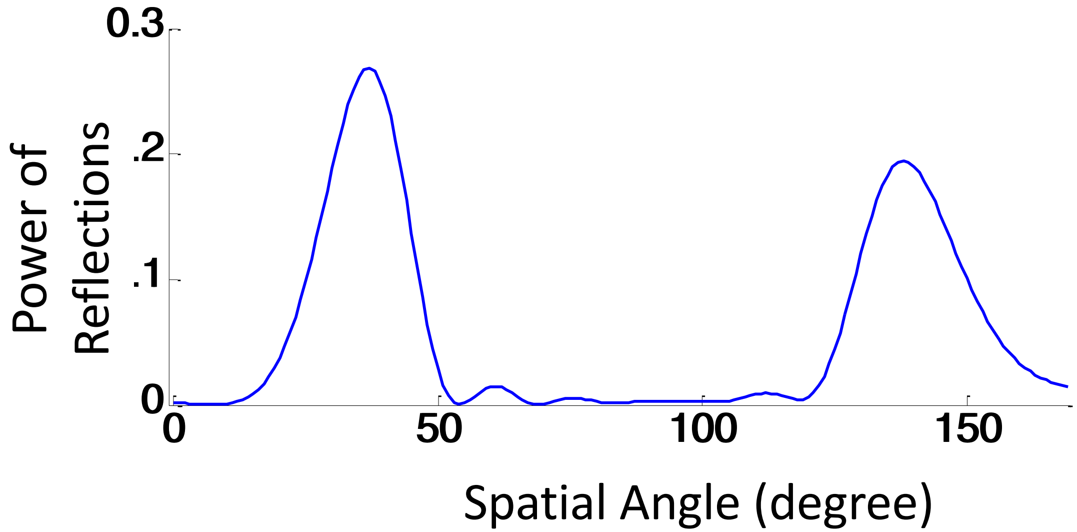


Multipath Profiles

Capturing Multipath Profiles with an Antenna Array



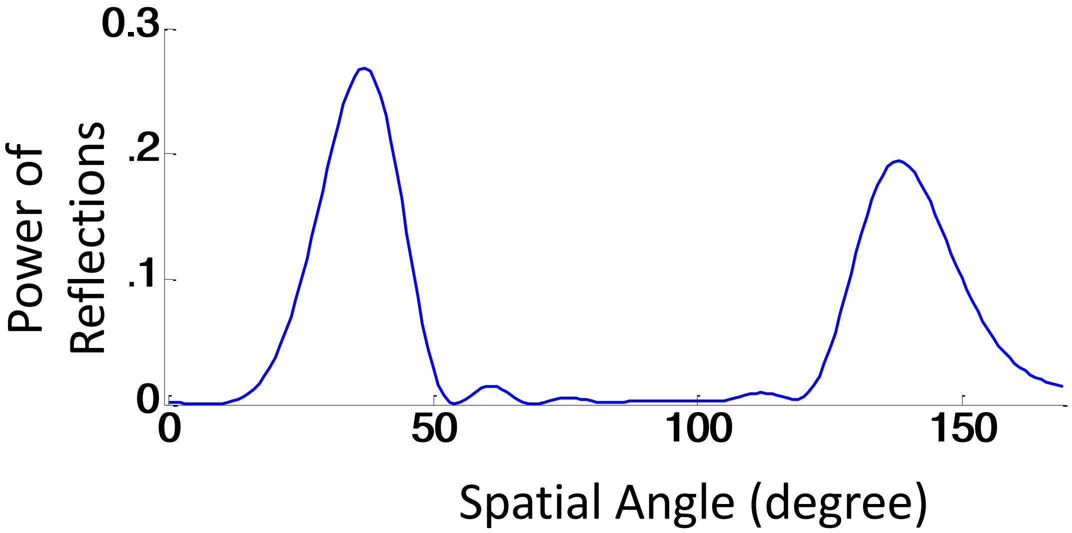
Last lecture we showed how to obtain the multipath profile



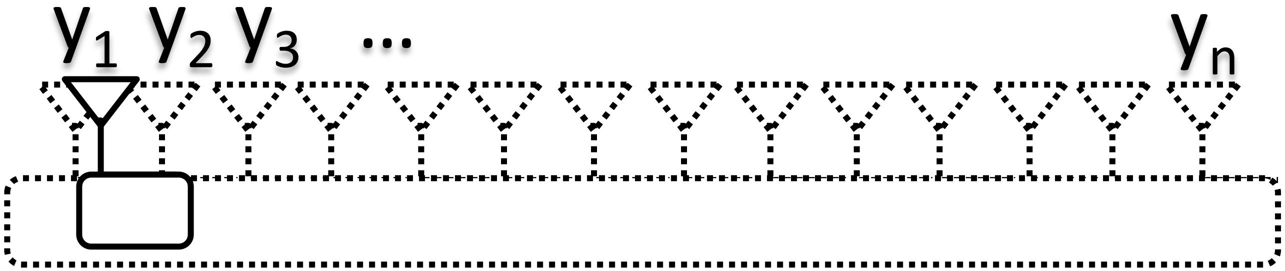
Capturing Multipath Profiles with an Antenna Array

Accurate multipath profiles require many antennas in the array

➔ Array is bulky and expensive



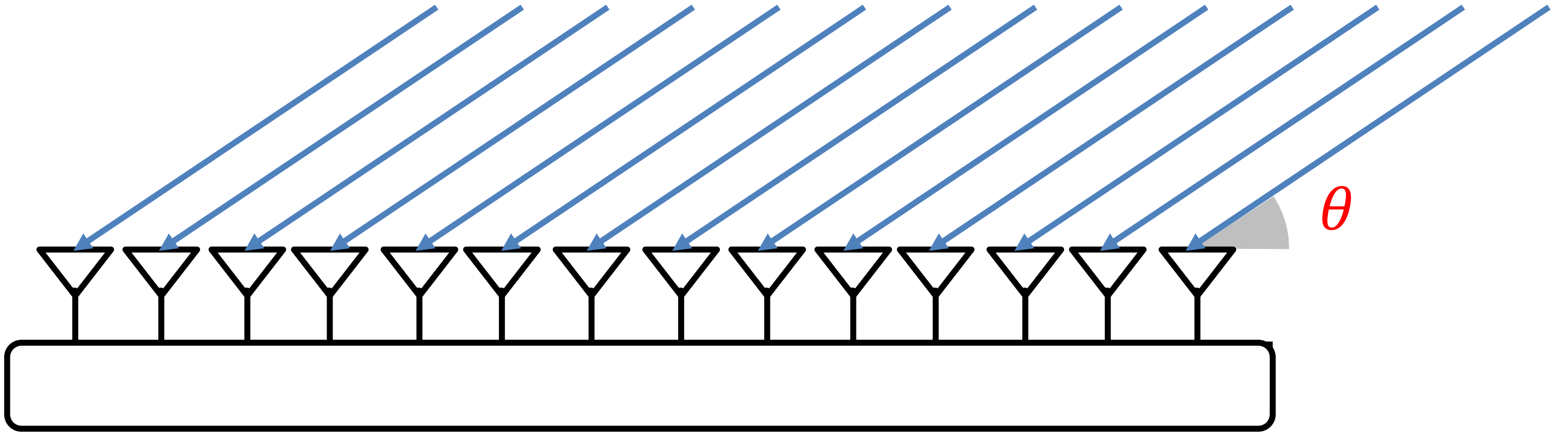
Capturing Multipath with a Sliding Antenna



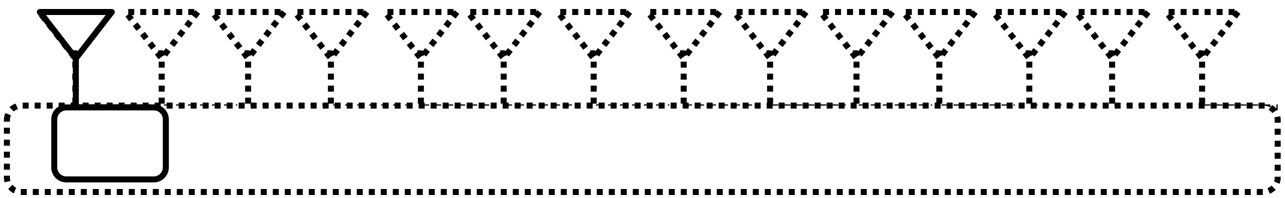
SAR: Synthetic Aperture Radar

Can capture very accurate multipath profiles with a single sliding antenna

Synthetic Aperture Radar



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



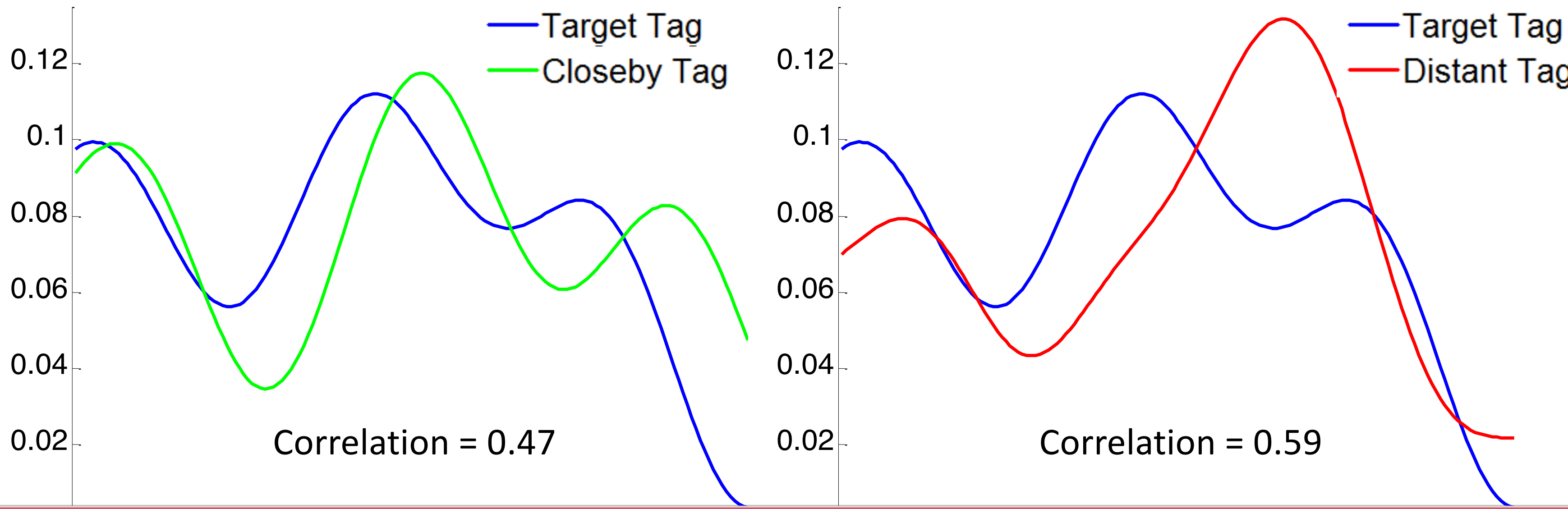
$$h_t = \alpha e^{-j2\pi \frac{d - vt \cos\theta}{\lambda}}$$

$\frac{v \cos\theta}{\lambda}$: *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!

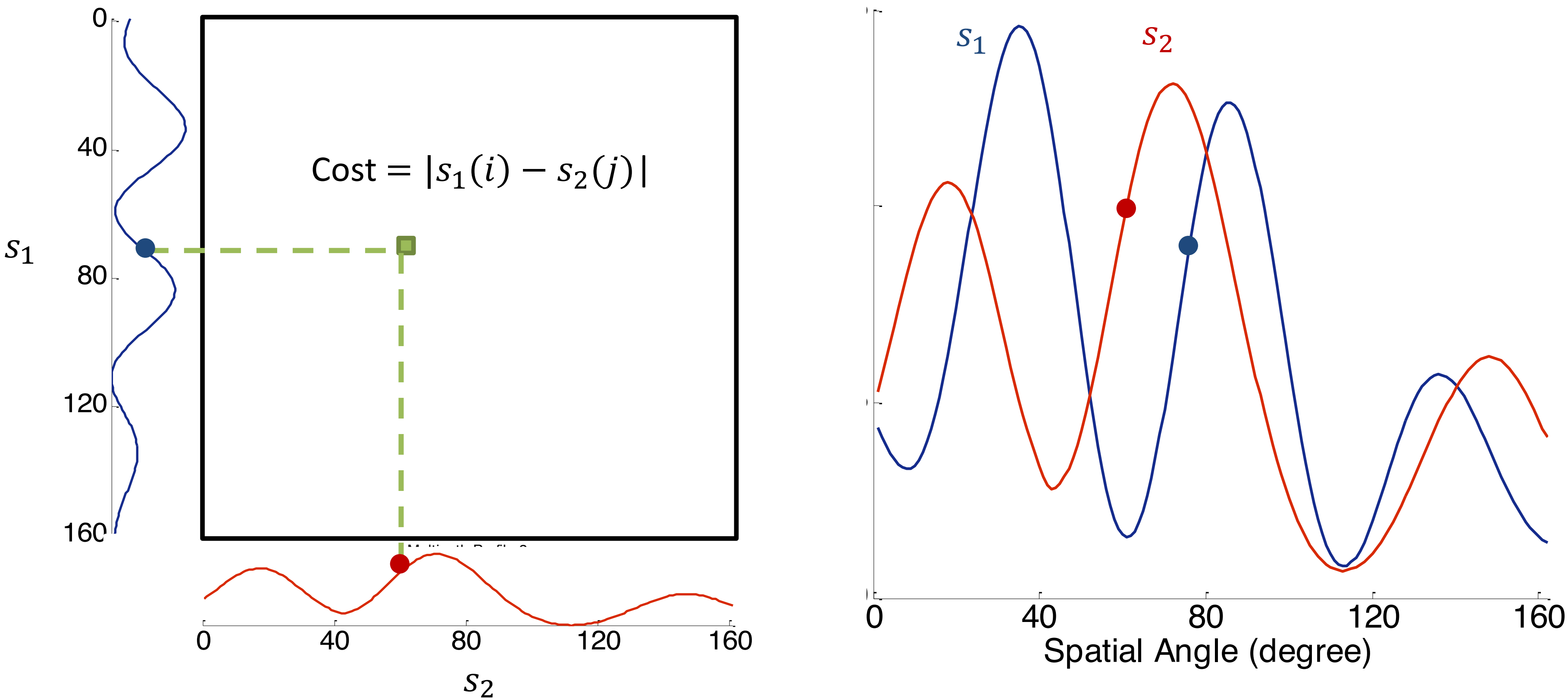


Correlation cannot capture peak shifts

Dynamic Time Warping (DTW)

Dynamic Time Warping (DTW)

Computes the total warping to obtain s_1 from s_2



Dynamic Time Warping (DTW)

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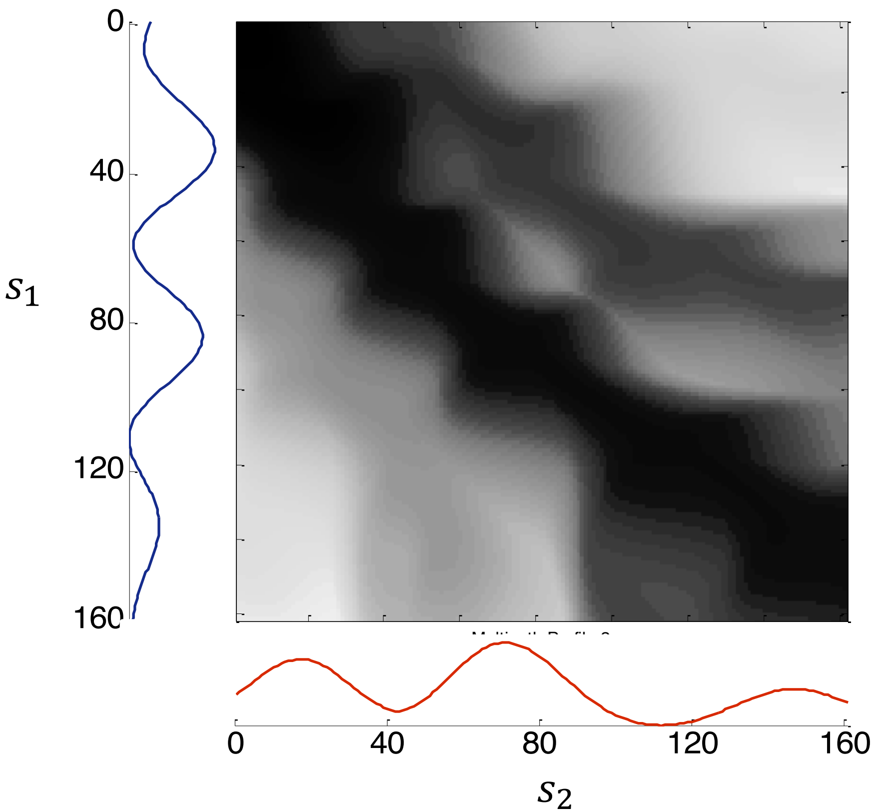

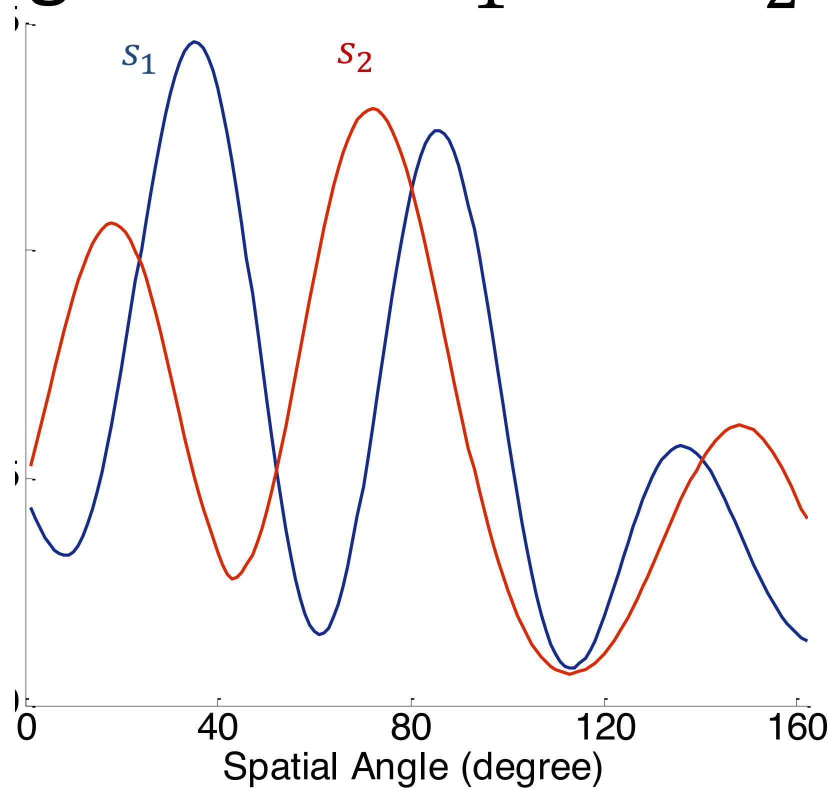

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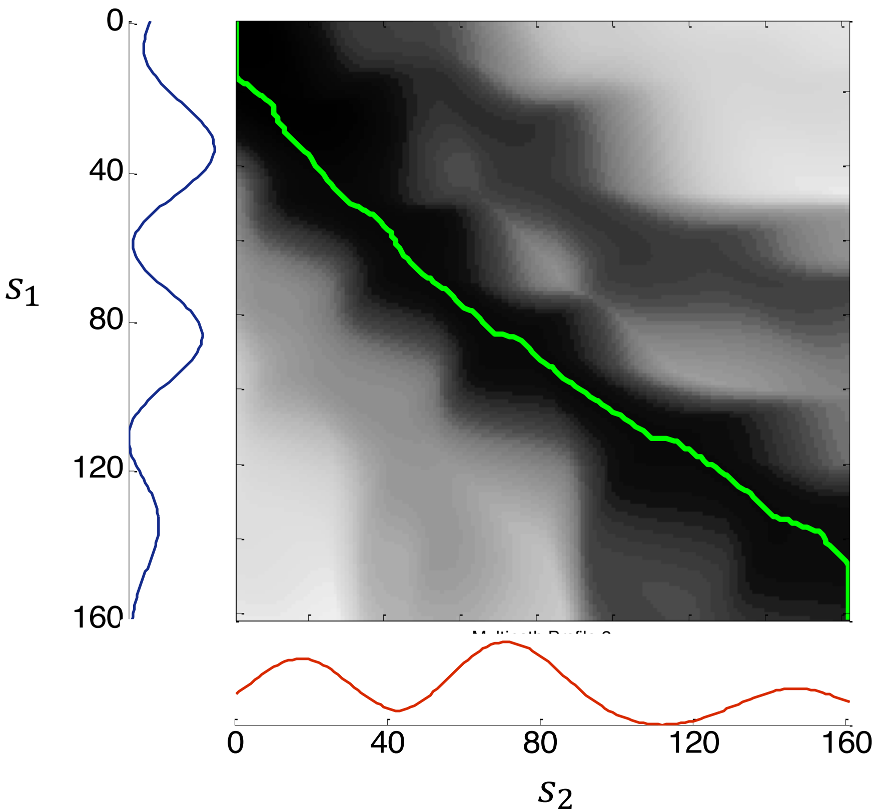
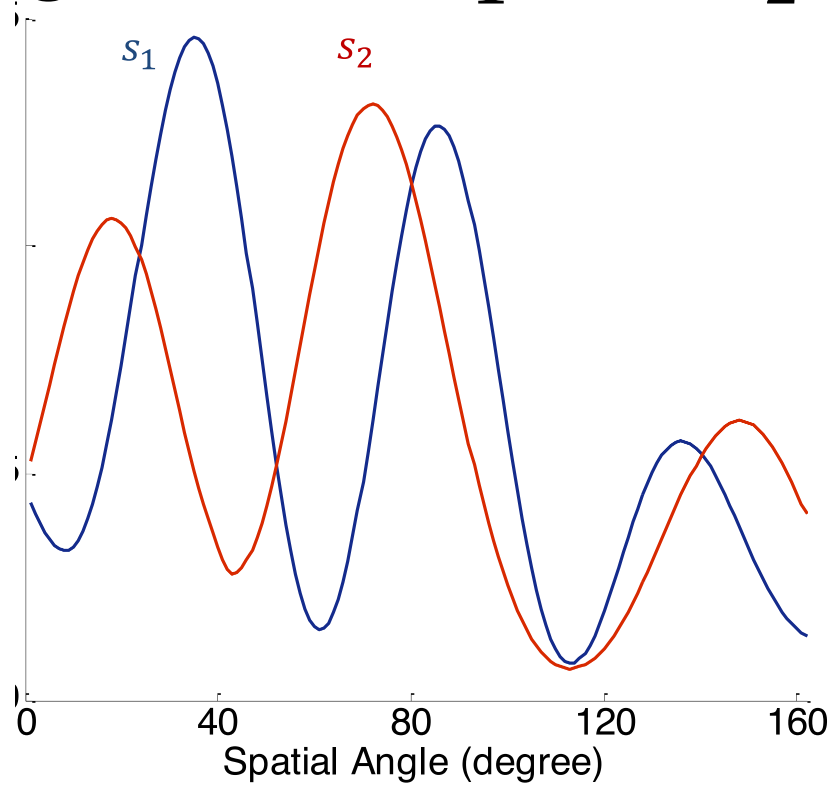
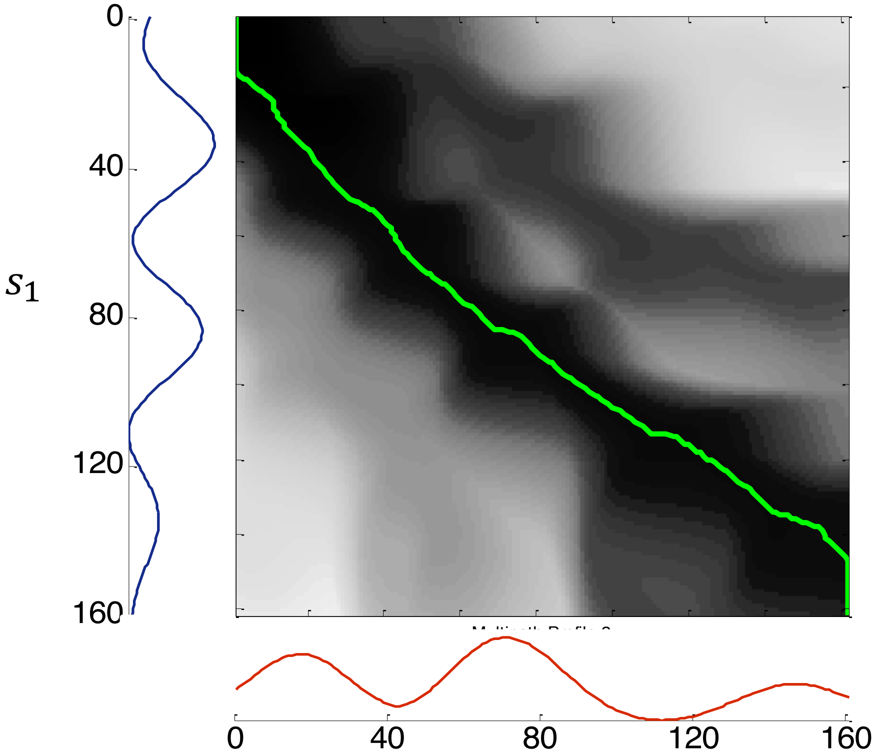


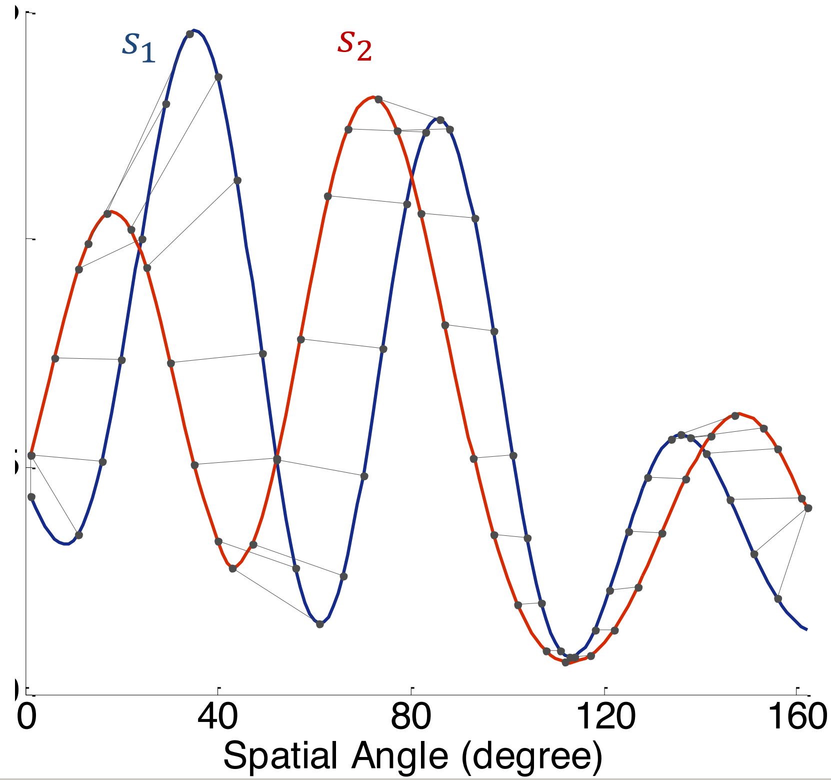


Compute DTW by finding the route with lowest total cost

Dynamic Time Warping (DTW)

Computes the total warping to obtain s_1 from s_2

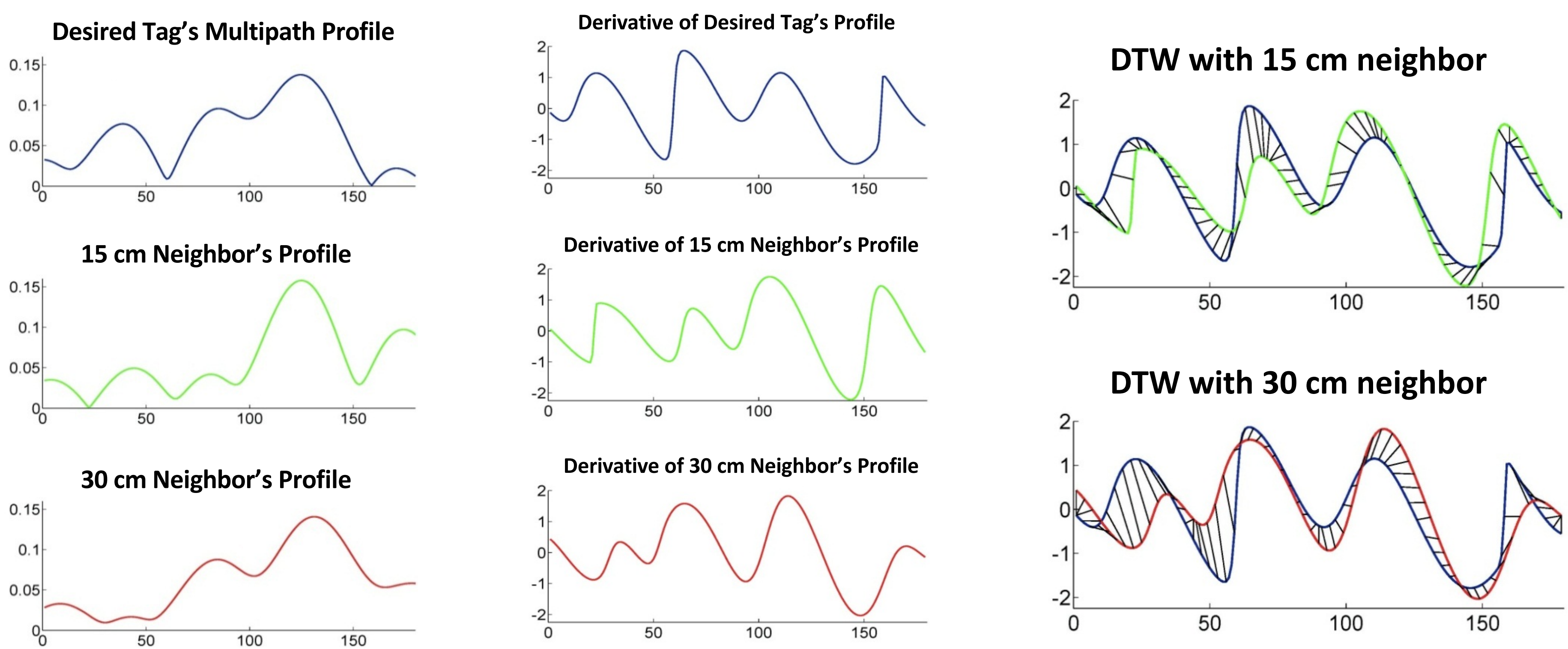




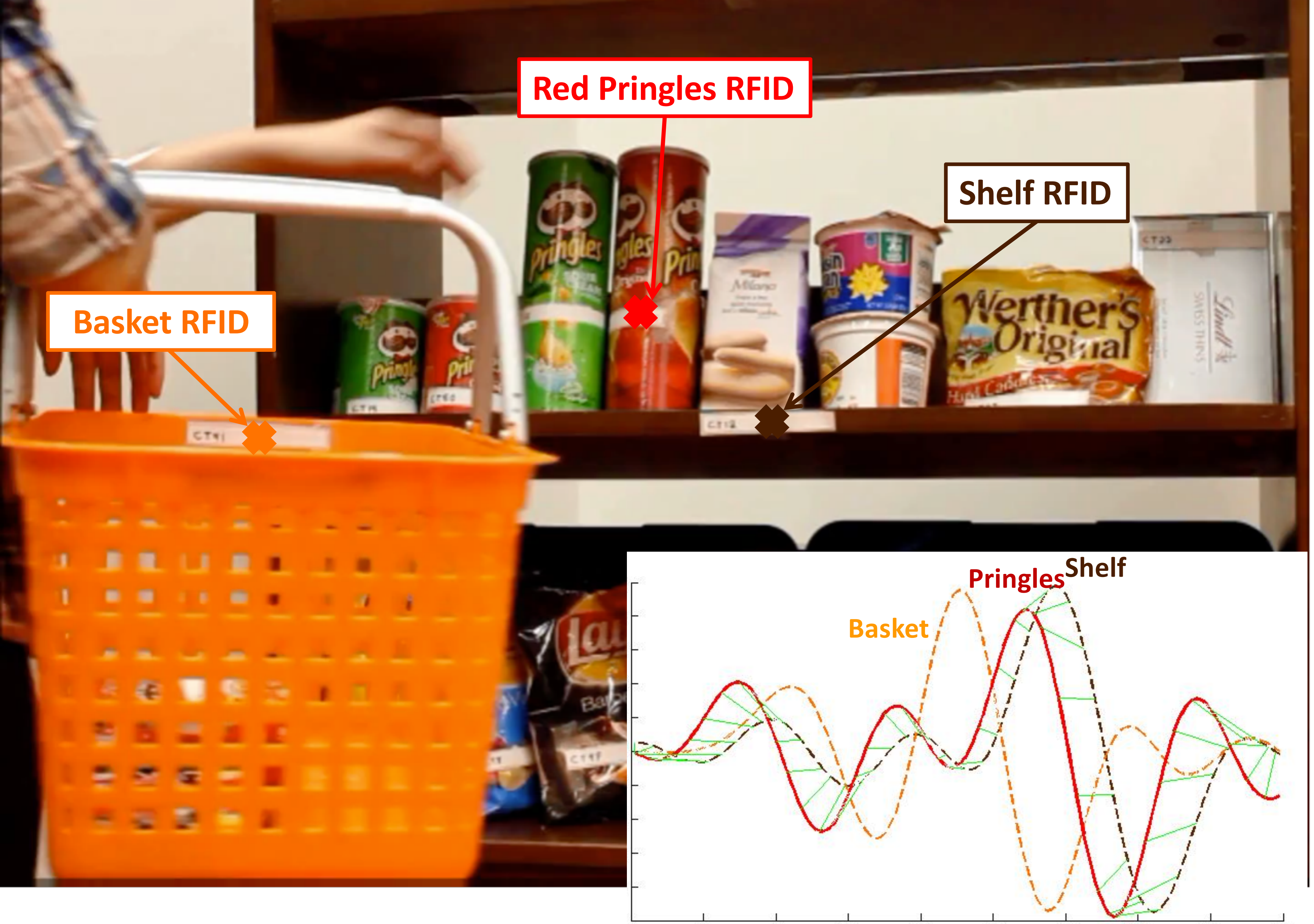
DTW captures proximity from multipath profiles

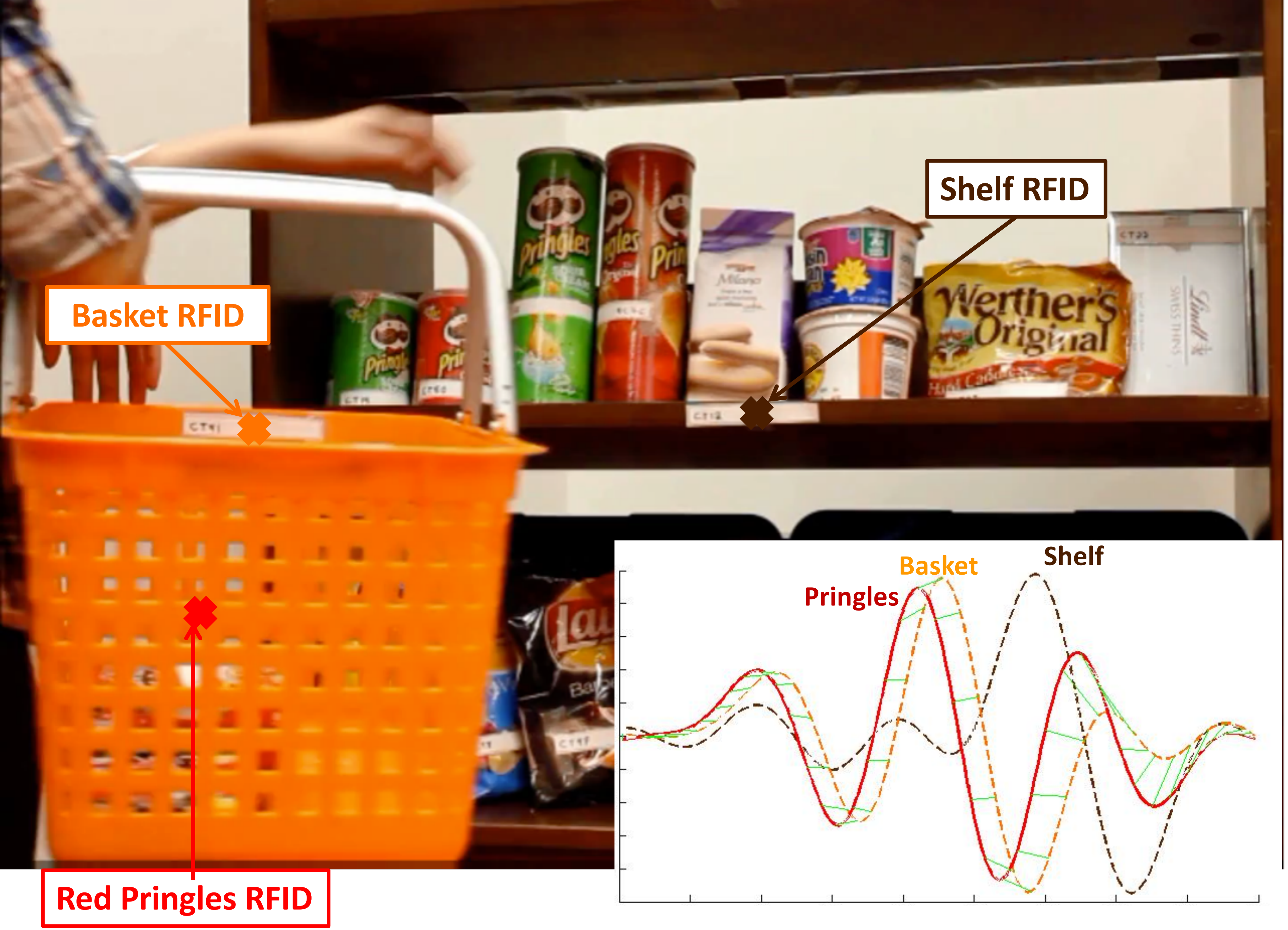
Antenna Gain & Orientation

Which one is closer?



To deal with antenna gain we actually apply DTW to the derivative of the multipath profiles


Red Pringles RFID
Shelf RFID
Basket RFID
Pringles
Shelf
Basket



Shelf RFID
Basket RFID
Red Pringles RFID
Basket
Shelf
Pringles


Pringles
Werther's Original
Lay's
CHEDDAR & SOUR CREAM
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

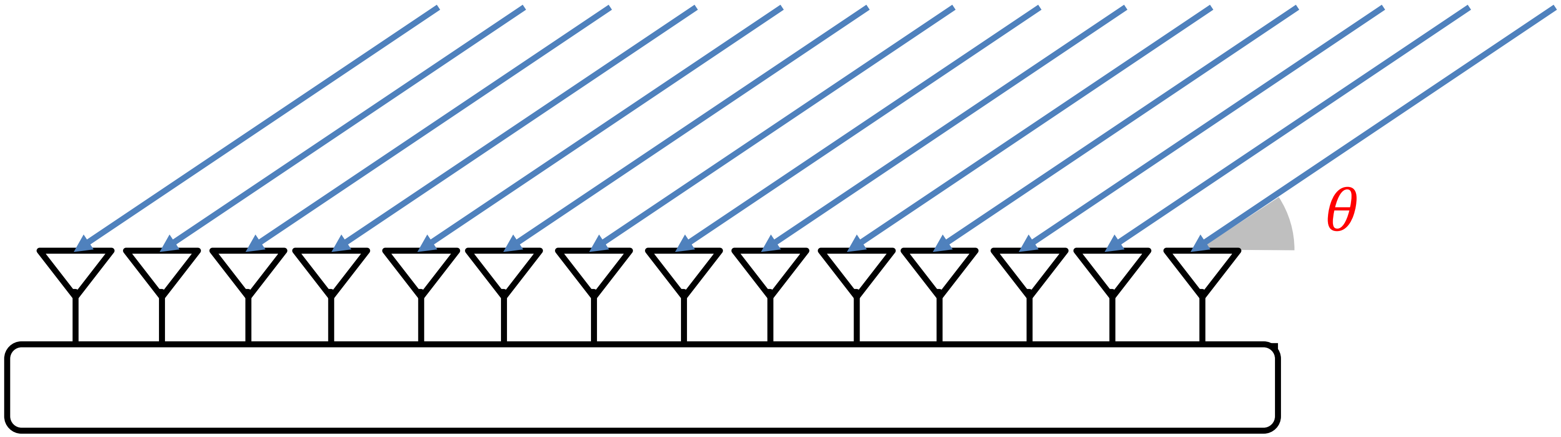
Cons:

- 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!

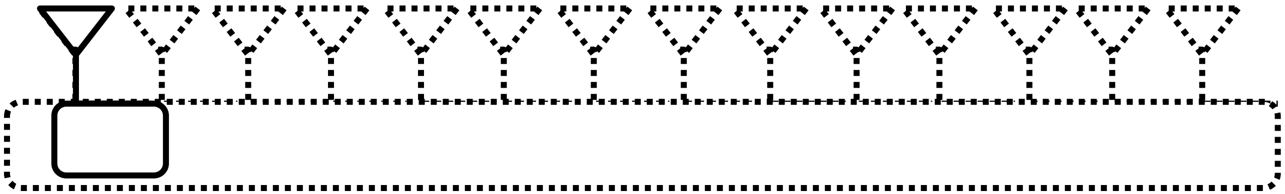
In antenna arrays: all antennas are synchronized!

→ 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

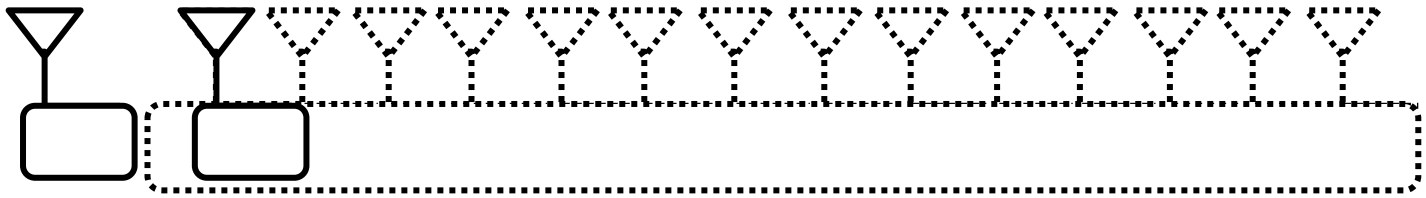
In WiFi,

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 $h_{2t} = \alpha e^{-j2\pi\frac{d_2}{\lambda} - j2\pi\Delta f_c t}$

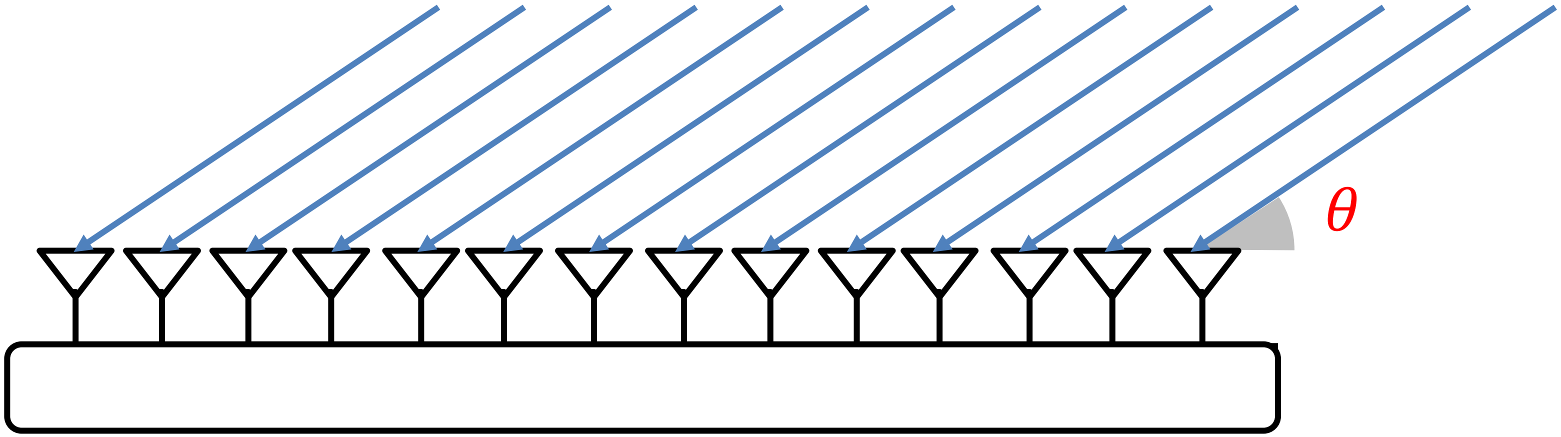
Taking ratio eliminates CFO: $\frac{h_{1t}}{h_{2t}} = e^{-j2\pi\frac{d_1 + d_2 - vt\cos\theta}{\lambda}}$

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

Why do we care about large antenna arrays?

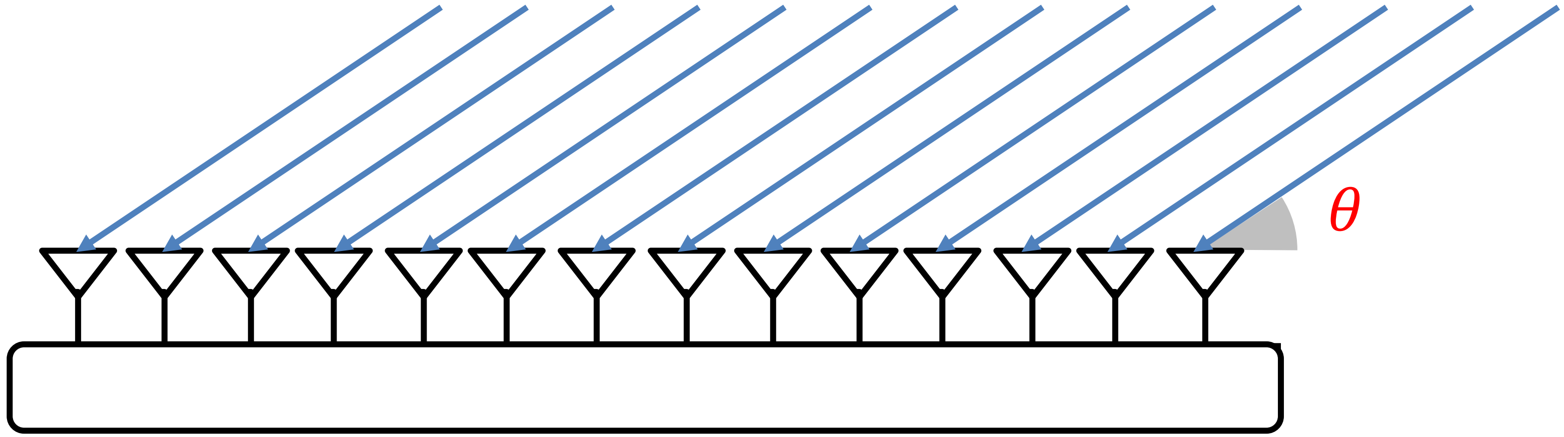
Larger antenna array
→ Higher AoA resolution

Antenna Arrays



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

Antenna Arrays



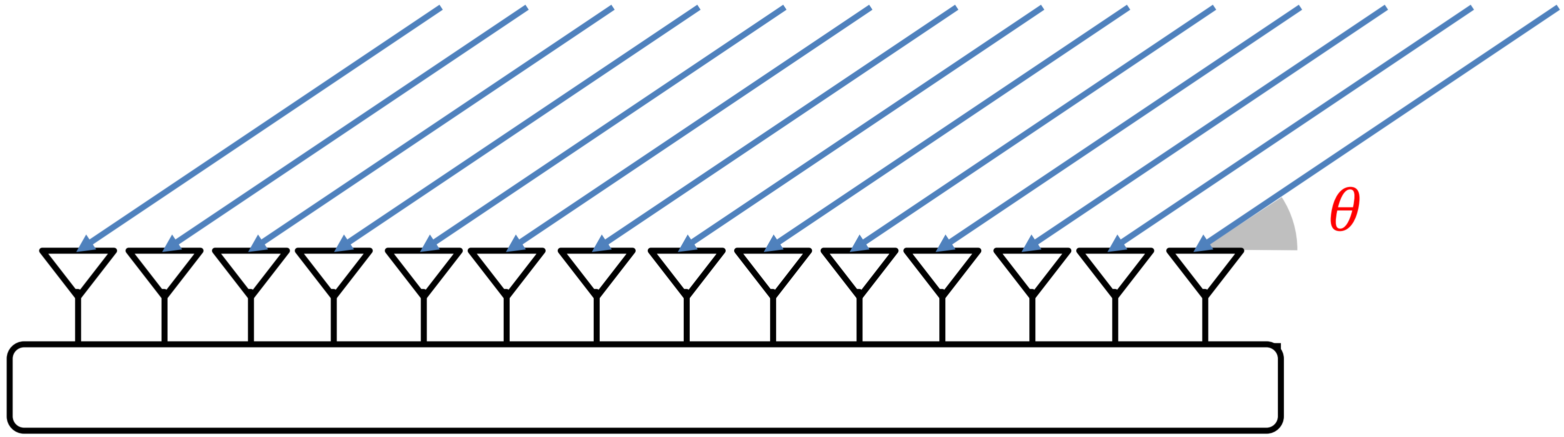
$$h_k = \sum_{l=1}^{L} \alpha_l e^{-j\phi_l} e^{j2\pi\frac{ks\cos\theta_l}{\lambda}}$$

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

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

Antenna Arrays are a Fourier Transform

Antenna Arrays as Fourier Transforms



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

Antennas ⟺ Time Samples

FFT ↓   FFT ↓

AoA Directions ⟺ Frequencies

Antenna Arrays ⟺ Fourier Transforms

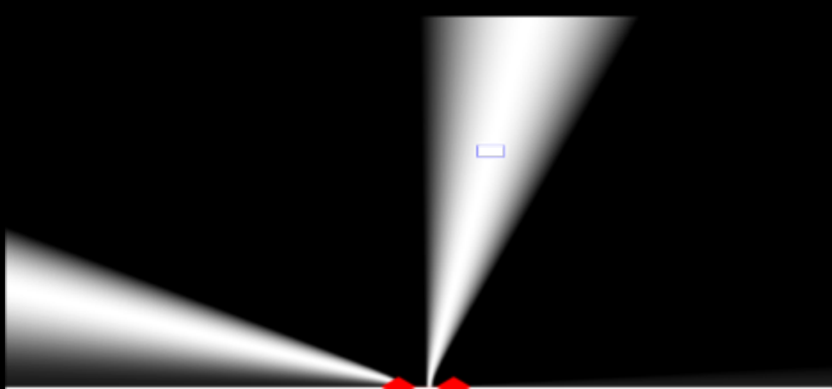
Antennas ⟺ Time Samples

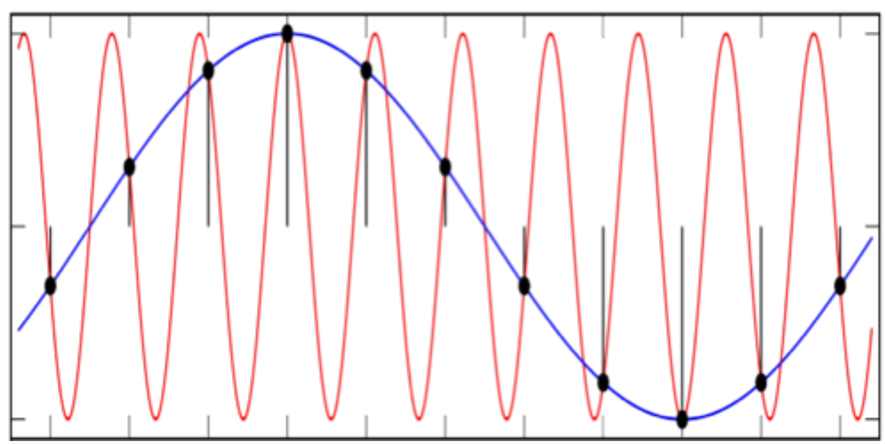
FFT ↓ FFT

AoA Directions ⟺ Frequencies

Sample at Nyquist rate $\lambda/2$ otherwise you get ➔ AoA ambiguity ⟺ Sample at Nyquist rate $1/(2B)$ otherwise you get aliasing ➔ frequency ambiguity

$$\frac{2\pi ks\cos\theta_1}{\lambda} = \frac{2\pi ks\cos\theta_2}{\lambda} \mod 2\pi$$





Antenna Arrays ⟷ Fourier Transforms

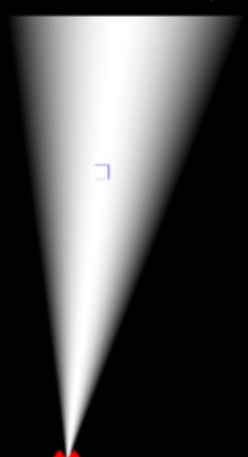
Antennas ⟷ Time Samples

FFT

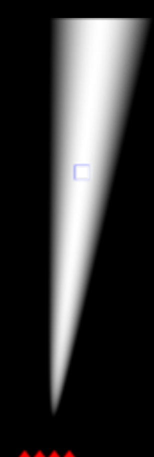
AoA Directions ⟷ Frequencies

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

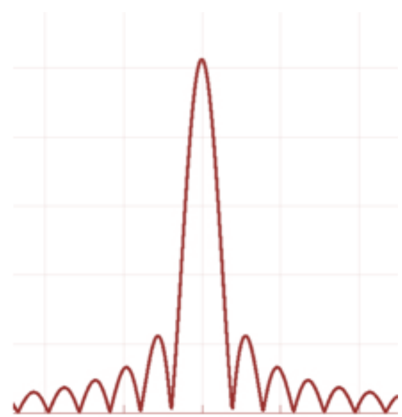
2 Antenna Array



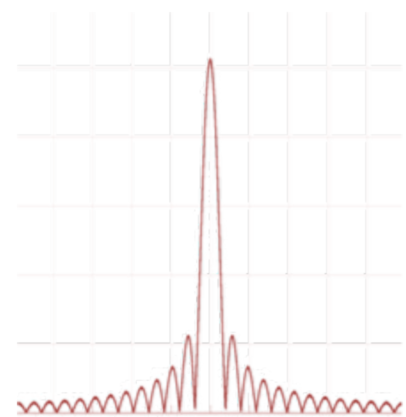
4 Antenna Array



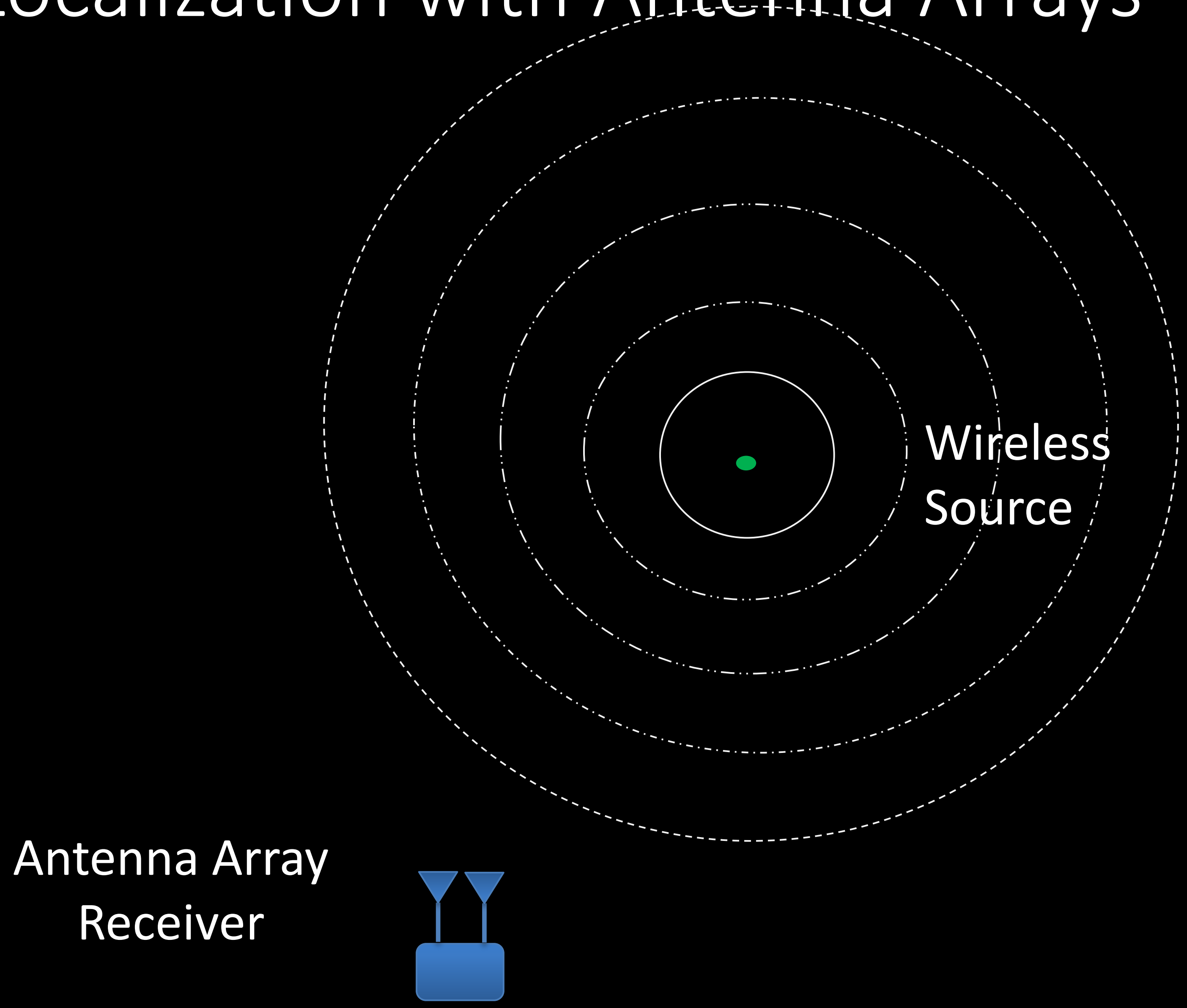
2ms Time Window



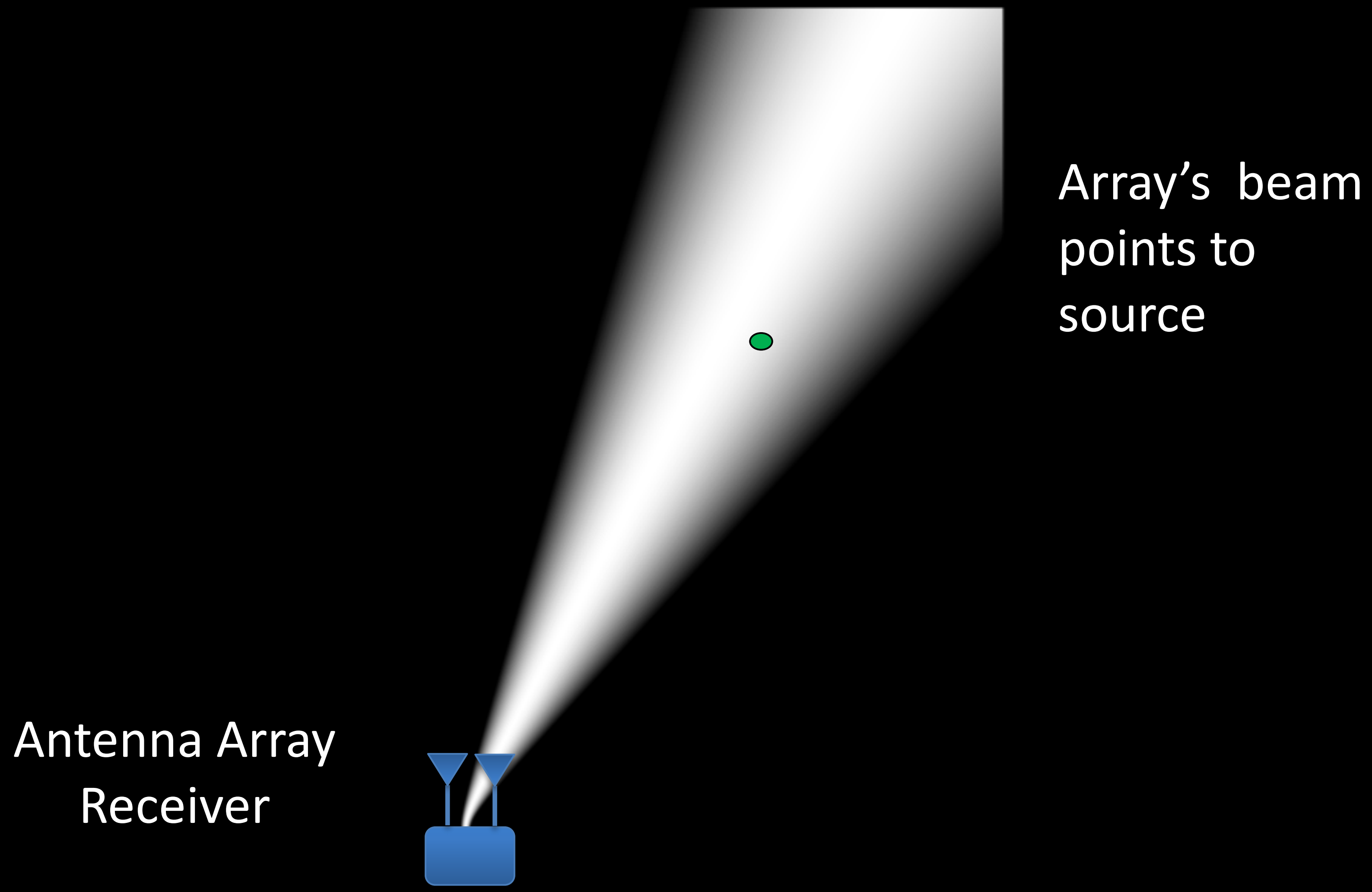
4ms Time Window



Localization with Antenna Arrays

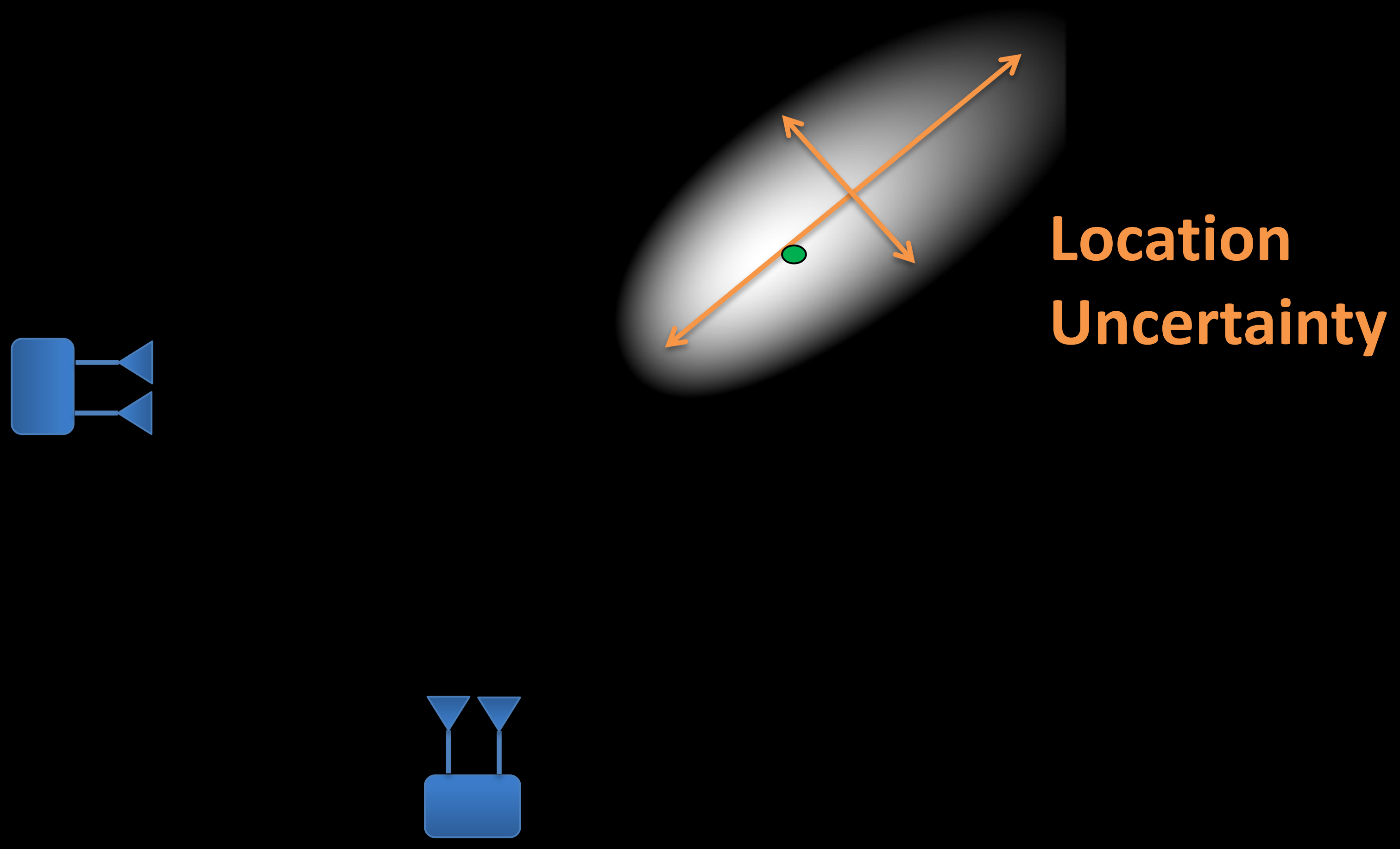


Localization with Antenna Arrays

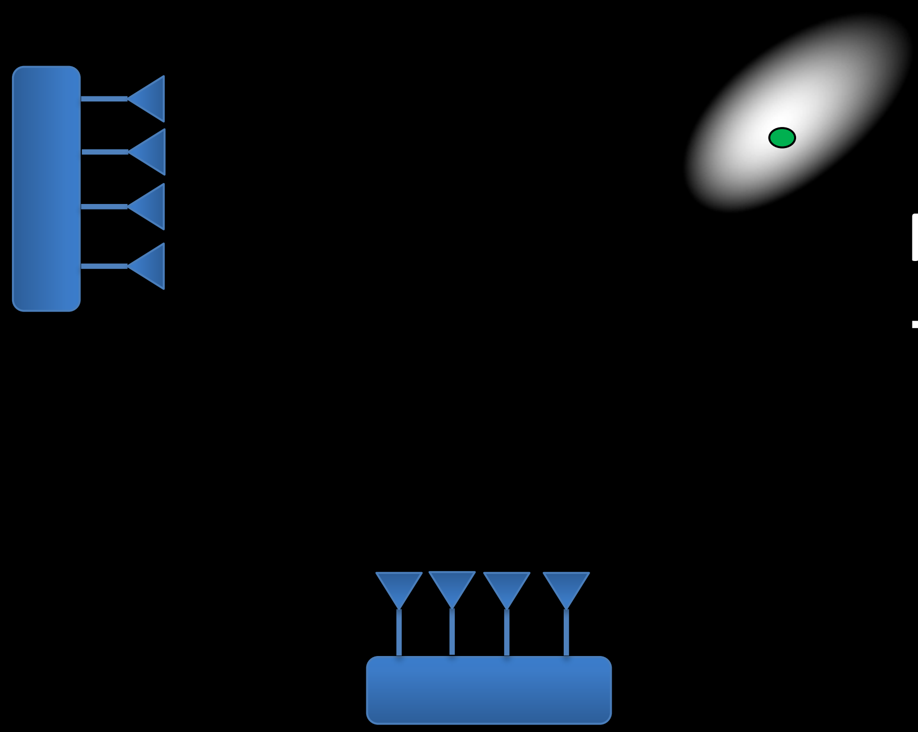


Localization with Antenna Arrays

Localization with Antenna Arrays

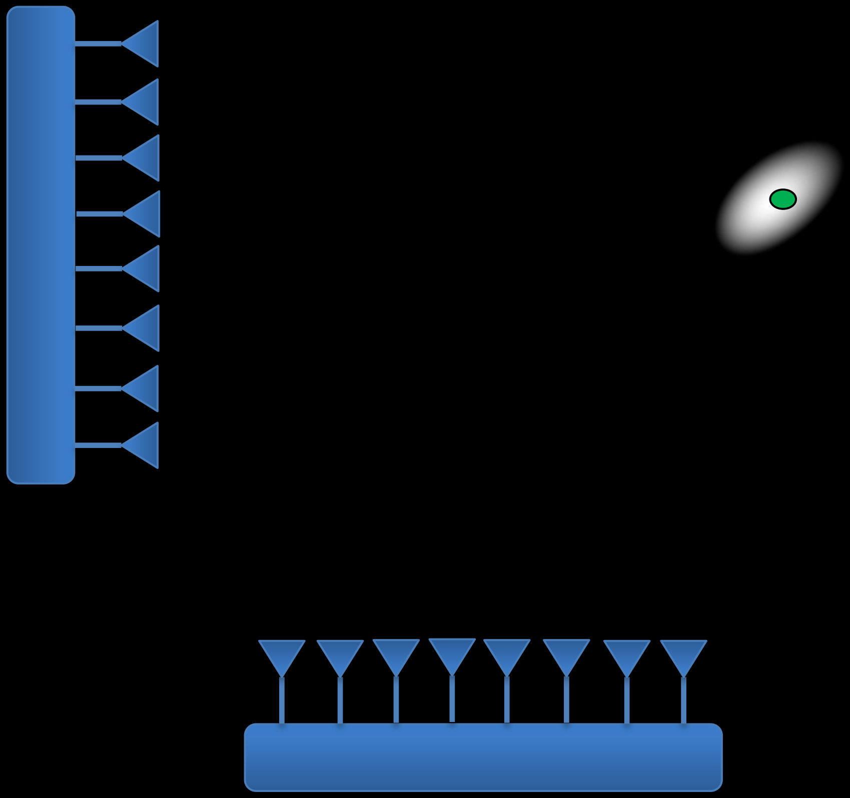


Localization with Antenna Arrays

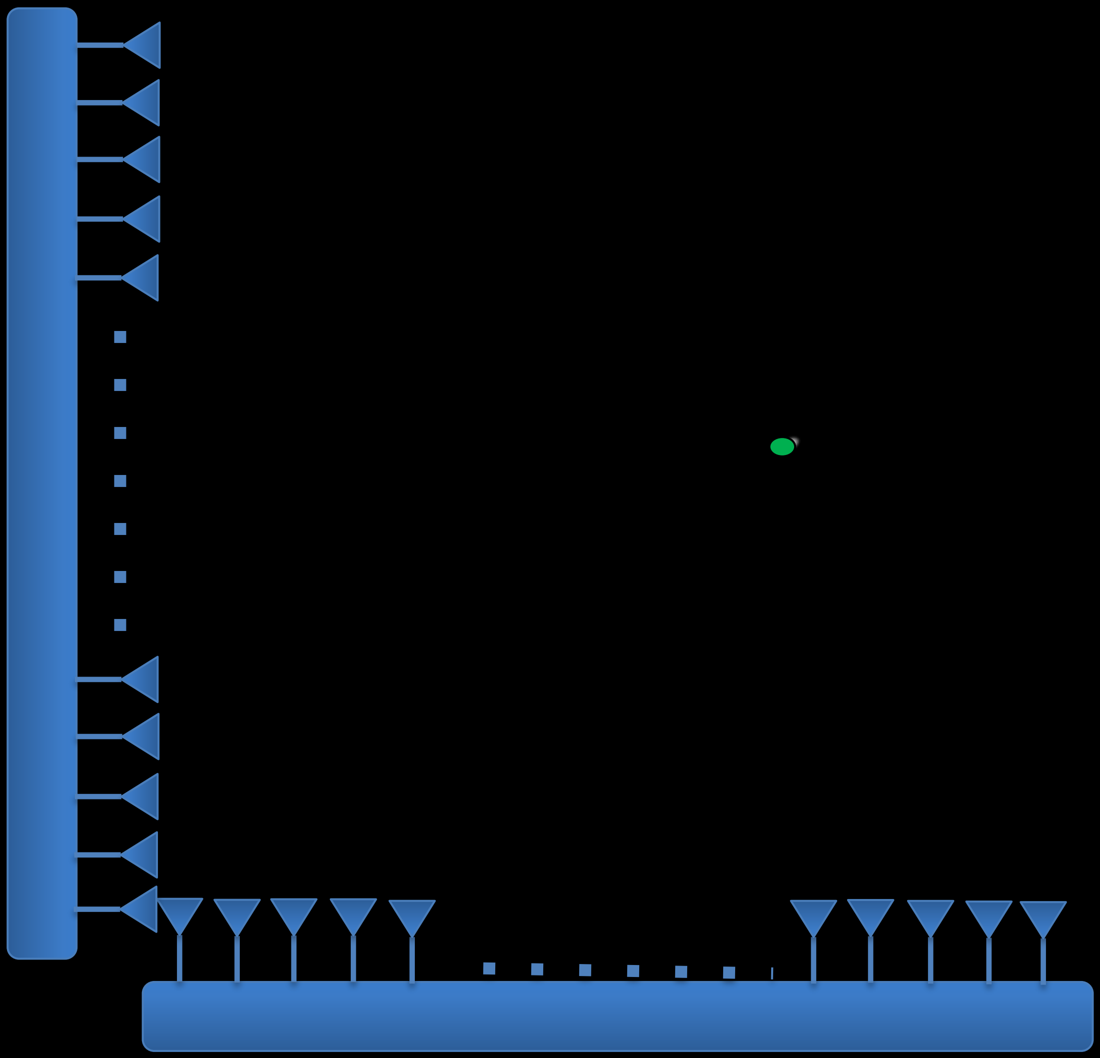


More Antennas
→ Less uncertainty

Localization with Antenna Arrays

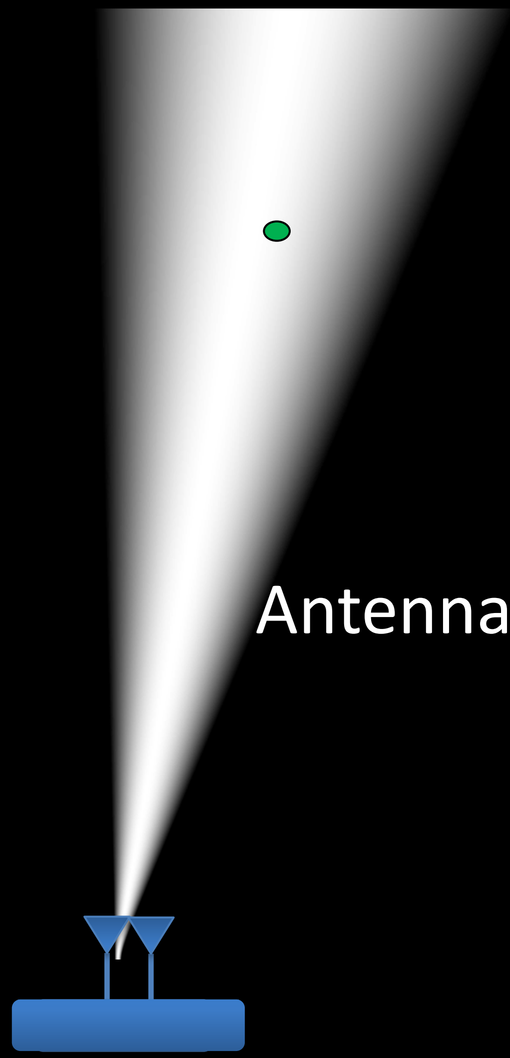


Not practical!



Ambiguity-Resolution Tradeoff

Ambiguity-Resolution Tradeoff

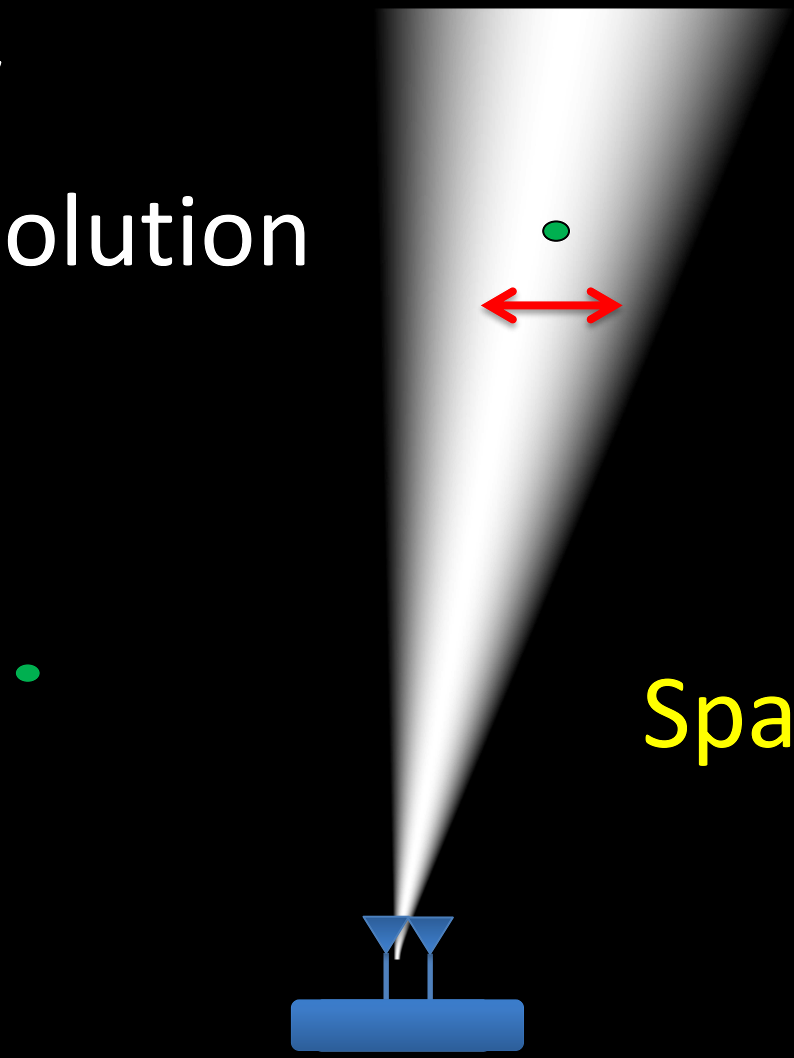


Antenna spacing is $\lambda/2$

Ambiguity-Resolution Tradeoff

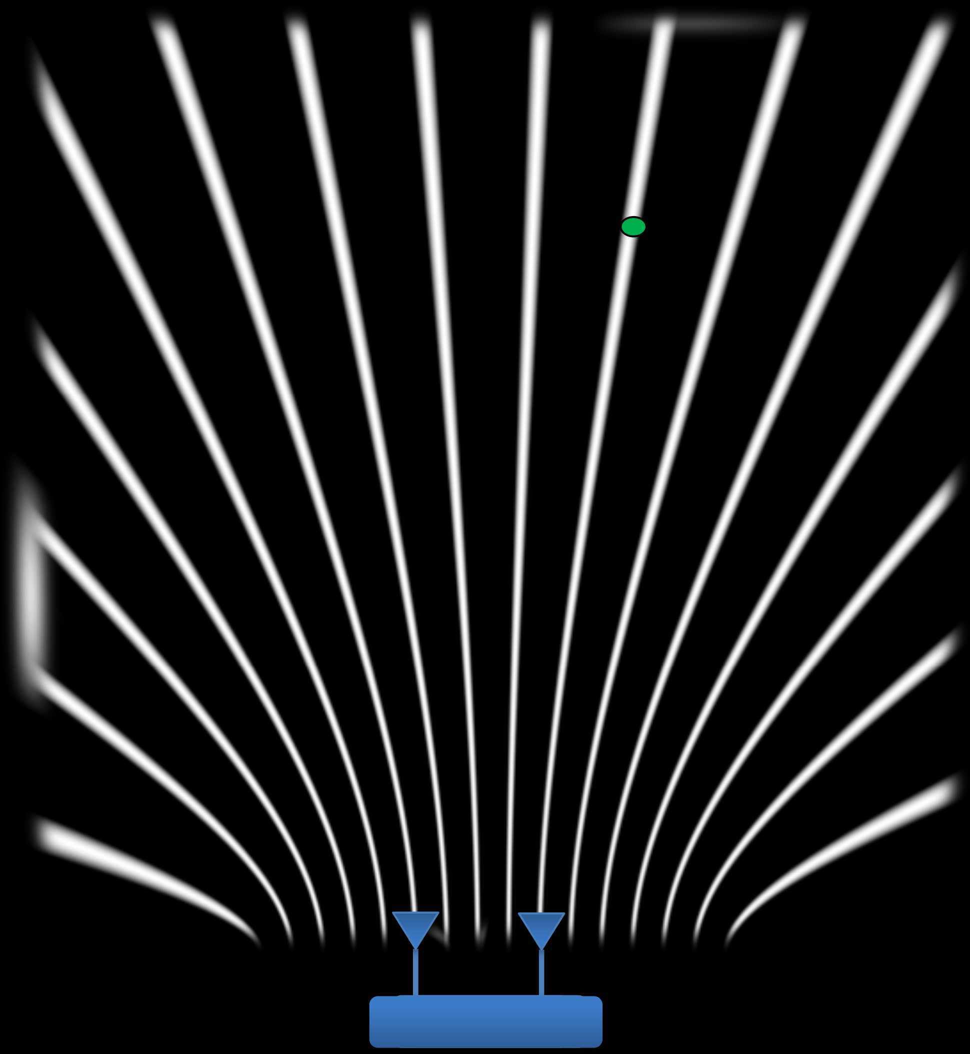
Ambiguity

Higher resolution



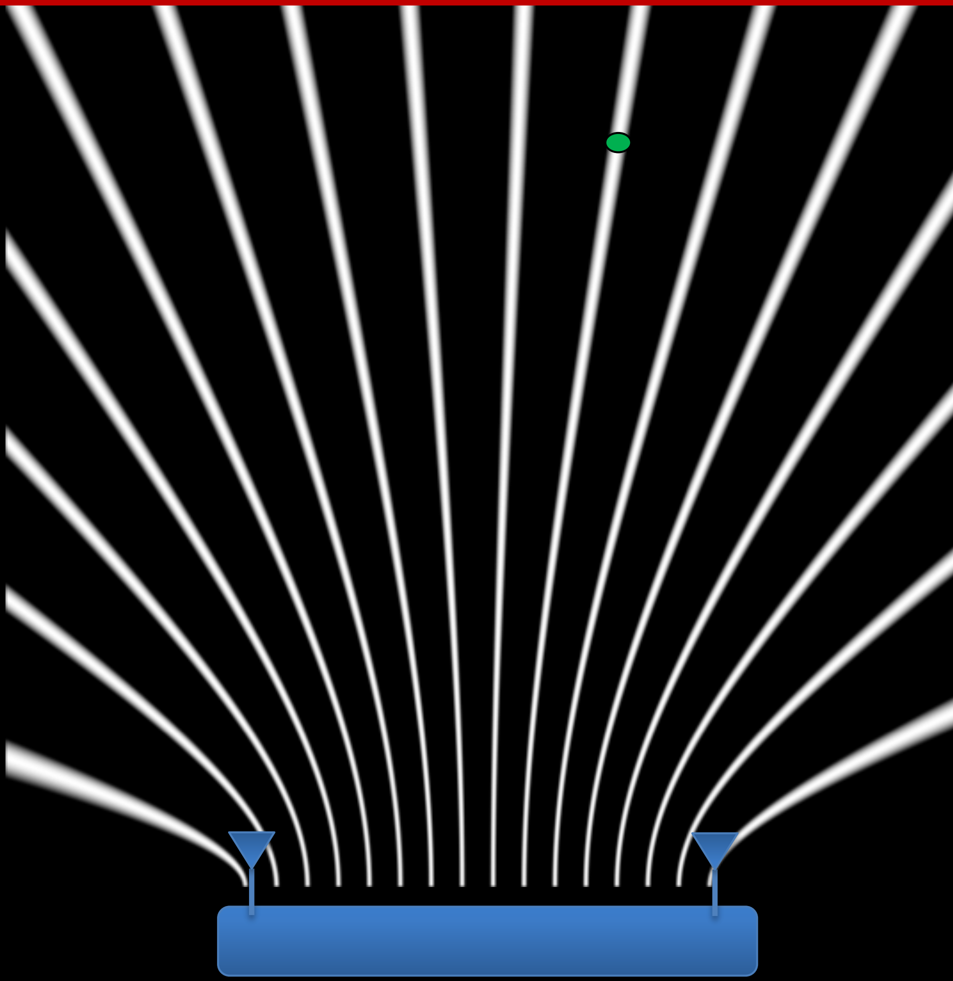
Spacing is λ

Ambiguity-Resolution Tradeoff



8 λ

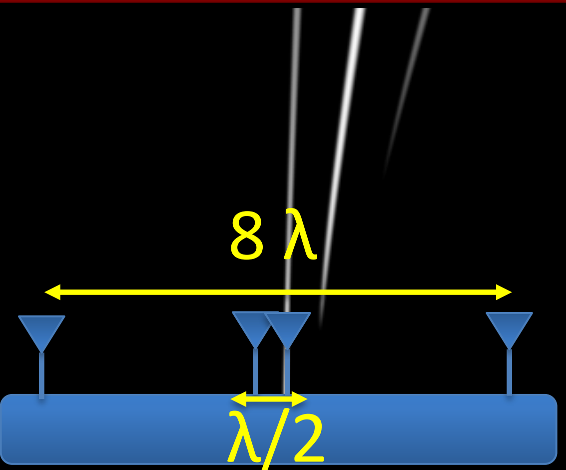
High resolution	Low resolution
Ambiguity in direction	No ambiguity



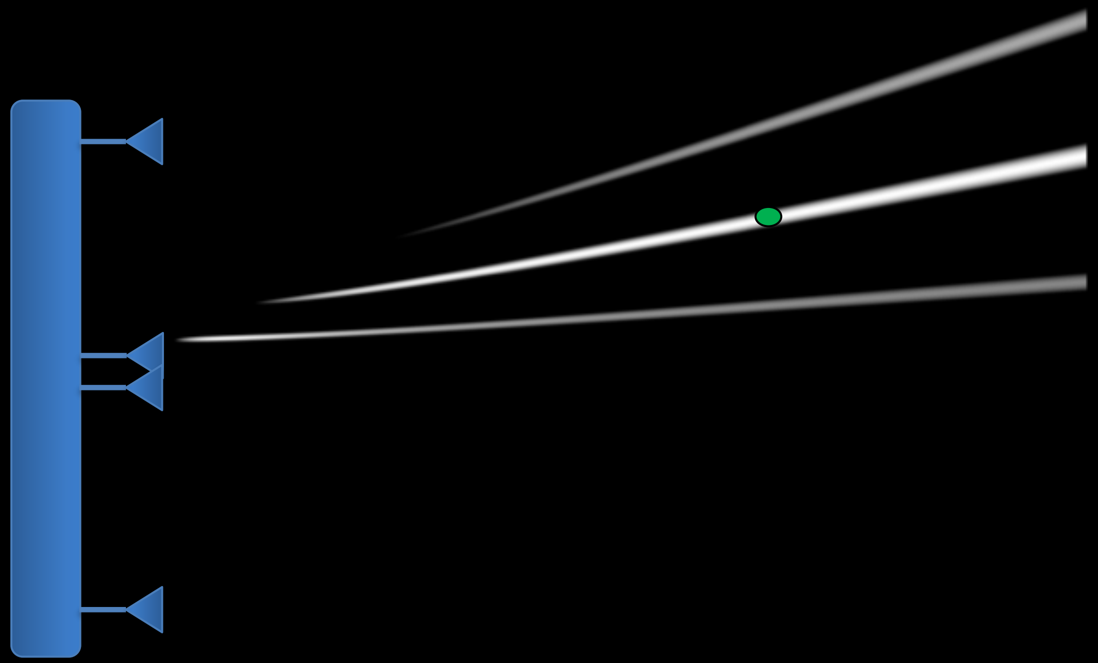
RF-IDraw: Multi-Resolution Array

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

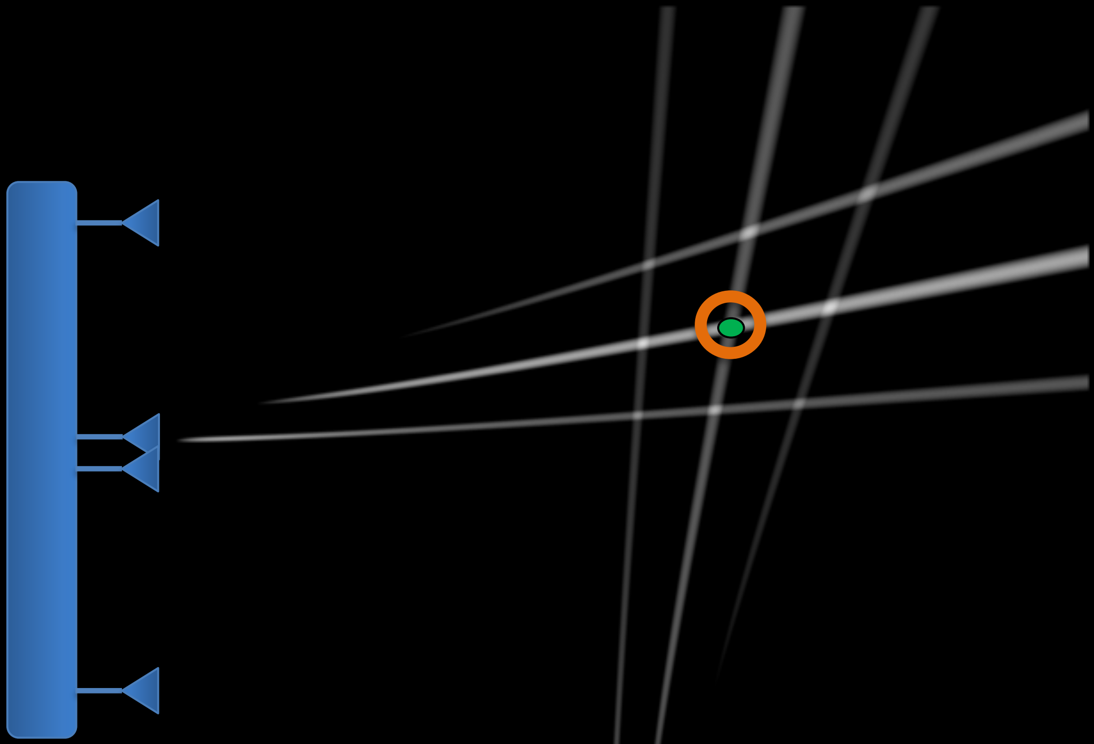
Use fewer antennas, but place them smartly



RF-IDraw Localization

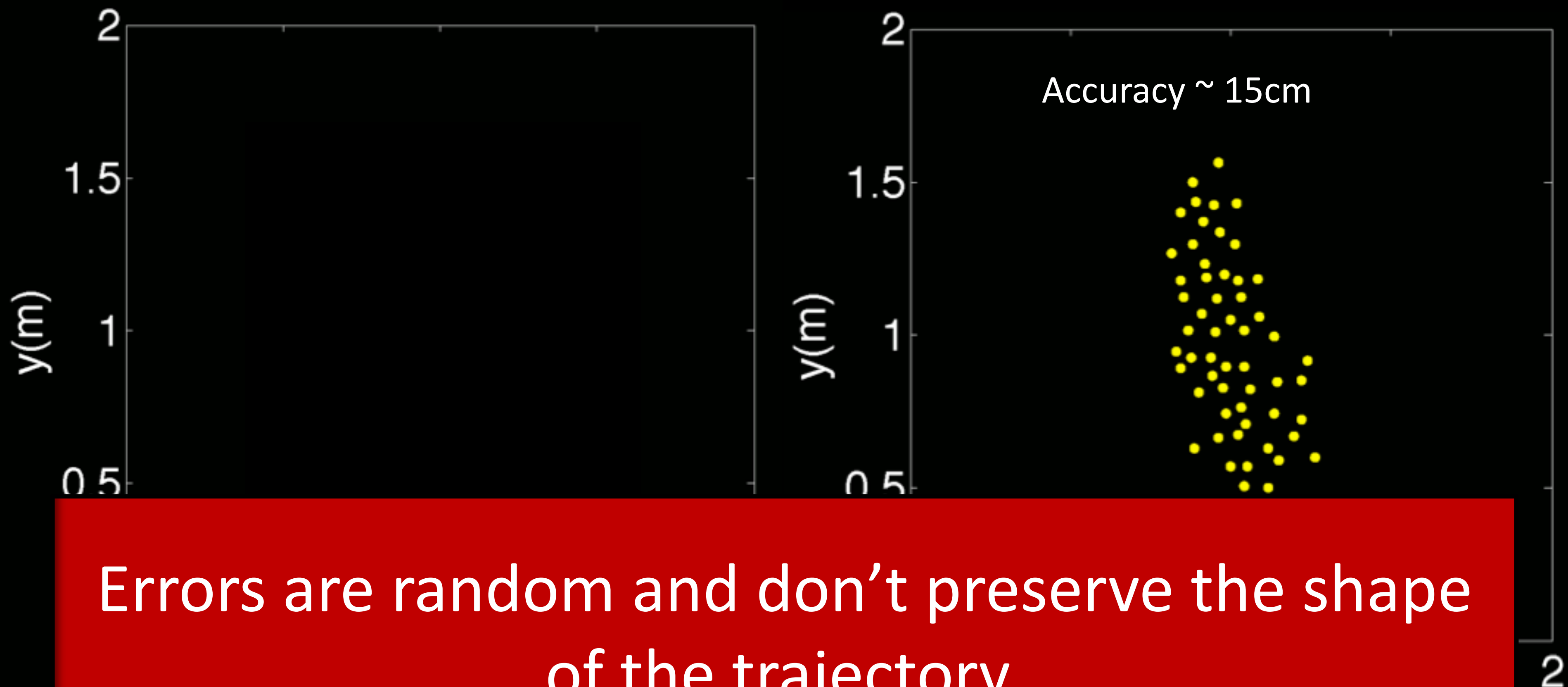


RF-IDraw Localization



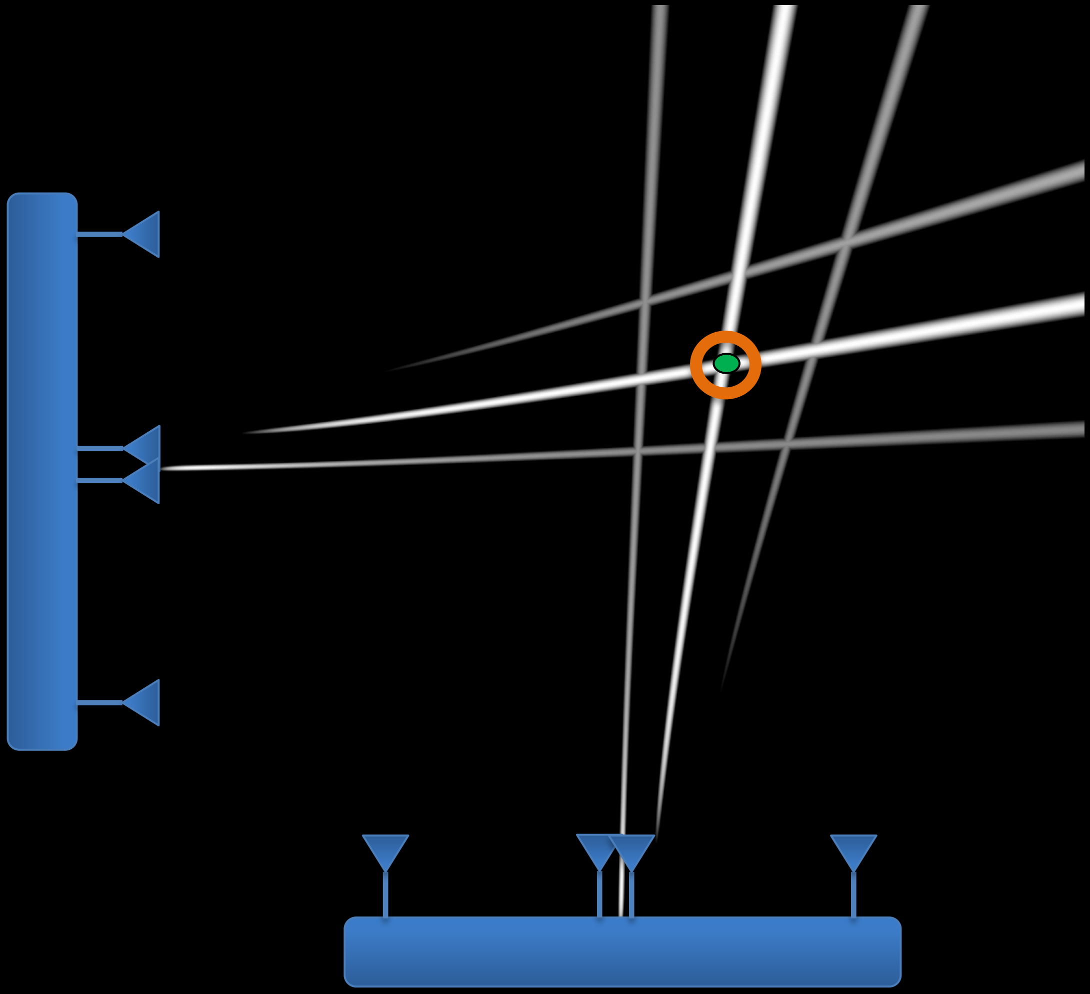
Are we done?

Let’s Try

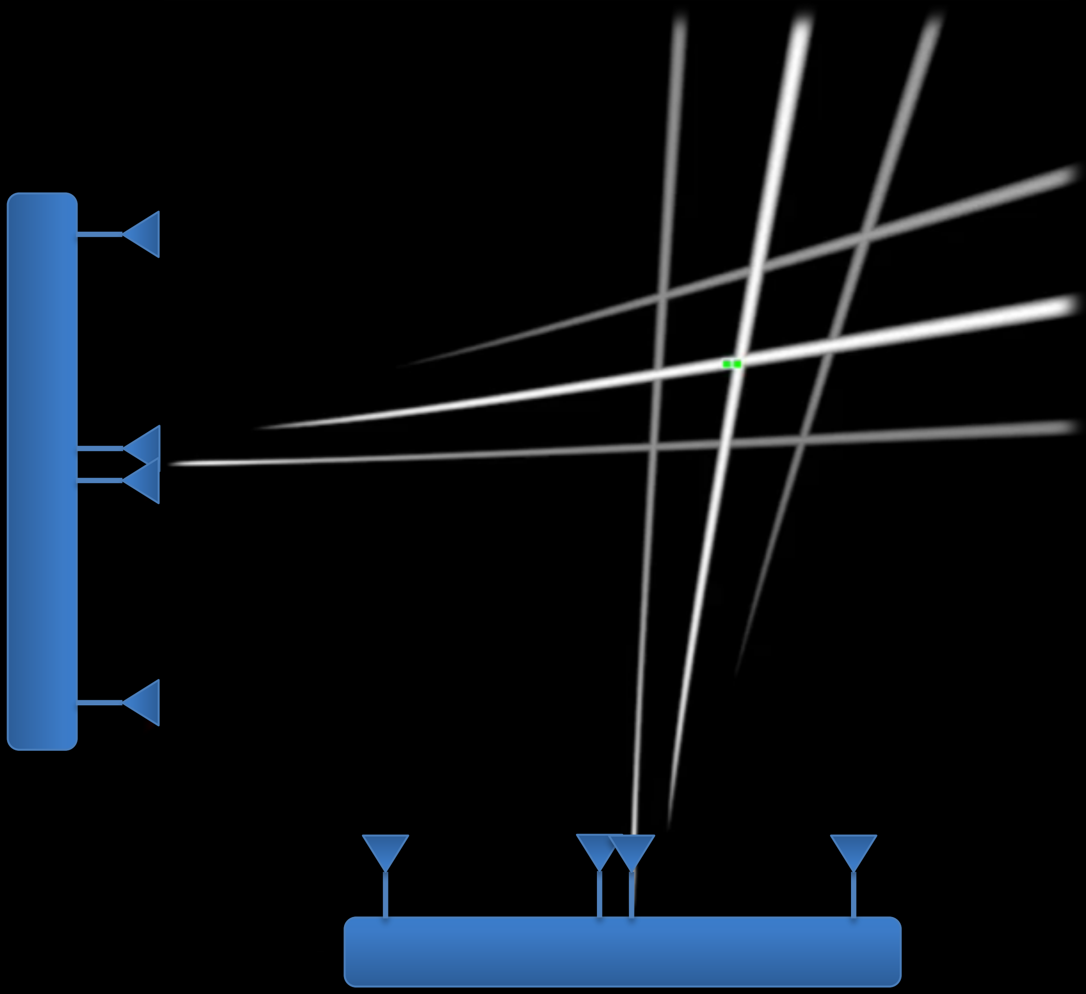


Errors are random and don’t preserve the shape of the trajectory.

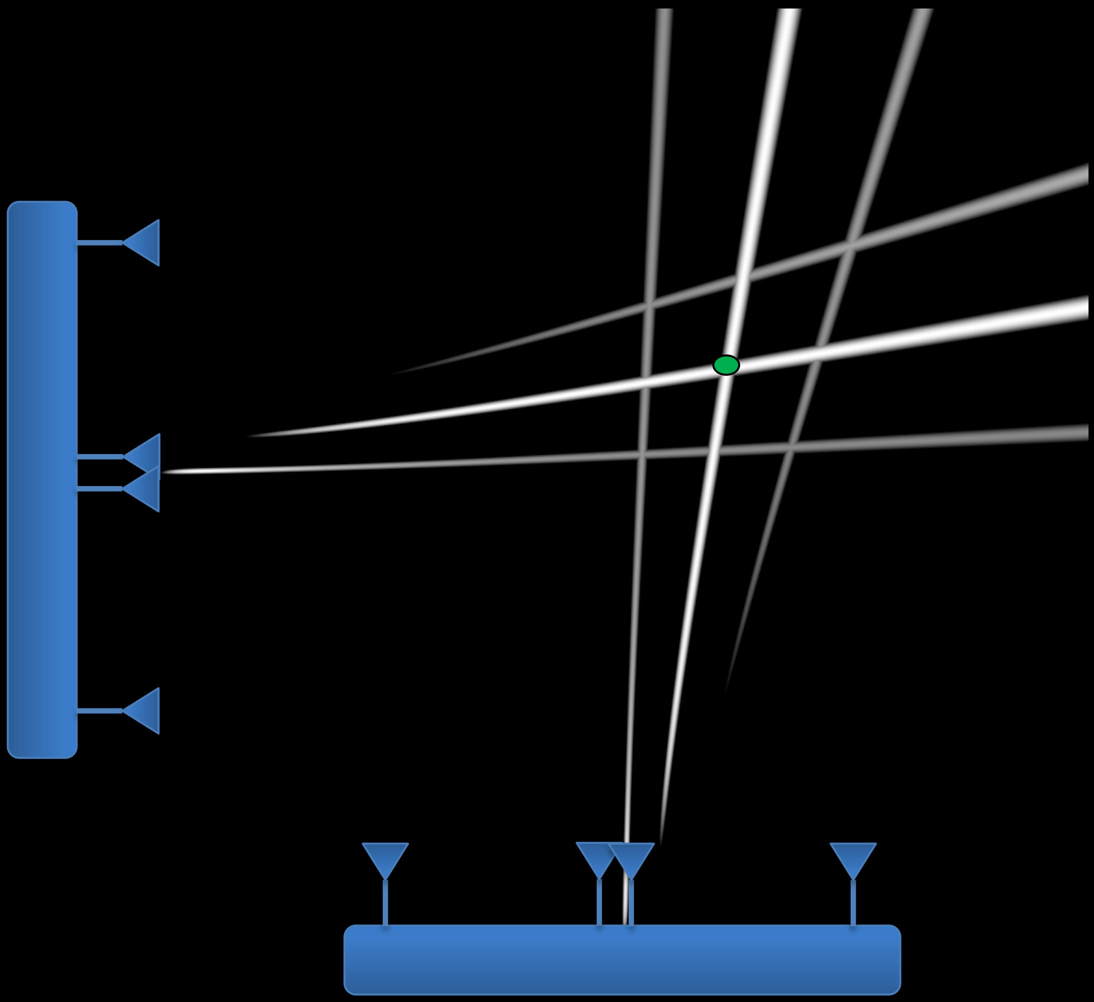
Noiseless Scenario



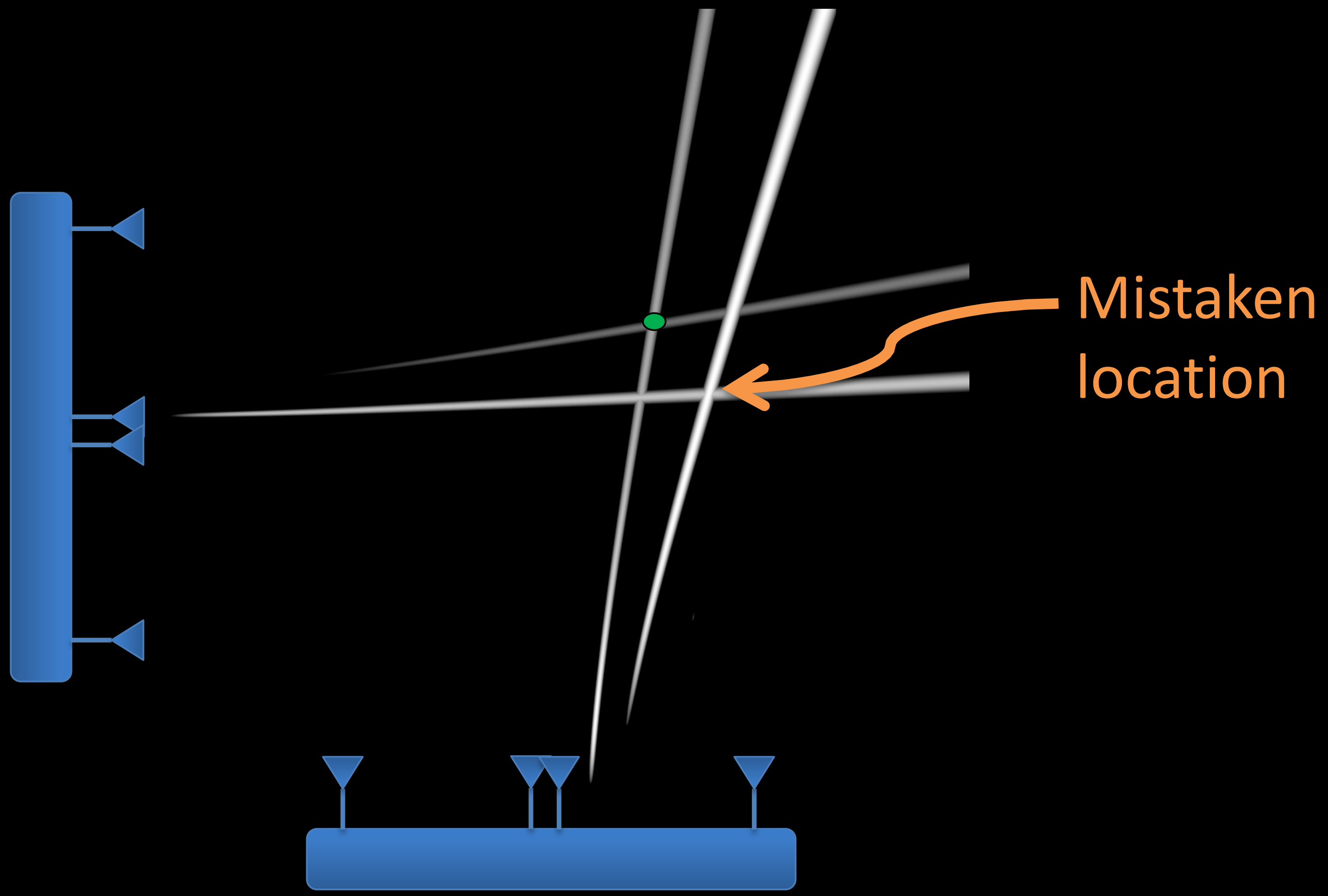
Noiseless Scenario



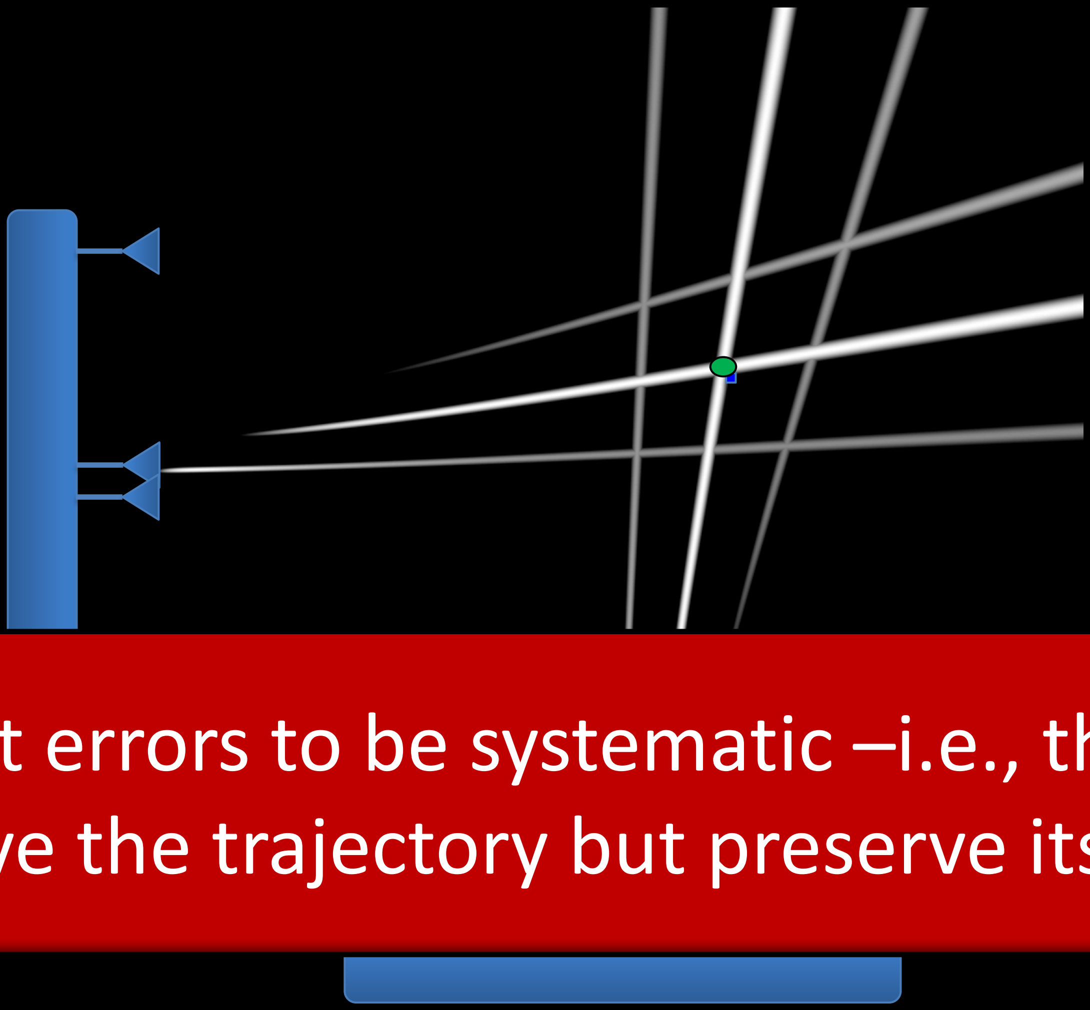
Noiseless Scenario



Impact of Noise



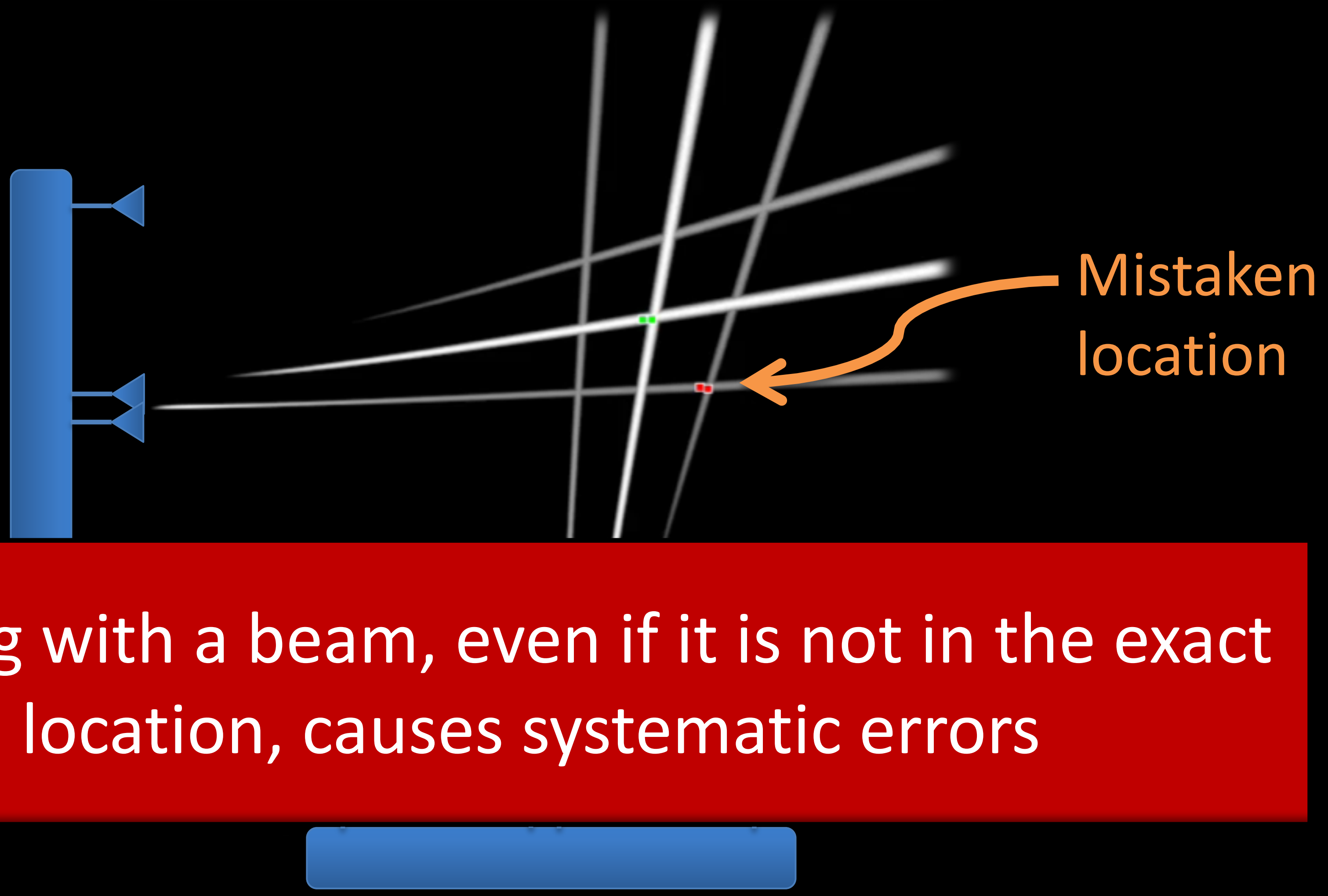
Impact of Noise



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

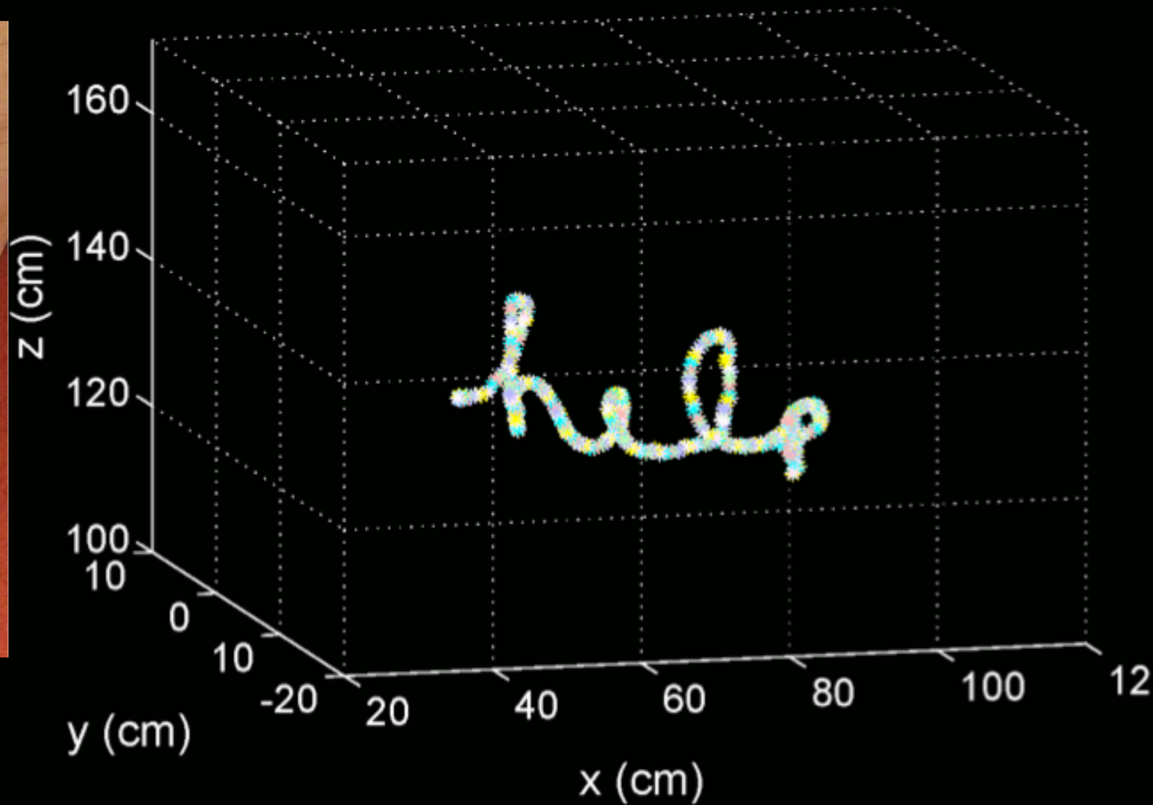
<u>Idea</u>: Stick with your choices

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:

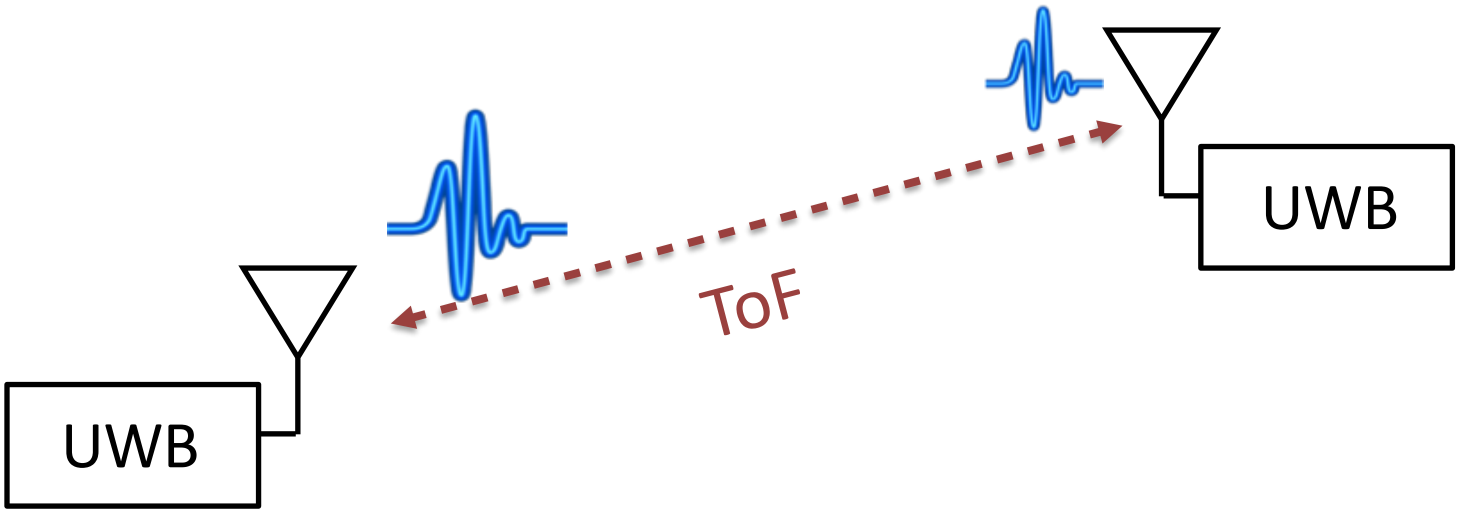
- Accurate RFID Tracking (4cm).
- Multi-Resolution Array→ Use few number of antennas
- No mobility or tagging environment

Cons:

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

How can we achieve cm RFID Localization?

UWB: Ultra-Wide Band

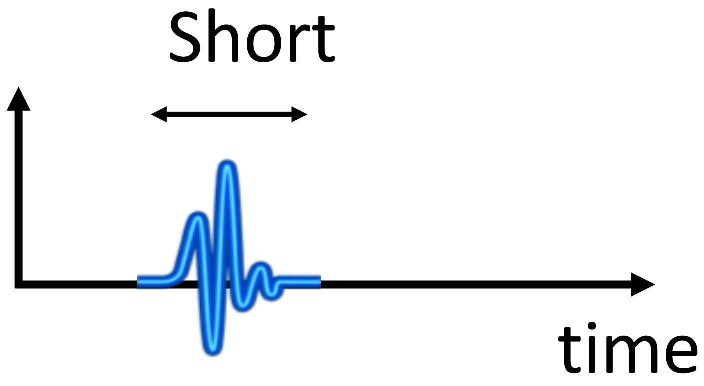


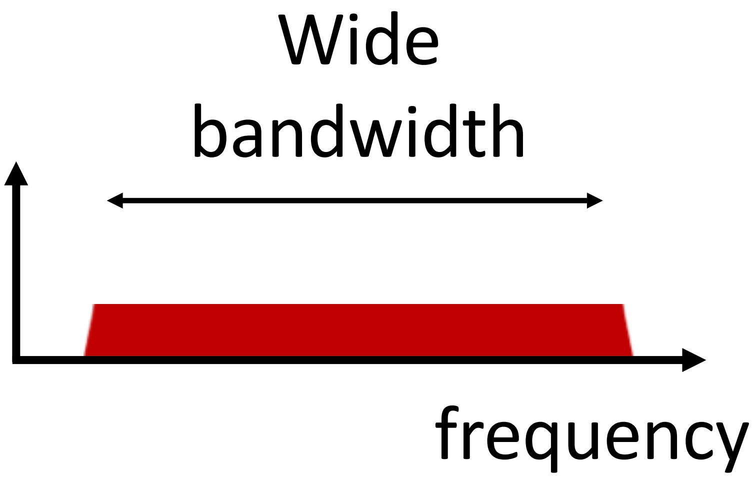
Localize by measuring the Time-of-flight

Distance = Time-of-flight × speed of light

UWB: Ultra-Wide Band

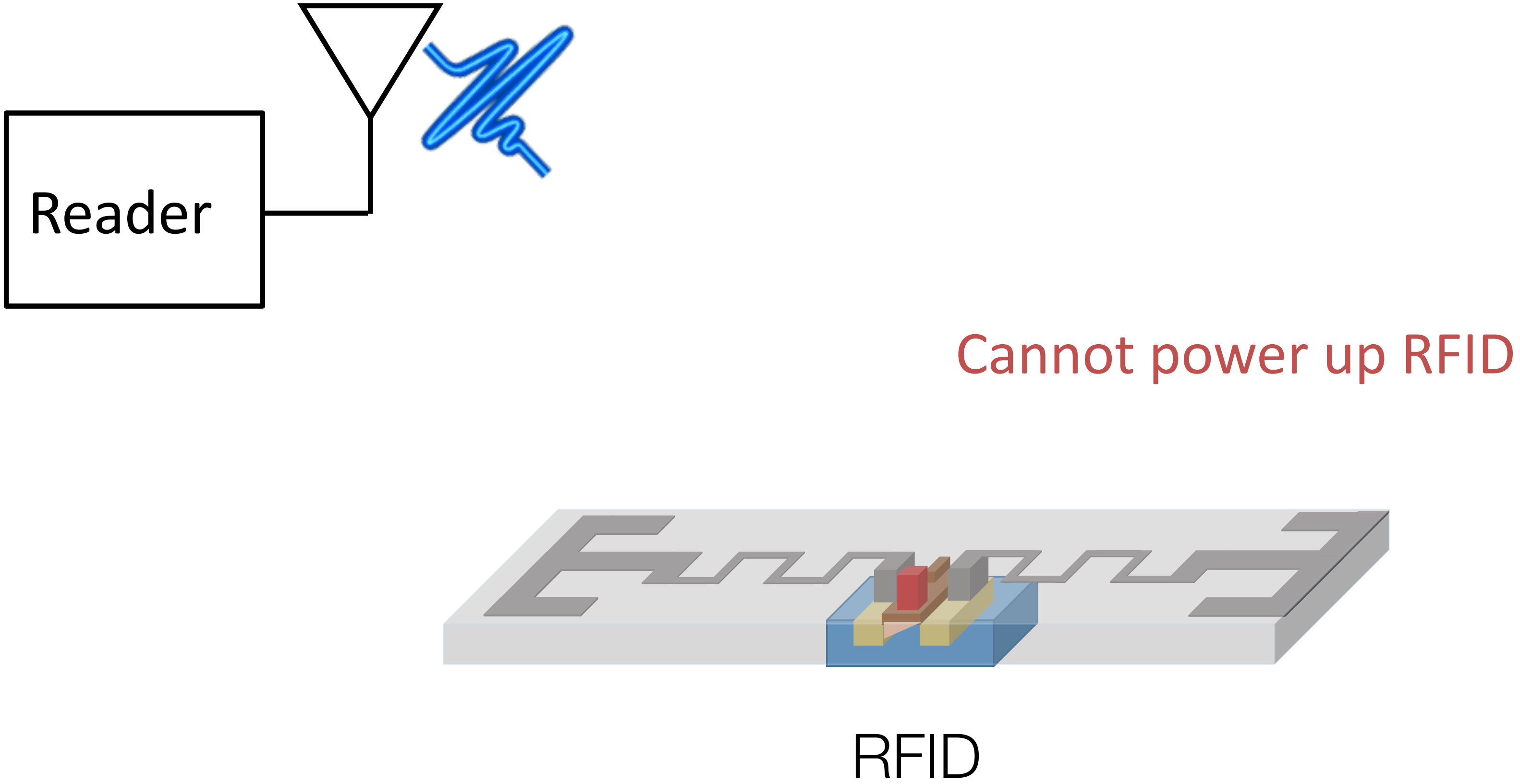
Short pulse allows measuring time at very fine granularity





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

How about we just transmit a very short pulse?

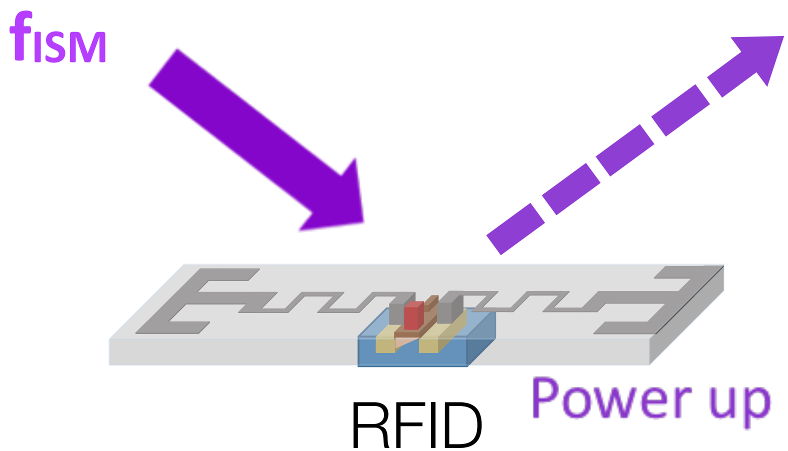


Problem: RFIDs cannot power up from a very short pulse

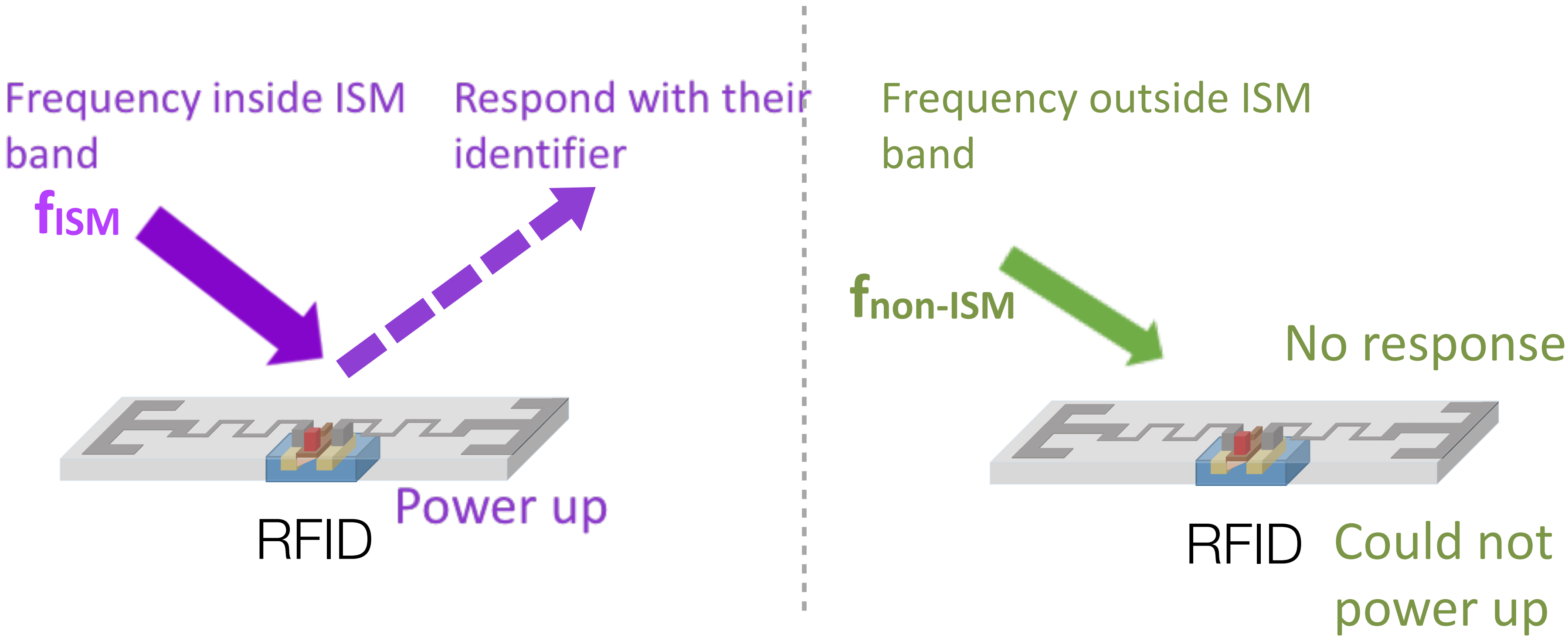
Problem: Battery-free RFIDs are designed to respond to a very narrowband signal

Frequency inside ISM band

Respond with their identifier

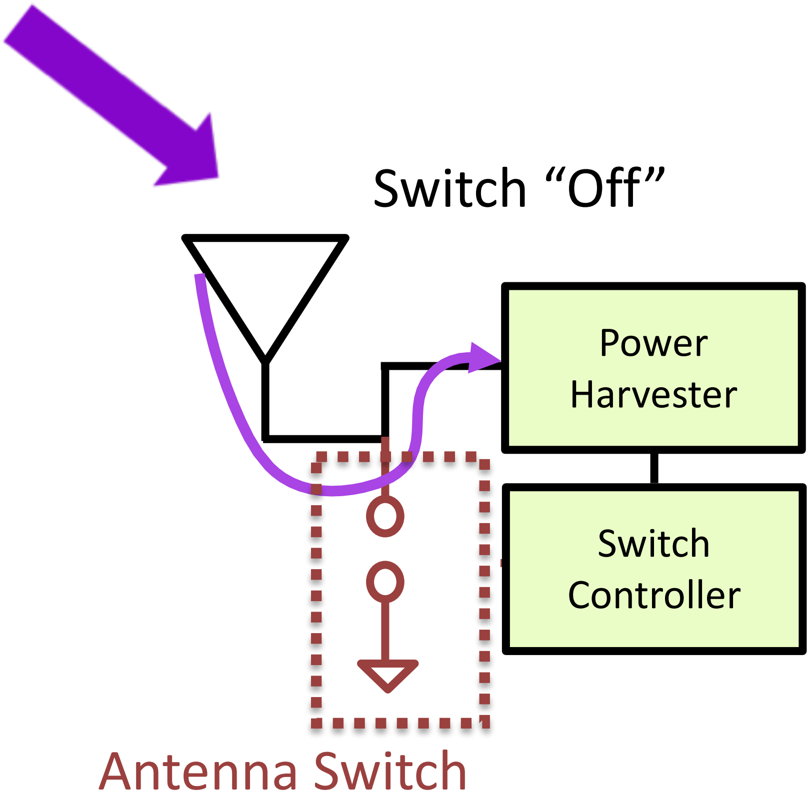


Problem: Battery-free RFIDs are designed to respond to a very narrowband signal



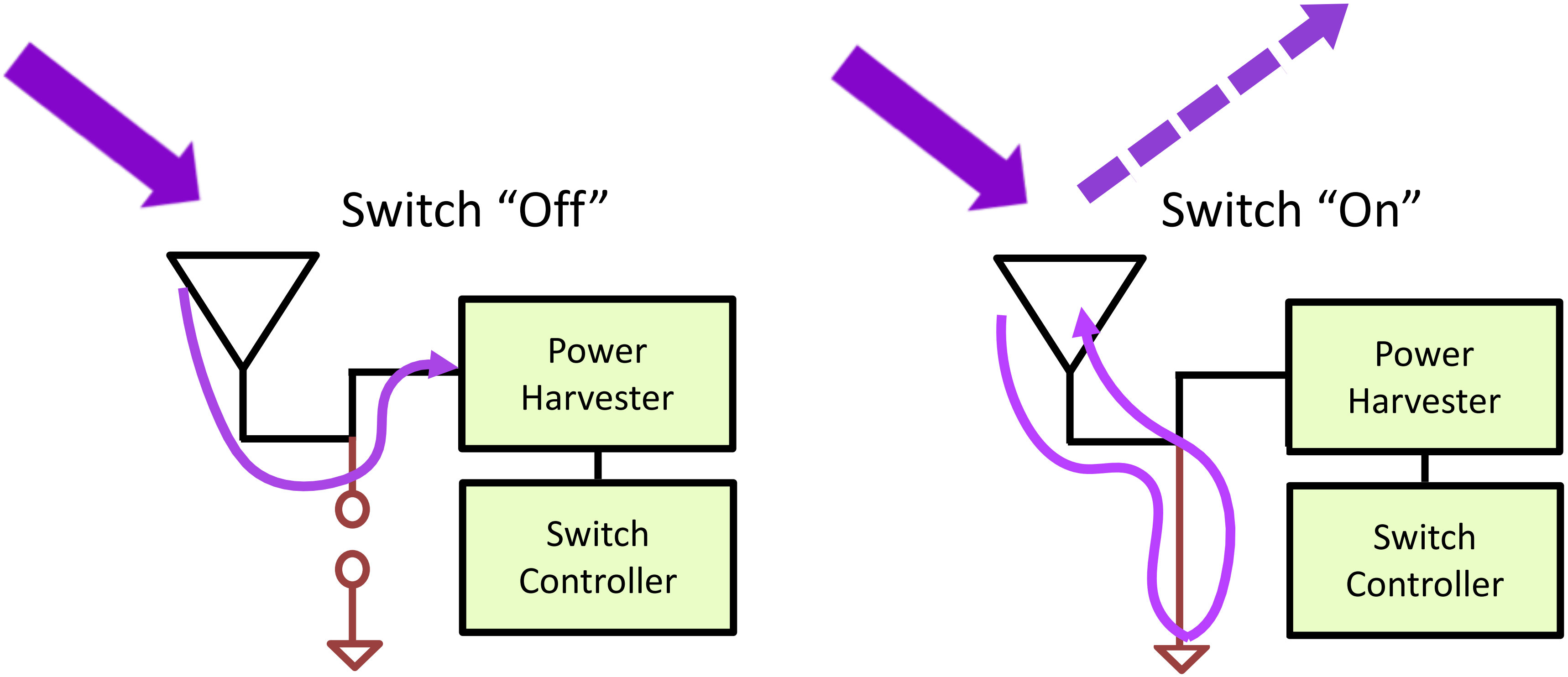
Battery-Free RFIDs are optimized to harness power from signals within the UHF

RFind Key Idea:
RFID Modulation is Frequency Agnostic

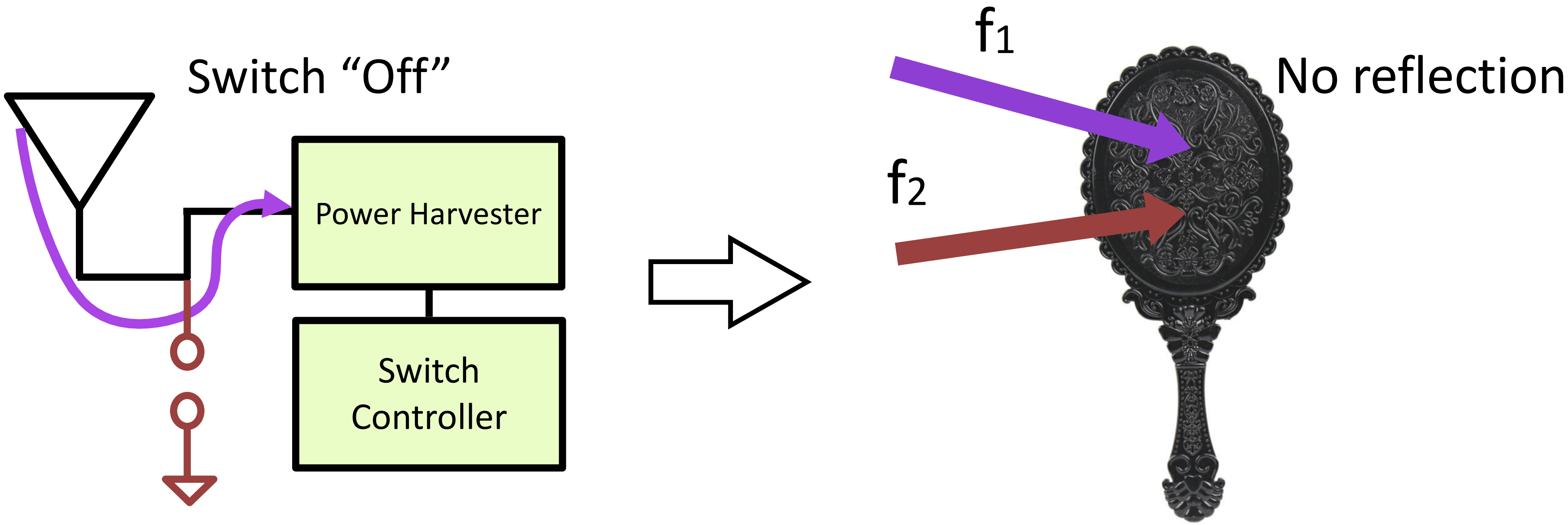


Simplified RFID schematic

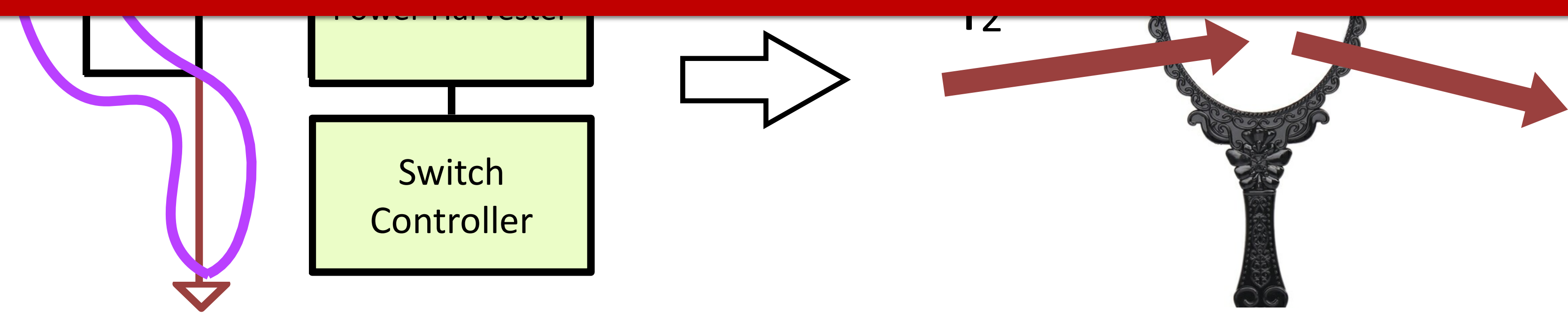
Key Realization:
RFID Modulation is Frequency Agnostic



Key Realization:
RFID Modulation is Frequency Agnostic



But we need to power up RFID in the first place

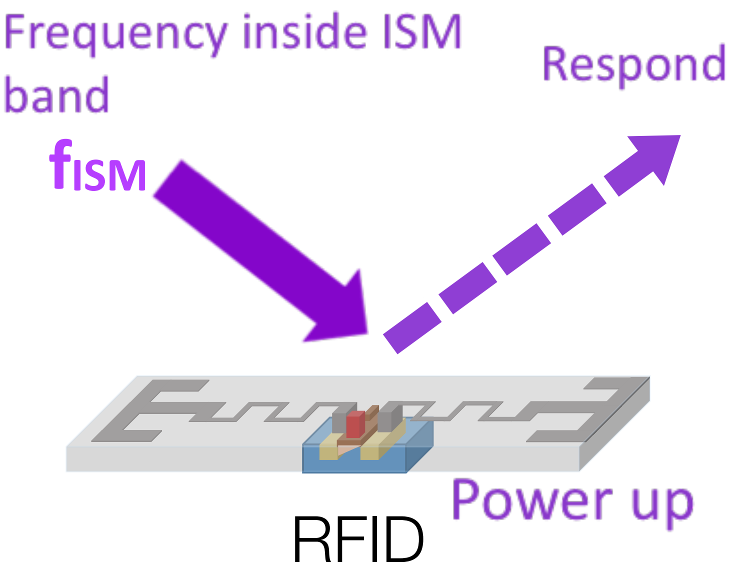


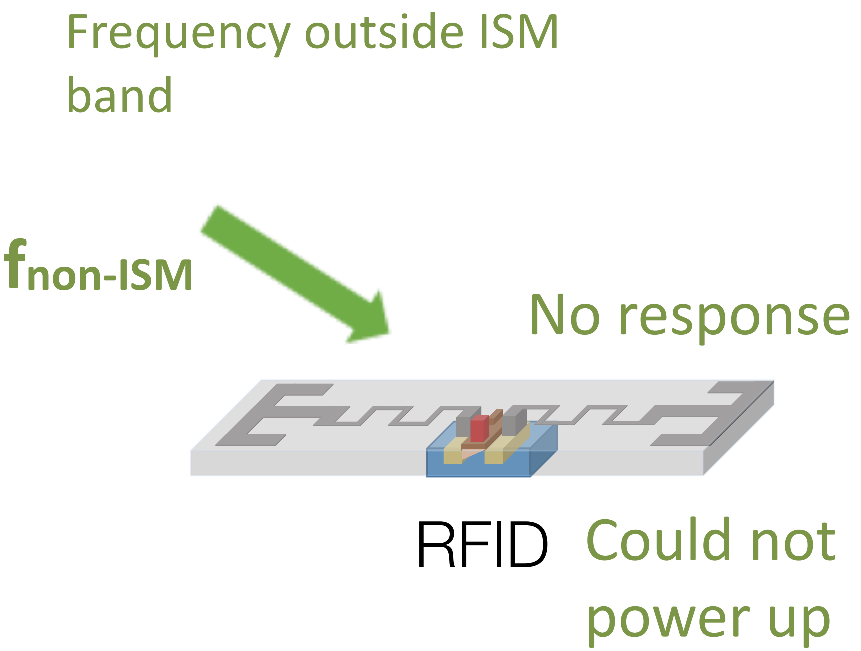
Dual-Frequency Excitation

A technique that decouples powering up from sensing in RFID localization

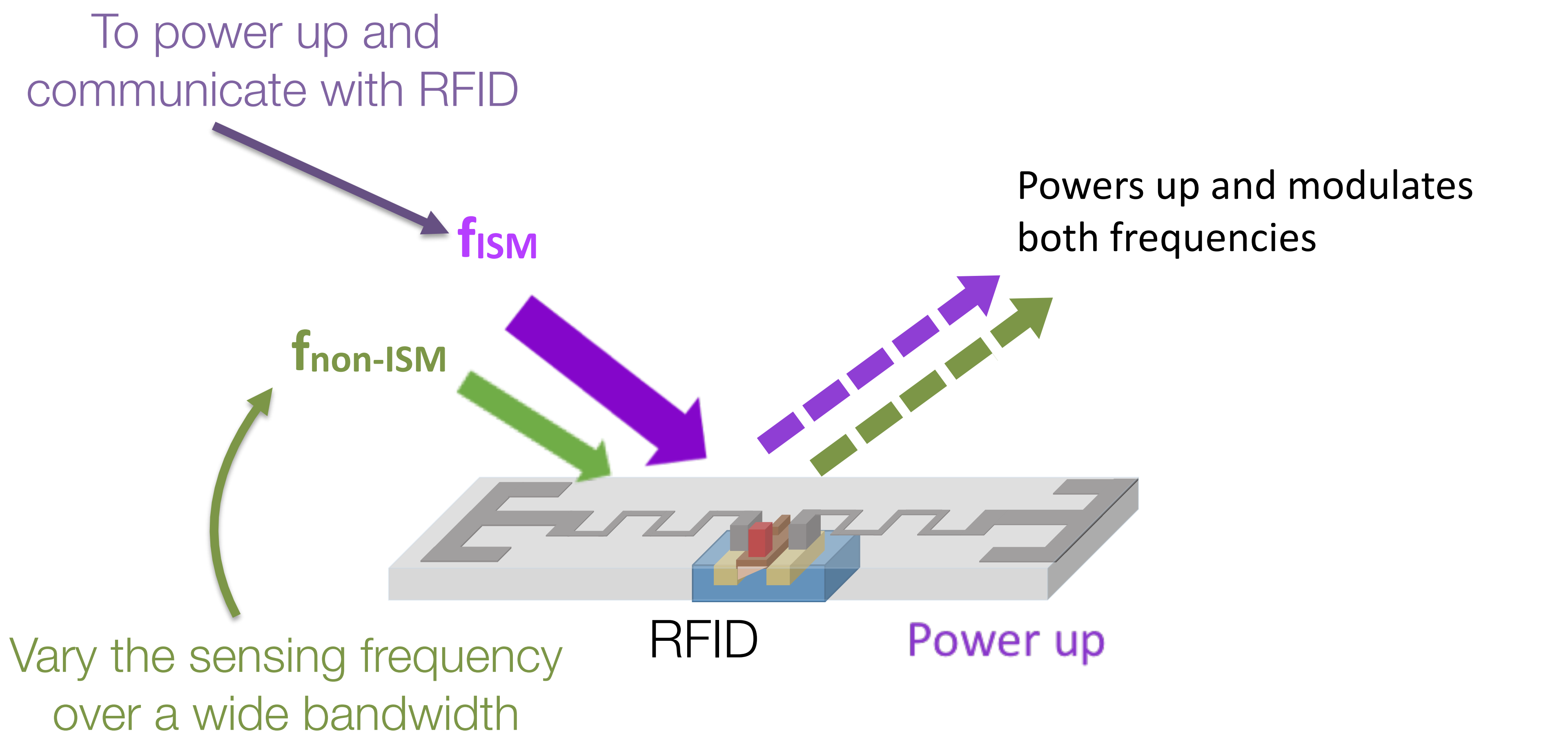
Dual-Frequency Excitation

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



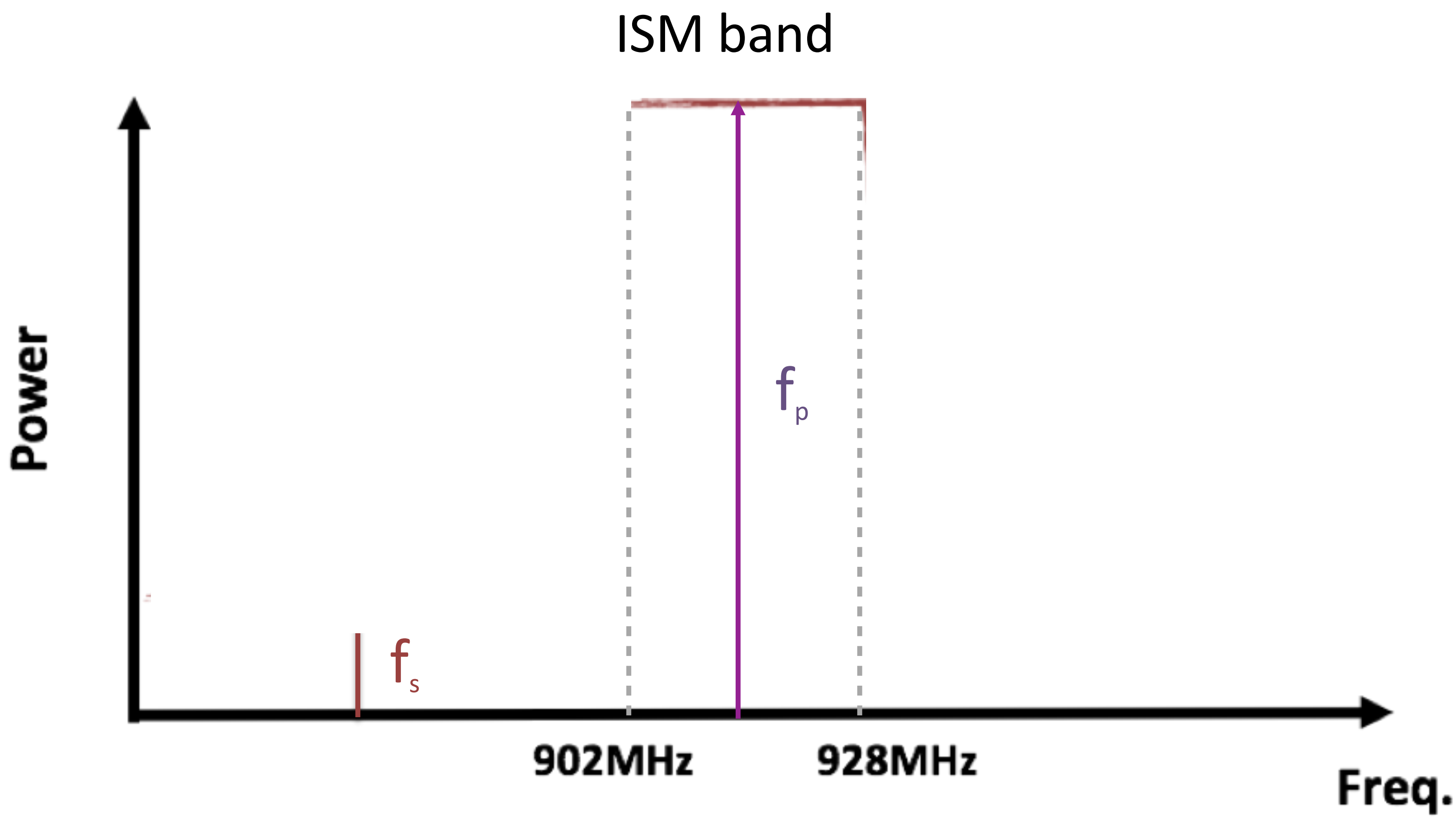


Dual-Frequency Excitation

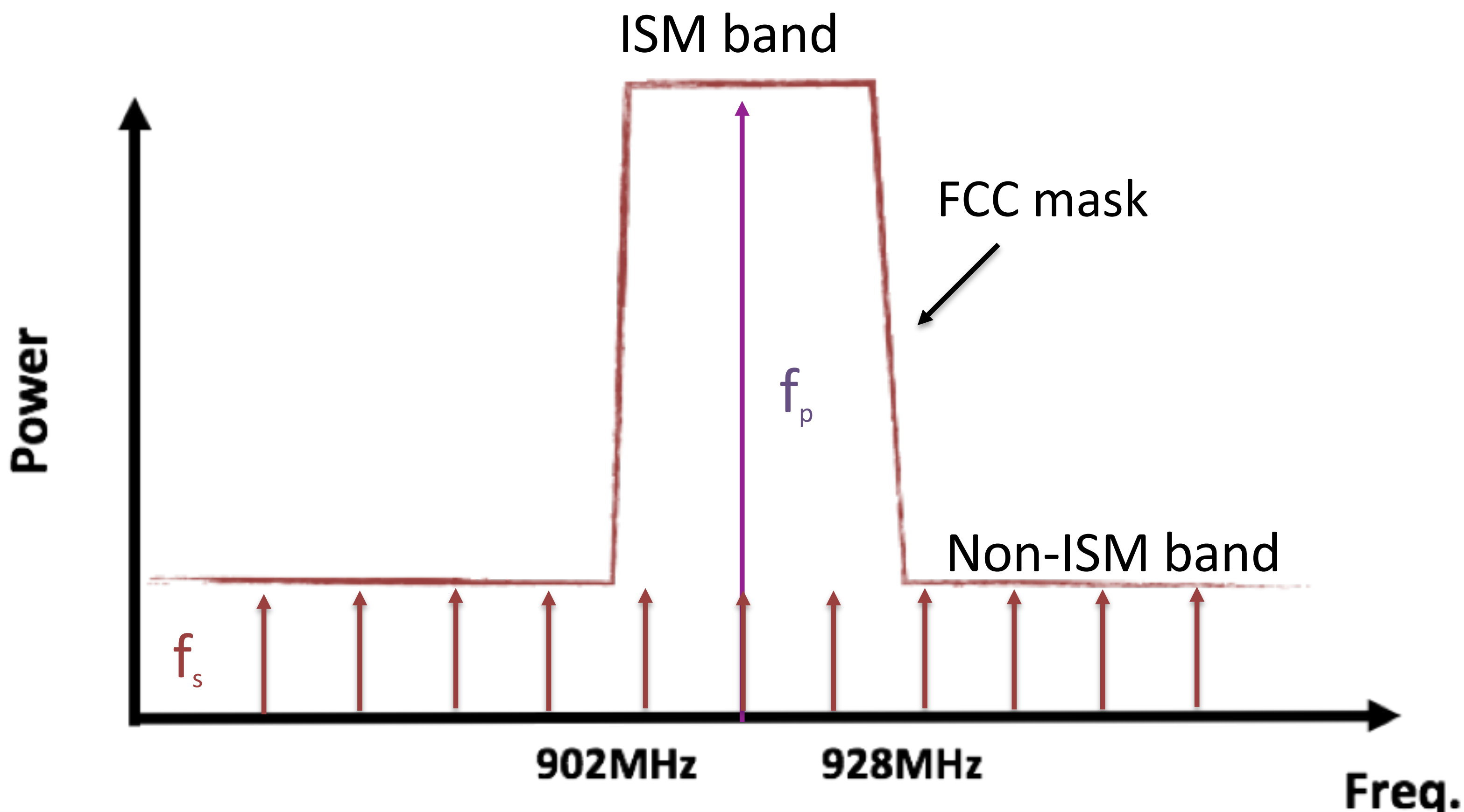


Wide Bandwidth → Time-of-flight → Accurate Localization

How can we perform wideband sensing despite FCC regulations?



How can we perform wideband sensing despite FCC regulations?

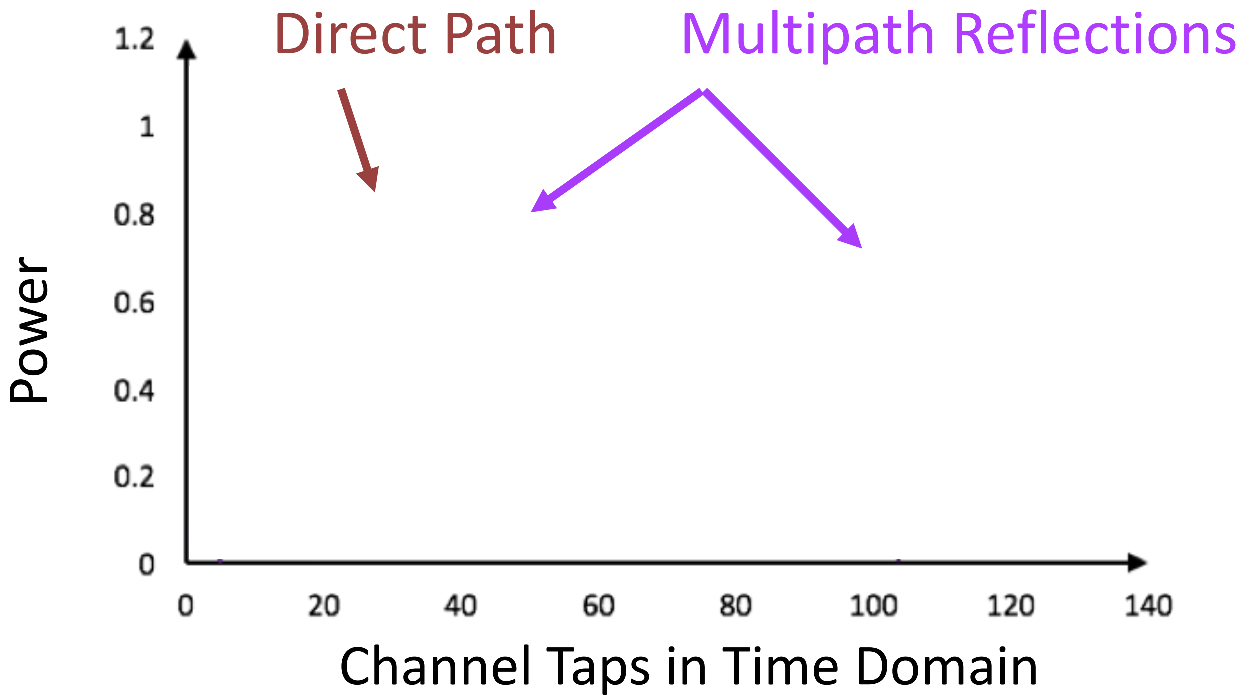


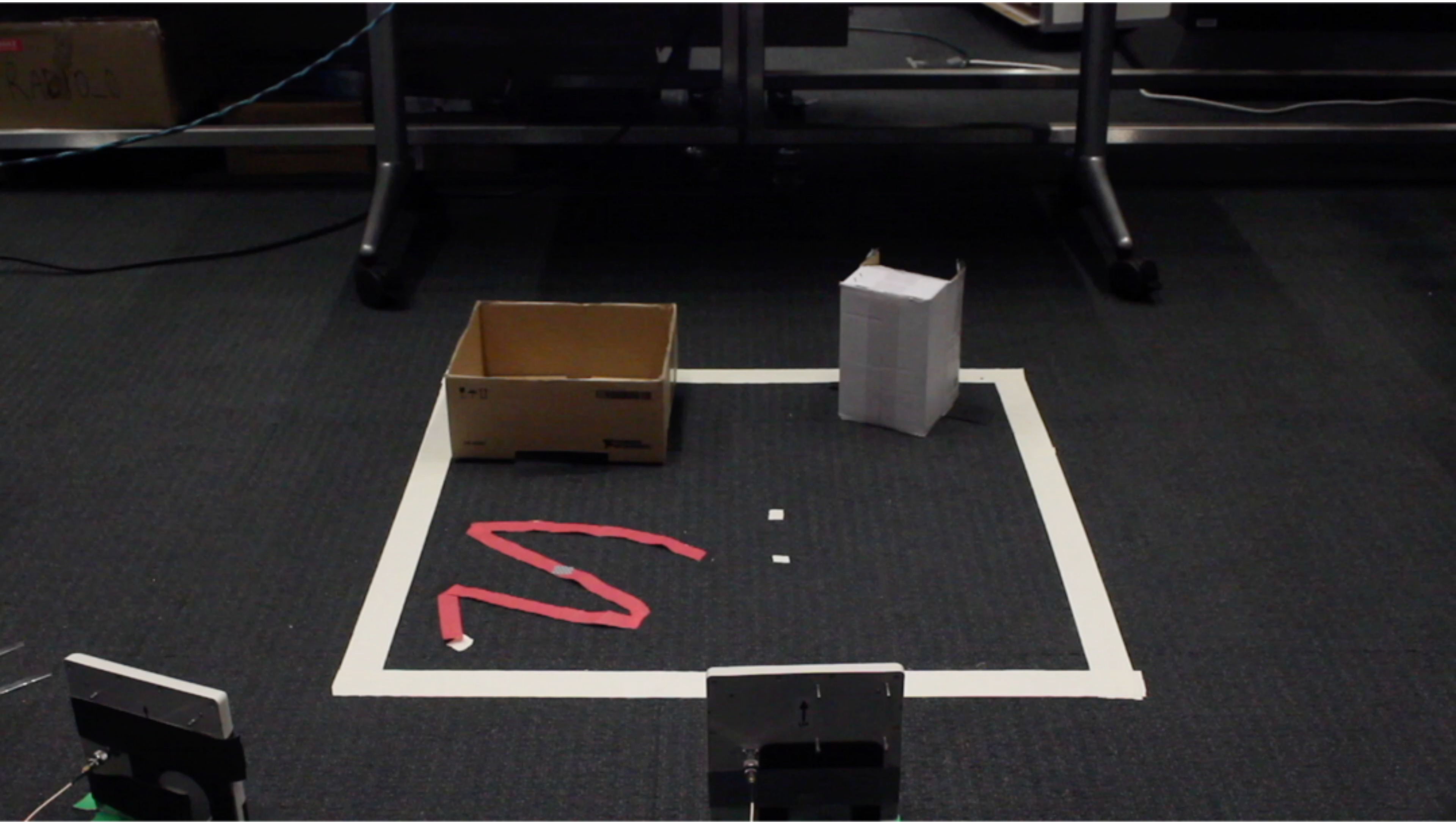
Sensing frequency can be transmitted at ultra-low power and swept over time

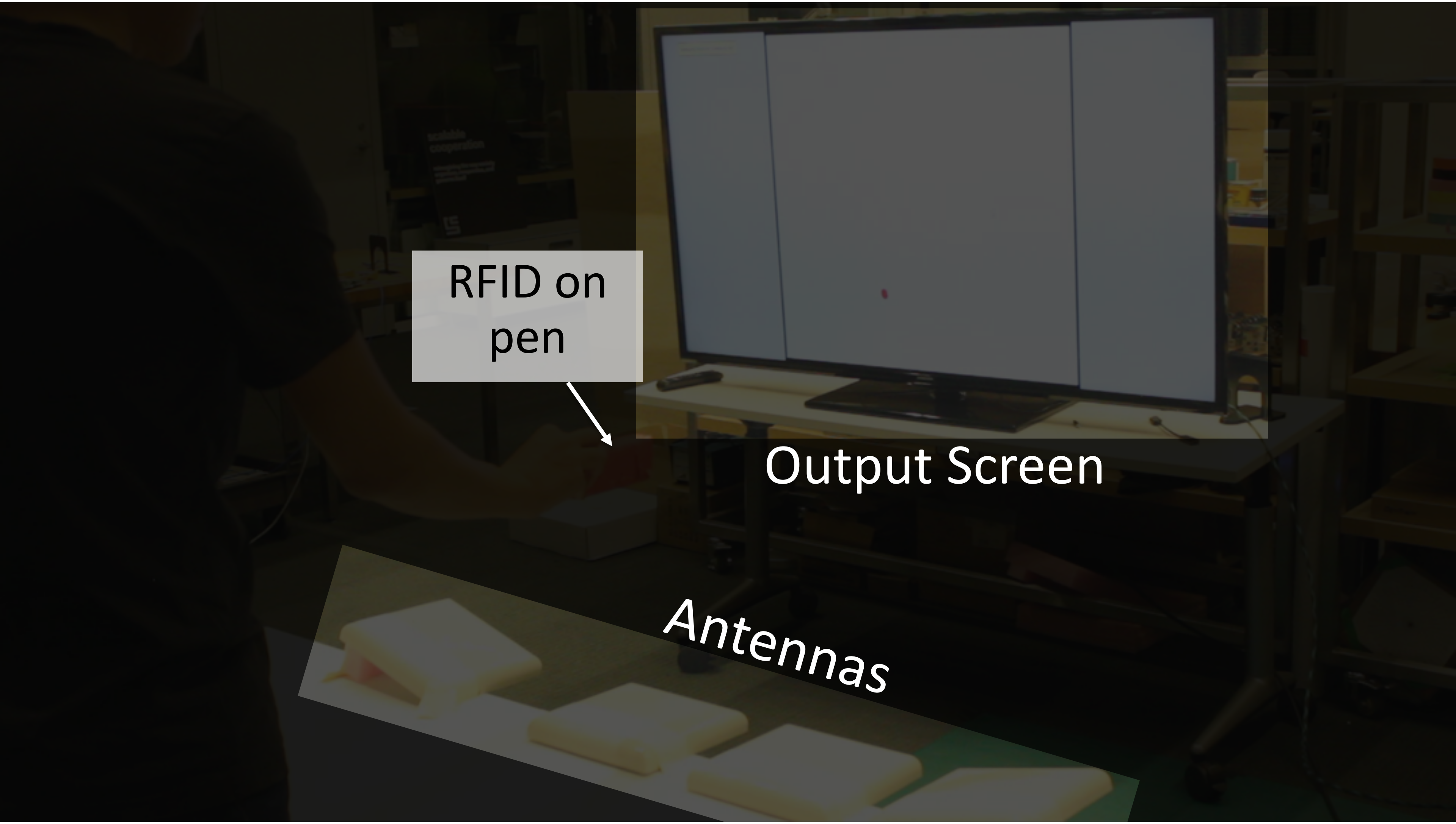
From Wide Bandwidth to Accurate Time-of-Flight Estimation

Estimating the Time-of-Flight

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







RFID on pen
Output Screen
Antennas

Wireless Localization / Positioning

Last Lecture: WiFi	This Lecture: RFID
Method 1: RSSI (Trilateration, Fingerprinting) **Method 2: AoA** (Angle of Arrival, Triangulation) **Method 3: Antenna Arrays** (Multipath Profile) **Method 4: ToF** (Time of Flight) **Method 5: 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

Many more systems out there! Different applications with variations on the core methods