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

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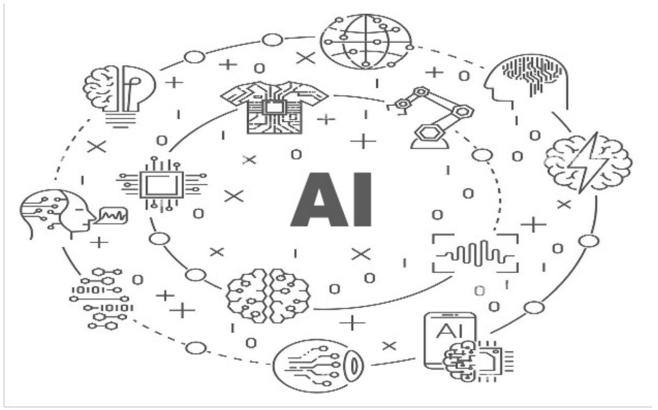
Lecture 4
Device-free Localization



University of Pennsylvania

*Slides Courtesy of Prof. Fadel Adib

Wireless Localization / Positioning

Past Lectures: Device-based Localization

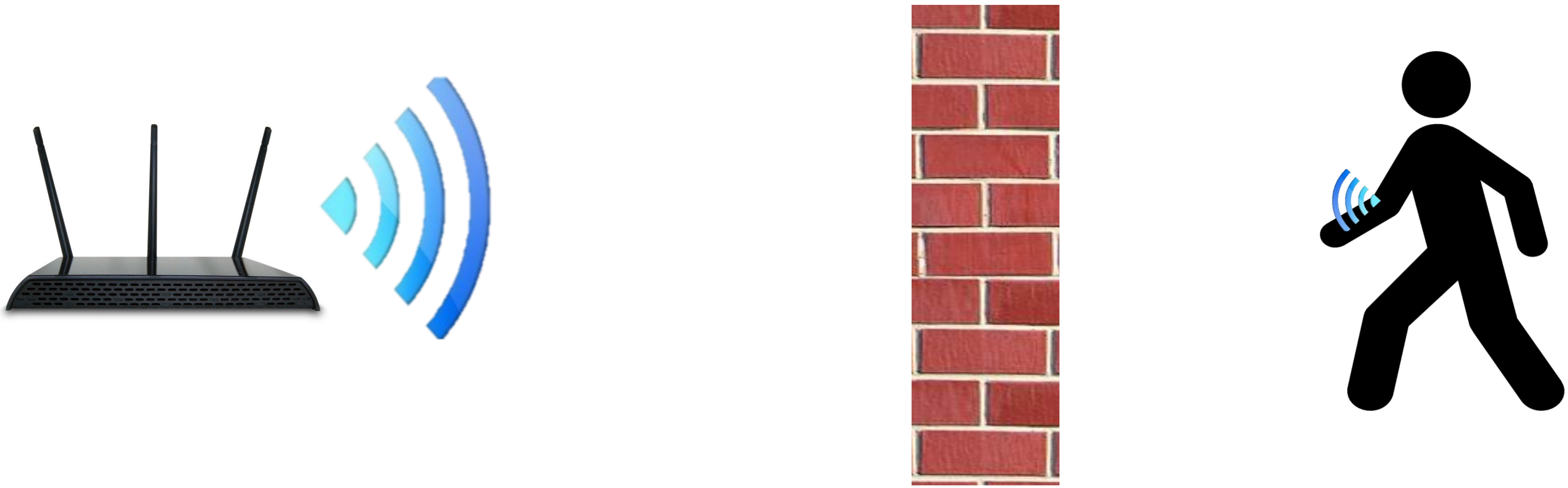
Wi-Fi

RFID

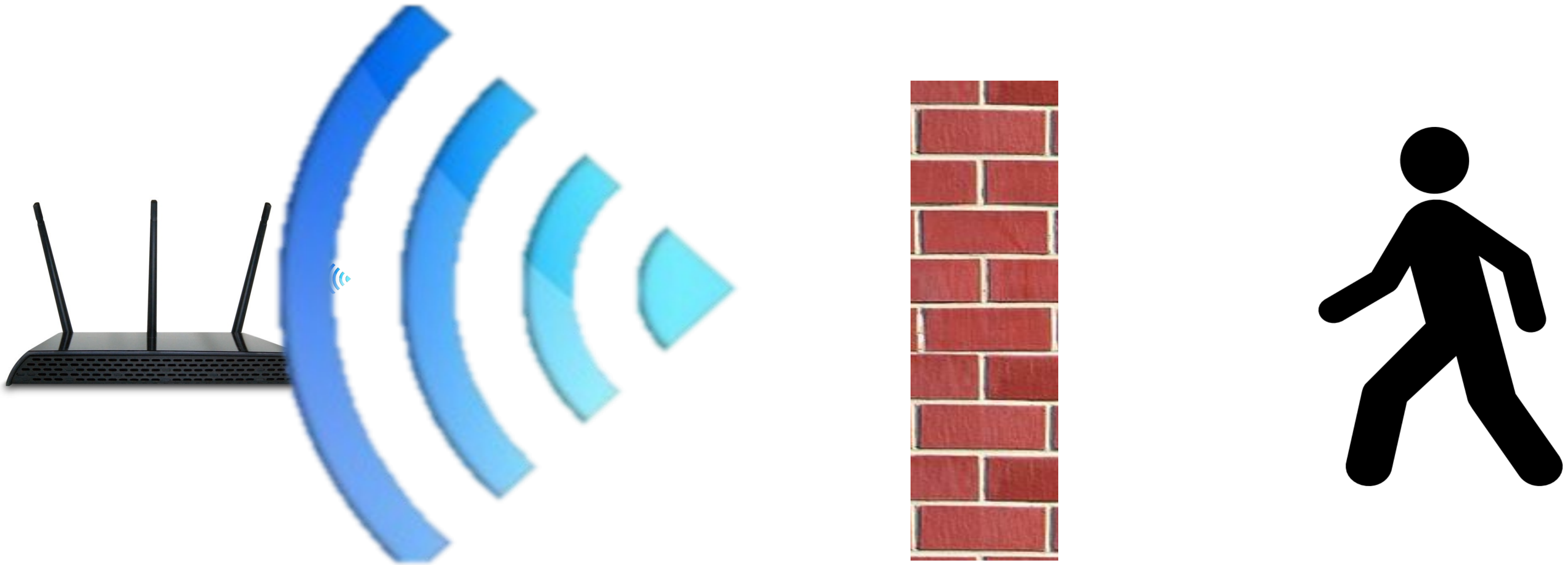
This Lecture: Device-free Localization

WiVi: Tracking People Through Walls with WiFi

Key Idea



Challenges



Challenge #1: Wall reflection is 10,000x stronger than any reflections coming from behind the wall

Challenge #2: Tracking people from their reflections

How Can We Eliminate the Wall’s Reflection?

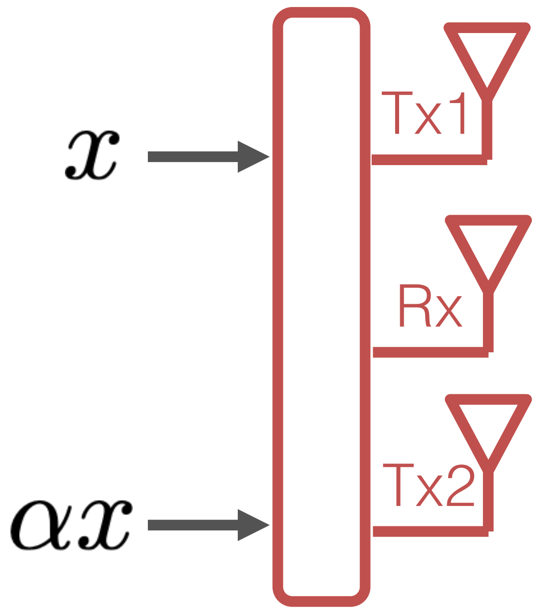
Idea: Transmit two waves that cancel each other when they reflect off static objects but not moving objects

Wall is static → disappears

People tend to move → detectable

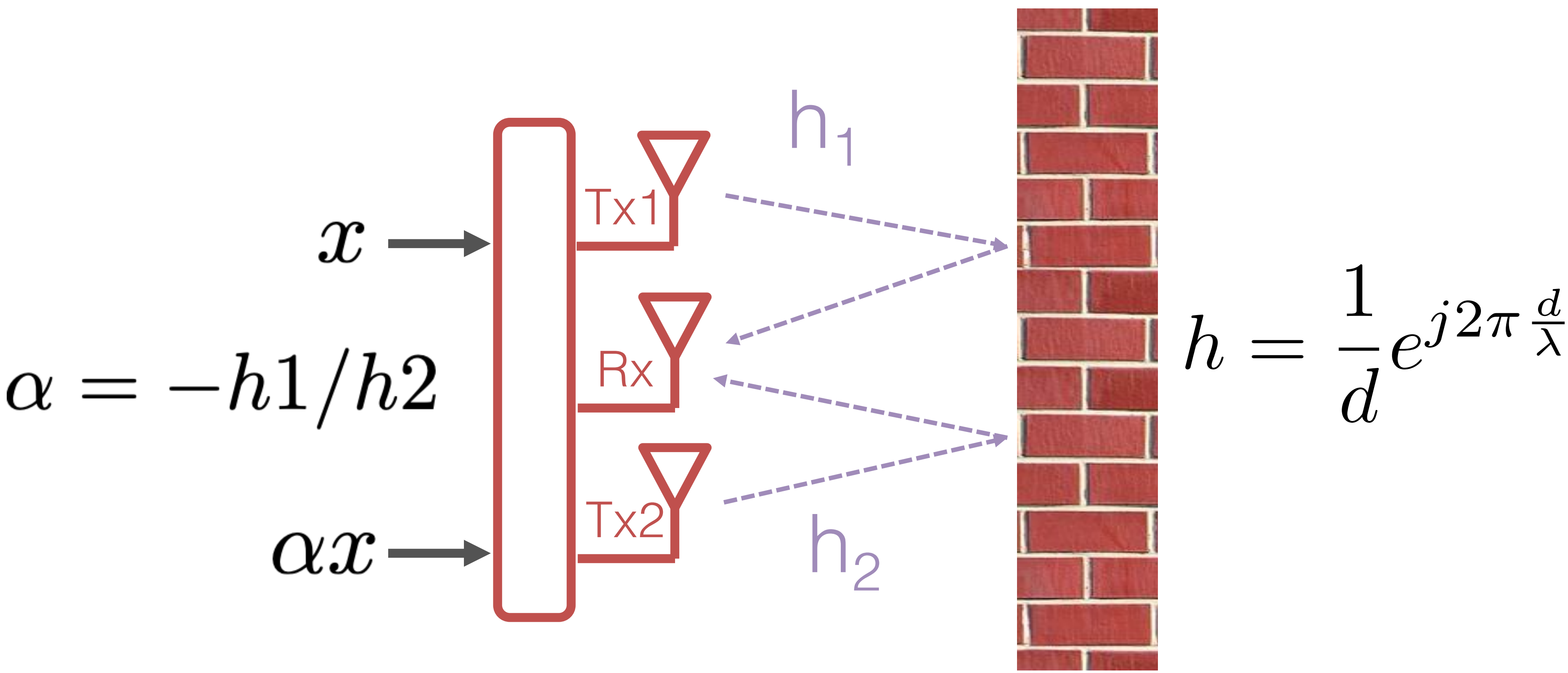
Eliminating the Wall's Reflection

Two transmit antennas and one receive antenna

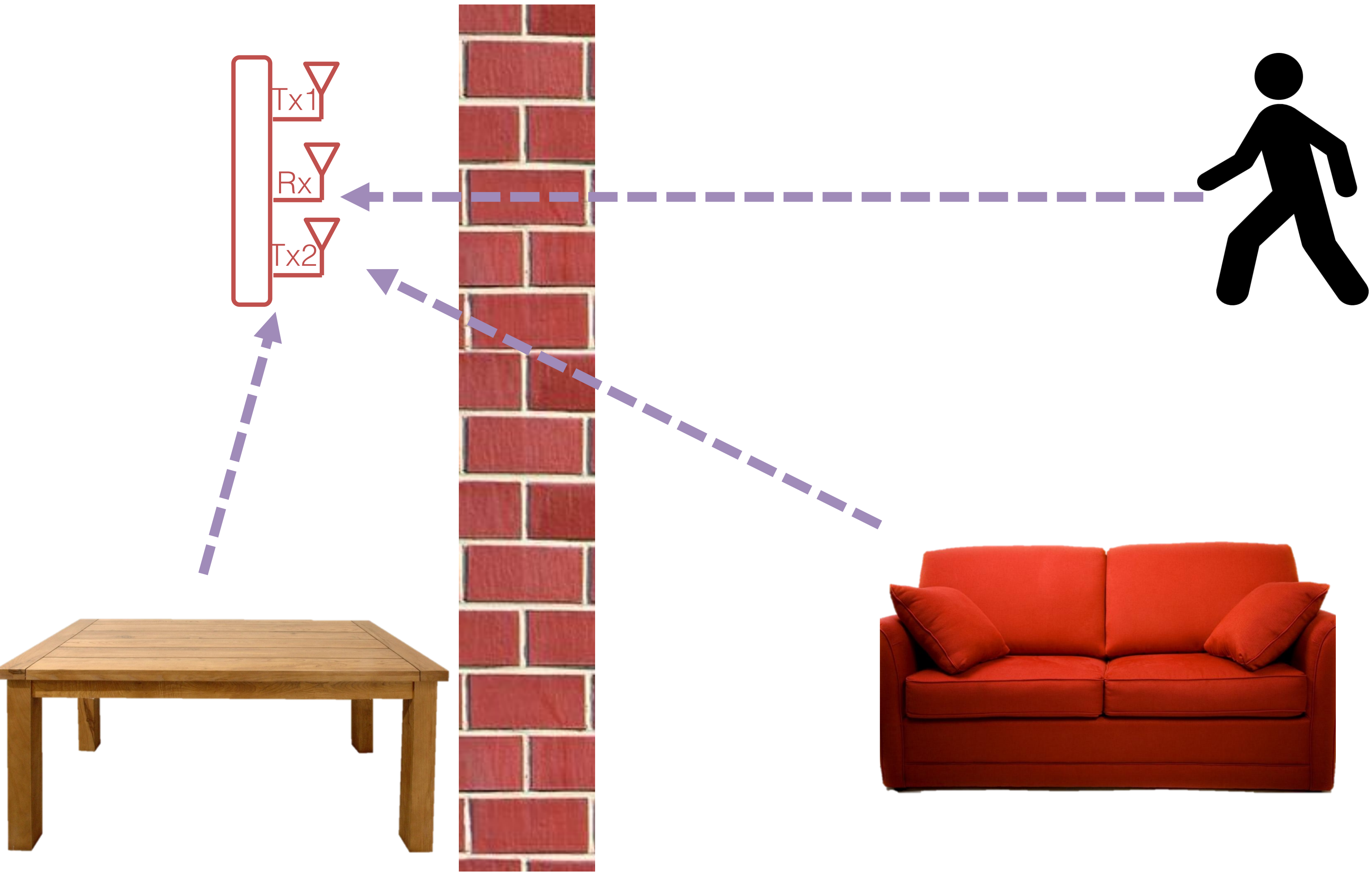


Eliminating the Wall's Reflection

Received signal: $y = h_1 x + h_2 \alpha x$ → 0



Eliminating All Static Reflections



Eliminating All Static Reflections

$$y = h_1 x + h_2 \alpha x$$

Reflections linearly combine over the wireless medium

$$y = \left(\sum_i h_{1i}\right) x + \left(\sum_i h_{2i}\right) \alpha x$$

reflector i

Static objects (wall, furniture, etc.) have constant channels

$$y_i = h_{1i}\, x + h_{2i}(- h_{1i} / h_{2i}) x \rightarrow 0$$

People move, therefore their channels change

$$y_i = h_{1i}'\, x + h_{2i}'(- h_{1i} / h_{2i}) x$$

Not Zero

Eliminating All Static Reflections

- Noise leads to errors in estimating the channel
  - Limits ability to cancel static reflections and sense motion behind the wall
  - Channel estimates $\hat{h} \neq h$

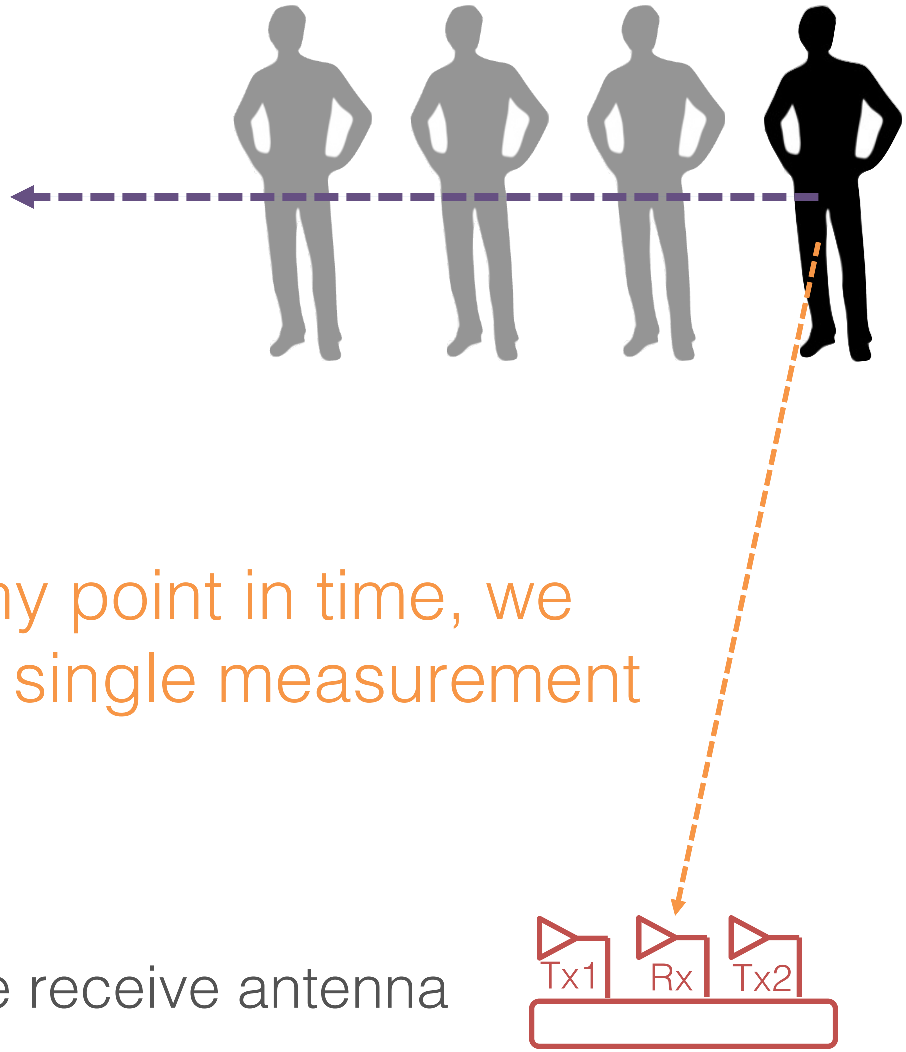
- Refine channel estimates through an iterative nulling algorithm

<u>If</u> $\left|\frac{\hat{h_2}-h_2}{h_2}\right| < 1$, then after ***i*** iterations, $|h_{res}^{(i)}| = |h_{res}^{(0)}| \left|\frac{\hat{h_2}-h_2}{h_2}\right|^i$

How Can We Track Using Reflections?

Tracking Motion

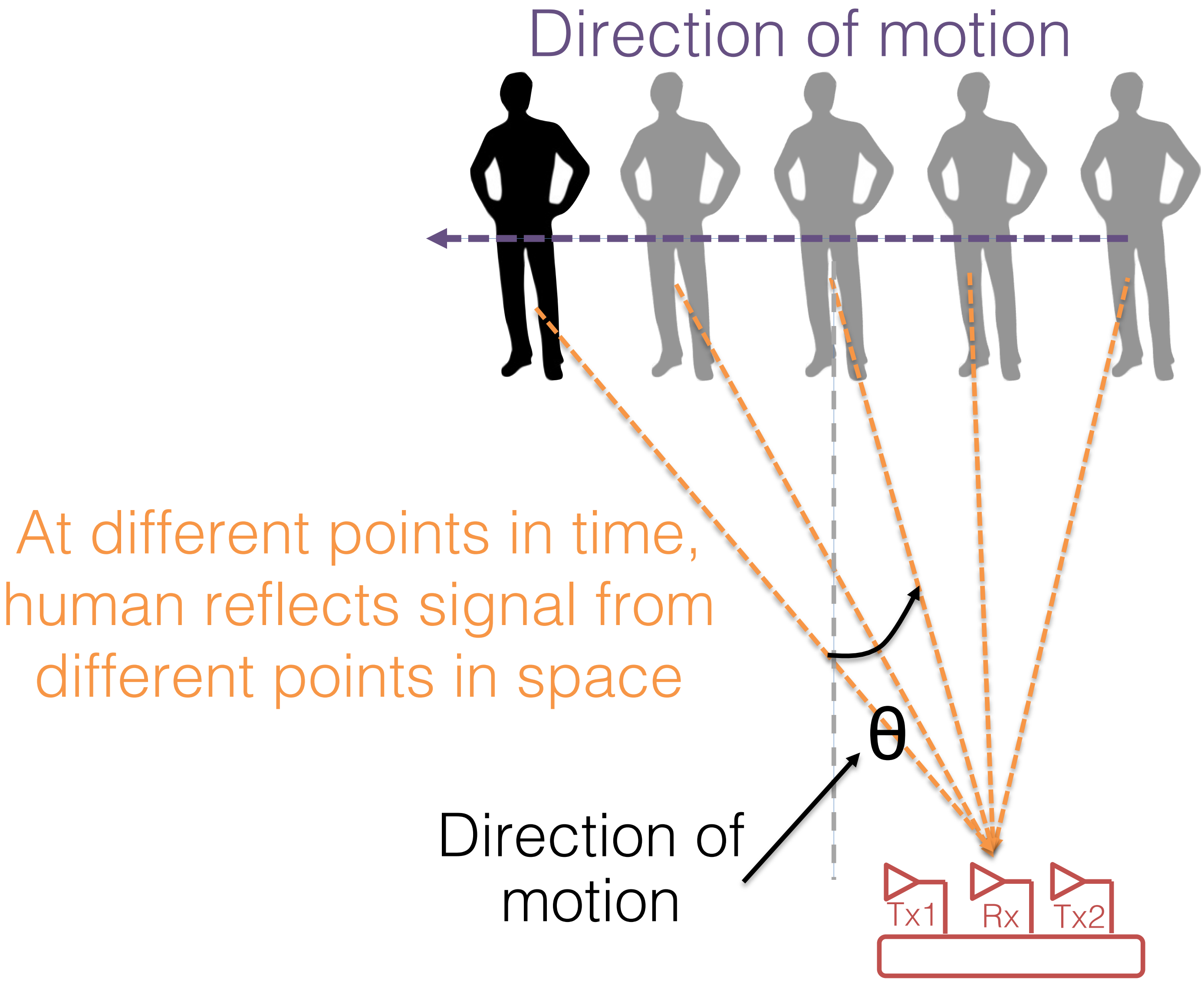
Direction of motion



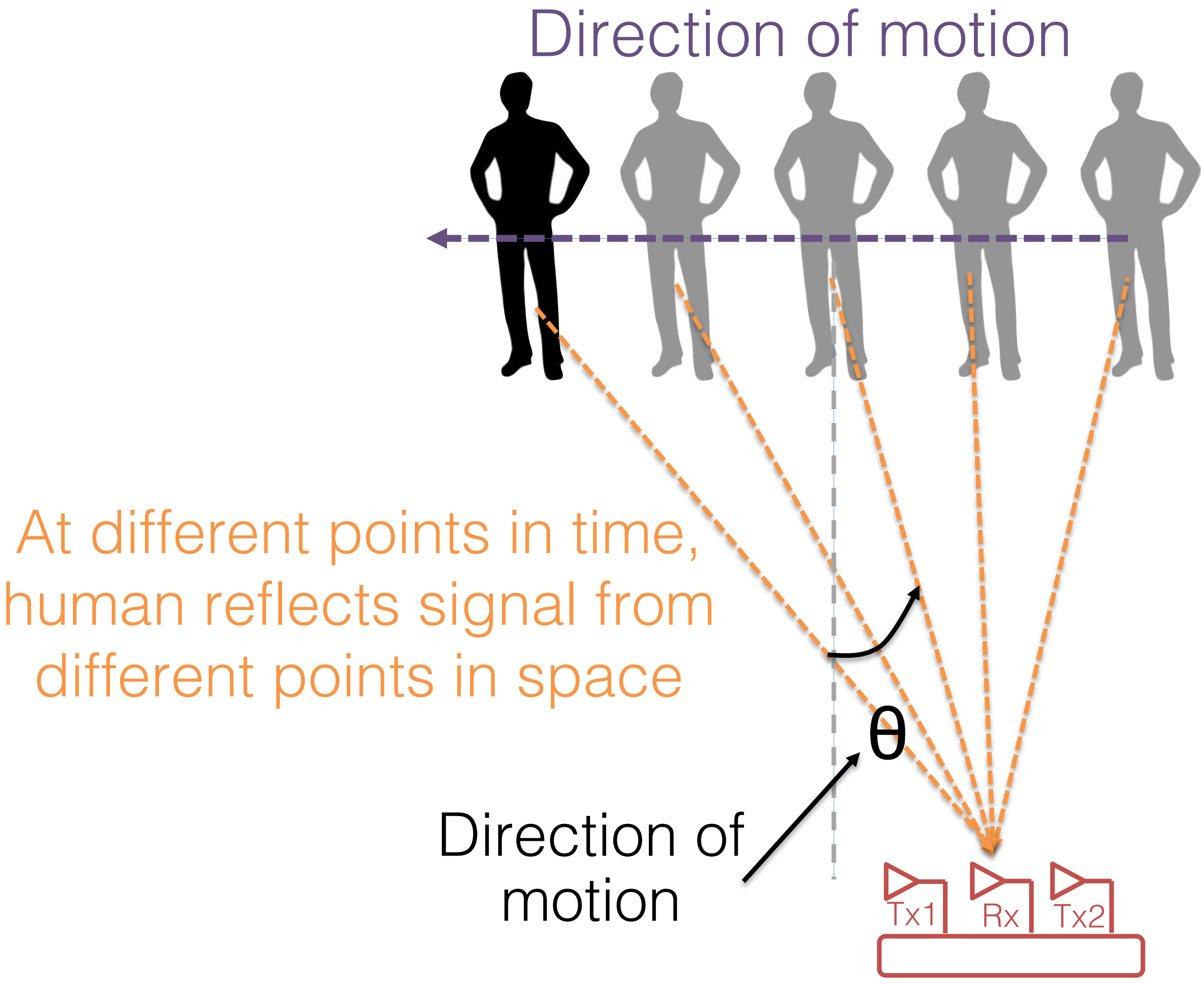
At any point in time, we have a single measurement

Device has one receive antenna

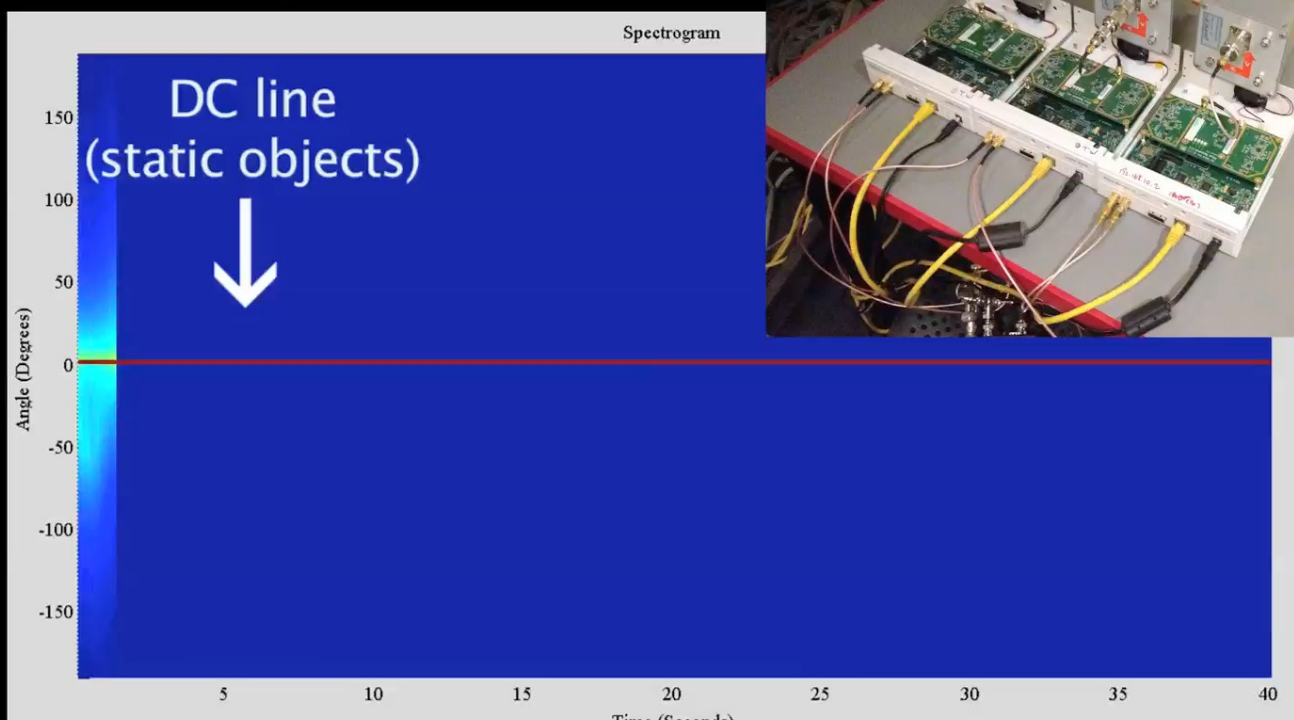
Tracking Motion

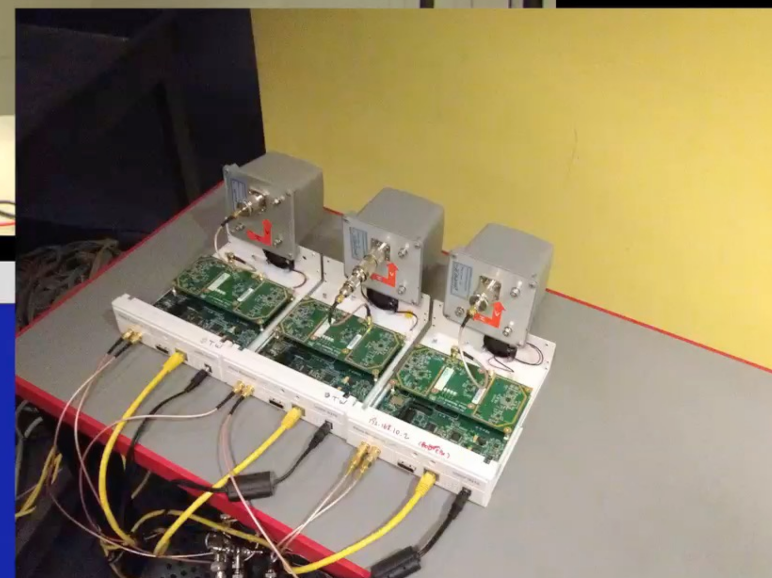


Human Motion Emulates an Antenna Array



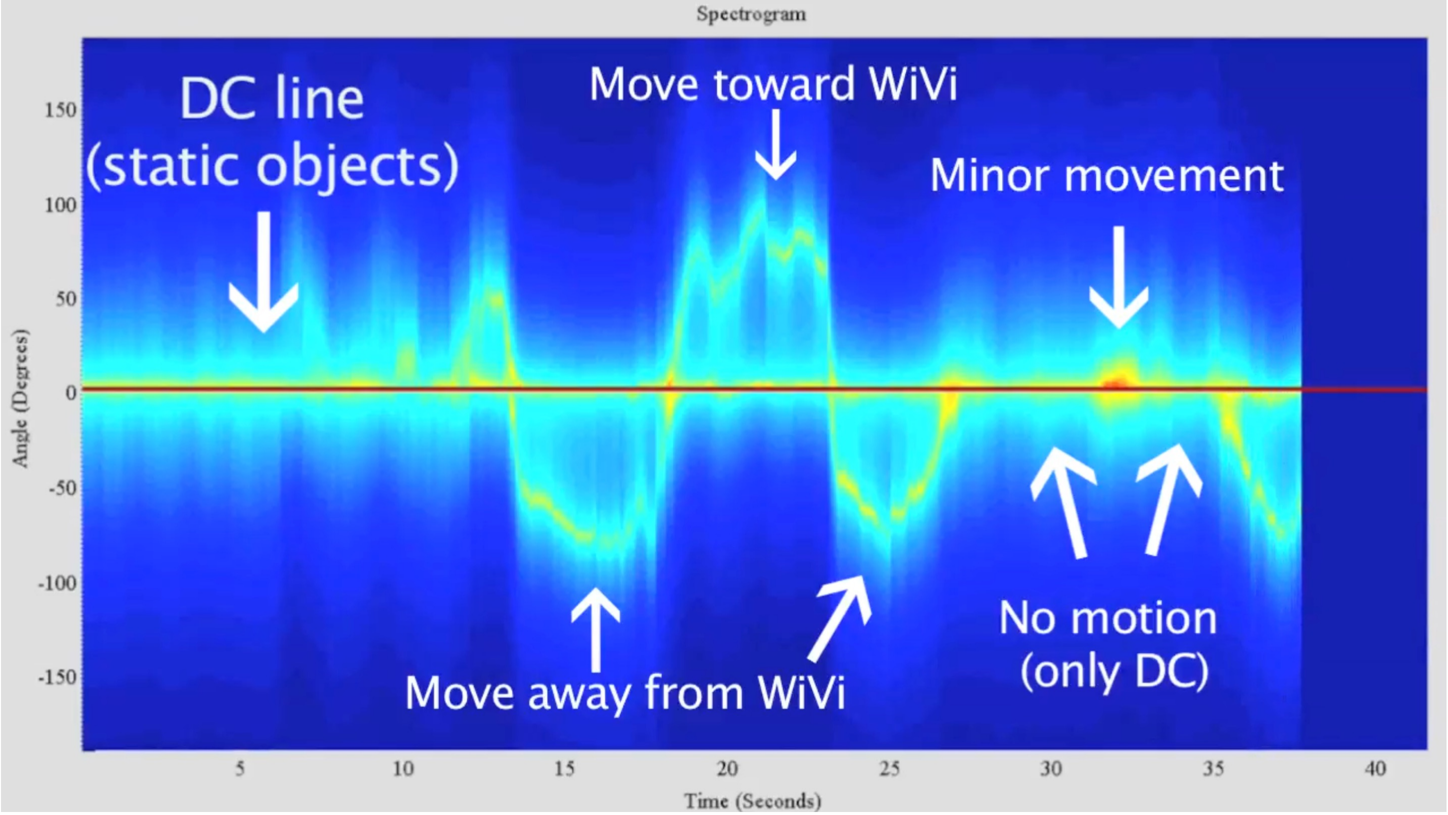

WiVi behind wall
over here


Spectrogram
DC line
(static objects)
Angle (Degrees)
150
100
50
0
-50
-100
-150
5
10
15
20
25
30
35
40
Time (Seconds)



Tracking Multiple Humans

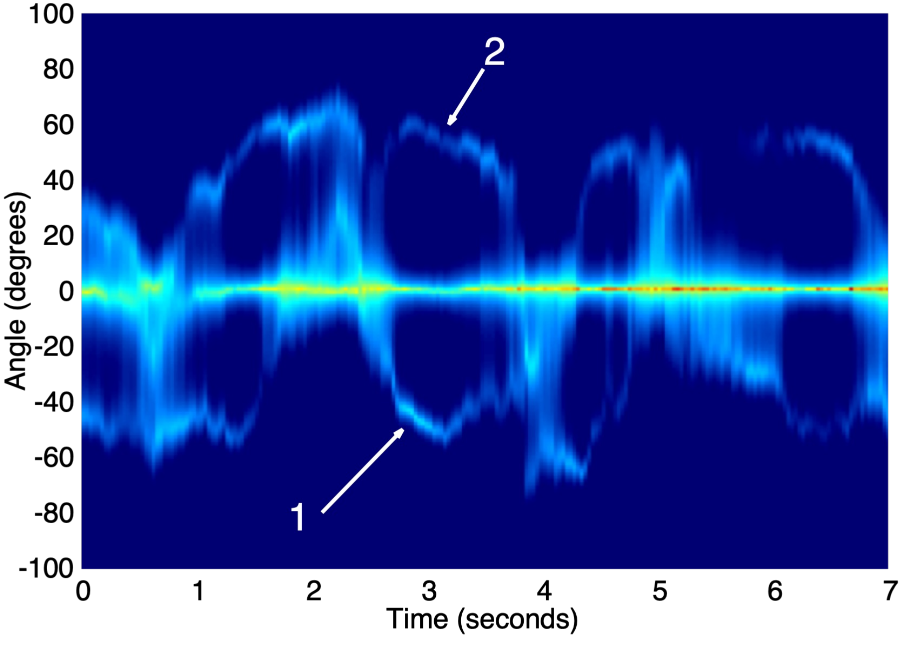
One moving person is indicated by a single curvy line



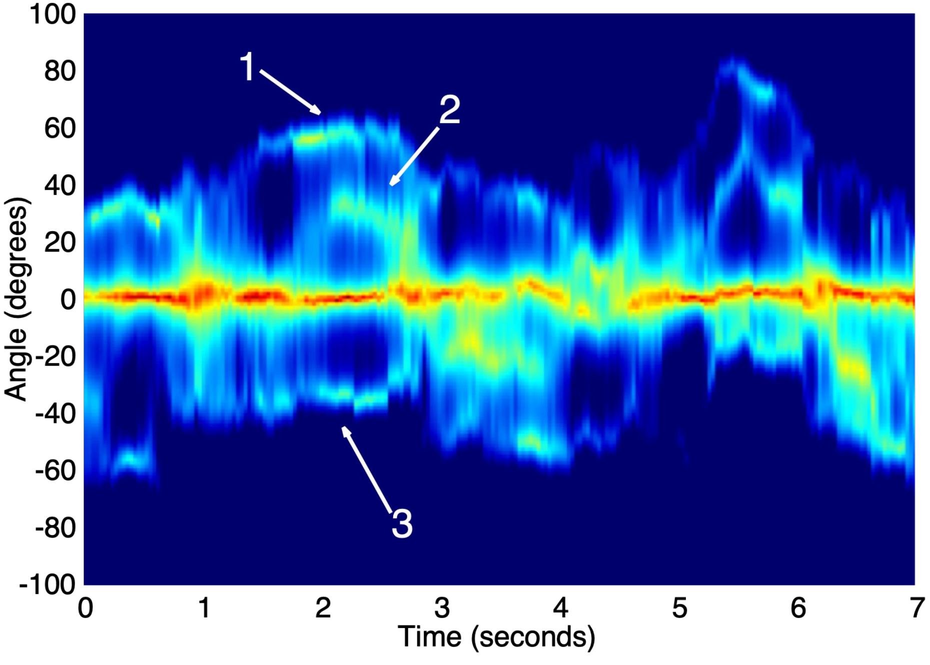
Tracking Multiple Humans

Number of distinct curves at the same time corresponds to the number of humans

Two Humans

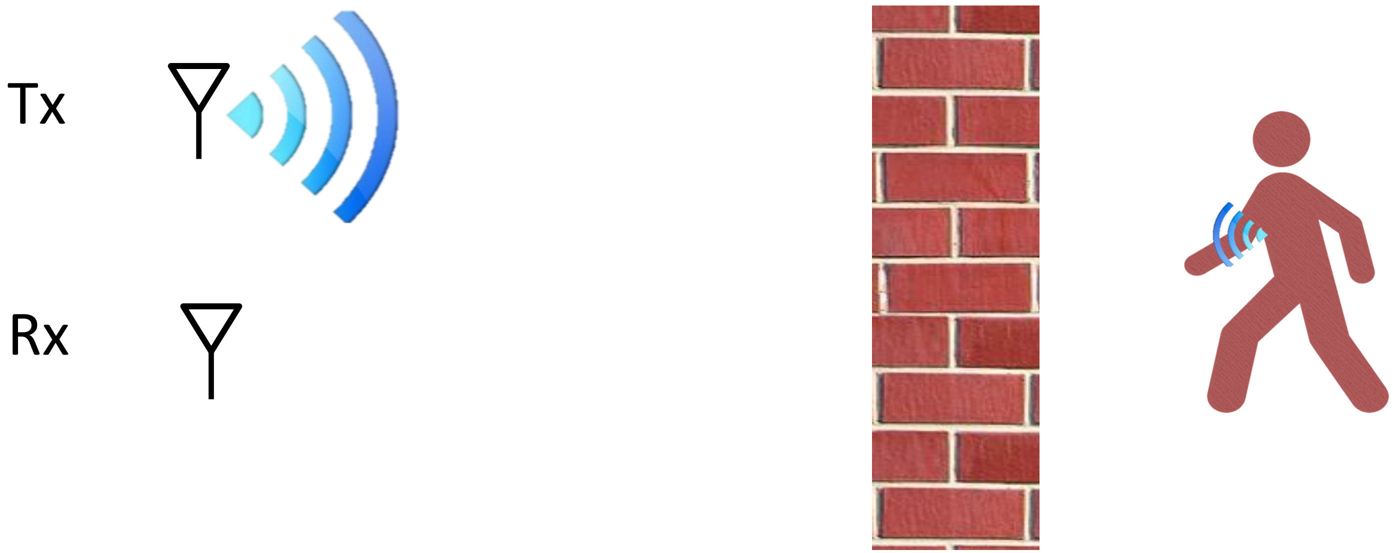


Three Humans



WiTrack

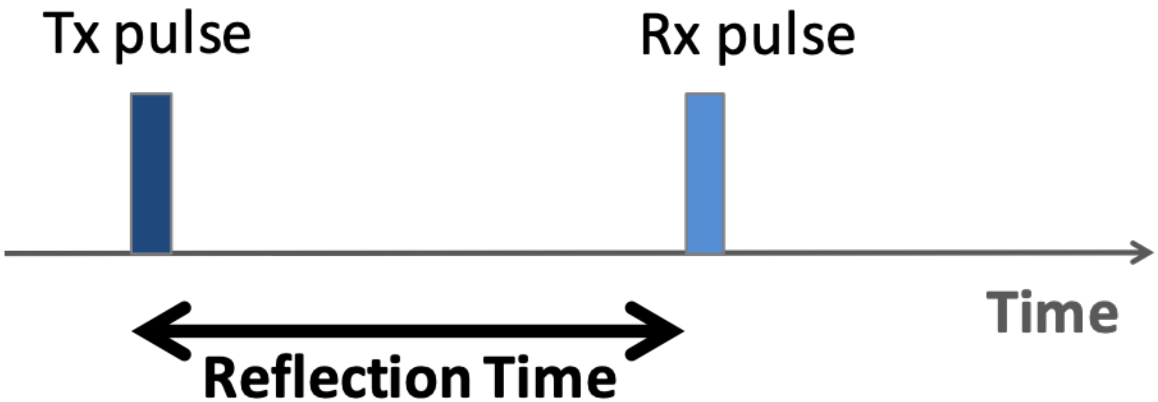
Measuring Distances



Distance = Reflection time x speed of light

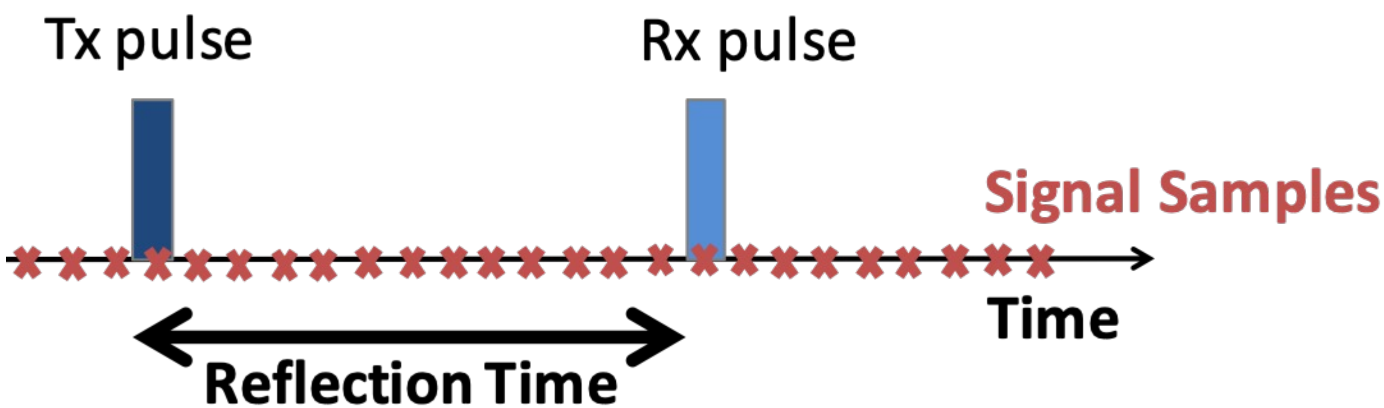
Measuring Reflection Time

- Option1: Transmit short pulse and listen for the echo.



Measuring Reflection Time

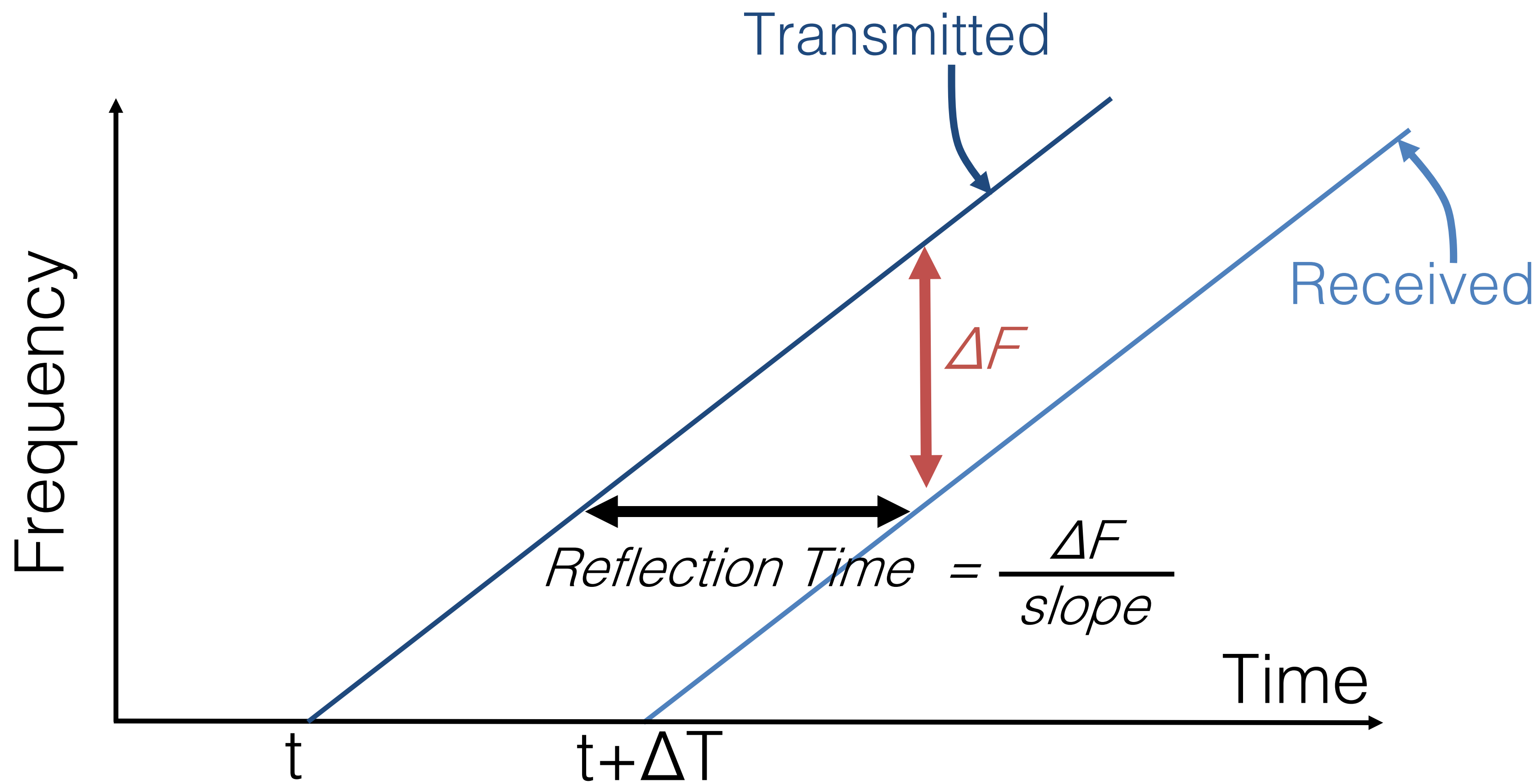
- Option1: Transmit short pulse and listen for the echo.



Need to sample at very high rate : UWB

Multi-GHz samplers are expensive and generate high noise: not suitable for this application

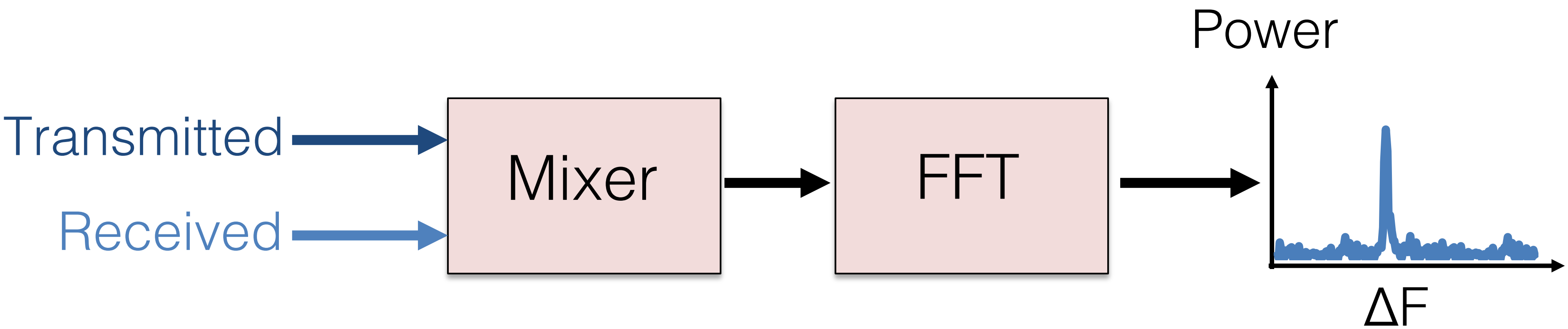
FMCW: Measure time by measuring frequency



How do we measure 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

FMCW

- FMCW Transmitted Signal

slope

Frequency is linear in time; hence phase is quadratic

$$x(t) = e^{j2\pi(\frac{k}{2}(t^2 + f_0 t))}$$

- FMCW Received Signal:

$$y(t) = \sum_i A_i e^{j2\pi(\frac{k}{2}((t-\tau_i)^2 + f_0(t-\tau_i)))}$$

Reflections linearly combine over the wireless medium

reflector i

delay τ_i

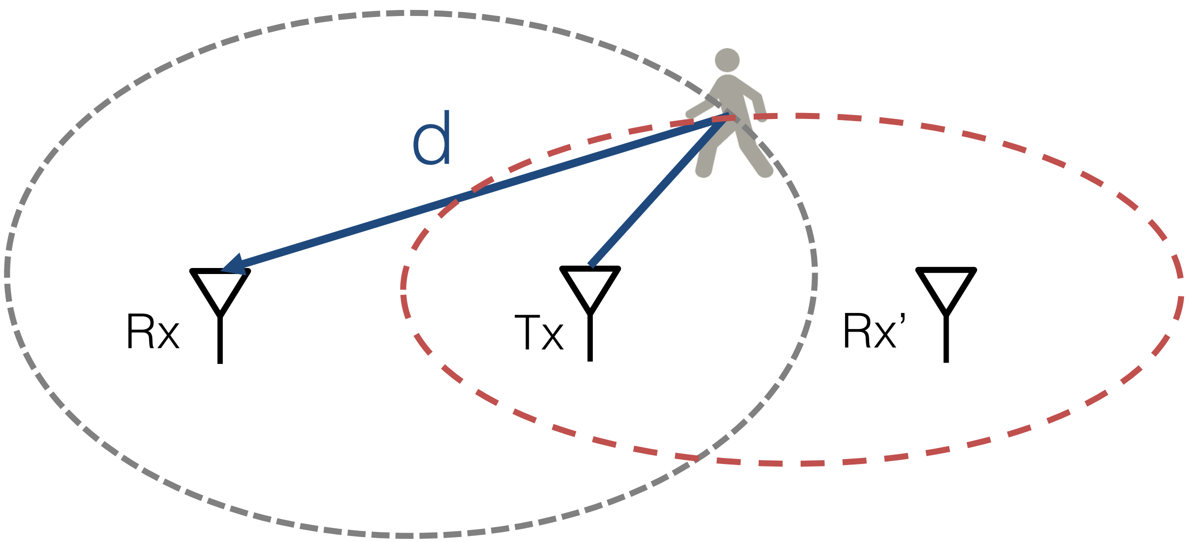
nconversion:

$$y_b(t) = \sum_i A_i e^{j2\pi(k\tau_i t + f_0 \tau_i)}$$

frequency k τ_i

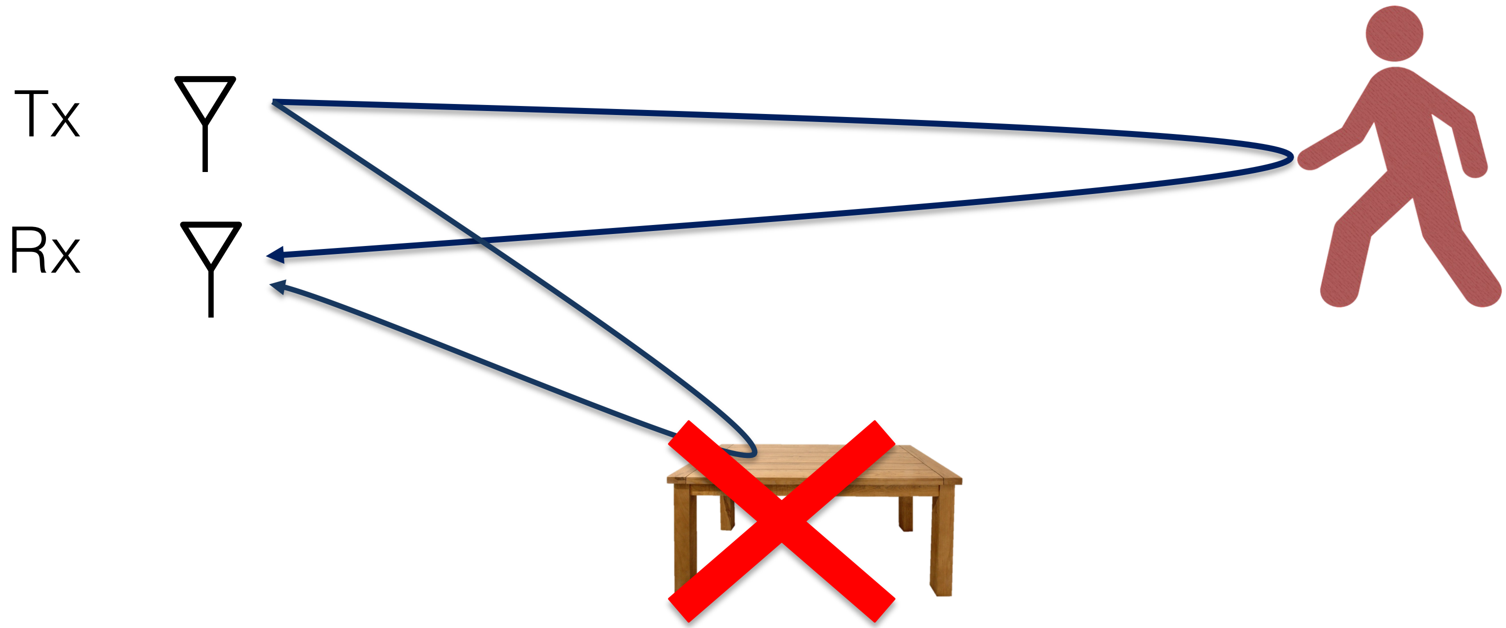
Mapping Distance to Location

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

Dealing with multi-path when there is one moving user

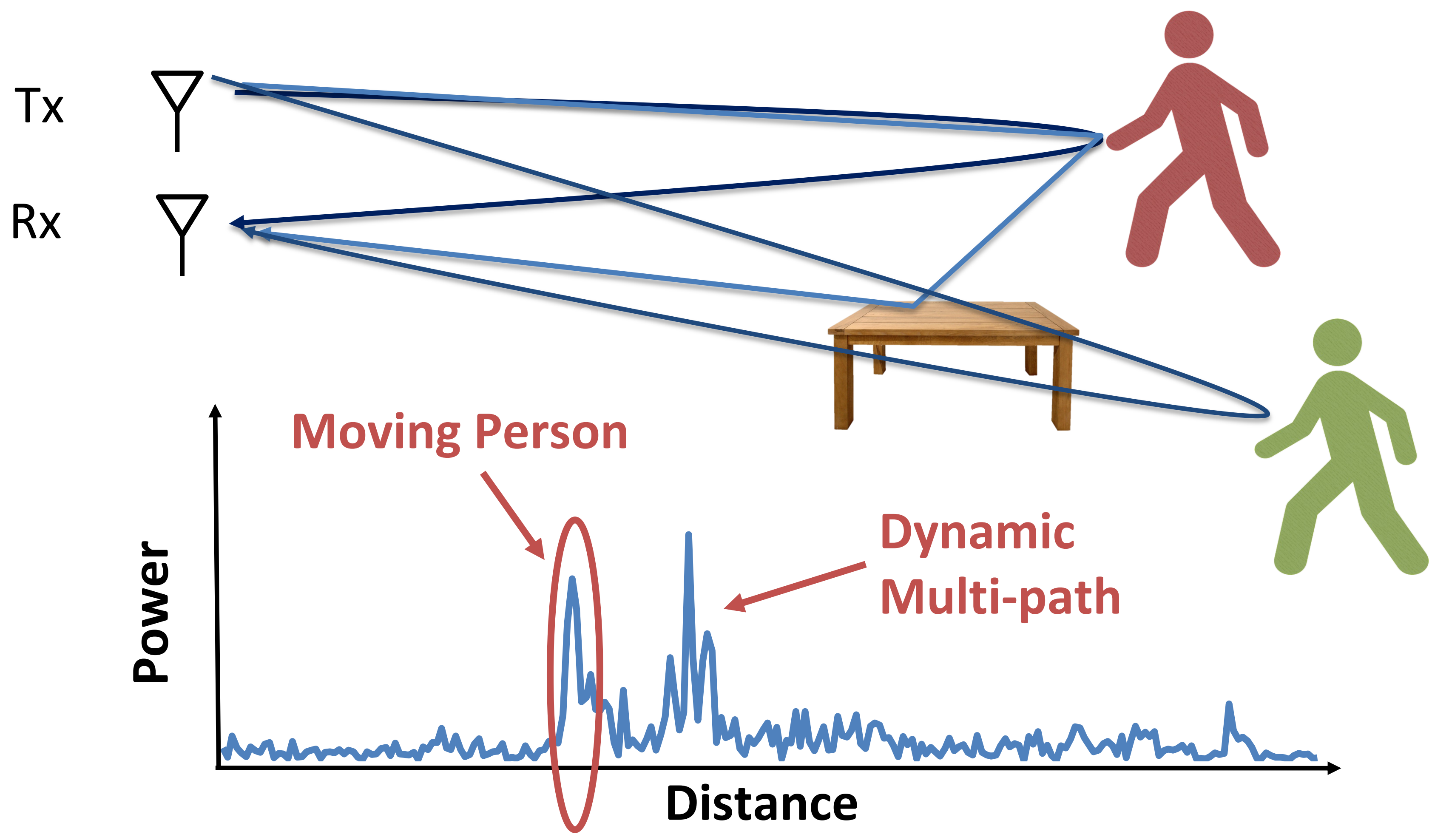


Direct furniture reflection:

eliminated by subtracting consecutive measurements

Needs User to Move

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



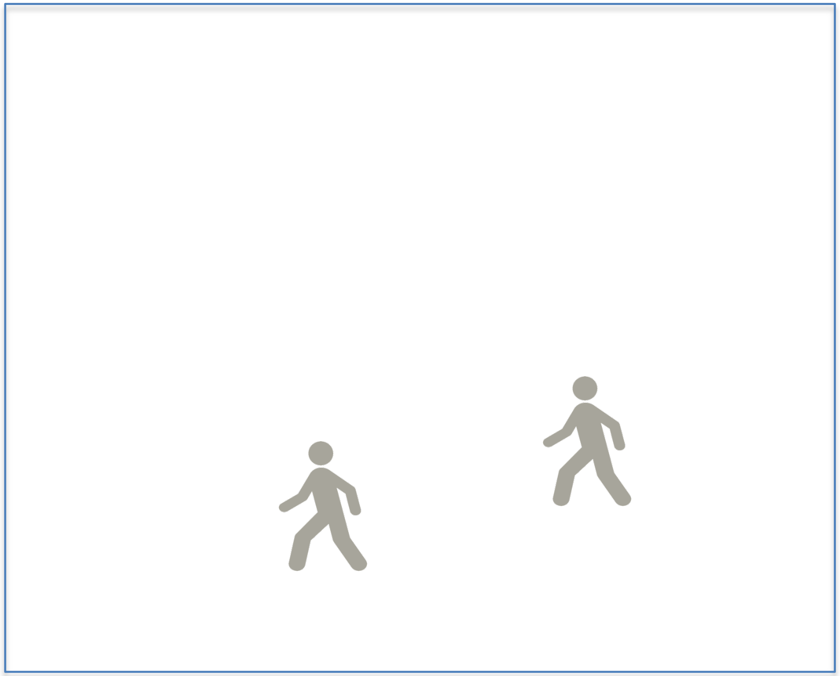
How can we deal with multi-path reflections when there are multiple persons in the environment?

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

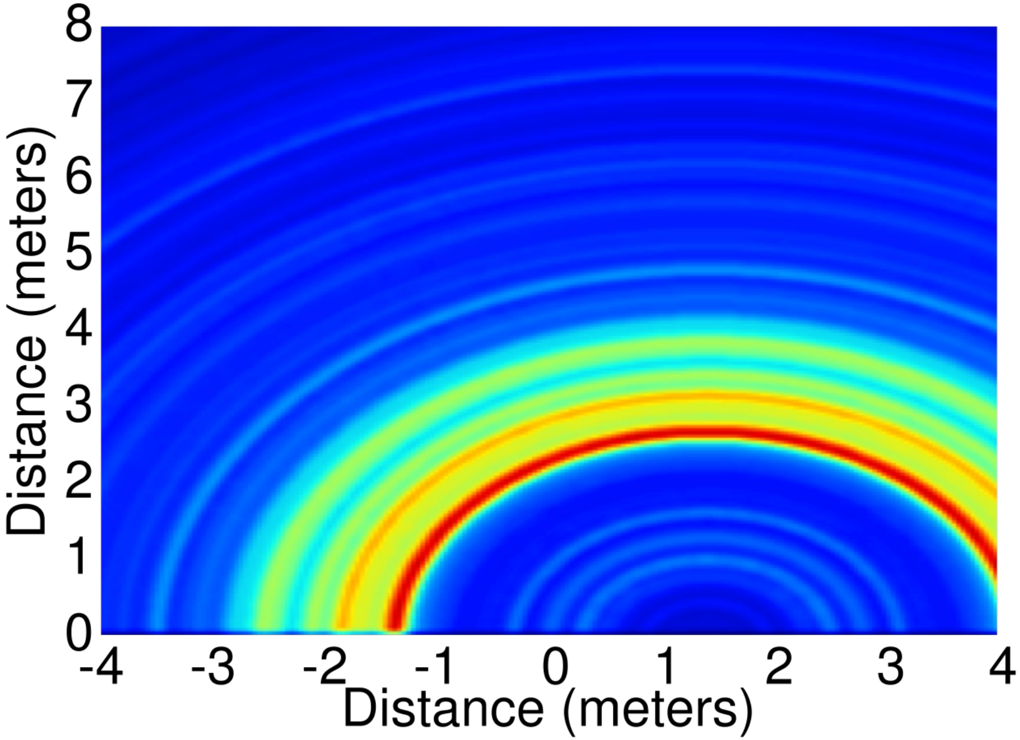
Combining across Multiple Vantage Points

Experiment: Two users walking

Setup



Single Vantage Point

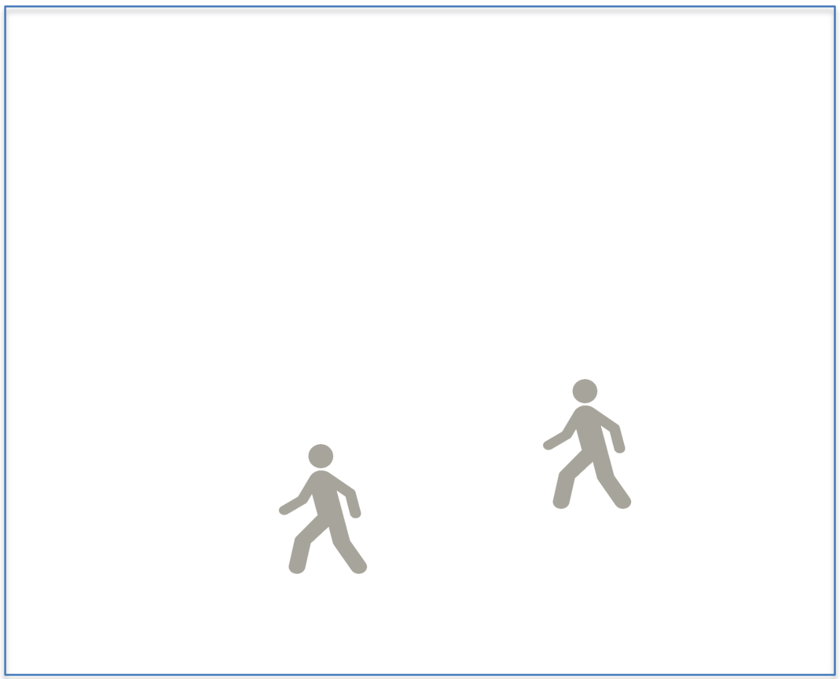


Mathematically: each round-trip distance can be mapped to an ellipse whose foci are the transmitter and the receiver

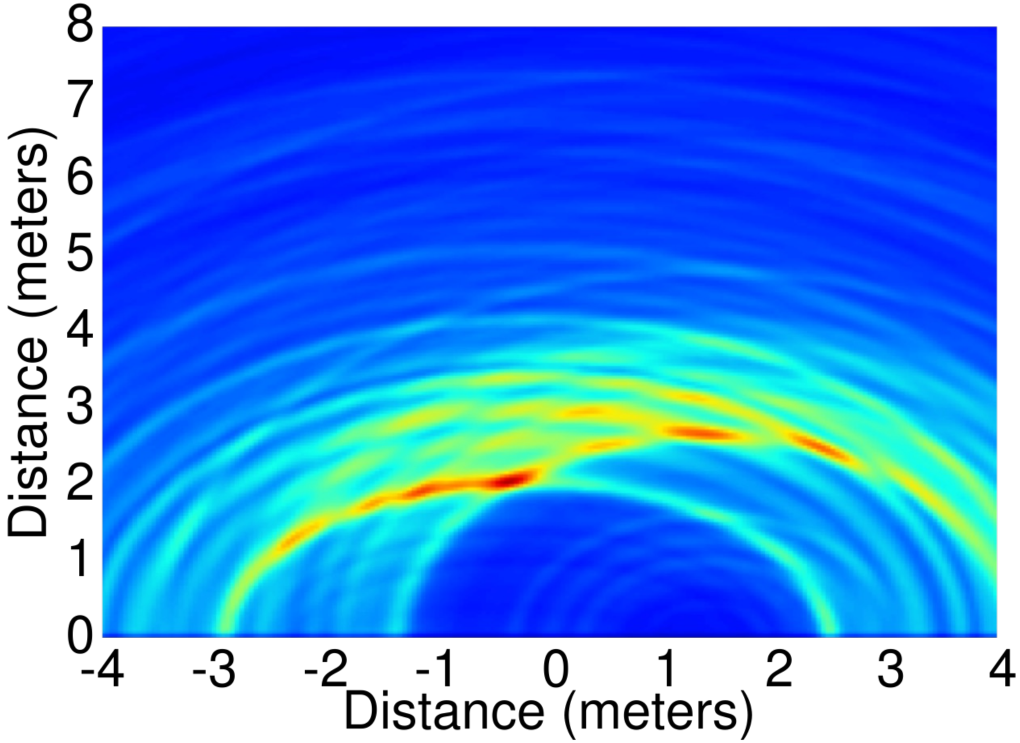
Combining across Multiple Vantage Points

Experiment: Two users walking

Setup



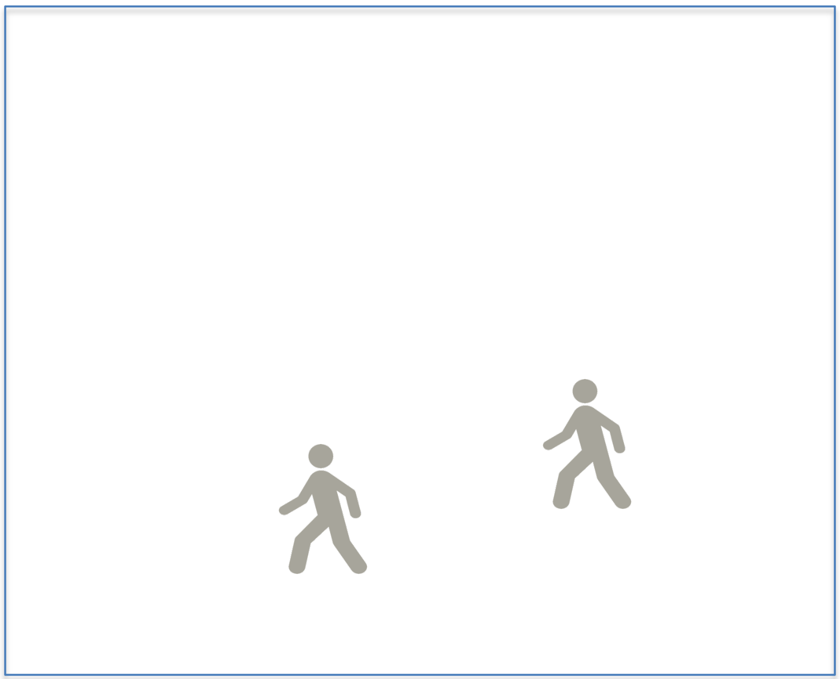
Two Vantage Points



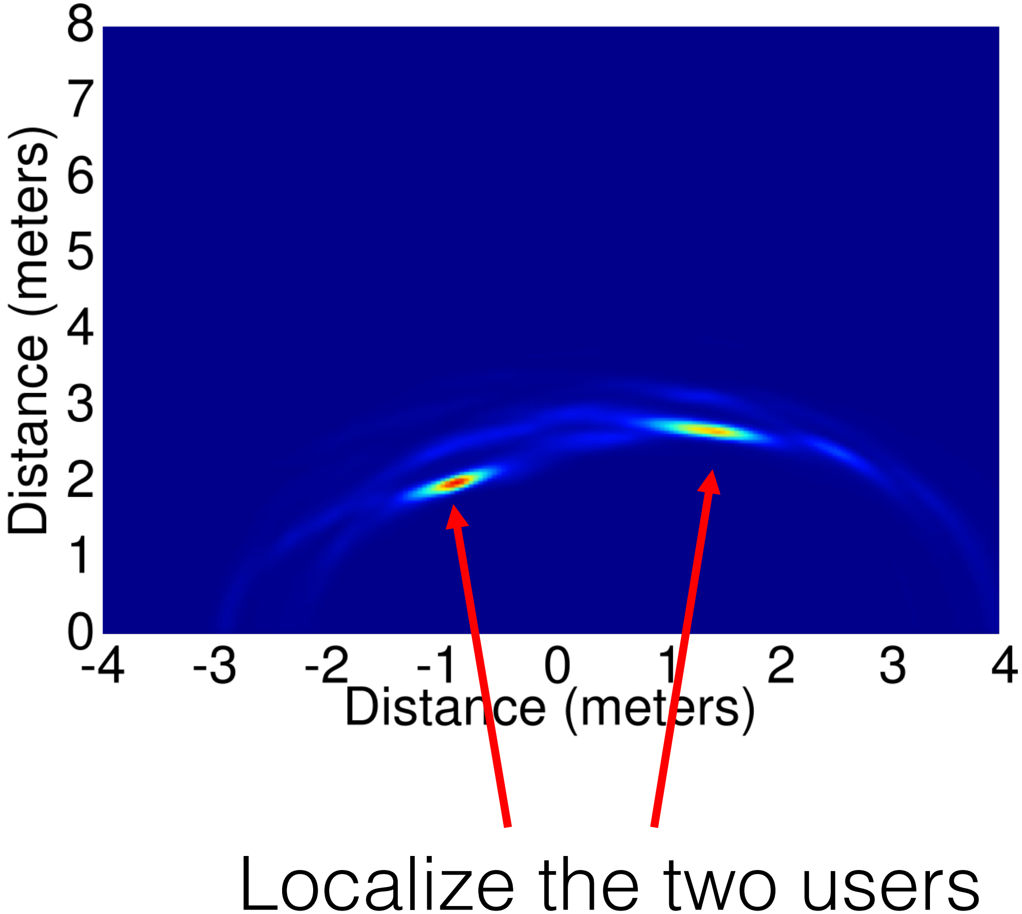
Combining across Multiple Vantage Points

Experiment: Two users walking

Setup



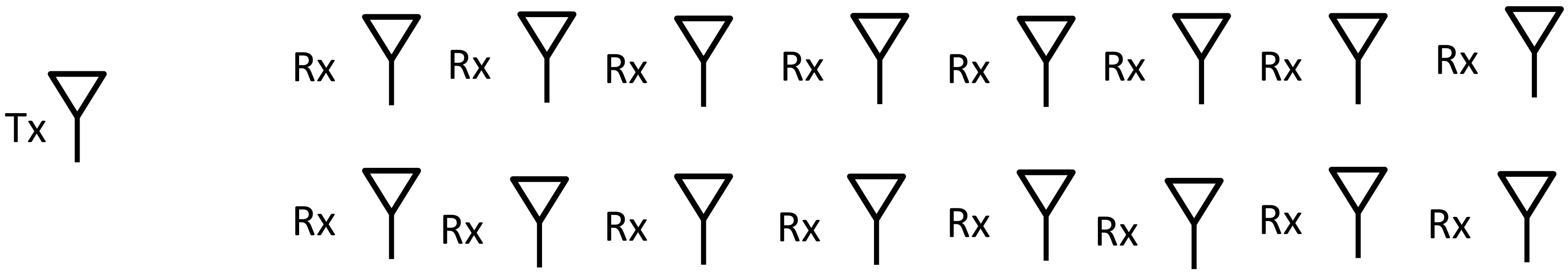
16 Vantage Points



How can we obtain 16 vantage points?

Achieving 16 vantage points

- Naïve solution: 1 Transmitter and 16 Receivers

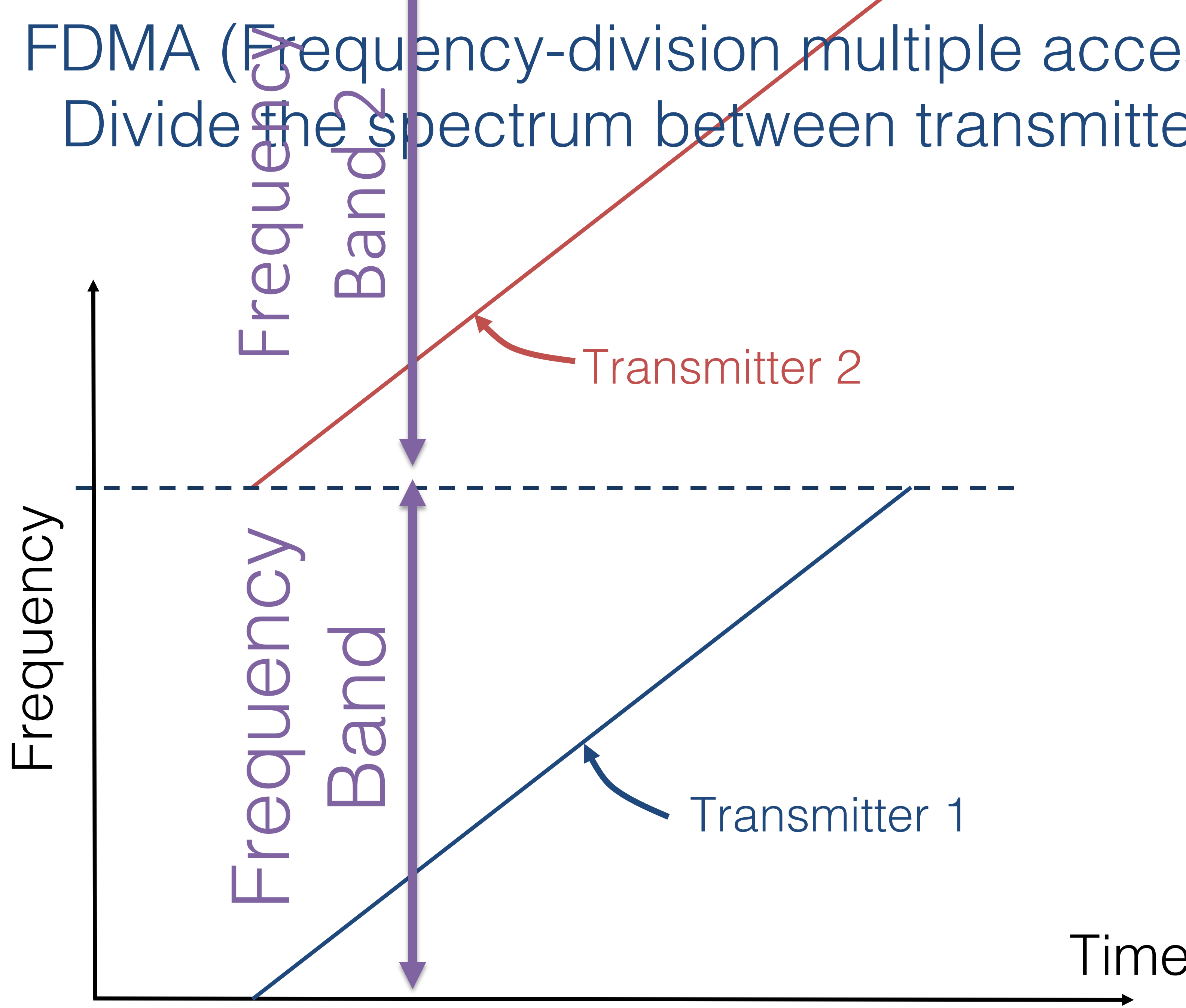


- Ideally: 4 Transmitters and 4 Receivers

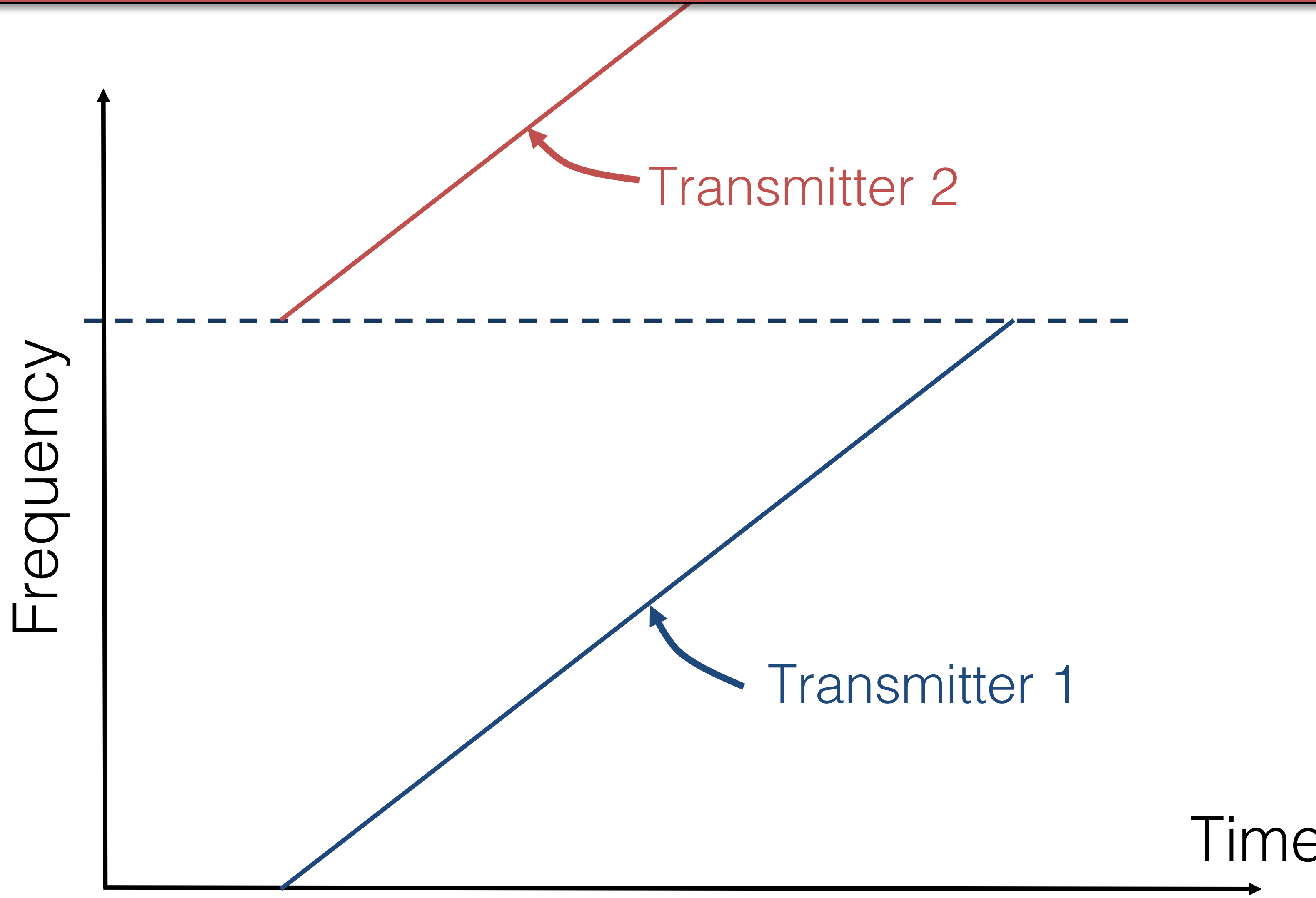
<u>Problem:</u> Different transmitters interfere with each other!

Let us look at standard mechanisms that are used to deal with interference

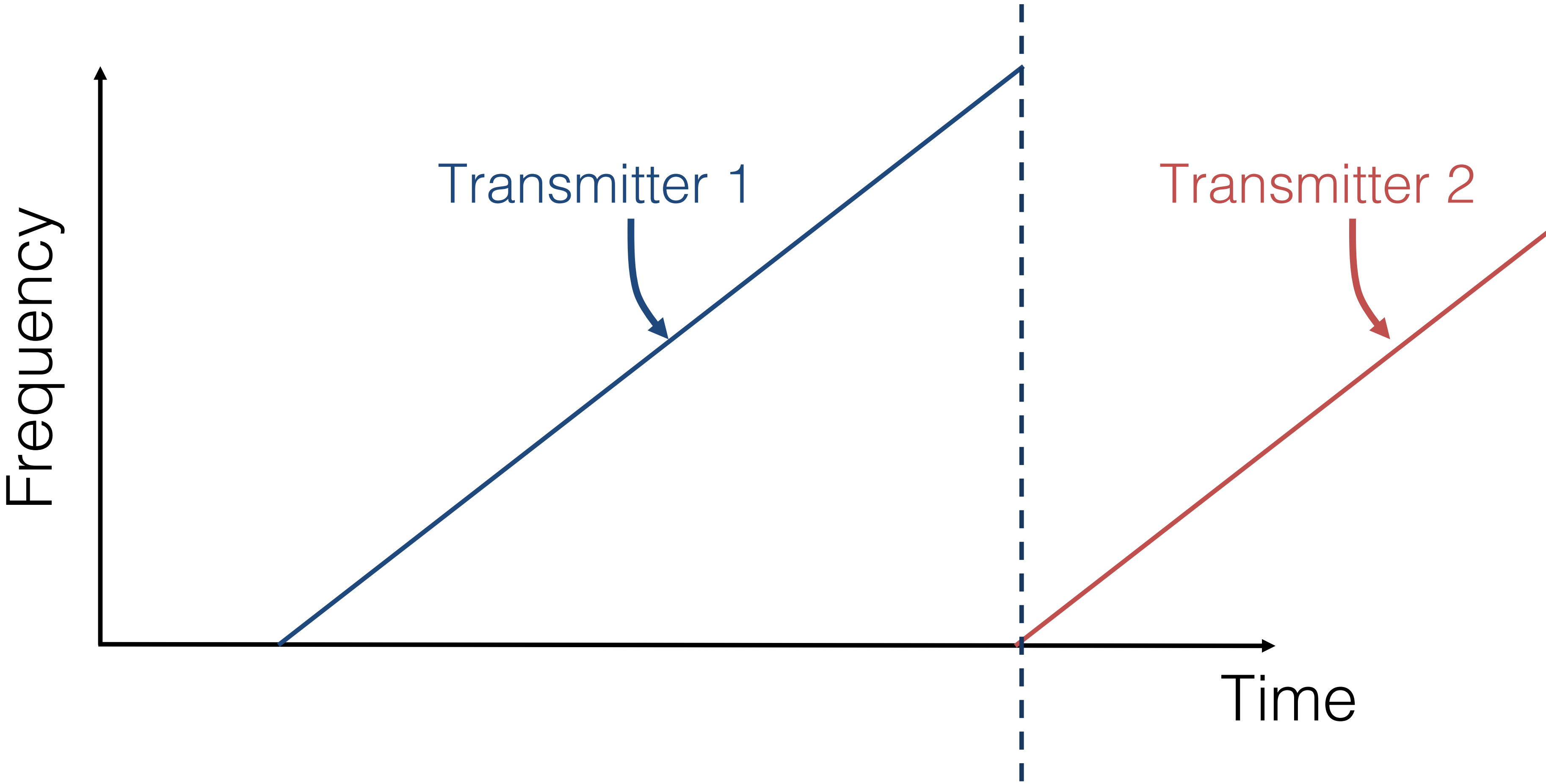
FDMA (Frequency-division multiple access): Divide the spectrum between transmitters



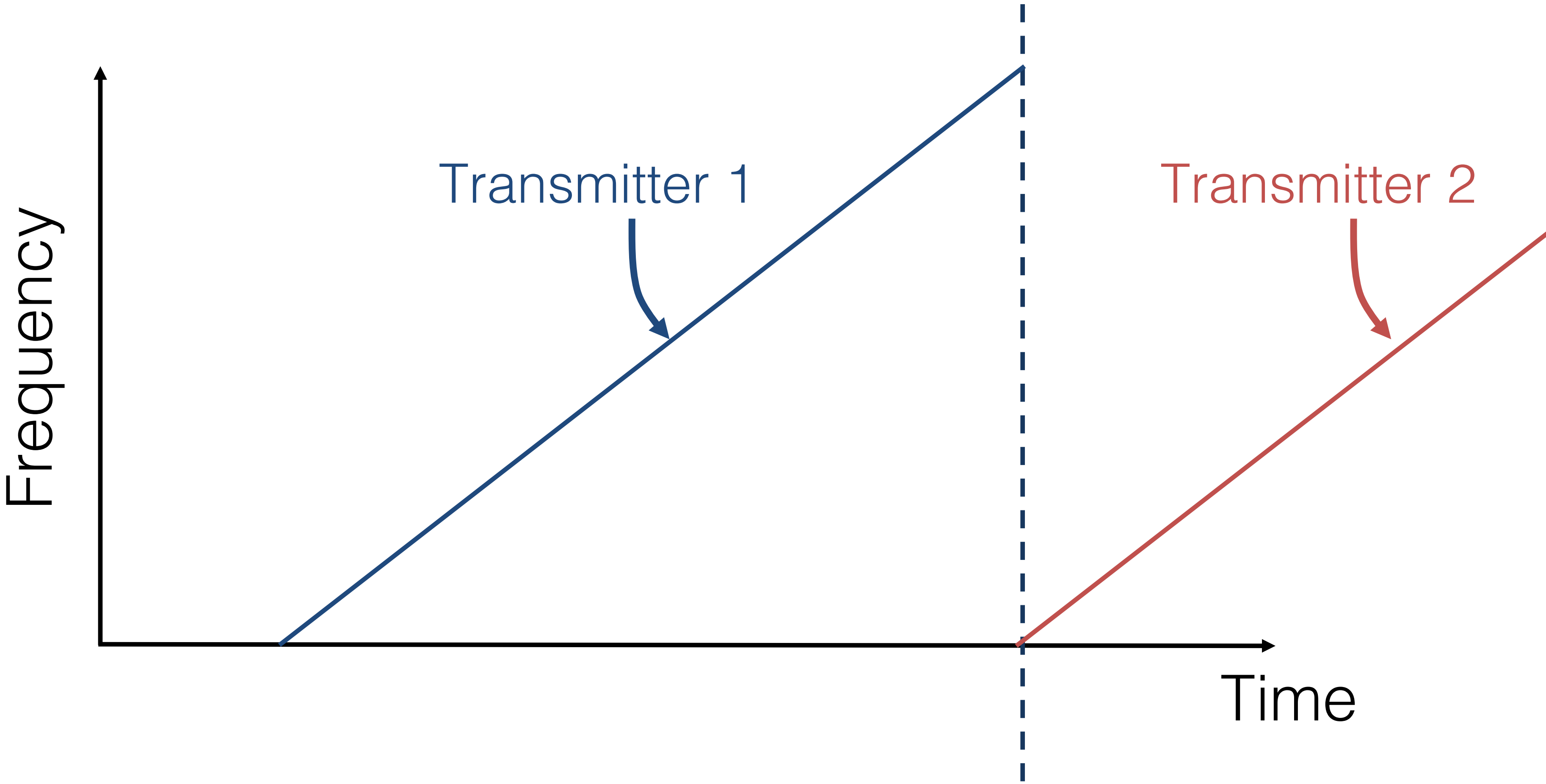
Would require N times the bandwidth!



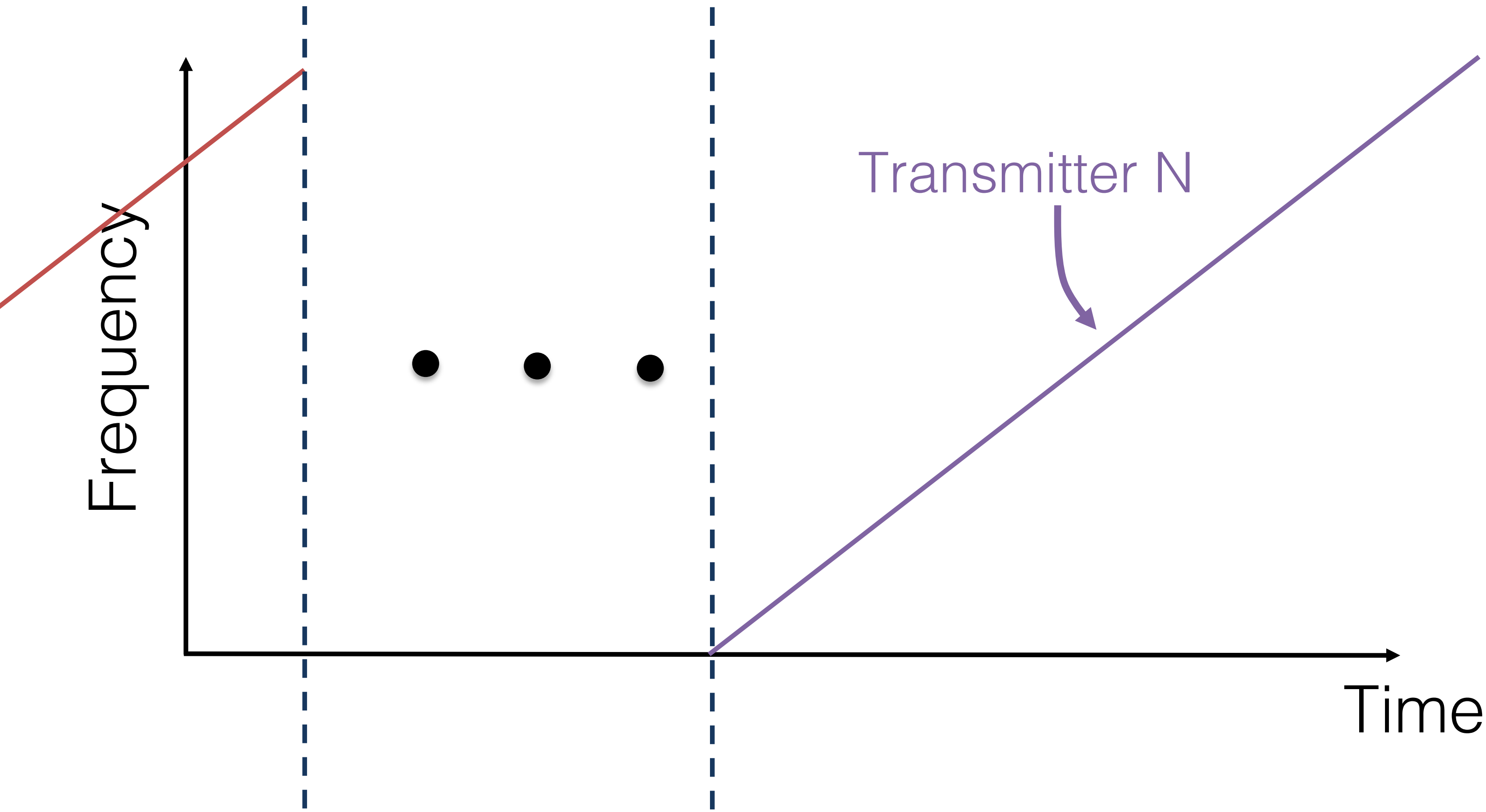
TDMA (Time-division multiple access)
: Transmitters take turns transmitting



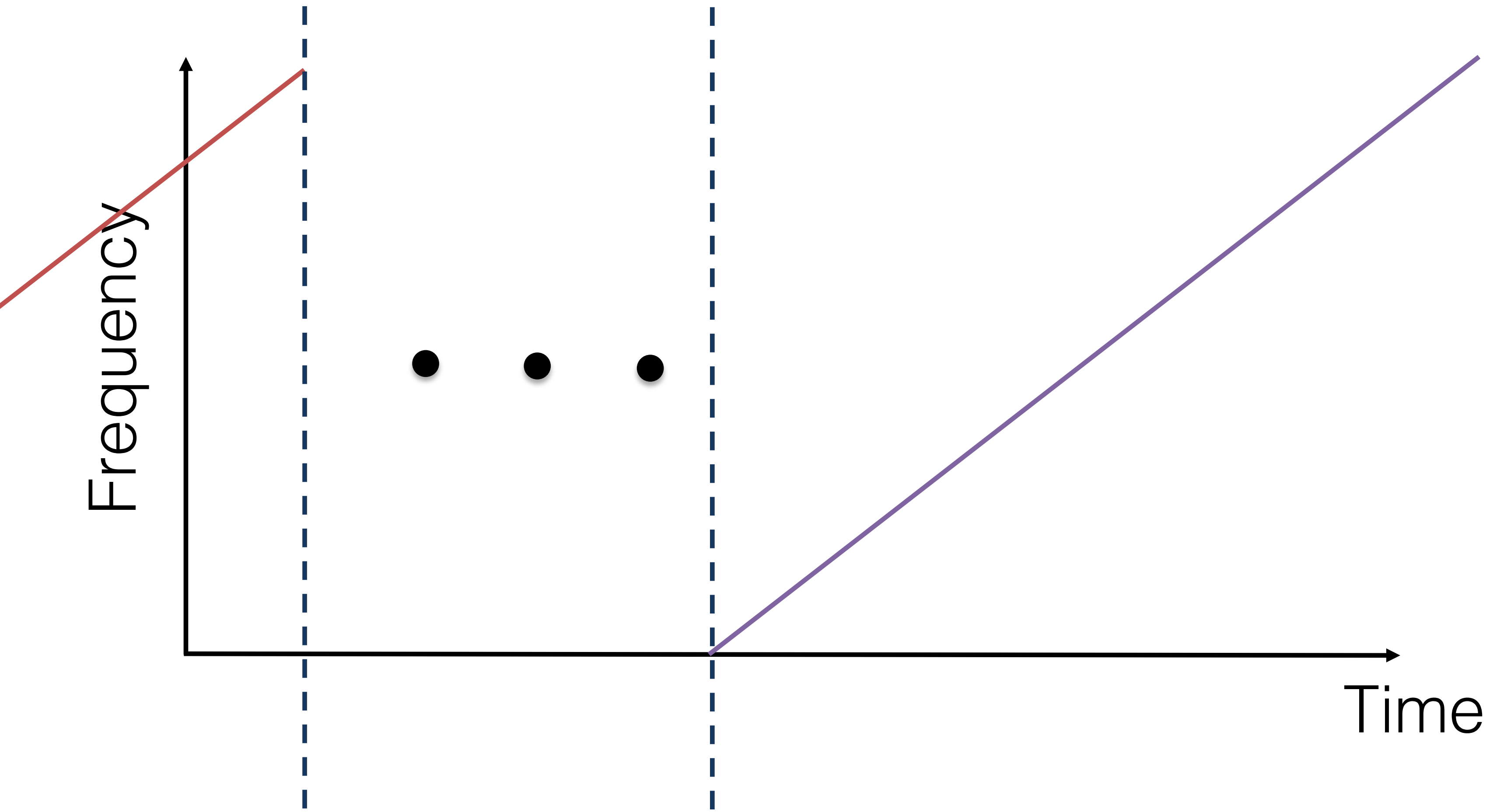
Would require N more time to localize



Ideally: Transmit in the same time and in the same frequency band without interfering



Ideally: Transmit in the same time and in the same frequency band without interfering

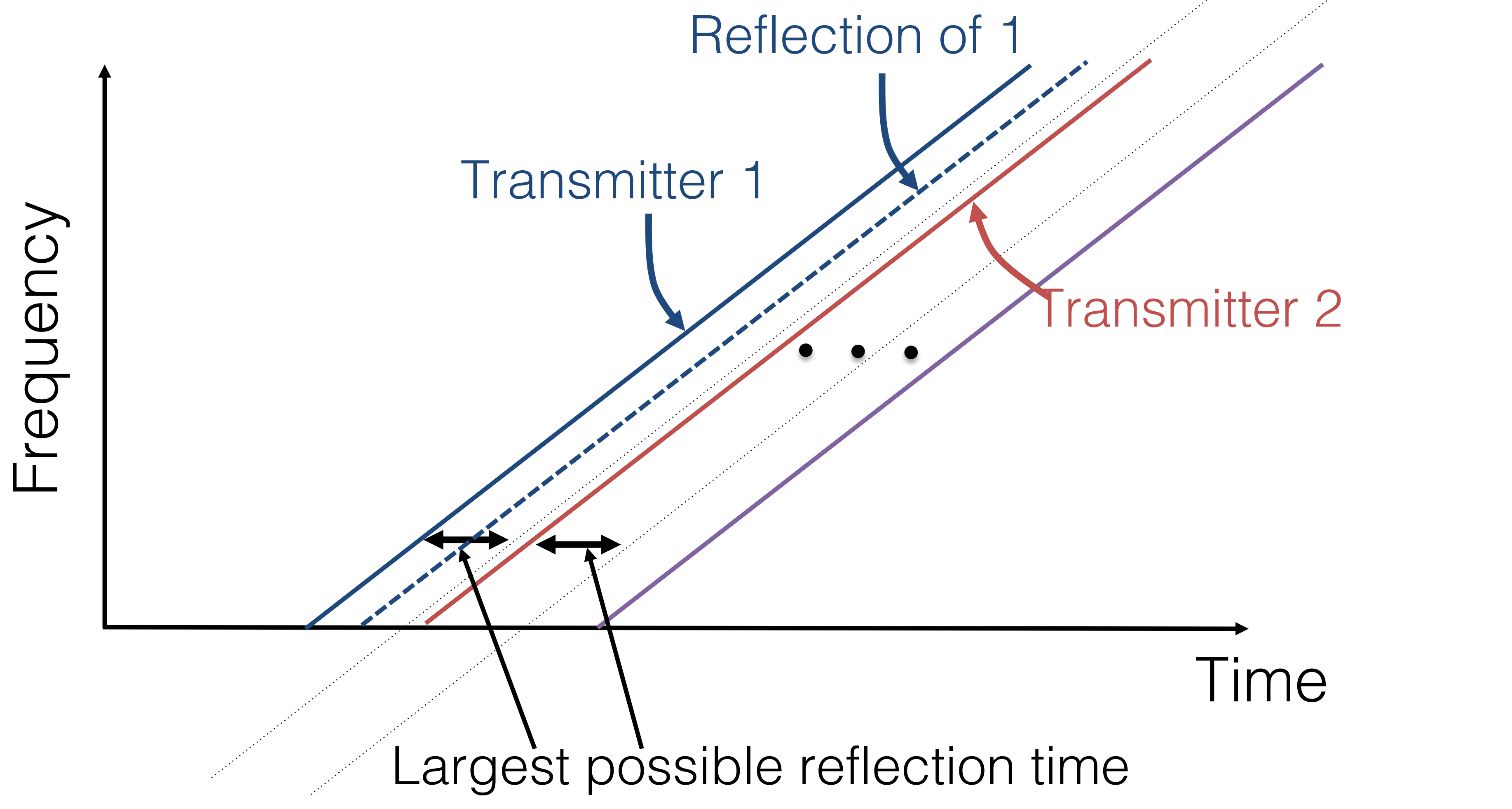


Multi-shift FMCW:

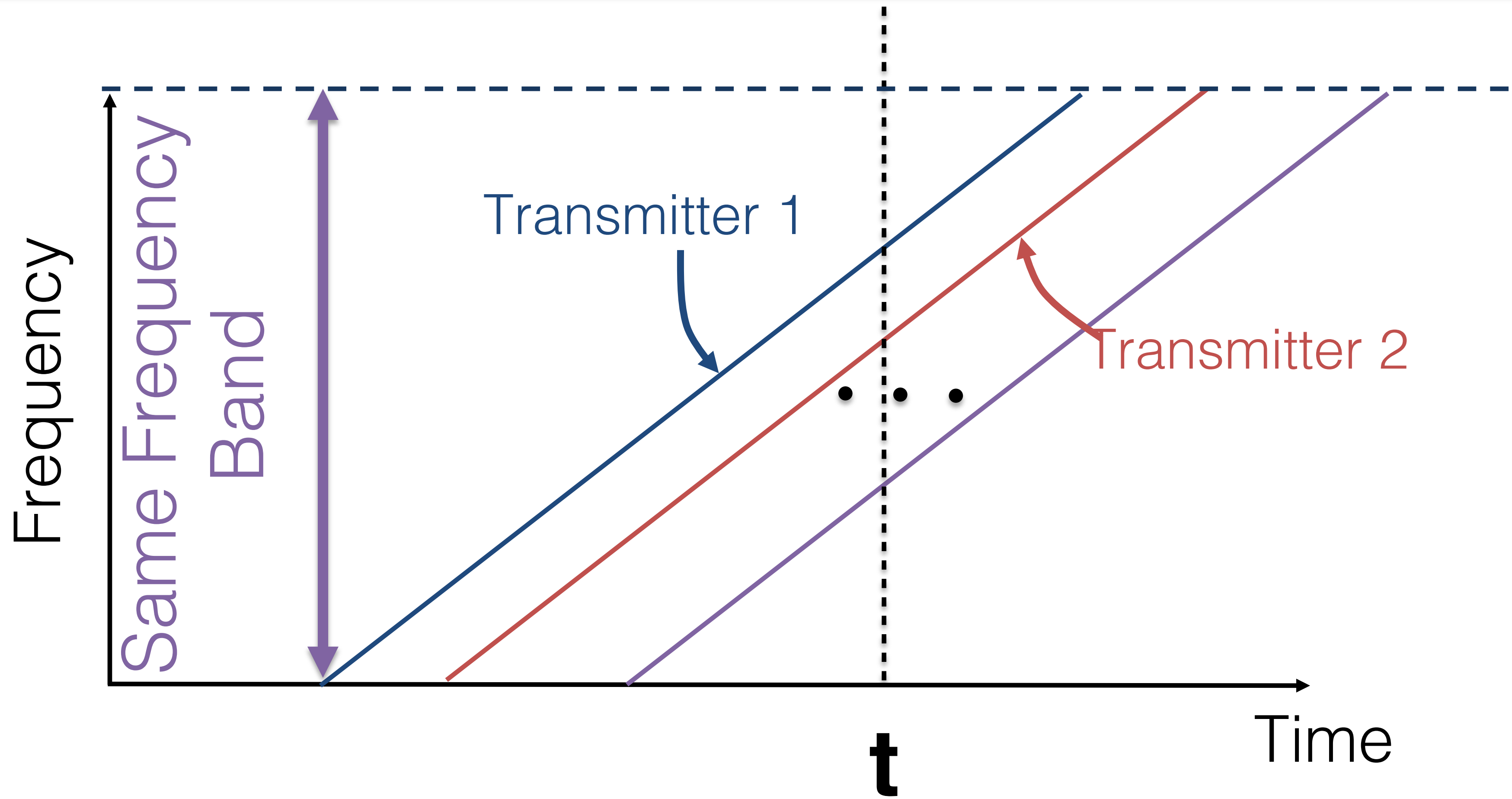
a new mechanism to divide resources between transmitters so that they don't suffer from interference

Objective: Transmit and Get Reflection

- Largest reflection time indoors: 100ns



Multi-shift FMCW enables multiple transmissions at the **same time** and in the **same frequency band** without interference



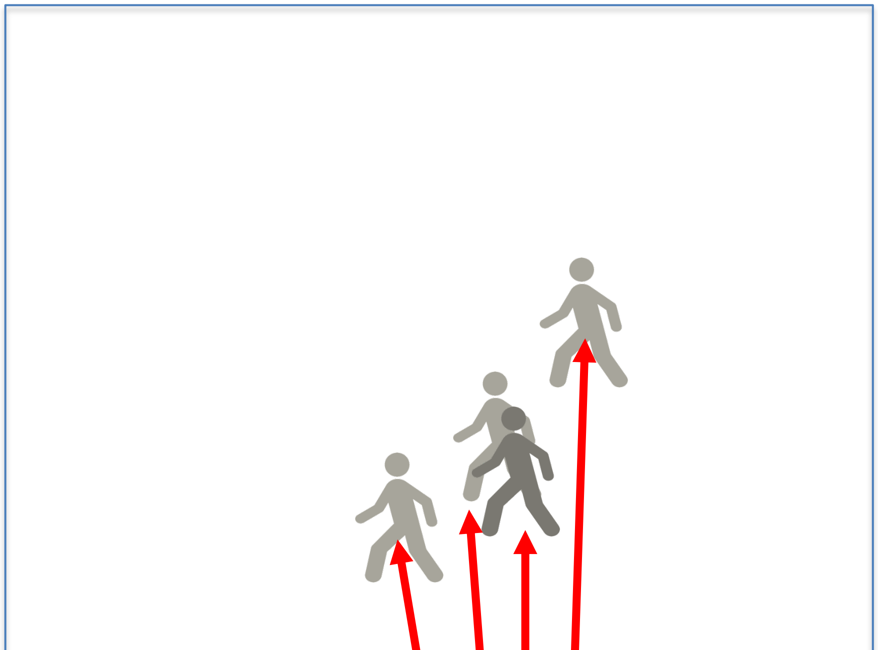
Multi-Person Localization

- Multi-shift FMCW enables a large number of vantage points for accurate localization of multiple subjects

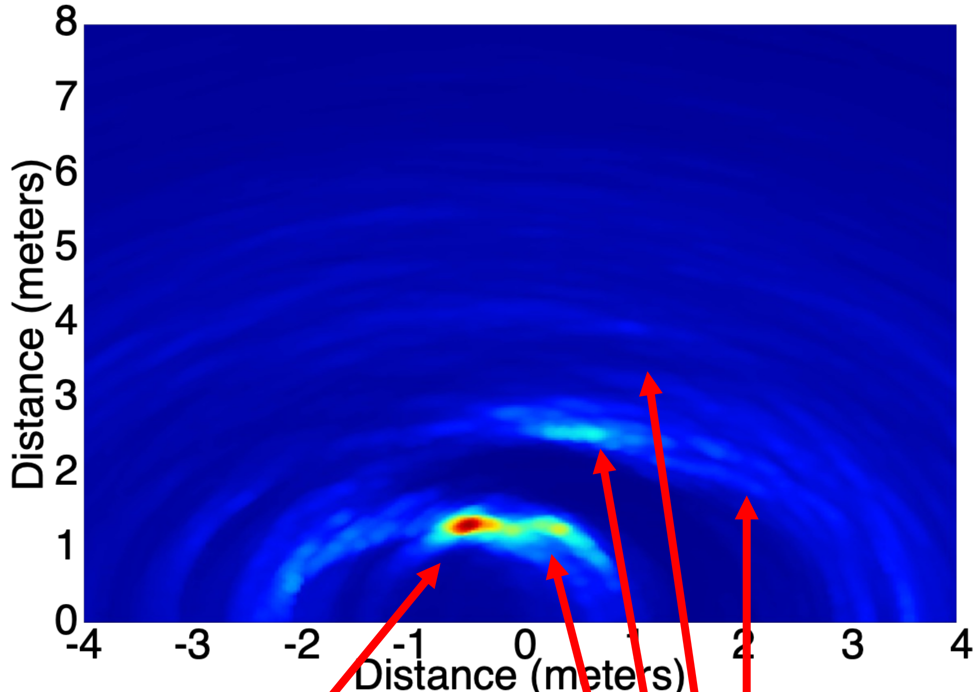
Multi-User Localization

<u>Experiment:</u> Four persons walking

Setup



All Vantage Points



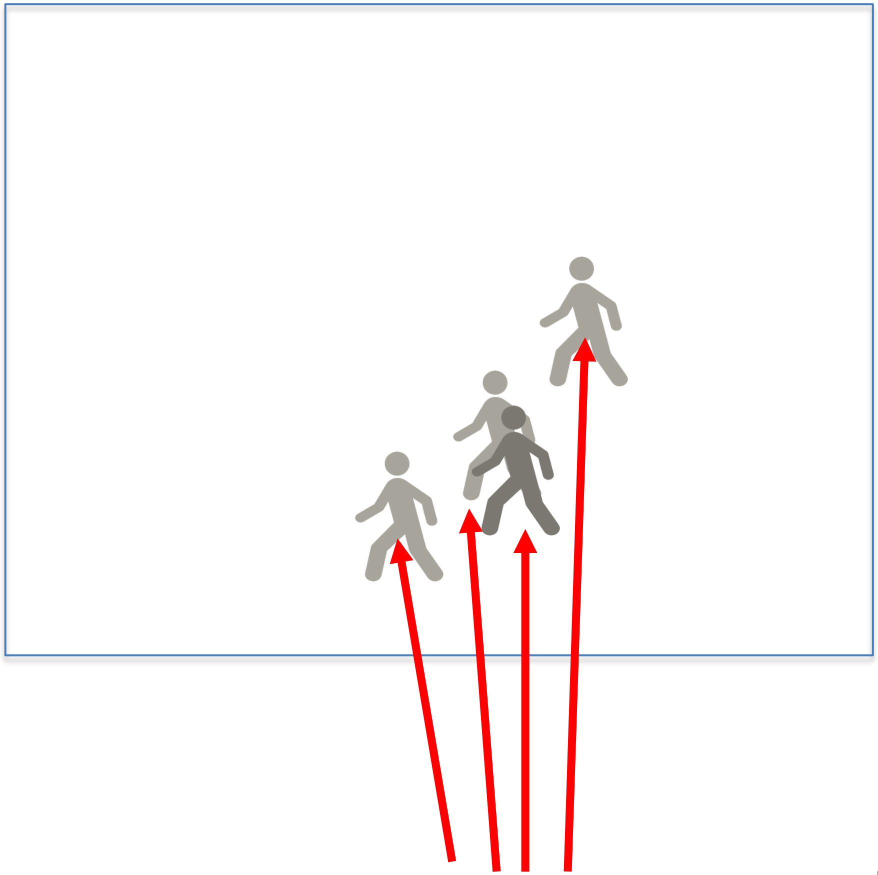
four persons

first person

other people or noise?

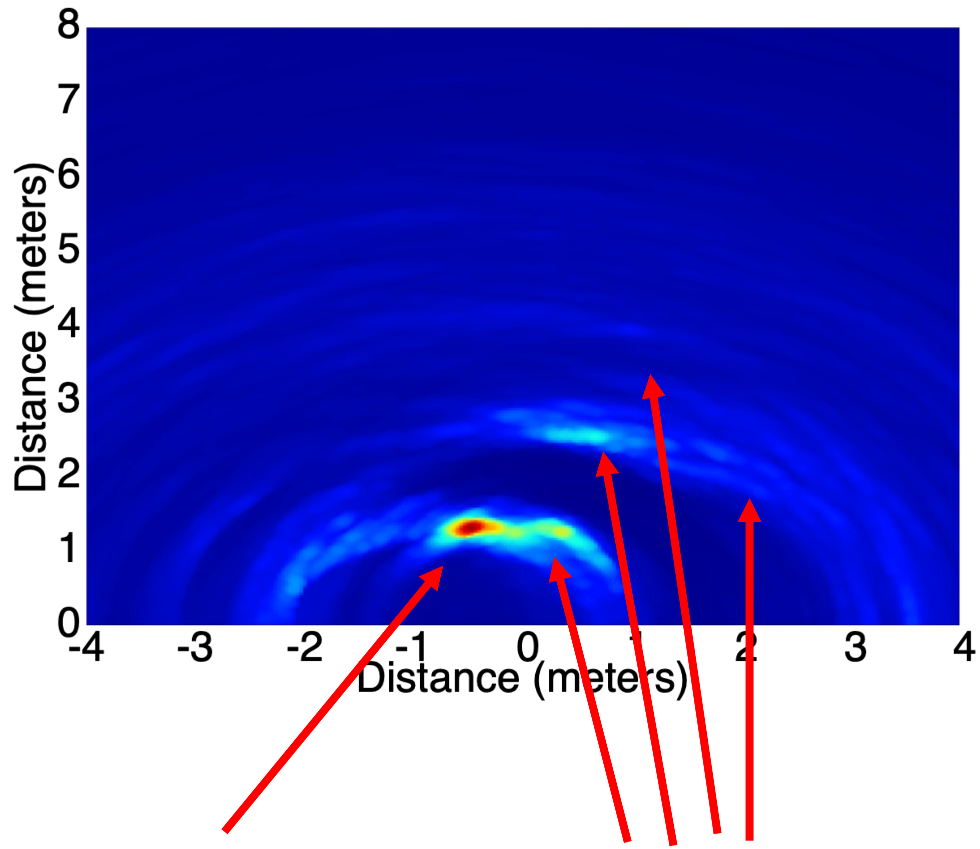
Near-Far Problem: Nearby persons have more power than distance reflectors and can mask them

Setup



four persons

All Vantage Points

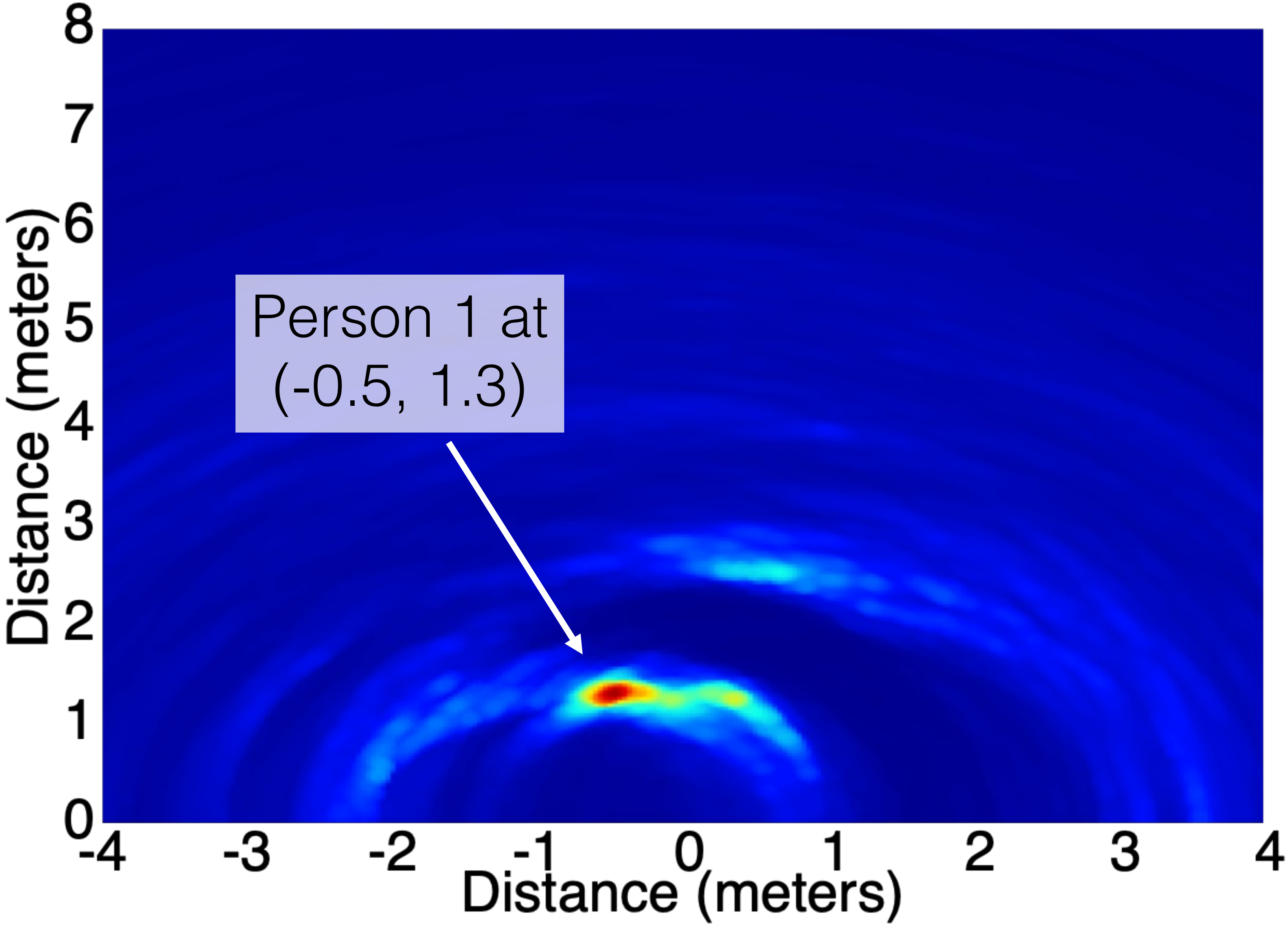


first person

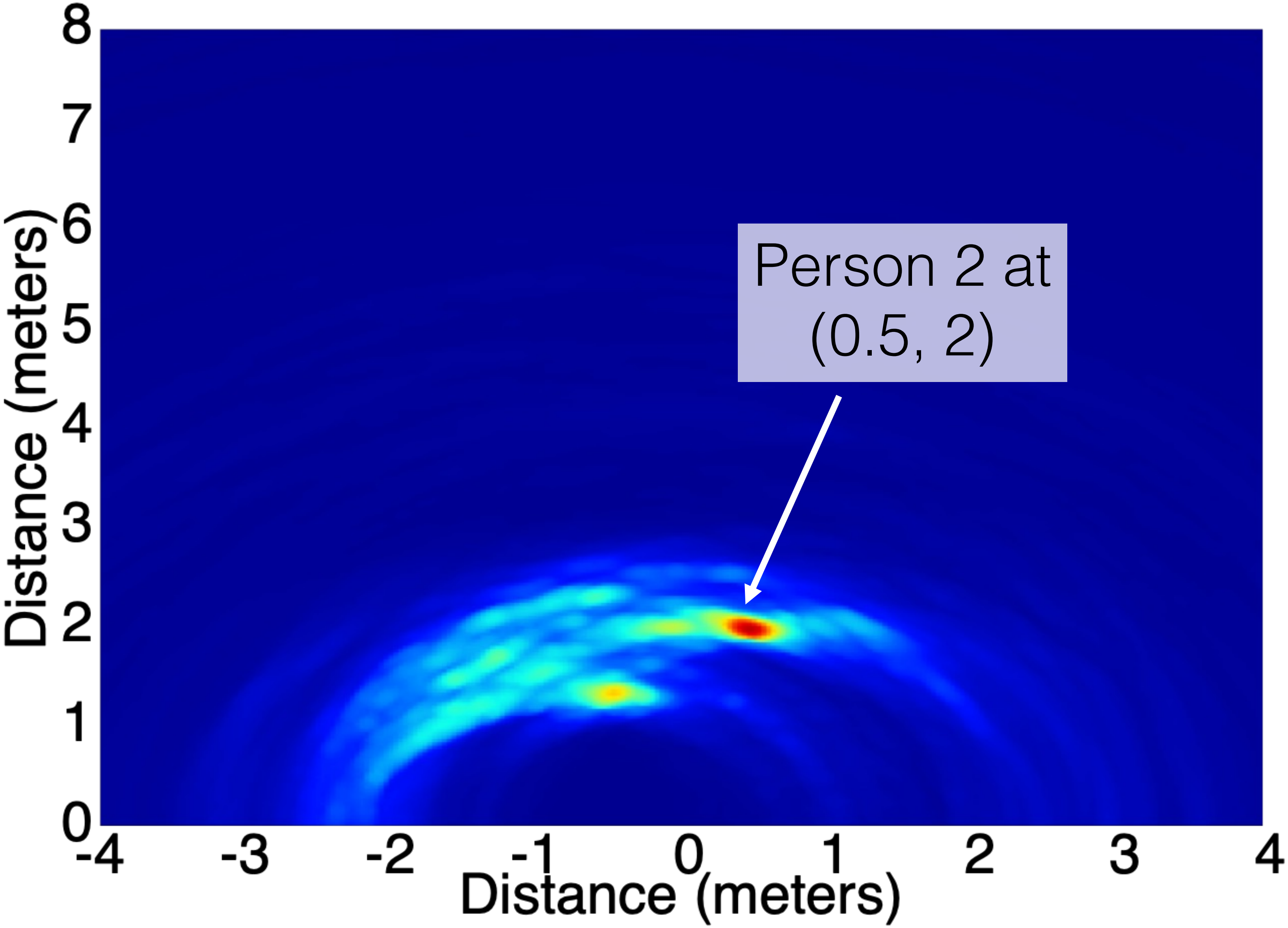
other people or noise?

Successive Silhouette Cancellation:
a new algorithm that localizes multiple persons in the scene by addressing the near-far problem

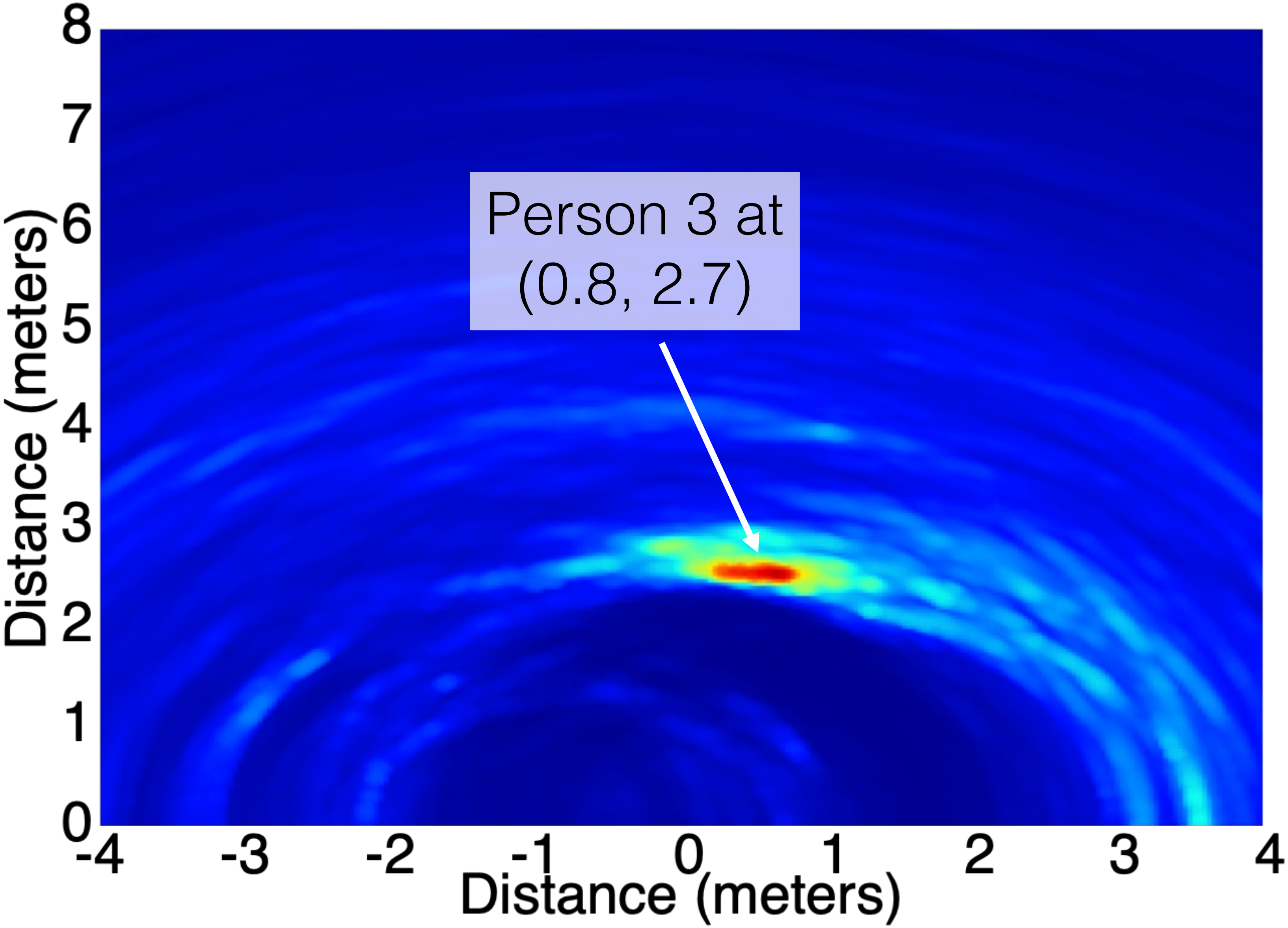
First localize the user with the strongest reflection



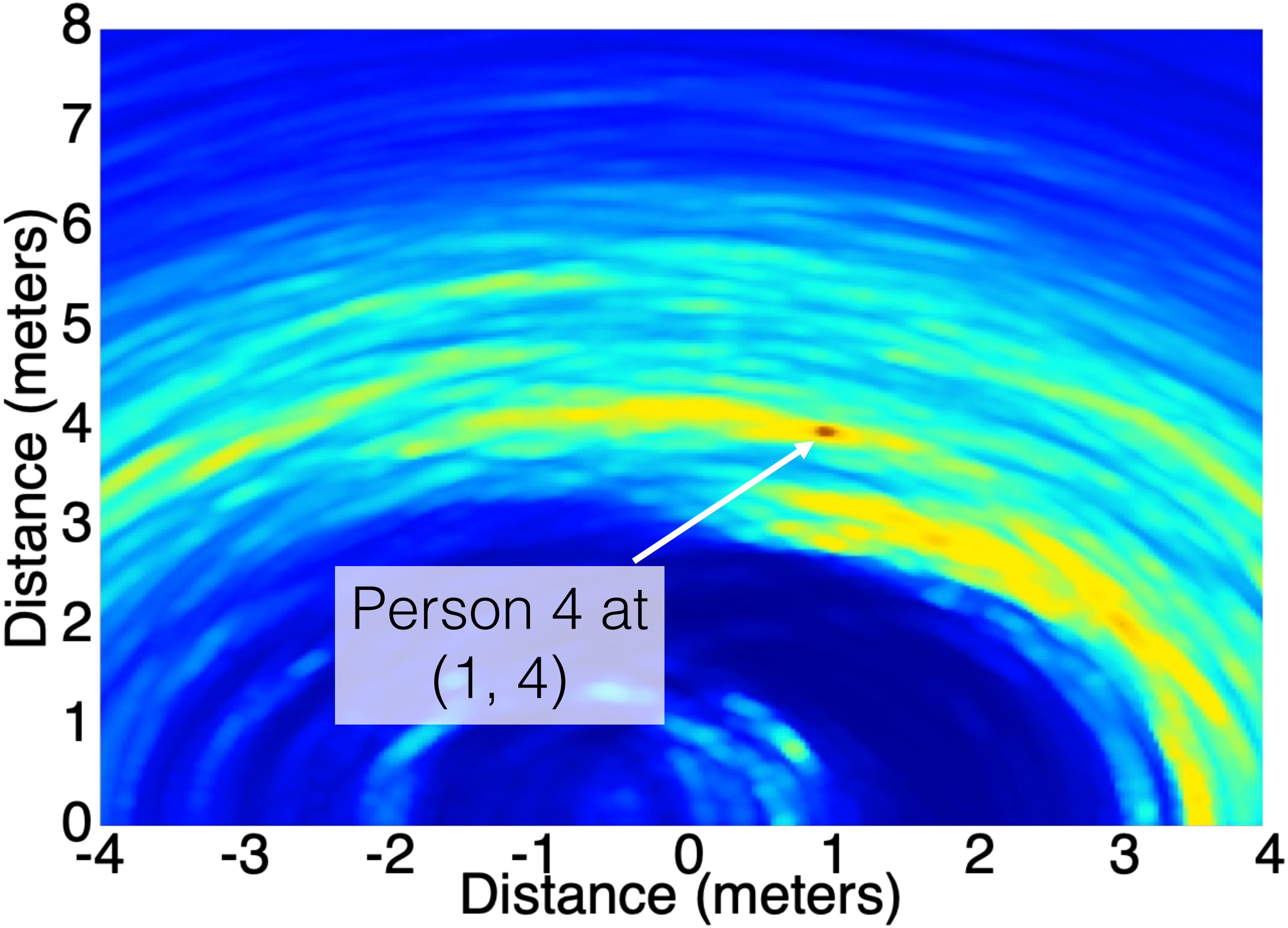
After reconstructing and cancelling the first user's reflections



Iteratively localize the remaining users in the scene

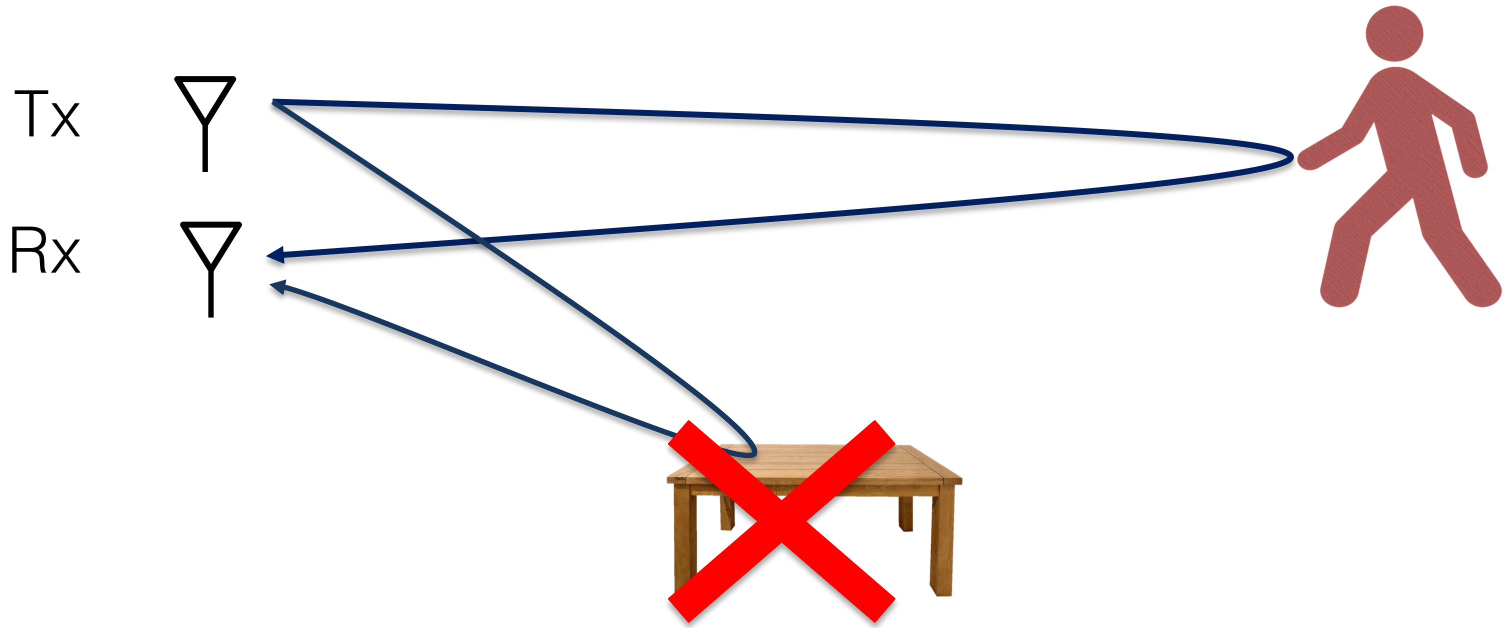


Iteratively localize the remaining users in the scene



How can we localize static users?

Dealing with multi-path when there is one moving user

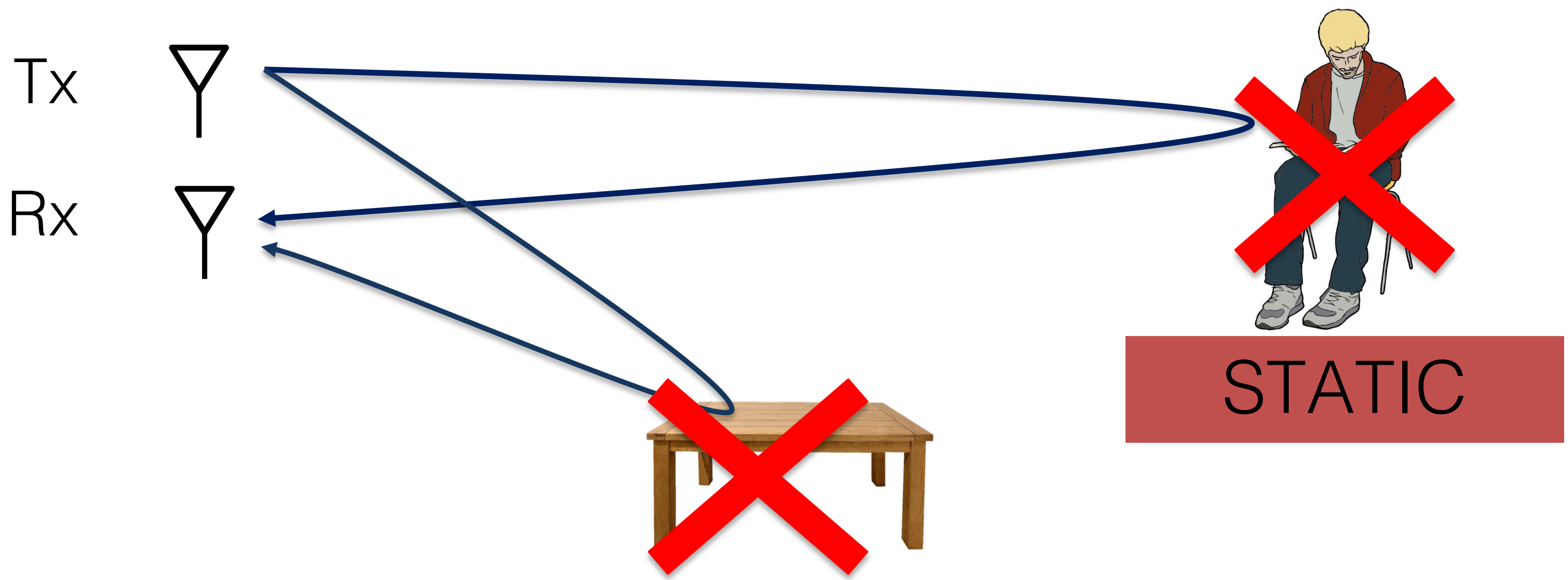


1. Direct furniture reflection:

eliminated by subtracting consecutive measurements

Needs User to Move

Dealing with multi-path when there is one moving user



1. Direct furniture reflection:

eliminated by subtracting consecutive measurements

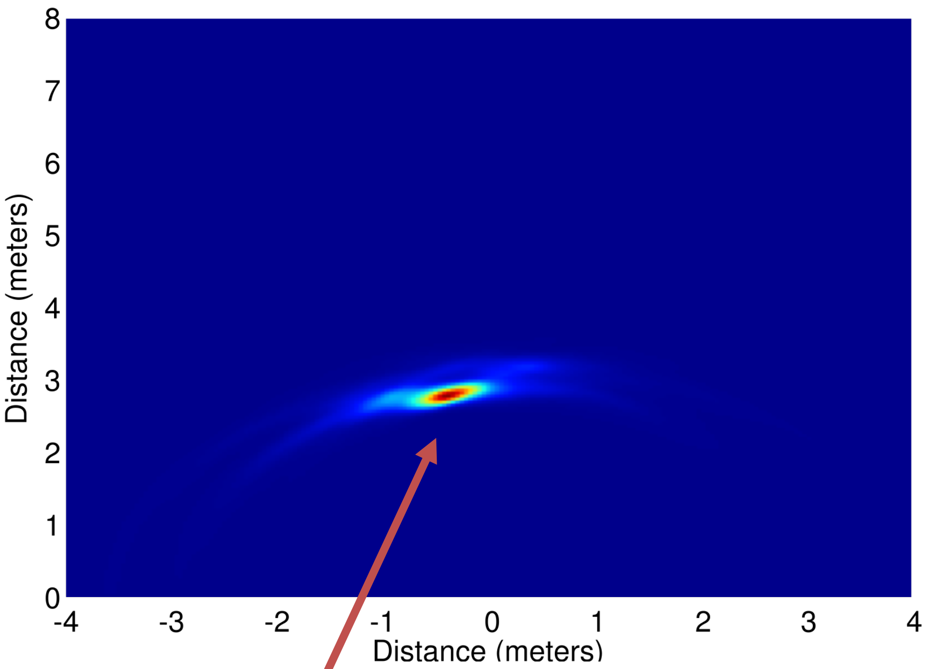
Needs User to Move

Exploit breathing motion for localize static users

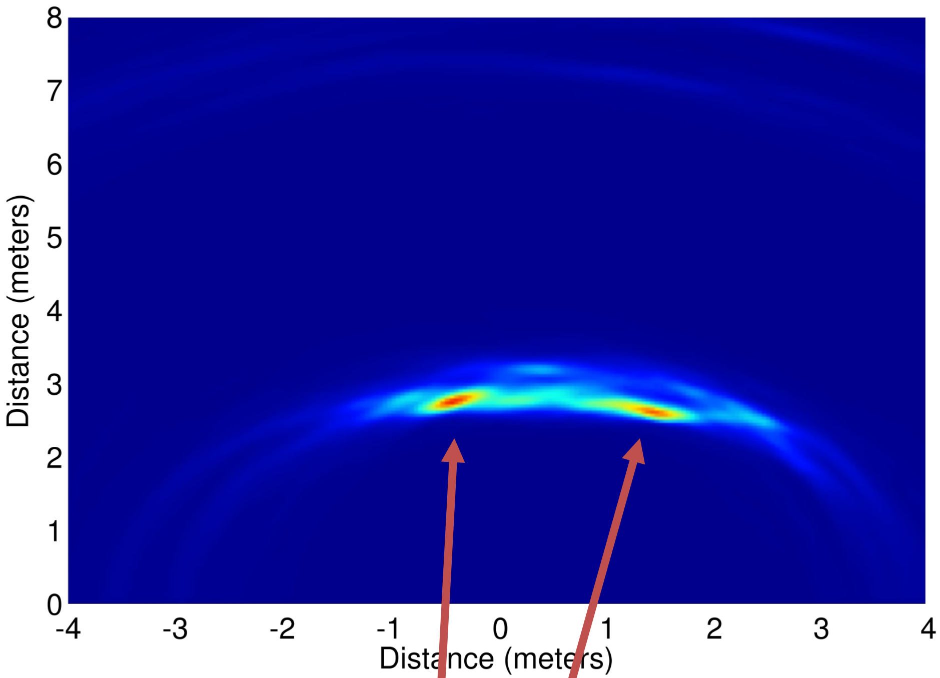
- Breathing and walking happen at different time scales
  - A user that is pacing moves at 1m/s
  - When you breathe, chest moves by few mm/s
- Cannot use the same subtraction window to eliminate multi-path

User Walking at 1m/s

30ms subtraction window



3s subtraction window

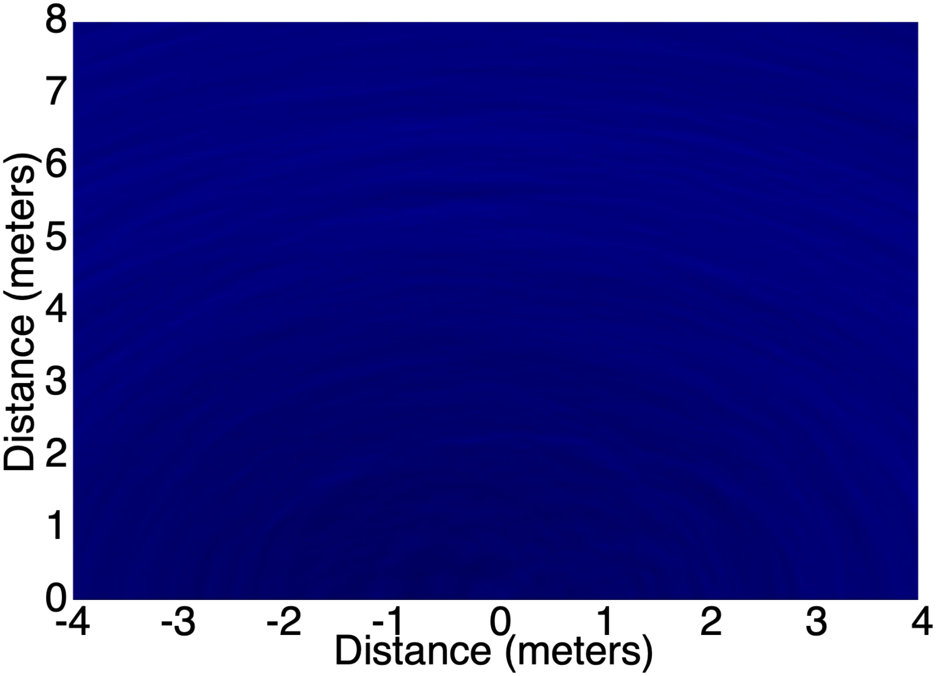


Localize the person

Person appears in two locations

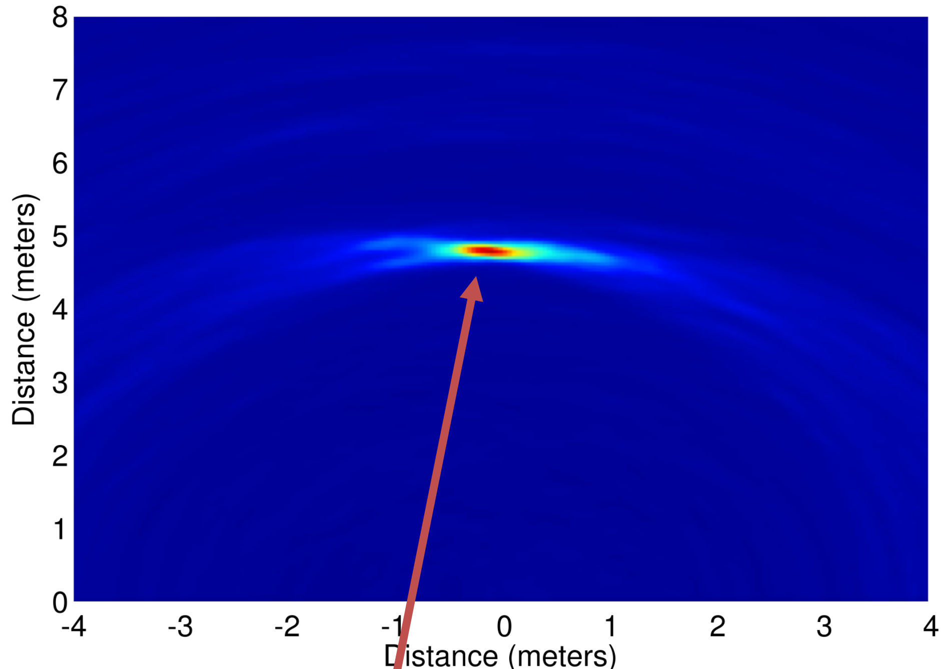
User Sitting Still (Breathing)

30ms subtraction window



Cannot localize

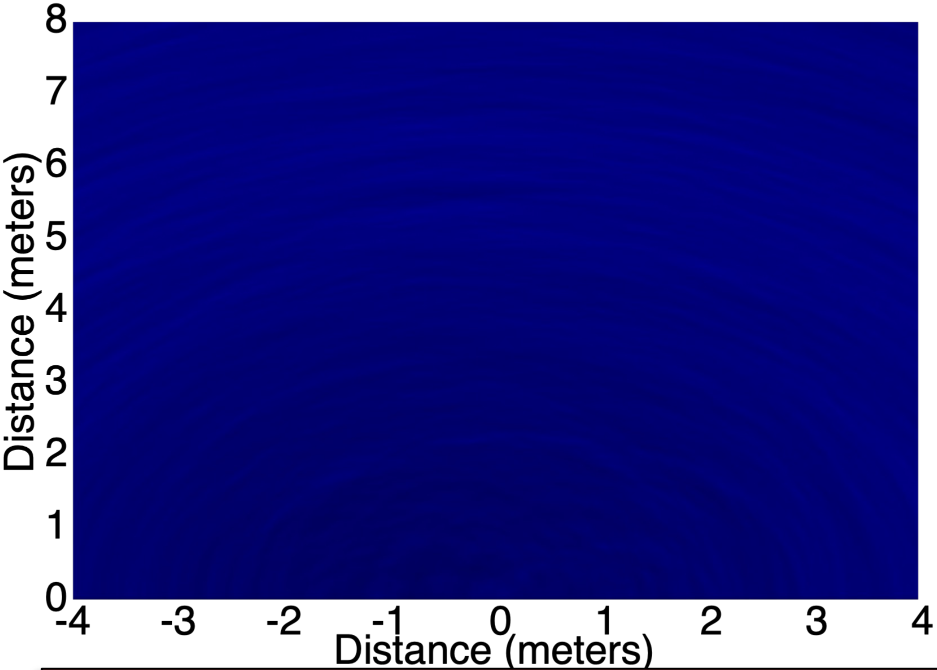
3s subtraction window



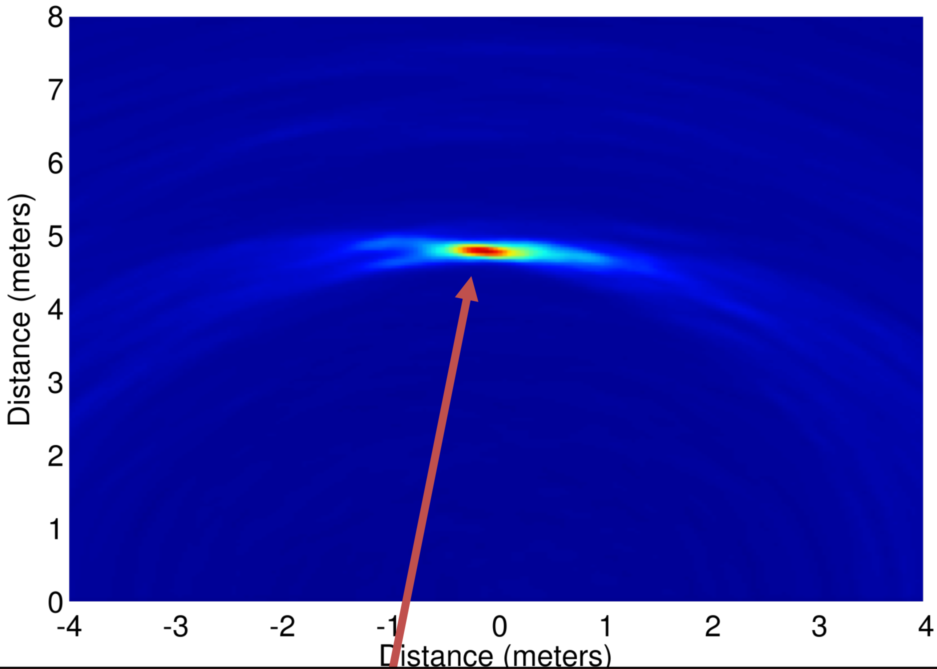
Localize the person

User Sitting Still (Breathing)

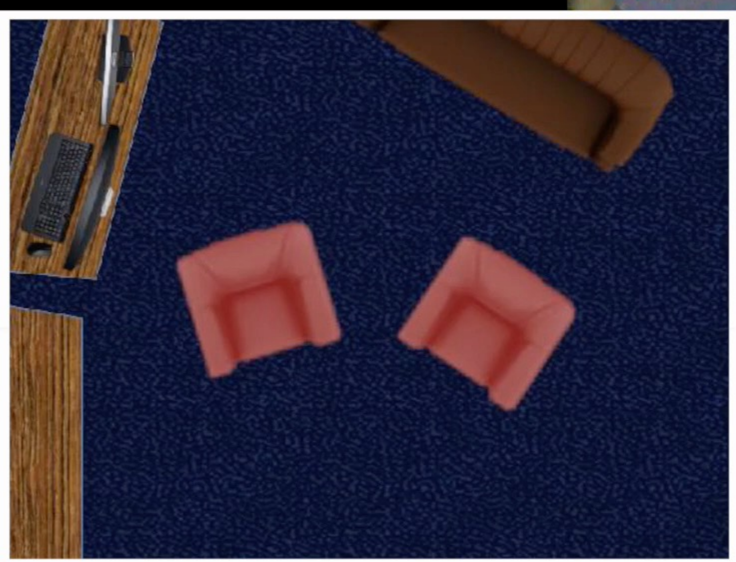
30ms subtraction window



3s subtraction window



Use multi-resolution subtraction window to eliminate multi-path while being able to localize both static and moving users



Next class

- Mon Jan 30th
- ✓ Wireless Localization
- Wireless Sensing: Physiological Signals