

ECE 257B: Principles of Wireless Networks

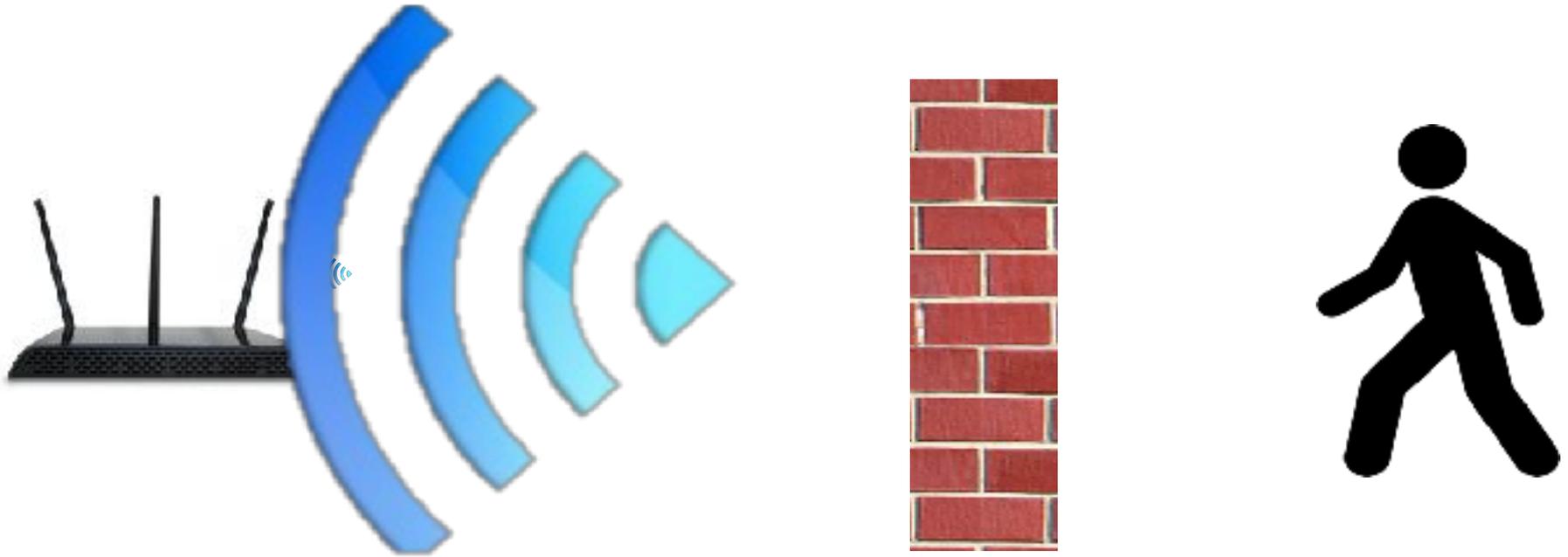
Lecture 11: Wireless Sensing Part 1
Dinesh Bharadia

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?

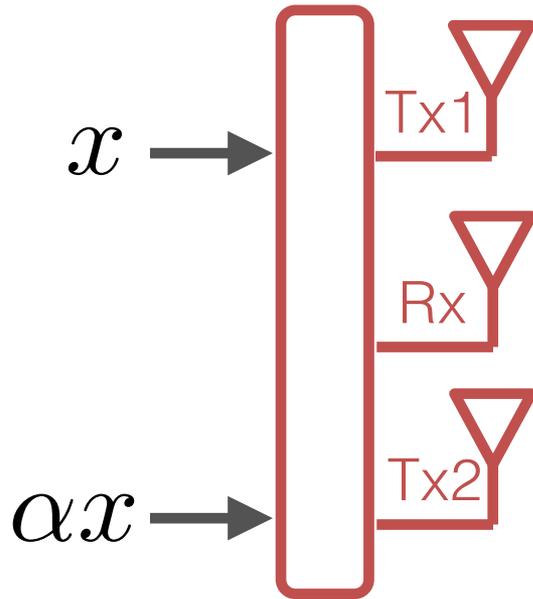
Idea: Transmit two waves that cancel each other when they reflect off static objects but not moving objects

Wall is static  disappears

People tend to move  detectable

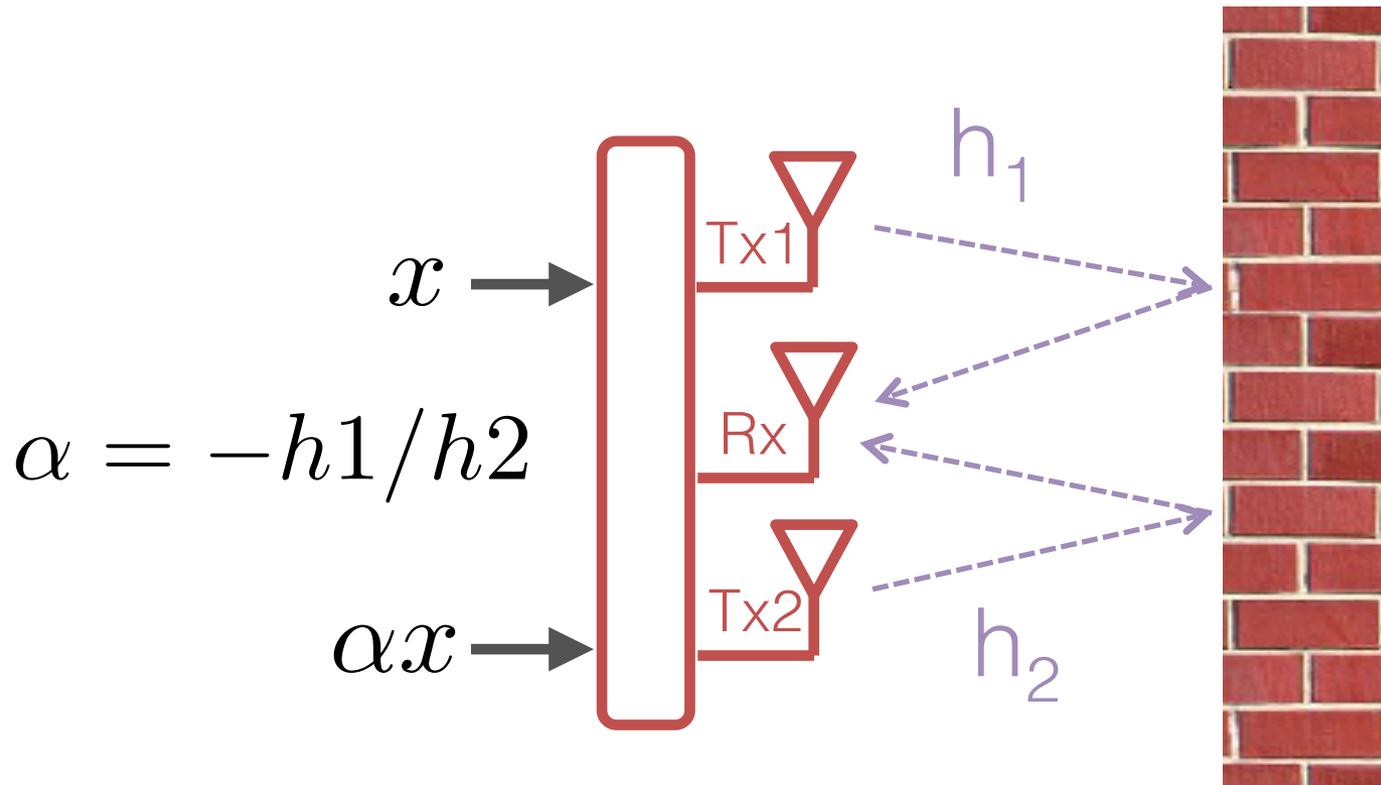
Eliminating the Wall's Reflection

Two transmit antennas and one receive antenna

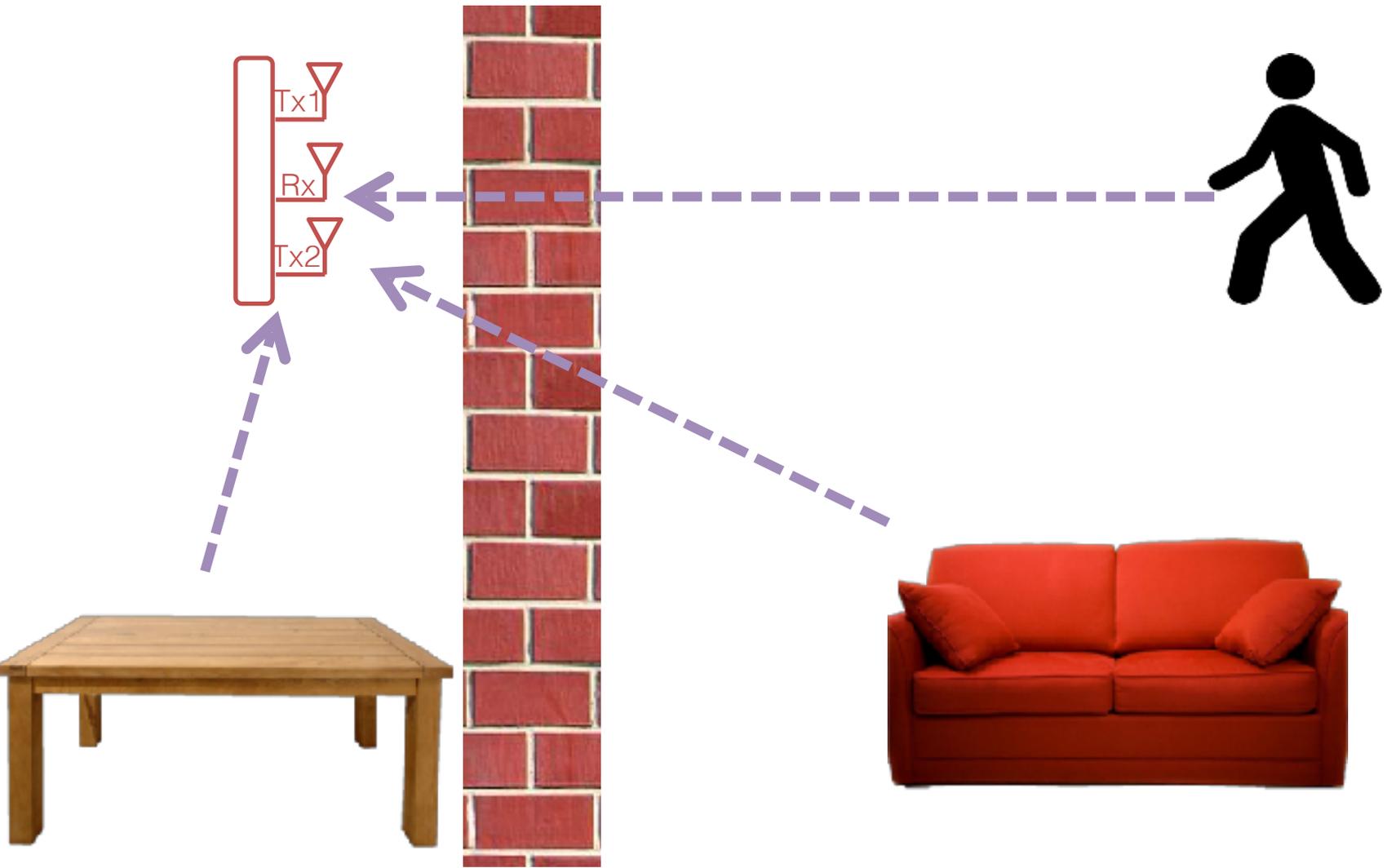


Eliminating the Wall's Reflection

Received signal: ~~$y = h_1x + h_2\alpha x$~~ $\rightarrow 0$



Eliminating All Static Reflections



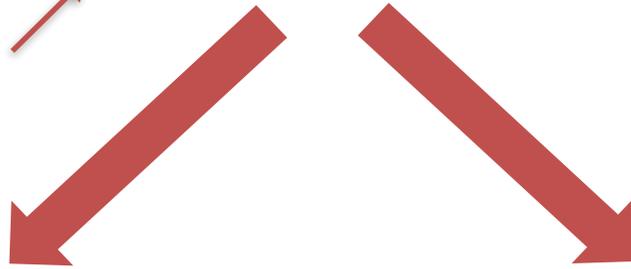
Eliminating All Static Reflections

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

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

People move, therefore their channels change

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

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

Not Zero

Eliminating All Static Reflections

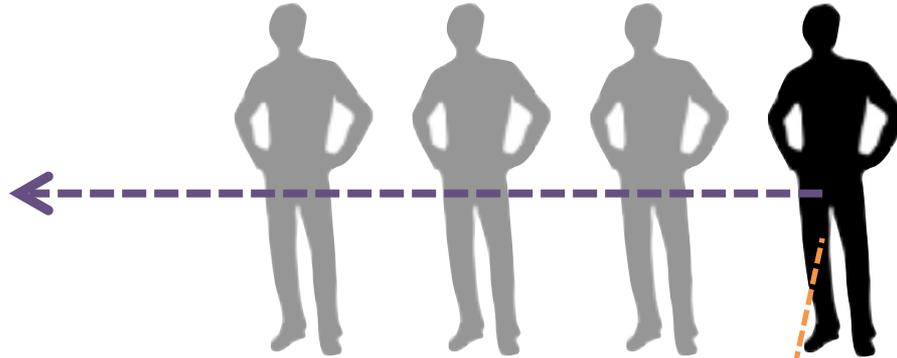
- Noise leads to errors in estimating the channel
 - Limits ability to cancel static reflections and sense motion behind the wall
 - Channel estimates $\hat{h} \neq h$
- Refine channel estimates through an iterative nulling algorithm

How to extend to wideband WiFi channels?

How Can We Track Using Reflections?

Tracking Motion

Direction of motion



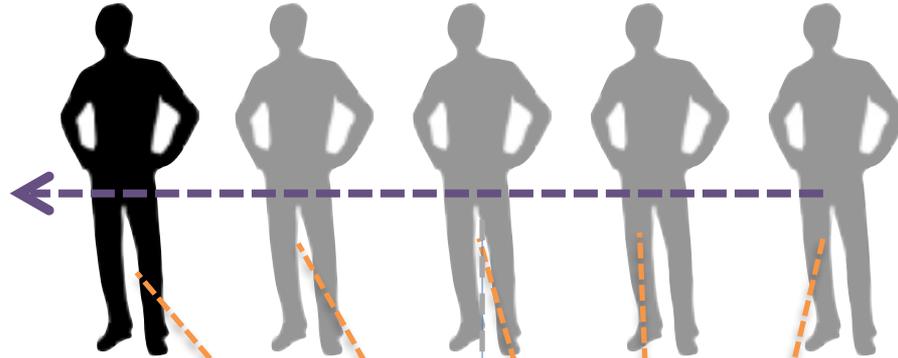
At any point in time, we have a single measurement

Device has one receive antenna



Tracking Motion

Direction of motion

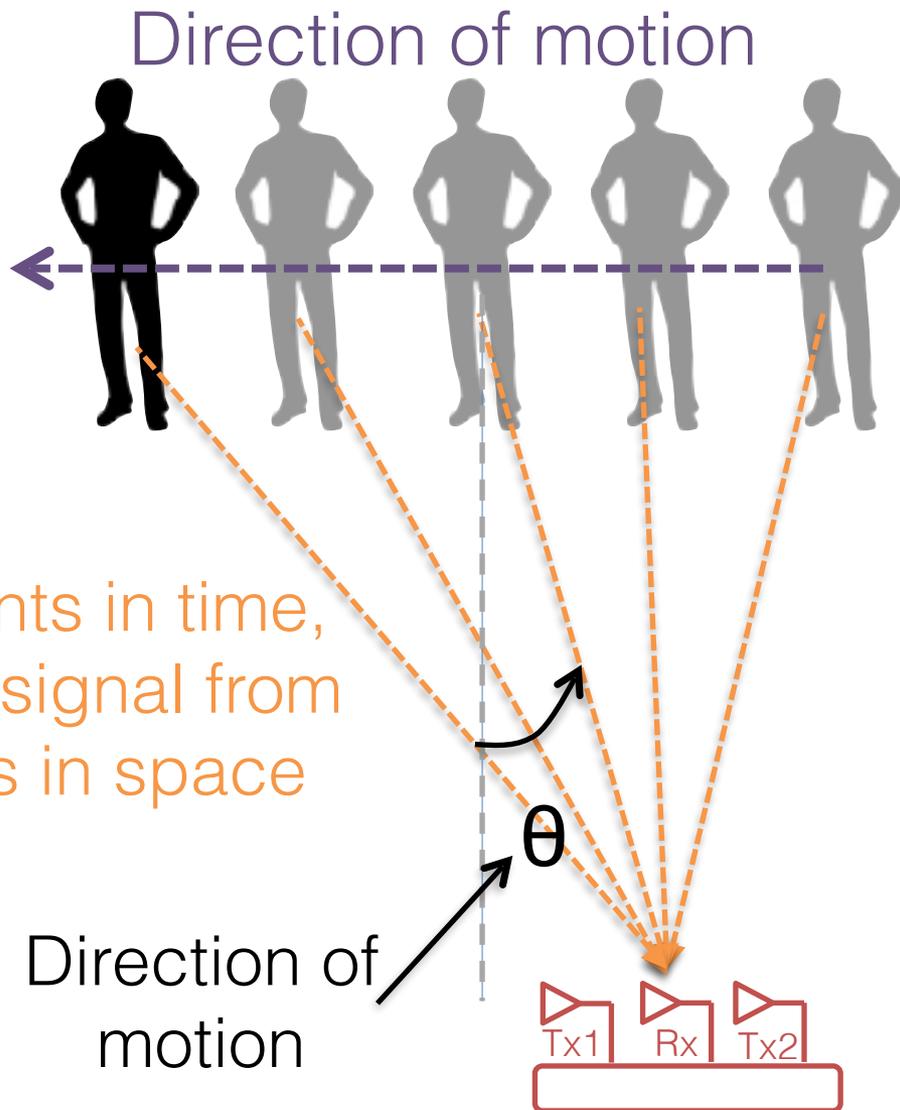


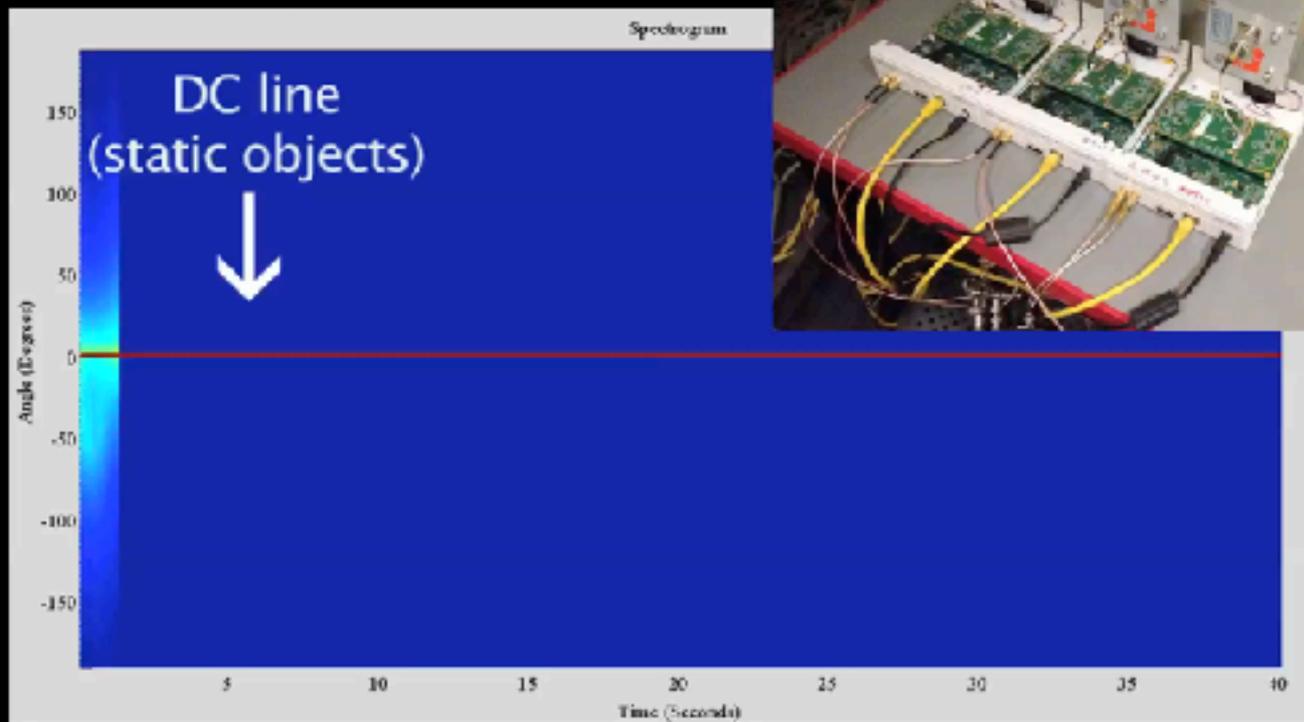
At different points in time, human reflects signal from different points in space

Direction of motion



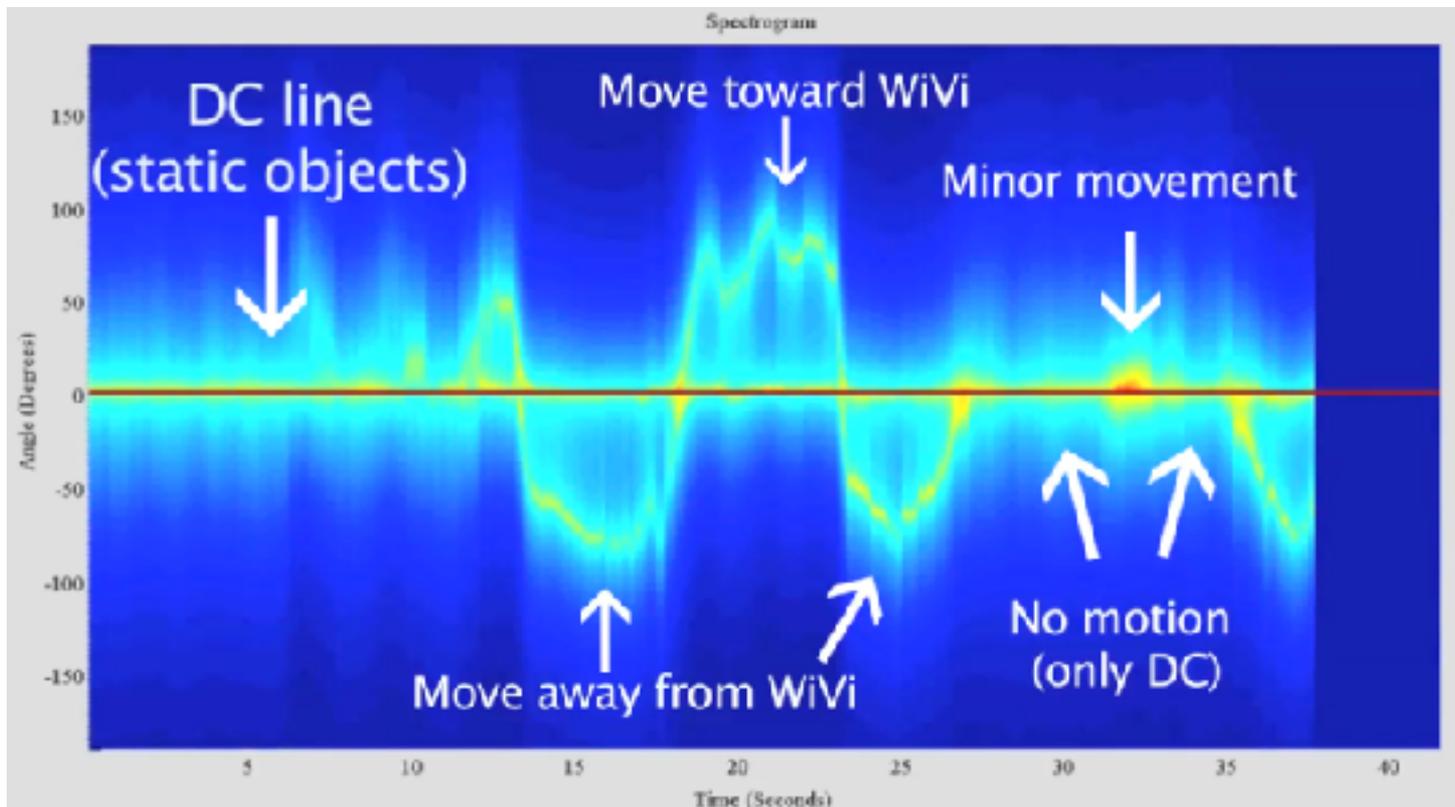
Human Motion Emulates an Antenna Array





Tracking Multiple Humans

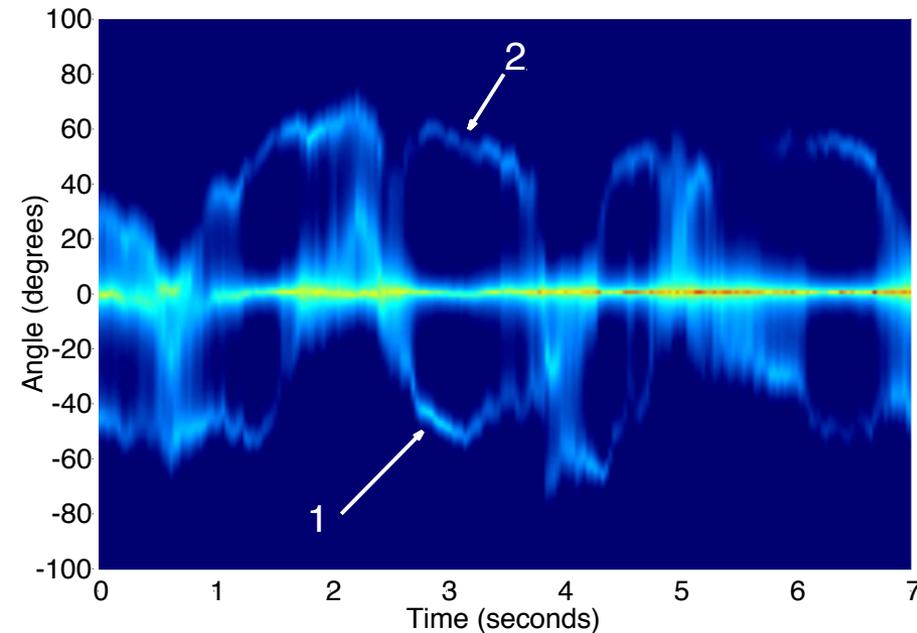
One moving person is indicated by a single curvy line



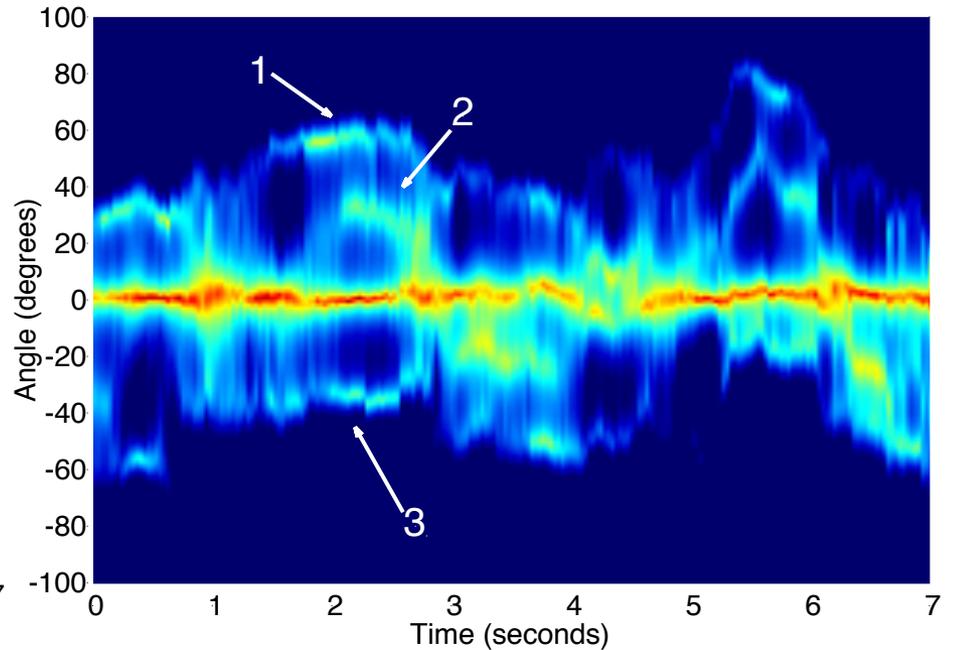
Tracking Multiple Humans

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

Two Humans

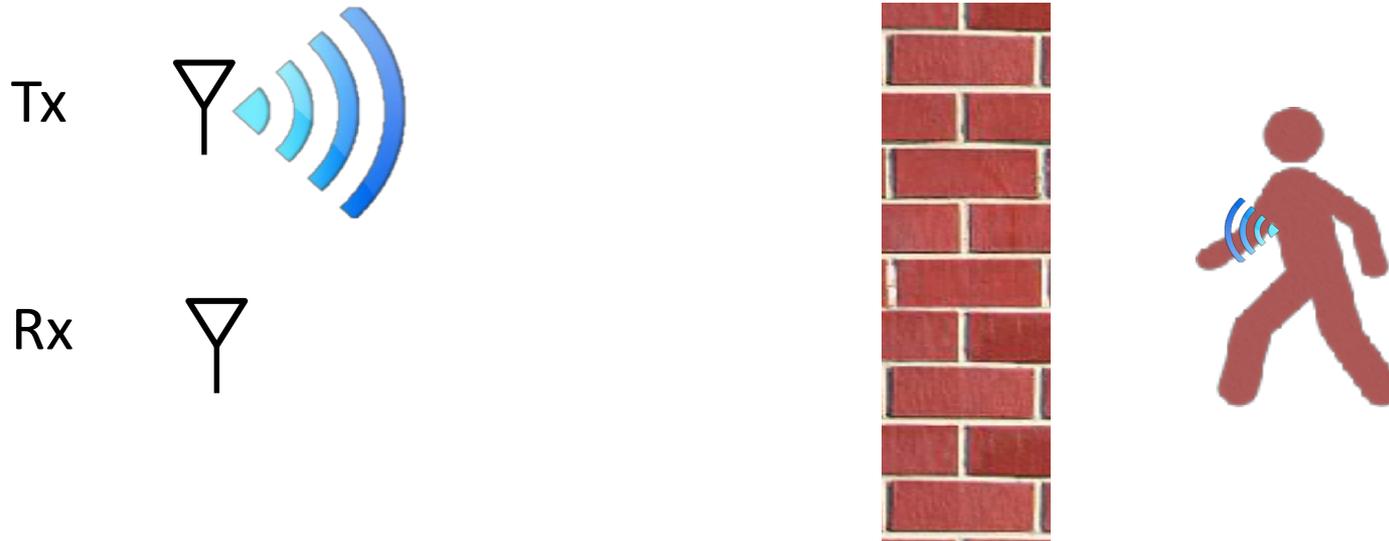


Three Humans



WiTrack

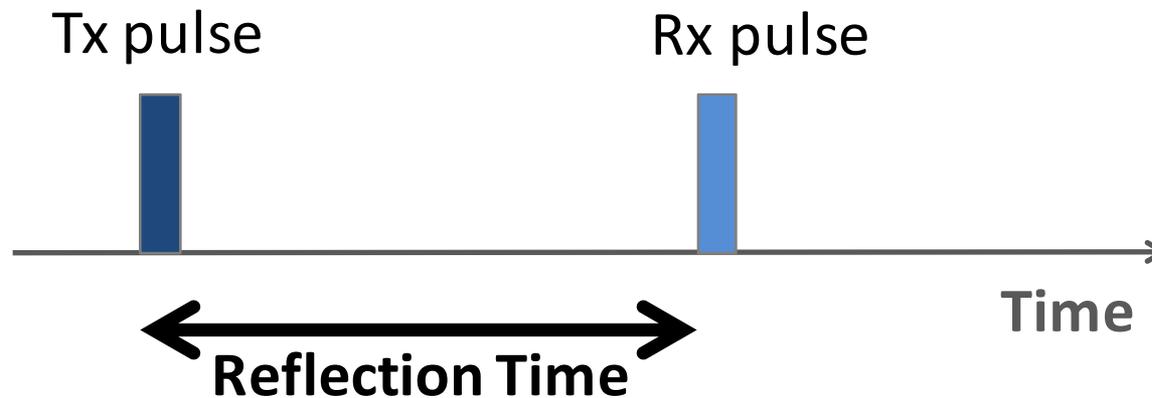
Measuring Distances



Distance = Reflection time x speed of light

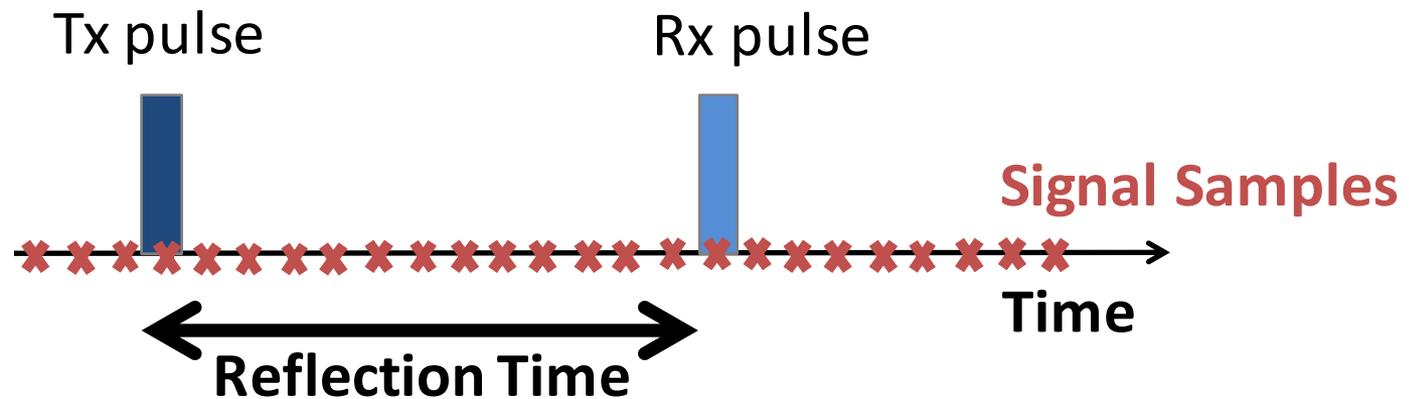
Measuring Reflection Time

- Option 1: Transmit short pulse and listen for the echo.



Measuring Reflection Time

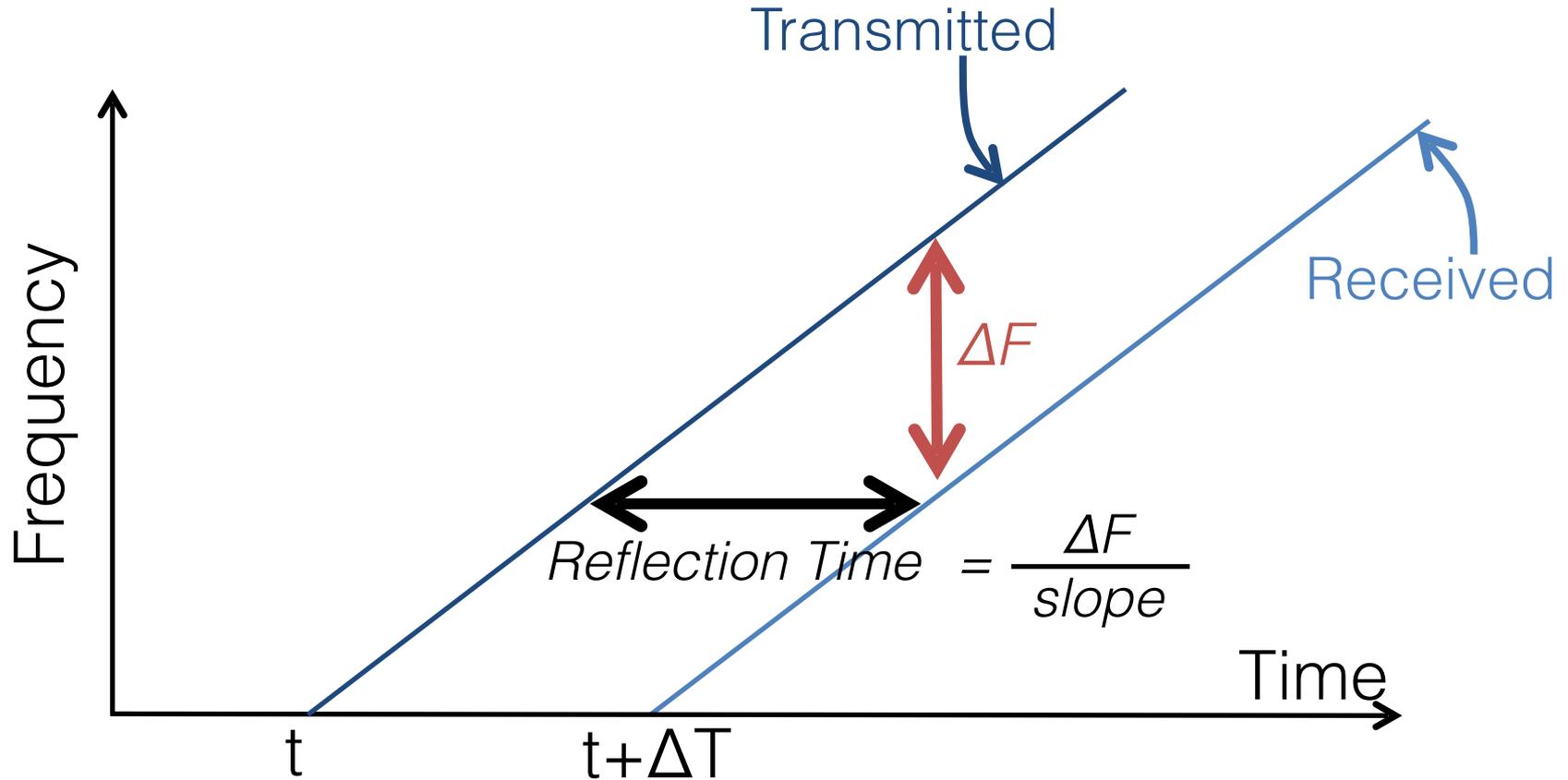
- Option 1: Transmit short pulse and listen for the echo.



Need to sample at very high rate : UWB

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

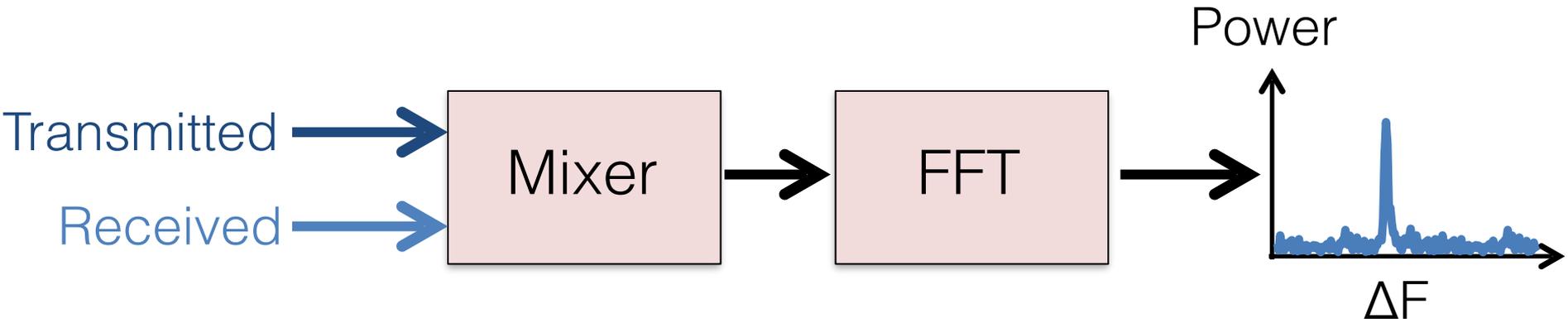
FMCW: Measure time by measuring frequency



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

$\Delta F \rightarrow$ Reflection Time \rightarrow Distance

FMCW

- FMCW Transmitted Signal

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

slope

Frequency is linear in time;
hence phase is quadratic

- FMCW Received Signal:

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

reflector i

delay τ_i

Reflections linearly
combine over the
wireless medium

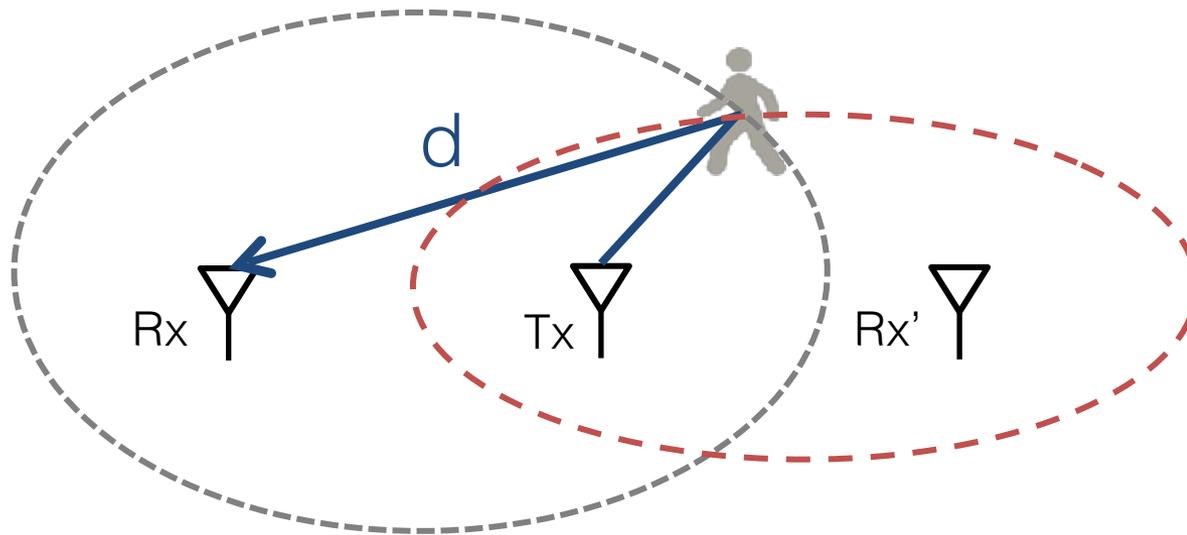
baseband conversion:

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

frequency $k \tau_i$

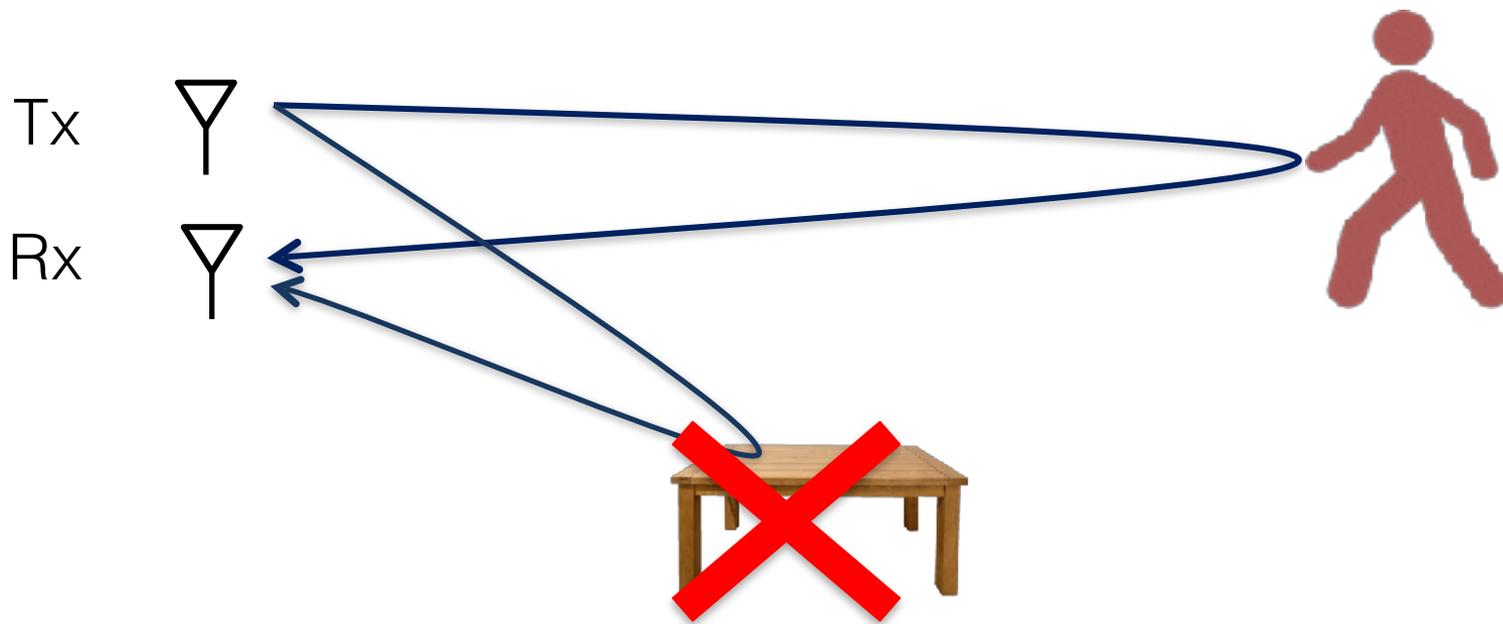
Mapping Distance to Location

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

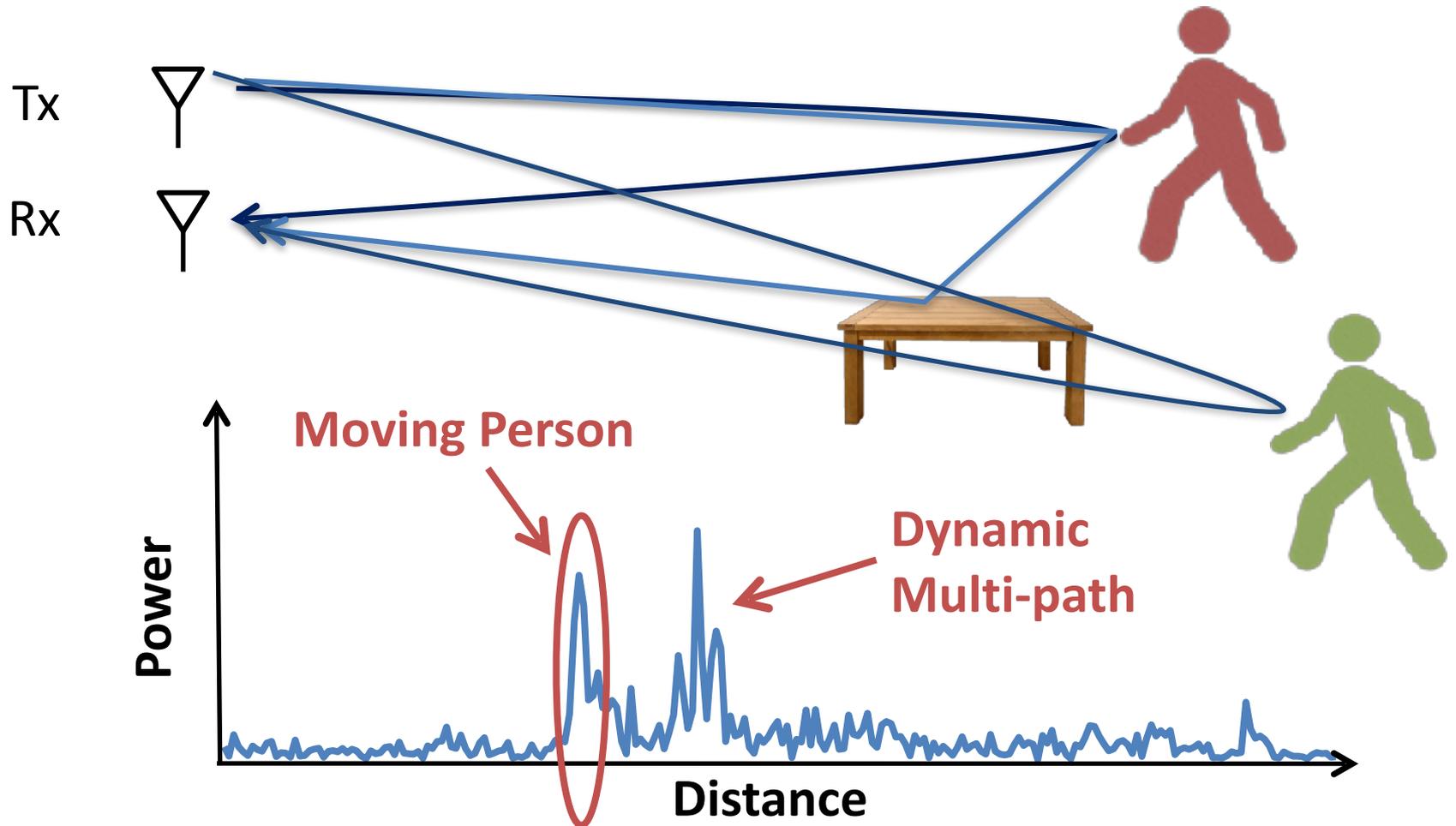
Dealing with multi-path when there is one moving user



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



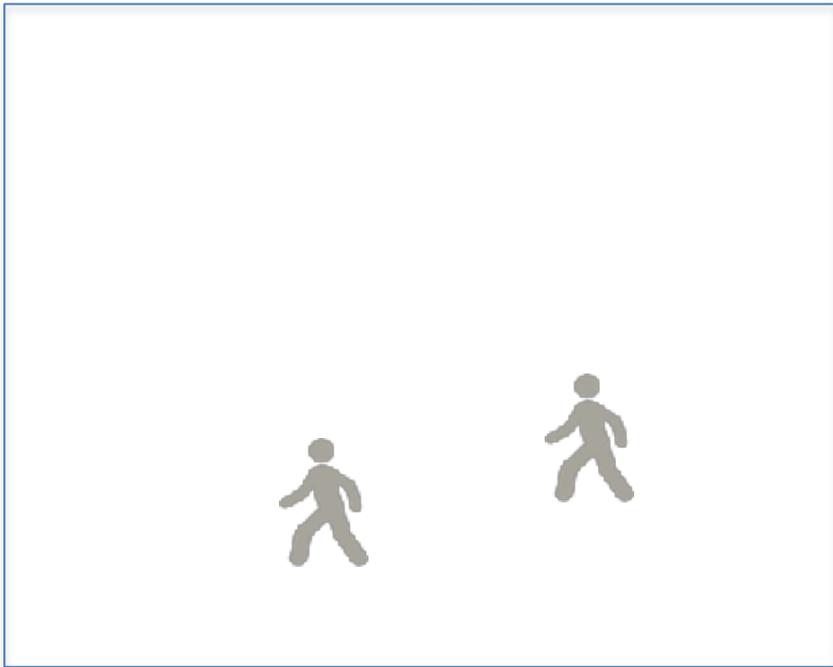
How can we deal with multi-path reflections when there are multiple persons in the environment?

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

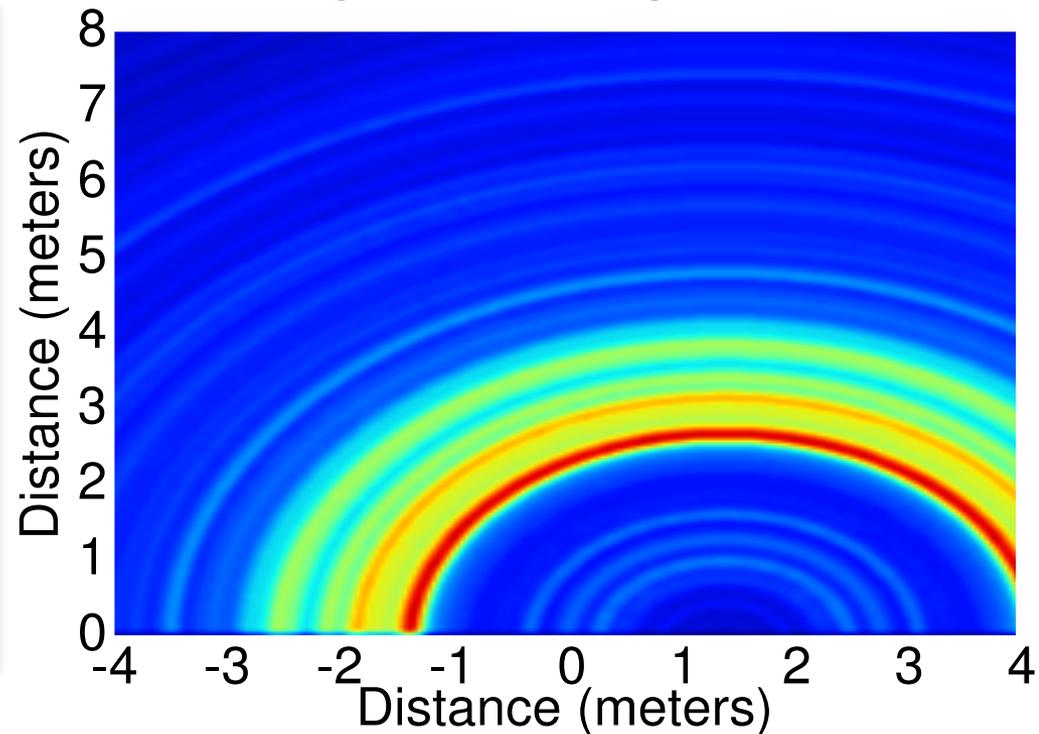
Combining across Multiple Vantage Points

Experiment: Two users walking

Setup



Single Vantage Point

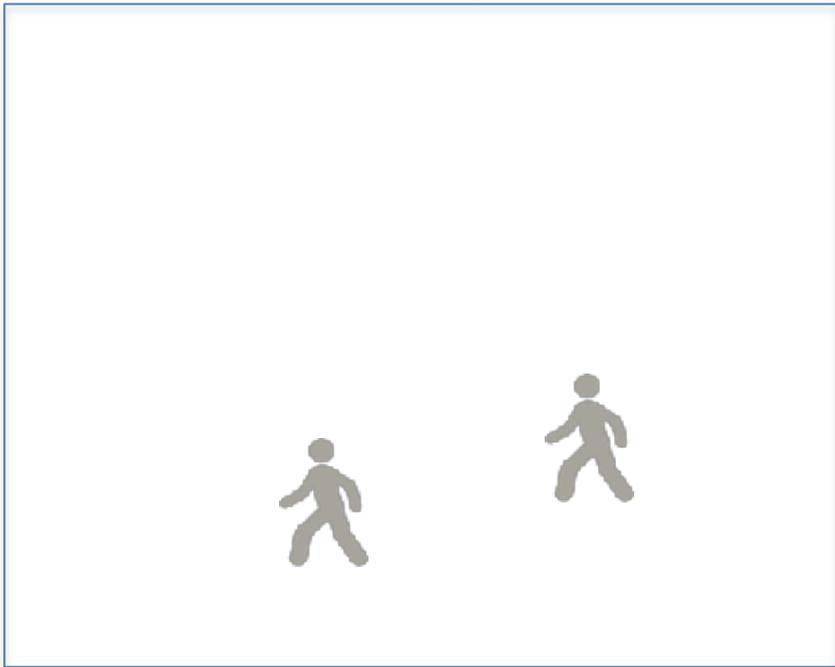


Mathematically: each round-trip distance can be mapped to an ellipse whose foci are the transmitter and the receiver

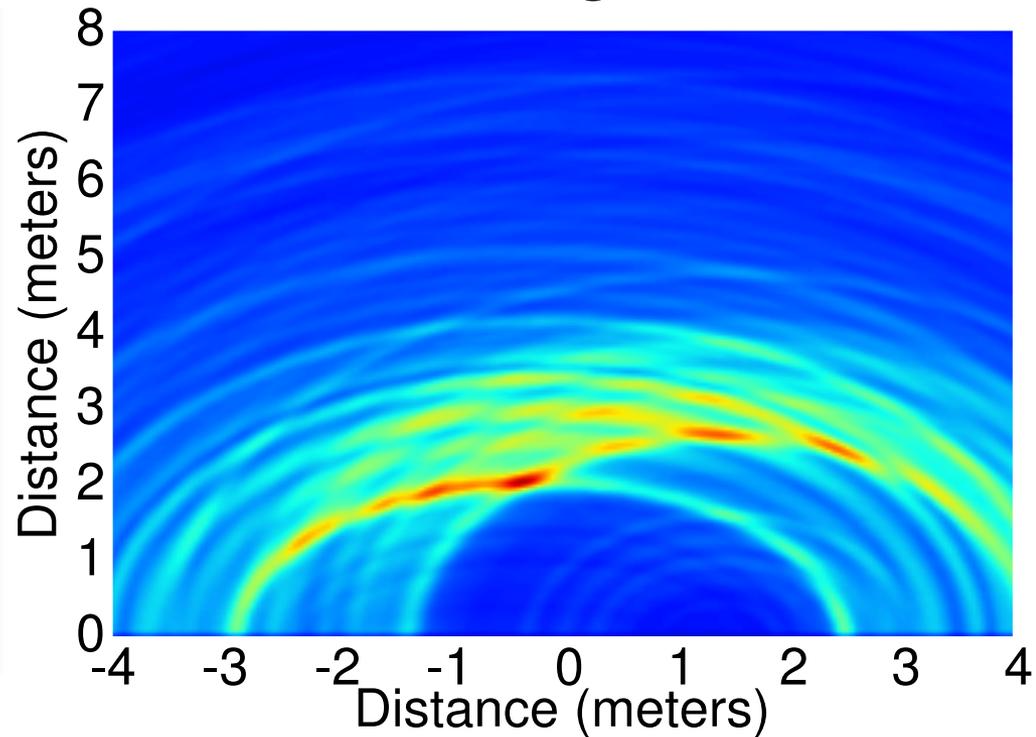
Combining across Multiple Vantage Points

Experiment: Two users walking

Setup



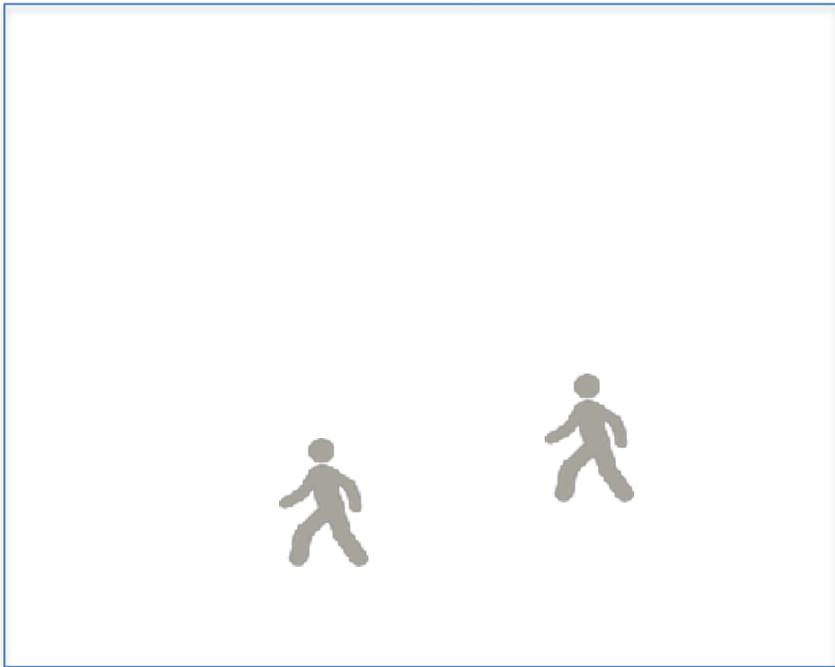
Two Vantage Points



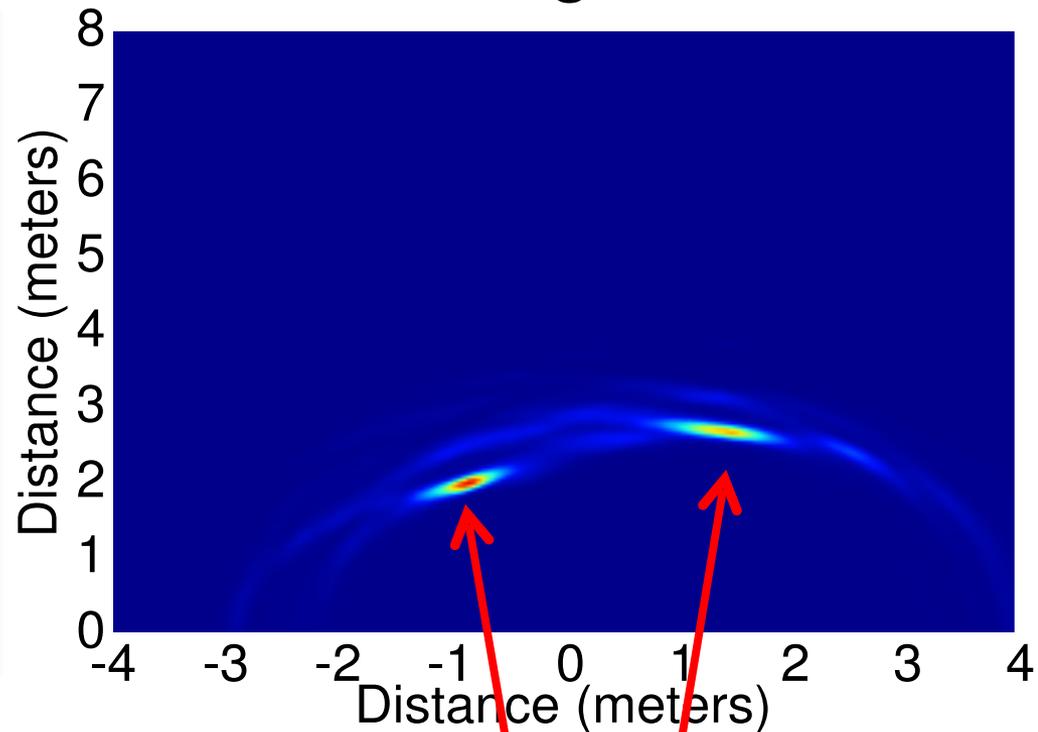
Combining across Multiple Vantage Points

Experiment: Two users walking

Setup



16 Vantage Points

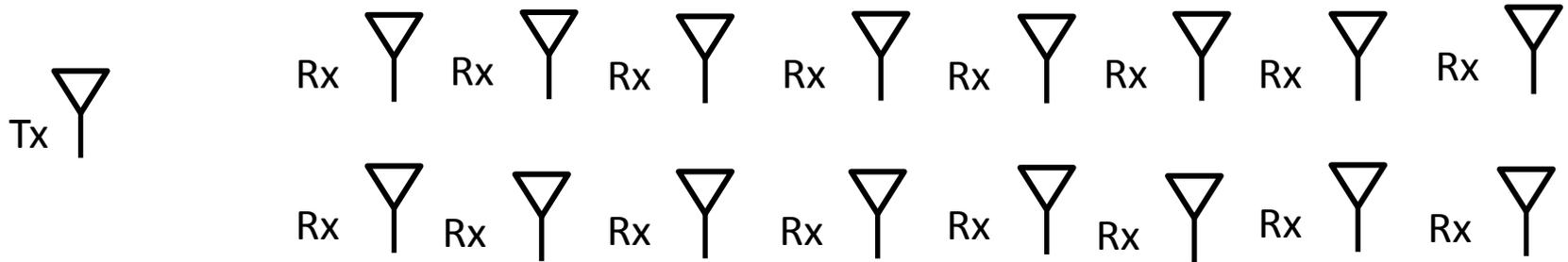


Localize the two users

How can we obtain 16 vantage points?

Achieving 16 vantage points

- Naïve solution: 1 Transmitter and 16 Receivers



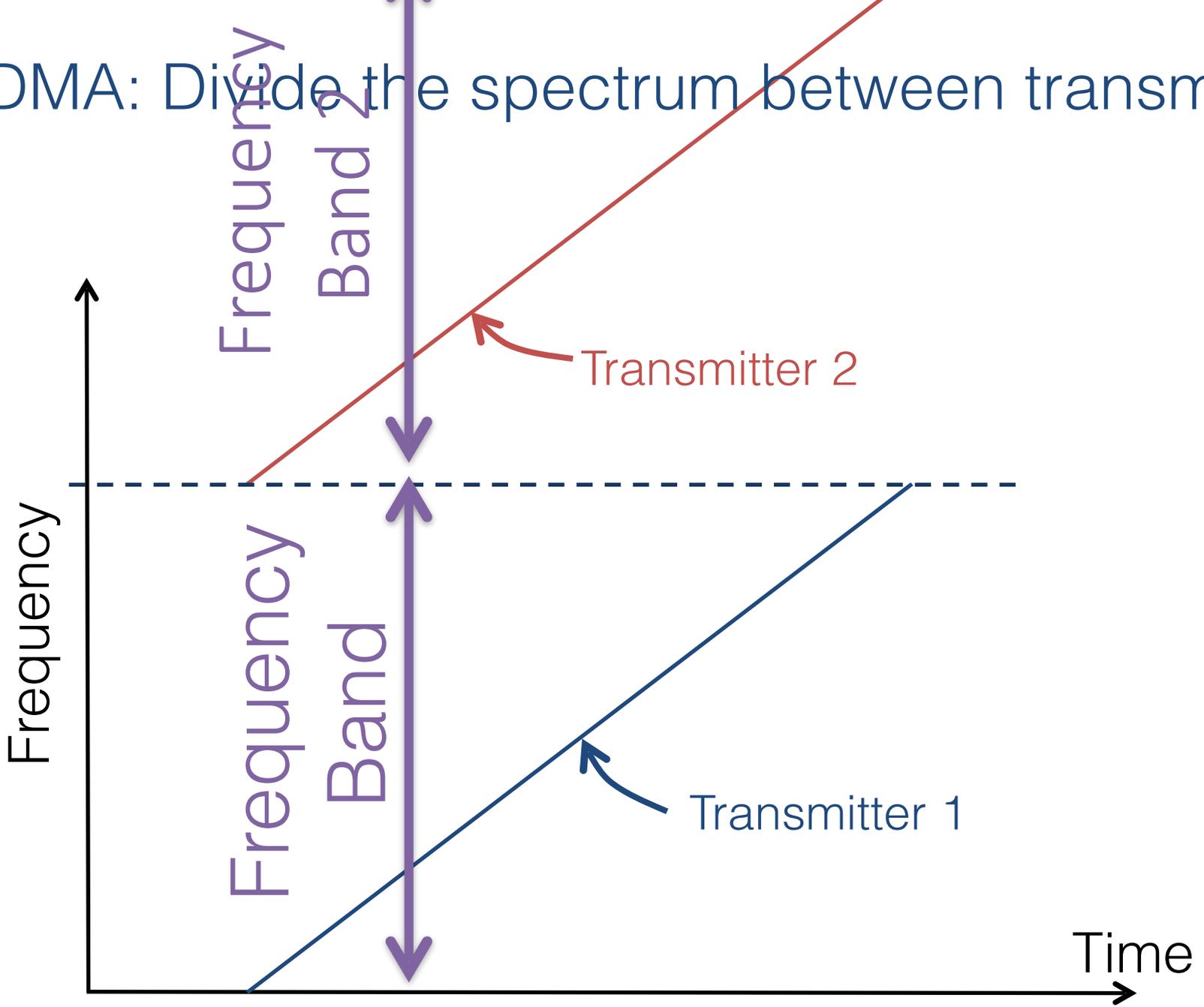
- Ideally: 4 Transmitters and 4 Receivers



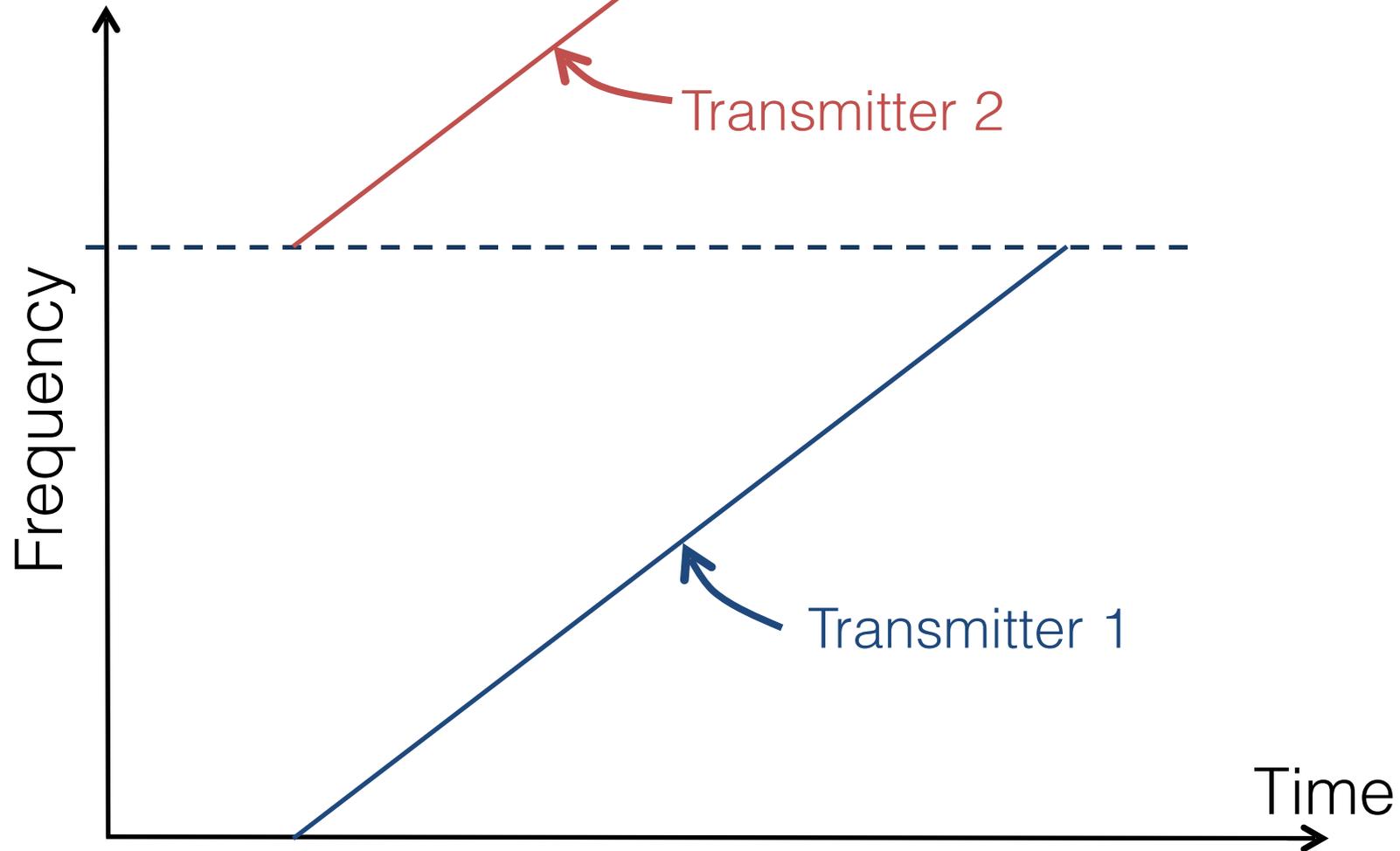
Problem: Different transmitters interfere with each other!

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

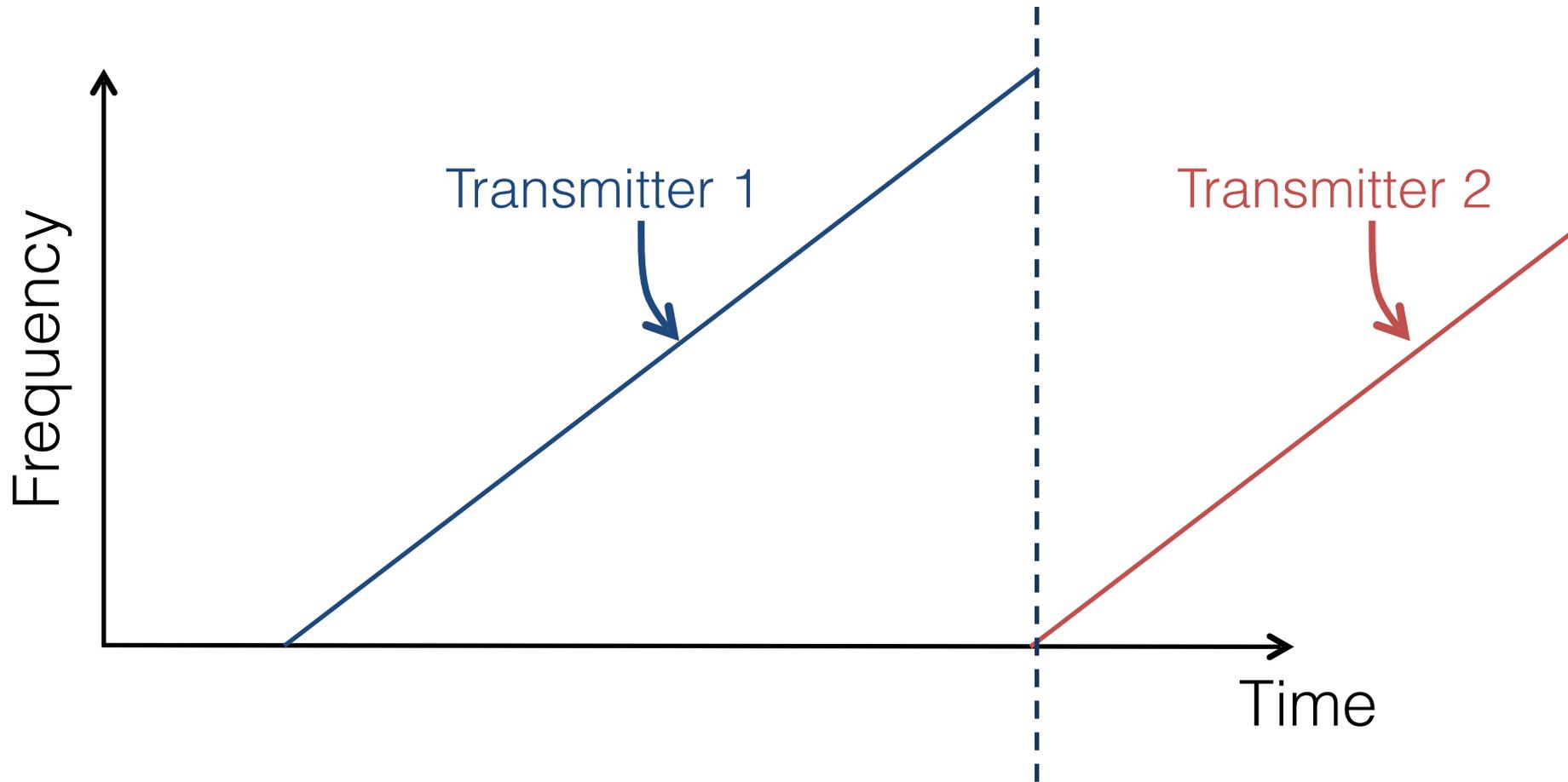
FDMA: Divide the spectrum between transmitters



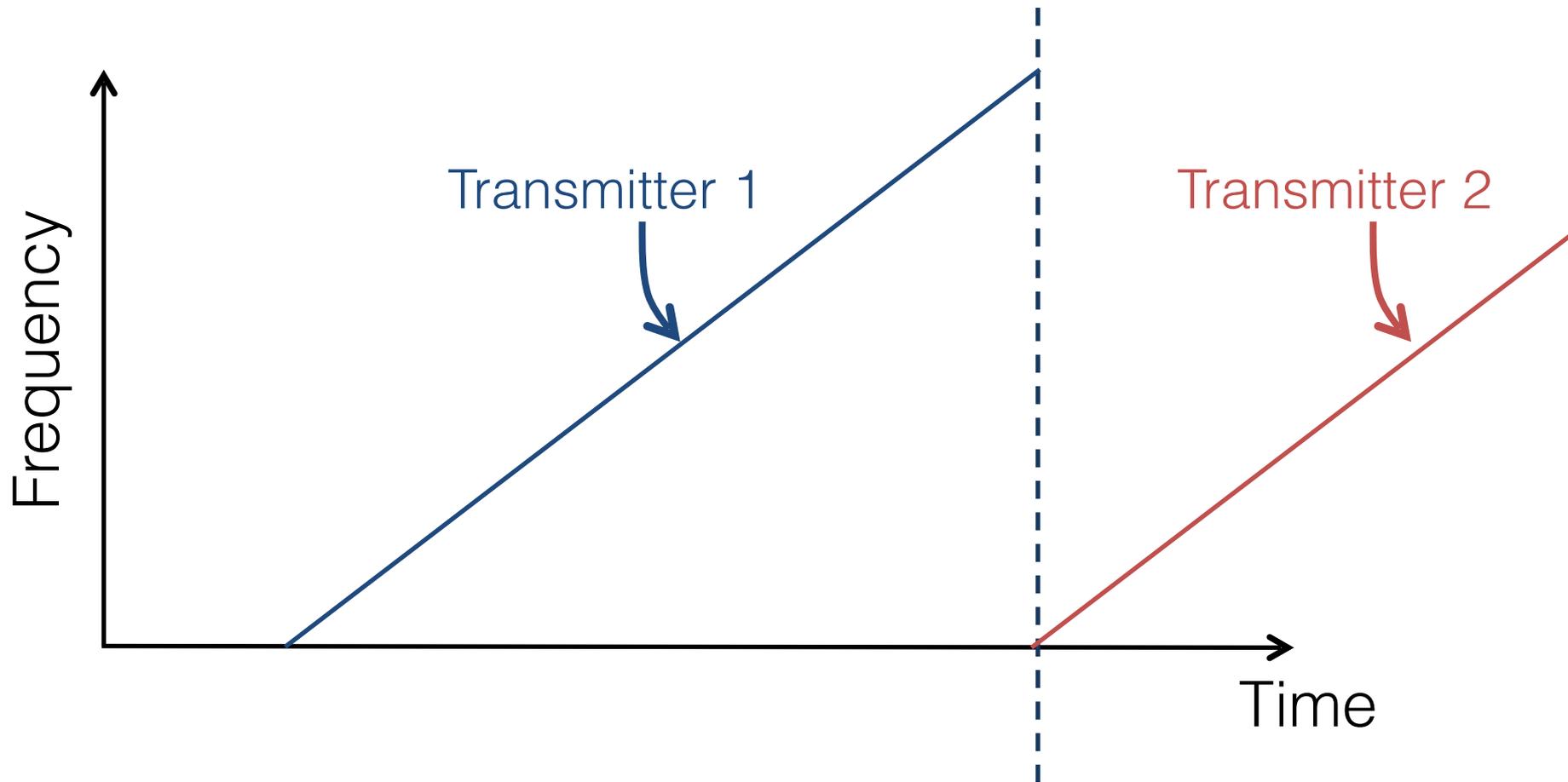
Would require N times the bandwidth!



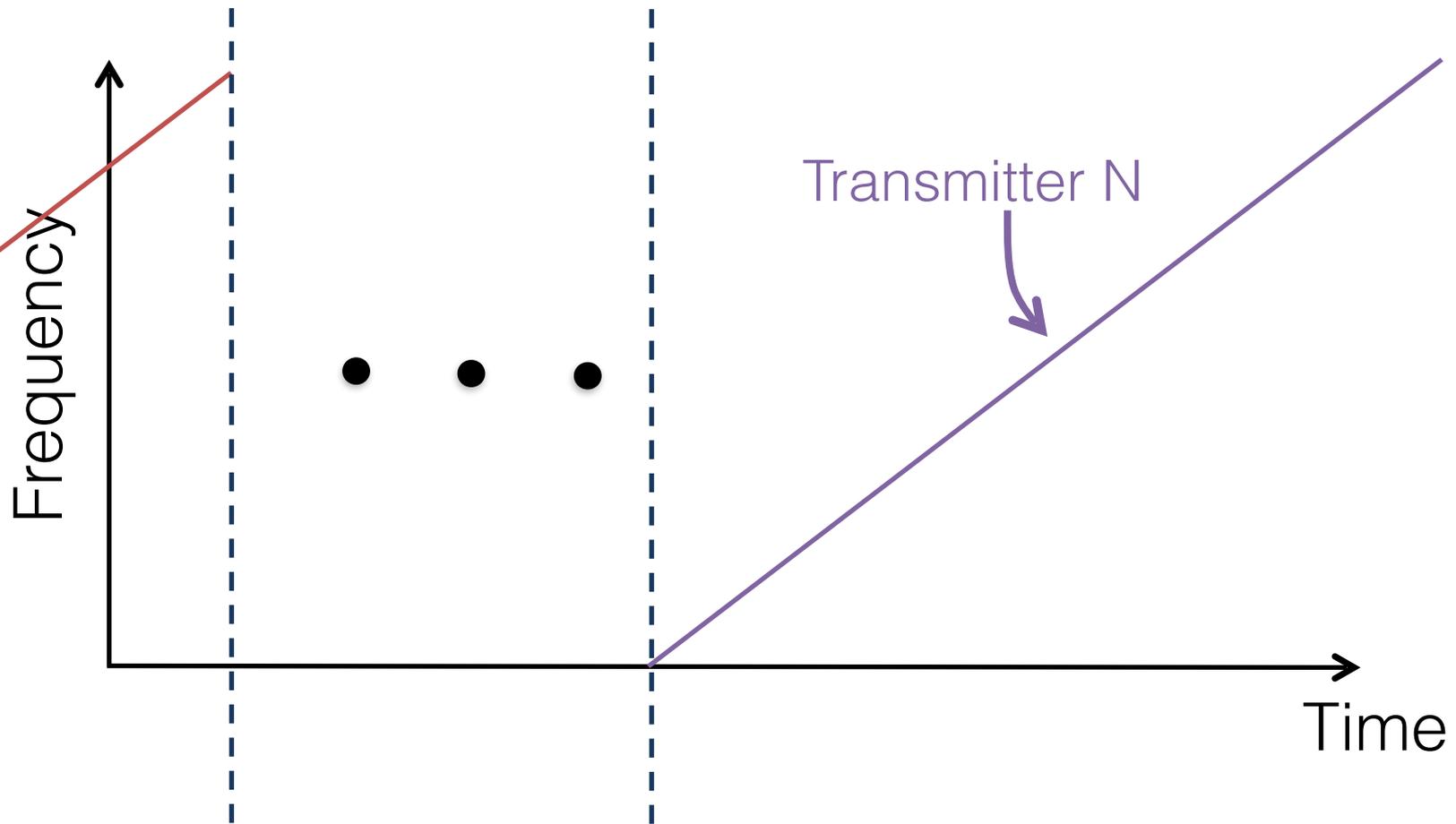
TDMA: Transmitters take turns transmitting



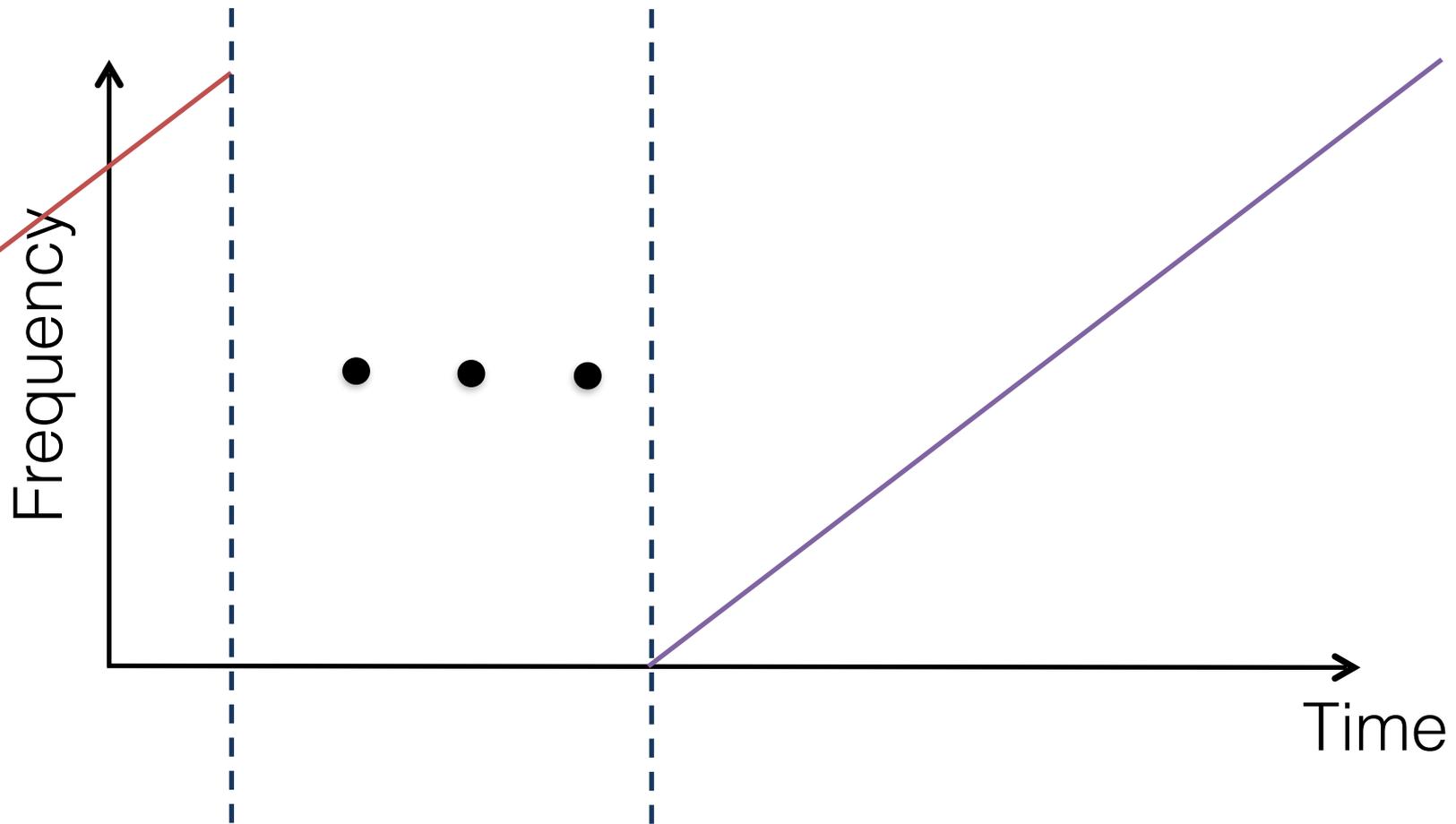
Would require N more time to localize



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

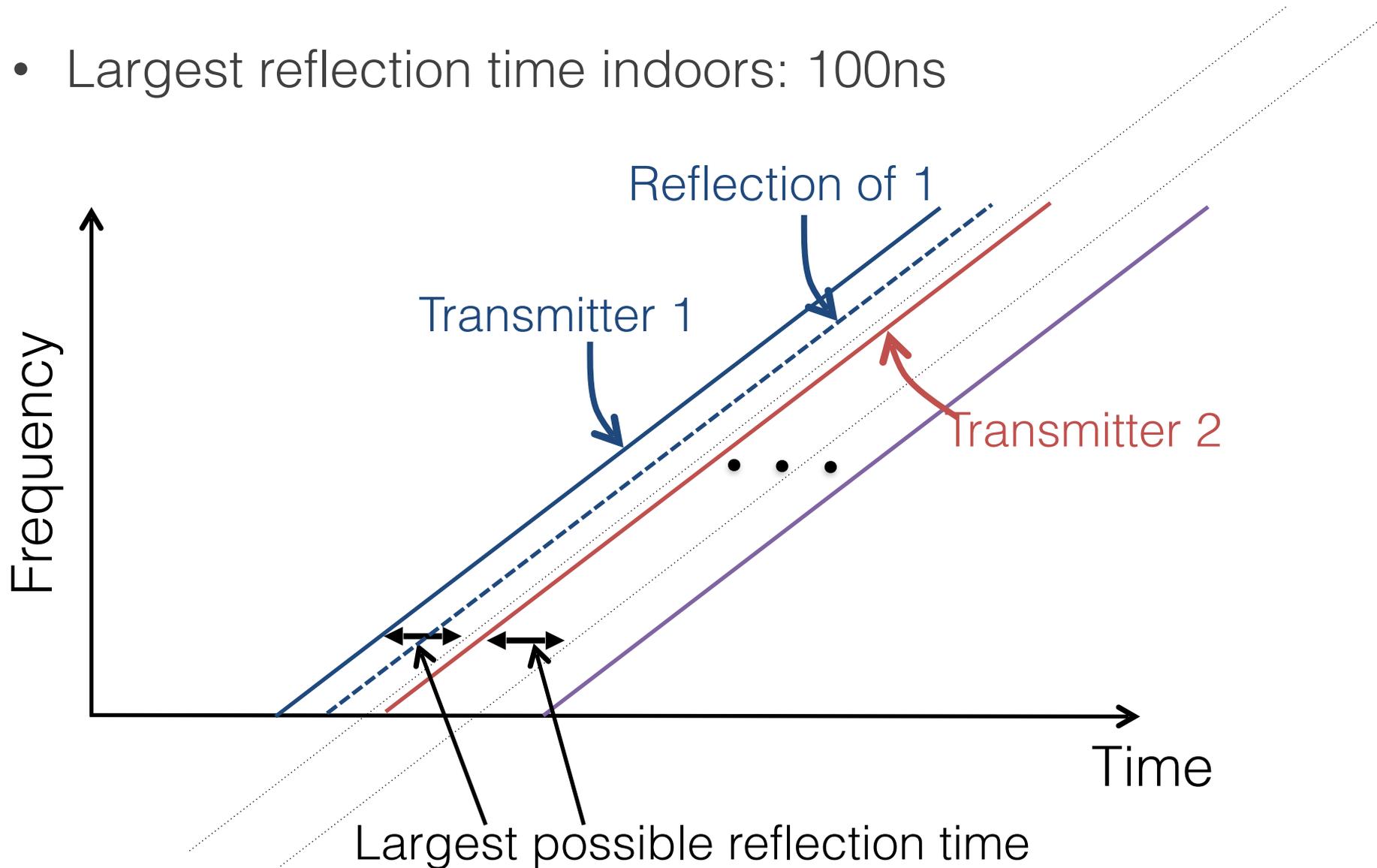


Multi-shift FMCW:

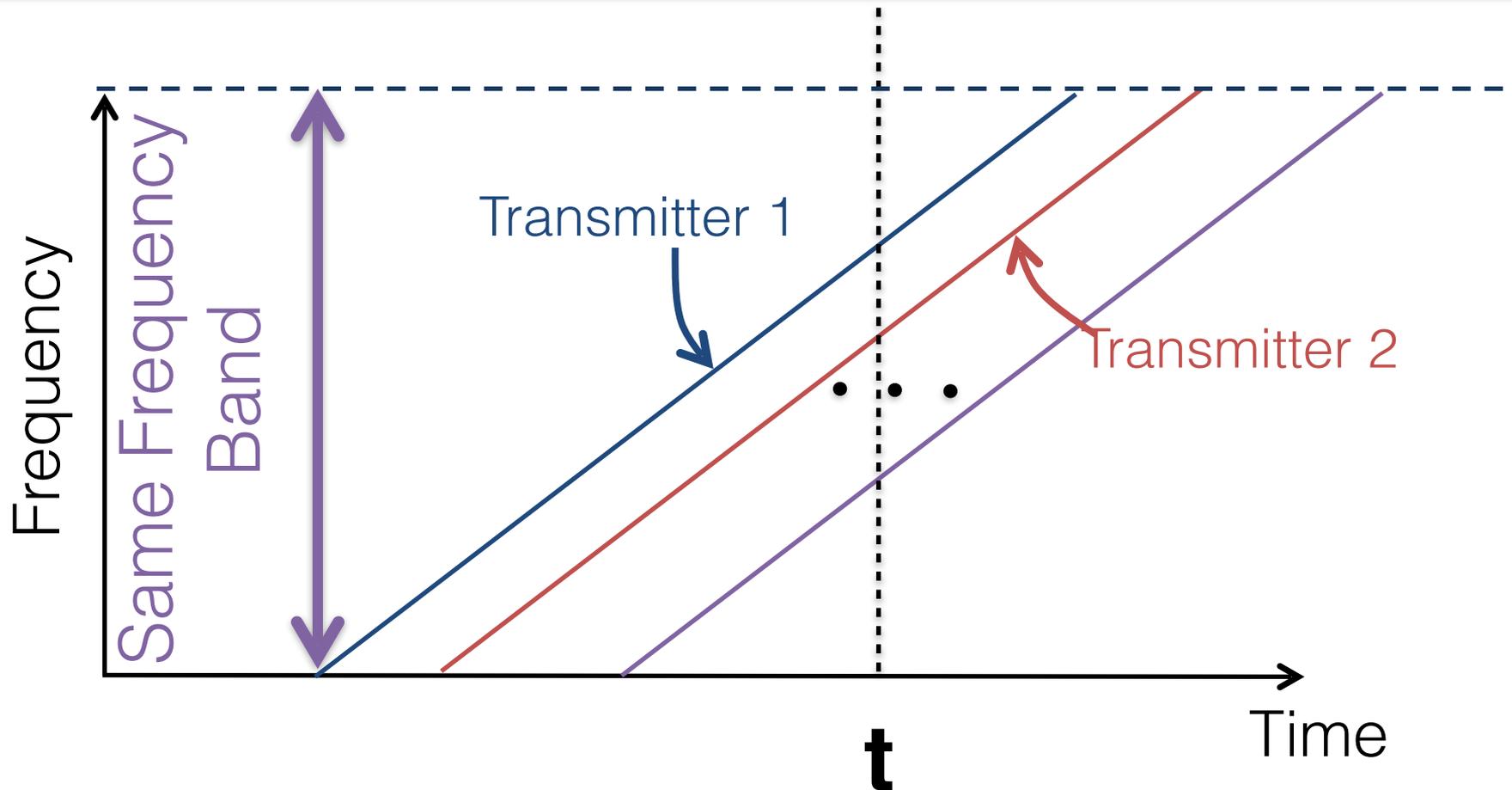
a new mechanism to divide resources between transmitters so that they don't suffer from interference

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



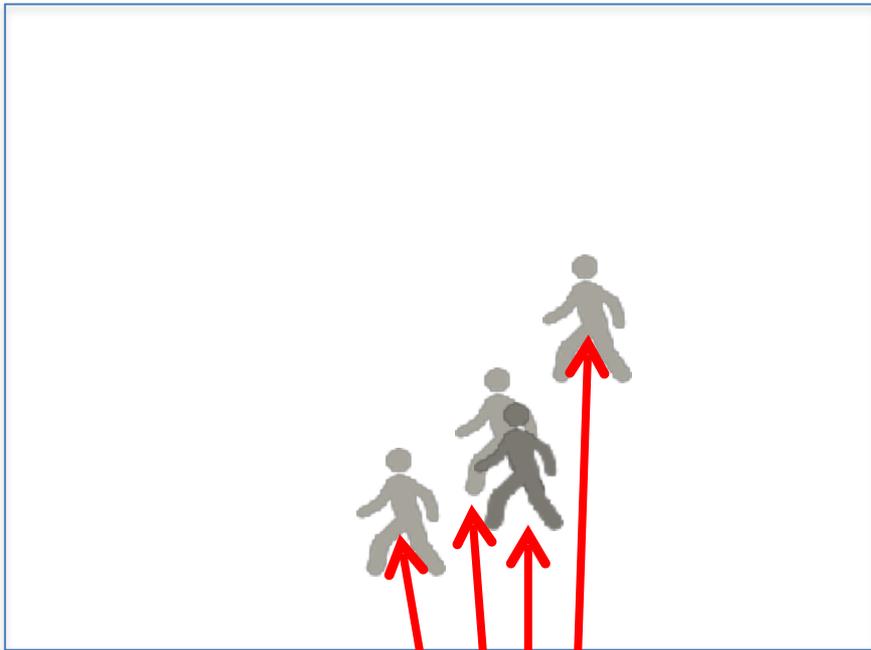
Multi-Person Localization

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

Multi-User Localization

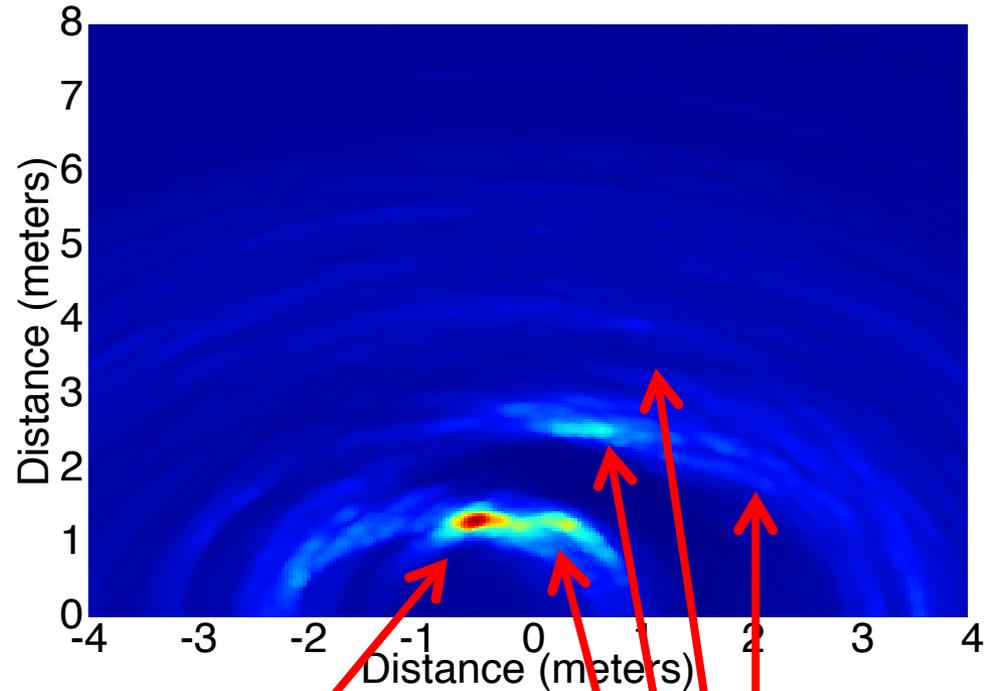
Experiment: Four persons walking

Setup



four persons

All Vantage Points

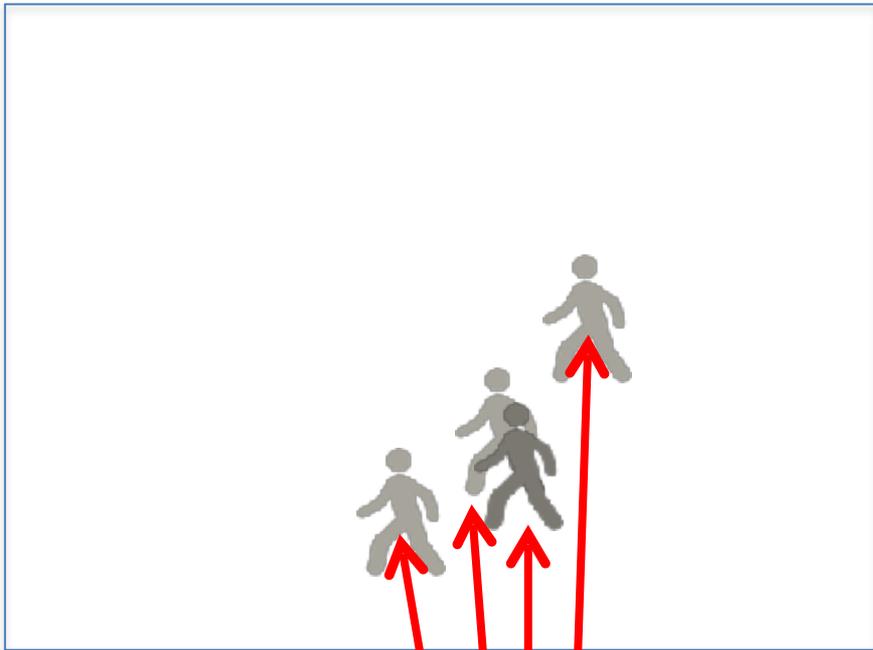


first person

other people or
noise?

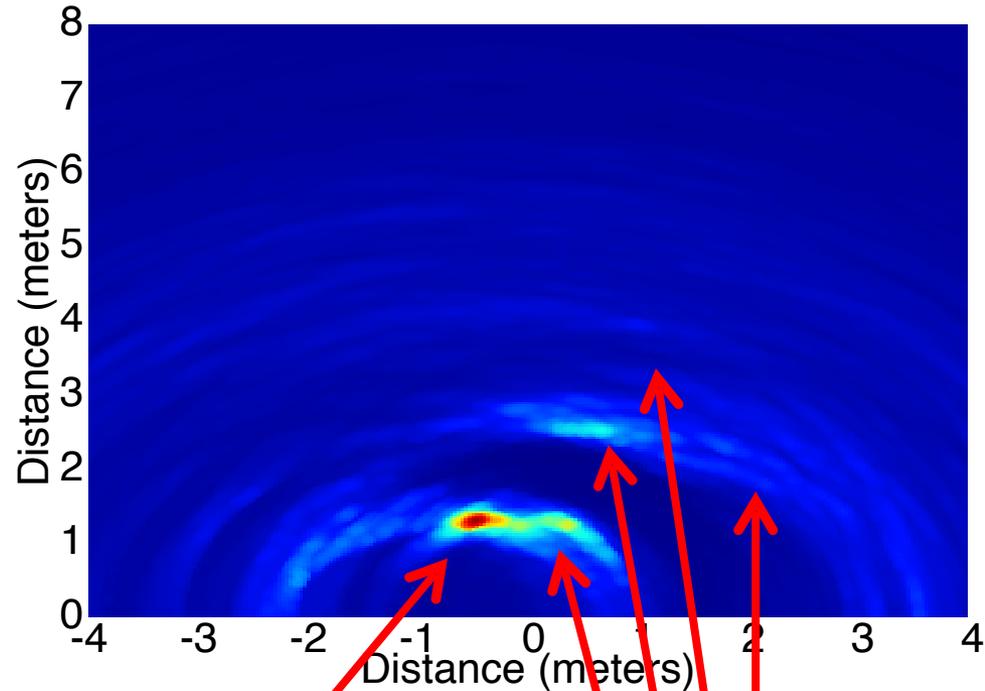
Near-Far Problem: Nearby persons have more power than distance reflectors and can mask them

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

Successive Silhouette Cancellation:

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

inspired by

Successive Interference Cancellation

iteratively decode interfering transmissions by addressing the near-far problem

Successive Interference Cancellation

Recover 0's and 1's

Decode 0's
and 1's

Subtract

Reconstruct
modulation &
coding

Deterministic

Successive Silhouette Cancellation

Recover human reflections

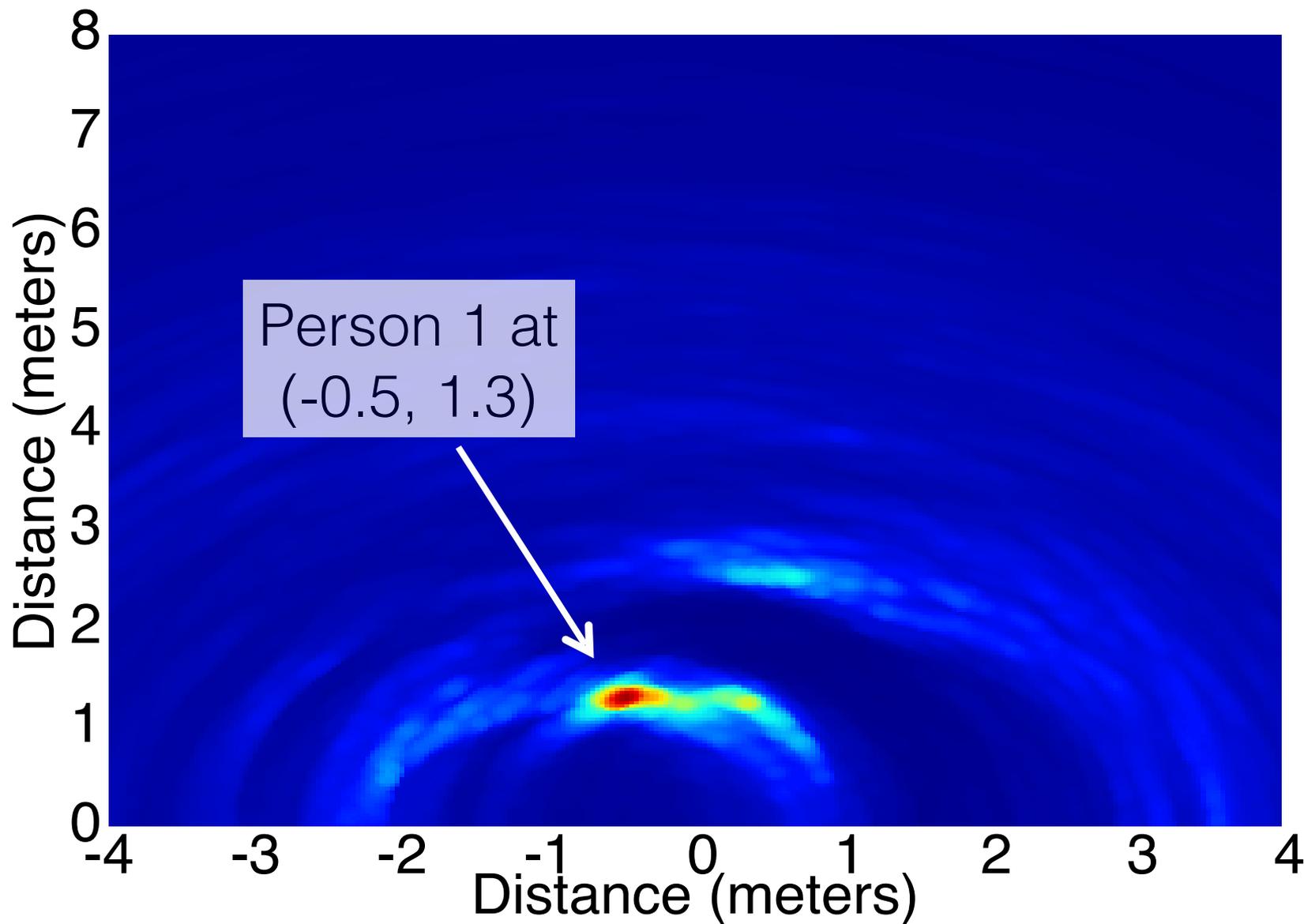
Decode human
location

Subtract

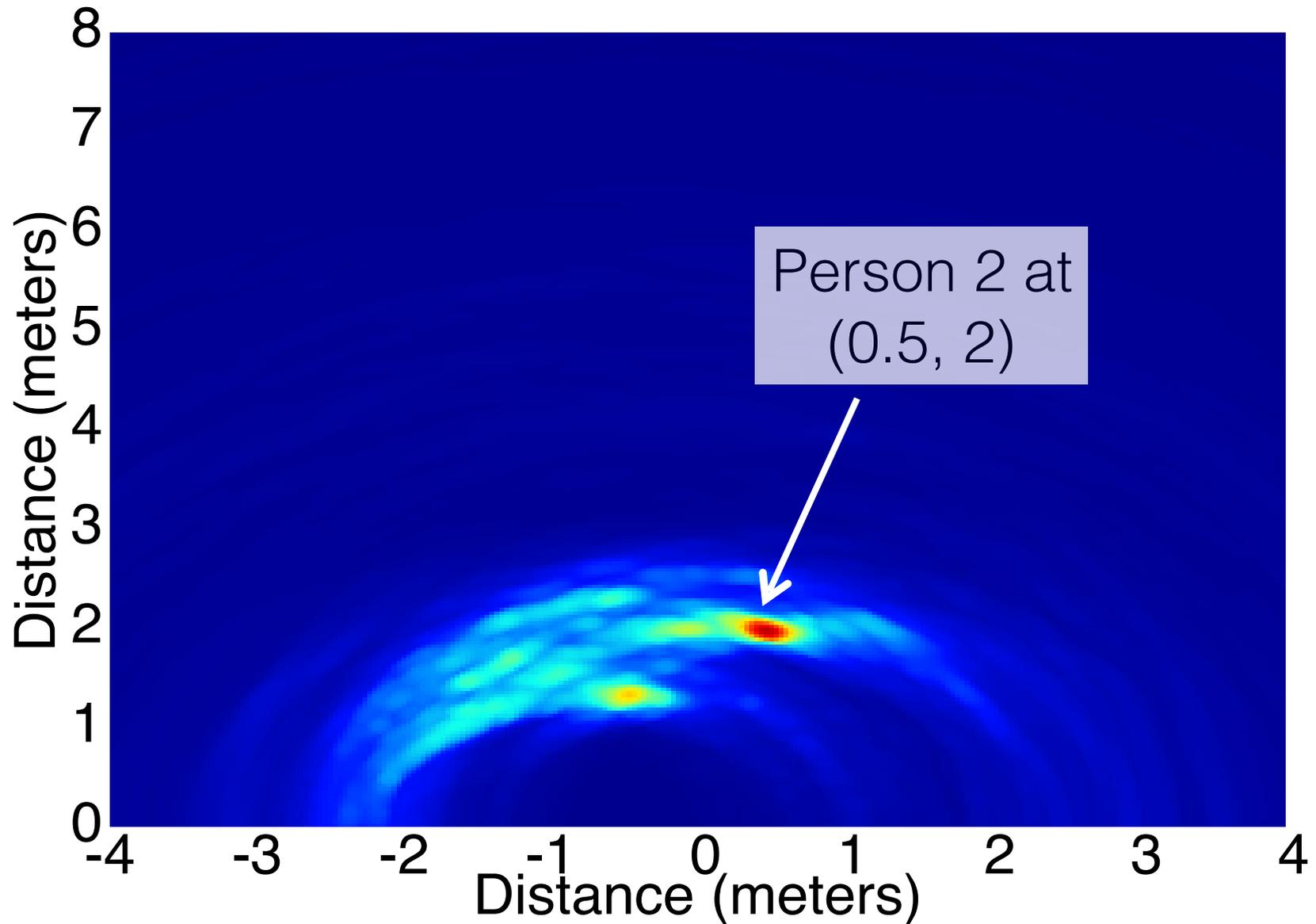
Model human and
reconstruct
reflection patterns

Stochastic

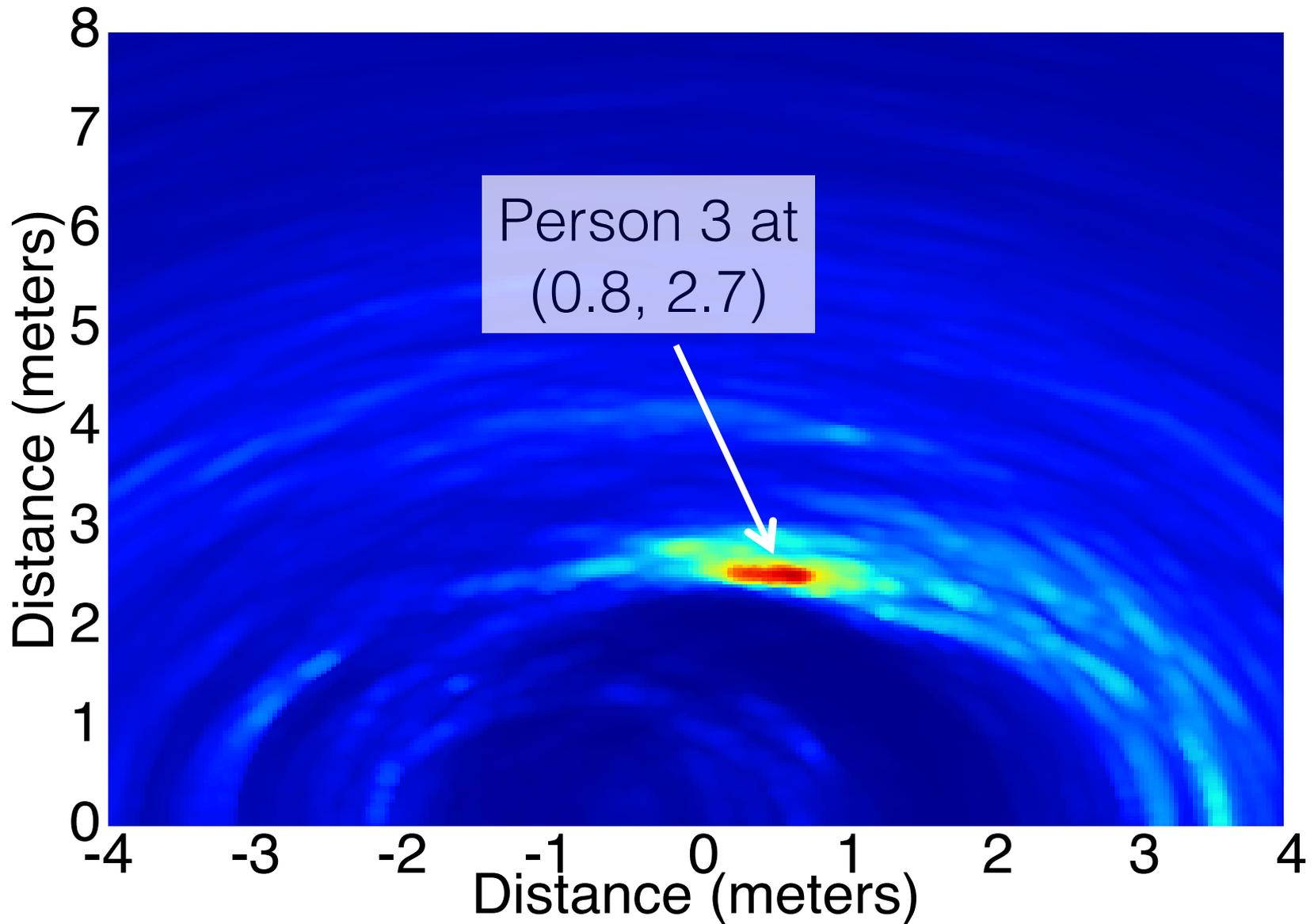
First localize the user with the strongest reflection



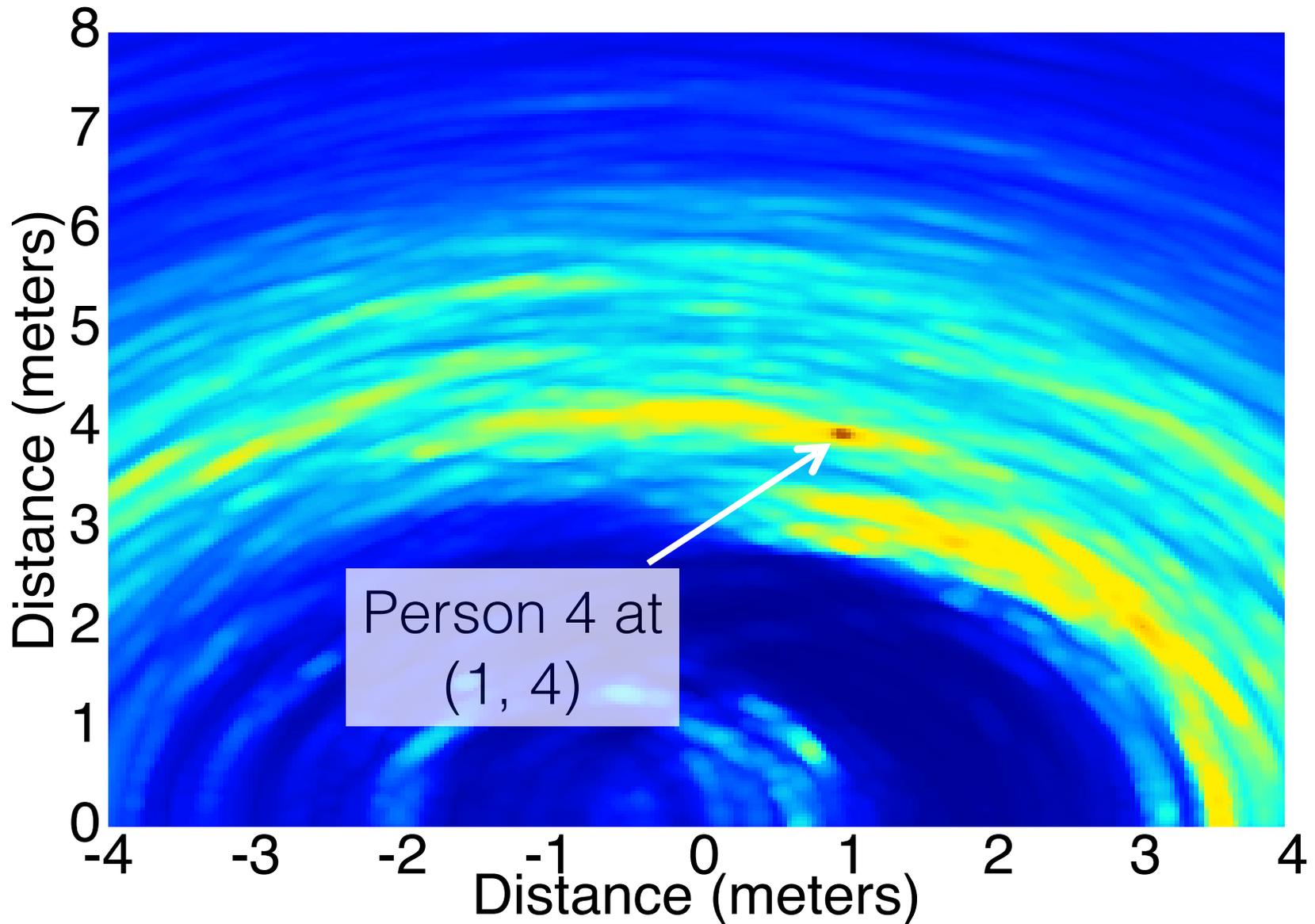
After reconstructing and cancelling the first user's reflections



Iteratively localize the remaining users in the scene

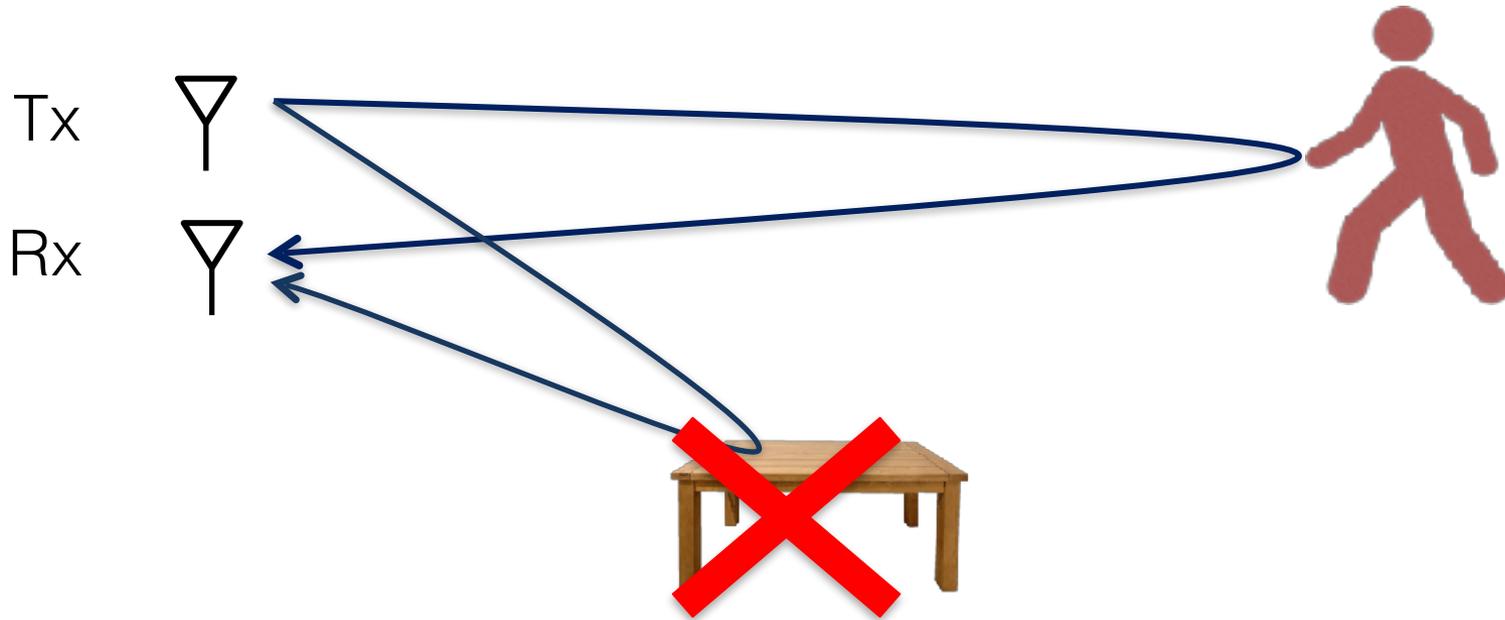


Iteratively localize the remaining users in the scene



How can we localize static users?

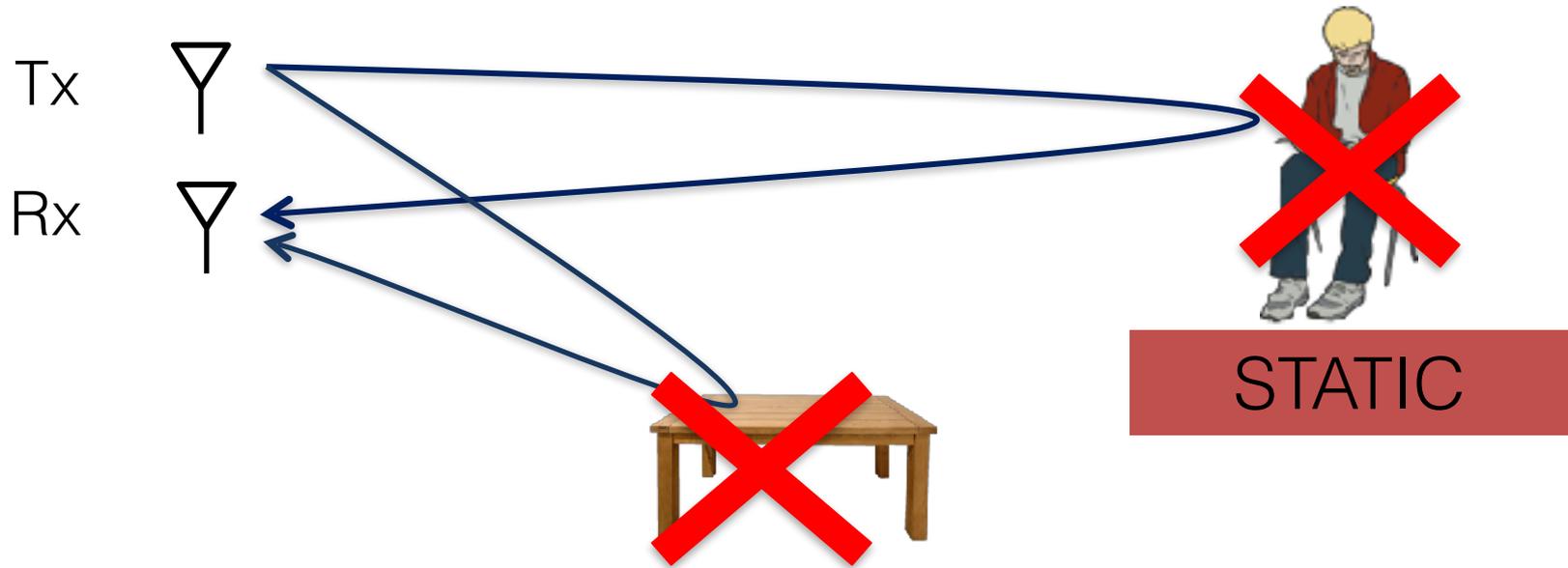
Dealing with multi-path when there is one moving user



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

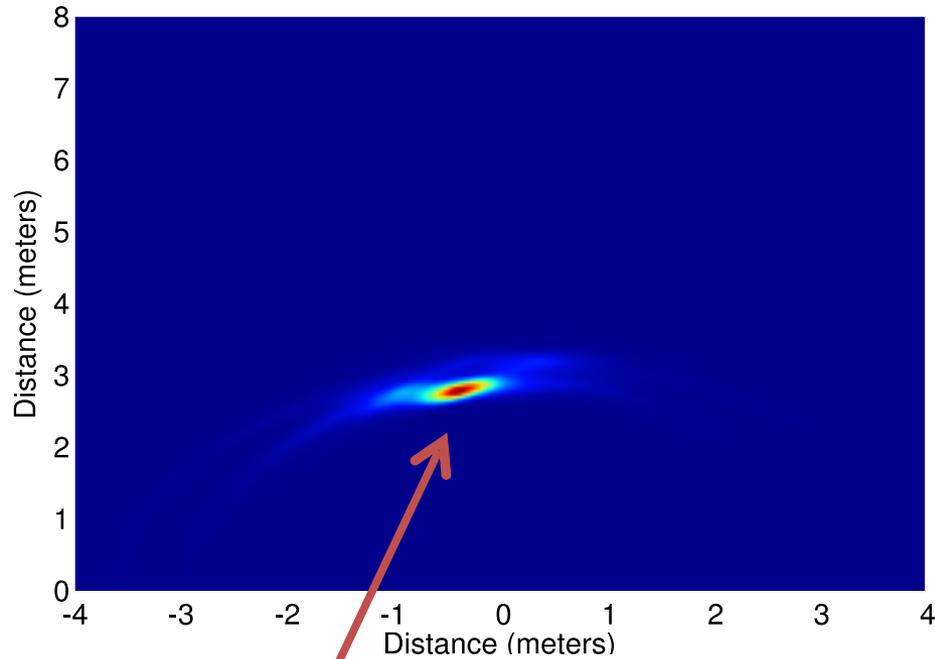
Needs User to Move

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

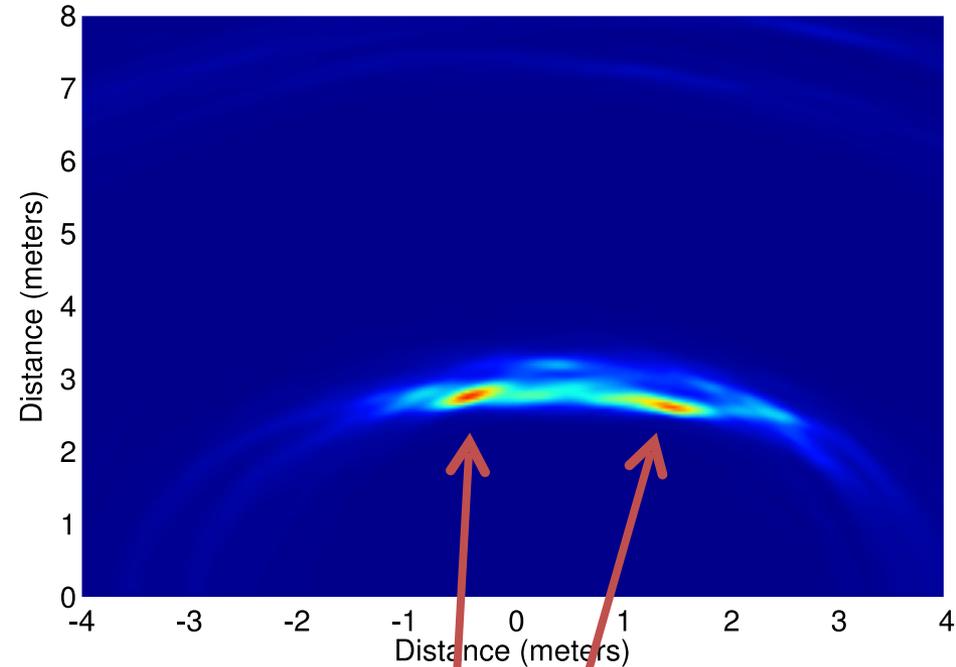
User Walking at 1m/s

30ms subtraction window



Localize the
person

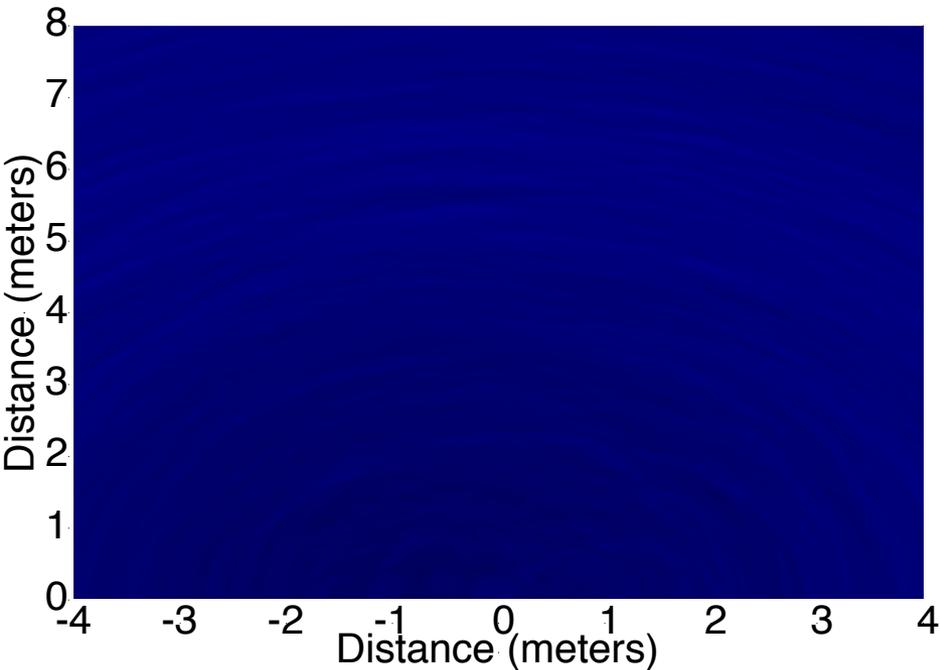
3s subtraction window



Person appears in two
locations

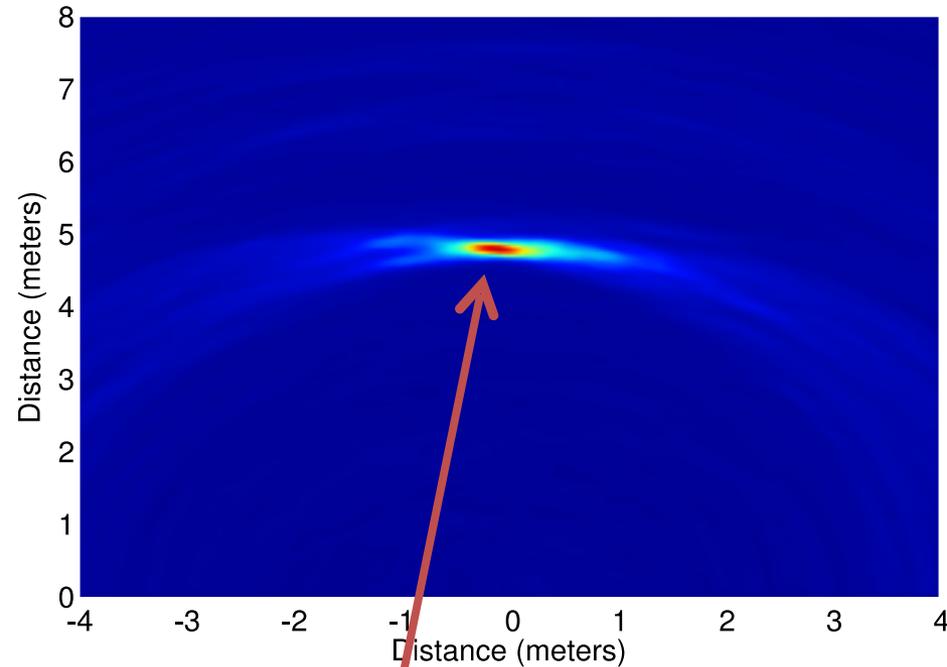
User Sitting Still (Breathing)

30ms subtraction window



Cannot localize

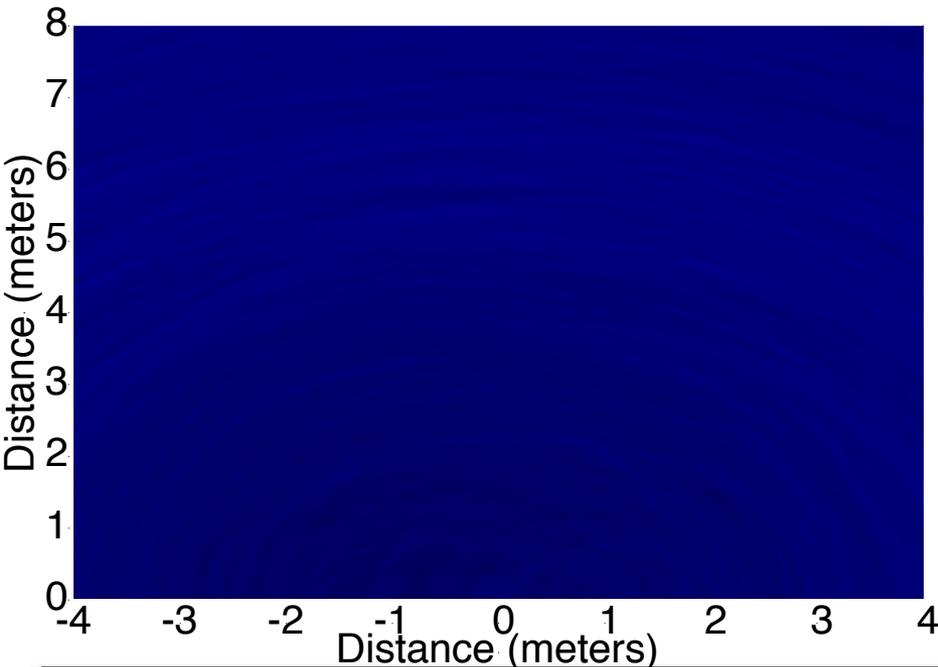
3s subtraction window



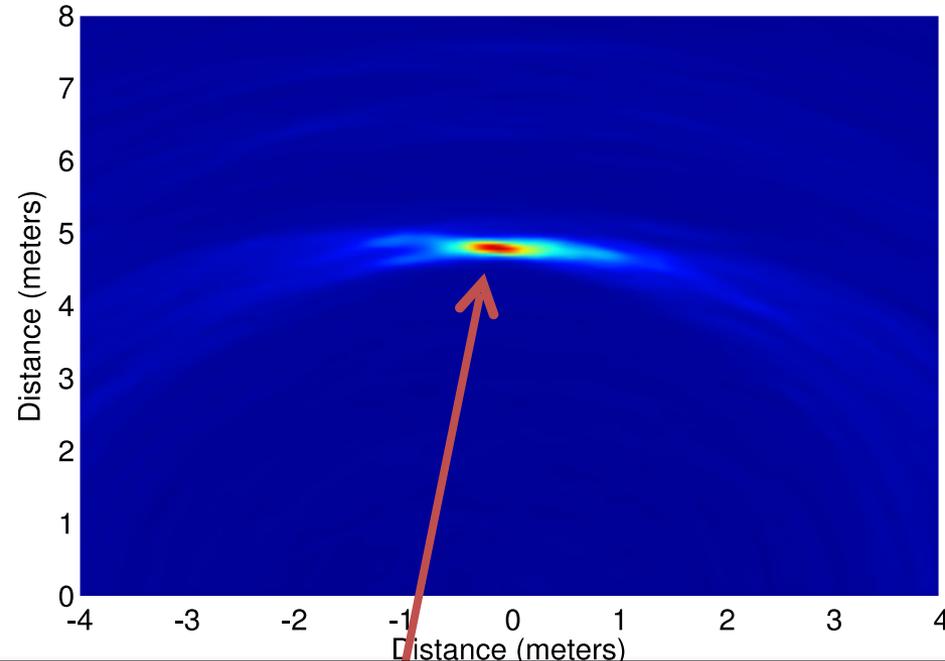
Localize the person

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

