Wireless Communication Systems
@CS.NCTU

Lecture 9: Localization

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Type of Approaches

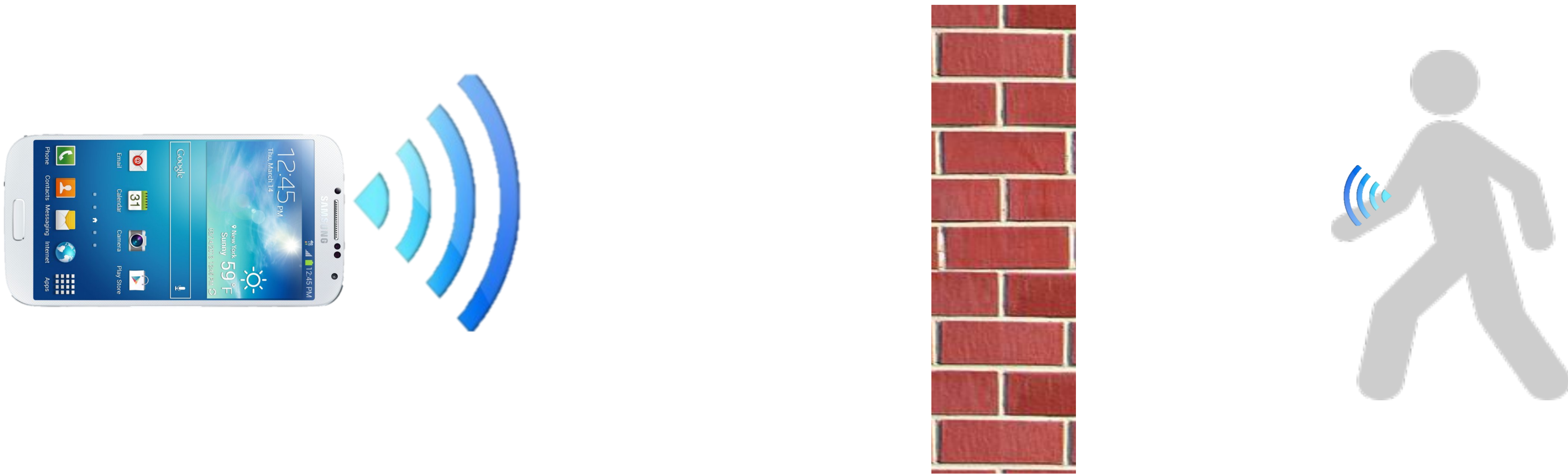
- RSSI-based
- Angle of Arrival (AoA)
- Time of Flight (ToF)
- Time Difference of Arrival (TDoA)

RF-based Localization

- See through walls
  - WiVi (SIGCOMM'13)
- ToF-based localization
  - WiTrack (NSDI'14, NSDI'15)
- AoA-based localization
  - ArrayTrack (NSDI'13)

Can you use WiFi to get X-ray vision?

Key Idea



Tracking people from **their reflections**

Challenges

Wall refection is 10,000x stronger than reflections coming from behind the wall

How to separate the person's reflections from the reflections of other objects?

WiVi [SIGCOMM'13]

- How to eliminate the wall's reflections?
  - Leverage multiple antennas to perform interference nulling
- How to track users using reflections?
  - Deem a mobile user as a **virtual antenna array** reflecting the signals

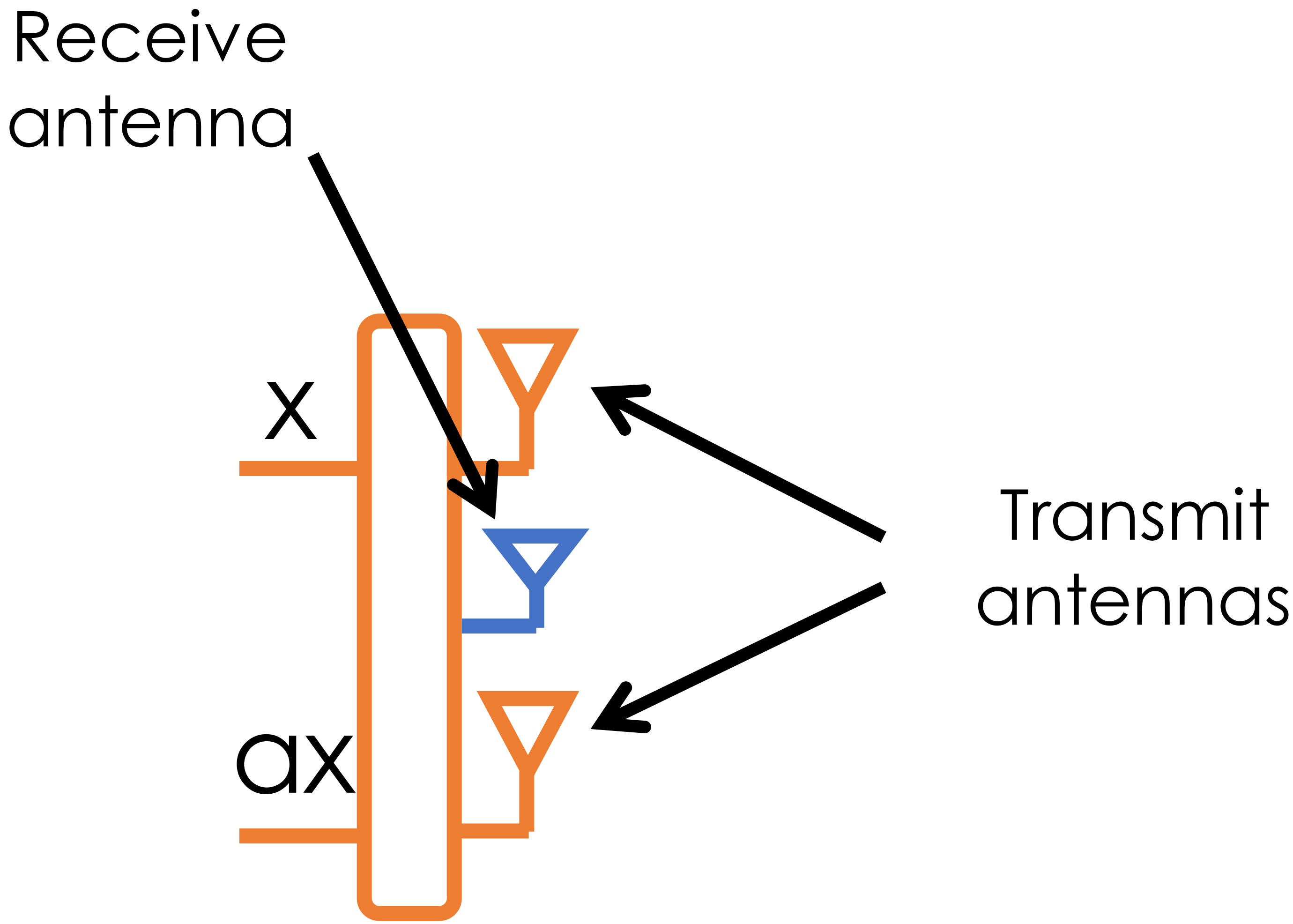
Eliminating Static Reflection

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

Wall is static → disappears

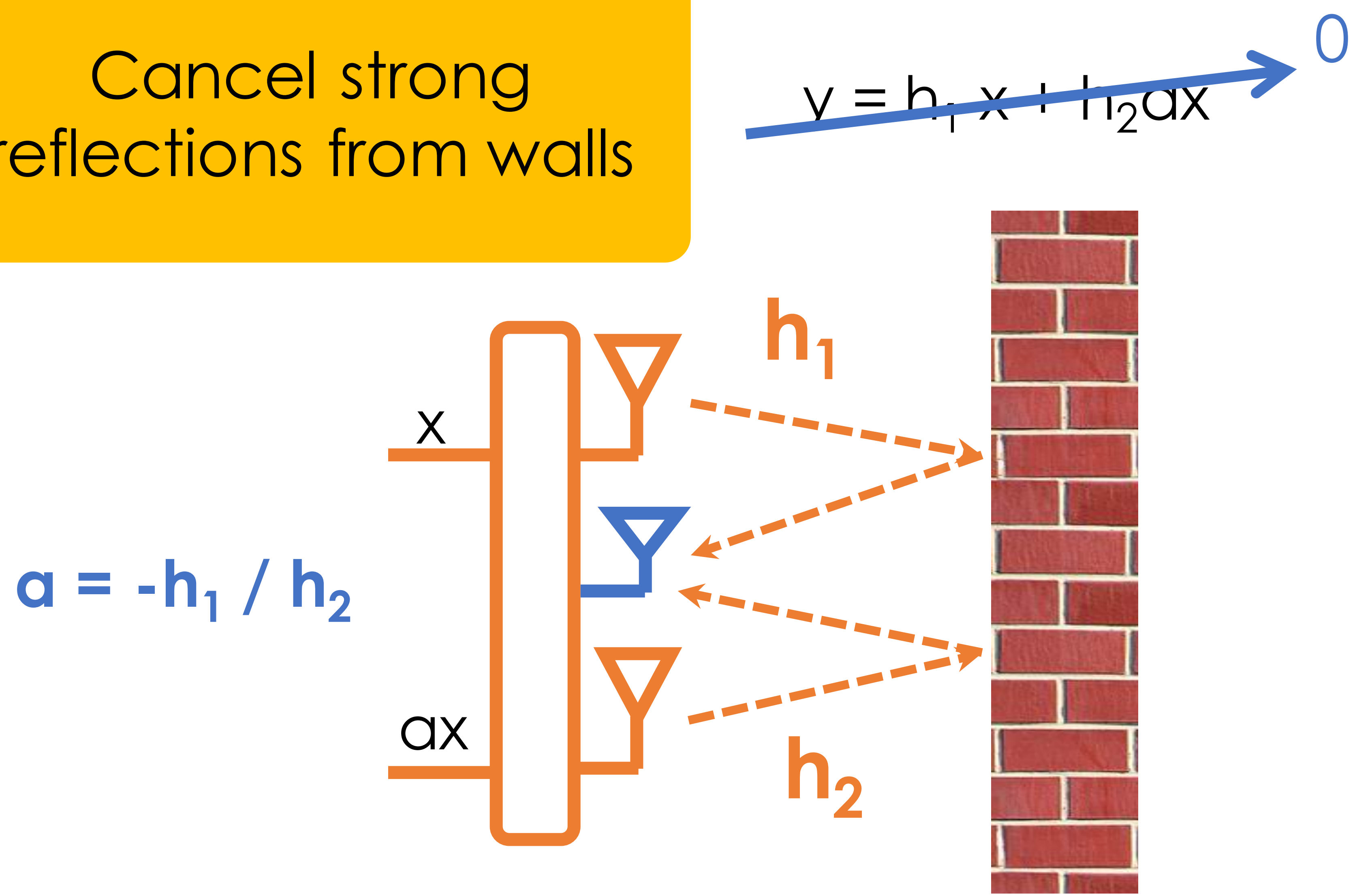
People tend to move → detectable

Eliminating via Multiple Antennas

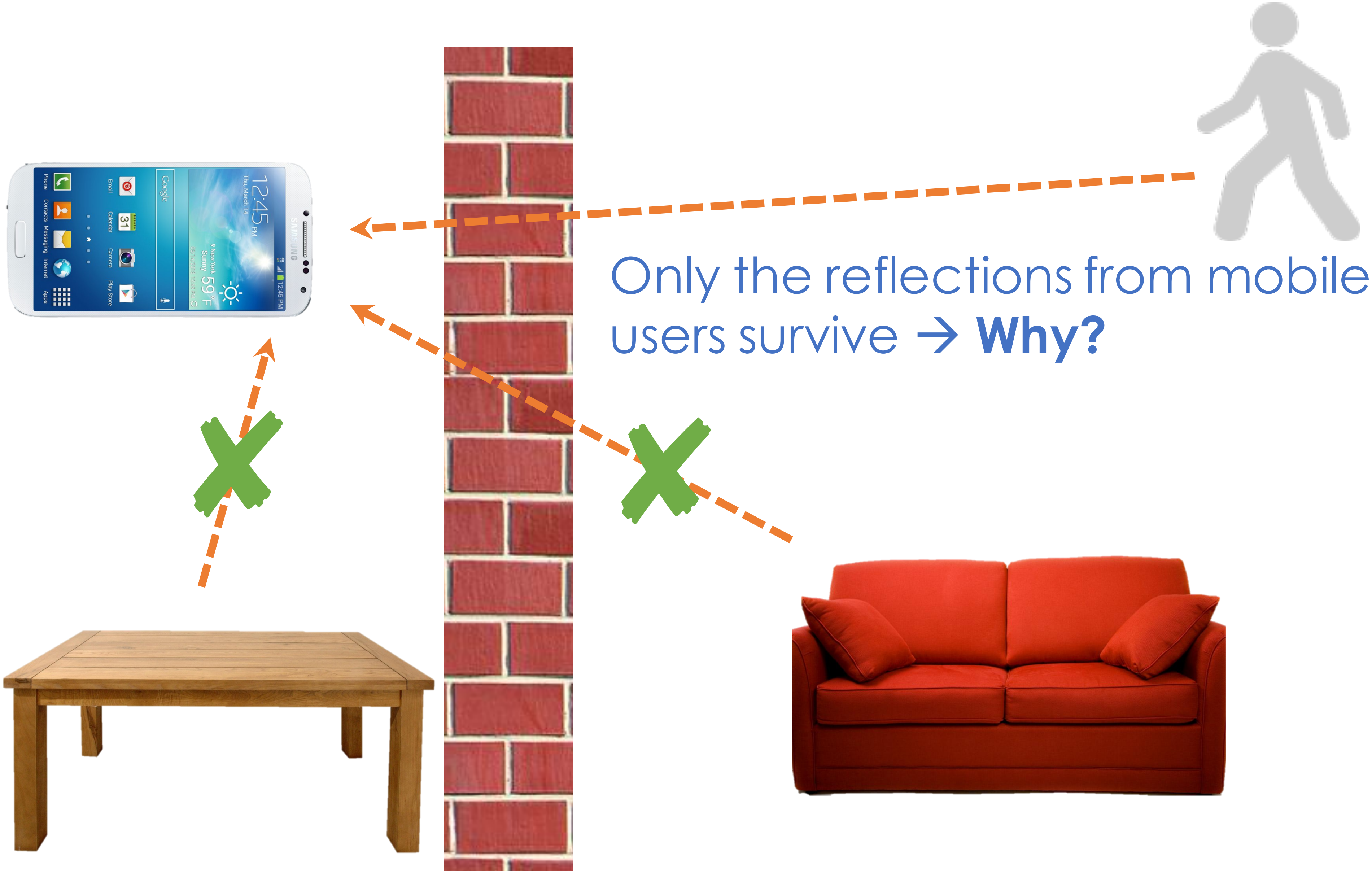


Eliminating via Multiple Antennas

Cancel strong reflections from walls

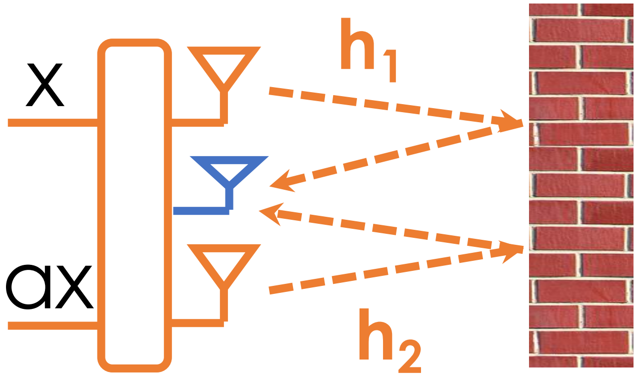


Eliminating All Static Reflections



Only the reflections from mobile users survive → **Why?**

Eliminating All Static Reflections



$$y = h_1\, x + h_2 a x$$

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

$$y = h_1\, x + h_2(- h_1 / h_2)x \rightarrow 0$$

People move, therefore their channels change

$$y = h'_1\, x + h'_2\,(- h_1 / h_2)x$$

Not Zero

WiVi [SIGCOMM'13]

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  - Leverage multiple antennas to perform interference nulling
- How to track users using reflections?
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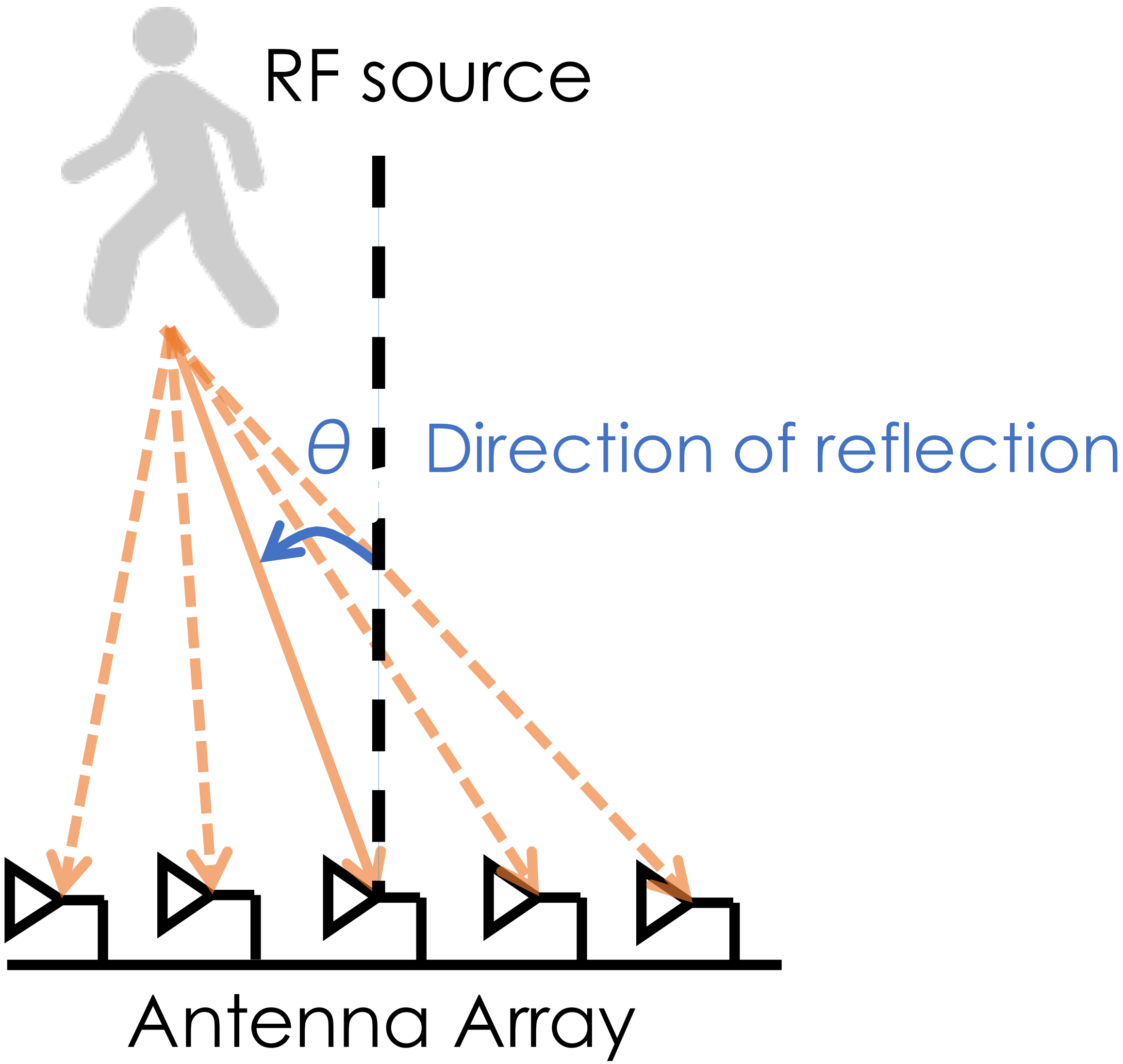
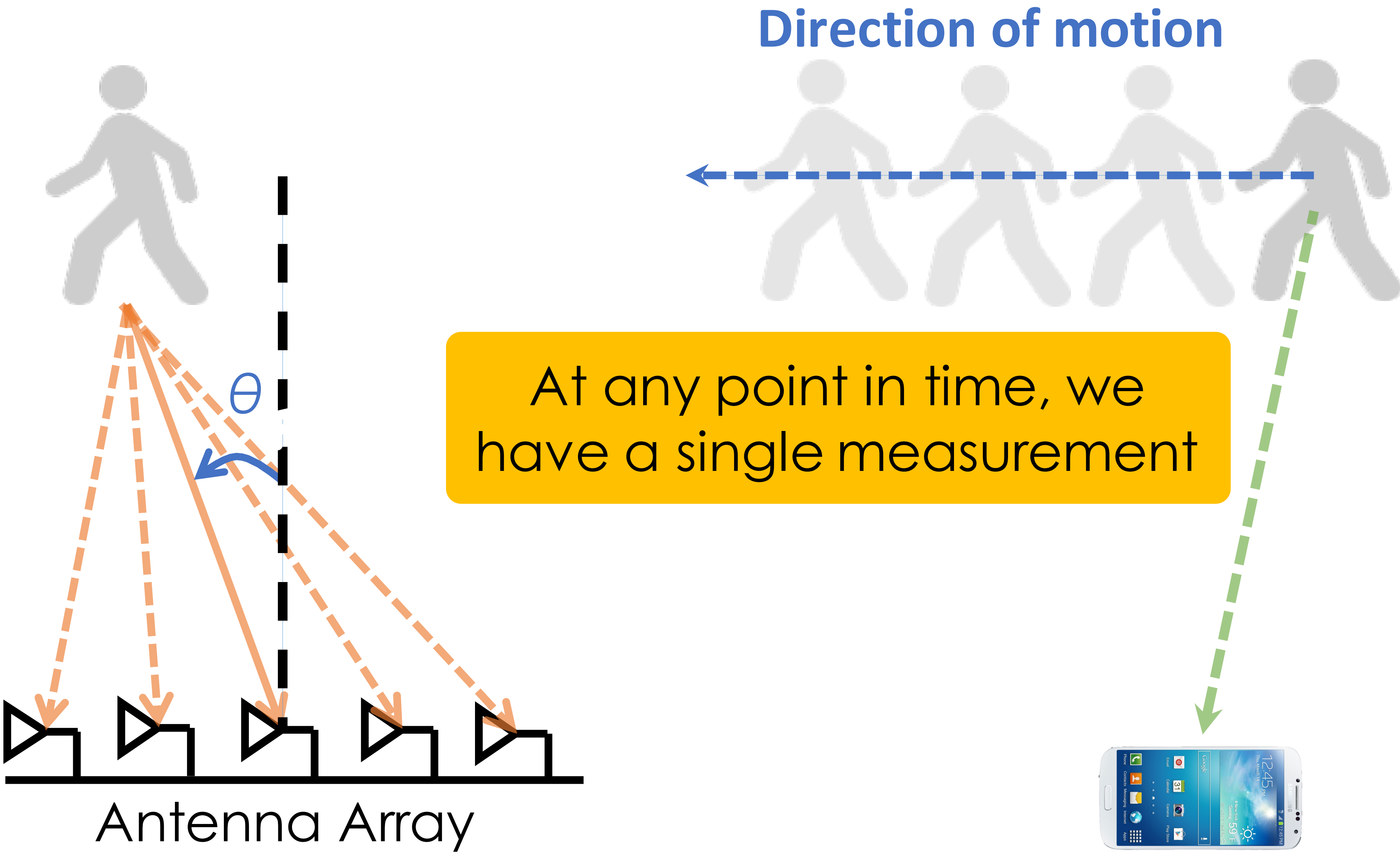
Tracking Motion

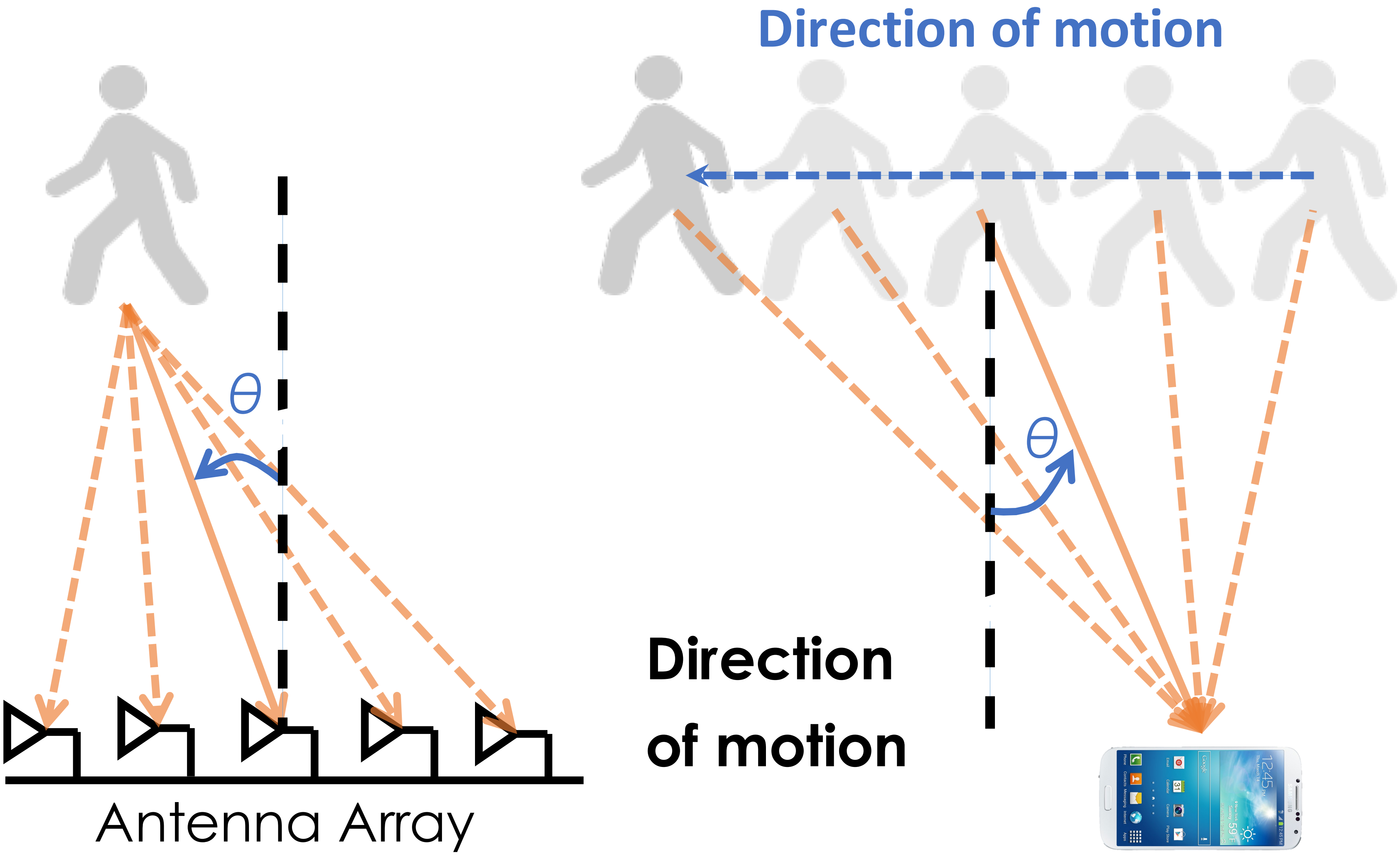


Tracking Motion

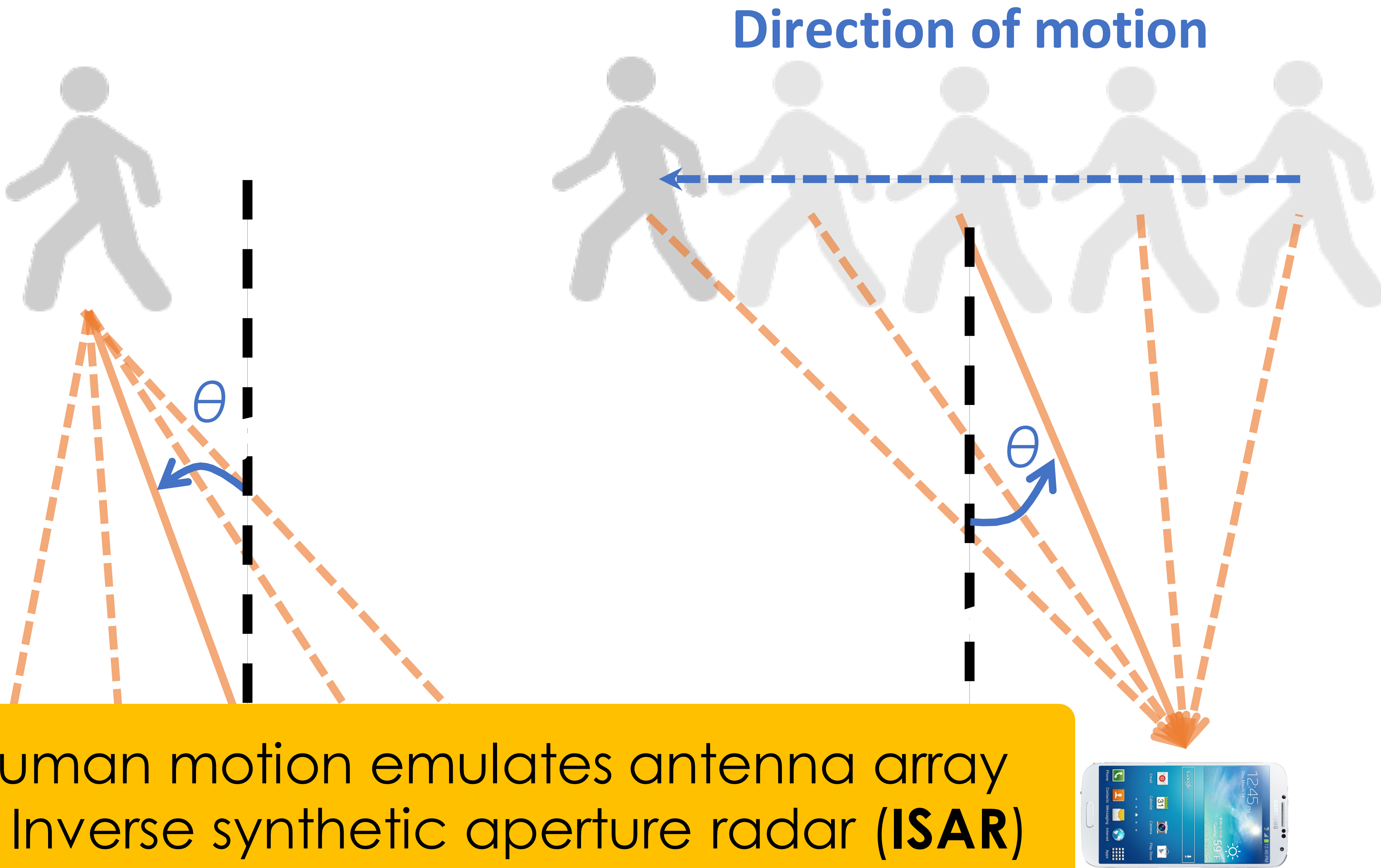


At any point in time, we have a single measurement

Tracking Motion



Tracking Motion



Human motion emulates antenna array
→ Inverse synthetic aperture radar (**ISAR**)

How to Calculate the Direction?

- Say we have w consecutive channel measures $h[n], \ldots, h[n+w]$ from time n to $(n + w)$
- The signal along the direction θ at time n is given by

$$A[\theta, n] = \sum_{i=1}^{w} h[n+i] e^{j \frac{2\pi}{\lambda} i \Delta \sin \theta}$$

spatial separation between successive antennas

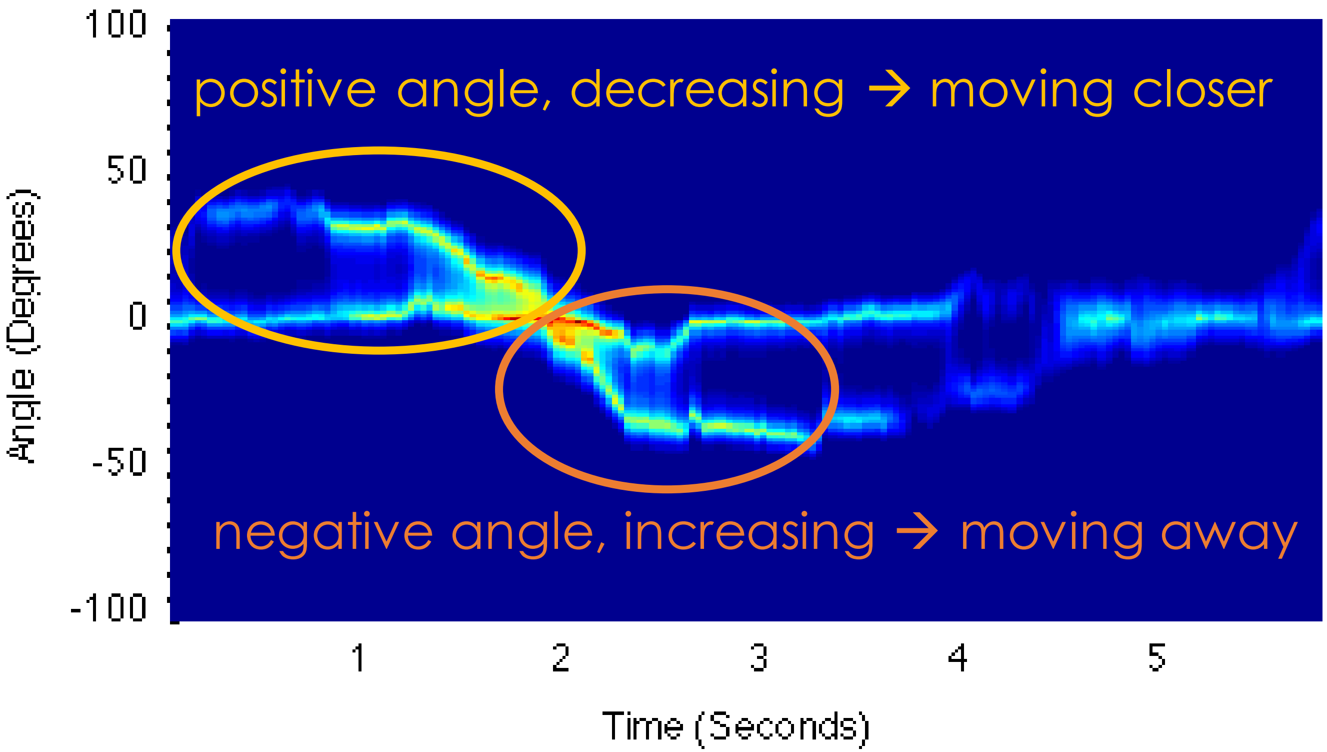
- The direction can be found by

$$\theta^* = \arg\max_{\theta} A[\theta, n]$$

How to get Δ given that user location is unknown?

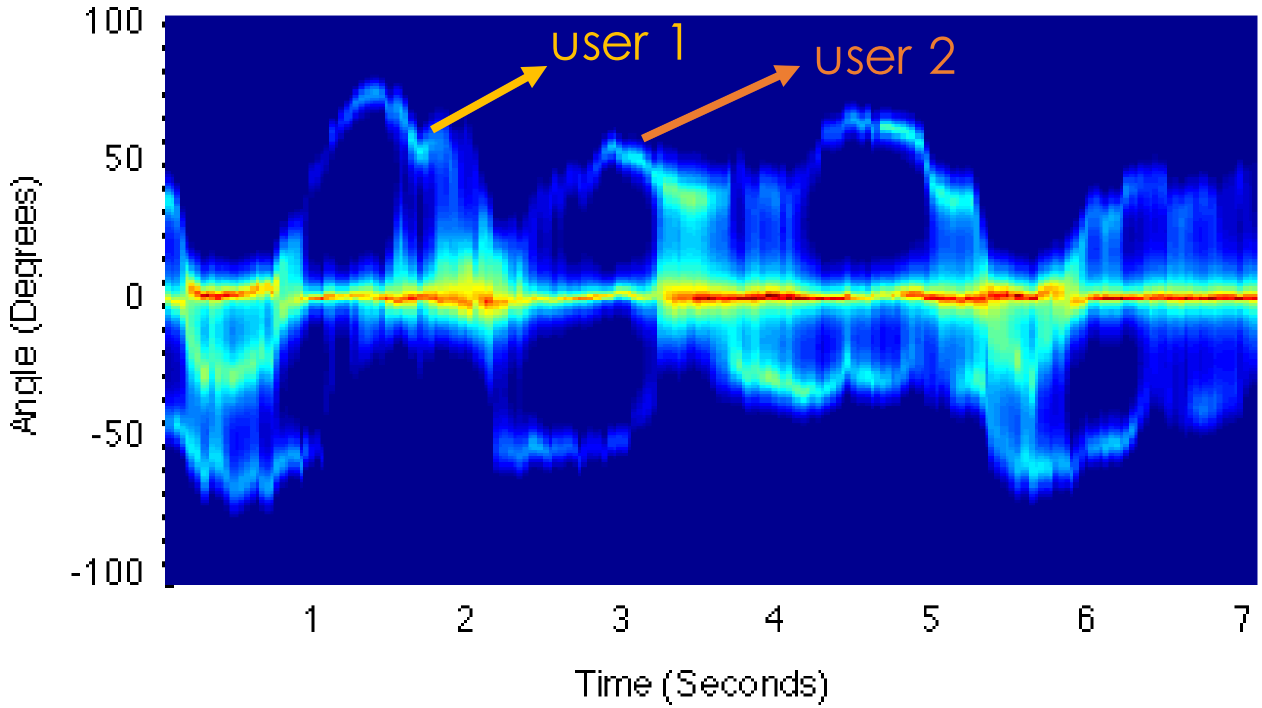
Tracking Users

- Rough estimation Δ = *vT*, where *v* is user mobility (~1m/s)
- WiVi only tracks users, instead of localizing them
  - Only need to know whether the user is moving closer or away from the device



Tracking Multiple Persons

- Human mobility is continuous!



RF-based Localization

- See through walls
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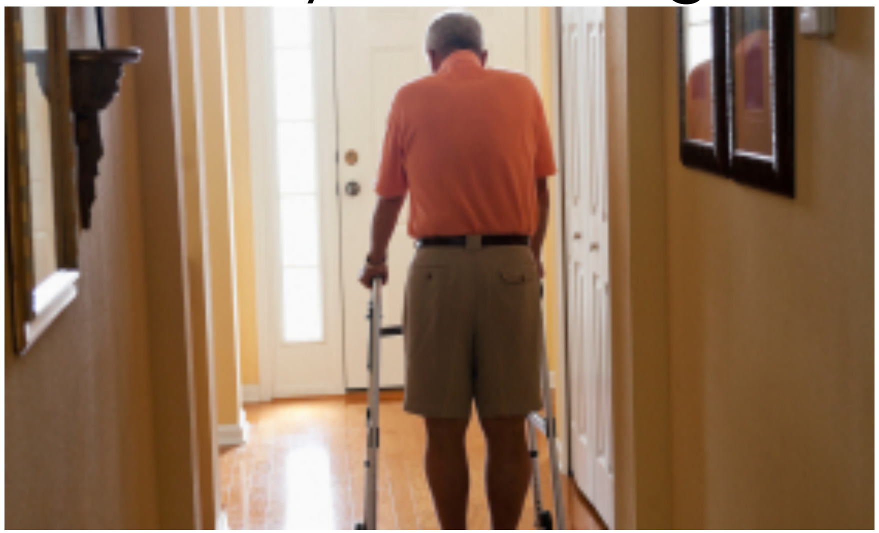
Applications

Gaming

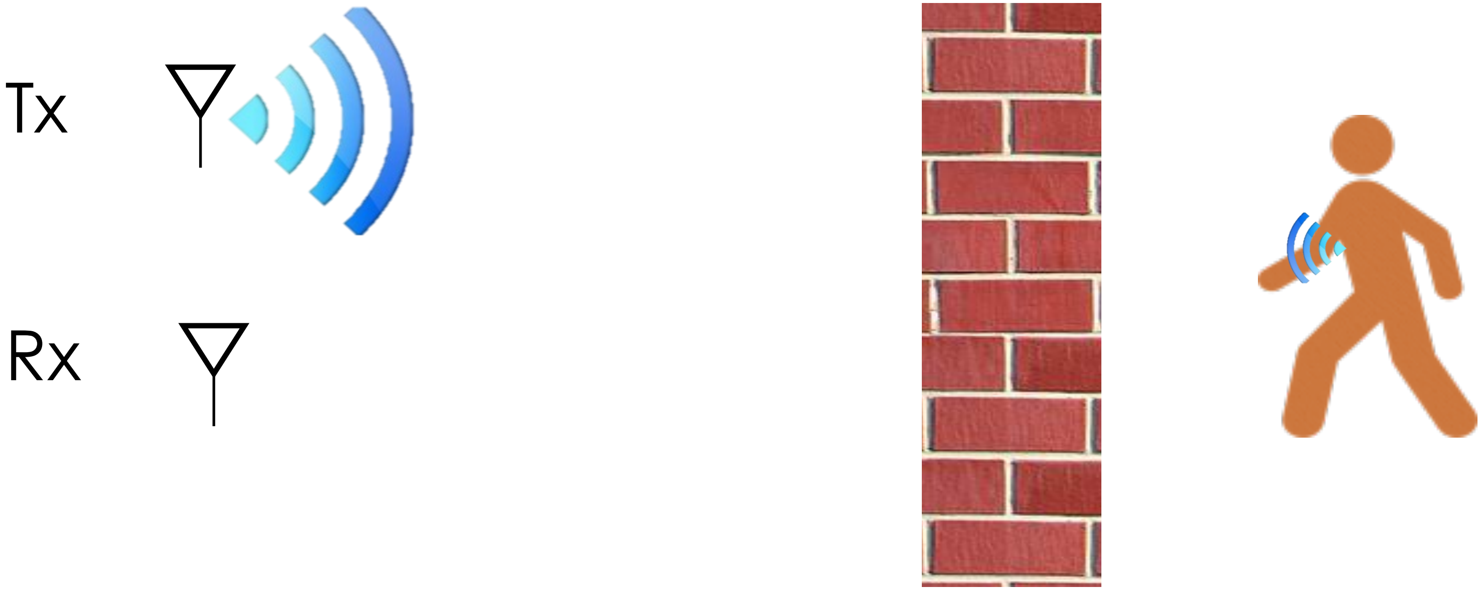
Gesture Control

First Responders

Elderly Monitoring



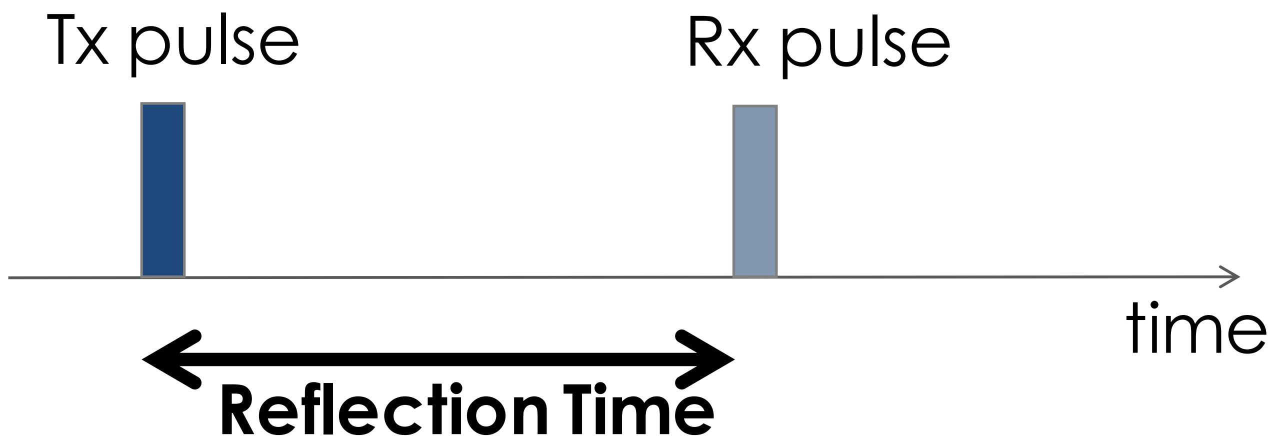
ToF-based Localization



Distance = Reflection time x Speed of light

How to Measure ToF?

Option1: Transmit short pulse and listen for echo



How to Measure ToF?

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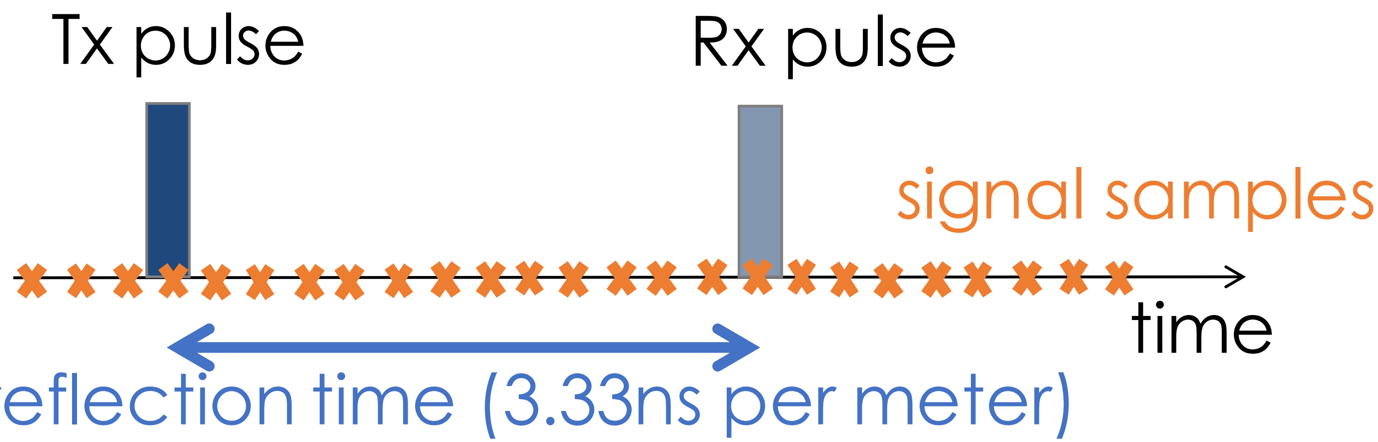
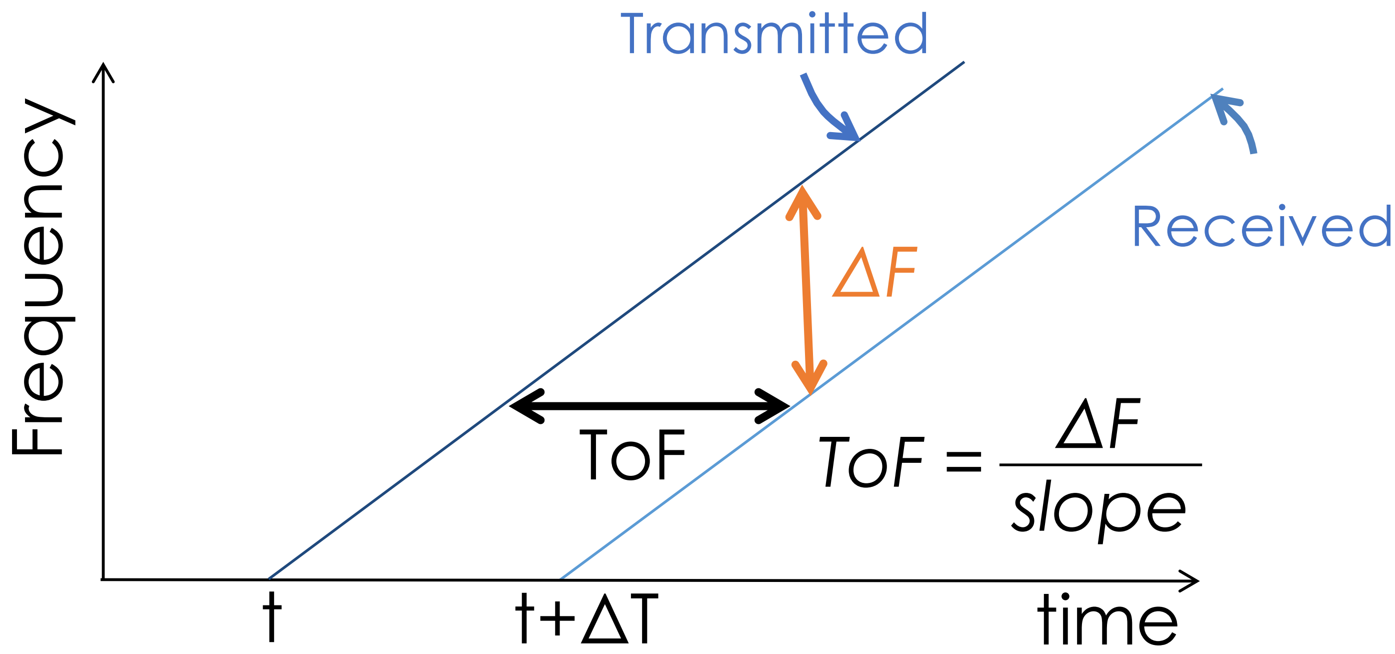


capturing the pulse needs sub-nanosecond sampling

Need multi-GHz samplers
→ expensive and with high noise

How to Measure ToF?

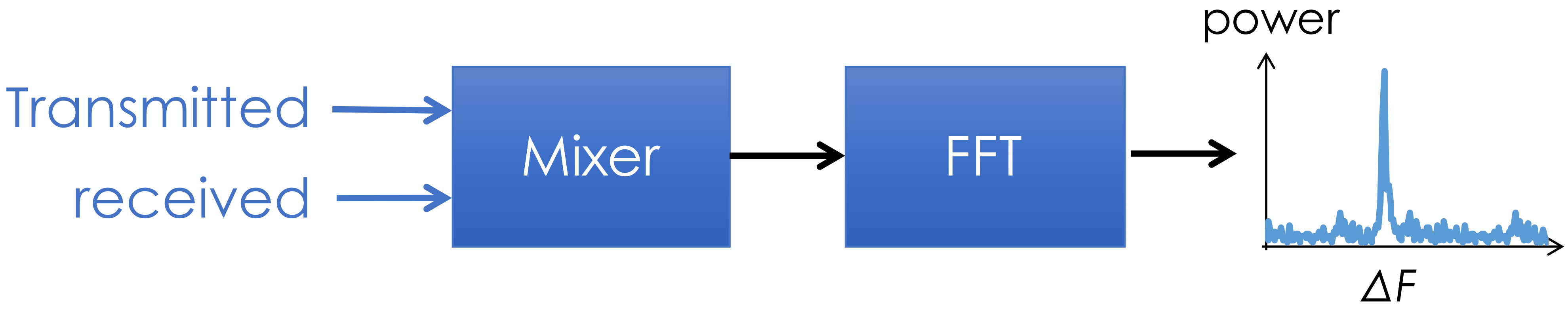
Option2: Frequency Modulated Carrier Wave (FMCW)



How to measure ***ΔF***?

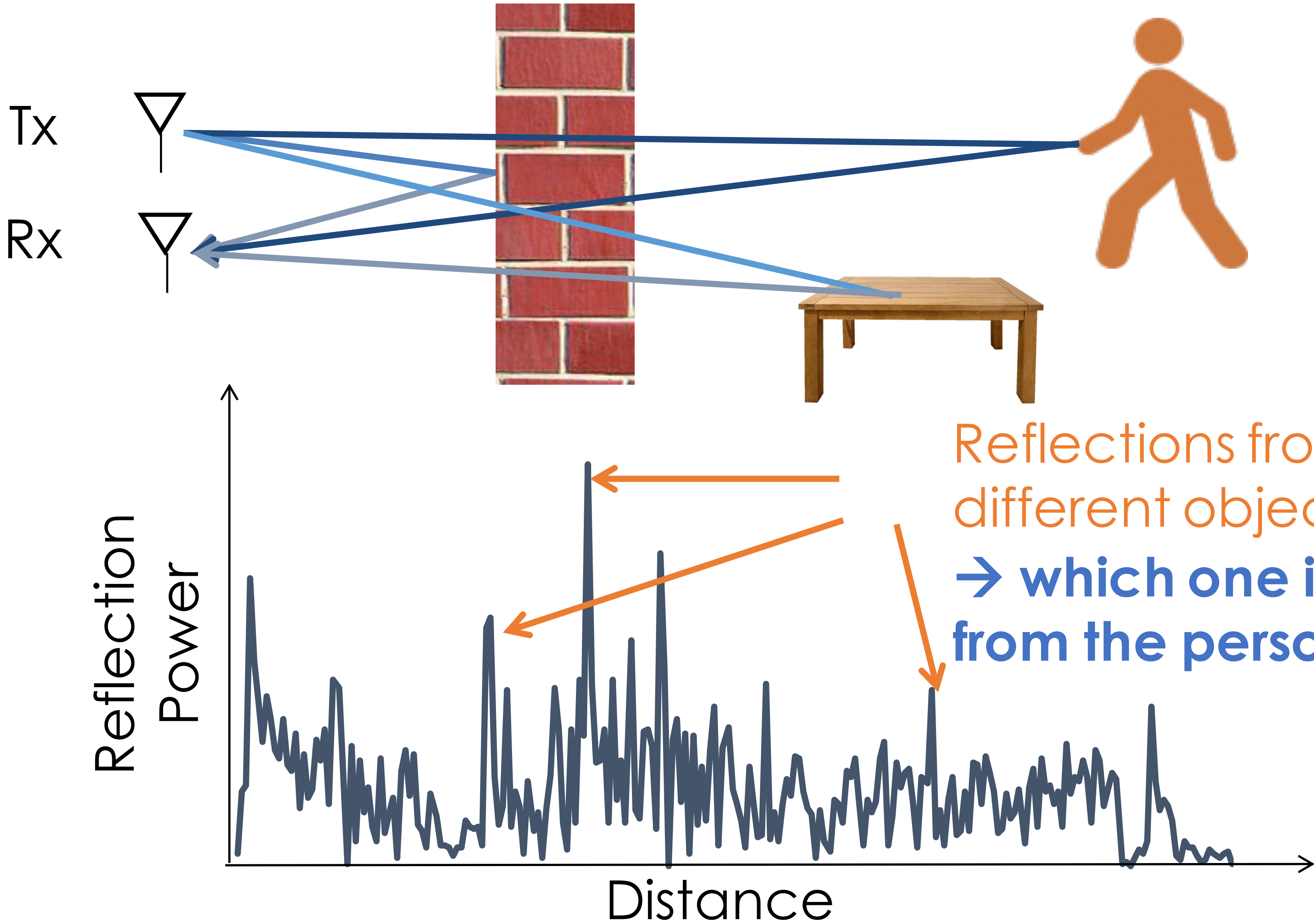
Measuring ΔF

- To find $\Delta F = f_{Rx} - f_{Tx}$,
  1. Use mixer to subtract f_{Tx} from the received signal → the signal whose frequency is ΔF
  2. Take FFT and identify the frequency with peak power



ΔF → Reflection Time → Distance

How to Deal with Multiple Reflections?

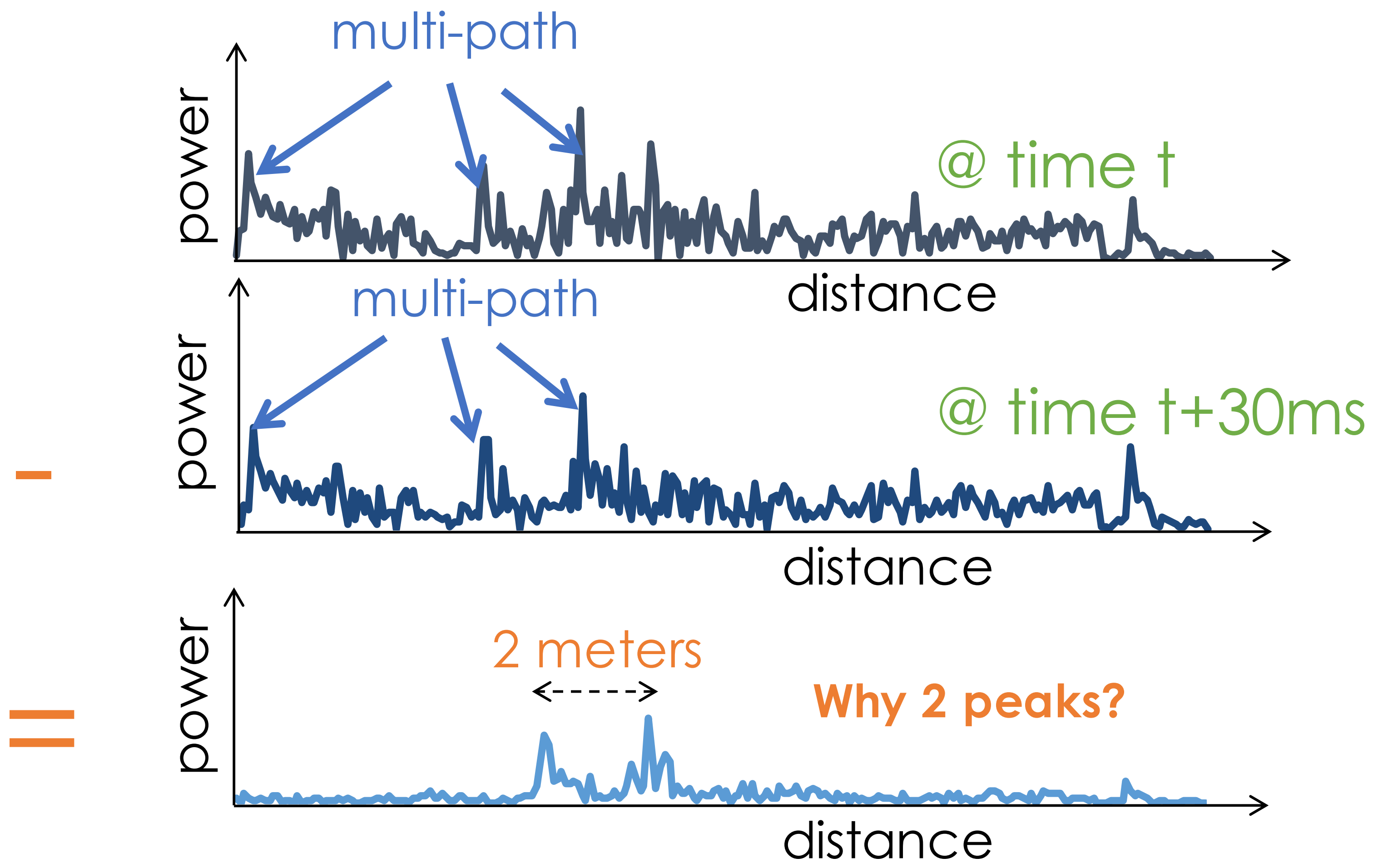


Reflections from different objects

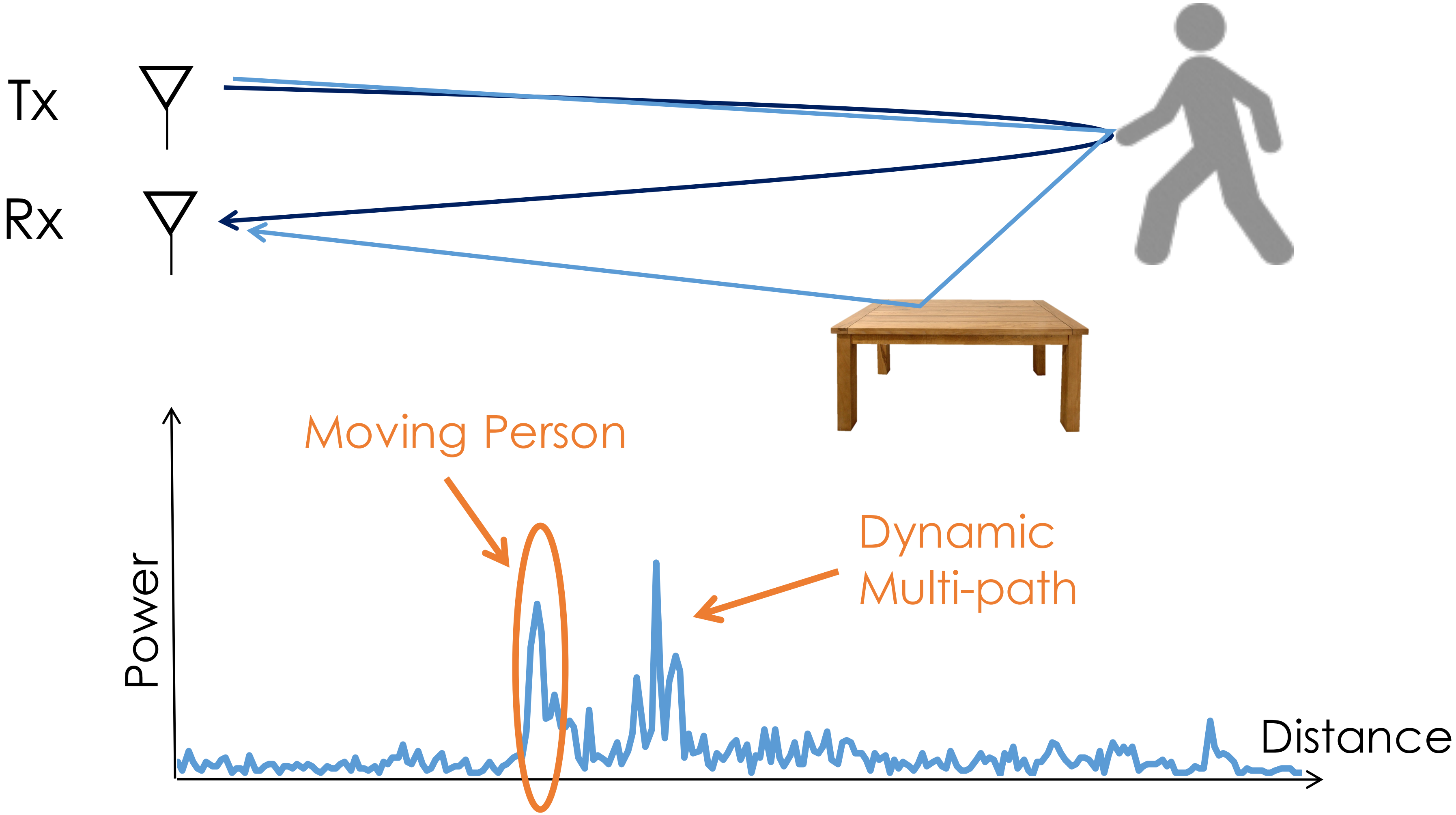
→ **which one is from the person?**

Subtract Static Paths

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



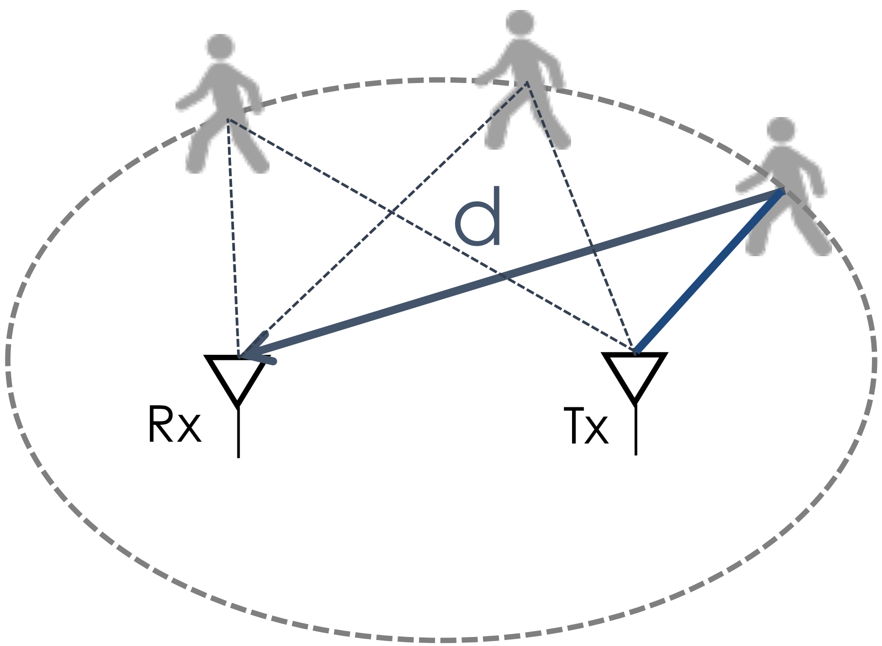
Dynamic Multipath



Find the first peak since the direct reflection arrives before other dynamic multipaths

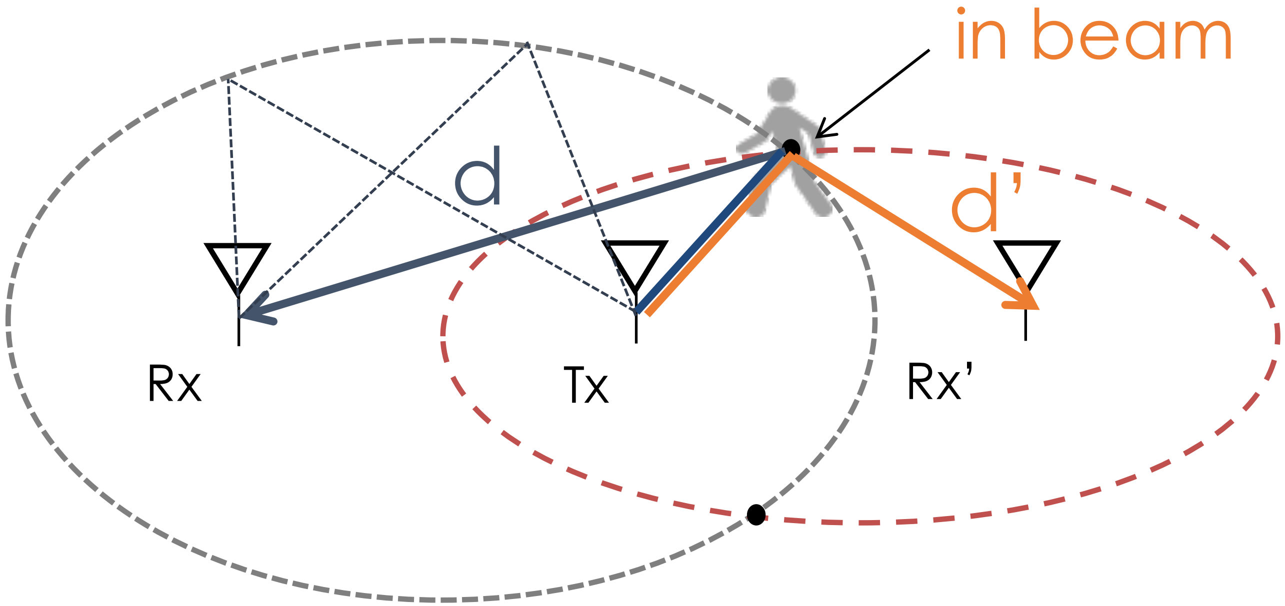
From Distances to Localization

- Person can be anywhere on an ellipse whose foci are (Tx,Rx)
- One ellipse is not enough to localize!



From Distances to Localization

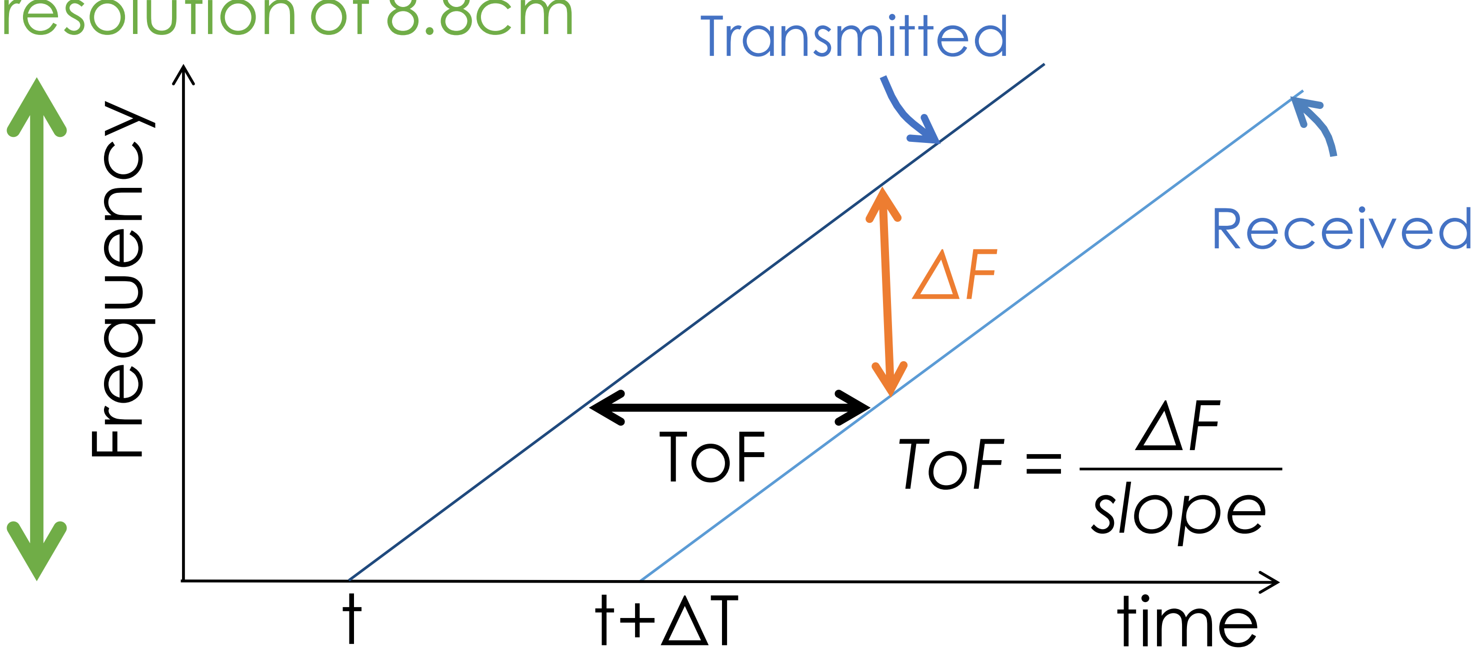
- Use two Rx antennas to find the intersection
- WiTrack uses directional antennas so only one point is in-beam
- Extend to 3D by using 3 Rx antennas and taking the intersection of ellipsoids



Key Issue of FMCW

- Don't need a high sampling rate
- But, need a very wide band channel

Bandwidth of 1.69GHz to support a distance resolution of 8.8cm



Cannot be applied in the unlicensed WiFi band

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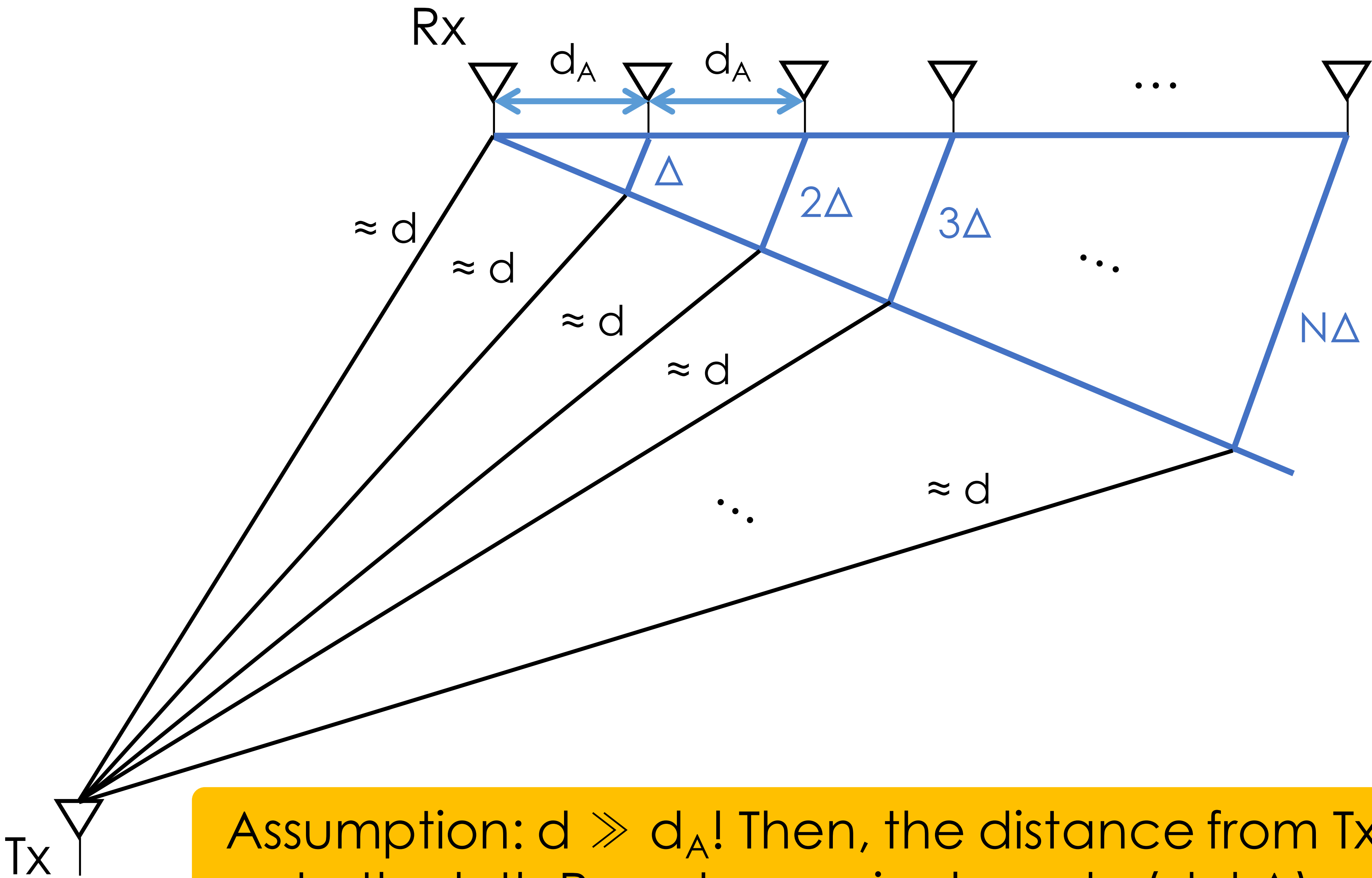
Angle of Arrival

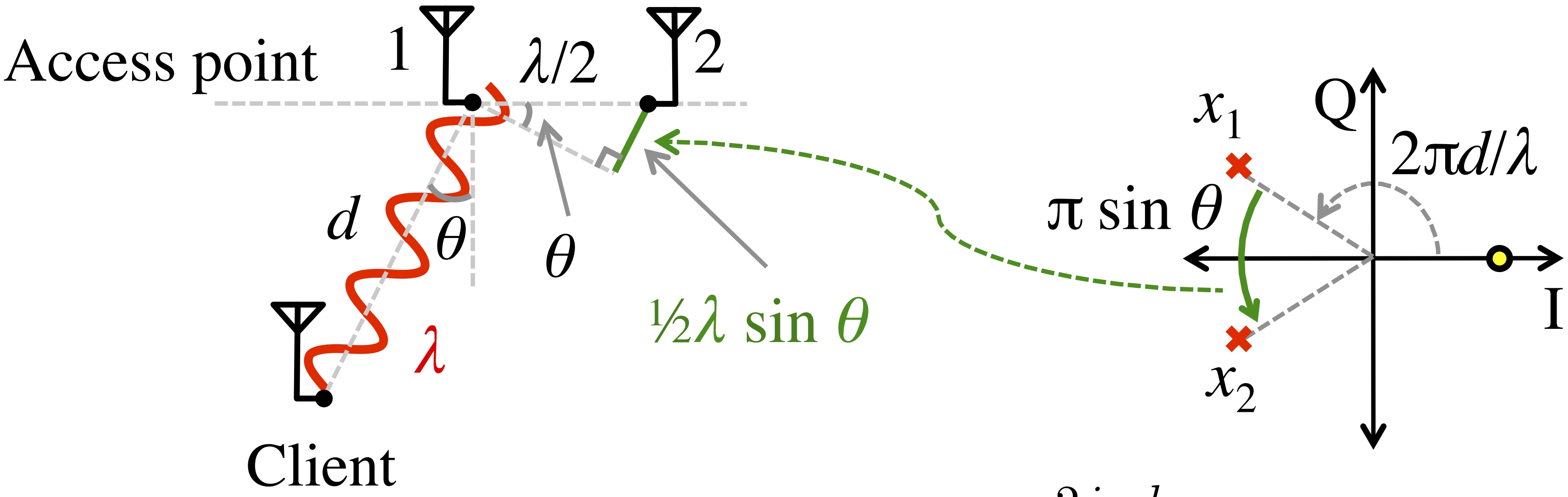
- Determine the direction of propagation of a radio-frequency wave using an antenna array
- Key idea:
  - The phase of the received signal is determined by the length of a path
  - The path lengths to different elements of an antenna array vary slightly
  - Leverage TDOA (time difference of arrival) at individual elements of the array to measure AoA

Time Difference of Arrival



Assumption: $d \gg d_A$! Then, the distance from Tx to the k-th Rx antennas is close do $(d+k\Delta)$

Time Difference of Arrival



Signal received at 1st antenna: $$\exp(\frac{-2j\pi d}{\lambda})$$

Signal received at 2nd antenna: $$\exp(\frac{-2j\pi(d+\Delta)}{\lambda})$$

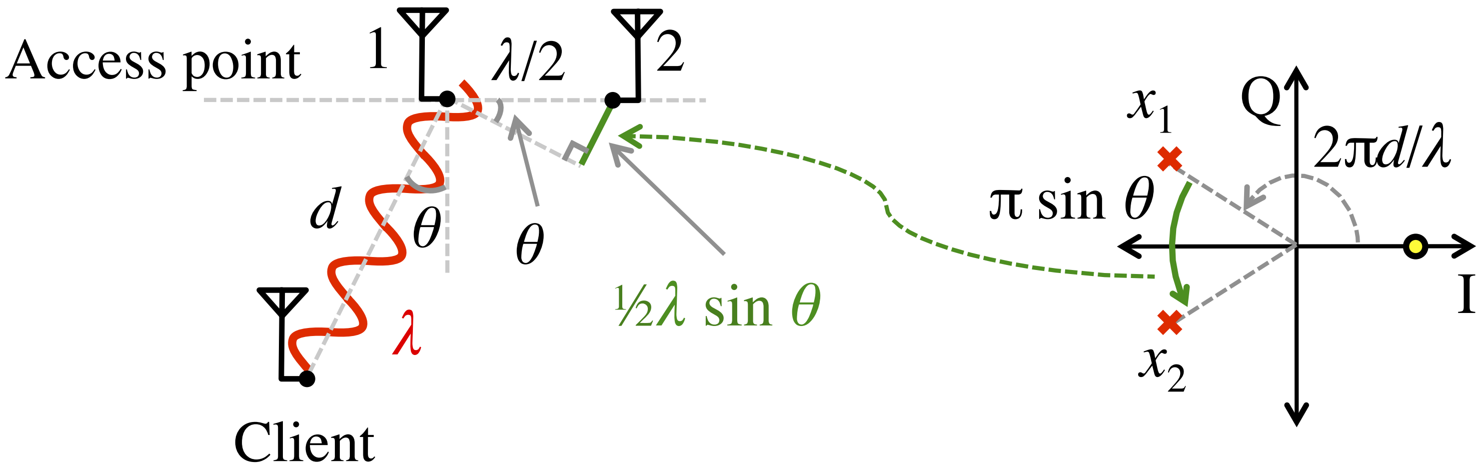
$$= \exp(\frac{-2j\pi d}{\lambda})\exp(\frac{-2j\pi\Delta}{\lambda})$$

⋮

Signal received at Nth antenna: $$\exp(\frac{-2j\pi(d+N\Delta)}{\lambda})$$

$$= \exp(\frac{-2j\pi d}{\lambda})\exp(\frac{-2j\pi N\Delta}{\lambda})$$

Time Difference of Arrival



Signal from angle θ: $$a(\theta) = \exp(\frac{-j2\pi d}{\lambda}) \begin{bmatrix} 1 \\ \exp(-j\pi \sin\theta) \\ \exp(-j\pi 2 \sin\theta) \\ \vdots \\ \exp(-j\pi(N-1)\sin\theta) \end{bmatrix}$$

Combined Signals from D paths

- If the Rx receives signals from D different paths

Final received signal: $$\mathbf{x}(t) = [\mathbf{a}(\theta_1)\ \mathbf{a}(\theta_2)\ \cdots\ \mathbf{a}(\theta_D)] \begin{bmatrix} s_1(t) \\ s_2(t) \\ \vdots \\ s_D(t) \end{bmatrix} + n$$

$$x(t) = e^{\frac{-j2\pi d}{\lambda}} \begin{bmatrix} 1 & 1 & \cdots \\ e^{-j\pi \sin\theta_1} & \cdots & e^{-j\pi \sin\theta_D} \\ e^{-j\pi 2 \sin\theta_1} & \cdots & e^{-j\pi 2 \sin\theta_D} \\ \vdots & \ddots & \cdots \\ e^{-j\pi (N-1) \sin\theta_1} & \cdots & e^{-j\pi (N-1) \sin\theta_D} \end{bmatrix} \begin{bmatrix} s_1(t) \\ s_2(t) \\ \vdots \\ s_D(t) \end{bmatrix} + n$$

MUSIC Algorithm

- MUltiple SIgnal Classification (MUSIC)
- Find the direction of the LOS path from

$$\mathbf{x}(t) = [\mathbf{a}(\theta_1)\ \mathbf{a}(\theta_2)\ \cdots\ \mathbf{a}(\theta_D)] \begin{bmatrix} s_1(t) \\ s_2(t) \\ \vdots \\ s_D(t) \end{bmatrix} + n$$

- High level idea:
  - We collect *N* received signals (*N* equations)
  - Assume there exist only *D* paths, *D* ≤ *N*, (*D* unknowns)
  - Use linear algebra to find the *D* components from *N* measures

MUSIC Algorithm

- Find the N x N source correlation matrix

$$\mathbf{R_{xx}} = \mathbb{E}[\mathbf{xx}^*]$$
$$= \mathbb{E}\left[(\mathbf{As}+\mathbf{n})(\mathbf{s}^*\mathbf{A}^* + \mathbf{n}^*)\right]$$
$$= \mathbf{A}\mathbb{E}\left[\mathbf{ss}^*\right]\mathbf{A}^* + \mathbb{E}\left[\mathbf{nn}^*\right]$$
$$= \mathbf{AR_{ss}A}^* + \sigma_n^2\mathbf{I}$$

↙ source correlation matrix

sorted →

- N eigenvalues of R_{xx} → **E** = [e_1 e_2 … e_{N-D} e_{N-D+1} … e_N]
  - D components with large eigenvalues → from D paths (angles)
  - (N – D) components with near-zero eigenvalues → noise

MUSIC Algorithm

Distance in the vector space, instead of the distance between Tx-Rx

- The distance between a signal coming from the arrival direction θ and the noise subspace

$$\text{dist}(\theta) = a(\theta)^* \mathbf{E}_N \mathbf{E}_N^* a(\theta)$$

$\mathbf{E}_N = [e_1 \; e_2 \; \ldots \; e_{N-D}]$

- D major components are orthogonal to the subspace of (N - D) noise components
  - dist(θ)~0 for the *D* paths from θ

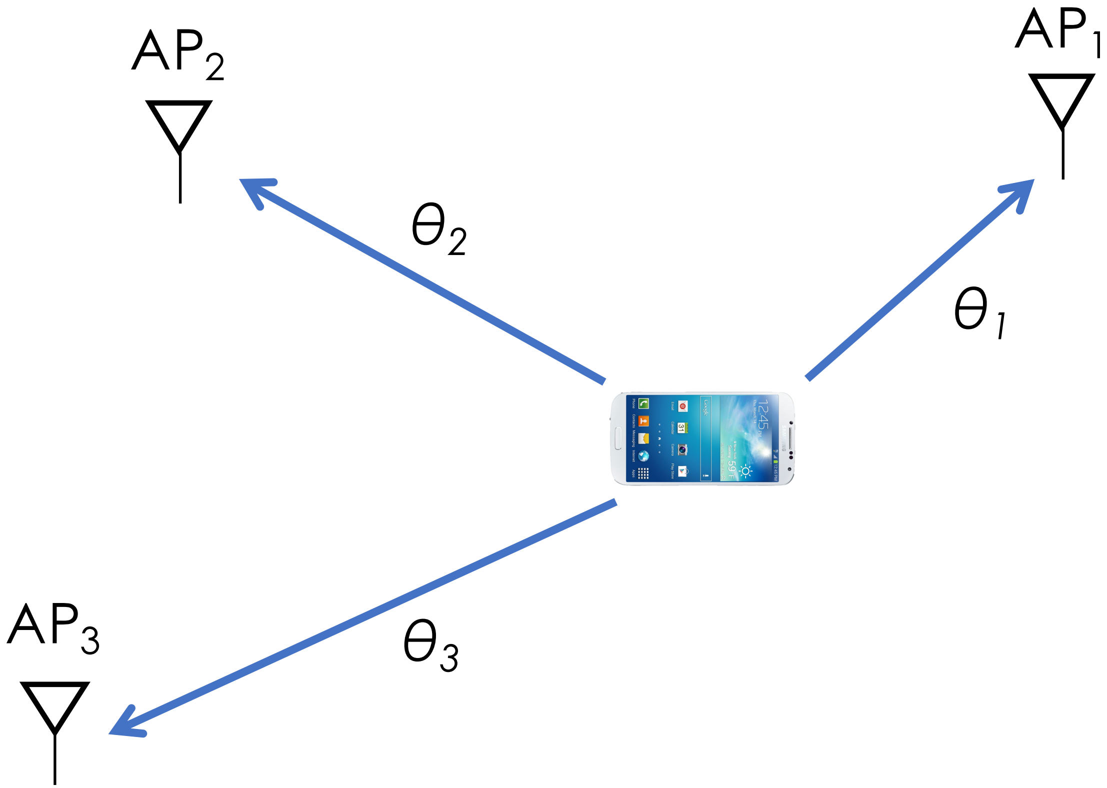
- Power function

$$P(\theta) = \frac{1}{\text{dist}(\theta)} = \frac{1}{a(\theta)^* \mathbf{E}_N \mathbf{E}_N^* a(\theta)}$$

AoA = $\max_\theta P(\theta)$

AoA-based Localization

- Find location via trigonometry



Quiz

- While interference nulling can only cancel static reflections, but not body reflections?