CSE610 Special Topics on Mobile Network & Mobile Sensing

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Lec04 Wireless Localization and Sensing

1846

Wireless Localization

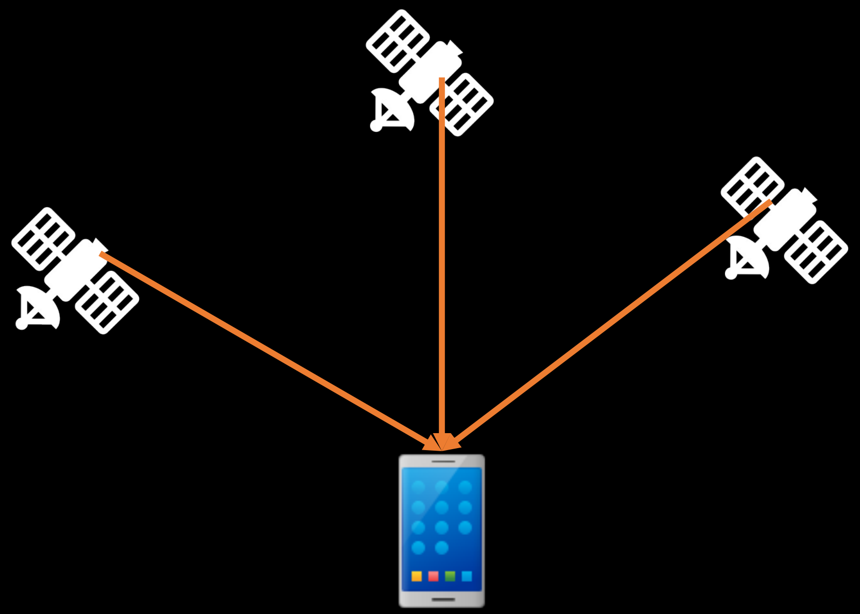
The process of obtaining a human or object's location using wireless signals

Applications:

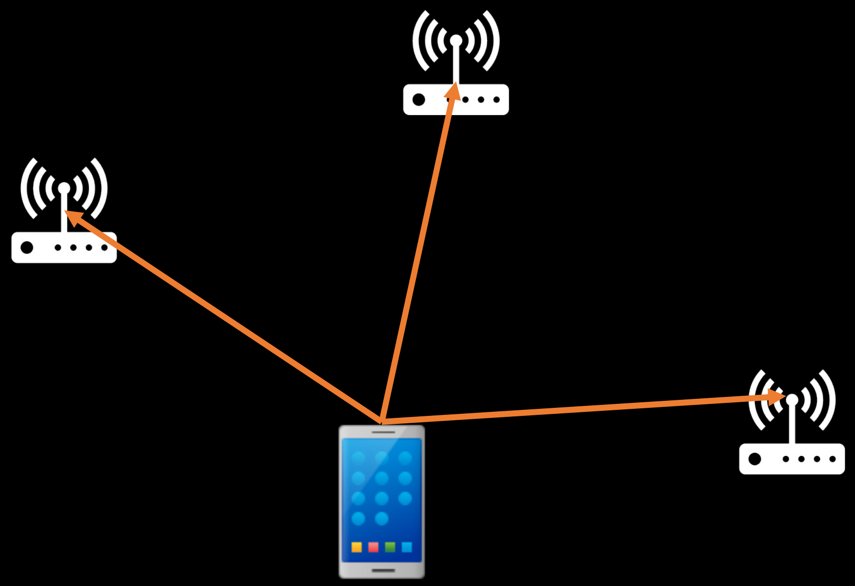
- Navigation: outdoors (GPS) and indoors (e.g., museum)
- Location based services: Tagging, Reminder, Ads
- Virtual Reality and Motion Capture
- Gestures, writing in the air
- Behavioral Analytics (Health, activities, etc.)
- Locating misplaced items (keys)
- Location based security
- Delivery drones

Wireless Localization System Architecture

Device based: a device leverages incoming signals from multiple ”anchors” (Satellites) to determine its own location

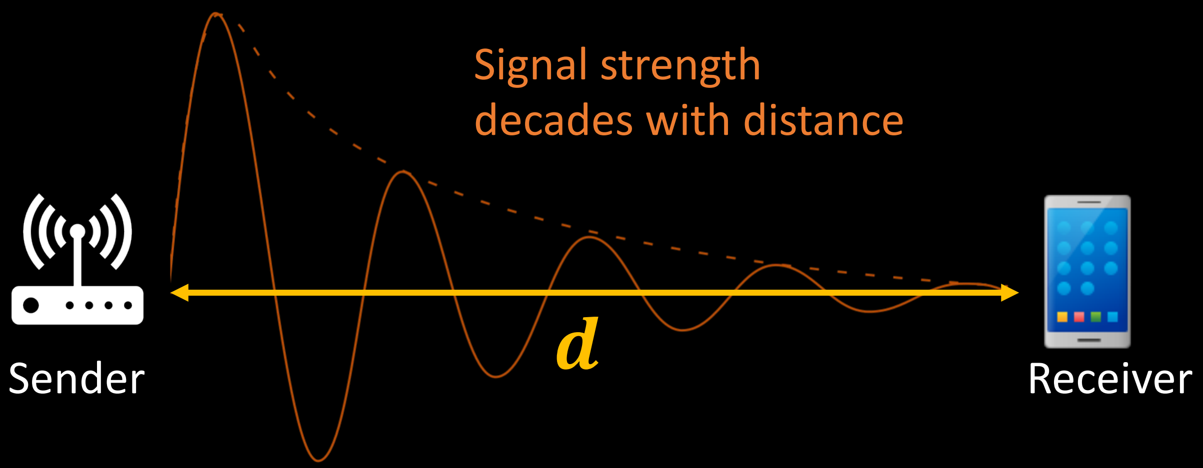


Network based: Networked ”anchors” (Access Points) leverages signal emitted by the mobile device to determine its location



Method 1: RSSI based localization

- Higher received signal power → Closer to the signal emitter
- Lower received signal power → Further away from the signal emitter



$$P_{rx} = G_{tx} G_{rx} \frac{\lambda^2}{(4\pi d)^2} P_{tx} \Longrightarrow RSSI \propto \frac{1}{d^2}$$

Leverage RSSI to estimate the distance

Method 1: RSSI based localization

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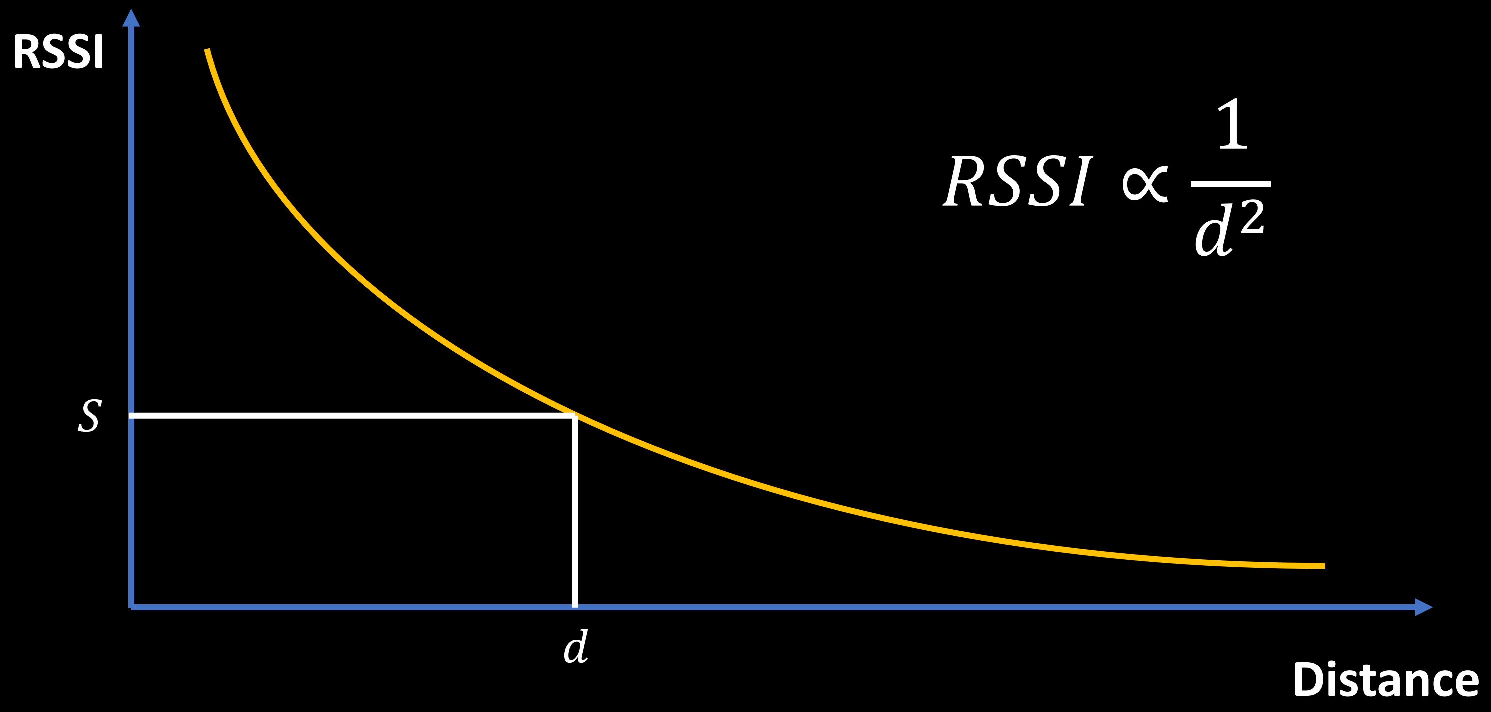
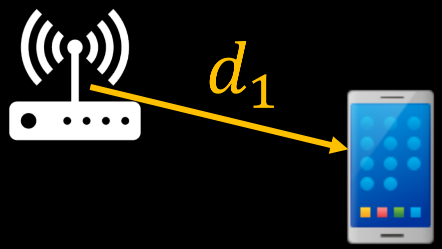


$$RSSI \propto \frac{1}{d^2}$$

Method 1: RSSI based localization



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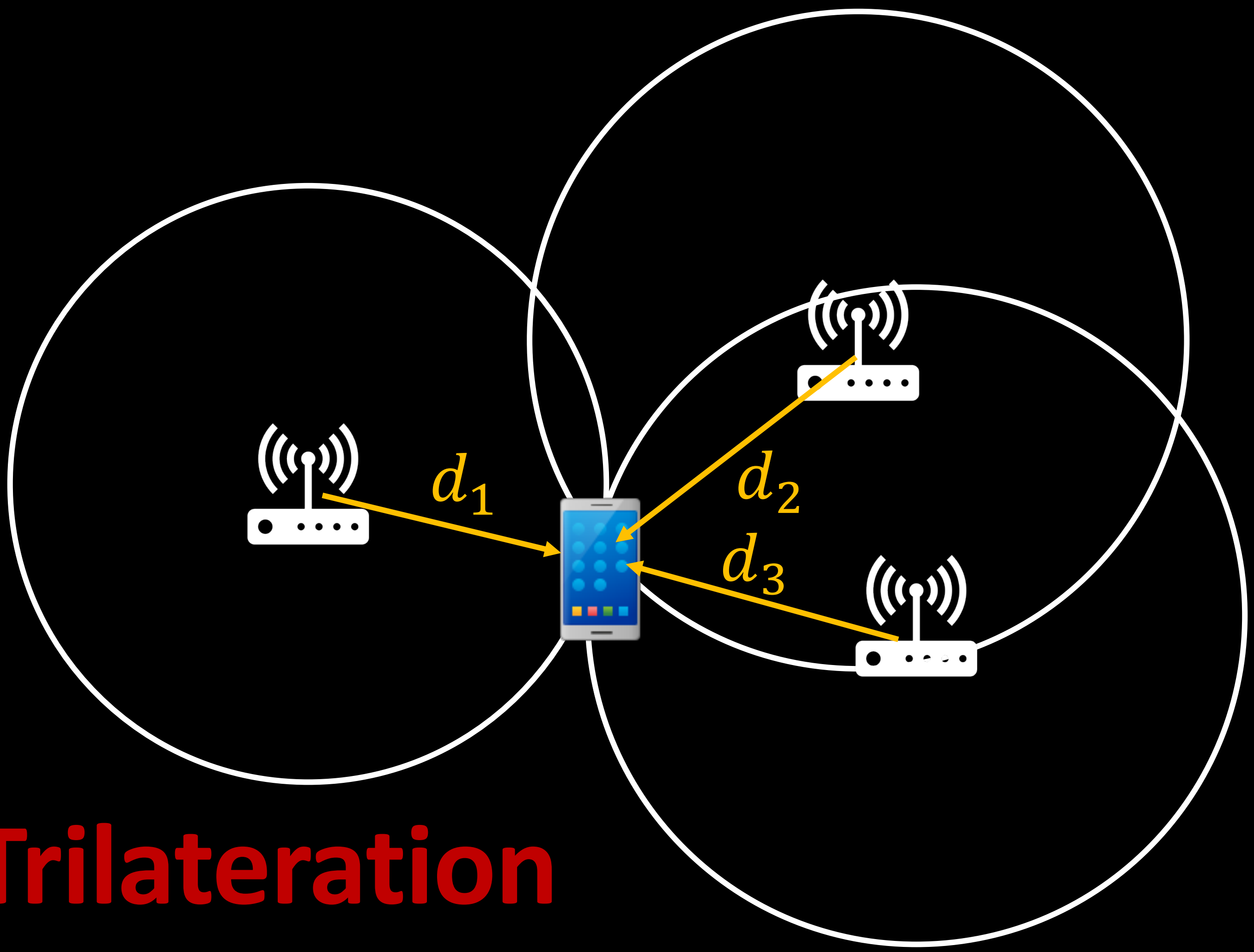

Trilateration

Method 1: RSSI based localization

Indoor navigation

Method 1: RSSI based localization

- **Pros:** Very simple, no hardware modifications
- **Cons:** Highly inaccurate!

Method 1: RSSI based localization

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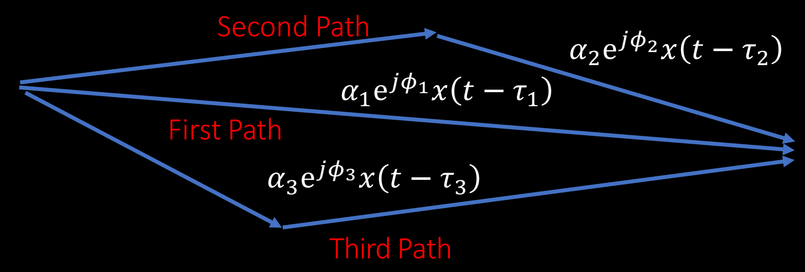
- **Cons:** Highly inaccurate!

  Doesn't work with multipath fading!



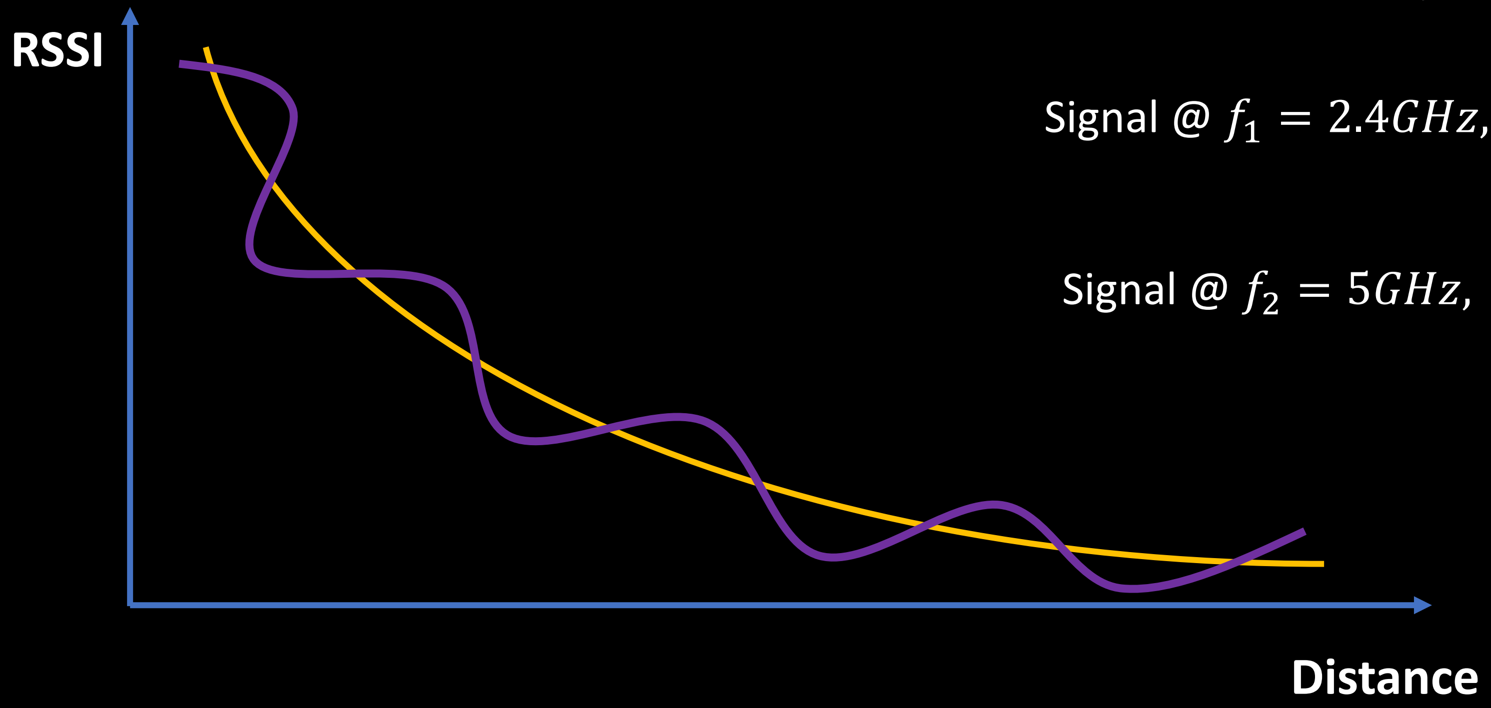
$$h = h_1 + h_2 = \frac{\lambda}{d_1} e^{j2\pi d_1/\lambda} + \frac{\lambda}{d_2} e^{j2\pi d_2/\lambda}$$

Signal @ $f_1 = 2.4GHz,\ \lambda_1 = 12cm$

$$h = 0.12\, e^{j\frac{2\pi}{3}} + 0.113\, e^{j\frac{5\pi}{3}} \approx 0.006$$

Signal @ $f_2 = 5GHz,\ \lambda_1 = 12cm$

$$h = 0.06\, e^{j\frac{5\pi}{3}} + 0.05\, e^{j\frac{5\pi}{3}} \approx 0.116$$



Method 1: RSSI based localization

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- **Cons:** Highly inaccurate!

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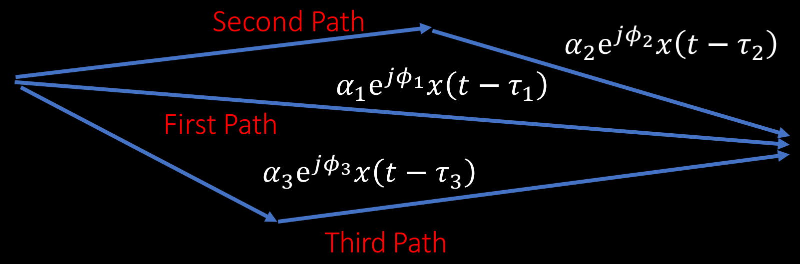

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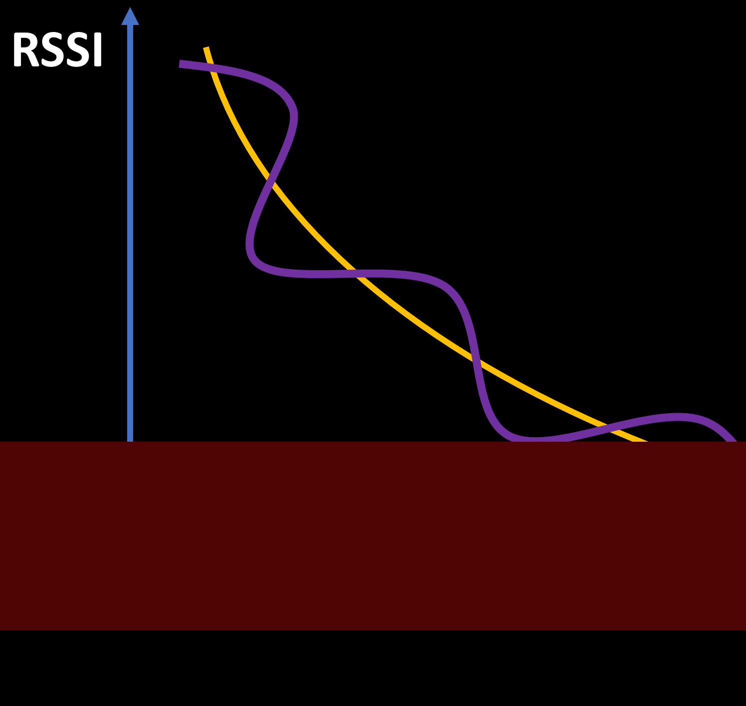

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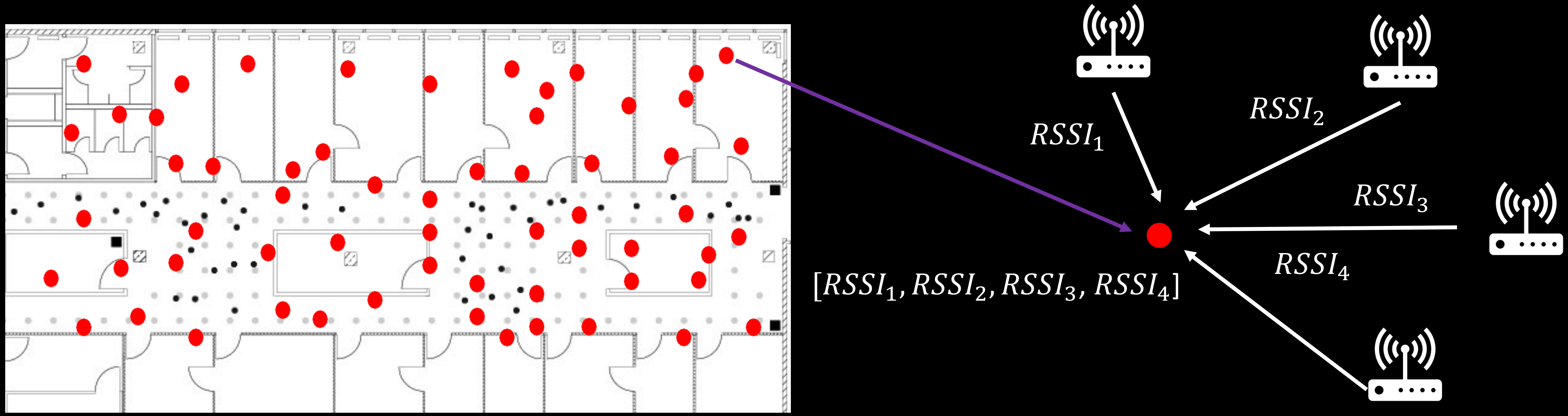
Any solutions?

Method 1: RSSI based localization

Solution: Fingerprinting

Measure and record RSSI at each location (war-driving)

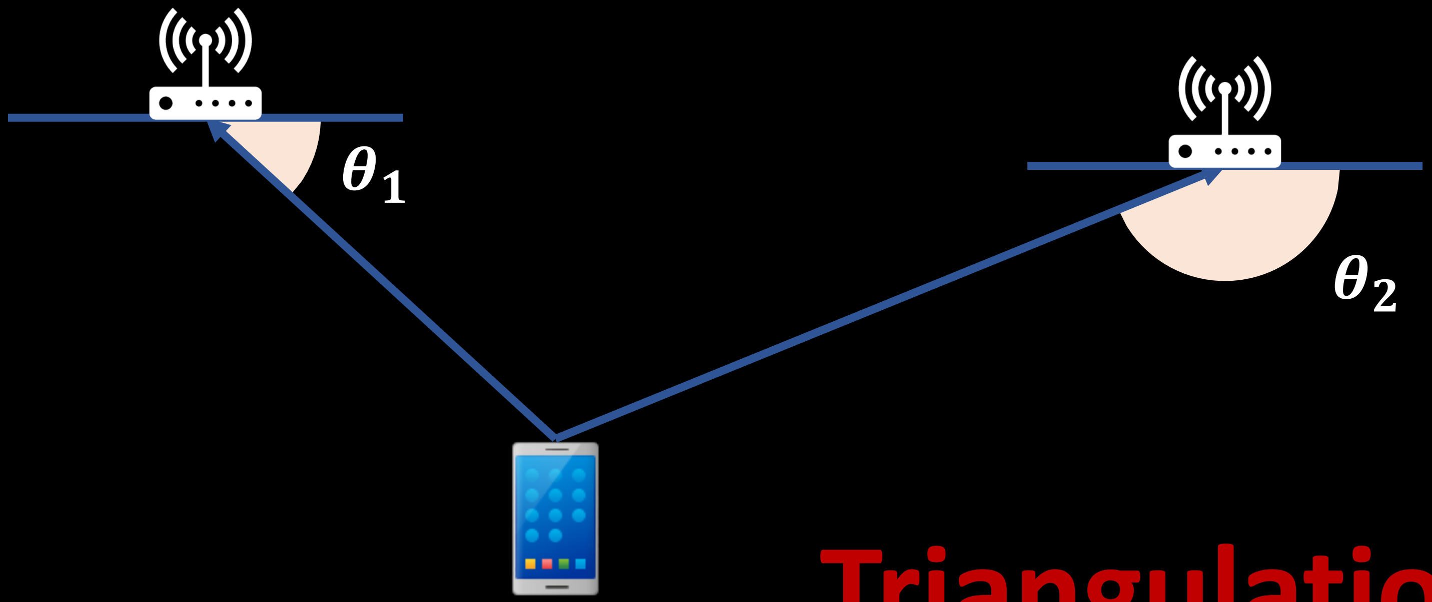


- **Pros:** Works with multipath, no need to know AP locations
- **Cons:** Changes in environment/movement → Changes in RSSI

  Continuously update the fingerprint database! Significant maintenance effort

Method 2: AoA based solution

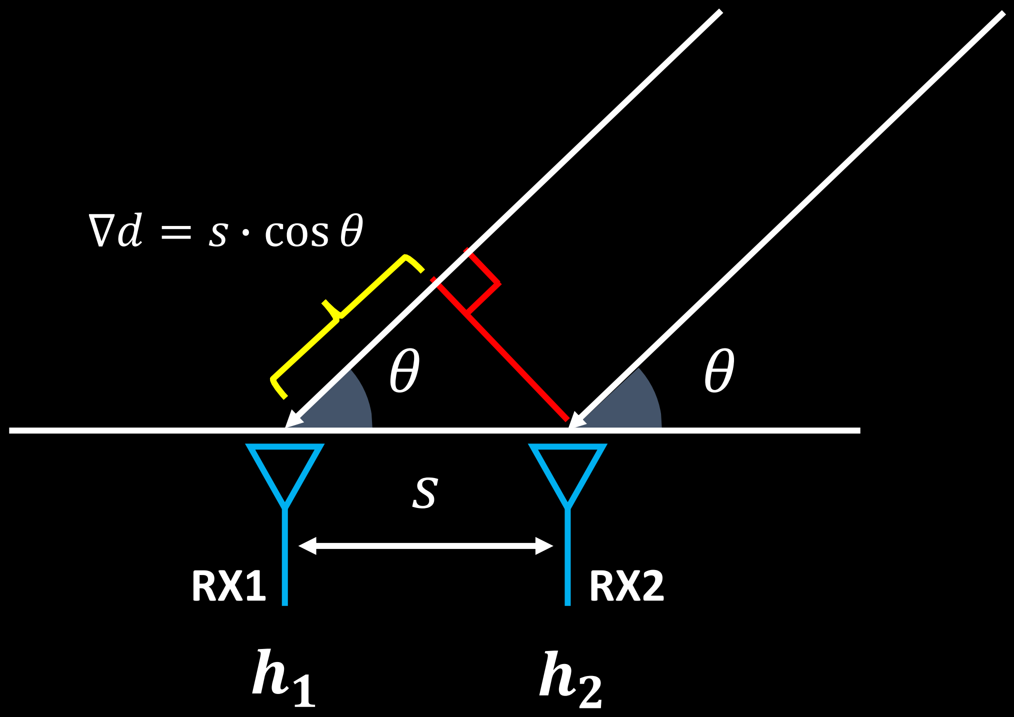
AoA: angle of arrival

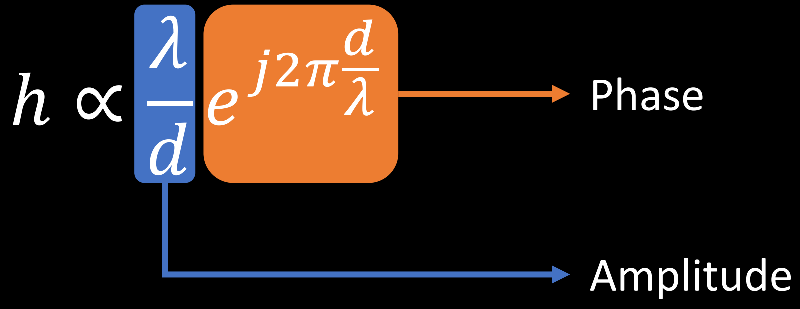


Triangulation

Method 2: AoA based solution

Estimating the AoA

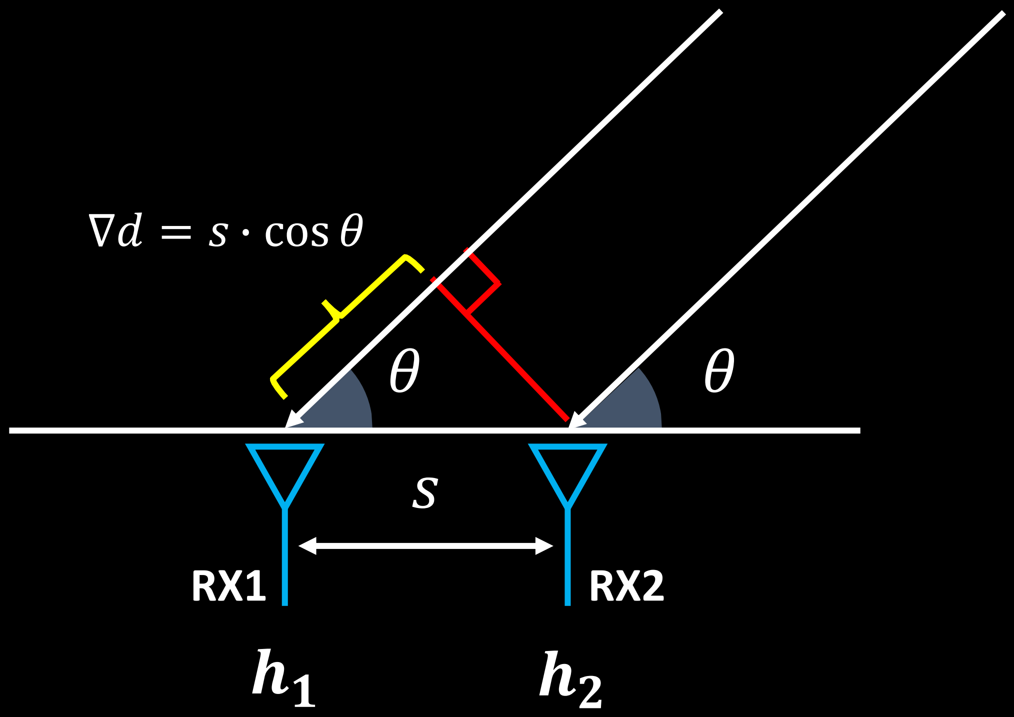




$$\nabla\Phi = \angle h_1 - \angle h_2 = 2\pi \frac{\nabla d}{\lambda}$$

$$\nabla\Phi = 2\pi \frac{s \cdot \cos\theta}{\lambda}$$

Method 2: AoA based solution
Estimating the AoA



$$h \propto \frac{\lambda}{d} e^{j2\pi\frac{d}{\lambda}}$$

Phase: $e^{j2\pi\frac{d}{\lambda}}$

Amplitude: $\frac{\lambda}{d}$

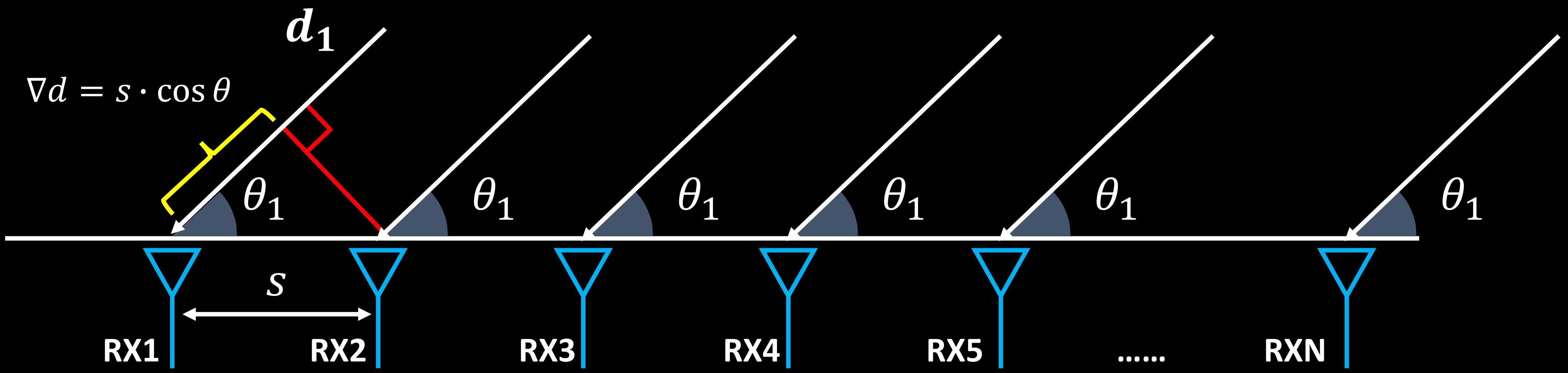
$$\nabla\Phi = \angle h_1 - \angle h_2 = 2\pi\frac{\nabla d}{\lambda}$$

$$\nabla\Phi = 2\pi\frac{s \cdot \cos\theta}{\lambda}$$

- **Pros:** Much more accurate than RSSI based solutions!
- **Cons:** Cannot work in presence of multipath

Method 2: AoA based solution

Estimating the AoA



$$\boldsymbol{\Phi_1}$$

$$\boldsymbol{\Phi_1} + 2\pi \frac{s \cdot \cos\theta_1}{\lambda}$$

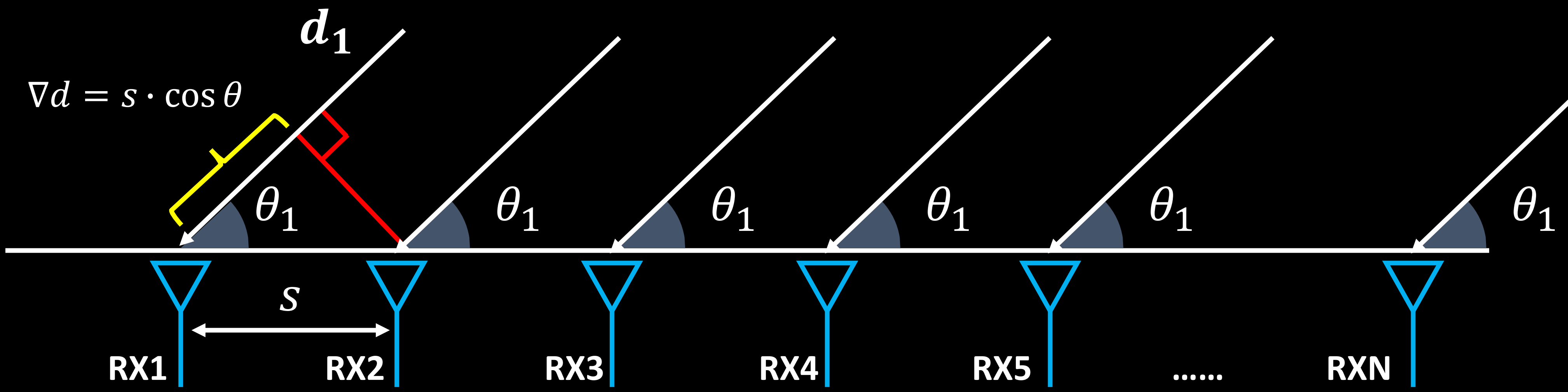
$$\boldsymbol{\Phi_1} + 2\pi \frac{2 \cdot s \cdot \cos\theta_1}{\lambda}$$

$$\boldsymbol{\Phi_1} + 2\pi \frac{3 \cdot s \cdot \cos\theta_1}{\lambda}$$

$$\boldsymbol{\Phi_1} + 2\pi \frac{(N-1) \cdot s \cdot \cos\theta_1}{\lambda}$$

Method 2: AoA based solution

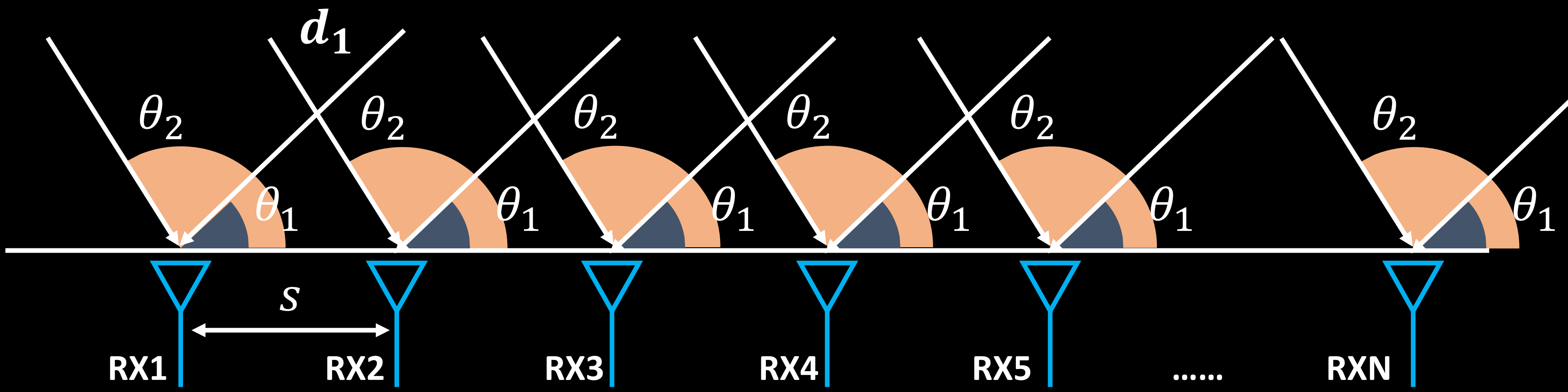
Estimating the AoA



$$\boldsymbol{\Phi}_{\mathrm{N}}(\theta_1) = \boldsymbol{\Phi}_{\mathbf{1}} + 2\pi \frac{(N-1)\cdot s \cdot \cos\theta_1}{\lambda}$$

$$\boldsymbol{h_k = \alpha_1 e^{j\Phi_k(\theta_1)}}$$

Method 2: AoA based solution
Estimating the AoA

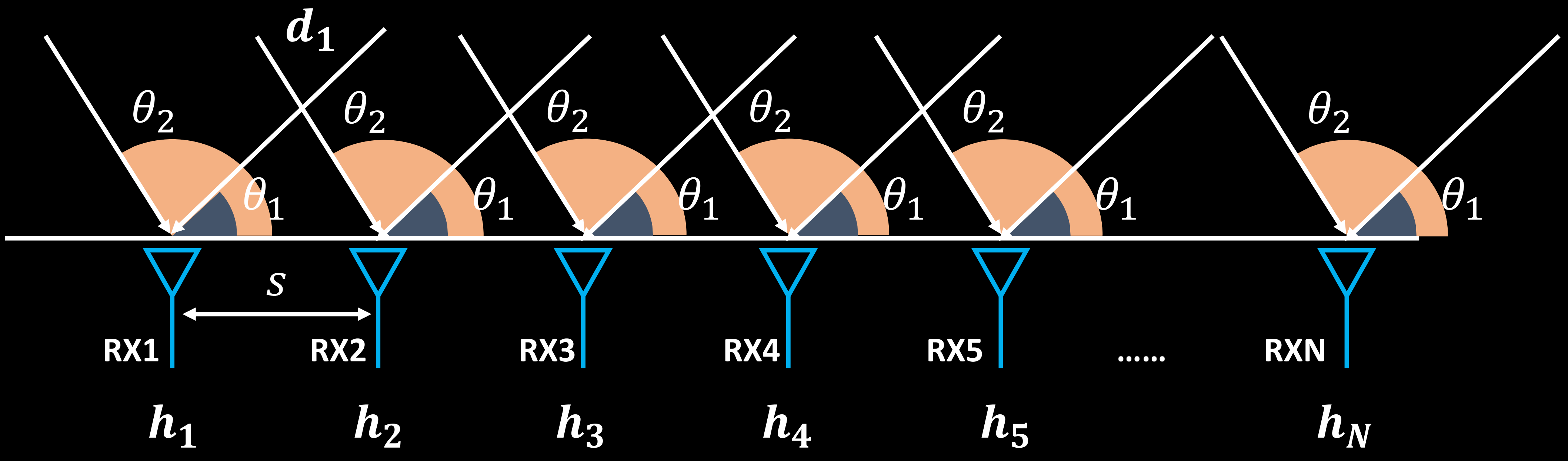


$$h_k = \alpha_1 e^{j\Phi_k(\theta_1)} + \alpha_2 e^{j\Phi_k(\theta_2)}$$

$$h_k = \sum_{l}^{L} \alpha_l e^{j\Phi_k(\theta_l)}$$

If there are L multipaths

Method 2: AoA based solution
Estimating the AoA



How to estimate the AoA of the multipath signals?

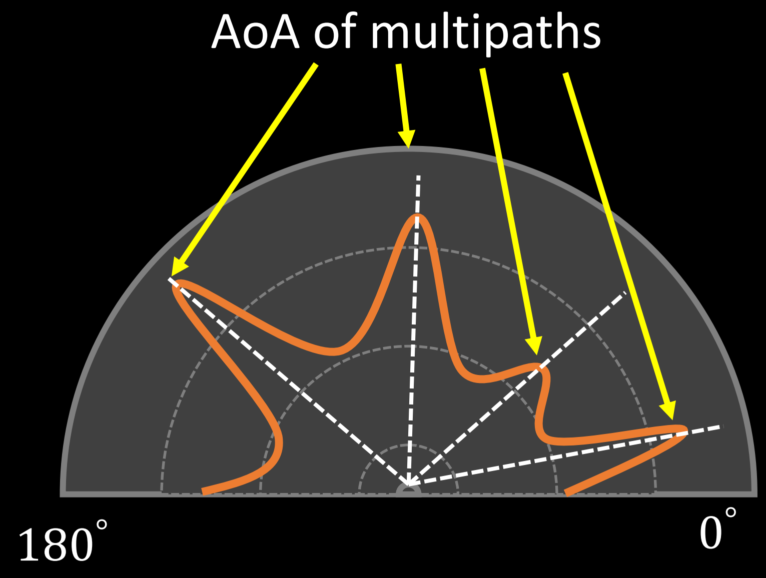
Method 2: AoA based solution
Estimating the AoA

MUSIC algorithm: MUltiple SIgnal Classification

$$H = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ \vdots \\ h_N \end{bmatrix}$$

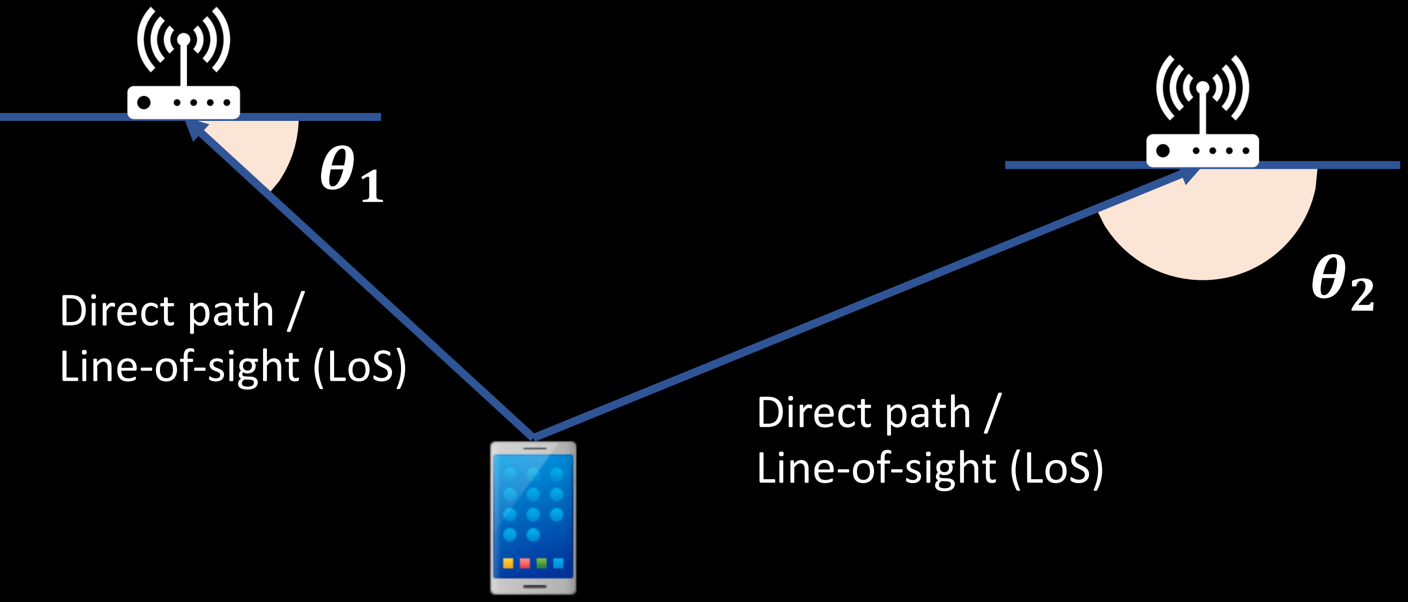
Channel measured from all antennas

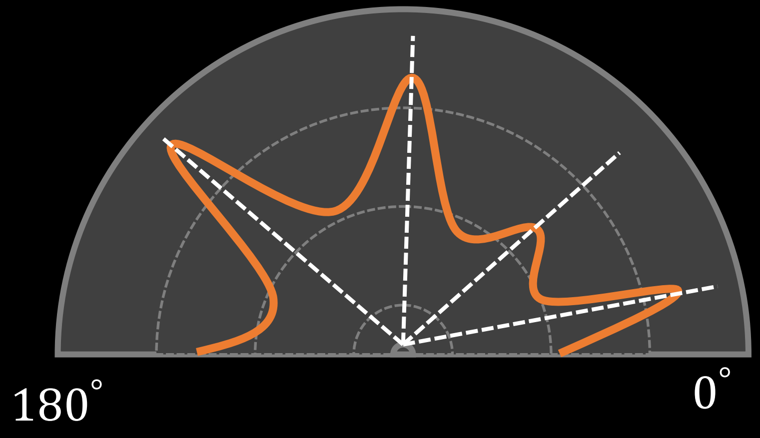
Input → **MUSIC algorithm** → **Output**



Method 2: AoA based solution
Estimating the AoA

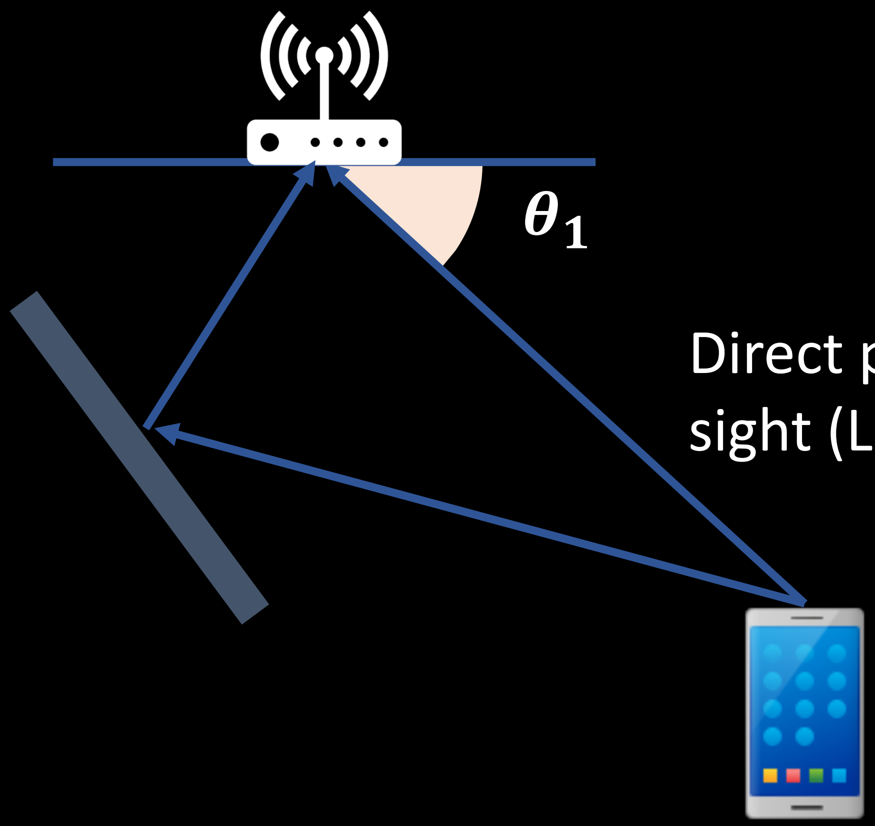
MUSIC algorithm: MUltiple SIgnal Classification

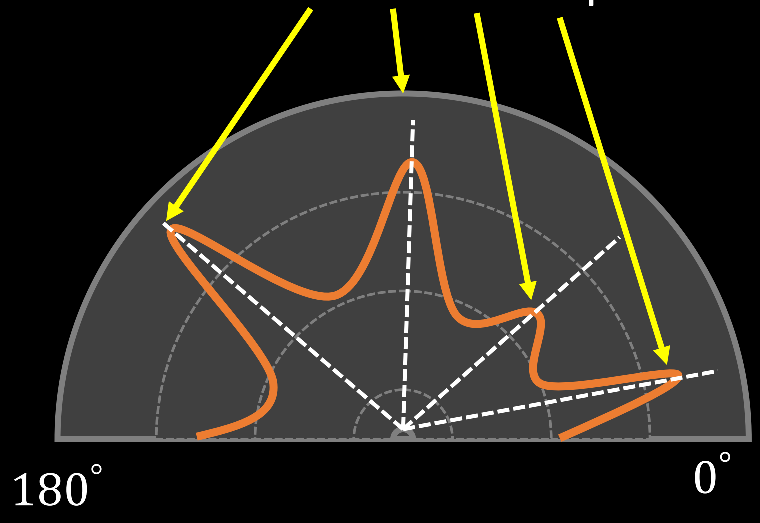




Method 2: AoA based solution
Estimating the AoA

MUSIC algorithm: MUltiple SIgnal Classification





Method 2: AoA based solution
Estimating the AoA

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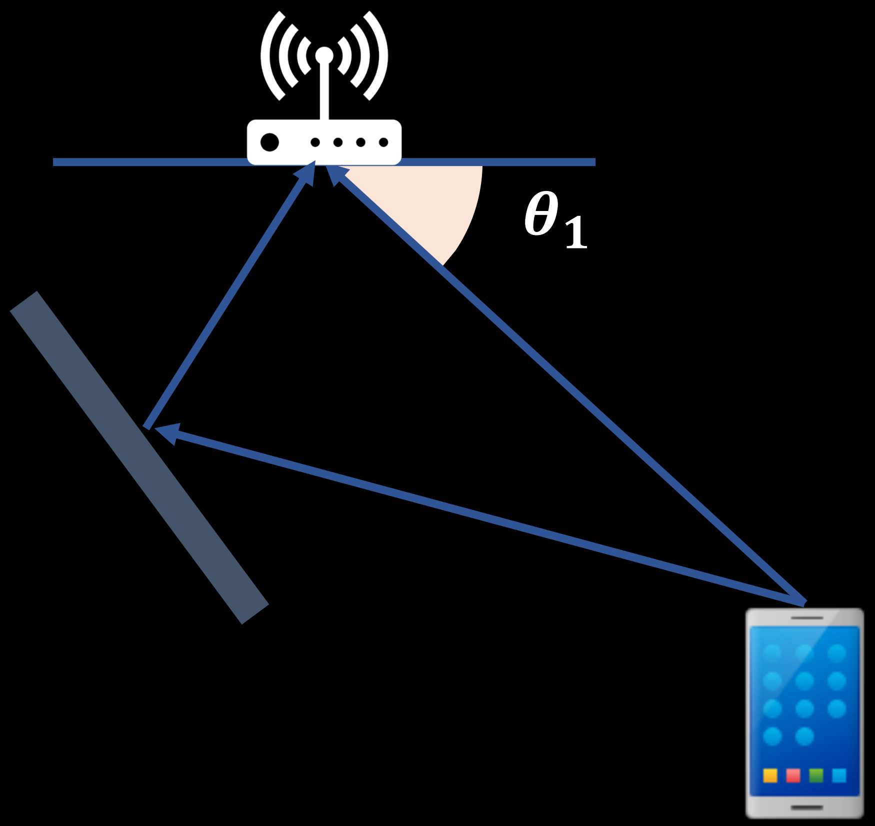
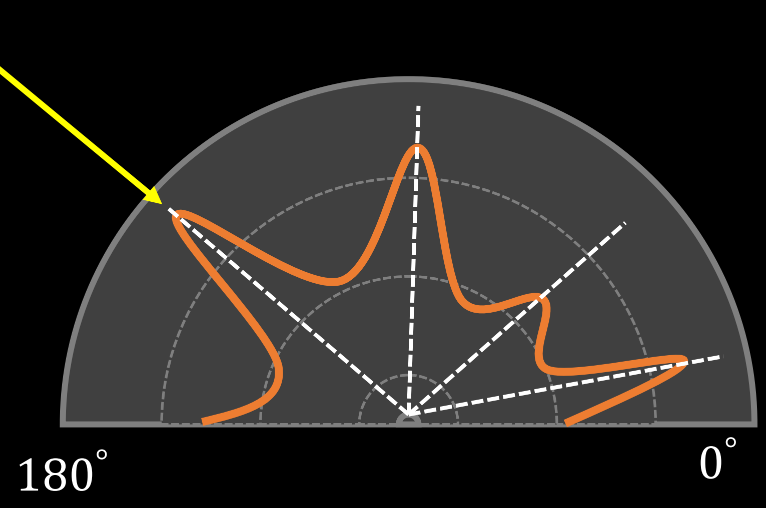


Hint 1: strongest path



Method 2: AoA based solution
Estimating the AoA

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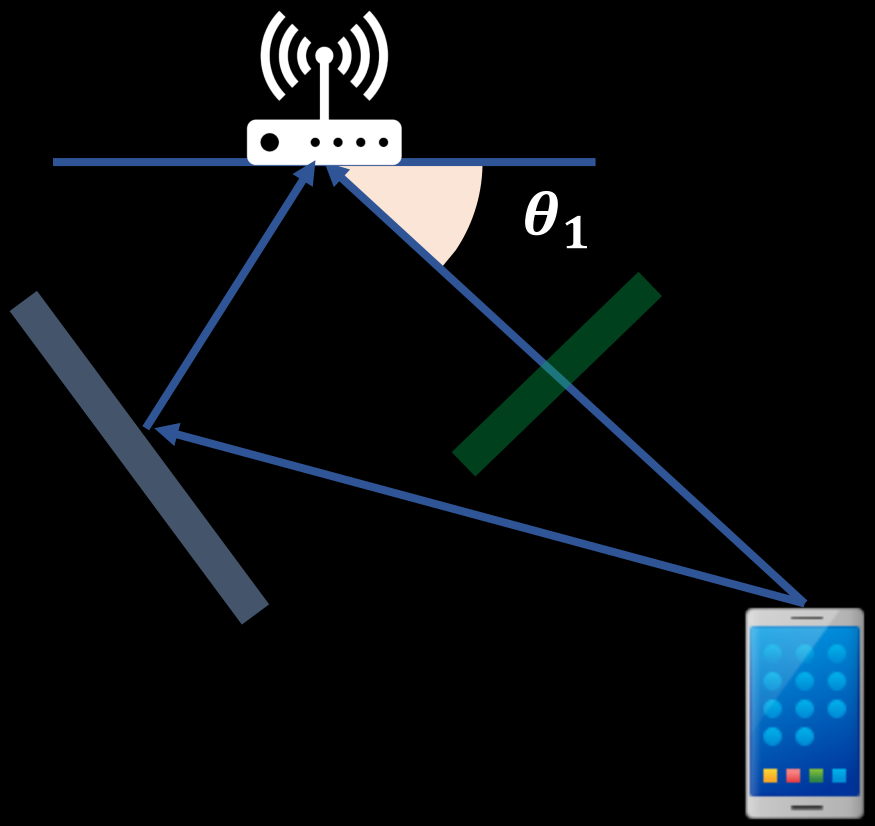
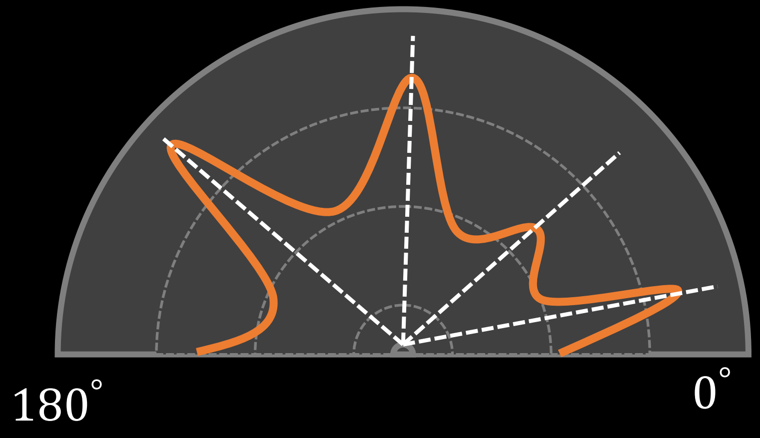


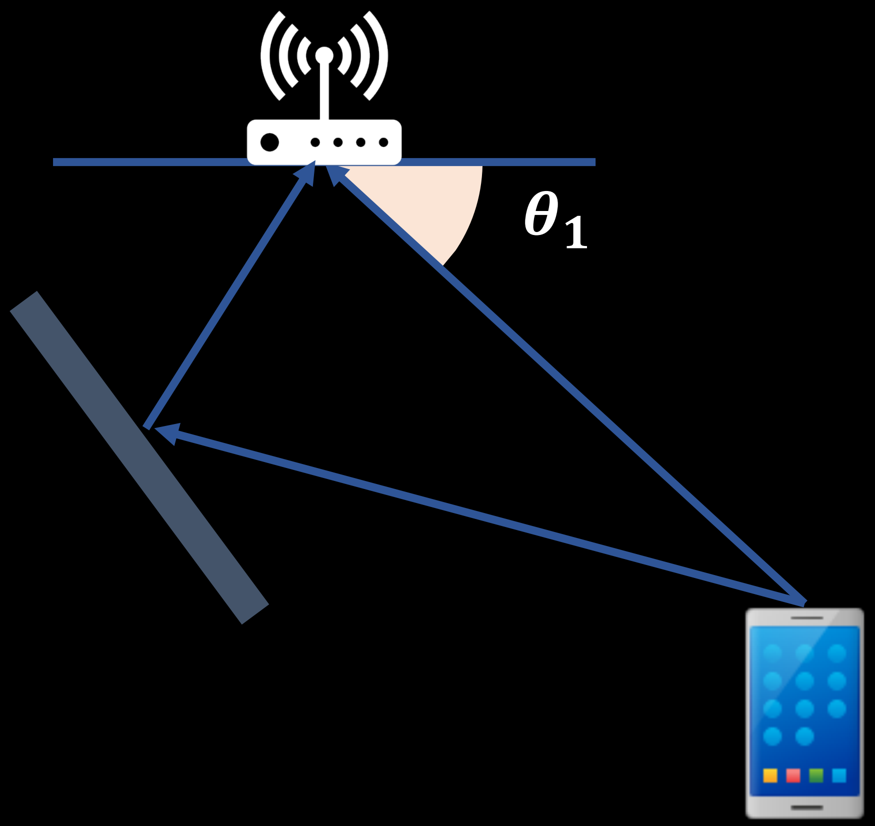
Hint 1: strongest path

Not always true, if the LoS path is blocked



Method 2: AoA based solution
Estimating the AoA

MUSIC algorithm: MUltiple SIgnal Classification

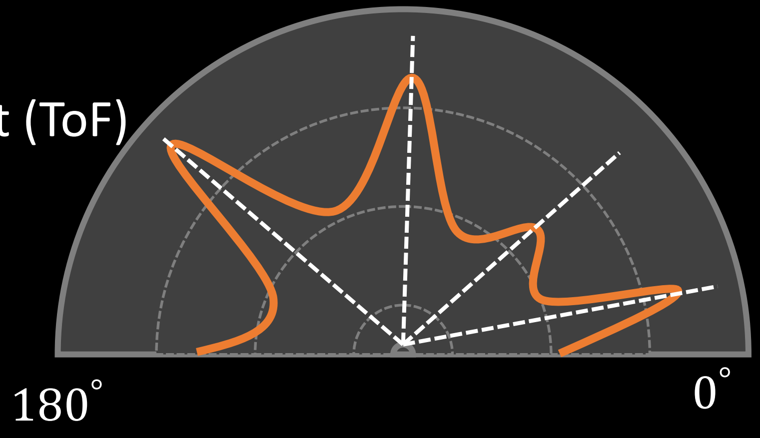


Hint 1: strongest path

Hint 2: mobility

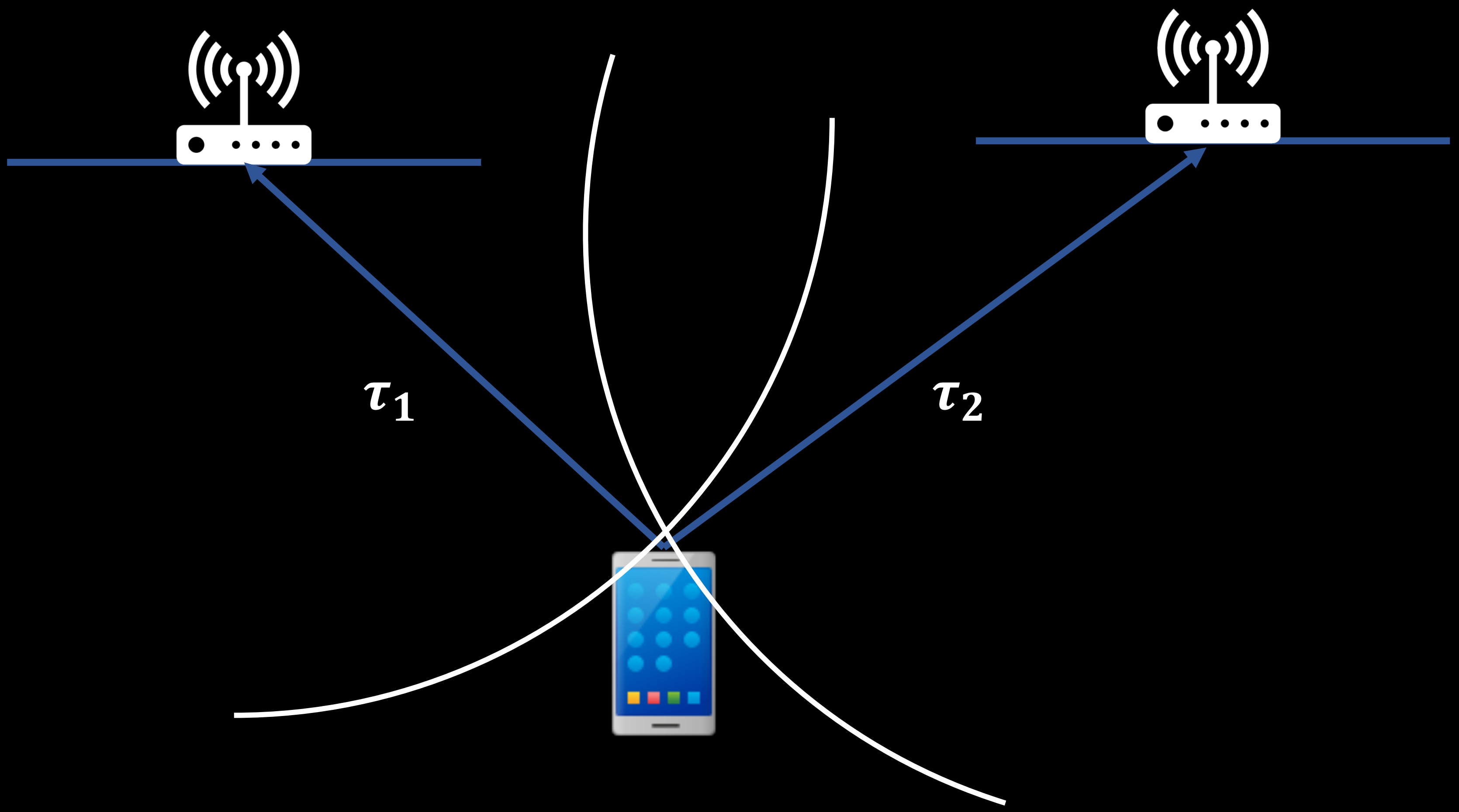
Hint 3: shortest path

→ smallest Time of Flight (ToF)

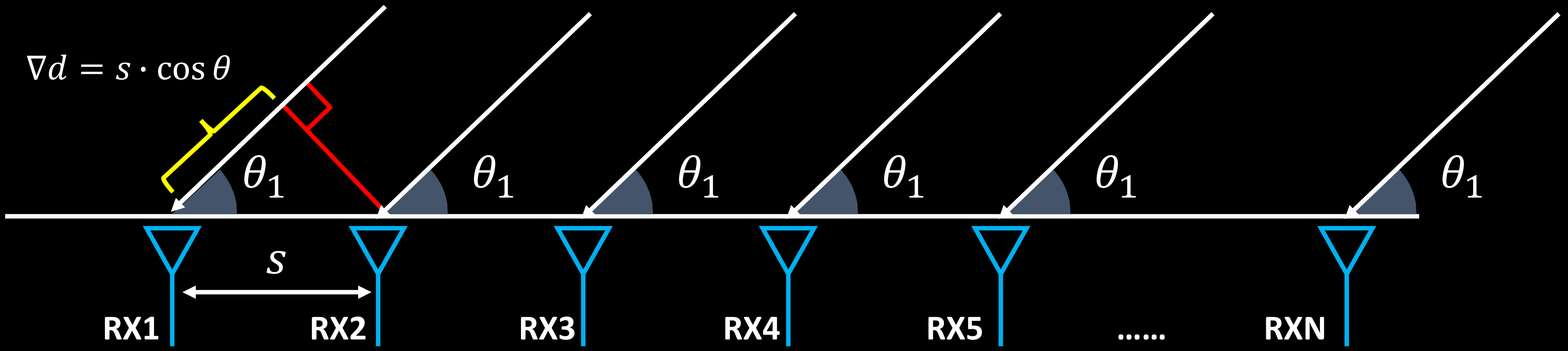


Method 3: ToF based solution

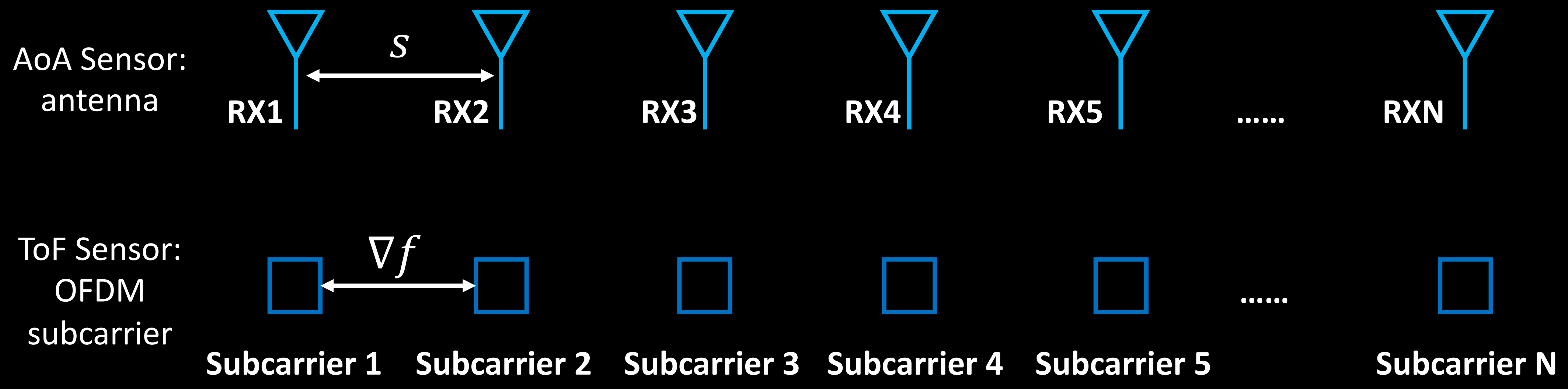
ToF: time of flight



Method 3: ToF based solution
Estimating the ToF



Method 3: ToF based solution
Estimating the ToF



Method 3: ToF based solution
Estimating the ToF

ToF Sensor: OFDM subcarrier

∇f

Subcarrier 1 | Subcarrier 2 | Subcarrier 3 | Subcarrier 4 | Subcarrier 5 | ...... | Subcarrier N

$\boldsymbol{h_1}$ $\boldsymbol{h_2}$ $\boldsymbol{h_3}$ $\boldsymbol{h_4}$ $\boldsymbol{h_5}$ $\boldsymbol{h_N}$

$$\angle \boldsymbol{h_1} = \boldsymbol{2\pi f_1 \tau}$$

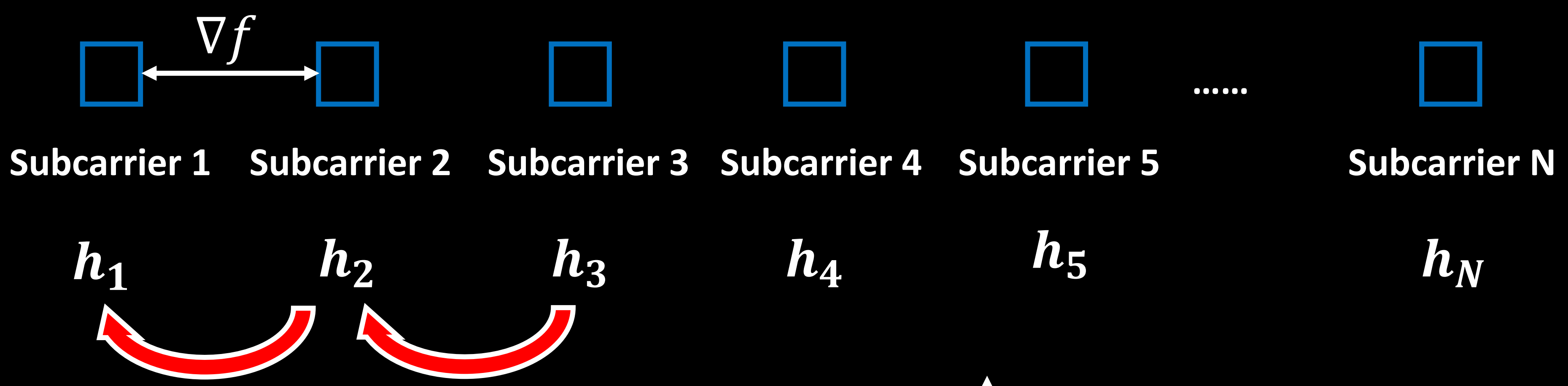
$$\angle \boldsymbol{h_2} = \boldsymbol{2\pi}(\boldsymbol{f_1}+\nabla f)\boldsymbol{\tau}$$

$$\angle \boldsymbol{h_3} = \boldsymbol{2\pi}(\boldsymbol{f_1}+2\nabla f)\boldsymbol{\tau}$$

$$\angle \boldsymbol{h_N} = \boldsymbol{2\pi}(\boldsymbol{f_1}+(N-1)\nabla f)\boldsymbol{\tau}$$

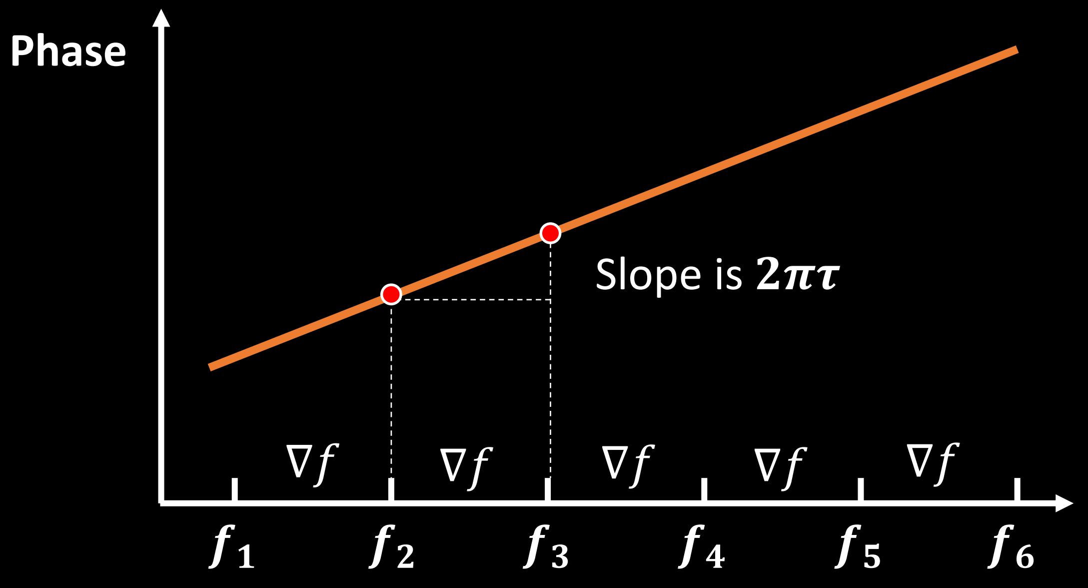
Method 3: ToF based solution
Estimating the ToF

ToF Sensor: OFDM subcarrier



$$\nabla\Psi = \angle h_2 - \angle h_1 = 2\pi \nabla f \tau$$

$$\nabla\Psi = \angle h_3 - \angle h_2 = 2\pi \nabla f \tau$$



Only works for a single path!

What about multipath?

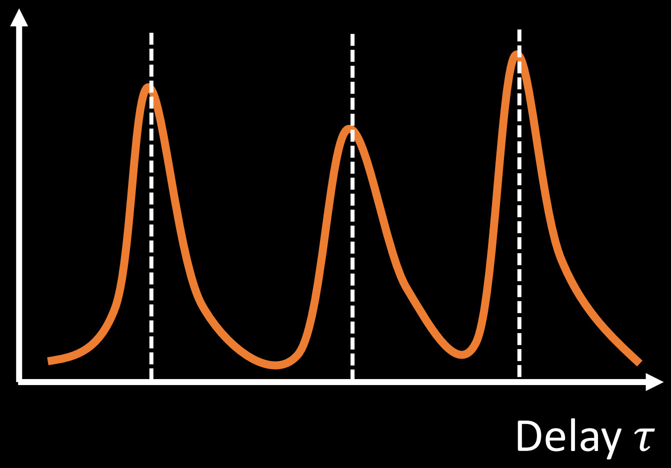
Method 3: ToF based solution
Estimating the ToF

MUSIC algorithm: MUltiple SIgnal Classification

$$H = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ \vdots \\ h_N \end{bmatrix}$$

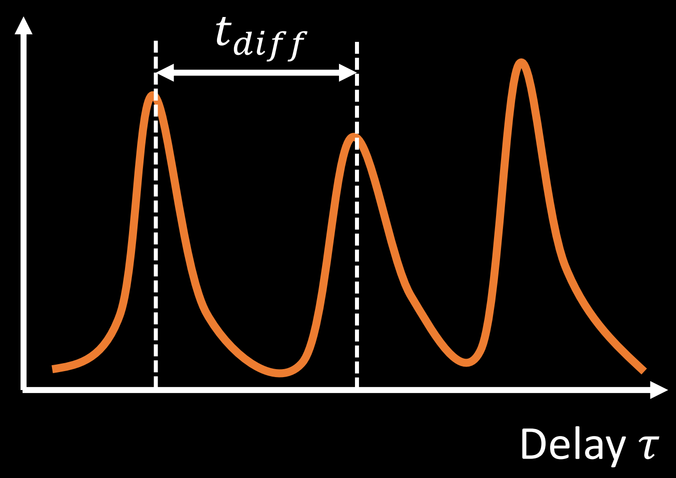
Channel measured from all subcarriers

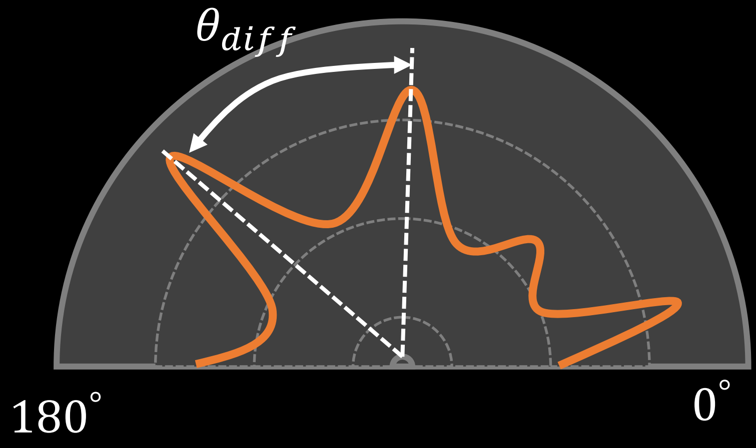
Input → **MUSIC algorithm** → **Output**



ToF and AoA: Resolution

Resolution: the capability of resolving two multipaths





ToF and AoA: Resolution

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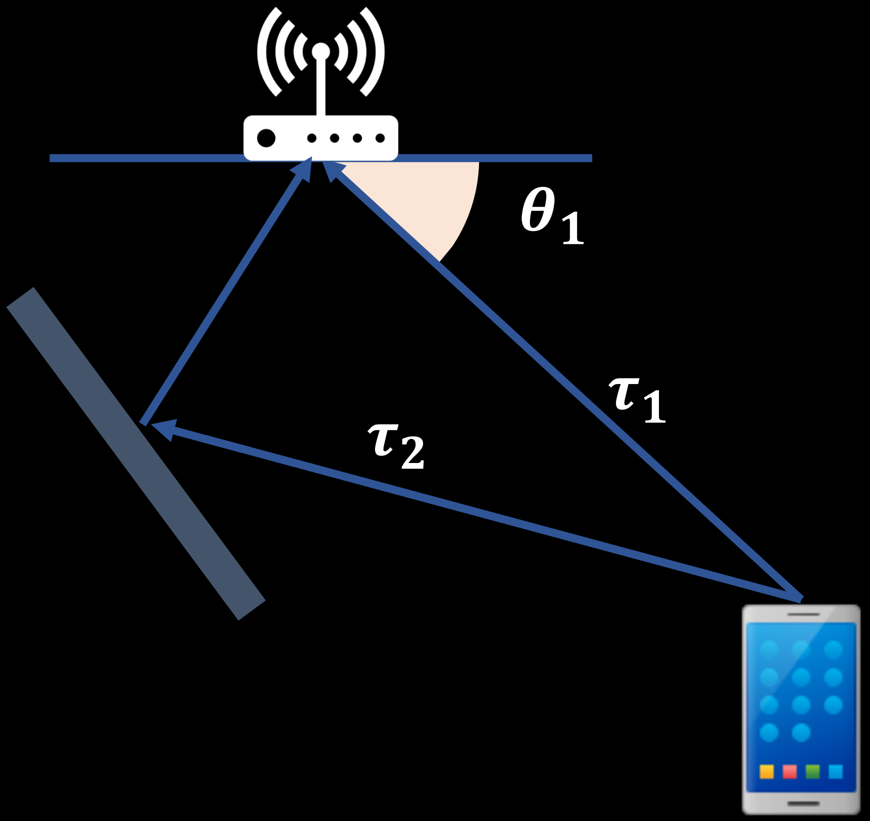
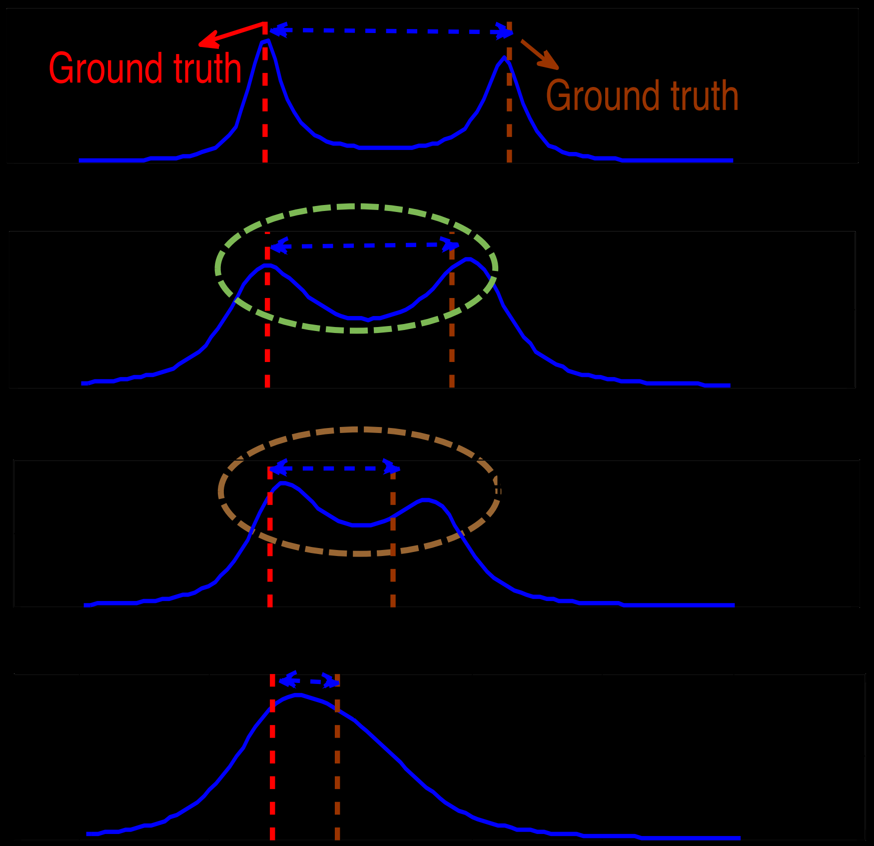


- We change the length of the reflection path to vary the ToF τ_2
- We use MUSIC algorithm to estimate the ToF of two paths

ToF and AoA: Resolution



Naïve: 15m resolution
(20MHz bandwidth)

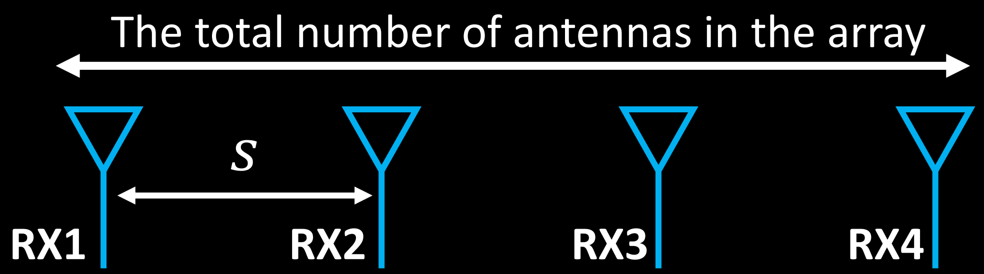
MUSIC: around 8m resolution

When two paths get closer, MUSIC fails to resolve them

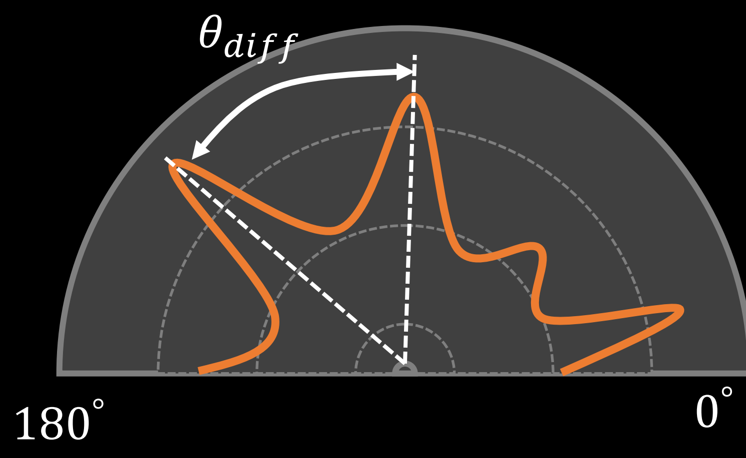
The two peaks merge into one eventually

ToF and AoA: Resolution

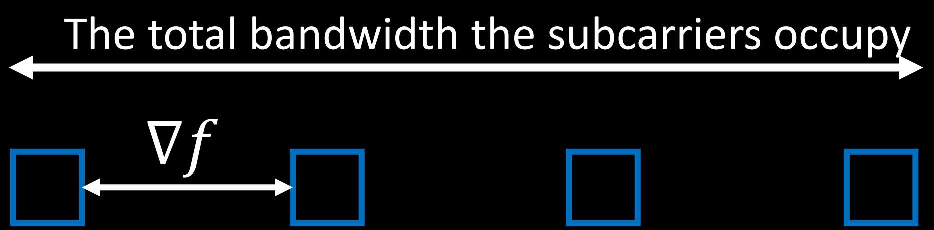
AoA Sensor: antenna

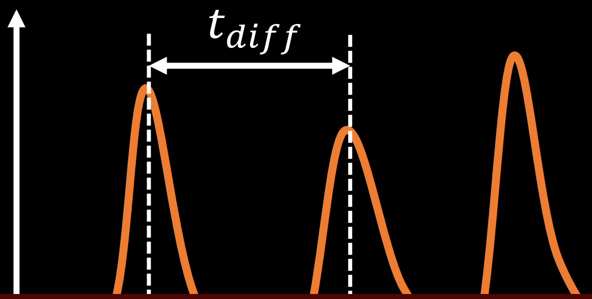


More antennas, higher spatial resolution



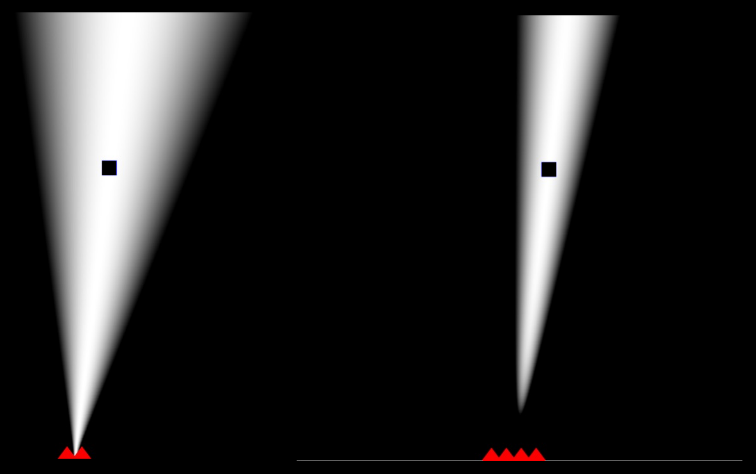
ToF Sensor: OFDM subcarrier



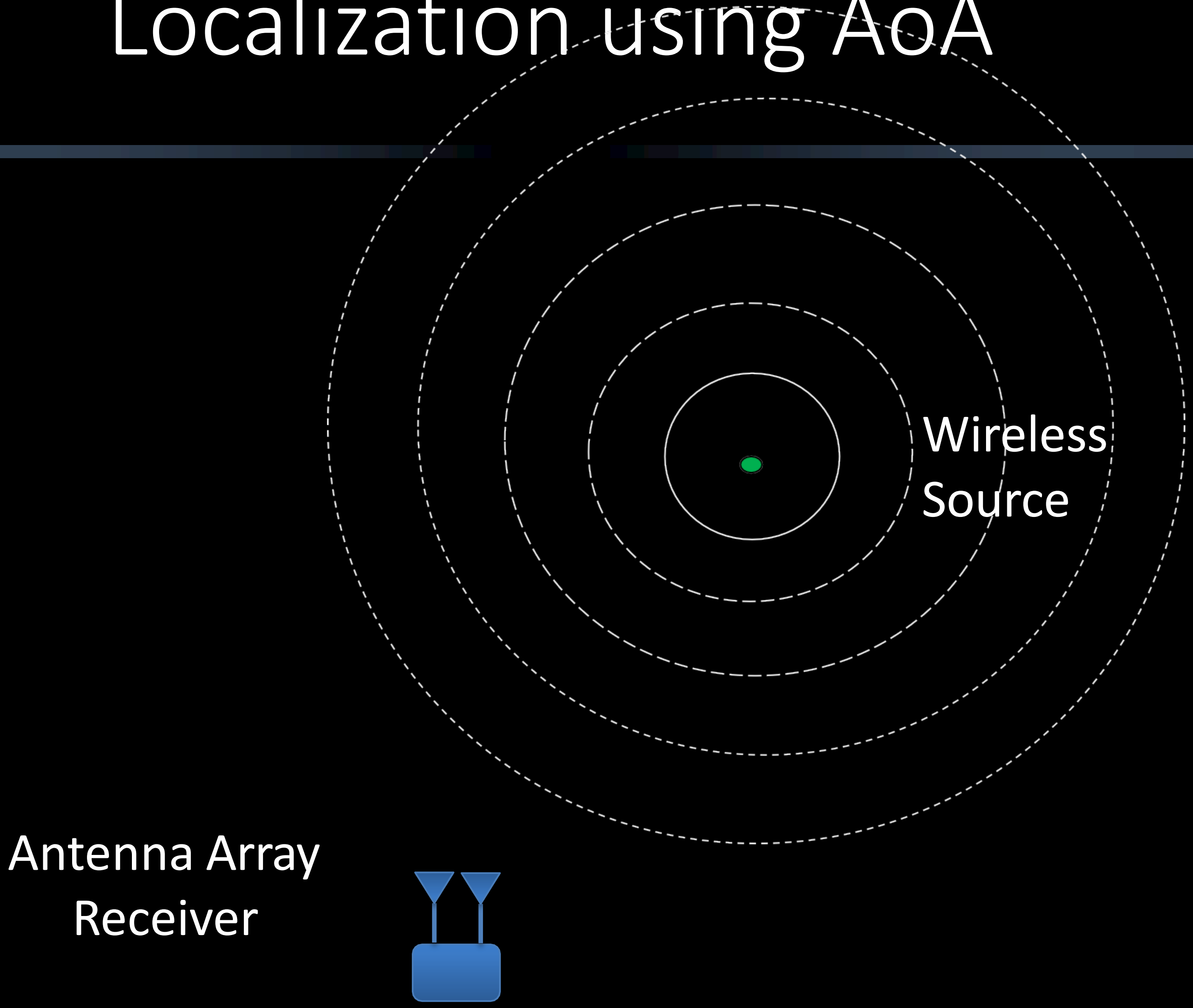


Why resolution is important?

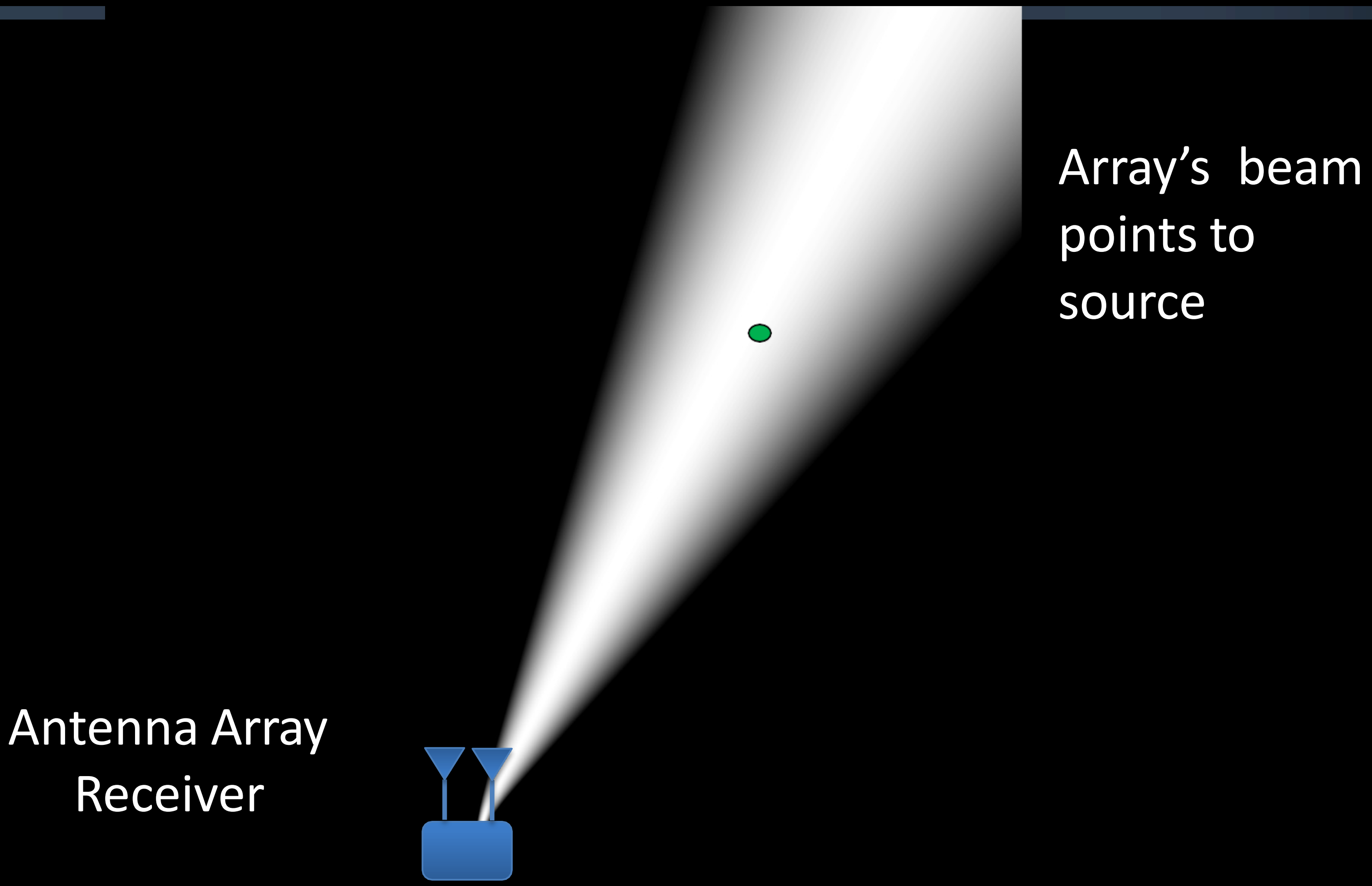
ToF and AoA: Resolution



Localization using AoA

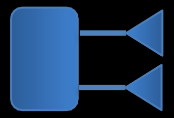


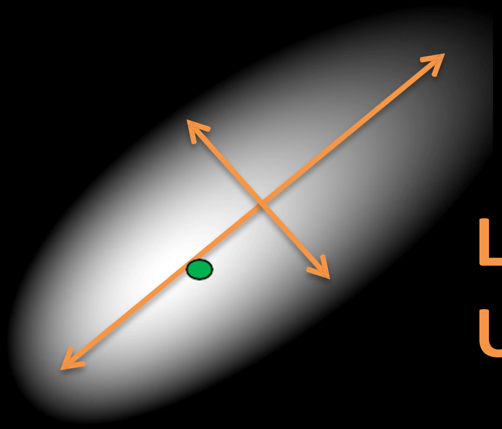
Localization using AoA



Localization using AoA

Localization using AoA

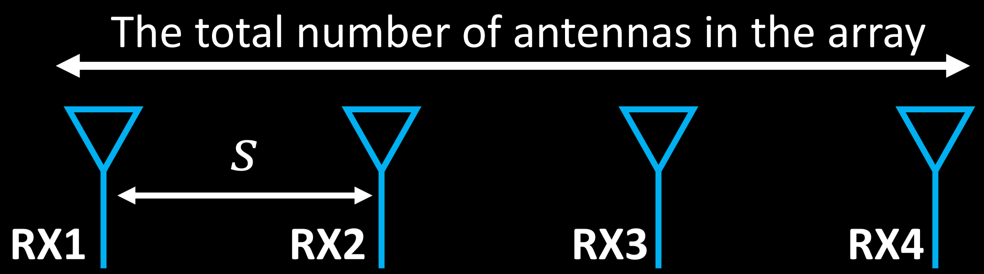




How to improve the resolution?

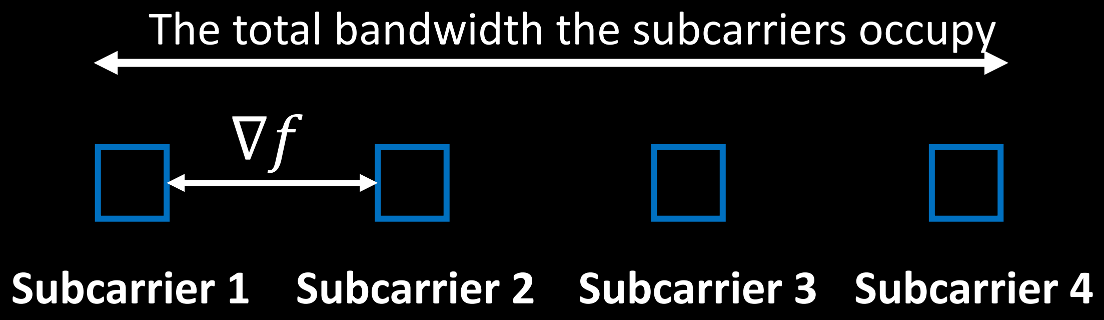
ToF and AoA: Resolution

AoA Sensor:
antenna



More antennas, higher spatial resolution

ToF Sensor:
OFDM
subcarrier



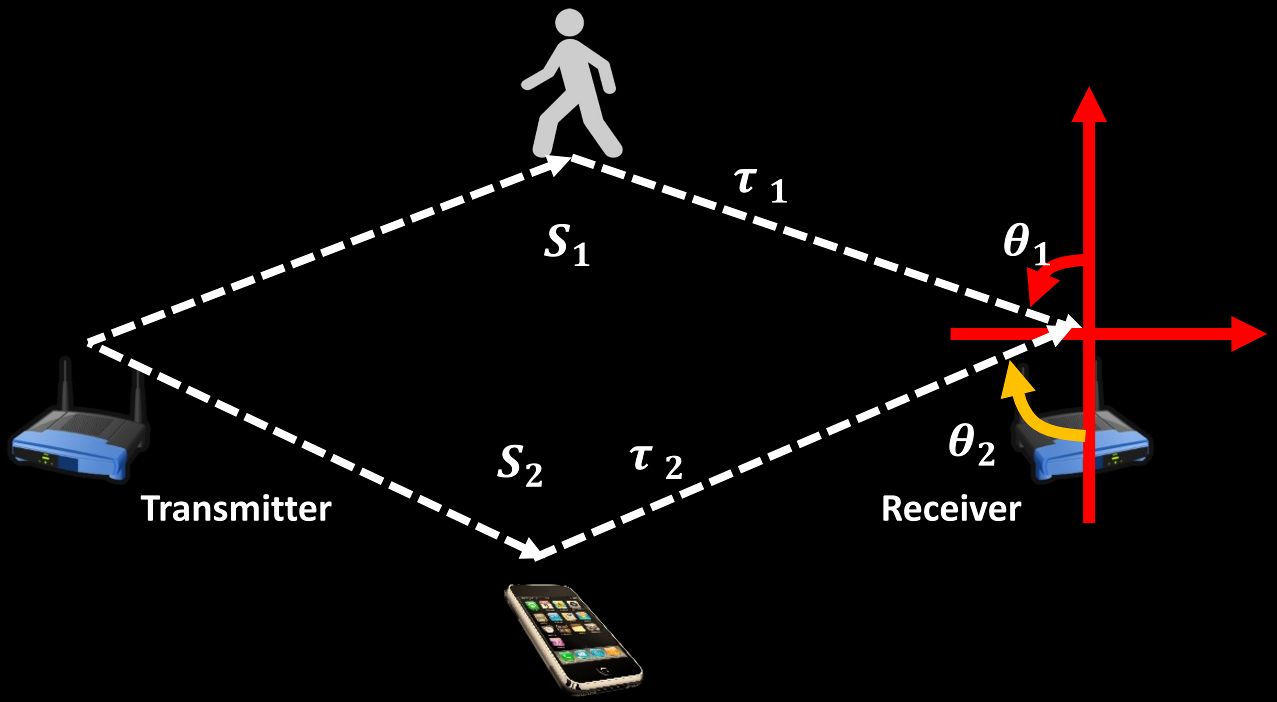
Larger bandwidth, higher time resolution

Increase the number of antennas

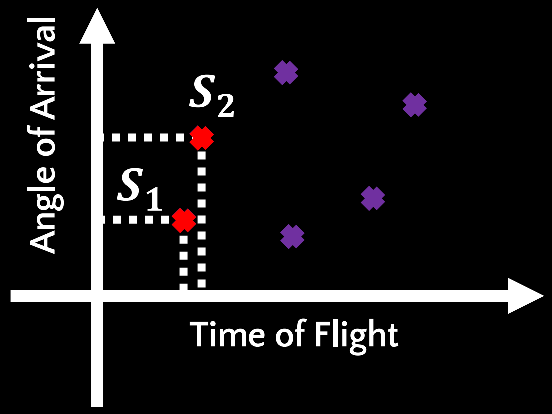
Any other solutions? ?

Increase the bandwidth

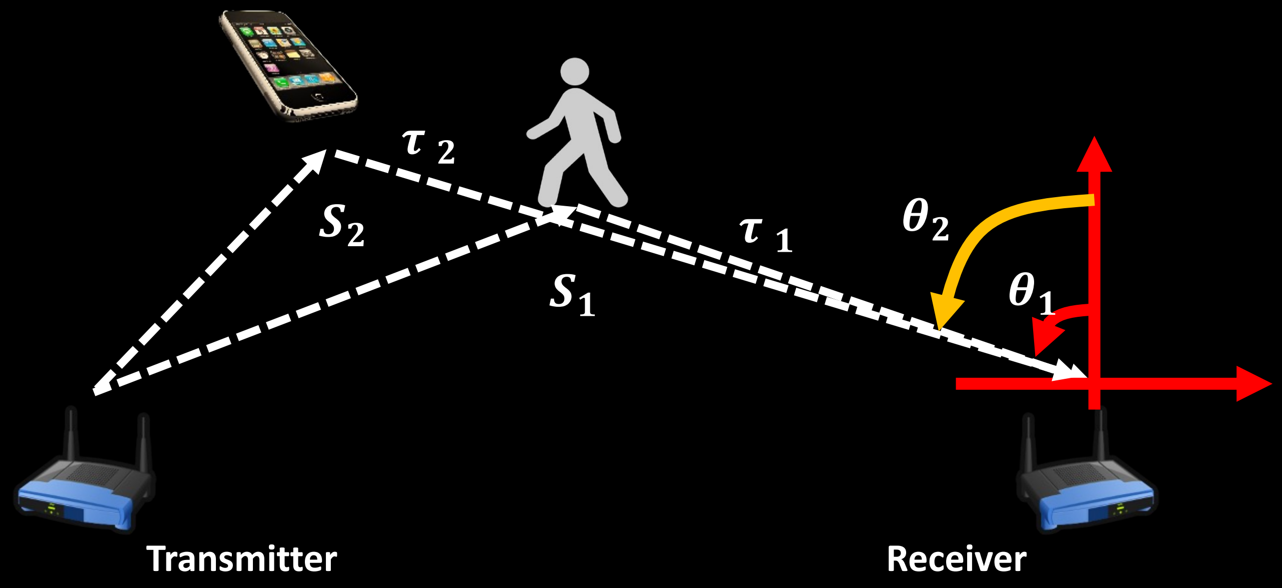
ToF and AoA: Resolution
Multi-dimensionality



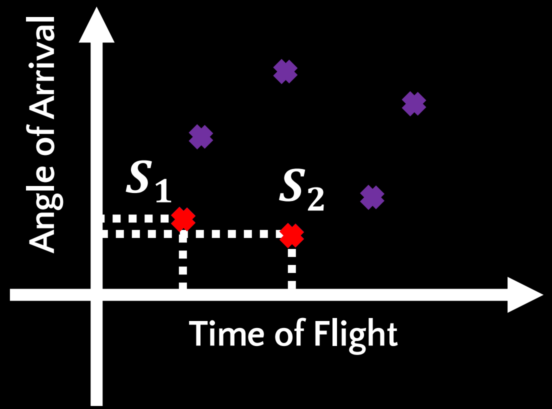
Two signals are close in time domain but far away in spatial domain



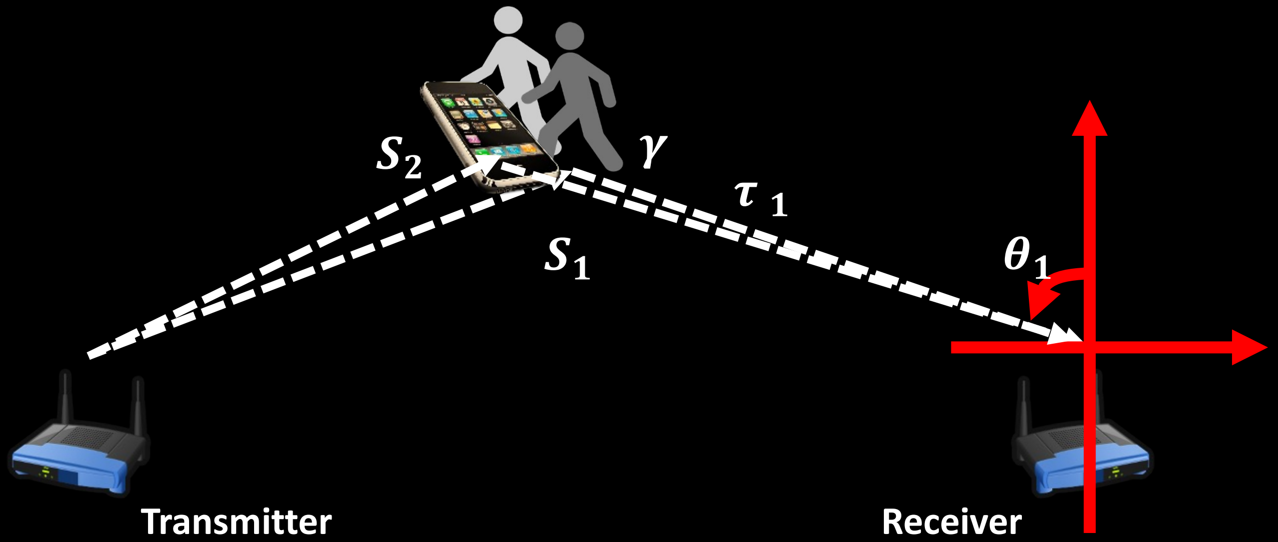
ToF and AoA: Resolution
Multi-dimensionality



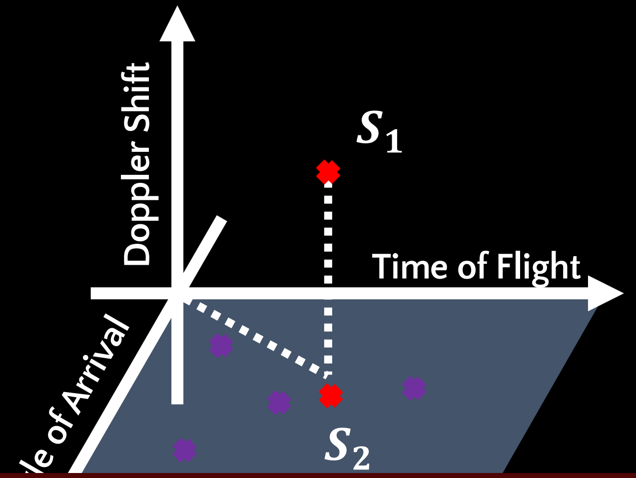
Two signals are close in spatial domain but far away in time domain



ToF and AoA: Resolution
Multi-dimensionality



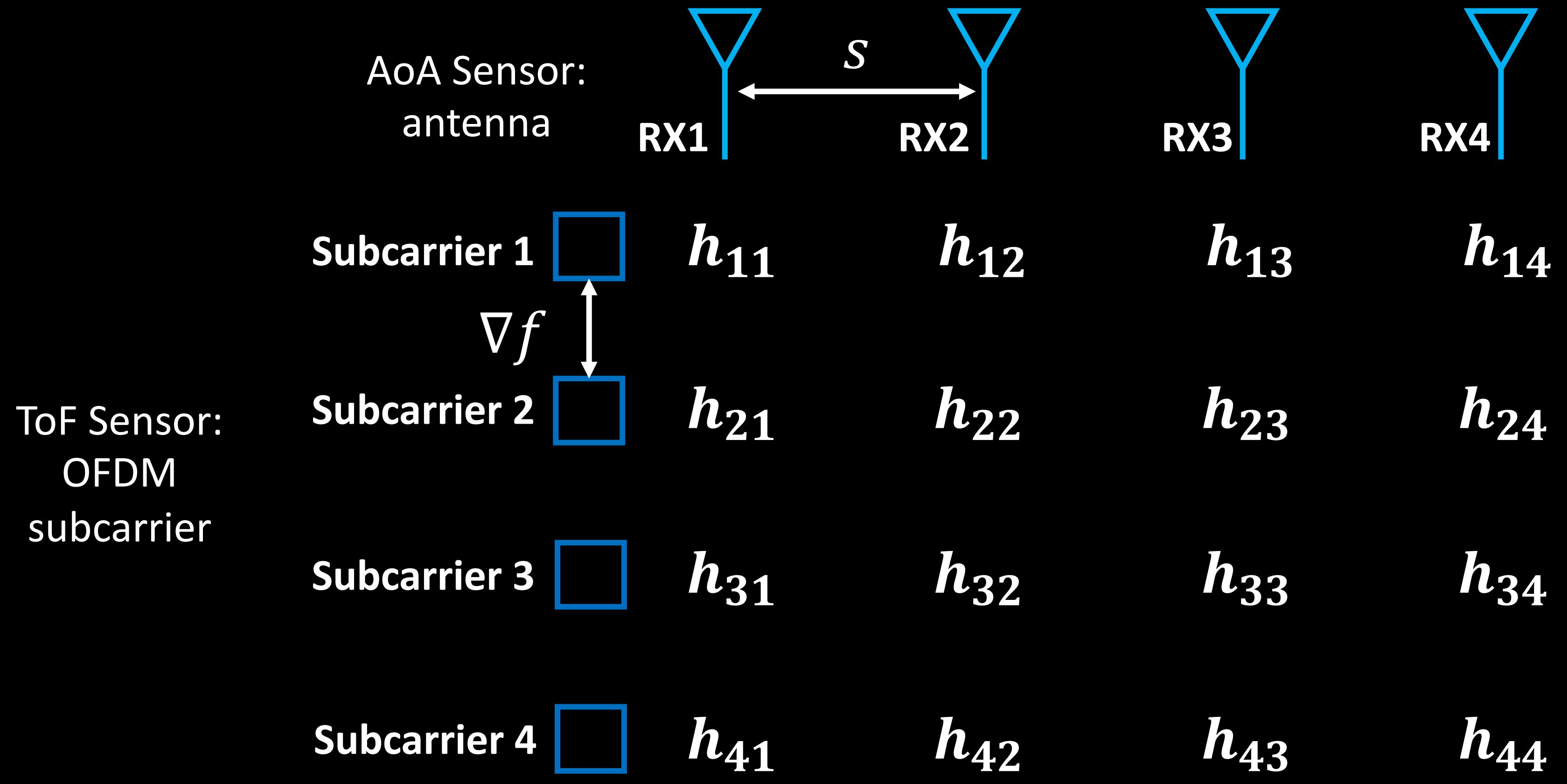
Two signals close in both spatial and time domain can be separated in frequency domain (Doppler shift)



How does the algorithm work? Input/output?

ToF and AoA: Resolution

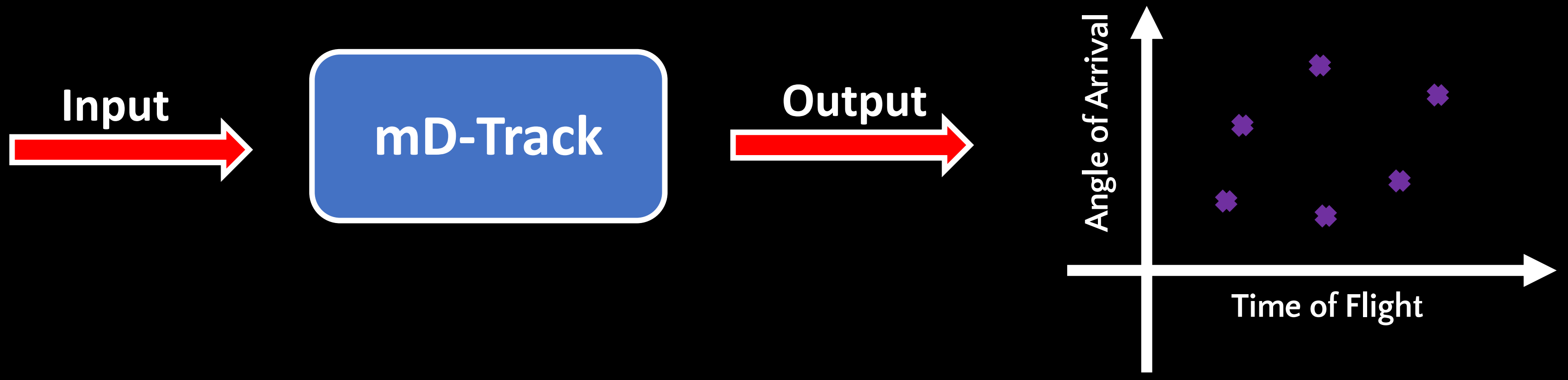
Multi-dimensionality



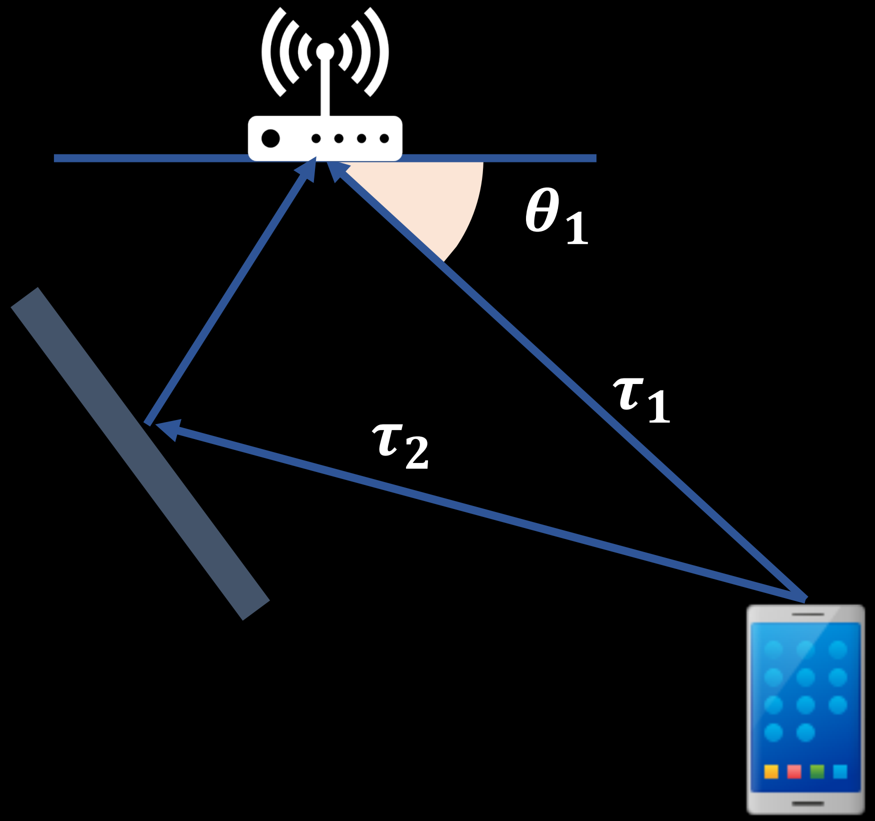
ToF and AoA: Resolution
Multi-dimensionality

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix}$$

Channel measured from all
antennas and all subcarriers



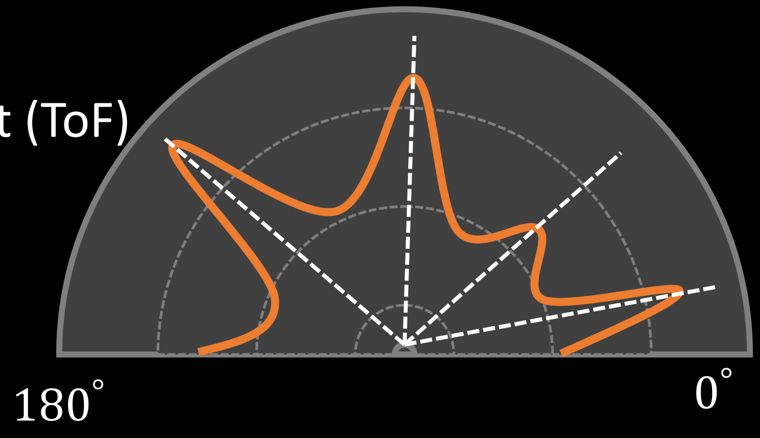
ToF and AoA: Resolution
Multi-dimensionality



Jointly estimate both ToF and AoA for each multipath

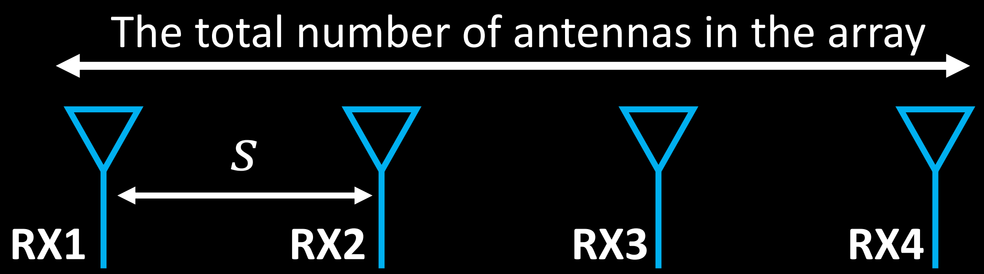
- Simultaneously ToF and AoA
- Higher resolution
- Higher accuracy

Hint 3: shortest path
→ smallest Time of Flight (ToF)



ToF and AoA: Resolution

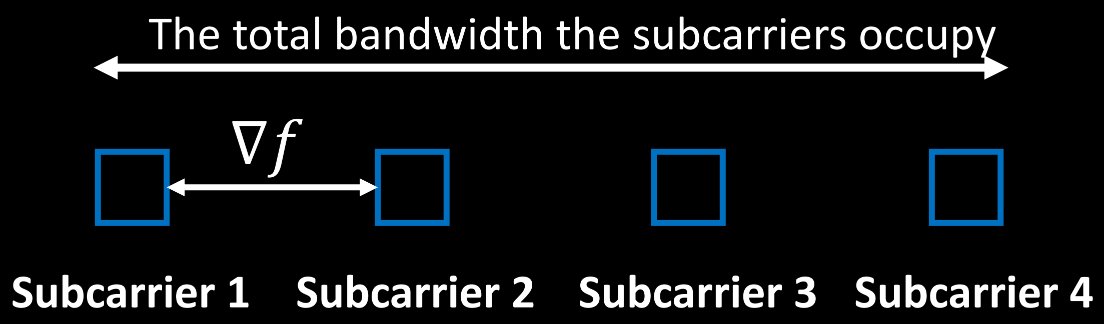
AoA Sensor: antenna



More antennas, higher spatial resolution

Increase the number of antennas

ToF Sensor: OFDM subcarrier



Larger bandwidth, higher time resolution

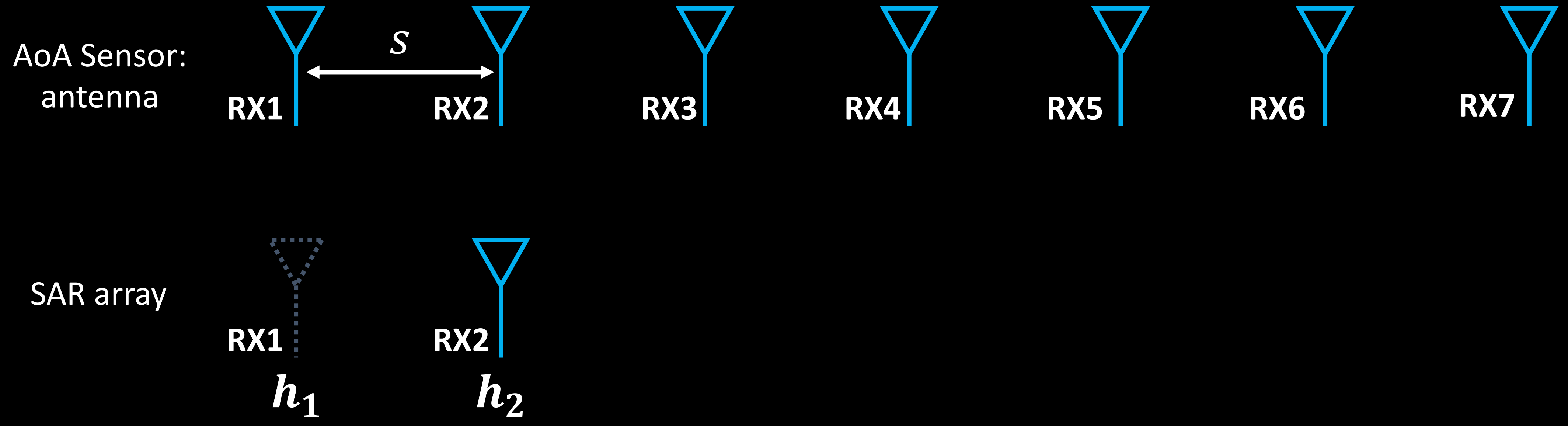
Increase the bandwidth

Improving the AoA resolution:
Synthetic Aperture Radar

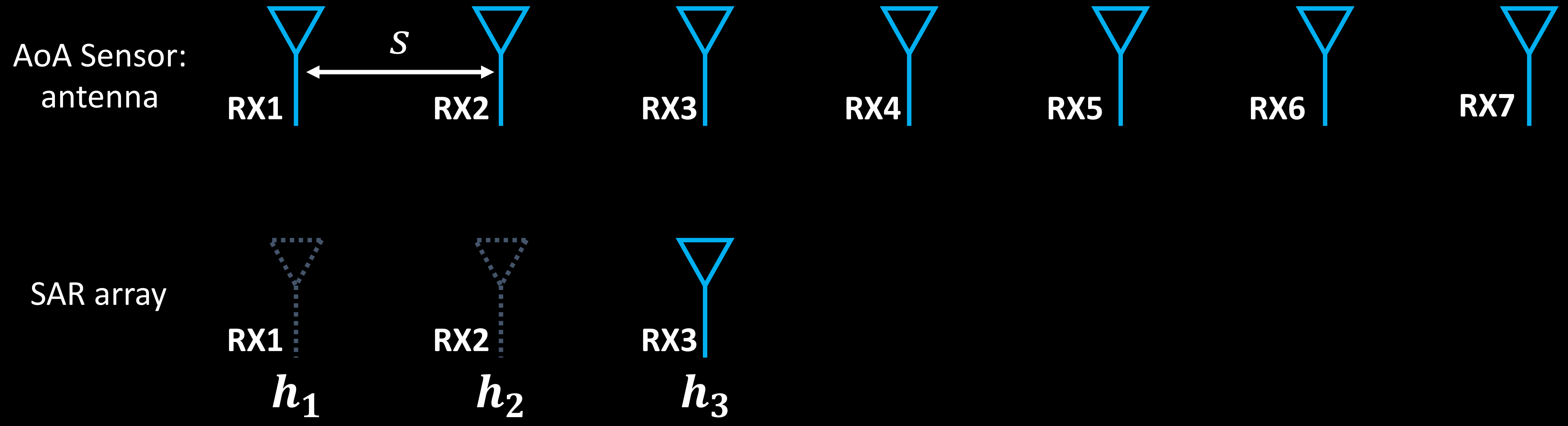
AoA Sensor:
antenna

Improving the AoA resolution:
Synthetic Aperture Radar

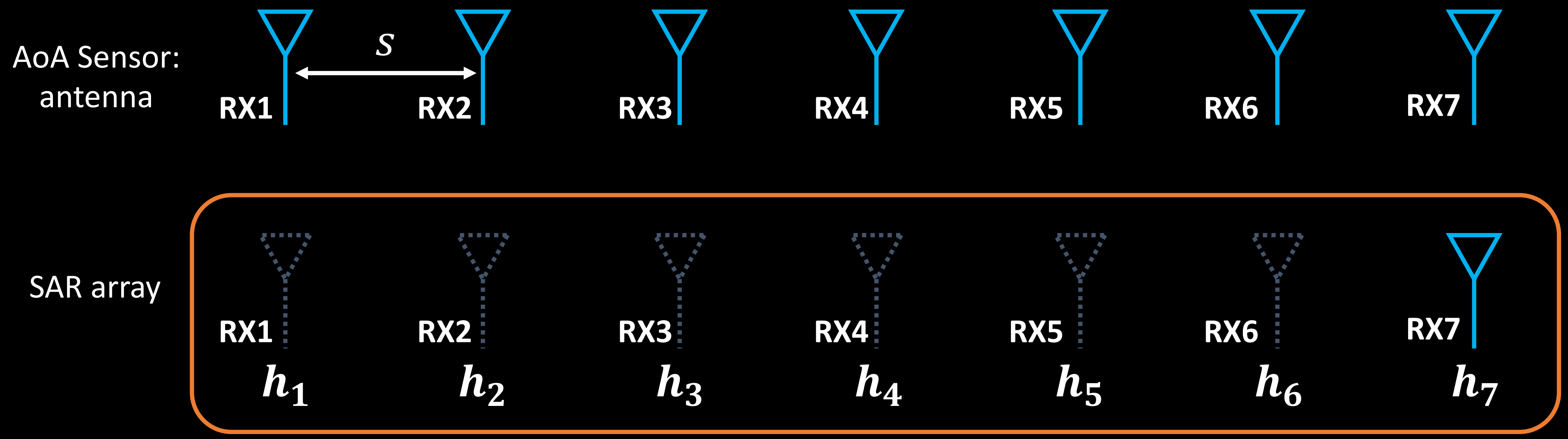
Improving the AoA resolution:
Synthetic Aperture Radar



Improving the AoA resolution:
Synthetic Aperture Radar

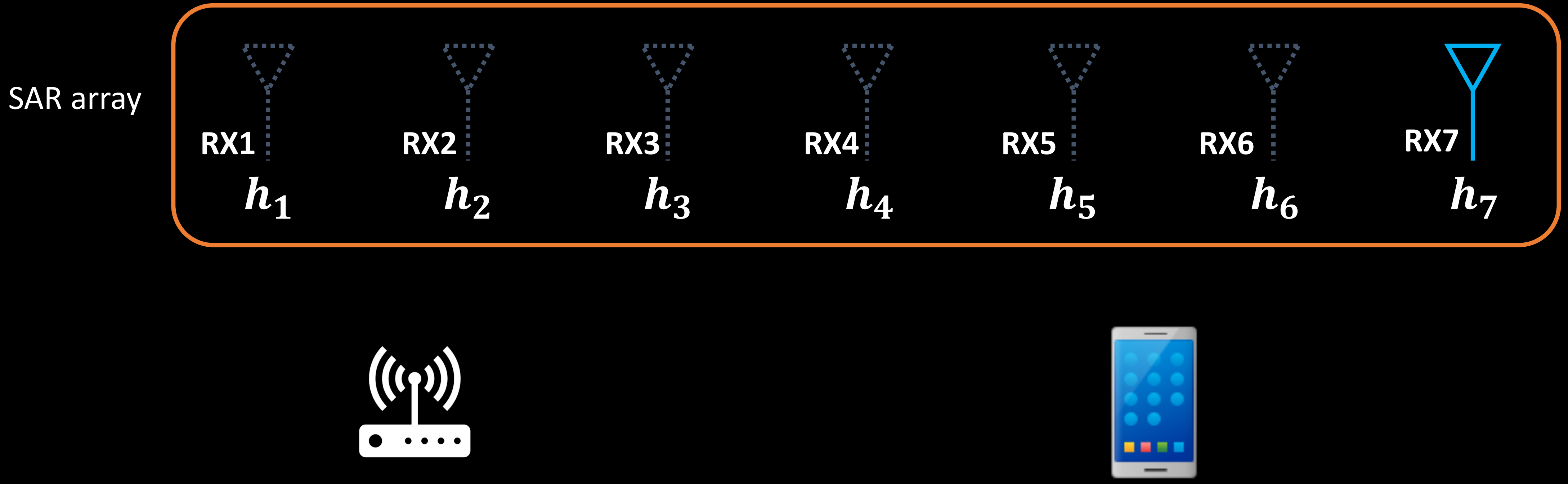


Improving the AoA resolution:
Synthetic Aperture Radar

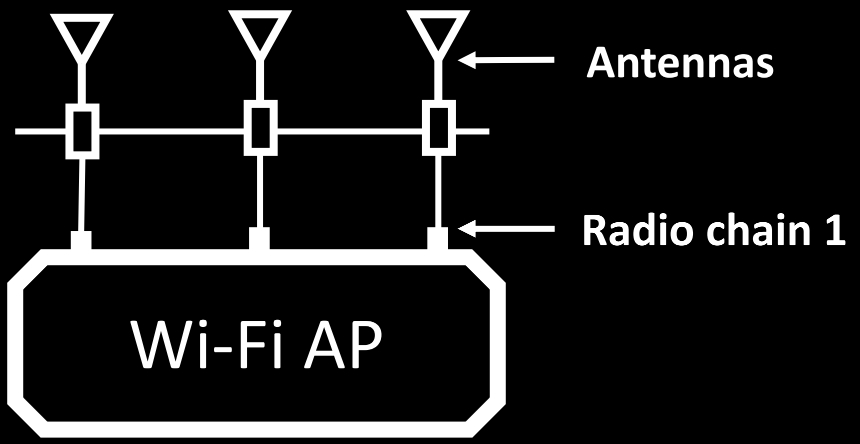


Improving the AoA resolution:

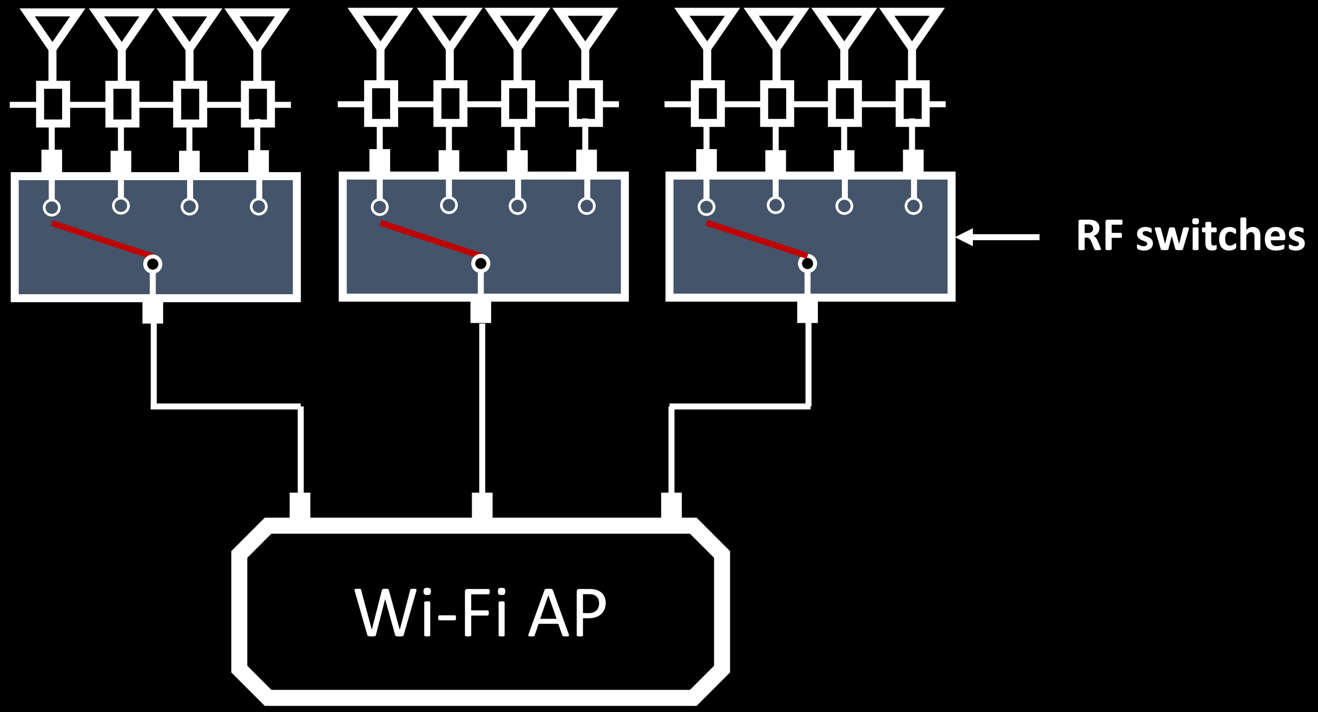
Synthetic Aperture Radar



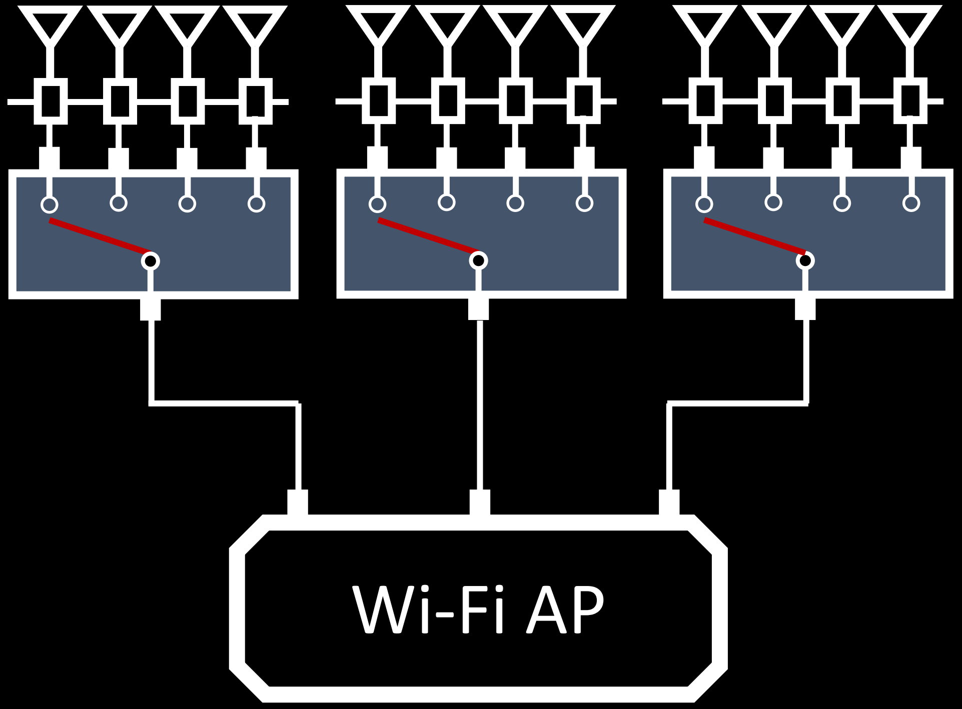
Improving the AoA resolution:
antenna switching



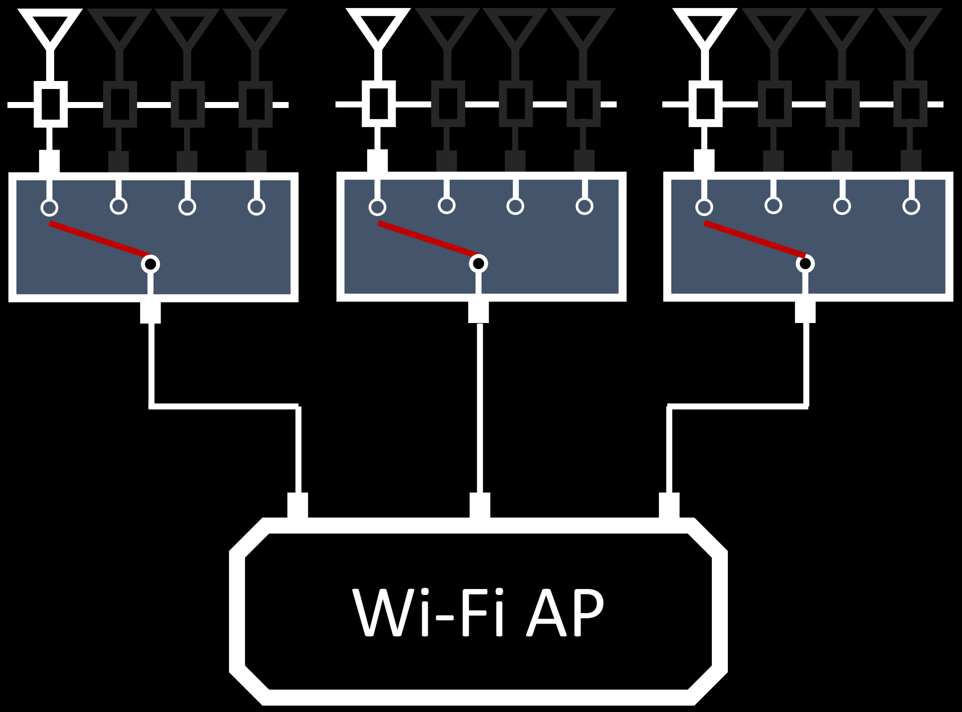
Improving the AoA resolution:
antenna switching

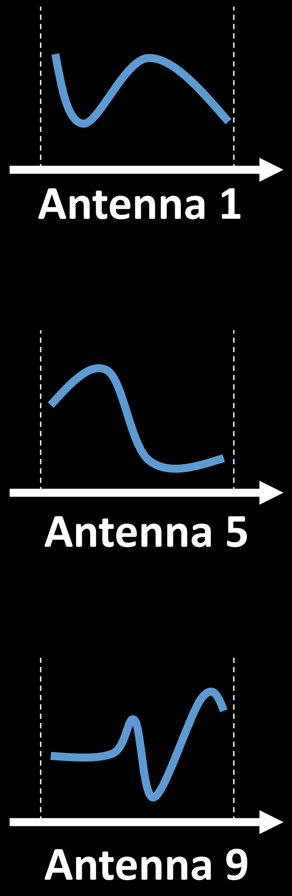


Improving the AoA resolution:
antenna switching

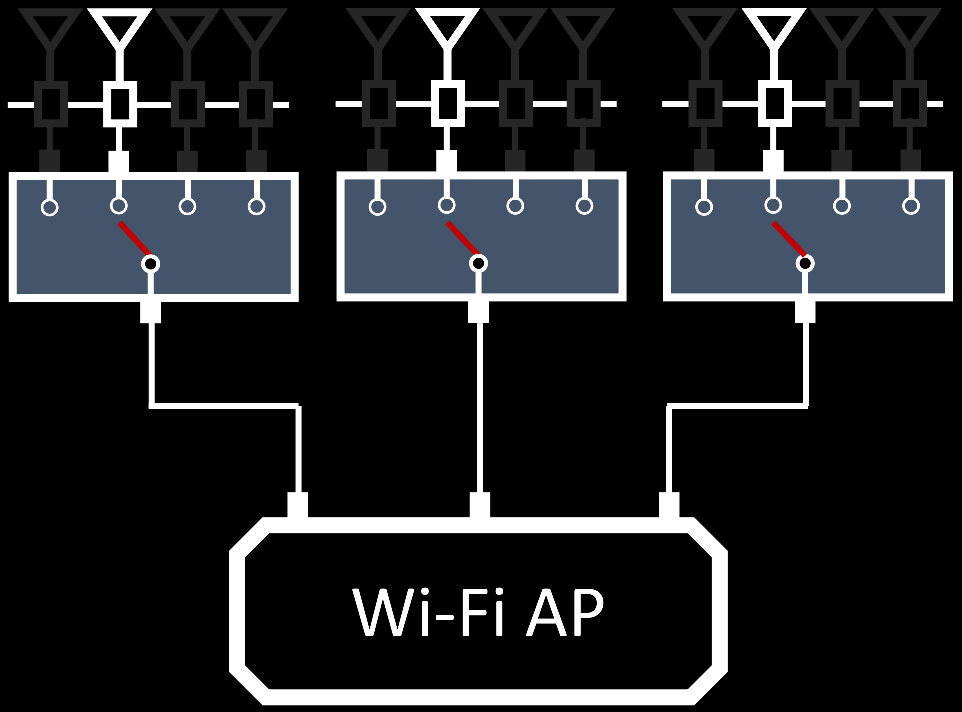


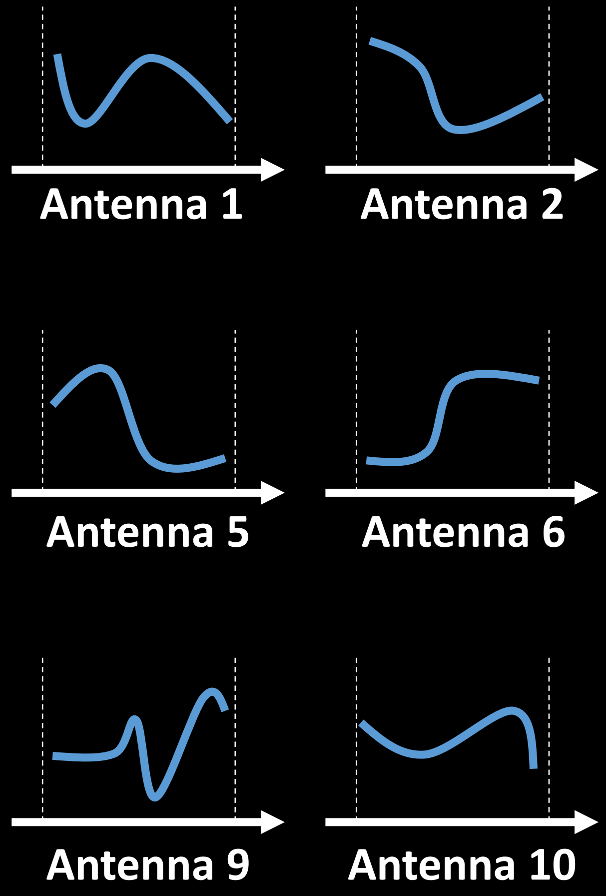
Improving the AoA resolution:
antenna switching



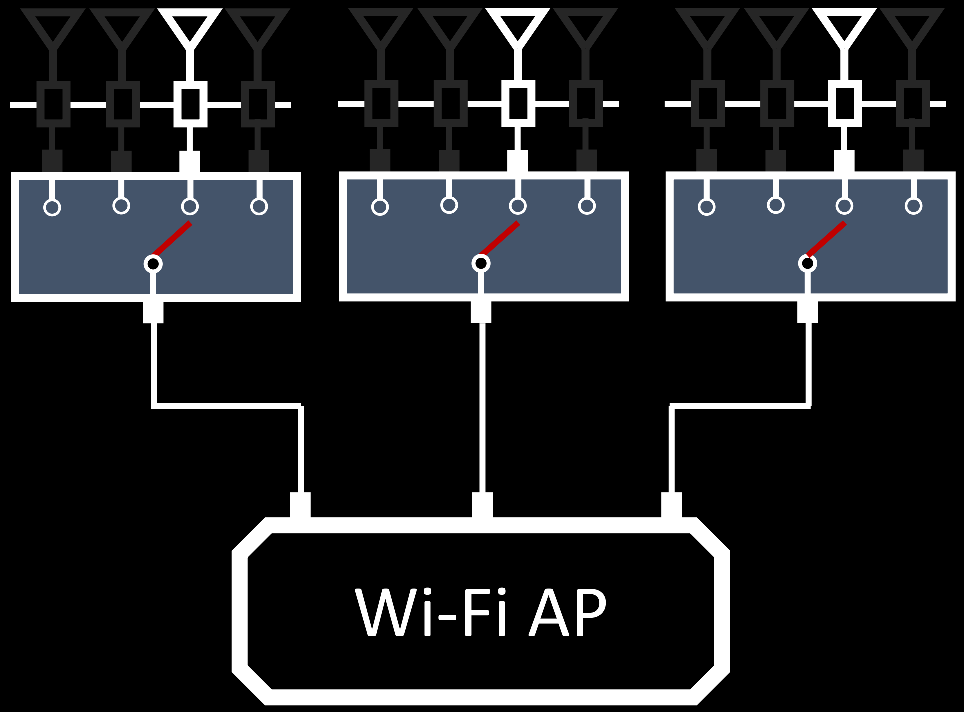


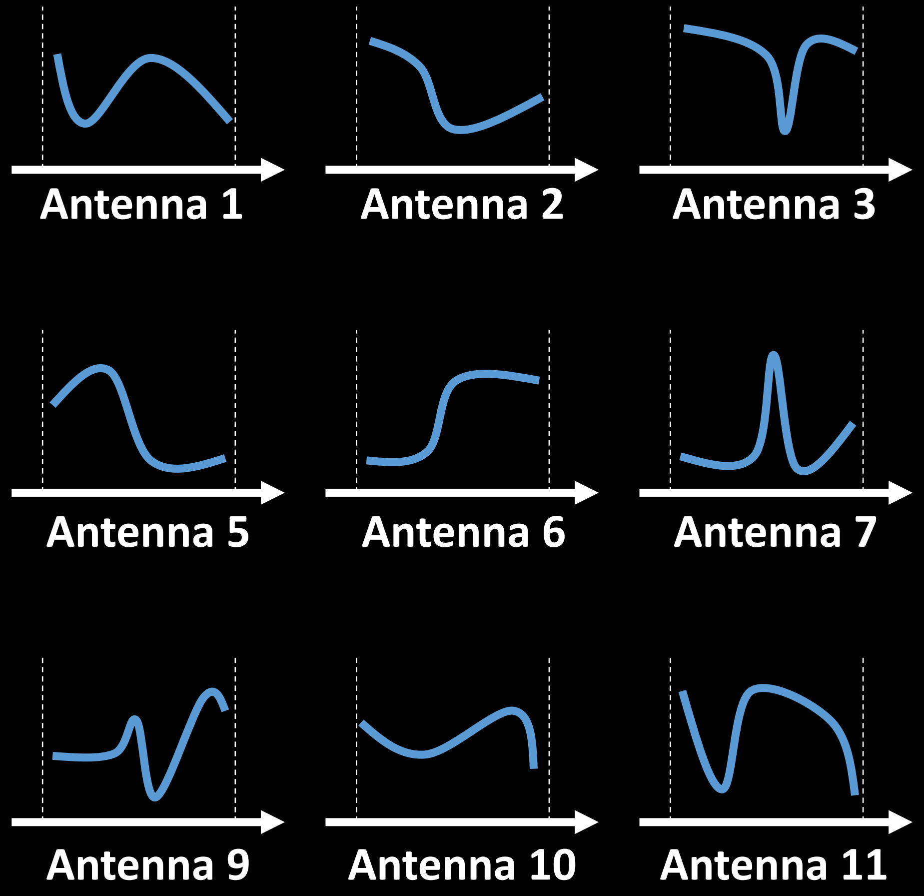
Improving the AoA resolution:
antenna switching



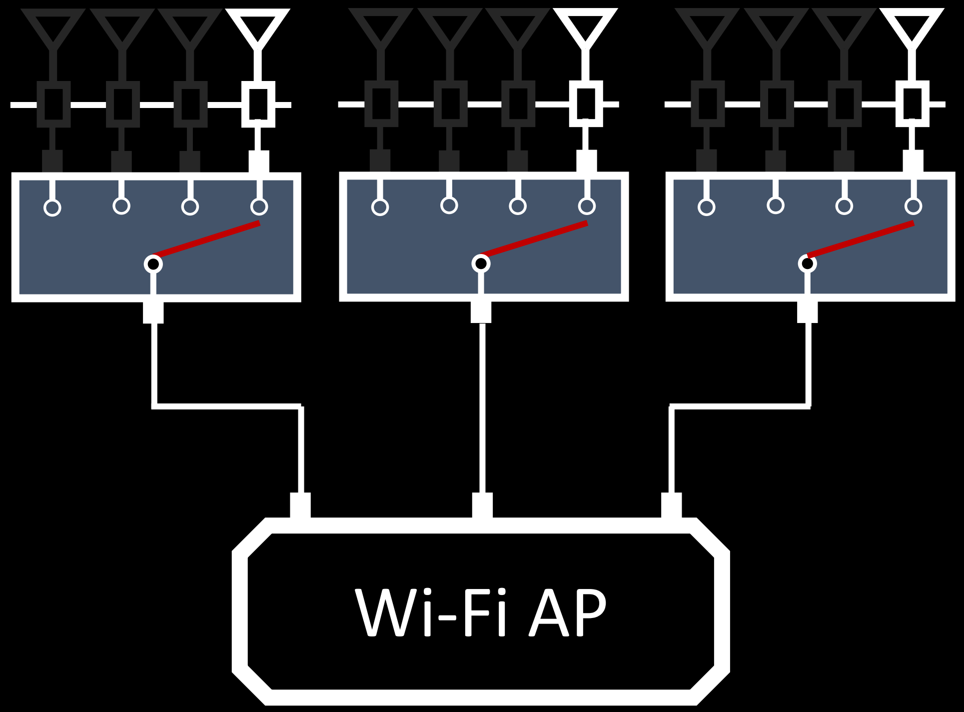


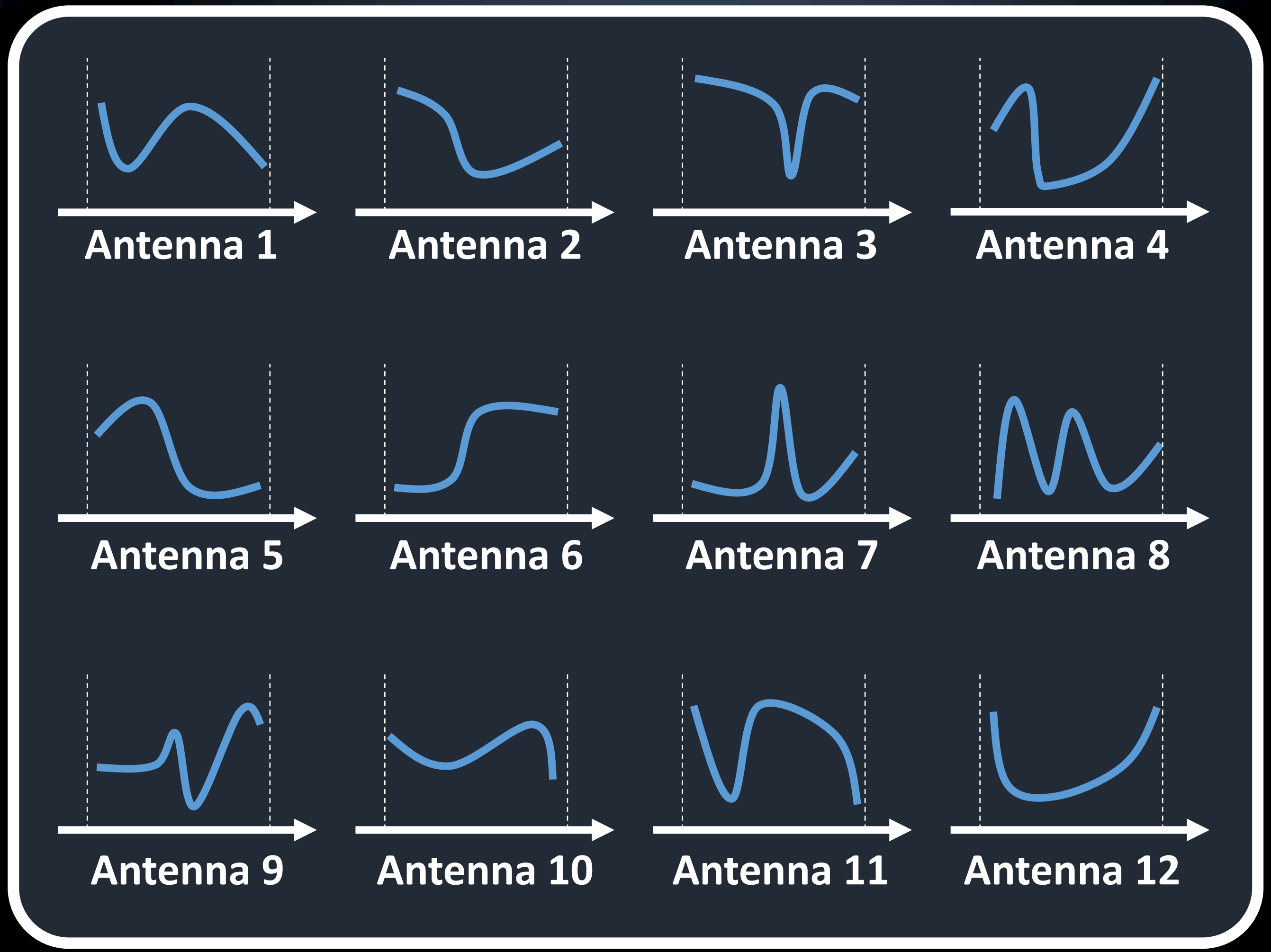
Improving the AoA resolution:
antenna switching





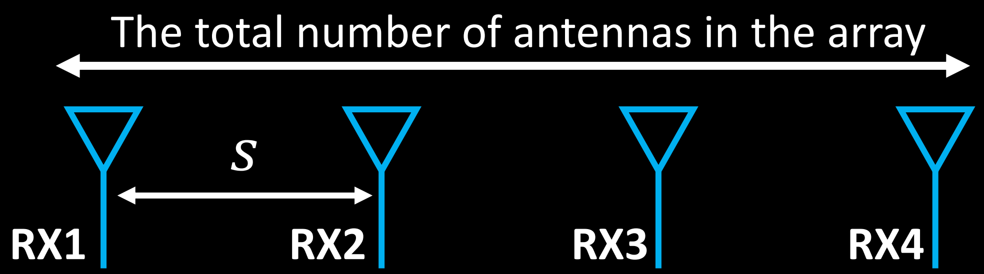
Improving the AoA resolution:
antenna switching





ToF and AoA: Resolution

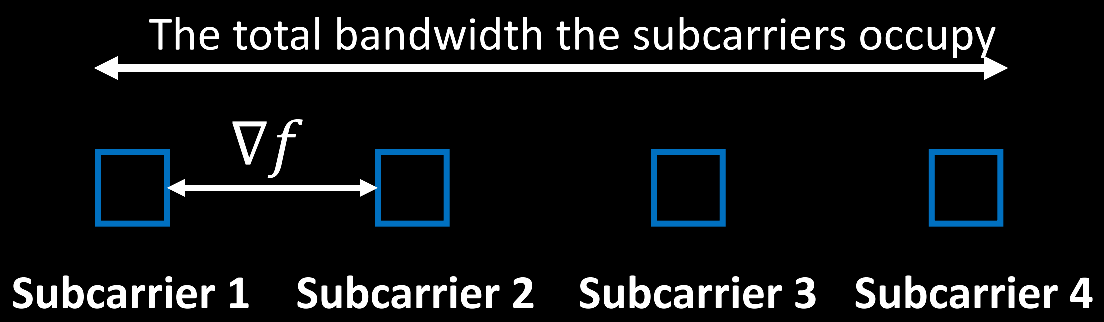
AoA Sensor: antenna



More antennas, higher spatial resolution

Increase the number of antennas

ToF Sensor: OFDM subcarrier



Larger bandwidth, higher time resolution

Increase the bandwidth

Improving the ToF resolution:
FMCW

Nyquist sampling theorem: *To truthfully recover a signal, we need to sample at twice the highest frequency, i.e.,* $2f$

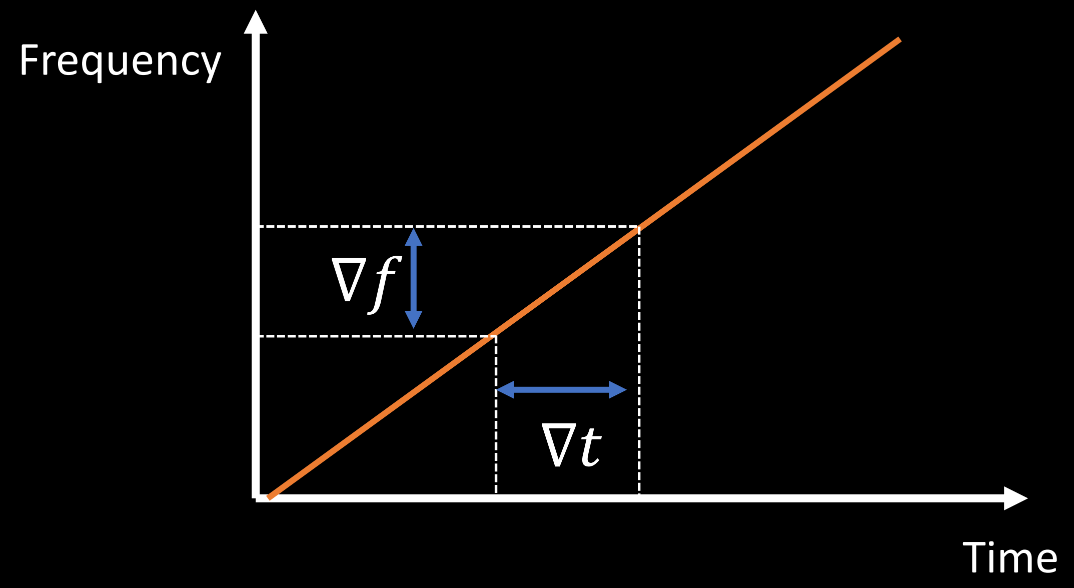
Wi-Fi bandwidth of 20 MHz requires an ADC/DAC that can sample at 40 MS/s

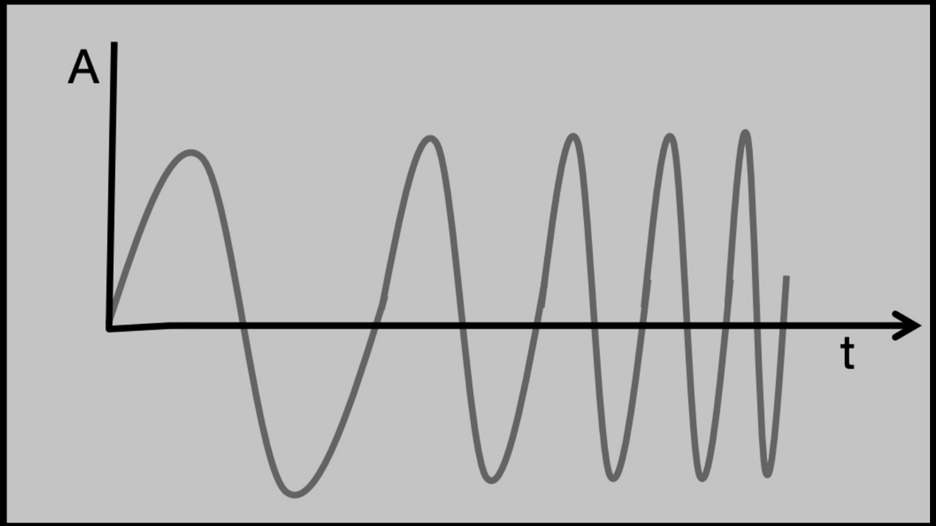
A signal bandwidth of 1 GHz requires an ADC/DAC that can sample at 2 GS/s

The interval between two samples is 0.5 ns !!

Improving the ToF resolution:
FMCW

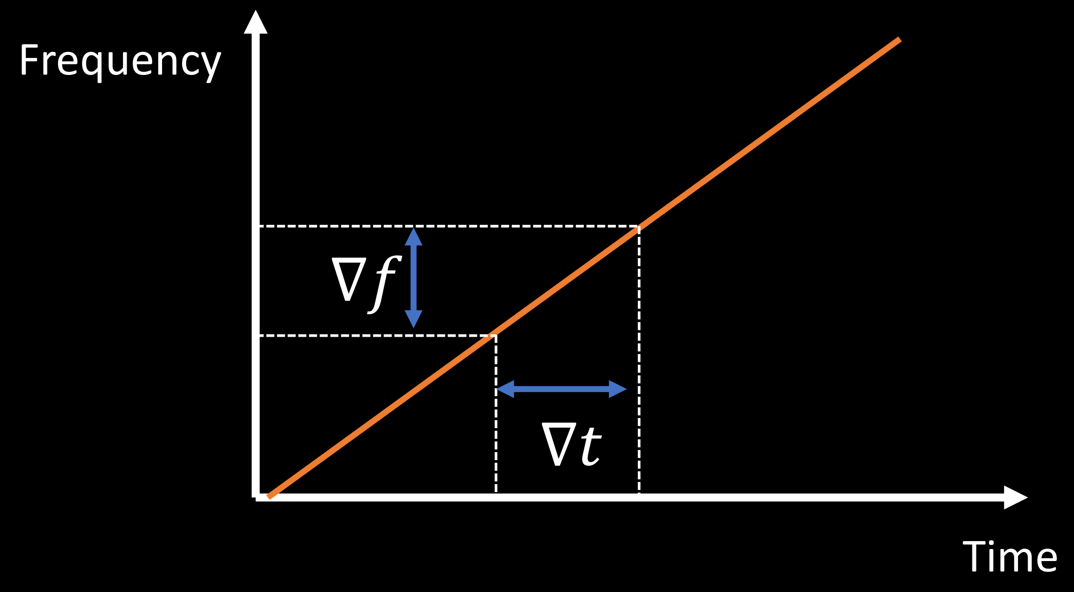
FMCW: Frequency-Modulated Continuous Wave





Improving the ToF resolution:
FMCW

FMCW: Frequency-Modulated Continuous Wave

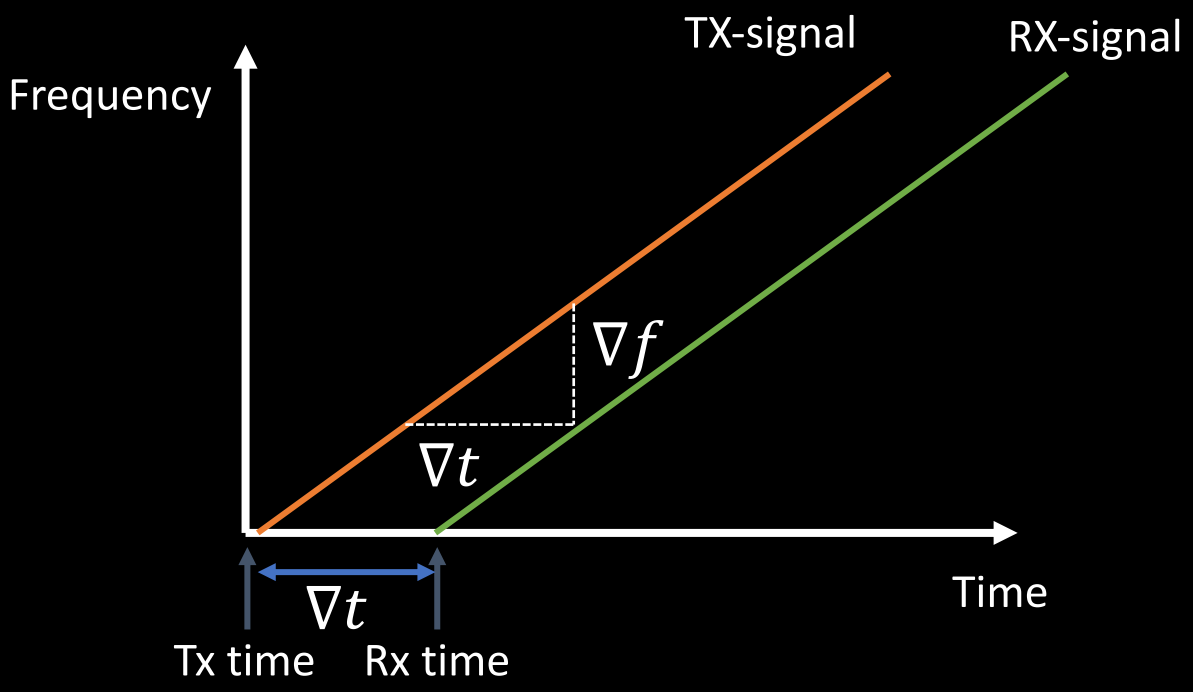


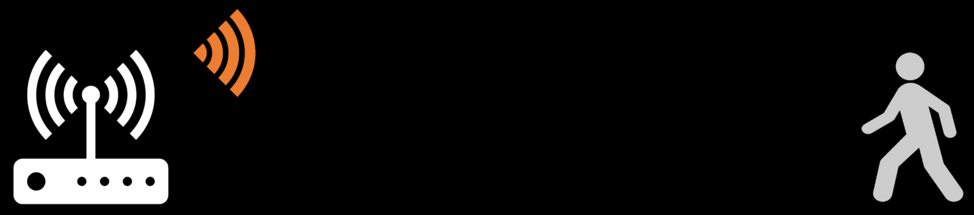
$$s(t) = \sin(2\pi f(t) \cdot t + \theta)$$

Frequency changes linearly with time

Improving the ToF resolution:
FMCW

FMCW: Frequency-Modulated Continuous Wave

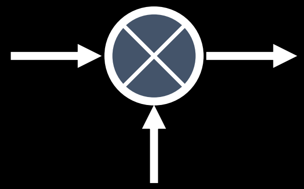




Improving the ToF resolution:
FMCW

FMCW: Frequency-Modulated Continuous Wave

$\sin(2\pi f t)$

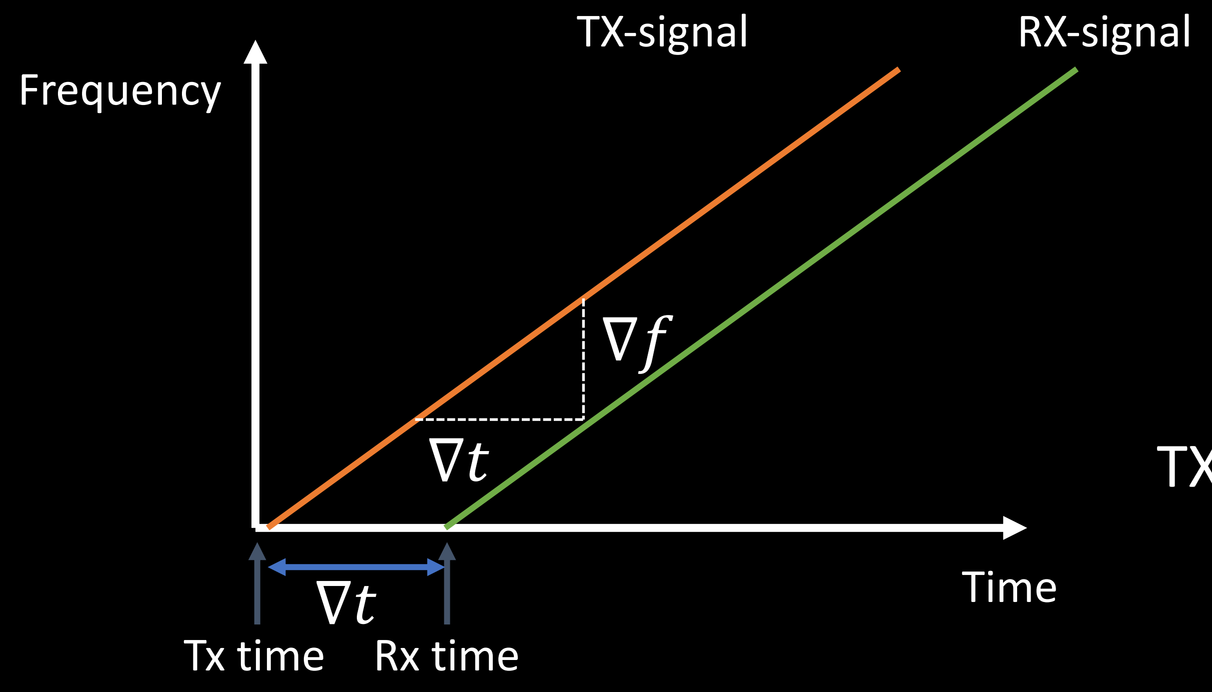


$\cos(2\pi f_c t)$

$$\sin(2\pi f t) \cdot \cos(2\pi f_c t) \quad = \frac{1}{2}[\sin(2\pi (f_c + f) t) - \sin(2\pi (f_c - f) t)]$$

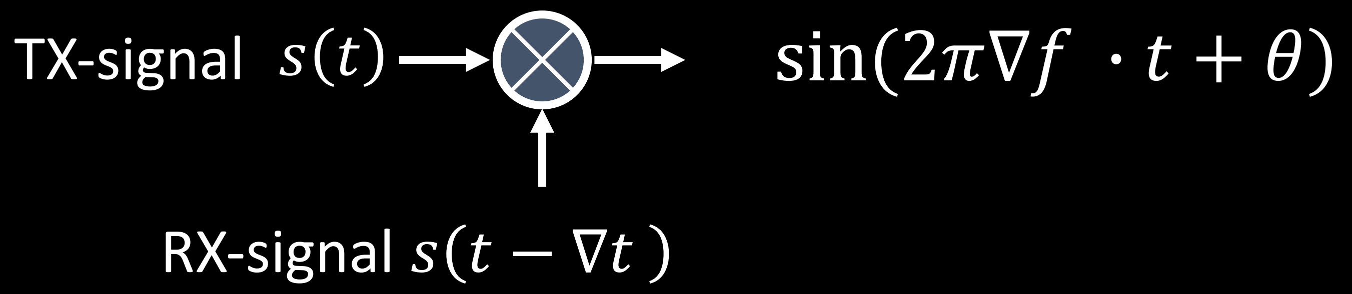
Improving the ToF resolution:
FMCW

FMCW: Frequency-Modulated Continuous Wave



$$s(t) = \sin(2\pi f(t) \cdot t + \theta)$$

$$s(t - \nabla t) = \sin(2\pi f(t - \nabla t) \cdot t + \theta)$$



Improving the ToF resolution:
FMCW

FMCW: Frequency-Modulated Continuous Wave