ECE 598HH: Advanced Wireless Networks and Sensing Systems

Lecture 10: Localization Part 1

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Wireless Localization / Positioning

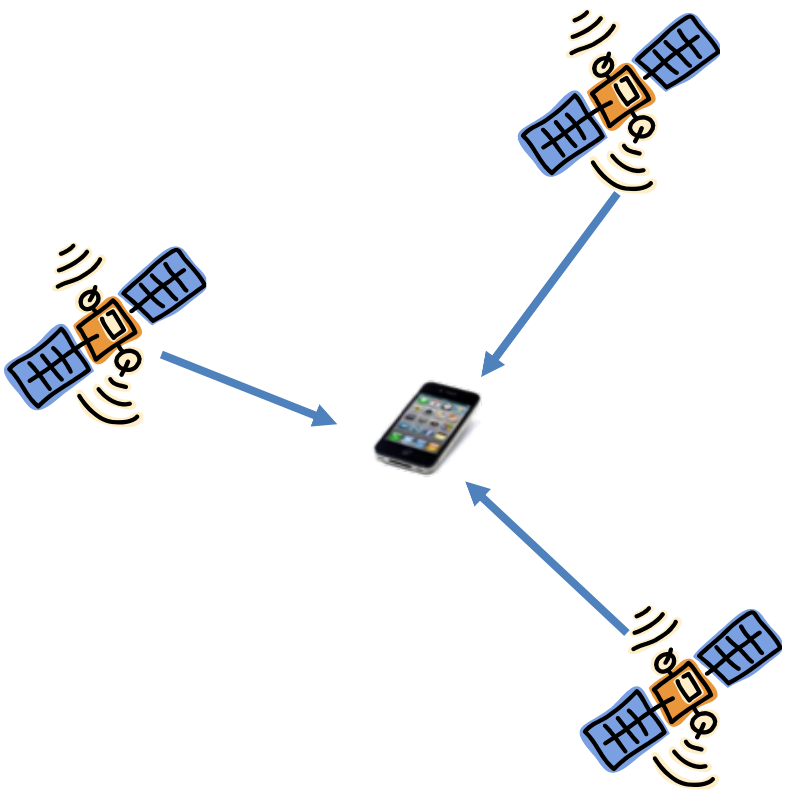
The process of obtaining a human or object's location using wireless signals

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 Architecture.

- Device based: A device uses incoming signal from one or more “anchors” to determine its own location



- Network based: Anchors (or Access points) use the signal coming from device to determine its location

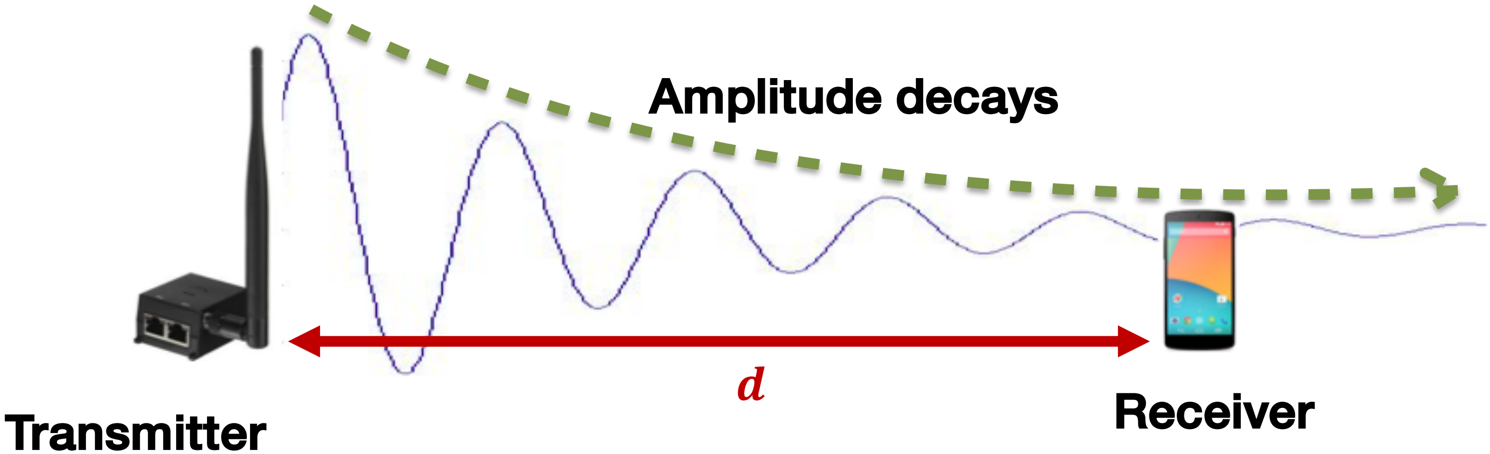
Wireless Localization

This Lecture: Focus on WiFi Localization

Future Lectures: Other wireless technologies

Method 1: RSSI Based Localization

- Higher received power → Closer
- Lower received power → Farther

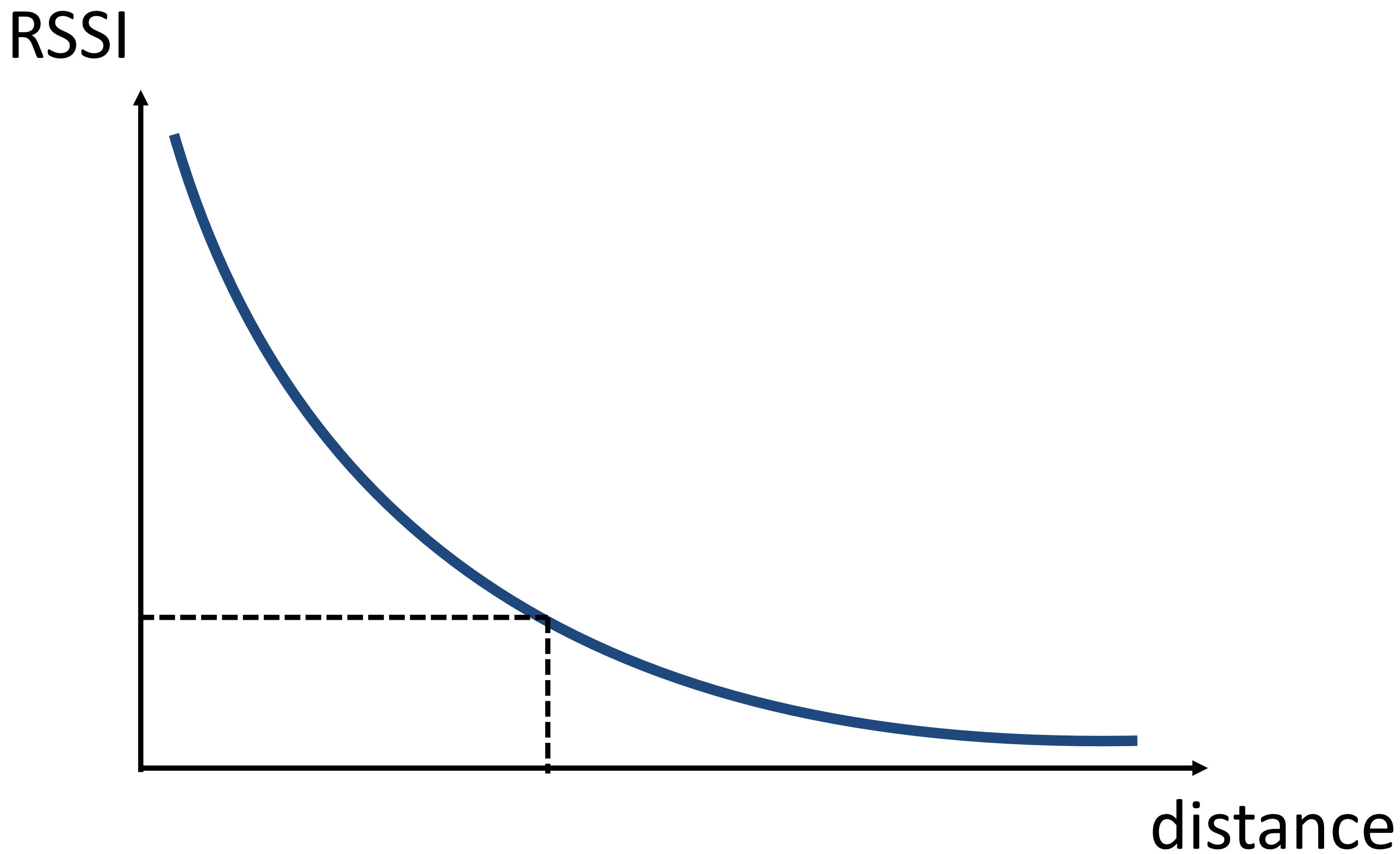


$$P_{Rx} = \frac{G_{Tx}\, G_{Rx}\, \lambda^2}{(4\pi d)^2}\, P_{Tx} \quad \Rightarrow \quad RSSI \propto \frac{1}{d^2}$$

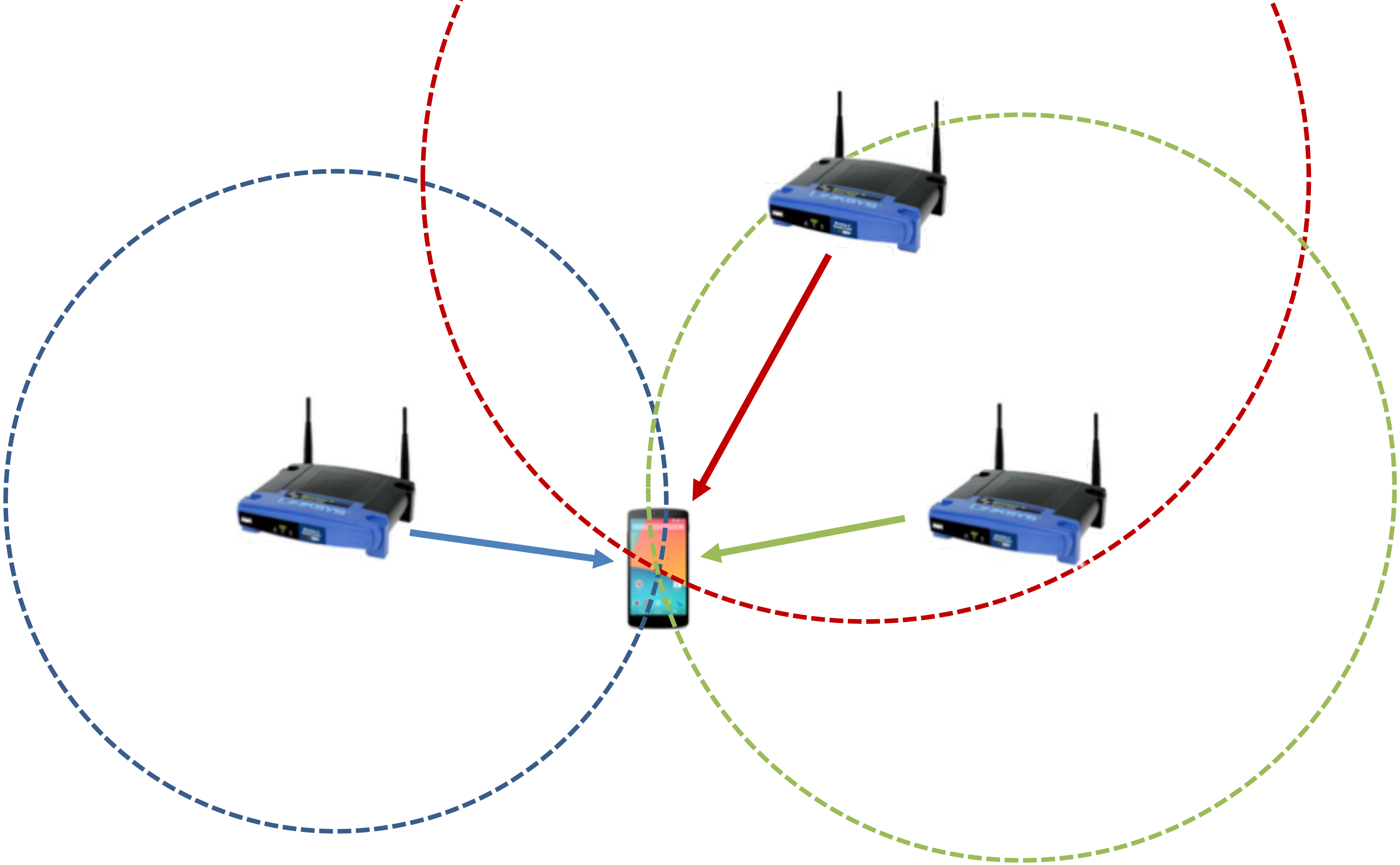
Use RSSI to estimate distance from APs!

Method 1: RSSI Based Localization

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



Method 1: RSSI Based Localization

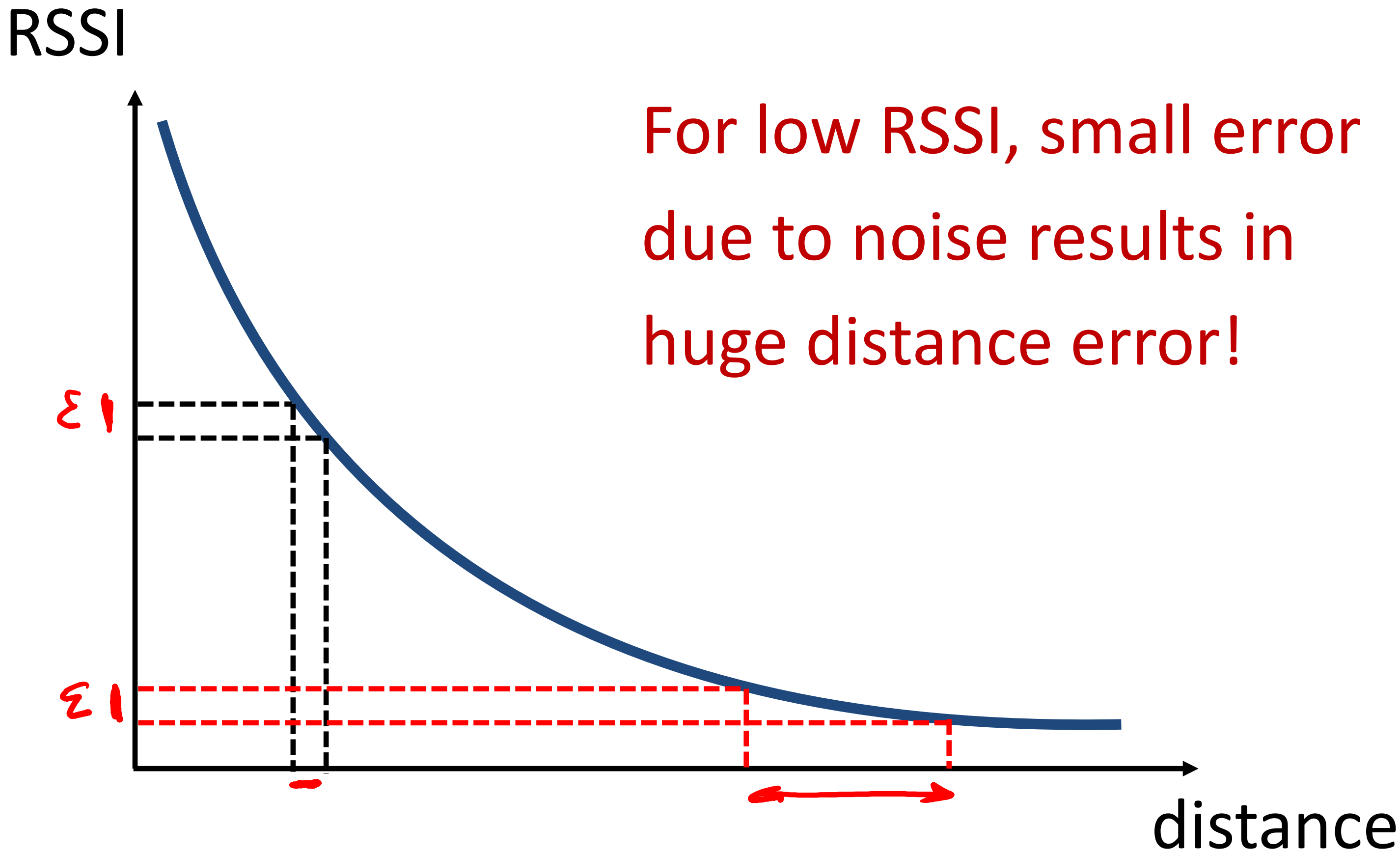


Trilateration

Method 1: RSSI Based Localization

Pros: Very simple, no hardware modifications

Cons: Highly inaccurate!



For low RSSI, small error due to noise results in huge distance error!

Method 1: RSSI Based Localization

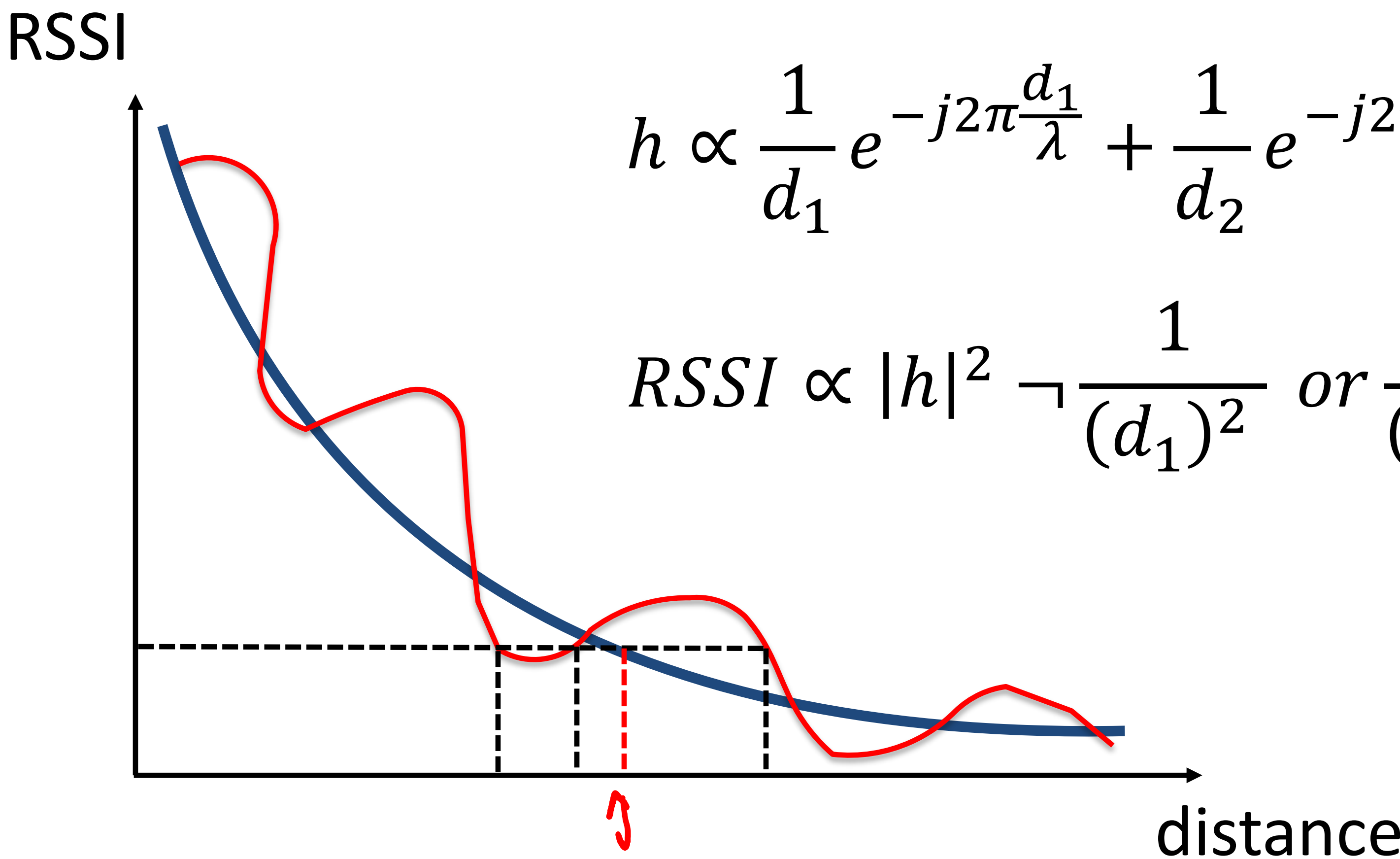
Pros: Very simple, no hardware modifications!

Cons: Highly inaccurate!

Does not work with multipath!

$$h \propto \frac{1}{d_1} e^{-j2\pi\frac{d_1}{\lambda}} + \frac{1}{d_2} e^{-j2\pi\frac{d_2}{\lambda}}$$

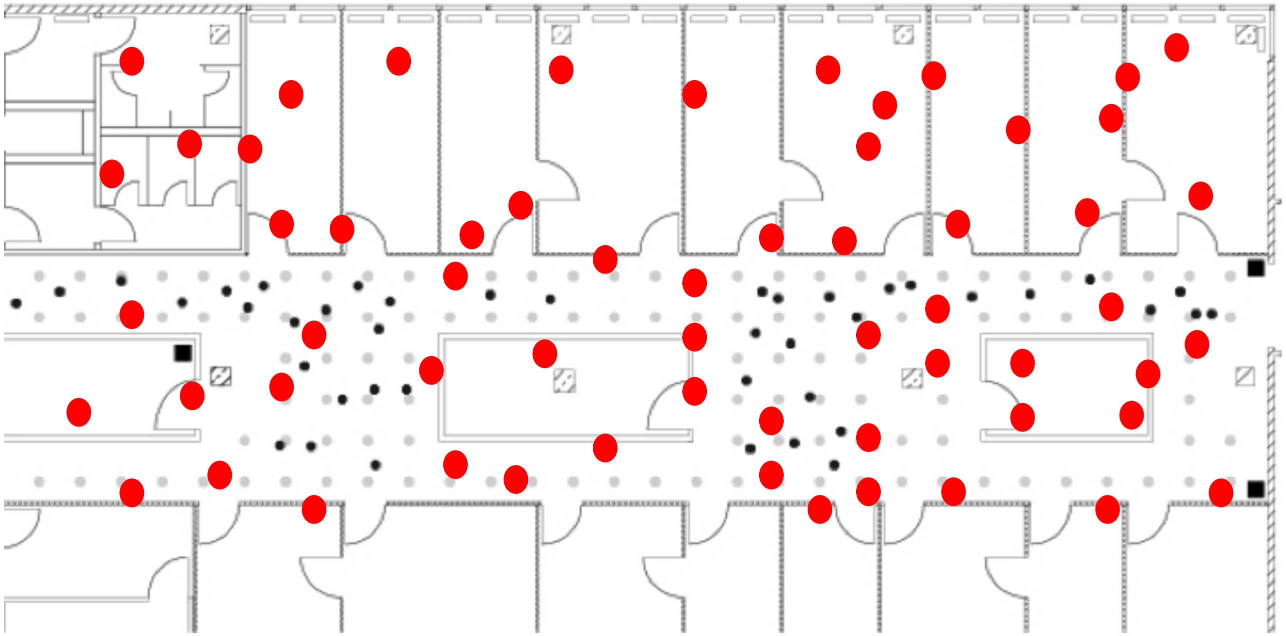
$$RSSI \propto |h|^2 \neg \frac{1}{(d_1)^2} \; or \; \frac{1}{(d_1)^2}$$



Method 1: RSSI Based Localization

Solution: Fingerprinting

Measure and records RSSI fingerprints at each location (war-driving)



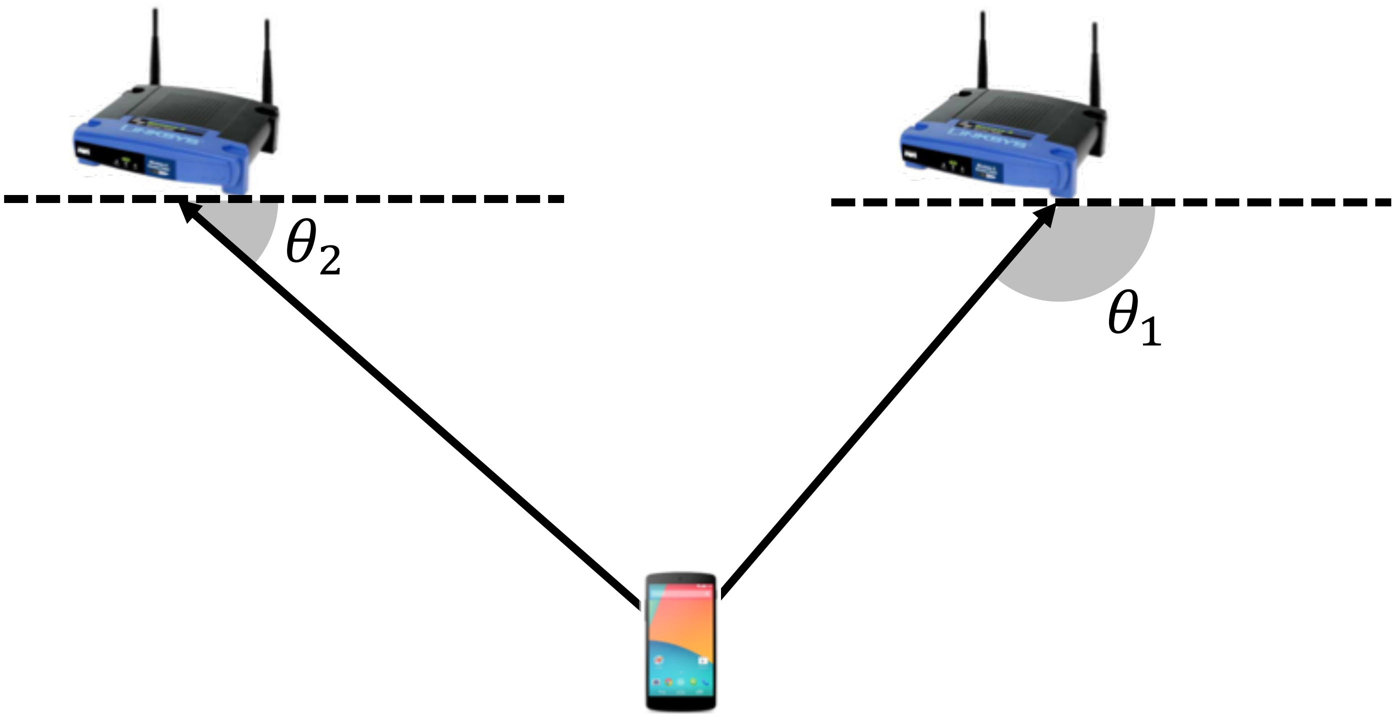
Pros: Works with multipath, No need to know AP locations!

Cons: Changes in environment/movement ➔ change RSSI!

Continuous training is needed. Lots of effort!

Method 2: AoA Based Localization

Measure Angle of Arrival (AoA) from device to each AP

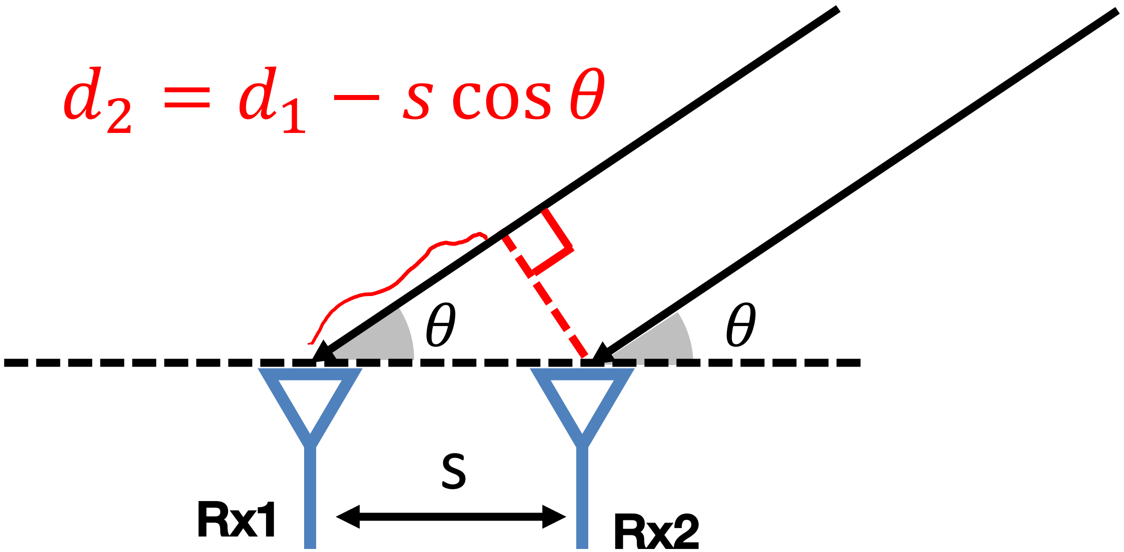


Triangulation

Method 2: AoA Based Localization

Measure Angle of Arrival (AoA) from device to each AP

$d_2 = d_1 - s\cos\theta$

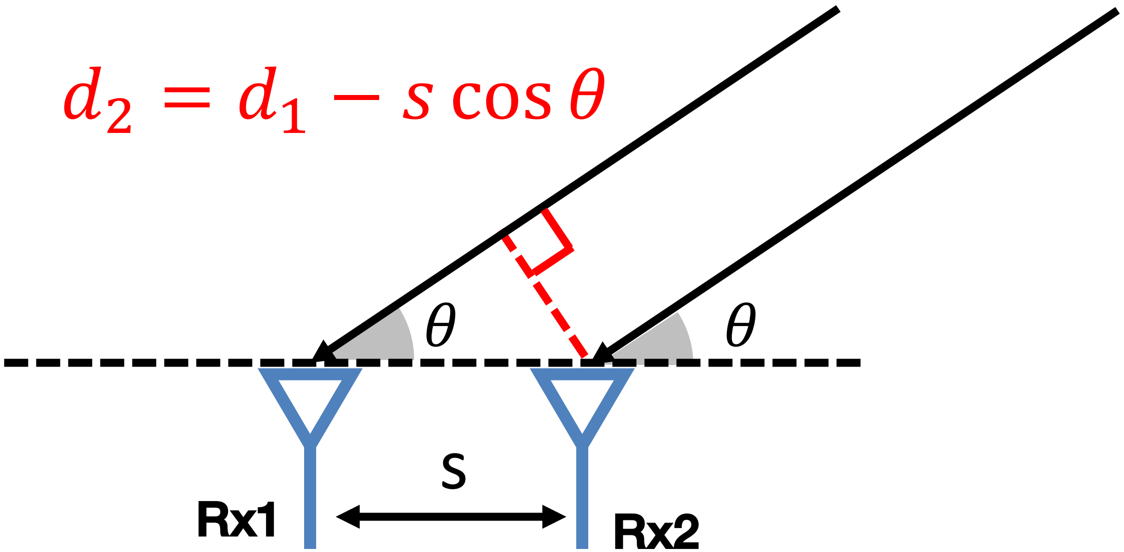


$h_1 \propto e^{-j2\pi\frac{d_1}{\lambda}}$ $\quad h_2 \propto e^{-j2\pi\frac{d_2}{\lambda}} = e^{-j2\pi\frac{d_1 - s\cos\theta}{\lambda}}$

$\Delta\Phi = \angle h_2 - \angle h_1 = 2\pi\, s\cos\theta\,/\lambda \ \mathrm{mod}\ 2\pi$

Method 2: AoA Based Localization

Measure Angle of Arrival (AoA) from device to each AP



$$\Delta\Phi = \angle h_2 - \angle h_1 = 2\pi\, s\cos\theta\,/\lambda \mod 2\pi$$

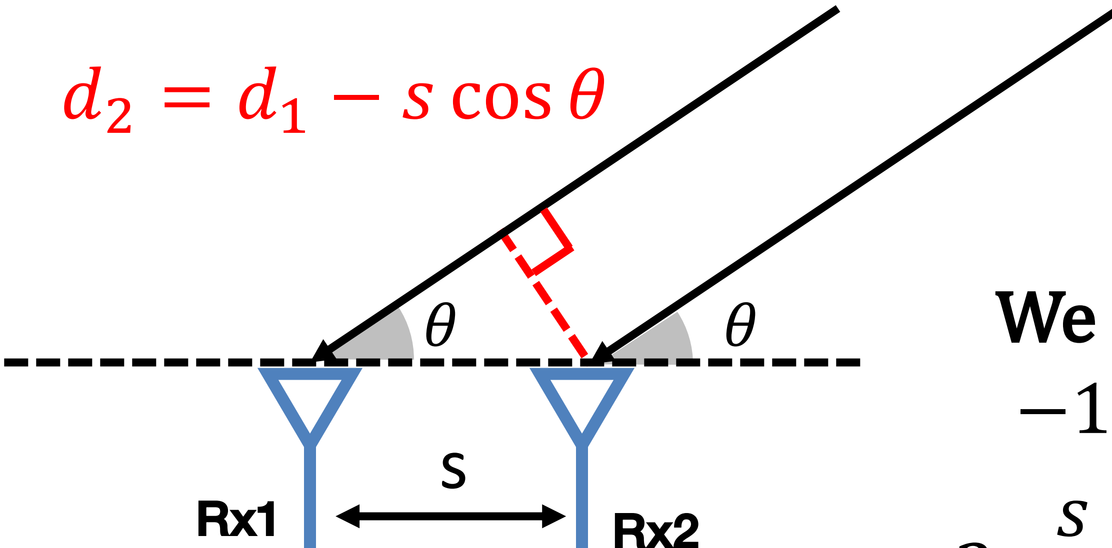
Ambiguity: $\exists\theta_1 \neq \theta_2 \mid \Delta\Phi_1 = \Delta\Phi_2 \mod 2\pi$

To avoid ambiguity, we want: $-\pi \leq \Delta\Phi \leq \pi$

Method 2: AoA Based Localization

Measure Angle of Arrival (AoA) from device to each AP

$$d_2 = d_1 - s\cos\theta$$



We want:

$$-\pi \le \Delta\Phi \le \pi$$

We have:

$$-1 \le \cos\theta \le 1$$

$$-2\pi\frac{s}{\lambda} \le 2\pi\frac{s}{\lambda}\cos\theta \le 2\pi\frac{s}{\lambda}$$

$$-2\pi\frac{s}{\lambda} \le \Delta\Phi \le 2\pi\frac{s}{\lambda}$$

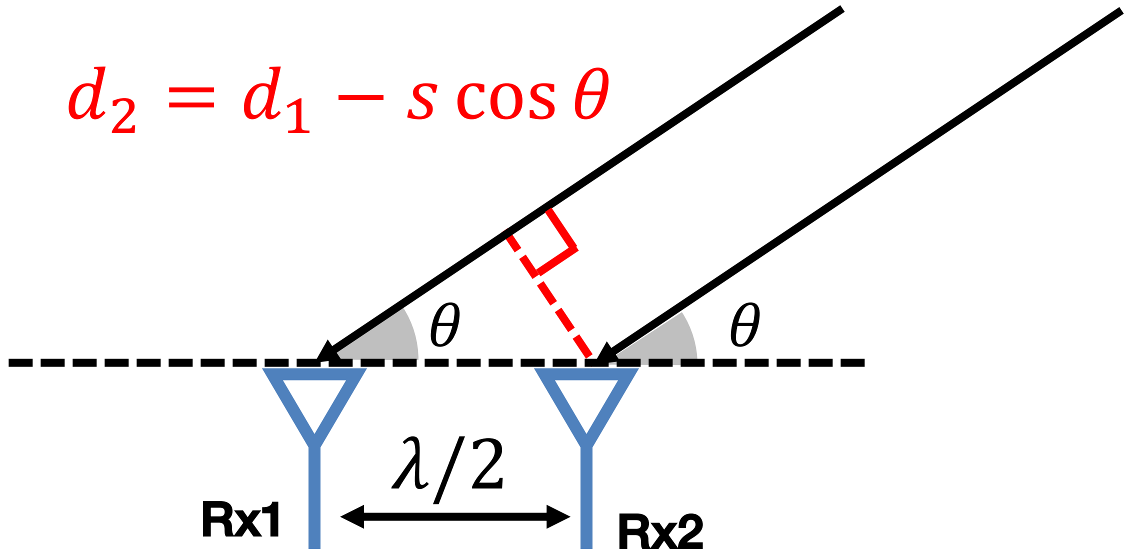
Set: $s = \lambda/2$

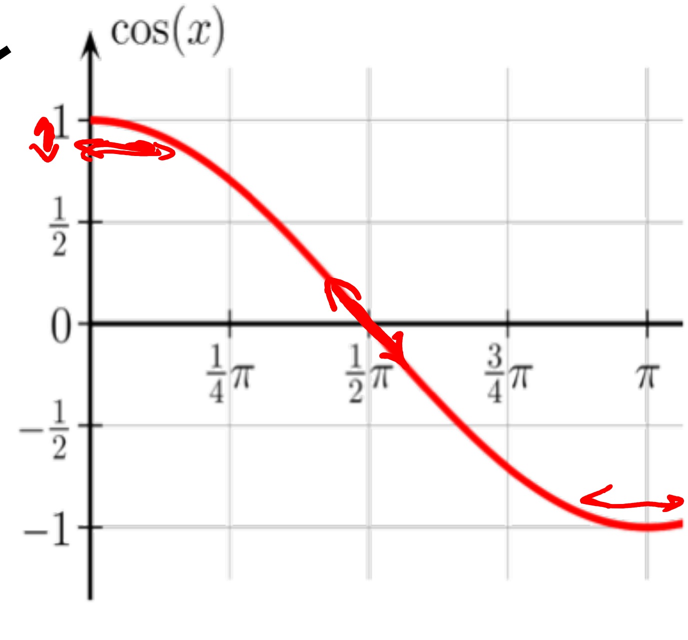
$$-\pi \le \Delta\Phi \le \pi$$

Method 2: AoA Based Localization

Measure Angle of Arrival (AoA) from device to each AP

$$d_2 = d_1 - s\cos\theta$$





Pros: More accurate than RSSI, Simple!

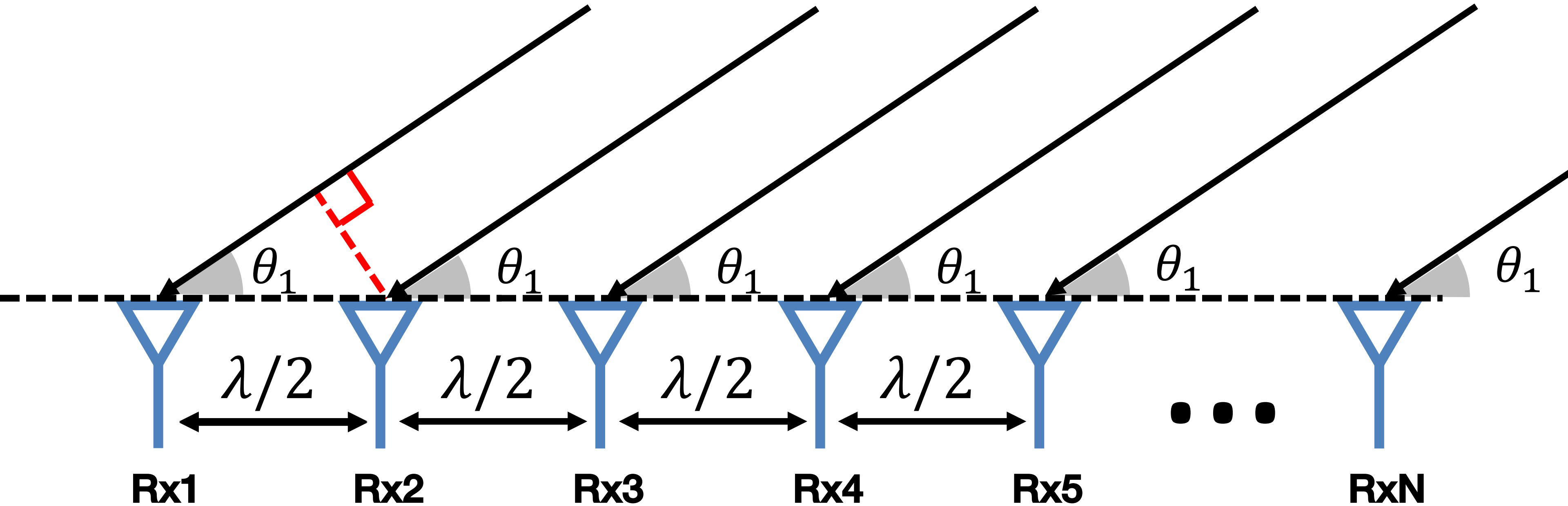
Cons: Ambiguity: $\cos\theta = \cos(-\theta)$

Error not linear with θ due to $\cos\theta$

Does not work with multipath!

• Requires 2 Ant.

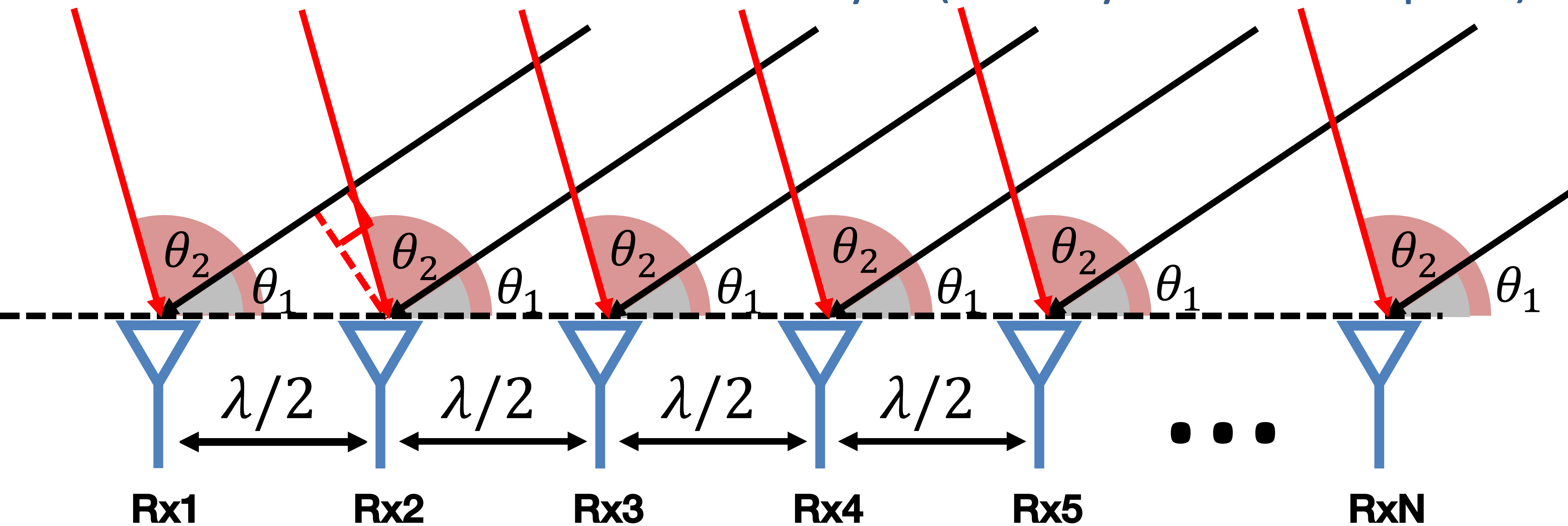
Method 3: Antenna Arrays (ArrayTrack Paper)



$$h_k = \alpha_1 e^{-j2\pi\frac{d_1 - k\, s \cos\theta_1}{\lambda}} = \alpha_1 e^{-j\phi_1 + k\pi\cos\theta_1}$$

ϕ_1

Method 3: Antenna Arrays (ArrayTrack Paper)

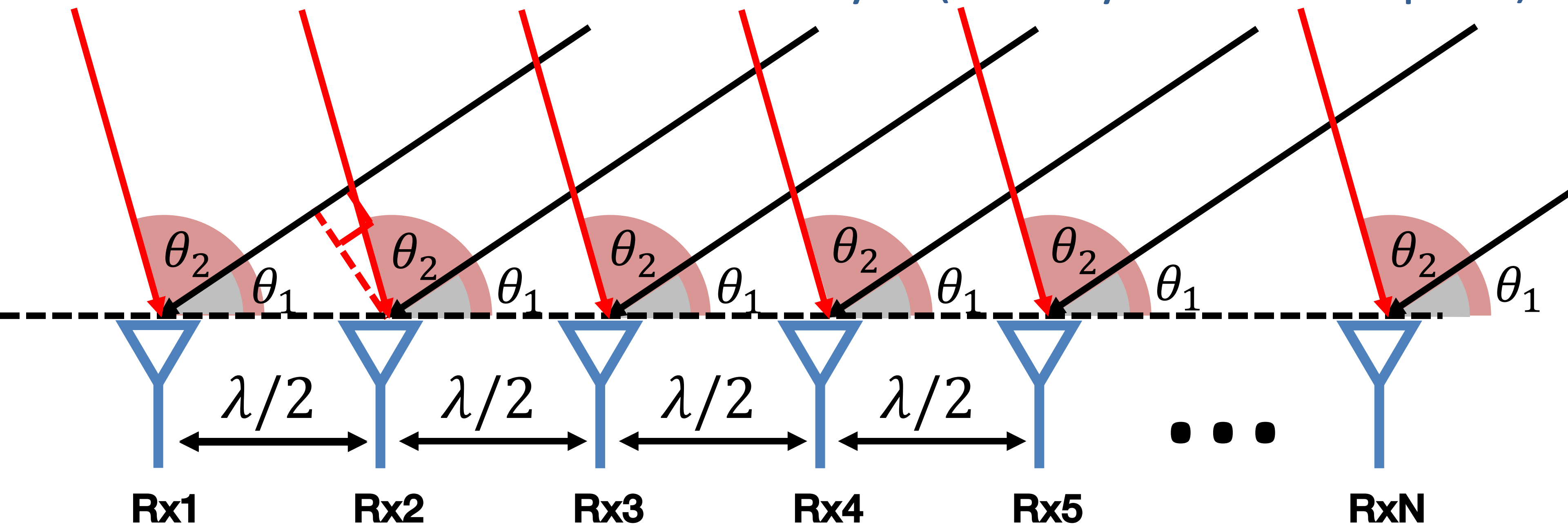


$$h_k = \alpha_1 e^{-j2\pi\frac{d_1 - k\, s \cos\theta_1}{\lambda}} = \alpha_1 e^{-j\phi_1 + k\pi \cos\theta_1}$$

$$+\alpha_2 e^{-j2\pi\frac{d_2 - k\, s \cos\theta_2}{\lambda}} \quad +\alpha_2 e^{-j\phi_2 + k\pi \cos\theta_2}$$

For L paths → $h_k = \sum_{l=1}^{L} \alpha_l e^{jk\pi \cos\theta_l - j\phi_l}$

Method 3: Antenna Arrays (ArrayTrack Paper)



$$h_k = \sum_{l=1}^{L} \alpha_l e^{jk\pi \cos\theta_l - j\phi_l}$$

Multipath Profile: $P(\theta) = \left| \sum_{k=1}^{N} h_k e^{-jk\pi \cos\theta} \right|^2$

Method 3: Antenna Arrays (ArrayTrack Paper)

$$P(\theta) = \left| \sum_{k=1}^{N} h_k e^{-jk\pi \cos\theta} \right|^2 \qquad h_k = \sum_{l=1}^{L} \alpha_l e^{jk\pi \cos\theta_l - j\phi_l}$$

$$P(\theta_1) = \left| \sum_{k=1}^{N} h_k e^{-jk\pi \cos\theta_1} \right|^2$$

$$= \left| \sum_{k=1}^{N} \left(\sum_{l=1}^{L} \alpha_l e^{jk\pi \cos\theta_l - j\phi_l} \right) e^{-jk\pi \cos\theta_1} \right|^2$$

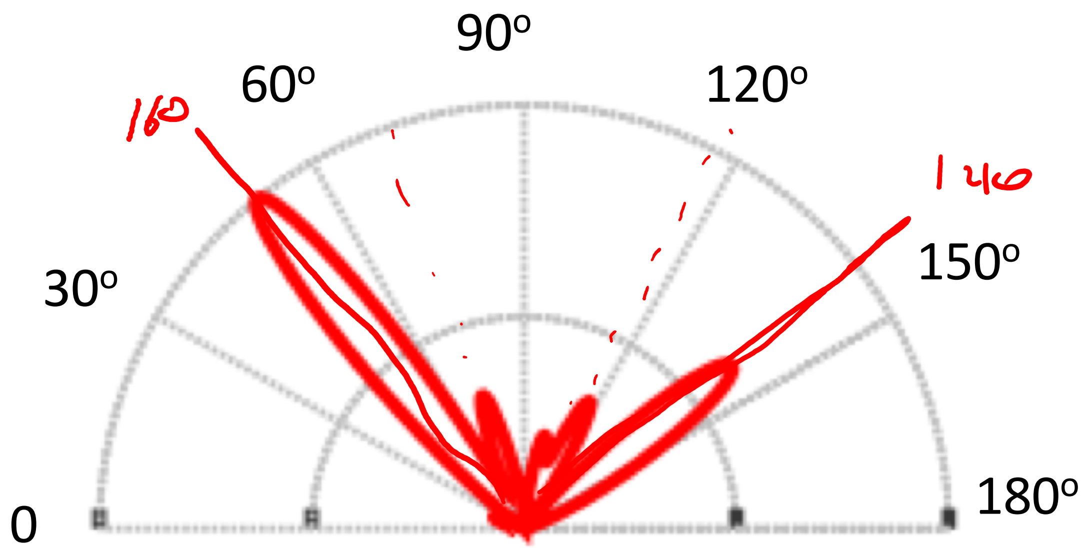
$$= \left| \sum_{k=1}^{N} \alpha_1 e^{-j\phi_1} + \sum_{k=1}^{N} \left(\sum_{l=2}^{L} \alpha_l e^{jk\pi(\cos\theta_l - \cos\theta_1) - j\phi_l} \right) \right|^2$$

$$= \left| N\alpha_1 e^{-j\phi_1} + \sum_{l=2}^{L} \alpha_l e^{-j\phi_l} \left(\sum_{k=1}^{N} e^{jk\pi(\cos\theta_l - \cos\theta_1)} \right) \right|^2 \approx N^2 \alpha_1^2$$

Method 3: Antenna Arrays (ArrayTrack Paper)

$$h_k = \sum_{l=1}^{L} \alpha_l e^{jk\pi \cos\theta_l - j\phi_l}$$

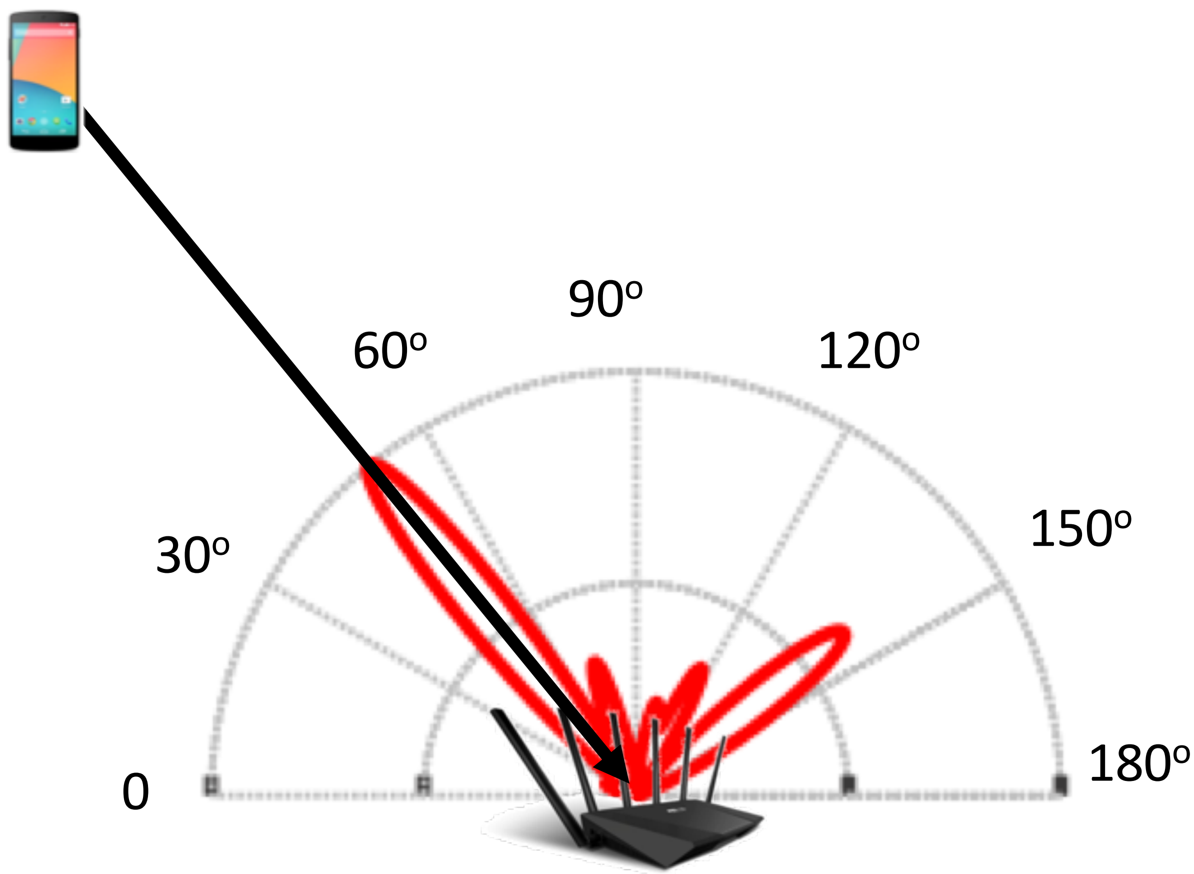
$$Multipath\ Profile:\ P(\theta) = \left| \sum_{k=1}^{N} h_k e^{-jk\pi\cos\theta} \right|^2$$



Method 3: Antenna Arrays (ArrayTrack Paper)

Which is the Line-of-Sight Path (Direct Path)?

Strongest Path!

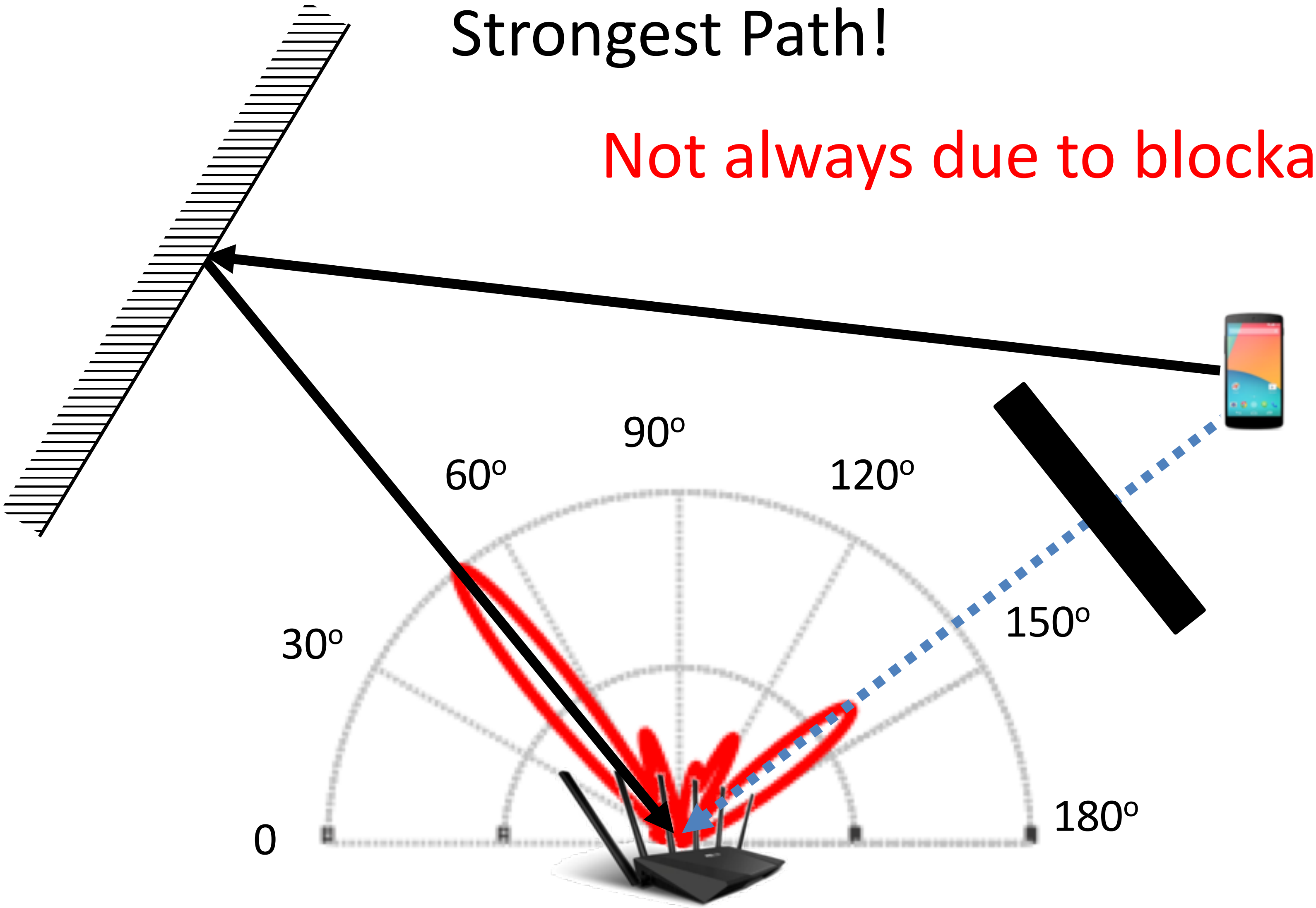


Method 3: Antenna Arrays (ArrayTrack Paper)

Which is the Line-of-Sight Path (Direct Path)?

Strongest Path!

Not always due to blockage!



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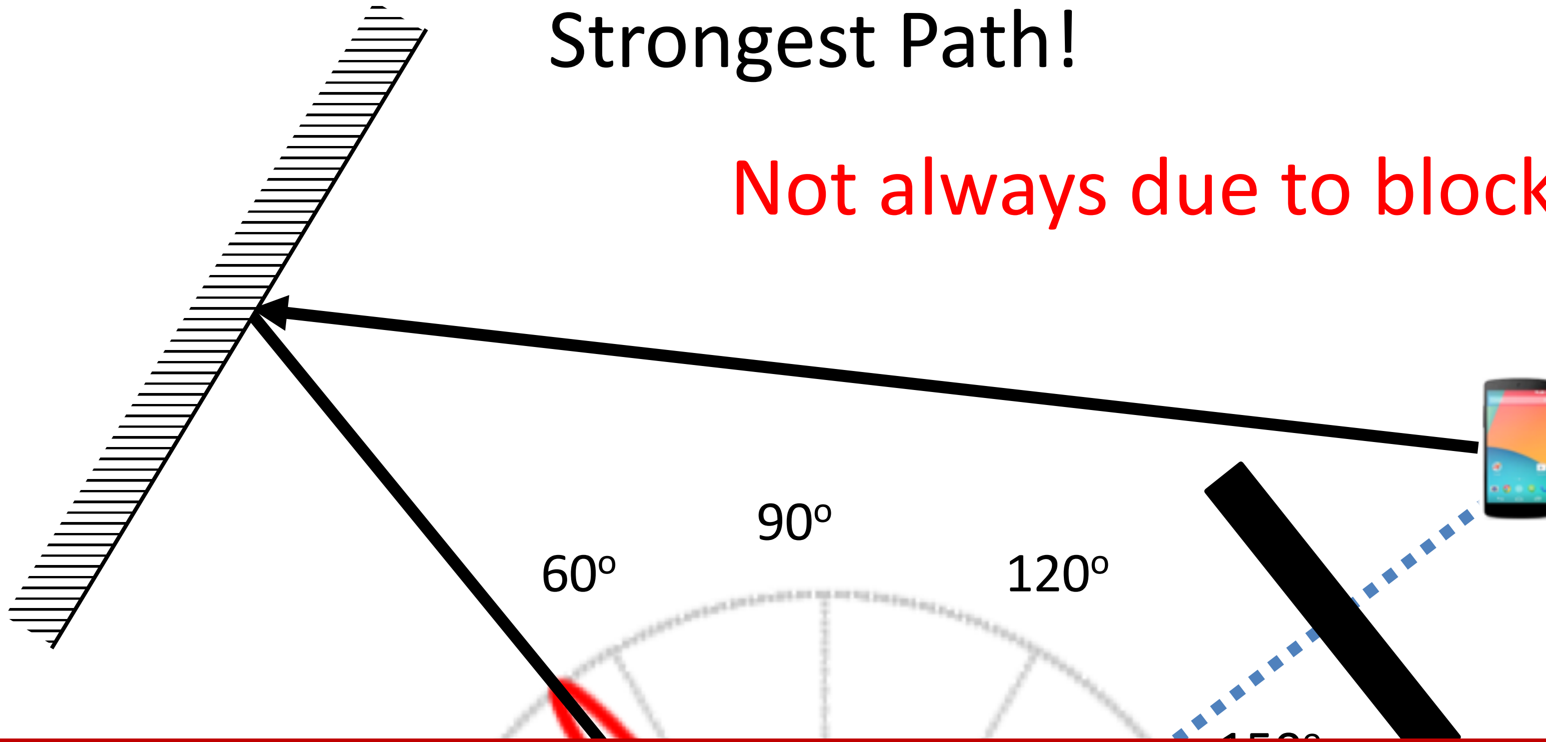


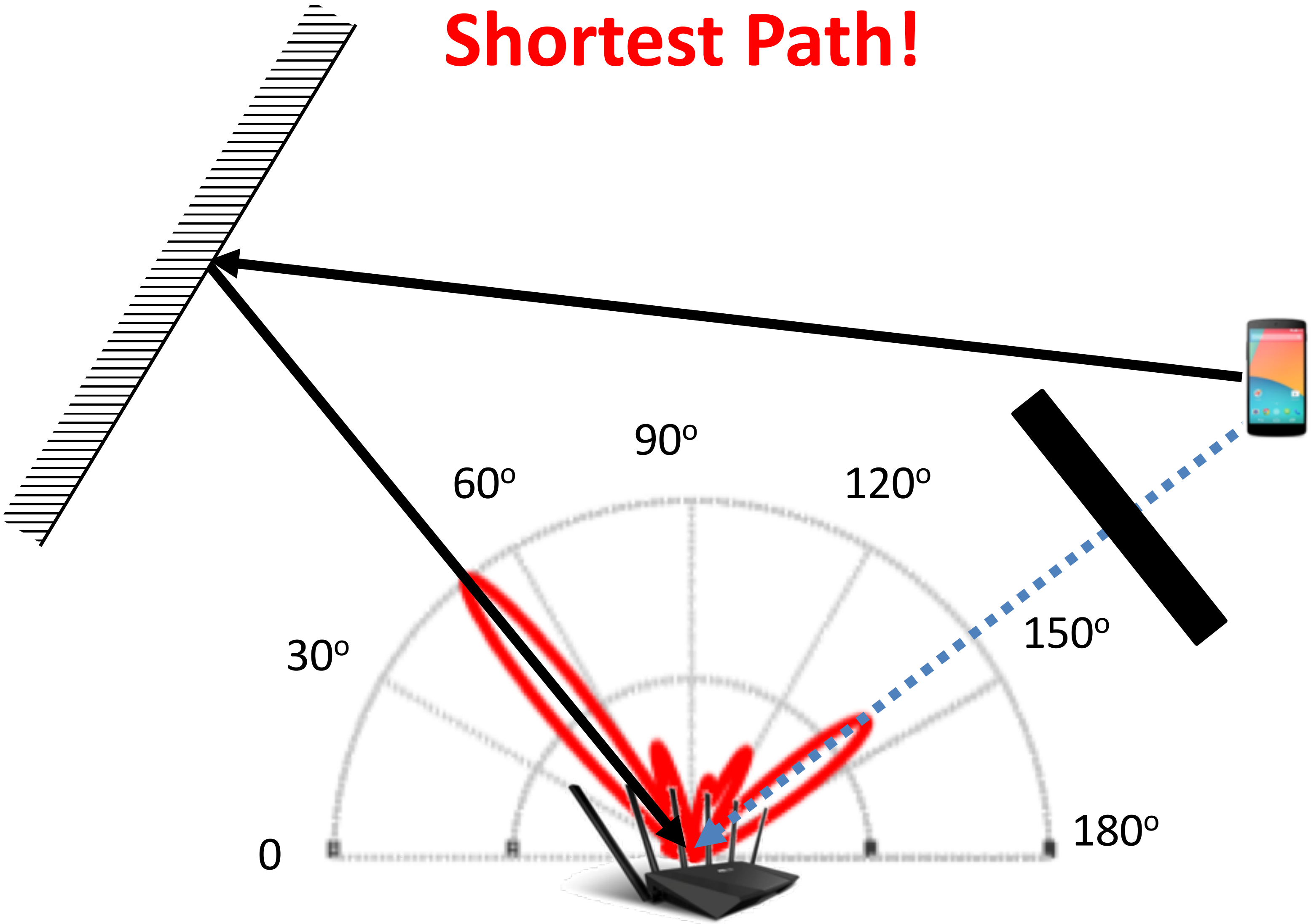
ArrayTrack: Leverage Mobility

- Line of sight path relatively stable with mobility
- Multipath reflection changes faster with mobility

Method 3: Antenna Arrays

Which is the Line-of-Sight Path (Direct Path)?

Shortest Path!



Method 3: Antenna Arrays

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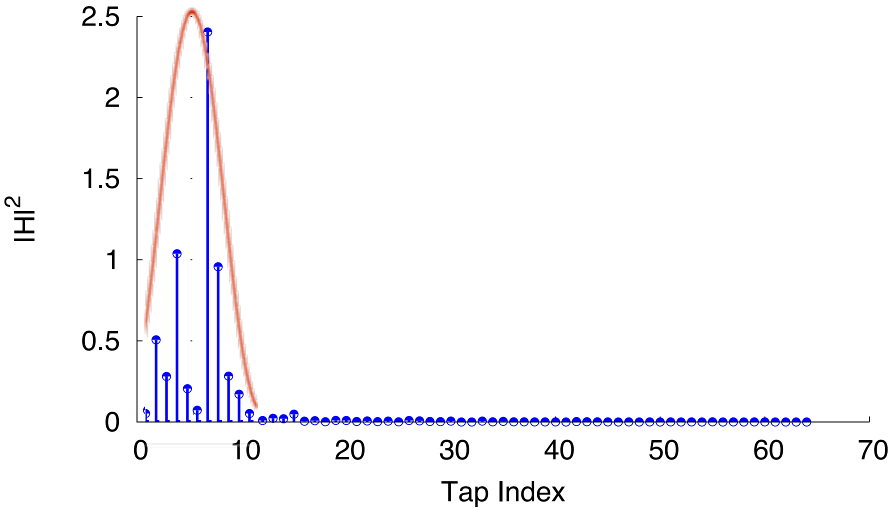


Multipath Profile vs Time

$$\Delta\tau = \frac{\Delta d}{c}$$

$$\Delta d = 1m$$

$$c = 3\times10^8 m/s$$

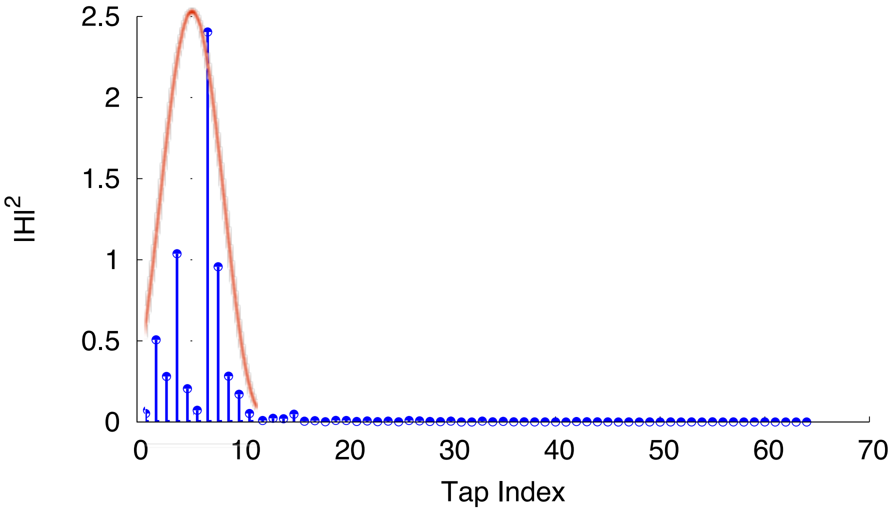
$\Delta\tau = 3.3ns$ ➡

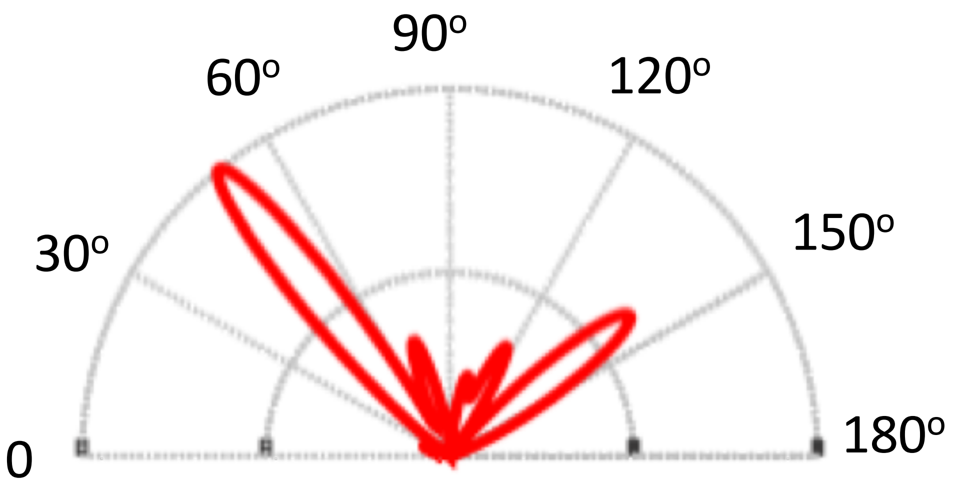
Requires a sampling rate $1/\Delta\tau = 300MHz$

802.11n bandwidth $= 40MHz$

Method 3: Antenna Arrays

Which is the Shortest Path (Direct Path)?





Multipath Profile vs Time

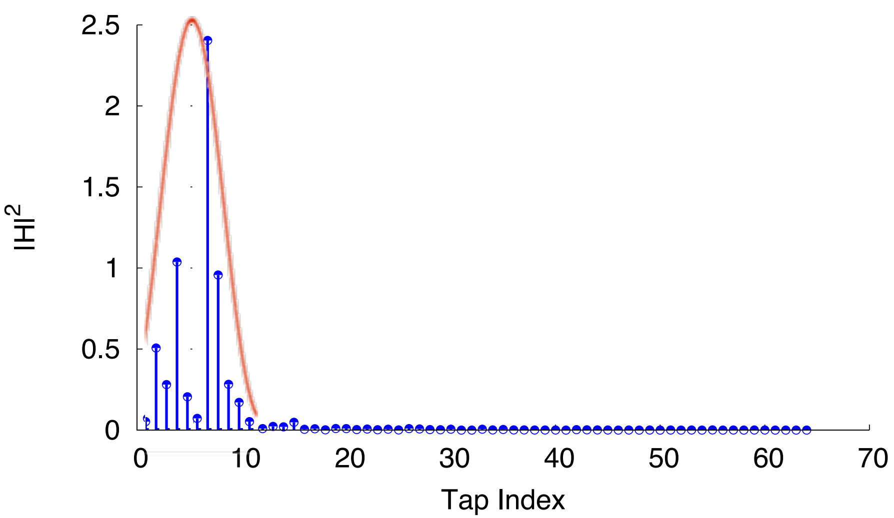
Multipath Profile vs AoA

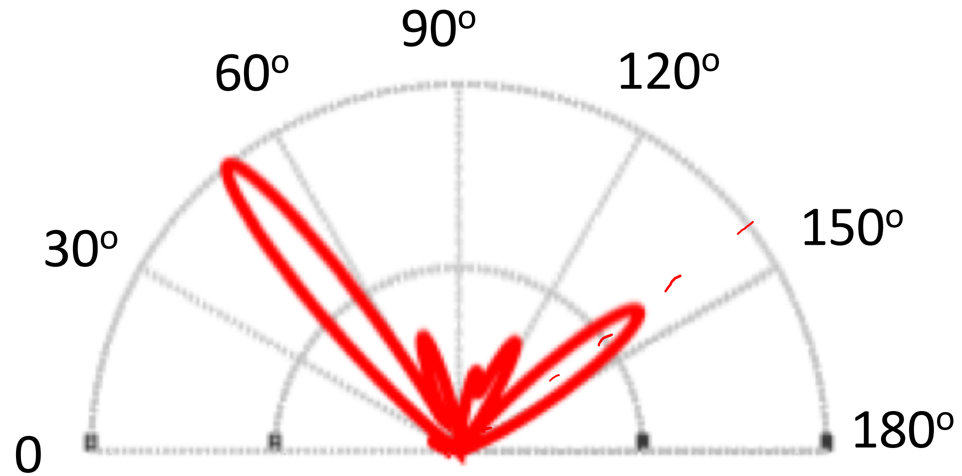
1. Use multipath profile as a filter to separate different paths
2. Estimate time of arrival of each path
3. Find the shortest path

But How?

Method 3: Antenna Arrays

Which is the Shortest Path (Direct Path)?





Multipath Profile vs Time

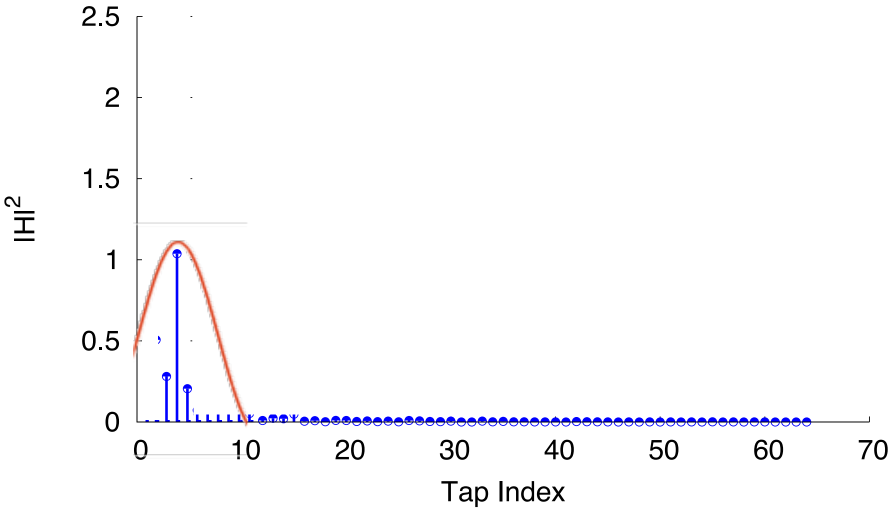
Multipath Profile vs AoA

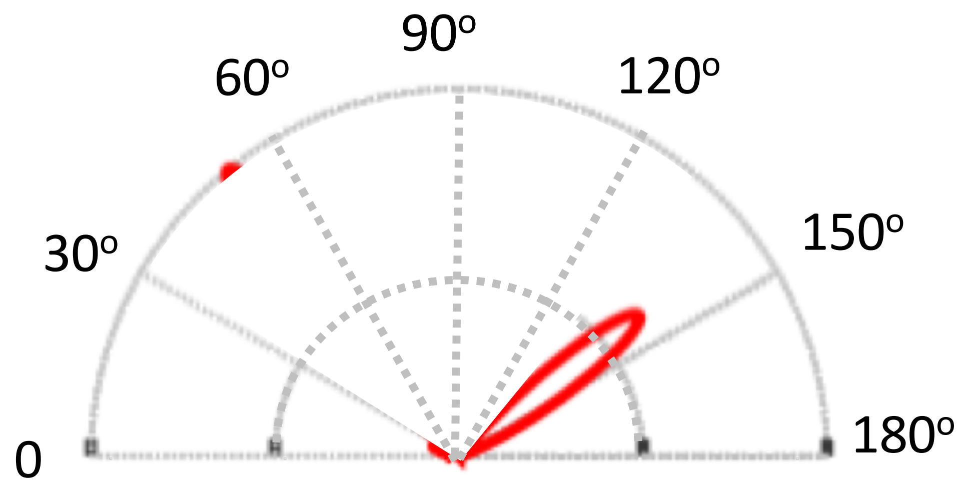
1. Use multipath profile as a filter to separate different paths

$$y_{\theta_1}(t) = \sum_{k=1}^{N} y(t)e^{-jk\pi \cos\theta_1}$$

Method 3: Antenna Arrays

Which is the Shortest Path (Direct Path)?





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Method 3: Antenna Arrays

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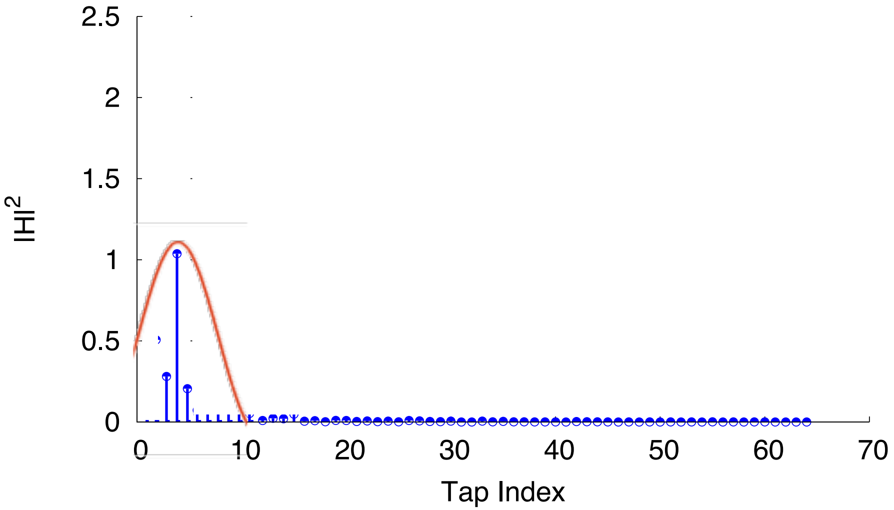
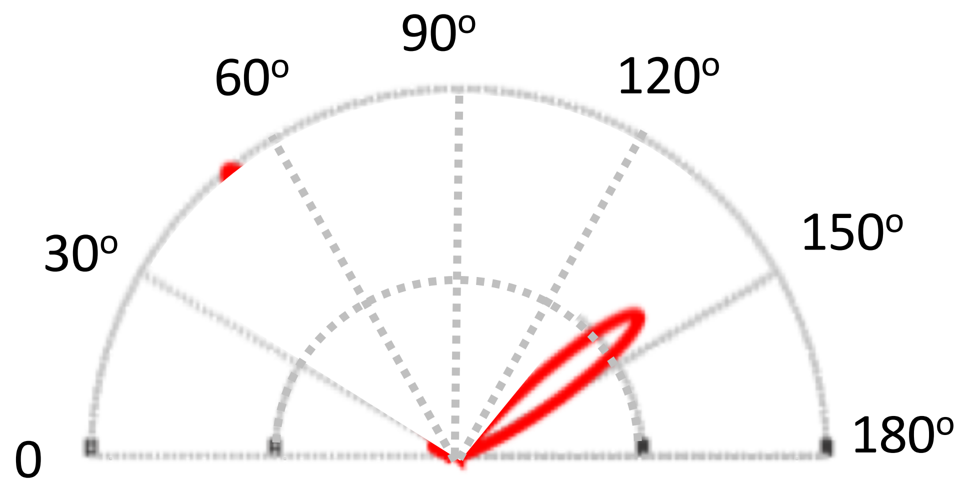


Multipath Profile vs Time



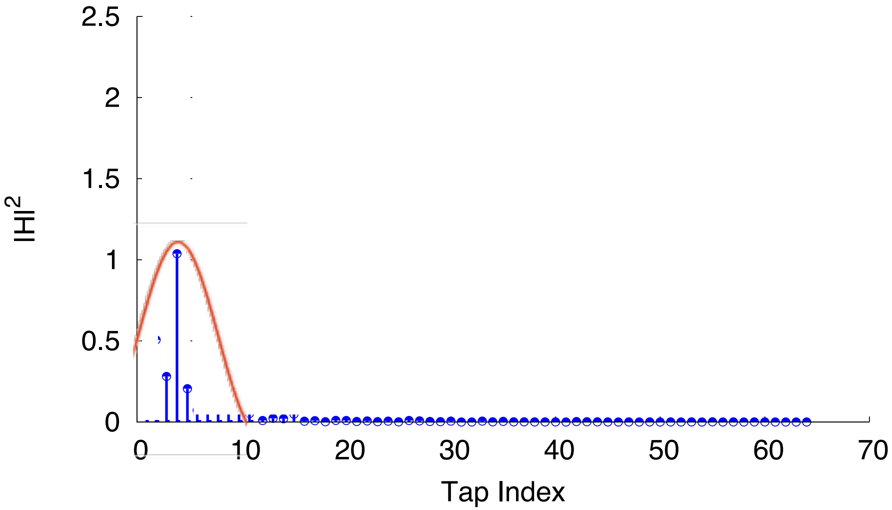
Multipath Profile vs AoA

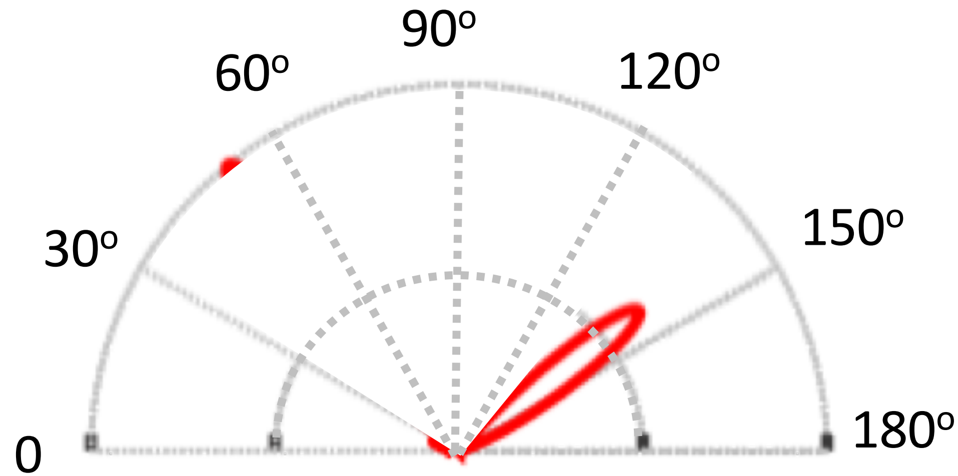
1. Use multipath profile as a filter to separate different paths
2. Estimate time of arrival of each path

Time Resolution still not enough ➡ Use OFDM

Method 3: Antenna Arrays

Which is the Shortest Path (Direct Path)?





Multipath Profile vs Time

Multipath Profile vs AoA

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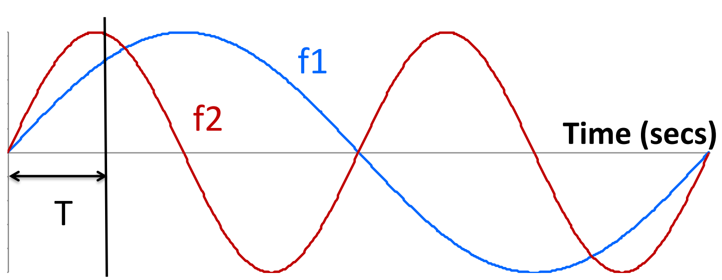
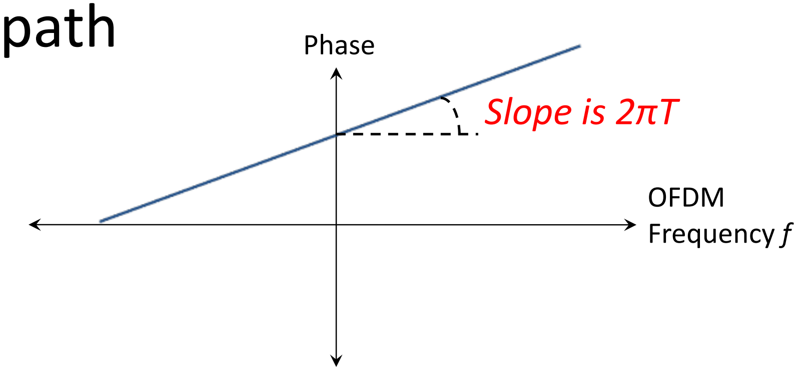
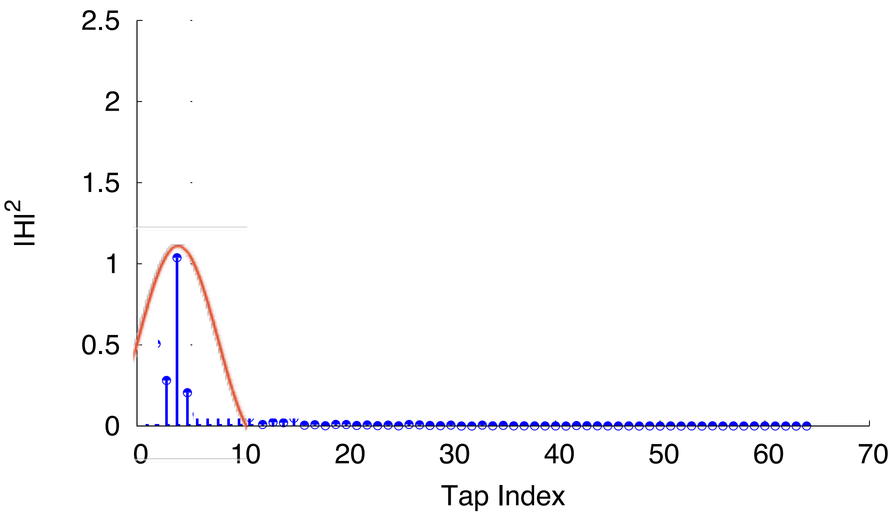


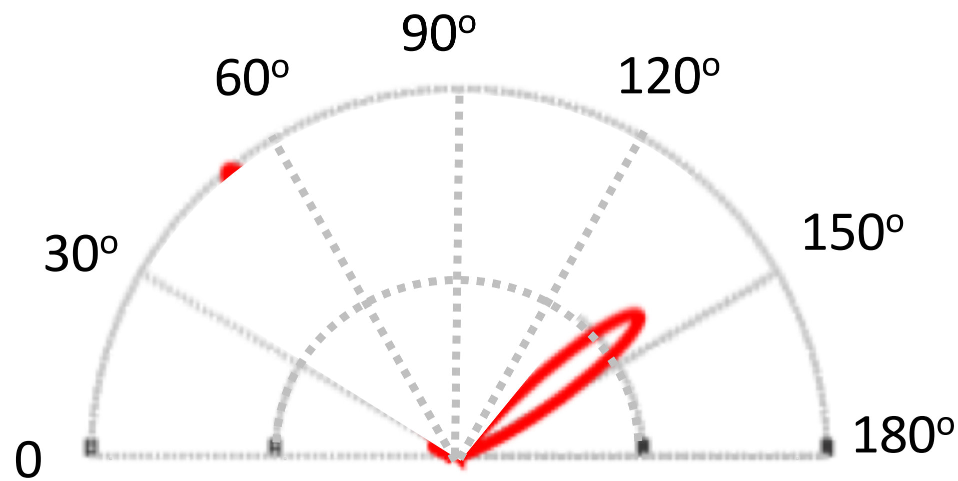


Method 3: Antenna Arrays

Which is the Shortest Path (Direct Path)?



Multipath Profile vs Time



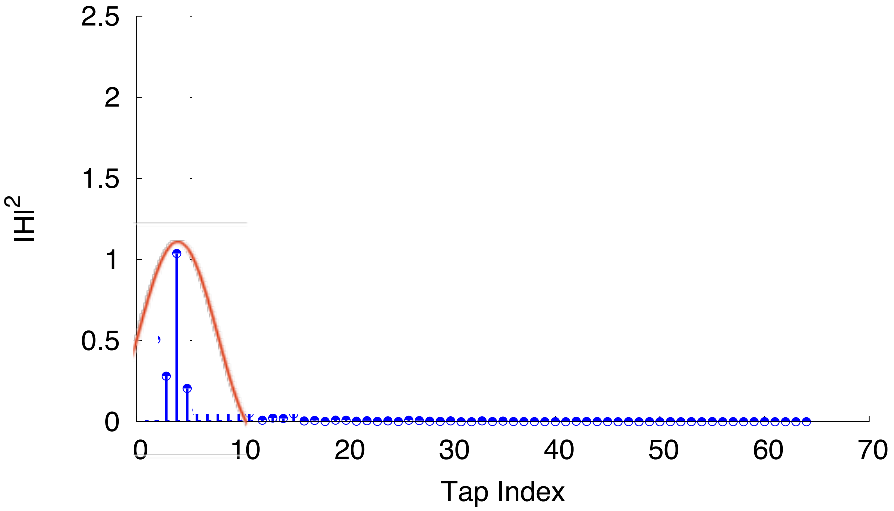
Multipath Profile vs AoA

1. Use multipath profile as a filter to separate different paths
2. Estimate time of arrival of each path
   - Use OFDM to estimate delay from slope of phase vs freq.

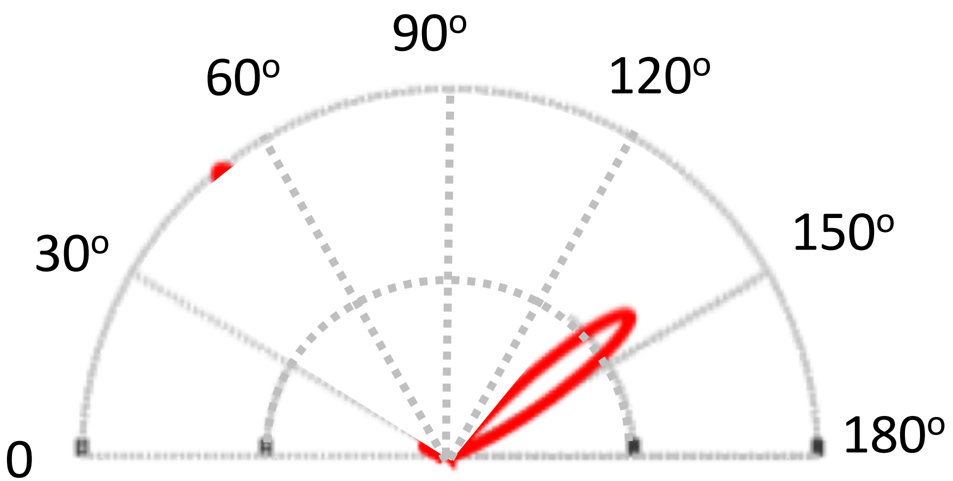
But this delay includes packet detection delay & processing delay, not just propagation delay!

Method 3: Antenna Arrays

Which is the Shortest Path (Direct Path)?



Multipath Profile vs Time

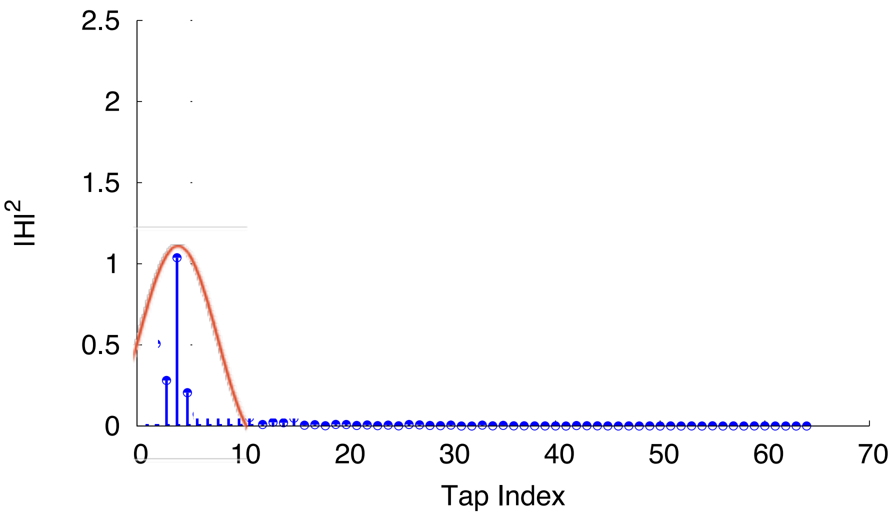


Multipath Profile vs AoA

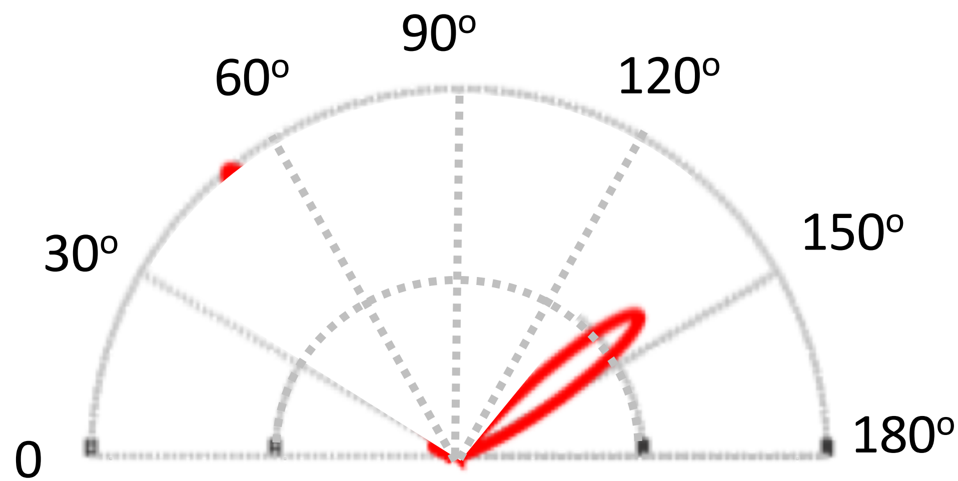
1. Use multipath profile as a filter to separate different paths
2. Estimate time of arrival of each path
   - Use OFDM to estimate delay from slope of phase vs freq.
   - Compute relative delay for different paths!

Method 3: Antenna Arrays

Which is the Shortest Path (Direct Path)?



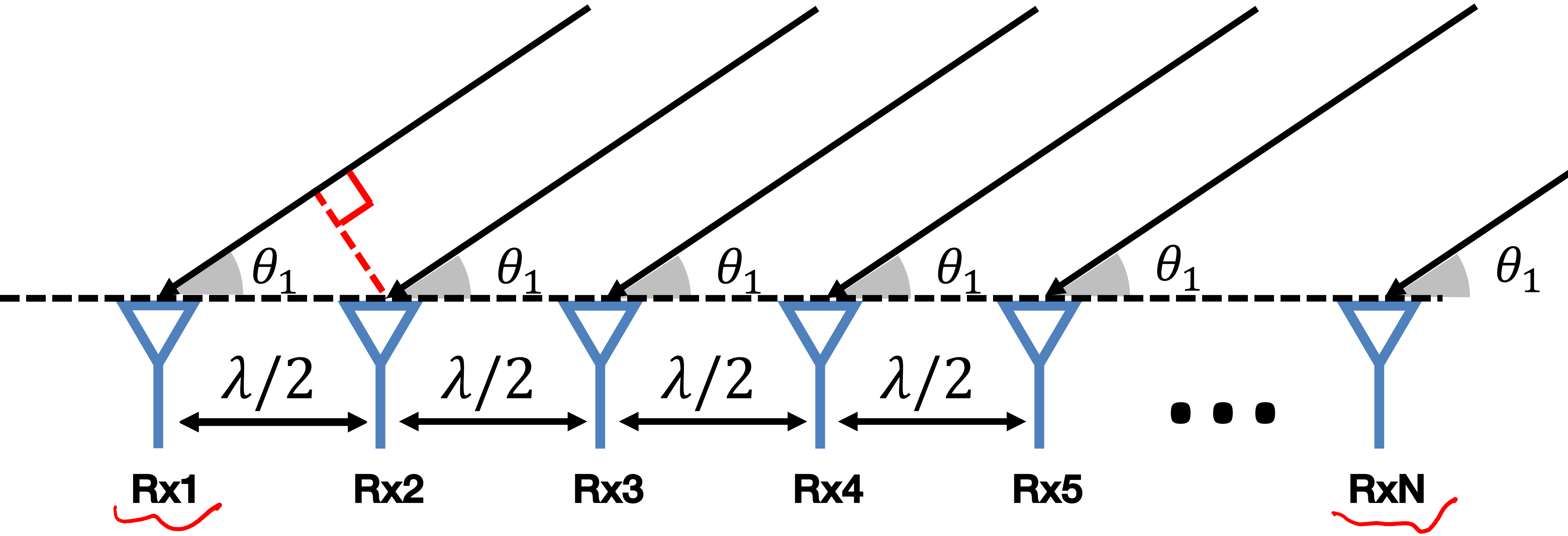
Multipath Profile vs Time



Multipath Profile vs AoA

1. Use multipath profile as a filter to separate different paths
2. Estimate time of arrival of each path
   - Use OFDM to estimate delay from slope of phase vs freq.
   - Compute relative delay for different paths!
3. Compare relative delays to find the shortest path

Method 3: Antenna Arrays



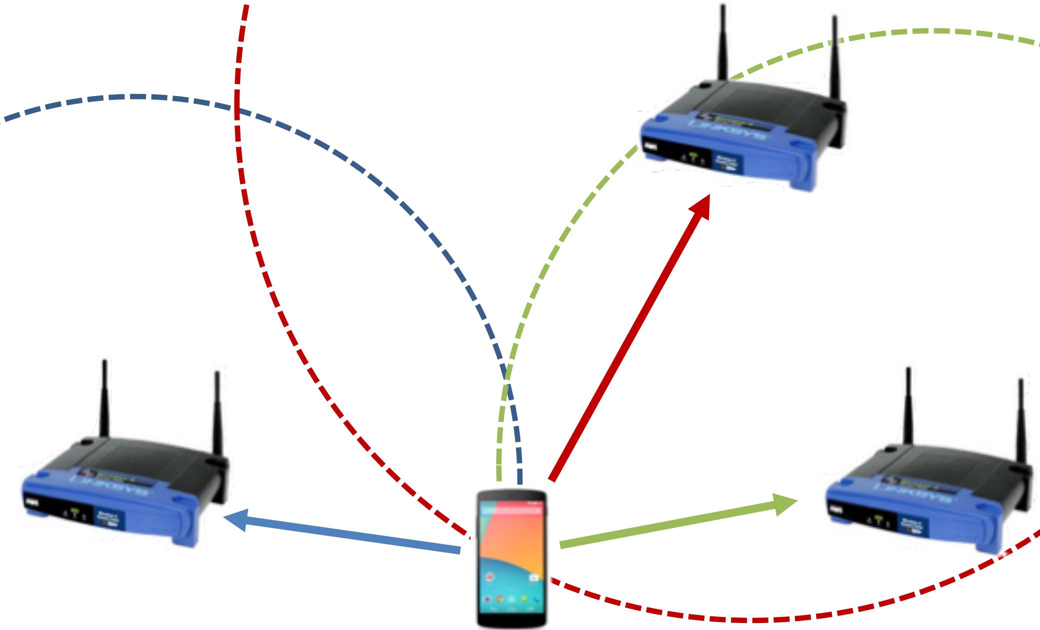
Pros: Works with multipath, No need for fingerprinting

Cons: Requires more hardware!

Assumes device is sufficiently far such that wavefront is parallel

Method 4: ToF Based Localization

Measure Time of Flight (ToF) from device to each AP



Distance = Time of flight × speed of travel

Measure ToF → Get distance → Trilateration

Method 4: ToF Based Localization

Measure Time of Flight (ToF) from device to each AP

Challenges:

- How do you know when signal was transmitted?

- How about packet detection delay & processing delay?

  - Use OFDM to correct for packet detection delay
  - Estimate and calibrate for processing delay

Not Practical!

Method 4: ToF Based Localization

Measure Time of Flight (ToF) from device to each AP

Challenges:

- Accuracy limited by sampling rate (bandwidth)!

$$\Delta d = \Delta\tau \times c$$

802.11n bandwidth $= 40MHz$ ➡ $\Delta\tau = 25ns$ ➡ $\Delta d = 12.5\ m$

- Other systems than WiFi can get accurate ToF:

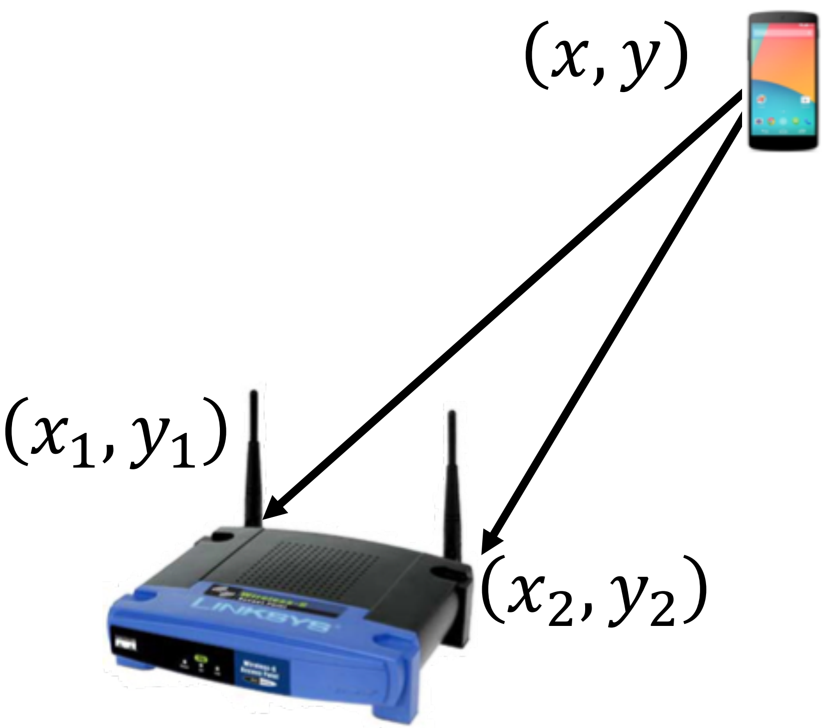
  - UWB: Ultra-Wide Band
  - FMCW: Frequency Modulated Carrier Wave

Not Supported in WiFi

(Will discuss in future lectures)

Method 5: TDoA Based Localization

Measure Time Difference of Arrival (TDoA) from device to AP's antennas



$$h_1 \propto e^{-j2\pi\frac{d_1}{\lambda}} \qquad h_2 \propto e^{-j2\pi\frac{d_2}{\lambda}}$$

$$\Delta\Phi = \angle h_2 - \angle h_1$$

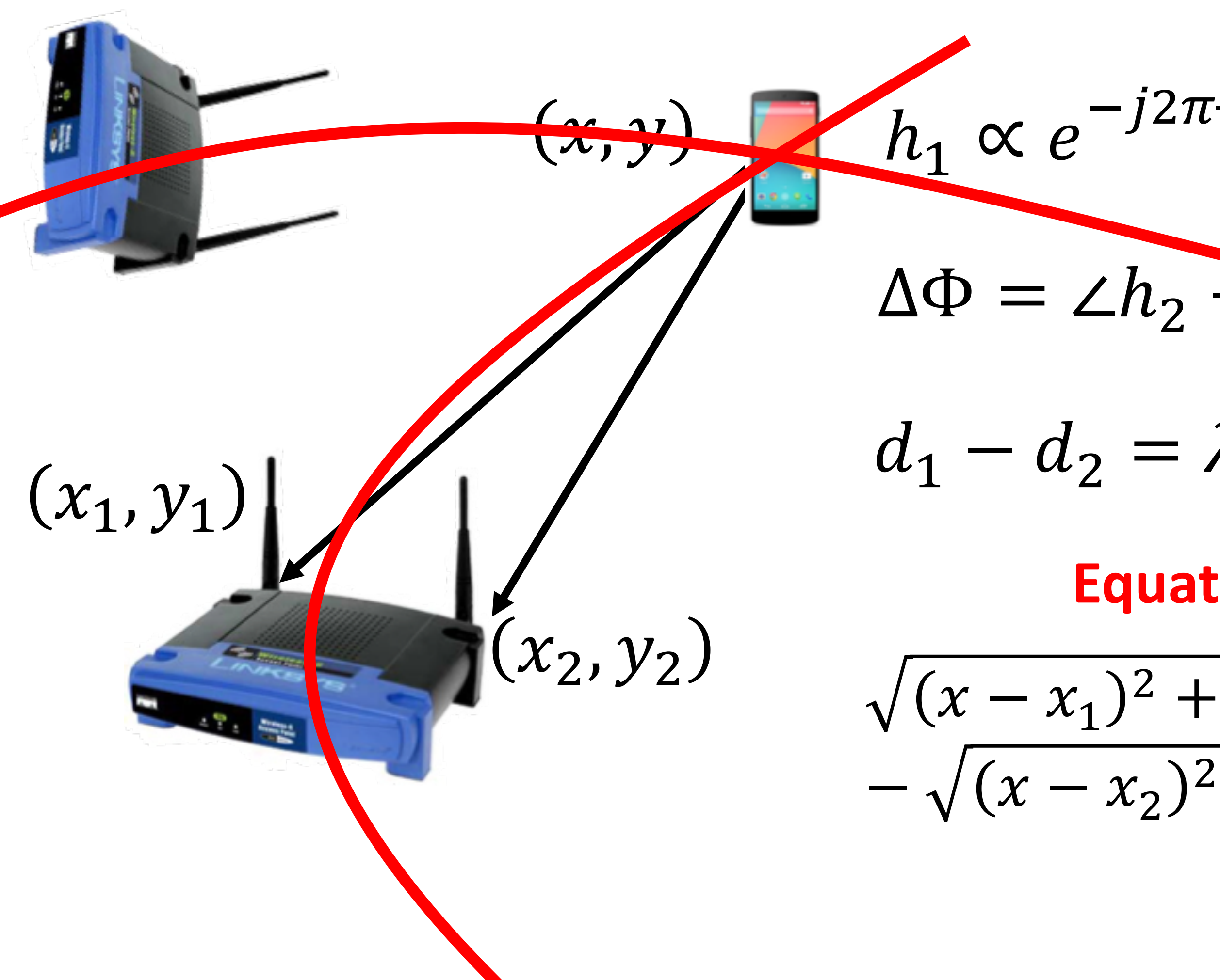
$$d_1 - d_2 = \lambda\Delta\Phi/2\pi = d'$$

Equation of Hyperbola

$$\sqrt{(x-x_1)^2 + (y-y_1)^2} - \sqrt{(x-x_2)^2 + (y-y_2)^2} = d'$$

Method 5: TDoA Based Localization

Measure Time Difference of Arrival (TDoA) from device to AP's antennas



$$h_1 \propto e^{-j2\pi\frac{d_1}{\lambda}} \qquad h_2 \propto e^{-j2\pi\frac{d_2}{\lambda}}$$

$$\Delta\Phi = \angle h_2 - \angle h_1$$

$$d_1 - d_2 = \lambda\Delta\Phi/2\pi = d'$$

Equation of Hyperbola

$$\sqrt{(x - x_1)^2 + (y - y_1)^2} - \sqrt{(x - x_2)^2 + (y - y_2)^2} = d'$$