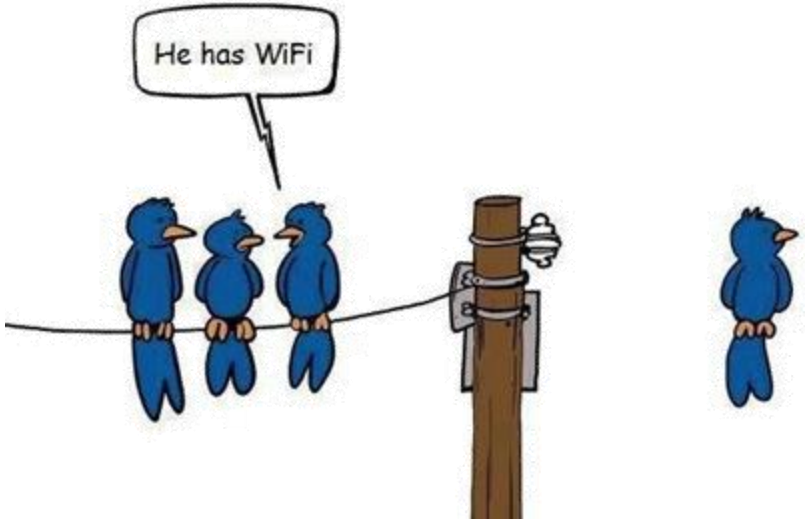
COM-405: Mobile Networks

Lecture 7.1: Wireless Localization

Haitham Hassanieh



EPFL

SENS
Laboratory of SEnsing
& Networking Systems

Wireless Localization / Positioning

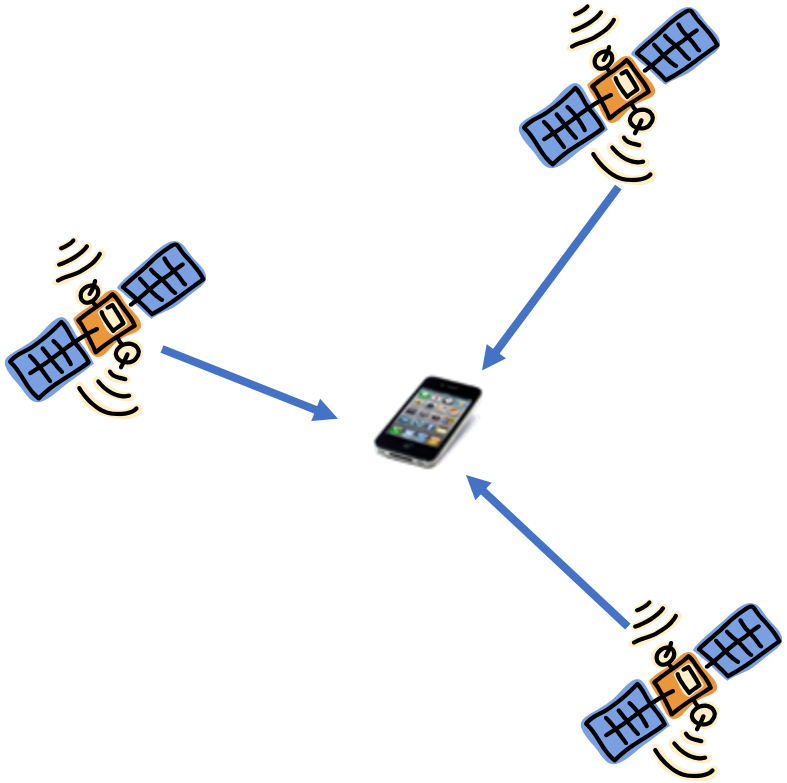
The process of obtaining a human or object's location using wireless signals

Applications:

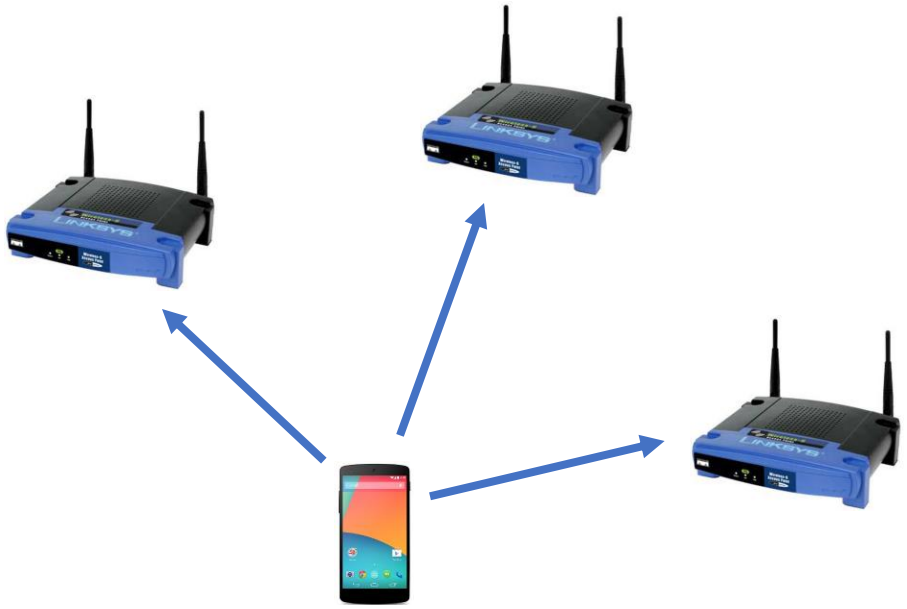
- Navigation: outdoors (GPS) and indoors (e.g., museum)
- Location based services: Tagging, Reminder, Ads
- Virtual Reality and Motion Capture
- Gestures, writing in the air
- Behavioral Analytics (Health, activities, etc.)
- Locating misplaced items (keys)
- Location based security
- Delivery drones

Wireless Localization Architecture.

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

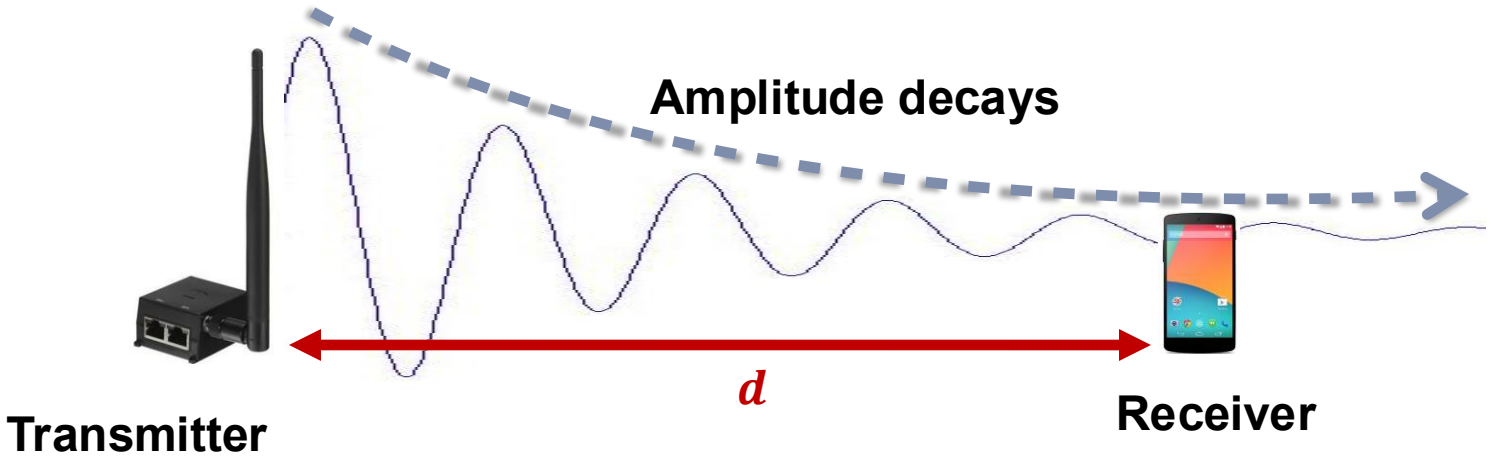


- Network based: Anchors (or Access points) use the signal coming from device to determine its location



Method 1: RSSI Based Localization

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

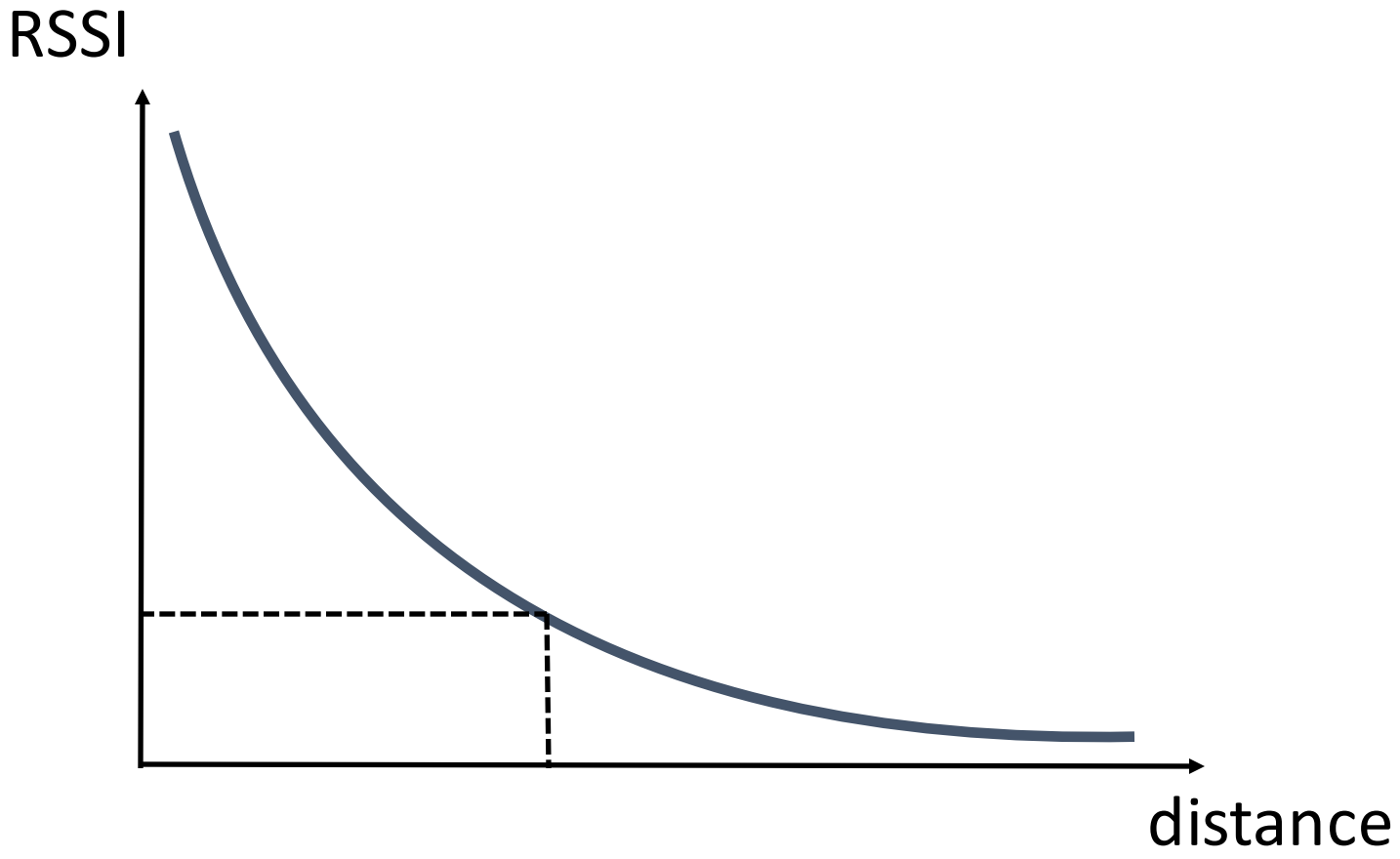


$$P_{Rx} = \frac{G_{Tx}\, G_{Rx}\, \lambda^2}{(4\pi d)^2}\, P_{Tx} \quad \Rightarrow \quad RSSI \propto \frac{1}{d^2}$$

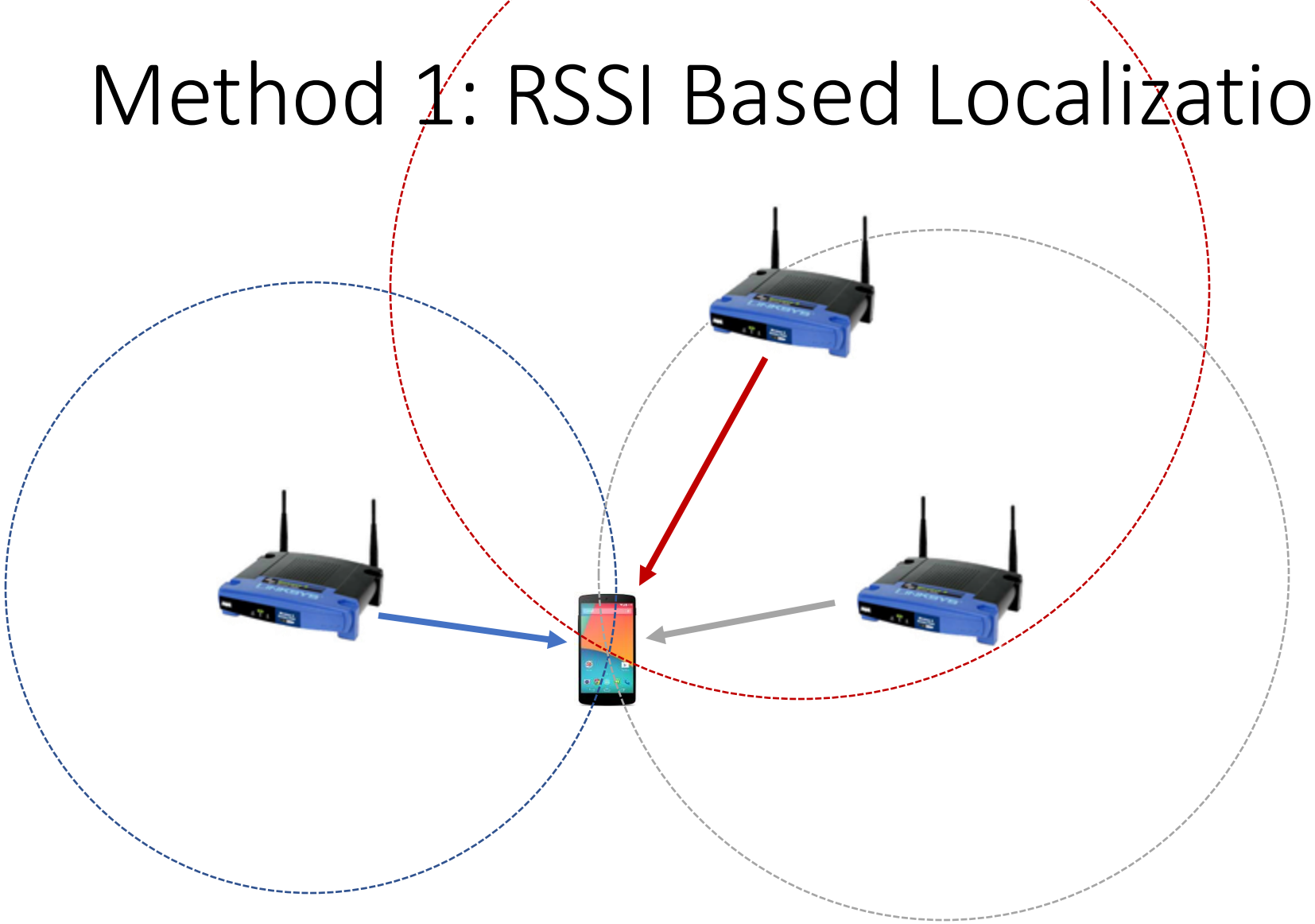
Use RSSI to estimate distance from APs!

Method 1: RSSI Based Localization

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



Method 1: RSSI Based Localization

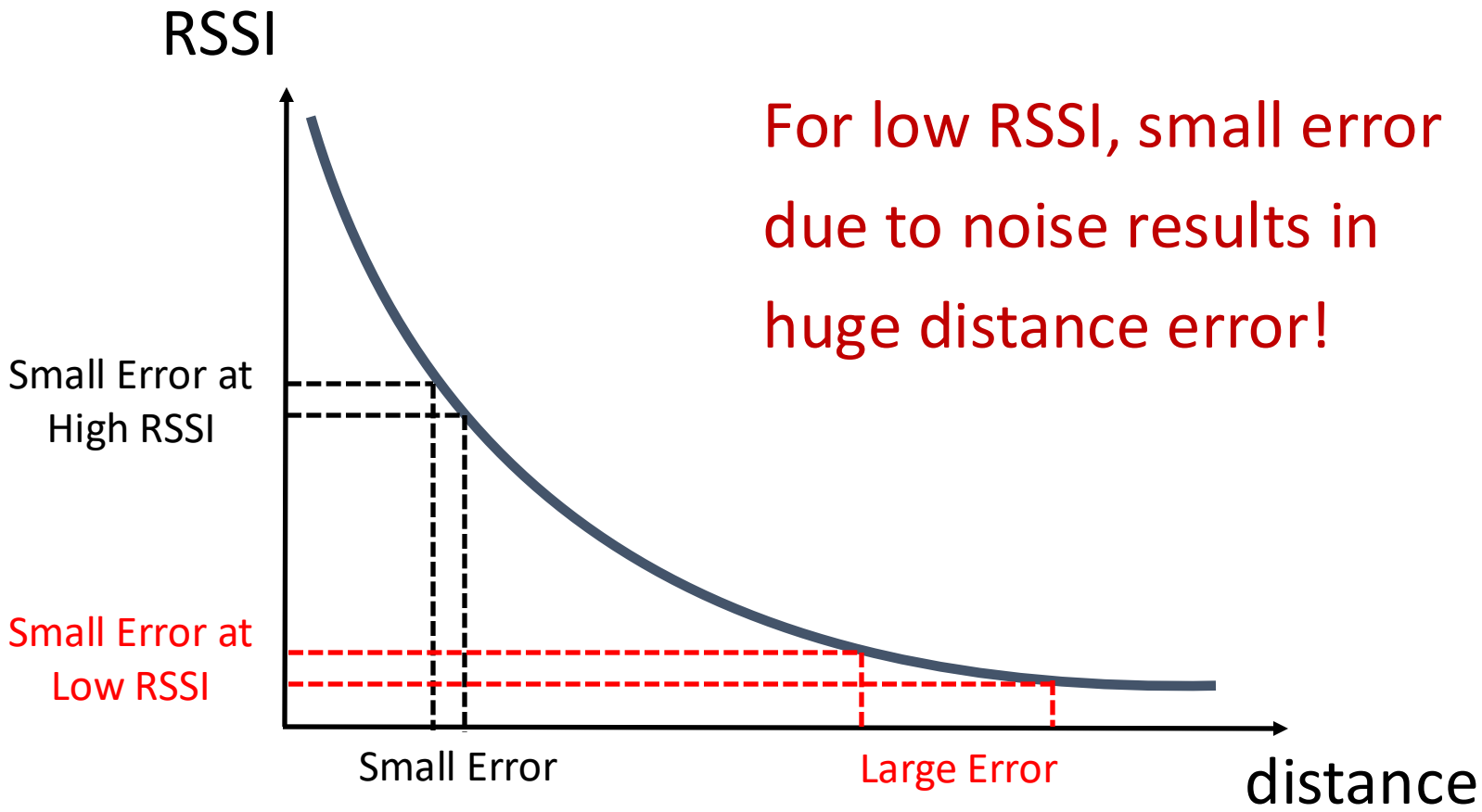


Trilateration

Method 1: RSSI Based Localization

Pros: Very simple, no hardware modifications

Cons: Highly inaccurate!



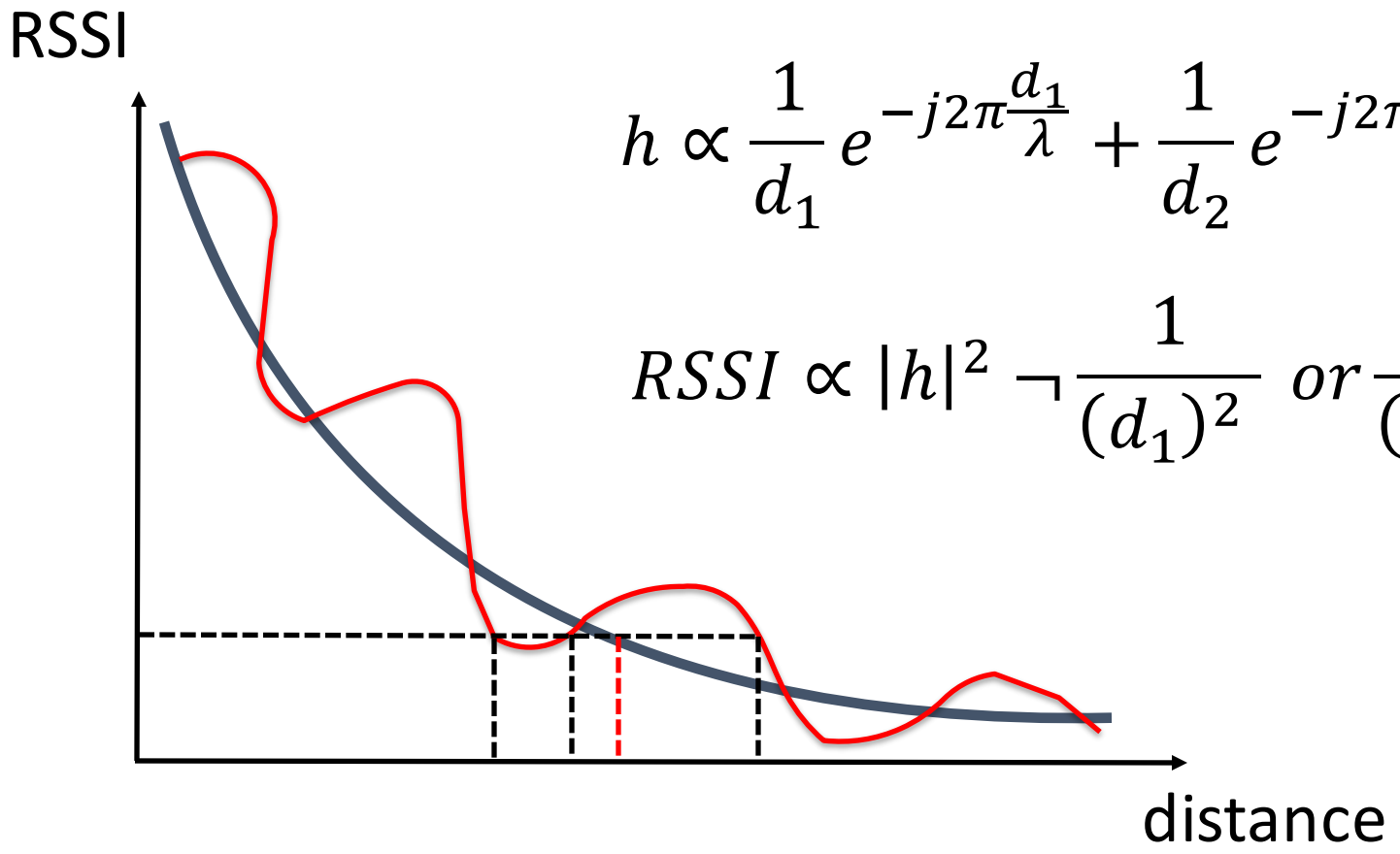
For low RSSI, small error due to noise results in huge distance error!

Method 1: RSSI Based Localization

Pros: Very simple, no hardware modifications!

Cons: Highly inaccurate!

Does not work with multipath!



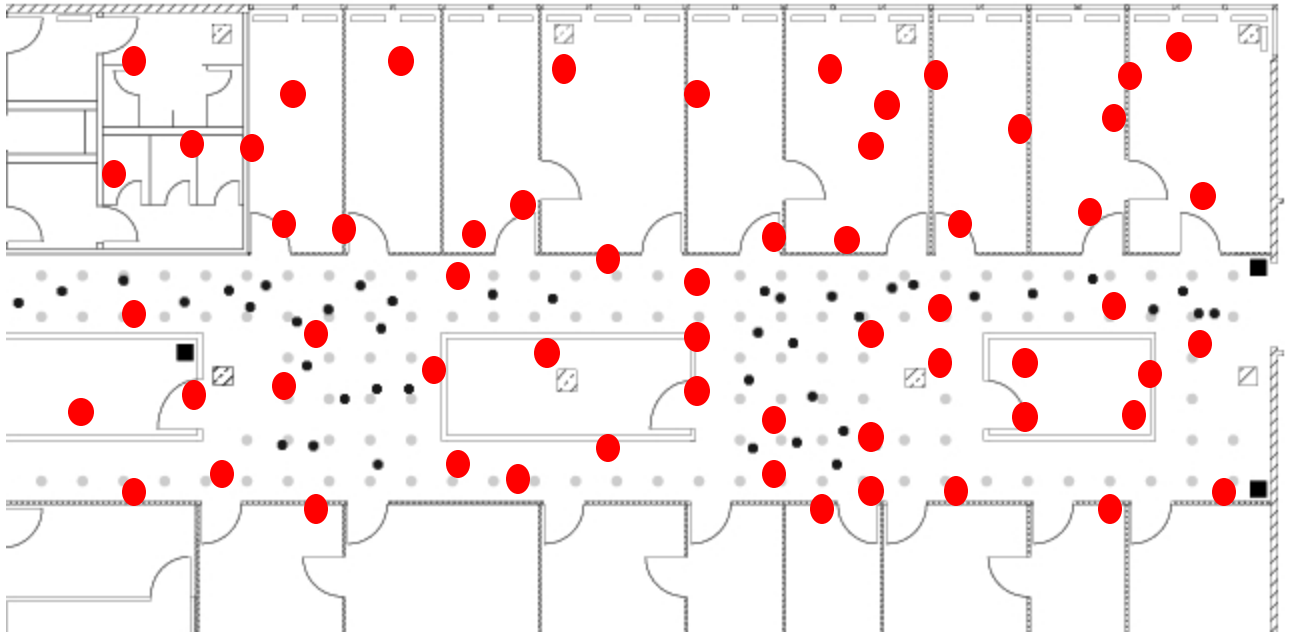
$$h \propto \frac{1}{d_1} e^{-j2\pi\frac{d_1}{\lambda}} + \frac{1}{d_2} e^{-j2\pi\frac{d_2}{\lambda}}$$

$$RSSI \propto |h|^2 \neg \frac{1}{(d_1)^2} \; or \frac{1}{(d_2)^2}$$

Method 1: RSSI Based Localization

Solution: Fingerprinting

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



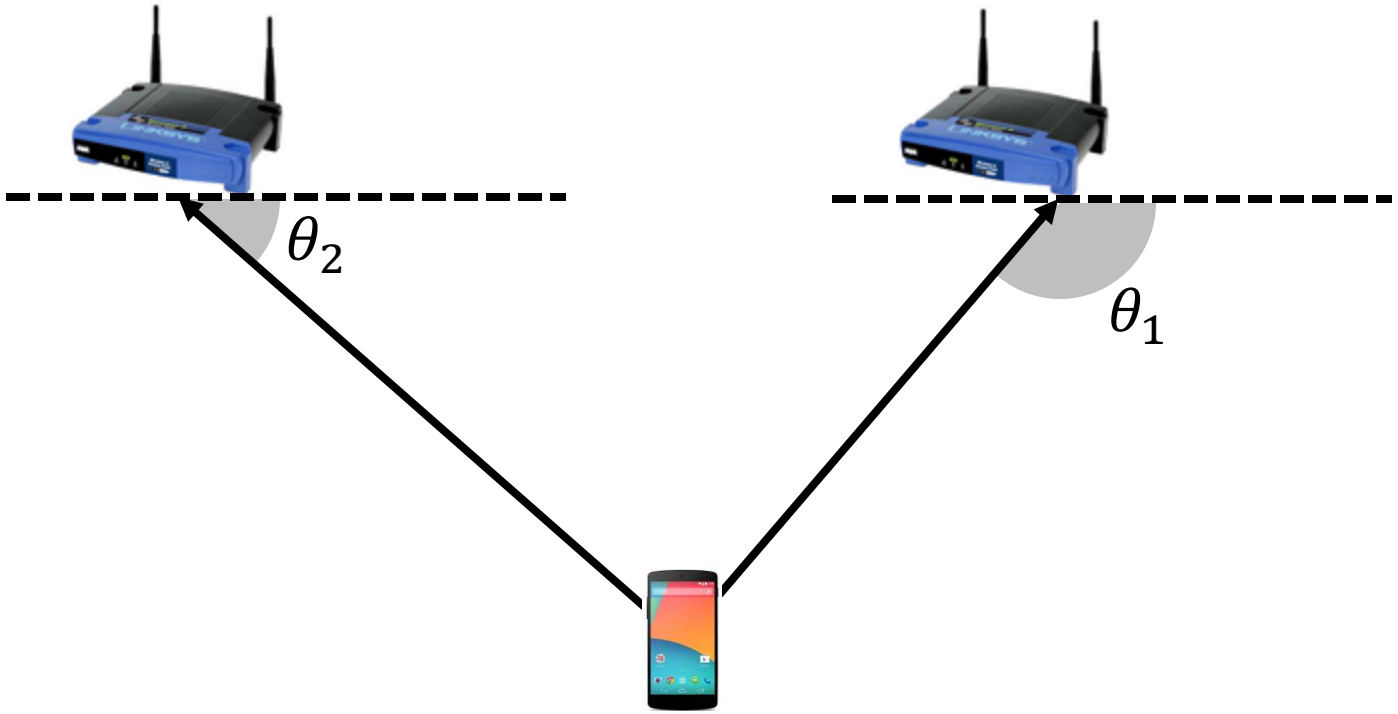
Pros: Works with multipath, No need to know AP locations!

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

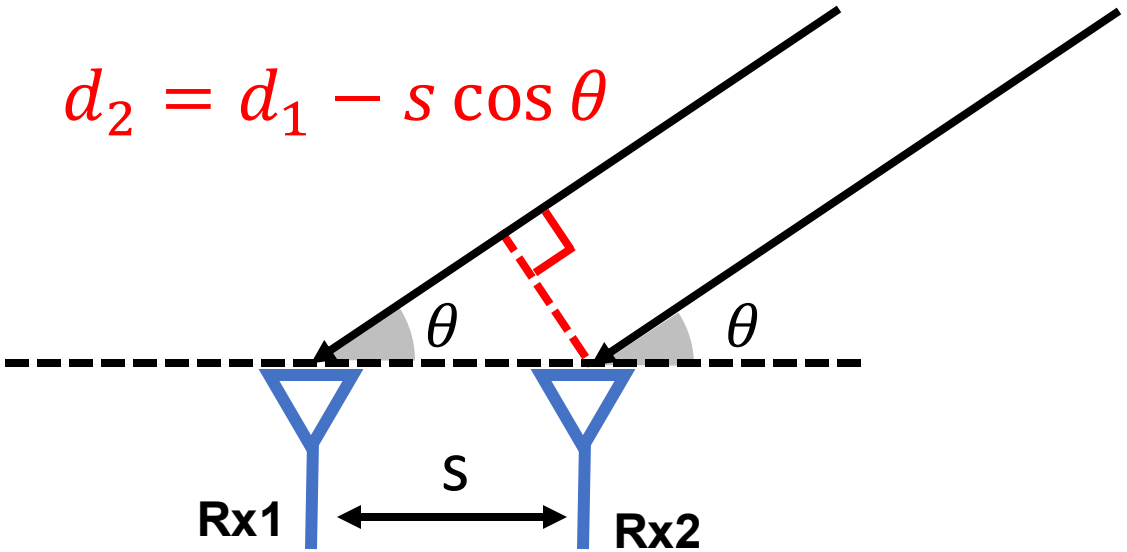


Triangulation

Method 2: AoA Based Localization

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

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

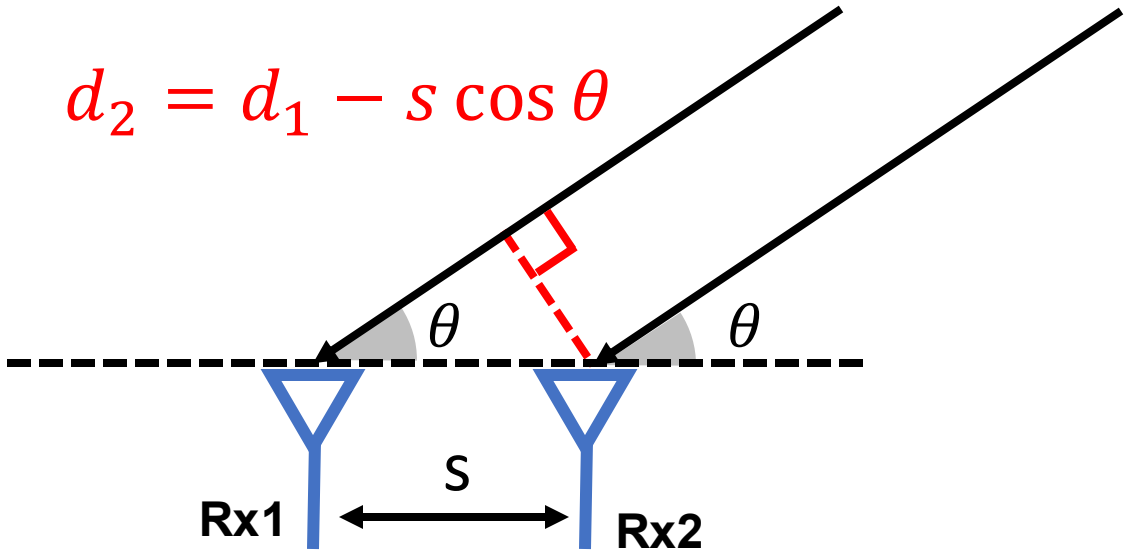


$$h_1 \propto e^{-j2\pi\frac{d_1}{\lambda}} \qquad h_2 \propto e^{-j2\pi\frac{d_2}{\lambda}} = e^{-j2\pi\frac{d_1 - s\cos\theta}{\lambda}}$$

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

Method 2: AoA Based Localization

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



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

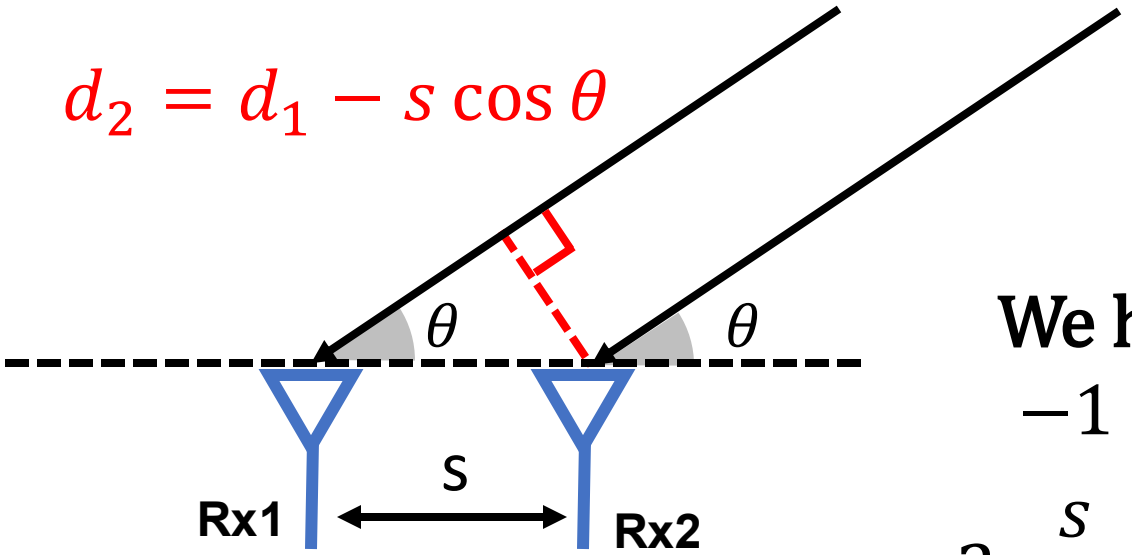
Ambiguity: $\exists\theta_1 \neq \theta_2 \mid \Delta\Phi_1 = \Delta\Phi_2 \mod 2\pi$

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:

$$-\pi \leq \Delta\Phi \leq \pi$$

We have:

$$-1 \leq \cos\theta \leq 1$$

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

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

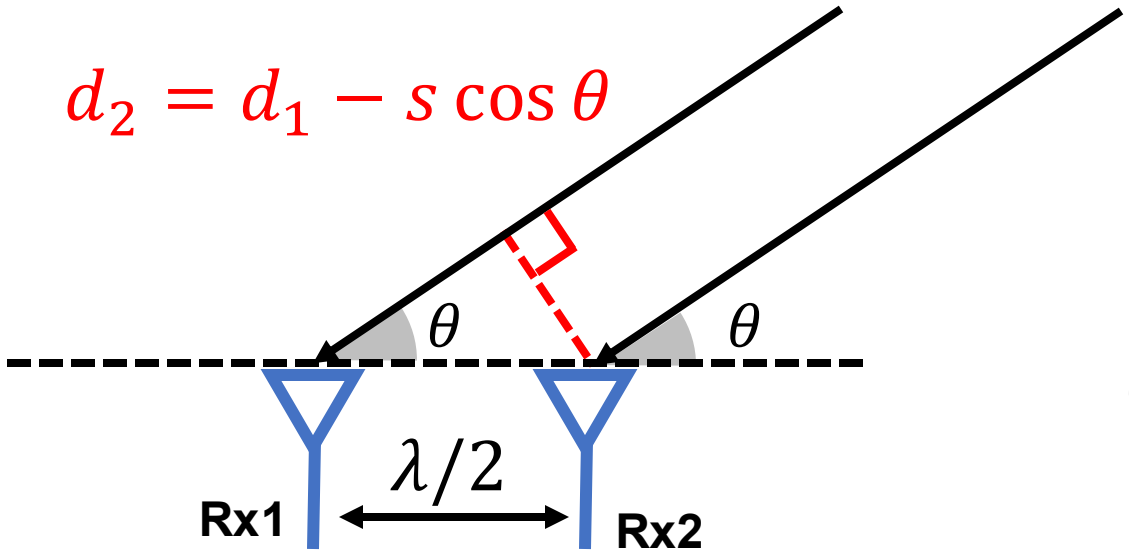
$$-\pi \leq \Delta\Phi \leq \pi$$

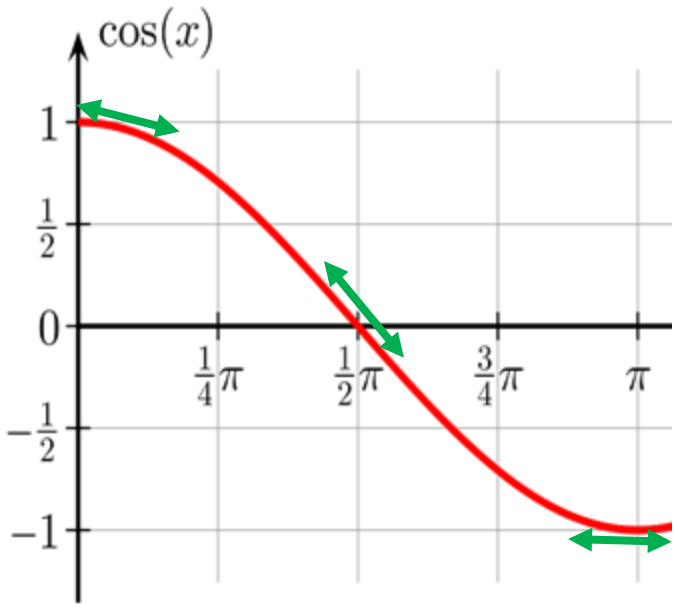
Set: $s = \lambda/2$

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!

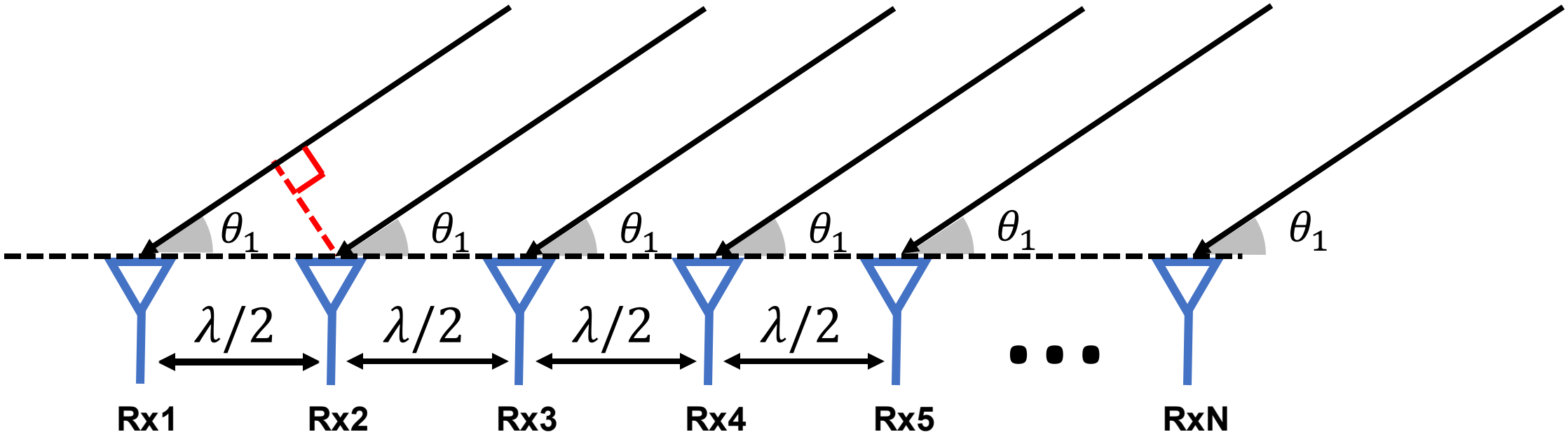
Cons: Ambiguity: $\cos\theta = \cos(-\theta)$

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

Requires 2 Antennas separated $\lambda/2$

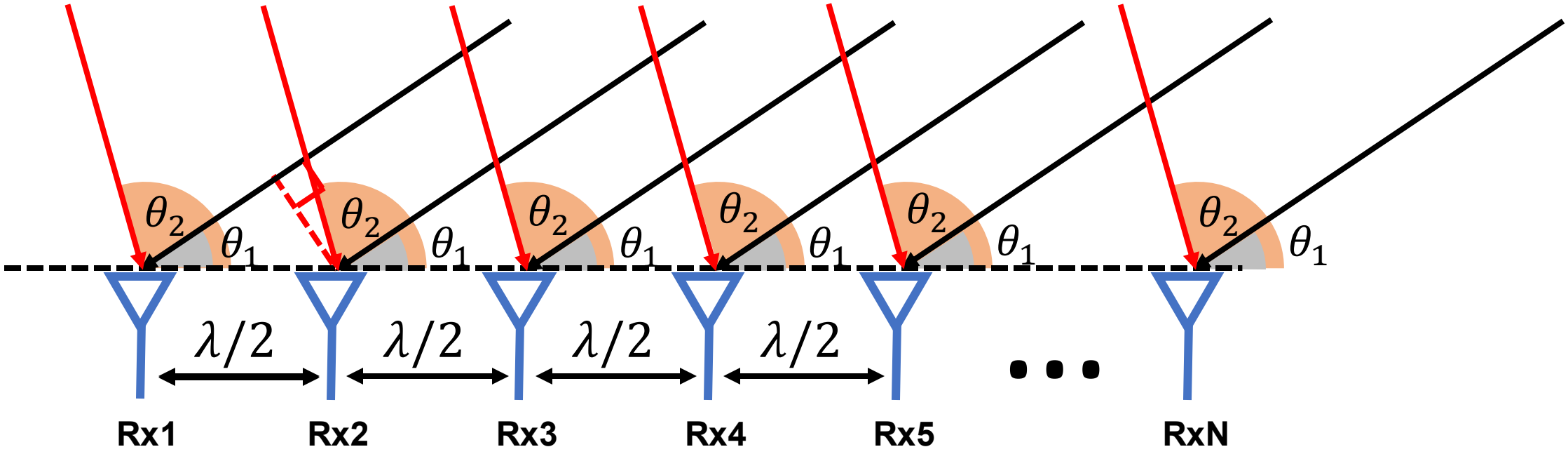
Does not work with multipath!

Method 3: Antenna Arrays



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

Method 3: Antenna Arrays

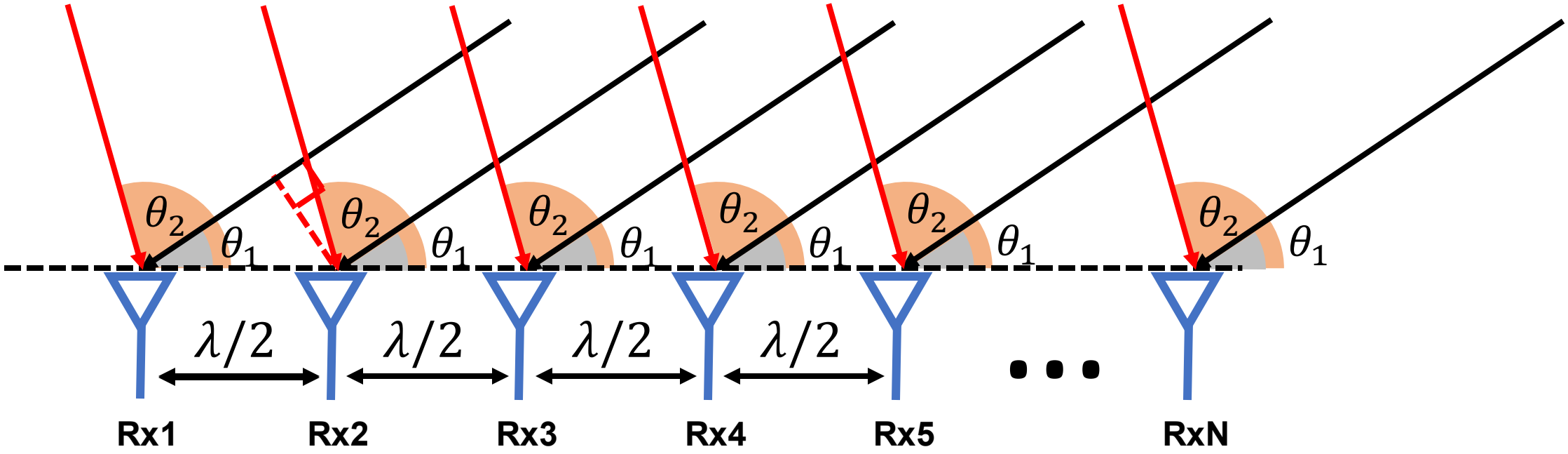


$$h_k = \alpha_1 e^{-j2\pi\frac{d_1 - k\,s\cos\theta_1}{\lambda}} = \alpha_1 e^{-j\phi_1 + k\pi\cos\theta_1}$$

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

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

Method 3: Antenna Arrays



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

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

Method 3: Antenna Arrays

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

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

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

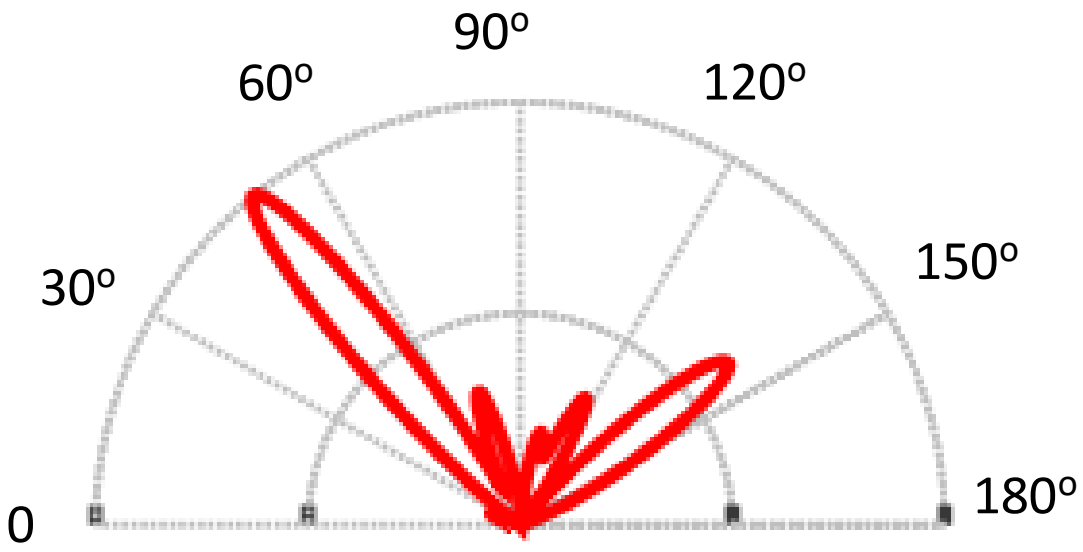
$$= \left| \sum_{k=1}^{N} \alpha_1 e^{-j\phi_1} + \sum_{k=1}^{N} \left(\sum_{l=2}^{L} \alpha_l e^{jk\pi(\cos\theta_l - \cos\theta_1) - j\phi_l} \right) \right|^2$$

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

Method 3: Antenna Arrays

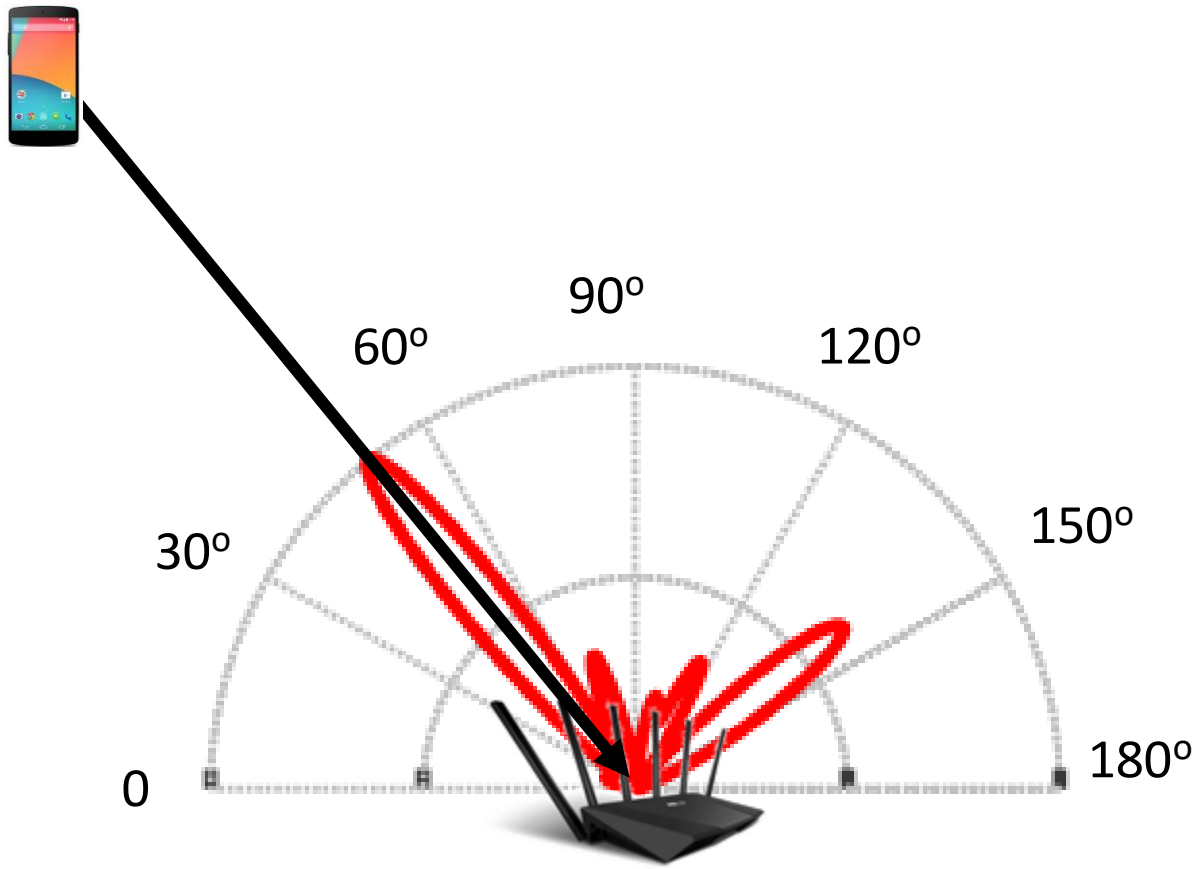
$$h_k = \sum_{l=1}^{L} \alpha_l e^{jk\pi \cos\theta_l - j\phi_l}$$

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



Method 3: Antenna Arrays

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

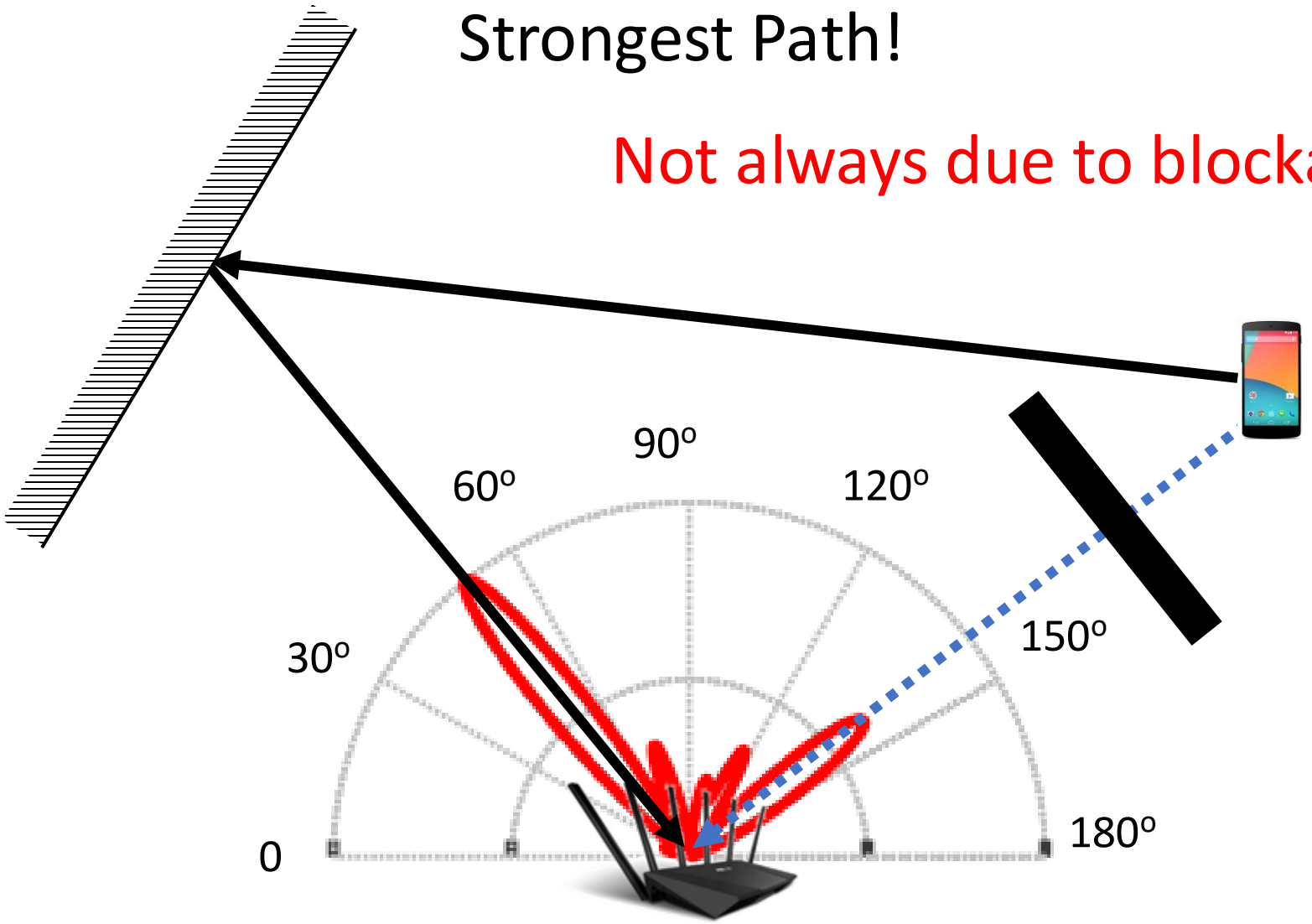


Method 3: Antenna Arrays

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

Strongest Path!

Not always due to blockage!



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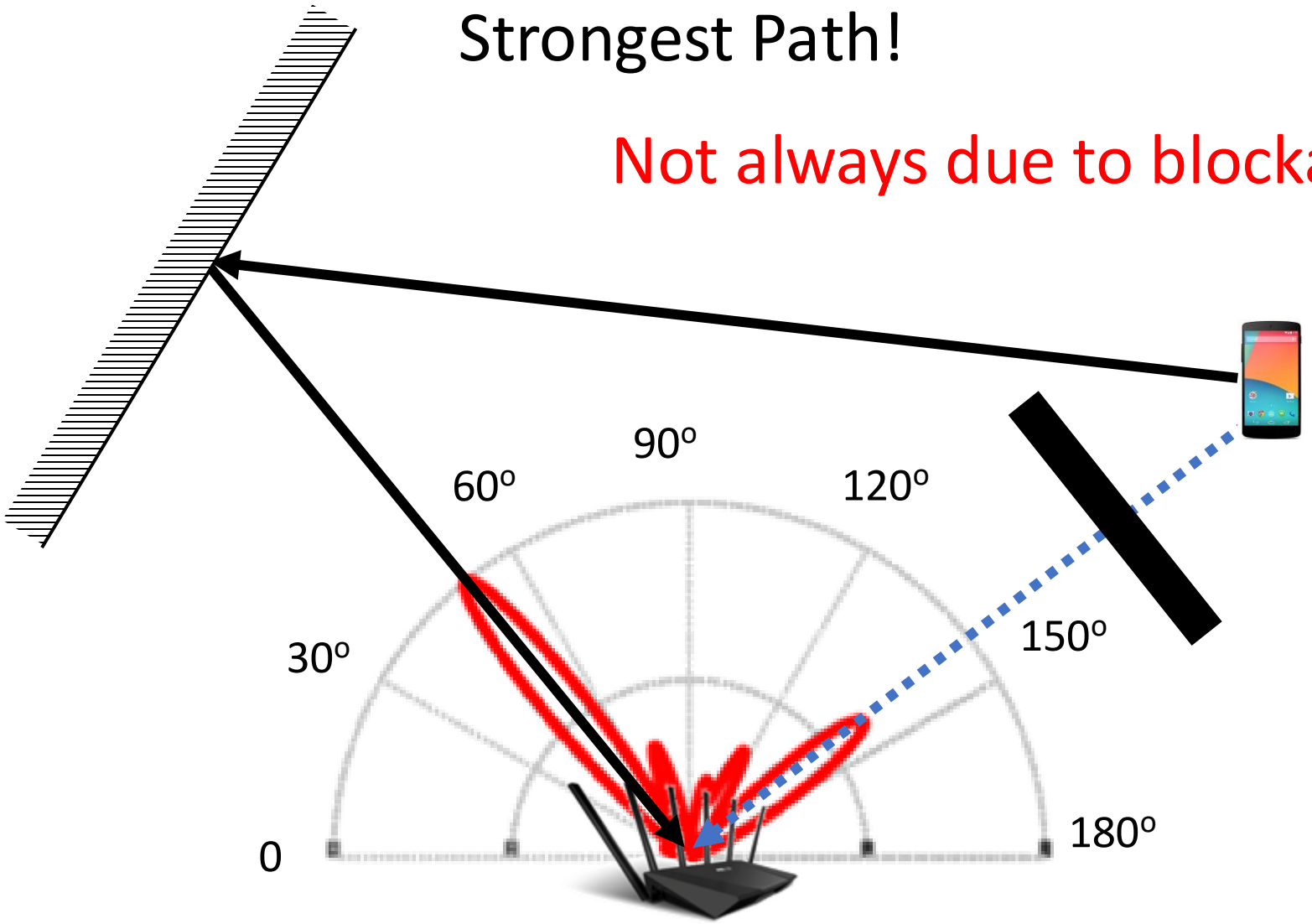

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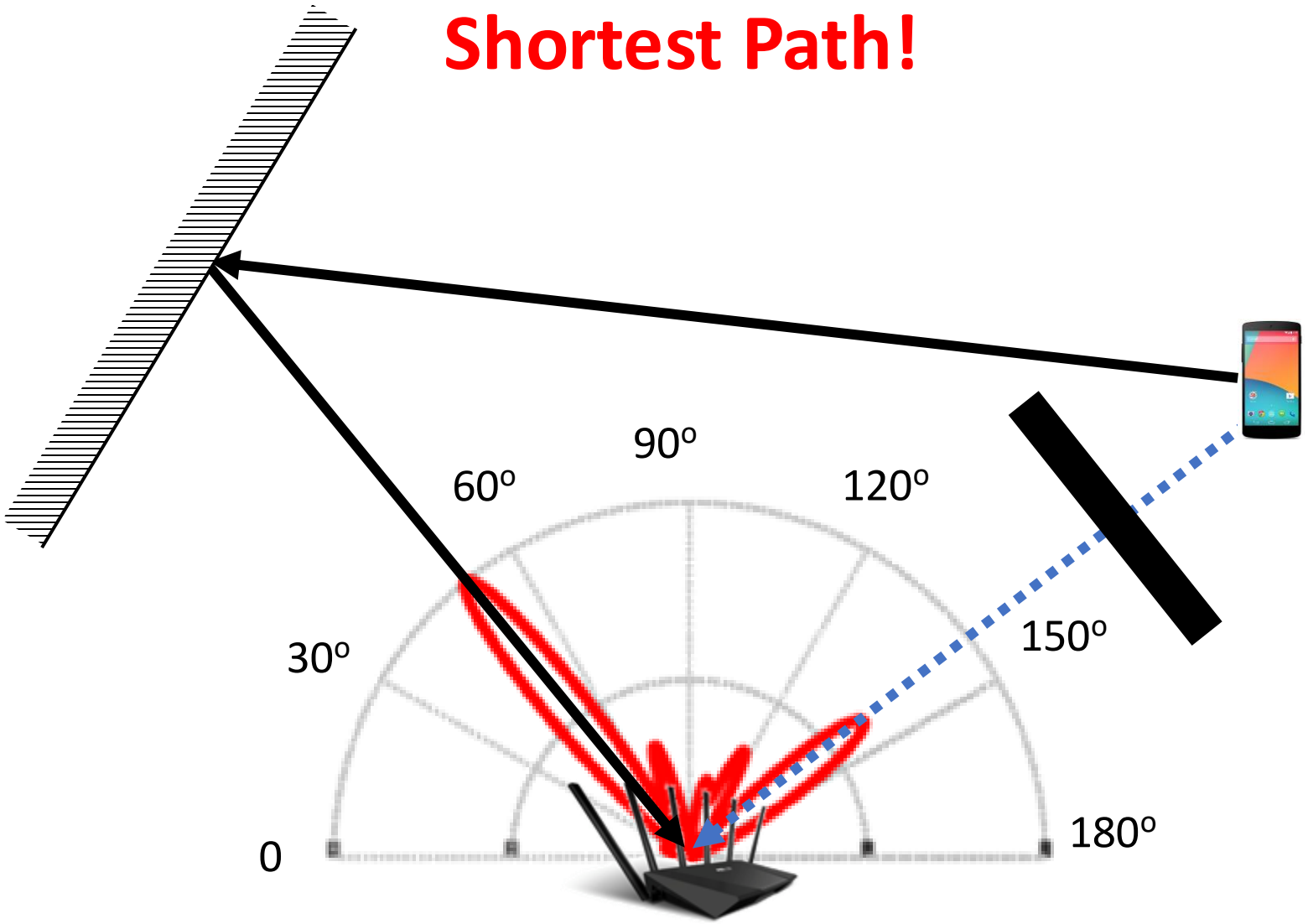
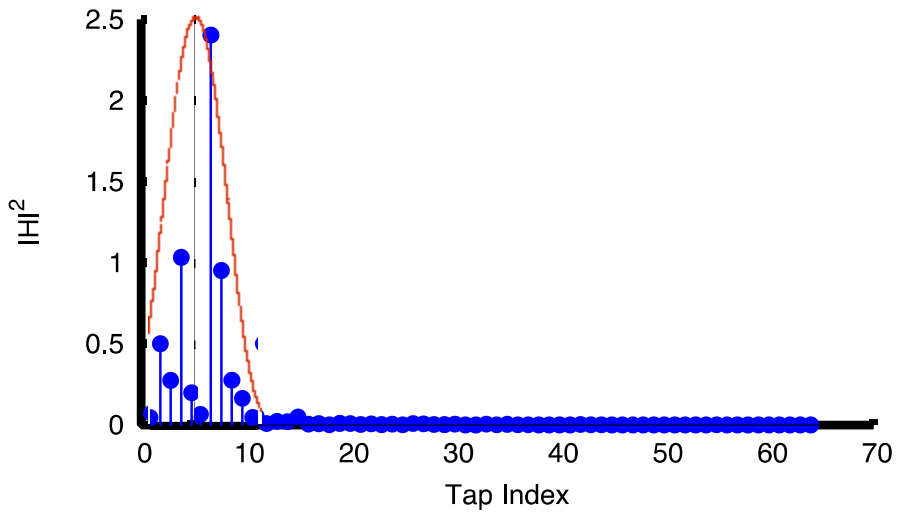


Method 3: Antenna Arrays

Which is the Shortest Path (Direct Path)?



Multipath Profile vs Time

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

$$\left.\begin{aligned} \Delta d &= 1m \\ c &= 3 \times 10^8 m/s \end{aligned}\right\} \Delta\tau = 3.3ns$$

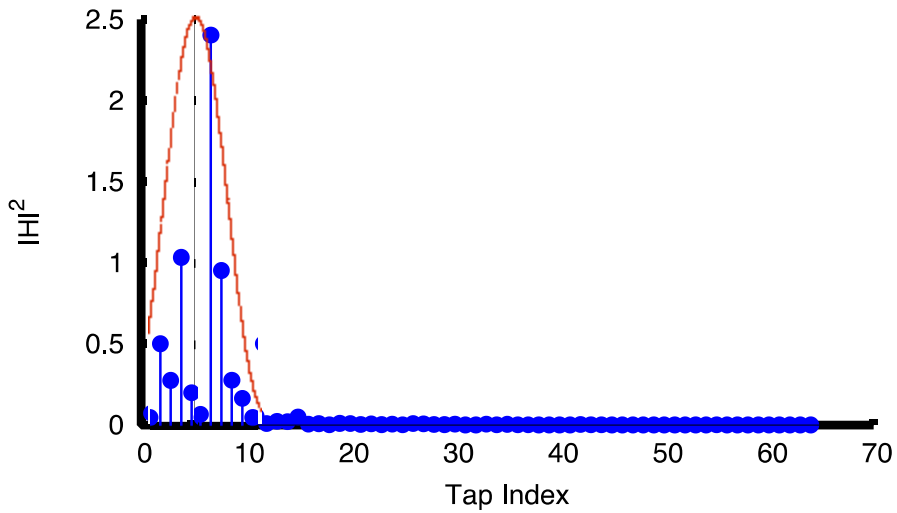
Requires a sampling rate

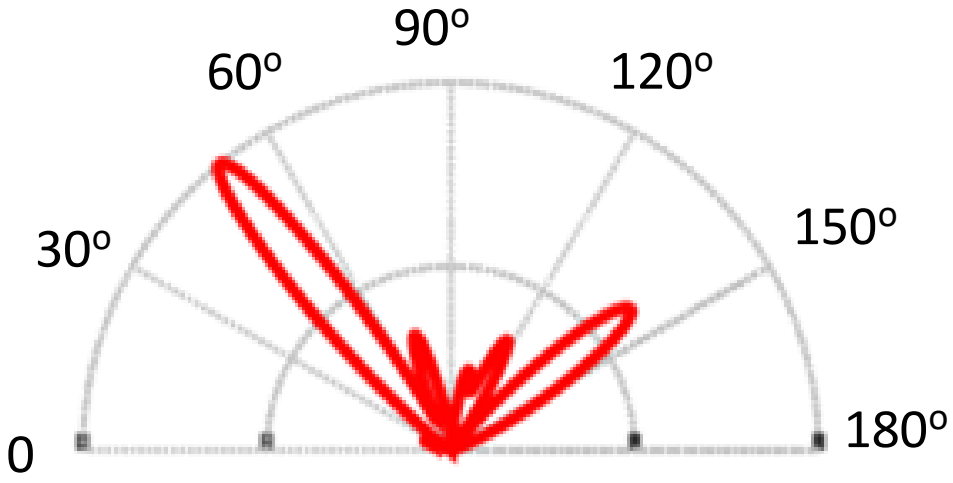
$1/\Delta\tau = 300MHz$

802.11n bandwidth $= 40MHz$

Method 3: Antenna Arrays

Which is the Shortest Path (Direct Path)?



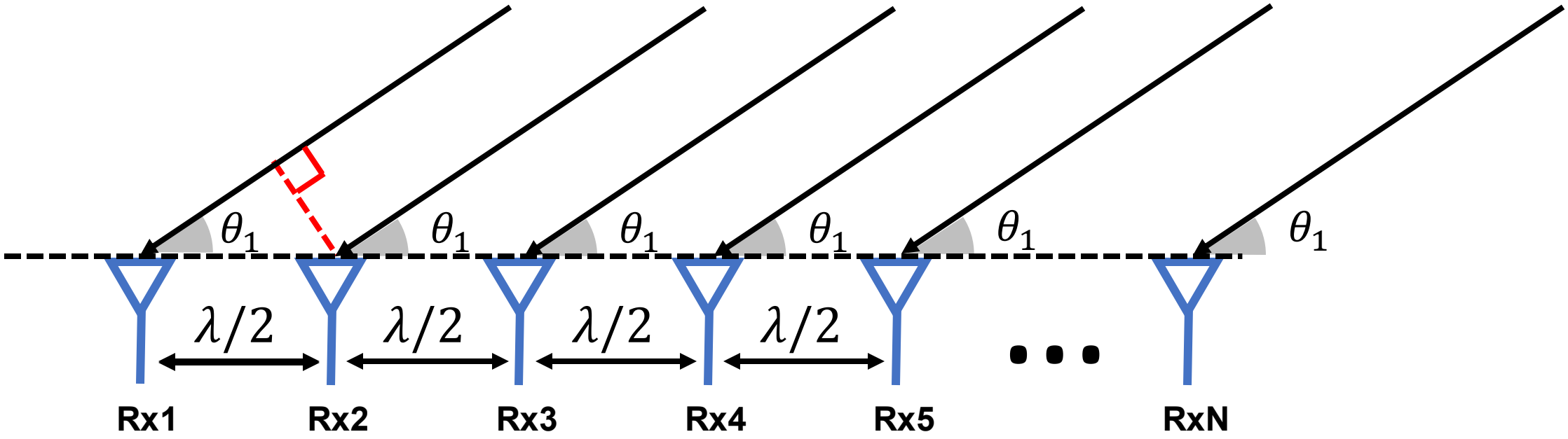


Multipath Profile vs Time

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

Method 3: Antenna Arrays

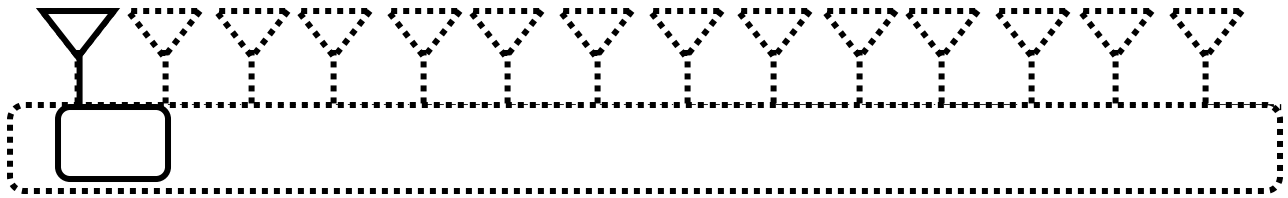


Pros: Works with multipath, No need for fingerprinting

Cons: Requires more hardware!

Assumes device is sufficiently far such that wavefront is parallel

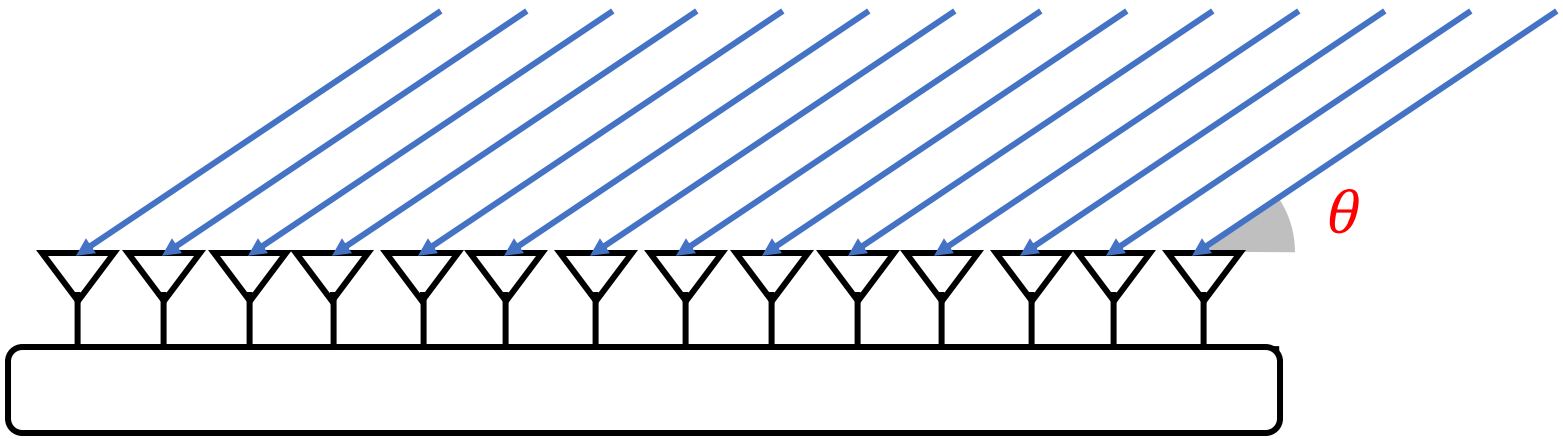
Method 4: SAR: Synthetic Aperture Radar



Move the antenna to emulate a very large array:

$$h_t = \alpha e^{-j2\pi \frac{d - vt\cos\theta}{\lambda}}$$

Method 4: SAR: Synthetic Aperture Radar



$$h_k = \alpha e^{-j2\pi\frac{d-k\,s\cos\theta}{\lambda} - j2\pi\Delta f_c t} = \alpha e^{-j2\pi\frac{d-k\,s\cos\theta}{\lambda} - j\phi(t)}$$

So far, we ignored CFO!

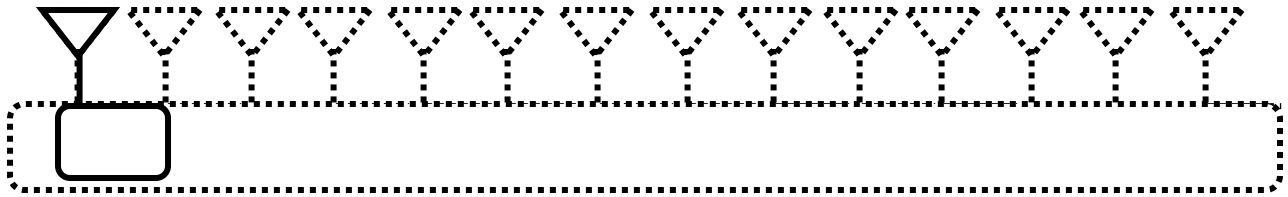
In antenna arrays: all antennas are synchronized!

→ All antennas see the same CFO relative to transmitter

Phase created by CFO is same on all antenna!

→ CFO is not a problem.

Method 4: SAR: Synthetic Aperture Radar



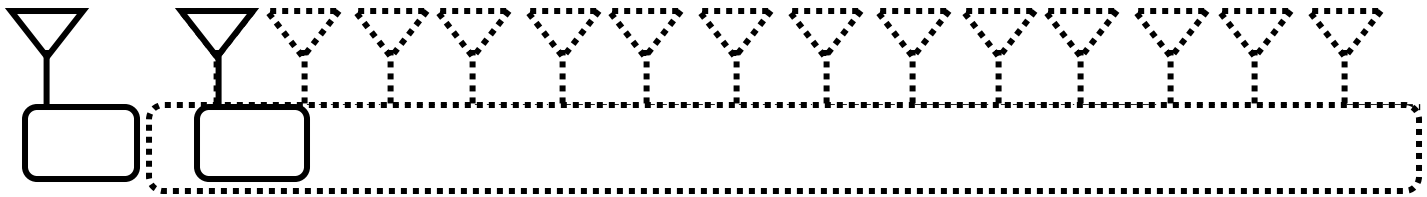
$$h_t = \alpha e^{-j2\pi\frac{d-vt\cos\theta}{\lambda}-j2\pi\Delta f_c t}$$

Channel at each location measured at different times

→Phase created by CFO is different for different antenna locations

Method 4: SAR: Synthetic Aperture Radar

How to use enable SAR for WiFi?



Use 2 antennas that are synched:

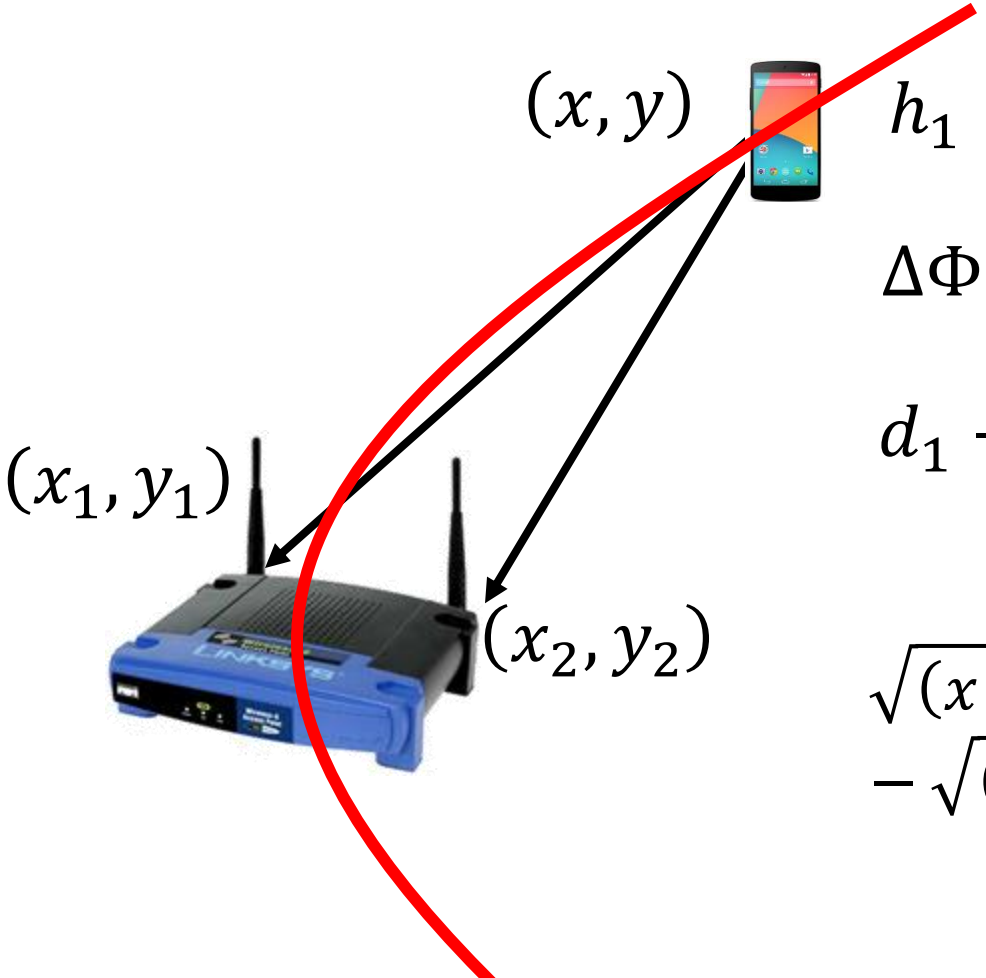
- 1 Moving antenna $h_{1t} = \alpha e^{-j2\pi\frac{d_1 - vt\cos\theta}{\lambda} - j2\pi\Delta f_c t}$
- 1 Static antenna $h_{2t} = \alpha e^{-j2\pi\frac{d_2}{\lambda} - j2\pi\Delta f_c t}$

Taking ratio eliminates CFO: $\frac{h_{1t}}{h_{2t}} = e^{-j2\pi\frac{d_1 + d_2 - vt\cos\theta}{\lambda}}$

Enable SAR with WiFi but … limited mobility
→ Emulate small arrays

Method 5: TDoA Based Localization

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



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

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

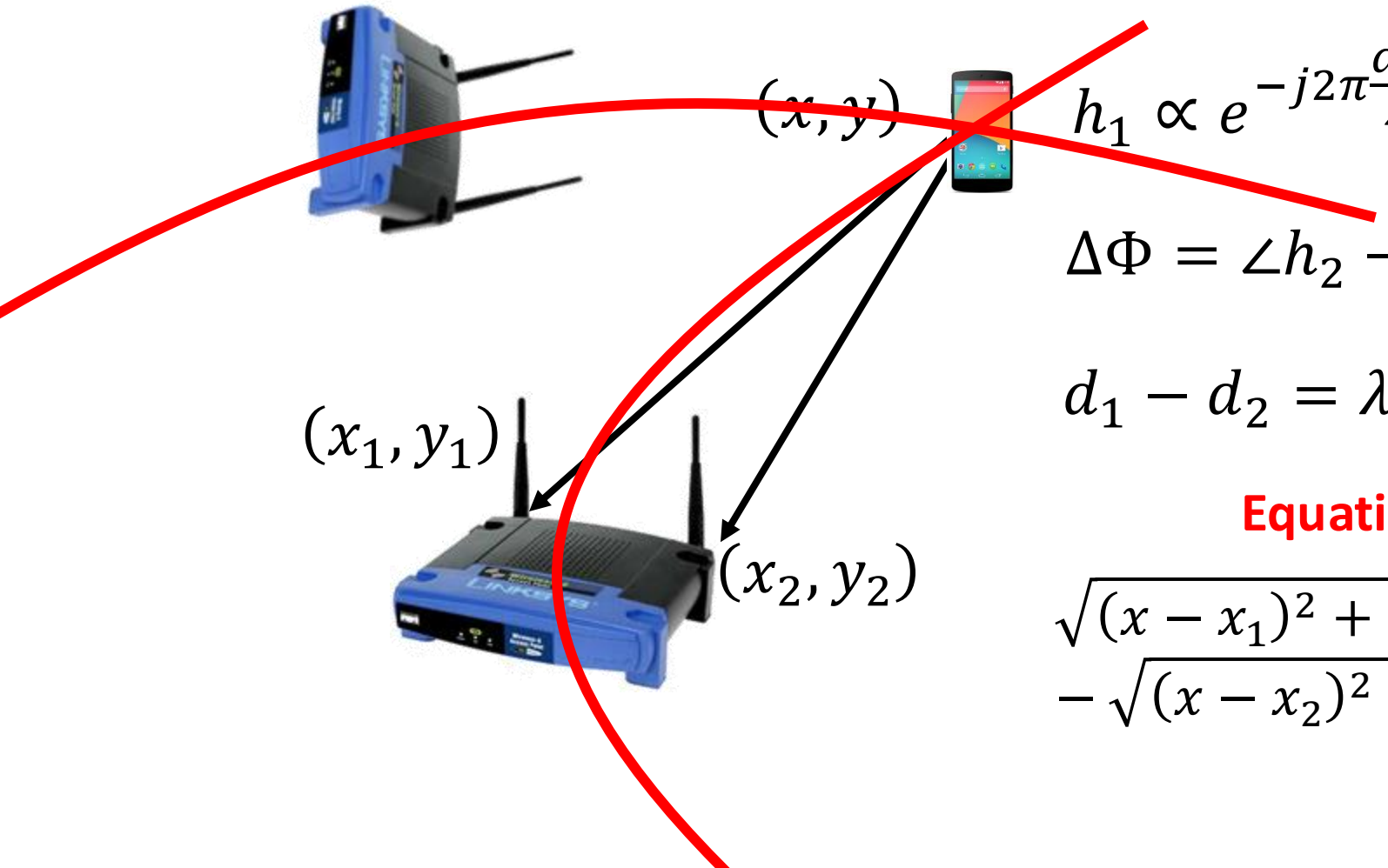
$$d_1 - d_2 = \lambda\Delta\Phi/2\pi = d'$$

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



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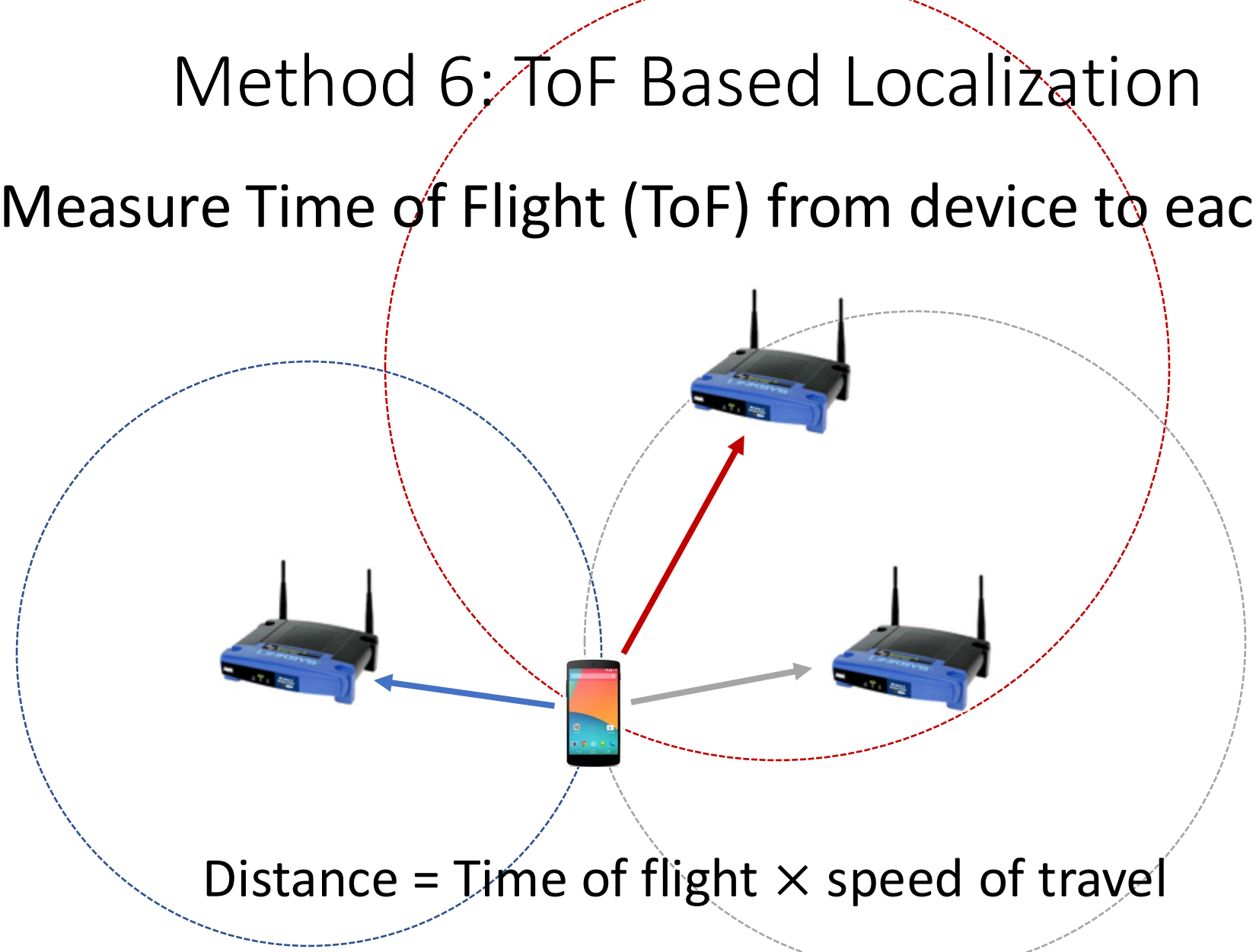
Method 6: ToF Based Localization

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



Distance = Time of flight × speed of travel

Measure ToF → Get distance → Trilateration

Method 6: ToF Based Localization

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

Challenges:

- How do you know when signal was transmitted?

Measure Round Trip

- How about packet detection delay & processing delay?

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

Not Practical!

Method 6: 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 (Apple Air Tag)
  - FMCW: Frequency Modulated Carrier Wave (Google Solis, Nest Hub, Amazon Halo, Emerald Innovations)