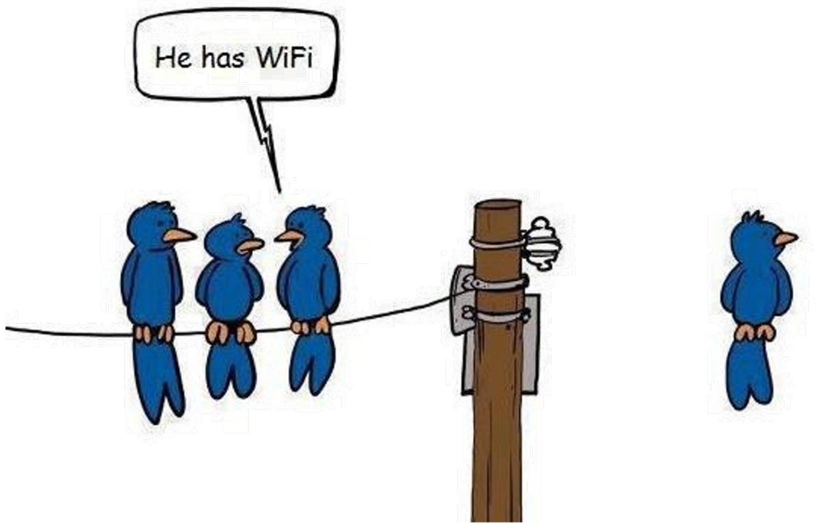
# COM-405: Mobile Networks

## Lecture 9.1: Wireless Localization

Haitham Hassanieh




EPFL

Laboratory of SEnsing
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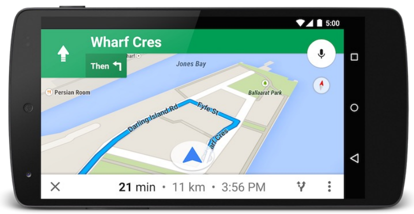
# Wireless Localization / Positioning

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

**Applications:**

- Navigation: outdoors (GPS) and indoors (e.g., museum)



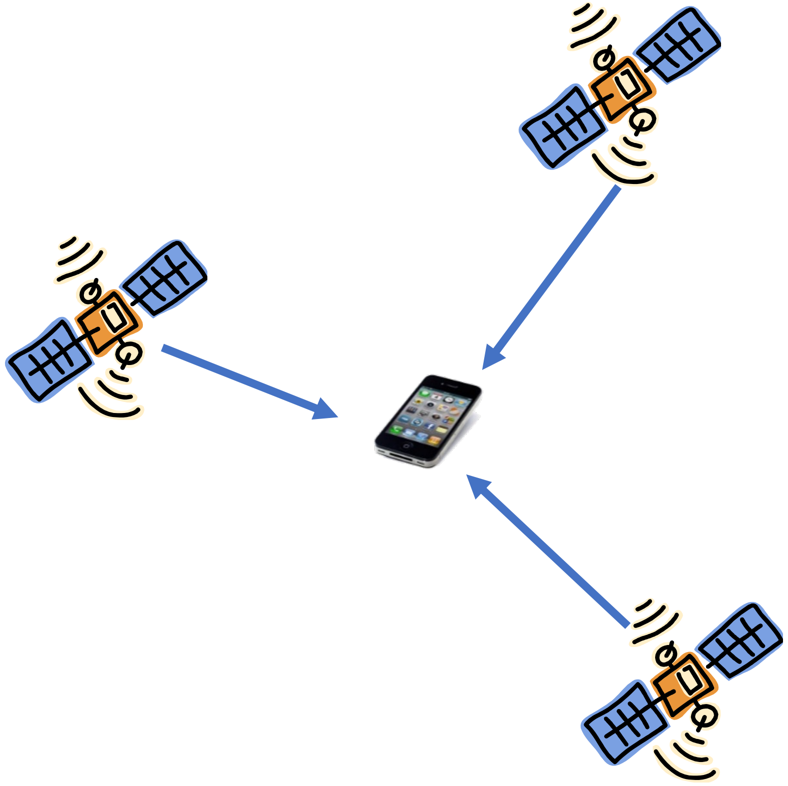

- Location based services: Tagging, Reminder, Ads

- Virtual Reality and Motion Capture
- Gestures, writing in the air
- Behavioral Analytics (Health, activities, etc.)

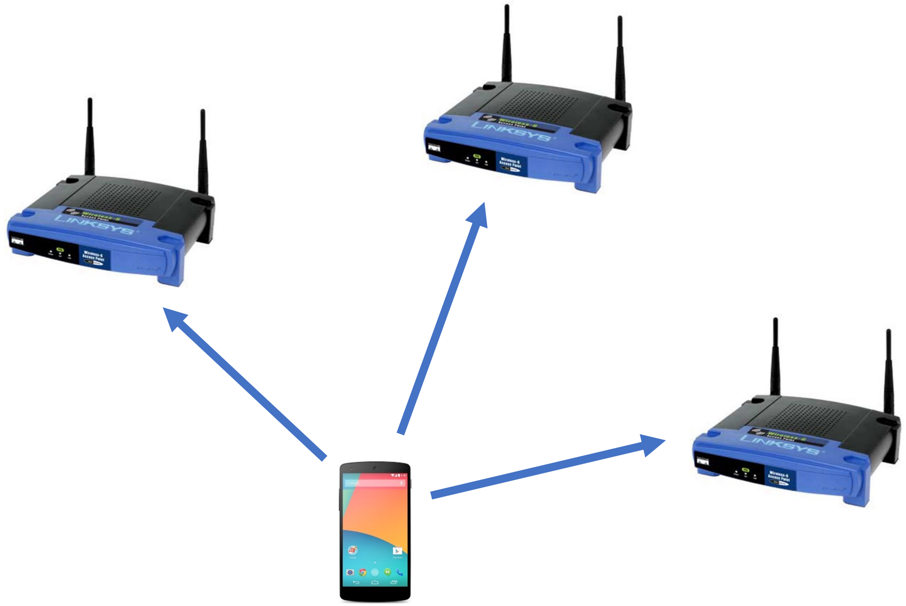
- Locating misplaced items (keys)
- Location based security
- Delivery drones

# Wireless Localization Architecture.

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

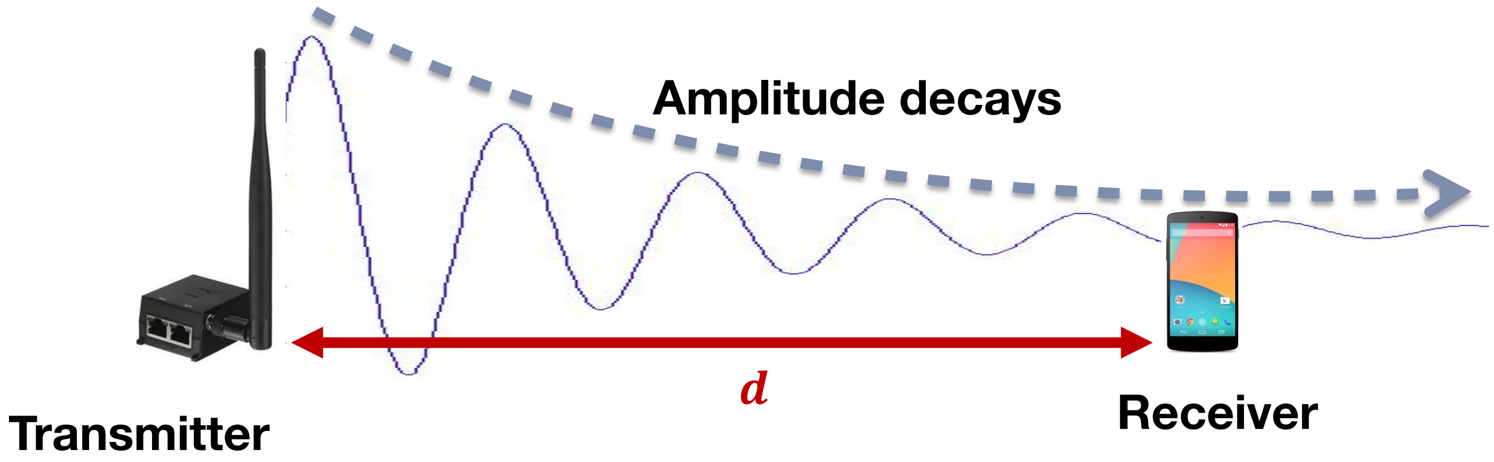


- Network based: Anchors (or Access points) use the signal coming from device to determine its location



# Method 1: RSSI Based Localization

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

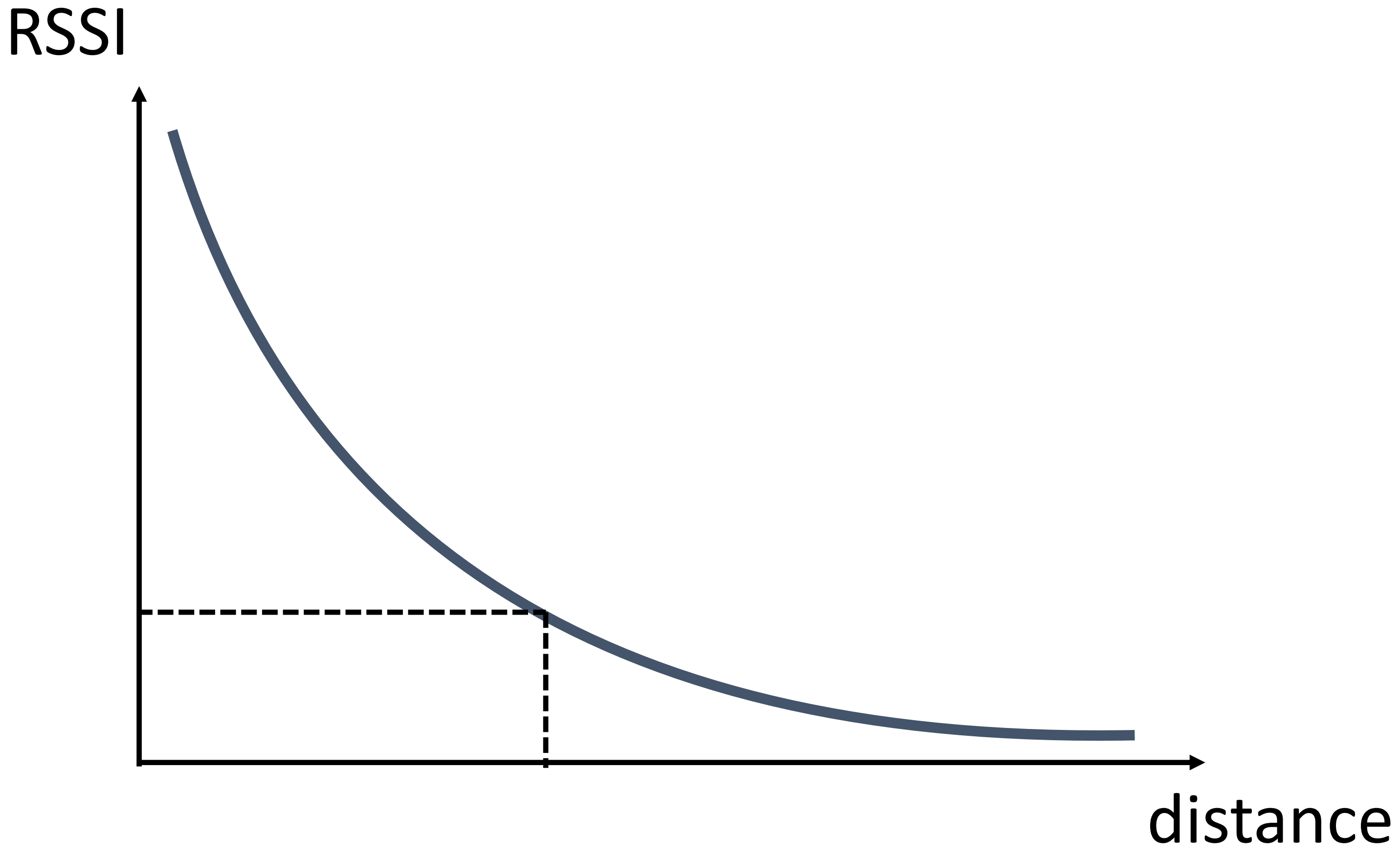



$$P_{Rx} = \frac{G_{Tx}\, G_{Rx}\, \lambda^2}{(4\pi d)^2} P_{Tx} \quad \Rightarrow \quad RSSI \propto \frac{1}{d^2}$$

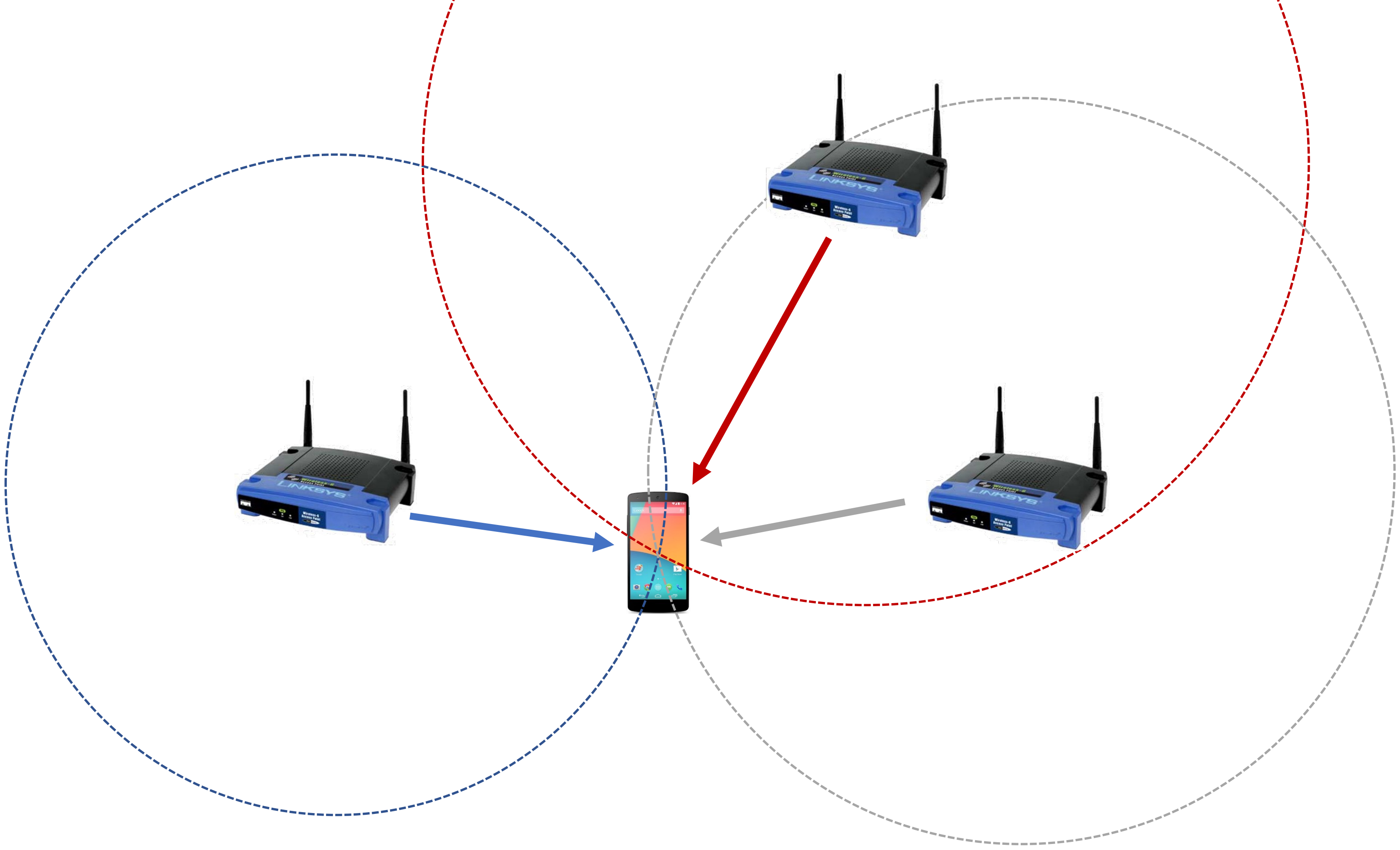
Use RSSI to estimate distance from APs!

# Method 1: RSSI Based Localization

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



# Method 1: RSSI Based Localization

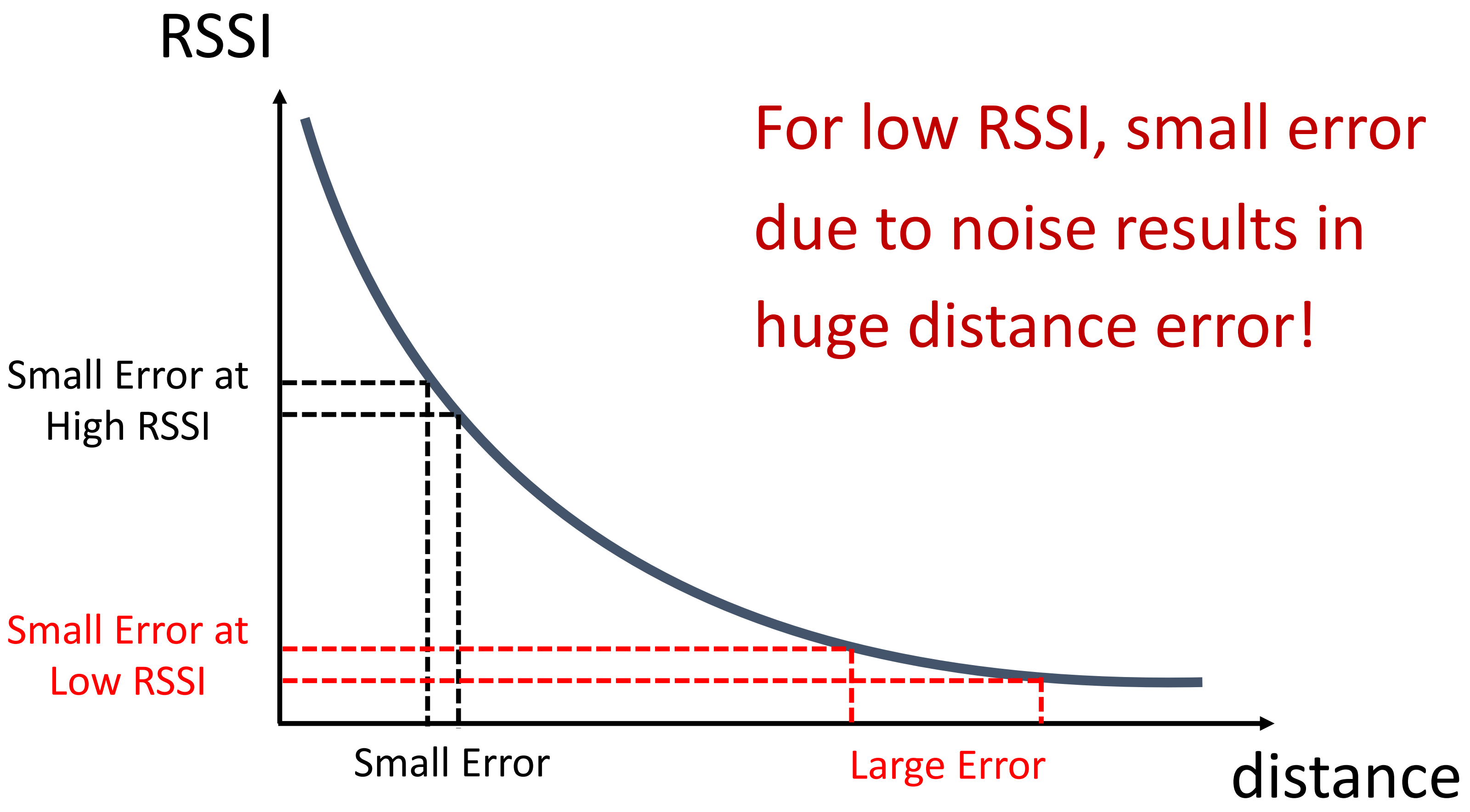


**Trilateration**

# Method 1: RSSI Based Localization

**Pros:** Very simple, no hardware modifications

**Cons:** Highly inaccurate!



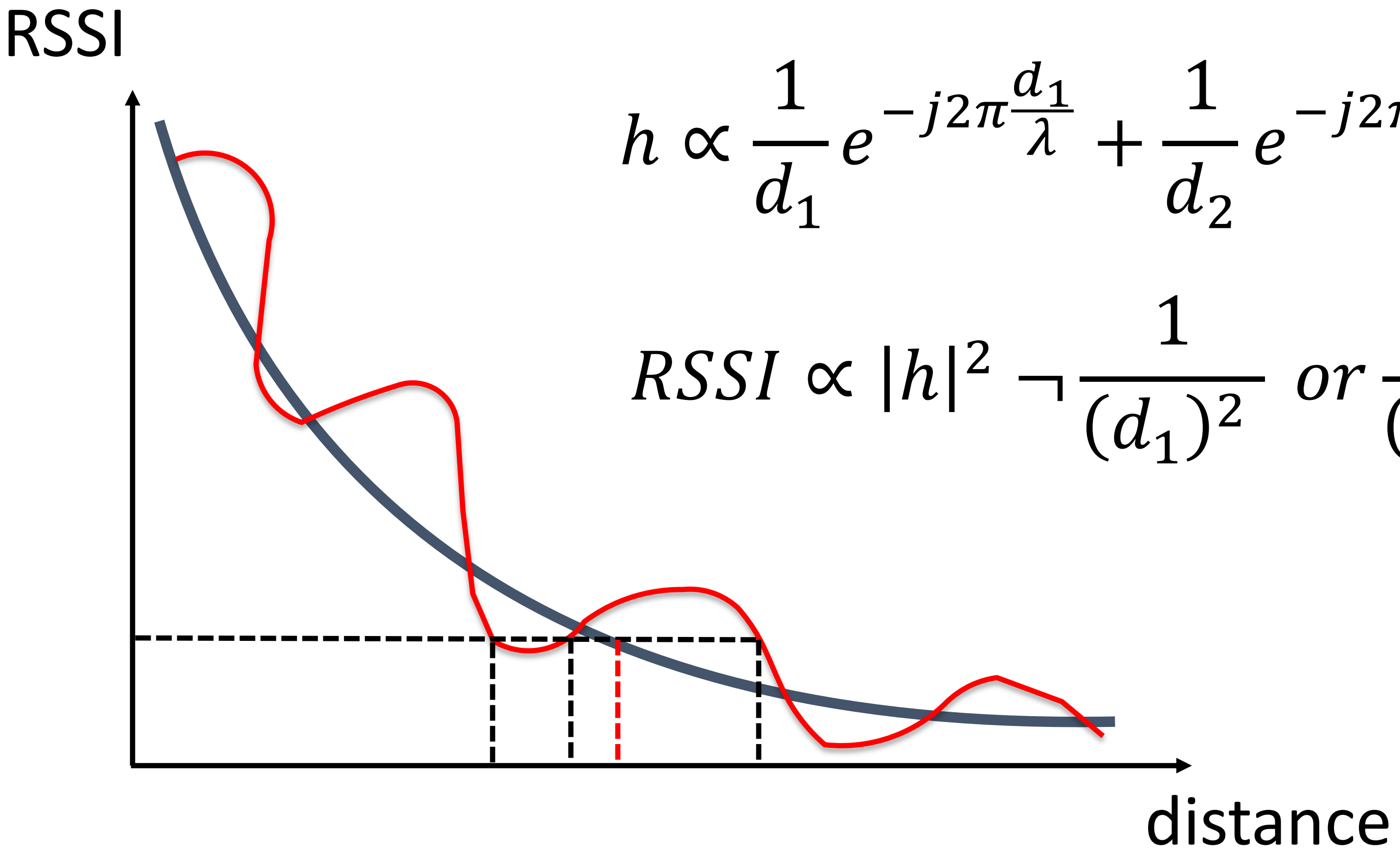

For low RSSI, small error due to noise results in huge distance error!

# Method 1: RSSI Based Localization

**Pros:** Very simple, no hardware modifications!

**Cons:** Highly inaccurate!

Does not work with multipath!



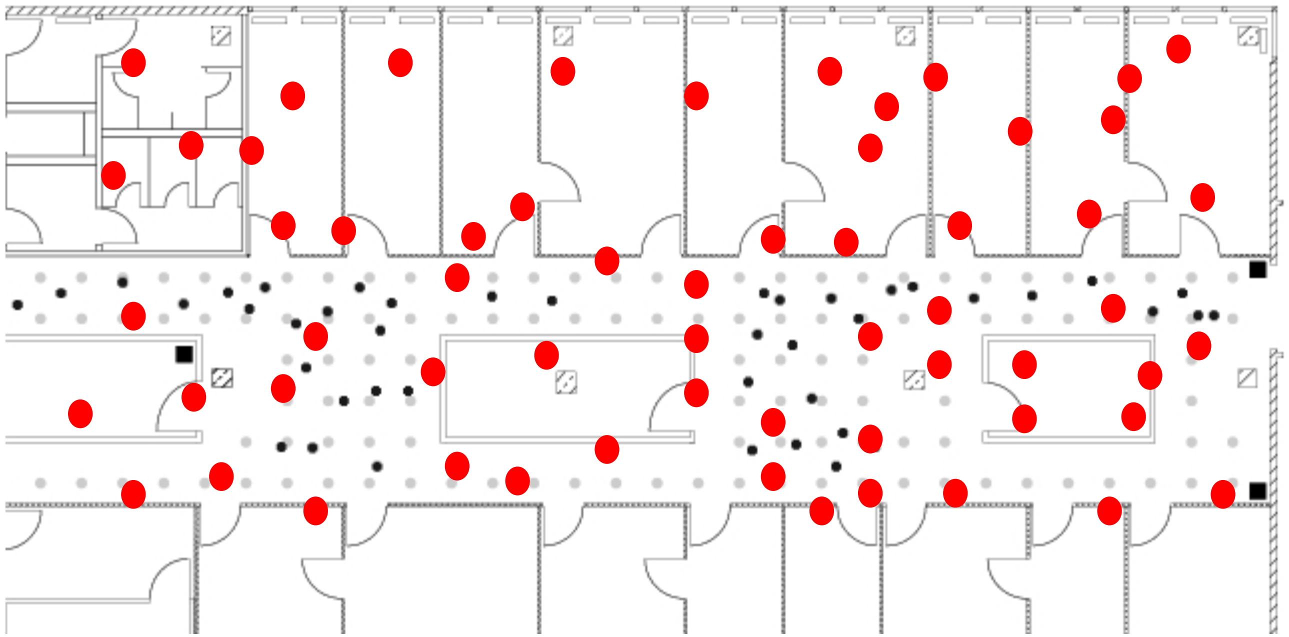

$$h \propto \frac{1}{d_1} e^{-j2\pi\frac{d_1}{\lambda}} + \frac{1}{d_2} e^{-j2\pi\frac{d_2}{\lambda}}$$

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

# Method 1: RSSI Based Localization

**Solution:** Fingerprinting

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



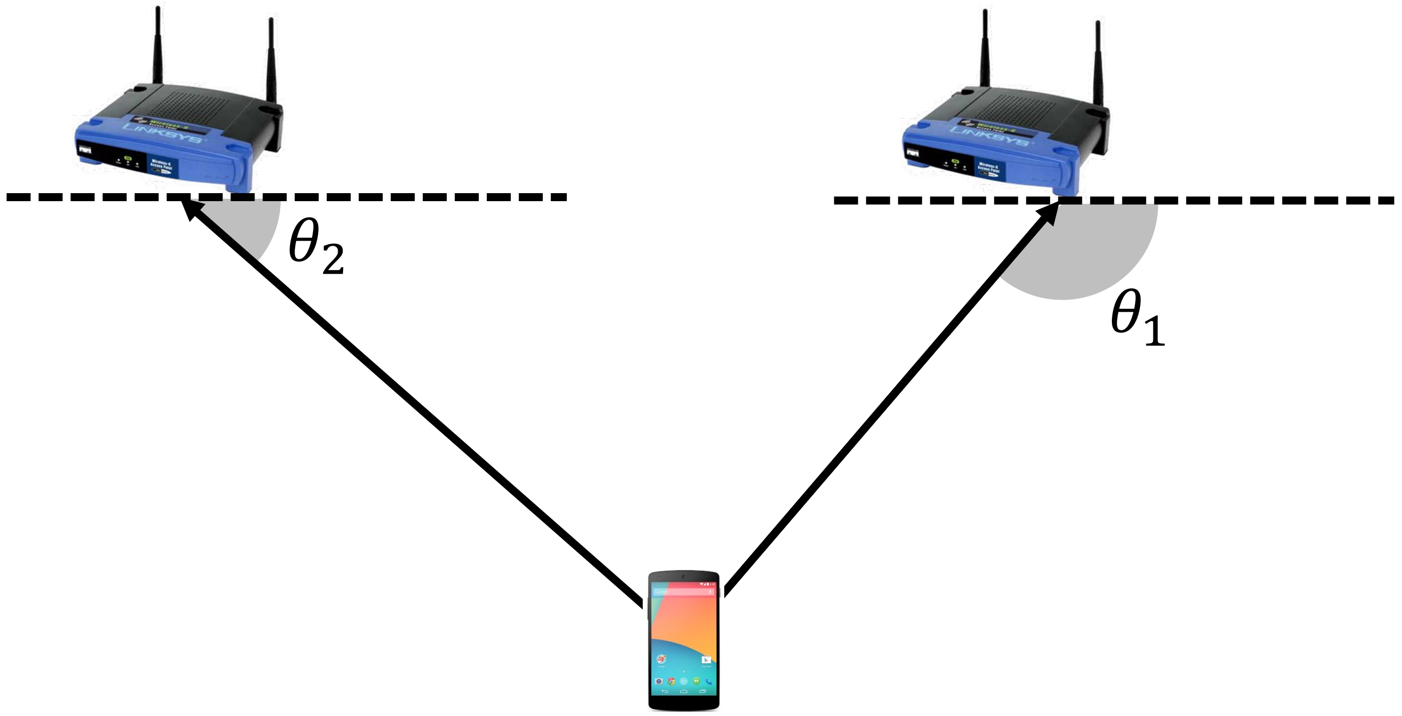
**Pros:** Works with multipath, No need to know AP locations!

**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

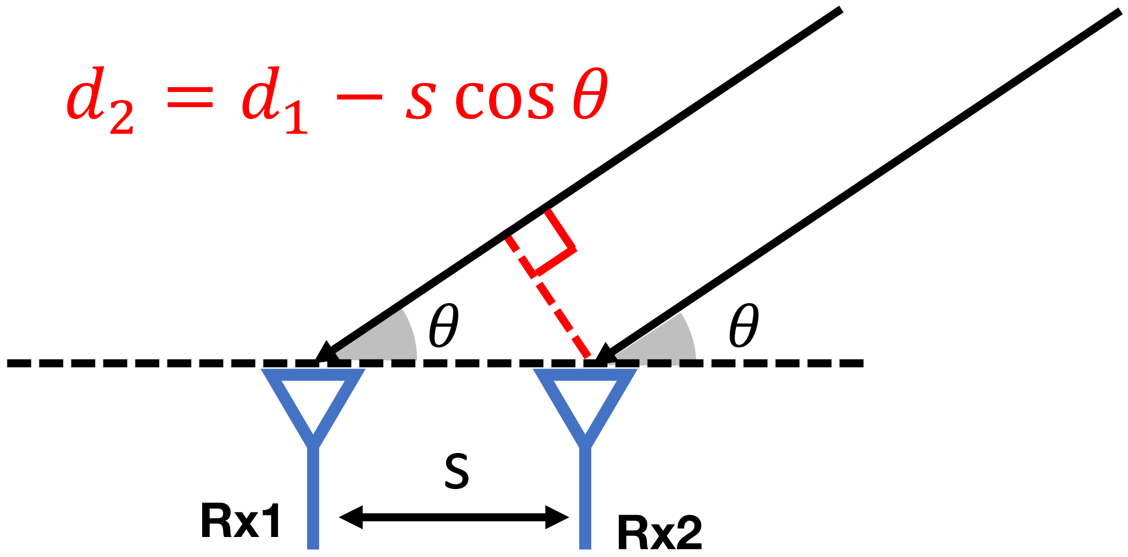



**Triangulation**

# Method 2: AoA Based Localization

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

$d_2 = d_1 - s\cos\theta$

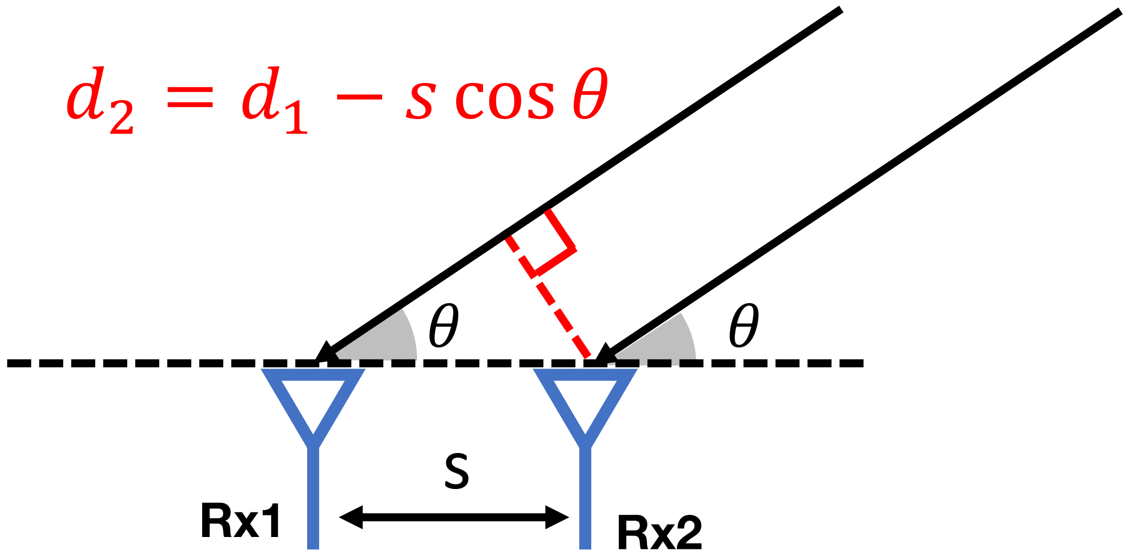



$h_1 \propto e^{-j2\pi\frac{d_1}{\lambda}}$ $\quad h_2 \propto e^{-j2\pi\frac{d_2}{\lambda}} = e^{-j2\pi\frac{d_1 - s\cos\theta}{\lambda}}$

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

# Method 2: AoA Based Localization

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




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

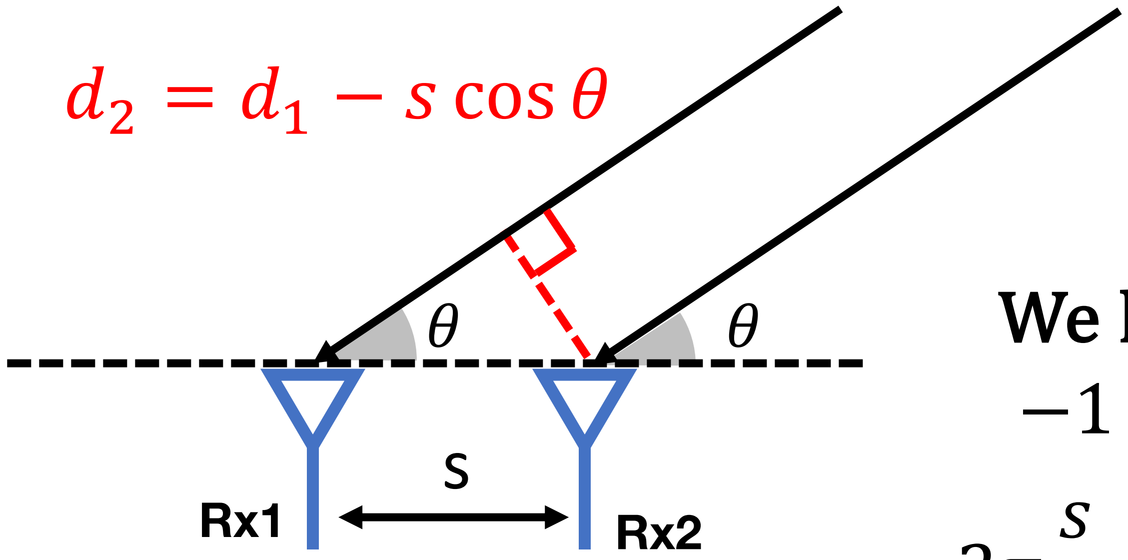
**Ambiguity:** $\exists\theta_1 \neq \theta_2 \mid \Delta\Phi_1 = \Delta\Phi_2 \mod 2\pi$

**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:**

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

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

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

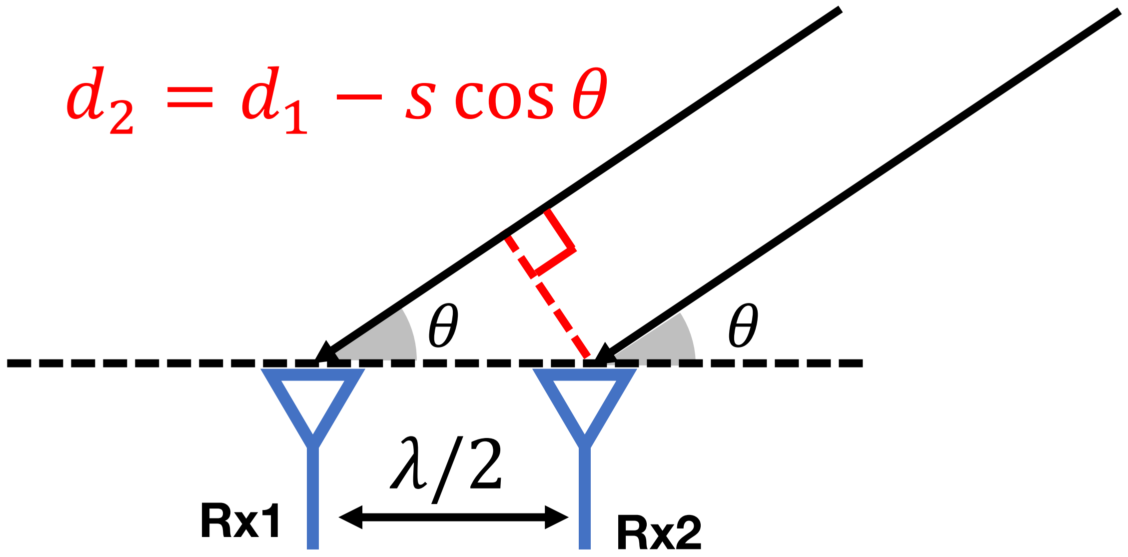
$$-\pi \leq \quad \Delta\Phi \quad \leq \pi$$

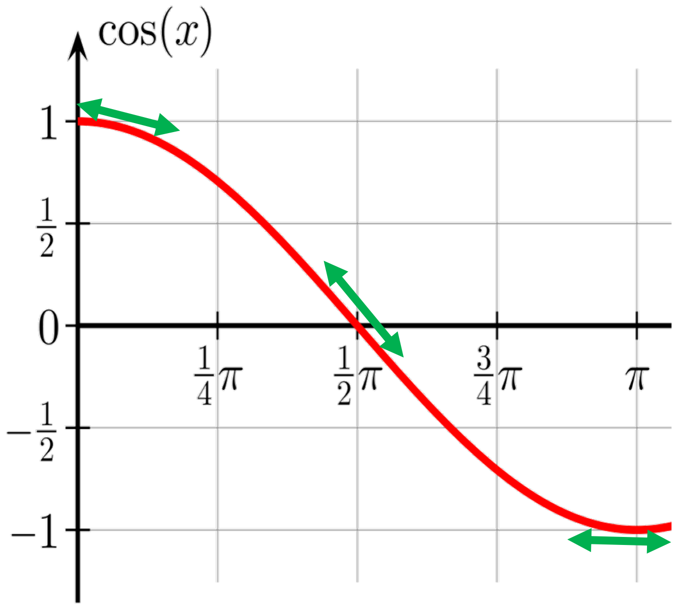
Set: $s = \lambda/2$

# 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!

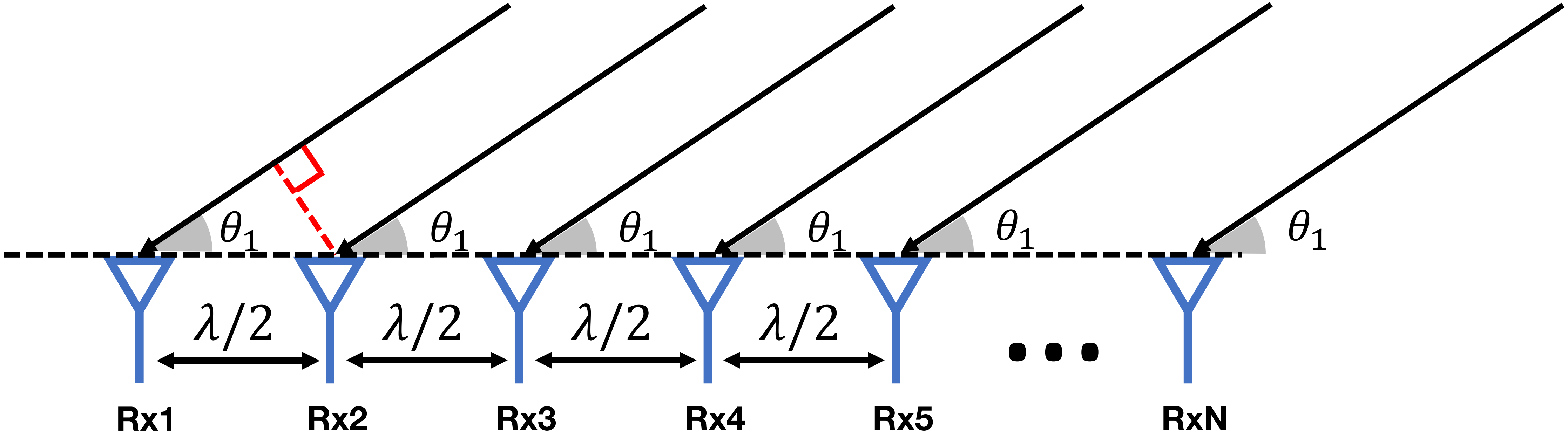
**Cons:** Ambiguity: $\cos\theta = \cos(-\theta)$

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

Requires 2 Antennas separated $\lambda/2$

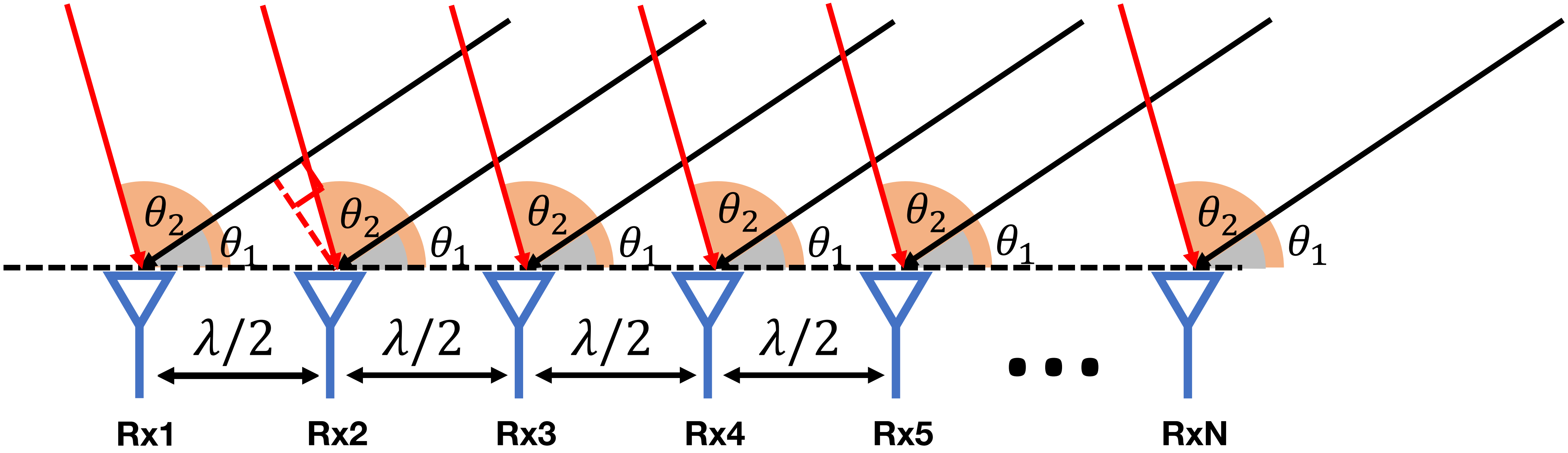
Does not work with multipath!

# 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

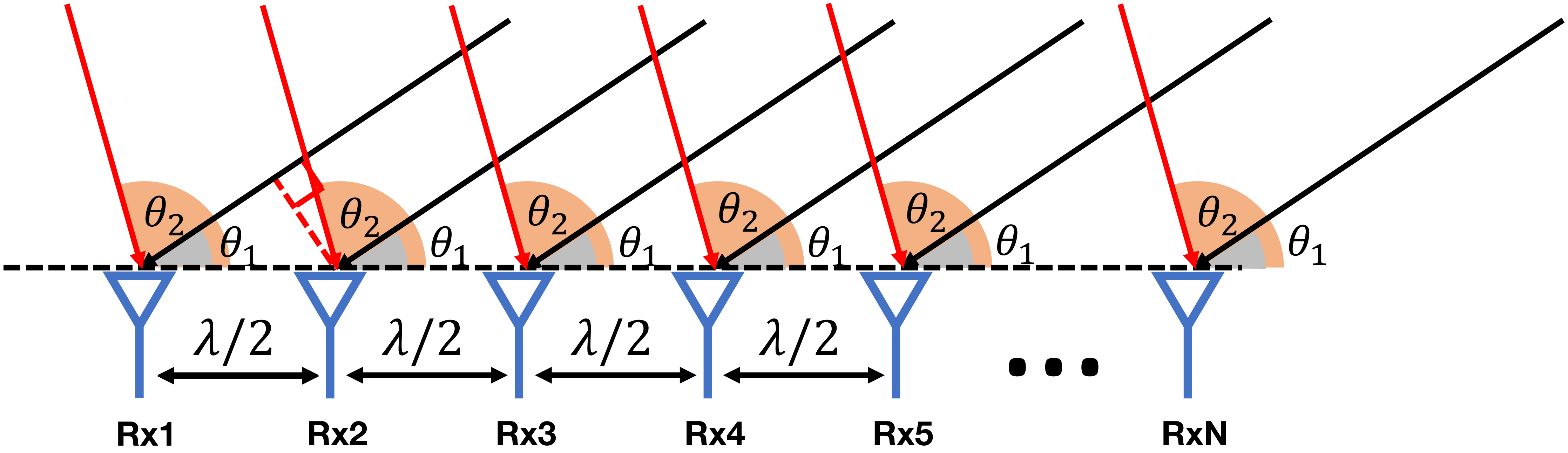



$$h_k = \alpha_1 e^{-j2\pi\frac{d_1 - k\,s\cos\theta_1}{\lambda}} = \alpha_1 e^{-j\phi_1 + k\pi\cos\theta_1}$$

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

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

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

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

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

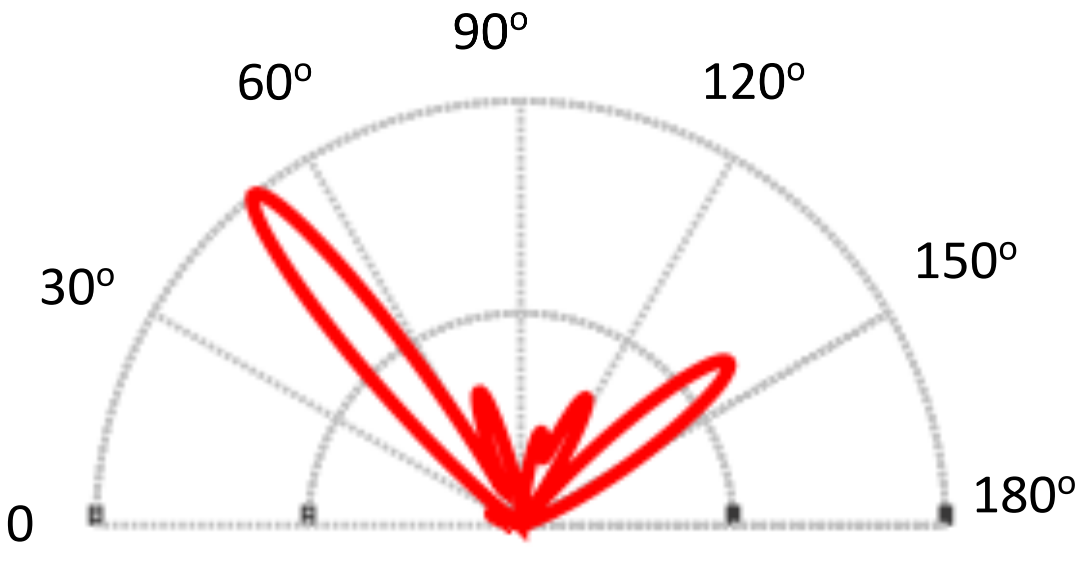
$$= \left|\sum_{k=1}^{N} \alpha_1 e^{-j\phi_1} + \sum_{k=1}^{N}\left(\sum_{l=2}^{L} \alpha_l e^{jk\pi(\cos\theta_l - \cos\theta_1) - j\phi_l}\right)\right|^2$$

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

# Method 3: Antenna Arrays

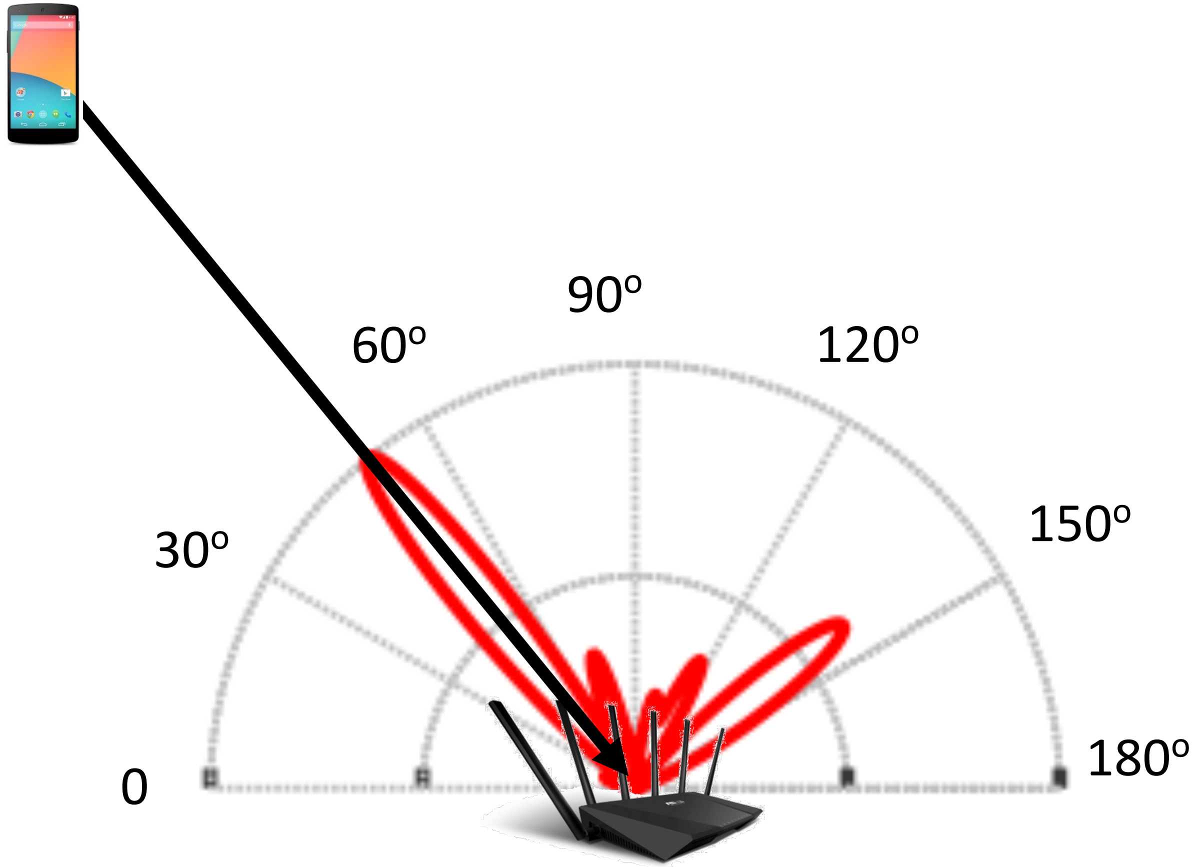
$$h_k = \sum_{l=1}^{L} \alpha_l e^{jk\pi\cos\theta_l - j\phi_l}$$

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



# Method 3: Antenna Arrays

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

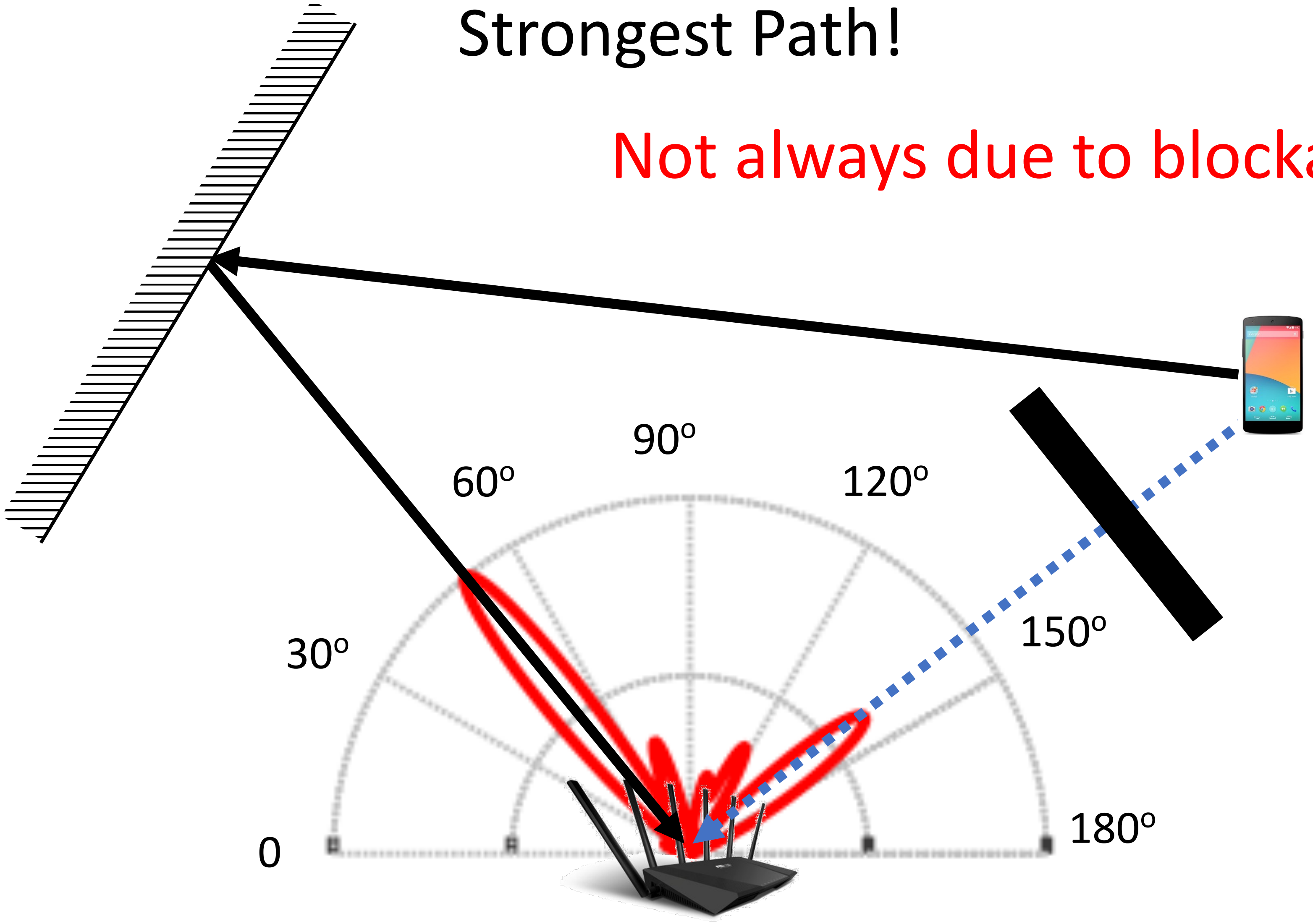


# Method 3: Antenna Arrays

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

Strongest Path!

Not always due to blockage!



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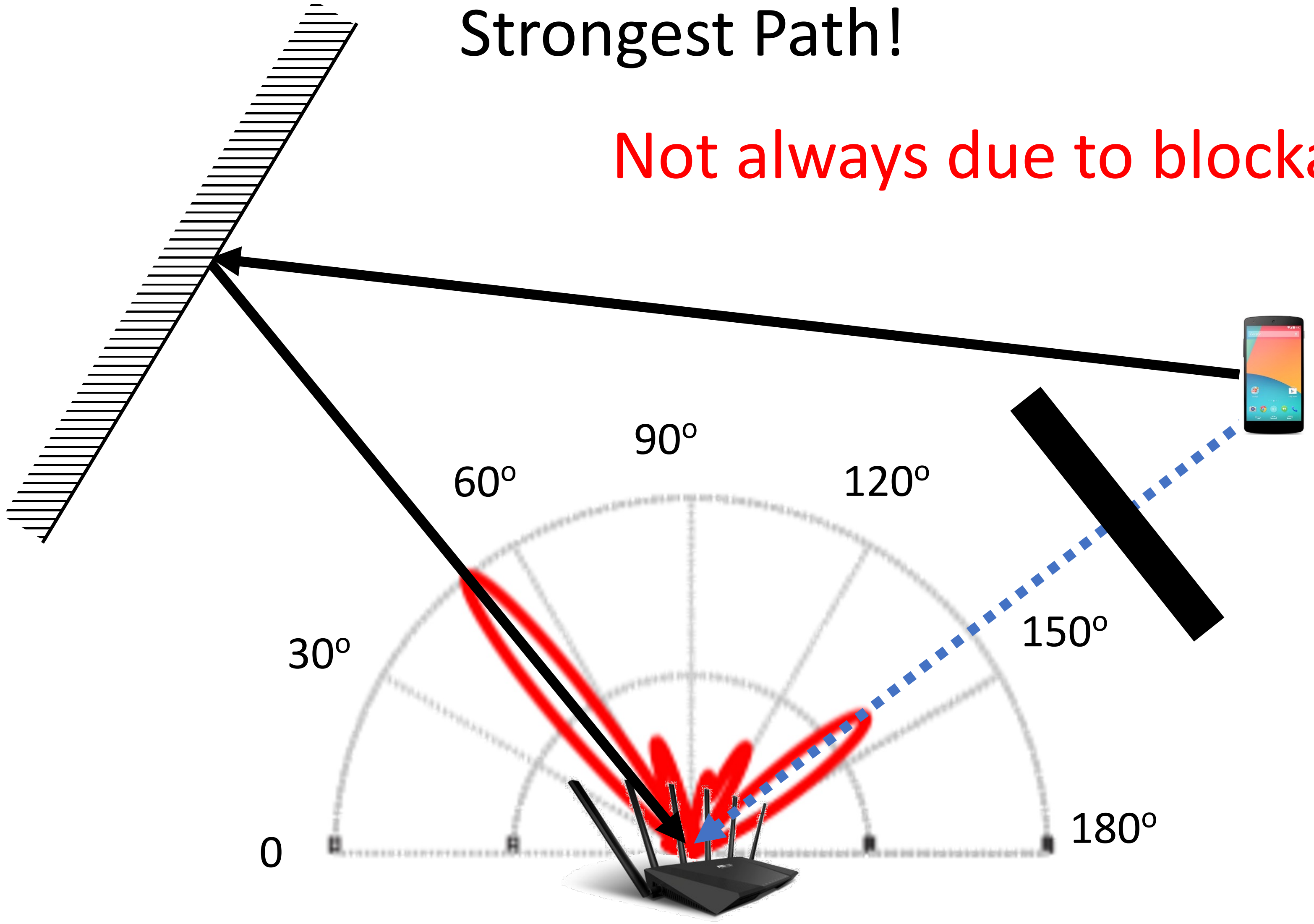
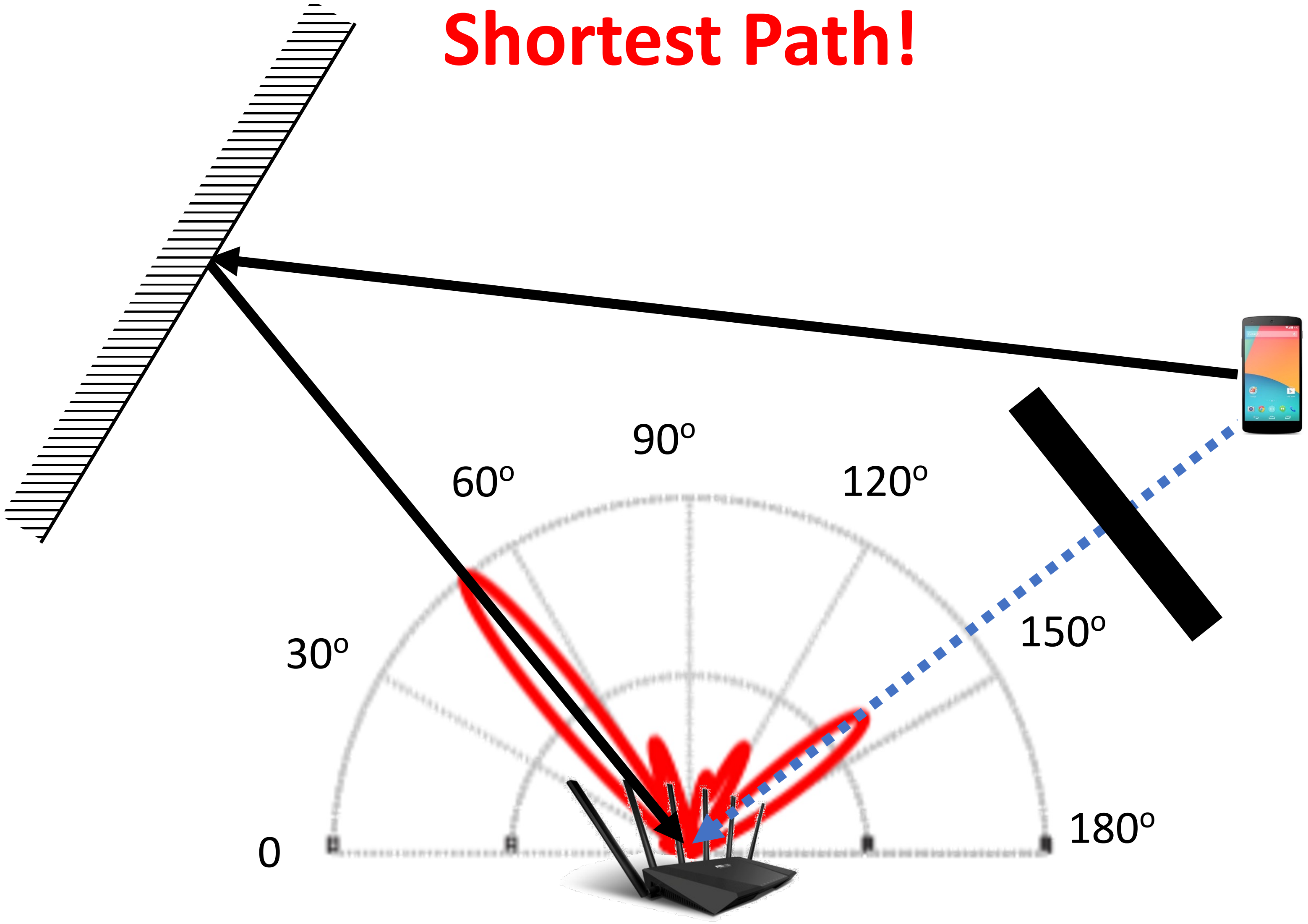


# Method 3: Antenna Arrays

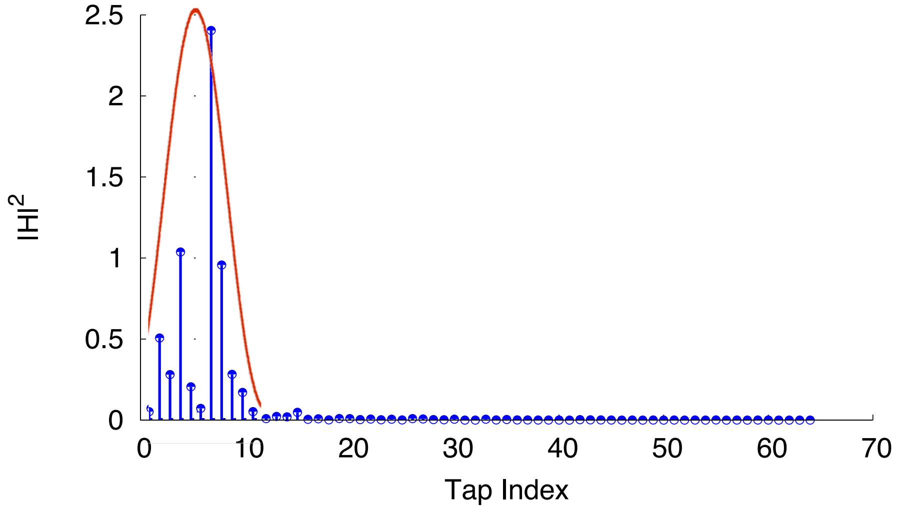
## Which is the Line-of-Sight Path (Direct Path)?

**Shortest Path!**



# Method 3: Antenna Arrays

## Which is the Shortest Path (Direct Path)?




Multipath Profile vs Time

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

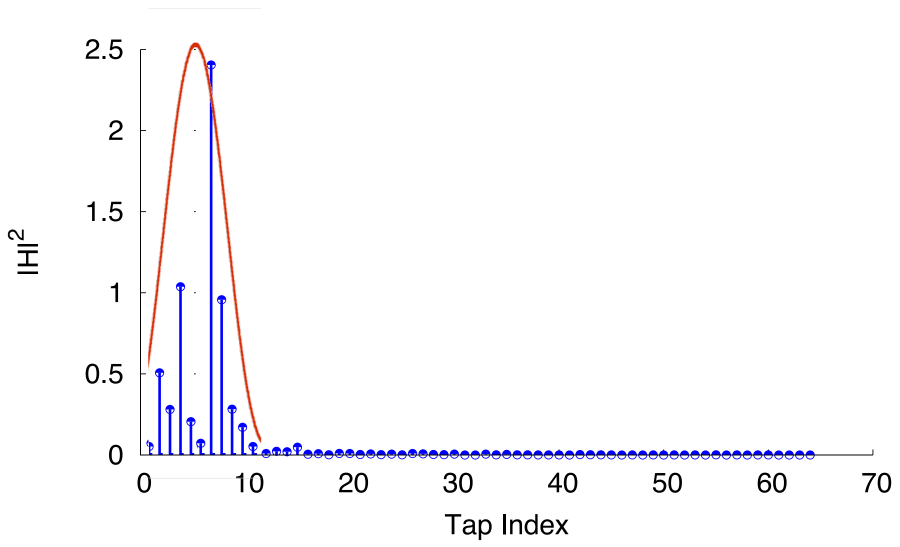
$$\left.\begin{array}{l}\Delta d = 1m \\ c = 3\times10^{8} m/s\end{array}\right\} \Delta\tau = 3.3ns$$

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

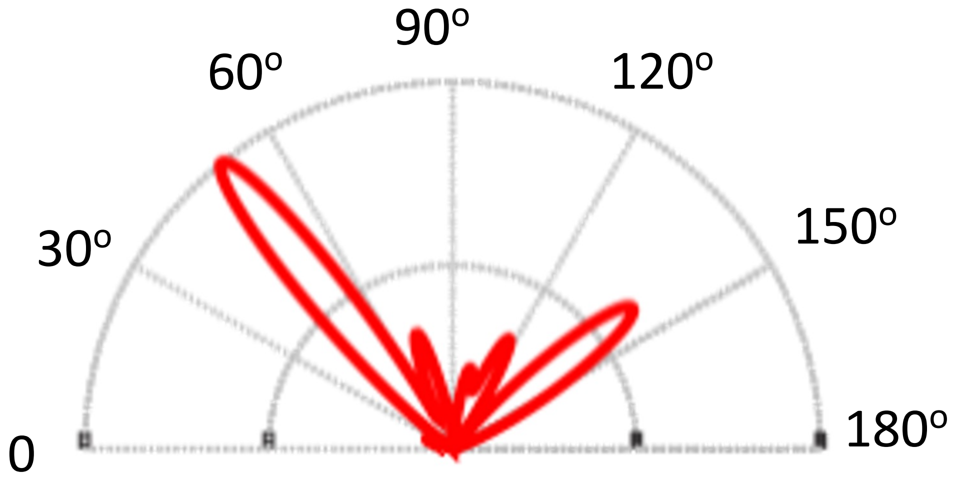
802.11n bandwidth $= 40MHz$

# Method 3: Antenna Arrays

## Which is the Shortest Path (Direct Path)?



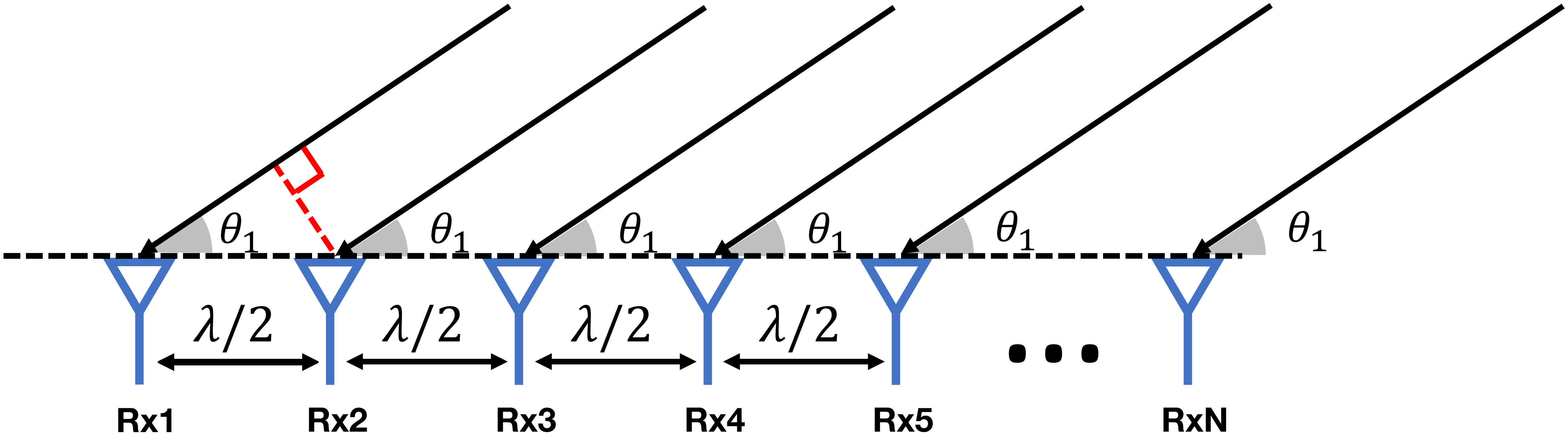

Multipath Profile vs Time




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

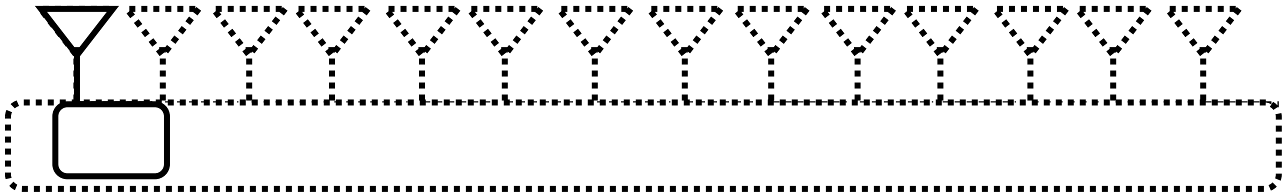



**Pros:** Works with multipath, No need for fingerprinting

**Cons:** Requires more hardware!

Assumes device is sufficiently far such that wavefront is parallel

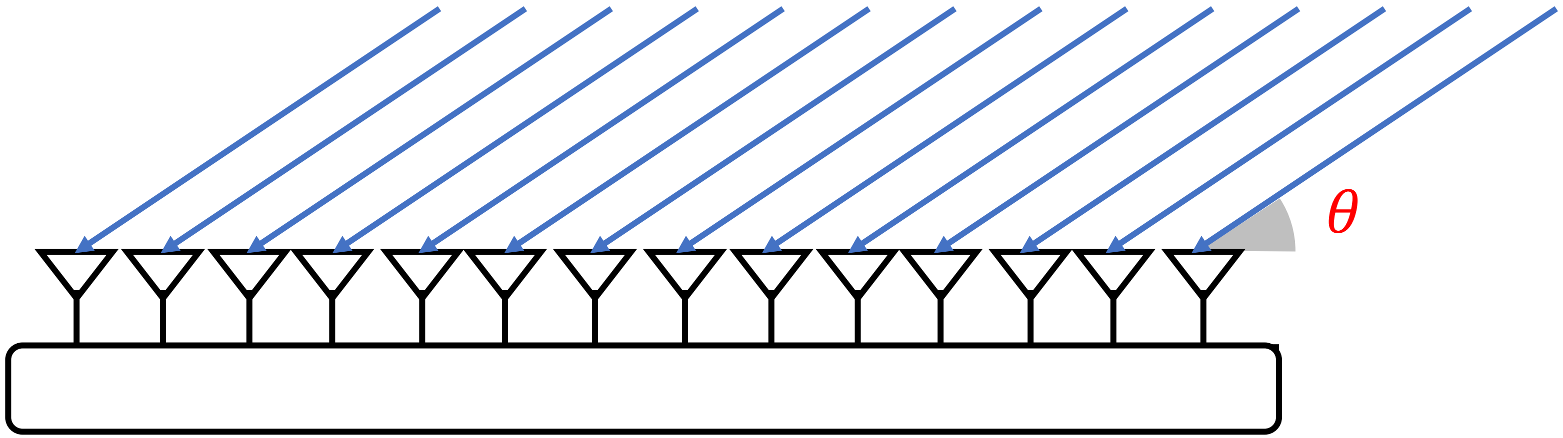
# Method 4: SAR: Synthetic Aperture Radar



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!

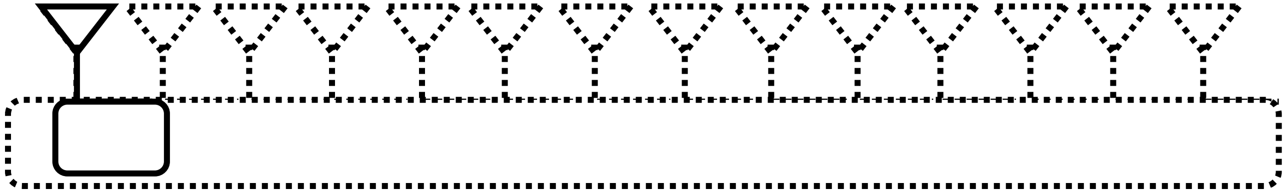
In antenna arrays: all antennas are synchronized!

→ 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



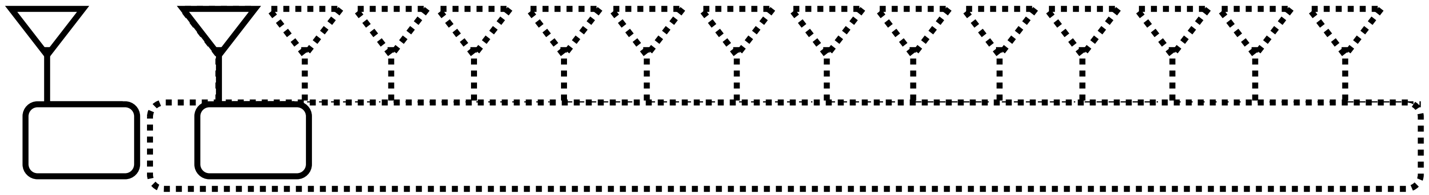
$$h_t = \alpha e^{-j2\pi\frac{d-vt\cos\theta}{\lambda}-j2\pi\Delta f_c t}$$

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:

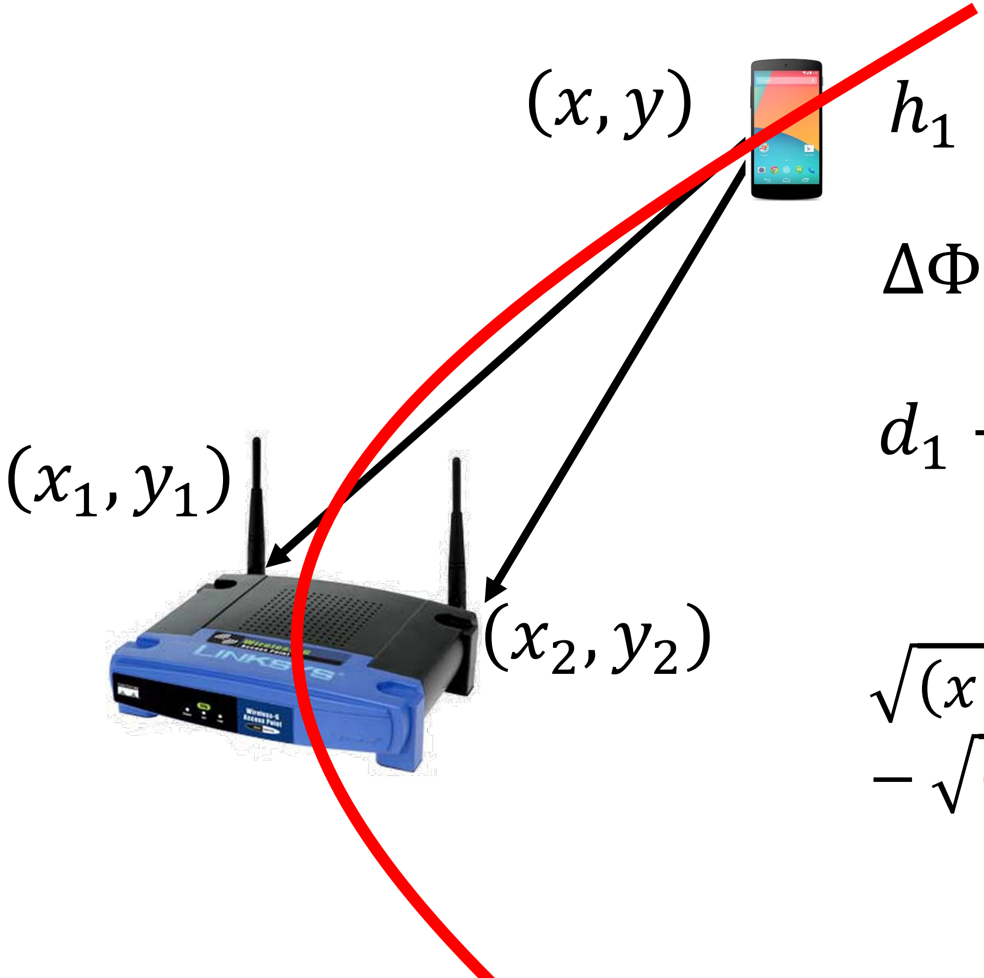
- 1 Moving antenna $h_{1t} = \alpha e^{-j2\pi\frac{d_1 - vt\cos\theta}{\lambda} - j2\pi\Delta f_c t}$
- 1 Static antenna $h_{2t} = \alpha e^{-j2\pi\frac{d_2}{\lambda} - j2\pi\Delta f_c t}$

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




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

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

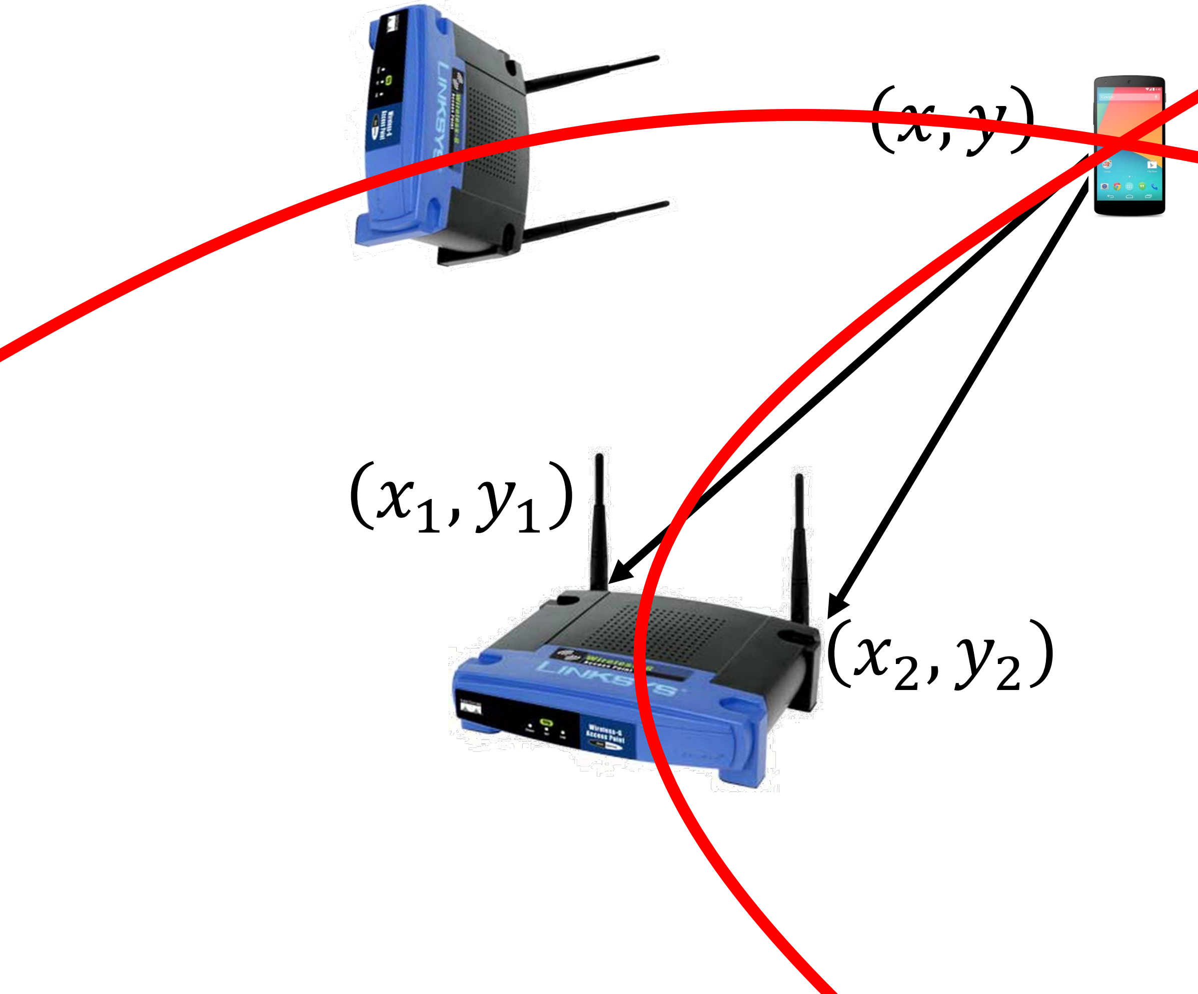
$$d_1 - d_2 = \lambda\Delta\Phi/2\pi = d'$$

**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




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

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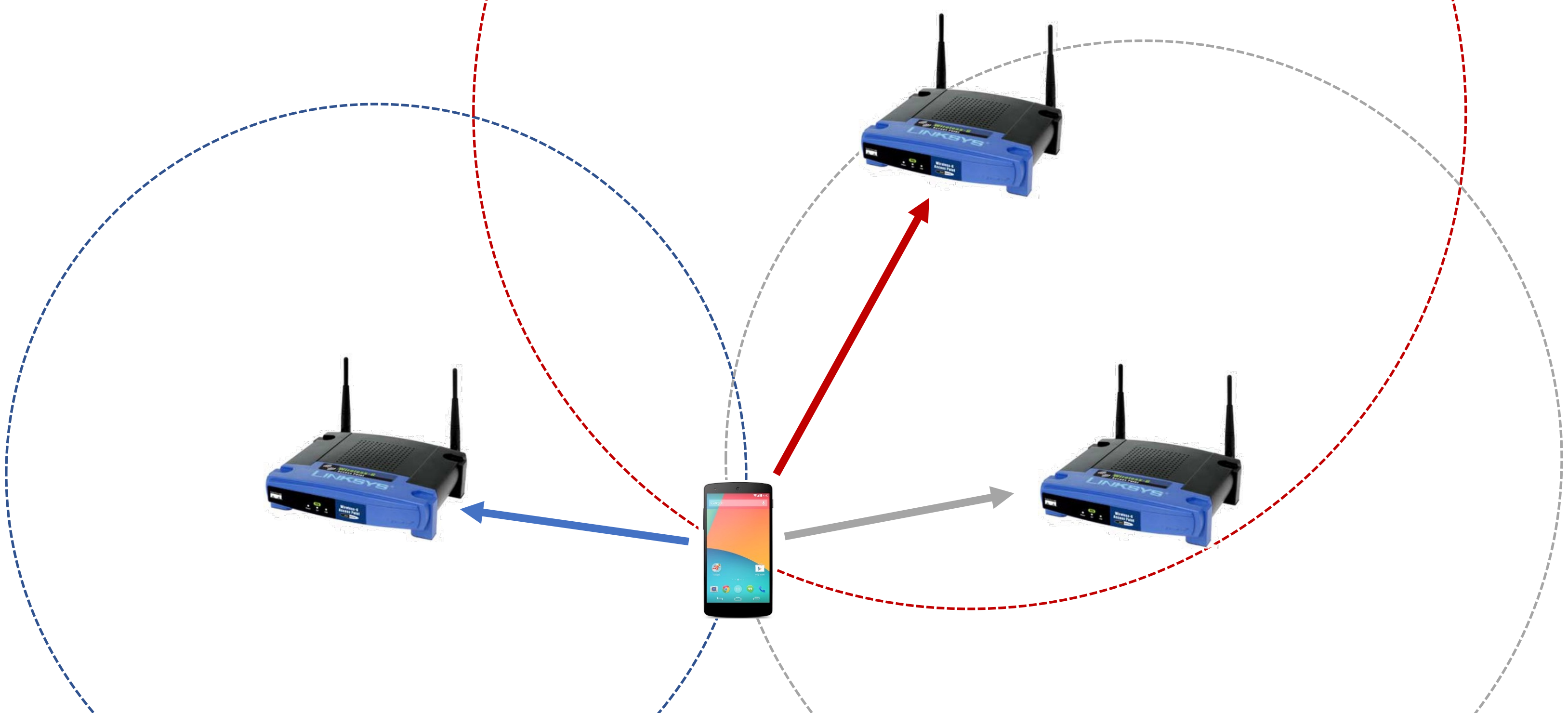
**Equation of Hyperbola**

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

# 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)