http://www.mit.edu/~fadel/courses/MAS.wireless

MAS.S61

Wireless & Mobile Sensing

Lecture 2:
Fundamentals of Wireless Sensing & Localization

Lecturers
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Reuters

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US FDA clears Apple Watch hypertension feature

By Reuters

September 13, 2025 1:32 AM EDT · Updated September 13, 2025

An Apple Watch series 11 titanium is displayed during Apple's event at the Steve Jobs Theater on its campus in Cupertino, California, U.S. September 9, 2025. REUTERS/Manuel Orbegozo/File Photo Purchase Licensing Rights

a new pair of smart glasses with a display, codenamed 'Hypernova'

wrist-worn electromyography (EMG) based controller for input

Wireless & Mobile Sensing

sensing the physical world & transmitting data wirelessly

sensing via the wireless signals or mobile devices

This lecture

Objectives of Today's Lecture

Learn the fundamentals, applications, and implications of
wireless localization and sensing

1. What are the unifying principles of wireless positioning & wireless sensing?
2. How do systems like GPS, WiFi positioning, seeing through walls work?
3. How do state-of-the-art positioning systems work?
4. What are the industry opportunities and societal implications of wireless positioning and sensing (today and in the near+far future)?

What is Wireless Positioning (aka Localization)?

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

Applications:

- Navigation: both outdoors (GPS) and indoors (e.g., inside 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)
- Security (e.g., only want to give WiFi access to customers inside a store)
- Delivery drones

What are the different ways of obtaining location?

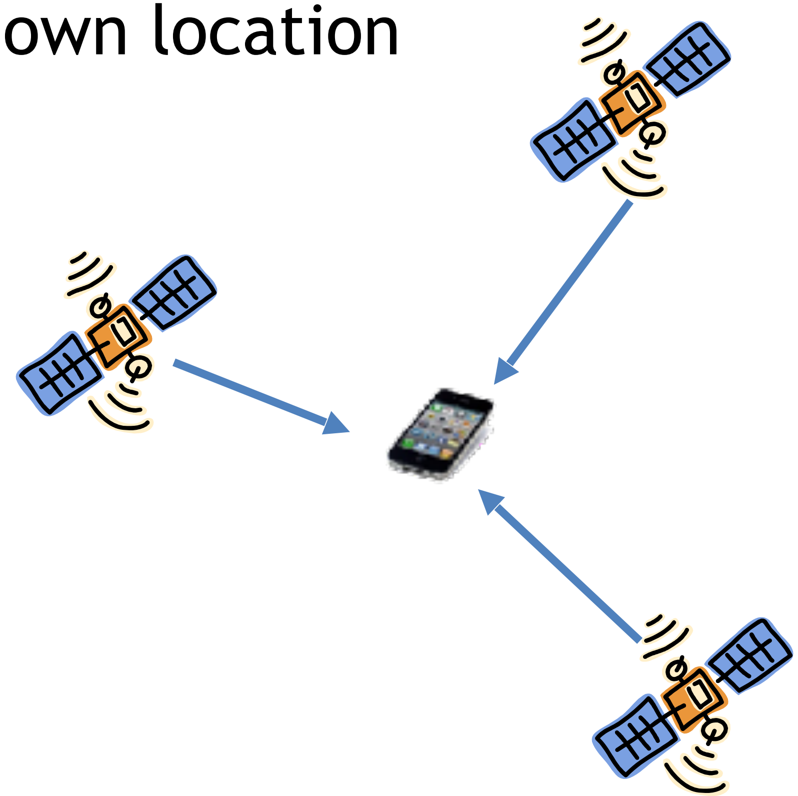
- Radio signals: GPS, Cellular, Bluetooth, WiFi
- Ultrasound signals: similar to those used in NEST
- Inertial
- Cameras, Vision, LIDAR

Focus of this lecture

We will discuss the localization techniques in increasing order of sophistication

Who performs the localization process?

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



- Example: GPS

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

- Example: Radar

1) Identity-based Localization

Idea: Use the identity and known location of anchor nodes

Example:

- Wardriving -- been used to improve the accuracy of GPS
- WiFi indoor localization

Localize by mapping to one of those locations.

Pros? Cons?

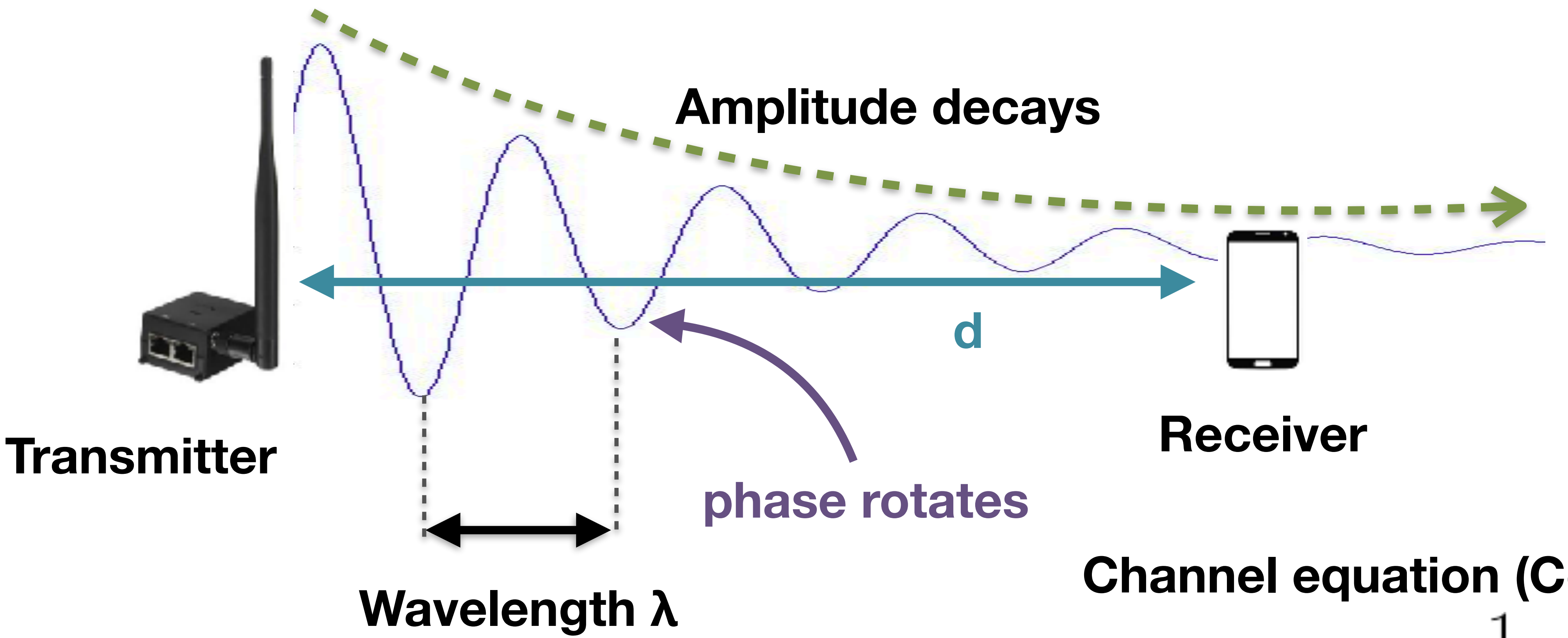
2) Received Signal Strength (RSSI)

Idea: Higher power -> closer; lower power-> further

In fact, we can extract more information about exact distance from measured power. Need to understand more about wireless signals

Wireless Signals are Waves

Wireless Signals are Waves



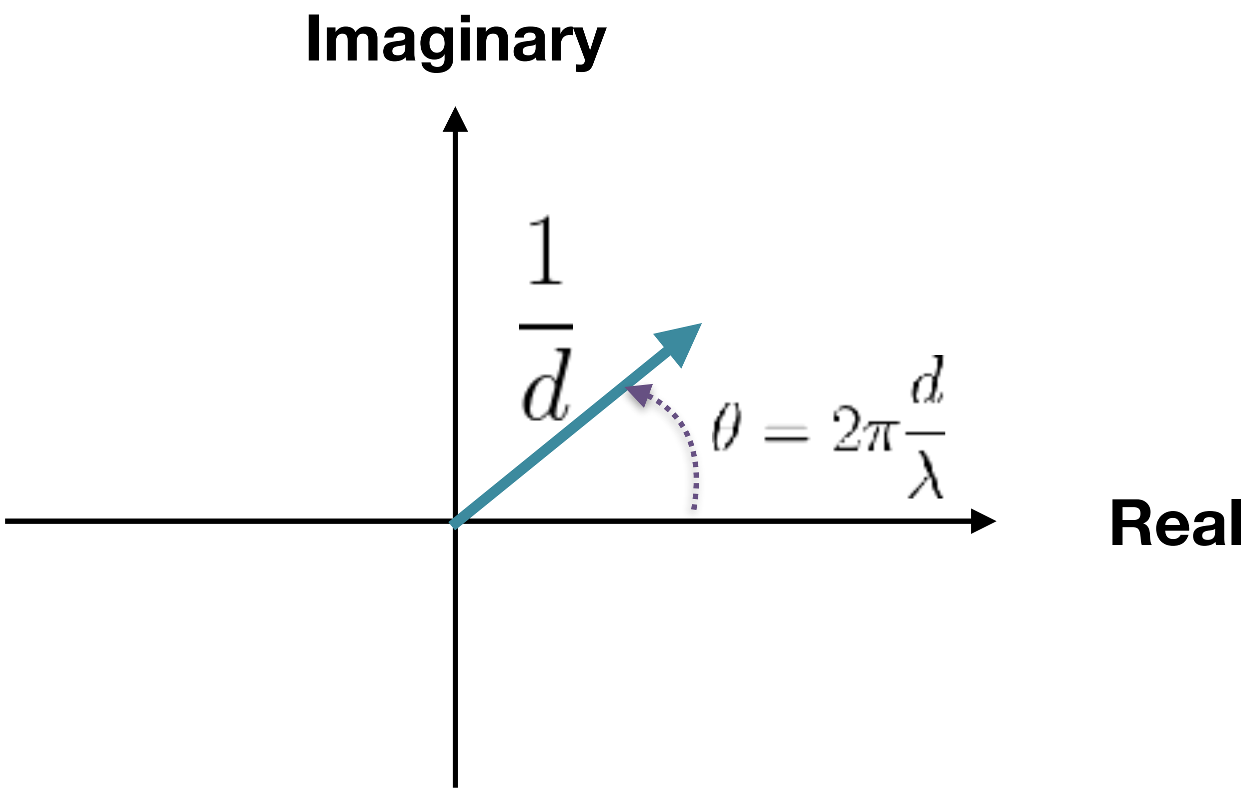
Channel equation (Complex number)

$$h = \frac{1}{d} e^{j 2\pi \frac{d}{\lambda}}$$

Wireless Signals are Waves

Channel equation (Complex number)

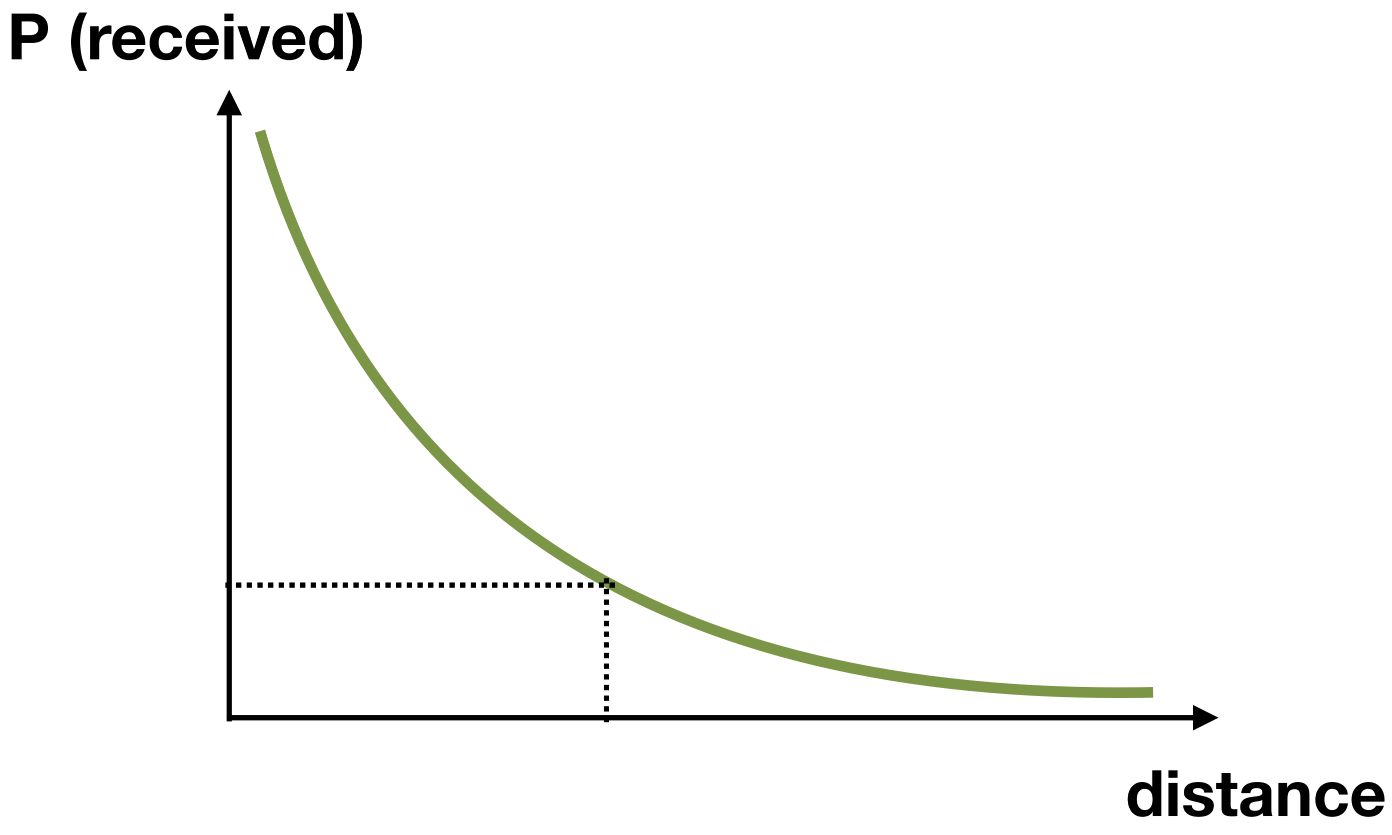
$$h = \frac{1}{d} e^{j2\pi \frac{d}{\lambda}}$$



2) Received Signal Strength (RSSI)

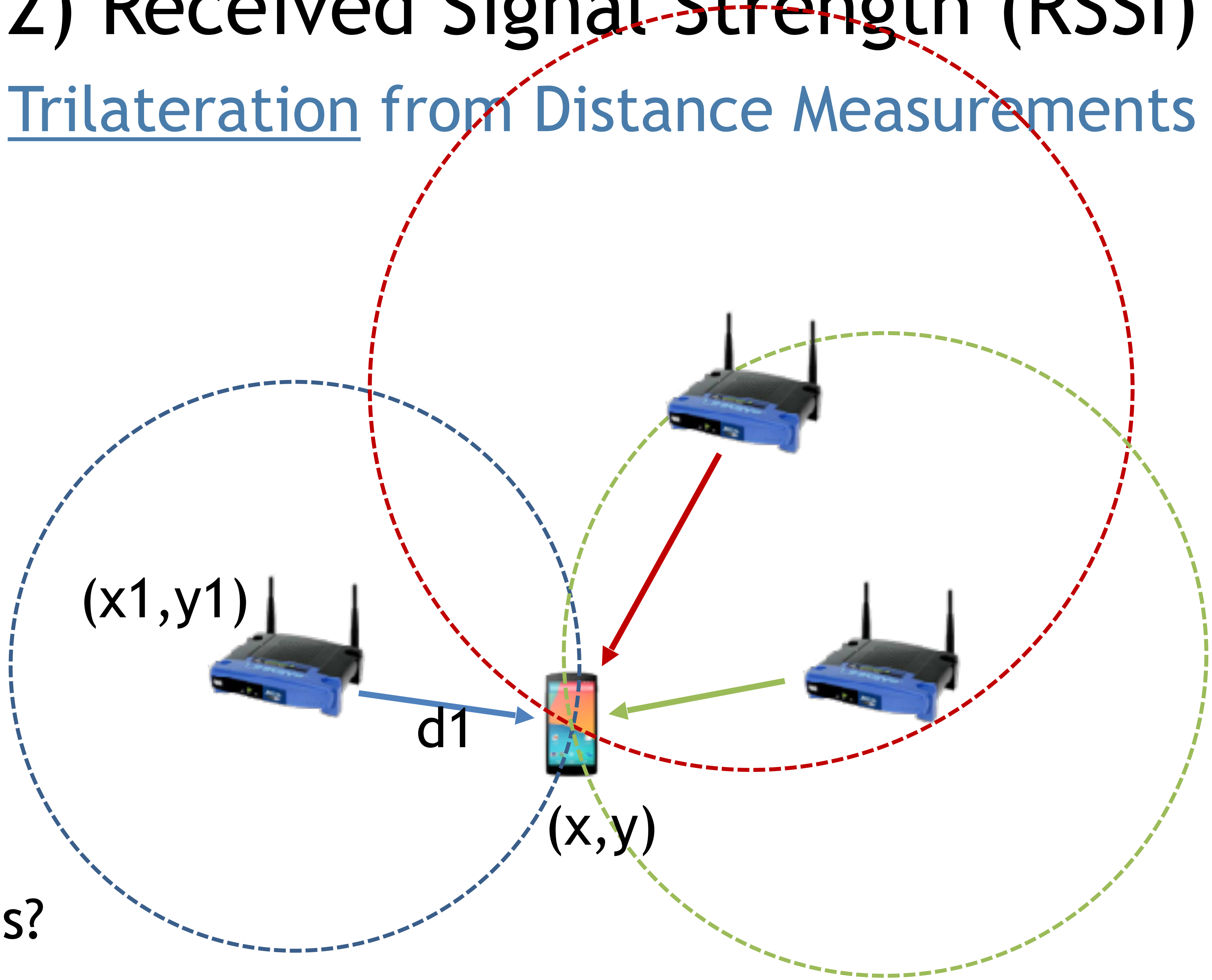
From power to distance

Power is proportional to $1/d^2$



2) Received Signal Strength (RSSI)

Trilateration from Distance Measurements

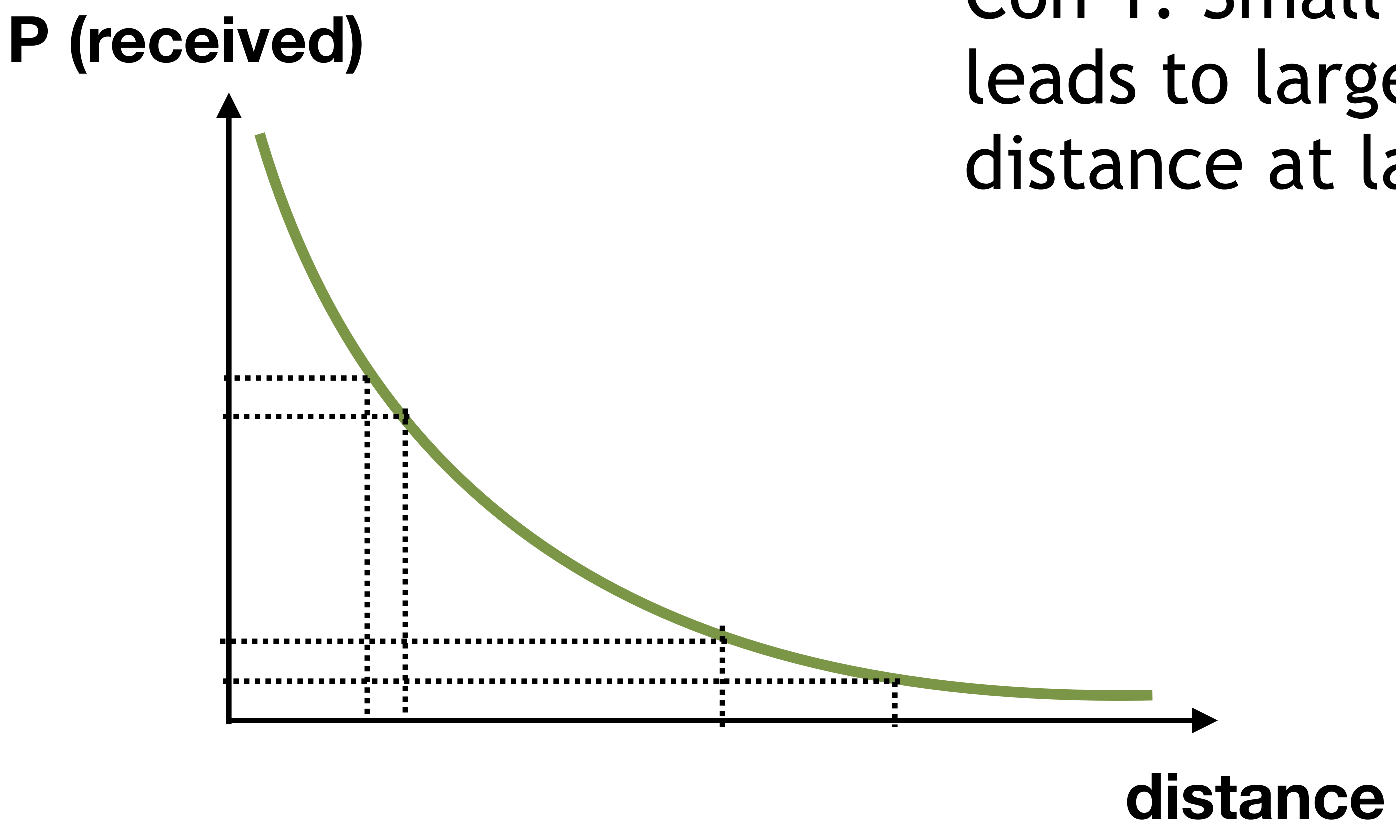


Pros? Cons?

2) Received Signal Strength (RSSI)

From power to distance

Power is proportional to $1/d^2$

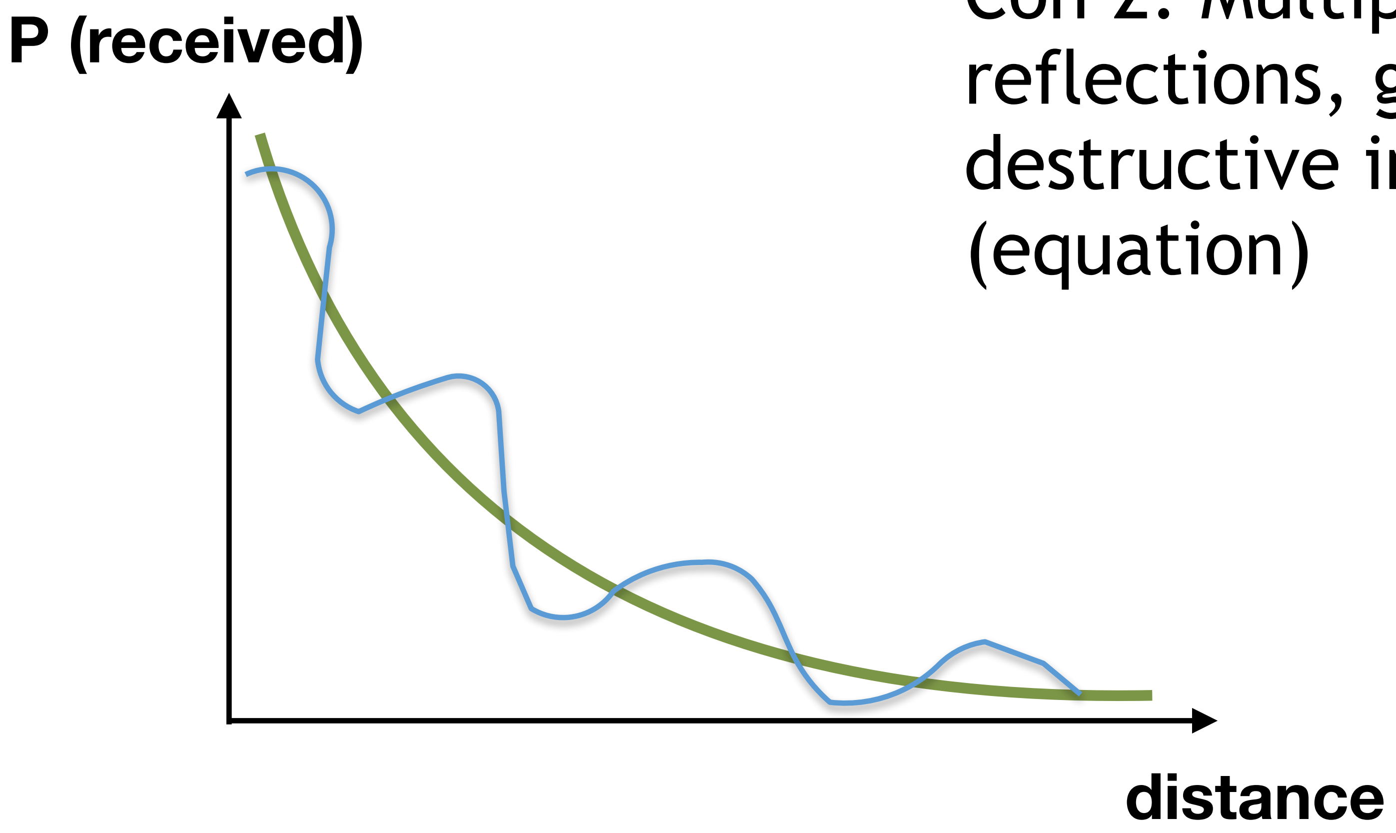


Con 1: Small change in power leads to large deviations in distance at larger distances

2) Received Signal Strength (RSSI)

From power to distance

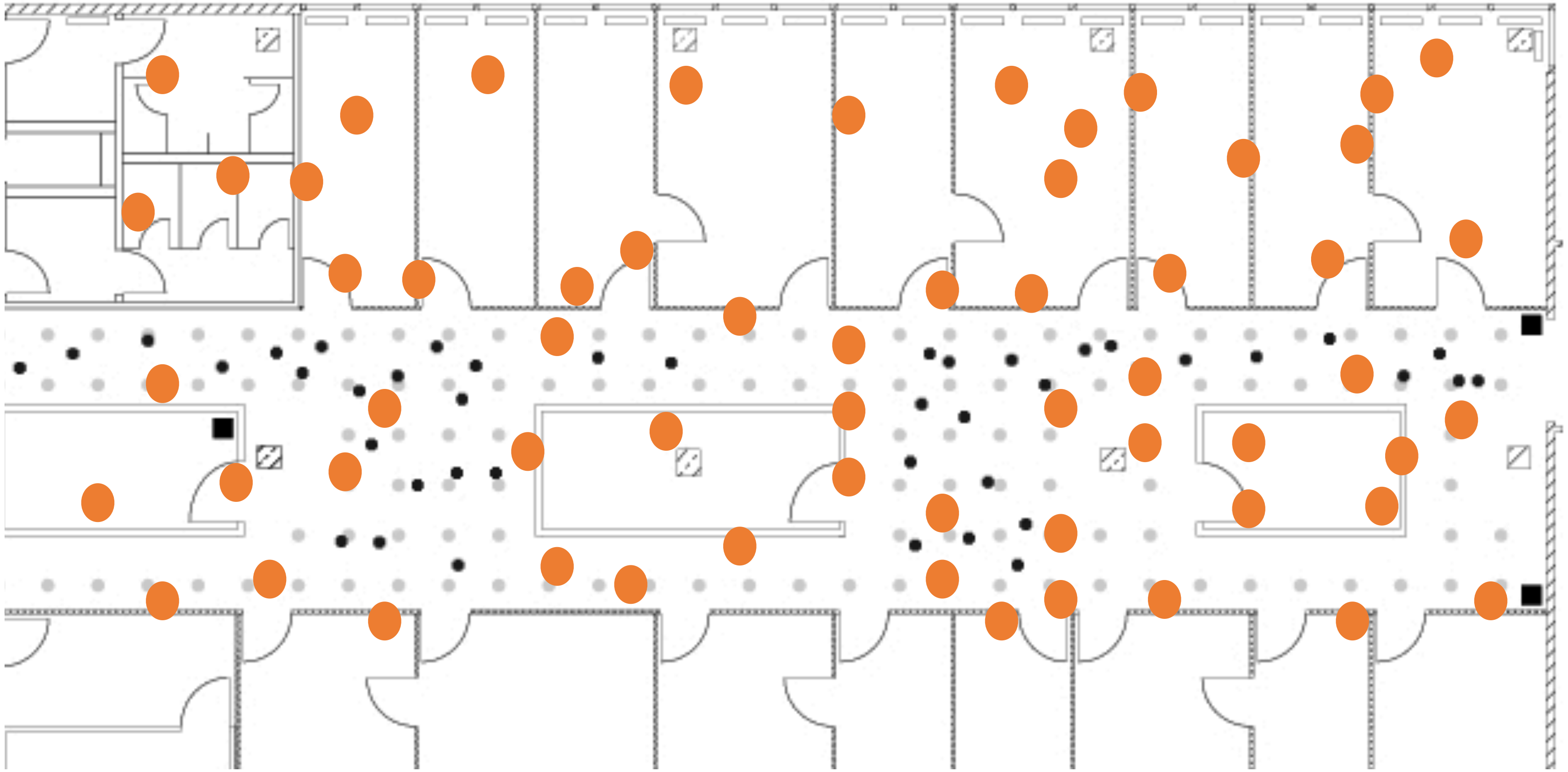
Power is proportional to $1/d^2$



Con 2: Multipath: Due to reflections, get constructive and destructive interference (equation)

2) Received Signal Strength (RSSI)

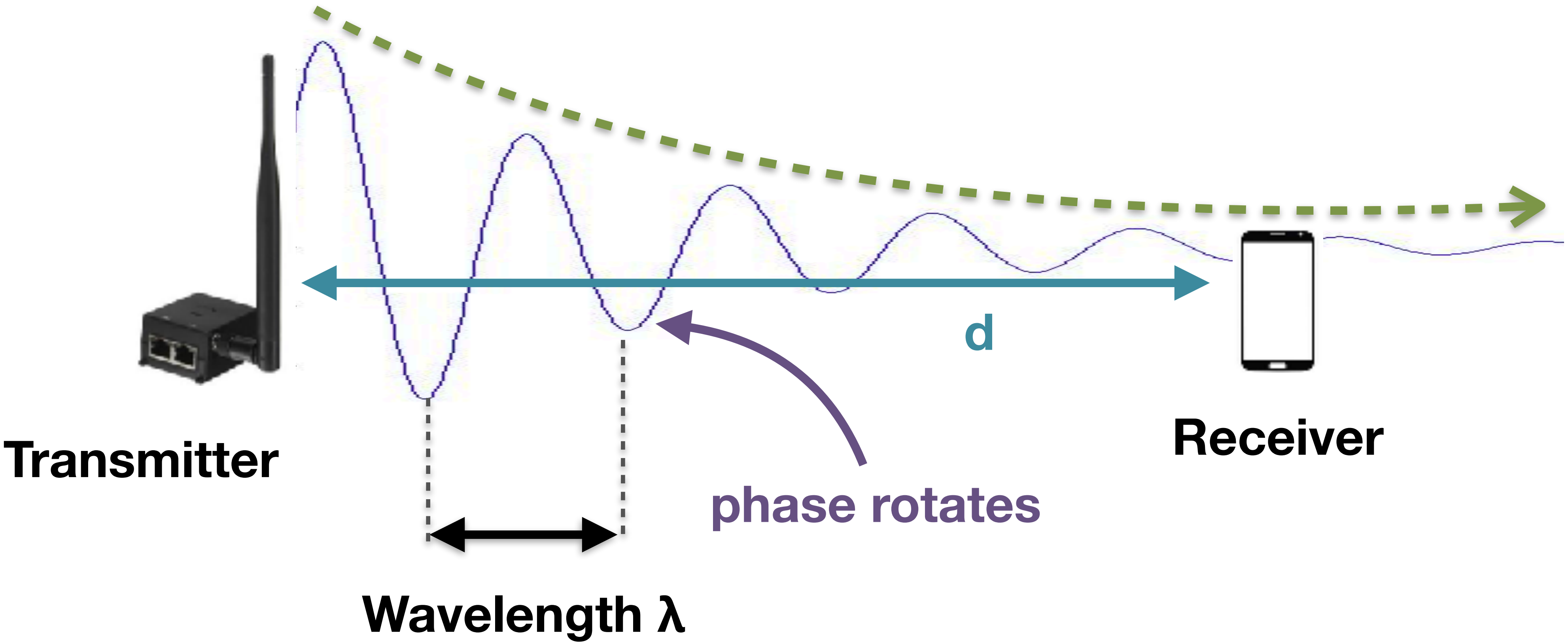
<u>Solution:</u> Fingerprinting
i.e., measuring device records signal strength fingerprints at each location



Pros? Cons?

3) Use the Signal "Phase"

Phase $\phi = 2\pi \frac{d}{\lambda}$

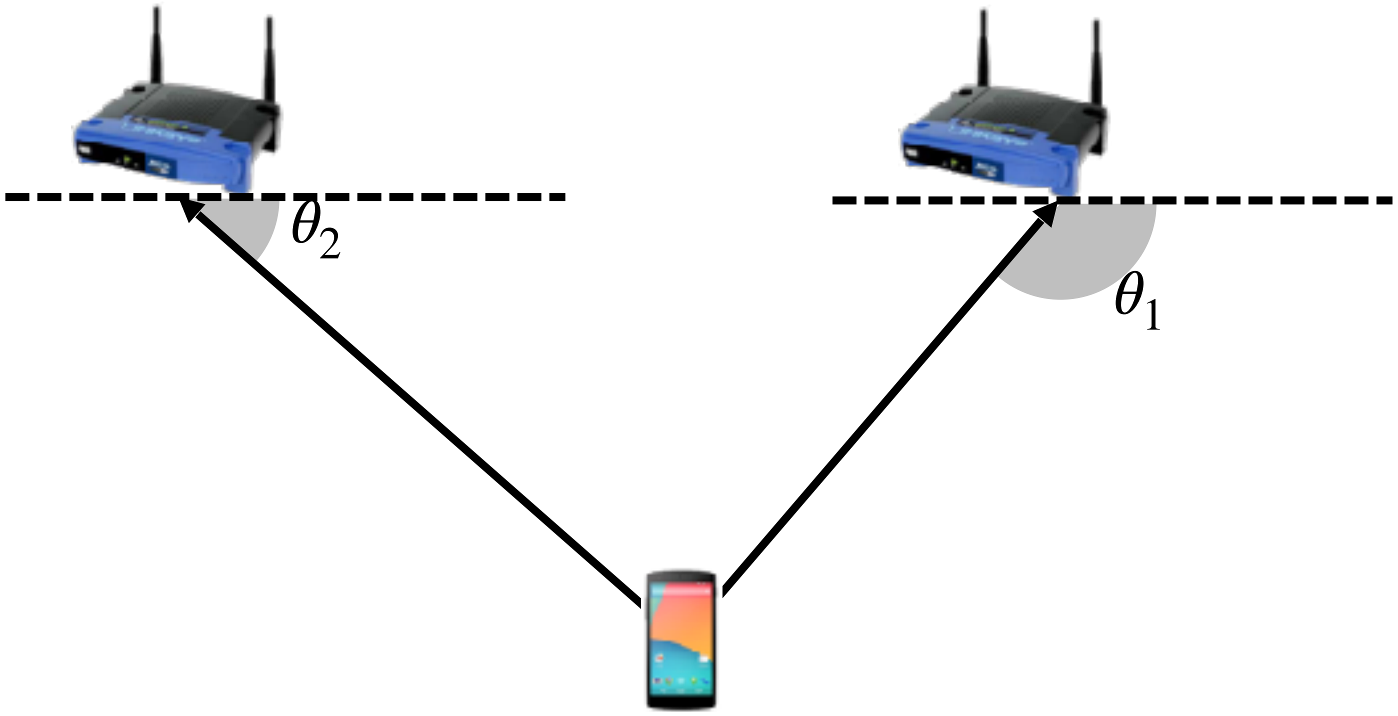


Pros? Cons?

4) Use Angle of Arrival (AoA)

Triangulation from Angular Measurements

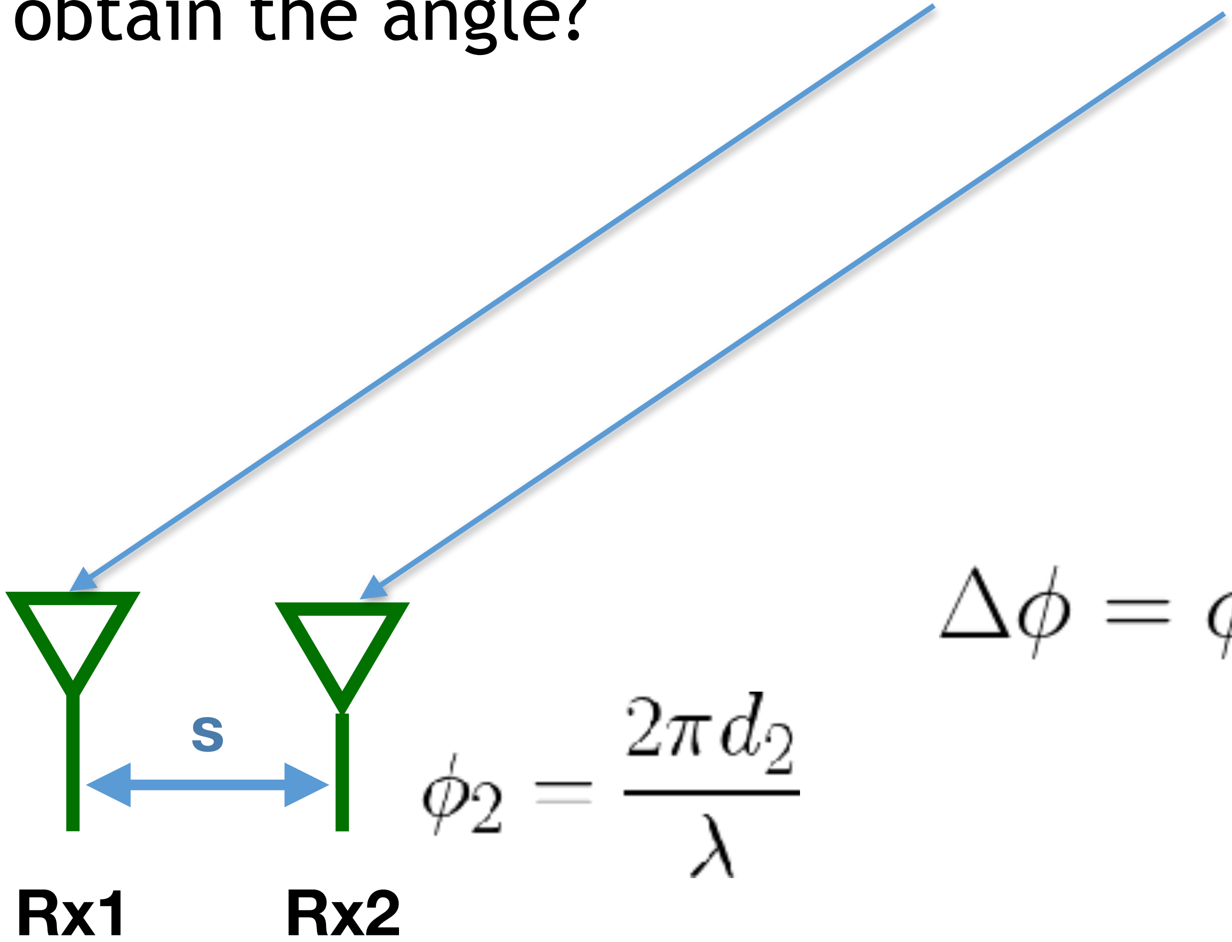
Measure Angle of Arrival (AoA) from device to each AP



4) Use Angle of Arrival (AoA)

Triangulation from Angular Measurements

How can we obtain the angle?



$$\phi_1 = \frac{2\pi d_1}{\lambda}$$

$$\phi_2 = \frac{2\pi d_2}{\lambda}$$

$$\Delta\phi = \phi_1 - \phi_2 = \frac{2\pi s \cos\theta}{\lambda}$$

Issues?

4) Use Angle of Arrival (AoA)

Triangulation from Angular Measurements

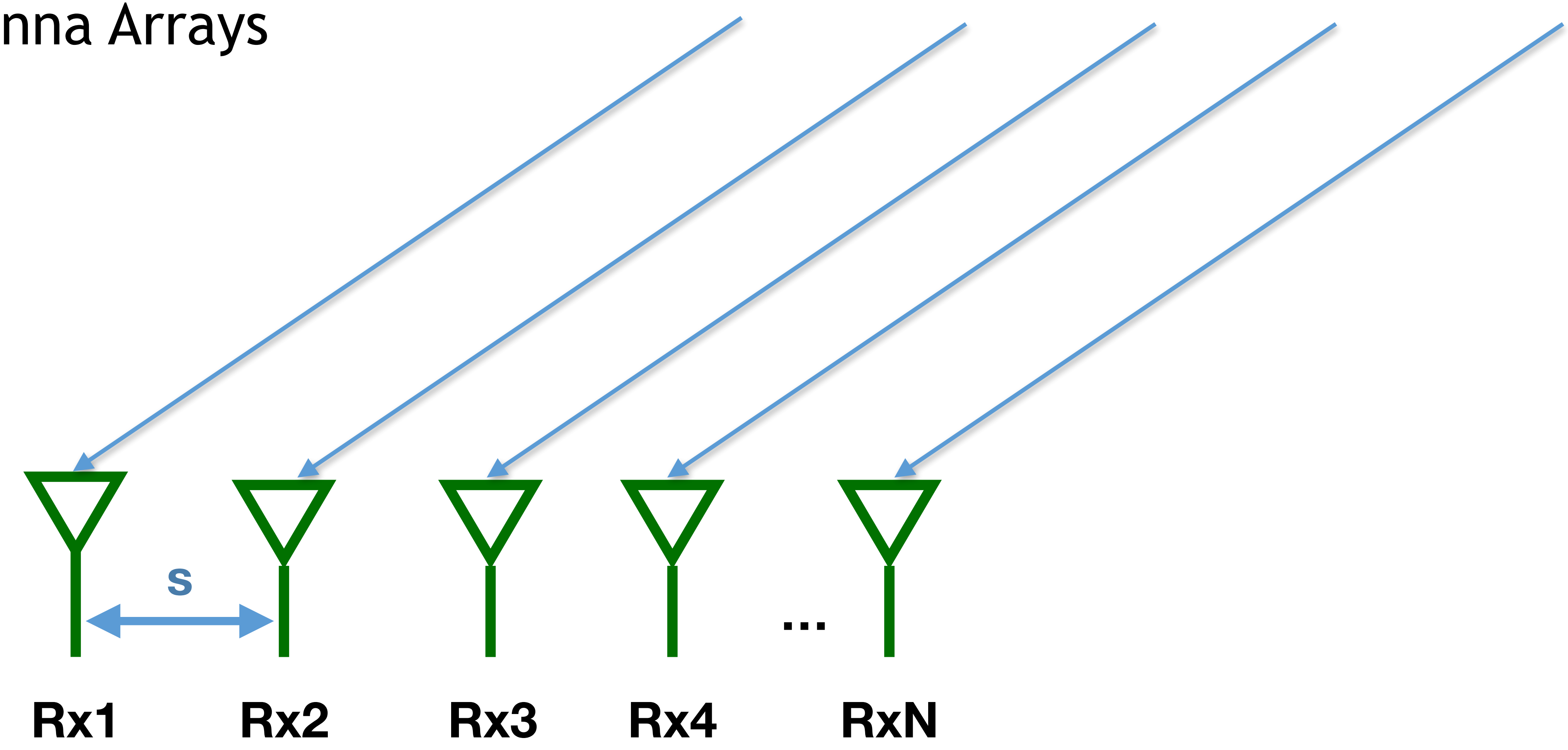
Issues

- Multipath
- Nonuniform resolution
- Half-circle vision

4) Use Angle of Arrival (AoA)

Triangulation from Angular Measurements

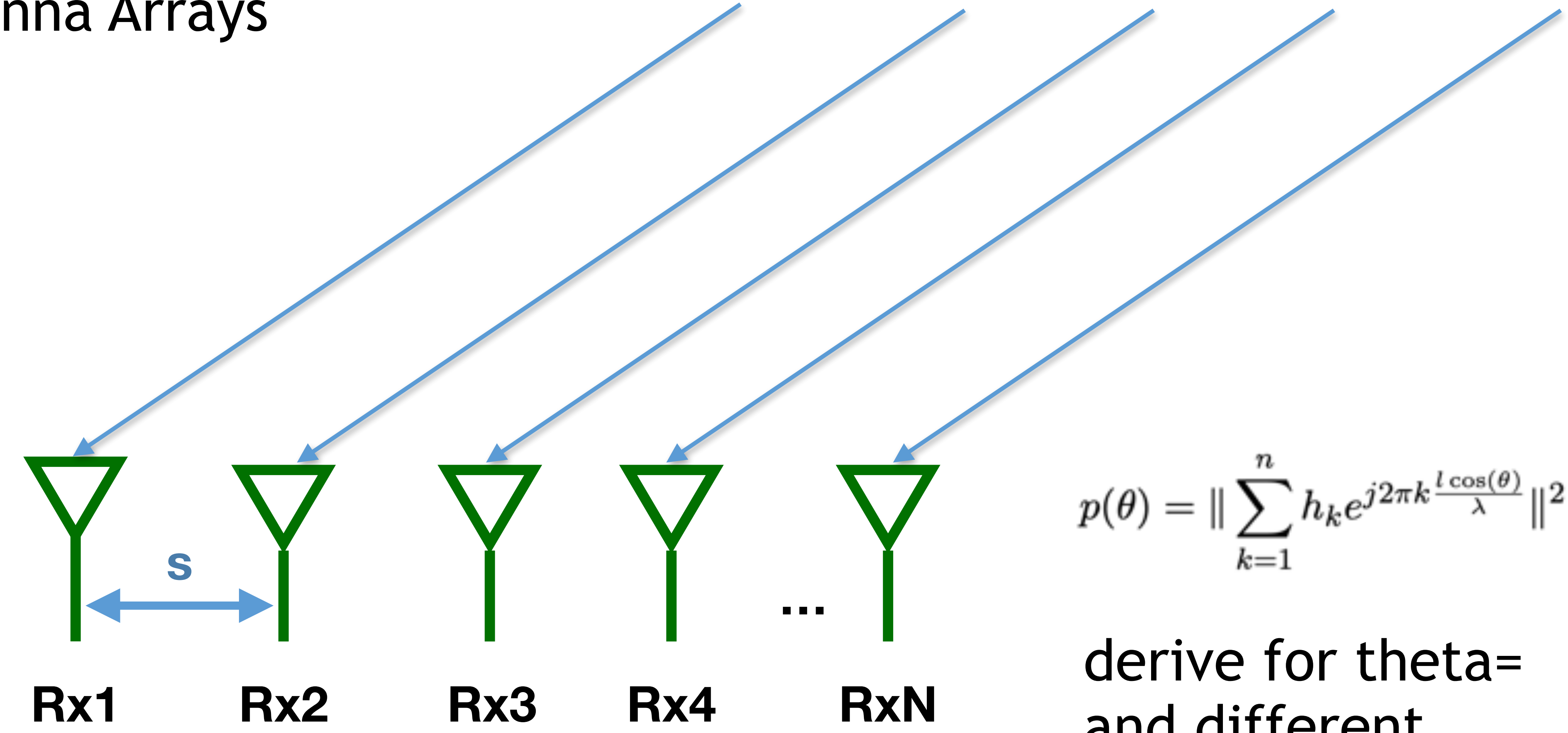
Use Antenna Arrays



4) Use Angle of Arrival (AoA)

Triangulation from Angular Measurements

Use Antenna Arrays



$$p(\theta) = \| \sum_{k=1}^{n} h_k e^{j2\pi k \frac{l\cos(\theta)}{\lambda}} \|^2$$

derive for theta=
and different

4) Use Angle of Arrival (AoA)

Triangulation from Angular Measurements

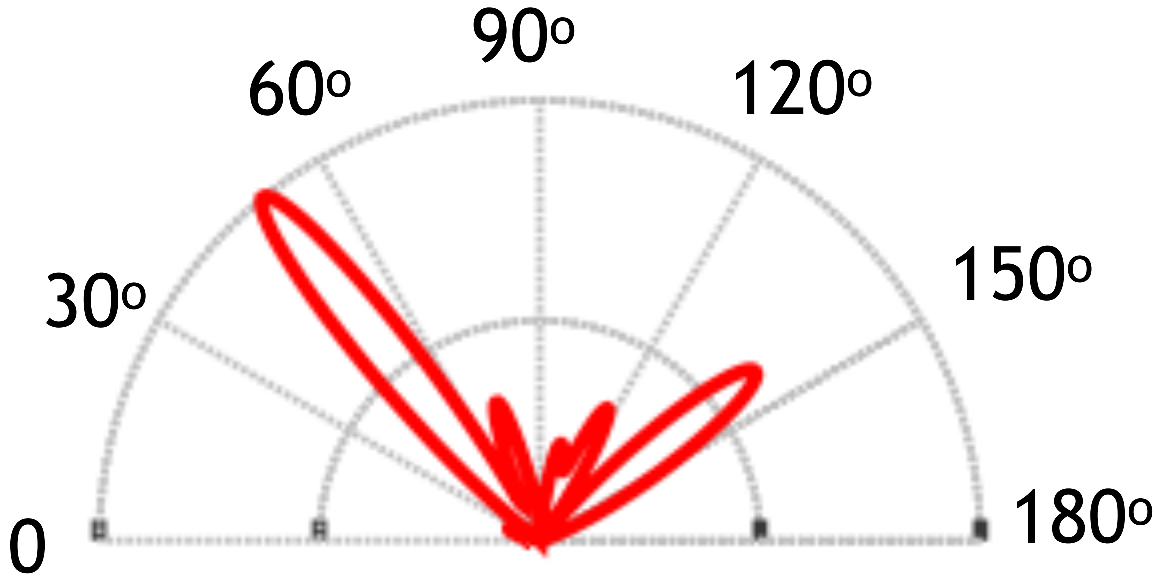
Use Antenna Arrays

$$
\begin{aligned}
p(\theta) &= \|\sum_{k=1}^{n} h_k e^{j2\pi k \frac{l\cos(\theta)}{\lambda}}\|^2 \\
&= \|\sum_{k=1}^{n} \frac{1}{d_k} e^{\Phi_k} e^{j2\pi k \frac{l\cos(\theta)}{\lambda}}\|^2 \\
&= \|\sum_{k=1}^{n} \frac{1}{d_k} e^{-2\pi j \frac{d_1+(k-1)l\cos(\theta^*)}{\lambda}} e^{j2\pi k \frac{l\cos(\theta)}{\lambda}}\|^2 \\
&= \|\sum_{k=1}^{n} \frac{1}{d_k} e^{-2\pi j \frac{d_1-l\cos(\theta^*)}{\lambda}} e^{j2\pi k \frac{l}{\lambda}(\cos(\theta)-\cos(\theta^*))}\|^2 \\
&\approx \|\frac{1}{d_1} e^{-2\pi j \frac{d_1-l\cos(\theta^*)}{\lambda}} \sum_{k=1}^{n} e^{j2\pi k \frac{l}{\lambda}(\cos(\theta)-\cos(\theta^*))}\|^2 \text{ (approximating } \tfrac{1}{d_k} \text{ by } \tfrac{1}{d_1}\text{)}
\end{aligned}
$$

4) Use Angle of Arrival (AoA)

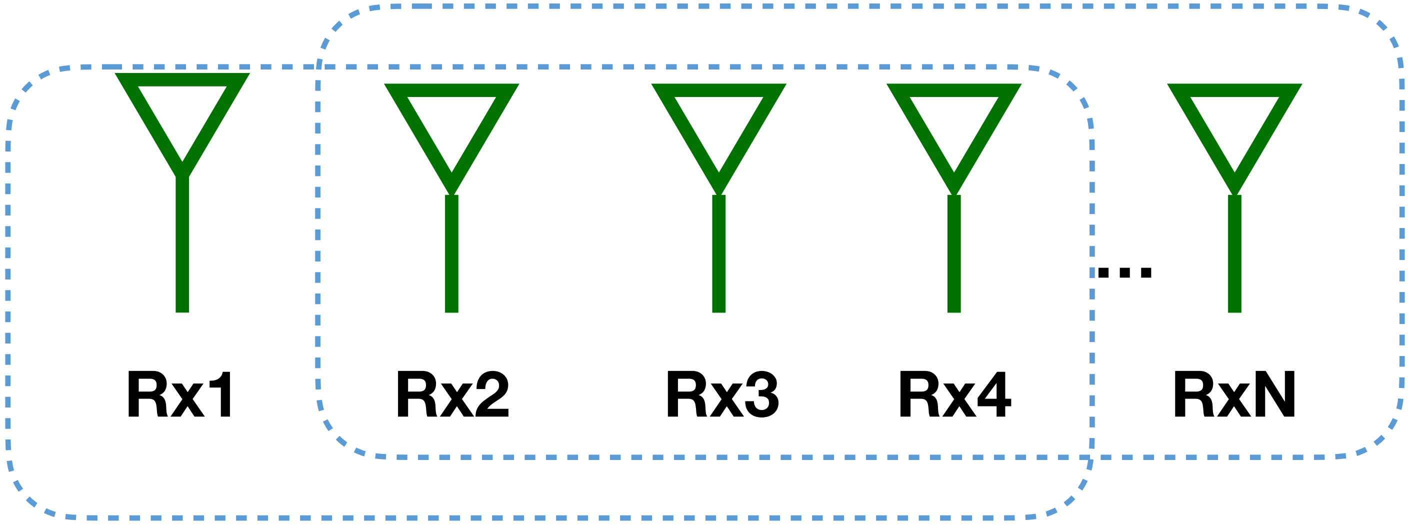
Triangulation from Angular Measurements

Use Antenna Arrays

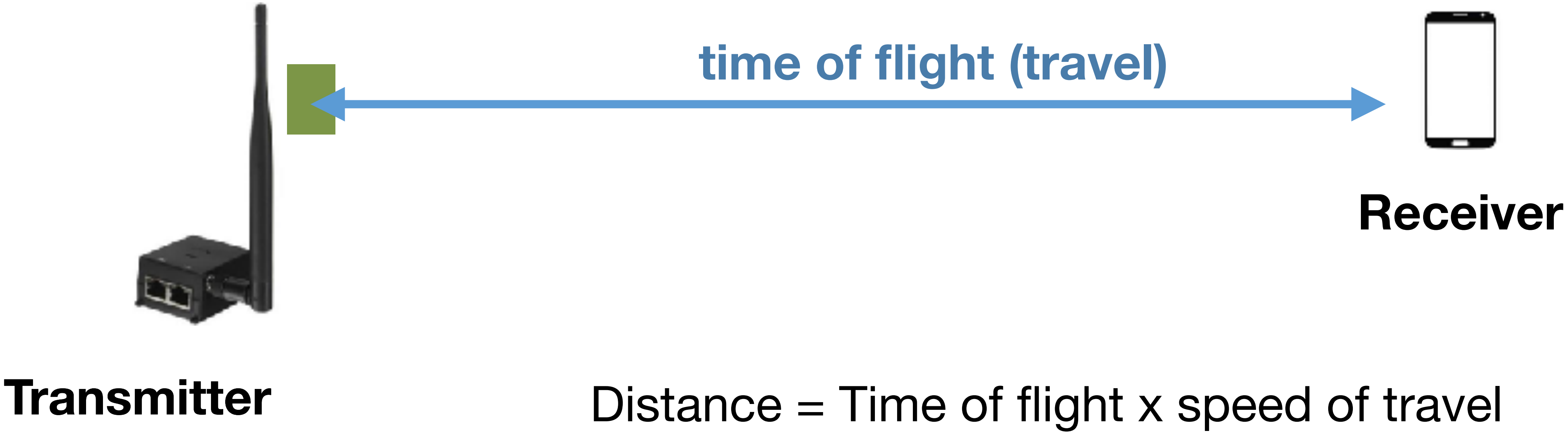


How do we know which direction corresponds to the direct path?

ArrayTrack (NSDI'14) deals with Multipath



5) Measure the Time-of-Flight (ToF)



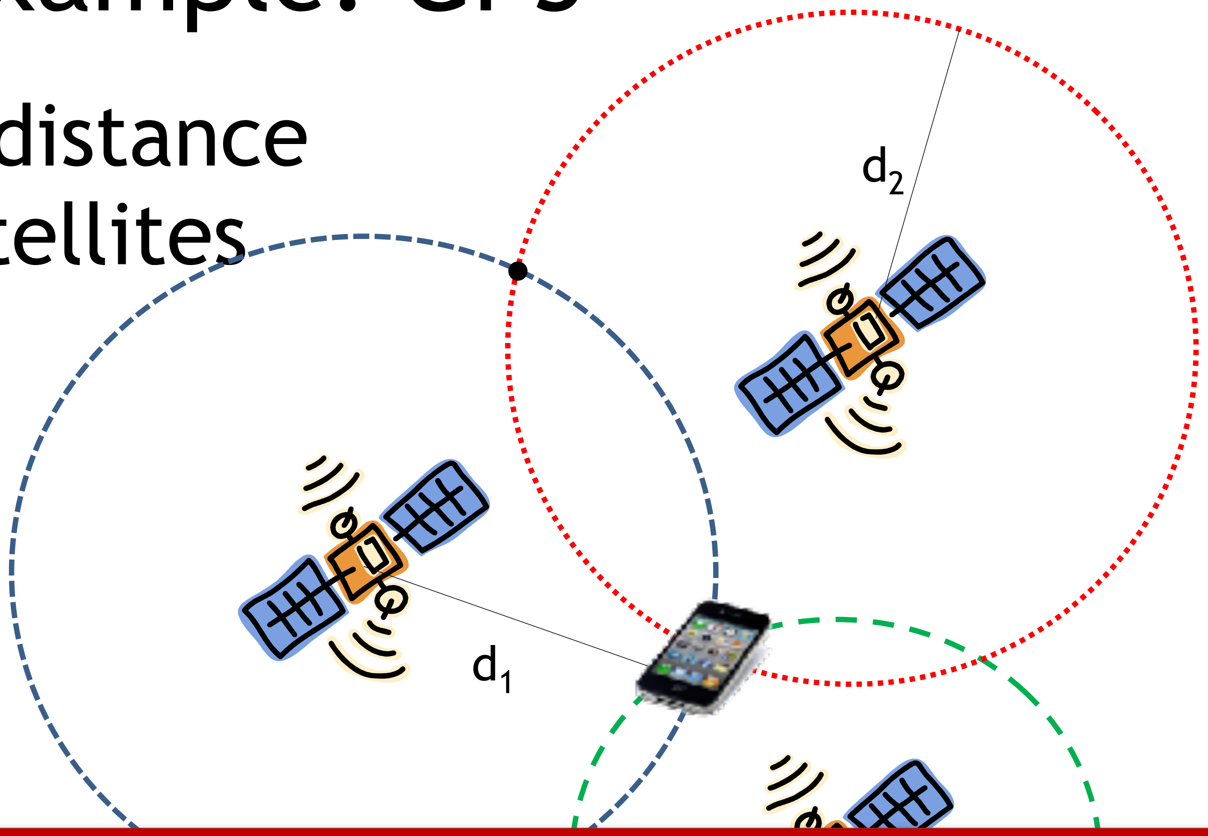
Distance = Time of flight x speed of travel

Can use trilateration (intersection circles/spheres)

How do we know when the signal was transmitted?

Example: GPS

Compute the distance to the GPS satellites



distance = propagation delay x speed of light

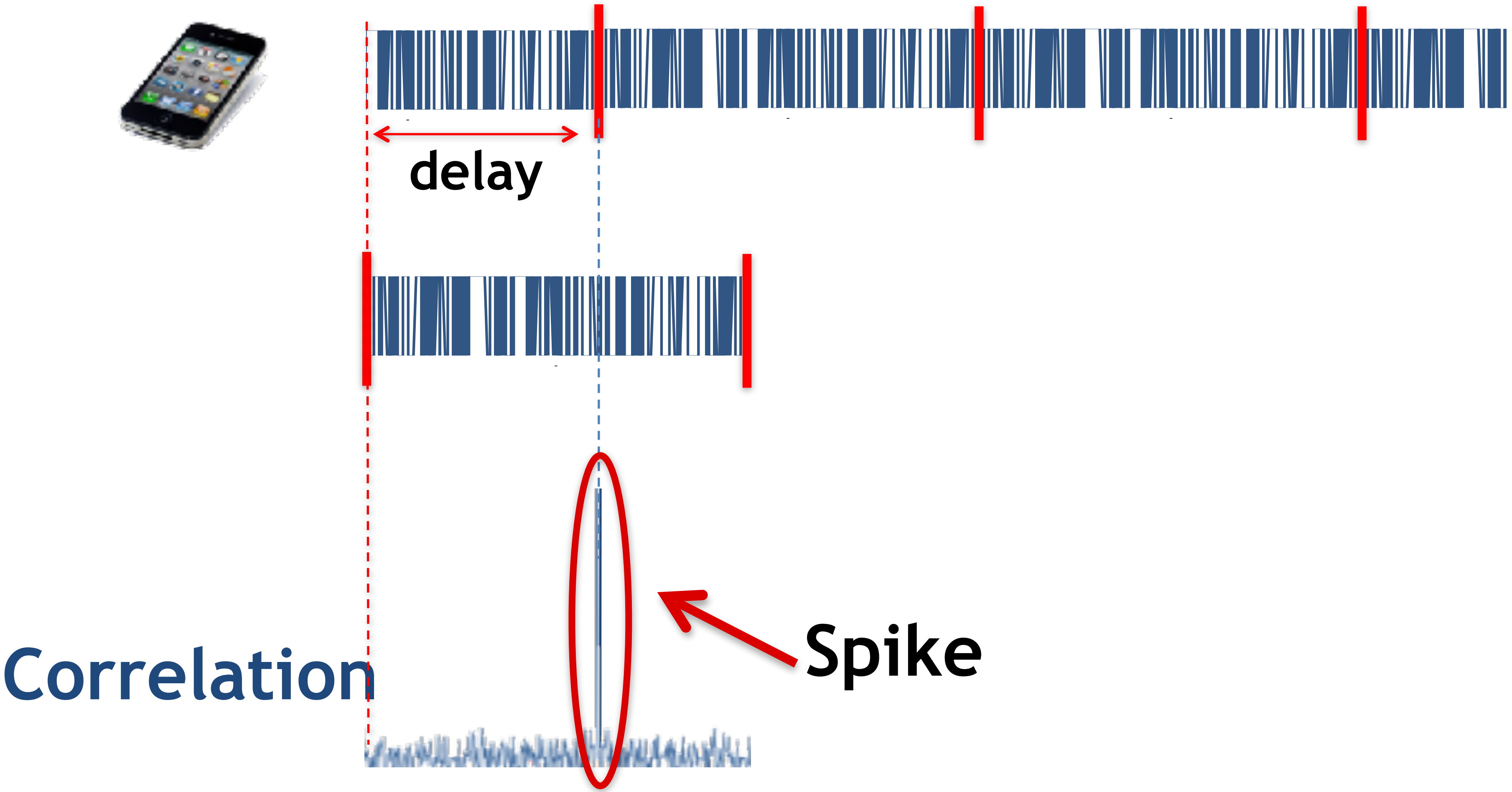
How to Compute the Propagation Delay?

Each satellite has its own code

How to Compute the Propagation Delay?

Code arrives shifted by propagation delay

How to Compute the Propagation Delay?



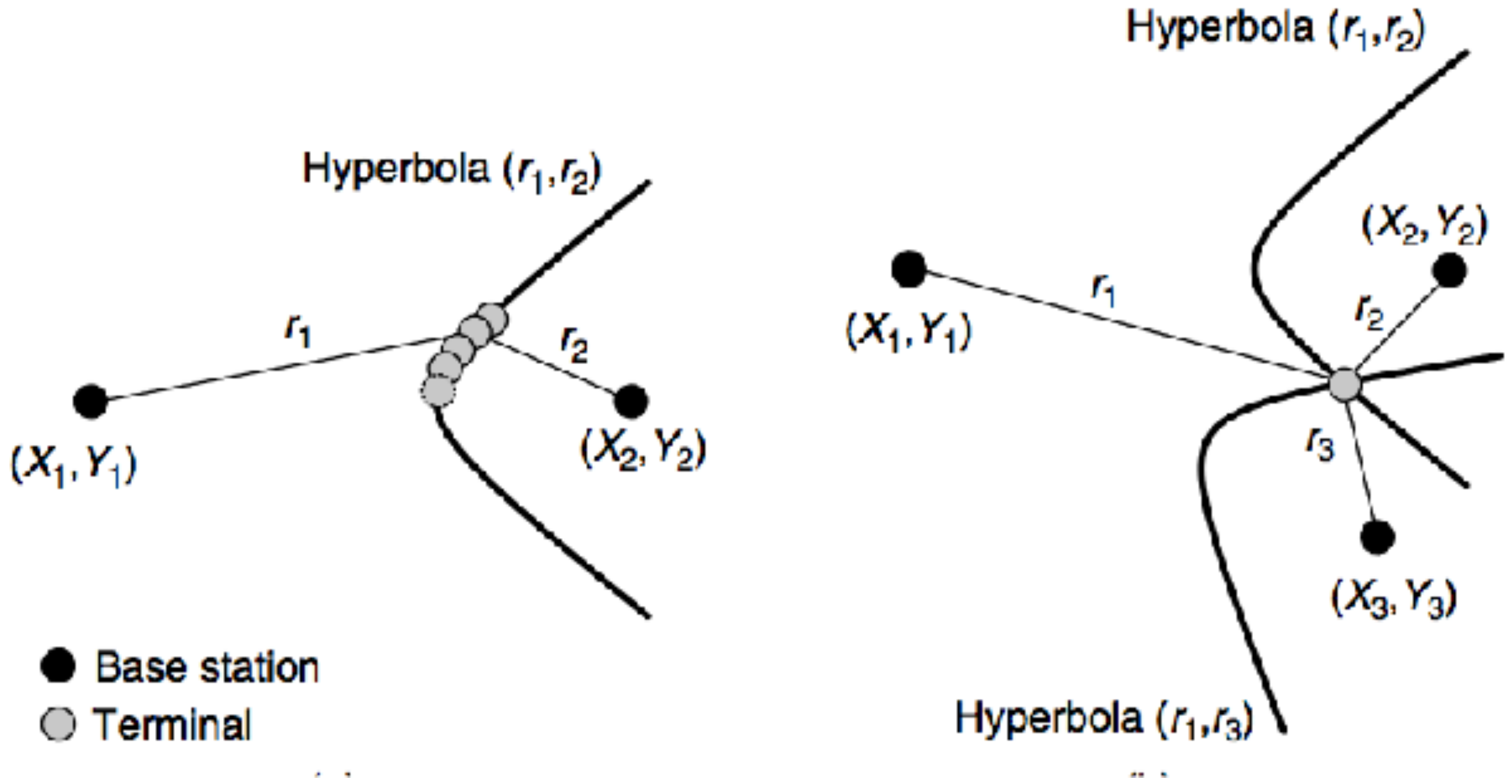
Spike determines the delay
use it to compute distance and localize

GPS Data Packet

- Almanac & ephemeris data
  - Satellite location, clock, orbital parameters, etc.
  - Bitrate?
    - 50 bits/second
  - Takes about 12.5 minutes to download

- How do today's systems use it?
  - A-GPS (Assisted GPS)
  - WiFi APs are mapped — war-driving

6) Time-difference-of-arrival (TDoA)



State-of-the-Art Techniques?

- Sophisticated Combinations of these techniques, e.g.,:
- Combine AoA with time-of-flight
- Use circular antennas and combine with inertial sensing
- Perform synthetic aperture radar and DTW
- Synthesize measurements from multiple frequencies
- …

Next Class: Wireless Communications

Required

- The Wireless Channel (Chapter) - **summary** required
- Underwater-to-Air Communications - review required