Lecture 16
Localization

CS397/497 – Wireless Protocols for IoT

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Materials in collaboration
with Pat Pannuto (UCSD)

Northwestern

Today's Goals

- Discuss ideas in localization
  - Uses wireless signals for the process
  - Important for the Internet of Things

- Describe background on GPS

- Overview of indoor localization techniques
  - Fingerprinting, Ultra-wideband, etc.

# Why care about localization?

- My opinion: location information is **critical** to the IoT

  - Interpreting sensed data relies on real-world location
    - Indoor: where is the motion sensed or temperature measured
    - City-scale: how do measurements change over geographical space

  - IoT applications use location context
    - "When I get home do X"
    - "Turn on all the lights in room X"

Outline

- **Localization Background**

- GPS

- Indoor Localization
    - Overview
    - Fingerprinting
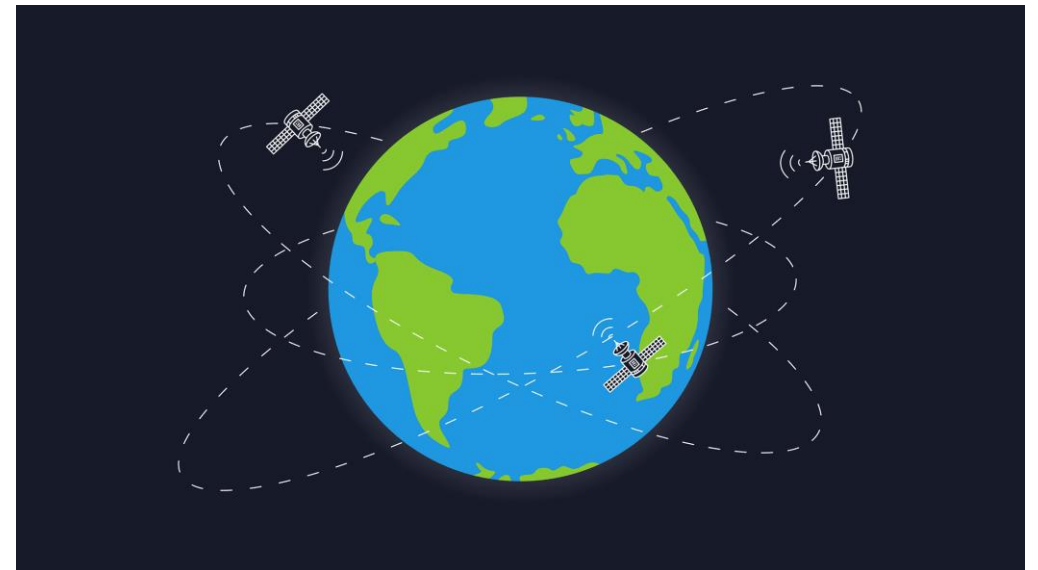   - Ultra-wideband
    - Other techniques

Background knowledge?
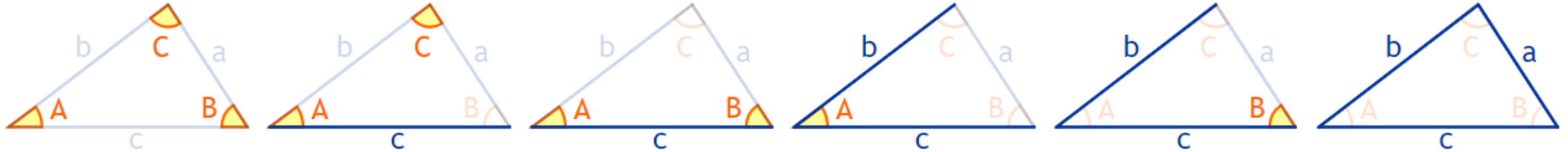
- **How does GPS work anyways?**
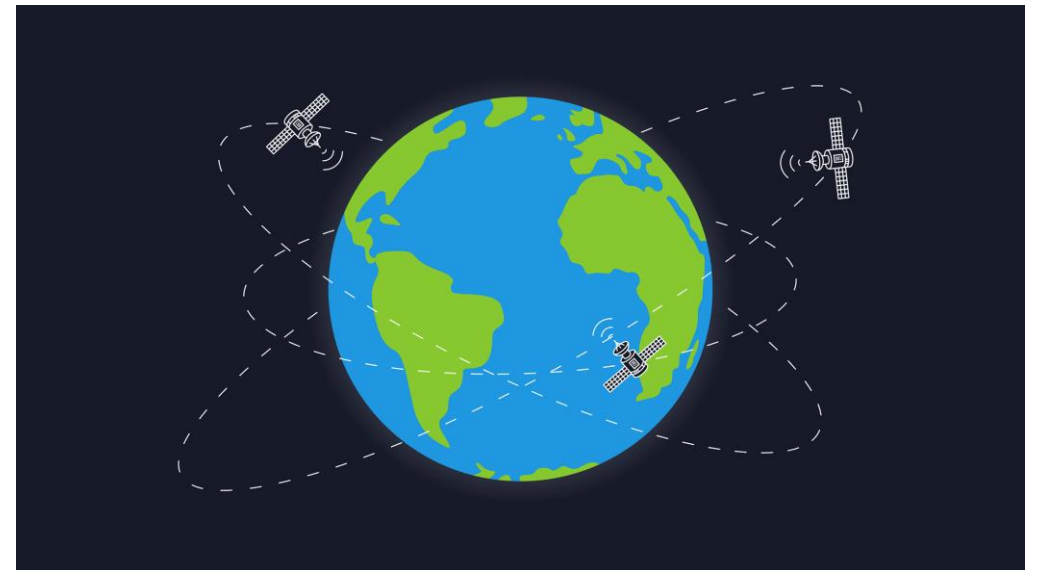
Background knowledge?

- **How does GPS work anyways?**
  - Know the position of all satellites
  - Receive signals from multiple satellites
  - Determine distance from each satellite
  - *Trilateration*

Background: trigonometry

- A triangle can be solved by knowing 3 features
  - Three sides
  - Two sides and any angle
  - Two angles and any side

- Three angles gets the type of the triangle, but not the size
  - Need at least one side to determine size

Trilateration

- Determine distance from each beacon, then find position
  - Apply trigonometry to solve triangle with beacons. Requires:
    - 3 lengths (or some angles and lengths...)
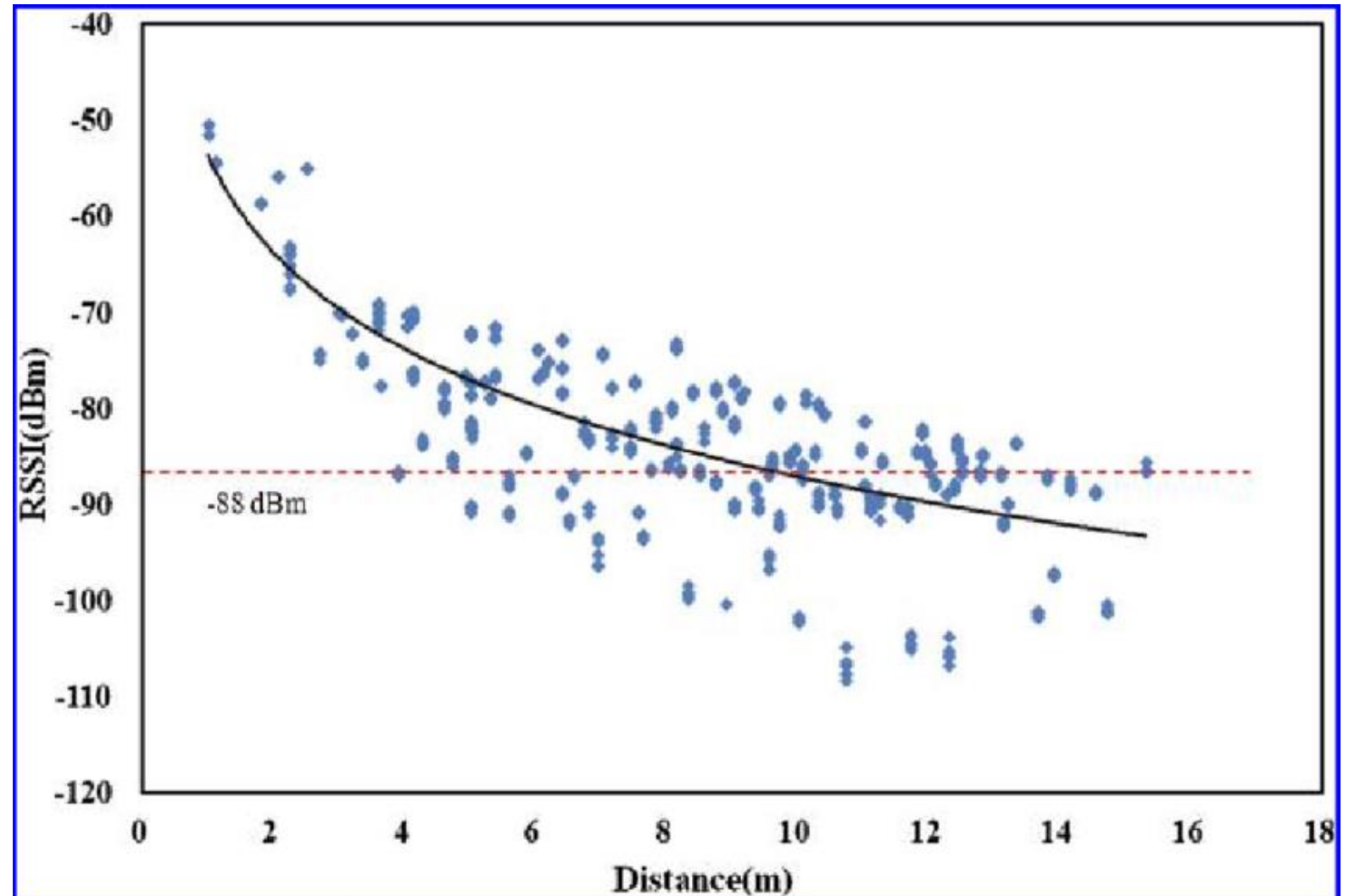 - Solve two triangles and get 3D position

- Most common and accurate localization approach

Determining distance

- Making trilateration work requires distance measurements

- Techniques
  - RSSI
  - Time of Flight
  - Time of Arrival

Reminder: problem with RSSI-based distance – not accurate

- Pathloss is NOT only due to distance

- RSSI is way worse at this than you hope it would be

Citation: literally everyone has made this figure at some point

Time of flight (also known as time of arrival, ToA)

- Determine distance by knowing:
  - Exact position of infrastructure
  - Transmit time
  - Receive time
  - Signal velocity (i.e. speed of light)

- Infrastructure transmits and device listens
  - Can happen all the time, but devices only listen when they want a position

- Requires time synchronization between infrastructure and device
  - Synchronization must be good: 1 µs = 300 meters

Time difference of arrival (TDoA)

- Device transmits and infrastructure receives transmission
  - Multiple infrastructure nodes receive at different times based on distance

- Determine distance by knowing
  - Exact position of infrastructure
  - Time of arrival at two different locations
  - Signal velocity (i.e. speed of light)

- Doesn't require synchronization with infrastructure!
  - Still requires synchronization between infrastructure nodes
  - Does require device to transmit loud enough for infrastructure to hear it...

How many anchors are needed?

- 3 anchors gets a 2D location
  - Two possible 3D locations are valid

- 4 anchors gets a 3D location

- Shortcut: if the alignment is right, 3 anchors can do 3D
  - 3 anchors result in two possible points that satisfy equations
  - One will be on the ground, the other somewhere mid-air or underground

Real-world complication: accuracy

- No distance measurement will be perfect

- Which means trilateration will not be perfect either
  - Need to solve equations in a fuzzy manner looking for least error

Outline

- Localization Background

- **GPS**

- Indoor Localization
  - Overview
  - Fingerprinting
  - Ultra-wideband
  - Other techniques

GPS overview

- Trilateration using Time of Flight from at least 4 satellites
  - Satellites in well-known orbits with VERY stable clocks

- Satellites placed in Medium Earth Orbit (20,000 KM)
  - Orbit earth twice per day
  - Placed such that 4 are in view everywhere, always
  - 31 total in orbit as of November 2020
    - Most recent launch June 17th 2021

- Comparisons
  - LEO 200-2000 km, ISS at 340 km
  - GEO 35,000 km
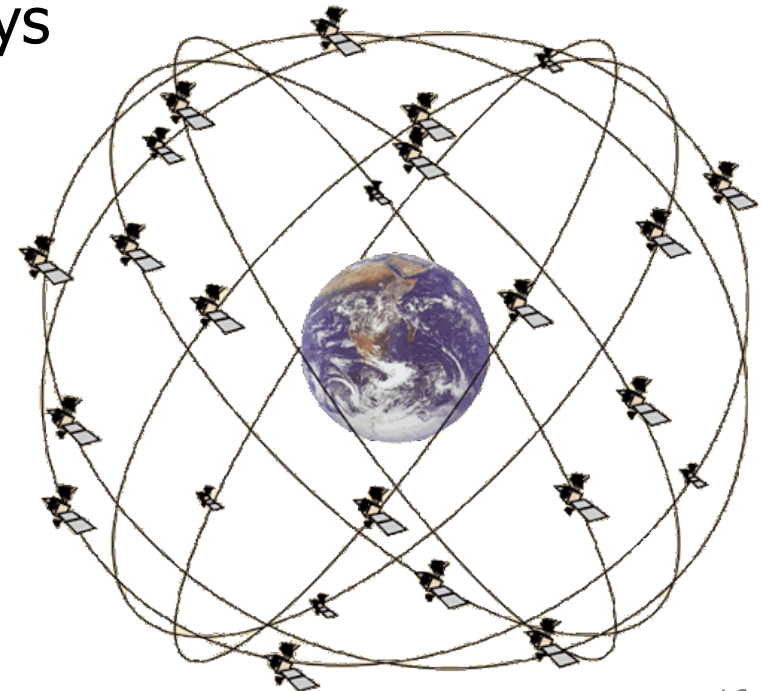
Satellite visibility overhead
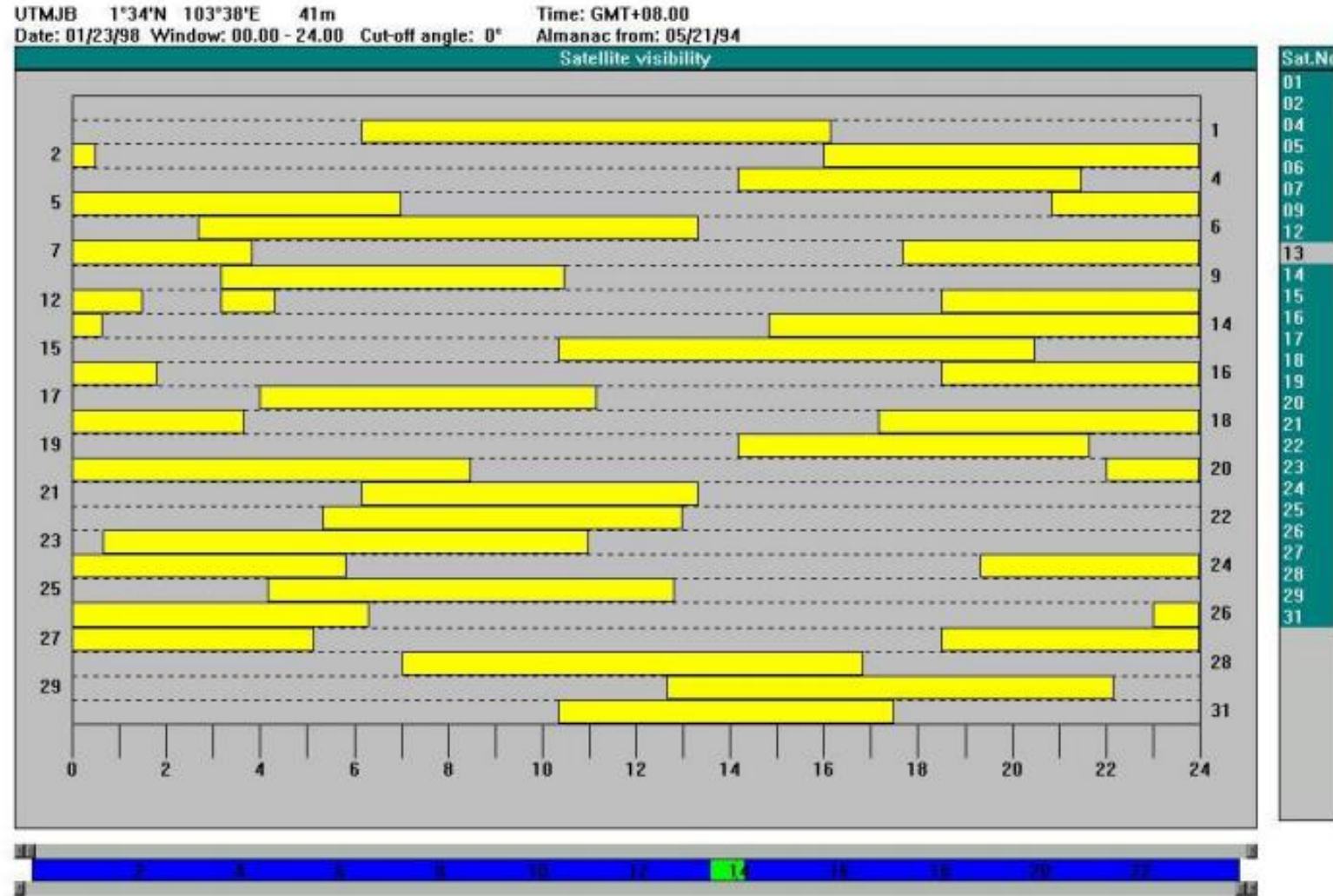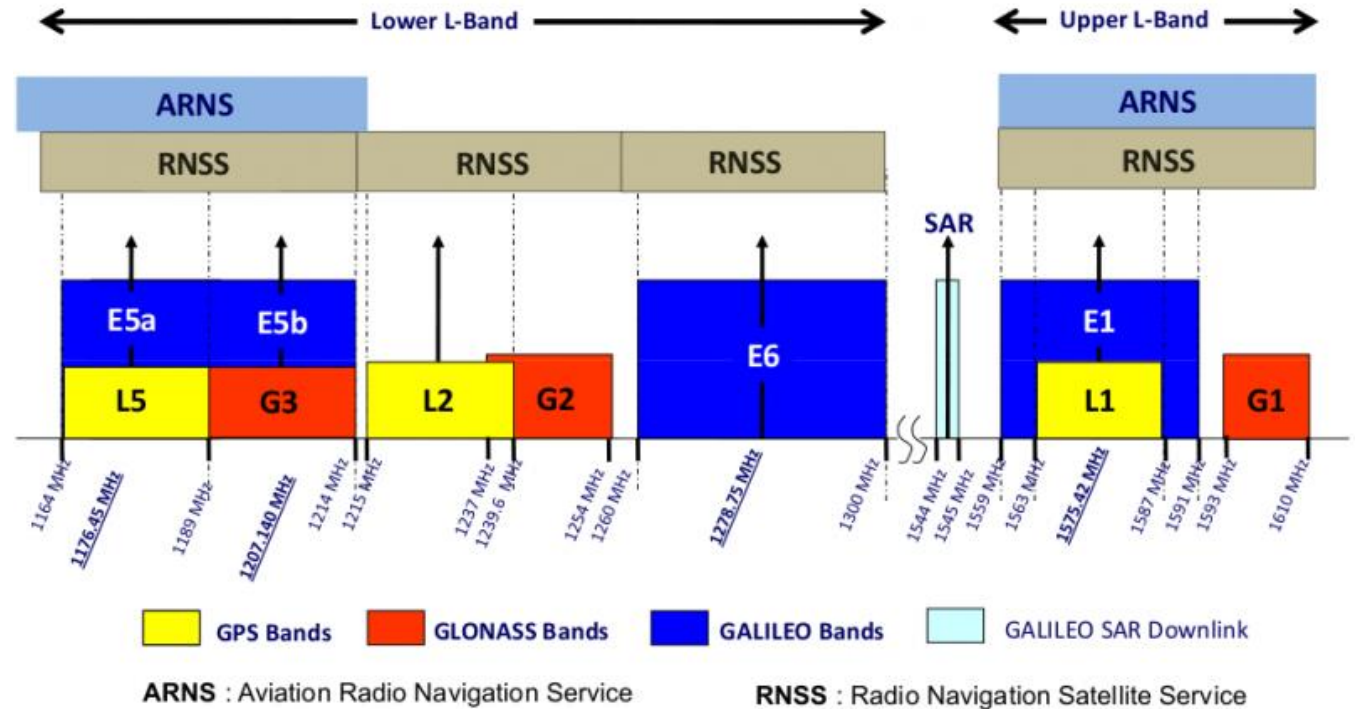
GPS PHY

- GPS frequency
  - 1.2 GHz and 1.5 GHz
 - 10-15 MHz bandwidth

- BPSK modulation

- Signal has to travel 20,000 km, but most of that is through space
  - Tx power 25 Watts (44 dBm)
  - Rx sensitivity -140 dBm to -160 dBm (50 bps data rate)
  - ~200 dBm total link budget

GPS transmissions

- Each satellite sends a unique pseudo-random number sequence
    - Sequence repeats in time (over minutes) and is well-known
    - Position in signal is used to calculate time of flight
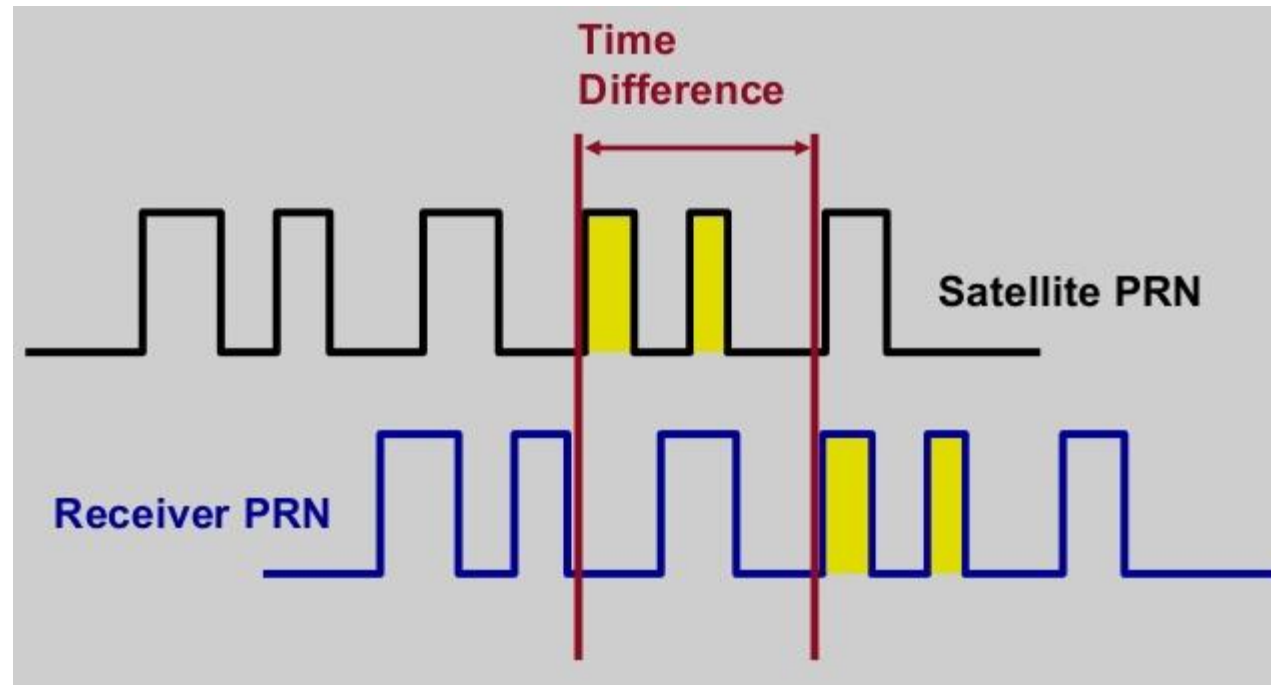
GPS requires signals from multiple satellites

- 4 satellites are needed to determine location and time
  - 3 for 2D location (assume on ground) and 1 for time offset
  - Solve for both as a single equation

- Steps to finding location
  - Initialize time to whatever you heard from a satellite (~100 ms sync)
  - Get time of arrival from four satellites
  - Four variables
    - x, y, z, and time offset

Additional GPS data

- Receiver needs to know additional information
  - Current time
  - Position of each satellite

- GPS transmission has this data layered on top (50 bps)
  - Listening for (up to) 30 seconds gets time and this satellite's position
    - Known as ephemeris
    - Valid for up to 4 hours
  - Listening for 12.5 minutes gets all satellites' positions
    - Known as almanac
    - Valid for up to two weeks

- Cold-start for an embedded device takes significant time

Break + Question

- How would you make a system connect to GPS faster?
  - Cell phones don't take 12.5 minutes to get a fix after booting

Assisted GPS

- How is cell phone GPS so quick?
  - Download almanac from the internet (only 1.8 kB)

- Bootstrap location information
  - Cell towers can give coarse position
  - Enables device to know which satellites are overhead
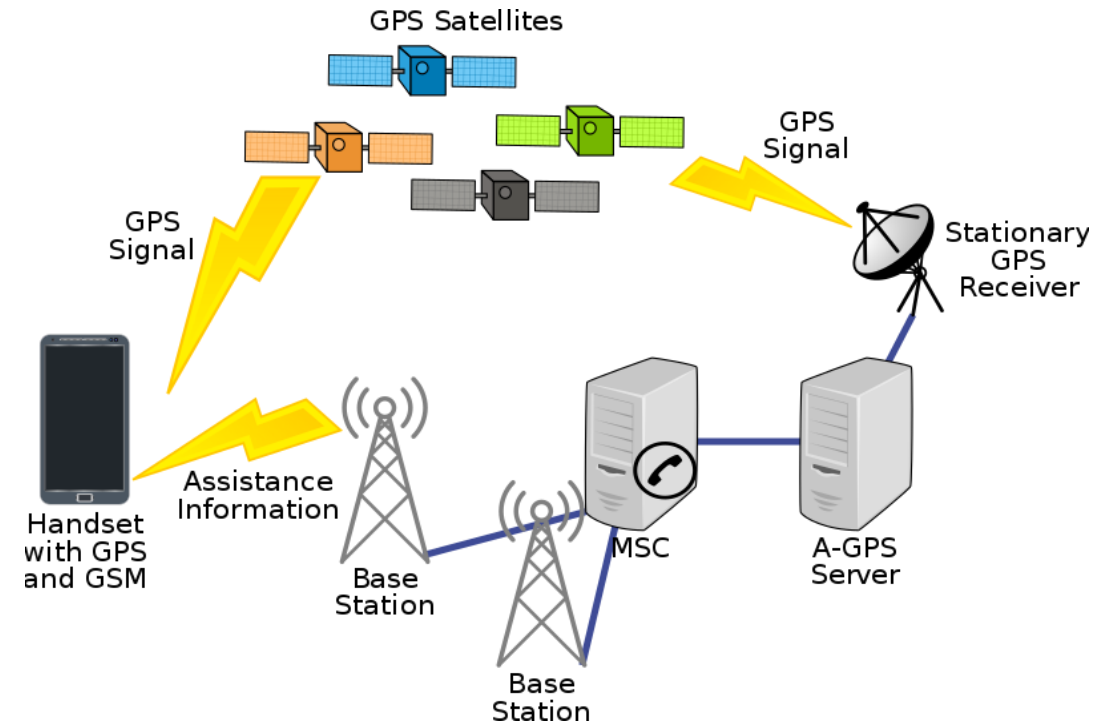
Outline

- Localization Background

- GPS

- **Indoor Localization**
    - **Overview**
    - Fingerprinting
    - Ultra-wideband
    - Other techniques

Clearing something up

- The goal is **NOT** directing people through a building

- Just because that's what GPS is used for outdoors doesn't mean we need that application indoors

Goal of indoor localization

- The goal is positioning *things* within a building
  - Where can I find **X**?
  - **X**: where am I located?
  - **X** and **Y**: are we near each other?

- Robotic navigation is also important
  - Although there are many approaches here

Localization classes

- Absolute location
  - X, Y, Z position based on already known infrastructure locations
    - Like GPS does
  - Installed localization hardware known as *anchors*

- Relative location
  - Position relative to some other device
    - Technically absolute location is a version of this
  - Might only need a few devices
  - How far is the smartphone from the computer?

Localization knowledge

- What kind of a result is actually useful?
  - You are at {15, 27.5, 1}
  - You are in Room 224

  - Depends on the application

- Additional systems on top of the localization method can translate between location representations

Barrier problem

- "I'm here to pick up fish"

- Walls are very contextually important, but difficult for localization systems to detect

Accuracy notation

- "40 cm median accuracy"
  - Majority of measurements are within 40 cm of reality!
  - *What about the other half?*

- 90$^{\text{th}}$ percentile error is often more important for real-world use

- My least favorite aspect of localization
 - Be wise to these tricks

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Mapping existing infrastructure

- Can we repurpose existing infrastructure for localization?
  - For example: WiFi access points
  - Benefit: localization works with unmodified hardware

- Mapping instead of trilateration
  - Make a map of infrastructure and use that to locate device

  - Coarse example: existence of WiFi network SSIDs

  - Fine-grained example: signal strength to each Access Point
    - Known as fingerprinting

Fingerprinting overview

- At setup time, for many locations throughout building
  - Measure signal strength to Access Point
  - Record measurement in a database with location

- At run time, for the device that wants a location
  - Measure signal strength to Access Point
  - Look up measurement in database to get location
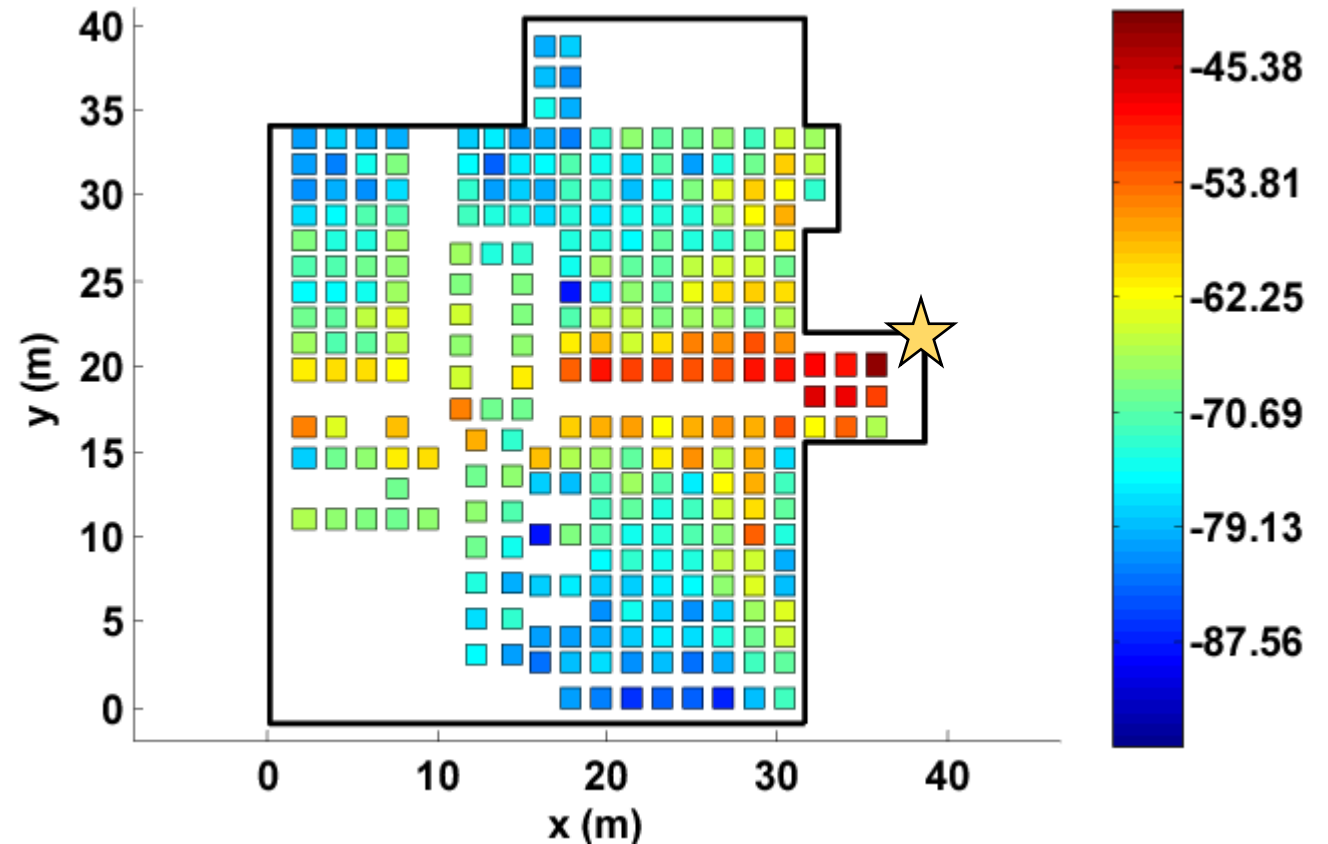
Fingerprinting improvements

- Measurements can use several Access Points simultaneously
  - Improves accuracy quite a bit

- Doesn't have to be WiFi based at all
  - Cellular networks can do fingerprinting
  - Deploy your own BLE beacons throughout environment

- Apply techniques for minimizing error in signal strength
  - Measurement won't match record exactly
  - But minimizing error should approach the same location

Fingerprinting challenges

- Effort to create database in the first place
  - Manually take measurements at every location

- Environment is not stable
  - Signal strength changes as chairs, doors, and people move
  - Need ability to periodically re-measure
    - Update database with most recent recording while in use

- Measurements vary between devices
  - Differ based on antennas, cases, how you hold it, etc.

Fingerprinting accuracy

- State-of-the-art: median accuracy of 0.5-1.5 meters
  - Not bad depending on the application!
  - Likely places you in the right room, or at least nearby
  - Long tail can be large, but more access points helps this

- Barrier problem capability depends on walls
 - Some materials attenuate signal strength more than others

Break + Open Question

- WiFi is only one example of a signal you could fingerprint. What else could you use?

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 - Fingerprinting
  - **Ultra-wideband**
  - Other techniques

Improving accuracy

- To get really good accuracy, let's return to trilateration

- Plan: Send an RF signal from one device and time how long it takes to reach another
  - Brief transmissions rather than continuous like GPS

- Problem: When does this signal arrive?
 - Need to pick somewhere in rise as the "arrival time"
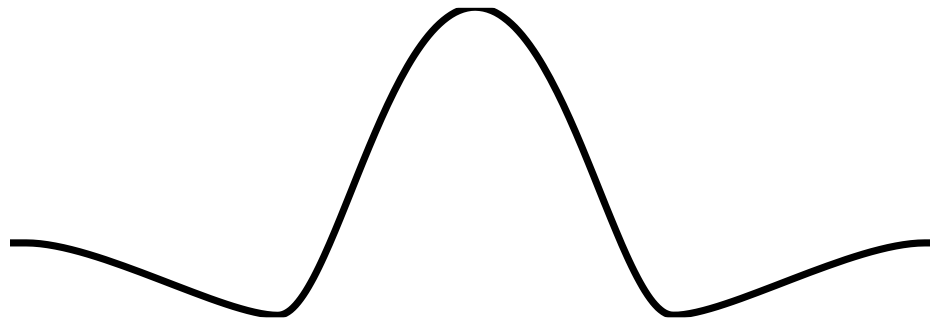
Multipath problem

- Real-world signals bounce off of things in the environment
  - Multiple, time-delayed versions of signal arrive at antenna
  - Result smears out the arrival of energy in time
    - More reflections mean more peak energy, but longer rise time
  - This isn't predictable. Depends on the exact environment configuration
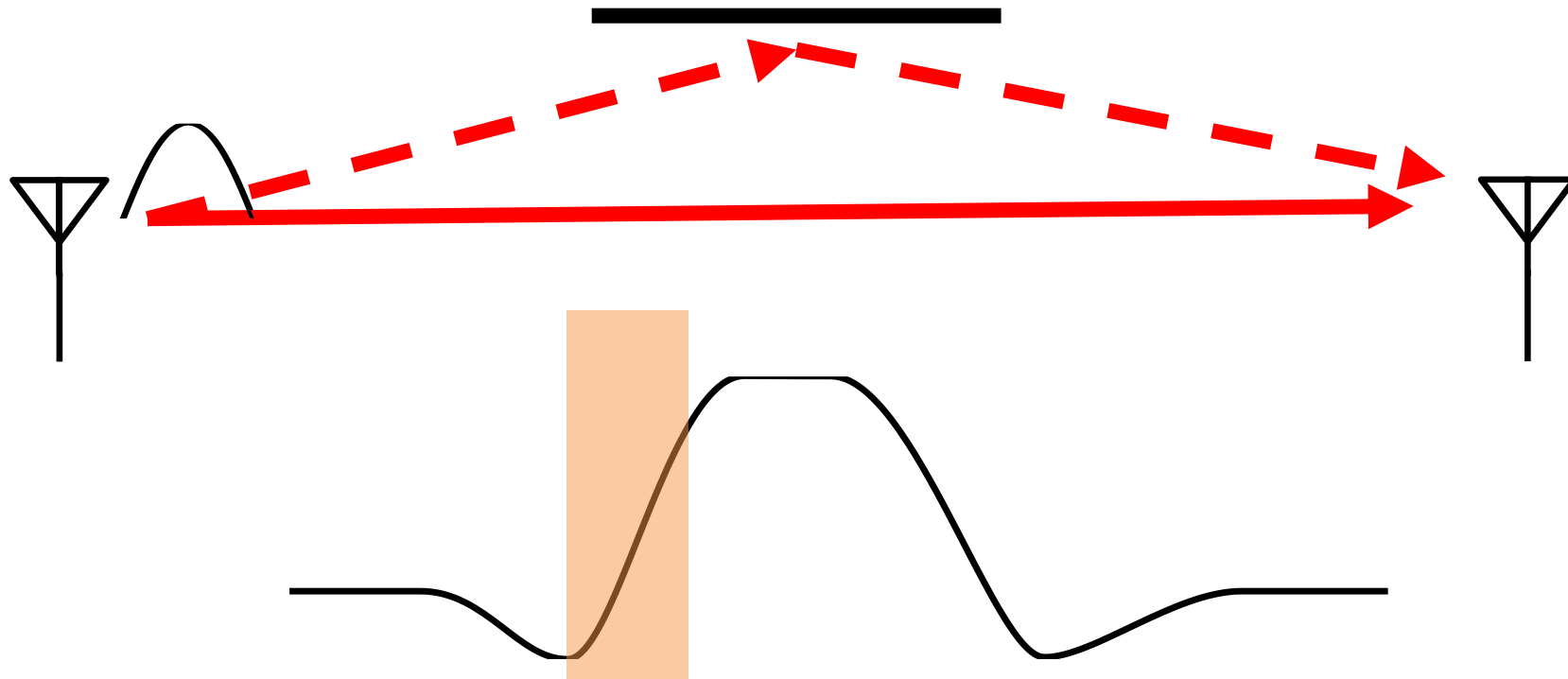
Why does ultra-wideband yield better localization performance?

- Wider bandwidth makes the RF pulse narrower in time
  - Make it narrow enough, and multipath becomes entirely separate
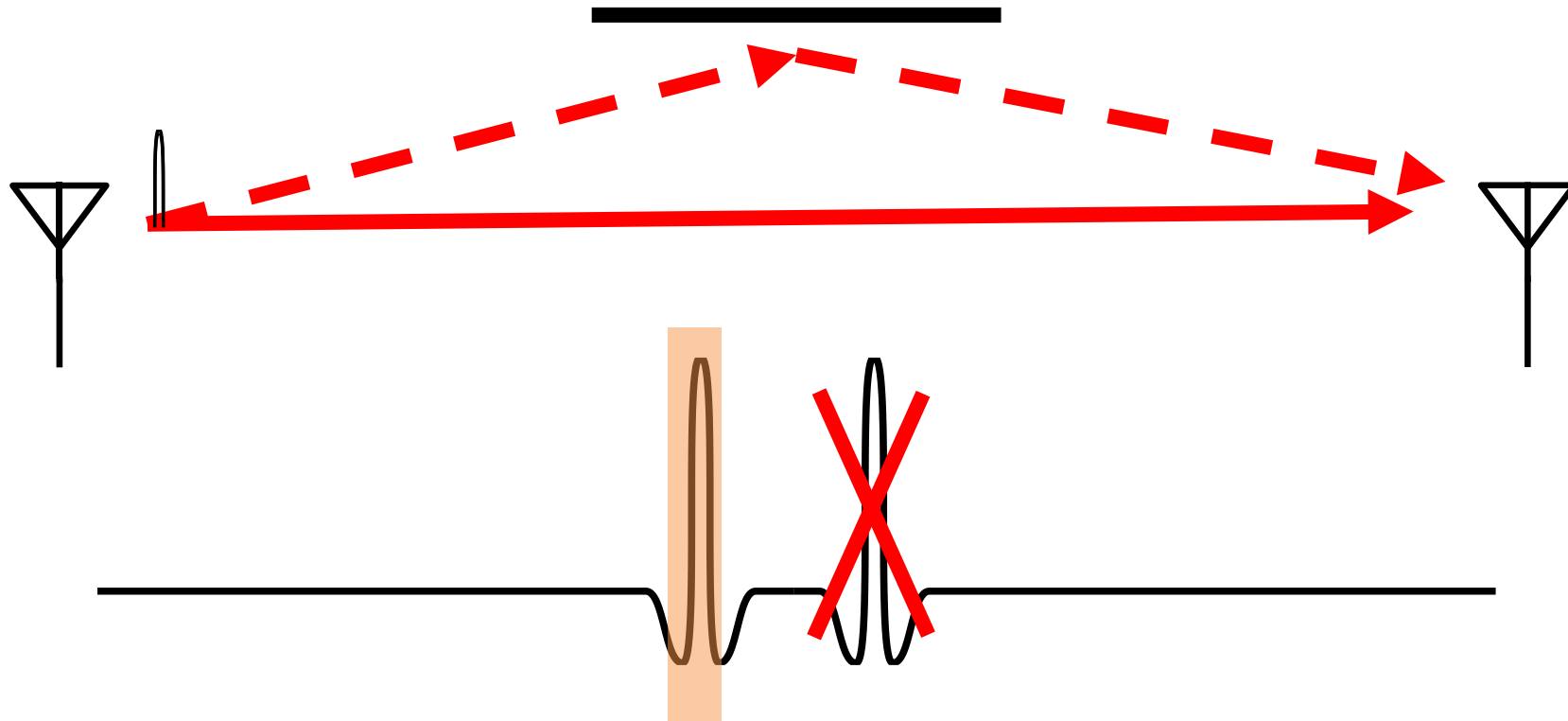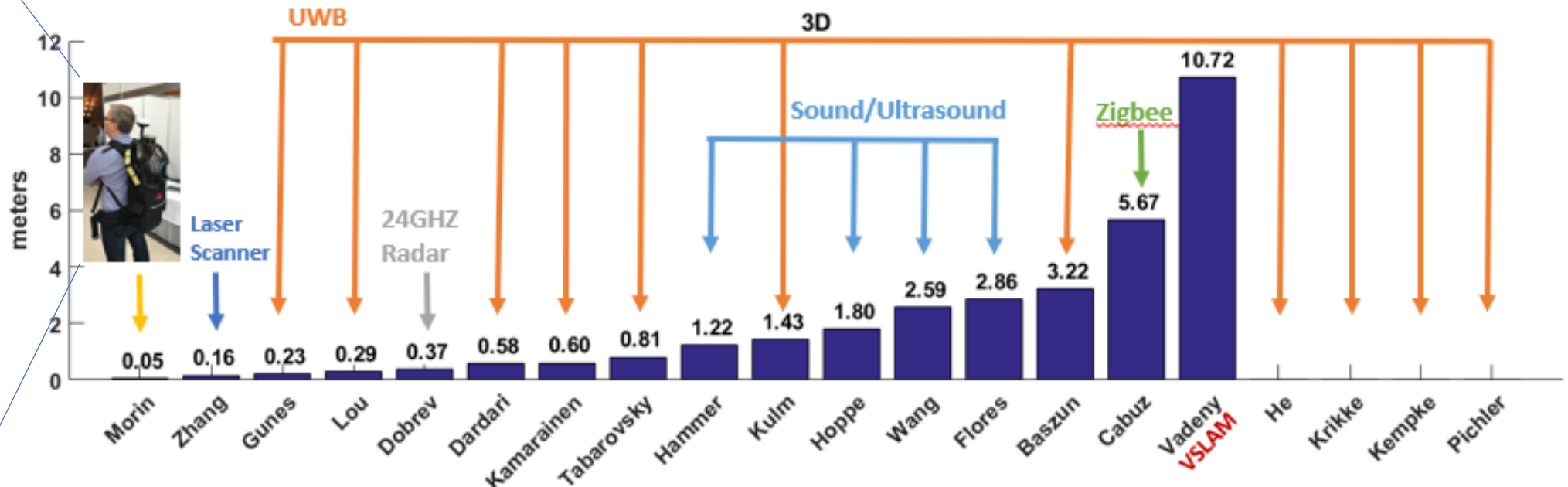
Ultra-wideband localization system

- Narrow ultra-wideband pulses makes arrival timing work

- The rest is a copy of well-known techniques
  - Deploy anchors in the environment with known positions
  - Measure distance between anchors and device
    - Time of Flight (if anchors transmit)
    - Time Difference of Arrival (if devices transmit)
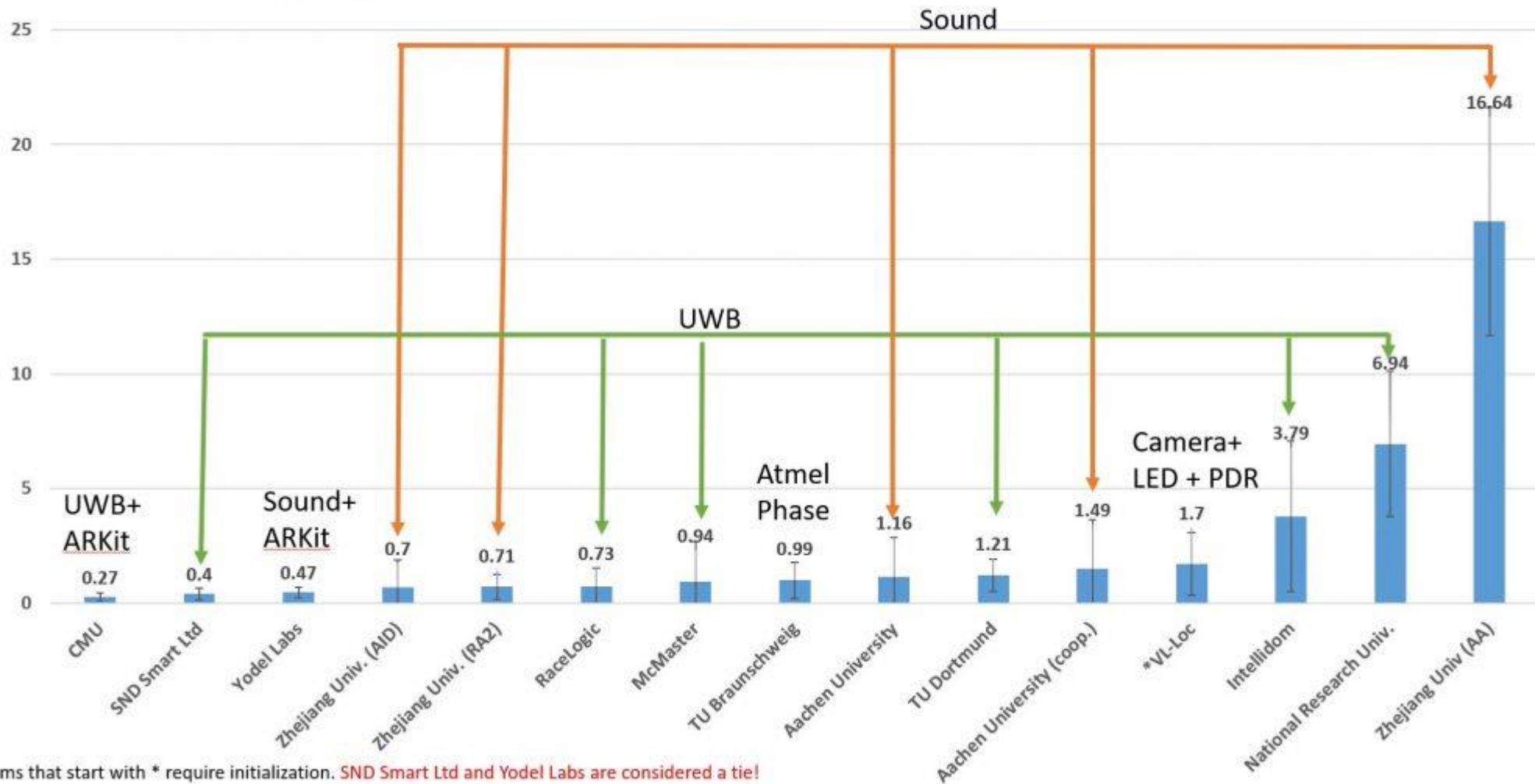 - Trilateration to find position

Localization state-of-the art

- Microsoft indoor localization competition, 2016
    - Teams are given a day to measure and deploy their systems in a space
    - Provide {x, y, z} coordinates using up to 5 anchors in large open room

# 2019 results (Microsoft indoor localization competition)

Improvements to ultra-wideband

- Improve results with multiple, diverse measurements
  - Sources of diversity
    - Send on multiple channels
    - Send with multiple antennas
    - Receive with multiple antennas
  - Measure each combination of these and average to get better results

- Combine with backscatter approaches
  - Result is very slow (minutes to locate device) but very low power (<1µW)
  - Most inventory doesn't move!

Bringing UWB to the real world

- Ultra-wideband radios have been fairly specialized
  - Needed to build special hardware to use them

- iPhone 11 and 12 have UWB radios!!!
  - Use cases are still a little unclear
  - Opens a big area of development
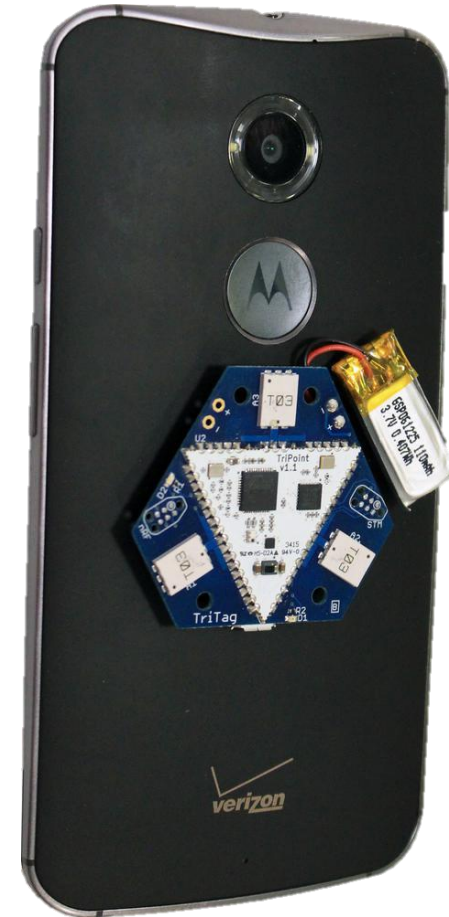
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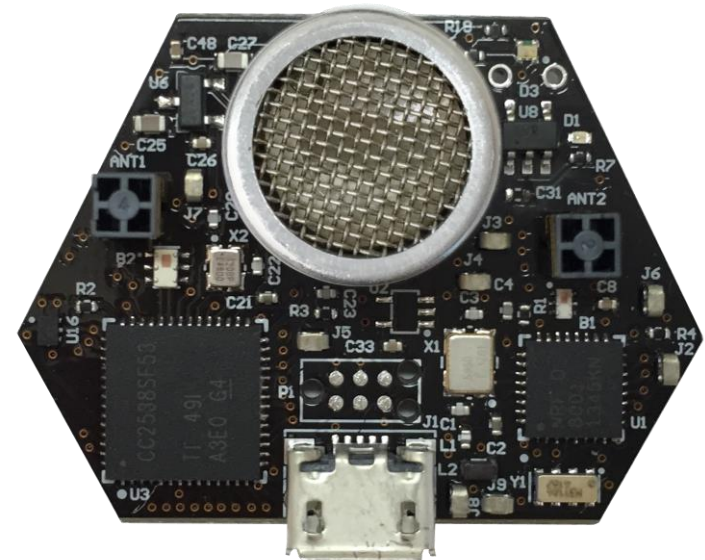 - **Other techniques**

Ultrasound

- Advantages
    - Solves the barrier problem
        - Human spaces already designed to contain sound
    - Easier to get high-accuracy results
        - Sound is ~1,000,000x slower than light
        - Less synchronization is needed to get same accuracy

- Disadvantages
    - More energy to transmit
    - Slower update rate (still sub-second)
    - Limited range
    - Pets can hear it…

Inertial navigation

- If you know acceleration, you can get position, just integrate!
  - With quite a bit of error

- Accurate over short distances with filtering approaches
  - Can be used to augment other systems
  - Get a fix every few seconds from localization system
  - Use inertial navigation to interpolate between measurements

- IMUs (Inertial Measurement Units) available in all smartphones
 - Accelerometer, Gyroscope, Magnetometer

ARKit (and other AR techniques)

- Leverage smartphone cameras for positioning
  - Pictures of a user's surroundings can be compared to floorplan
  - Related to SLAM techniques (Simultaneous Localization And Mapping)

- Can build an incredibly accurate system
  - With a bit of bootstrapping
  - Probably applies most to robotics use cases

Vibrations

- Determine shared context of a table
  - Vibratory motors and IMUs are common
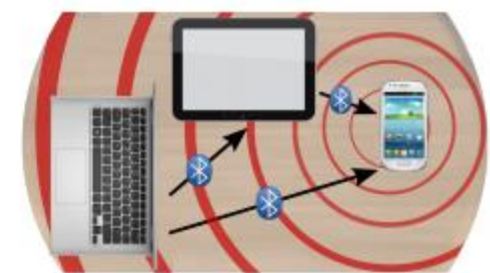 - Signaling demonstrates nearby devices
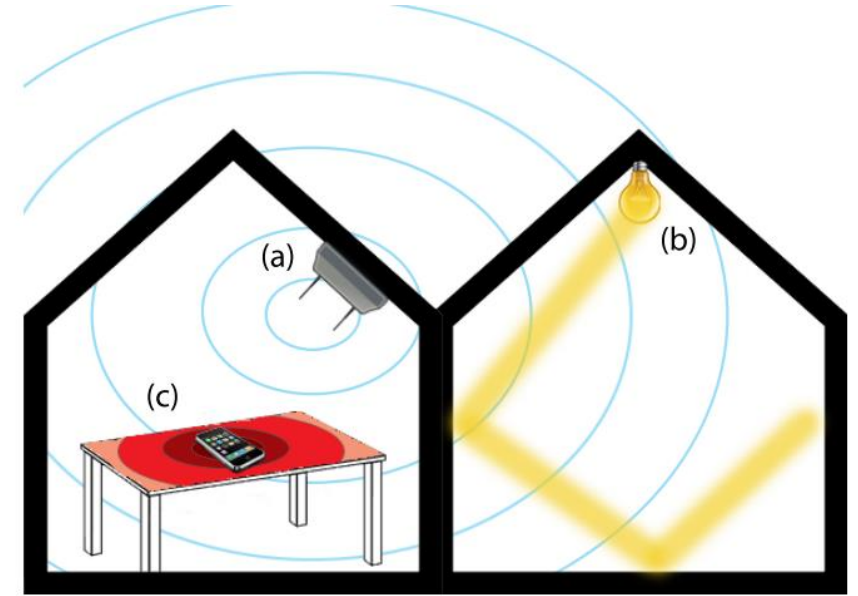
(a) Establishing a first-time Bluetooth connection

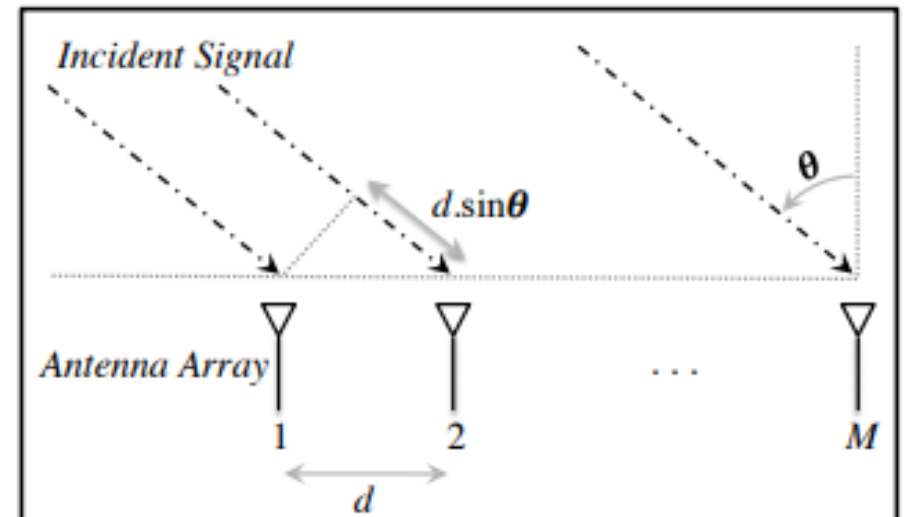(b) Desktop detection for pre-connected devices

(c) Connecting with hidden table-level services

(d) Establishing a desktop area network

Angle of arrival (AoA)

- Trilateration doesn't only require distances, angles work

- Antenna arrays can be used to determine the angle of an incoming signal
  - Allows the use of normal RF communication (WiFi or BLE)

- BLE 5.1 includes AoA localization

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