Lecture 16
Localization

CS433 – Wireless Protocols for IoT

Branden Ghena – Spring 2025

Materials in collaboration with
Pat Pannuto (UCSD) and Brad Campbell (UVA)

Northwestern

Administrivia

- Assignments
  - Hw: Cellular due today

- Office Hours
  - **No Lab Session this week – I can't attend**

- Last quiz next week Tuesday
  - Topics: Cellular, LPWANs, Localization

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

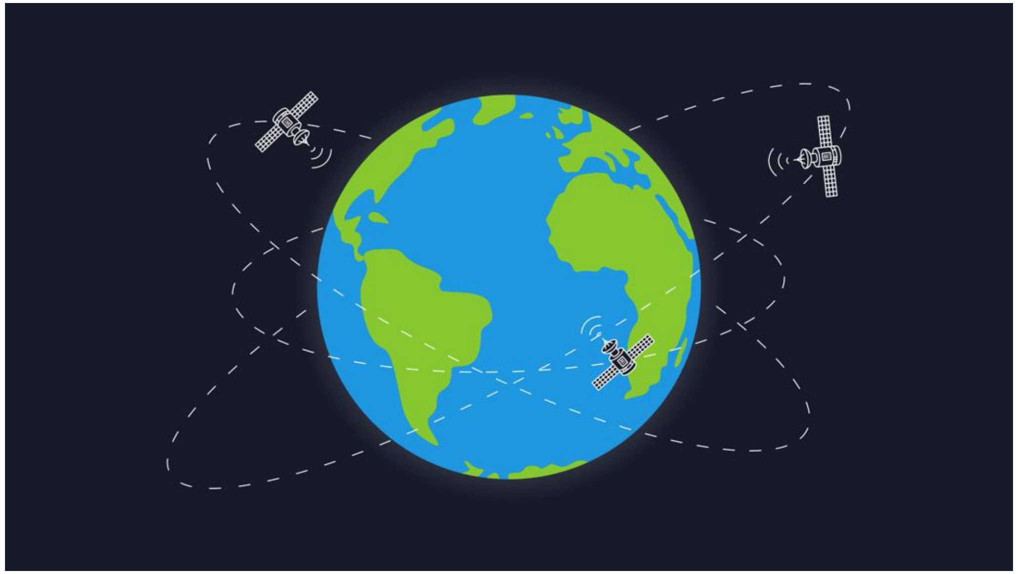
- **Localization Background**

- GPS

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

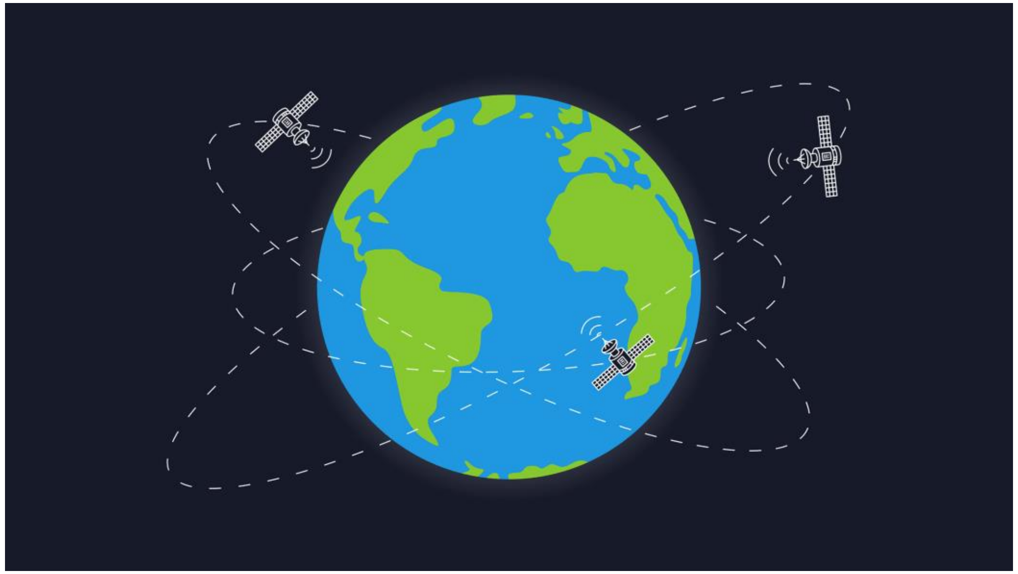
Background knowledge?

- **How does GPS work anyways?**

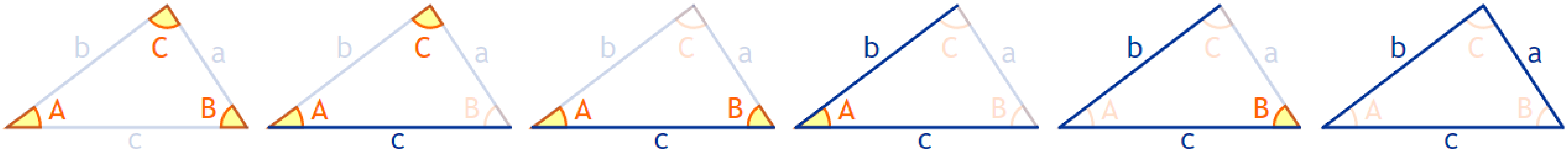


Background knowledge?

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



Background: trigonometry

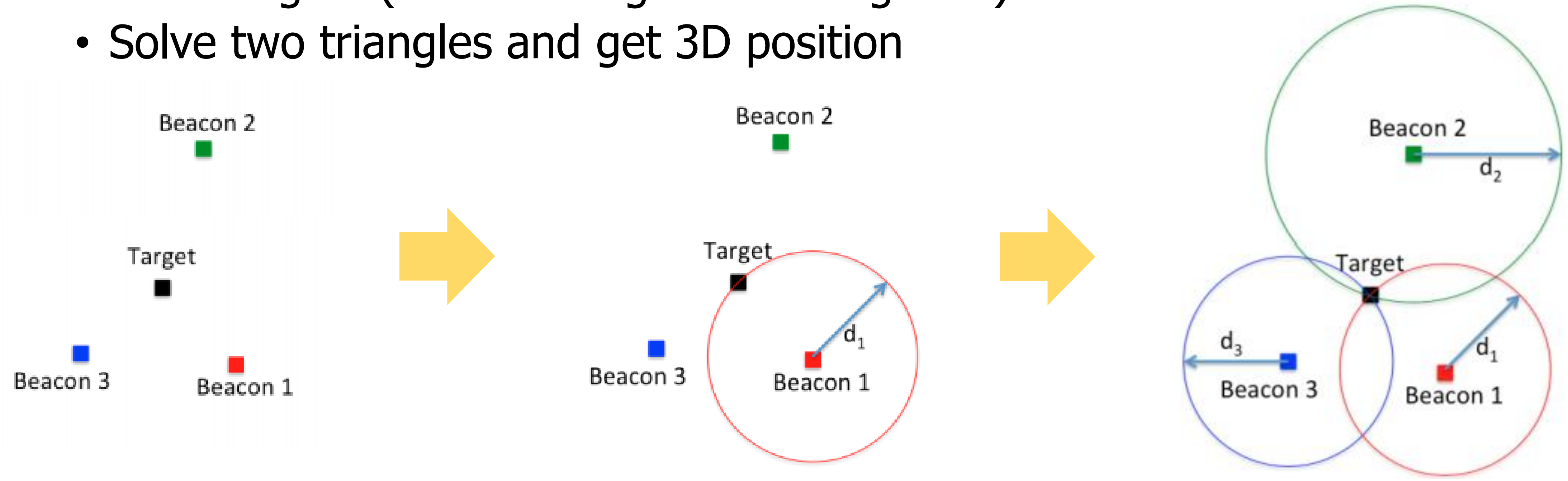


- A triangle can be solved by knowing 3 features
  - Three sides
  - Two sides and any angle
  - Two angles and any side

- 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

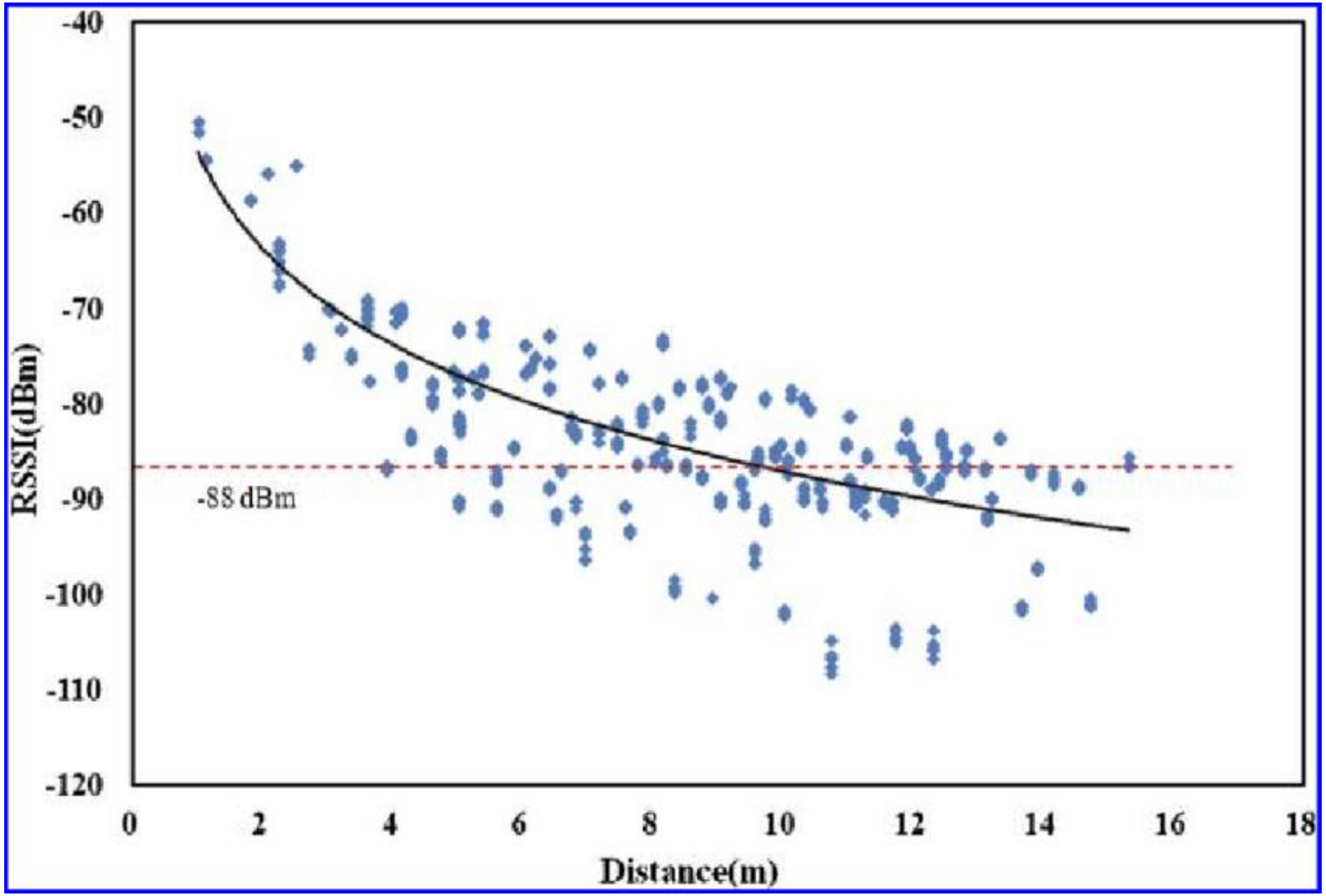
Determining distance

- 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
  - Transmissions can happen all the time
  - But devices only listen when they want a position

- Requires time synchronization between infrastructure and device
  - Synchronization must be **very** good: 1 μs = 300 meters, 1 ns = 0.3 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 (maybe easier?)
  - Requires the 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 guess 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

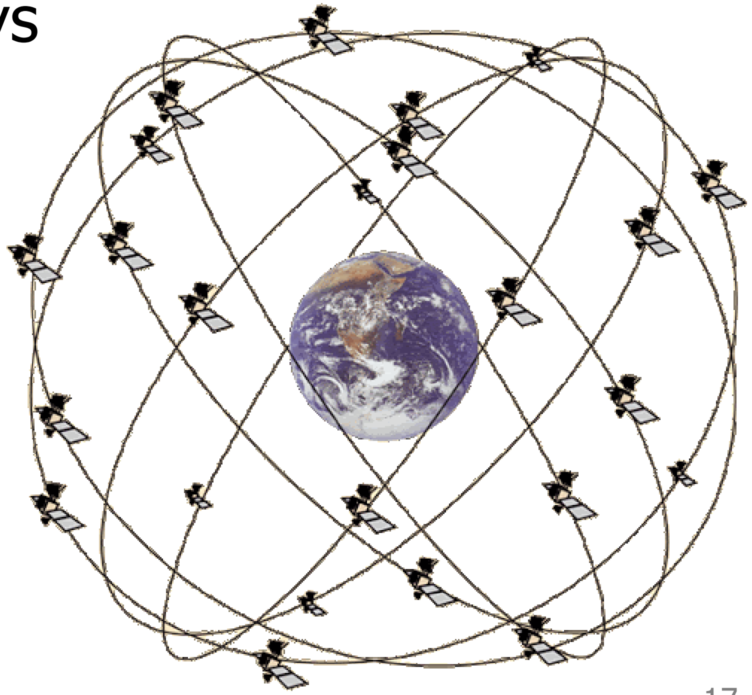
- Localization Background
- **GPS**
- Indoor Localization
  - Overview
  - Fingerprinting
  - Ultra-wideband
  - Other techniques

GPS overview

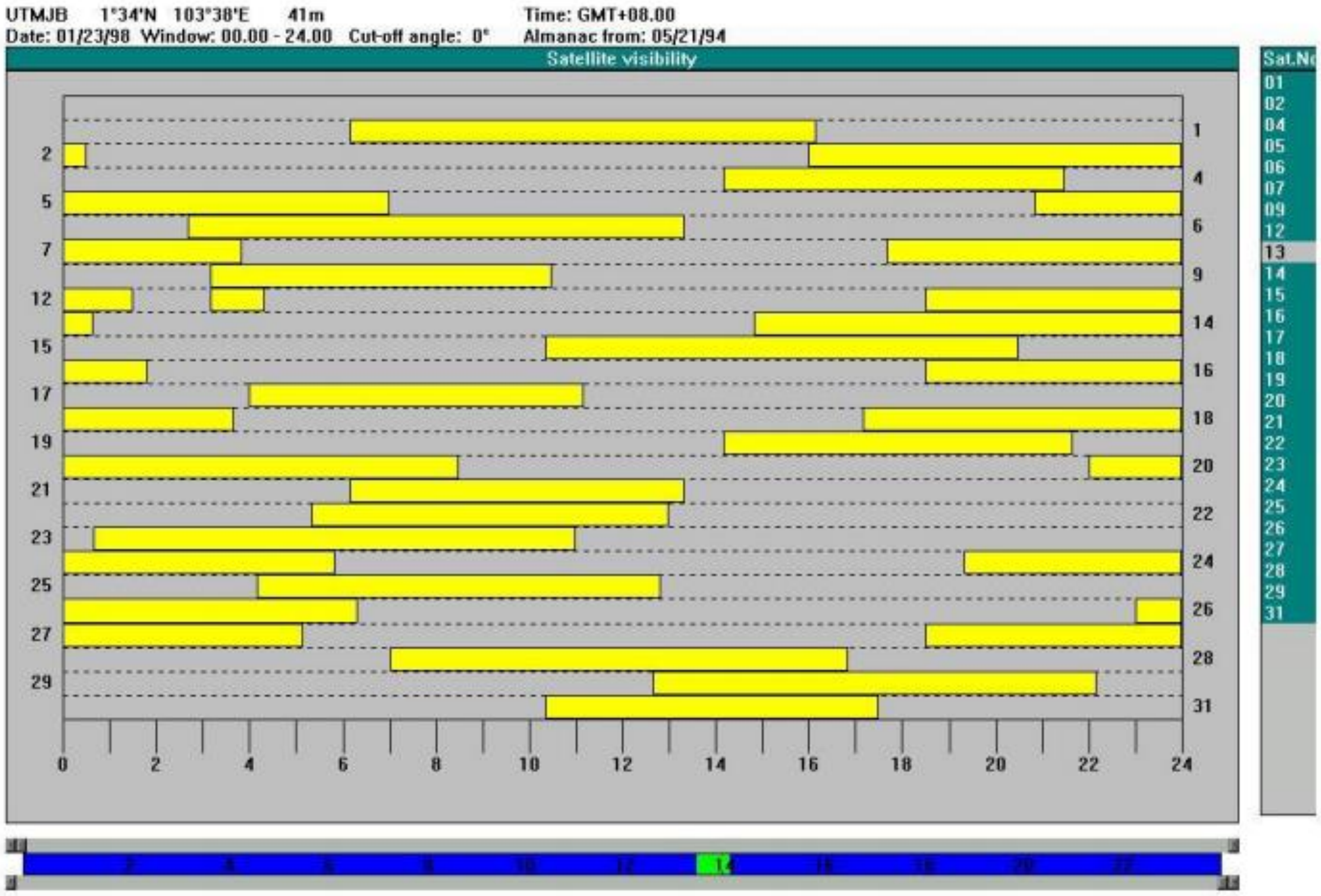
- Trilateration using Time of Flight from at least 4 satellites
  - Satellites in well-known orbits with VERY stable clocks

- Satellites placed in Medium Earth Orbit (20,000 KM)
  - Orbit earth twice per day
  - Placed such that 4 are in view everywhere, always
  - 31 operational satellites as of January 2025
    - Most recent launch December 2024
    - Next launch: tomorrow

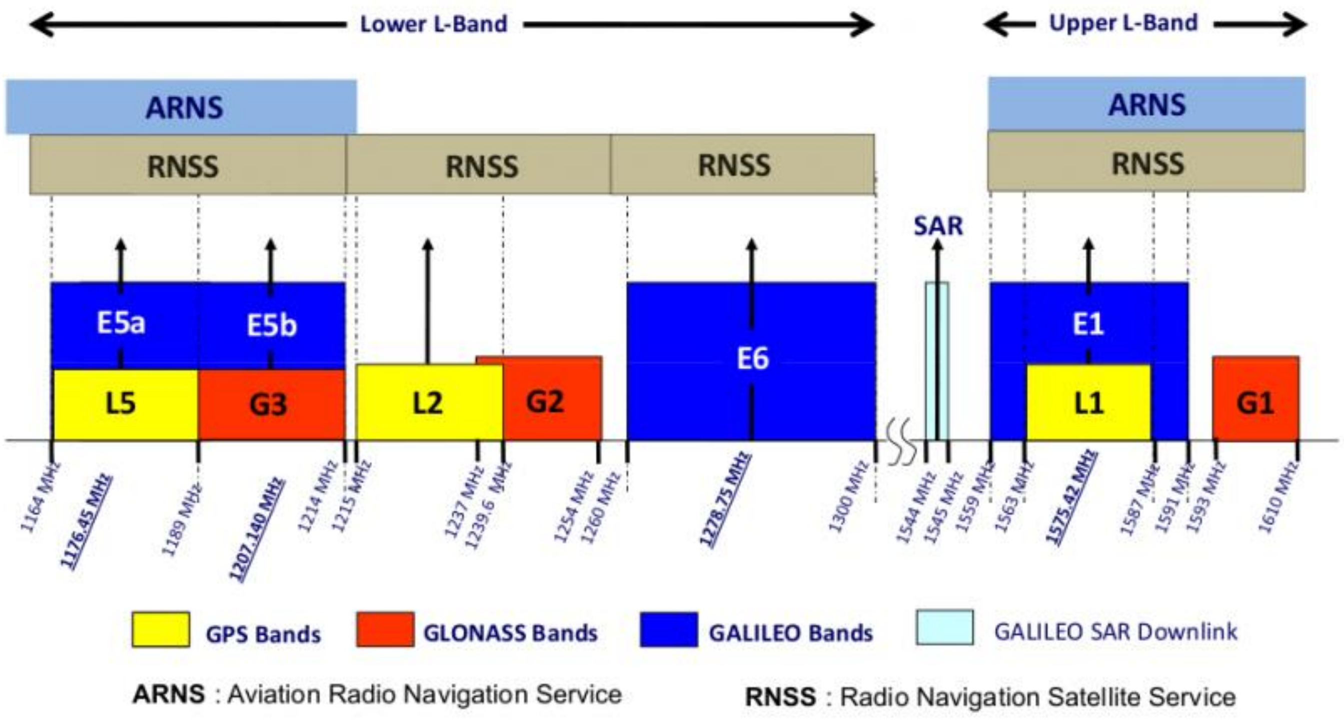
- Comparisons
  - LEO 200-2000 km, ISS at 340 km
  - GEO 35,000 km



Satellite visibility overhead



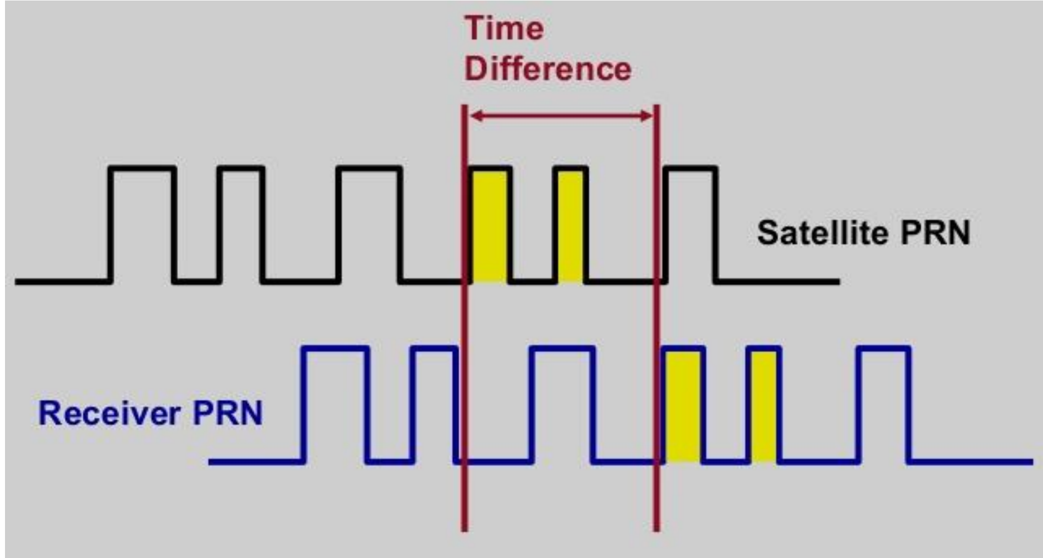
GPS PHY



- 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 (if you know precise time)
  - Different and manually selected for each satellite



- Why pseudo-random?
  - Spreads tiny data over a wide bandwidth for reliability (same DSSS technique at 802.15.4 and 802.11b)

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 (at 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

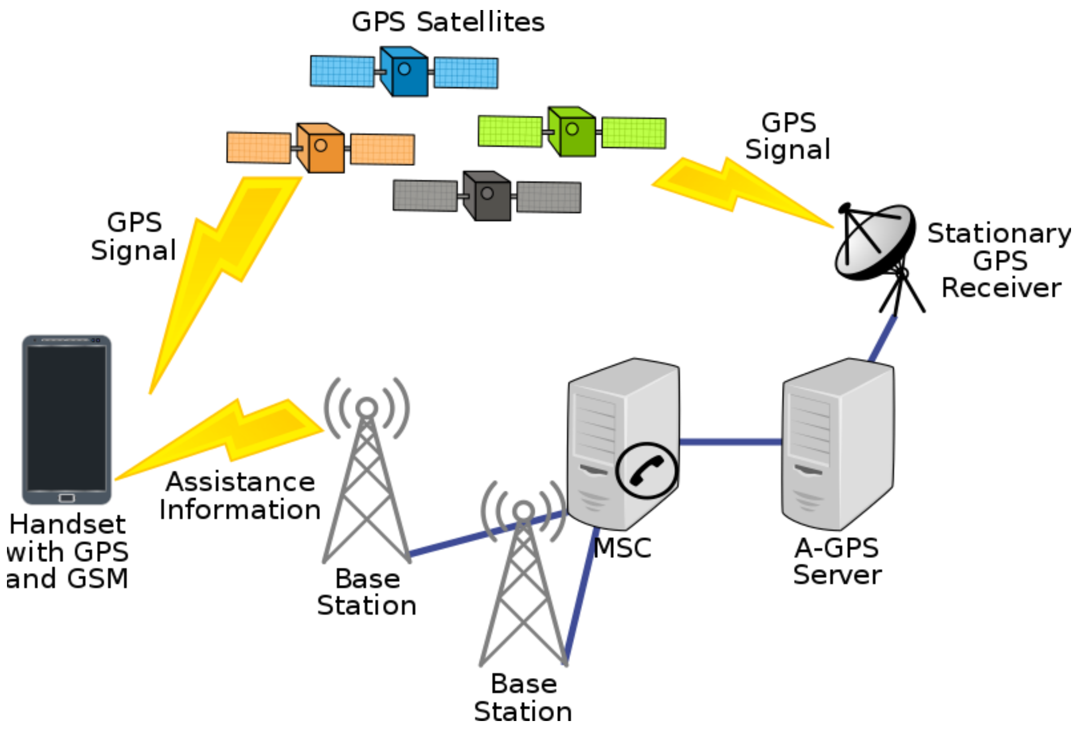
- Cold-start for an embedded device takes significant time

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



Original GPS had a built-in accuracy limitation

- Selective Availability
  - Pseudorandom adjustment to the signals to reduce accuracy
  - Could be recovered if you know the specific pseudorandom key

- Public use (no key)
  - 50 m accuracy horizontally
  - 100 m accuracy vertically

- Original GPS was intended for military only
  - With limited GPS for everyone else (i.e., other nations)
  - In 2000, was removed from GPS, leading to about 5 m accuracy

Other positioning system implementations

- Global Navigation Satellite System (GNSS)
    - Formal name for a global localization system

- US: GPS
- Russia: GLONASS
- China: BeiDou
- EU: Galileo
- India and Japan have regional systems
- Lunar system in design!

- Modern GNSS hardware can use multiple at once for better accuracy

Using GPS in the real-world

- Usually connected over a serial connection and send “human-readable” NMEA messages

```
$GPGGA,210230,3855.4487,N,09446.0071,W,1,07,1.1,
370.5,M,-29.5,M,,*7A
```

GPS sentence type

- Usually connected over a serial connection and send “human-readable” NMEA messages

```
$GPGGA,210230,3855.4487,N,09446.0071,W,1,07,1.1,
370.5,M,-29.5,M,,*7A
```

- Format of data
  - GGA = “Global Positioning System Fix Data”
  - Specifies what the other comma-separated fields will be

Time in a GPS sentence

- Usually connected over a serial connection and send “human-readable” NMEA messages

```
$GPGGA,210230,3855.4487,N,09446.0071,W,1,07,1.1,
370.5,M,-29.5,M,,*7A
```

- Current time in UTC
  - HHMMSS format

Lat/Lon in a GPS sentence

- Usually connected over a serial connection and send "human-readable" NMEA messages

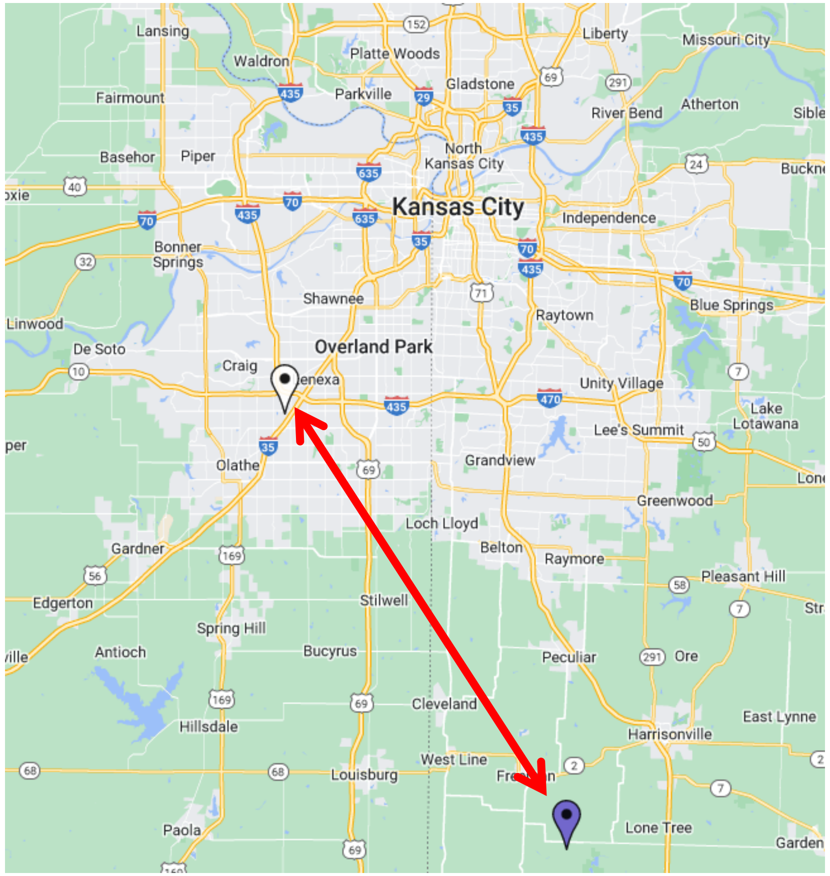
```
$GPGGA,210230,3855.4487,N,09446.0071,W,1,07,1.1,
370.5,M,-29.5,M,,*7A
```

- Latitude (blue) and Longitude (red)
  - DDMM.MMMM format (degrees and minutes [60th of a degree])
  - Warning: normal GPS coordinates are in DDD.DDDDDD format
    - Need to translate by dividing minutes by 60

Make sure you use the correct GPS coordinates

- 38 degrees, 55.4487 minutes N -> 38.924145 degrees
- 94 degrees, 46.0071 minutes W -> -94.766785 degrees

  - About 49 km apart



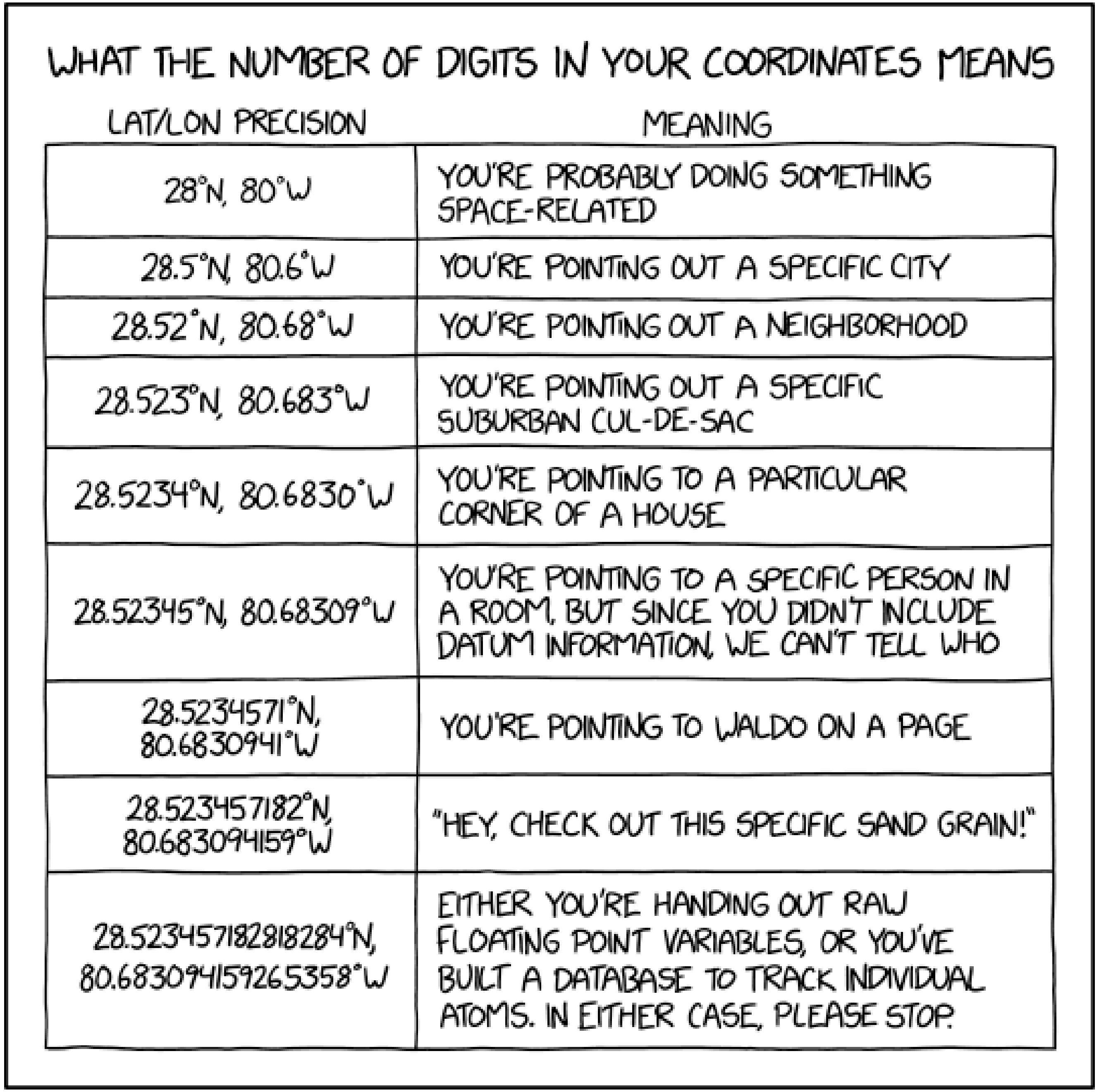
Other GPS “sentence” parameters

- Usually connected over a serial connection and send “human-readable” NMEA messages

```
$GPGGA,210230,3855.4487,N,09446.0071,W,1,07,1.1,
370.5,M,-29.5,M,,*7A
```

- Number of Satellites seen (red)
- Altitude in meters (blue)
  - More satellites can give you true 3D positioning

Break + xkcd


WHAT THE NUMBER OF DIGITS IN YOUR COORDINATES MEANS

LAT/LON PRECISION	MEANING
28°N, 80°W	YOU'RE PROBABLY DOING SOMETHING SPACE-RELATED
28.5°N, 80.6°W	YOU'RE POINTING OUT A SPECIFIC CITY
28.52°N, 80.68°W	YOU'RE POINTING OUT A NEIGHBORHOOD
28.523°N, 80.683°W	YOU'RE POINTING OUT A SPECIFIC SUBURBAN CUL-DE-SAC
28.5234°N, 80.6830°W	YOU'RE POINTING TO A PARTICULAR CORNER OF A HOUSE
28.52345°N, 80.68309°W	YOU'RE POINTING TO A SPECIFIC PERSON IN A ROOM, BUT SINCE YOU DIDN'T INCLUDE DATUM INFORMATION, WE CAN'T TELL WHO
28.5234571°N, 80.6830941°W	YOU'RE POINTING TO WALDO ON A PAGE
28.523457182°N, 80.683094159°W	"HEY, CHECK OUT THIS SPECIFIC SAND GRAIN!"
28.523457182818284°N, 80.683094159265358°W	EITHER YOU'RE HANDING OUT RAW FLOATING POINT VARIABLES, OR YOU'VE BUILT A DATABASE TO TRACK INDIVIDUAL ATOMS. IN EITHER CASE, PLEASE STOP.

https://xkcd.com/2170/

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- 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 object **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

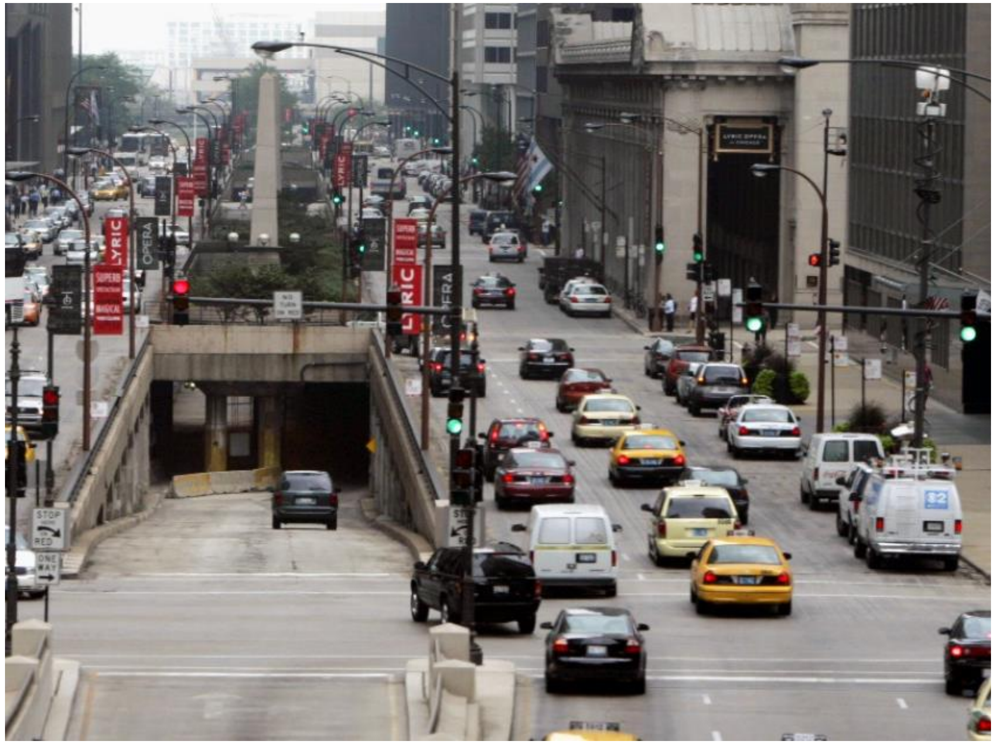
- “I’m here to pick up fish”

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

GPS version of barrier problem: overlapping roads

- GPS can’t always tell which road you’re on if multiple overlap
  - And you might not get GPS at all in a tunnel

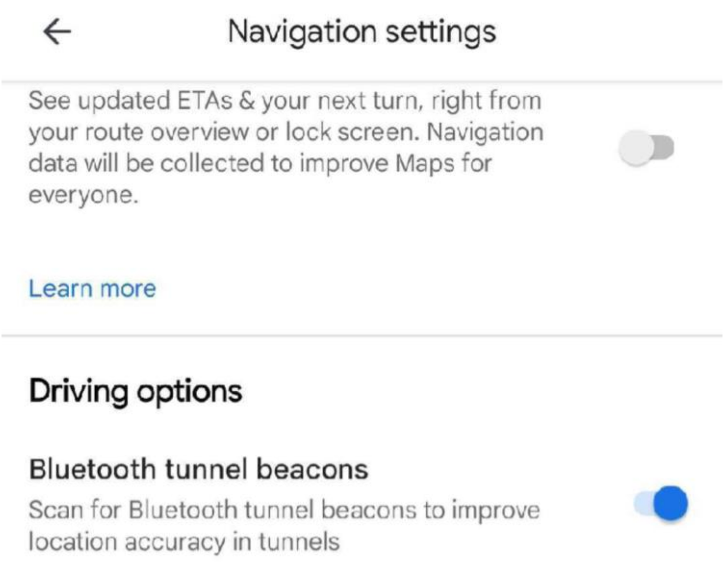
- Chicago example: Wacker Drive
  - Upper for local traffic
  - Lower for express route



GPS barrier solution

- Add BLE beacons
  - Short range such that they can only be detected if you're actually on the road near them

- Navigation apps can use BLE beacons to determine your real location
  - Deployed in Chicago right now!
  - Google Maps added the feature in early 2024
    - It was off on my phone, go into Settings and then "Navigation Settings" to enable it.



https://chicago.curbed.com/2018/9/7/17786634/waze-beacons-wacker-drive-chicago-signal
https://www.theverge.com/2024/1/16/24039896/google-maps-android-tunnels-bluetooth-beacons

Accuracy notation

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

- 90^{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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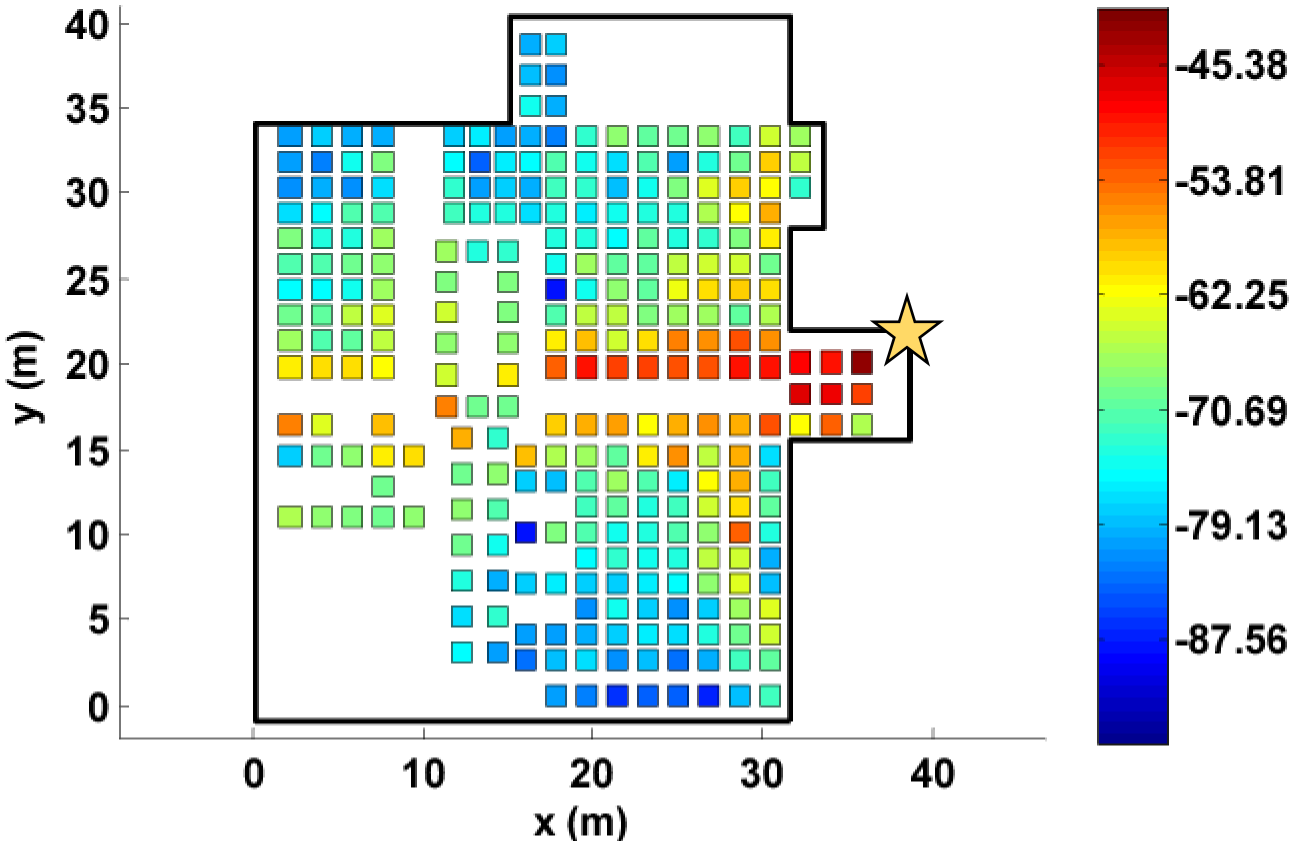
Mapping existing infrastructure

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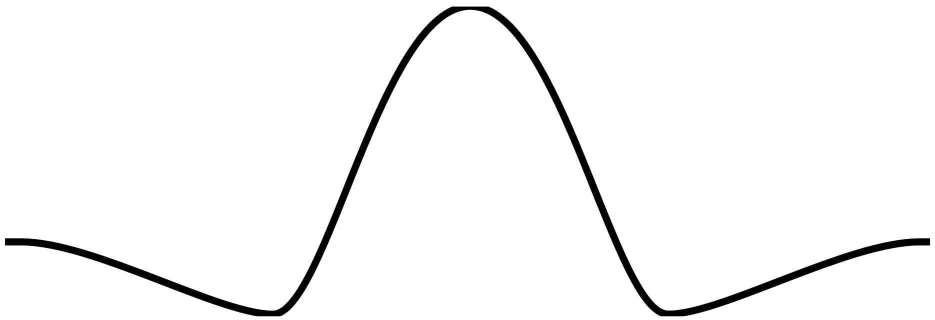
  - **Ultra-wideband**
  - Other techniques

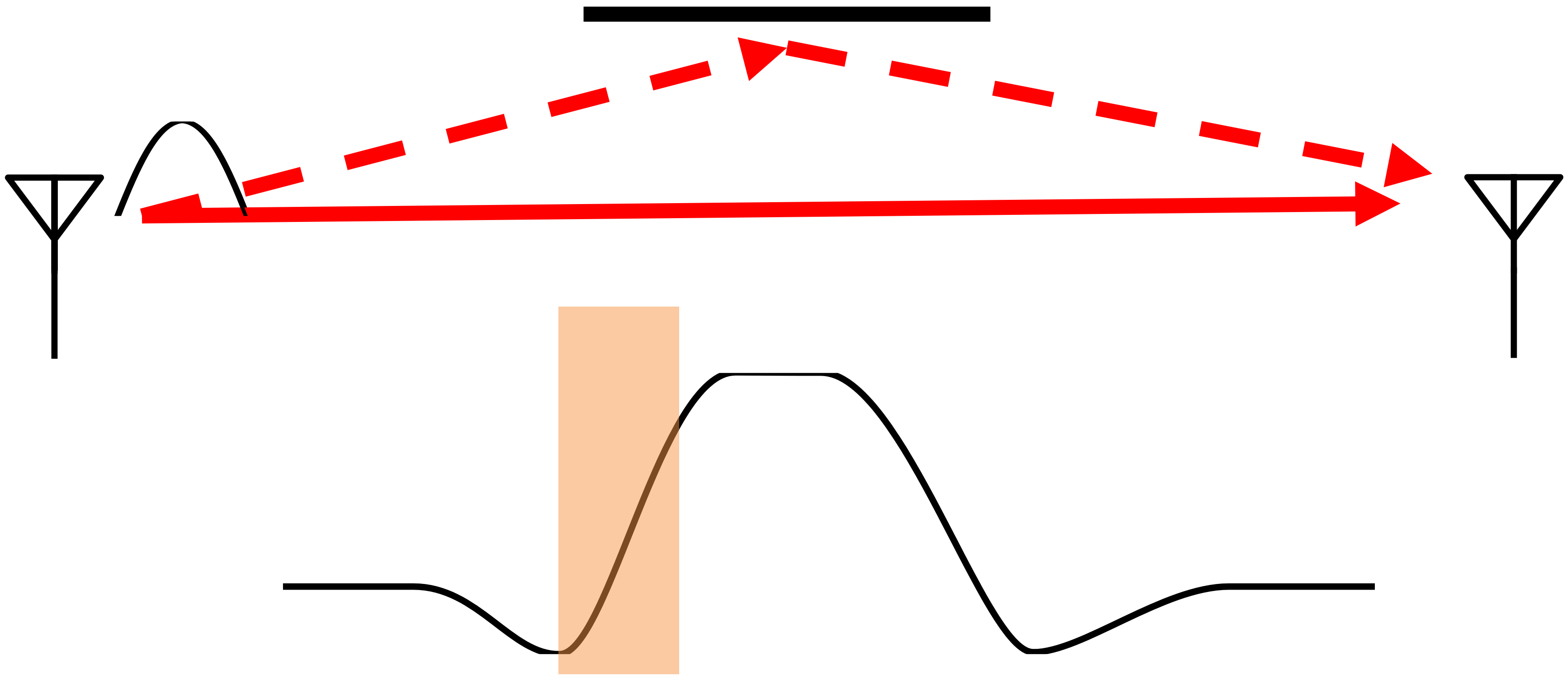
Improving accuracy

- 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”



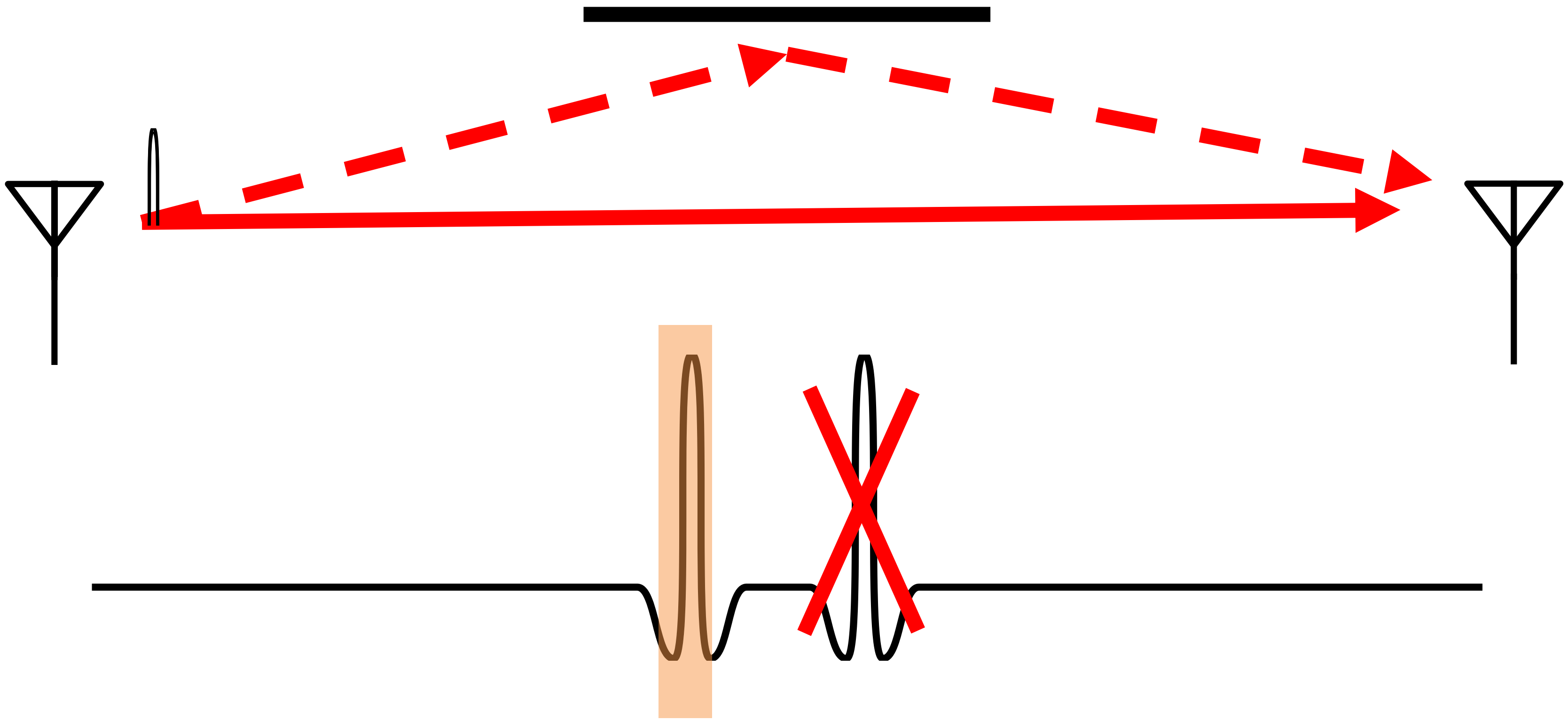
Multipath problem

- 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



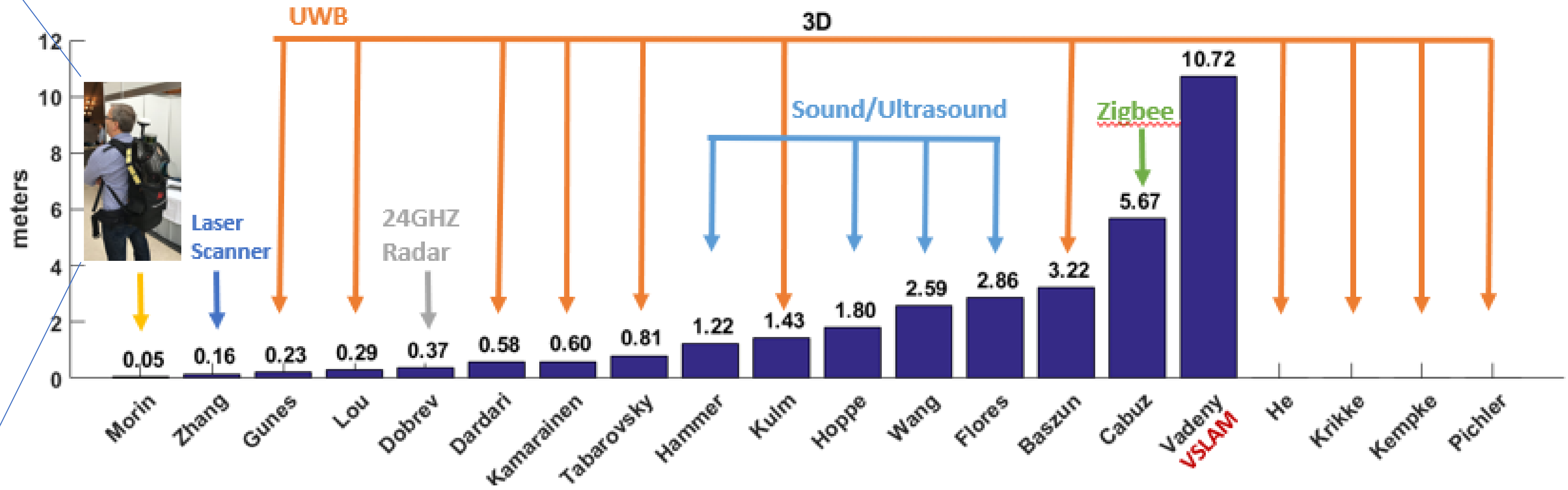
Ultra-wideband localization system

- Narrow ultra-wideband pulses makes arrival timing work

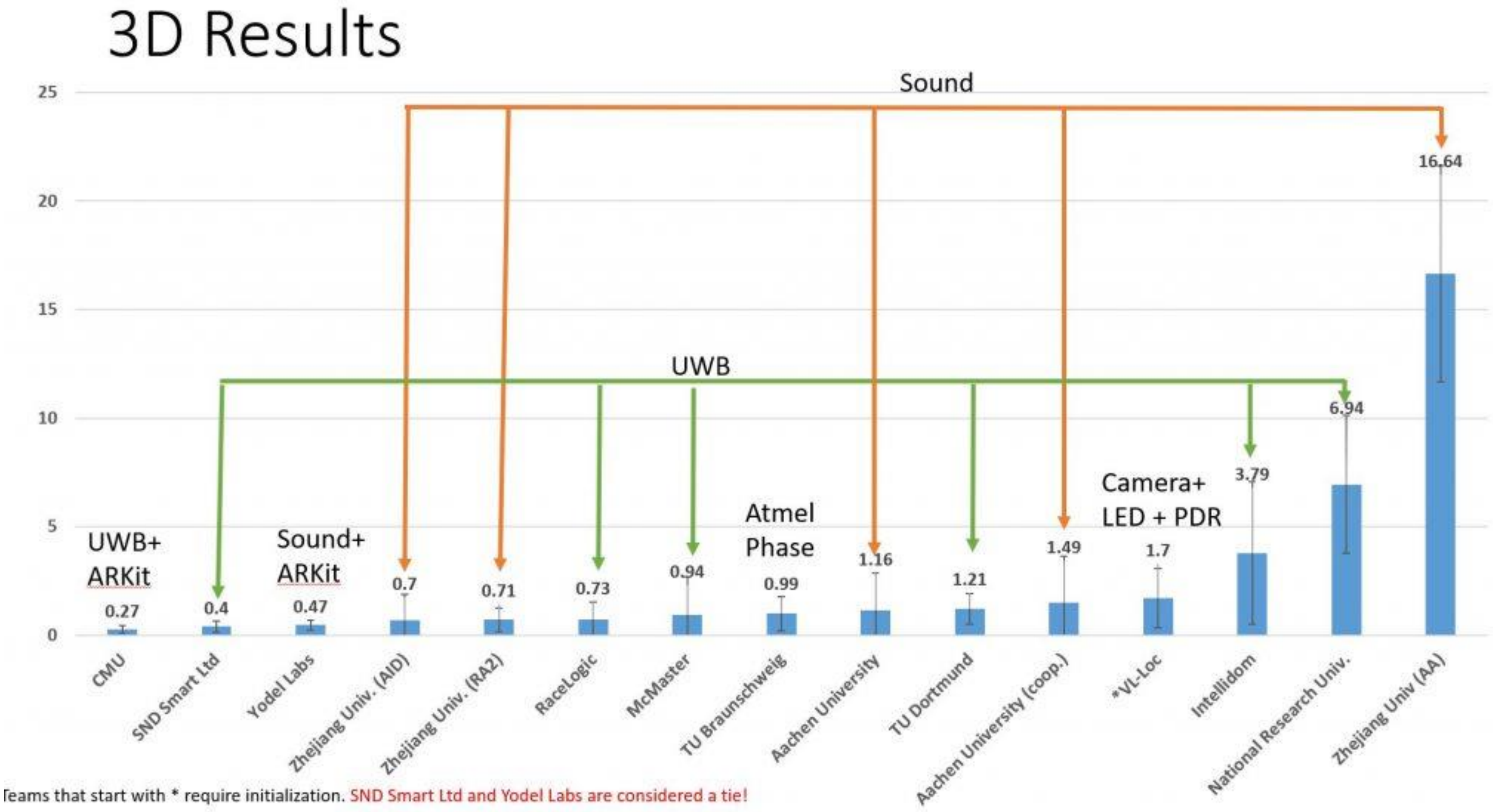
- The rest is a copy of well-known techniques
  - Deploy anchors in the environment with known positions
  - Measure distance between anchors and device
    - Time of Flight (if anchors transmit)
    - Time Difference of Arrival (if devices transmit)
  - Trilateration to find position

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

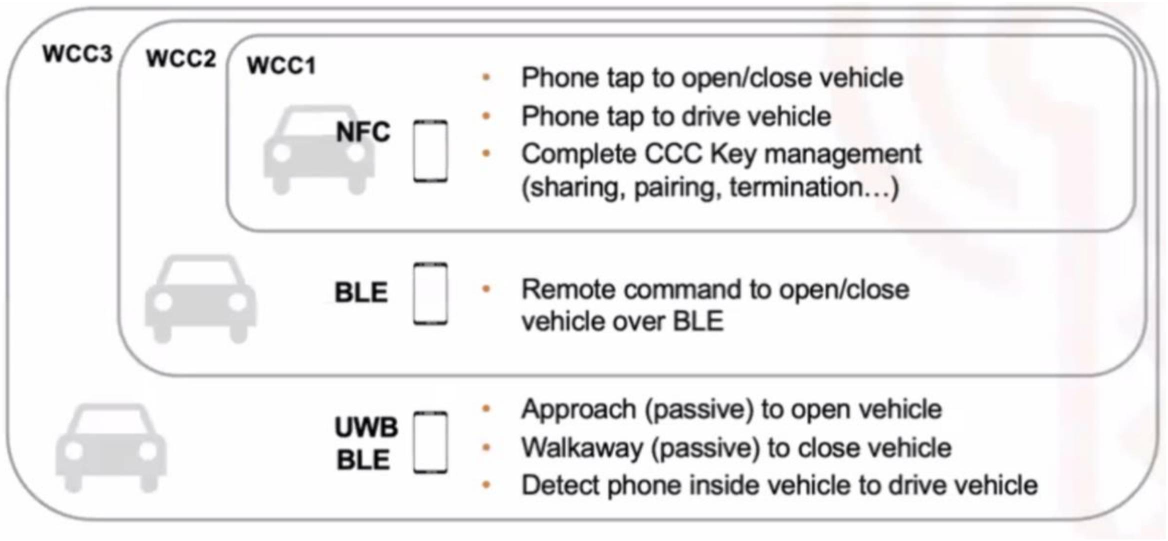
- Combine with backscatter approaches
  - Result is very slow (minutes to locate device) but very low power (<1μW)
  - Most inventory doesn’t move!

Bringing UWB to the real world

- Ultra-wideband radios were previously specialized
  - Needed to build special hardware to use them

- Modern smartphones are now including UWB radios!!!
  - Apple, Google, and Samsung

- Opens a big area of development
- Use cases are still a little unclear
  - Smartphone as a car key is one



https://www.theverge.com/23970875/digital-car-key-iphone-unlock-start-ccc-standard

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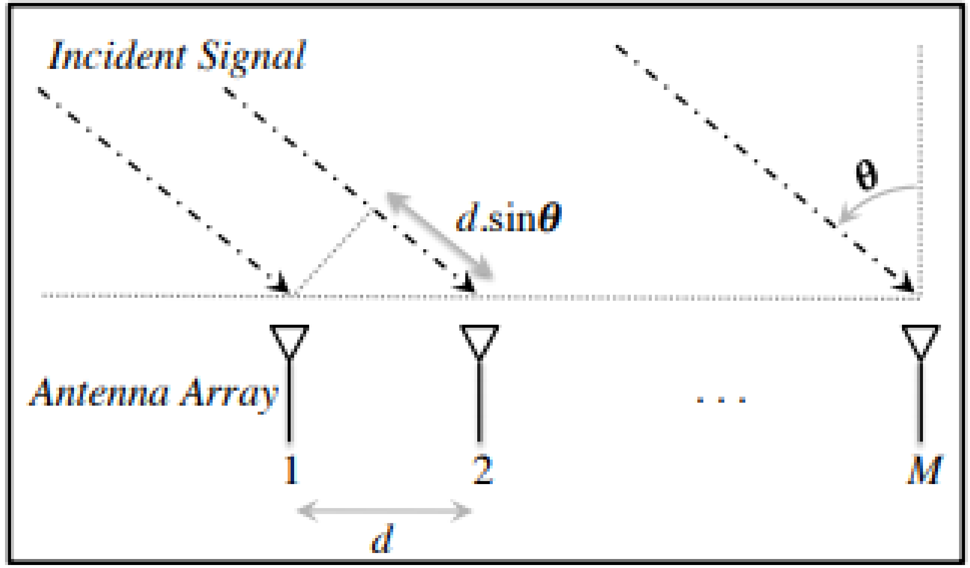
  - **Other techniques**

Angle of arrival (AoA)

- Trilateration doesn't only require distances, angles work
  - Although you still need at least one distance to form triangle

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

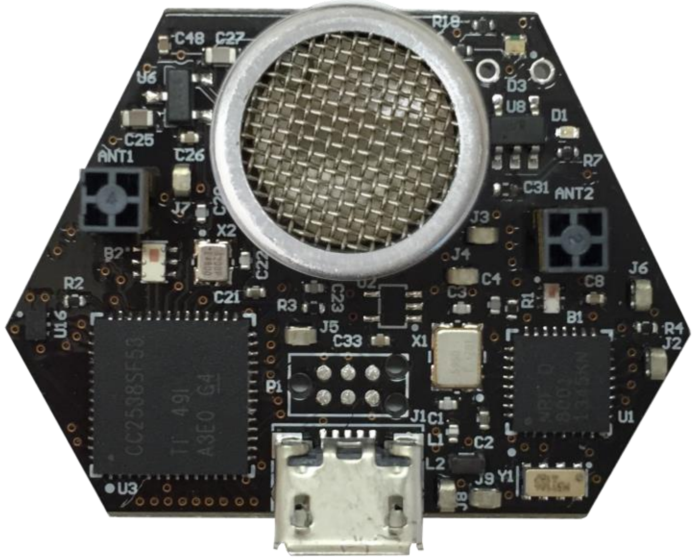
- BLE 5.1 includes AoA localization



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

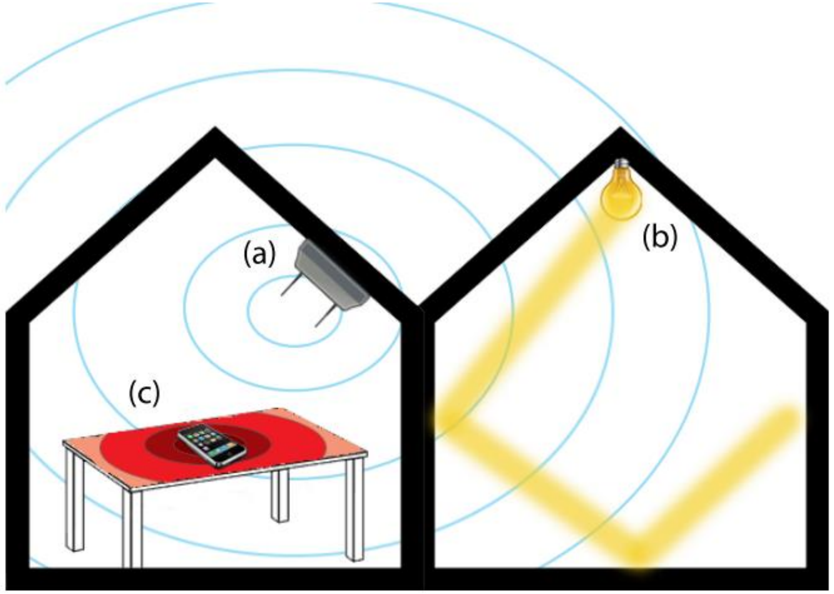
ARKit (and other AR techniques)

- 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

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