

Lecture 16

Localization

CS433 – Wireless Protocols for IoT

Branden Ghen a – Spring 2026

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

Administrivia

- Last assignments
 - Hw: Cellular – due Thursday (05/28)
 - Lab: LoRa – due next week Thursday (06/04)
 - Final Design Project – due exam week Tuesday (06/09)
- Last quiz next week Tuesday
 - Topics: Cellular, LPWANs, Localization, Satellite Communications

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?

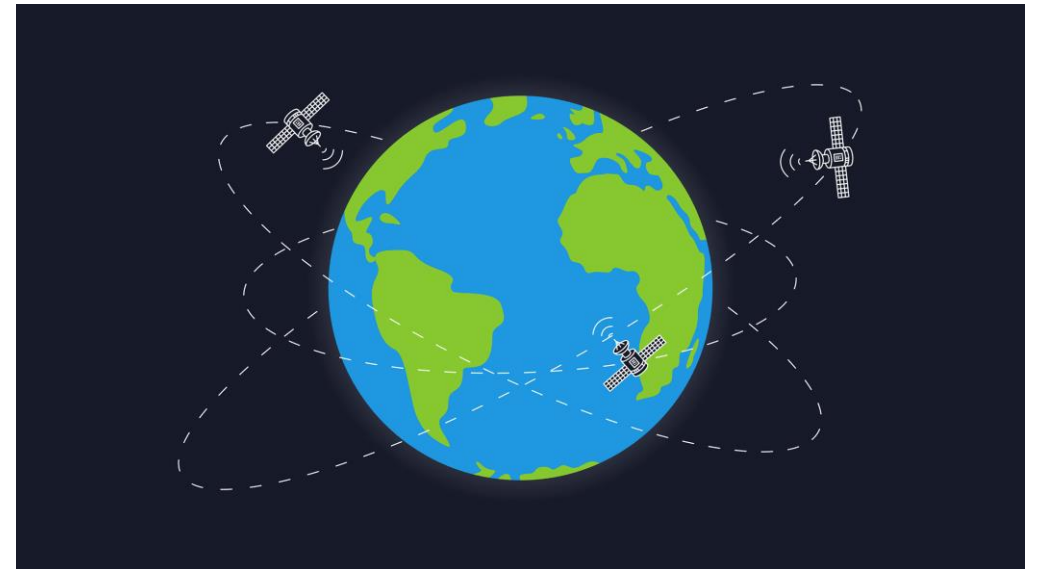
- My opinion: location information is **critical** to the IoT
 - Interpreting sensed data relies on real-world location
 - Indoor: where is the motion sensed or temperature measured
 - City-scale: how do measurements change over geographical space
- IoT applications use location context
 - “When I get home do X”
 - “Turn on all the lights in room X”

Outline

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

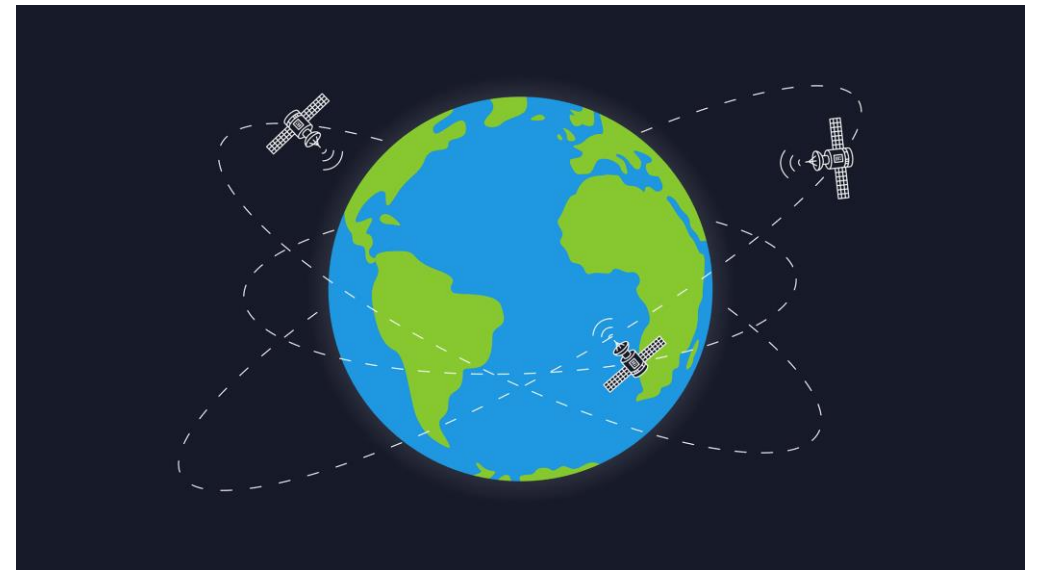
Background knowledge?

- **How does GPS work anyways?**

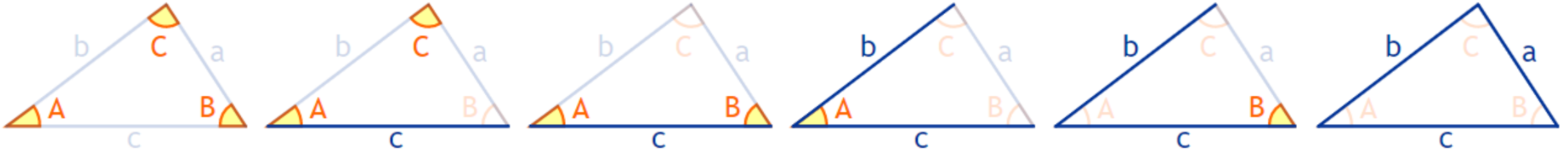


Background knowledge?

- **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



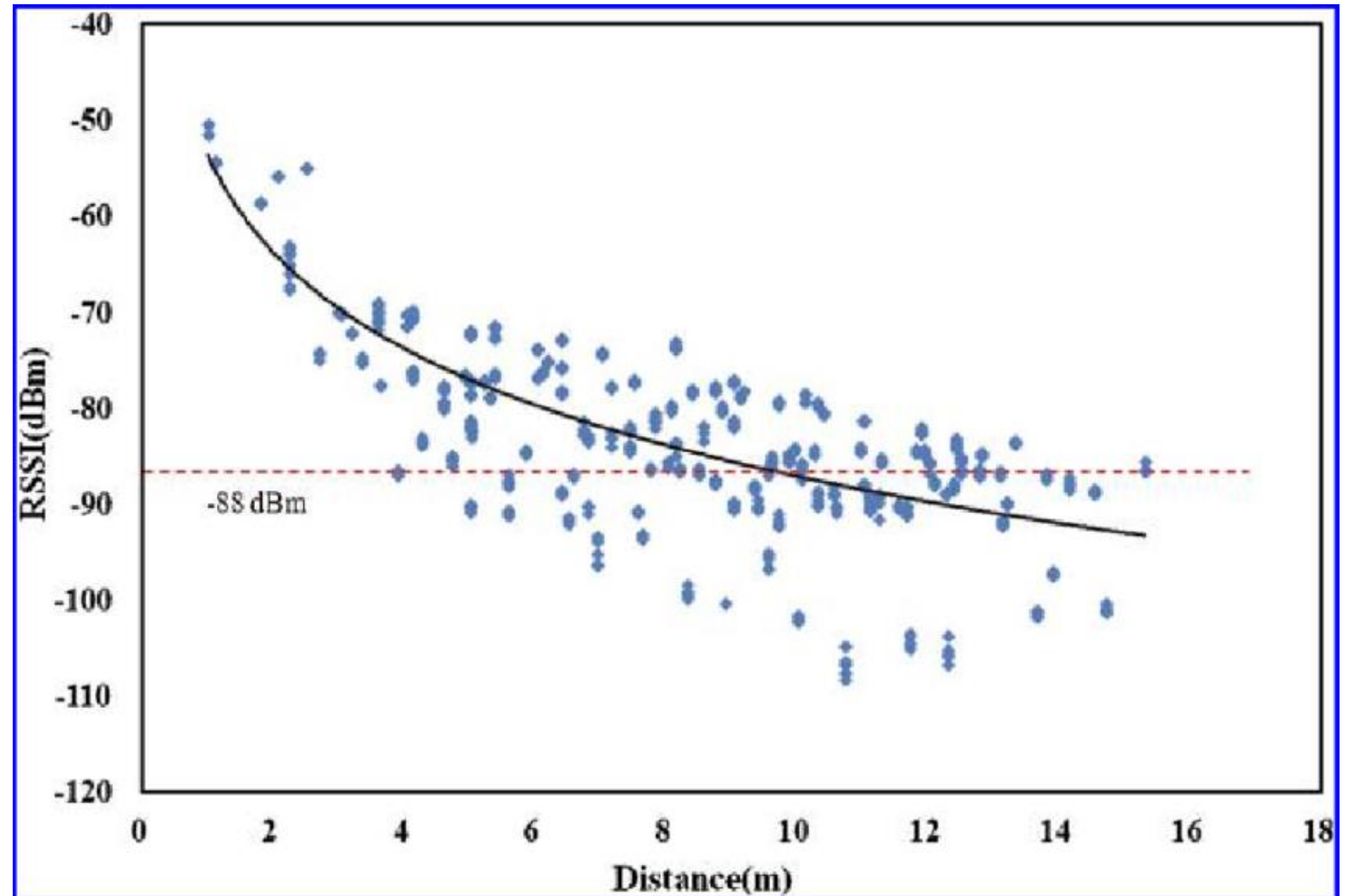
- Most common and accurate localization approach

Determining distance

- Making trilateration work requires distance measurements
- Techniques
 - RSSI
 - Time of Flight
 - Time Difference 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)
- One side transmits and the other listens
 - Device to tower, for instance
- Requires time synchronization between infrastructure and device
 - Synchronization must be **very** good: $1\text{ }\mu\text{s} = 300\text{ meters}$, $1\text{ ns} = 0.3\text{ meters}$

Time difference of arrival (TDoA)

- Device transmits and infrastructure receives transmission
 - Multiple infrastructure nodes receive at different times based on distance
 - Can go other direction too with some complications
- 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

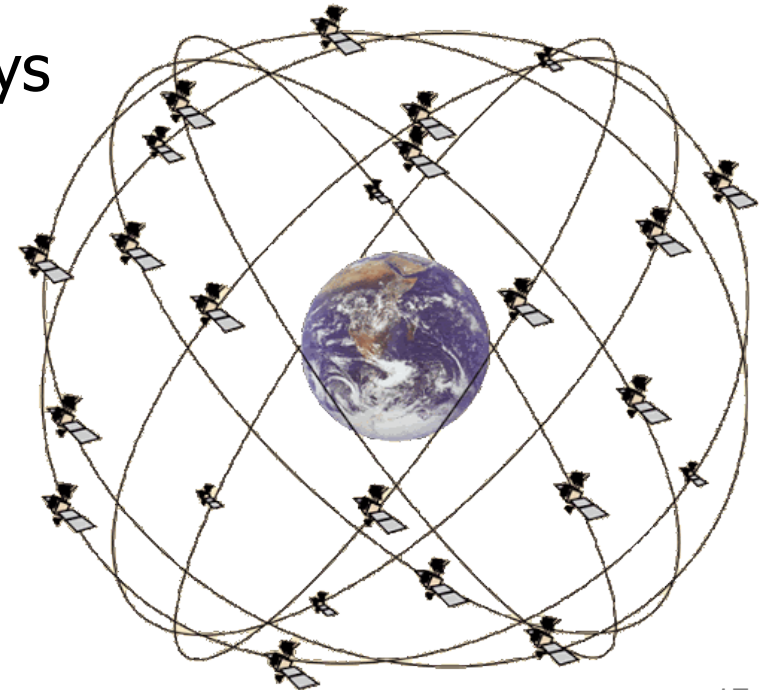
- No distance measurement will be perfect
- Which means trilateration will not be perfect either
 - Need to solve equations in a fuzzy manner looking for least error

Outline

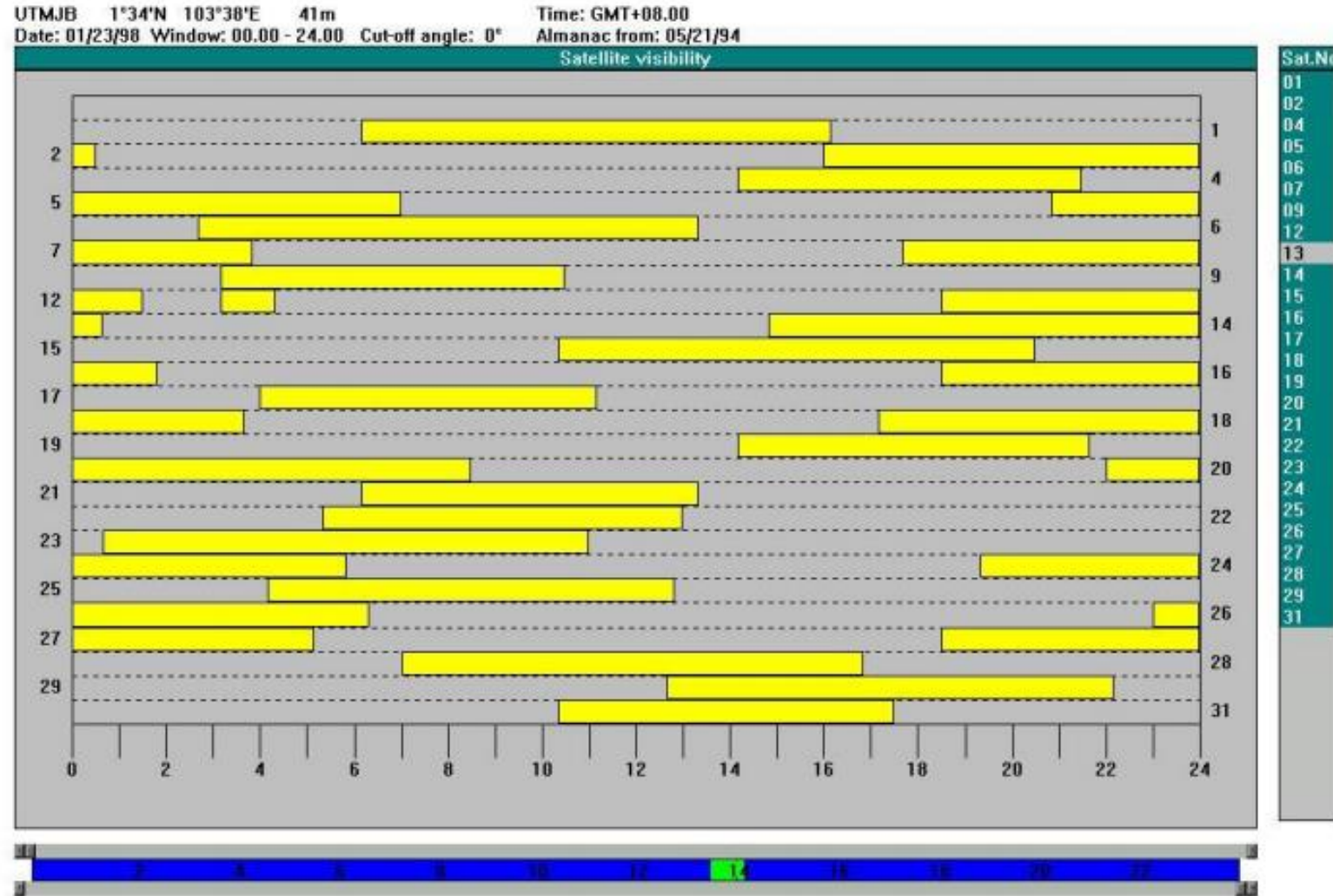
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GPS overview

- 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 April 2026
 - [Most recent launch](#) April 2026
- Comparisons
 - LEO 200-2000 km, ISS at 340 km
 - GEO 35,000 km

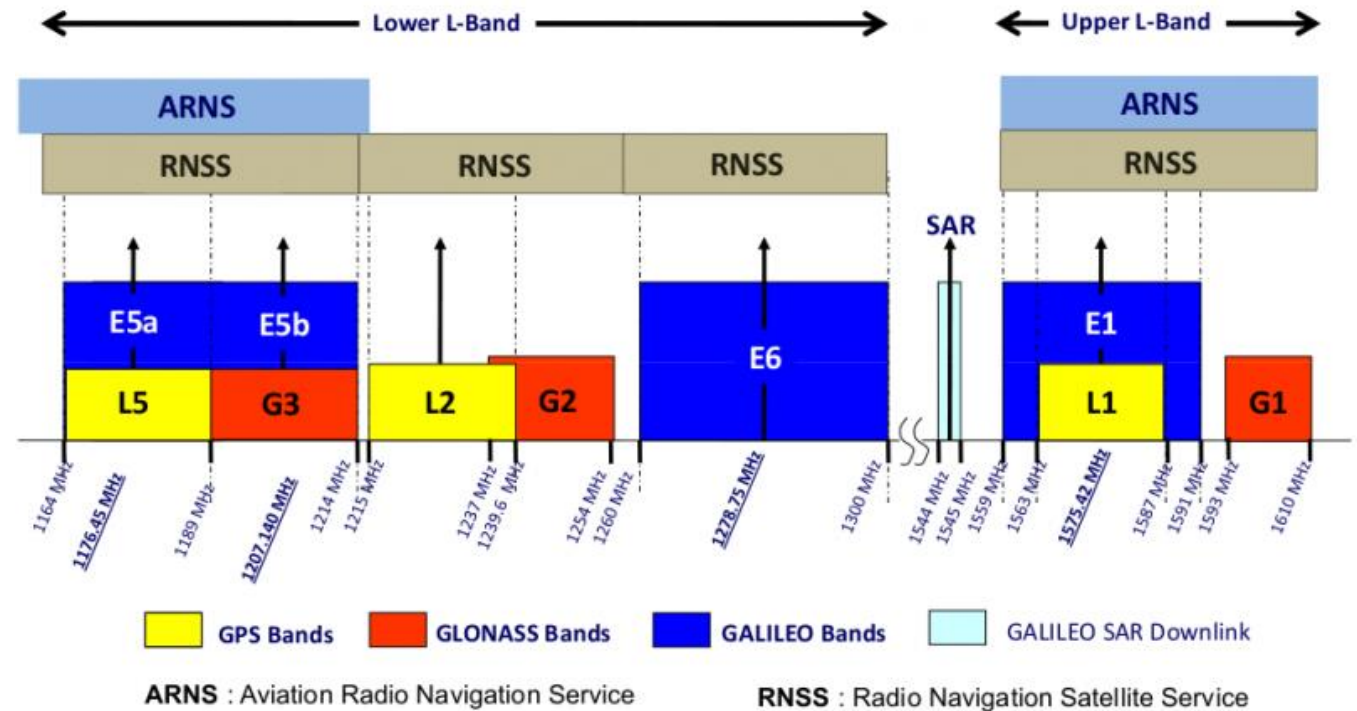


Satellite visibility overhead



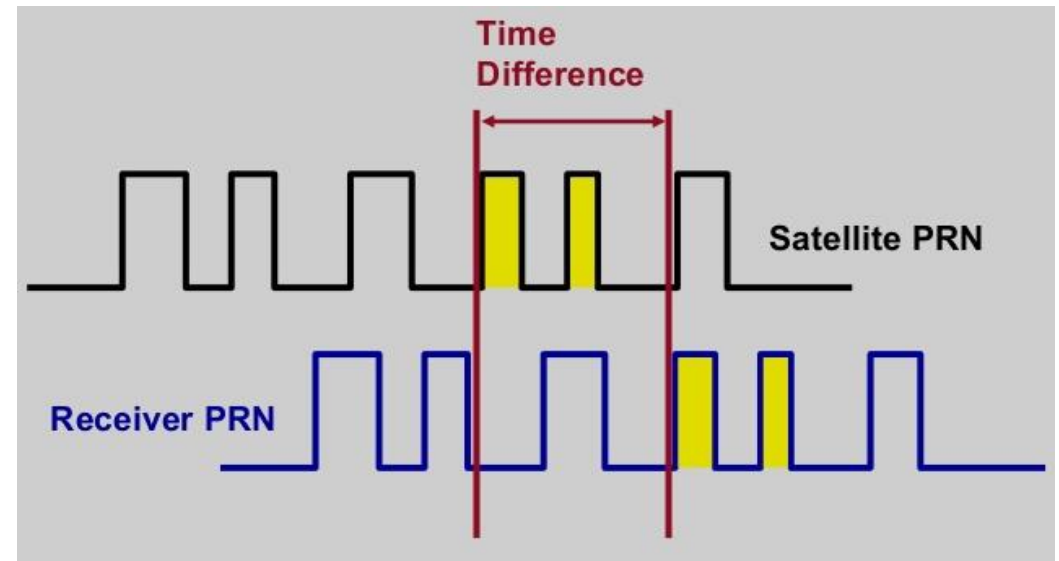
GPS PHY

- 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

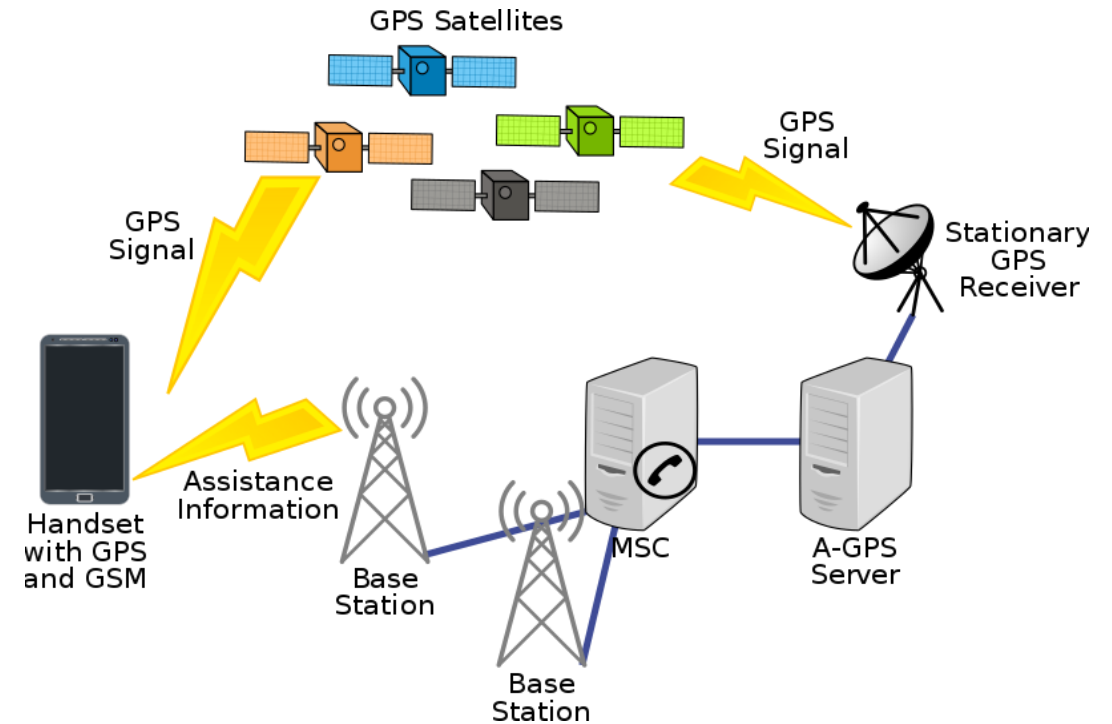
- Receiver needs to know additional information
 - Current time
 - Position of each satellite
- GPS transmission has this data layered on top (at 50 bps)
 - Listening for (up to) 30 seconds gets time and this one satellite's position
 - Known as **ephemeris**
 - Valid for up to 4 hours
 - Listening for 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



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,21.0230,38.554487,N,094.460071,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

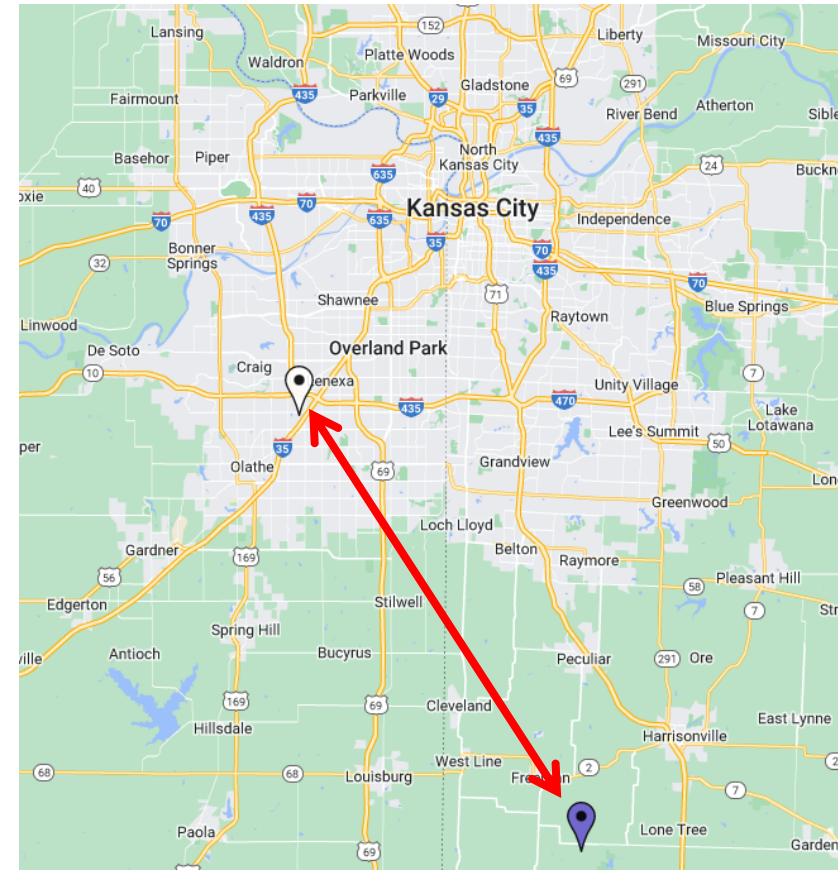
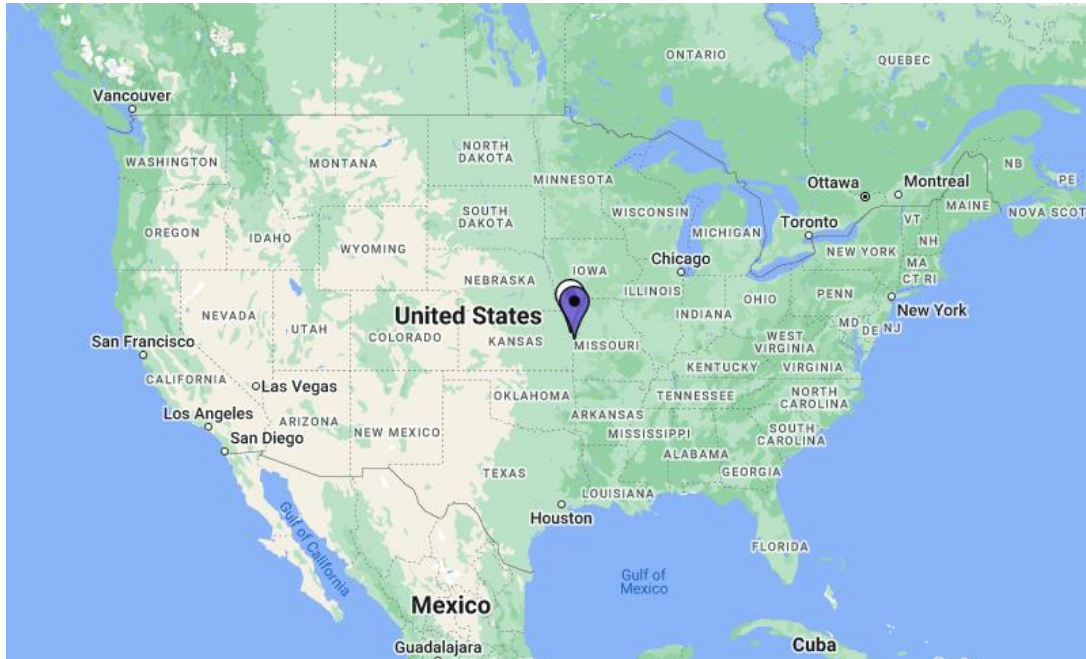
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```
$GPGGA,210230,3855.4487,N,09446.0071,W,1,07,1.1,  
370.5,M,-29.5,M,,*7A
```

- 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,21.0230,38.554487,N,094.460071,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

Original GPS had a built-in accuracy limitation

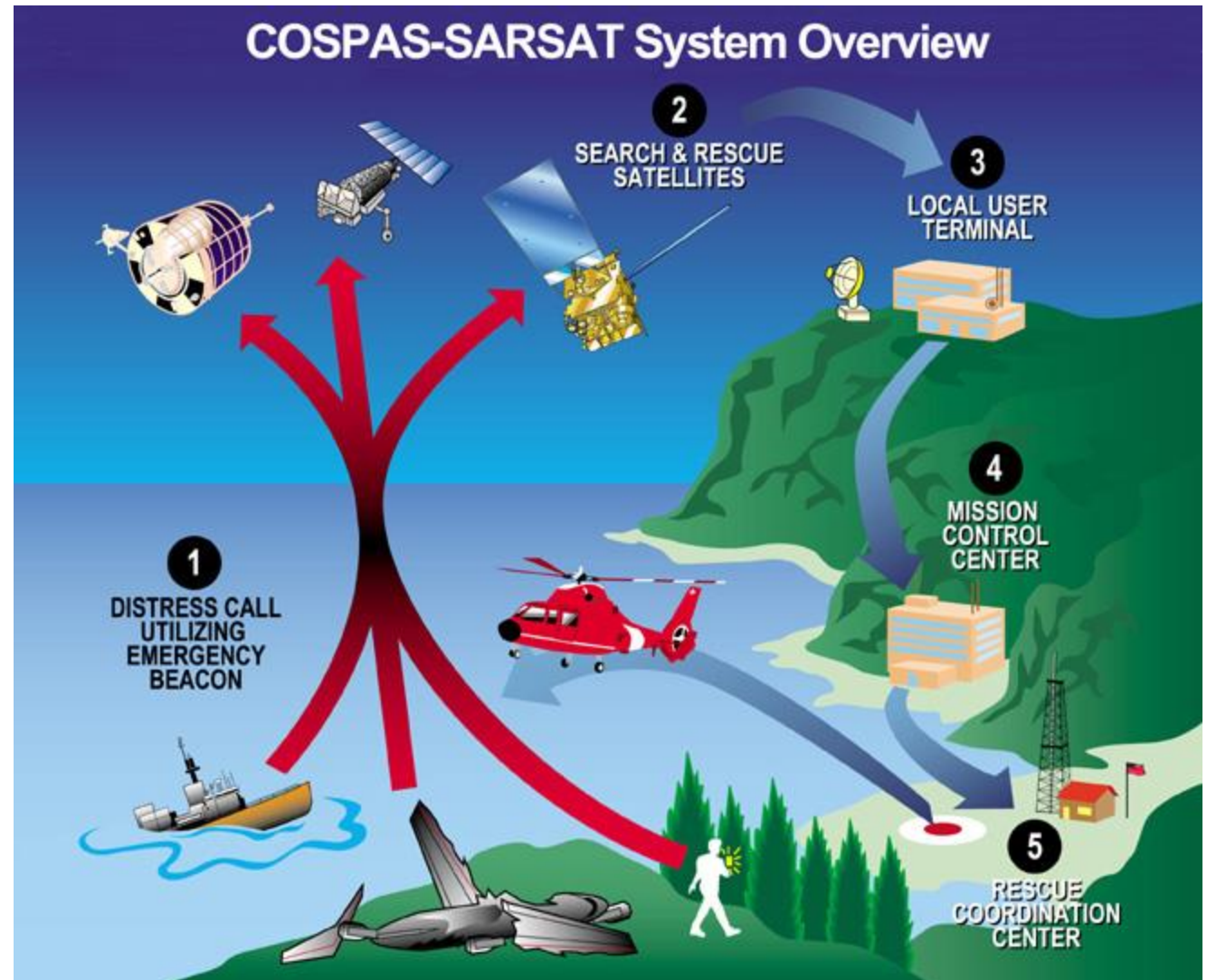
- Selective Availability
 - Pseudorandom adjustment to the signals to reduce accuracy
 - Could be recovered if you know the specific pseudorandom key
- Public use (no key)
 - 50 m accuracy horizontally
 - 100 m accuracy vertically
- Original GPS was intended for military only
 - With limited GPS for 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
- Some systems have additional features
 - Search and rescue support
 - Messaging
 - Anti-spoofing technology

Search and Rescue Functionality

- 406 MHz band reserved for rescue beacons
 - 100 kHz bandwidth
- Galileo, GLONASS, GPS, and BeiDou support
 - Plus some other satellites
- Galileo can also send custom respond messages
 - "Return Link Service"



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.

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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

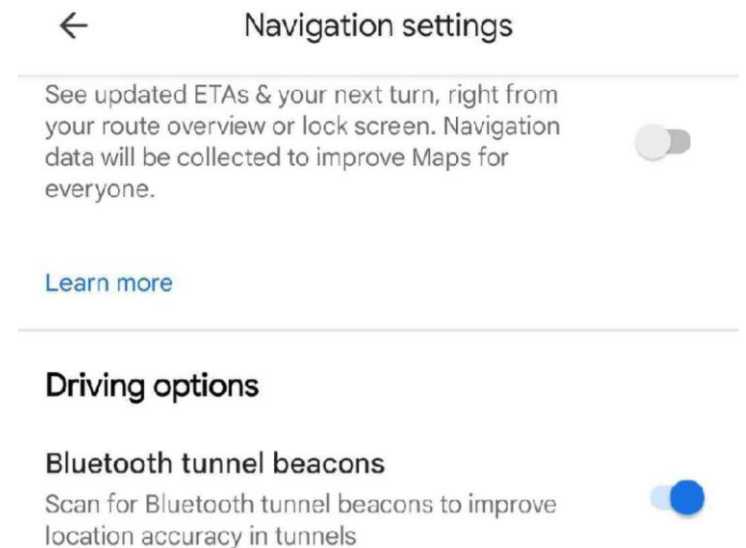
GPS version of barrier problem: overlapping roads

- 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
 - Google Maps added the feature in early 2024
 - It was off on my phone, go into Settings and then "Navigation Settings" to enable it.
 - Was deployed in Chicago
 - Seems that the batteries have died...



<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?*
- 90th percentile error is often more important for real-world use
- My least favorite aspect of localization
 - Be wise to these tricks

Outline

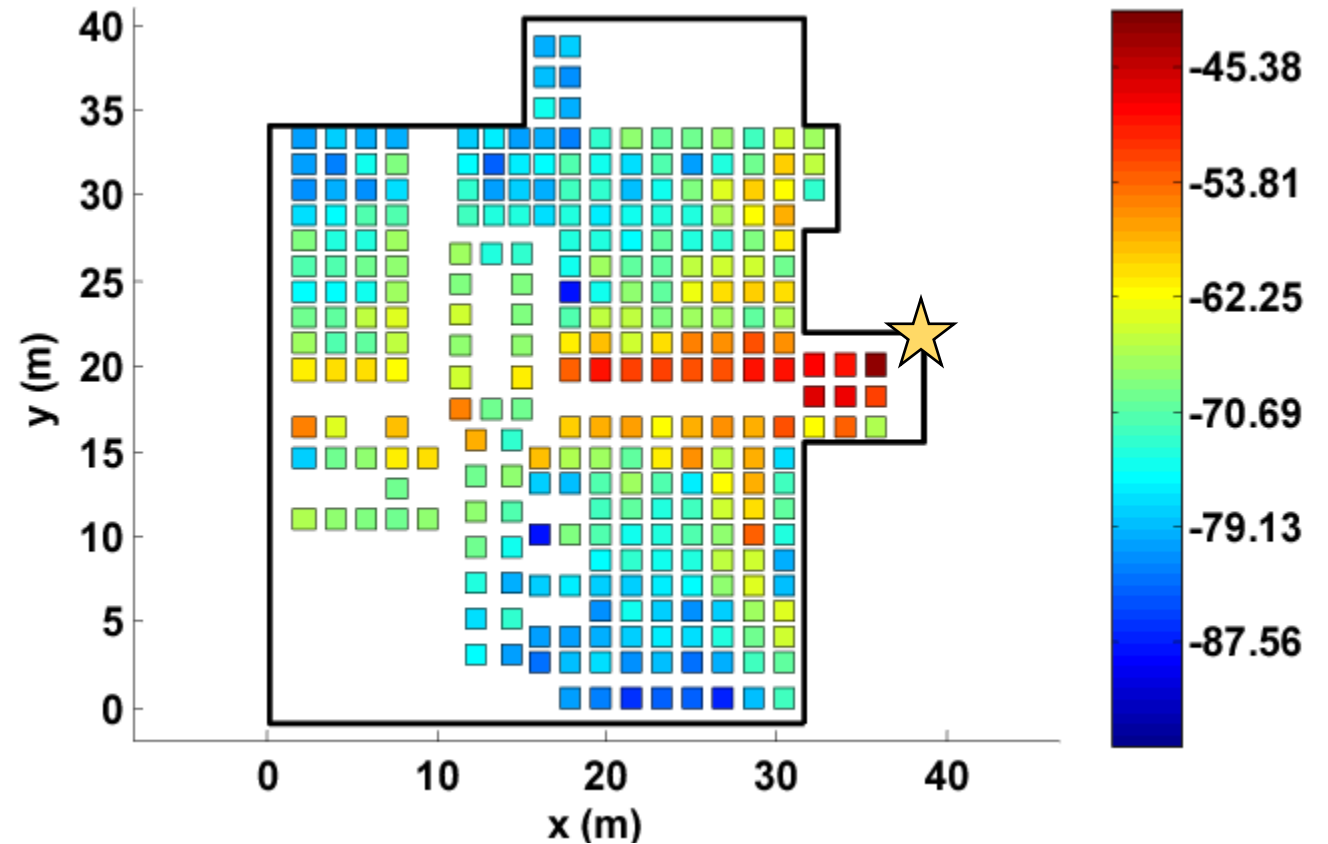
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Mapping existing infrastructure

- 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

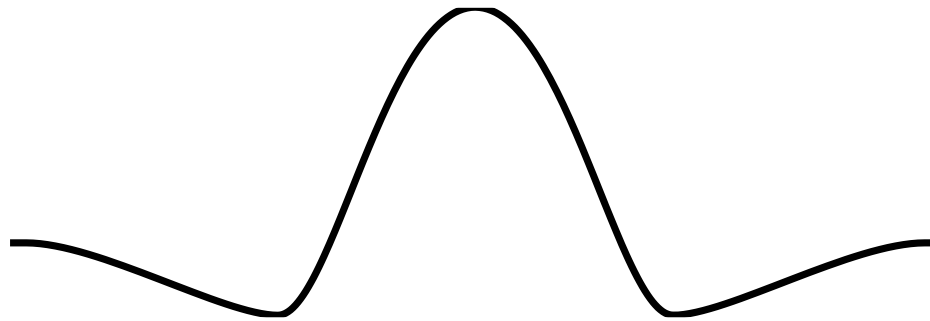
- WiFi is only one example of a signal you could fingerprint.
What else could you use?

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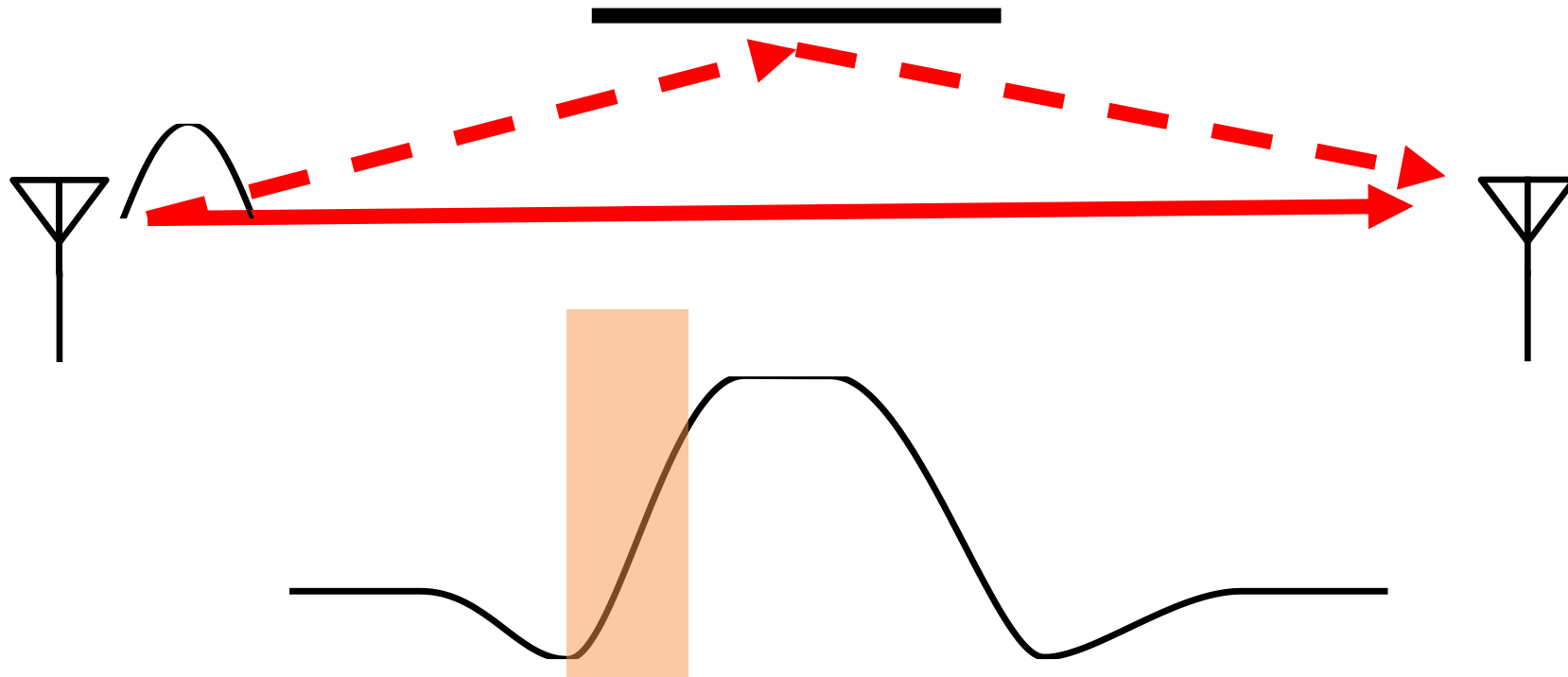
Improving accuracy

- 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"



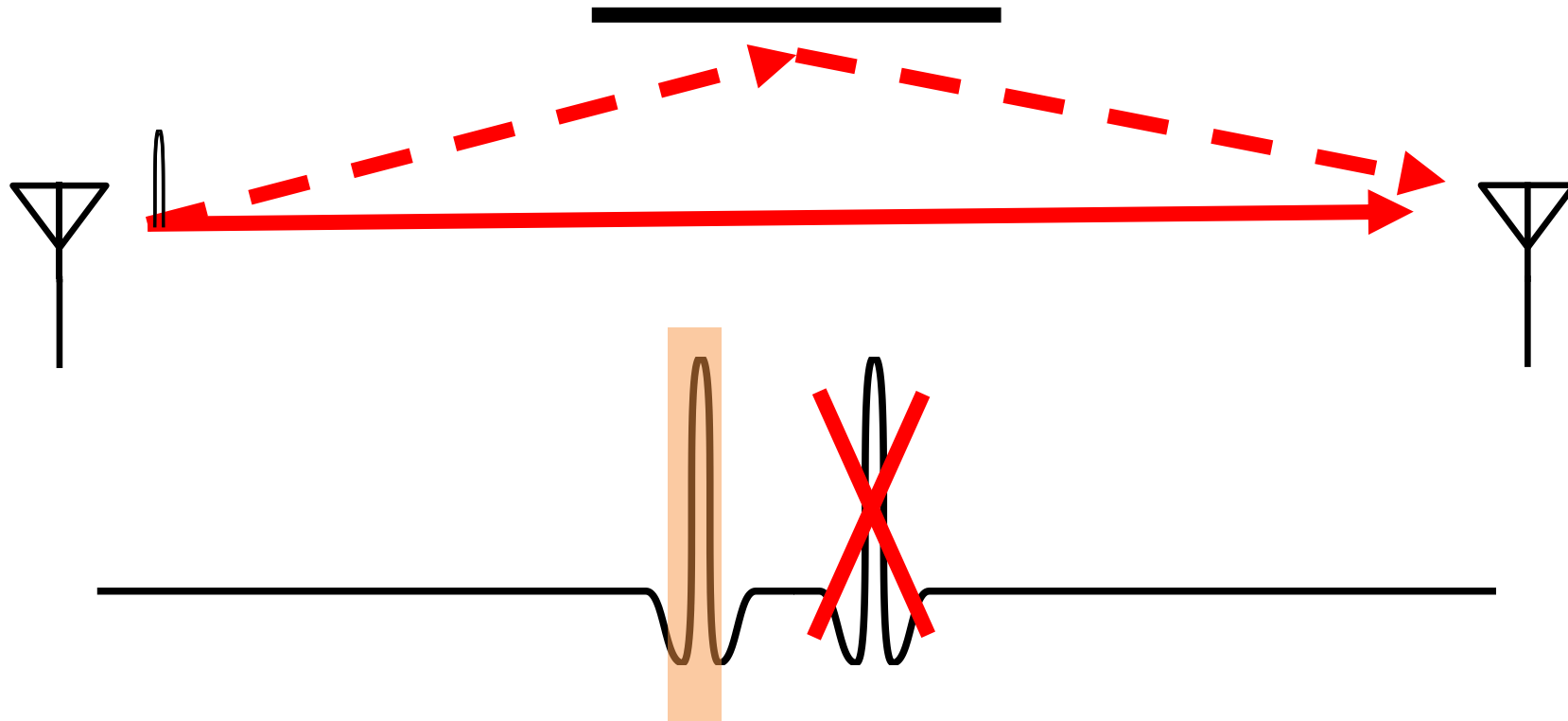
Multipath problem

- 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

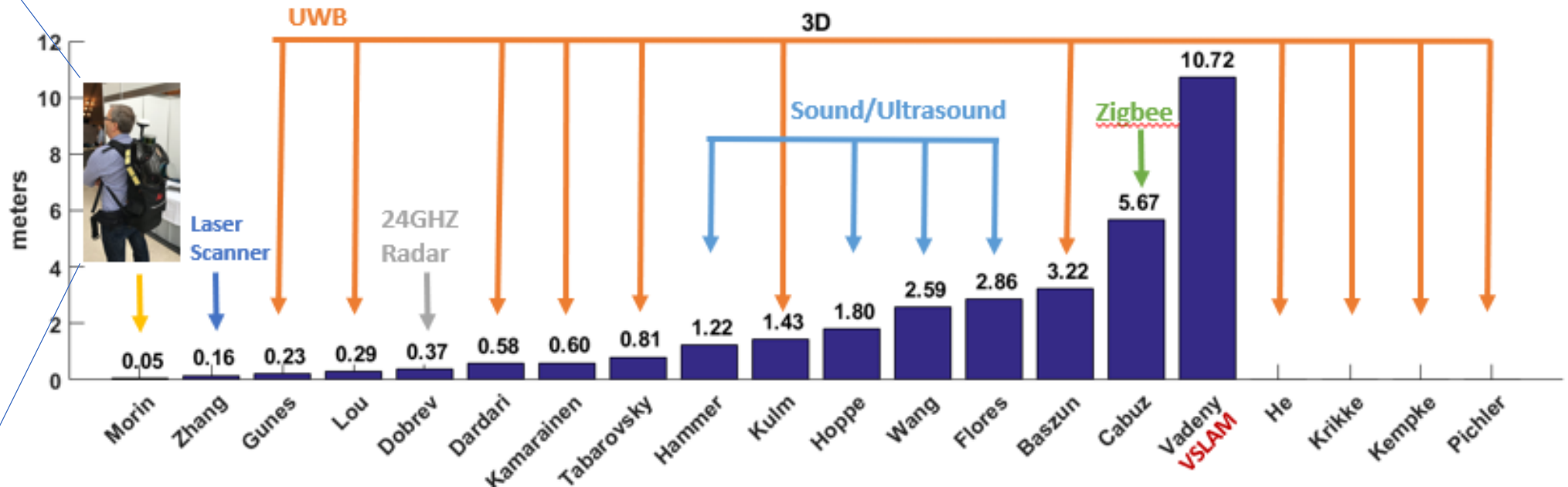


Ultra-wideband localization system

- 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

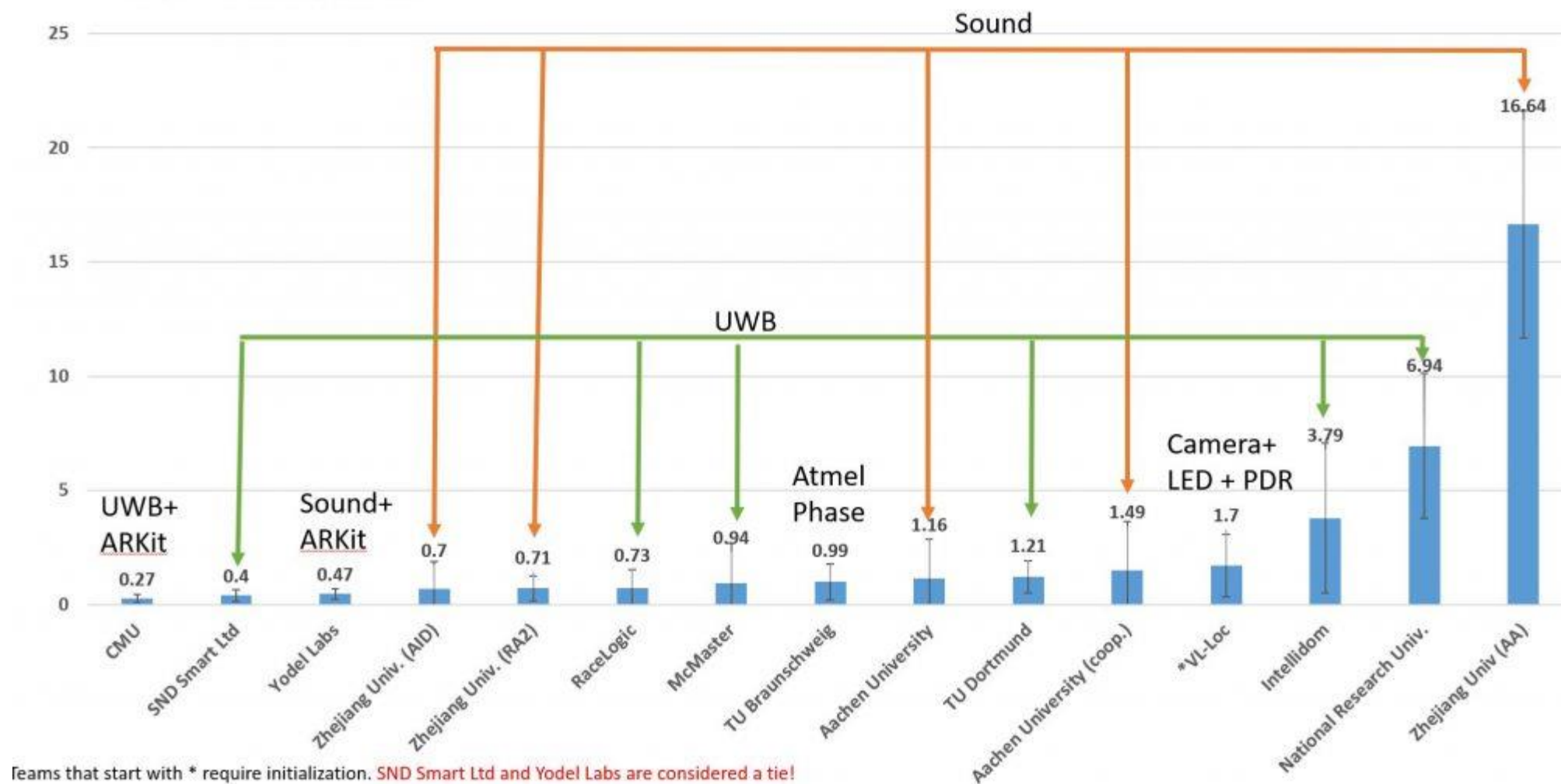
Localization state-of-the-art

- 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)

3D Results

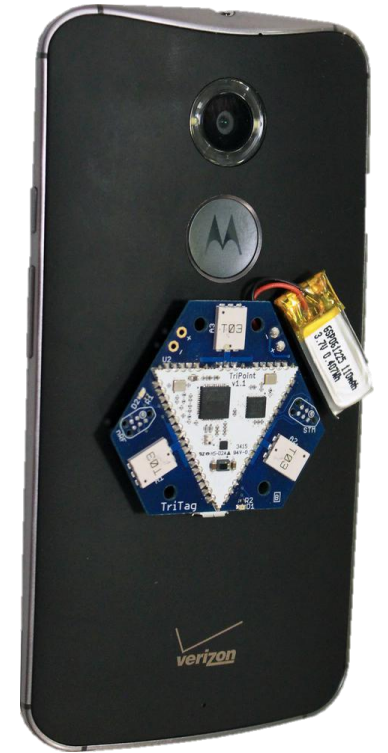


Improvements to ultra-wideband

- 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 ($<1\mu\text{W}$)
 - Most inventory doesn't move!

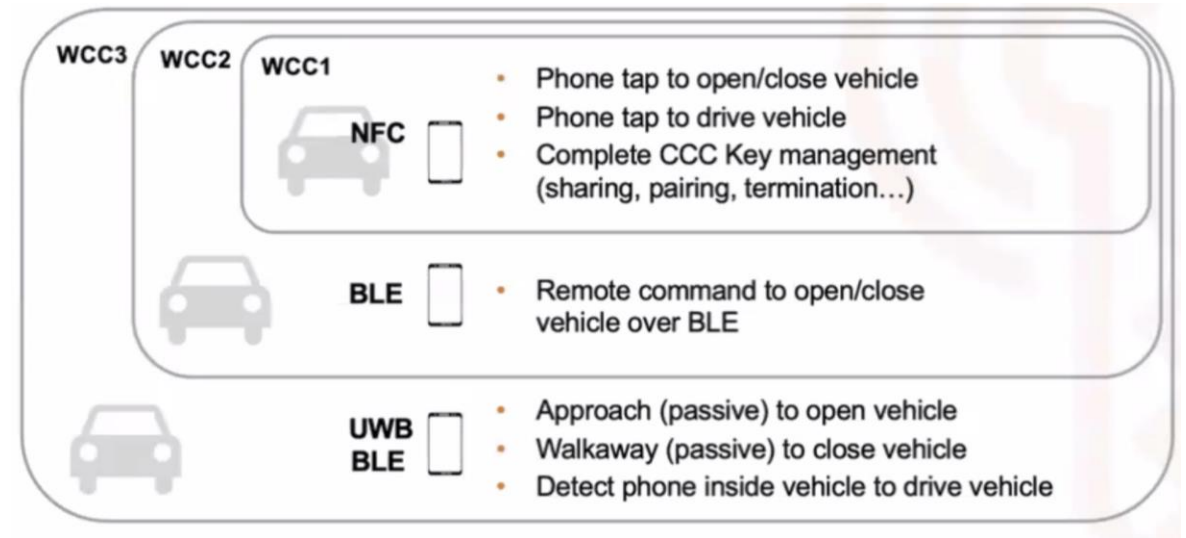
Bringing UWB to the real world

- Ultra-wideband radios were previously specialized
 - Needed to build special hardware to use them
- Modern smartphones are now including UWB radios!!!
 - Apple, Google, Samsung, and others
 - Opens a big area of development
- Ranging capabilities and possibly communication



UWB applications

- Asset tracking
 - “Find My” and new smart tags
- Digital car key
 - Apps already exist for this on Android and iOS
 - Typically communication over BLE plus ranging over UWB
 - Similarly home IoT locks and hotel keycards



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

UWB IoT capabilities

- Decawave was a company that made UWB radios
 - Decawave bought by Qorvo
- Develops UWB radio chips and modules
- UWB module: \$45 (at quantity one)

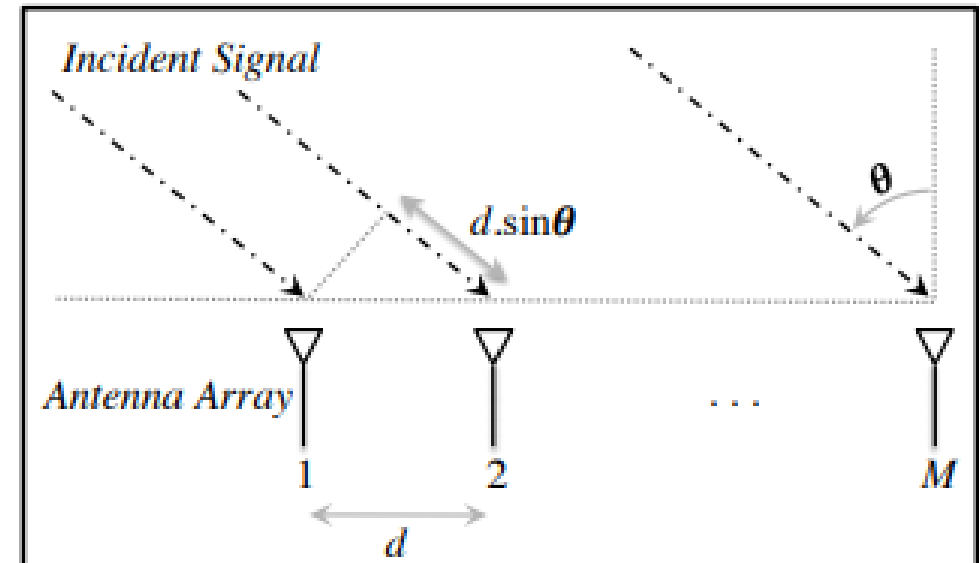


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Angle of arrival (AoA)

- 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



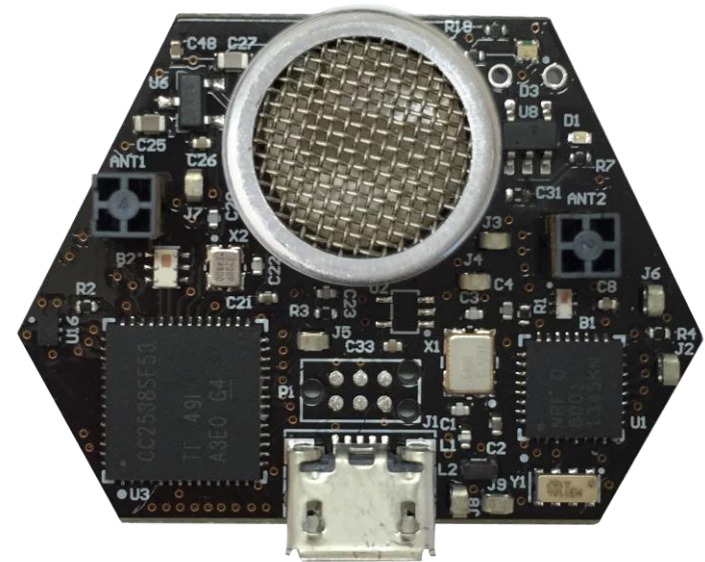
Ultrasound

- Advantages

- Solves the barrier problem
 - Human spaces already designed to contain sound
- Easier to get high-accuracy results
 - Sound is $\sim 1,000,000\times$ 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

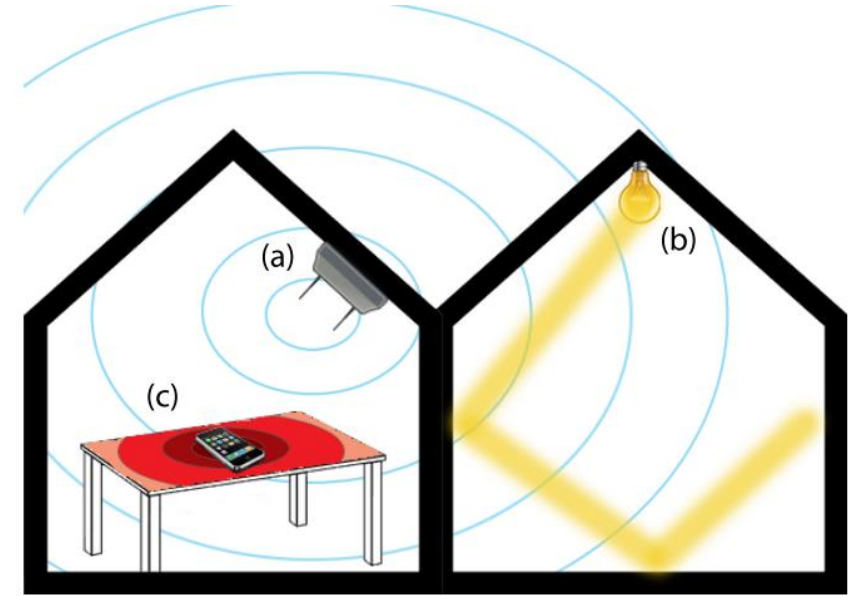
ARKit (and other AR techniques)

- 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



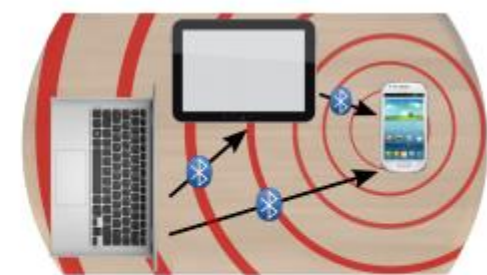
(a) Establishing a first-time Bluetooth connection



(b) Desktop detection for pre-connected devices



(c) Connecting with hidden table-level services



(d) Establishing a desktop area network

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