18-452/18-750
Wireless Networks and Applications
Lecture 23: Localization

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http://www.cs.cmu.edu/~prs/wirelessS24/

Announcements

- I added a slide with a sketch of the binary search algorithm for RFID tags to the lecture
- Homework 3 has been posted
  - » It uses gradescope for submission and grading
- Please sign up for P2 meetings next week
  - » See Piazza for URL

Outline

- Properties of localization procedures
- Approaches
  - » Proximity
  - » Trilateration and triangulation (GPS)
  - » Finger printing (RADAR)
  - » Hybrid systems

Properties of localization procedures

- Data types used for specifying locations
- Reference systems
- Processing: localized vs centralized
- Data quality
  - » Accuracy and precision
  - » Scale
- Deployment aspects
  - » Limitations
  - » Cost

➡ Very diverse systems – lots of research

Data types

- **Point locations in terms of coordinates:**
  - » ***physical*** **or** ***geometric locations***
  - » **GPS: latitude and longitude, height**
  - » **Cartesian coordinate system based on three orthogonal planes**
- **Extended region locations given by names:**
  - » ***symbolic locations***
  - » **CMU, Wean Hall, room 8202**

Location-awareness

- **Location model: data structure that organizes locations**
- **Location-based routing**
  - » **symbolic location model**
  - » **geometric location model**
  - » **hybrid location model**

Examples

- » **symbolic location model:** address hierarchy DH.Floor2.2105
- » **geometric location model:** GPS coordinate (12.3456°N, 123.456°E)
- » **hybrid location model:** combination of address and coordinate DH.Floor2.2105.Seat(0,4)

Quality of Position Information

Positioning accuracy:

largest distance between an estimated position and the true position

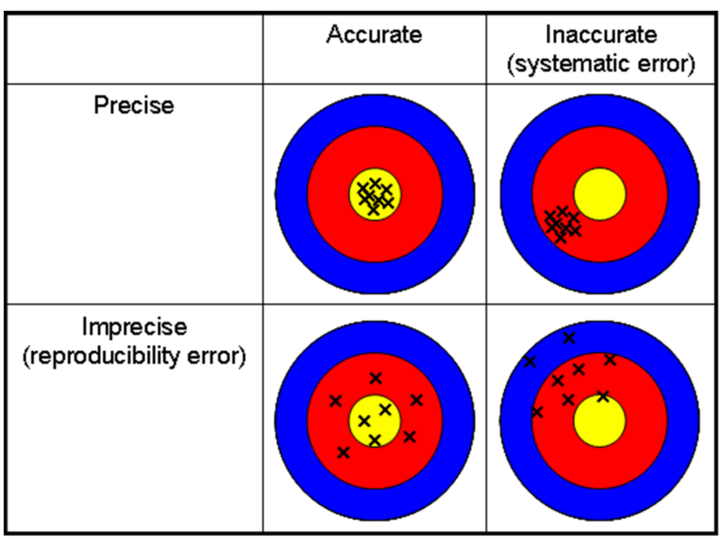
Precision:

the ratio with which a given accuracy is reached, averaged over many repeated attempts

Only pairs of precision and accuracy make sense

Example:
average error of less than 20cm in 95% of cases

Precision vs. Accuary



https://www.sophia.org/tutorials/accuracy-and-precision--3

Approaches

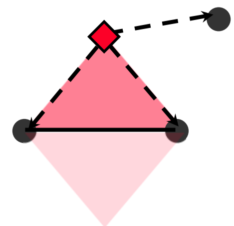
- Proximity: estimate distance between two nodes
- Trilateration and triangulation
  - » using elementary trigonometric properties: a triangle is completely determined,
    - – if two angles and a side length are known
    - – if the lengths of all three sides are known
  - » infer a 3d position from information about two triangles
- Fingerprinting (scene analysis)
  - » using radio characteristics as fingerprint to identify it
- Hybrid methods: multiple sources of information

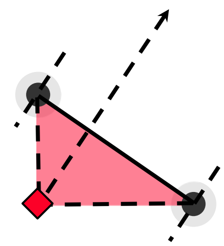
Proximity and Distance

- Binary nearness: using finite range of wireless communication and/or threshold
  - » within range of a beacon signal from a source with known position
  - » yields region locations, e.g.: cell in cellular network
- Distance measurement (ranging)
  - » Received signal strength
  - » Time of flight (time of arrival)
  - » Time difference of arrival

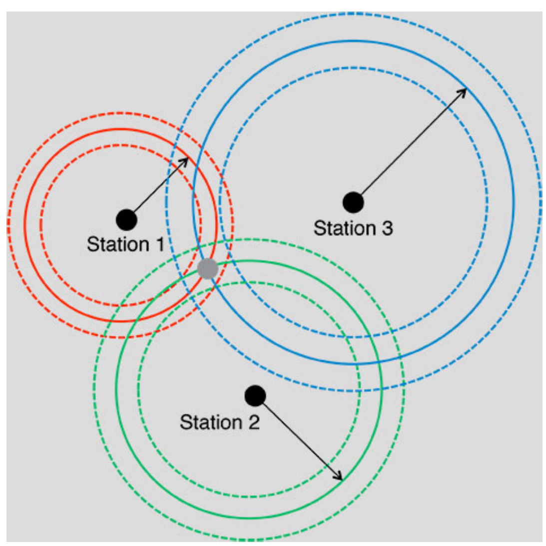
Measuring Location: Trigonometry Basics

- **Triangles in a plane**
  - » **Lateration: distance measurement to known reference points**
    - – **a triangle is fully determined by the length of its sides**
    - – **Time of Flight (e.g. GPS, Active Bat)**
    - – **Attenuation (e.g. RSSI)**
  - » **Angulation: measuring the angle with respect to two known reference points and a reference direction or a third point**
    - – **a triangle is fully determined by two angles and one side as shown**
    - – **Phased antenna arrays**
    - – **aircraft navigation (VOR)**



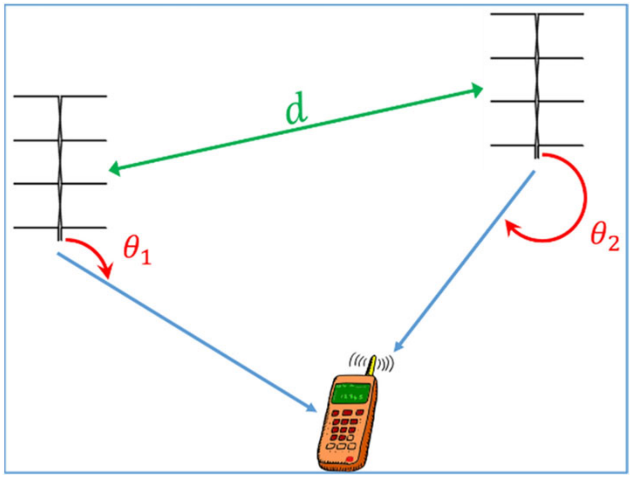


Trilateration



http://gpsworld.com/innovation-where-are-we/

Angulation



Peter A. Steenkiste, CMU https://www.researchgate.net/figure/Angulation-using-two-known-angles-and-known-distance_fig3_349450502 13

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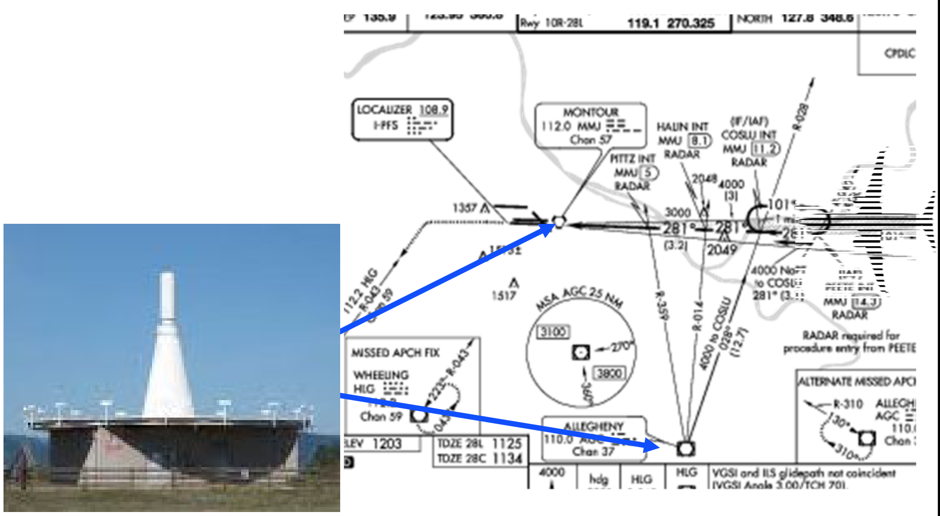
Angulation



Peter A. Steenkiste, CMU https://flightaware.com/resources/airport/KPIT/IAP/ILS+OR+LOC+RWY+28L 14

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Mathematical Background

- Computing positions between three known positions (x_i, y_i) and an unknown position (x_u, y_u) given distances r_i btw (x_i, y_i) and (x_u, y_u)
- Yields three equations $(x_i-x_u)^2 + (y_i-y_u)^2 = r_i^2$
- Linear equations by subtracting 3rd from 1st and 2nd: quadratic terms x_u^2 and y_u^2 disappear
  - » $2(x_3 - x_1)x_u + 2(y_3 - y_1)y_u = (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2)$
  - » $2(x_3 - x_2)x_u + 2(y_3 - y_2)y_u = (r_2^2 - r_3^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2)$
- In 3D: yields two points
- Positioning with imprecise information:
  - » Add redundancy: over determined solution
  - » Least squares estimates

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GPS

- Radio-based navigation system developed by DoD
  - » Initial operation in 1993
  - » Fully operational in 1995
- System is called NAVSTAR
  - » NAVigation with Satellite Timing And Ranging
  - » Referred to as GPS
  - » Has been improved over time
- Series of 24 (now 32) satellites, in 6 orbital planes
- Works anywhere in the world, 24 hours a day, in all weather conditions and provides:
  - » Location or positional fix
  - » Velocity, direction of travel
  - » Accurate time

Peter A. Steenkiste, CMU *www.fws.gov/southeast/gis/training_2k5/GPS_overview_APR_04.ppt* 16

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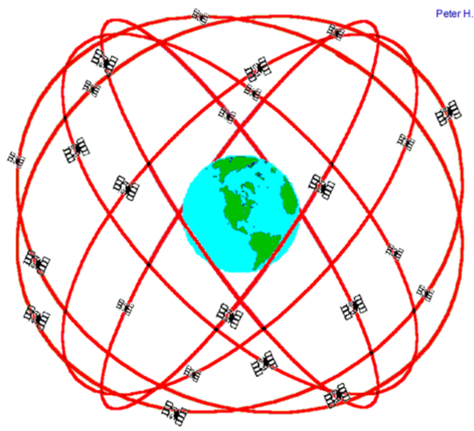
GPS Constellation

Peter H. Dana 9/22/98



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

- 24 satellites are needed to guarantee that 4 are always visible everywhere
- Extra satellites provide redundancy
  - » Deal with maintenance, replacement, …

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https://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html

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GPS involves 5 Basic Steps

- Satellite Ranging
  - » Determining distance from satellite
- Trilateration
  - » Intersection of spheres
- Timing
  - » Why consistent, accurate clocks are required
- Positioning
  - » Knowing where satellite is in space
- Correction of errors
  - » Correcting for ionospheric and tropospheric delays

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How GPS works?

- Range from each satellite calculated

  range = time delay X speed of light
- Technique called <u>trilateration</u> is used to determine your position or "fix"
  - » Intersection of spheres as described earlier
- At least 3 satellites required for 2D fix
- However, 4 satellites are used
  - » The 4^{th} satellite used to calculate drift of clock in GPS receivers relative to that of the satellites
  - » Yields much better accuracy and provides 3D fix

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Satellite Positions

- Each satellite has an atomic clock that keeps time very accurately
  - » Satellites synchronize their clocks
  - » Also periodically synchronize with the true time maintained on earth
- Satellites also know their location very accurately

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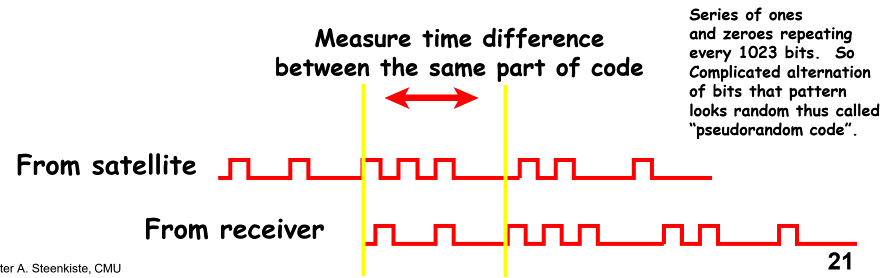
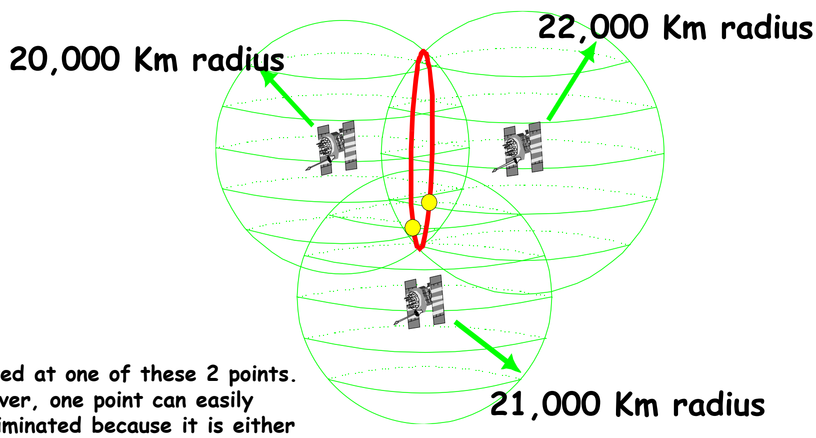
Determining Range

- Each satellite periodically generates a pseudo random code
  - » Receivers also locally generate the codes in synchronized fashion
- Receivers measure Time of Arrival (TOA) of codes
- Transmission includes Time of Transmission (TOT) of code and the location of the satellite at that time
  - » Allows receiver to calculate Time of Flight and distance



Three Satellite Ranges Known



Located at one of these 2 points. However, one point can easily be eliminated because it is either not on earth or moving at impossible rate of speed.

Accurate Timing is the Key

- Satellites have very accurate atomic clocks
- Receivers have less accurate clocks
- Measurements made in nanoseconds
  - » Speed of light (c) ~ 1 ft/nanosecond
- 1/100th of a second error could introduce error of 1,860 miles
- Discrepancy between the satellite clock and the receiver clocks must be resolved
- Fourth satellite is used to solve the 4 unknowns (X, Y, Z and receiver clock error)

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Satellite Positioning

- Required in the equation to solve the 4 unknowns is the actual location of the satellite.
  - » 3 coordinates for location, plus clock drift of receiver relative to the satellite clocks
- Satellites are in relatively stable orbits and constantly monitored on the ground
- Satellite's position is broadcast in the "ephemeris" data streamed down to receiver
  - » Downloading complete set of almanac data requires 12.5 minutes (transmitted at 50 bps)

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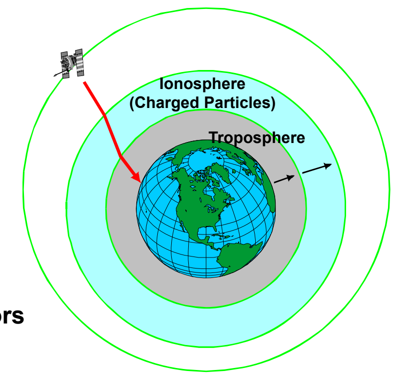
Sources of Errors

- Largest source is due to the atmosphere
  - » Atmospheric refraction
    - – Charged particles
    - – Water vapor



- Other sources:
  - » Geometry of satellite positions
  - » Multi-path errors
  - » Satellite clock errors
  - » Satellite position or “ephemeris” errors
  - » Quality of GPS receiver

Limits of Localization Using Signal Strength

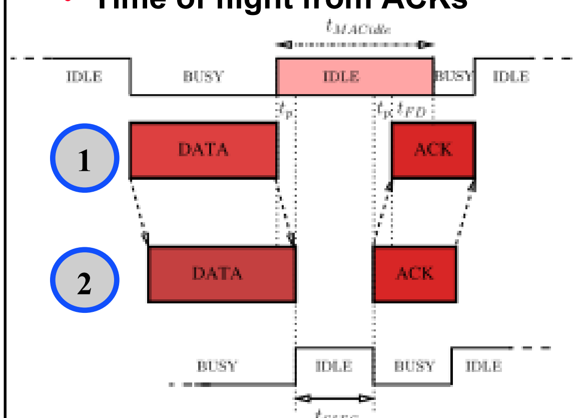
- Measuring distance based on signal strength is an attractive idea
  - » RSS does not require additional hardware
  - » RSS declines with distance
- But accuracy is quite limited
  - » 802.11 technology with a range of methods and environments tested
  - » Median localization error of 10ft and 97th percentile of 30ft
- Many technologies have higher accuracy
  - » E.g., UWB, use of AoA (multiple antennas), …
- How about using time of arrival?
  - » E.g., based on sound, radar-like techniques, …
  - » Reflections can also create inaccuracies: longer path!

CAESAR: Carrier Sense-based Ranging

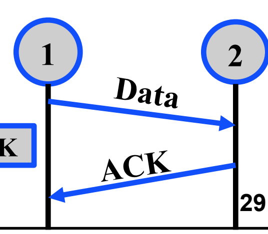
- Question: can we use time of flight ranging using commodity WiFi hardware?
- Yes, but it gets a bit messy
  - » Need to include SNR measurement
- Local station determines location of (mobile) remote stations
- Design criteria
  - » Exploit standard 802.11 protocol implementations
  - » Real time results
  - » Low cost (low network usage, no additional hardware, minimal calibration)

CAESAR: Key Idea

- Time of flight from ACKs



- Speed of light: c = ~300m/s
- WLAN clock 44MHz
- ➢ Resolution: 300/(2*44) = 3.4m
- ➢ Distance
  $d = c*(t_{MacIdle}-t_{SIFS}-t_{FD})/2$



Distance = ½ time from end of data to beginning of ACK

CAESAR: Adjustment to Noise

- Method depends on correct estimation of response time, which depends on the SNR
- Automatic gain control is used if
  - » Preferred region (PR): no AGC
  - » Strong signal detected (SSD): e.g. subtract 30dB from from signal
  - » Weak signal detected (WSD): may need adjust signal to to bring it into PR (or signal is not detected)
- Proposed solution:
  - » Detect states SSD, WSD, and preferred range
  - » Use different values for Time for Frame Detection (t_{FD})

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  - » Hybrid systems

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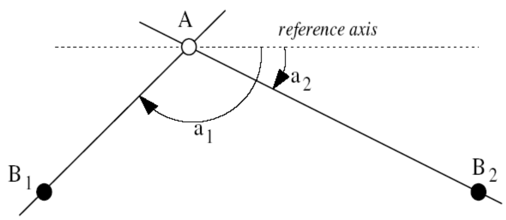
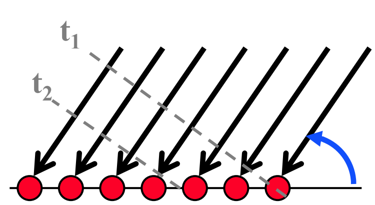
Angle of Arrival (AoA)

- A measures the direction of the incoming signal using a radio array.
- By using 2 anchors, A can determine its position
- Alternatively: the anchor measure the angle of A's signal and coordinate



Angle of Arrival Techniques

- Antenna arrays are increasingly popular
- They are usually used to steer the signal, but can be used to identify the angle at which it arrives
- Difference in arrival time can be used to measure angle



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Location Fingerprinting

- Fingerprint Methods for Recognizing Locations
  - » Examples
    - – Visual identification of places from photos
    - – Recognition of horizon shapes
    - – Measurement of signal strengths of nearby networks (e.g. RADAR)
  - » Method: computing the difference between a feature set extracted measurements with a feature database
  - » Advantages: passive observation only (protect privacy, prevent communication overhead)
  - » Disadvantage: access to feature database needed

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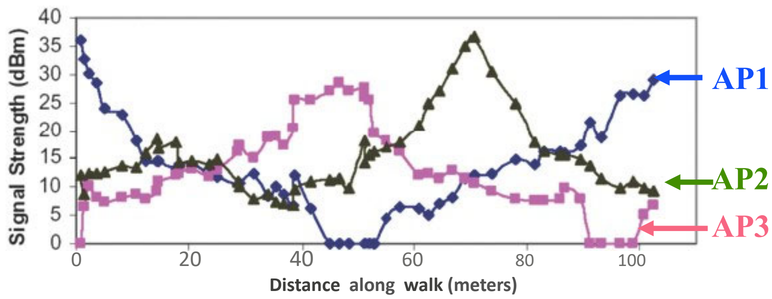
RADAR: Key Idea

- RSS from multiple APs tends to be unique to a location



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Hybrid Technologies

- Cell phones: have many other sensors
  - » Accelerometer, compass, …
- Can be used to estimate the user's walking speed, direction, …
- This information can be combined with finger printing based techniques
- Especially useful if finger printing provides accurate location in specific locations
  - » When entering a store, escalator, elevators
  - » Can use the other sensors starting with these well-knownlocations

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Literature

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- P. Bahl and V. N. Padmanabhan (2000). RADAR: An In-Building RF-based User Location and Tracking System. IEEE INFOCOM 2000, pp. 775-784.
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