This lecture is being recorded

18-452/18-750
Wireless Networks and Applications
Lecture 22: Localization

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http://www.cs.cmu.edu/~prs/wirelessS21/

Outline

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

Properties of localization procedures

- Physical position vs data types
- 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

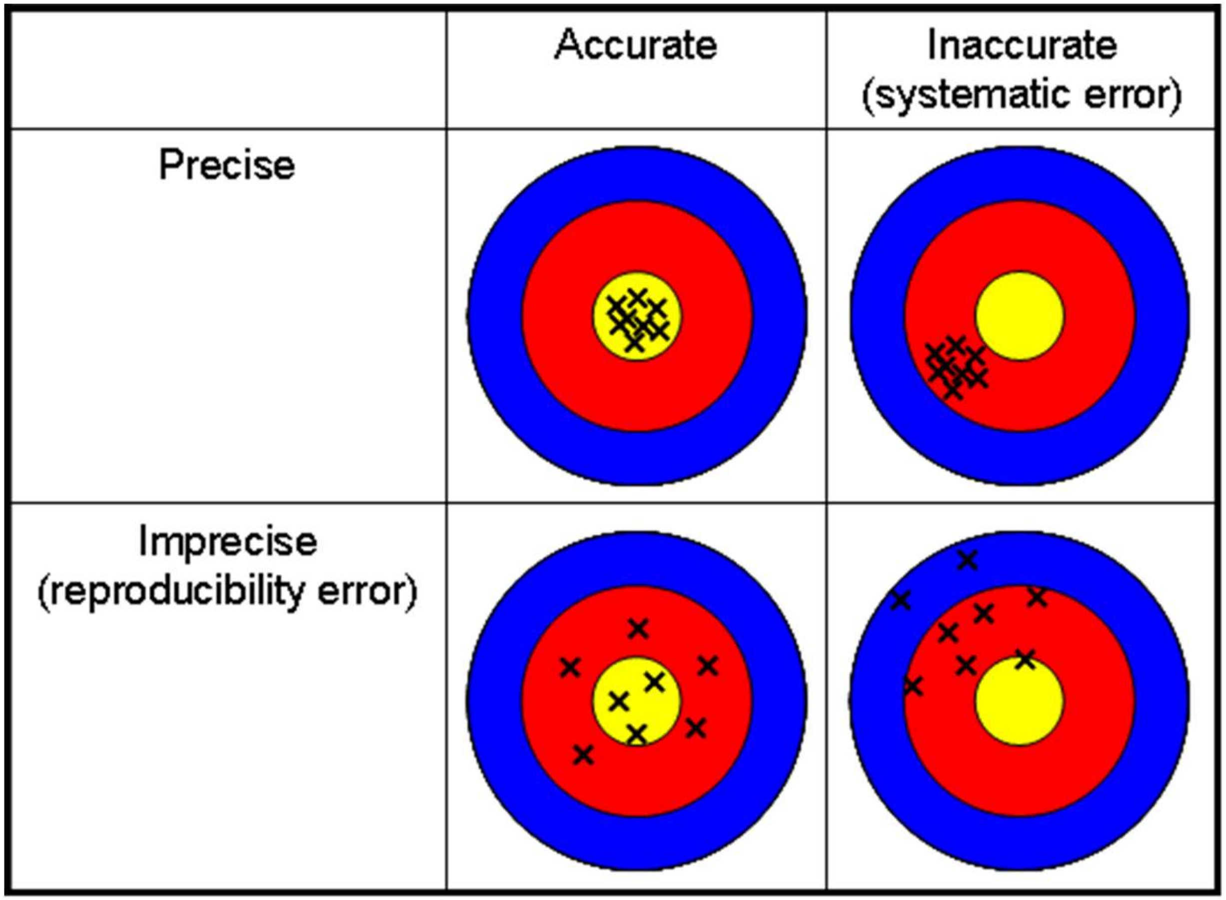
Precision:

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

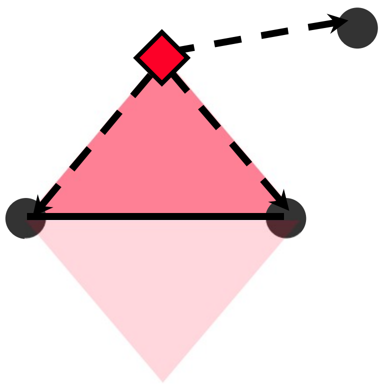
Approaches

- Proximity: estimate distance between two nodes
- Trilateration and triangulation
  - » using elementary trigonometric properties: a triangle is completely determined,
    - – if two <u>angles</u> and a side length are known
    - – if the <u>lengths</u> 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

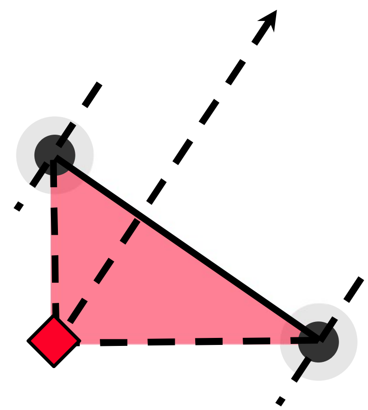
Proximity and Distance

- **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)



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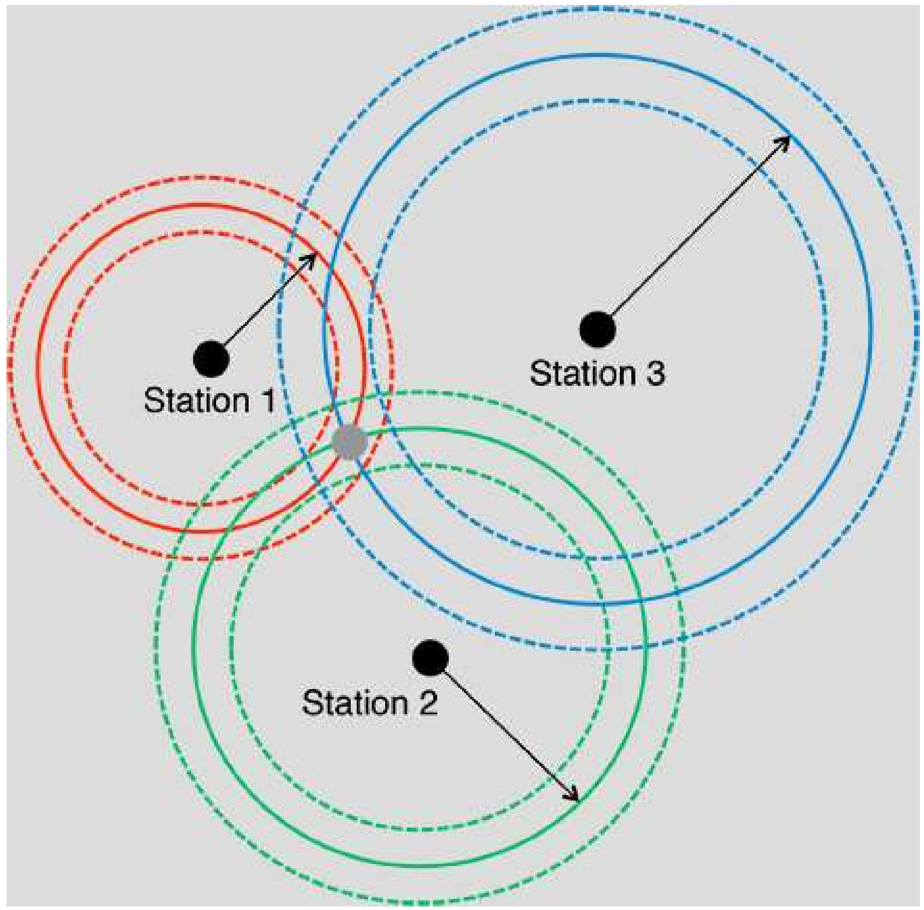
Trilateration



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

Mathematical Background

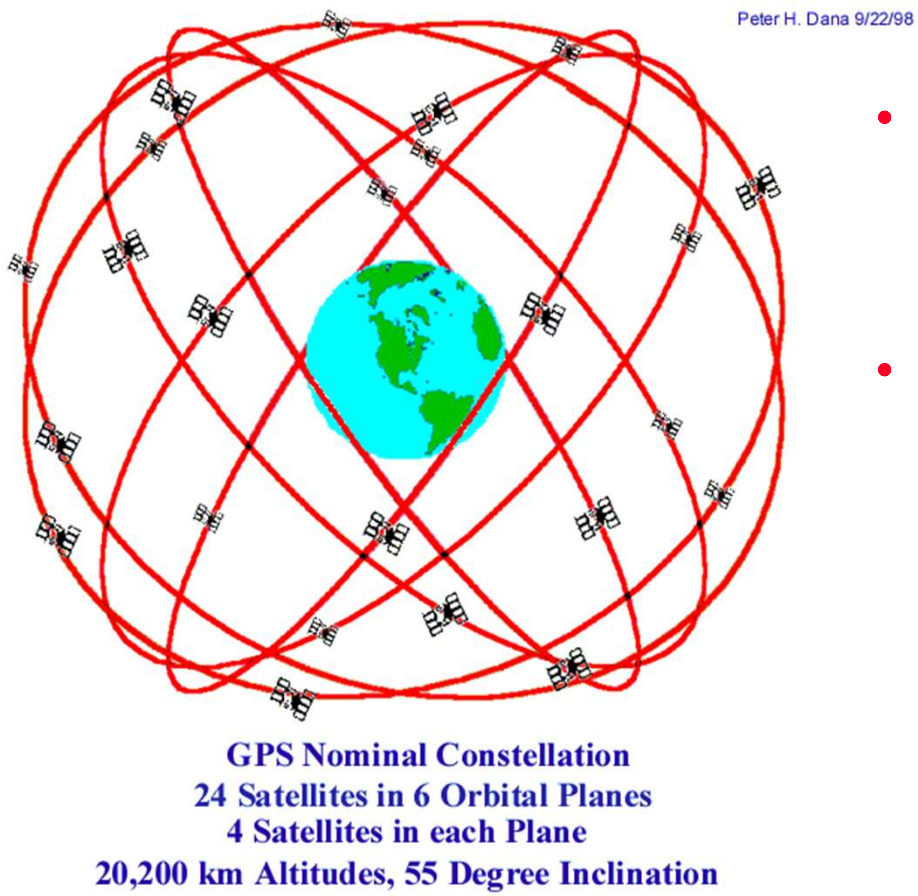
- Computing positions between three known positions (x_i, y_i) and an unknown position (x_u, y_u) given distances r_i btw (x_i, y_i) and (x_u, y_u)
- Yields three equations $(x_i-x_u)^2 + (y_i-y_u)^2 = r_i^2$
- Linear equations by subtracting 3rd from 1st and 2nd: quadratic terms x_u^2 and y_u^2 disappear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

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

www.fws.gov/southeast/gis/training_2k5/GPS_overview_APR_04.ppt

GPS Constellation



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

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

How GPS works?

- Range from each satellite calculated

  range = time delay X speed of light

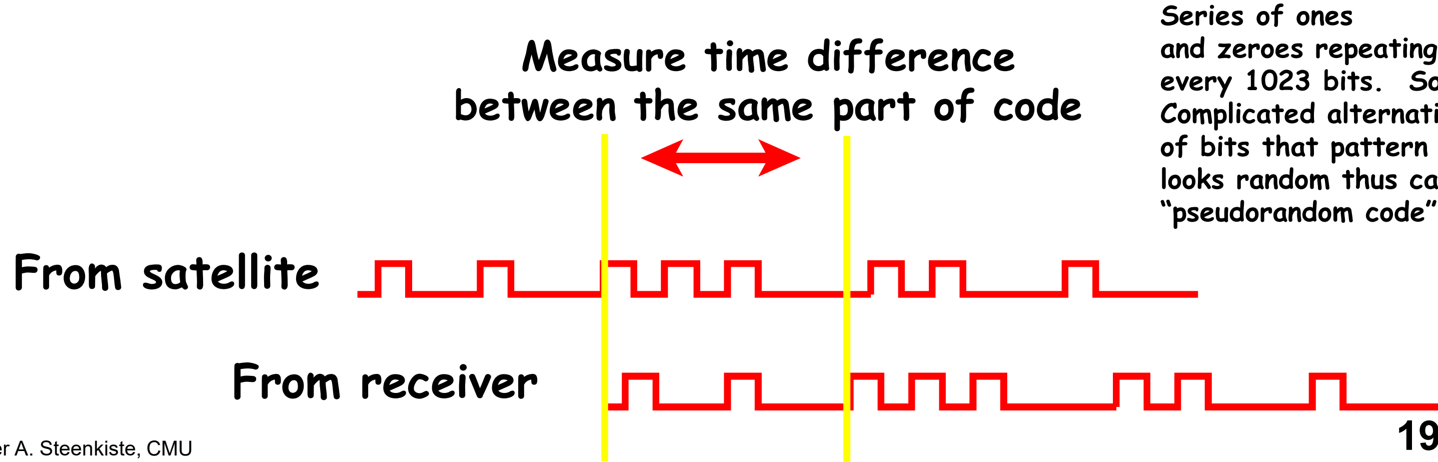
- Technique called <u>trilateration</u> is used to determine your position or "fix"
  - » Intersection of spheres as described earlier
- At least 3 satellites required for 2D fix
- However, 4 satellites are used
  - » The 4th satellite used to calculate drift of clock in GPS receivers relative to that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

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

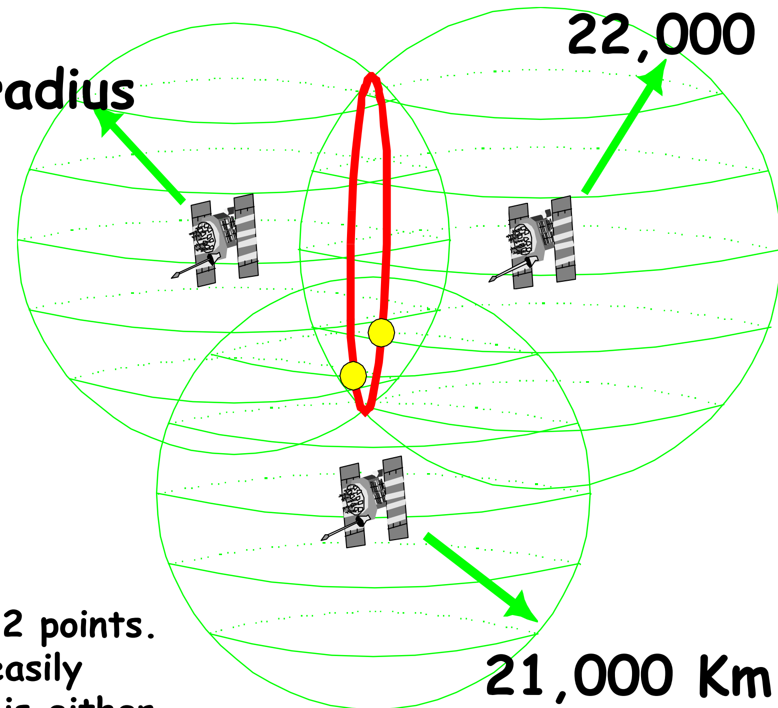
Determining Range

- **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**



Series of ones and zeroes repeating every 1023 bits. So Complicated alternation of bits that pattern looks random thus called "pseudorandom code".

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

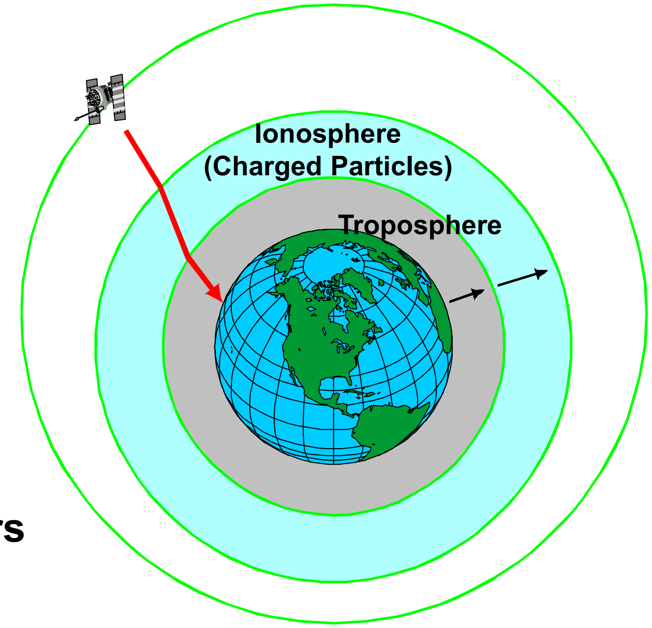
- Satellites have very accurate atomic clocks
- Receivers have less accurate clocks
- Measurements made in nanoseconds
  - » Speed of light (c) ~ 1 ft/nanosecond
- $1/100^{th}$ of a second error could introduce error of 1,860 miles
- Discrepancy between the satellite clock and the receiver clocks must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

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)**

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



How about Indoors?

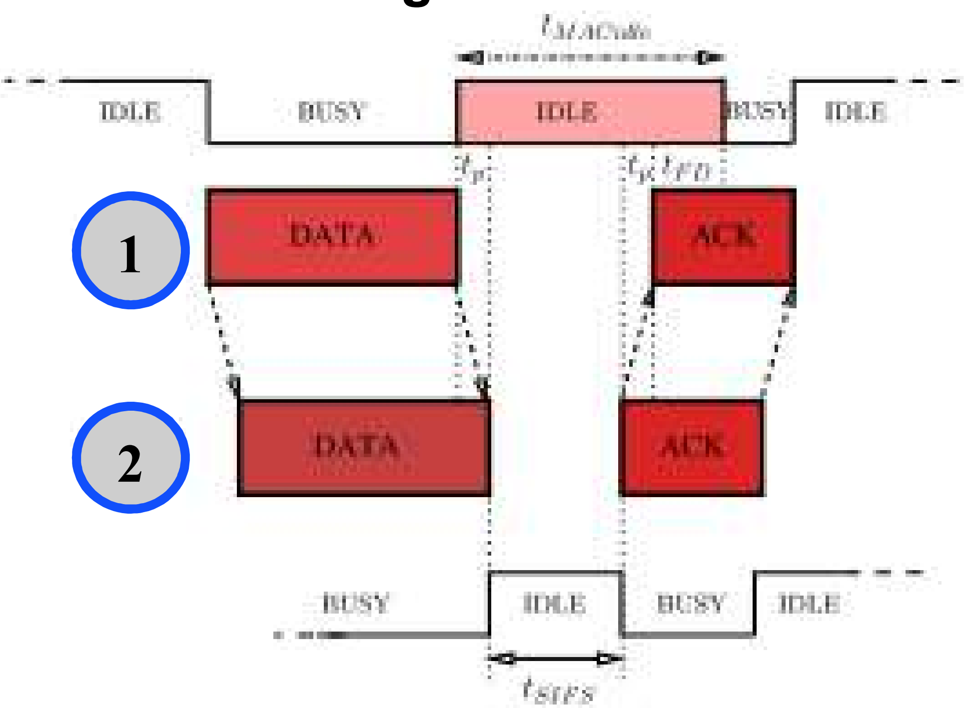
- We can use received WiFI signal strength (RSS) to measure distance to APs with known location!
- Does not work in practice: too many factors affects RSS: objects, people, …
  - » Triangulation based on RSS tends to results tend to give large, unpredictable errors
- How about using time of arrival?
  - » E.g., based on sound, radar-like techniques, …
  - » Works better, but it is still hard
  - » Can work well but often requires special infrastructure
  - » Reflections can also create inaccuracies: longer path!

CAESAR: Carrier Sense-based Ranging

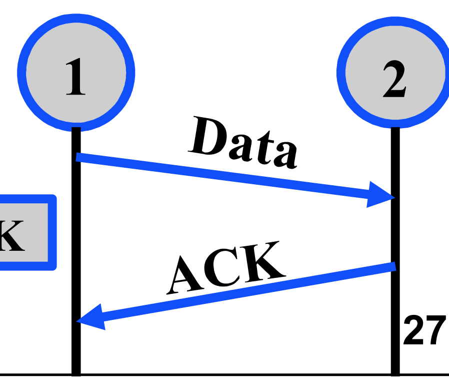
- **Question: can we use time of flight ranging using commodity WiFi hardware?**
- **Yes, but it gets a bit messy**
  - » **Need to include SNR measurement**
- **Local station determines location of (mobile) remote stations**
- **Design criteria**
  - » **Exploit standard 802.11 protocol implementations**
  - » **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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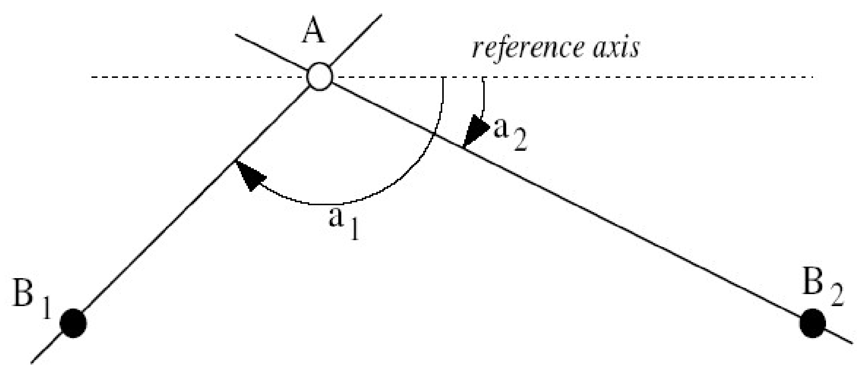
  - » Finger printing (RADAR)
  - » Hybrid systems

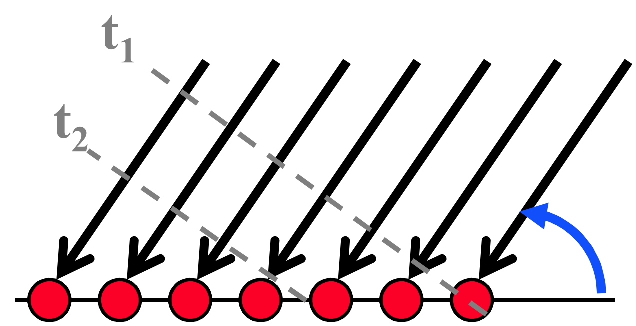
Angle of Arrival (AoA)

- 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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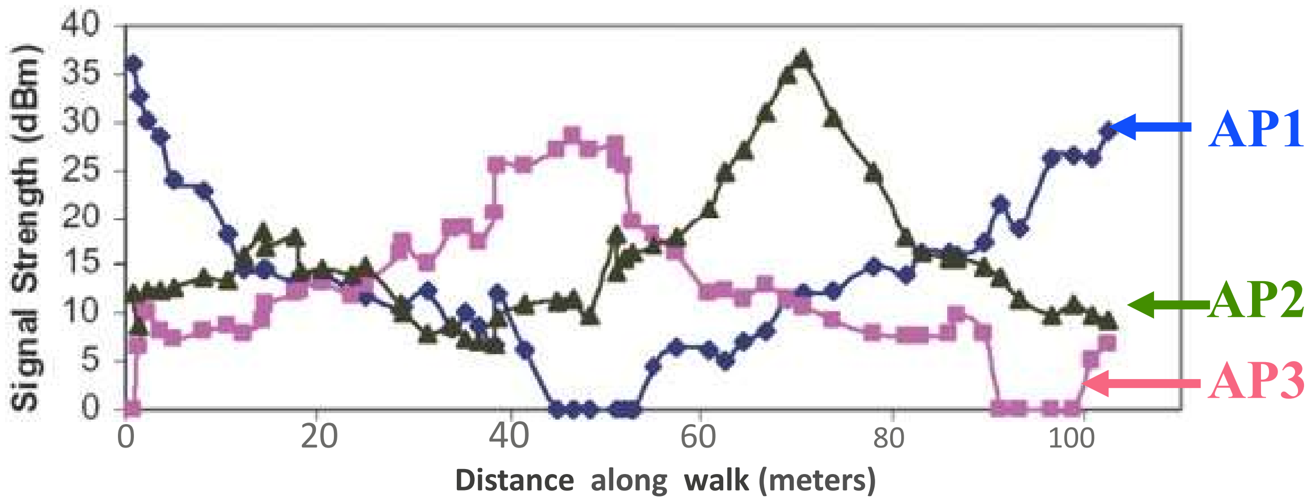
Location Fingerprinting

- 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

RADAR: Key Idea

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



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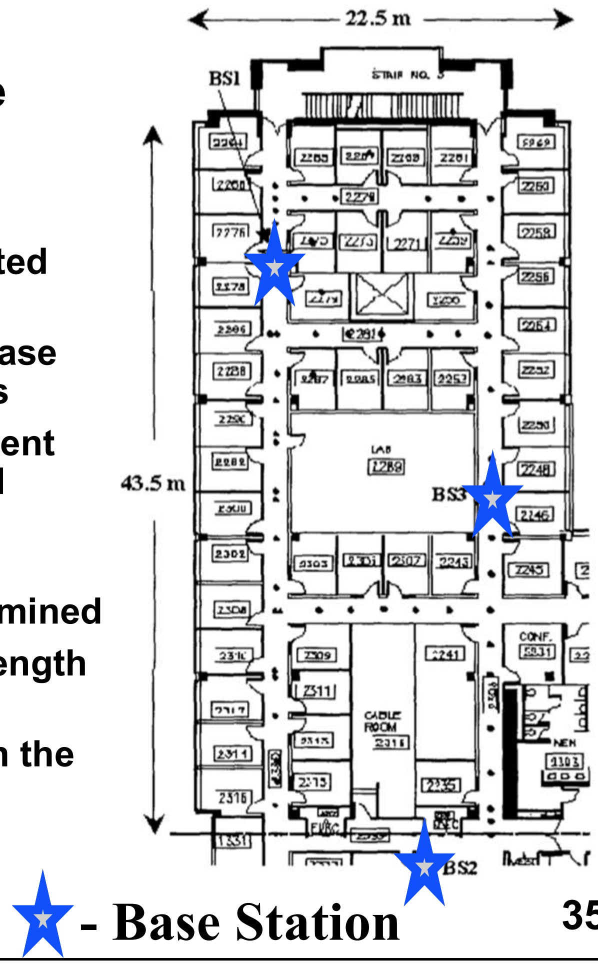
RADAR Approach

- Scenario: floor layout with three base stations (in the hallways)
- Empirical method
  - » offline phase: database is constructed
    - – collect signal strength measurements from all three base stations at 70 distinct locations
    - – store each of the 70 measurement triples together with the spatial location and orientation in a database
  - » online phase: position can be determined
    - – measure the current signal strength from all three base stations
    - – find the most similar triple(s) in the database
  - » Resolution 2.94m (50th percentile)

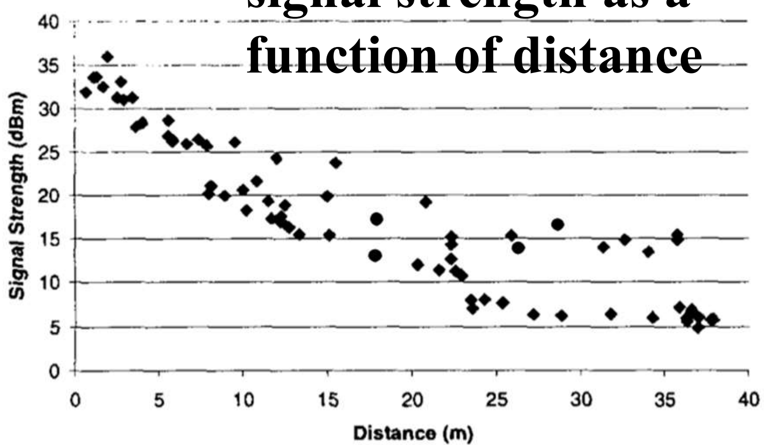


Model-Based Radio Map

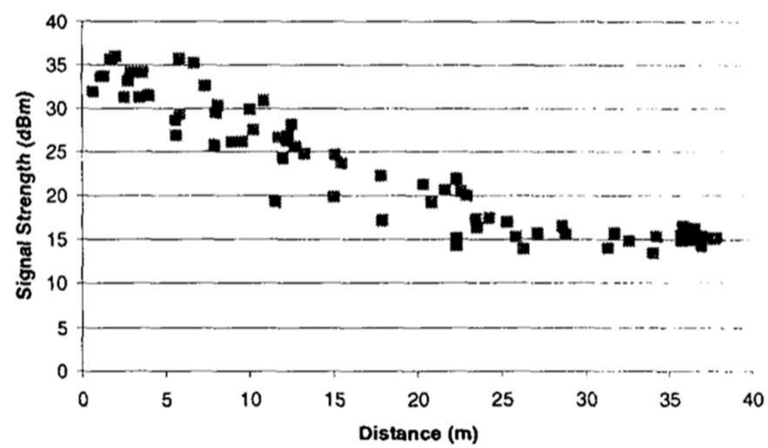
- Model set-up phase has high cost
- Alternative use radio propagation model and floor plan (instead of measurements)
  - » Considered models
    - – Rayleigh fading model: small-scale rapid amplitude fluctuation to model multi-path fading
    - – Rician distribution model: like Rayleigh but with additional LoS component
    - – Floor Attenuation Factor propagation model: large scale path loss with building models
    - – Wall Attenuation Factor model: considers effects from walls between transmitter and receiver
  - » Resolution 4.3m (50th percentile)

Effects of applying correction

signal strength as a function of distance



with correction for walls



Limits of Localization Using Signal Strength

- **Measuring distance based on signal strength is an attractive idea for wireless sensor networks:**
  - » **RSS does not require additional hardware**
  - » **RSS declines with distance**
  - » **Many different promising methods proposed**
- **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 with higher accuracy have been developed**
  - » **E.g., UWB, use of AoA, …**

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 points
  - When entering a store, escalator, elevators
  - Can use the other sensors starting with these well-knownlocations

Literature

- H. Karl and A. Willig (2005). Protocols and Architectures for Wireless Sensor Networks, Ch. 9 Localization and positioning. John Wiley & Sons.
- P. Bahl and V. N. Padmanabhan (2000). RADAR: An In-Building RF-based User Location and Tracking System. IEEE INFOCOM 2000, pp. 775-784.
- E. Elnahrawy et al. (2004). The limits of localization using signal strength: a comparative study. IEEE SECON 2004, pp. 406-414 .
- D. Giustiniano, and S. Mangold (2011). CAESAR: Carrier Sense-Based Ranging in Off-The-Shelf 802.11 Wireless LAN. ACM CoNEXT 2011.