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Wireless Networks and Applications
Lecture 20: Localization

Peter Steenkiste
Carnegie Mellon University
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http://www.cs.cmu.edu/~prs/wirelessS20/

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

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

**Precision vs. Accuracy**

<table>
<thead>
<tr>
<th>Accurate</th>
<th>Inaccurate (systematic error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precise</td>
<td><img src="image1" alt="Precise Accurate" /></td>
</tr>
<tr>
<td>Imprecise (reproducibility error)</td>
<td><img src="image2" alt="Imprecise Inaccurate" /></td>
</tr>
</tbody>
</table>

**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

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 3\textsuperscript{rd} from 1\textsuperscript{st} and 2\textsuperscript{nd}: quadratic terms \(x_u^2\) and \(y_u^2\) disappear
  » \(2(x_2 - x_1)x_u + 2(y_2 - y_1)y_u = (r_1^2 - r_2^2) - (x_1^2 - x_2^2) - (y_1^2 - y_2^2)\)
  » \(2(x_3 - x_1)x_u + 2(y_3 - y_1)y_u = (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2)\)

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

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
  \[ \text{range} = \text{time delay} \times \text{speed of light} \]
- Technique called trilateration 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

Three Satellite Ranges Known

20,000 Km radius
22,000 Km radius
21,000 Km radius

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)
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: $c \approx 300\text{m/s}$
- WLAN clock 44MHz
  - Resolution: $300/(2\times44) = 3.4\text{m}$
  - Distance $d = c\times(t_{\text{MacIdle}}-t_{\text{SIFS}}-t_{\text{FD}})/2$

Distance $= \frac{1}{2}$ 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 signal
  - Weak signal detected (WSD): may need adjust signal 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 ($t_{\text{FD}}$)

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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

RADAR: Key Idea

- RSS from multiple APs tends to be unique to a location
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
- Experimental study:
  - 802.11 technology with a range of methods and environments tested
  - Median localization error of 10ft and 97th percentile of 30ft
- Fundamental limitations that require
  - more complex environment models
  - additional infrastructure
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-known locations

Literature