18-452/18-750
Wireless Networks and Applications
Lecture 19: Localization

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http://www.cs.cmu.edu/~prs/wirelessS18/

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

- Many ways to measure location, e.g.
  - » GPS location of a mobile phone
  - » Area where an access point has sufficient reception
- Corresponding data types
  - » point locations in terms of coordinates: *physical* or *geometric locations*
  - » extended region locations given by names: *symbolic locations*

Spatial Information

- Sources of location information
  - » Location of a device can be measured using positioning methods
  - » Additional spatial information can be retrieved from a spatial information system
- Additional information
  - » Geometric information
    - – coordinate system and unit transformations
    - – precision and accuracy of measurement
  - » Region information
    - – location hierarchies

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

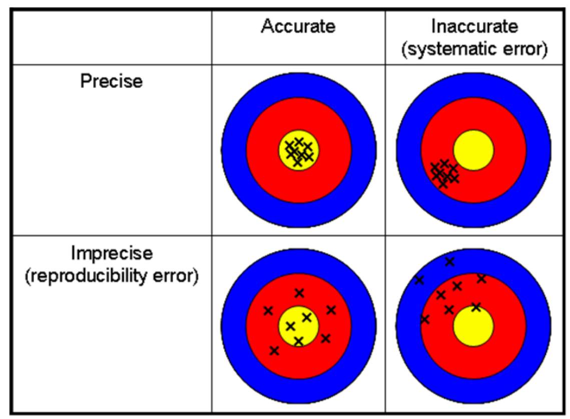
Positioning accuracy:
largest distance between an estimated position and the true position

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

Only pairs of precision and accuracy make sense

Precision vs. Accuary



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

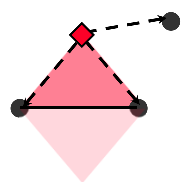
Approaches

- 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 of a location as fingerprint to identify it
- Hybrid methods: combine multiple sources of information

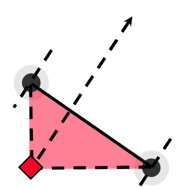
Proximity and Distance

- 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

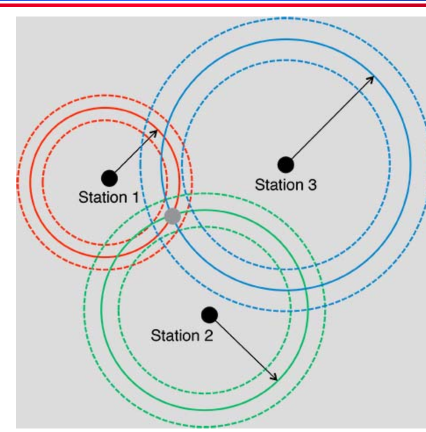
Measuring Location: Trigonometry Basics



- Triangles in a plane
  - » Lateration: <u>distance</u> 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 <u>angle</u> 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)

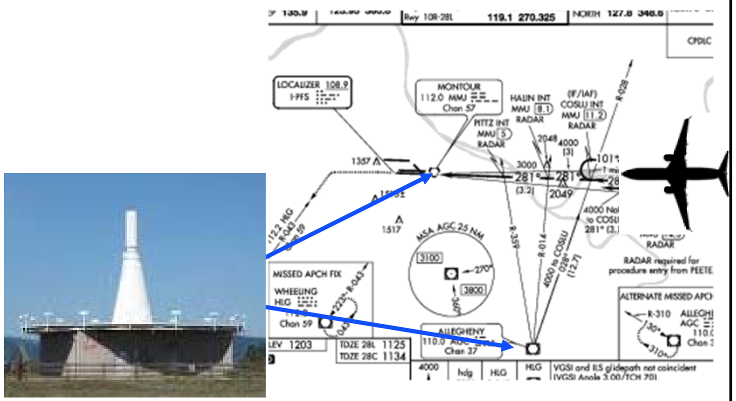


Trilateration



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

Angulation



https://flightaware.com/resources/airport/KPIT/IAP/ILS+OR+LOC+RWY+28L

Mathematical Background

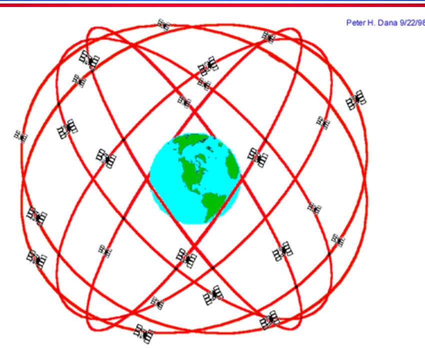
- Computing positions between three known positions (x_i, y_i) and an unknown position (x_u, y_u) given distances r_i btw (x_i, y_i) and (x_u, y_u)
- Yields three equations $(x_i-x_u)^2 + (y_i-y_u)^2 = r_i^2$
- Linear equations by subtracting 3rd from 1st and 2nd: quadratic terms x_u^2 and y_u^2 disappear
  - » $2(x_3 - x_1)x_u + 2(y_3 - y_1)y_u = (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2)$
  - » $2(x_3 - x_2)x_u + 2(y_3 - y_2)y_u = (r_2^2 - r_3^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2)$
- 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
- Series of 24 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



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

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

GPS involves 5 Basic Steps

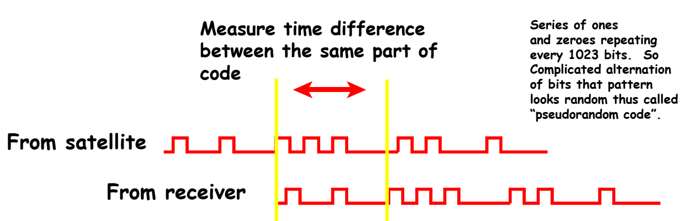
- Satellite Ranging
  - » Determining distance from satellite
- Trilateration
  - » Intersection of spheres
- Timing
  - » Why consistent, accurate clocks are required
- Positioning
  - » Knowing where satellite is in space
- Correction of errors
  - » Correcting for ionospheric and tropospheric delays

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
- **At least 3 satellites required for 2D fix**
- **However, 4 satellites should always be used**
  - » The 4th satellite used to compensate for inaccurate clock in GPS receivers
  - » Yields much better accuracy and provides 3D fix

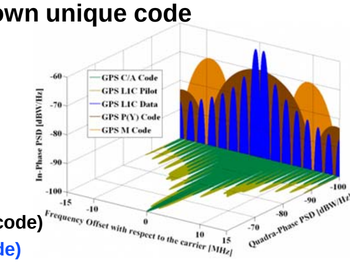
Determining Range

- Receiver and satellite use same code
- Synchronized code generation
- Compare incoming code with receiver generated code



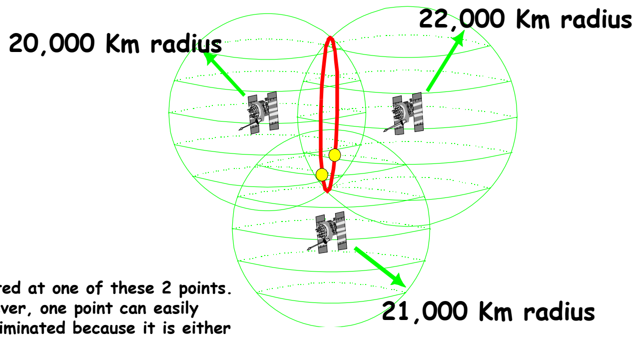
Signal Structure

- Each satellite transmits its own unique code
- Two frequencies used
  - » <u>L1 Carrier</u> 1575.42 MHz
  - » <u>L2 Carrier</u> 1227.60 MHz
  - » L5 Carrier 1176.45 MHz
- Codes
  - » CA Code uses L1 (civilian code)
  - » P(Y) Code uses L1 & L2 (military code)
  - » M Code uses L1 & L2 (military code)



http://www.navipedia.net/index.php/GPS_Signal_Plan

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

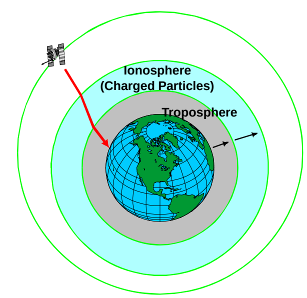
- Satellites have very accurate atomic clocks
- Receivers have less accurate clocks
- Measurements made in nanoseconds
  - » 1 nanosecond = 1 billionth of a second
  - » Speed of light (c) ~ 1 ft/nanosecond
- 1/100th of a second error could introduce error of 1,860 miles
- Discrepancy between satellite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

Satellite Positioning

- Also required in the equation to solve the 4 unknowns is the actual location of the satellite.
- 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
  - » SV position or "ephemeris" errors
  - » Quality of GPS receiver



How about Indoors?

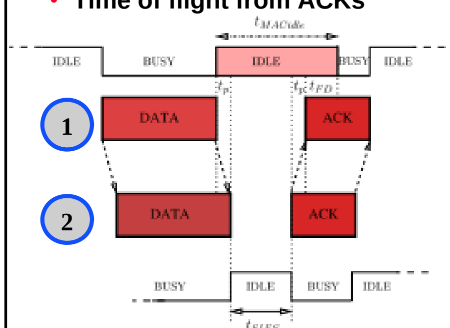
- We can use received WiFI signal strength (RSS) to measure distance to APs with known location!
- Does not work in practice: too many factors affects RSS: objects, people, …
  - » Triangulation based on RSS tends to results tend to give large, unpredictable errors
- How about using time of arrival?
  - » 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)

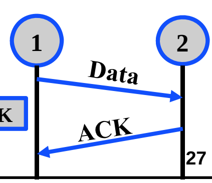
CAESAR: Key Idea

- Time of flight from ACKs



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

- 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



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})

Outline

- Properties of localization procedures
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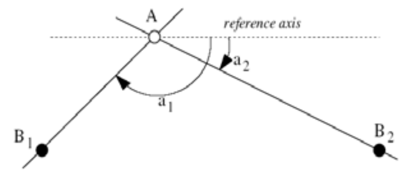
  - » Finger printing (RADAR)
  - » Hybrid systems

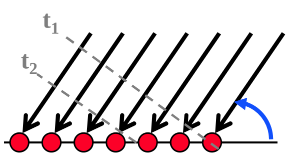
Angle of Arrival (AoA)

- 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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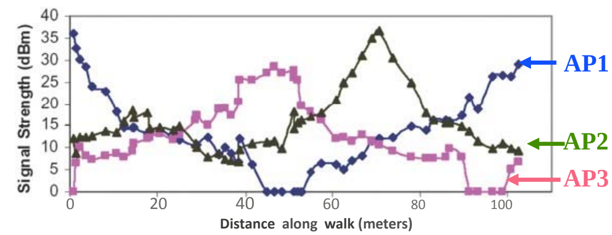
Location Fingerprinting

- 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

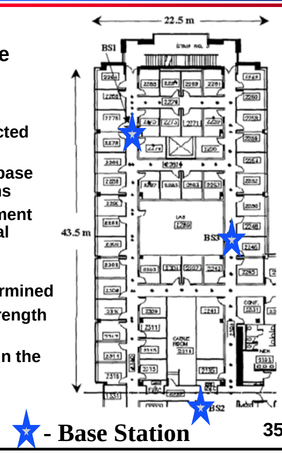
RADAR: Key Idea

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



RADAR Approach

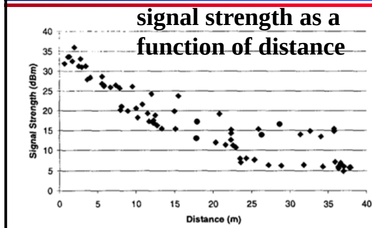
- Scenario: floor layout with three base stations (in the hallways)
- Empirical method
  - » offline phase: database is constructed
    - – collect signal strength measurements from all three base stations at 70 distinct locations
    - – store each of the 70 measurement triples together with the spatial 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)



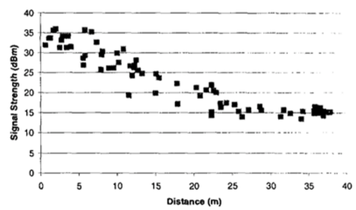
Model-Based Radio Map

- 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

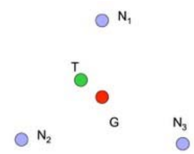


with correction for walls



Localization

- Find nearest neighbor in single space (NNSS)
  - » Default metric is Euclidean distance
- Physical coordinates of NNSS —> estimated user location
- Refinement: k-NNSS
  - » Average the coordinates of k nearest neighbors

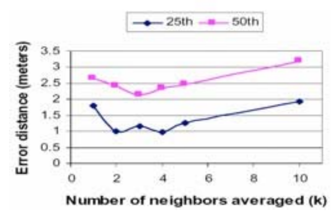


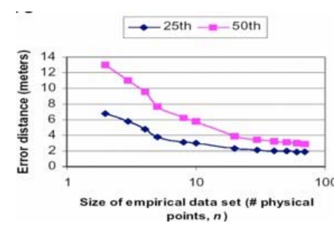
- N1,N2,N3: neighbors
- T: true location of user
- G: Guess based on averaging

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

Results





Median error distance is 2.13 meters when averaging is done over 3 neighbors

Diminishing as the number of physical points (training values) mapped increased

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

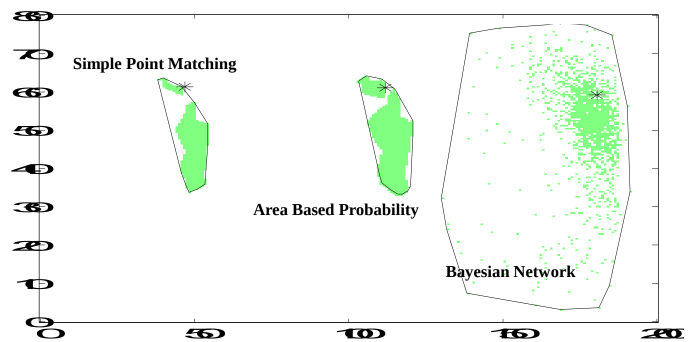
Literature

- 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.

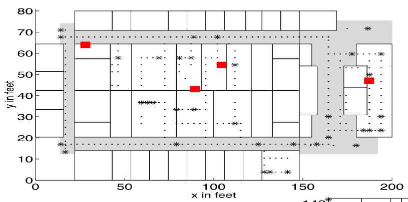
Study

- Three area-based algorithms:
  - » Simple Point Matching
  - » Area Based Probability
  - » Bayesian Network
- Yield a region instead of a point
  - » allows representation of uncertainty
  - » can trade accuracy for precision
    - – accuracy: likelihood that point is in region
    - – precision: size of region
- Comparison: eight point-based alg.s
  - » Bayesian Point
  - » Averaged Bayesian
  - » RADAR
  - » Averaged RADAR
  - » Gridded RADAR
  - » Highest Probability
  - » Averaged Highest Probability
  - » Gridded Highest Probability

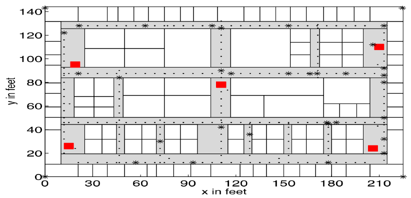
Area-based Algorithms



Two Office Environments

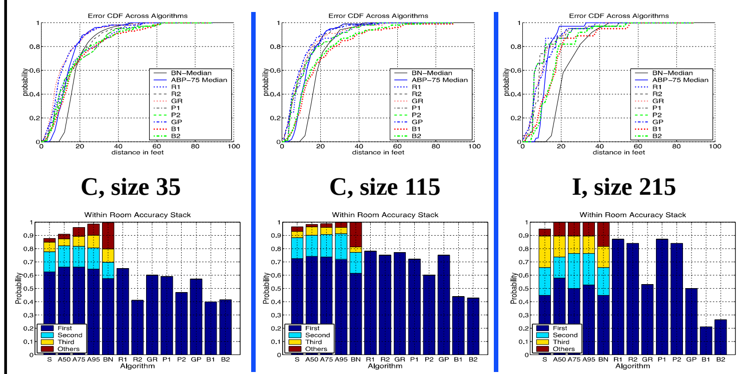


C: campus office environment

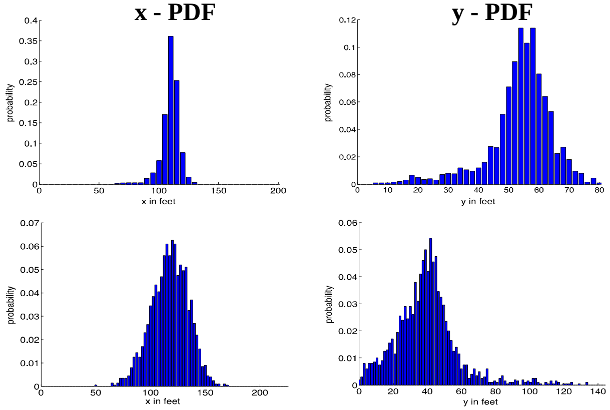


I: industrial office environment

Results



Uncertainty



Other Direct Methods

- **Active Badge: infrared beacons in rooms**
- **Active Office: location of specific device**
  - » **arrays of ultrasound receivers**
  - » **central controller sending radio signal**
  - » **time difference of arrival (95%, 8cm)**
- **Cricket**
  - » **device queries anchors**
  - » **anchors provide ultrasound and radio signal for TDoA**
- **Overlapping connectivity**
- **Approximate point in triangle**
- **Angle of arrival: narrow, rotating beams**

Multi-hop Environments

- Given position of some anchor nodes, estimate positions of other nodes in network
- Connectivity-based methods (based on topology)
  - Model as a type of linear program optimization
  - Multi-dimensional scaling improving estimates from an all-pair shortest path algorithm
- Multi-hop range estimation: estimate distance between node and anchor
  - Hop-count distance
  - using lateration, Euclidean distance estimate
- Iterative multi-lateration: estimate position relative to neighbors
- Probabilistic positioning description based on RSSI