Wireless Networks

Lecture IV – Localization

Computer Science and Technology Department
Nanjing University

2020 Spring

Contents

Overview

- Location Based Services (LBS)
  - Navigation
  - Location based social networks
  - Tracking
  - Proximity-based notification
  - Information tagging
- Localization methods
  - Range-based methods
  - Range-free methods

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Range-Based Localization

- Range-Based Localization
  Utilize specific range or angle measurements
- Typical Solutions
  - GPS
  - CDMA
  - Radar and sonar

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- Typical Solutions
  - GPS
  - CDMA
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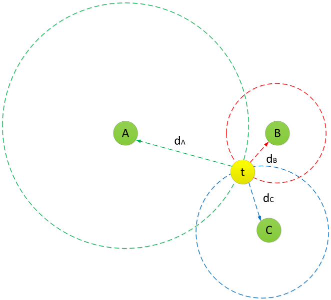
Trilateration Basics

- **Assumptions**
  Known locations of at least three nodes (Anchors or Beacons): $(x_A, y_A), (x_B, y_B), (x_C, y_C)$
- **Trilateration**

$$\begin{aligned}
\sqrt{(x_t - x_A)^2 + (y_t - y_A)^2} &= d_A \\
\sqrt{(x_t - x_B)^2 + (y_t - y_B)^2} &= d_B \\
\sqrt{(x_t - x_C)^2 + (y_t - y_C)^2} &= d_C
\end{aligned}$$



Linearization $\rightarrow$

$$\begin{bmatrix} x_B - x_A & y_B - y_A \\ x_C - x_A & y_C - y_A \end{bmatrix} \begin{bmatrix} x_t \\ y_t \end{bmatrix} = \frac{1}{2} \begin{bmatrix} x_B^2 + y_B^2 - d_B^2 - (x_A^2 + y_A^2 - d_A^2) \\ x_C^2 + y_C^2 - d_C^2 - (x_A^2 + y_A^2 - d_A^2) \end{bmatrix}$$

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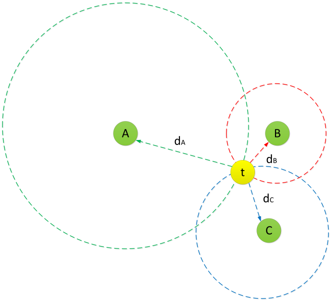

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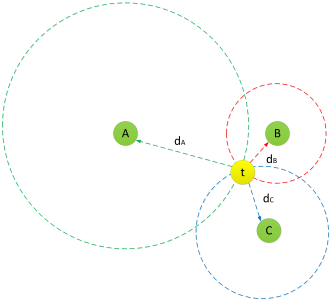

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Ranging Methods

- TOA (Time of Arrival)
  - Used by GPS, CDMA, etc..
  - Limitations
    – Strict requirement on time synchronization
- TDOA (Time Difference of Arrival)
  - Measure the difference of arrival time
  - Combine with acoustic signals [12]
    Speed of light: 3×10^8m/s, Speed of sound: $\approx$ 300 m/s
- RSSI (Received signal strength indication)
  - Infer distance from RSSI
  - Low accuracy

TOA – GPS

- GPS (Global Positioning System):
  - developed in 1970s
  - provides location and time information
- System Components:
  - Space segment:
    $24 \sim 32$ satellites
  - Control segment:
    Master control station, one backup MCS and several monitor stations
  - User segment:
    GPS receivers

GPS

- Carrier frequency:
  - L1: 1575.42 MHz
  - L2: 1227.60 MHz
- Pseudo-Random Codes
  - C/A code: 1.023M chips/s
  - P code: 10.23M chips/s
- Message format
  - Transmission rate: 50 bit/s
  - Frame format – 1500 bit super-frame:
    - sub-frame 1: time and basic info
    - sub-frame 2-3: ephemeris
    - sub-frame 4-5: almanac
  - Complete message: 750 seconds

GPS

- t_i – Time transmitted by ith satellite (synchronized time)
- $\tilde{t}_r$ – Time received by the device (device local time)
- b – Device clock bias
- Actual time of fly: $\tilde{t}_r + b - t_i$, pseudo-range: $p_i = (\tilde{t}_r - t_i)c$
- Ranging equations:
  $(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = ([\tilde{t}_r + b - t_i]c)^2, \ i = 1, 2, \ldots, n$
- Need at least 4 satellites
- Time accuracy for C/A code:

  $\frac{1}{1.023 \times 10^6 Hz} \approx 1000ns \to \approx 300m$, 1% error $\to \approx 3m$

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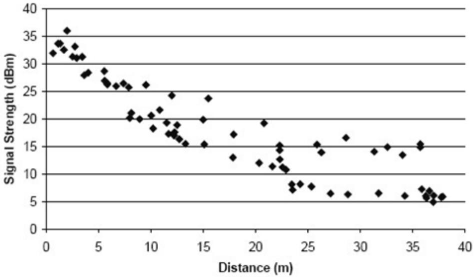
RSSI based system (Radar) [1]



Source: Radar INFOCOM 2000 [1]

- Signal strength model:

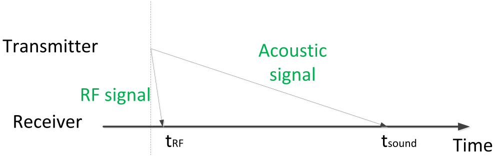
$$P(d)[dBm] = P(d_0)[dBm] - 10n\log\left(\frac{d}{d_0}\right) - \begin{cases} nW \times WAF & nW < C \\ C \times WAF & nW \geq C \end{cases}$$

- Well-known drawbacks
  - accuracy suffers from obstacles, reflections, interferences, etc.

TDOA – Cricket [12]

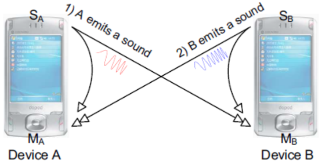
- Basic Idea:
  - Sound wave travels much slower than RF
  - Measure the TOA difference between RF signal and ultrasound signal
  - $c_{sound} = (331.3 + 0.606 \times T)m/s$
  - $d \approx \frac{t_{sound} - t_{RF}}{c_{sound}}$
  - Precision 1-3 cm

- Limitations:
  - Specialized device
  - Limited range

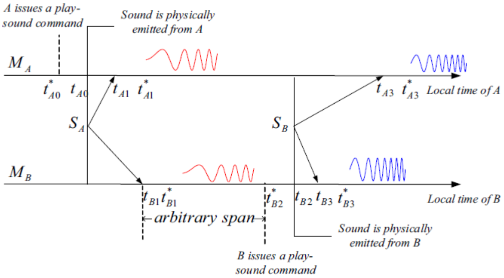


BeepBeep [11]

- BeepBeep [11]
  - Mobile based solution
  - Precision 0.8 cm



Source: BeepBeep Sensys 2007 [11]



Source: BeepBeep Sensys 2007 [11]

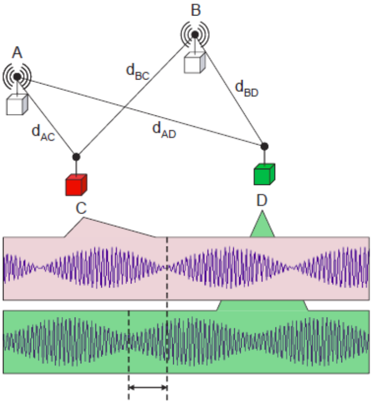
$$D = c_{sound}\left(\left(t_{A3} - t_{A1}\right) - \left(t_{B3} - t_{B1}\right)\right)/2 + \left(d_{BB} + d_{AA}\right)/2$$

Radio Interferometric Ranging [9]

- Exploit radio interferometric for ranging
- Phase offset:

$$2\pi \frac{d_{AD} - d_{BD} + d_{BC} - d_{AC}}{\lambda}$$

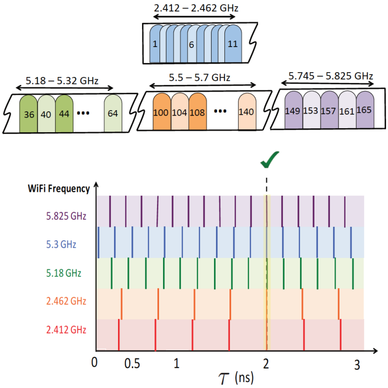
- Sensor based (433M Hz)
- Precision: $\sim$ 3 cm
- Limitations
  - Complex system
  - Line Of Sight solution



Source: Radio Interferometric, SenSys 2005 [9]

Phase based Solution [20]

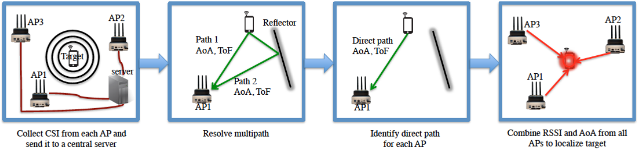
- Measure the phase offset in multiple channels $\rightarrow$ Larger channel bandwidth
- Resolve the phase alias using Chinese Remainder theorem
- Challenges
  - Remove phase offsets
  - Multipath effect
- Precision: $\sim$ 65 cm



Source: Chronos, NSDI 2016 [20]

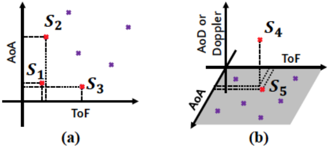
Combining Different Solutions

- SpotFi [6]
  - Combines AoA and ToF
  - Precision $\sim$ 40cm



Source: SpotFi, SIGCOMM 2015 [6]

- md-Track [22]
  - Device-free ranging
  - Combines AoA, ToF, AoD, and Doppler



Source: md-Track, MobiCom 2019 [22]

Noise in measurements

- What if the distance measurements contains errors?
  - Single Node (non-linear regression) [7]
    $\min_{x_t, y_t} \left\{ (\hat{d}_A - d_A)^2 + (\hat{d}_B - d_B)^2 + (\hat{d}_C - d_C)^2 \right\}$
    where $\hat{d}_A = \sqrt{(x_t - x_A)^2 + (y_t - y_A)^2}, \ldots$
  - Multiple Nodes (global optimization) [16]

- Remaining issues
  - Error propagation
  - Non-linear optimization, may contain local minima

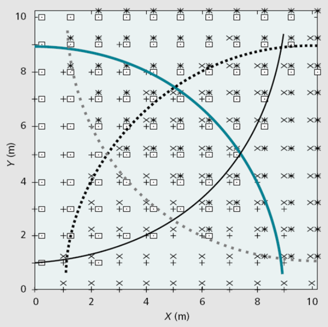
Range-Free Localization

- Range-Free Localization
  Localization methods without precise distance or angle measurements

- Approaches
  - Basic geometric solutions
  - Hop-count based solutions
  - Optimization based solutions
  - Fingerprint
  - Device-free localization

Centroid [3]

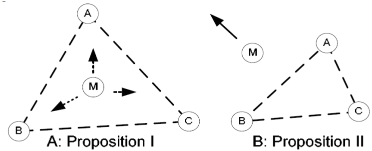
- Assumption
  - Uniformly distributed beacons
  - Beacons has GPS and precise location
- Procedure:
  - Beacons:
    broadcast signals containing its location
  - Each node:
    finds out beacons it can hear from, located as the centroid of overheard beacons
- Issues
  - Large portion of beacons



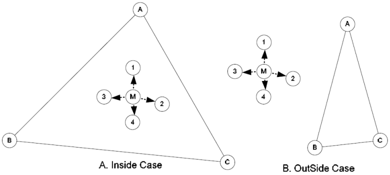
Source: Centroid, IEEE Magazine 2000 [3]

APIT [5]

- Point-In-Triangulation Test (PIT)
  - Exist a direction for nodes outside triangle where it is further or closer to all three anchors
- APIT:
  - Use neighbors as virtual movements
  - In-Out error and Out-In error
- Aggregation over all combinations of anchors



Perfect PIT Test



Approximate PIT Test
Source: APIT, ACM MobiCom 2003 [5]

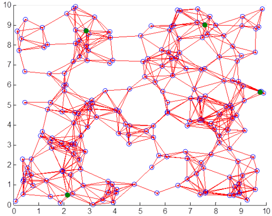
DV-hop [10]

- Basic Idea
  - Use hop count to infer distace
- Procedure
  - Each node computes the hop-distance to anchors
  - Anchors calculate the per-hop distance

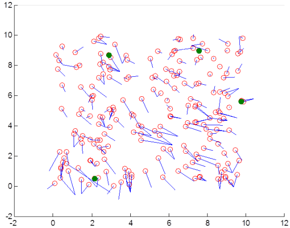
$$c_i = \frac{\sum_{j \neq i} d_{ij}}{\sum_{j \neq i} h_{ij}}$$

  - Node uses the correction information to estimate the distance

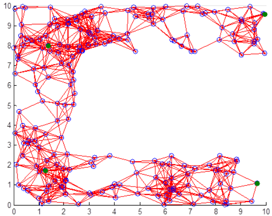
Isotropic vs. anisotropic

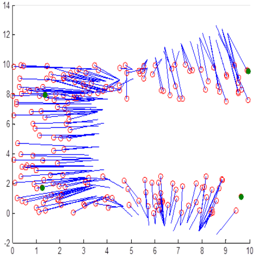


200 nodes, r=1.25, average node degree 8.69



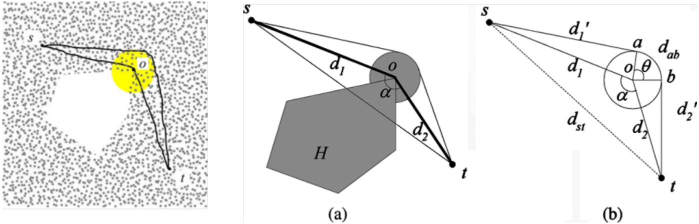
Non-linear opt., mean error=0.5492 r





Handle holes

- Virtual hole (Rendered path [8])



Source: Rendered path, ACM MobiCom 2007 [8]

$$d_{st} = \sqrt{d_1^2 + d_2^2 - 2 d_1 d_2 \cos\alpha}$$

$$\alpha = 2\pi - \frac{d_{ab}}{r} - \arccos\frac{r}{d_1} - \arccos\frac{r}{d_2}$$

- Problem: How to define a hole?

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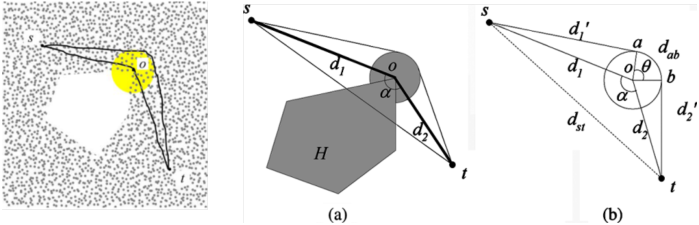

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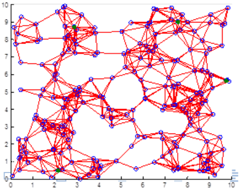

Connection based approach

- Can we directly use connection information?
- Basic Idea
  - Node i can hear node $j \iff d_{ij} \le r$
- Convex position estimation [4]

$$\text{Find out } \{(x_1, y_1), (x_2, y_2), \ldots\}$$
$$s.t. \quad (x_i - x_j)^2 + (y_i - y_j)^2 \le r^2 \qquad \text{if edge } (i, j) \text{ exists}$$

- Constraint is convex, easy to solve by SDP

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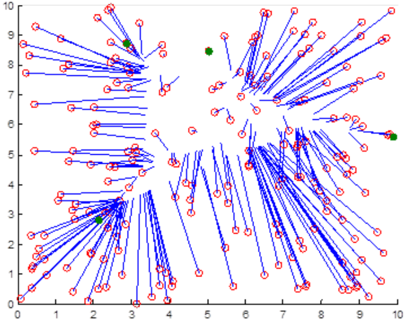
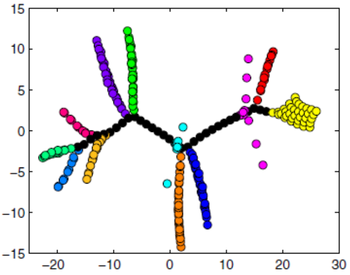
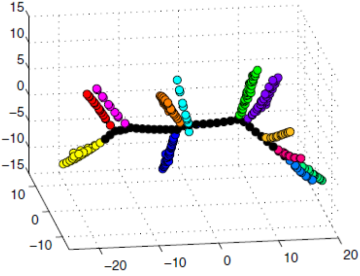


- Limitations
  - Only consider pulling force
  - Anchors should be placed in the perimeter
- Improvements
  - SOCP relaxation [19]
  - SDP relaxation [2]

Multidimensional Scaling [18]

- Multidimensional Scaling
  - Input: distance between every pair of nodes
  - Output: $n \times m$ matrix X where $\sqrt{\sum_{k=1}^{m}(X_{ik} - X_{jk})^2} = d_{ij}$





Source: Fingerprint Space, MobiCom 2012 [23]

Multidimensional Scaling

- Assume $m = 2$, centroid of X at $(0, 0)$

$$\sum_i X_{i1} = 0, \sum_i X_{i2} = 0$$

- Define

$$Y = XX^T$$

$$\text{e.g. } Y = \begin{bmatrix} X_{11}^2 + X_{12}^2 & X_{11}X_{21} + X_{12}X_{22} & X_{11}X_{31} + X_{12}X_{32} \\ X_{21}X_{11} + X_{22}X_{12} & X_{21}^2 + X_{22}^2 & X_{21}X_{31} + X_{22}X_{32} \\ X_{31}X_{11} + X_{32}X_{12} & X_{31}X_{21} + X_{32}X_{22} & X_{31}^2 + X_{32}^2 \end{bmatrix}$$

$$\sum_i X_{i1} = 0, \sum_i X_{i2} = 0 \rightarrow \sum_i Y_{ij} = 0, \sum_j Y_{ij} = 0$$

- $d_{ij}^2 = Y_{ii} + Y_{jj} - 2Y_{ij}$
- $Y_{ij} = -\frac{1}{2}\left(d_{ij}^2 - \frac{1}{n}\sum_i d_{ij}^2 - \frac{1}{n}\sum_j d_{ij}^2 + \frac{1}{n^2}\sum_i\sum_j d_{ij}^2\right)$

Multidimensional Scaling

- Y is symmetric and positive semidefinite
- Eigendecomposition: $Y = UVU^T$
- $X = UV^{1/2}$
- Dimension reduction, select the first k largest eigenvalue in V

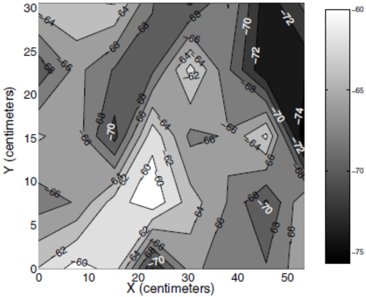
Multidimensional Scaling

- Procedure
  1. Estimate the pairwise distance through hop count
  2. Use MDS to find relative positions
  3. Map beacons to known positions
  4. Refinement [17]

  $$\min \sum_{i,j} w_{ij} \left(d_{ij} - \sqrt{\sum_{k=1}^{m} (X_{ik} - X_{jk})^2} \right)^2$$

- Limitations
  - Centralized computing
  - Anisotropic topology
  - Distance error tolerance

RSSI fingerprinting



Source: Horus, MobiSys 2005 [24]

1. Collect the histogram of RSSI at every location
2. Use maximum likelihood matching to find the position

Collecting fingerprints

- Labour intensive task for fingerprint collection
- How to reduce the cost?
- Idea [15, 23]
  - Crowdsourcing
  - Use sensors to infer location relationships
  - Integrate with floor-plan

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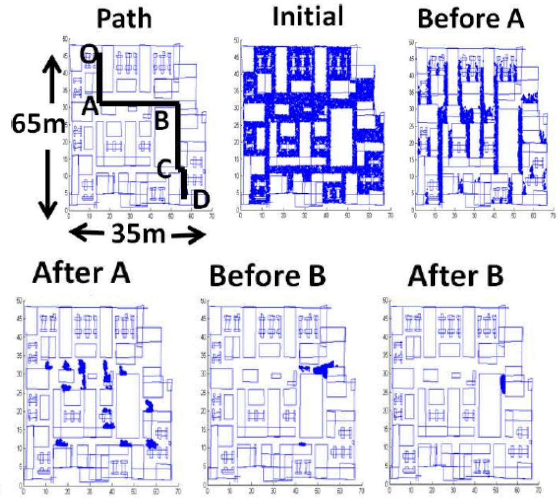
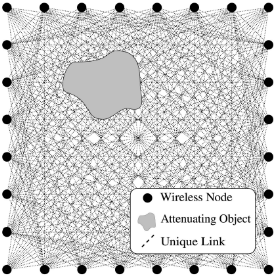


Source: zee, MobiCom 2012 [15]

Device-Free Localization



Source: Radio tomographic, TMC 2010 [21]

- Radio tomographic [21]
  - Edges can be blocked by the target
  - Use tomographic algorithms to localize the target
- Speed Based Solutions [13, 14]

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