CS-541

Wireless Sensor Networks

Lecture 13: Localization in WSNs

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Prof Panagiotis Tsakalides, Dr Athanasia Panousopoulou, Dr Gregory Tsagkatakis
Overview

➢ Geometric-based

➢ Learning-based

➢ Hardware-based
Location information and network services

- Routing
- Topology Control
- Coverage
- Boundary Detection
- Clustering

- Medical care
- Smart space
- Logistics
- Environment monitor
- Mobile P2P
- Social Networks
- Gaming
Localization steps

• *Distance/angle estimation*: estimating information about the distances and/or angles between two nodes.

• *Position computation*: computing a node’s position based on available information concerning distances/angles and positions of anchor nodes.

• *Localization algorithm*: determines how the available information will be manipulated in order to allow the nodes of a WSN to estimate their positions.
Global Positioning System (GPS)

Usage of Global Positioning System (GPS) devices
• The satellites carry synchronized atomic clocks
• GPS satellites continuously transmit their current time and position

Why not is WSN?
• High cost of the device
  • value/energy/computation power/space
• Unavailability/poor precision of the service
  • Indoors
  • Underground
  • Non line-of-sight
  • Relying on DoD (ESA Galileo)
Taxonomy

- Range vs. Range-free (connectivity) based
  - Received Signal Strength Indicator (RSSI)
  - Time/Angle of Arrival (ToA & AoA)
  - Hop-Counting Techniques

- Anchor-based vs. Anchor-free
  - Mobile source/sink
  - # of anchors (beacons)

- Centralized vs. Distributed
  - # Hops
  - Hybrid schemes

- Parametric vs. Non-parametric
  - Model and learning
Challenges

Sources of uncertainties in location sensing:

- Multipath,
- No-line-of-sight (NLOS)/blockage,
- Interference,
- Measurement noise,
- System/hardware limitations
Distance estimation - RSSI

Received Signal Strength (RSS)

• Measure the power of the signal at the receiver.
• Based on the known transmit power, the respective propagation loss can be calculated.
• Theoretical or empirical models are used to translate this loss into a distance estimate.

This method has been used mainly for RF signals.

Free Space Equation

\[ P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \]
Distance estimation - RSSI

• Radio Signal Strength (RSS): noisy but cheap
  path-loss exponent

\[ P(d) = P(d_0) - \eta 10 \log \left( \frac{d}{d_0} \right) + X_\sigma \]

Received power at distance \( d \)  
Received power at some reference distance \( d_0 \)  
   
   
   
   fading effects
“Cheap and Ubiquitous Received-Signal-Strength”?

Signal attenuation along with distance nonlinear

Signal Distribution at a fixed location noisy
Timing-based approaches

- **Time based methods (ToA, TDoA)** record the time-of-arrival (ToA) or time-difference-of-arrival (TDoA).
- Propagation time can be directly translated into distance, based on the known signal propagation speed.
- Active vs. Passive
- One-way propagation time and roundtrip propagation time measurements
- Types of signals
  - RF (wireless)
  - Acoustic
  - Infrared (Ultrasound)
TDoA Distance estimation

TDoA: better resolution but costly

Need line-of-sight conditions

Uncertainties: temperature, humidity, synchronization & delay.
Angle-based approaches

**Angle-of-Arrival (AoA):** estimate the angle at which signals are received and use simple geometric relationships to calculate node positions.

Localization accuracy \(\rightarrow\) measurement accuracy

Requires multiple antennas

- Antenna array
- Sensor array
Hop-count

Anchors
- flood network with known position
- flood network with avg hop distance

Nodes
- count #hops to anchors
- multiply with avg hop distance

\[ D = h_{ij} \times R \]

Number of hops Communication range

\[ d_{hop} = R \left( 1 + e^{-n_{local}} - \int_{-1}^{1} e^{-(n_{local}/\pi) \arccos t - t\sqrt{1-t^2}} dt \right) \]

The expected number of neighbors

\[ D = h_{ij} \times d_{hop} \]
Failed in anisotropic network!
Comparative Study & Future work

<table>
<thead>
<tr>
<th>Physical Measurements</th>
<th>Accuracy</th>
<th>Hardware Cost</th>
<th>Computation Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>RSS</td>
<td>Median</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>TDoA</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Angle</td>
<td>AoA</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Area</td>
<td>Single reference</td>
<td>Median*</td>
<td>Median*</td>
</tr>
<tr>
<td></td>
<td>Multi-reference</td>
<td>Median*</td>
<td>Median*</td>
</tr>
<tr>
<td>Hop Count</td>
<td>Per-hop distance</td>
<td>Median</td>
<td>Low</td>
</tr>
<tr>
<td>Neighborhood</td>
<td>Single neighbor</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Multi-neighbor</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

*: depends on the diverse geometric constrains

Promising technique: UWB and Chirp Spread Spectrum
Comparison

- Range measurement
  - Very accurate: Euclidean
  - Reasonable: Sum-dist
  - None / very bad: DV-hop
Possible Implementations/ Computation Models

1. Centralized
   Only one node computes

2. Locally Centralized
   Some of unknown nodes compute

3. (Fully) Distributed
   Every unknown node computes

- Each approach may be appropriate for a different application
- Centralized approaches require routing and leader election
- Fully distributed approach does not have this requirement
Localization of Nodes

**Anchor Nodes:** These are nodes that know their coordinates a priori and are used to calculate global coordinates in Anchor-based systems.

1. **Determine the distance between unknown and anchor nodes**
2. **Derive the position of each node from its anchor distances**
3. **Refine the node positions using information about the range and positions of neighbouring nodes**
Calculating Distance to Anchor Nodes

Anchors: Prelocalized nodes

Relative vs. Absolute localization

- (N+1) non-collinear beacon nodes required to define a global coordinate system in N dimensions

There are three algorithms

- Sum-Dist (DV-Distance)
- DV-Hop
- Euclidean

Anchors flood the network with their position
Example of lateration

To obtain localization a node has to have at least 3 neighbors with known position
Area Based Estimation

Single Reference Area Estimation

• Distance, angle, etc.

Compute the intersection of overlapping regions -> centroid
Trilateration in practice

Ideal scenario

Realist scenario
Multilateration

The distances from an unknown node to several references constrain the presence of this node

\[ \mathbf{H} \mathbf{x} = \mathbf{z} \]

\[
\begin{bmatrix}
2(x_N - x_1) & 2(y_N - y_1) \\
2(x_N - x_2) & 2(y_N - y_2) \\
\vdots & \vdots \\
2(x_N - x_{N-1}) & 2(y_N - y_{N-1})
\end{bmatrix}
\begin{bmatrix}
x_0 \\ y_0
\end{bmatrix}
= 
\begin{bmatrix}
D_1^2 - D_N^2 - x_1^2 - y_1^2 + x_N^2 + y_N^2 \\
D_2^2 - D_N^2 - x_2^2 - y_2^2 + x_N^2 + y_N^2 \\
\vdots \\
D_{N-1}^2 - D_N^2 - x_{N-1}^2 - y_{N-1}^2 + x_N^2 + y_N^2
\end{bmatrix}
\begin{bmatrix}
z
\end{bmatrix}
\]

\[ x = (\mathbf{H}^T \mathbf{H})^{-1} \mathbf{H}^T \mathbf{z}. \]
Min-Max (Bounding box)

Distance to anchors determines a bounding box
Center of box estimates node position

**Main idea:**

construct a bounding box for each anchor using its position and distance estimate
determine the intersection of these boxes.
The position of the node is set to the centre of the intersection box.
Centroid-based Localization

Nodes localize themselves to the centroid of their proximate reference points

- Simple to implement
- Assume perfect spherical radio propagation.
- Assume Identical transmission range for all radios.
- Every anchor beacon's location information \((X_i, Y_i)\)

\[
(X_{\text{est}}, Y_{\text{est}}) = \left( \frac{X_{i1} + \ldots + X_{ik}}{k}, \frac{Y_{i1} + \ldots + Y_{ik}}{k} \right).
\]
Multi-Dimensional Scaling (MDS)

MDS maps objects from a high-dimensional space to a low-dimensional space, while preserving distances between objects.

similarity between objects <-> coordinates of points

Classical metric MDS:
• Proximities are treated as distances in an Euclidean space

Optimality:
• Exact reconstruction if the proximity data are from an Euclidean space

Efficiency:
• Singular Value Decomposition
Applying Classical MDS

1. Create a proximity matrix of distances $D$
2. Convert into a double-centered matrix $B$

$$B = -\frac{1}{2} \left( I - \frac{1}{N} U \right) D^2 \left( I - \frac{1}{N} U \right)$$

- $N \times N$ identity matrix
- $N \times N$ matrix of 1s

3. Take the Singular Value Decomposition of $B$

$$B = VAV^T$$

4. Compute the coordinate matrix $X$

$$X = VA^2$$
Example: Localization Using Multidimensional Scaling (MDS) (Yi Shang et. al)

The basic MDS-MAP algorithm:
1. Compute shortest paths between all pairs of nodes.
2. Apply classical MDS to construct a relative map.
3. Given sufficient anchor nodes, transform the relative map to an absolute map.
RECURSIVE POSITION ESTIMATION

• A node determines its reference nodes.
• The node estimates its distance to these reference nodes.
• The node computes its position using trilateration (becoming a settled node).
• The node becomes a reference node by broadcasting its newly estimated position to its neighbors.

When a node becomes a reference, it can assist other nodes in computing their positions as well.
Learning Based Approaches

• Employ a metric for location determination (e.g. RSS)

• localization is usually divided into: **training** and **serving** (testing)

• **Training**
  • involve the **site survey** process in which engineers record the RSS fingerprints at every position of an interesting area and build a **fingerprint database**

• **Serving**
  • user sends a location query with its current RSS fingerprint, localization algorithms **return the matched locations**
RSS Fingerprinting

Training

Runtime

RSS measurements are collected for each position.

Signature map

<table>
<thead>
<tr>
<th>$T_{AP_1, Cell_1}$</th>
<th>$T_{AP_1, Cell_2}$</th>
<th>...</th>
<th>$T_{AP_1, Cell_D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{AP_2, Cell_1}$</td>
<td>$T_{AP_2, Cell_2}$</td>
<td>...</td>
<td>$T_{AP_2, Cell_D}$</td>
</tr>
<tr>
<td>$T_{AP_3, Cell_1}$</td>
<td>$T_{AP_3, Cell_2}$</td>
<td>...</td>
<td>$T_{AP_3, Cell_D}$</td>
</tr>
</tbody>
</table>

Runtime measurements

| $R_{AP_1}$ | $R_{AP_2}$ | $R_{AP_3}$ |

Localization Server (LS)

Compare

Location Estimation
Issues with RSSI

wall-penetrating effect

- signals may encounter a considerable abrupt change while passing through a wall
- RSS of a same AP can vary significantly in two rooms

Figure 1: Abrupt signal changes through a wall. AP1 is deployed in Room I and AP2 in an adjacent Room II. Both data are measured at fixed locations.
Runtime Phase

The location of mobile device is sparse in space.
Localization based on Jointly Sparsity

Motivation
Exploit correlation structures
Reduce the amount of RSS exchanged data

Key idea
✓ Jointly Compressed Sensing
  ▪ Multiple collection points capture related phenomena \( \Rightarrow \) joint structure

Approach
❑ Decentralized Localization
Training Phase

• Construction of the signature map

```
<table>
<thead>
<tr>
<th>Time</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{1,1}$</td>
<td>$R_{J,1}$</td>
</tr>
<tr>
<td>$R_{1,t}$</td>
<td>$R_{J,t}$</td>
</tr>
</tbody>
</table>
```

• Construction of the measurement matrix
• Each BS contracts a random measurement matrix $\Phi$
Decentralized Localization

- Runtime phase

- Initial estimation

Each BS $j$ samples locally RSS measurements $\Rightarrow$ measurement vector $y_j$

Each BS creates initial estimations

$y_1 \Rightarrow b_1(0)$

$y_2 \Rightarrow b_2(0)$

$\vdots$

$y_j \Rightarrow b_j(0)$
Decentralized Localization

- Runtime phase

- Decision Fusion

  Average consensus algorithm

**Pairwise Gossip**
Random pairs of nodes iteratively average their estimations
Decentralized Localization

- Runtime phase

- Fine Localization

Upon convergence each BS detects the position $p$ of the mobile user
Localization performance

CDF

Location Error (m)

CS-based, Pairwise, 50% CS meas.
CS-based, Selective - q = 0.5, 50% CS meas.
KNN
Bayesian
Multi-modal localization

- *Site Survey*
  - time-consuming
  - labor-intensive
  - easily affected by environmental dynamics
- Exploiting user motions from mobile phones
- Tri-axial accelerometers
  - obtain user movements and utilizes moving traces to assist localization
  - explore reachability between different areas
- Achieve competitive room level accuracy
WILL: Wireless Indoor Localization Without Site Survey
Room-level localization

Figure 7: Accelerometer over different postures. I: the phone is horizontally placed; II: the phone is sideways up; III: the phone is vertically placed

Figure 13: CDF of per user accuracy.
UltraWide Band

• UWB is a technology developed to transfer large amounts of data wirelessly over short distances over a very wide spectrum of frequencies in a short period of time

• This technology operates at a level that most systems interpret as noise and, as a result, does not cause interference to other radios such as cell phones, cordless phones or broadcast television sets

• UWB will be ideally suited for transmitting data between consumer electronics (CE), PC peripherals, and mobile devices within short range at very high speeds while consuming little power
What is UltraWideBand?

- Communication that occupies more than 500 MHz of spectrum
- Communication with fractional bandwidth of more than 0.2

**Frequency Modulation**

- 2.4 GHz
- Narrowband Communication

**Impulse Modulation**

- 3-10 GHz
- Ultrawideband Communication

- (FCC Min=500Mhz)
UWB in WSNs

IEEE 802.15.4 (2003) low data rate communications systems (Zig-Bee)

The 802.15.4a (2007) support higher data rates and accurate ranging capability

Benefits for WSNs

• Trade power for bandwidth vs. power
• Excellent robustness against fading
• Limited interference from concurrent transmitters
• Resistant to jamming
UWB based localization

- \( L_{RT} = T_{RR} - T_{SB} \)
- \( L_{TA} = T_{SF} - T_{RR} \)
- \( F_{RT} = T_{RF} - T_{SR} \)
- \( F_{TA} = T_{SR} - T_{RB} \)

\[
2T_l = (T_{RR} - T_{SB}) - (T_{SR} - T_{RB})
\]

\[
2T_f = (T_{RF} - T_{SR}) - (T_{SF} - T_{RR})
\]

\[
T = \frac{2T_l + 2T_f}{2 \times 2}
\]
Evaluation of IR-UWB for localization

(a) Outdoor LOS  (b) Indoor LOS  (c) Soft NLOS  (d) Hard NLOS

- Average Ranging Error vs LOS Distance Measurement (m)
- Distance vs Number of Obstructions

- Bar graph showing distance measurements under different conditions.

- Chart displaying ranging error along LOS distances.

Spring Semester 2017-2018
CS-541 Wireless Sensor Networks
University of Crete, Computer Science Department
Reading List

• Wireless Sensor Networks by Akyildiz, Vuran, Chapter 12 Localization

• Material Used
Slides prepared by Lanchao Liu and Zhu Han, ECE Department, University of Houston, Mar. 2010