CS-541
Wireless Sensor Networks

Lecture 13: Localization in WSNs

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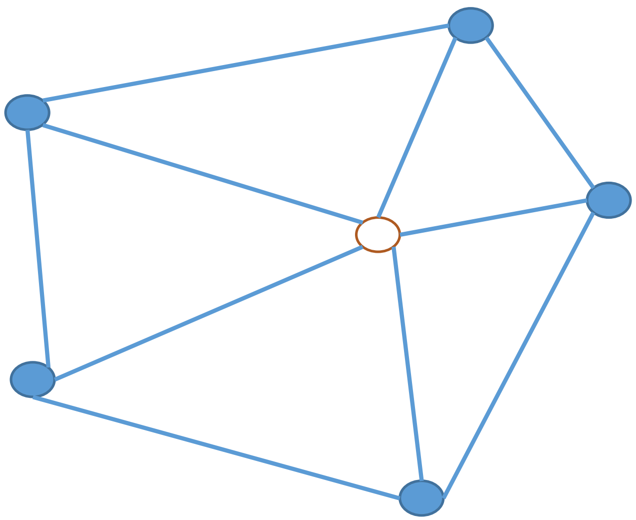
Overview

- Geometric-based
- Learning-based
- Hardware-based



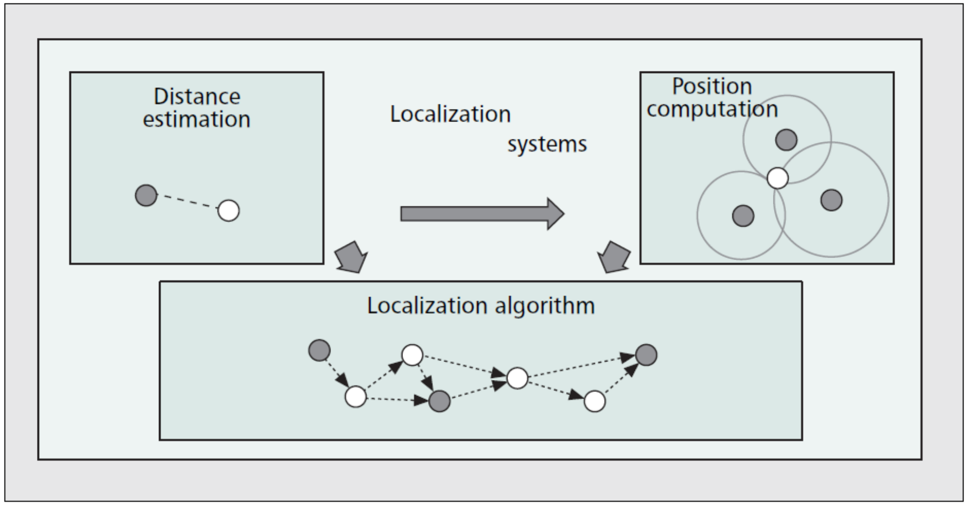
Location information and network services

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

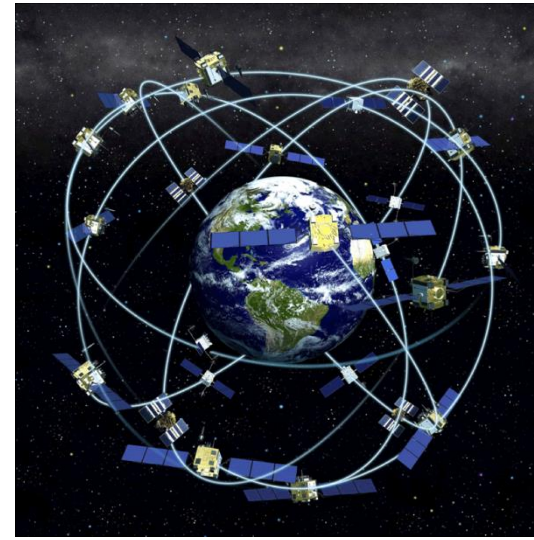
- Medical care
- Smart space
- Logistics
- Environment monitor
- Mobile P2P
- Social Networks
- Gaming

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)

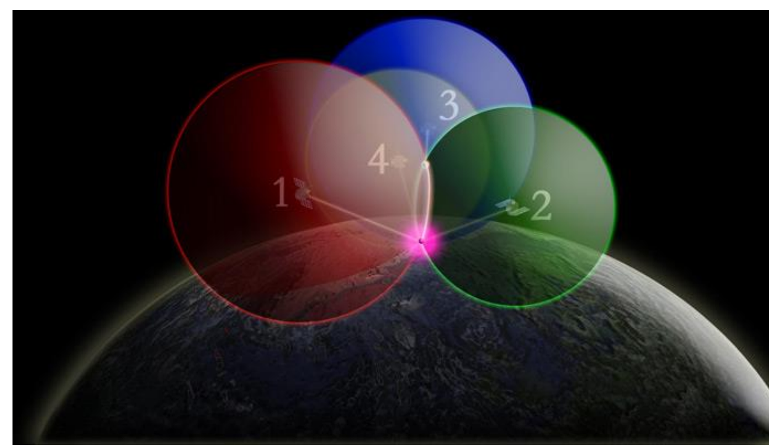


Usage of Global Positioning System (GPS) devices

- 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)



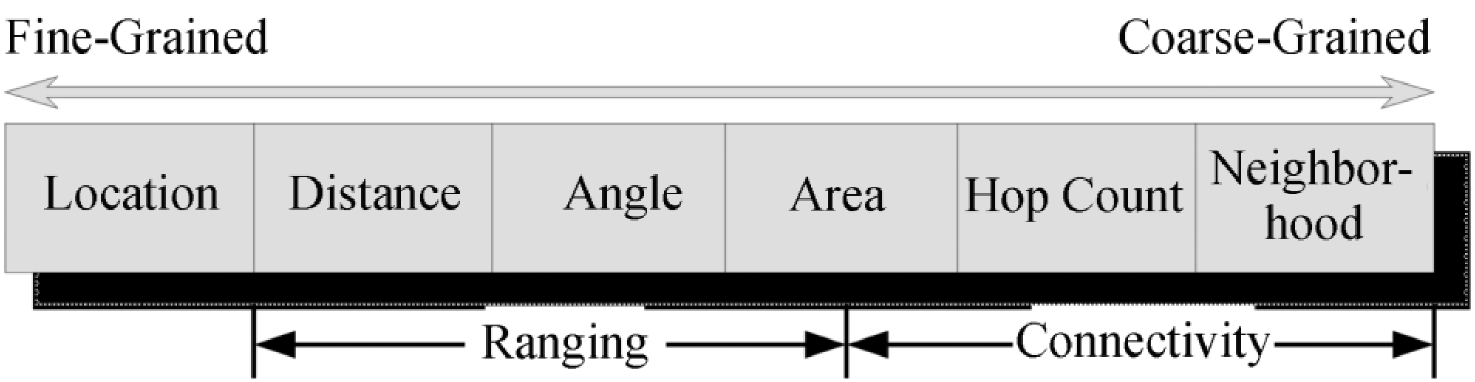
Taxonomy

- 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

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

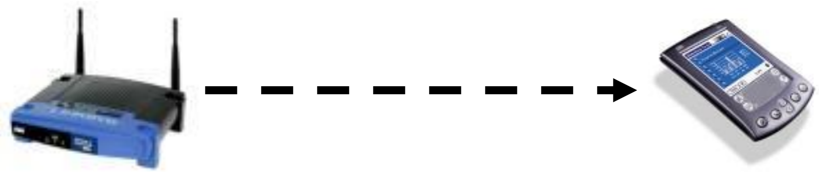
path-loss exponent

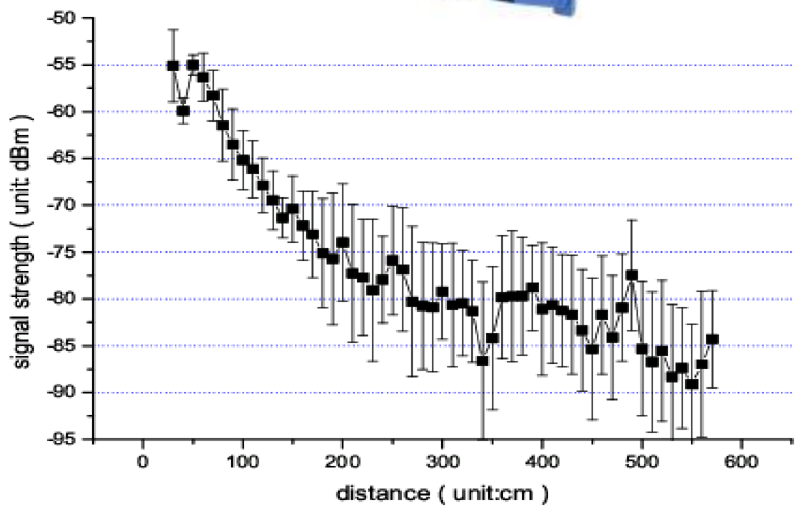
fading effects

Received power at distance d

Received power at some reference distance d_0

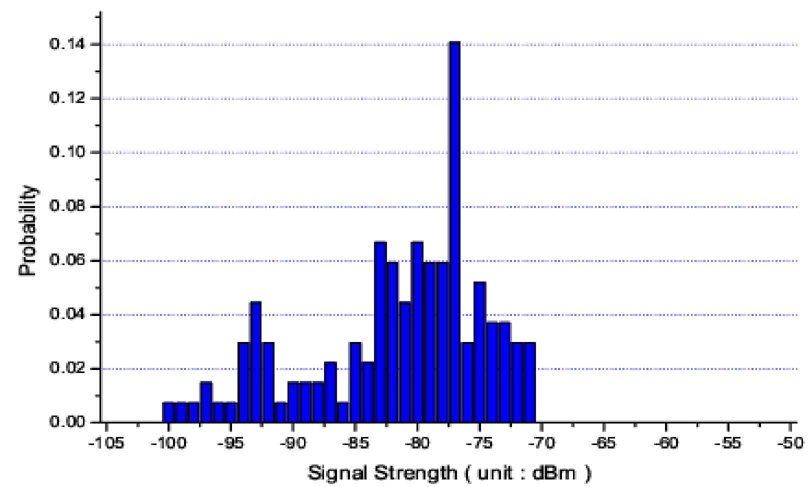
“Cheap and Ubiquitous Received-Signal-Strength” ?





Signal attenuation along with distance

nonlinear

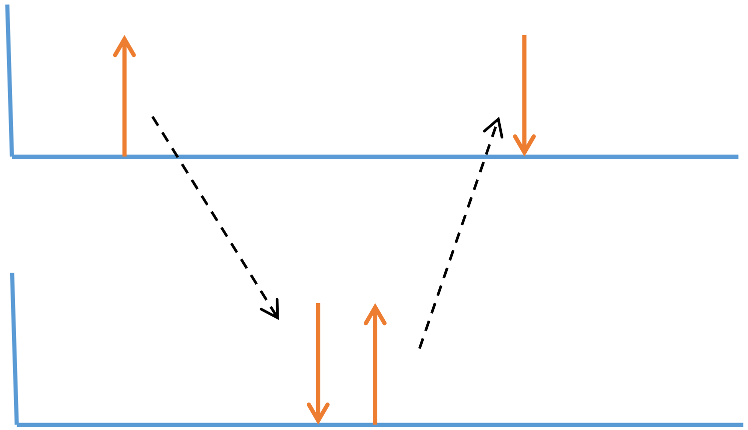


Signal Distribution at a fixed location

noisy

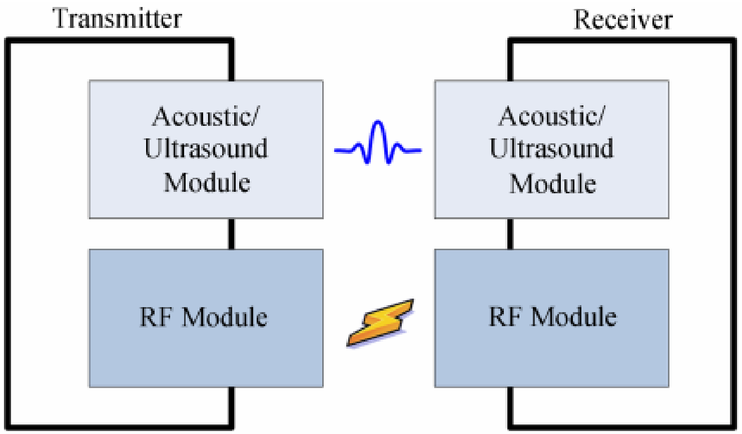
Timing-based approaches

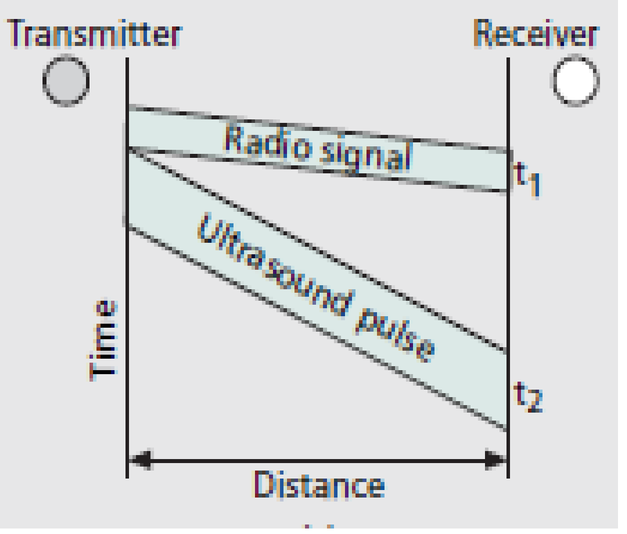
- **Time based methods (ToA, TDoA)** record the time-of-arrival (ToA) or time-difference-of-arrival (TDoA).
- Propagation time can be directly translated into distance, based on the known signal propagation speed.
- Active vs. Passive
- One-way propagation time and roundtrip propagation time measurements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



TDoA Distance estimation

TDoA: better resolution but costly





$$\hat{d} = (c - s_s)(t_2 - t_1)$$

Need line-of-sight conditions

Uncertainties: temperature, humility, synchronization & delay.

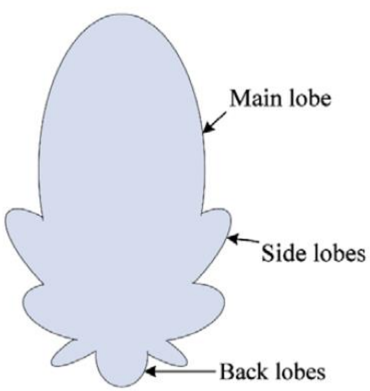
Angle-based approaches

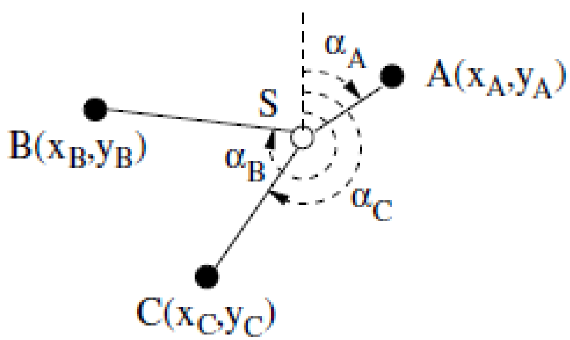
Angle-of-Arrival (AoA): estimate the angle at which signals are received and use simple geometric relationships to calculate node positions

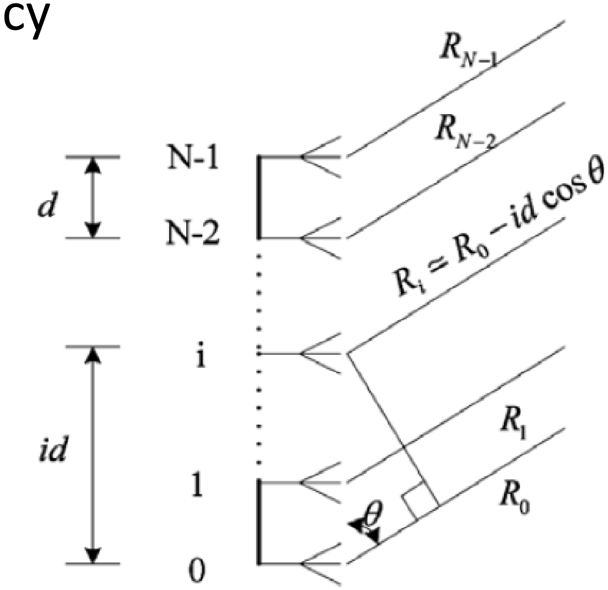
localization accuracy <-> measurement accuracy

Requires multiple antennas

- Antenna array
- Sensor array

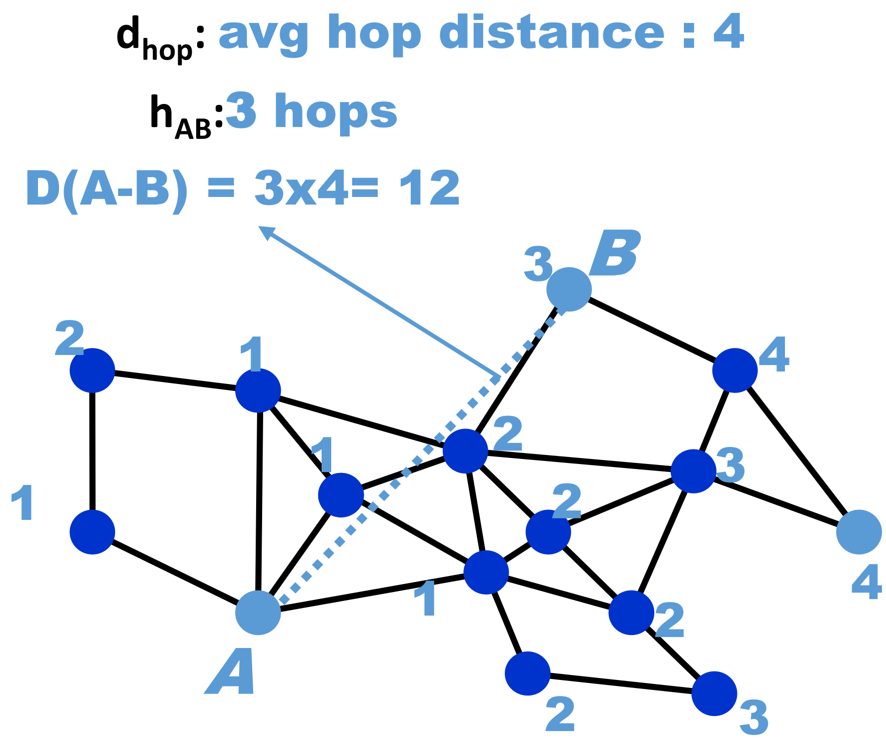






$$R_i \approx R_0 - id \cos\theta,$$

Hop-count



Anchors

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

Nodes

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

$$D = h_{ij} * R$$

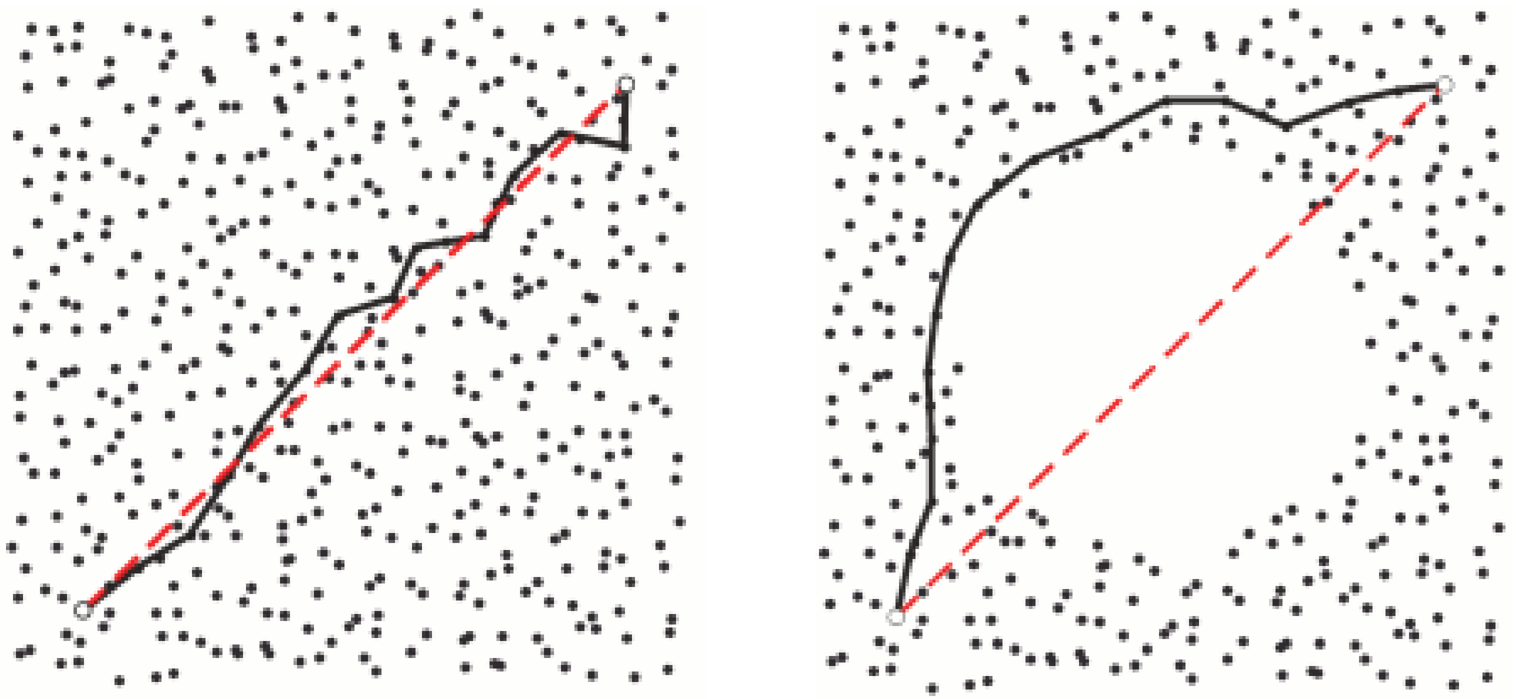
Number of hops — Communication range

$$d_{\mathrm{hop}} = R\left(1 + e^{-n_{\mathrm{local}}} - \int_{-1}^{1} e^{-(n_{\mathrm{local}}/\pi)\arccos t - t\sqrt{1-t^2}}\,\mathrm{d}t\right)$$

The expected number of neighbors

$$D = h_{ij} * d_{hop}$$

Hop-count - Limitation



Failed in anisotropic network !

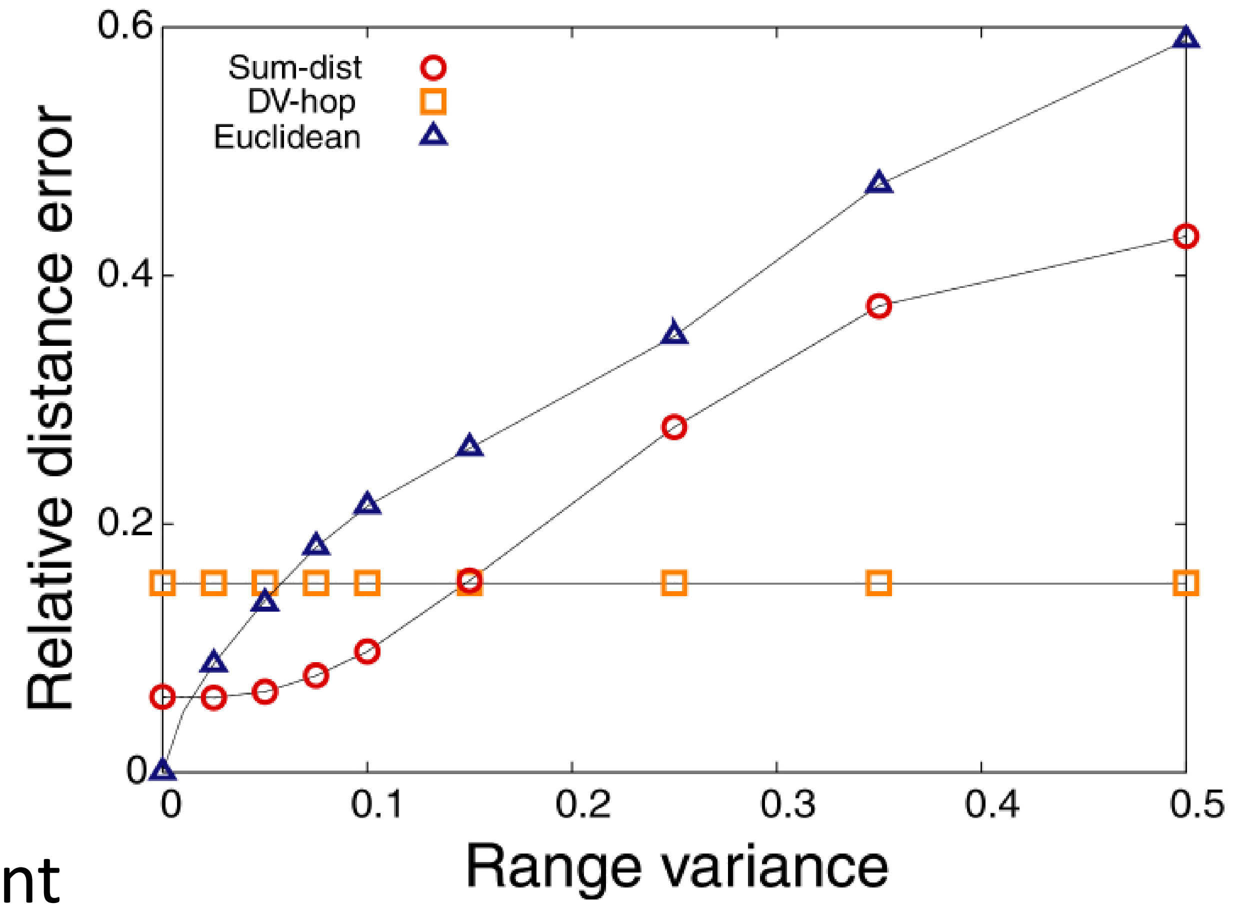
Comparative Study & Future work

Physical Measurements		Accuracy	Hardware Cost	Computation Cost
Distance	RSS	Median	Low	Low
	TDoA	High	High	Low
Angle	AoA	High	High	Low
Area	Single reference	Median*	Median*	Median
	Multi-reference	Median*	Median*	High
Hop Count	Per-hop distance	Median	Low	Median
Neighborhood	Single neighbor	Low	Low	Low
	Multi-neighbor	Low	Low	Low

$*$: depends on the diverse geometric constrains

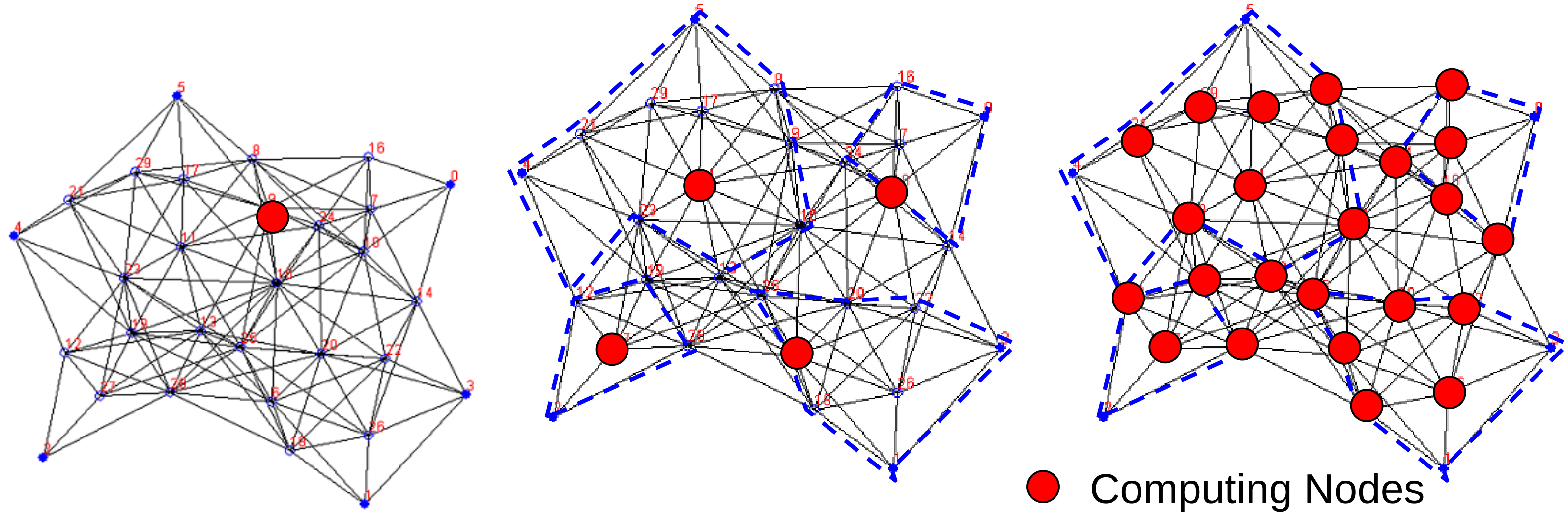
Promising technique: UWB and Chirp Spread Spectrum

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

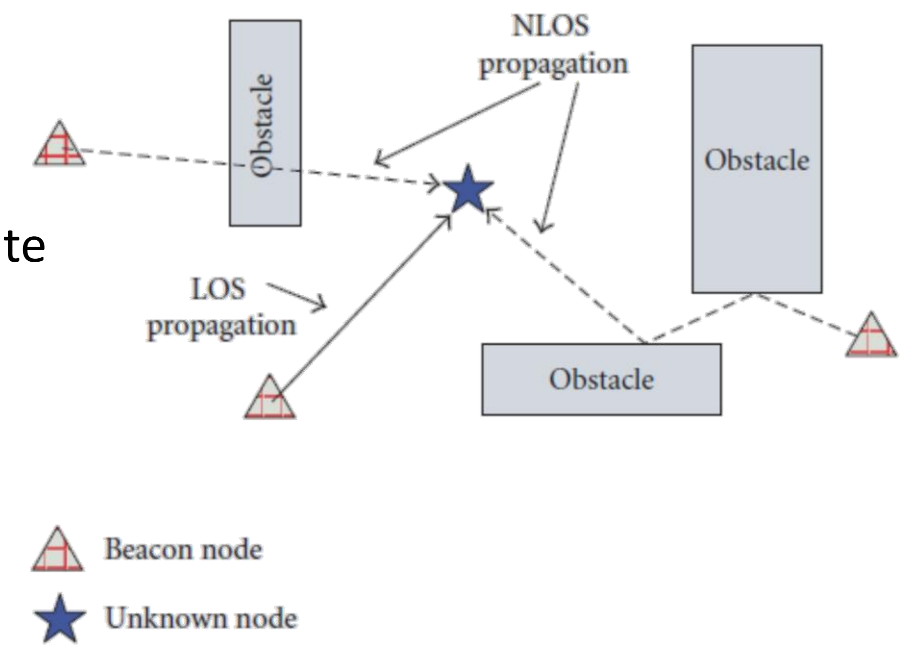
Relative vs. Absolute localization

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

There are three algorithms

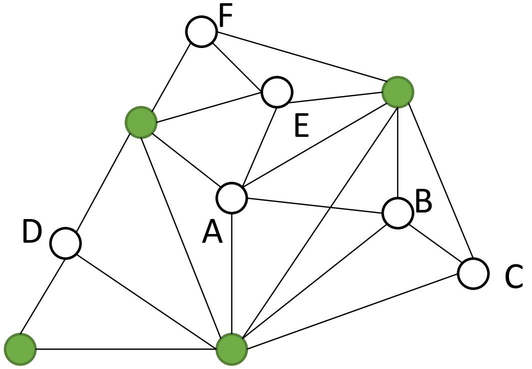
- Sum-Dist (DV-Distance)
- DV-Hop
- Euclidean

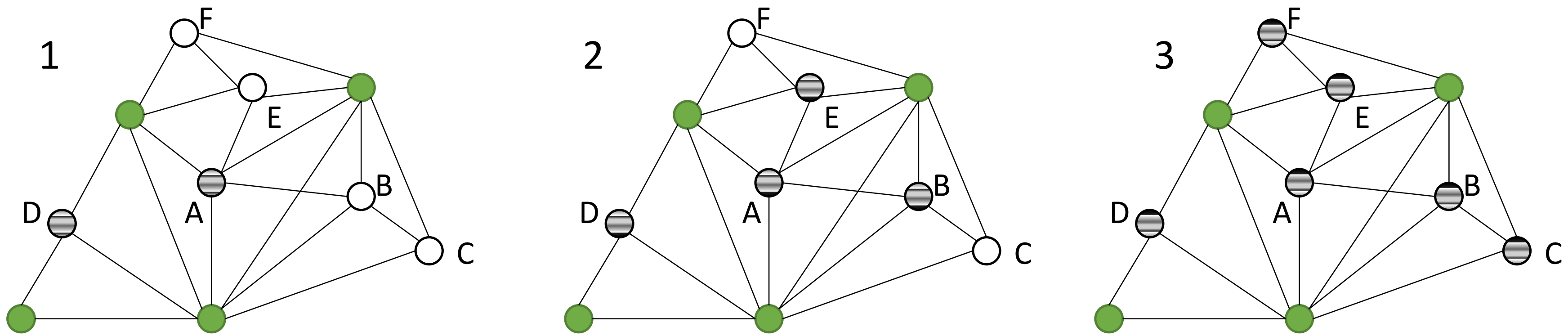
Anchors flood the network with their position



Example of lateration

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



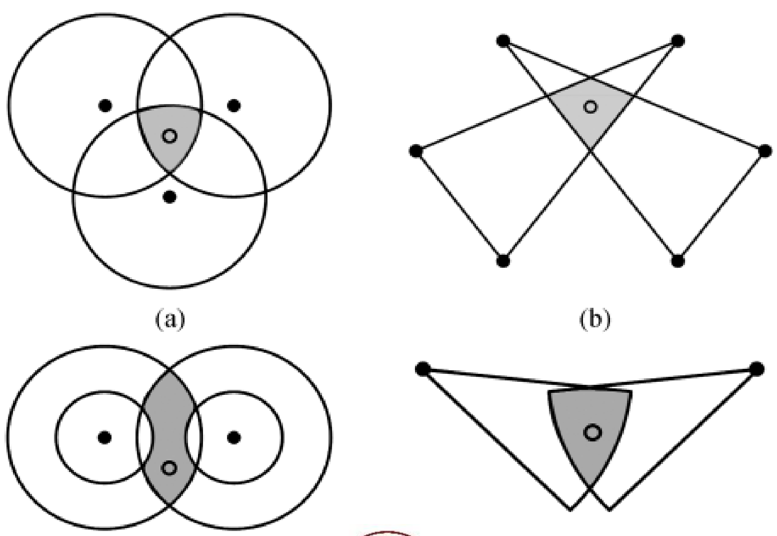


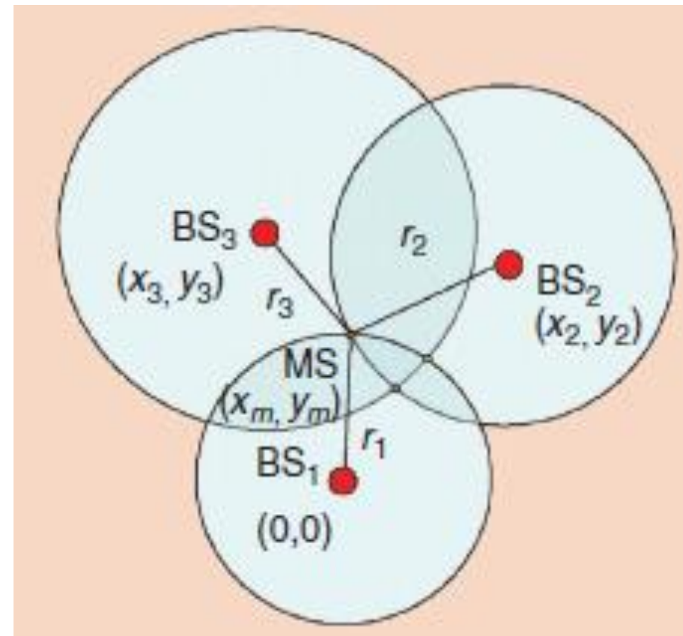
Area Based Estimation

Single Reference Area Estimation

- Distance, angle, etc.

Compute the intersection of overlapping regions -> centroid

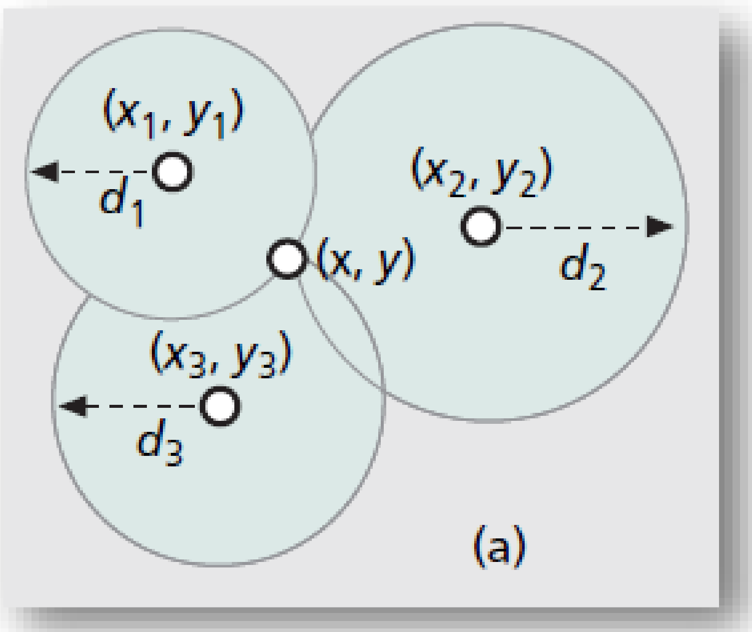




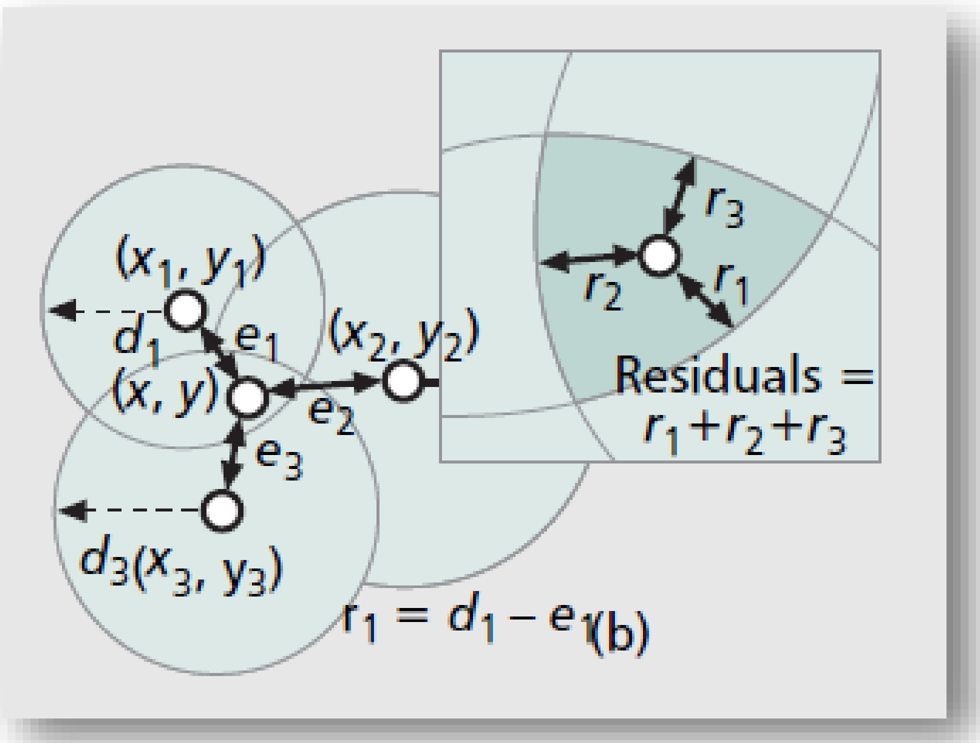
$$r_1^2 = x_m^2 + y_m^2$$
$$r_2^2 = (x_2 - x_m)^2 + (y_2 - y_m)^2$$
$$r_3^2 = (x_3 - x_m)^2 + (y_3 - y_m)^2.$$

Trilateration in practice

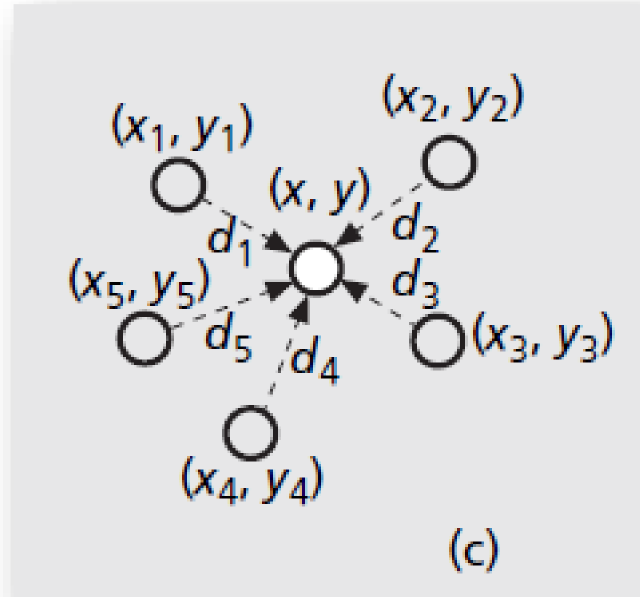
Ideal scenario



Realist scenario



Multilateration



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

$$\mathbf{Hx} = \mathbf{z}$$

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

$$x = (H^T H)^{-1} H^T z.$$

Min-Max (Bounding box)

Distance to anchors determines a bounding box

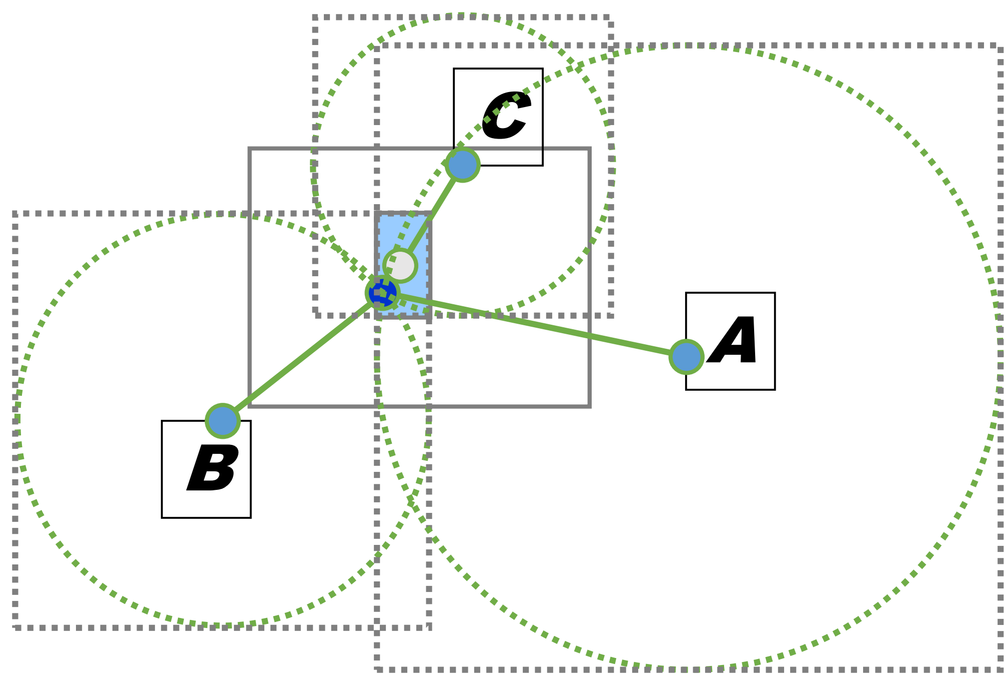
Center of box estimates node position

Main idea:

construct a bounding box for each anchor using its position and distance estimate

determine the intersection of these boxes.

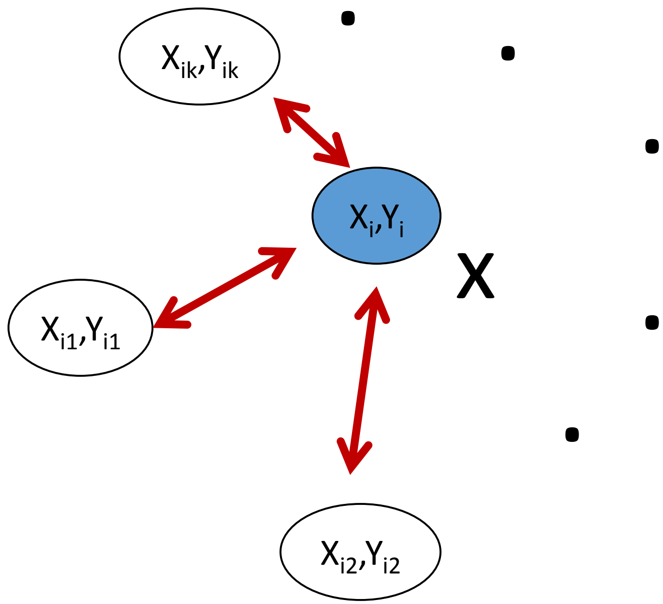
The position of the node is set to the centre of the intersection box.



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 beacons location information (Xi,Yi)



$$(X_{est}, Y_{est}) = \left(\frac{X_{i1} + \ldots + X_{ik}}{k}, \frac{Y_{i1} + \ldots + Y_{ik}}{k} \right).$$

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

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

NxN identity matrix

NxN matrix of 1s

NxN matrix of 1s

3. Take the Singular Value Decomposition of B

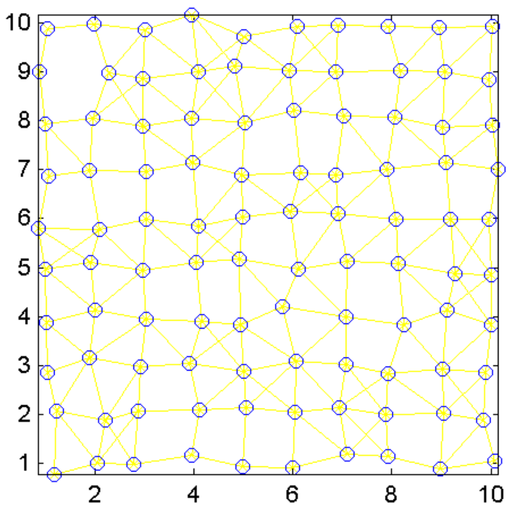
$$B = VAV^T$$

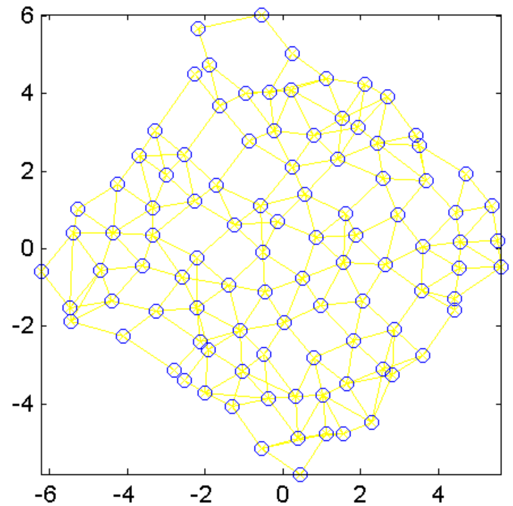
4. Compute the coordinate matrix X $\quad X = VA^{\frac{1}{2}}$

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.



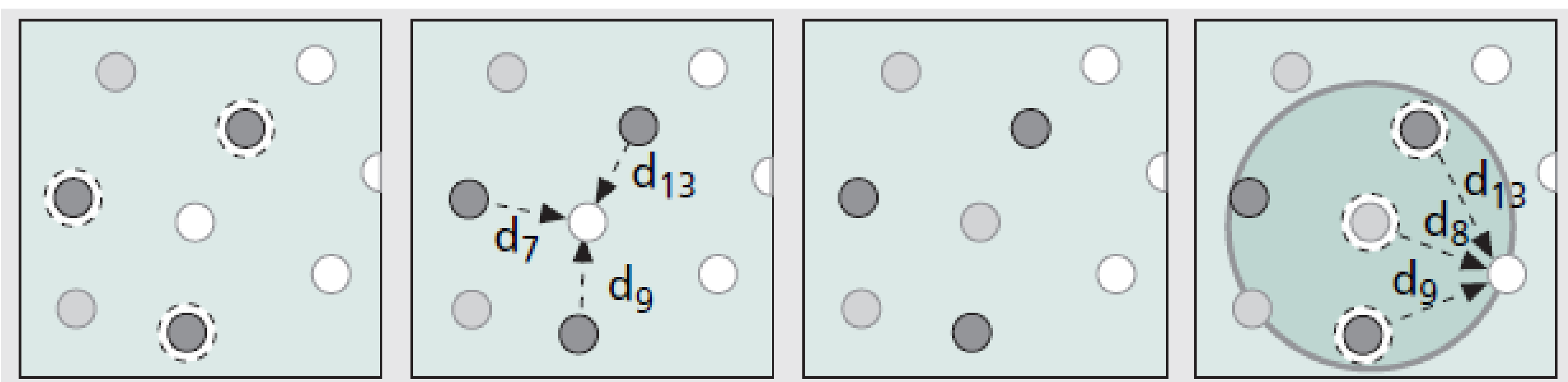


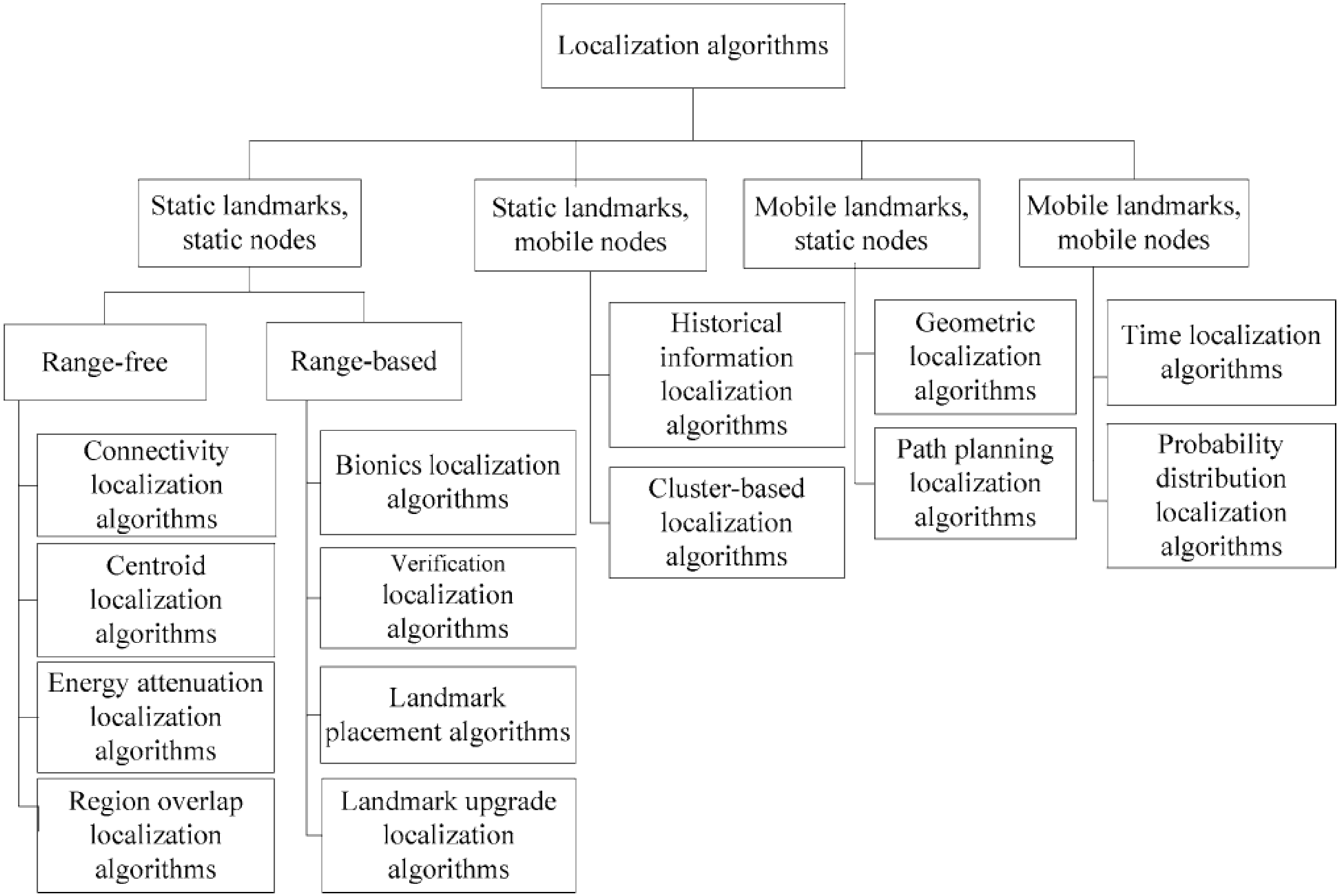
3. Given sufficient anchor nodes, transform the relative map to an absolute map.

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.



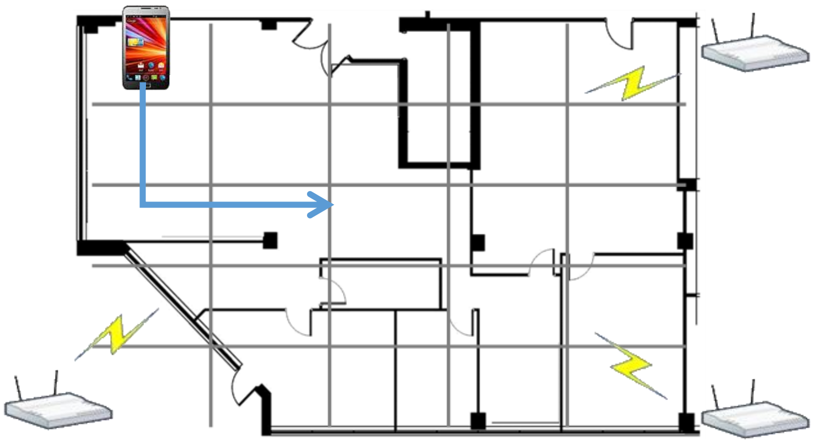

Localization algorithms
Static landmarks, static nodes
Static landmarks, mobile nodes
Mobile landmarks, static nodes
Mobile landmarks, mobile nodes
Range-free
Range-based
Connectivity localization algorithms
Centroid localization algorithms
Energy attenuation localization algorithms
Region overlap localization algorithms
Bionics localization algorithms
Verification localization algorithms
Landmark placement algorithms
Landmark upgrade localization algorithms
Historical information localization algorithms
Cluster-based localization algorithms
Geometric localization algorithms
Path planning localization algorithms
Time localization algorithms
Probability distribution localization algorithms

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

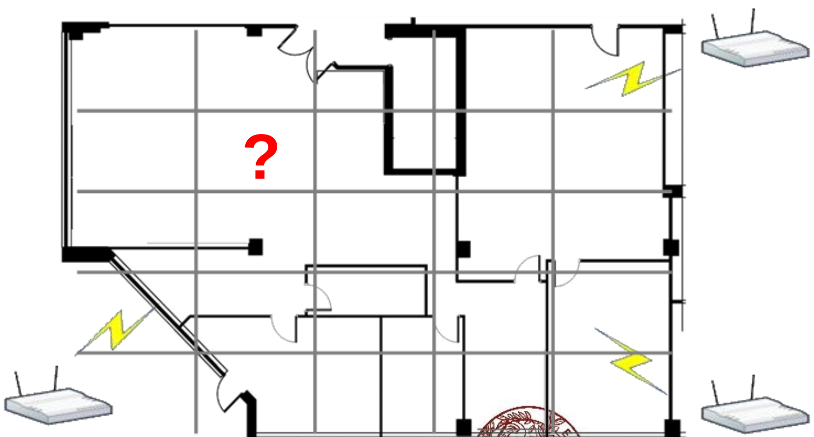


RSS measurements are collected for each position.

Signature map

$T_{AP_1,Cell_1}$	$T_{AP_1,Cell_2}$	…	$T_{AP_1,Cell_D}$
$T_{AP_2,Cell_1}$	$T_{AP_2,Cell_2}$	…	$T_{AP_2,Cell_D}$
$T_{AP3,Cell_1}$	$T_{AP_3,Cell_2}$	…	$T_{AP3,Cell_D}$

Runtime



Runtime measurements

R_{AP_1}	R_{AP_2}	R_{AP3}

Compare

$T_{AP_1,Cell_1}$	$T_{AP_1,Cell_2}$	…	$T_{AP_1,Cell_D}$
$T_{AP_2,Cell_1}$	$T_{AP_2,Cell_2}$	…	$T_{AP_2,Cell_D}$
$T_{AP_3,Cell_1}$	$T_{AP_3,Cell_2}$	…	$T_{AP_3,Cell_D}$

Localization Server (LS)

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

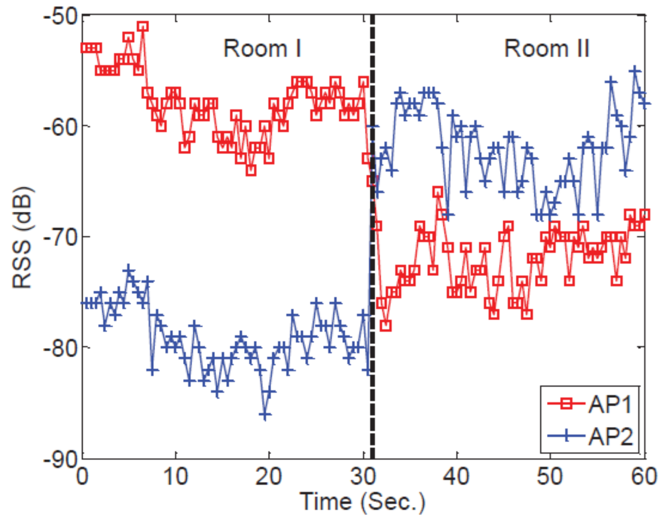
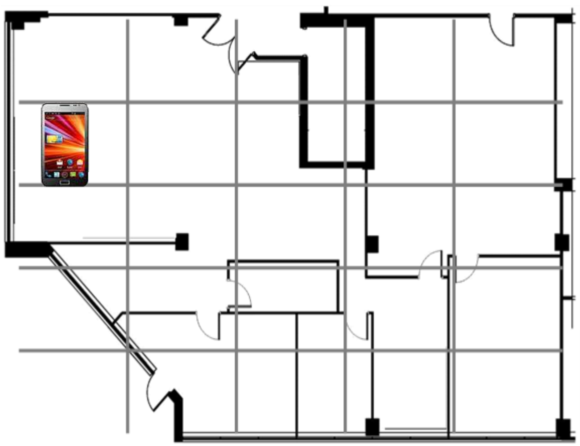


Figure 1: Abrupt signal changes through a wall. AP1 is deployed in Room I and AP2 in an adjacent Room II. Both data are measured at fixed locations.

Runtime Phase

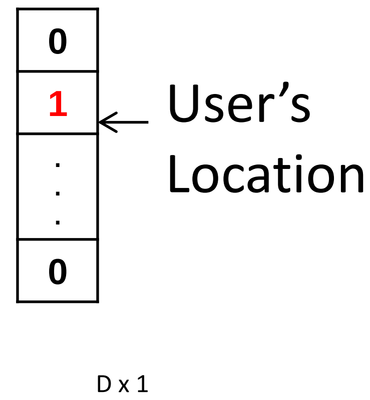


0	0	0	0	0
1	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

D cells

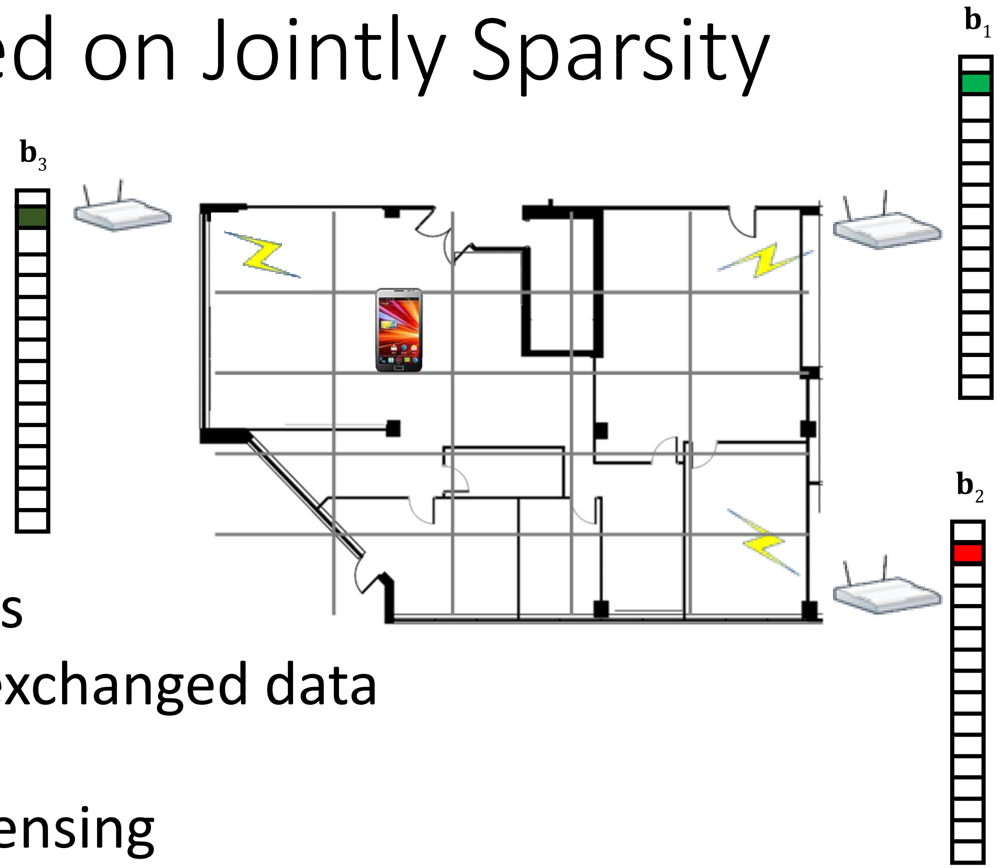
Space Vectorization

Sparse vector: b



- **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

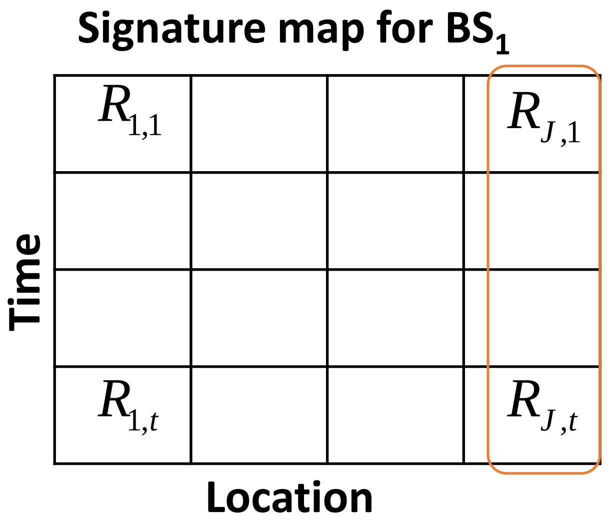
- Multiple collection points capture related phenomena ⇨ joint structure

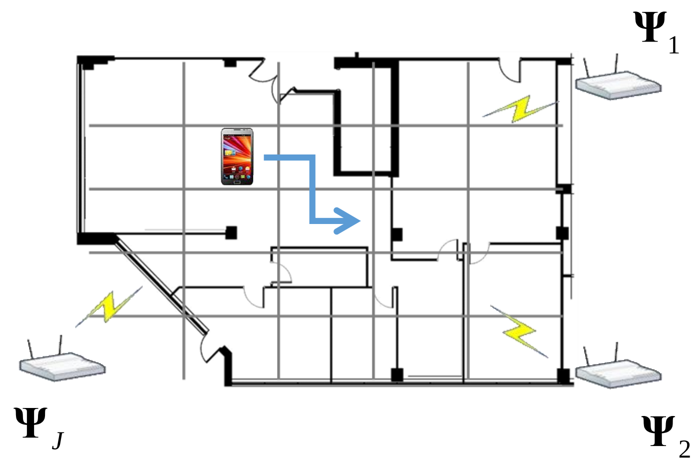
Approach

❑ Decentralized Localization

Training Phase

- Construction of the signature map





- Construction of the measurement matrix
- Each BS contracts a random measurement matrix Φ

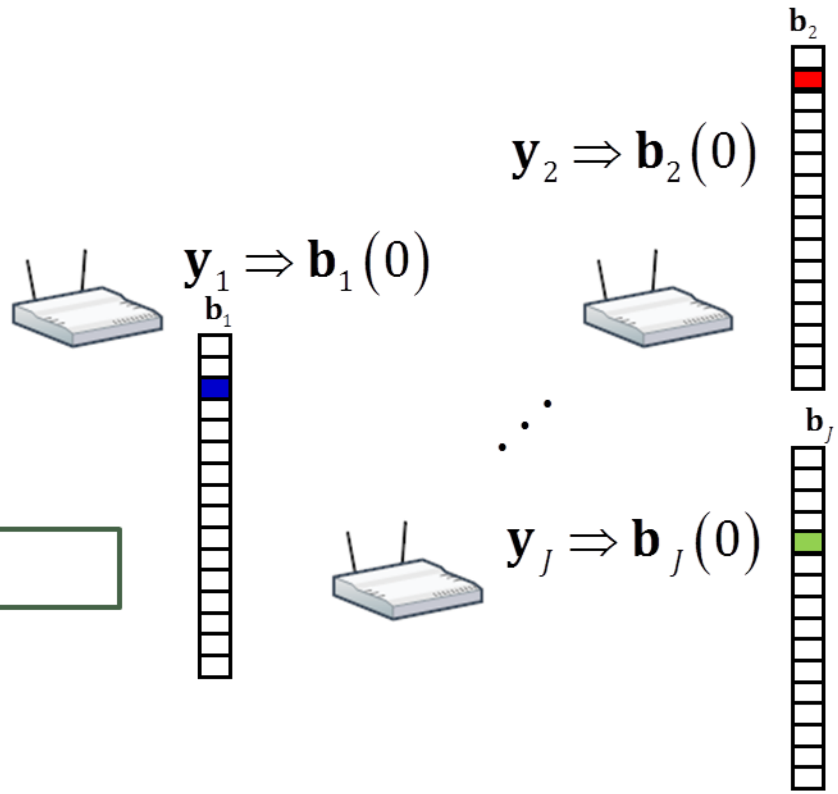
Decentralized Localization

- Runtime phase

❑ Initial estimation

Each BS j samples locally RSS measurements ⇨ measurement vector $\mathbf{y}_j$

Each BS creates initial estimations



Decentralized Localization

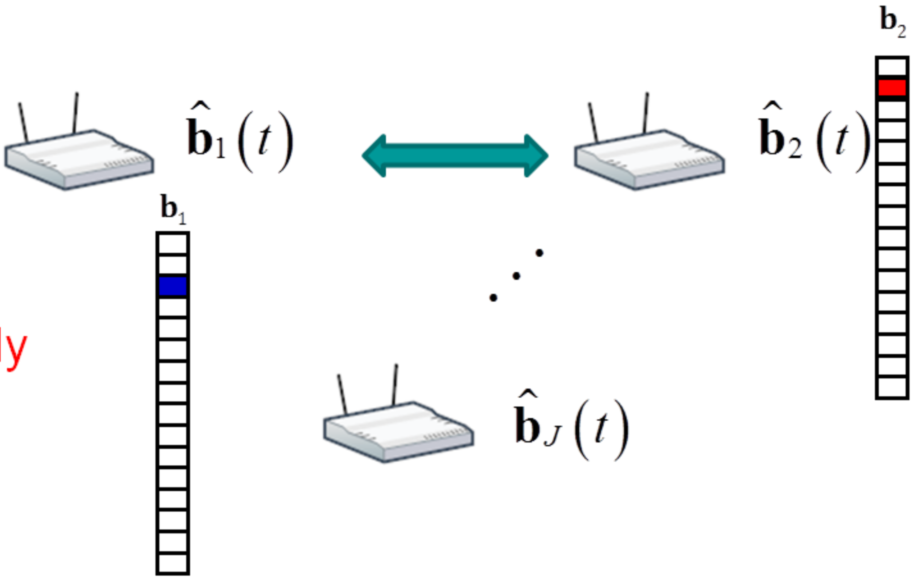
- Runtime phase

❑ Decision Fusion

Average consensus algorithm

Pairwise Gossip

Random pairs of nodes iteratively average their estimations

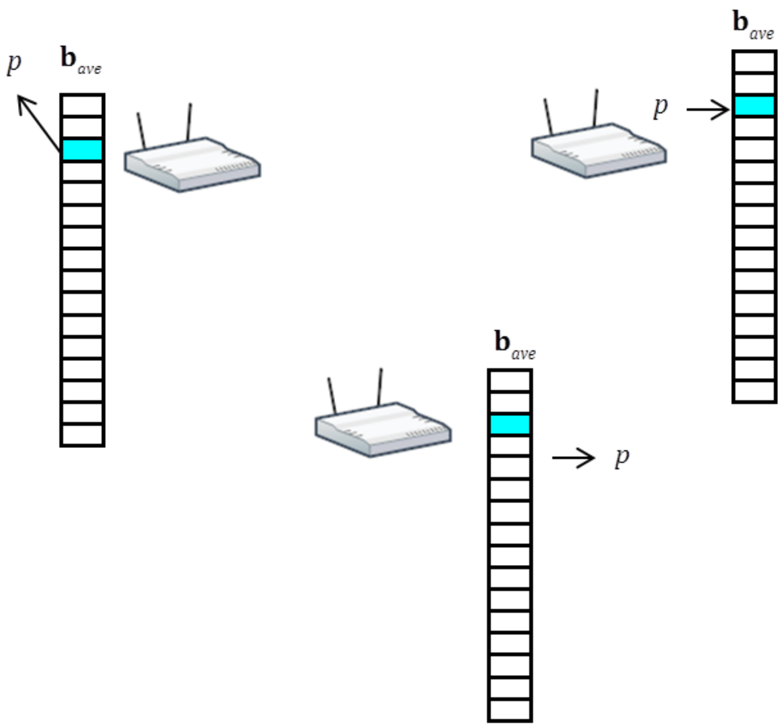


Decentralized Localization

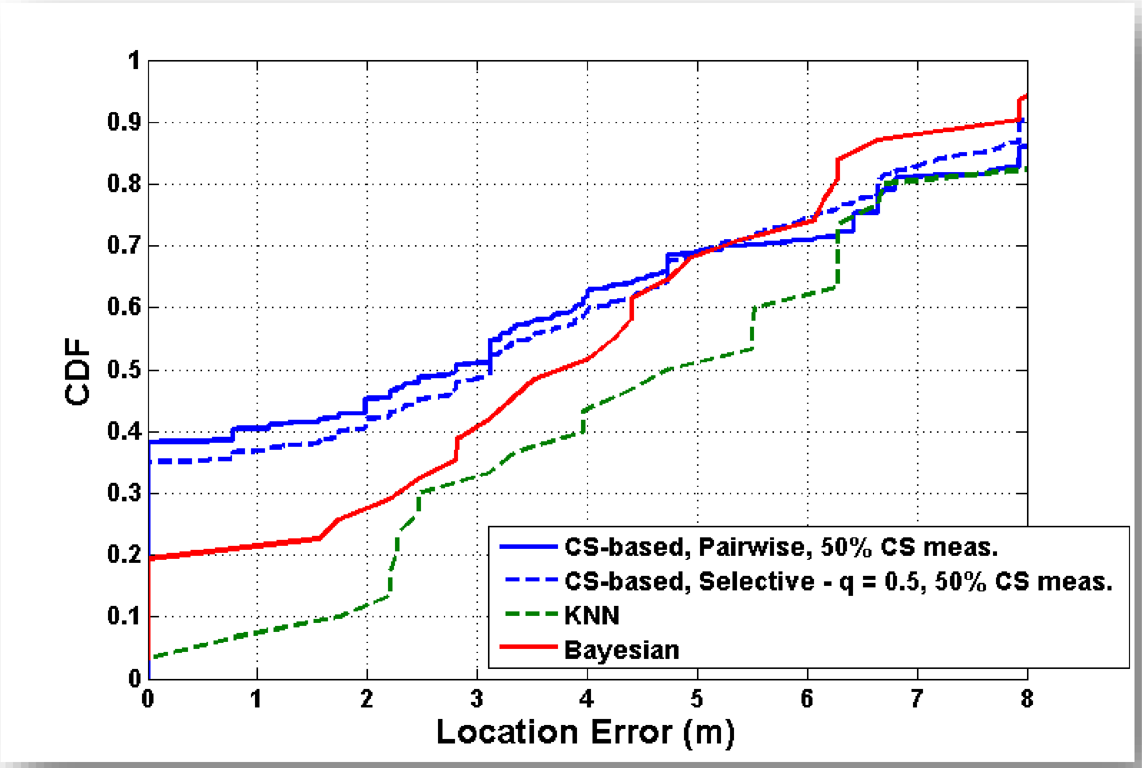
- Runtime phase

❑ Fine Localization

Upon convergence each BS detects the **position p** of the mobile user



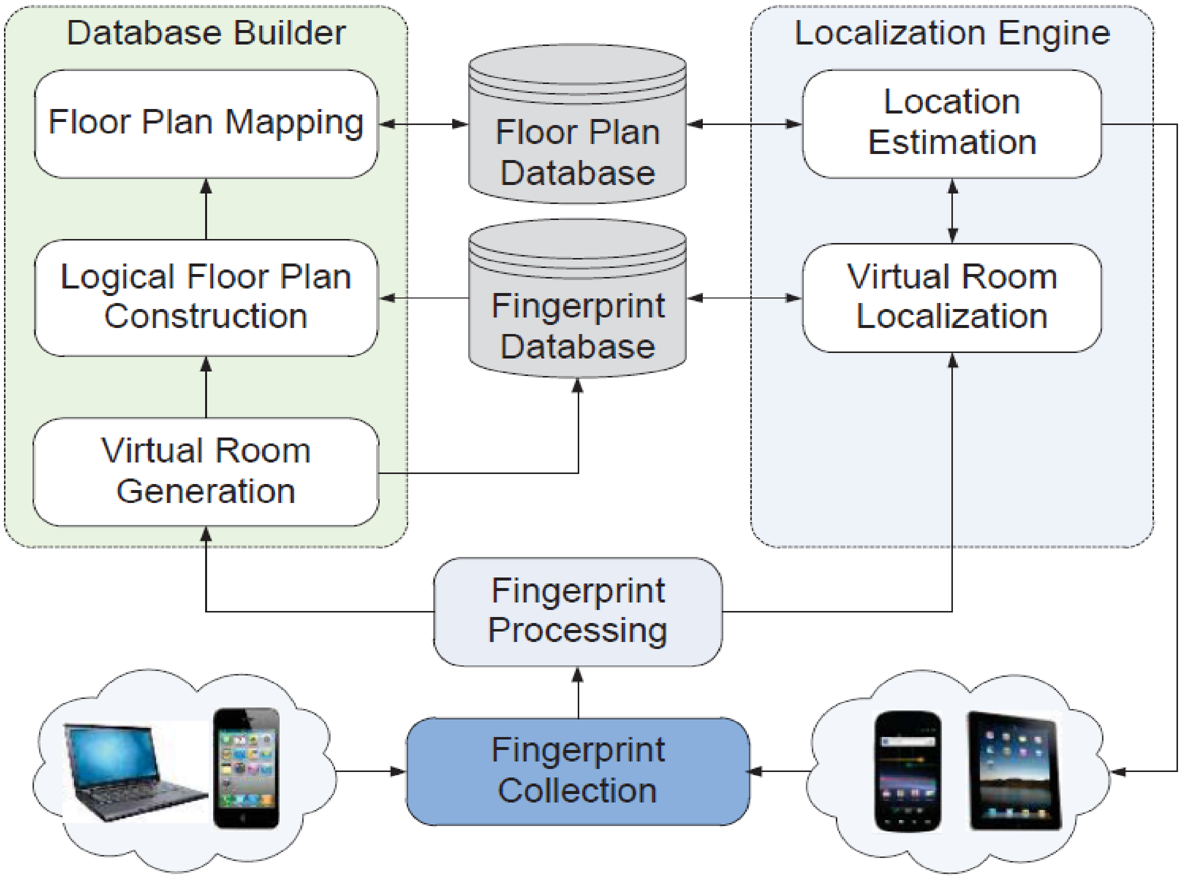
Localization performance



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

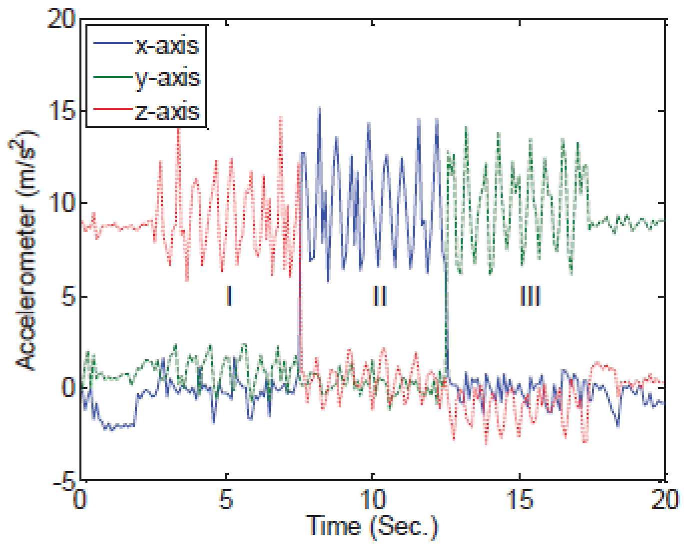


Figure 7: Accelerometer over different postures. I: the phone is horizontally placed; II: the phone is sideways up; III: the phone is vertically placed

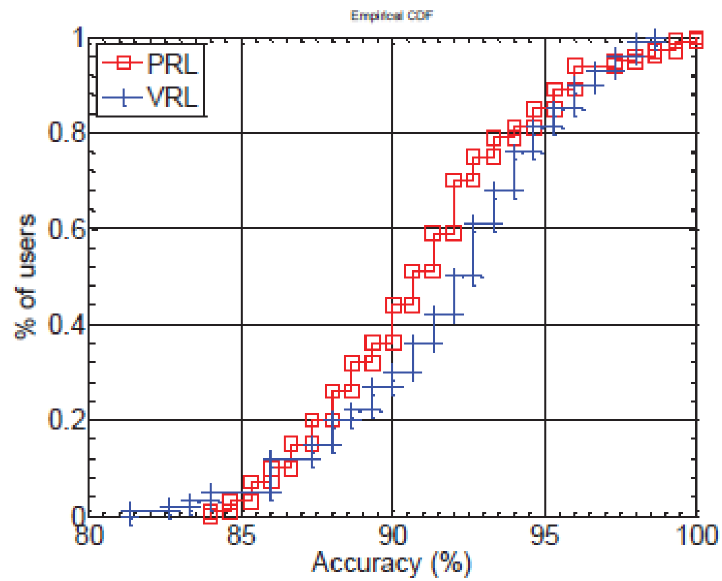
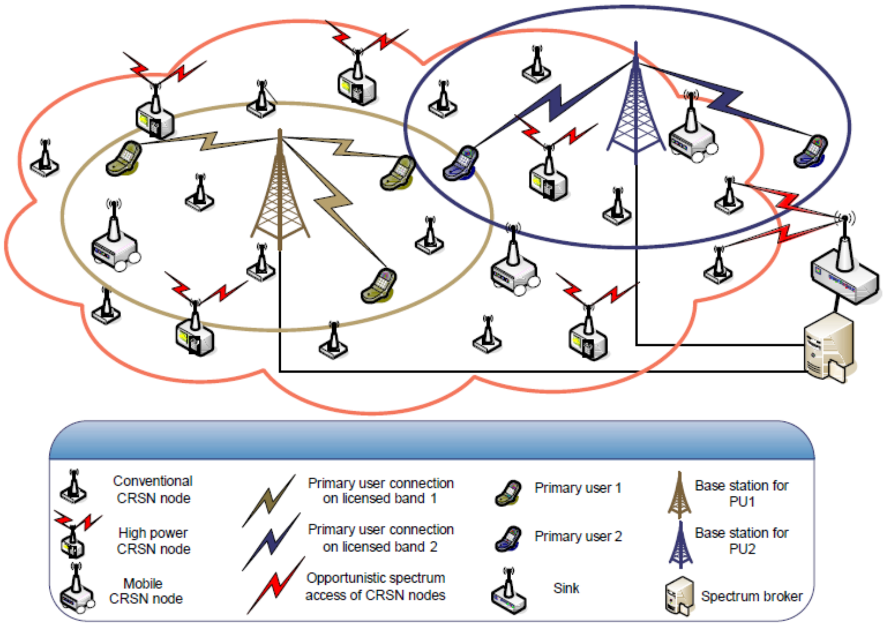


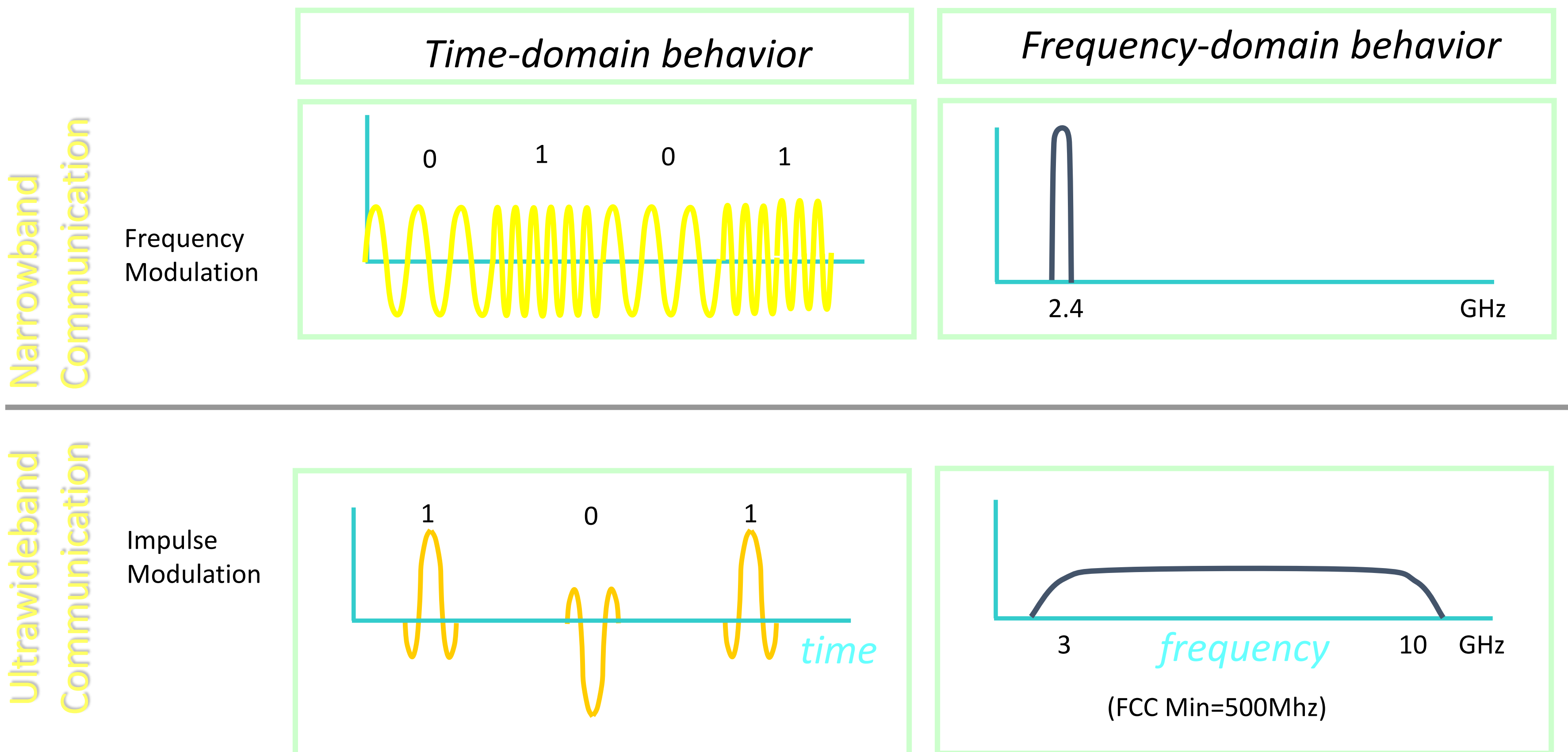
Figure 13: CDF of per user accuracy.

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

UWB in WSNs

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

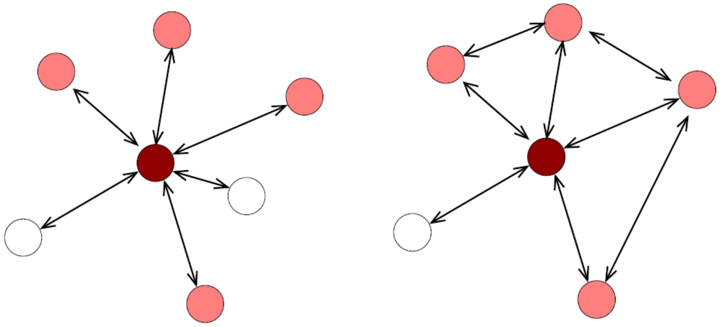
The 802.15.4a (2007) support higher data rates and accurate ranging capability

Benefits for WSNs

- Trade power for bandwidth vs. power
- Excellent robustness against fading
- Limited interference from concurrent transmitters
- Resistant to jamming

CHANNELIZATION SCHEME IN IEEE 802.15.4A

Channel	Center frequency (MHz)	Bandwidth (MHz)
0	499.2	499.2
1	3494.4	499.2
2	3993.6	499.2
3	4492.8	499.2
4	3993.6	1331.2
5	6489.6	499.2
6	6988.8	499.2
7	6489.6	1081.6
8	7488.0	499.2
9	7987.2	499.2
10	8486.4	499.2
11	7987.2	499.2
12	8985.6	499.2
13	9484.8	499.2
14	9984.0	499.2
15	9484.8	1355



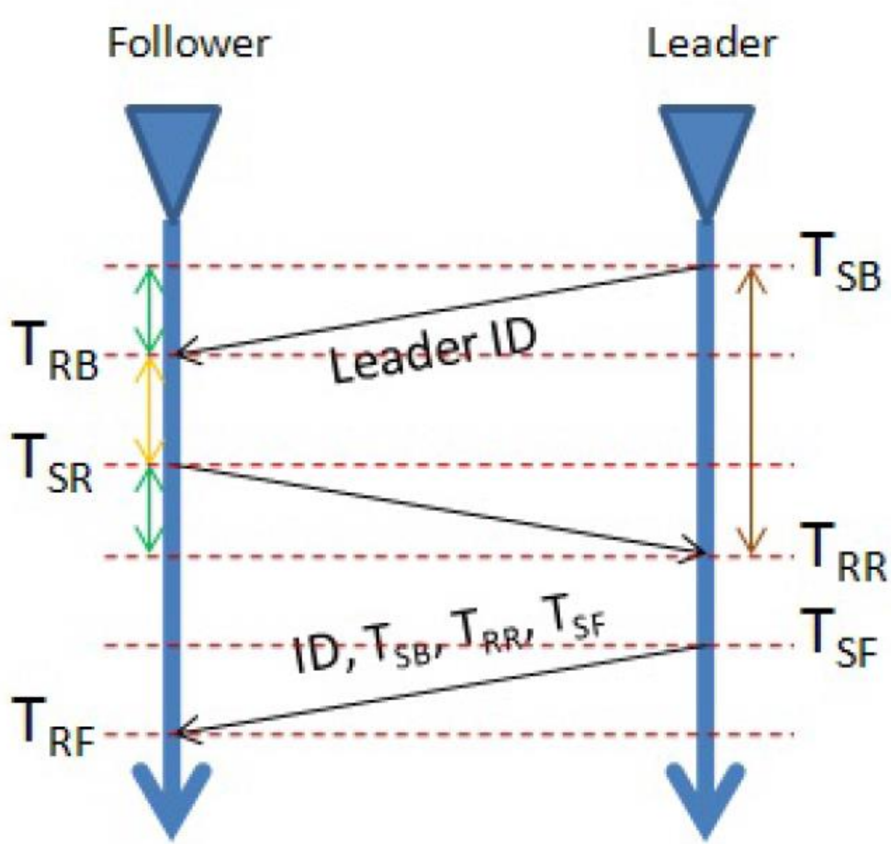
UWB based localization

- $L_{RT} = T_{RR} - T_{SB}$
- $L_{TA} = T_{SF} - T_{RR}$
- $F_{RT} = T_{RF} - T_{SR}$
- $F_{TA} = T_{SR} - T_{RB}$

$$2T_l = (T_{RR} - T_{SB}) - (T_{SR} - T_{RB})$$

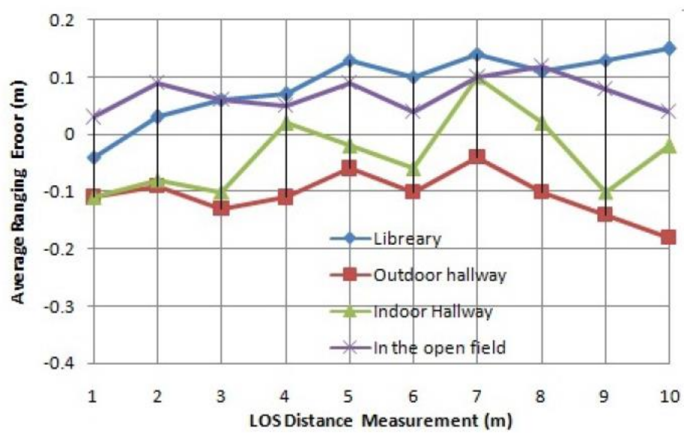
$$2T_f = (T_{RF} - T_{SR}) - (T_{SF} - T_{RR})$$

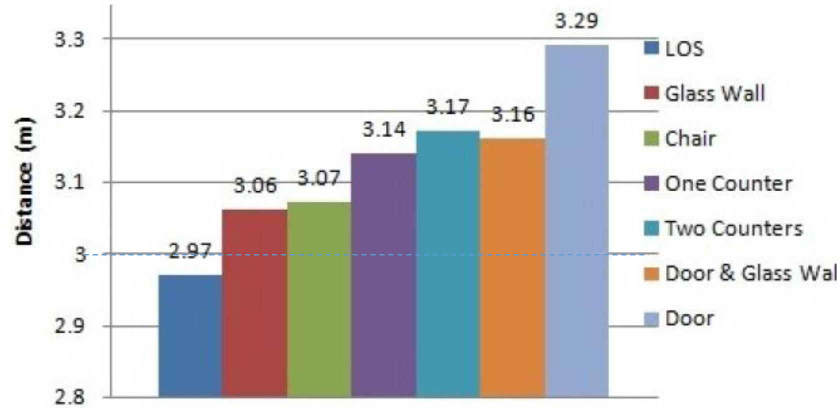
$$T = \frac{2T_l + 2T_f}{2 \times 2}$$

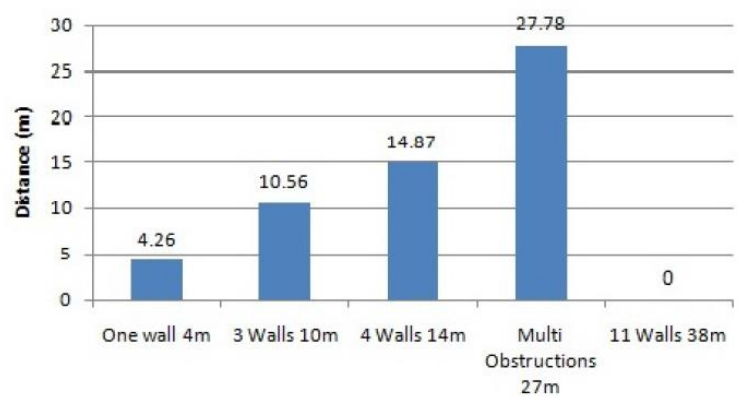


Evaluation of IR-UWB for localization

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







Reading List

- Wireless Sensor Networks by Akyildiz, Vuran, Chapter 12 Localization
- Han, Guangjie, Huihui Xu, Trung Q. Duong, Jinfang Jiang, and Takahiro Hara. "Localization algorithms of wireless sensor networks: a survey." Telecommunication Systems 52, no. 4 (2013): 2419-2436.
- Boukerche, Azzedine, H. A. B. Oliveira, Eduardo F. Nakamura, and Antonio AF Loureiro. "Localization systems for wireless sensor networks." wireless Communications, IEEE 14, no. 6 (2007): 6-12.

- Material Used

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