Localization

Sensor Networks

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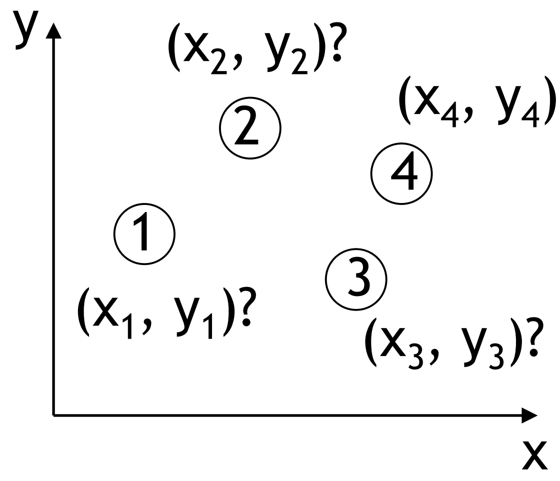
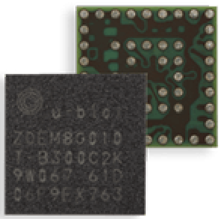
Localization of Sensor Nodes

- Estimation of node coordinates (x,y,z) in (Euclidean) coordinate system
- Why needed?
  - Interpretation of sensor data
  - Data fusion
  - Geo routing
  - ...
- Large design space
  - Intern vs. extern
  - always vs. sometimes
  - All nodes vs. some
  - Points vs. intervals
  - ...

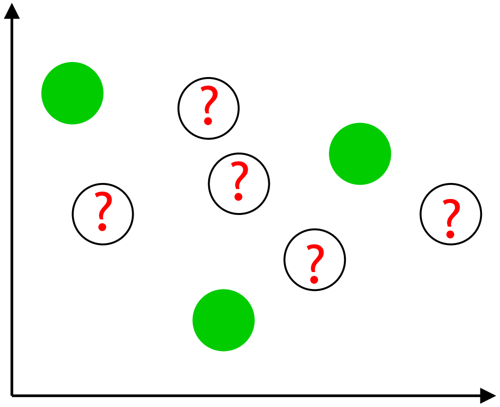


GPS?

- GPS for sensor nodes?
- Example: U-blox ZOE-M8B SiP
  - Very small (4.5 x 4.5 x 1.0 mm)
  - Accuracy: 2.5m
  - Energy: 12-72 mW, 1.8 V
  - Startup time: 26 sec

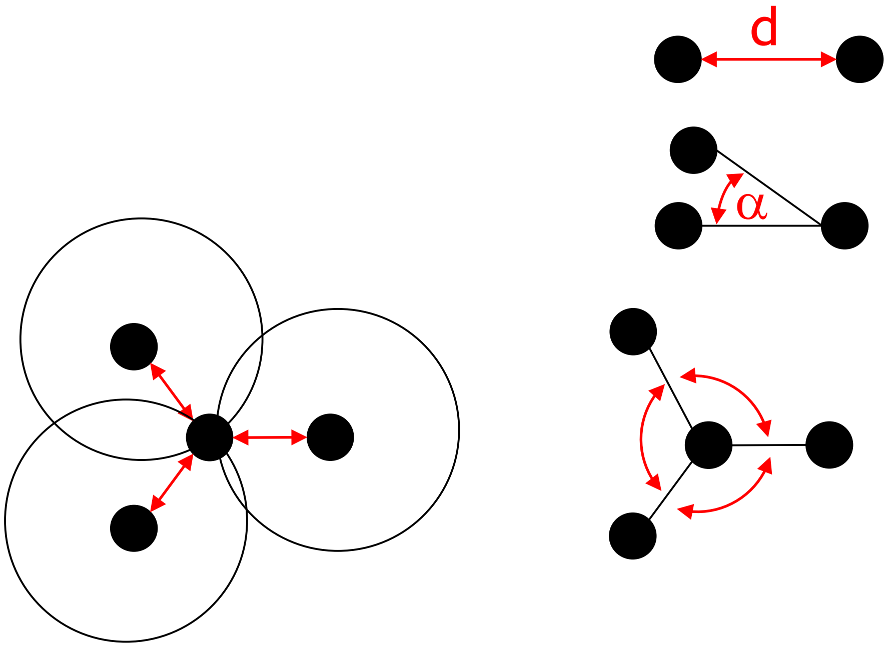


- But: some nodes with GPS may act as anchor nodes for localization of others
  - < 10% of nodes
- Localization task: Estimation of positions of remaining nodes



Localization Algorithms

- Distributed localization algorithms with three phases
  - Measure relations between nodes
    - Distance (range)
    - Angle
    - ...
  - Initial positioning
    - Lateration
    - Angulation
    - ...
  - Refinement
    - Iterative refinement of initial positions

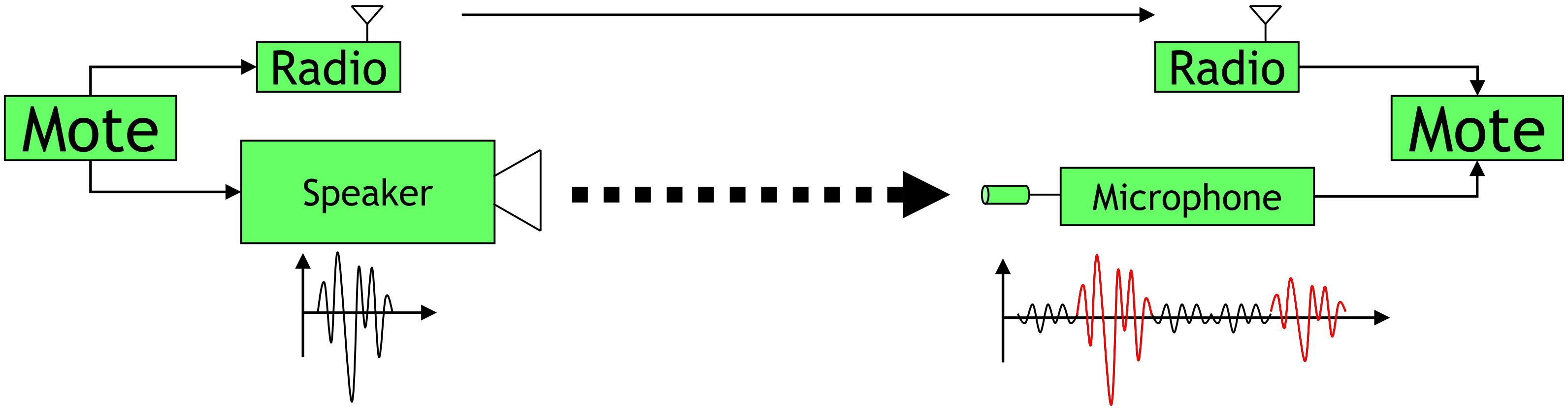


Node Relations

- Mostly distance-based
  - Why not angles?
- Signals
  - Radio
  - (Ultra) sound
  - Light
- Indicators
  - Amplitude (signal strength)
  - Time of arrival
  - Frequency
  - Phase

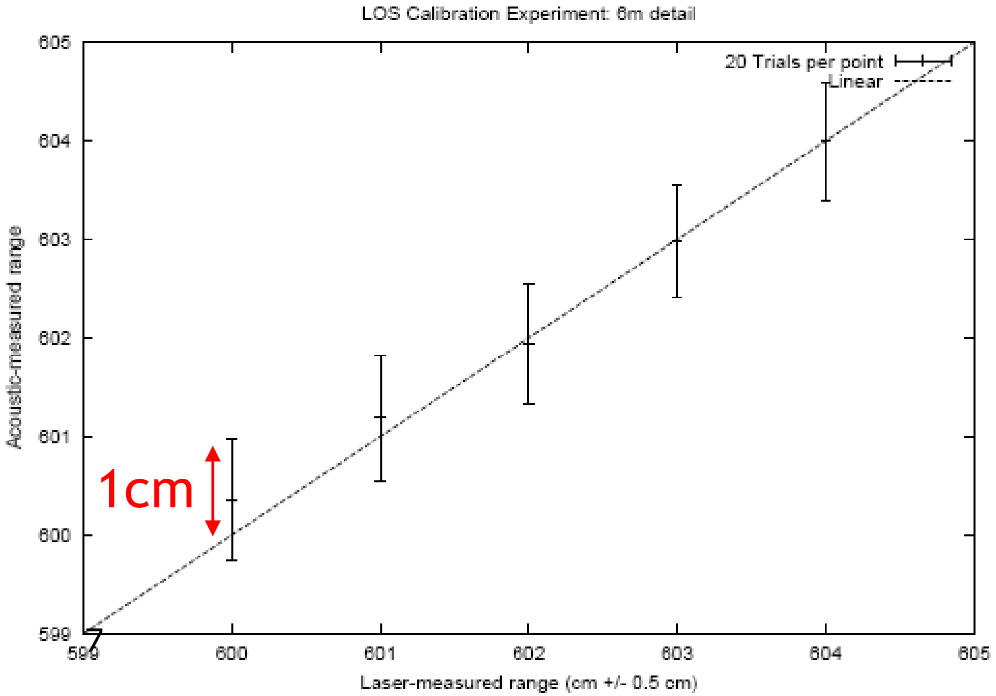
Sound: Propagation Time

- Measurement of propagation time of ultrasound from sender to receiver
  - Synchronization via radio
  - $s = t \, v_{sound}$
- Coding of sound signal
  - Robustness
  - Pseudo noise
- Receiver finds earliest occurrence of sound pattern
  - Echoes!



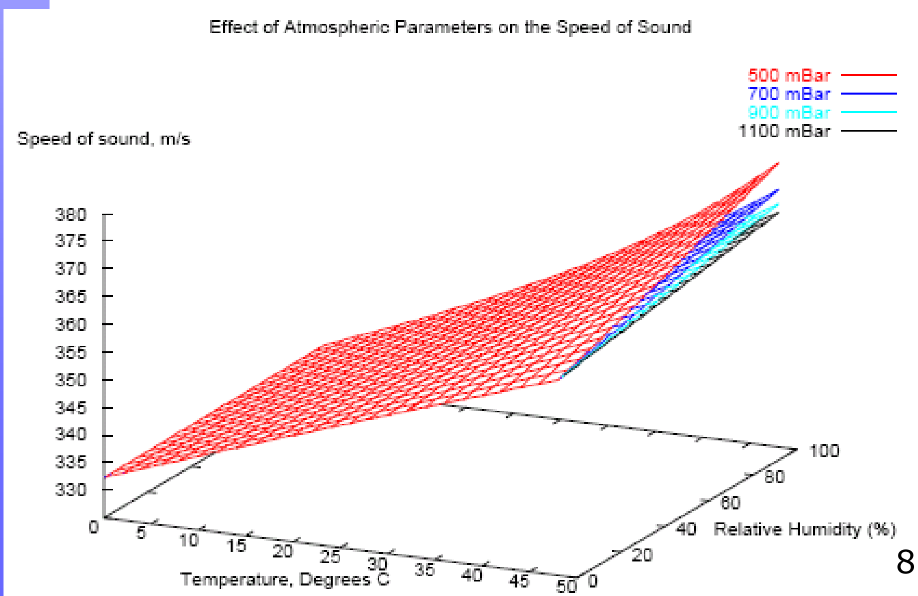
Accuracy: Best Case

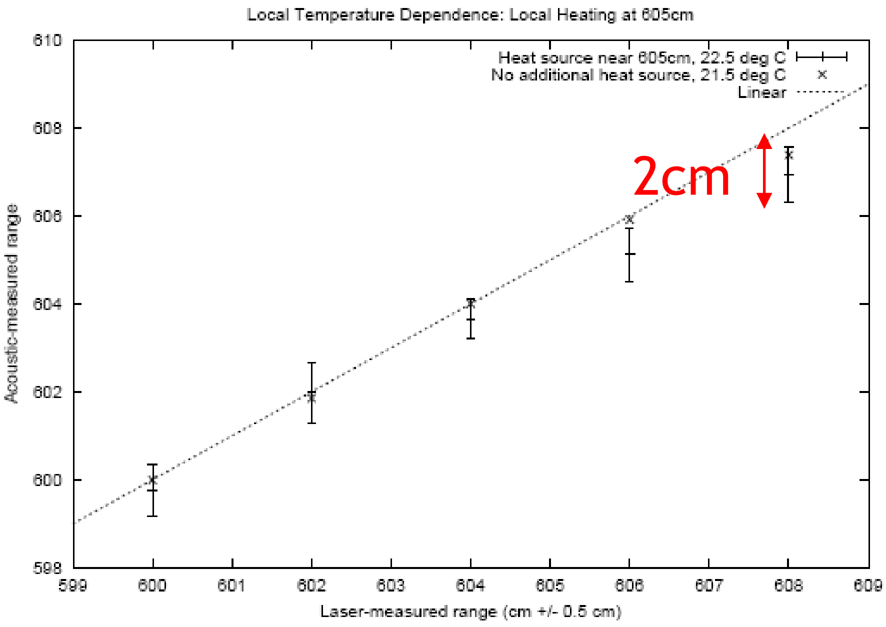
- Accuracy ~ 1 cm
- Range ~ 10m
- Conditions
  - Free line of sight
  - Speaker and microphone facing each other



Accuracy: Temperature

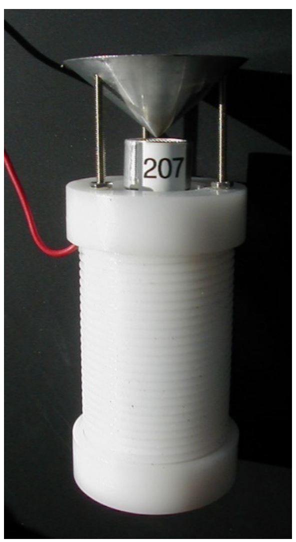
- Sound propagation speed depends on air temperature
  - ~ 10% error per 50 K
  - Countermeasure: temperature sensor!

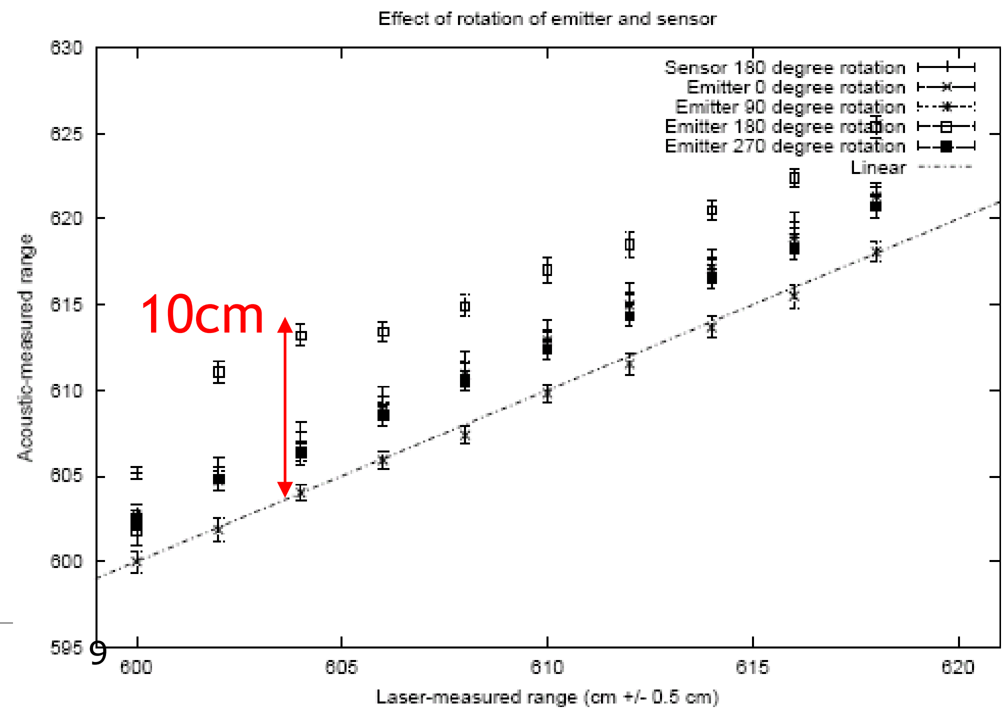




Accuracy: Orientation

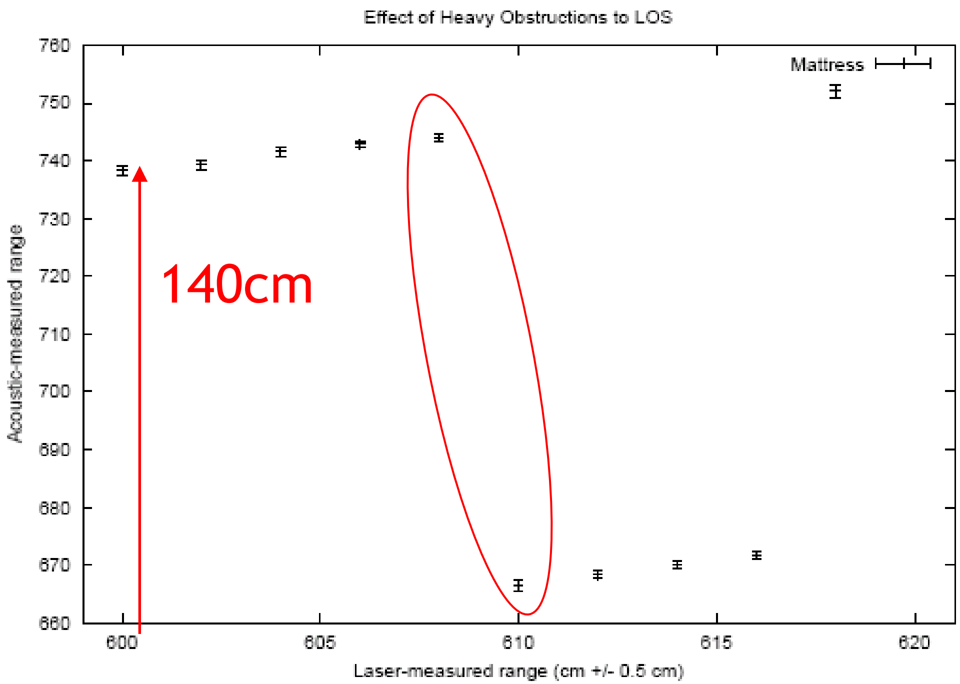
- Relative orientation of speaker and microphone has big impact
  - Countermeasure: Scattering reflectors, multiple speakers / micros

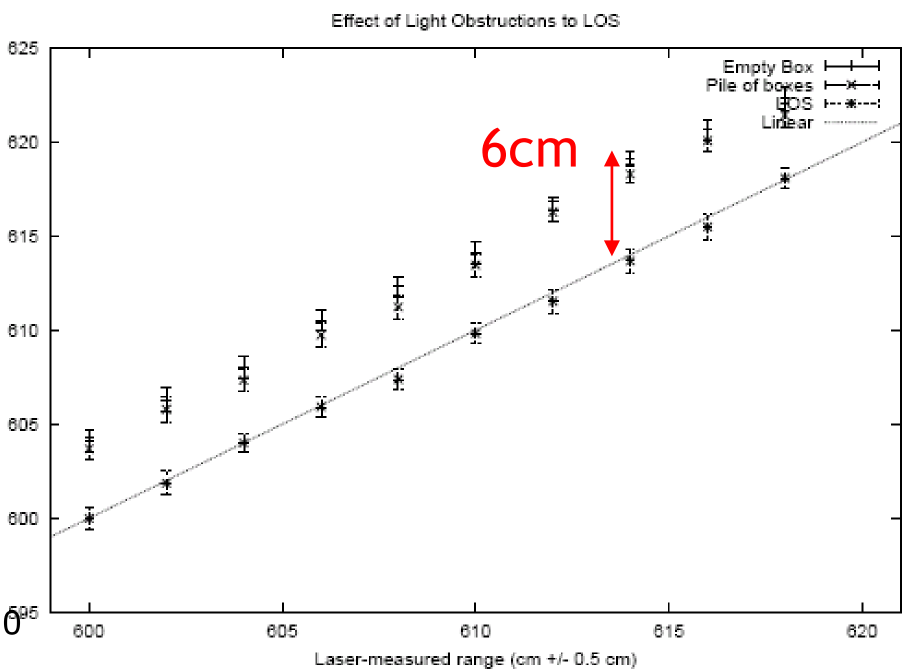




Accuracy: Obstacles

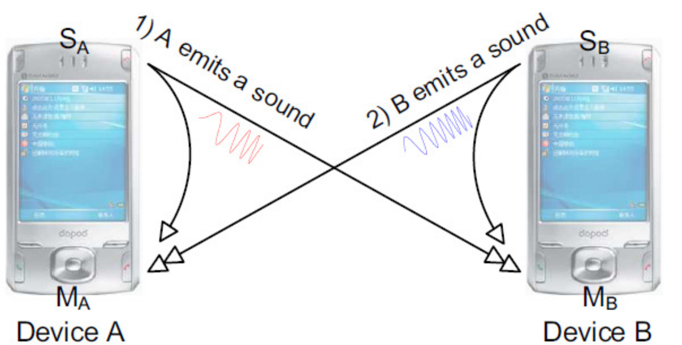
- Light obstacles (e.g., card box)
  - Sound travels through / around obstacle
  - Small offset
- Massive obstacles (e.g., mattrass)
  - Multipath
  - Big offset
- Countermeasure: Test for free LOS (e.g., using light)

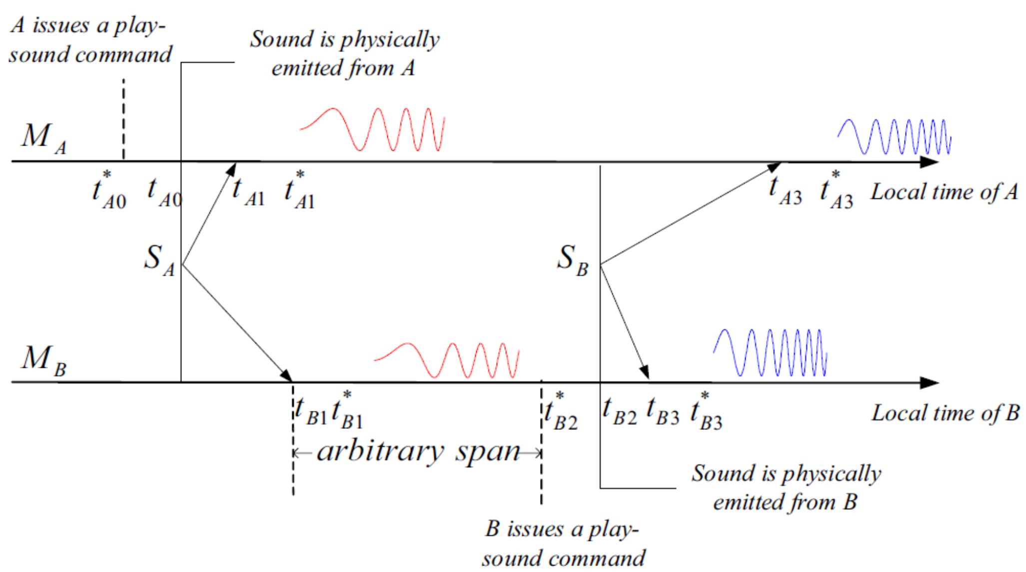




BeepBeep

- Idea: both devices beep with a constant known delay and they record their own as well as the other's beep
- Time is measured by sample counting since continuous sampling is utilized
- No time sync needed!





$$\frac{c}{2}\cdot\left(\left(t_{A3}-t_{A1}\right)-\left(t_{B3}-t_{B1}\right)\right)+d_{B,B}+d_{A,A}$$

Received Signal Strength

- RSS is function of distance and channel between sender and receiver

$$P_r(d) \approx P_s \frac{1}{d^n}$$

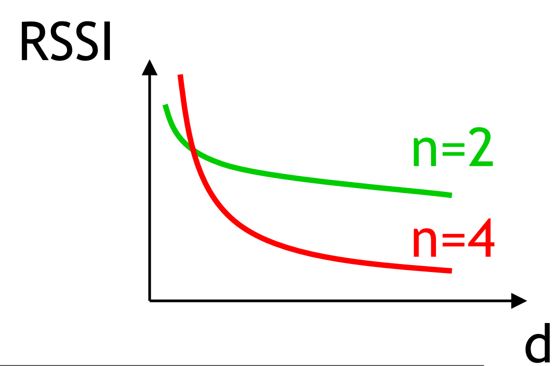
n = 2 … 6?

- Radio outputs P_r as RSS indicator
  - Received Signal Strength Indicator [dBm]

$$\mathrm{RSSI} = 10\log_{10}(P_r / 1\mathrm{mW})$$

0 dBm =	1 mW
-10 dBm =	0.1 mW
-20 dBm =	0.01 mW
-30 dBm =	0.001 mW
-40 dBm =	0.0001 mW

$$\boxed{\mathrm{RSSI} = 10\log_{10} P_s - 10n\log_{10} d}$$



Transmitted Signal Strength

- Indirect measurement of transmitted signal strength at reference distance d_0
  - Dependent on antenna gain

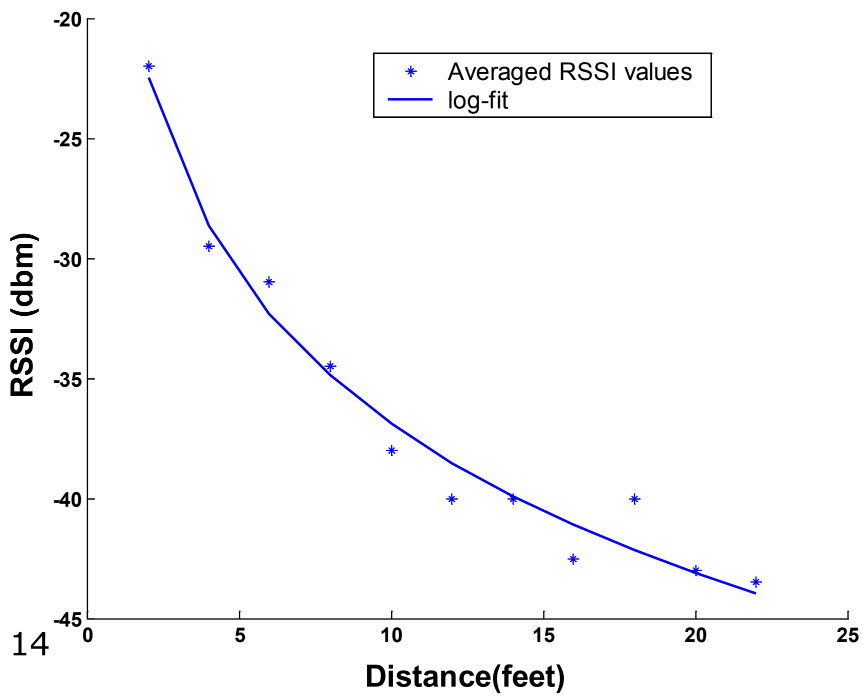
$$P_r(d_0) \approx P_s \frac{1}{d_0^n} \qquad\qquad P_s \approx P_r(d_0)\, d_0^n$$

$$\boxed{\mathrm{RSSI} = 10\log_{10} P_r(d_0) + 10n\log_{10} d_0/d}$$

- $P_r(d_0)$ typically given in the data sheet
  - cc2420: $10\log_{10}P_r(2m)$ = -46dbm at transmit power 0dBm

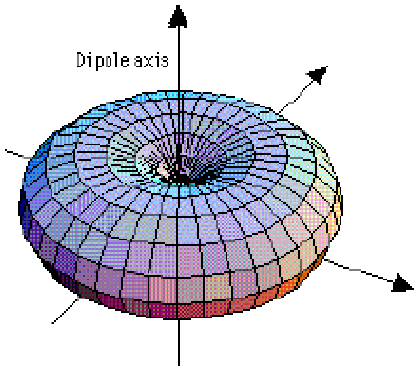
Accuracy: Best Case

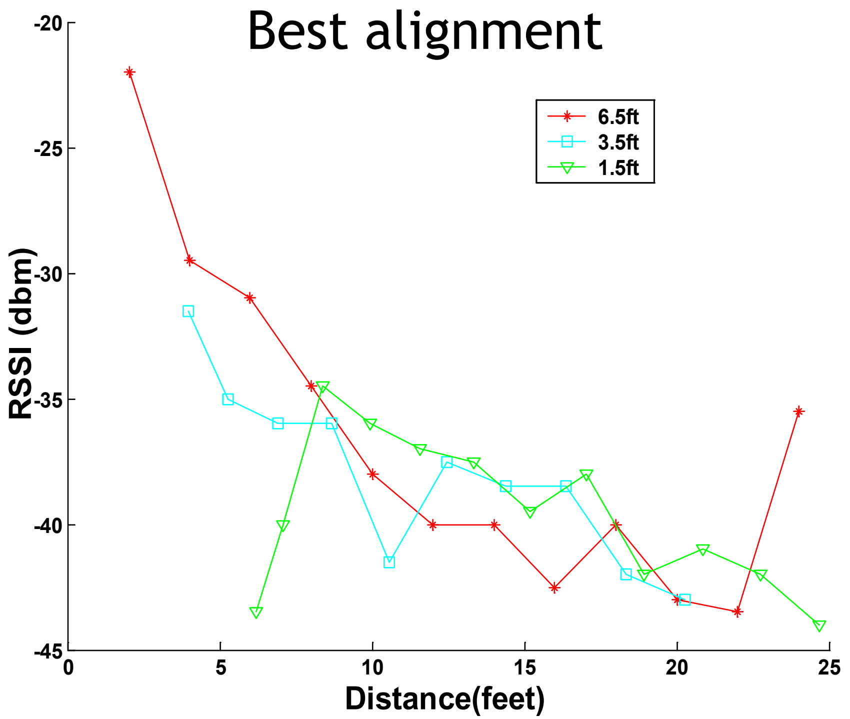
- Accuracy of 2-3m possible
- Range 10-100m
- Conditions
  - Free space, no walls, buildings, objects etc.
  - Nodes at equal height above ground
  - Large distance from ground
  - Aligned antennas

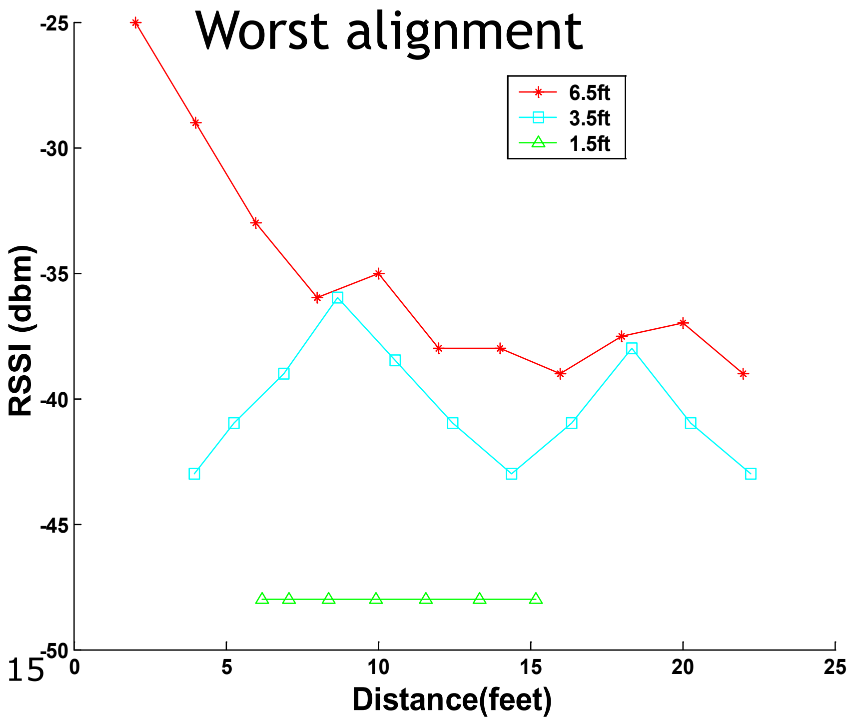


Accuracy: Orientation

- Relative orientation of antennas has big impact
- Distance above ground has big impact



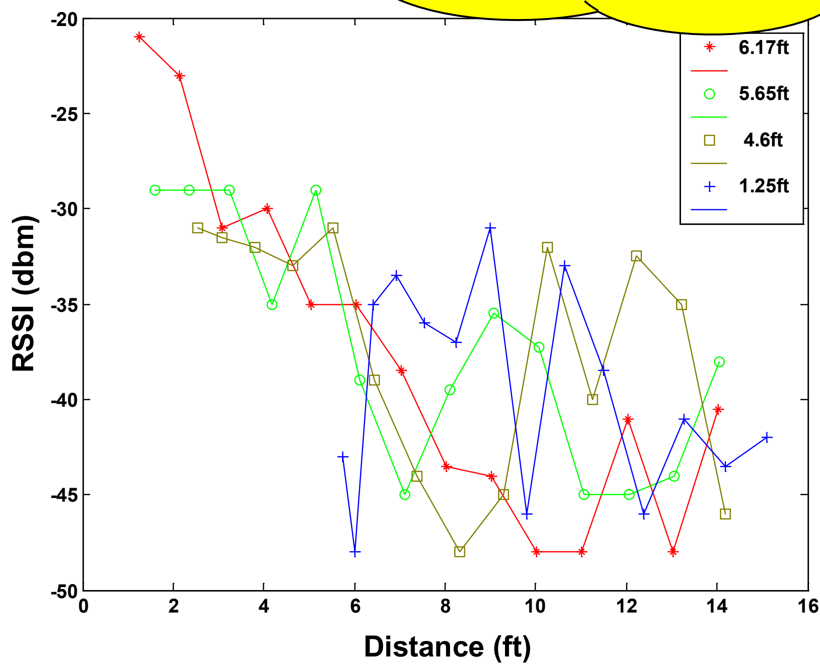


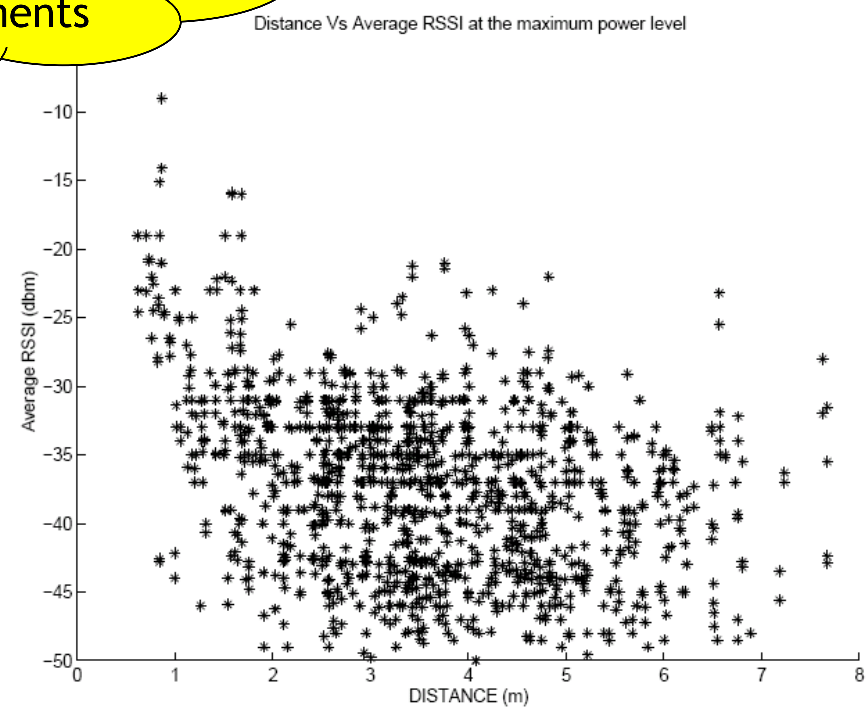


Accuracy: Indoor

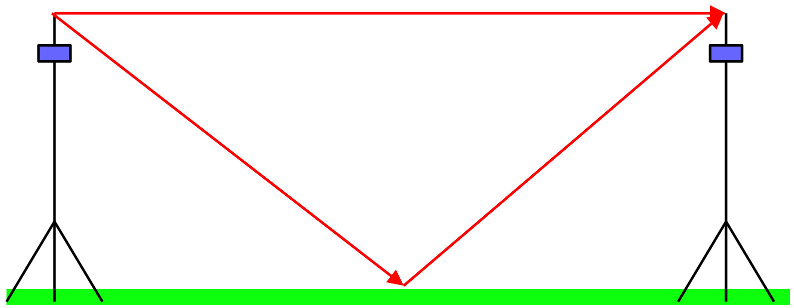
- In buildings strong multipath effects
  - Distance and RSSI almost uncorrelated

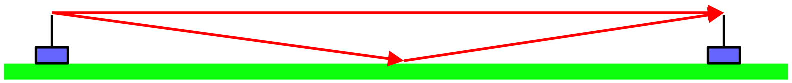
Can be exploited for detecting moving obstacles and changing environments

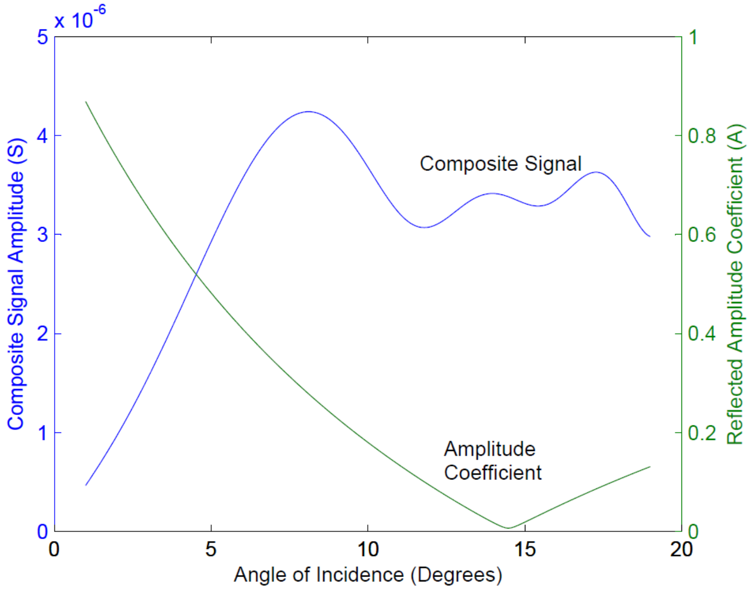




Why is RF Ranging Challenging?





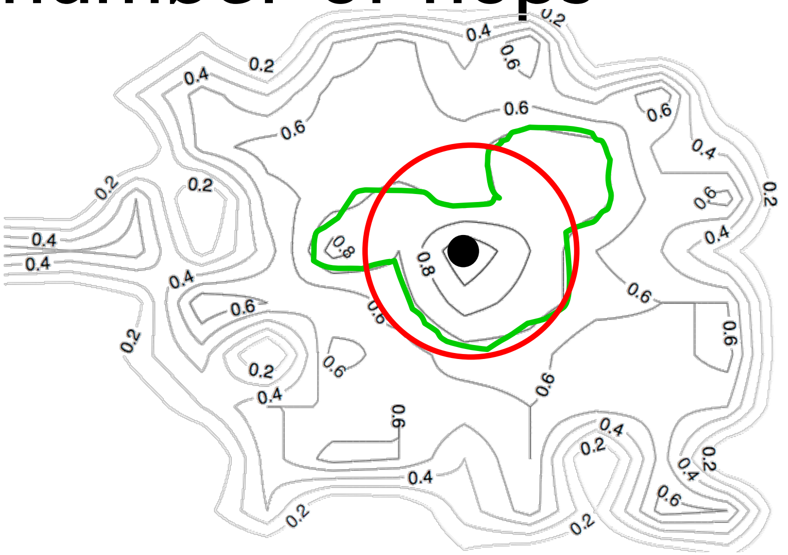


Two nodes 30m apart at varying heights

- Multipath including ground reflection
  - At low angles, reflection has a phase shift of PI, distance difference between LOS and ground reflected signal is minimal: destructive interference
  - Any additional even weak multipath can affect amplitude and phase significantly

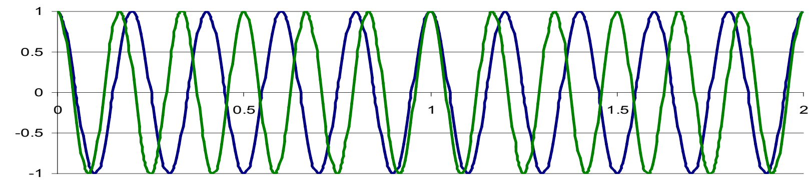
Connectivity

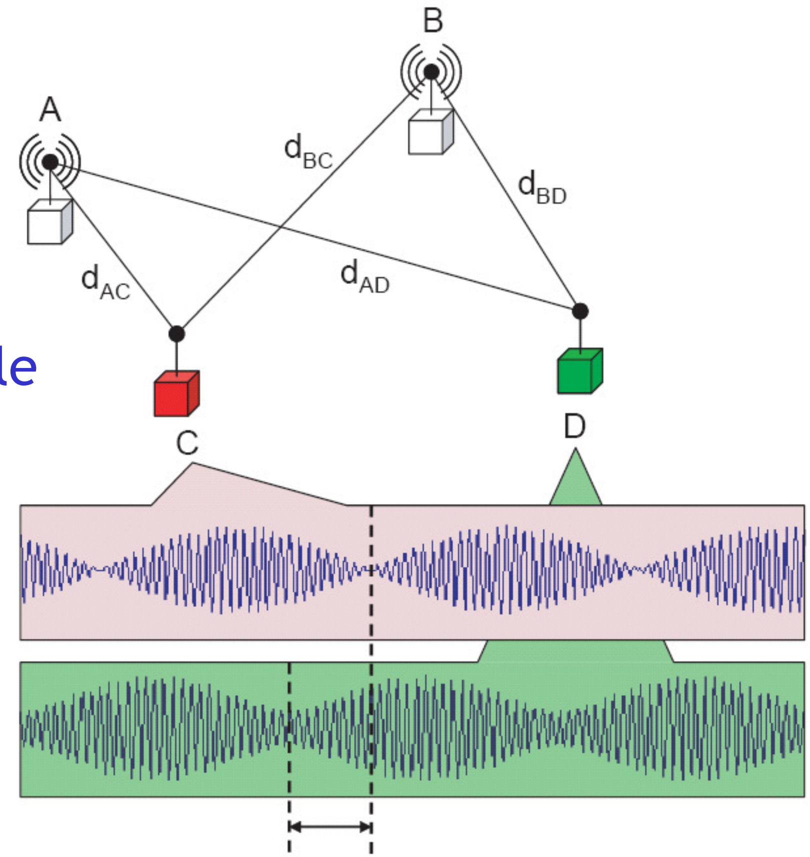
- RSS often not useful
- Binary distance measure?
  - d=1: Within communication range
  - d=∞: Outside communication range
- Distance measured by number of hops



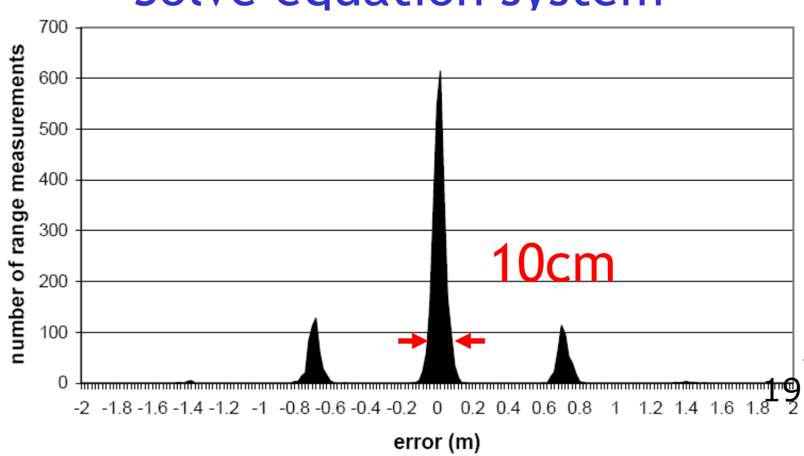
Radio Interferometry

- A and B transmit carrier signal at slightly different frequencies
  - Few 100 Hz
- Phase of interfered signal depends on receiver location
- Measurement of d_{ABCD}
  - Measure phase offset at multiple frequencies
  - Solve equation system





$$\text{phase offset} = 2\pi \frac{d_{AD} - d_{BD} + d_{BC} - d_{AC}}{\lambda_{carrier}} \pmod{2\pi}$$

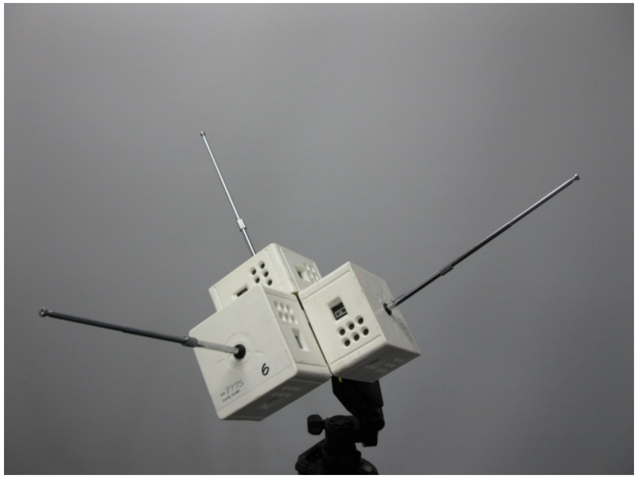


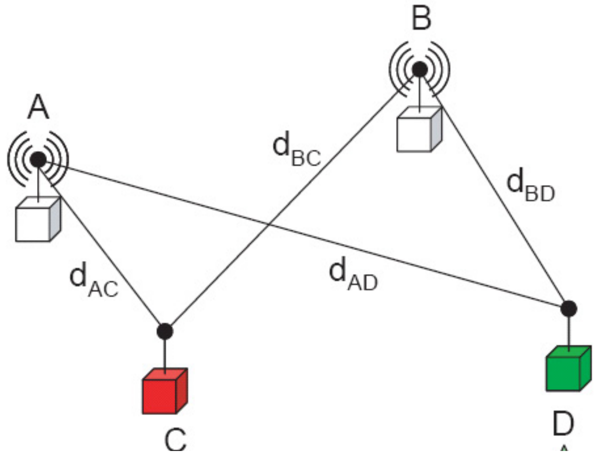
Radio Interferometry

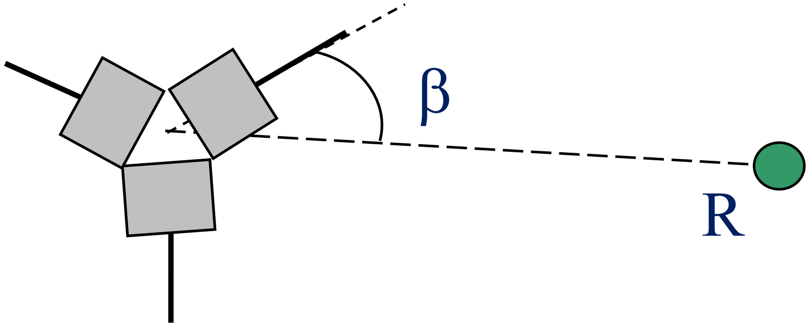
- Very accurate outdoors
  - Few cm
- Range up to 160 m
- Requires
  - Accurate time sync of C and D: 1 us
  - Accurate tuning of transmitter frequencies
- „Strange“ distance measure
  - Solve complex optimization problem
  - Find node locations that minimize difference from measured values

Radio Interferometric AOA

- Motivation: Measure AOA with motes without any additional hardware
- Group 3 nodes to form an anchor array
  - Orthogonal antennas to minimize parasitic effects
  - Array uses radio interferometry to estimate bearing to target node

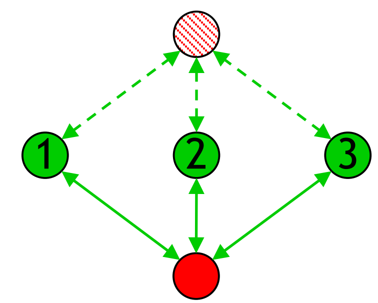


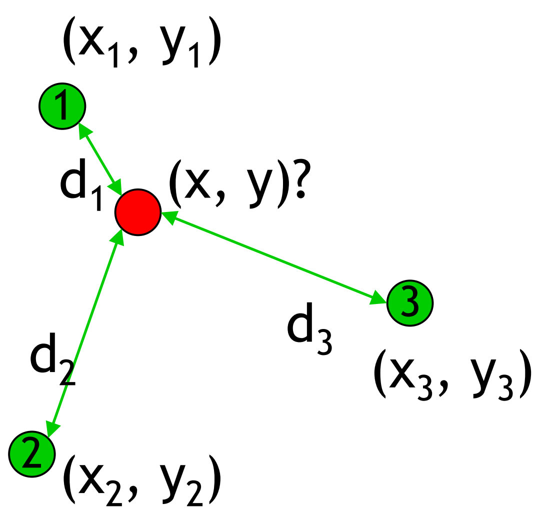




Initial Positions

- Input
  - Anchors with known locations
  - Relations among nodes
- Output
  - Position of non-anchor nodes
- Challenges
  - Inaccurate relations
  - Relations only among neighbors
  - Sparse anchors
  - Arrangement of anchor nodes

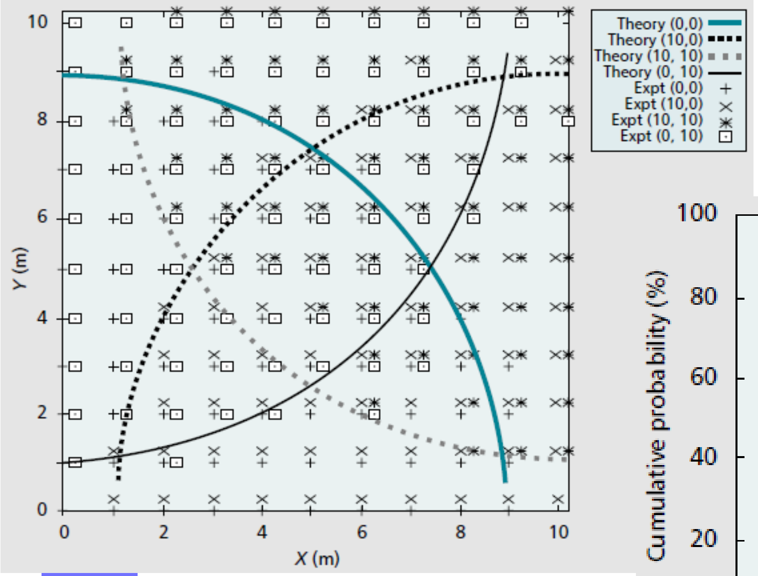


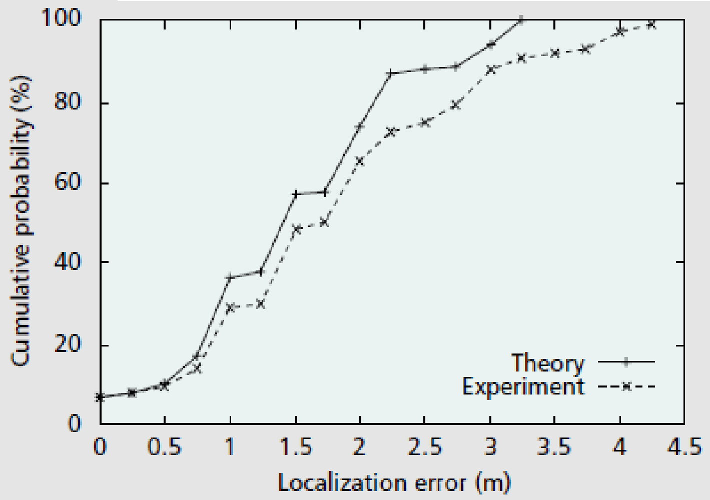


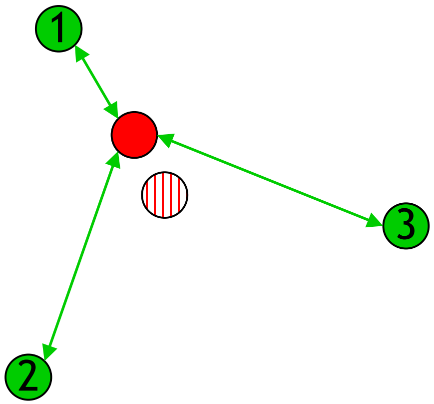
Centroid

- Position node at centroid of all anchors within communication range

$$x = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad y = \frac{1}{n}\sum_{i=1}^{n} y_i$$







Bounding Box

- Position node at center point of intersection of bounding boxes around anchors i=1..N with position (x_i, y_i) and distance d_i

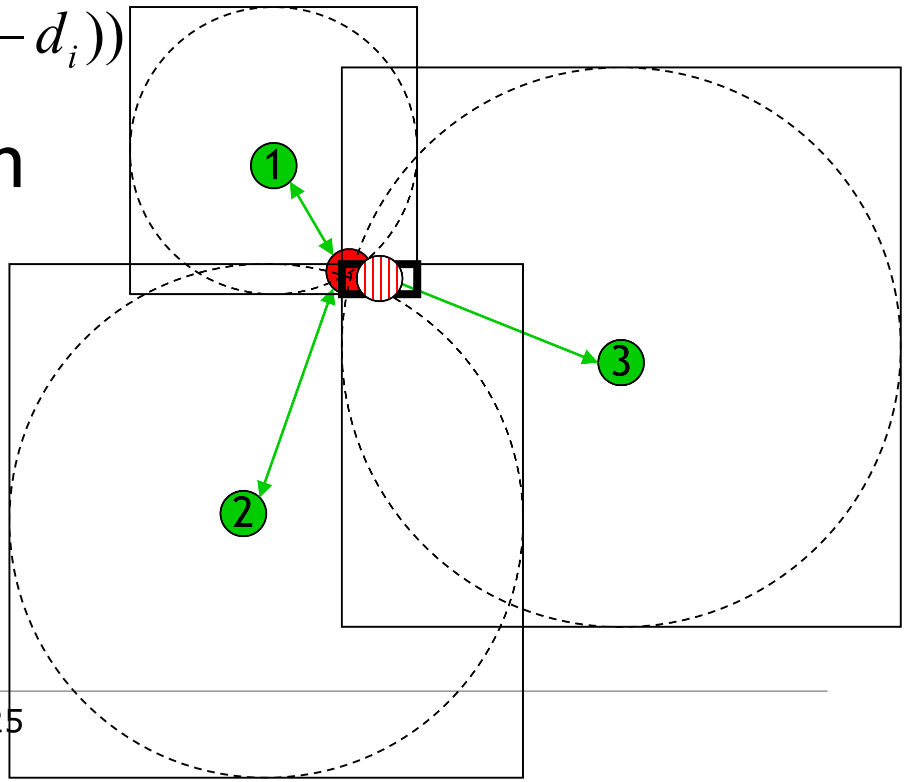
$$x = \tfrac{1}{2}(\min_i(x_i + d_i) + \max_i(x_i - d_i))$$

$$y = \tfrac{1}{2}(\min_i(y_i + d_i) + \max_i(y_i - d_i))$$

- Variant: Weighted sum of corners j

$$W(j) = \frac{1}{\sum_{i=1..N}(D_{ij} - d_i)^2}$$

$$x = \frac{\sum W(j) \cdot ex_j}{\sum W(j)} \qquad y = \frac{\sum W(j) \cdot ey_j}{\sum W(j)}$$



Lateration

- Position node at intersection of circles around anchors

$$(x - x_1)^2 + (y - y_1)^2 = d_1^2$$

$$(x - x_2)^2 + (y - y_2)^2 = d_2^2$$

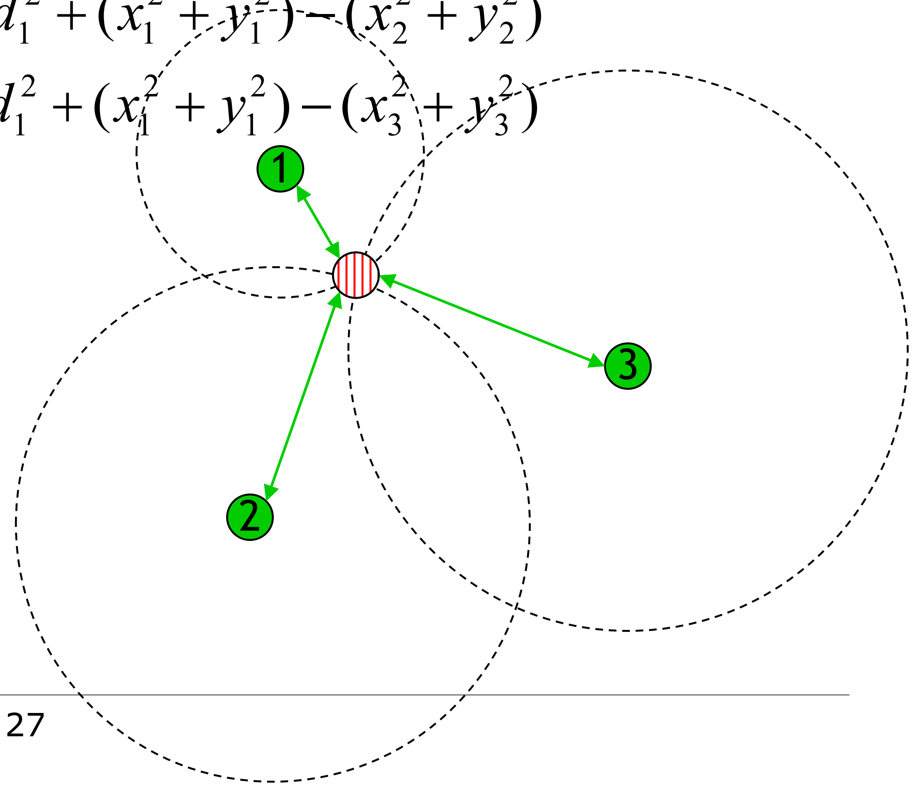
$$(x - x_3)^2 + (y - y_3)^2 = d_3^2$$

$$2(x_1 - x_2)x + 2(y_1 - y_2)y = d_2^2 - d_1^2 + (x_1^2 + y_1^2) - (x_2^2 + y_2^2)$$

$$2(x_1 - x_3)x + 2(y_1 - y_3)y = d_3^2 - d_1^2 + (x_1^2 + y_1^2) - (x_3^2 + y_3^2)$$

$$\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}$$

$$\boxed{A \begin{pmatrix} x \\ y \end{pmatrix} = b}$$

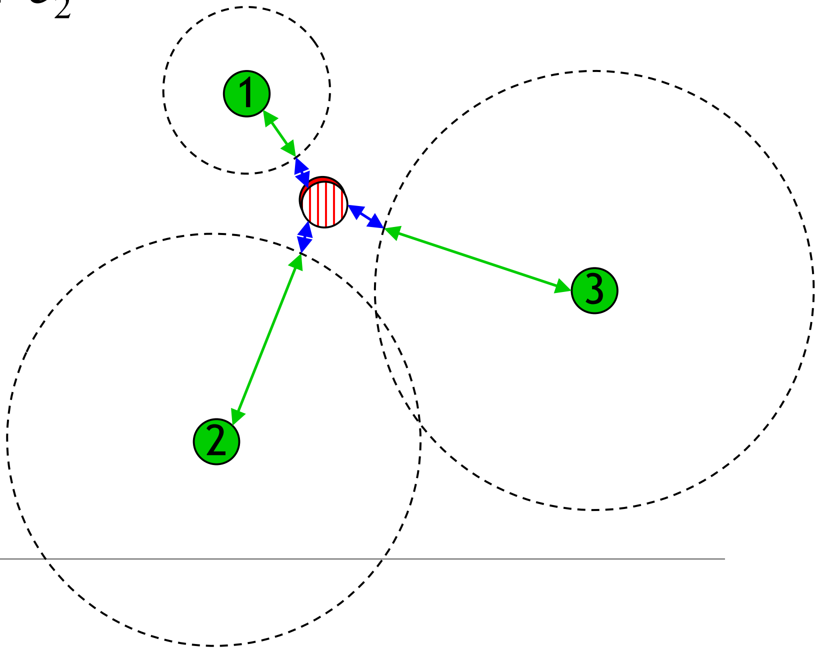


Lateration

- Problem: inaccurate distances
  - No common intersection point
  - Equation system does not have a solution!
- Approach: formulate optimization problem

$$A\begin{pmatrix} x \\ y \end{pmatrix} - b = \begin{pmatrix} e_1 \\ e_2 \end{pmatrix} \qquad \min_{x,y} e_1^2 + e_2^2$$

$$\boxed{(A^T \cdot A)\begin{pmatrix} x \\ y \end{pmatrix} = A^T b}$$



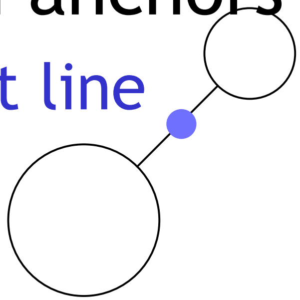
Multilateration

- Same approach, but n instead of 3 anchors
  - A has n-1 rows
  - $A^T A$ still 2x2 matrix
  - $A^T b$ still vector of length 2
- Similar for 3D

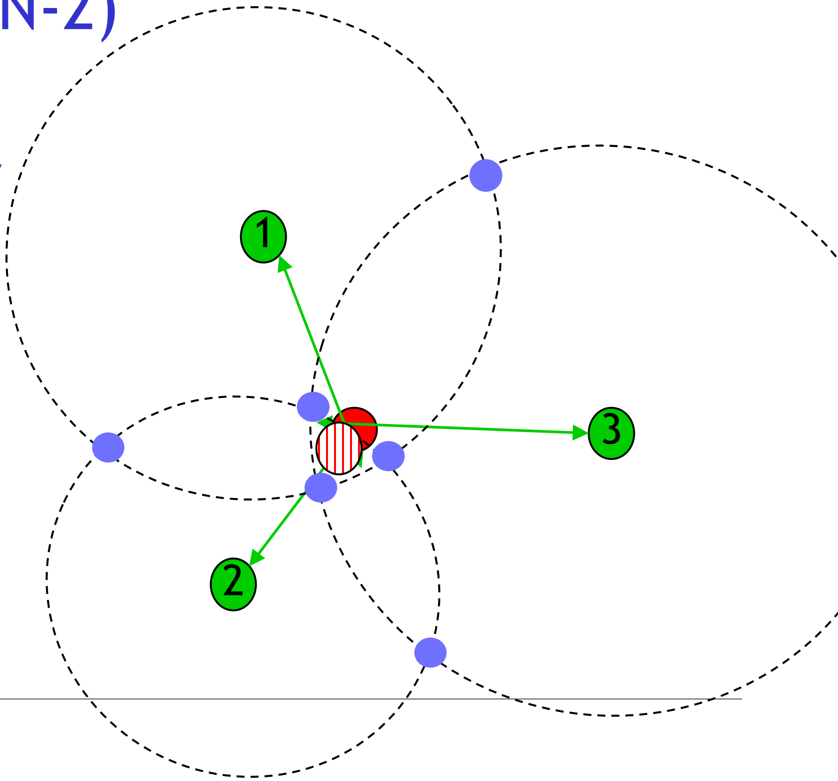
$$(A^T \cdot A)\begin{pmatrix} x \\ y \end{pmatrix} = A^T b$$

Intersecting Circle Pairs

- Pairwise intersection of circles around anchors
  - If no intersection use midpoint of shortest line connecting the circles

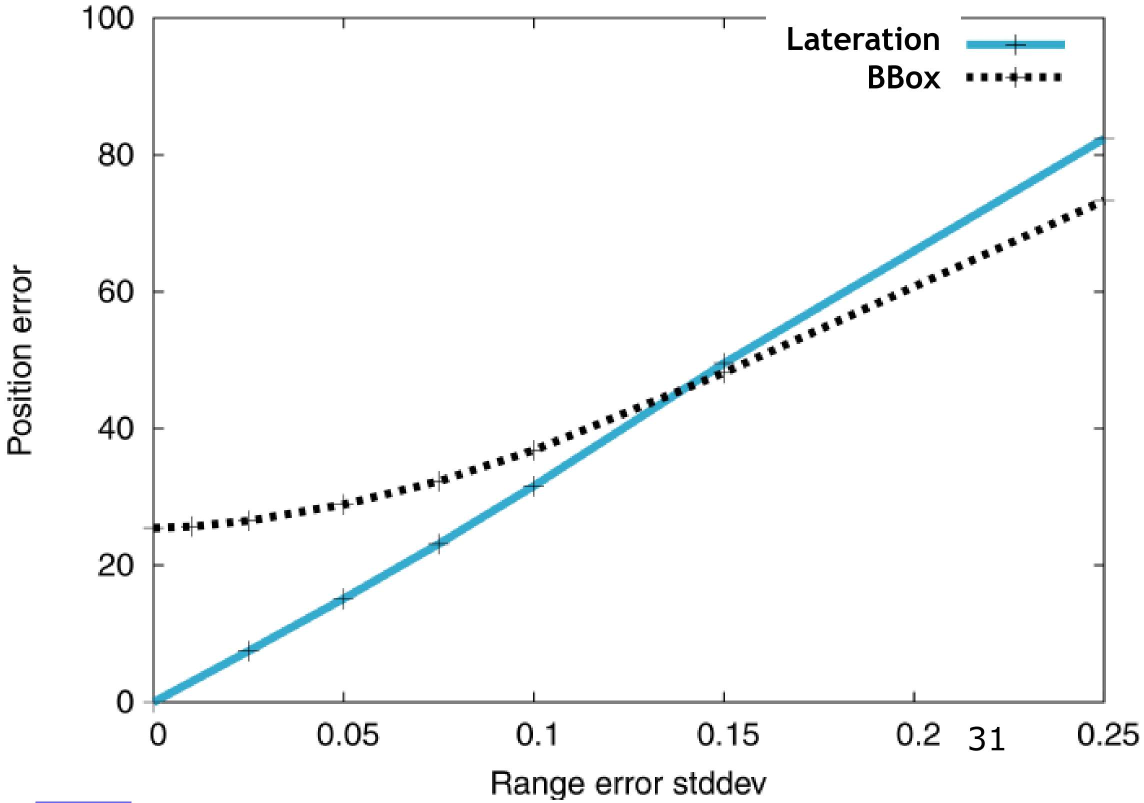


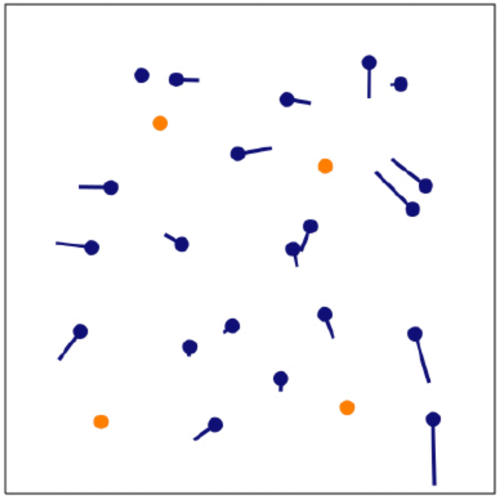
- Remove outlier intersections
  - Not contained in most (< N-2) circles around anchors
  - Sum of distances to other intersections larger than median
- Compute centroid of remaining intersections



Bounding Box vs. Lateration

- Bounding Box better as inaccuracy of ranging grows
- Anchor arrangement important





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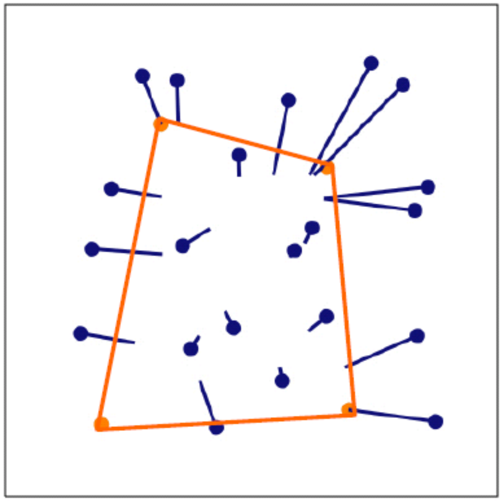
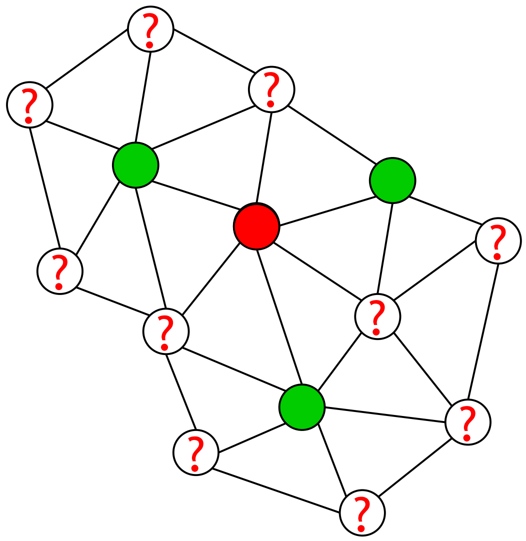


Bounding Box

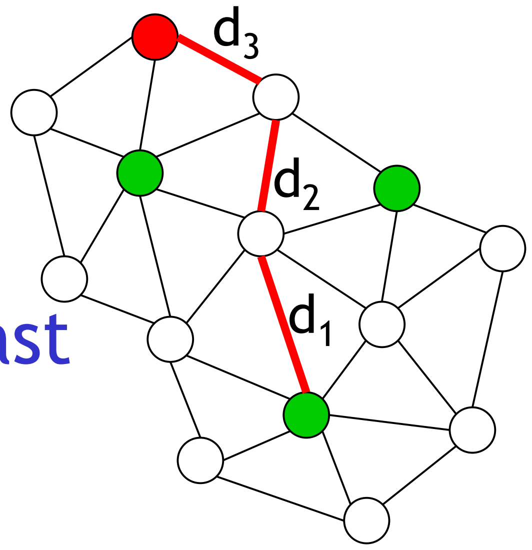
Multi-Hop Localization

- Up to now: every node needs 3 anchor neighbors
  - Or even more for high accuracy
- Approaches
  - Dense anchors
  - Multi-Hop relations
    - Distance to anchors that are not neighbors
  - Recursion
    - Positioned nodes as additional anchors



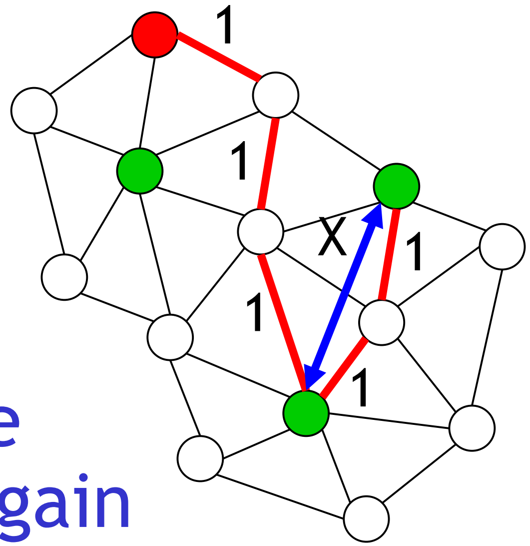
Multi-Hop Relations

- Compute shortest paths (Euclidean) to anchors
  - $D = d_1 + d_2 + d_3$
  - Never smaller than true distance
  - Zigzag paths lead to error
- Implementation
  - Anchors flood network
  - Nodes compute and rebroadcast shortest distance to anchor



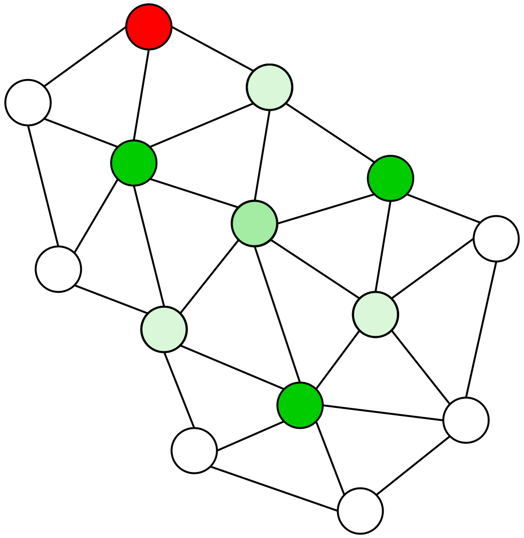
Multi-Hop Relations

- Estimate average hop distance
  - L = X / (1+1)
- Compute shortest paths (Hops) to anchors
  - D = (1+1+1) x L
  - No bounds
  - Zigzag
- Implementation
  - Anchors flood network
  - Anchors compute hop-distance among each other and flood again

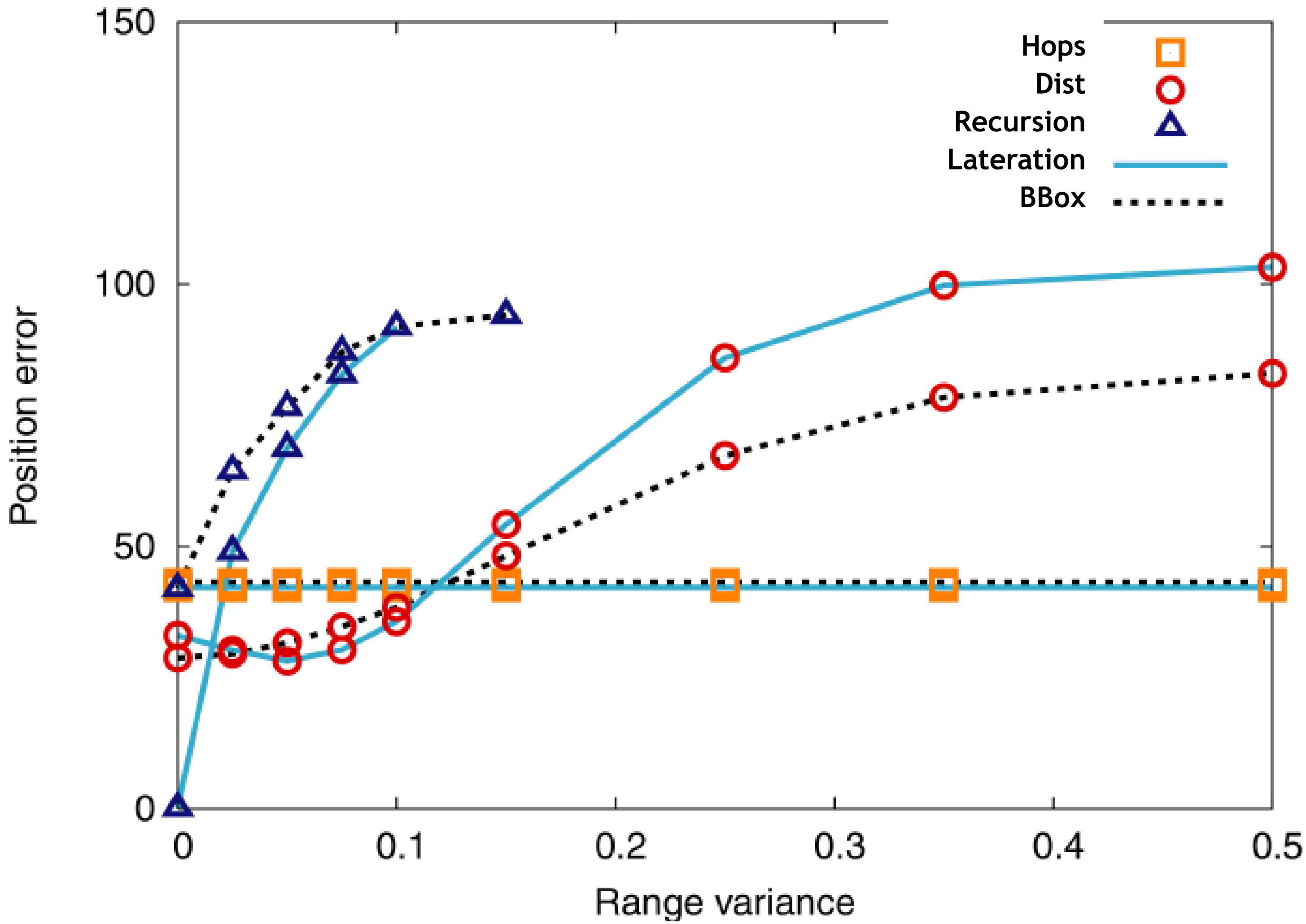


Recursion

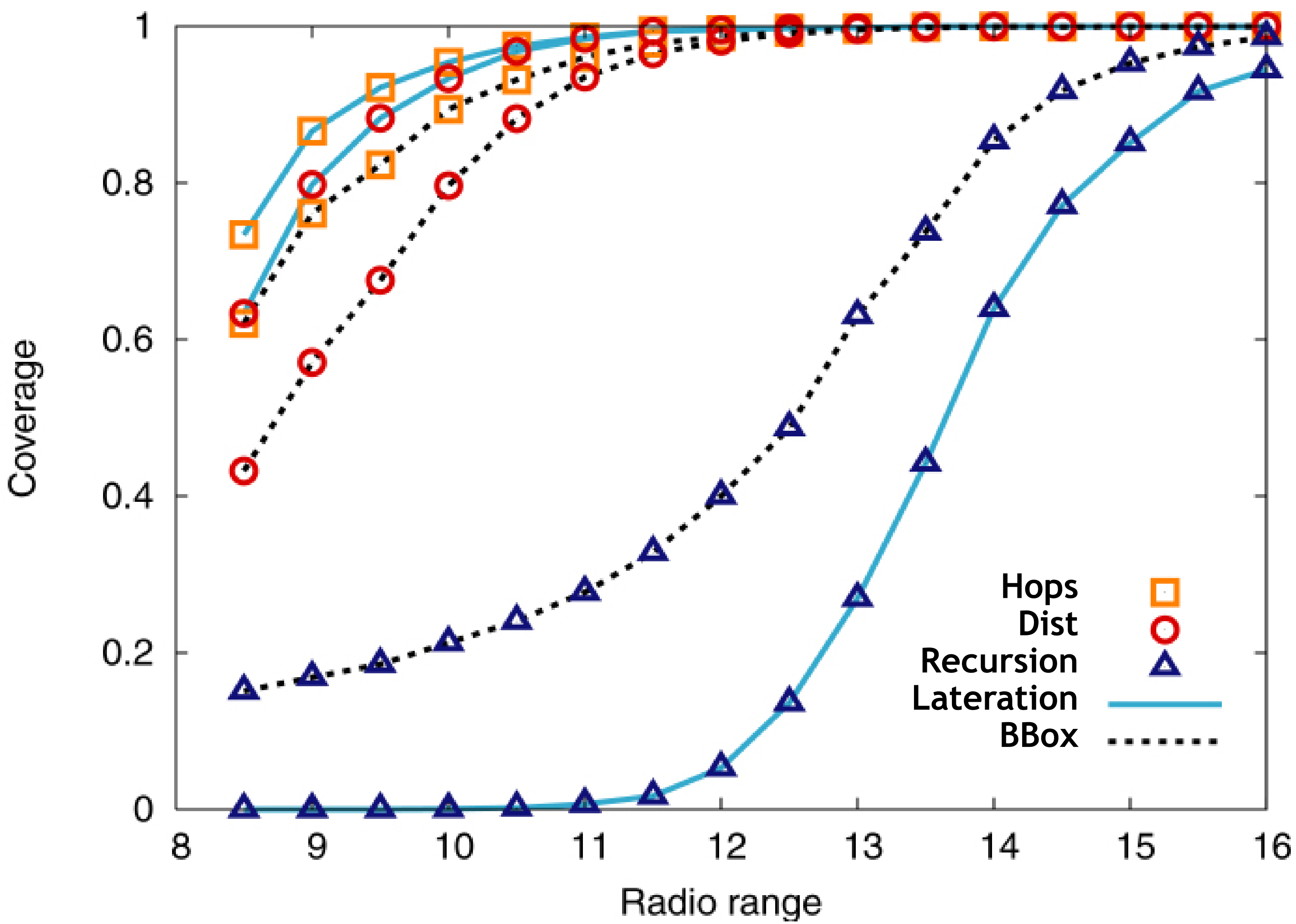
- Use newly positioned nodes as additional anchors
  - Errors accumulate
  - May get stuck



Multi-Hop: Accuracy



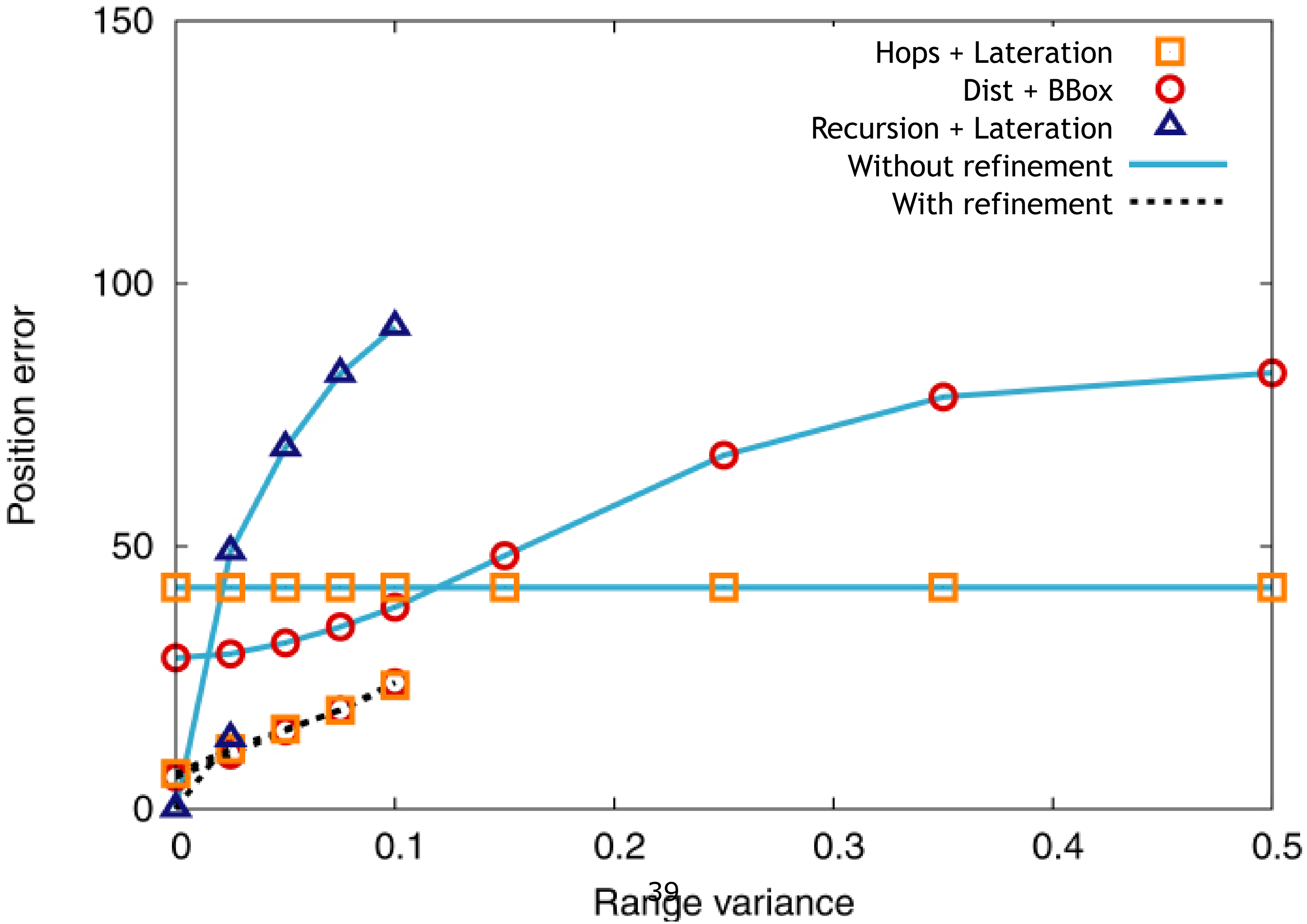
Multi-Hop: Coverage



Iterative Improvement

- Nodes have initial positions
- Iterative improvement
  - Each node recomputes position using all neighbors as anchors
  - Iterate until positions converge to a fixed point
- May not converge

Iterative Improvement



Other Approaches

- Centralized algorithms
  - Mass-spring models (cf. graph layout)
  - Convex optimization
  - Genetic optimization
  - ...
- Probabilistic algorithms
- Optimizing anchor locations
- Anchor-free approaches
- Support for mobility
- ...

References

- Slides contain material by following authors
  - Lewis Girod – UCLA
  - Dimitrios Lymberopoulos – Yale
  - Branislav Kusy – Vanderbilt
  - Alec Woo – Berkeley
  - Nirupama Bulusu – Portland State
  - Koen Langendoen – TU Delft
  - Akos Ledeczi - Vanderbilt