A Practical Approach to Landmark Deployment for Indoor Localization

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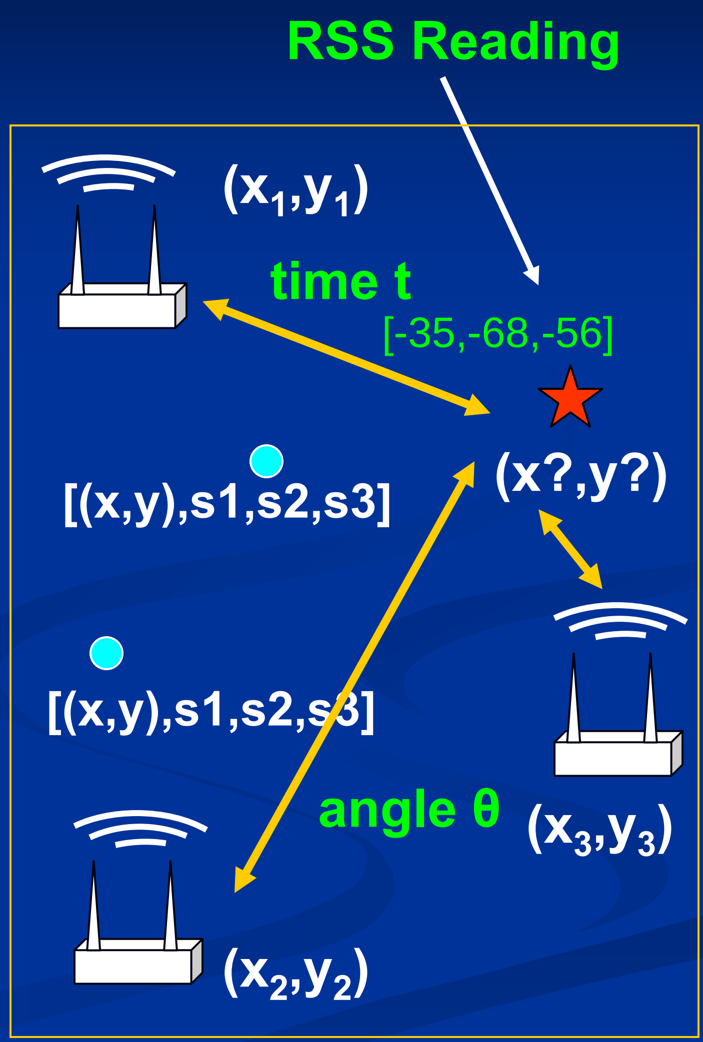
May 15th, 2006

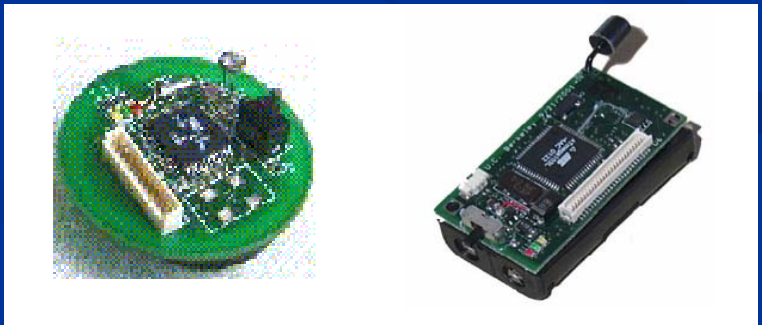
Background

- Transmit Packet at unknown location
- Landmarks Rx
- Modality
  - Received Signal Strength (RSS)
  - Time-Of-Arrival (TOA)
  - Angle-Of-Arrival (AOA)
- Principle to compute position
  - Lateration/Angulation
  - Scene matching
    - Training data/radio map
- Localization results



Motivation

- Localizing sensor nodes is a critical input for high-level networking applications:
  - Tracking, monitoring, and geometric-based routing
  - Location-based services become more prevalent
- Recent active research efforts have resulted in a plethora of localization methods.
- Study to improve the deployment of landmarks and thus help a wide variety of algorithms.



Contributions

- Impact of landmark placement on localization performance
  - Analytic Model
  - Experimental Results
- Compute upper bound on the maximum location error given the placement of landmarks.
- Find optimal patterns for landmark placement
  - Novel algorithm *maxL-minE*
- Generic analysis works for a variety of:
  - algorithms, networks, and ranging modalities.

Outline

- Background and motivation
- Theoretical Analysis
- Finding an Optimized Landmark Deployment
- Experimental Study
- Conclusion
- Related work

Analysis with Least Squares in Localization

- Ranging step:
  - Distance estimation between unknown and landmarks
  - Various methods available
  - Focus on RSS and TOA
- Lateration step:

$$(\hat{x}, \hat{y}) = arg\min_{x,y} \sum_{i=1}^{N} [\sqrt{(x_i - x)^2 + (y_i - y)^2} - d_i]^2$$

  - Traditional: Non-linear Least squares method

Error Analysis

- Reduce to Linear Least Squares: $\mathrm{Ax} = \mathrm{b}$
- Localization result: ideal

$$\mathbf{x} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b}$$

- Localization result: actual

$$\tilde{\mathbf{x}} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\tilde{\mathbf{b}}$$

- Location estimation error:

$$\|\mathbf{x} - \tilde{\mathbf{x}}\| \leq \|\mathbf{A}^+\|\|\mathbf{e}\|$$

With $\tilde{\mathbf{b}} = \mathbf{b} + \mathbf{e}$

Error Analysis

The landmark deployments with equal eigenvalues $\lambda_1 \cong \lambda_2$ minimize errors!

- $\|A^+\| = \frac{1}{\gamma_2}$, where $\gamma_1 \geq \gamma_2$ are the singular values of **A**
- The eigenvalues of $\mathbf{A}^T\mathbf{A}$ are the squares of the singular values of **A**
- The eigenvalues of $\mathbf{A}^T\mathbf{A}$ can be found as:

$$\lambda = 4(a+c) \pm 2\sqrt{(a-c)^2 + 4b^2}$$

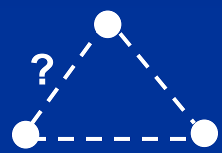
$$a = \sum_{i=1}^{N}(x_i - \frac{1}{N}\sum_{i=1}^{N} x_i)^2$$

$$b = \sum_{i=1}^{N}[(x_i - \frac{1}{N}\sum_{i=1}^{N} x_i)(y_i - \frac{1}{N}\sum_{i=1}^{N} y_i)]$$

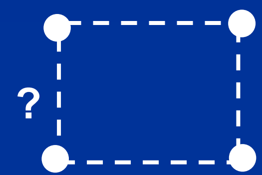
$$c = \sum_{i=1}^{N}(y_i - \frac{1}{N}\sum_{i=1}^{N} y_i)^2$$

Patterns
for Optimal Landmark Placements

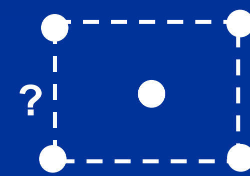
3 landmarks (equilateral triangle)



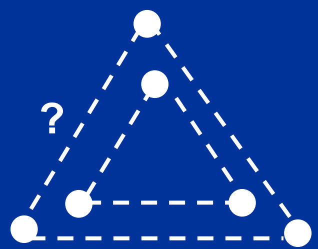
4 landmarks (square)



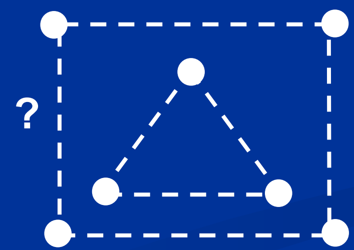
5 landmarks (square plus center of mass)



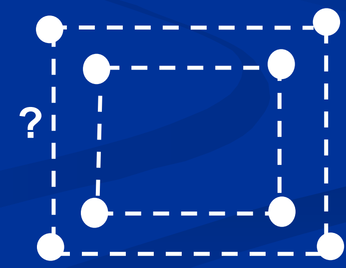
6 landmarks (nested triangles)



7 landmarks (square plus nested triangle)



8 landmarks (nested squares)



Finding the Optimal Deployment

- Analytic analysis gives us shape
- Length of sides unknown
- Physical constrains of a building
- *MaxL-MinE* Algorithm:
  - Get optimal pattern based on geometry
  - Fit optimal pattern into maximum floor size
  - Stretch/shrink the deployment shape until such movements stop reducing localization errors
  - An iterative search algorithm

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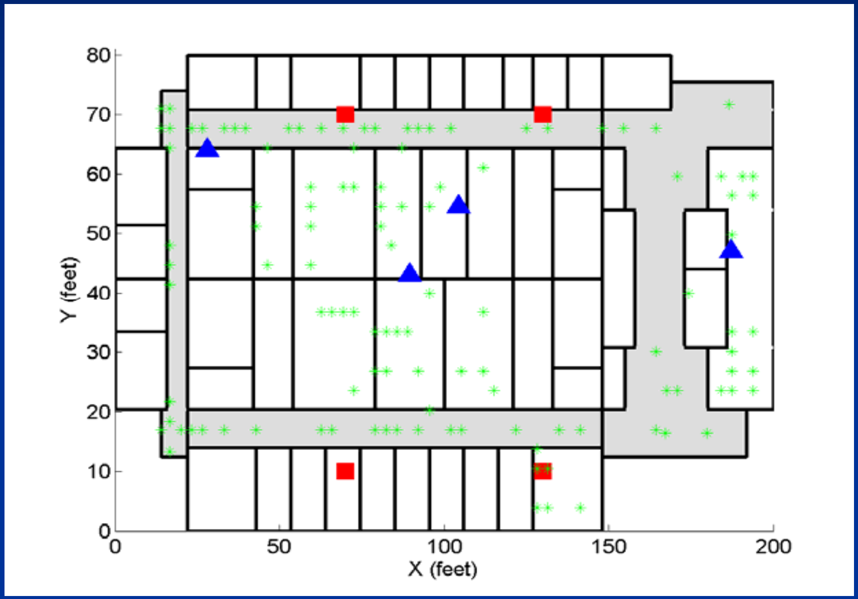
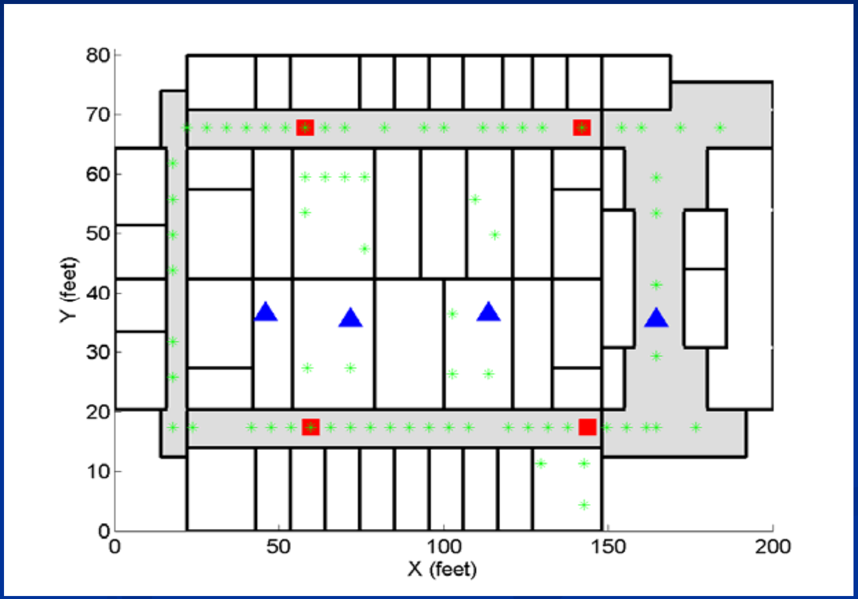
Experimental Study

- Networks:
  - 802.11 (WiFi)
  - 802.15.4 (ZigBee)
- Localization algorithms:
  - Point-based: RADAR
  - Area-based: ABP (Area Based Probability)
  - Lateration:
    - BN (Bayesian Networks)
    - LS (Least Squares)
- Ranging modalities:
  - RSS (Received Signal Strength)
  - TOA (Time of Arrival)

Experimental Setup





- 802.11 network
- 4 landmarks in two deployments:
  - Colinear case
  - Square case
- 115 training points

- 802.15.4 network
- 4 landmarks in two deployments:
  - Horizontal case
  - Square case
- 70 training points

Evaluation Metrics

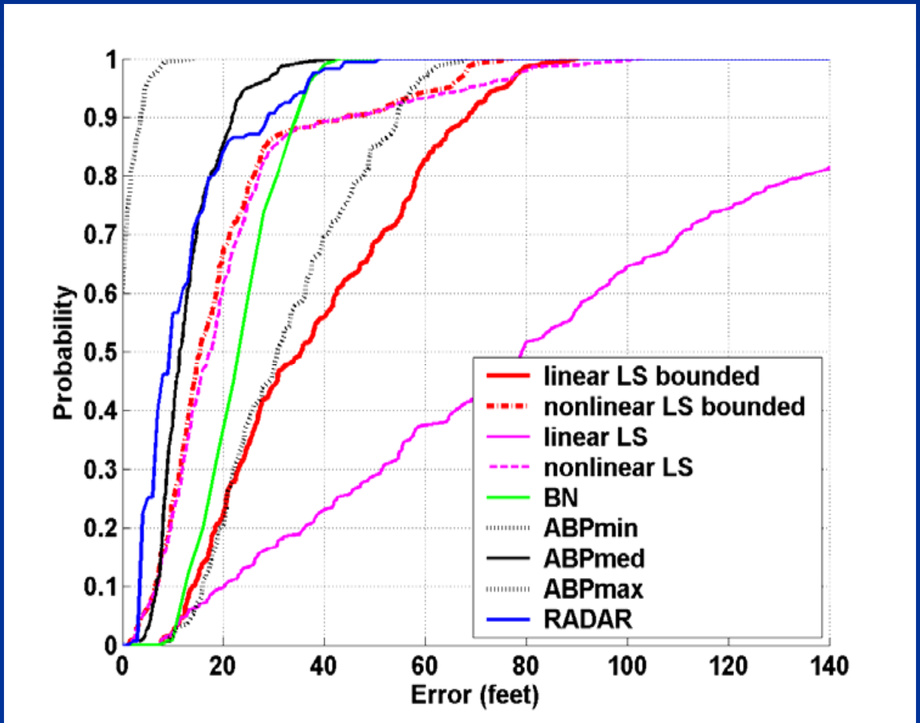
- Error CDF
  - Provide statistical specification of the localization accuracy
- Average error
  - Average of the distances between the estimated location to the true location
- Hölder metrics
  - Relates the magnitude of the perturbation in signal space to its effect on the localization results

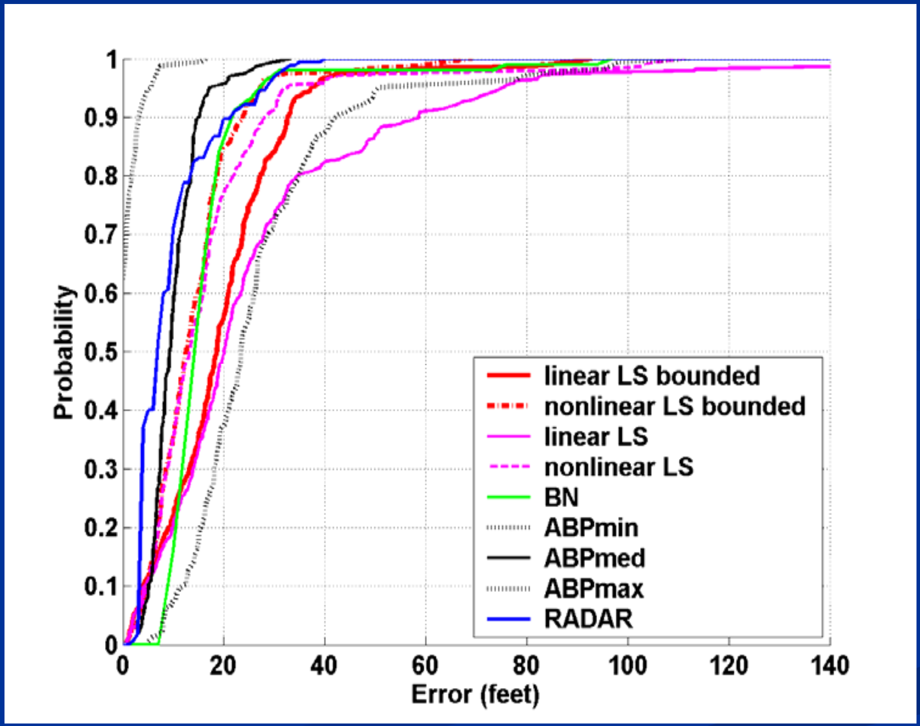
$$\mathrm{H}^{p}_{alg} = \max_{\mathbf{s},\mathbf{v}} \frac{||L^{p}_{alg}(\mathbf{s}) - L^{p}_{alg}(\mathbf{v})||}{||\mathbf{s}-\mathbf{v}||}$$

Localization Accuracy

RSS 802.11 Network

Error CDF across algorithms





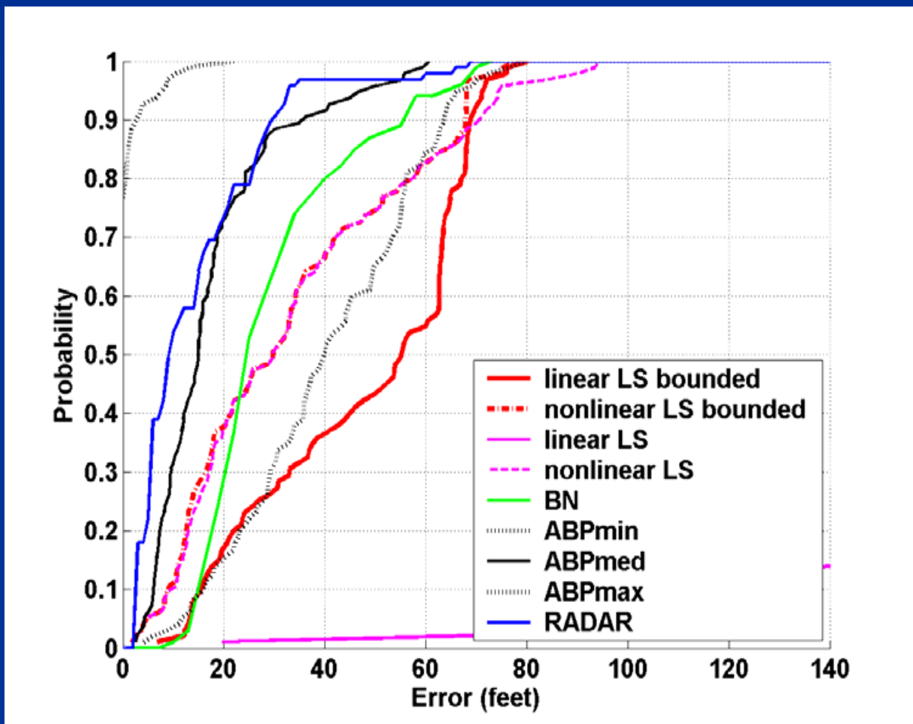
Colinear case

Square case

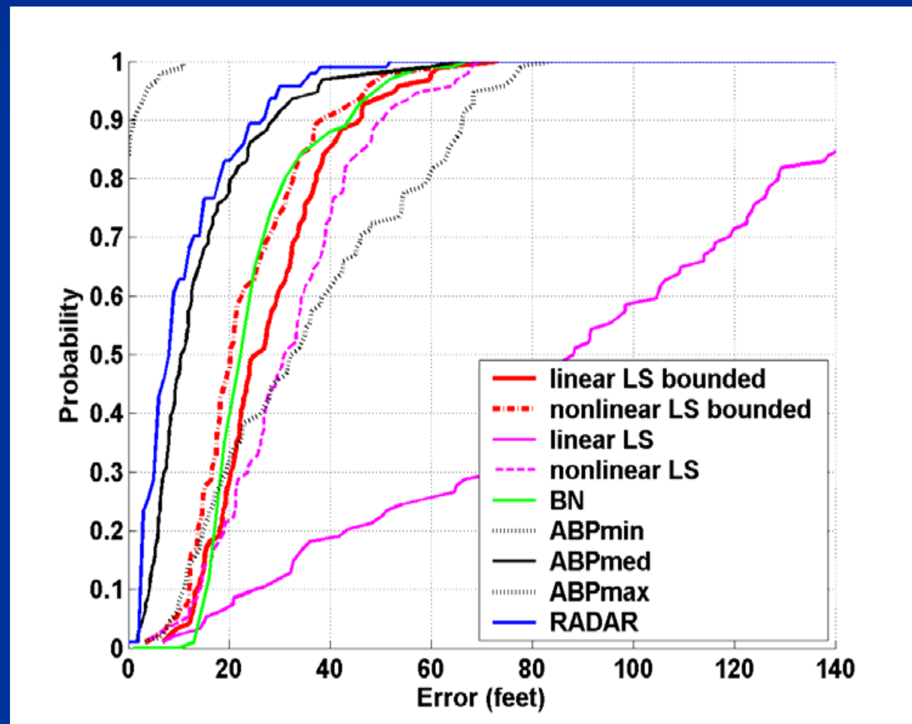
Localization Accuracy

RSS 802.15.4 Network

Error CDF across algorithms



Horizontal case

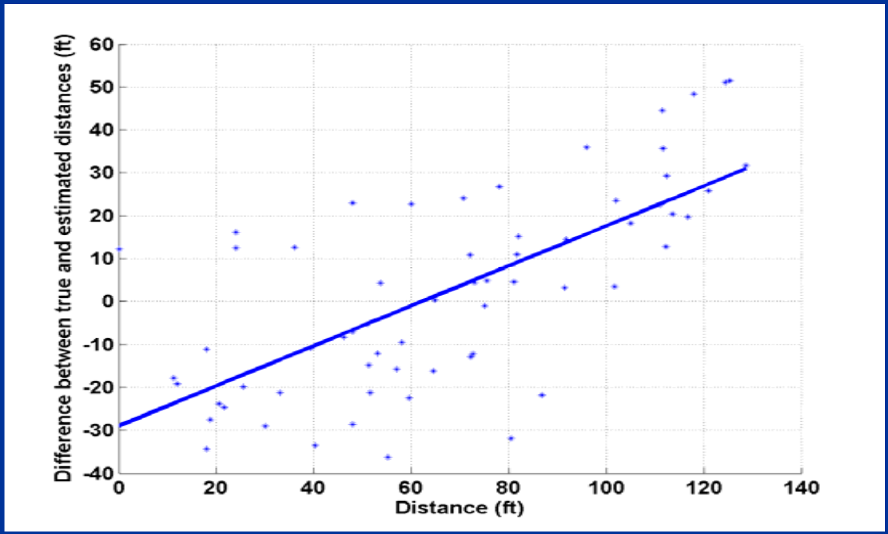


Square case

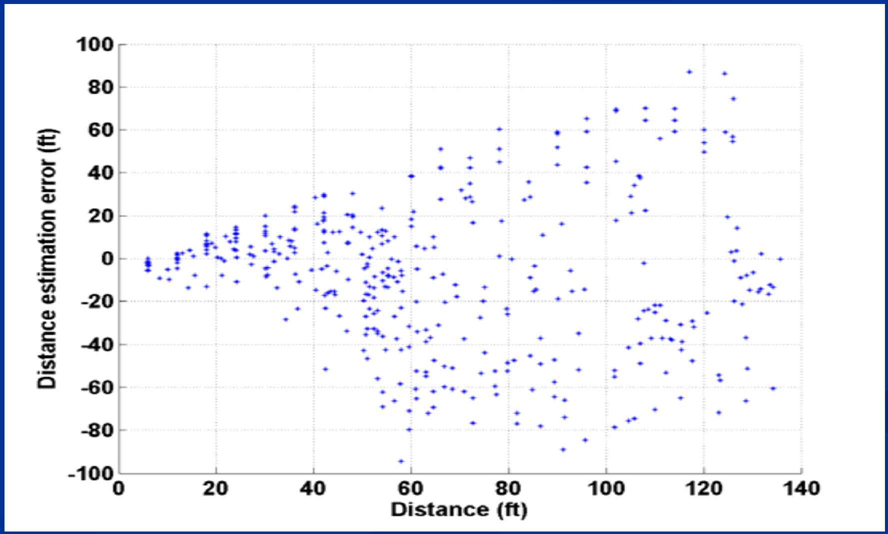
Using Time of Arrival

- Distance estimation based on round trip time between a node and a landmark
- Distance error analysis: TOA vs. RSS
- TOA error modeling:

$$\text{error} \sim N(\mu, \sigma^2) \text{ with } \hat{\mu} = b_0 + b_1 d_i \text{ and } \hat{\sigma^2} = \frac{\sum_{i=1}^{n}(\tilde{d}_i - \hat{\mu})^2}{n-1}$$



TOA

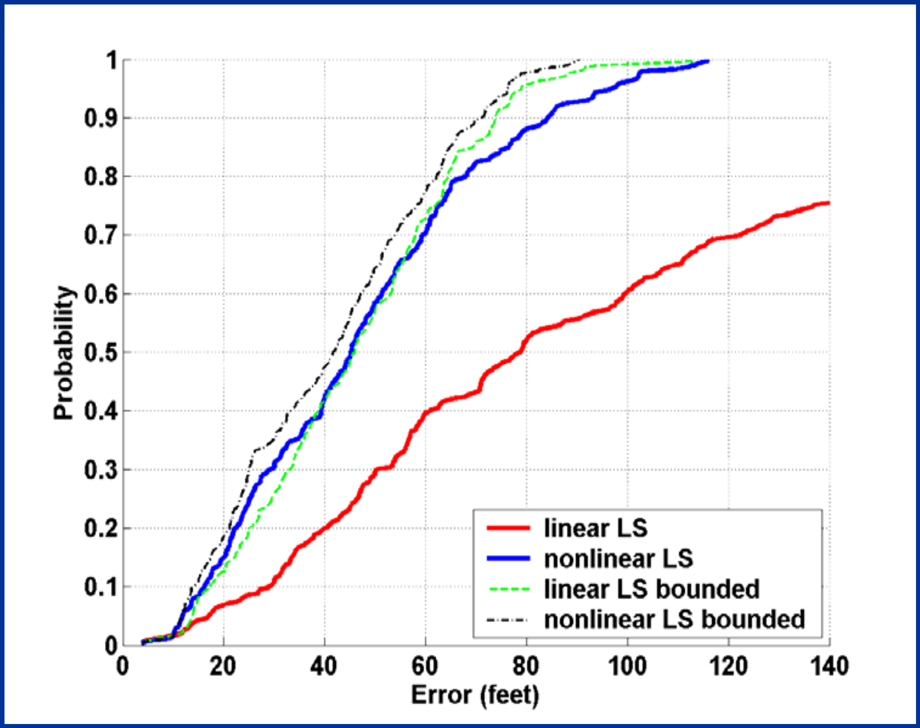


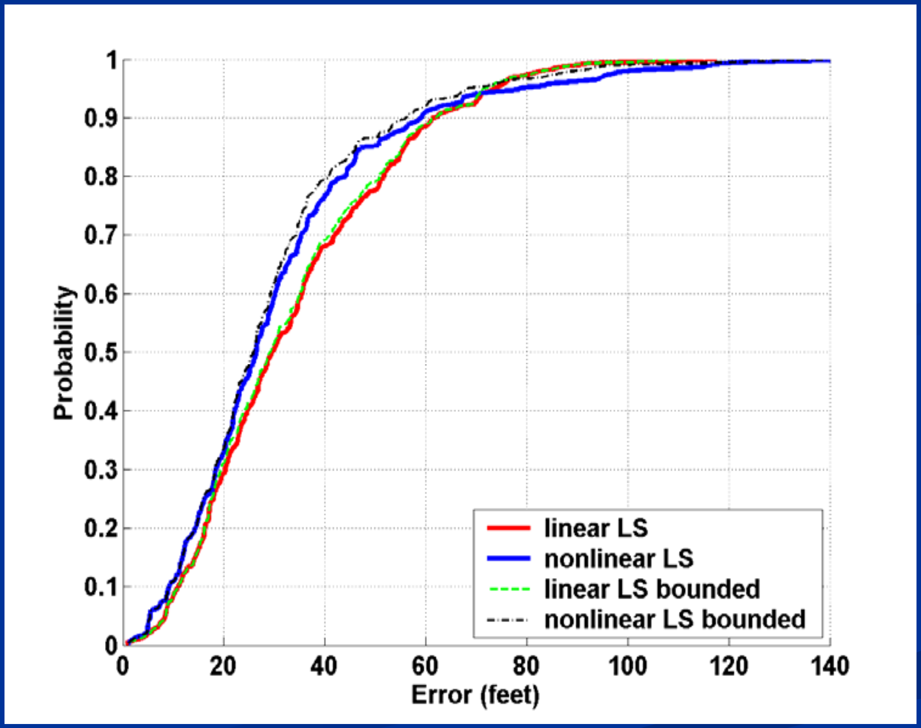
RSS

Localization Accuracy

TOA 802.11 Network

Error CDF across algorithms



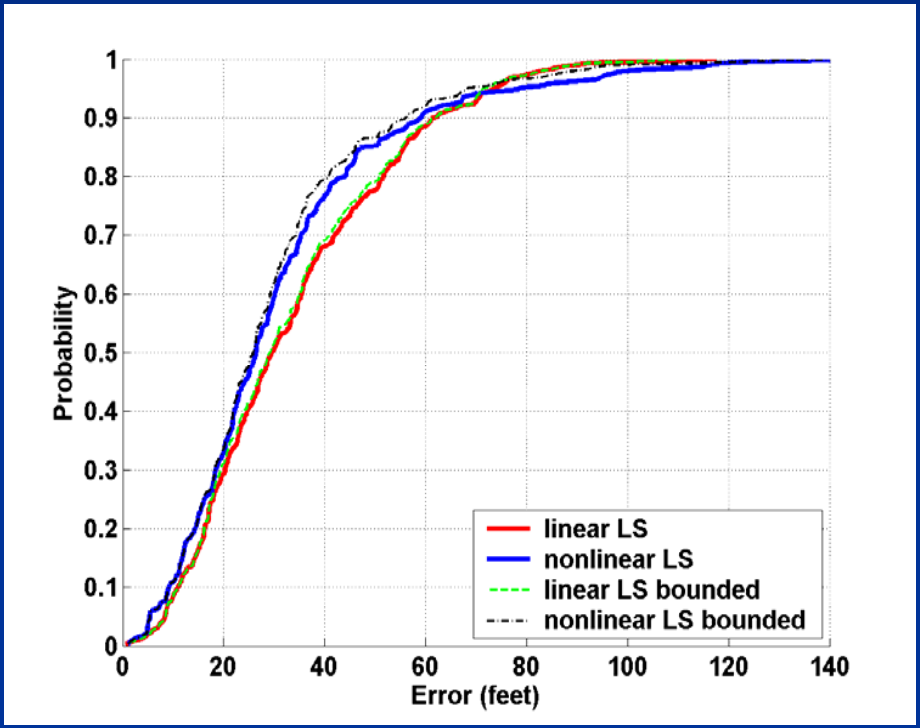


Colinear case

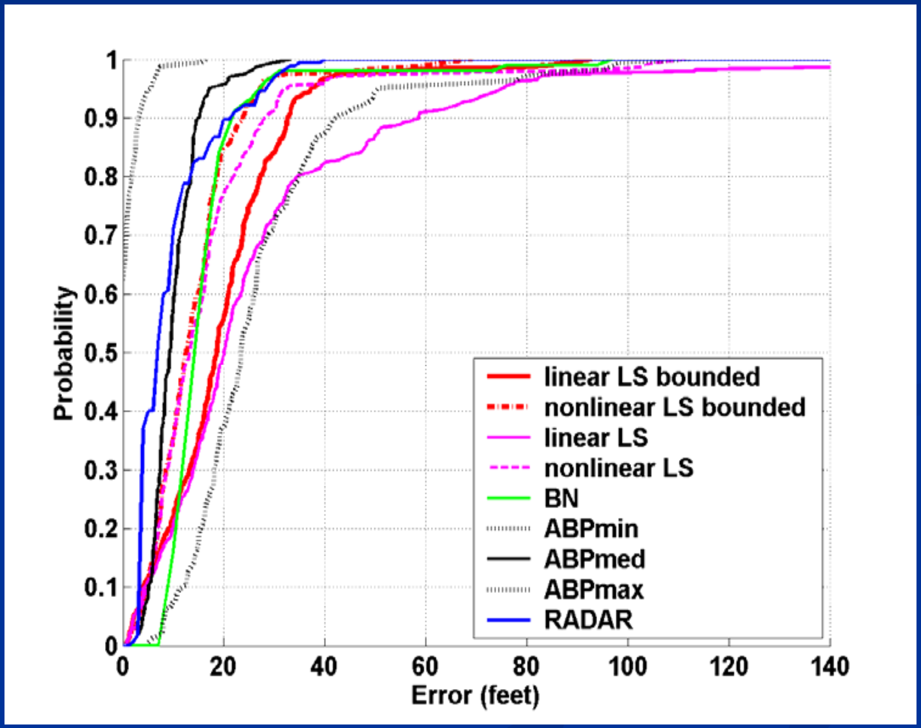
Square case

Localization Accuracy

Optimized landmark deployment



TOA



RSS

Conclusion

- Derived an upper bound on the maximum location error given the placement of landmarks
- Developed a novel algorithm, maxL-minE, for finding the optimal landmark placement
- Significant performance improvement of a wide variety of algorithms
  - ABP and RADAR: > 20%
  - LS: > 30%
  - BN: ~ 10%
- Tension between optimized landmark deployment for localization vs. deployments that optimize for signal coverage

Related Work

- Localization strategies:
  - Range-based [patwari05loc]: RSS [bahl00,elnahrawy04limits], TOA [GPS, toa04berlin] and TDOA [nissanka00]; or range-free [shang03, niculescu01aps]
  - Lateration [Langendoen03Survey,GPS,niculescu01aps,
  - zang05robust,chinta04ad]; angulation; or scene-matching [youssef03localization,roos02stat,bahl00,elnahrawy04limits]
  - Aggregate [dohertyl01, shang03] or singular (only refer to landmarks)
- Study of AP deployment for localization:
  - Simulation to study the location error and signal strength model for a few AP configurations [chen02signal]
  - Developed a set of heuristic search algorithms to find optimal AP deployment [battiti03optimal]
  - examined placement, but did not find optimal solutions [krish05accuracy]
- Network signal coverage perspective:
  - AP placement to maximize coverage and throughput properties of wireless LANs and sensor networks

Thank you
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Questions