Demonstrating Distributed Signal Strength Location Estimation

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Problem Statement

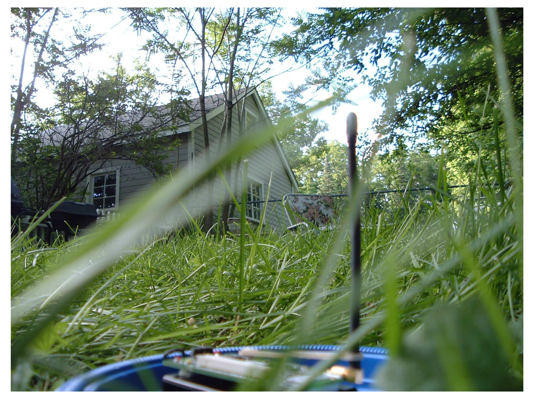
Implement a robust distributed sensor localization algorithm on a network of wireless sensors running TinyOS with **NO CENTRALIZED COMPUTATION**. Desired features:

- **Fully distributed** measurement and calculation;
- **Constant per-node complexity**: $\mathcal{O}(k)$ for k neighbors;
- **Received Signal Strength (RSS)**-based range estimation;
- **Robustness** to poor range estimates caused by the fading channel;
- **Low estimator variance** close to Cramér-Rao lower bound.

Motivation

Automatic localization of sensors in **large-scale** wireless networks. Key enabling technology for applications such as:

- Environmental monitoring
- Bar-code replacement
- Security, 'Panic-Button'
- Precision agriculture
- Manufacturing **logistics**
- Geographical routing
- Animal group tracking



Distance Estimation from Averaged RSS

Channel Model:

$$\bar{P}(d) = P_0 - 10 n_p \log \frac{d}{d_0}$$
$$P_{i,j} \sim \mathcal{N}\left(\bar{P}(d_{i,j}), \sigma_{dB}^2\right)$$
$$d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

- n_p: Path-loss exponent,
- σ_{dB}: Standard deviation of fading,
- P_0: Received power (dBm) at distance d_0 (1 m).
- First network measurement set is used to estimate $\{n_p, \Pi_0\}$.

The maximum likelihood estimator (MLE) of distance given $P_{i,j}$ is

$$\delta_{i,j}^{MLE} = d_0 10^{\frac{P_0 - P_{i,j}}{10 n_p}}$$

RSS Variance Reduction

Measurement Averaging:

- **Frequency Averaging**: Frequency-hop & Measure RSS at many (14) frequencies, use (dB) average.
- **Time Averaging**: Average few measurements over time. Cons: Tradeoff with tracking latency; and signal is non-ergodic.
- **Reciprocal Averaging**: Average $P_{i,j}$ with $P_{j,i}$ to reduce variations caused by TX & RX device, battery.

Our Approach: dwMDS

We implement a **Gossip version** of the **distributed weighted Multi-Dimensional Scaling** (dwMDS) algorithm [Costa 04, Costa 06]

- **Task distribution**: Global cost S is divided into individual sensors' local cost S_i, so that $S = \sum_i S_i$.
- **Majorization Approach**: For cycling algorithm, in each round, cost is guaranteed non-increasing.
- **Non-cycling**: We do not attempt to find a Hamiltonian cycle for sensors $1, \ldots, n$.
- **Gossip Version**: Each sensor computes **new coordinate estimate each period**, and sends it to its neighbors.

dwMDS Algorithm Calculation

Local cost function:

$$S_i = \sum_i w_{i,j} \left(\|\mathbf{z}_i - \mathbf{z}_j\| - \delta_{i,j}^{MLE} \right)^2 + r_i \|\mathbf{z}_i - \bar{\mathbf{z}}_i\|^2$$

Constants $w_{i,j}$ calculated from non-parametric LOESS formula.

S_i is **minimized by** a simple **weighted average** of coordinates of sensor i's neighbors.

$$\mathbf{z}_i^{(m+1)} = b_i \mathbf{z}_i^{(m)} + \sum_{j \in H(i)} b_j \mathbf{z}_j^{(m)}$$

Requires $\mathcal{O}(k)$ **multiplies and adds in each round,** where k is the number of neighbors.

Algorithm Specifications

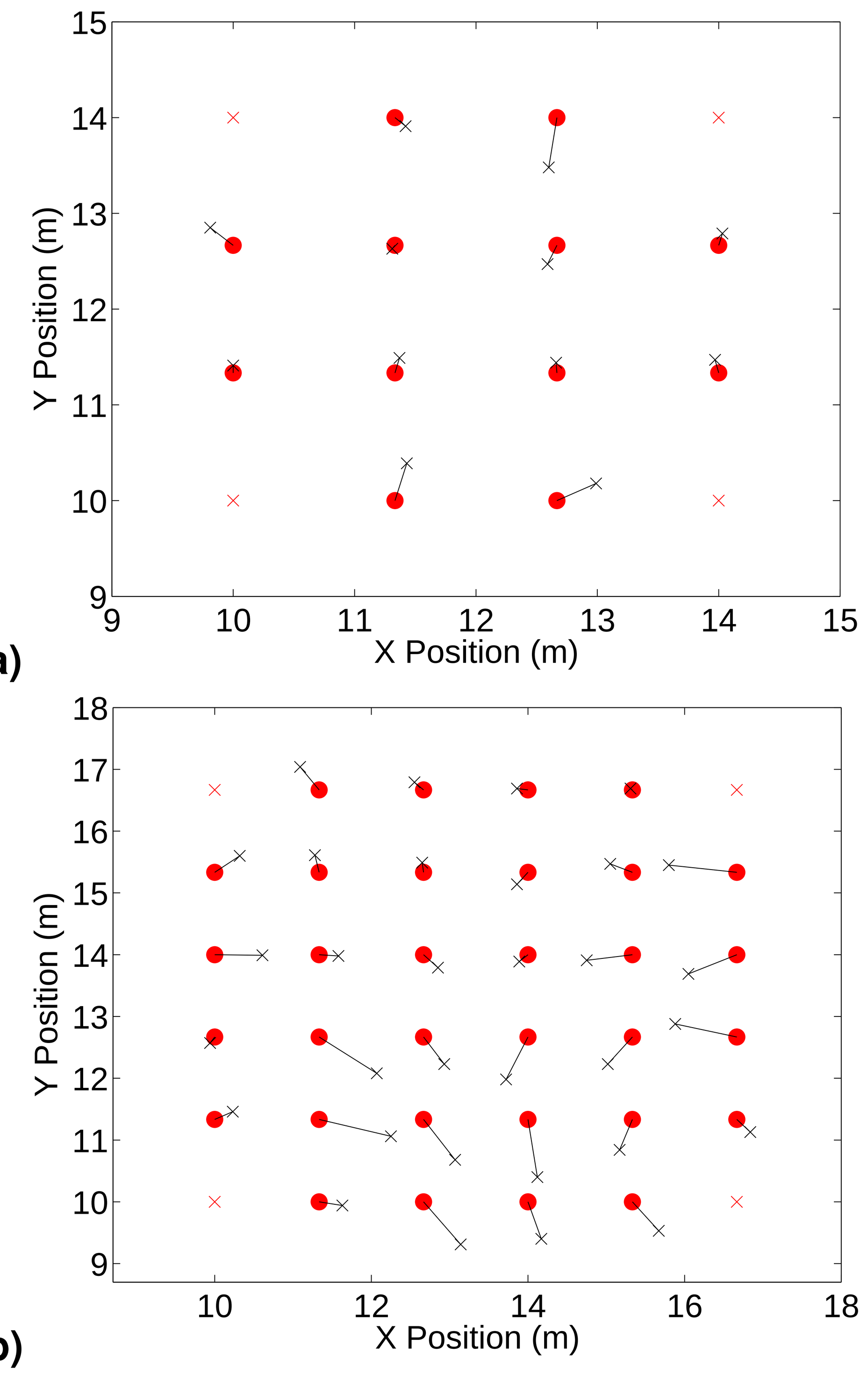
- **Synchronization**: Nodes synch. to fastest neighbor's clock.
- **Periodicity**: Each period is divided into two parts, a packet transmission time, and a silent period.
- Silent Period: Time to change frequency, run dwMDS update calculation.
- Packet Transmission Period: Nodes send one packet each period. Slotted by bit-reversal of node ID.
- **RSS Data**: Nodes send measured path loss integers (8 bits) and node ID of up to 8 neighbors.
- **Coordinate Data**: Nodes send two independent coordinate estimates, the 'best' estimate, and an alternate (which can be switched with the best estimate).
- **Packet Reception**: Nodes record the path loss integer of each received packet, and store it with the current frequency and node ID for later averaging.
- **Frequency Hopping**: Nodes hop among 14 different frequencies in a predetermined order

Experiment Test Setup

Two tests in the grass on University of Michigan's campus, achieving RMS location error of **(a) 25.6 cm, and (b) 55.3 cm**.

- **Sensor Geometry**: (a) 4 by 4 grid, and (b) 6 by 6 grid
- **Reference Nodes**: Four, in corners
- **Area Size**: (a) 4 m by 4 m, and (b) 6.67 m by 6.67 m

Experimental Results



(a)

(b)

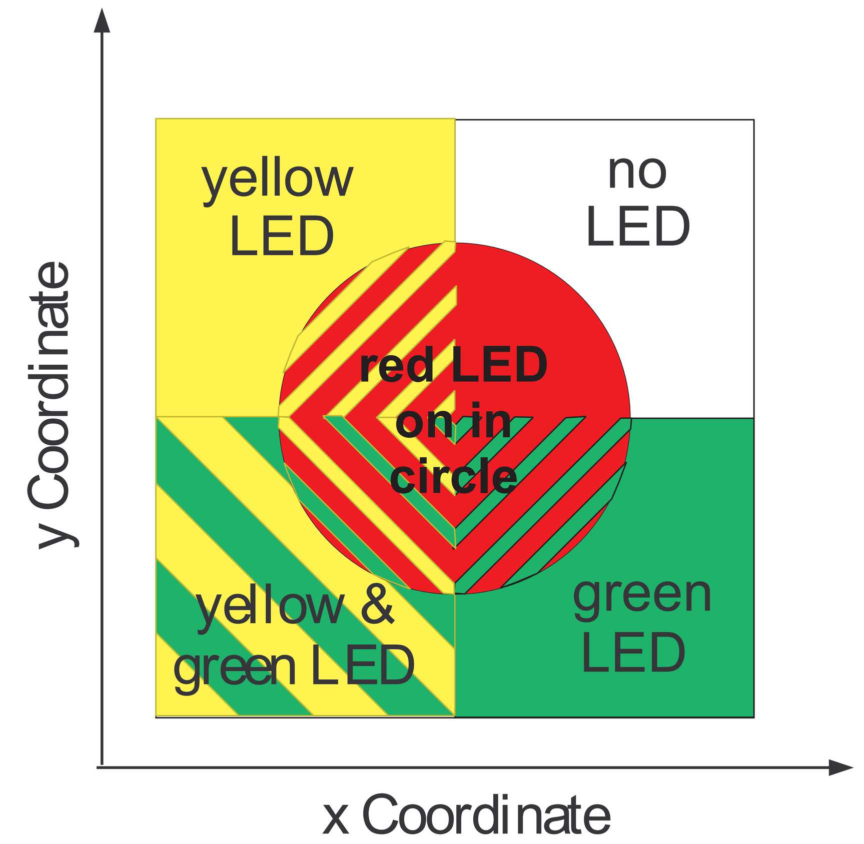
Figure: Actual (•) and estimated (—x) coordinates of unknown-location nodes, along with reference coordinates (x). Achieved RMSE **(a) of 25.6 cm, and (b) 55.3 cm**.

Demonstration Setup

Nodes are in a square area, with reference devices in the corners of the area. The nodes are placed on or among boxes, which are filled with packing peanuts.

Problem: Nodes only have three LEDs as output! How can they 'show' their coordinate estimate?

Solution: Divide the area into 8 areas and use the LEDs (RYG) to encode the area in which its coordinate estimate falls:



Future Improvements

- **Automatic Channel Parameterization**: Of n_p, P_0.
- **Implement bias-reduction**: [Costa 06] shows bias due to **neighbor selection**, and how to eliminate it.
- **Multiple initializations for coordinates**: May be used to escape from local minima.

Conclusion

Distributed sensor localization and tracking based on pair-wise measurements of **RSS** is possible with the following features:

- **Fully distributed** (local) measurement and communication. No message-passing across the network.
- Accurate with respect to the statistical lower bound.
- **Constant computational complexity** per node.

TinyOS Module Available: Contact `npatwari@ece.utah.edu`. Plan: Post on `tinyos.net`.

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