EE 579: Wireless and Mobile Networks Design & Laboratory

Lecture 5

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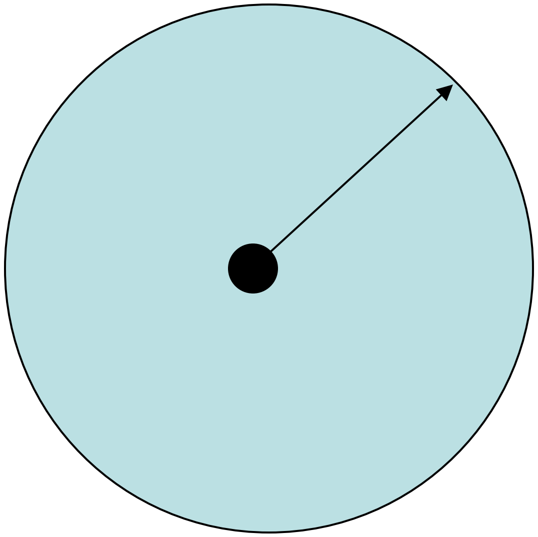
Lecture notes and course design based upon prior semesters taught by Bhaskar Krishnamachari and Murali Annavaram.

Outline

- Administrative Stuff
- Wireless Links
- GPS and Localization in Sensor Networks
- Open Forum

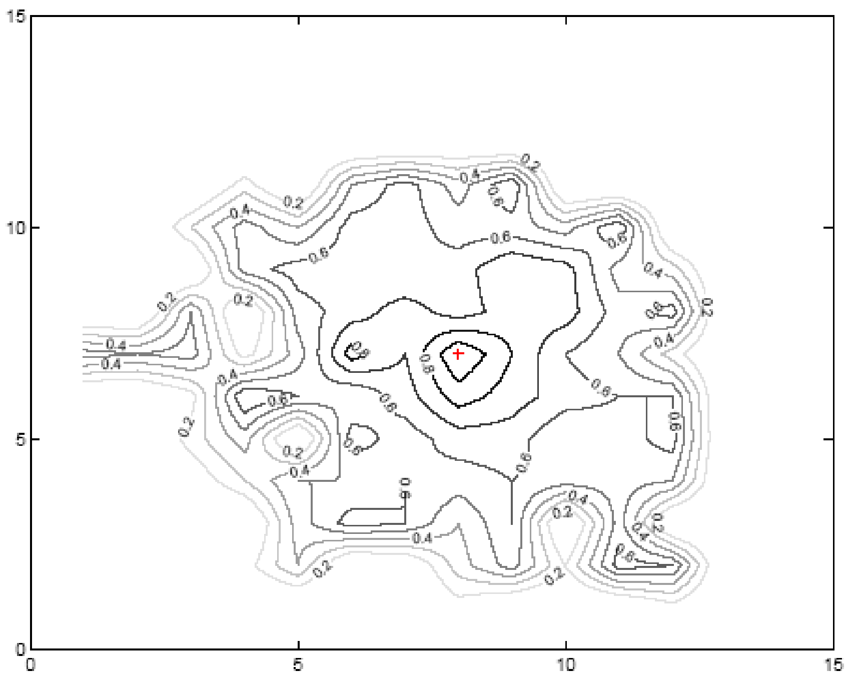
Wireless Links

- Most wireless networking research has used a very simple binary model for connectivity

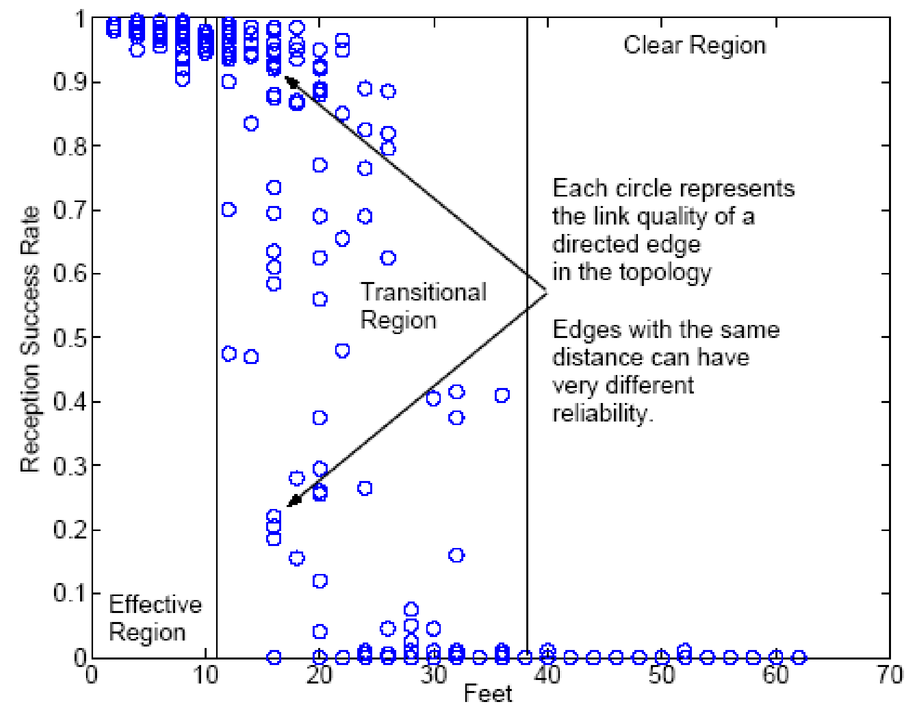


Circular radio range with perfect reception within & zero reception outside

Reality

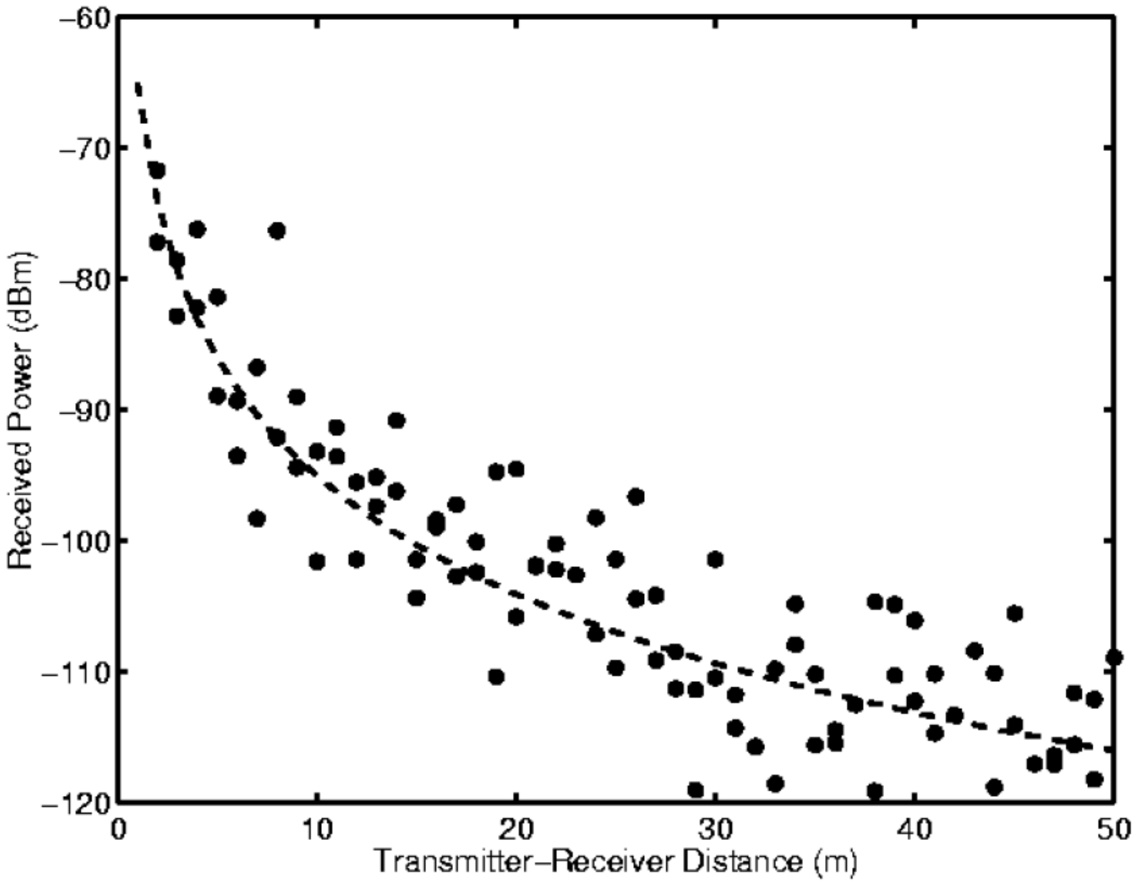


Ganesan et al. ‘02



Woo et al. ‘03

Radio Propagation



Basics

- Doppler spread D_s~ 2 f_c*v/c (20-500Hz)
- Coherence time T_c ~ 1/ D_s (2-50 ms)
- Delay Spread T_D (.1 to 1 ns)
- Coherence Bandwidth W_c ~ 1/(2 T_D) (200-2000MHz)

- Fast Fading: low Tc
- Flat Fading: W << W_c
- Frequency-selective Fading: W >> Wc

A Simple Model

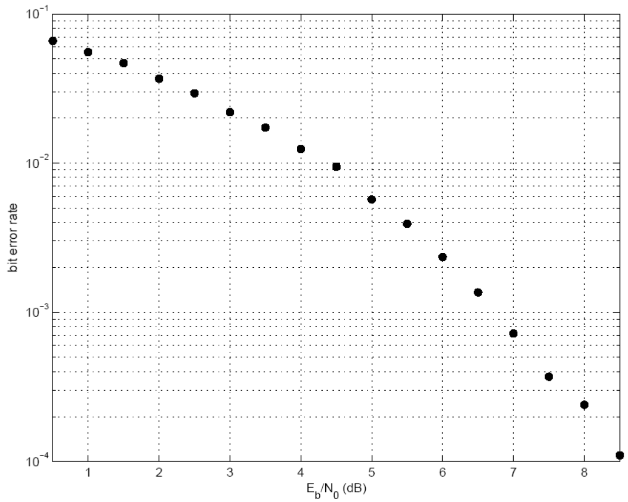
- Exponential path loss with log-normal fading:

$$P_{r,dB}(d) = P_{t,d}B - PL_{dB}(d)$$

$$PL_{dB}(d) = PL_{dB}(d_0) + 10n \log_{10} (d/d_0) + X_{\sigma,dB}$$

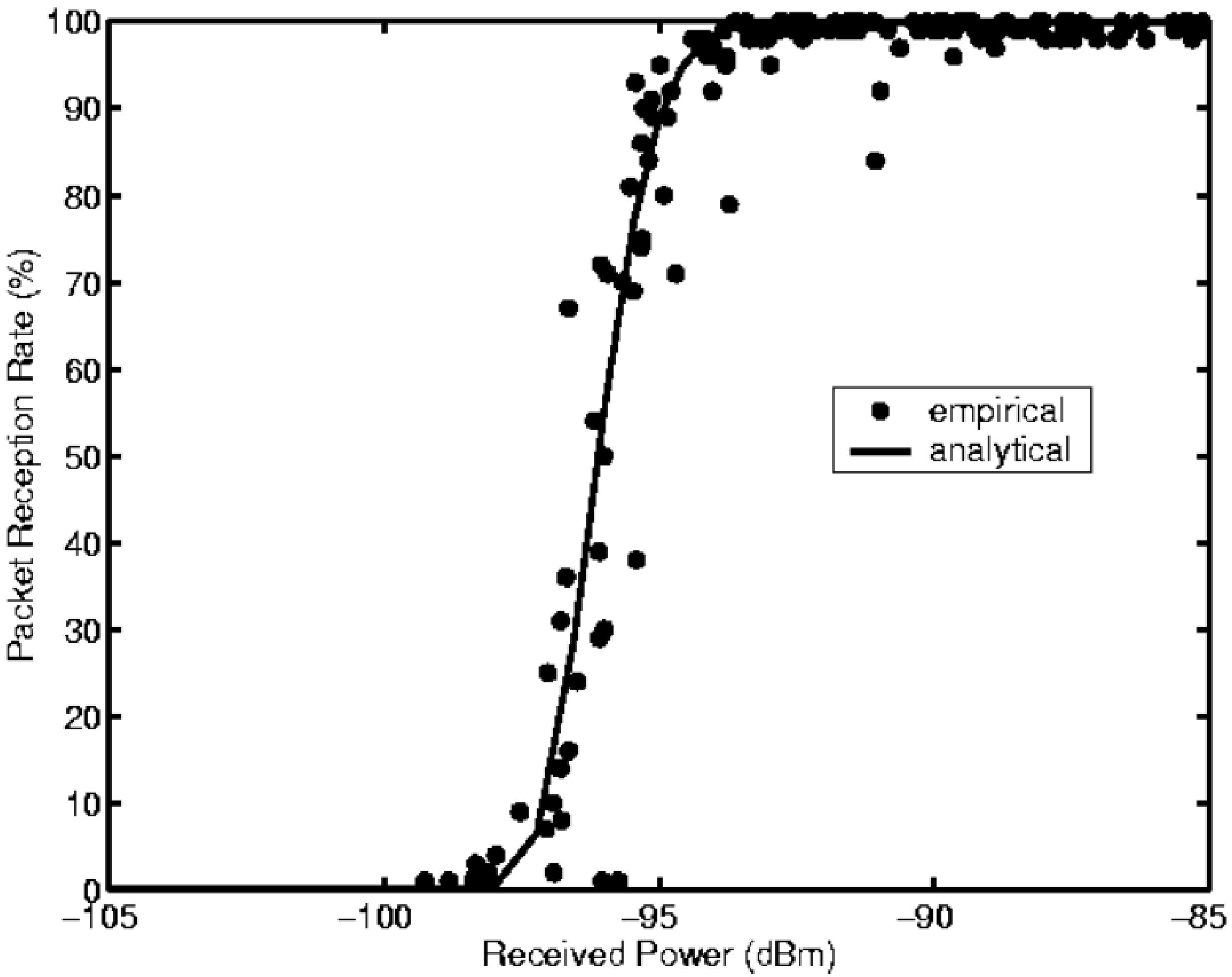
Radio Specifics

- The choice of modulation scheme, spread spectrum, error correction codes, etc. all have a significant effect on physical layer performance, that is typically measured by the BER vs. SNR curve



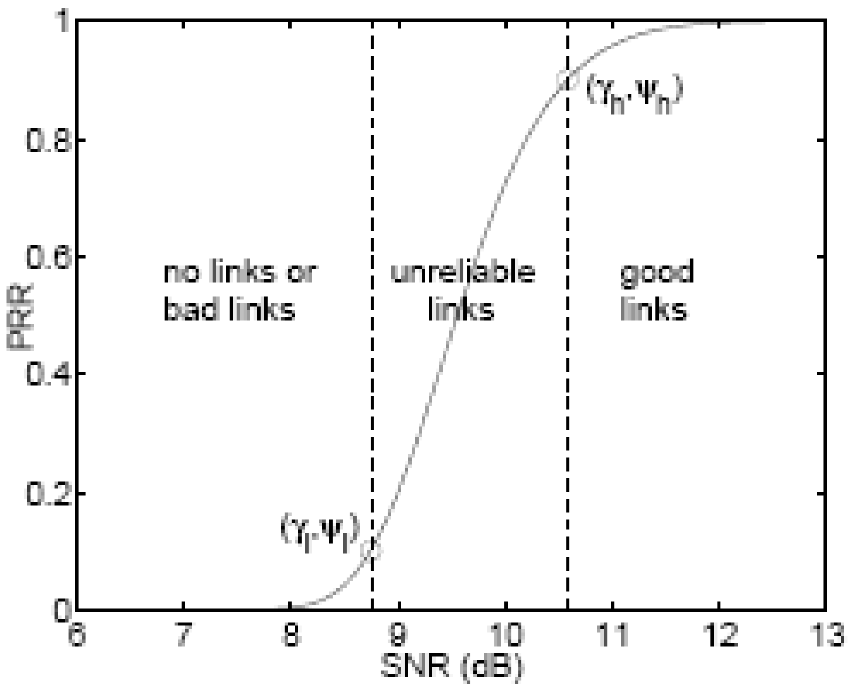
- At the link level we are interested in packets. Can trivially convert this to a PRR vs. SNR curve

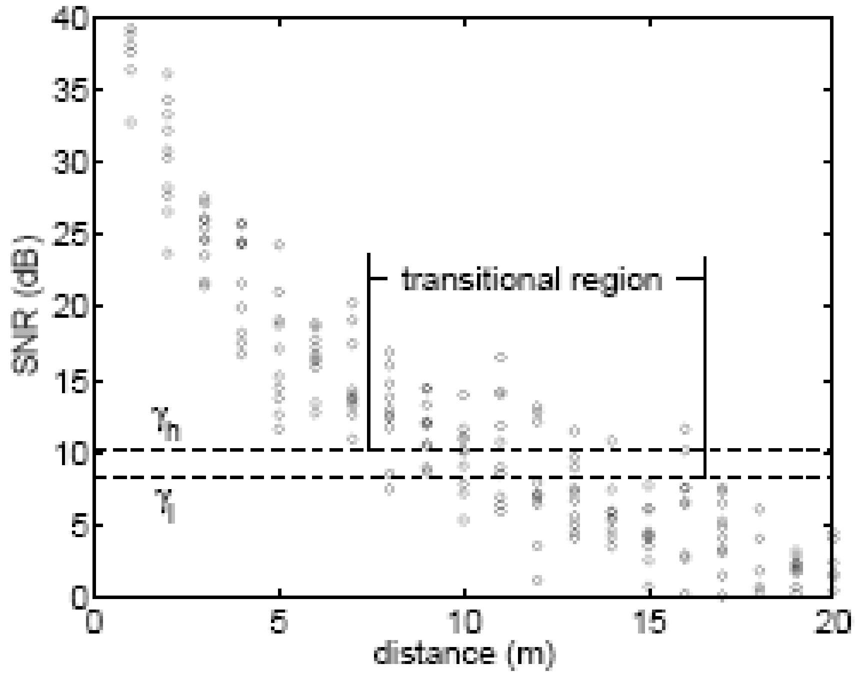
PRR versus SNR



Putting it Together

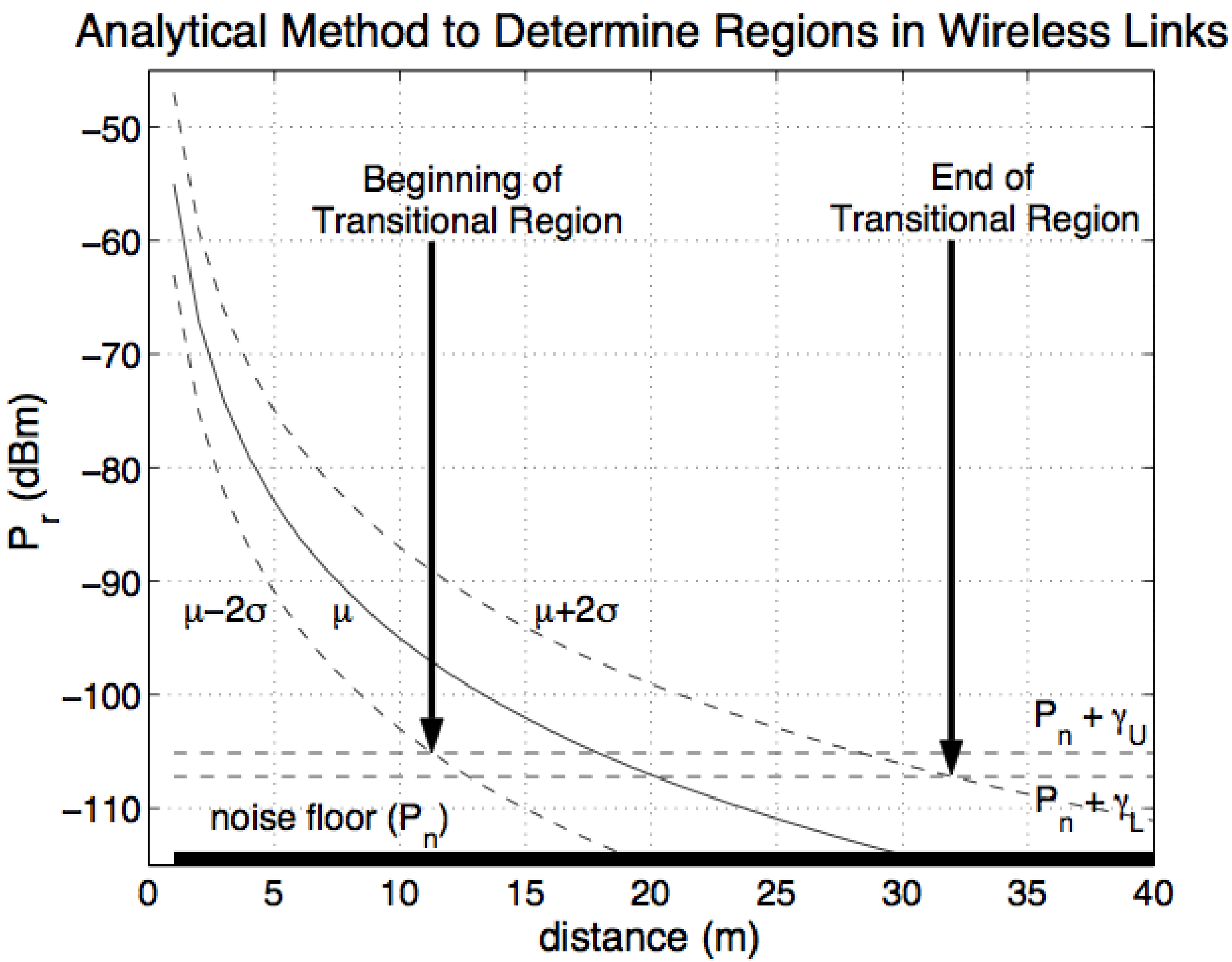
- Compose the following figures
  - PRR versus SNR
  - SNR versus distance





Zuniga-Krishnamachari '04, '07

Transitional Region

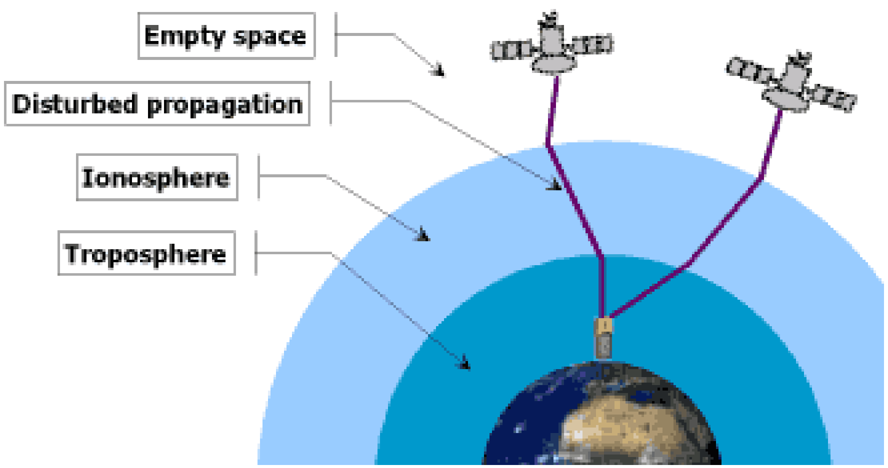


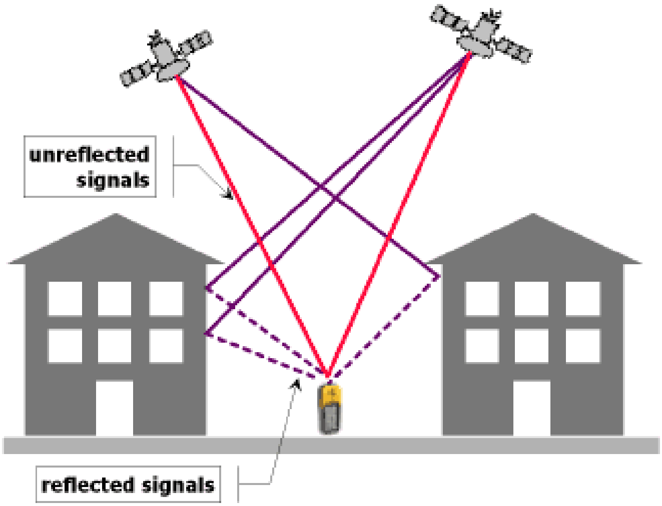
Global Positioning System

- Atomic clocks on satellites have VERY slow drift
  - +/- one second in 10s of thousands of years
- Quartz clocks on ground receiver drift rapidly (relatively)
  - If it were not for the time drift, three satellites could triangulate the spatial location of a receiver
  - Due to clock uncertainty, need four satellites
- Sources of error
  - Security (selective availability)
  - Geometric spread of satellites (narrow – not good, broad – good)
  - Ionosphere variable delay
  - Multipath
  - Clock inaccuracies

GPS Sources of Error

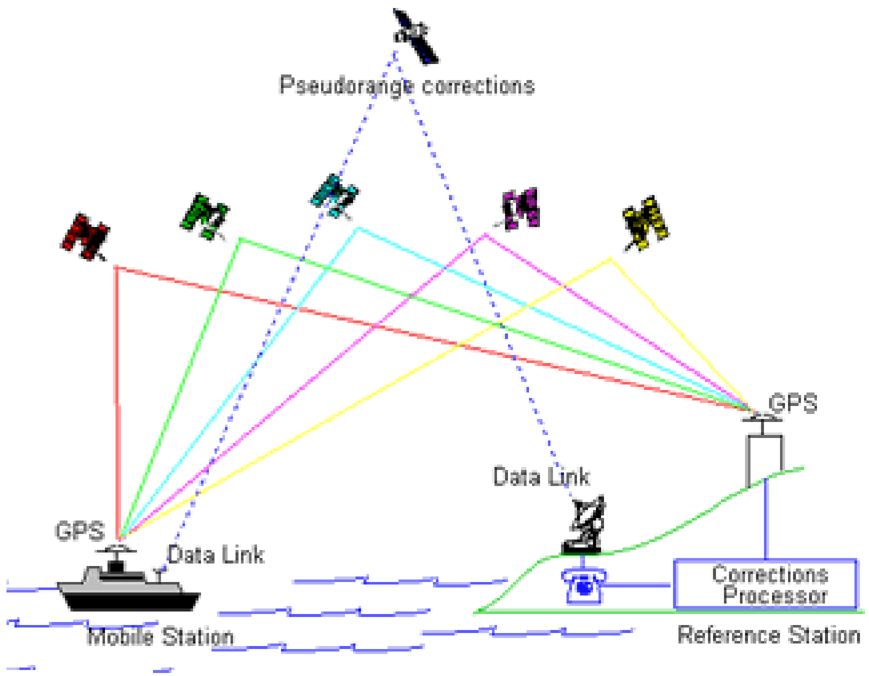
Ionospheric effects	± 5 meters
Shifts in the satellite orbits	± 2.5 meter
Clock errors of the satellites' clocks	± 2 meter
Multipath effect	± 1 meter
Tropospheric effects	± 0.5 meter
Calculation- und rounding errors	± 1 meter

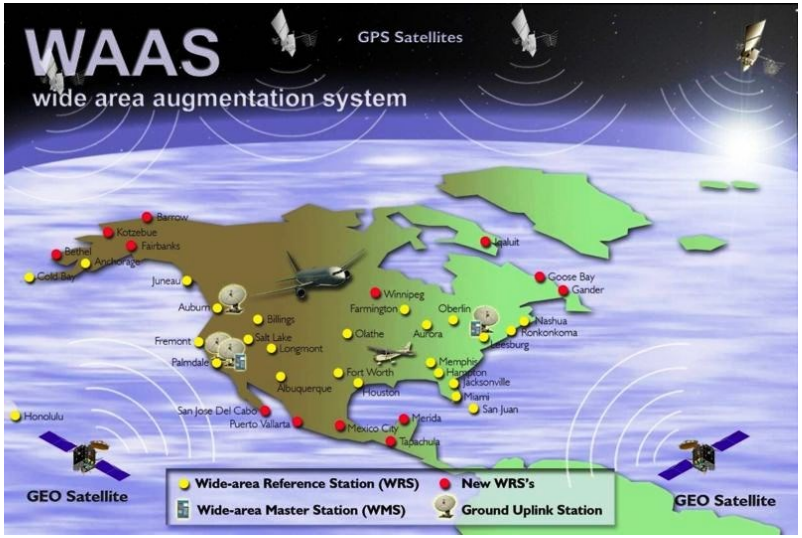




Differential GPS

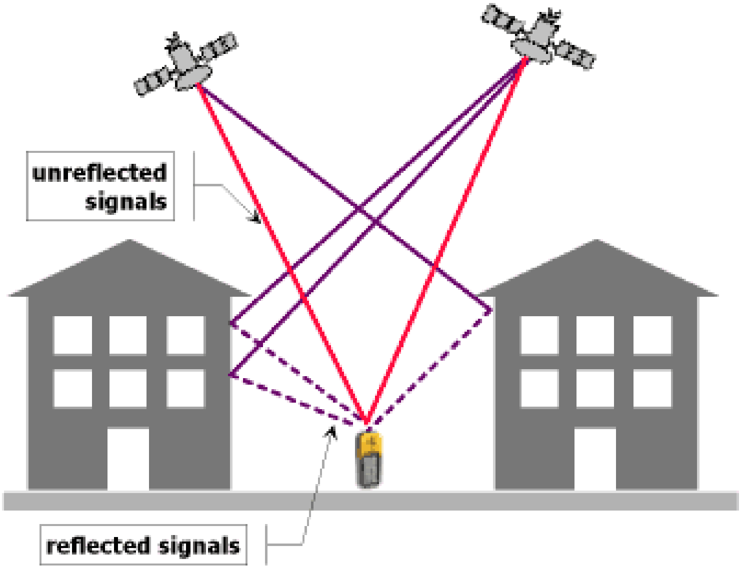
- Differential GPS uses signal reception at known locations to determine corrections to sources of errors
- Reduces error to about 5 m
- Implemented as Wide Area Augmentation System (WAAS) and implemented by the FAA in North America for flights





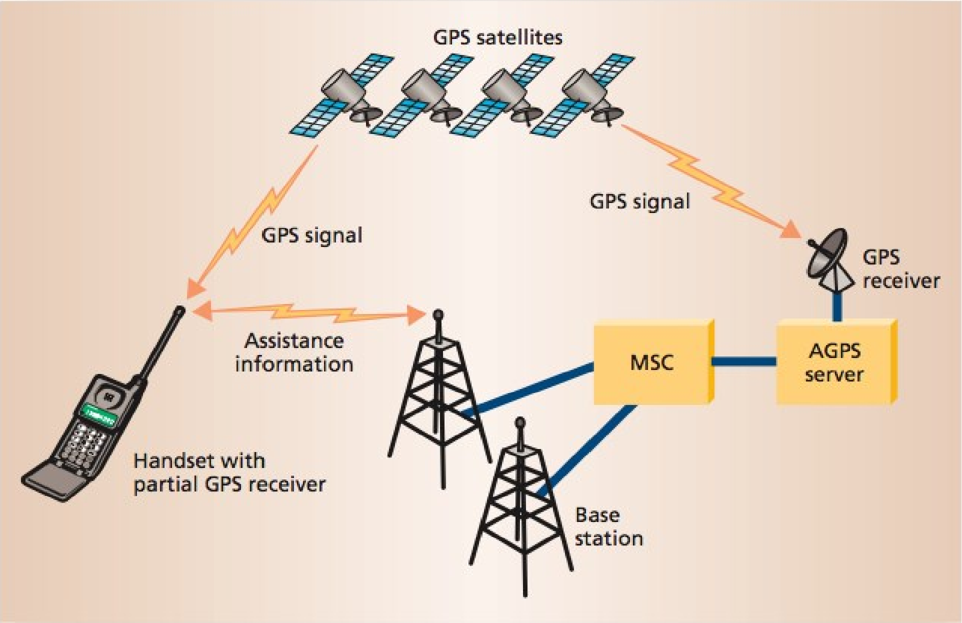
Assisted GPS

- In poor environments (cities with lots of multipath and obstructions), it can take upwards of 12 minutes for satellite lock
  - Even when sufficient satellites are being overheard
  - Complex processing is required, and reception of precise satellite location
- This is slow, expensive



Assisted GPS

- Assisted GPS solves these problems
  - Combines concepts from differential GPS
  - Leverages data backbone to download precise orbital data
  - Offloads complex calculations from GPS receiver / cell processor onto AGPS receiver
  - Rapid and precise time synchronization



Localization

Unfortunately, the earth is not flat. This would simplify things substantially.

And it's not spherical either (despite appearance from space)

Localization Overview

- Localization – To determine the location of objects

- Location information is necessary / useful for many functions
  - Location stamps
  - Coherent signal processing
  - Tracking and locating objects
  - Cluster formation
  - Efficient addressing
  - Efficient querying and routing

Localization Design Issues

- What to localize?
  - Unknown node vs. reference node
  - Mobile vs. static node
  - Node localization vs. network localization
  - Cooperative vs. non-cooperative nodes
- When to localize?
  - Static vs. dynamic
- How well to localize?
  - Coarse vs. fine grained
- Where to localize?
  - Central server vs. localizing object
- How to localize?
  - Technology: RF, IR, Ultrasound, Combination, UWB
  - What methodology to use?

Node Localization Approaches

- Coarse-grained
  - Use minimal information
  - Use minimal computation power
- Fine-grained
  - Gather and use as much information as possible
  - Requires higher computation power
- Trade-off
  - Accuracy vs. implementation / computation / cost

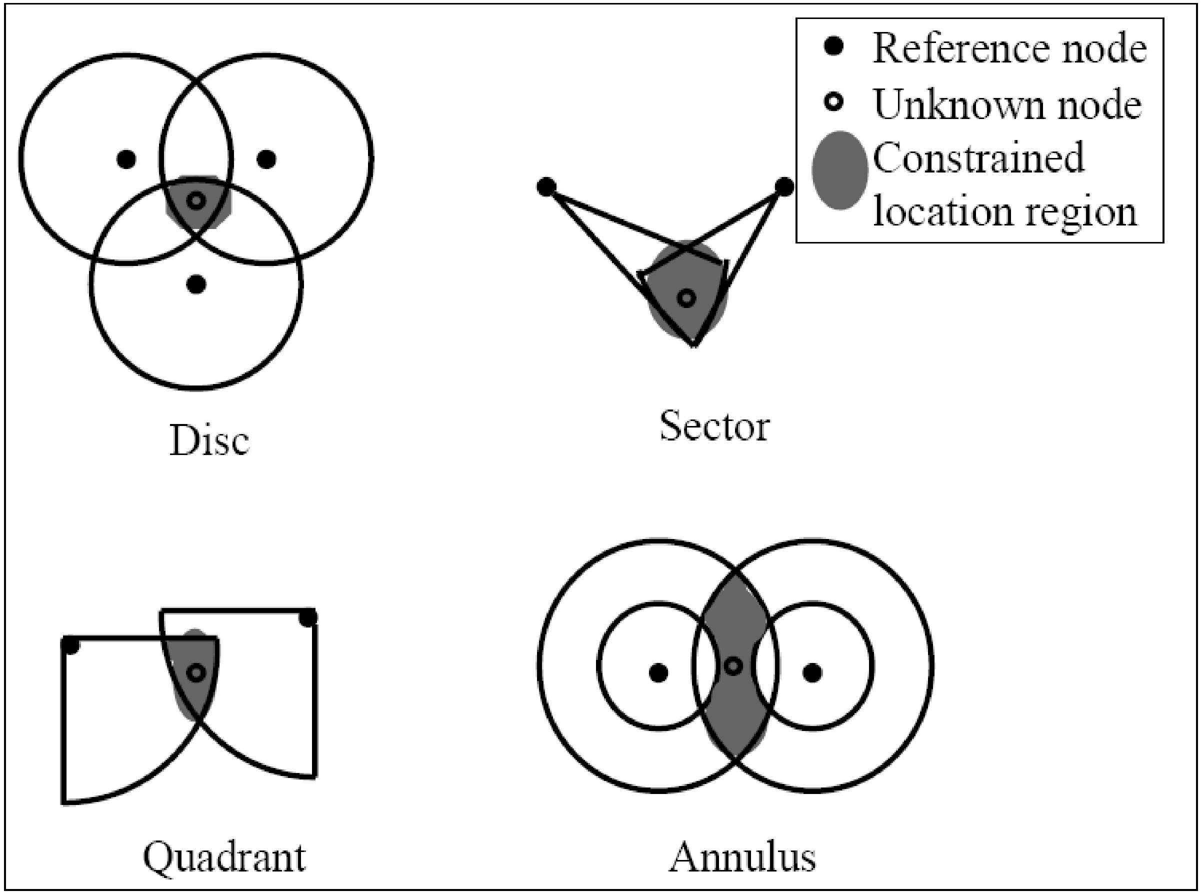
Coarse-Grained Node Localization

Several techniques provide approximate solutions for node localization based on the use of minimal information

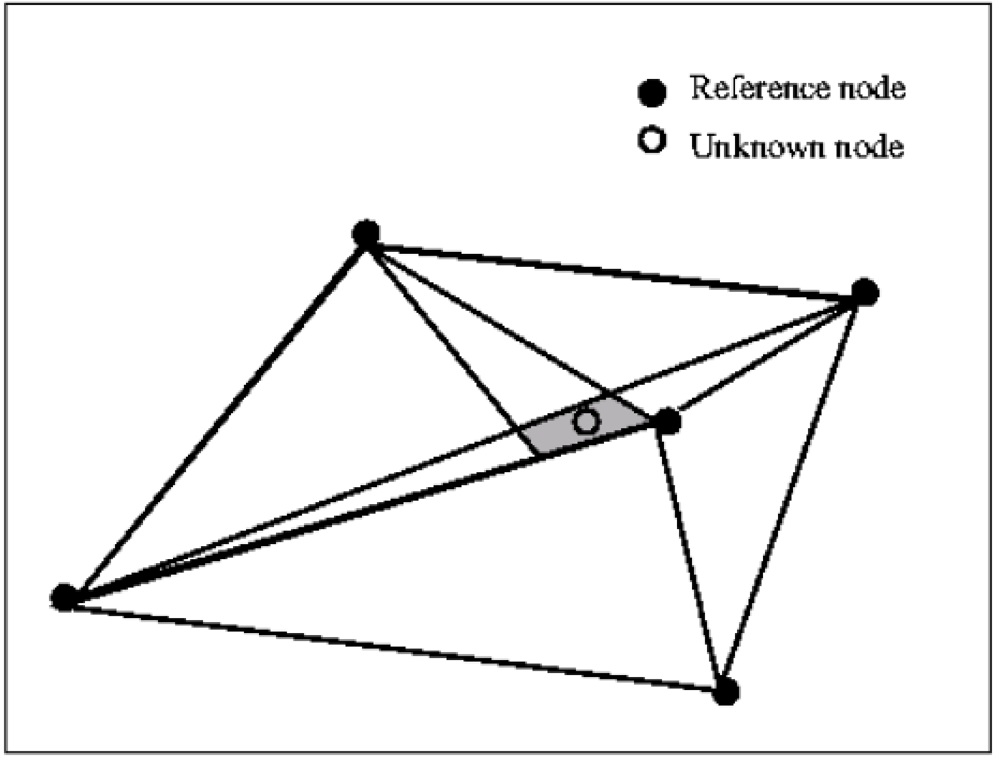
- Binary proximity
  - Location of the closest reference node
- Centroid
  - Center of gravity of reference nodes in the radio range

- Geometric constraints
- Approximate point in triangle (APIT)
- Identifying codes

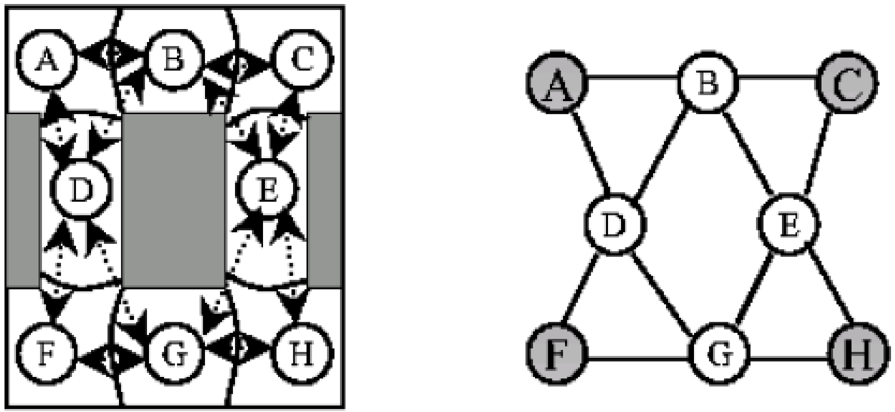
Geometric Constraints



Approximate Point in Triangle



Identifying Codes



Node Locations　　　Connectivity Graph

Transmitters A, F, C, H provide unique IDs for all node locations

V:	A	B	C	D	E	F	G	H
ID:	A	A,C	C	A,F	C,H	F	F,H	H

Fine-Grained Node Localization

- Ranging-based
  - Use of estimation theory
- Pattern matching
  - Many versions
- Ecolocation
- Sequence-based localization

Ranging-Based

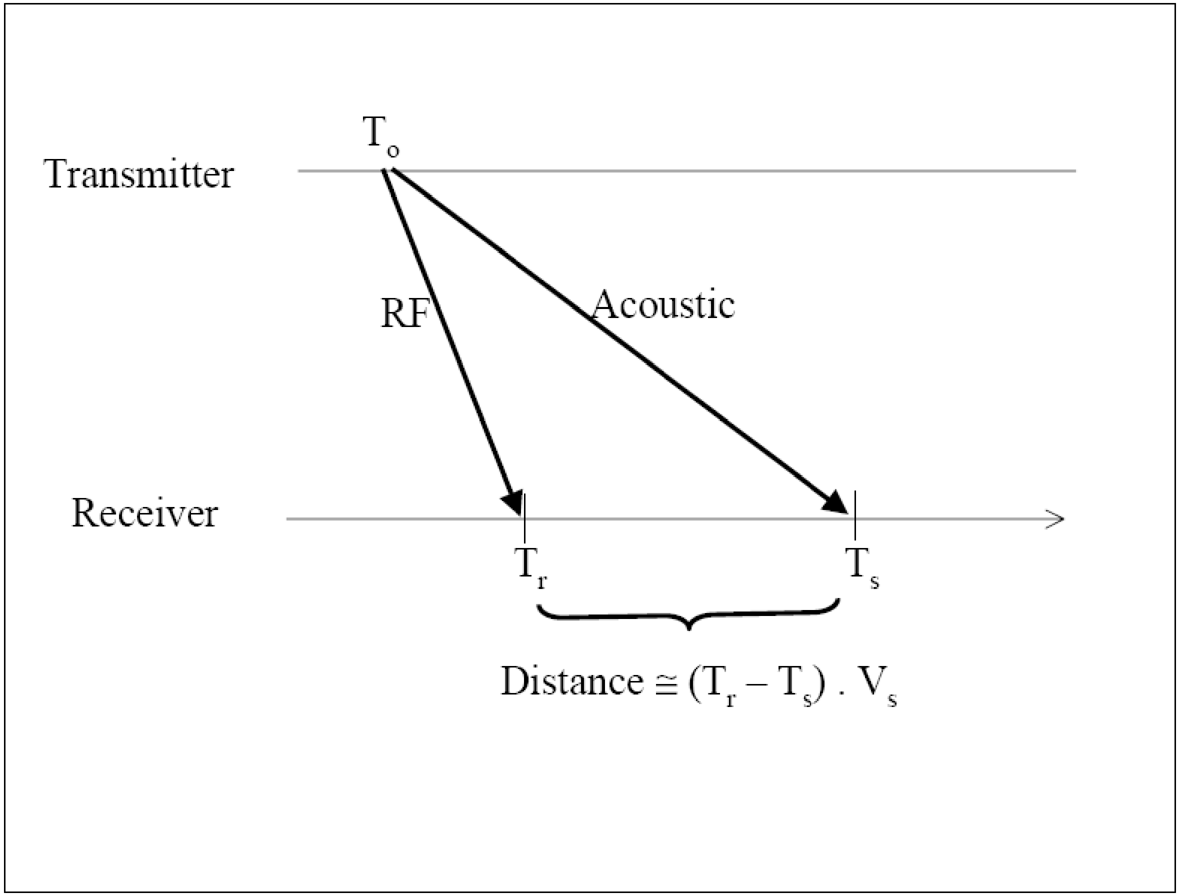
- Ranging
  - Using signal strength (RSS) – meter level accuracy
  - Using time difference of arrival (TDoA) – cm level accuracy over short distances

- Position estimation in a Least Squares problem
  - Find (x,y) to minimize the squared error

$$\sum_{i=1}^{n} \left(d_i^{(x,y)} - d_i^{measured} \right)^2$$

- Angle of Arrival (AoA) techniques can also be used in conjunction with ranging

Time Difference of Arrival

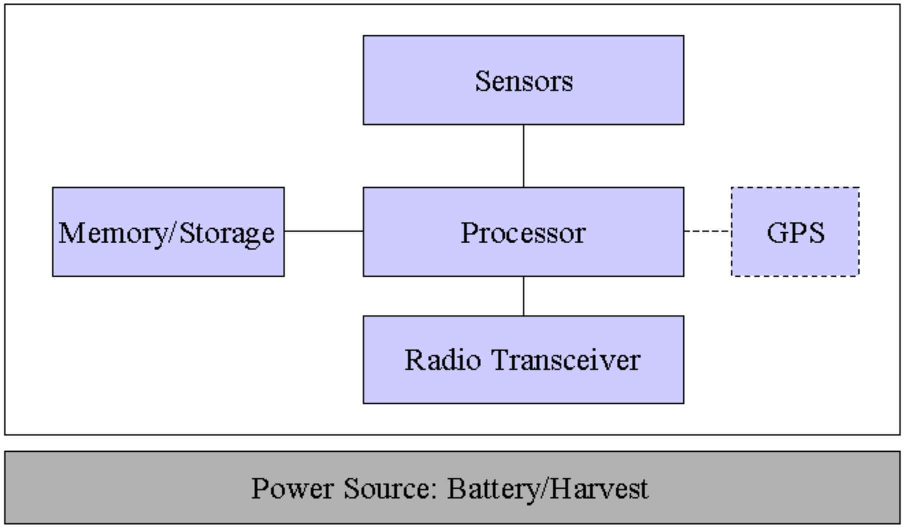


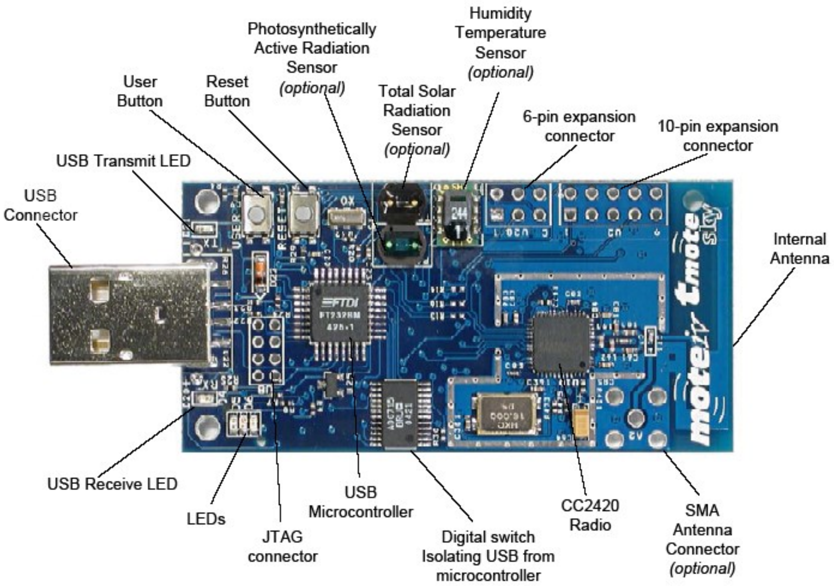
Pattern Matching

- E.g., RADAR
- Requires pre-training of signal strength measurements at different places in the environment
- Create database
- Search through the database for the closest matching pattern
- Highly dependent on environmental features

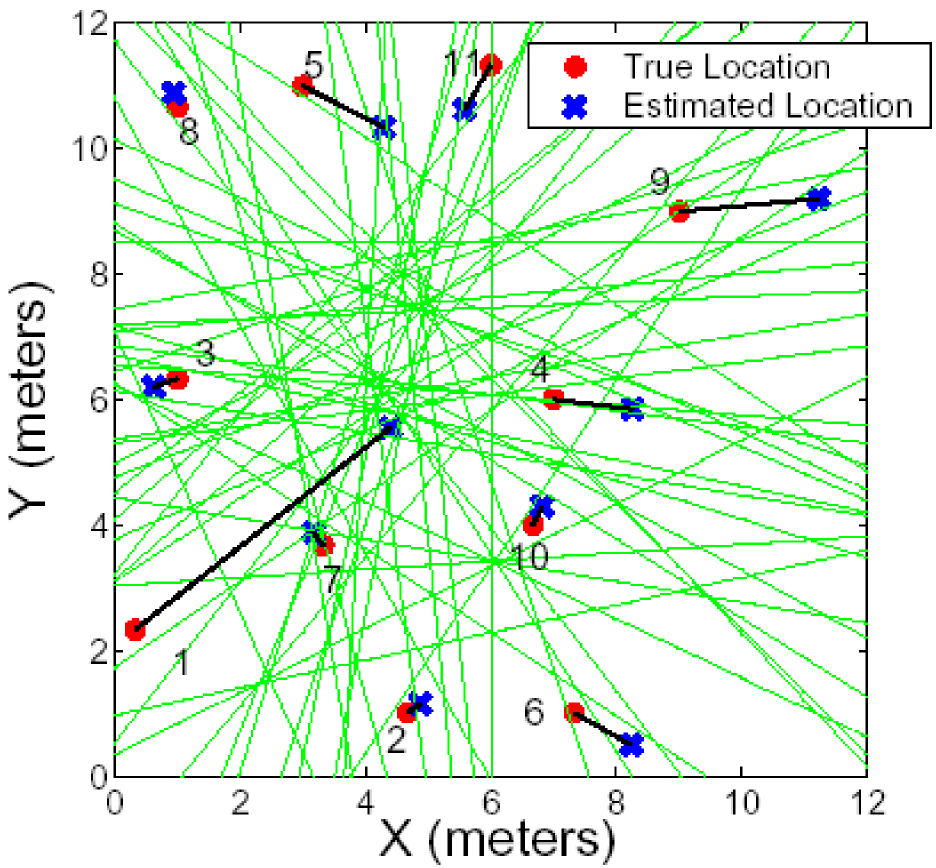
Wireless Sensor Networks

- Collection of low-power embedded wireless devices that are each capable of computation, communication, and sensing





Radio Signal Strength Based Localization



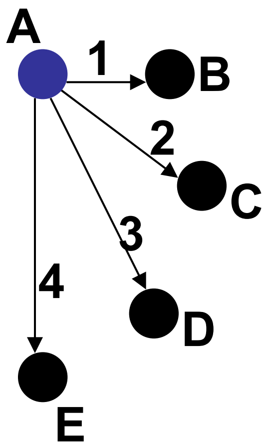
- Developing local positioning systems suitable for embedded wireless devices
- Low cost alternatives to GPS that can also work well under foliage / indoor environments
- Ecolocation and sequence-based localization

Ecolocation

- Unknown node initiates localization process
  - Sends out a localization request
- Reference nodes in the radio range send response packets
- Measure signal strength of received packets (RSSI)
- Rank reference nodes based on RSSI values
  - Ranks can be written as a set of constraints on the location of the unknown node
- The locations of reference nodes with respect to the grid points can also be written as distance constraints

Location Constraints

- Relationship between distances of a pair of reference nodes with respect to the unknown node
  - N reference nodes => n(n-1)/2 constraints (A constraint set)

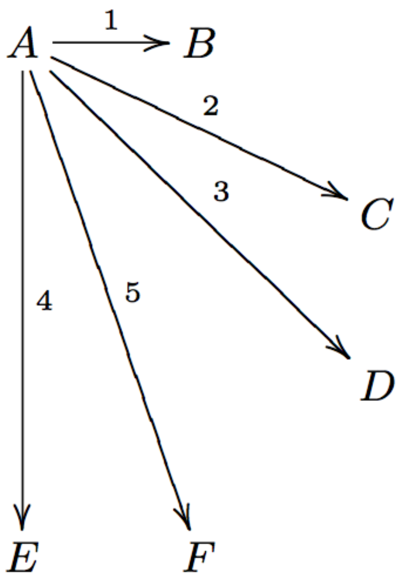


Location Constraint Set for A

$$\{d_B < d_C,\ d_B < d_D,\ d_B < d_E,\ d_C < d_D,\ d_C < d_E,\ d_D < d_E\}$$

Redundancy in the constraint set

Location Constraints



B:1	C:2	D:3	E:4	F:5
R_1	$R_2 < R_1$	$R_3 < R_1$ $R_3 < R_2$	$R_4 < R_1$ $R_4 < R_2$ $R_4 < R_3$	$R_5 < R_1$ $R_5 < R_2$ $R_5 < R_3$ $R_5 < R_4$

Constraints on the unknown node w.r.t. the reference nodes

$$M_{\alpha\times\alpha}(i,j) = \begin{matrix} 1 & \text{if } R_i < R_j \\ 0 & \text{if } R_i = R_j \\ -1 & \text{if } R_i > R_j \end{matrix}$$

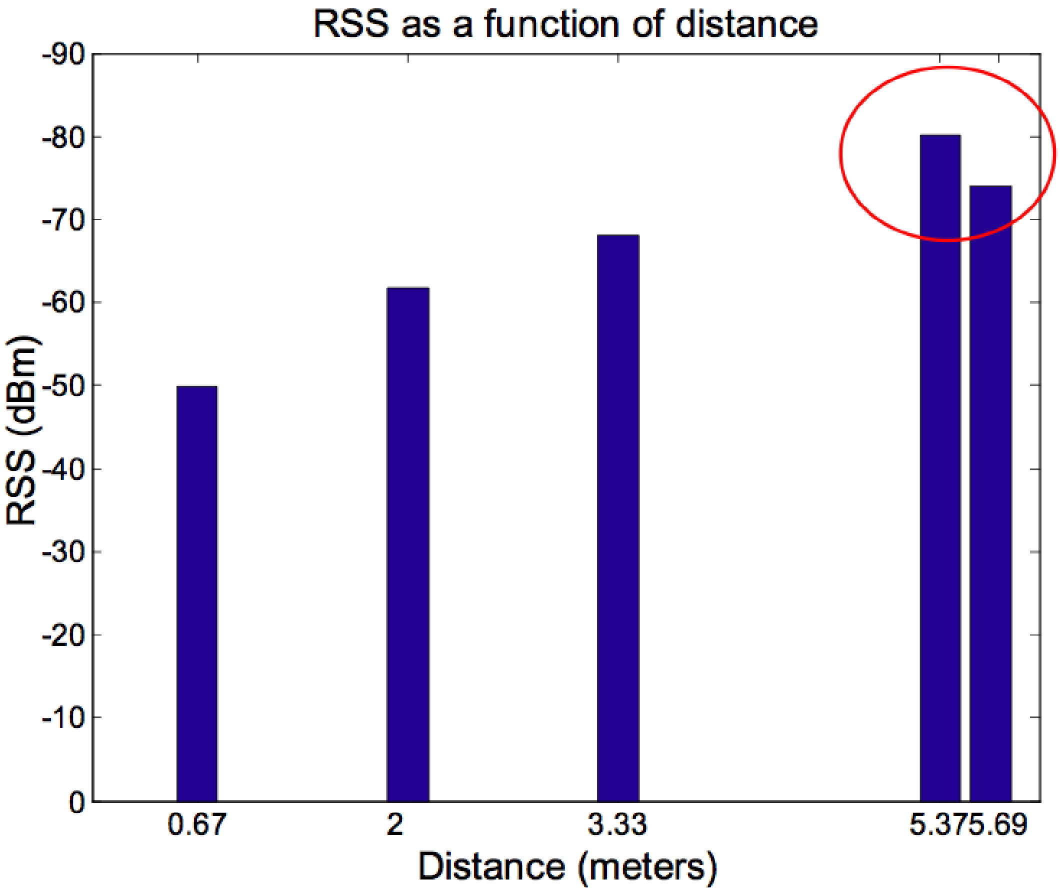
Constraints on the reference nodes w.r.t. each of the grid points

$$C^{ij}_{\alpha\times\alpha}$$

Ecolocation

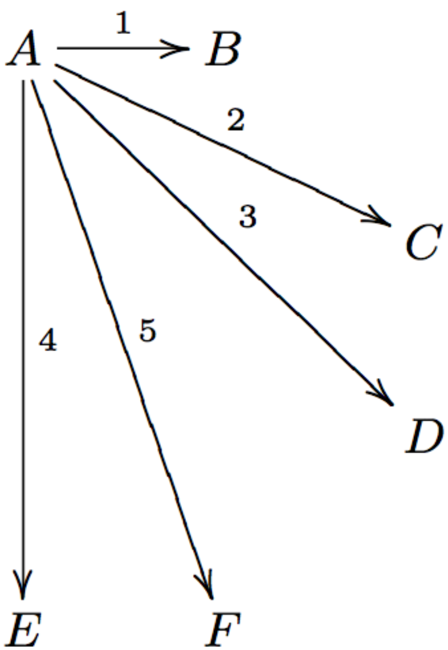
- For each grid point in the space, compare RSSI constraints with distance constraints
- Grid point with the highest matched constraints is the location estimate
  - If more than one grid point have highest matching, their centroid is the location estimate

Multipath Effects



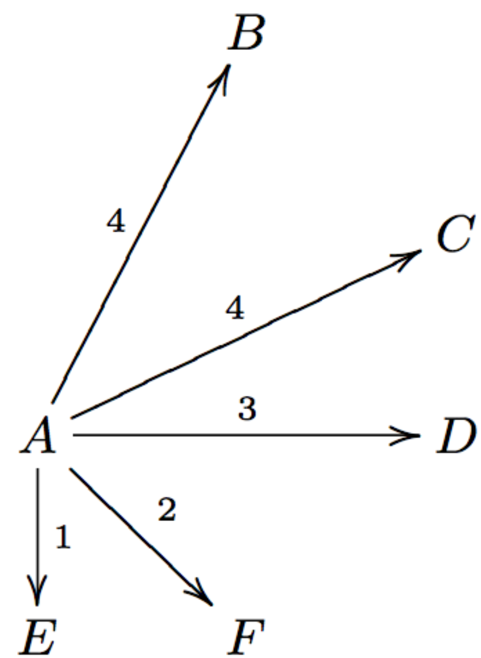
Multipath effects

Location Constraints: Looking Closely



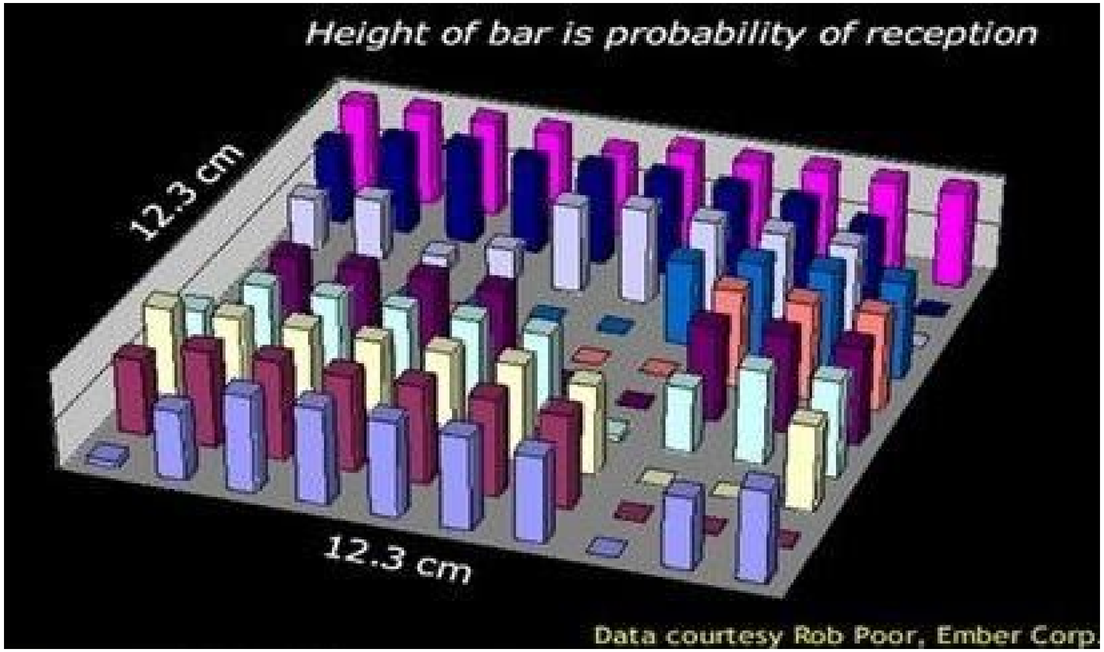
B:1	C:2	D:3	E:4	F:5
R_1	$R_2 < R_1$	$R_3 < R_1$	$R_4 < R_1$	$R_5 < R_1$
		$R_3 < R_2$	$R_4 < R_2$	$R_5 < R_2$
			$R_4 < R_3$	$R_5 < R_3$
				$R_5 < R_4$

B:1	C:2	D:3	E:5	F:4
R_1	$R_2 < R_1$	$R_3 < R_1$	$R_5 < R_1$	$R_4 < R_1$
		$R_3 < R_2$	$R_5 < R_2$	$R_4 < R_2$
			$R_5 < R_3$	$R_4 < R_3$
				$R_4 < R_5$



RF Channel and Ecolocation

- RF Channel
  - Multipath fading and shadowing
  - Causes errors in RSSI measurements
  - Leads to errors in reference node ranks
  - Leads to violation of location constraints

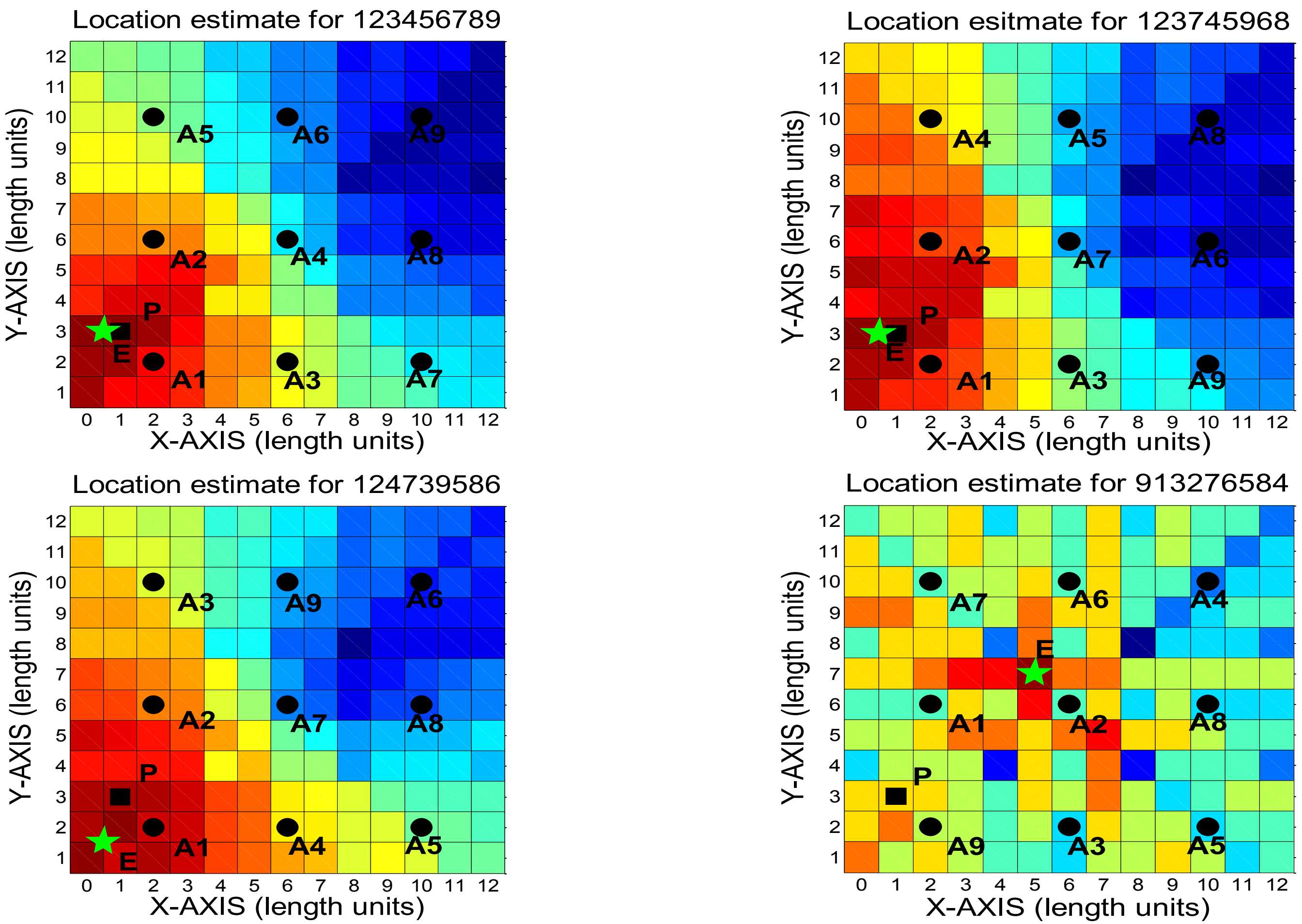


RF Channel and Ecolocation

- RF Channel
  - Multipath fading and shadowing
  - Causes errors in RSSI measurements
  - Leads to errors in reference node ranks
  - Leads to violation of location constraints

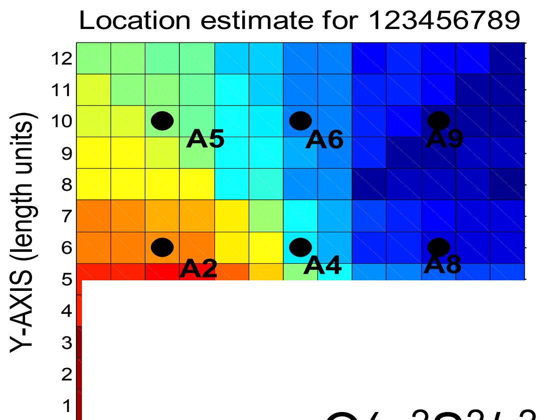
- Ecolocation
  - Location estimate accuracy depends on the number of violated constraints
  - Helped by inherent redundancy in constraint set (analogous to error control coding)
  - Constraint tolerance to RF channel errors up to difference in path loss

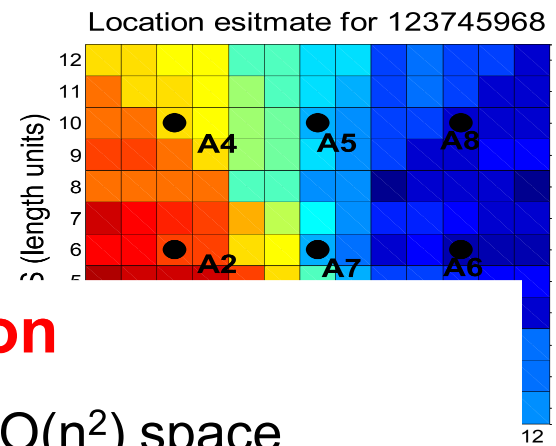
Ecolocation Results



A: Reference Node P: True Location of unknown node E: Ecolocation Estimated Location

Ecolocation Results





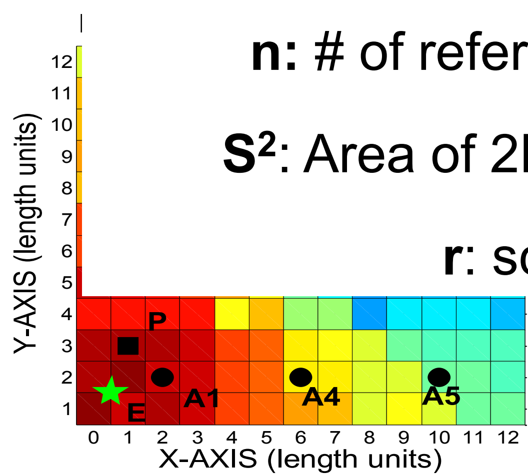
Operation

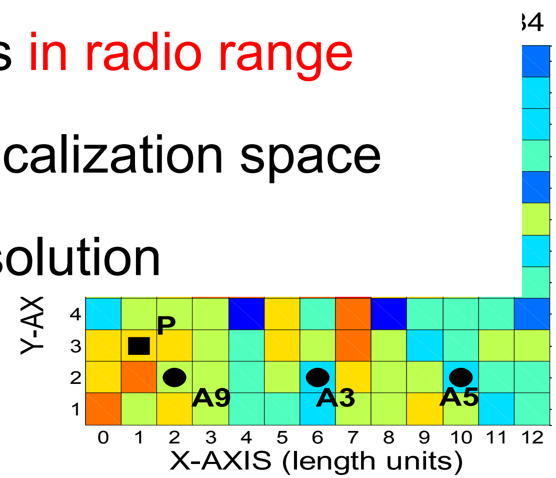
$O(n^2S^2/r^2)$ time and $O(n^2)$ space

n: # of reference nodes in radio range

S^2: Area of 2D square localization space

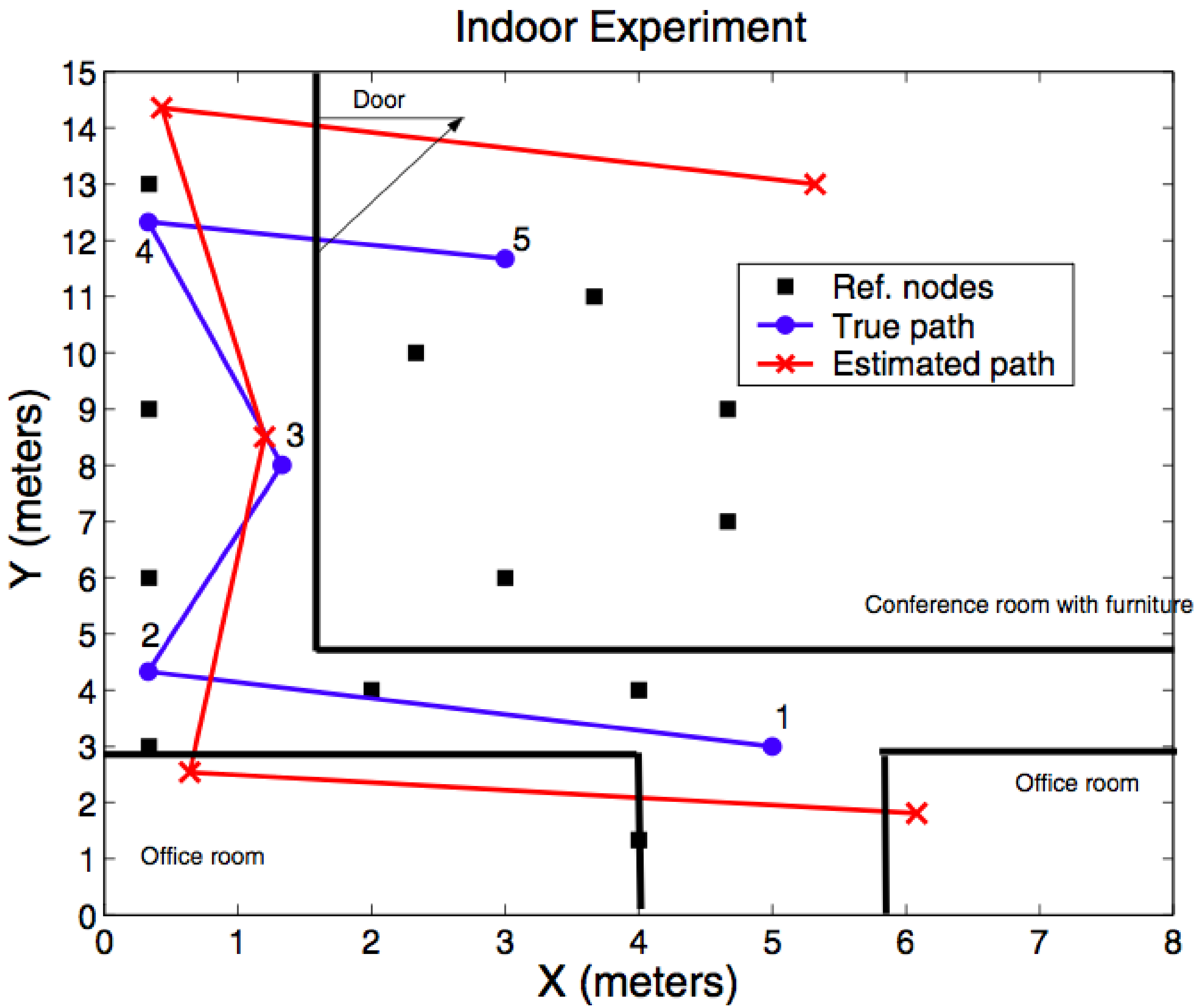
r: scanning resolution



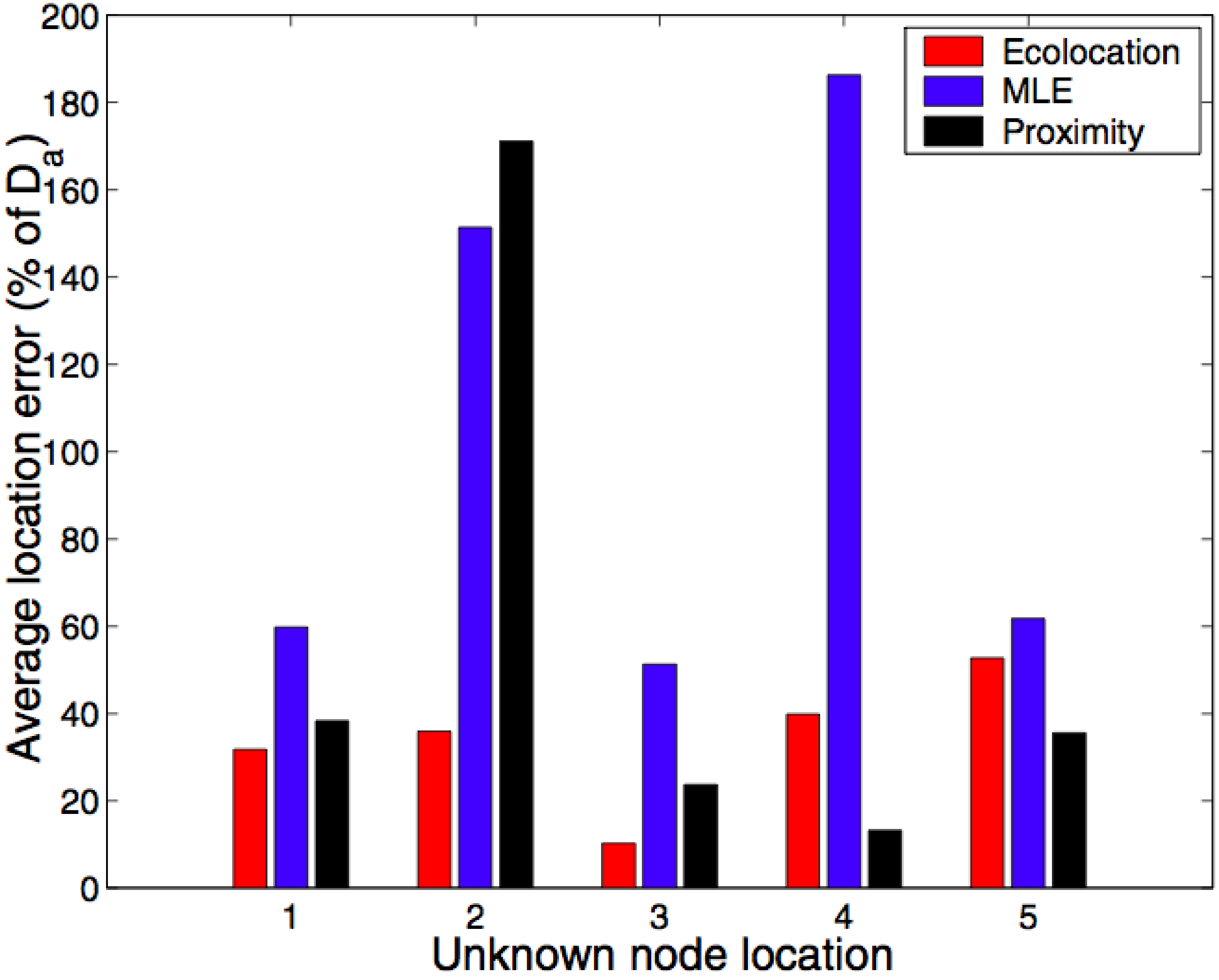


A: Reference Node P: True Location of unknown node E: Ecolocation Estimated Location

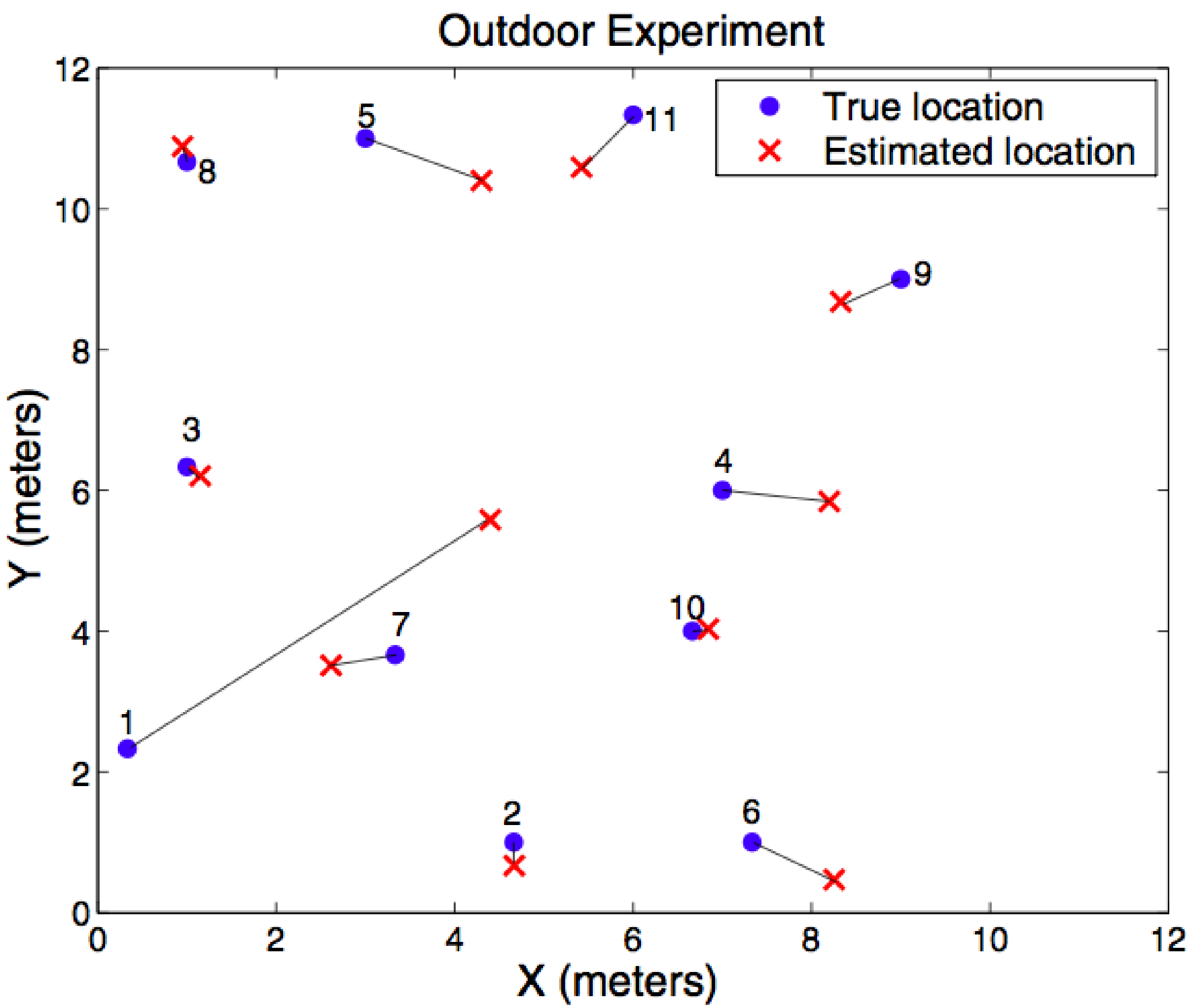
Indoor Tracking



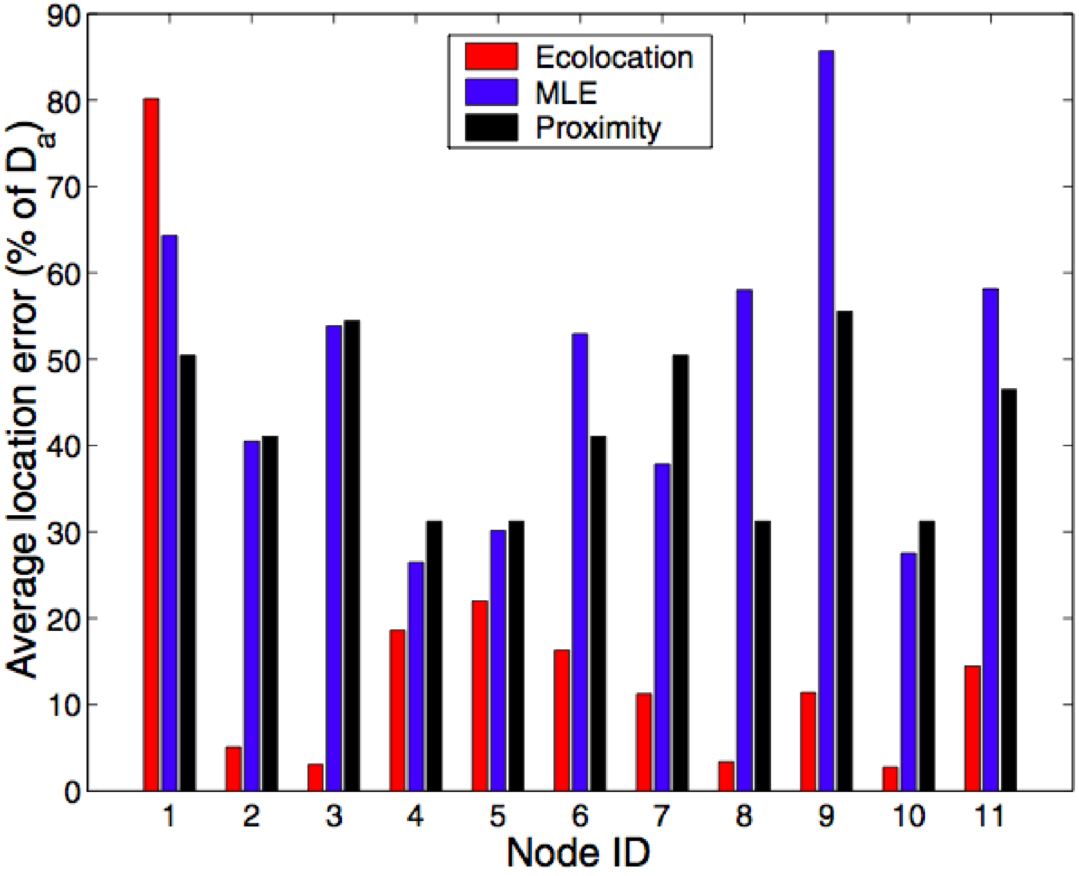
Indoor Tracking Error



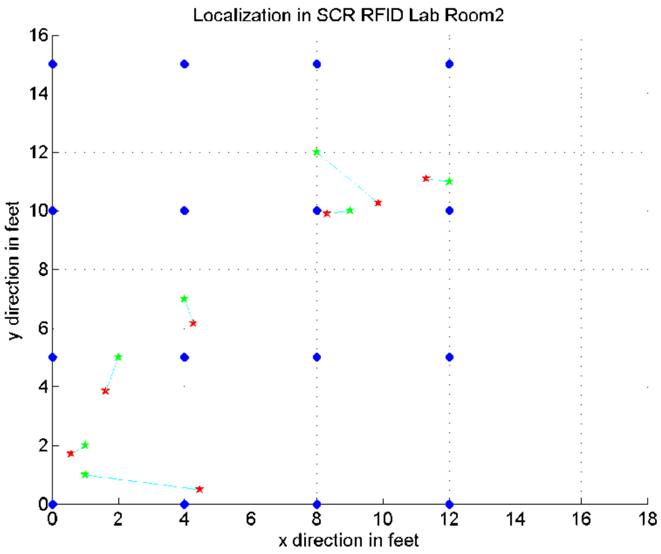
Outdoor Experiment

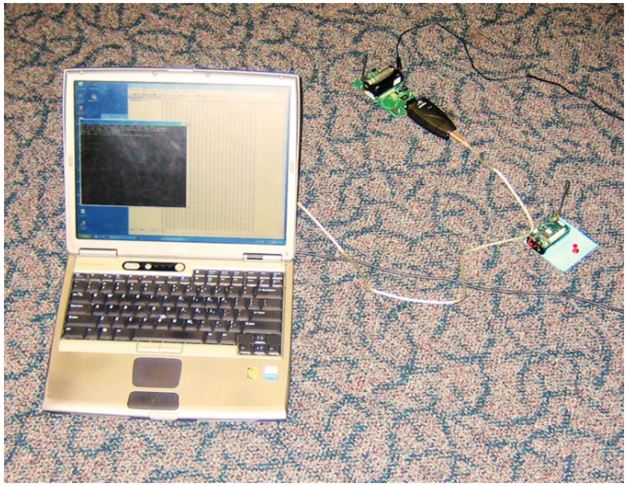


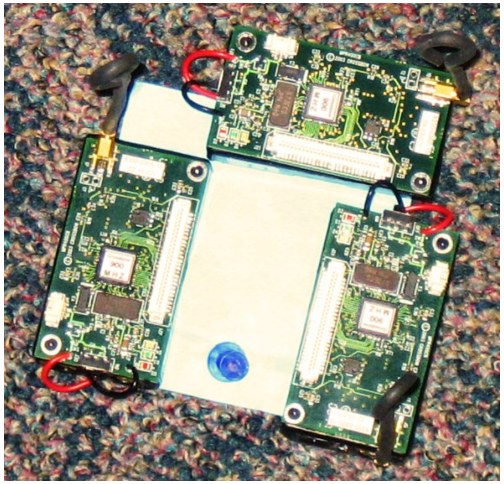
Outdoor Experiment Error



Maximum Ratio Combining





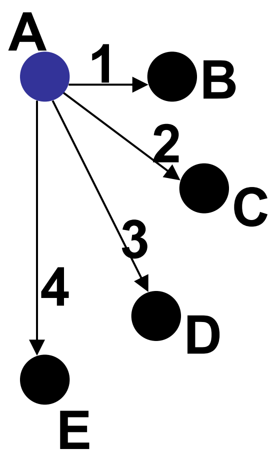


Sequence-Based Localization

- Unknown node initiates localization process
  - Sends out a localization request
- Reference nodes in the radio range send response packets
  - Packets contain ref. node location coordinates
- Unknown node measures the RSSI and ranks the reference nodes based on RSSI values
  - Ranks of reference nodes are written as an ordered sequence called "location sequence"
- The reference node coordinates and the RSSI-based location sequence are used to estimate the unknown node's location

Location Sequence

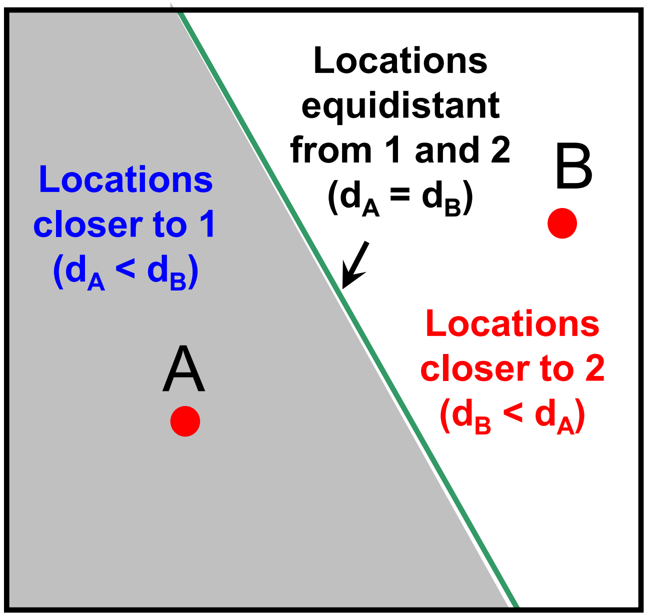
- The ordered sequence of distance ranks of reference nodes from a given location



Location Sequence for A

B C D E

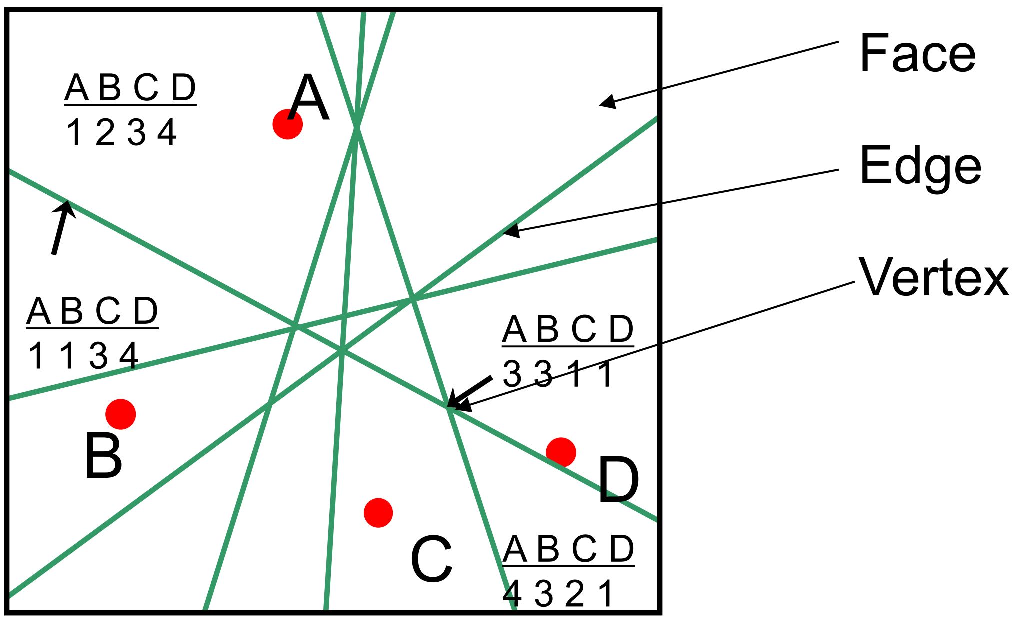
1 2 3 4



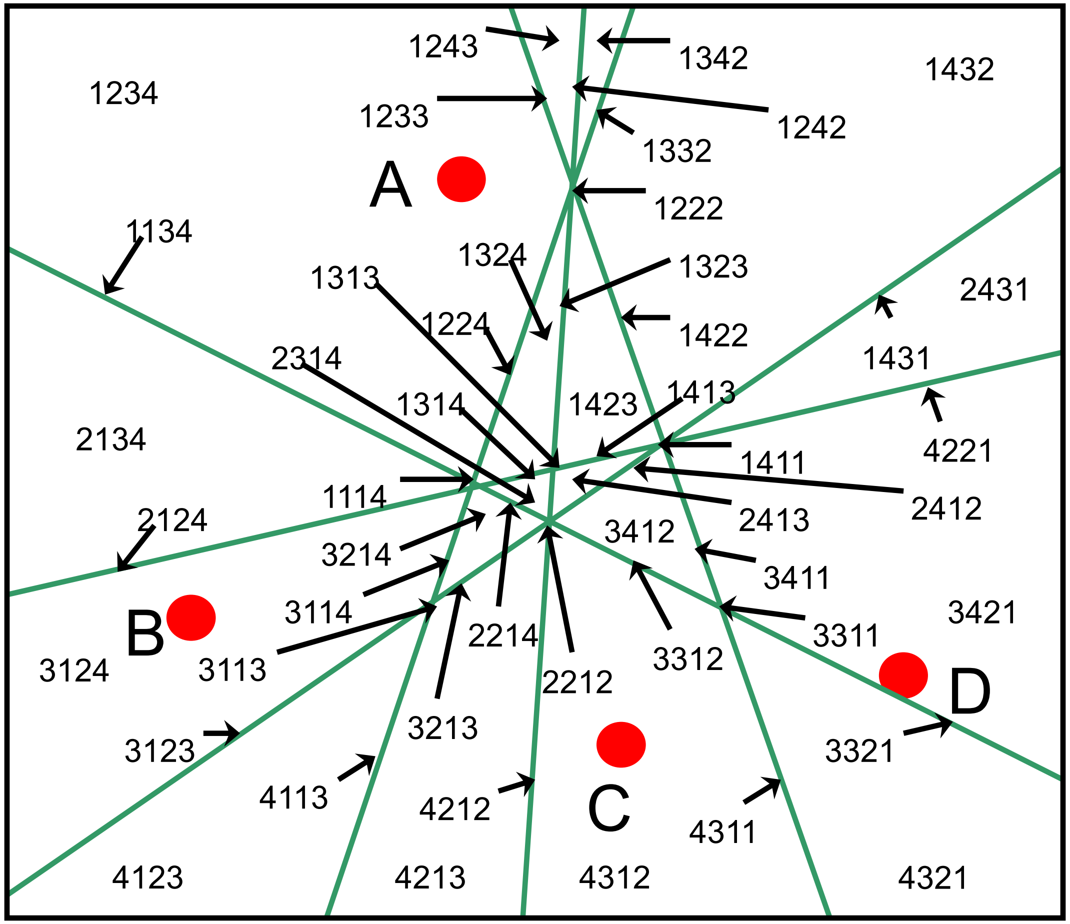
Rank order between two reference nodes is defined by the perpendicular bisector between them.

Location Sequence

- Location sequences are unique to each region
- All locations in a region have the same location sequence
- One-to-one mapping with centroid of the region they represent



Feasible Location Sequences



RF Channel and Location Sequence

- RF Channel
  - Multipath fading and shadowing
  - Causes errors in RSSI measurements
  - Leads to errors in reference node ranks
  - Leads to corruption of location sequences

- Location Sequence Robustness
  - But rank ordering based on RSSI values offers some protection
    - Rank order of two reference nodes I and j is tolerant to errors in RSSI measurements for up to difference in path loss
    - Low density of location sequences ensures that many infeasible sequences to a single feasible sequence

Localization Procedure

- Construct the location sequence table
  - Contains all feasible location sequences for the area in the radio range of the unknown node
  - Maps each location sequence to the corresponding region's centroid
- Determine the location sequence of the unknown node location
  - Using RSSI measurements of response packets
  - This sequence is a corrupted version of the true response
- Search in the location sequence table for the nearest (in terms of rank order) feasible sequence
  - The centroid it points to is the location estimate

Distance Between Sequences

From Statistics

Let $X = \{x_i\}$, $Y = \{y_i\}$ be two location sequences (x_i and y_i ranks, $1 \le i \le n$)

1. Spearman's rank order correlation coefficient:

$$\rho = 1 - \frac{6\sum_{i=1}^{n}(x_i - y_i)^2}{n(n^2-1)}$$

2. Kendall's Tau:

$$\tau = \frac{(n_c - n_d)}{\sqrt{n_c + n_d + n_{tx}}\sqrt{n_c + n_d + n_{ty}}}$$

n_c: number of concordant pairs, n_d: number of discordant pairs,

nt_x: number of ties in x, nt_y: number of ties in y.

Concordant Pair:
$x_i < x_j \Rightarrow y_i < y_j$ or
$x_i > x_j \Rightarrow y_i > y_j$

Discordant Pair:
$x_i < x_j \Rightarrow y_i > y_j$ or
$x_i > x_j \Rightarrow y_i < y_j$

Tie:
n_{tx}: $x_i = x_j$
n_{ty}: $y_i = y_j$

Distance calculation is a $O(n^2)$ operation.

How Many Feasible Sequences?

- If there are n reference nodes in the radio range of the unknown node

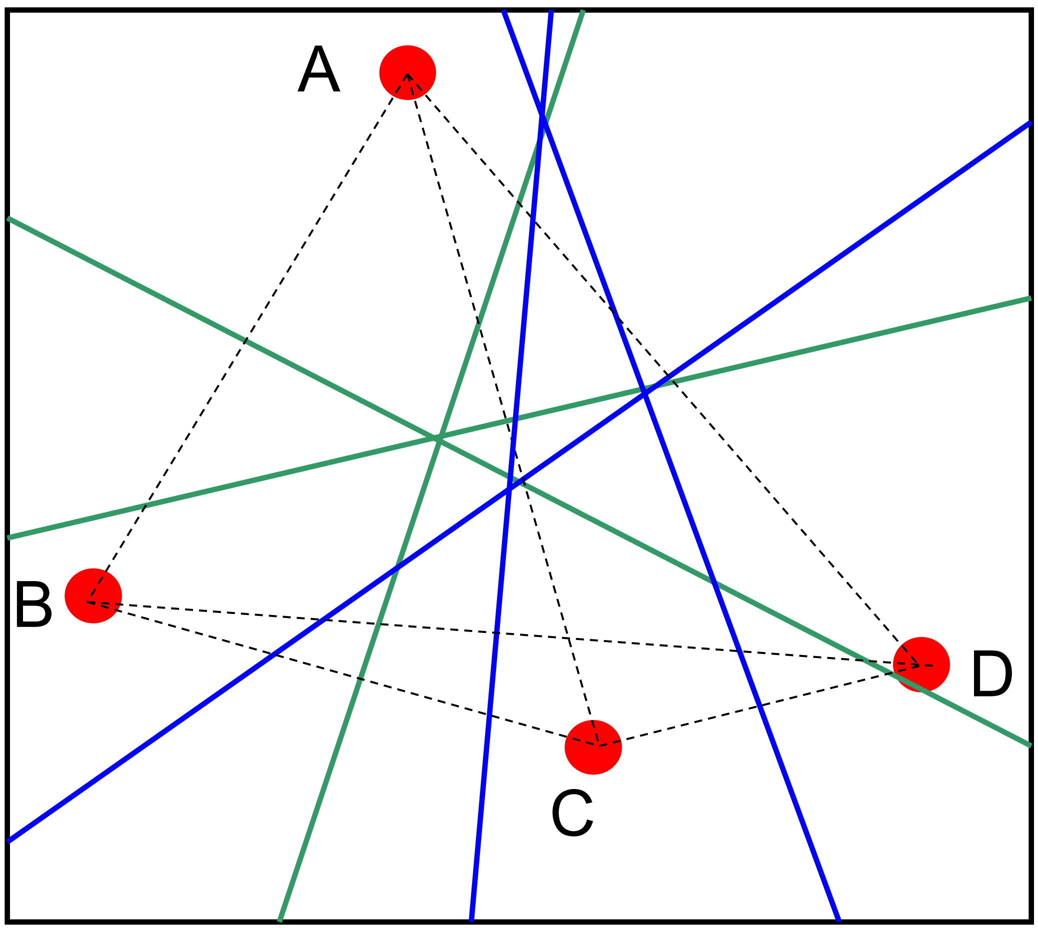
Combinatorially:
$O(n^n)$

Actually:
Only $O(n^4)$

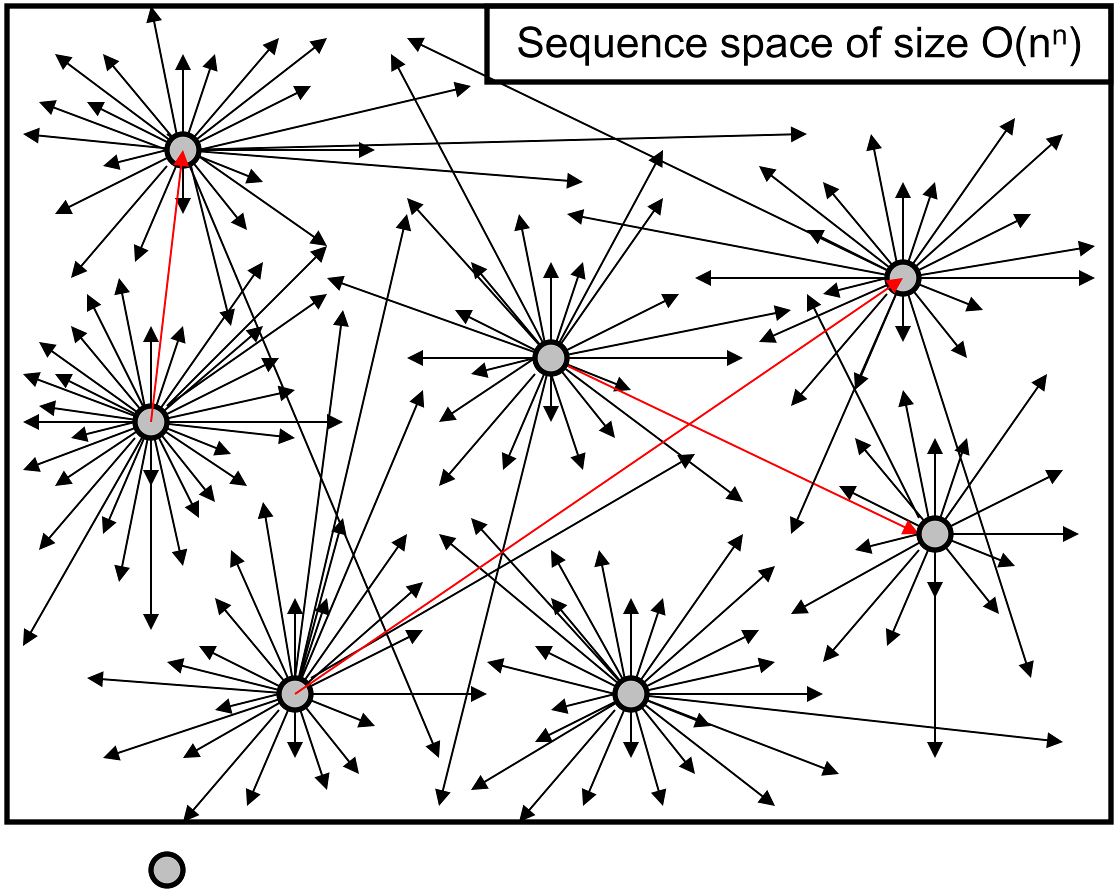
Theorem: The maximum number of unique location sequences due to *n* reference nodes is

$$\frac{n^4}{2} - 2n^3 + \frac{7n^2}{2} - 2n + 1$$

How Many Feasible Sequences?



Feasible and Infeasible Sequences



Feasible sequence space of size $O(n^4)$

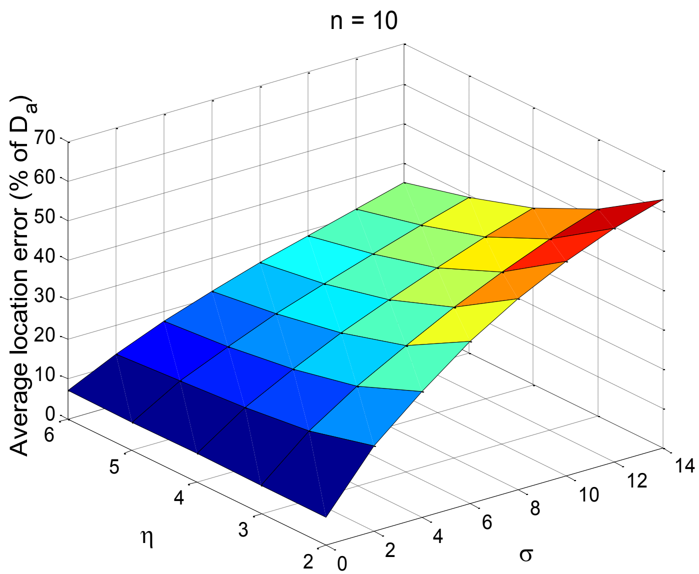
Corruption due to RF channel non-idealities

SBL Nuts and Bolts

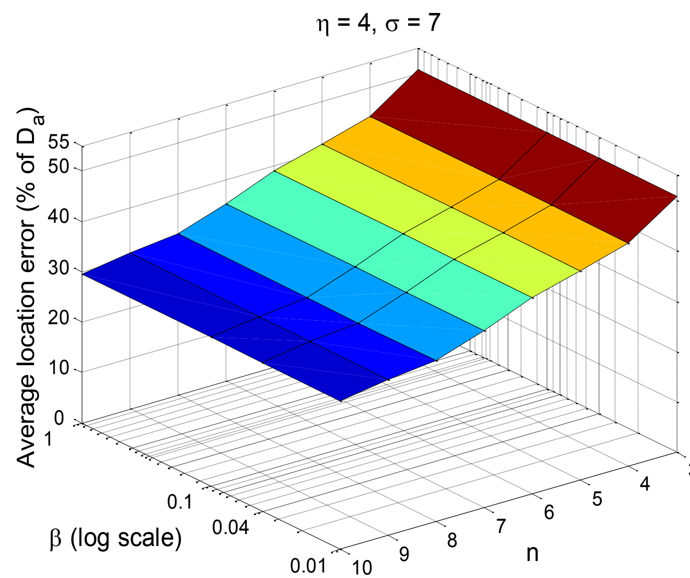
- Location sequence table construction
  - Used tools from computational geometry
  - Uses double-connected linked lists for optimality
  - $O(n^5 \log n)$ time and $O(n^5)$ space optimally
- Searching through it
  - $O(n^6)$ time for a naïve search
  - Smarter table lookup can be used for lower operational complexity
- Not bad!
  - Typically $n <= 15$ (not much gain for $n > 15$, already 19321 regions). Assume $n = 10$
  - If the unknown node is an IPAQ (300 MHz, 128 MB)
    - Location sequence table construction: ~milliseconds, ~ 32 KB
    - Searching through it: ~milliseconds
    - Total: ~ 10s of milliseconds, ~ 32 KB

Performance Study

RF Channel Parameters



Node Deployment Parameters



Higher path loss exponent *η*

Lower Standard Deviation *σ*

⇒ Lower Location Error ⇐

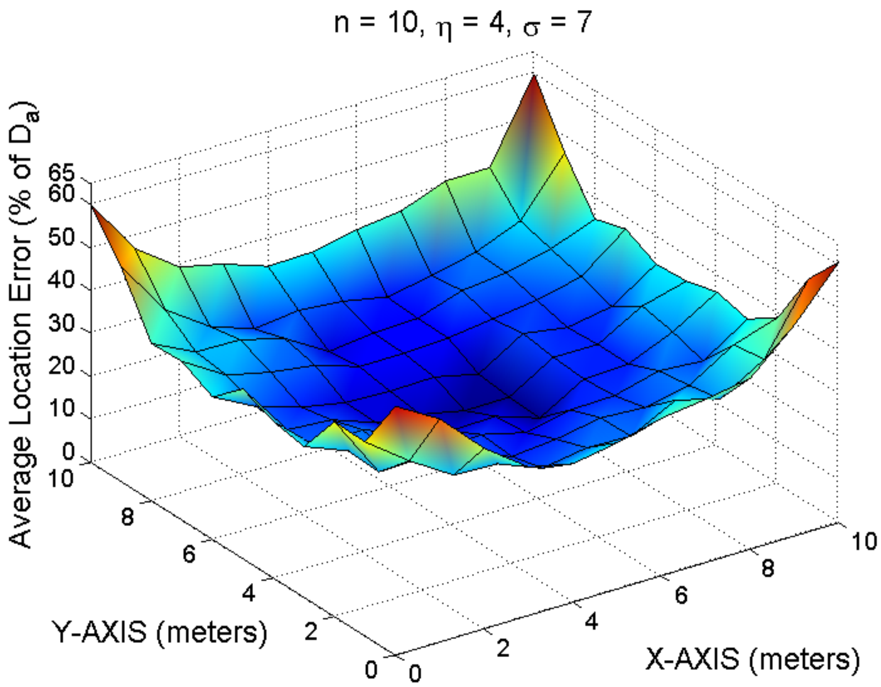
Higher # of ref. nodes *n*

Higher ref. node density *β*

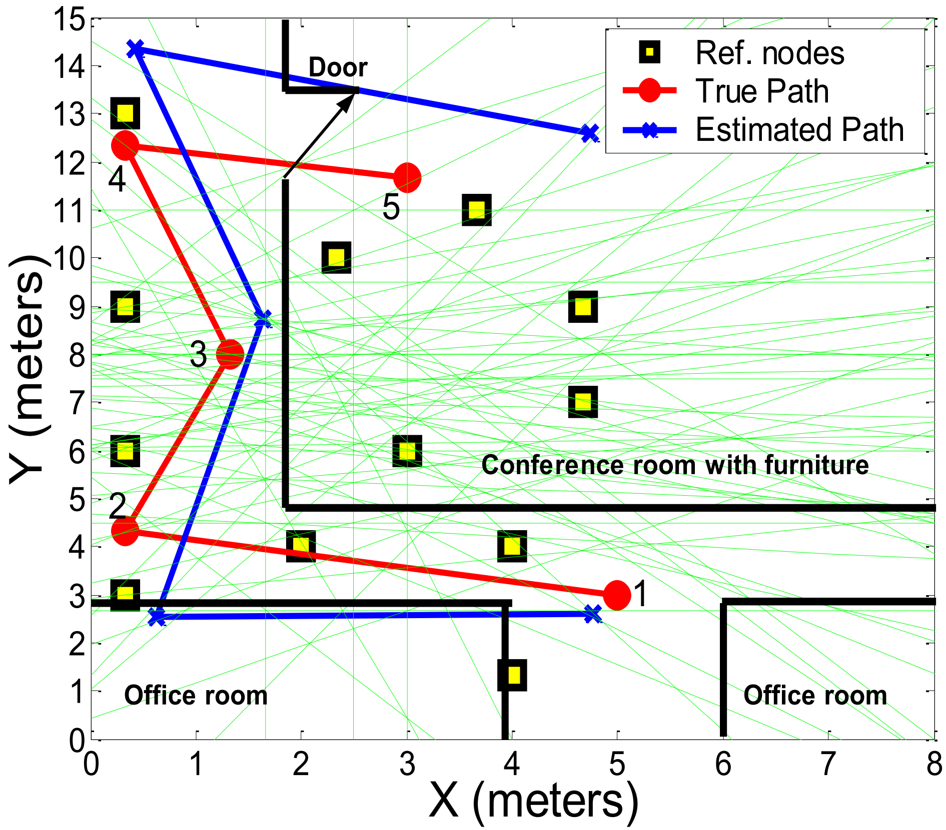
D_a: Average inter-reference node distance, ≈ 35% of the radio range

Performance Study

Unknown node location in Localization Space



Indoor Experiment: Office Building

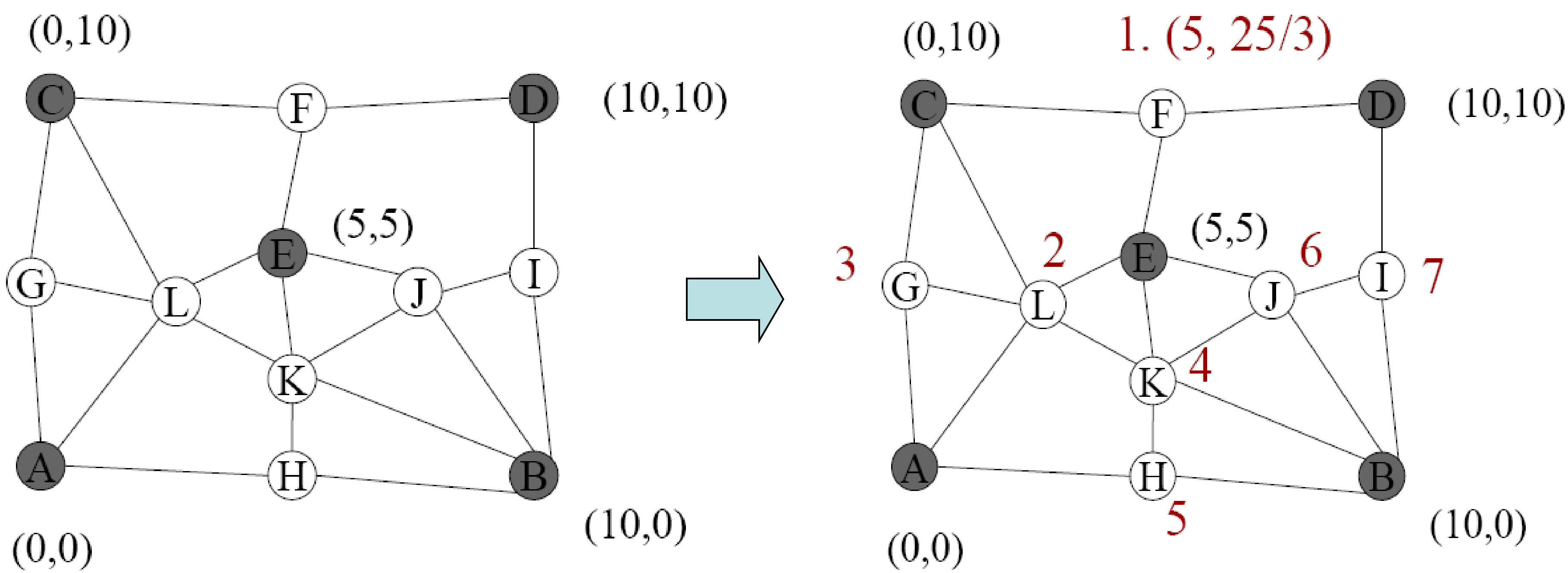


Network Localization

- Different from node localization
  - Few reference nodes and several networked unknown node

- Several approaches
  - Constraint satisfaction / optimization (centralized)
  - Joint estimation using ranging estimates (centralized)
  - Multi-hop distance estimation (distributed)
  - Iterative localization (distributed)
  - Potential fields (distributed)
  - Multi-dimensional scaling (MDS) (centralized)

Iterative Localization



Open Forum

- Nitish: WSN internship, Germany, Univ. of Braunschweig, pressure sensors (Dr. Sandor Fekete), deployed on the floor and walk down, play the piano, Wiselib
- Abhishek: proximity detection with smartphone app
- Hithesh: application for blind people, grabbing objects using intensity of vibration
- Rohit: remote control of your laptop using phone app, video download
- Onuk: maximize goodput while increasing fairness

References

[1] Kiran Yedavalli, Bhaskar Krishnamachari, Sharmila Ravula, and Bhaskar Srinivasan, “Ecolocation: A Sequence Based Technique for RF-only Localization in Wireless Sensor Networks,” *The Fourth International Conference on Information Processing in Sensor Networks (IPSN ’05)*, Los Angeles, CA, April 2005.

[2] Kiran Yedavalli and Bhaskar Krishnamachari, “Sequence-Based Localization in Wireless Sensor Networks,” *IEEE Transactions on Mobile Computing*, Vol. 7, no. 1, January 2008.