CS649
Sensor Networks
IP Lecture 7: Self-Localization I

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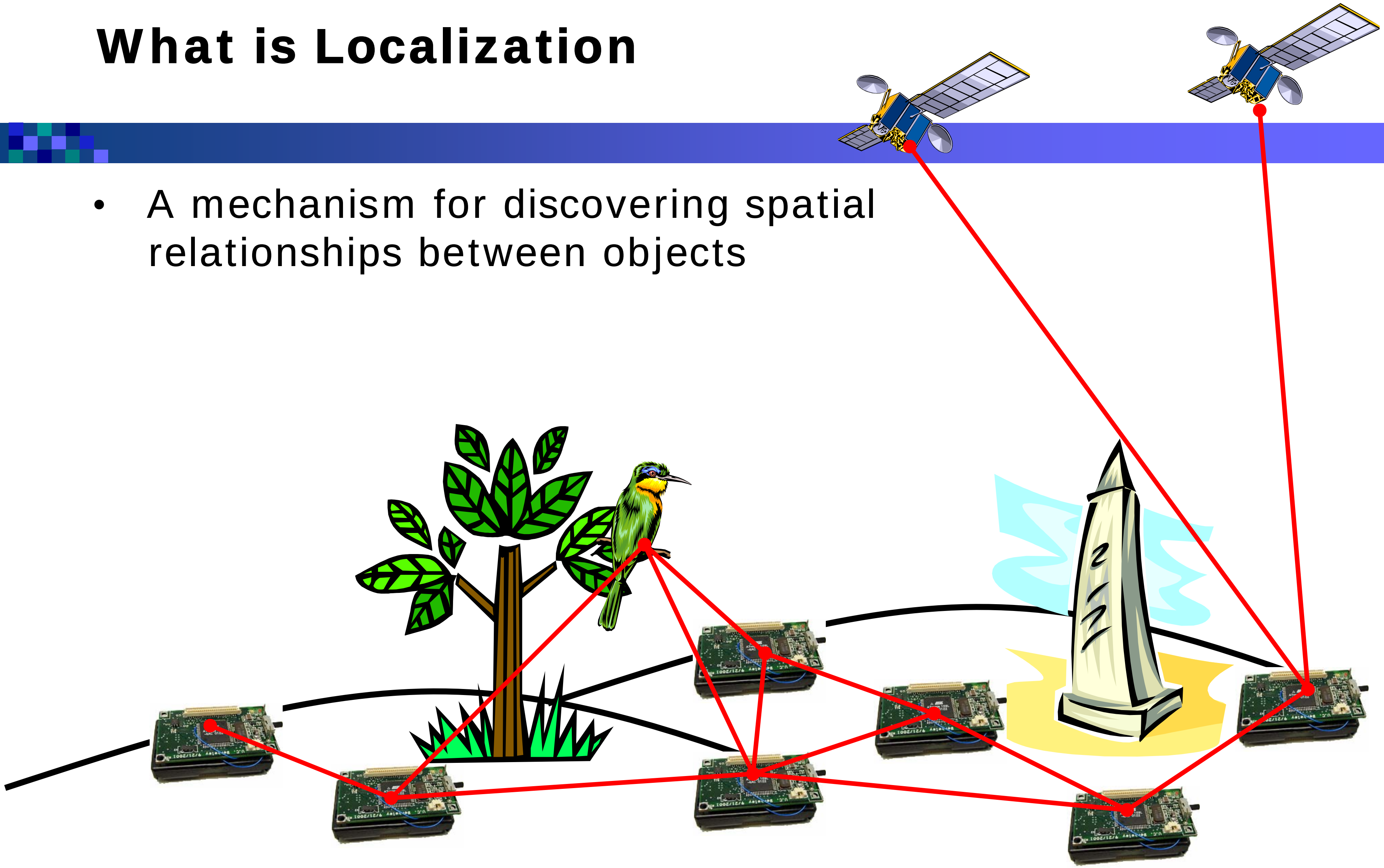
What is Localization

- A mechanism for discovering spatial relationships between objects

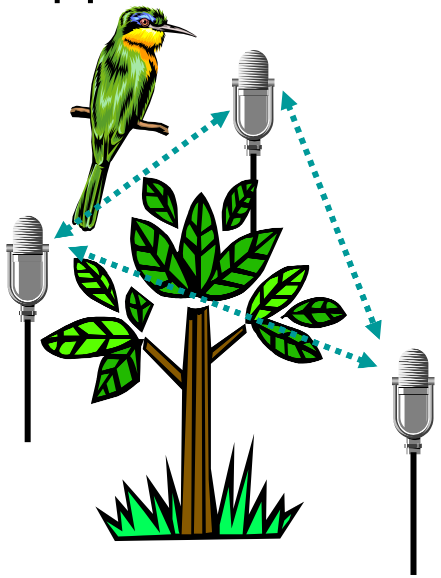


Why is Localization Important?

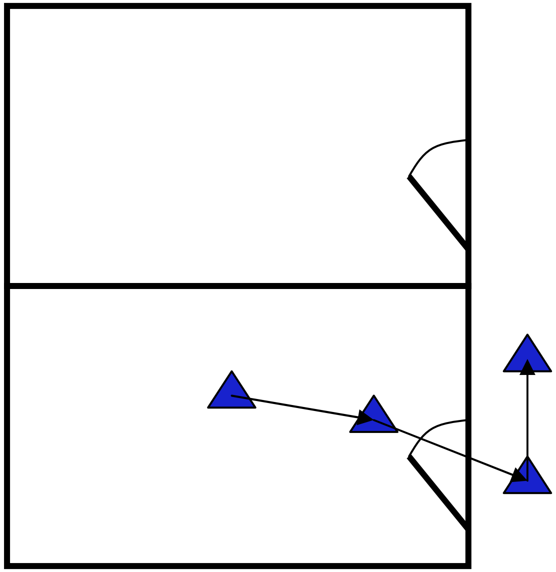
- Large scale embedded systems introduce many fascinating and difficult problems…
  - This makes them much more difficult to use…
  - BUT it couples them to the physical world
- Localization measures that coupling, giving raw sensor readings a physical context
  - Temperature readings ⇒ temperature map
  - Asset tagging ⇒ asset tracking
  - “Smart spaces” ⇒ context dependent behavior
  - Sensor time series ⇒ coherent beamforming

Variety of Applications

- Two applications:



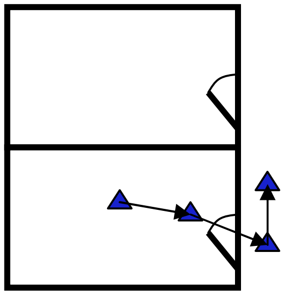
Passive habitat monitoring:
Where is the bird?
What kind of bird is it?



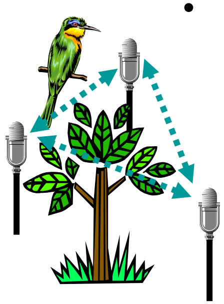
Asset tracking:
Where is the projector?
Why is it leaving the room?

Variety of Application Requirements

- Very different requirements!



- Outdoor operation
  - Weather problems
- Bird is not tagged
- Birdcall is characteristic but not exactly known
- Accurate enough to photograph bird
- Infrastructure:
  - Several acoustic sensors, with known relative locations; coordination with imaging systems



- Indoor operation
  - Multipath problems
- Projector is tagged
- Signals from projector tag can be engineered
- Accurate enough to track through building
- Infrastructure:
  - Room-granularity tag identification and localization; coordination with security infrastructure

Multidimensional Requirement Space

- Granularity & Scale
- Accuracy & Precision
- Relative vs. Absolute Positioning
- Dynamic vs. Static (Mobile vs. Fixed)
- Cost & Form Factor
- Infrastructure & Installation Cost
- Communications Requirements
- Environmental Sensitivity
- Cooperative or Passive Target

Axes of Application Requirements

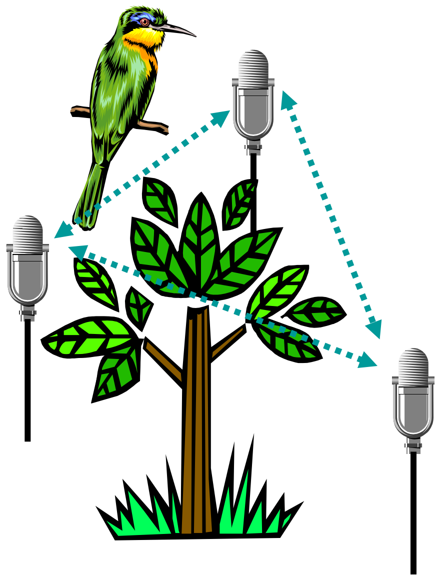
- Granularity and scale of measurements:
  - What is the smallest and largest measurable distance?
  - e.g. cm/50m (acoustics) vs. m/25000km (GPS)
- Accuracy and precision:
  - How close is the answer to “ground truth” (accuracy)?
  - How consistent are the answers (precision)?
- Relation to established coordinate system:
  - GPS? Campus map? Building map?
- Dynamics:
  - Refresh rate? Motion estimation?

Axes of Application Requirements

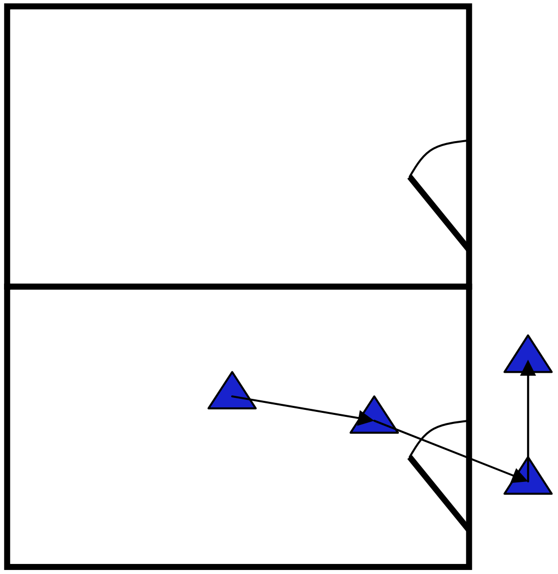
- Cost:
  - Node cost: Power? $? Time?
  - Infrastructure cost? Installation cost?
- Form factor:
  - Baseline of sensor array
- Communications Requirements:
  - Network topology: cluster head vs. local determination
  - What kind of coordination among nodes?
- Environment:
  - Indoor? Outdoor? On Mars?
- Is the target known? Is it cooperating?

Returning to our two Applications…

- Choice of mechanisms differs:



Passive habitat monitoring:
Minimize environ. interference
No two birds are alike



Asset tracking:
Controlled environment
We know exactly what tag is like

Taxonomy of Localization Mechanisms

- Active Localization
  - System sends signals to localize target
- Cooperative Localization
  - The target cooperates with the system
- Passive Localization
  - System deduces location from observation of signals that are “already present”
- Blind Localization
  - System deduces location of target without *a priori* knowledge of its characteristics

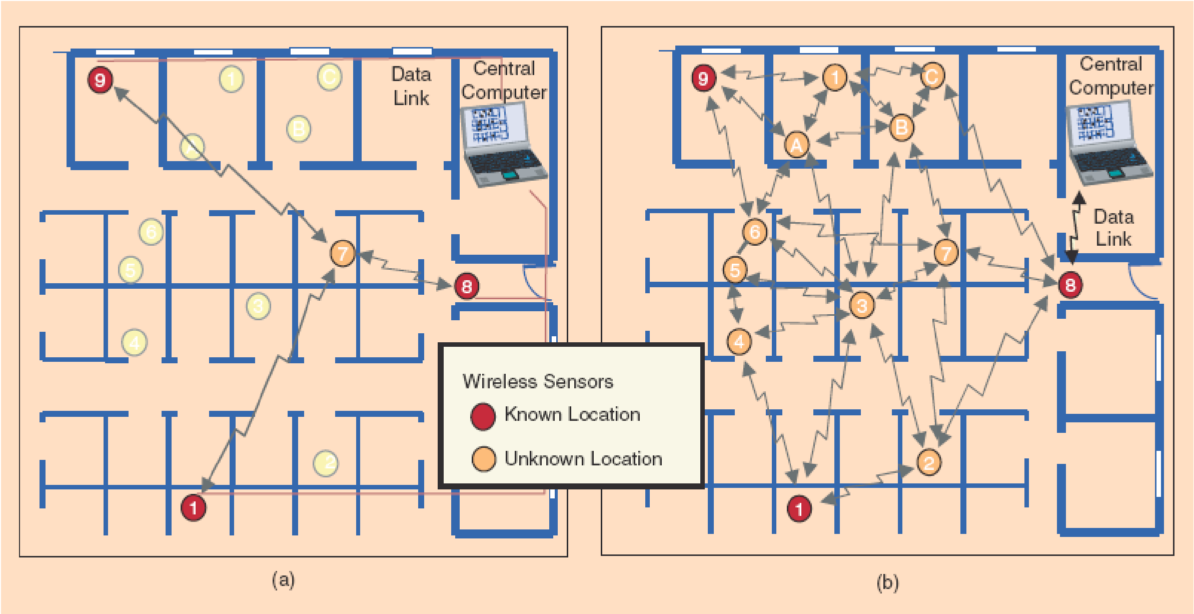
Self-Localization in Wireless Sensor Networks

- *Active* and *Cooperative* Localization
- Basic Problem Statement (2D):
  - Estimate unknown locations of n nodes $\theta = [\theta_x, \theta_y]$

    $$\theta_x = [x_1, \ldots, x_n],\ \theta_y = [y_1, \ldots, y_n]$$

  - Given the m known reference locations $[x_{n+1}, \ldots, x_{n+m}, y_{n+1}, \ldots, y_{n+m}]$; and
  - Pair-wise measurements $\{X_{i,j}\}$ between nodes: $X_{i,j}$ is the measurement between nodes i and j; $X_{i,j}$ is only available for a *subset* of pairs (i, j)

Traditional Multilateration



Cooperative Localization

Measurements for Self-Localization

- Measurements are noisy and contain errors
  - Physical medium introduces both time-varying and static errors
  - Errors are environment dependent (building, tree, etc.)
  - Knowledge on the statistical characterization of measurement errors is critical to accurate self-localization
- Types of measurements
  - Received Signal Strength (RSS)
  - Time of Arrival (TOA)
  - Angle of Arrival (AOA)

Properties of RSS Measurements

- RSS can be measured by a receiver's received signal strength indicator (RSSI) circuit
- Based on the appropriate signal propagation model (power decays proportional to d^{-2} in free space), the range (distance) between the sender and receiver can be estimated
- RSSI measurements of RF signals are readily available during communications
- Issues with RSS measurements:
  - Multipath: frequency selective fading
  - Shadowing: function of the environment
  - Variations in transmit power and RSSI circuits from device to device; transmit power can change as batteries deplete
    - treat the power as an unknown or consider the difference between RSS measurements at different sensors

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$$\bar{P}(d) = P_0 - 10 n_p \log \frac{d}{d_0}$$

(dBm)

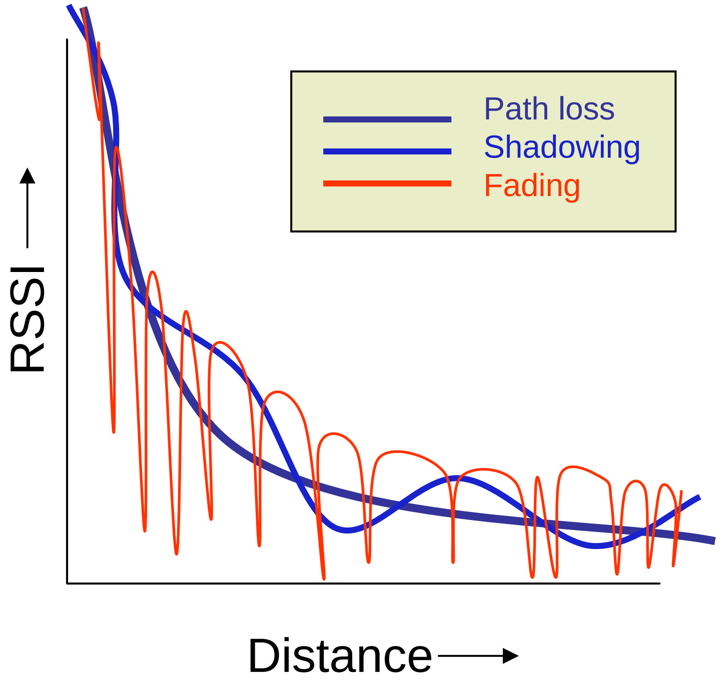
$$f\left(P_{i,j} = p | \boldsymbol{\theta}\right) = \mathcal{N}\left(p; \bar{P}(d_{i,j}), \sigma^2_{\mathrm{dB}}\right)$$

path loss exponent

constant ⇒ multiplicative range error

Practical Difficulties with RSSI

- RSSI is extremely problematic for fine-grained, ad-hoc applications
  - Path loss characteristics depend on environment (1/rn)
  - Shadowing depends on environment
  - Short-scale fading due to multipath adds random high frequency component with huge amplitude (30-60dB) – very bad indoors
    - Mobile nodes might average out fading.. But static nodes can be stuck in a deep fade forever
- Potential applications
  - Approximate localization of mobile nodes, proximity determination
  - "Database" techniques (RADAR)



Ref. Rappaport, T, *Wireless Communications Principle and Practice*, Prentice Hall, 1996.

Properties of the TOA Measurements

- Using measured propagation delay and the known signal propagation velocity to estimate the range (acoustic: 1ms $\rightarrow$ 1ft; RF:1ns $\rightarrow$ 1ft)
- Additive noise: limit the accuracy of arrival detection

$$\mathrm{var(TOA)} \geq \frac{1}{8\pi^2 \, B \, T_s \, F_c^2 \, \mathrm{SNR}}$$

- Multipath:
  - Attenuated LOS: sever in sparse network (larger distances)
  - Early-arriving multipath
    - Wider bandwidths necessary (narrow autocorrelation peak) for greater temporal resolution
    - Wider bandwidths (DS-SS, UWB) imply faster signal processing, higher device costs, and possibly higher energy costs

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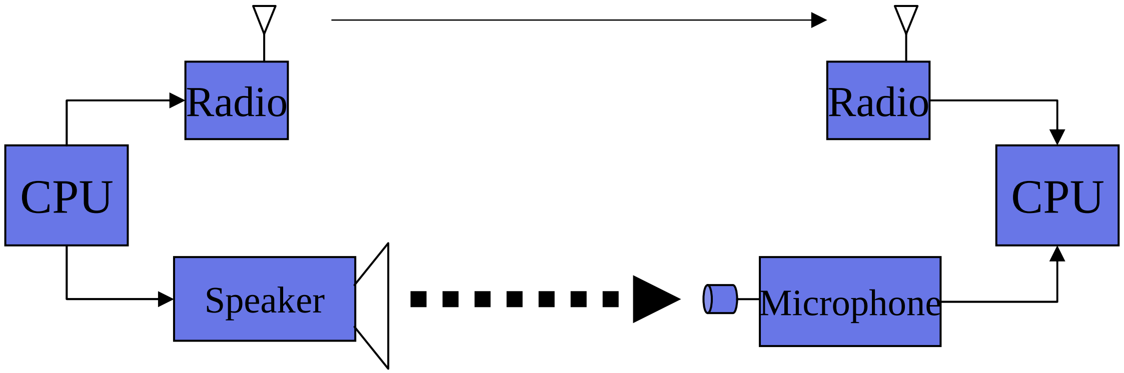
$$f\left(T_{i,j} = t|\theta\right) = \mathcal{N}\left(t; d_{i,j}/v_p + \mu_T, \sigma_T^2\right)$$

TOA : Issue with Clock Synchronization between the Sender and the Receiver

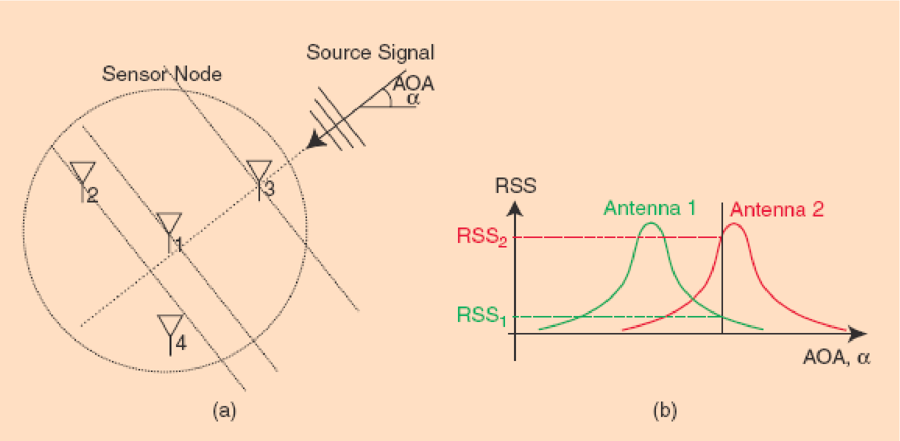
- Direct implementation of TOA requires clock synchronization between the sender and the receiver (accuracy of existing algorithms ~10μs inadequate for RF)
- Generic approaches to combat synchronization issue
  - Two-way (round-trip) TOA measurements
  - Estimate the unknown clock bias as an additional parameter
  - Time Difference of Arrivals (TDOA) of multiple (and typically multimodal) signals



- Radio channel is used to synchronize the sender and receiver
- Coded acoustic signal is emitted at the sender and detected at the emitter. TOF determined by comparing arrival of RF and acoustic signals

AOA Measurements

- Estimate the angle of arrival of the signal through
  - Array signal processing at a node
  - RSS ratio among multiple directional antennas at a node
- Require multiple antenna elements that can contribute to higher cost and larger device size
  - However, advances in VLSI technology will make the AOA approach more feasible and affordable
- Major sources of error
  - Additive noise
  - Multipath
  - Sensor orientation



Qualitative Comparison among RSS, TOA, and AOA from Statistical Models

- TOA is less sensitive to increases in distances among sensors hence more appropriate for low-density networks
- In general TOA and AOA can achieve higher accuracy than RSS, however with higher device costs
  - Typically AOA > TOA > RSS in terms of device costs
- RSS is attractive for low-cost deployments of denser networks with lower accuracy requirement

RF versus Acoustic Signals

- RF signal
  - Pros
    - Lower costs, readily available in sensor networks
    - Does not require LOS
  - Cons
    - Accurate, deterministic transponders hard to build
    - TOA measurements require fast, synchronized clocks to achieve high precision
- Acoustic signal
  - Pros
    - Slower propagation, can achieve higher accuracy with LOS
    - Lower path loss than RF near the ground, because ground reflections in acoustics don't cancel
    - Audible acoustics have very wide range of wavelengths
  - Cons
    - Poor penetration $\Rightarrow$ detector picks up reflections in Non-LOS
    - Audible sound: good channel properties, but often inappropriate

The Cricket Location-Support System

N. Priyantha, A. Chakraborty, H. Balakrishnan
MOBICOM 2000

Goal

- User Privacy
- Decentralized administration
- Network heterogeneity
- Low cost
- Room-sized granularity

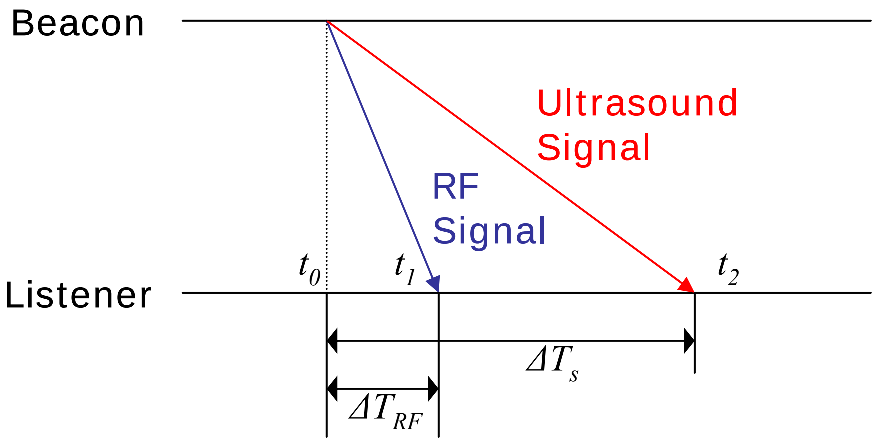
System Architecture

- Beacon:
  - Disseminate the string of space information about a geographic space to listeners.
- Listener: Infer its current location from the set of beacons (by determine the closest beacon).

Approach

Use combination of RF and ultrasound to provide a location-support service to users.

Cricket Operation



- v_{RF}, v_s are known:

measured

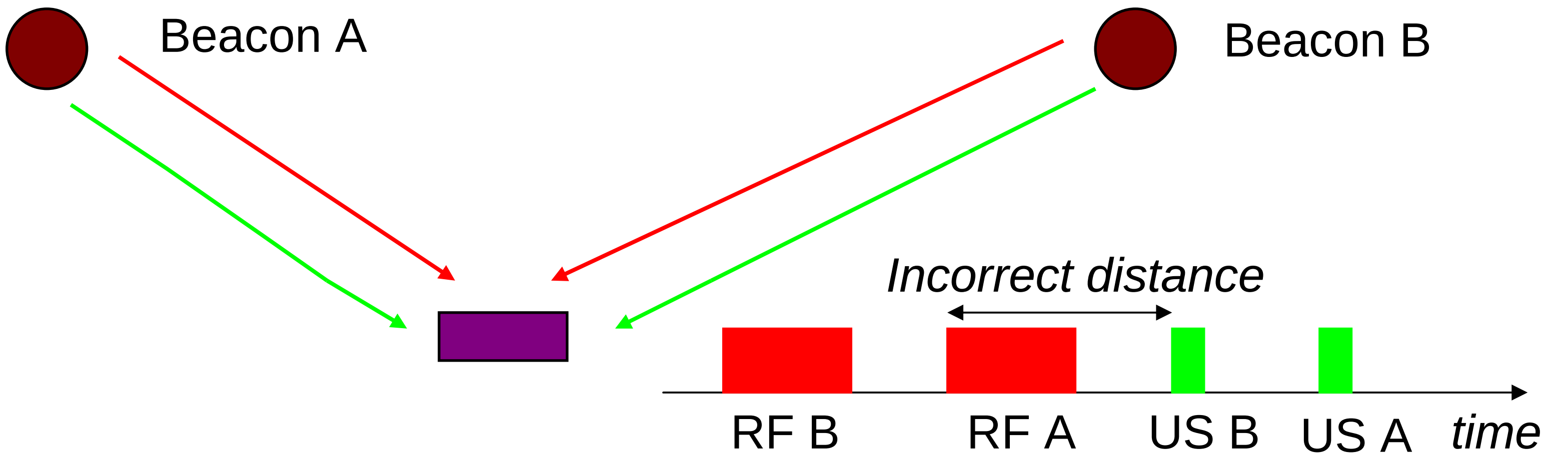
$$v_{RF}\Delta t_{RF} = v_s \Delta t_s \Rightarrow t_0 = \frac{v_{RF} t_1 - v_s t_2}{v_{RF} - v_s}$$

- Can then calculate distance s from beacon as:

$$s = v_s \Delta t_s = v_s (t_2 - t_0)$$

Complications

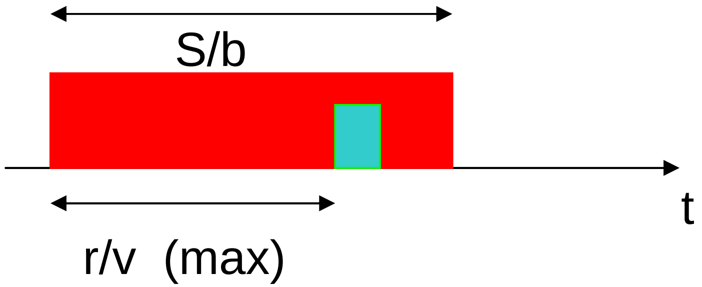
- RF signals from multiple beacons may collide
  - Randomization
- Wrong correlation of the RF data of one beacon with the ultrasonic signal of another
  - System Parameters
  - Listener Inference Algorithms



System Parameters Selection

- Use a relatively sluggish RF data transmission rate.

S - size of space string
b - RF bit rate
r - ultrasound range
v - velocity of ultrasound



$$\frac{S}{b} > \frac{r}{v}$$

(RF transmission time) (Max. RF US separation at the listener)

Interference Scenarios

- RF-A:US-RA
  - Align the beacons
- RF-A:US-I
  - Using RF signal with long range
- RF-A:US-RI
  - Ensure less than 5 beacons within range of each other

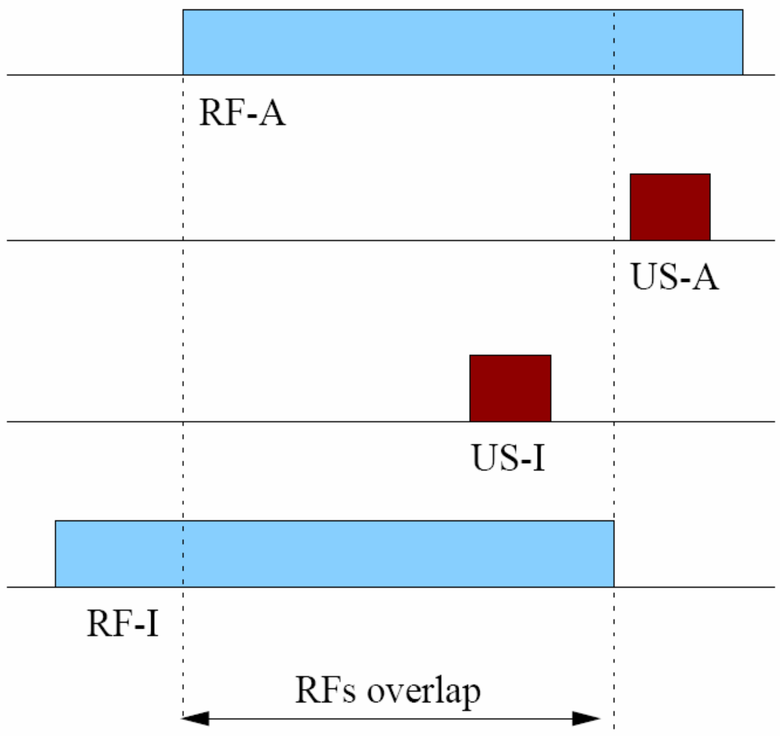
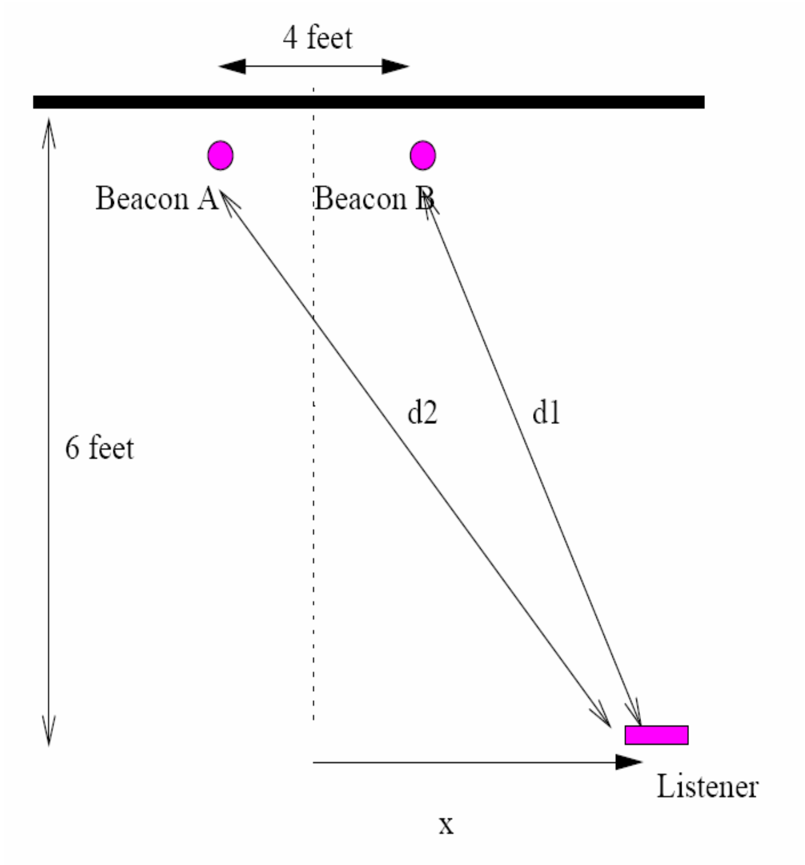
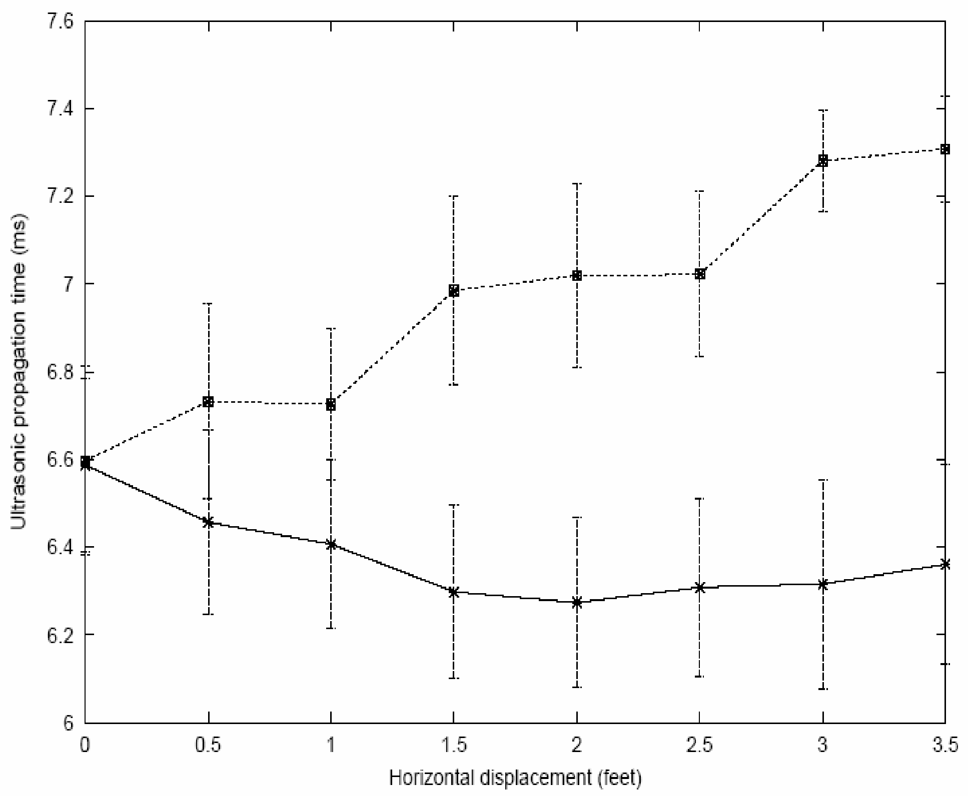


Figure 1: RF-A:US-I interaction, with US-A arriving after US-I. The two RF transmissions overlap in time at the listener.

Experiment:
Boundary Performance





The MoteTrack System

- K. Lorincz and M. Welsh, “MoteTrack: A Robust, Decentralized Approach to RF-Based Location Tracking,” In *Proceedings of the International Workshop on Location- and Context-Awareness (LoCA 2005)* at Pervasive 2005, May 2005.
- Targeting emergency response applications: pre-installation and manual calibration not feasible
- Rely RF RSSI measurements from beacon nodes for localization
  - Each node build up a *signature* based on received beacon messages (ID, power level) and measured RSSIs
  - Node localize itself by comparing its signature with *reference signatures* (from offline calibration) available at the beacons
- Focus on robustness rather than high accuracy in localization