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 \( (i, j) \)
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.

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

(dBm)  \hspace{2cm} \text{path loss exponent}  \hspace{2cm} \text{constant} \Rightarrow \text{multiplicative range error}

\[
f(P_{i,j} = p|\theta) = \mathcal{N}\left(p; \bar{P}(d_{i,j}), \sigma_{dB}^2\right)
\]

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Practical Difficulties with RSSI

- RSSI is extremely problematic for fine-grained, ad-hoc applications
  - Path loss characteristics depend on environment \((1/r^n)\)
  - 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)

Properties of the TOA Measurements

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

\[
\text{var}(\text{TOA}) \geq \frac{1}{8\pi^2 B T_s F_c^2 \text{SNR}}
\]

- 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

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

\[ v_{RF} \Delta t_{RF} = v_s \Delta t_s \implies t_0 = \frac{v_{RF} t_1 - v_s t_2}{v_{RF} - v_s} \]

• 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

![Diagram showing RF and ultrasonic signals from two beacons with incorrect distance indication.](image)
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

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The MoteTrack System

- 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