Wireless Localization Techniques

CS441
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
Variety of Localization Mechanisms

- Bird is not tagged
  - Passive detection of bird presence
- Birdcall is characteristic but not exactly known
- Bird does not have radio; TDOA measurement
  - Passive target localization
    - Requires
      - Sophisticated detection
      - Coherent beamforming
      - Large data transfers

- Projector is tagged
  - Projector might know it had moved
- Signals from projector tag can be engineered
  - Tag can use radio signal to enable TOF measurement
- Cooperative Localization
  - Requires
    - Basic correlator
    - Simple triangulation
    - Minimal data transfers

Very different mechanisms indicated!
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
Active Mechanisms

• Non-cooperative
  • System emits signal, deduces target location from distortions in signal returns
  • e.g. radar and reflective sonar systems

• Cooperative Target
  • Target emits a signal with known characteristics; system deduces location by detecting signal
  • e.g. ORL Active Bat, GALORE Panel, AHLoS

• Cooperative Infrastructure
  • Elements of infrastructure emit signals; target deduces location from detection of signals
  • e.g. GPS, MIT Cricket
Passive Mechanisms

• Passive Target Localization
  • Signals normally emitted by the target are detected (e.g. birdcall)
  • Several nodes detect candidate events and cooperate to localize it by cross-correlation

• Passive Self-Localization
  • A single node estimates distance to a set of beacons (e.g. 802.11 bases in RADAR [Bahl et al.], Ricochet in Bulusu et al.)

• Blind Localization
  • Passive localization without a priori knowledge of target characteristics
  • Acoustic “blind beamforming” (Yao et al.)
Active vs. Passive

- **Active techniques tend to work best**
  - Signal is well characterized, can be engineered for noise and interference rejection
  - Cooperative systems can synchronize with the target to enable accurate time-of-flight estimation

- **Passive techniques**
  - Detection quality depends on characterization of signal
  - Time difference of arrivals only; must surround target with sensors or sensor clusters
    - TDOA requires precise knowledge of sensor positions

- **Blind techniques**
  - Cross-correlation only; may increase communication cost
  - Tends to detect “loudest” event. May not be noise immune
Introduction to WSN

- A large number of self-sufficient nodes
- Nodes have sensing capabilities
- Can perform simple computations
- Can communicate with each other
Beacon (Anchor) node:

It’s a node that’s aware of it’s location, either through GPS or manual pre-programming during deployment.
In a Wireless sensor nodes thousands of sensors need to know their position.

Many applications need position info:
- in-home
- forest-fire detection
- atmospheric (temperature, pressure, ...)
- military (target detection, ...)
- police
Introduction to WSN (Cont.)

- **Advantages:**
  1. It avoids a lot of wiring
  2. It can accommodate new devices at any time
  3. It's flexible to go through physical partitions
  4. It can be accessed through a centralized monitor
Introduction to WSN (Cont.)

- Disadvantages
  1. It's easy for hackers to hack it as we can't control propagation of waves
  2. Comparatively low speed of communication
  3. Gets distracted by various elements like Blue-tooth
Localization

- **Localization** is a process to compute the locations of wireless devices in a network.

- WSN Composed of a large number of inexpensive nodes that are densely deployed in a region of interests to measure certain phenomenon.

- The primary objective is to determine the location of the target.
Usage

- Coverage
- Deployment
- Routing
- Location service
- Target tracking
- rescue
Introduction

• Location Information Utility
  – Wide Range of Applications
    • Military Maneuvers
    • Emergency Search & Rescue Operations
    • Tracking Mobile Users
    • Location based Commercial & Residential Services
Introduction

• Location Estimation
  – Time of Flight or Signal Strength
  – Triangulation or Trilateration

• Error in Measured Distance between Sender and Receiver
  – NLOS Error
  – Gaussian Random Noise

• Can be Measured or Pre-computed
**Distance/angle estimation:** Estimating position related parameters between two nodes.

**Position computation:** Computing a node’s position based on available information and anchor nodes positions.

**Localization algorithm:** Manipulating available information in order to localize other nodes in a WSN.
Localization

- The **distance estimation** phase involves measurement techniques to estimate the relative distance between the nodes.

- The **Position computation** consists of algorithms to calculate the coordinates of the unknown node with respect to the known anchor nodes or other neighboring nodes.

- The **localization algorithm**, in general, determines how the information concerning distances and positions, is manipulated in order to allow most or all of the nodes of a WSN to estimate their position. Optimally the localization algorithm may involve algorithms to reduce the errors and refine the node positions.
Introduction

• Modeling of indoor environments difficult
  – Environments vary widely
  – NLOS Error Time and Location Dependent
    • Requires Non-parametric Approaches
  – Time and Cost Prohibitive Factors
    • 500 Human-hours for Constructing Database of 50 km² Metropolitan Area
    • Cost $1000 per Cell
Introduction

• Global Positioning System (GPS)
  – Provide Accurate Location
  – High Infrastructure Cost
    • Constellation of Satellites
  – Suitable only for Outdoor Rural Environments
  • Suffers from NLOS errors
  • Signal Reflection and Obstruction in Indoor Environments
GPS .. Why not?

- We need to determine the physical coordinates of a group of sensor nodes in a wireless sensor network (WSN).

- Due to application context and massive scale, use of GPS is unrealistic, therefore, sensors need to self-organize a coordinate system.
Introduction

- Most Existing Approaches attempt Location Estimation
  - Least Squares Method
  - Residual Weighing Algorithm (RWGH)
  - Computationally Intensive
  - Probabilistic Measure
  - No Error Bound Guaranteed
System Model

\[ r_{uv} = d_{uv} + \eta_{uv} + c\tau_{uv} \]

- \( r_{uv} \): Measured range between Nodes \( u \) and \( v \)
- \( d_{uv} \): Distance between Nodes \( u \) and \( v \)
- \( c\tau_{uv} \): Represents NLOS Distance Error
System Model

- $\eta_{uv}$: Models Combined Additive Effects
  - Thermal Receiver Noise
  - Signal Bandwidth
  - Signal-to-Noise Ratio
  - Zero-Mean Normal Random Variable

NLOS Error is Dominant Error Contributor
System Model

• Nodes may be Stationary or Mobile
• All Communication Links assumed Symmetric and Bi-directional
• Small Percentage of Nodes Initially know Location Accurately
  – Reference Nodes
• **Beacon** – Any Node used for computing Location of another Node
Error Bounds Analysis

• Error in Advertised Co-ordinates of Reference Nodes
  – Maximum Error of $\pm \varepsilon$

• Error in Measured Range between any two Nodes
  – Maximum Error of $\pm \delta$
  – Delay Channel
  – Receiver Circuit consists of Matched Filter and Threshold Detector
Error Bounds Analysis

• Representative $\varepsilon$ values
  – GPS accuracy 1 to 5 meters in Outdoor Environments, 95-99% of time.
  – Microsoft Radar accuracy 3 to 4.3m
  – PinPoint 3D-iD and WhereNet location accuracy 1 to 3m
  – Cricket system accuracy 4x4 feet regions nearly 100% of time.
Error Bounds Analysis

• Computing Upper Bound on $\delta$
  – Estimating Transmitted Signal correctly at Receiver
    • Presence of NLOS and Gaussian Random Errors
    • Time-shift of Received Pulse less than Time Period of Pulse
Error Bounds Analysis

• Representative $\delta$ values
  – UWB-based Networks Pulse Width of the order of 1ns
    • Equivalent to 0.3m of distance covered by radio wave.
  – Proposed 802.11n standard Pulse Width would be between 5ns to 1.85ns
    • Estimated Data Rate between 200 to 540 Mbps
    • Translates to 1.5m to 0.555m for $c\tau_{uv}$ in equation 1
Error Bounds Analysis
Active and Cooperative Ranging

• Measurement of distance between two points
  – Acoustic
    • Point-to-point time-of-flight, using RF synchronization
    • Narrowband (typ. ultrasound) vs. Wideband (typ. audible)
  – RF
    • RSSI from multiple beacons
    • Transponder tags (rebroadcast on second frequency), measure round-trip time-of-flight.
    • UWB ranging (averages many round trips)
    •Psuedoranges from phase offsets (GPS)
    • TDOA to find bearing, triangulation from multiple stations
  – Visible light
    • Stereo vision algorithms
      – Need not be cooperative, but cooperation simplifies the problem
Passive and Non-cooperative Ranging

- Generally less accurate than active/cooperative
  - Acoustic
    - Reflective time-of-flight (SONAR)
    - Coherent beamforming (Yao et al.)
  - RF
    - Reflective time-of-flight (RADAR systems)
    - “Database” techniques
      - RADAR (Bahl et al.) looks up RSSI values in database
      - “RadioCamera” is a technique used in cellular infrastructure; measures multipath signature observed at a base station
  - Visible light
    - Laser ranging systems
      - Commonly used in robotics; very accurate
      - Main disadvantage is directionality, no positive ID of target
Using RF for Ranging

• Disadvantages of RF techniques
  – Measuring TOF requires fast clocks to achieve high precision \((c \approx 1 \text{ ft/ns})\)
  – Building accurate, deterministic transponders is very difficult
    • Temperature-dependence problems in timing of path from receiver to transmitter
  – Systems based on relative phase offsets (e.g. GPS) require very tight synchronization between transmitters

• Ultrawide-band ranging for sensor nets?
  – Current research focus in RF community
  – Based on very short wideband pulses, measure RTT
  – May encounter licensing problems
• RSSI is extremely problematic
  – 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

• Possible applications
  – Crude localization of mobile nodes
  – “Database” techniques (RADAR)

Using Acoustics for Ranging

• Key observation: Sound travels slowly!
  – Tight synchronization can easily be achieved using RF signaling
  – Slow clocks are sufficient (\(v = 1 \text{ ft/ms}\))
  – With LOS, high accuracy can be achieved cheaply
  – Coherent beamforming can be achieved with low sample rates

• Disadvantages
  – Acoustic emitters are power-hungry (must move air)
  – Obstructions block sound completely \(\Rightarrow\) detector picks up reflections
  – Existing ultrasound transducers are narrowband
Localization methods taxonomy

- Localization in wireless sensor network
  - Target/source localization
    - Single-target localization in WSN
    - Multiple-target localization in WSN
    - Single-target localization in WBSN
    - Multiple-target localization in WBSN
  - Node self-localization
    - Range-based localization
      - TOA
      - TDOA
      - RSSI
      - AOA
      - Pattern matching localization
    - Range-free localization
      - Hop-count-based localization
1- Target/Source Localization

- Most of the source localization methods are focused on the measured signal strength.

- To obtain the measurements, the node needs complex calculating process.
1- Target/Source Localization (Cont.)

1. The received signal strength of single target/source localization in WSN during time interval $t$:

$$y_i(t) = g_i \frac{S(t)}{d_{ik}^2(t)} + n_i(t),$$

where $g_i$ represents the gain factor of the $i$th sensor. We assume that $g_i = 1$. $S(t)$ is the signal energy at 1 meter away. And $d_{ik}$ is the Euclidean distance between the $i$th sensor and the source. In addition $n_i$ is the measurement noise modeled as zero mean white Gaussian with variance $\sigma_i^2$, namely, $n_i \sim N (0, \sigma_i^2)$. 
2. The received signal strength of multiple target/source localization in WSN during time interval $t$:

$$y_i(t) = g_i \sum_{k=1}^{K} \frac{S_k(t)}{d_{ik}^\alpha(t)} + \epsilon_i(t),$$

where $d_{ik}(t)$ is the distance between the $i$th sensor and the $k$th source. $K$ is the number of the sources. $g_i$ is the gain of $i$th sensor. $\epsilon_i(t)$ is random variable with mean $\mu_i$ and variance $\sigma_i^2$. $S_k(t)$ is the signal energy at 1 meter away for $k$th source. $\alpha$ is the attenuation exponent.
2- Node Self-localization

- **Range-based Localization:** uses the measured distance/angle to estimate the indoor location using geometric principles.

- **Range-free Localization:** uses the connectivity or pattern matching method to estimate the location. Distances are not measured directly but hop counts are used. Once hop counts are determined, distances between nodes are estimated using an average distance per hop and then geometric principles are used to compute location.
2-1 Range based localization

Range-based localization

- TOA
- TDOA
- RSSI
- AOA
1. **Time of arrival: (TOA)**

- It’s a method that tries to estimate distance between 2 nodes using time based measures.

- Accurate but needs synchronization
2. Time Difference Of Arrival: (TDOA)

- It’s a method for determining the distance between a mobile station and a nearby synchronized base station. (Like AT&T)

- No synchronization needed but costly.
2-1 Range based localization (Cont.)

3. Received Signal Strength Indicator: (RSSI)
- Techniques to translate signal strength into distance
- Low cost but very sensitive to noise
2-1 Range based localization (Cont.)

4. Angle Of Arrival: (AOA)
- It’s a method that allows each sensor to evaluate the relative angles between received radio signals.
- Costly and needs extensive signal processing.
Bearing Calculation and Error

- Precision of bearing estimate function of angle of incidence, baseline, array geometry, and phase resolution of detector
- Phase resolution of a wideband detector is function of sample rate and channel capacity
  - In our experiments primary limitation is sample rate

\[
\begin{align*}
\theta &= \frac{\angle XAB + \angle YAB}{2}, \\
\Delta &= \frac{\angle YAB - \angle XAB}{2}, \\
B &= \overline{AB}
\end{align*}
\]

Want to find \( \Delta = f(\theta, \varepsilon, B) \)

\[
\cos(\theta - \Delta) - \cos(\theta + \Delta) = \frac{\varepsilon}{B}
\]

\[
\Delta = \sin^{-1}\left(\frac{\varepsilon}{2\sin(\theta)B}\right)
\]
Trilateration Techniques (TOA)

Beacon Nodes

Sensor Node Which need to estimate its location

\[(x_0, y_0), (x_1, y_1), (x_2, y_2)\]
Range-based Solutions - MMSE

MMSE:
- Minimum Mean Square Estimation

Beacon Nodes
Sensor Node Which need to estimate its location

How to estimate \((x_0, y_0)\)?