Localization Technology
Outline

• Defining location

• Methods for determining location
  • Triangulation, trilateration, RSSI, etc.

• Location Systems
Introduction

We are here!
What is Localization

• A mechanism for discovering spatial relationships between objects
Location Tracking

- Satellite Based Correction
- Differential Correction Signal
- Roving Receiver
- GPS & Radio Beacon "Reference Receiver"
- Real-time Differential GPS
Applications

• Wildlife Tracking
• Weather Monitoring
• Location-based Authentication
• Routing in ad-hoc networks
• Surveillances
Applications of Location Information

• Location aware information services
  • e.g., E911, location-based search, target advertisement, tour guide, inventory management, traffic monitoring, disaster recovery, intrusion detection

• Scientific applications
  • e.g., air/water quality monitoring, environmental studies, biodiversity

• Military applications

• Resource selection (server, printer, etc.)

• Sensor networks
  • Geographic routing
  • “Sensing data without knowing the location is meaningless.” [IEEE Computer, Vol. 33, 2000]

• New applications enabled by availability of locations
Localization

- Well studied topic (3,000+ PhD theses??)
- Application dependent
- Research areas
  - Technology
  - Algorithms and data analysis
  - Visualization
  - Evaluation
Properties of Localization

- Physical position versus symbolic location
- Absolute versus relative coordinates
- Localized versus centralized computation
- Precision
- Cost
- Scale
- Limitations
Representing Location Information

- **Absolute**
  - Geographic coordinates (Lat: 33.98333, Long: -86.22444)

- **Relative**
  - 1 block north of the main building

- **Symbolic**
  - High-level description
  - Home, bedroom, work
No One Size Fits All!

- Accurate
- Low-cost
- Easy-to-deploy
- Ubiquitous

- Application needs determine technology
Consider for Example...

- Motion capture
- Car navigation system
- Finding a lost object
- Weather information
- Printing a document
Lots of Technologies!

- GPS
- WiFi Beacons
- Ultrasonic time of flight
- VHF Omni Ranging
- Ad hoc signal strength
- Array microphone
- Infrared proximity
- Laser range-finding
- Stereo camera
- Ultrasound
- Floor pressure
- E-911
- Physical contact
Some Outdoor Applications

- Car Navigation
- Child tracking
- Bus view
- E-911

Car Navigation

Bus view

Child tracking

E-911
Some Indoor Applications

Elder care
Outline

• Defining location

• **Methods for determining location**
  • Triangulation, trilateration, RSSI, etc.

• Location Systems
Approaches for Determining Location

• Localization algorithms
  • Proximity
  • Lateration
  • Angulation
  • RSSI
  • ToA, TDoA
  • Fingerprinting

• Distance estimates
  • Time of Flight
  • Signal Strength Attenuation
Proximity

• Simplest positioning technique
• Closeness to a reference point
  • It can be used to decide whether a node is in the proximity of an anchor
  • Based on loudness, physical contact, etc.
• Can be used for positioning when several overlapping anchors are available
  • Centronoid localization
Lateration

- Measure distance between device and reference points
- 3 reference points needed for 2D and 4 for 3D
Lateration vs. Angulation

• When distances between entities are used, the approach is called **lateration**
• when angles between nodes are used, one talks about **angulation**
Determining Angles

- Directional antennas
  - On the node
  - Mechanically rotating or electrically “steerable”
  - On several access points
    - Rotating at different offsets
    - Time between beacons allows to compute angles
Triangulation, Trilateration

- Anchors advertise their coordinates & transmit a reference signal
- Other nodes use the reference signal to estimate distances anchor nodes
Optimization Problem

- Distance measurements are noisy!
- Solve an optimization problem: minimize the mean square error
Estimating Distances – RSSI

• Received Signal Strength Indicator
  • Send out signal of known strength, use received signal strength and path loss coefficient to estimate distance

\[ P_{\text{recv}} = \frac{P_{\text{tx}}}{d^\alpha} \quad \Leftrightarrow \quad d = \sqrt[\alpha]{\frac{cP_{\text{tx}}}{P_{\text{recv}}}} \]

• Problem: Highly error-prone process (especially indoor)
  • Shown: PDF for a fixed RSSI
Estimating Distances – Other Means

• Time of arrival (ToA)
  • Use time of transmission, propagation speed, time of arrival to compute distance
  • Problem: Exact time synchronization

• Time Difference of Arrival (TDoA)
  • Use two different signals with different propagation speeds
  • Example: ultrasound and radio signal
    •Propagation time of radio negligible compared to ultrasound
  • Compute difference between arrival times to compute distance
  • Problem: Calibration, expensive/energy-intensive hardware
Fingerprinting

• Mapping solution
• Address problems with multipath
• Better than modeling complex RF propagation pattern
Fingerprinting

<table>
<thead>
<tr>
<th>SSID (Name)</th>
<th>BSSID (MAC address)</th>
<th>Signal Strength (RSSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>linksys</td>
<td>00:0F:66:2A:61:00</td>
<td>18</td>
</tr>
<tr>
<td>starbucks</td>
<td>00:0F:C8:00:15:13</td>
<td>15</td>
</tr>
<tr>
<td>newark wifi</td>
<td>00:06:25:98:7A:0C</td>
<td>23</td>
</tr>
</tbody>
</table>
Fingerprinting

• Easier than modeling
• Requires a dense site survey
• Usually better for symbolic localization

• Spatial differentiability
• Temporal stability
Received Signal Strength (RSS) Profiling Measurements

• Construct a form of map of the signal strength behavior in the coverage area
• The map is obtained:
  • Offline by a priori measurements
  • Online using sniffing devices deployed at known locations
• They have been mainly used for location estimation in WLANs
Received Signal Strength (RSS) Profiling Measurements

• Different nodes:
  • Anchor nodes
  • Non-anchor nodes,
  • A large number of sample points (e.g., sniffing devices)
• At each sample point, a vector of signal strengths is obtained
  • jth entry corresponding to the jth anchor’s transmitted signal
• The collection of all these vectors provides a map of the whole region
• The collection constitutes the RSS model
• It is unique with respect to the anchor locations and the environment
• The model is stored in a central location
• A non-anchor node can estimate its location using the RSS measurements from anchors
Correlation between Temperature, Humidity and RSSI

- Correlation between temperature and RSSI
  - Higher temperature $\rightarrow$ Weaker RSSI

- Correlation between humidity and RSSI
  - Less humid environment $\rightarrow$ Weaker RSSI
Temperature vs. RSSI

- In the datasheet of CC2420 (antenna of MicaZ, Telosb), it mentioned the temperature will affect the antenna, both the receiver and transmitter.

Based on that, in theory, we should observe 7 db attenuation when the temperature rise from 25 to 65 centi-degree.
Existing Study: the Temperature Effects on RSSI

- Sender side: 4.5 db attenuation
- Receiver side: 3 db attenuation
- Approximately 7 db attenuation, which matches the analysis in theory according to CC2420’s manual
Humidity vs. RSSI

- 2.4GHz signal attenuation is no more than 0.03 db/km, in all kinds of atmosphere environment (rainy, foggy, different percentage of humidity, etc.)

- Since sensor’s communication range is around 50m, such an insignificant attenuation can be neglected (in theory)
Further Experiment

- Keep temperature constant, and exploited humidifier, dehumidifier and air conditioner to get different humidity
Brief Conclusions

• We concluded that temperature can affect the transmission of WSNs significantly
  • Taking account of temperature effects is necessary in designing of WSNs in some challenging environment, since sometime high temperature can break down the original designed topology
• We also verified that the variation of humidity would not actually affect the functionality of WSNs
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• Location Systems
  • GPS
  • Active Badge, MIL, Active Bat, Cricket
  • RSS-based indoor localization
  • RSS-based smartphone indoor localization
  • Power-line based localization
  • Passive location tracking
GPS (Global Position Systems)

- Use 24 satellites
- GPS satellites are essentially a set of wireless base stations in the sky
- The satellites simultaneously broadcast beacon messages
- A GPS receiver measures time of arrival to the satellites, and then uses “triangulation” to determine its position
- Civilian GPS
  - L1 (1575 MHZ)
    - 10 meter acc.
Why We Need 4 Satellites?

- Assume receiver clock is sync’d with satellites

\[ t^{R1} = t^{S} + \frac{\|p - p_1\|}{c} \quad \rightarrow \quad \|p - p_1\| = c(t^{R1} - t^{S}) \]

- In reality, receiver clock is not sync’d with satellites

- Thus need one more satellite to have the right number of equations to estimate clock

\[ t^{R1} = t^{S} + \frac{d_1}{c} + \delta_{\text{clock-drift}} \quad \rightarrow \quad \|p - p_1\| = c(t^{R1} - t^{S} - \delta_{\text{clock-drift}}) \]

\[ = c(t^{R1} - t^{S}) - c\delta_{\text{clock-drift}} \]

called pseudo range
Active Badge

- IR-based: every badge periodically, sends unique identifier, via infrared, to the receivers
- Receivers, receive this identifiers and store it on a central server
- Proximity
MIL (Mobile Inequality Localization)

- Illustration for relative distance constraints
- Static Constraint
- Velocity Constraint
- “Weighted center” based position estimation

\[
X(k) = X_{\text{min}} + \frac{(X_{\text{max}} - X_{\text{min}}) \times (2k + 1)}{2P}
\]
Active Bat

- Ultrasonic
- Time of flight of ultrasonic pings
- 3cm resolution
Cricket

- Similar to Active Bat
- Decentralized compared to Active Bat
Cricket: Introduction

- Location system
- Project started in 2000 by the MIT
- Other groups of researchers in private companies
- Small, cheap, easy to use

Cricket node v2.0
Cricket: 5 Specific Goals

• User privacy
  • location-support system, not location-tracking system
  • position known only by the user
• Decentralized administration
  • easier for a scalable system
  • each space (e.g. a room) owned by a beacon
• Network heterogeneity
  • need to decouple the system from other data communication protocols (e.g. Ethernet, WLAN)
• Cost
  • less than U.S. $10 per node
• Room-sized granularity
  • regions determined within one or two square feet
Cricket: Determination of the Distance

• First version
  • purely RF-based system
  • problems due to RF propagation within buildings

• Second version
  • combination of RF and ultrasound hardware
  • measure of the one-way propagation time of the ultrasonic signals emitted by a node
  • main idea: information about the space periodically broadcasted concurrently over RF, together with an ultrasonic pulse
  • speed of sound in air: about 340 m/s
  • speed of light: about 300 000 000 m/s
Cricket: Determination of the Distance

1. The first node sends a RF message and an ultrasonic pulse at the same time.

2. The second node receives the RF message first, at $t_{RF}$ and activates its ultrasound receiver.

3. A short instant later, called $t_{ultrasonic}$, it receives the ultrasonic pulse.

4. Finally, the distance can be obtained using $t_{RF}$, $t_{ultrasonic}$, and the speed of sound in air.
Cricket: Difficulties

• Collisions
  • no implementation of a full-edged carrier-sense-style channel-access protocol to maintain simplicity and reduce overall energy consumption
  • use of a decentralized randomized transmission algorithm to minimize collisions

• Physical layer
  • decoding algorithm to overcome the effects of ultrasound multipath and RF interferences

• Tracking to improve accuracy
  • a least-squares minimization (LSQ)
  • an extended Kalman filter (EKF)
  • outlier rejection
Cricket: Deployment

- Common way to use it: nodes spread through the building (e.g. on walls or ceiling)
- 3D position known by each node
- Node identification
  - unique MAC address
  - space identifier
- Boundaries
  - real (e.g. wall separating 2 rooms)
  - virtual, non-physical (e.g. to separate portions of a room)
- Performance of the system
  - precision
  - granularity
  - accuracy
Cricket: Deployment

At the MIT lab: on the ceiling
Cricket: Different Roles

A Cricket device can have one of these roles

• Beacon
  • small device attached to a geographic space
  • space identifier and position
  • periodically broadcast its position

• Listener
  • attached to a portable device (e.g. laptop, PDA)
  • receives messages from the beacons and computes its position

• Beacon and listener (symmetric Cricket-based system)
Cricket: Passive Mobile Architecture

In a passive mobile architecture, fixed nodes at known positions periodically transmit their location (or identity) on a wireless channel, and passive receivers on mobile devices listen to each beacon.
Cricket: Active Mobile Architecture

In an active mobile architecture, an active transmitter on each mobile device periodically broadcasts a message on a wireless channel.
Cricket: Hybrid Mobile Architecture

- Passive mobile system: used in normal operation
- Active mobile system: at start-up or when bad Kalman filter state is detected

![Diagram](image)

*Figure 4: Flow chart of a mobile device using a hybrid architecture.*
Cricket: Architecture

Cricket hardware unit – beacon or listener
Cricket: Architecture

- **Microcontroller**
  - the Atmega 128L operating at 7.3728 Mhz in active and 32.768 kHz in sleep mode
  - operates at 3V and draws about 8mA(active mode) or 8μA(sleep mode)

- **RF transceiver**
  - the CC1000 RF configured to operate at 433 Mhz
  - bandwidth bounded to 19.2 kilobits/s
Cricket: Architecture

- Ultrasonic transmitter
  - 40 kHz piezo-electric open-air ultrasonic transmitter
  - generates ultrasonic pulses of duration 125 μs
  - voltage multiplier module generates 12 V from the 3 V supply voltage to drive the ultrasonic transmitter

- Ultrasonic receiver
  - open-air type piezo-electric sensor
  - output is connected to a two-stage amplifier with a programmable voltage gain between 70 dB and 78 dB
Cricket: Architecture

- RS 232 interface
  - used to attach a host device to the Cricket node
- Temperature sensor
  - allows to compensate for variations in the speed of sound with temperature
- Unique ID
  - an 8-byte hardware ID, uniquely identifies every Cricket node
- Powering the Beacons and Listeners
  - each Cricket node may be powered using two AA batteries, a power adapter, or solar cells
  - beacon can operate on two AA batteries for 5 to 6 weeks
Evaluation – Test of Cricket

The experimental setup and schematic representation of the train's trajectory
Evaluation – Test of Cricket

Experimental facts

- Three architectures: passive mobile, active mobile, and hybrid with Extended Kalman Filter (EKF) or least-squares minimization (LSQ)
- Computer-controlled Lego train set running at six different speeds: 0.34 m/s, 0.56 m/s, 0.78 m/s, 0.98 m/s, 1.21 m/s, and 1.43 m/s
- Multiple beacons (five or six in all experiments) interacting with one another
- Gathered about 15,000 individual distance estimates in the active mobile architecture and about 3,000 distance estimates in the passive mobile architecture
Evaluation – Test of Cricket

For speed of 0.78m/s

Passive mobile architecture (EKF)
– median error is about 10cm
Passive mobile architecture (LSQ)
– 30th percentile error is less than 30cm
Active mobile architecture
– median error is about 3cm
Hybrid mobile architecture
– median error is about 7cm

For speed of 1.43m/s

Passive mobile architecture (EKF)
– median error is about 23cm
Passive mobile architecture (LSQ)
– only 30th percentile error is less than 50cm
Active mobile architecture
– median error is about 4cm
Hybrid mobile architecture
– median error is about 15cm
Evaluation – Test of Cricket

Linear relationship between speed and accuracy
# Cricket: Summary

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive Mobile Architecture</td>
<td>• privacy • scalability • decentralization</td>
<td>• weak accuracy at higher speed (above 1 m/s)</td>
</tr>
<tr>
<td>Active Mobile Architecture</td>
<td>• accuracy</td>
<td>• reduced scalability • privacy concern • requires a network infrastructure</td>
</tr>
<tr>
<td>Hybrid Mobile Architecture</td>
<td>• privacy (usage of active mobile information is less than 2%) • scalability • accuracy • decentralization</td>
<td></td>
</tr>
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  • RSS-based smartphone indoor localization
  • Power-line based localization
  • Passive location tracking
# RSS-based Indoor Localization

<table>
<thead>
<tr>
<th>Technology</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio Frequency Identification (RFID)</td>
<td>LANDMARC [INFOCOM’04], Wang et al. [INFOCOM’07], Seco et al. [IPIN’10]</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>Ficsher et al. [CWPNC’04], PlaceLab [Pervasive’04], Pei et al. [JGPS’10]</td>
</tr>
<tr>
<td>Wireless Sensor</td>
<td>Chang et al. [Sensys’08], Chung et al. [MobiSys’11], Pirkl et al. [UbiComp’12]</td>
</tr>
<tr>
<td>GSM</td>
<td>Otsason et al. [UbiCom’05]</td>
</tr>
<tr>
<td>Wireless Local Area Network (WLAN)</td>
<td>RADAR [INFOCOM’00], Horus [MobiSys’05], Chen et al. [Percom’08]</td>
</tr>
</tbody>
</table>
RADAR

- WiFi-based localization
- Reduce need for new infrastructure
- Fingerprinting, RSSI profiling
Using reference tags, which are deployed at the fixed positions, LANDMARC calculates the accurate location of the tracking object:
- Attach a tracking tag
- 4-nearest tags
- Standard placement

High accuracy demand ➔ dense deployment of reference tags ➔ severe interference among tags
Analysis

- The relationship between the distance and the RSSI values
VIRE: Core Idea

- Using virtual reference tags (VRTs) to replace real tags as references

- The RSSI values of VRTs can be obtained by following equations

\[
S_k(T_{p,b}) = S_k(T_{a,b}) + p \times \frac{S_k(T_{a+n,b}) - S_k(T_{a,b})}{n+1}
\]

The horizontal lines

\[
= p \times S_k(T_{a+n,b}) + (n+1-p) \times S_k(T_{a,b})
\]

- The vertical lines

\[
S_k(T_{a,q}) = S_k(T_{a,b}) + q \times \frac{S_k(T_{a,b+n}) - S_k(T_{a,b})}{n+1}
\]

\[
= q \times S_k(T_{a,b+n}) + (n+1-q) \times S_k(T_{a,b})
\]

- The VRTs in central parts

\[
S_k(T_{i,j}) = \frac{S_k(T_{p,b}) + S_k(T_{p,b+n}) + S_k(T_{a,q}) + S_k(T_{a+n,q})}{2}
\]

\[
= \frac{(2n-p-q+2)S_k(T_{a,b}) + (n+1-p+q)S_k(T_{a,b+n}) + (n+1-q+p)S_k(T_{a+n,b}) + (p+q) \times S_k(T_{a+n,b+n})}{2(n+1)}
\]
RSS-based Smartphone Indoor Localization

- **WiFi enabled**
  - Chintalapudi et al. [MobiCom’10], OIL [MobiSys’10], WiGEM [CoNects’11]

  ➢ Improve WiFi accuracy

- **Hybrid**
  - Zee[MobiCom’12], UnLoc[MobiSys’12], WILL[INFOCOM’12], LiFS[MobiCom’12], ABS[MobiSys’11], Liu et al.[MobiCom’12], SurroundSense [MobiCom’09], Escort [MobiCom’10]
RSS-based Smartphone Indoor Localization

- Hybrid Approach (*WiFi + Inertial Sensors*)
- User Motion Information
RSS-based Smartphone Indoor Localization

- Hybrid Approach (*WiFi + Acoustic*)
- Physical Constraints

Provide physical constraints from nearby peer phones

[MobiCom’12] Push the Limit of WiFi based Localization for Smartphones
RSS-based Smartphone Indoor Localization

• Hybrid Approach
  • Logical Map + Real Map Mapping

Inertial sensors
RSS is NOT a Reliable Location Feature!

Modeling
- Accuracy will be decreased by the erroneous RSS measurement

Fingerprinting
- High variant RSS will make the location signature becomes not unique
What is CSI?

In 802.11 n OFDM system, the received signal over multiple subcarriers is

\[ y = Hx + n \]

\[ H = \frac{y}{x} \rightarrow CSI \]

Channel gain

\[ h = |h|e^{j\sin\{\angle h\}} \]

amplitude phase

Previously, CSI \rightarrow Rate Adaptation [SIGCOMM’10, MobiCom’11]
CSI Properties

Frequency diversity

RSS vs. CSI

Receiver

2.4GHz

RF band

S/P

Baseband

S/P

FFT

single value

multiple values

CSI-based Indoor Localization: FILA [INFOCOM’12]
CSI Properties

Temporal Stability

RSS vs. CSI

- **RSS**: variant
- **CSI**: relatively stable
CSI is a fine-grained PHY layer information that owns the potential of being a suitable location feature.
CSI-based Modeling

[INFOCOM’12] FILA

(1) Collect CSI
Channel Estimation

(2) Process CSI

CSI eff

(2)' Distance Calculator

(3) Locate Rx

OFDM Demodulator

OFDM Decoder

Normal Data

Two processing mechanisms:
1. Time-domain Multipath Mitigation
2. Frequency-domain Fading Compensation
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Power Line Positioning

• Indoor localization using standard household power lines
Signal Detection

- A tag detects these signals radiating from the electrical wiring at a given location.
Signal Map

1st Floor

2nd Floor
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Passive Location Tracking

- No need to carry a tag or device
  - Hard to determine the identity of the person
- Requires more infrastructure (potentially)
Active Floor

- Instrument floor with load sensors
- Footsteps and gait detection
Motion Detectors

- Low-cost
- Low-resolution
Computer Vision

- Leverage existing infrastructure
- Requires significant communication and computational resources
- CCTV
Transceiver-Free Object Tracking

- In the static environment, the environment factors are stable and the received radio signal of each wireless link will be stable too.
- When an object comes into this area and cause the signals of some links to change (influential links).
- The influential links will tend to be clustered around the object.
Theoretical Background

Total received power

Static environment:
\[ P_0 \propto \left| E_1 + E_2 + E_{other} \right|^2 \]

Dynamic environment:
\[ P \propto \left| E_1 + E_2 + E_{other} + E_{obj} \right|^2 \]

when \( P_{obj} \ll P_0 \), \[ \Delta P \approx P_{obj} = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 r_1^2 r_2^2} \]

Relationship between object position and the change of the signal

An object comes in to this area \( \rightarrow \) will cause an additional signal reflection path \( \rightarrow \) the additional received power is much smaller than previous received power.
**RSSI dynamics**: The difference of the *received signal strength indicator* (RSSI) between static and dynamic environment

**Signal dynamic property**: Along each PL or VL, if the object position is closer to its midpoint, the RSSI dynamics are larger
DDC (Distributed Dynamic Clustering)

- Multiple objects in the tracking area
- Distributed Dynamic Clustering
  - Dynamically form a cluster of those wireless communication nodes whose received signal strengths are influenced by the objects
- Using a probabilistic methodology, can more easily determine the number of objects in the area
- Moreover, by dynamically adjusting the transmission power when forming clusters, the interference between nodes will be reduced
DDC (Distributed Dynamic Clustering)

Probabilistic Cover Algorithm

- Estimate a possible object area for each influential link based on our model
- As there may be many influential links, many such areas will be created
- Based on these areas, a probabilistic method is used to obtain the final estimated object position
The End!