Detecting Intra-Room Mobility with Signal Strength Descriptors

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RUTGERS WINLAB
Background: Internet of Things (IoT)

- Attaching sensing and networking to everyday objects
  - Coffee mugs, doors, chairs, beds

- Building applications using the state of these objects
  - Spatial (E.g., location, velocity)
  - Temperature, vibration, switches, weight

- Historical communities centered around enabling technologies
  - Passive RFID
  - Active RFID
  - Semi-Passive RFID
  - Motes/Sensor networks
  - Cell-phone camera + QR (bar) codes
Why now?

IoT enablers

• Low-power tags using transmit-only communication
  – Extend beaconing and sensing to >4 years on a $0.20 battery

• Rich infrastructure available indoors
  – Dense sets of receivers, fast backhaul networks, powerful servers

• Novel-Spatial Temporal Sensing

• Software Architectures and Application Stacks
  – Octopus project and GRAIL 3.0

• Applications
  – Lab Usage
  – Coffee Pot
  – Washing machine
  – Healthcare
  – Inventory Control
Novel Spatial-Temporal Primitives

- **Location**
  - The (X,Y,Z) position of a wireless device at time T

- **Mobility**
  - Whether a device is moving or stationary at time T

- **Passive Localization and Mobility**
  - An object’s (no wireless) position or movement at time T

- **Proximity**
  - Two devices are close (< distance) to each other at time T

- **Co-mobility**
  - Two objects moving together (on a person or in container) over time T

- **Velocity**

- **Path Mobility**
  - Movement along a defined path P (corridor or road) during time T

- **Given sufficient resolution for location, all others can be derived**
  - Not at a sufficient level of resolution yet.
Novel Spatial-Temporal Primitives

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What is Radio-Based Mobility Detection?

- Detect when a transmitter moves
  - By observing signal strength
  - Detection done using observations of a set of receivers

- Radio-Based because
  - Detection **only** based upon radio signal from the target
  - No sensor hardware needed
    - No accelerometers, etc
  - The transmitter does not need to interact in the mobility detection, other than by transmitting.
    - Can monitor a transmitter without it sending any special data
Motivations for Radio-Based Mobility Detection

- Mobility detection is useful
  - Security
  - Usage detection
  - Fills in gaps in other technology
    - Localization is not accurate at intra-room distances
    - Motion sensors use too much energy/are too costly in many systems

- Find a universal approach to mobility detection
  - Without specialized hardware
  - With minimal or no training
  - In changing environments
  - Across different frequencies, hardware, and environments
Our Approach

- **Focus on mobility at the room level**
  - Inside a room, in and out of a room
  - Using received signal strength (RSS)
  - Differentiate variance from transmitter motion from environmental motion

- **Evaluate effects of various parameters**
  - Transmission rate
  - Allowed prediction latency
  - Number of receivers
  - Complexity of multipath environment
Causes of Signal Strength Variations

- With no movement (environmental stability) RSS at a receiver is steady
Causes of Signal Strength Variations

- If the transmitter moves, all components of the signal change

![Graph showing RSS vs Distance with components Path Loss, Shadowing, Multipath Fading]
Causes of Signal Strength Variations

- An object moves (environmental instability)
  - Possible cause of false positive
    - shadows the signal
    - changes the multipath environment
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Using RSS Descriptors for Mobility Classification

- Descriptor – statistic of RSS measurements over time
- Three descriptors are tested
  - Standard deviation (σ) of received signal strength (RSS)
  - Absolute change in mean RSS (ΔRSS)
  - Histogram distance of RSS using the Earth Mover's Distance (EMD)
    - An ensemble of the three is also tested
- The average value from multiple receiver is compared to a threshold for mobile/immobile classification
  - Classification tool (JRip) determines best threshold
    - Uses 10-fold cross-validation
Calculating RSS Descriptor Values

- **\( \sigma \) RSS**
  - The standard deviation is taken across two time windows.

- **\( \Delta \) RSS**
  - The absolute value of the difference between the mean RSS for window 1 and for window 2 is calculated.

- **Earth Mover’s Distance (EMD)**
  - The number of steps to change a histogram of RSS values in time window 1 into the histogram for time window 2
A mobility event is classified when a descriptor goes above the threshold. The event does not end until the descriptor goes below the threshold. If this identifies two events as a single event then we consider the second event missed.
Study Environments

- Two rooms
  - A conference room for testing
    - Very empty – ideal environment
  - A storage room for testing universal applicability
    - Very cluttered – Techniques like localization do not work here
Finding the Threshold Value

- Conference room
  - Threshold and results determined from 10-fold cross-validation

- Storage room
  - No training done
    - Used threshold from conference room
    - Test applicability of threshold across different environments
Evaluating RSS Descriptors - Methodology

- Tested descriptor performance with several events
  1. Movement in close proximity to the transmitter:
     - Local Instability (LI)
  2. Movement in the room with the transmitter:
     - Global Instability (GI)
  3. Transmitter: Mobility
  4. Antenna orientation changes

- All of these will be tested with a Wi-Fi and a 902.1 MHz (active RFID) transmitter and multiple receivers.
Metrics

- Treated as a detection problem
  - Did mobility occur in a time window (from $T_0$ to $T_N$)?

- Recall
  - Percent of mobility events correctly identified

- Precision
  - Likelihood that a mobility prediction actually matches a real mobility event

- F-Measure
  - Way to compare different thresholds with different recall and precision values
Wi-Fi, Conference Room

- Window size of 2 seconds and packet rate of 10 packets per second
- Standard deviation shows the sharpest differences between events
  - Best results with $\sigma \text{ RSS} = 3.43$
RFID, Conference Room

- Window size of 3 seconds and packet rate of 1 packet per second
- RFID very similar to Wi-Fi, despite the different frequency and packet rates
  - Best results with $\sigma_{\text{RSS}} = 4.58$
Small Mobility Test Results – Conference Room

Wi-Fi

RFID

Local Movement,
Transmitter immobile
Small Mobility Test Results – Conference Room

Train on the peaks during mobility compared to peaks that occur during immobility
<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Precision</th>
<th>Recall</th>
<th>F-measure</th>
<th>Window Size (seconds)</th>
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<td>0.979</td>
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Large Test – Threshold Value
Works for Both Environments

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WINLAB
WIRELESS INFORMATION NETWORK LABORATORY
The Effect of the Number of Receivers

2.4GHz @ 10 packets/second

902.1MHz @ 1 packet/second
Conclusions

- Mobility detection can be done without special hardware "for free" in existing networks
  - A standard deviation descriptor and a threshold can predict mobility across different frequencies and environments
    - Single threshold gives acceptable results in multiple environments
      - Very high recall ( > 99% ) for tested systems
      - Without retraining in the new environment
      - Different devices need different thresholds
  - Mobility of a transmitter can be distinguished from mobility in the environment
Backup slides
Small Mobility Test Results – Conference Room

- σ RSS is the best mobility detector
  - For Wi-Fi and RFID
  - Wi-Fi has slightly better results

[Graphs showing Wi-Fi and RFID mobility test results]
Impact of Packet Rate upon Detection (Wi-Fi)

- High packet rates are better
  - Only slightly

![Graph showing impact of packet rate on Wi-Fi detection](image-url)
Impacts of Window Size upon Latency and Detection (Wi-Fi)

- Window sizes the same duration as mobility events are best
- Latency is proportional to duration of mobility events
Antenna Orientation Test -- Wi-Fi

![Graph showing time (seconds) vs. σ RSS with descriptor peaks from rotations highlighted.](image-url)
Antenna Orientation – RFID

![Graph showing antenna orientation over time with R markers at certain time intervals.](image-url)
Changes in Orientation can Appear Similar to Mobility

- Orientation changes do cause descriptor peaks
  - From antenna directionality
  - Not as high as true mobility
Related Work

- Location Distinction\(^1\)
  - Similar to mobility detection
  - Not robust to changing environments
  - Requires many training measurements
  - Requires data unavailable on commodity hardware

- Mobility Detection\(^2\)
  - Mobility detection using RSS variance
  - 802.11 network with 1 to 3 APs
  - Effects of differing latency are studied

Small Mobility Test

- Evaluate how RSS changes under different conditions
  - Stability (empty room)
  - Global Instability (people walk around the room)
  - Local Instability (object moves near the transmitter)
  - Mobility (object moves)
- Approximately 20 – 50 events for instability and mobility and 10's of minutes of stability data
- Performed in the conference and storage rooms
Large Mobility Test

- Only stability and mobility
- Three mobility routes were used
  1. Linear
  2. Triangular
  3. Triangular moving inside and outside of the room
- Intervals between movement were 15 seconds, 1 minute, 3 minutes, or 10 minutes.
- 930 mobility events recorded in total.
- 13 hours of stable environment data
- Only done in the conference room
Test Topology

Conference Room

Storage Room
Small Mobility Test Results – Conference Room