Positioning for Smartphone Applications

Accuracy ^{-1} (Error)  

Celltower-based Localization

GPS

Energy Cost
Celltower-based Localization

- Less power-intensive
  - Errors in the order of several hundreds of meters, as high as 2km

![Map and CDF graph showing position error distribution. The map illustrates a route labeled '1km' with a GPS route and a Net route. The CDF graph shows a cumulative distribution of position error with a median of 347 meters.]
Maybe I was unlucky just once?

Not only inaccurate but also inconsistent
Maybe just one bad route?

Celltower-based localization is inaccurate
Can we achieve reasonable position accuracy at the energy cost close to that of celltower-based scheme?
CAPS: Cell-ID Aided Positioning System

- An energy-efficient positioning system that uses *cell-ID sequence matching* along with history of `<cell-ID, GPS coordinates>` sequences to estimate user’s current position without turning on GPS

- Design Goal
  - Significantly reduce the amount of energy spent on positioning while still providing sufficiently accurate position information

- Challenges
  - Accurately estimate current user position without turning on GPS
  - Determine when to turn on and off GPS efficiently
Cell-ID Transition Point and User Position

- When the cell-ID changes from 1 to 2,
  - Can you tell where you are?
Time-of-day as a Hint

- This time, cell-ID changes from 2 to 1...

9:00 AM Morning route

Grocery store

Evening route

Home
Can estimate user position at the cell-ID transition points because users have consistency in their everyday routes
CAPS Components

Position Estimation
• Uses spatial and temporal mobility history of a user to estimate user position within the route that she has used in the past

Sequence Matching & Selection
• Uses Cell-ID sequence matching to identify a cell-ID sequence in the user’s history which matches with the current sequence of recently visited cell-IDs

Sequence Learning
• Opportunistically learns and builds the history of a user’s routes associated with GPS readings
Position Estimation

- If $\Delta t$ has passed since crossing a cell-ID boundary,
  - Position estimate is simple interpolation

\[
\begin{align*}
(x_1, y_1, t_1) & \quad (x_2, y_2, t_2) \\
(x_3, y_3, t_3) & \\
\end{align*}
\]

\[
\begin{align*}
(x_1 + \frac{(x_2 - x_1)}{(t_2 - t_1)} \Delta t, y_1 + \frac{(y_2 - y_1)}{(t_2 - t_1)} \Delta t)
\end{align*}
\]
Position Estimation

- Additional GPS points between cell-ID boundaries can provide better estimate

\[
(x_{2,3} + \frac{(x_{2,4} - x_{2,3})}{(t_{2,4} - t_{2,3})} \cdot (\Delta t - (t_{2,3} - t_{2,1})), y_{2,3} + \frac{(y_{2,4} - y_{2,3})}{(t_{2,4} - t_{2,3})} \cdot (\Delta t - (t_{2,3} - t_{2,1}))
\]
Whenever GPS is on, use \(<\text{cell-ID}, x, y, t>\) information to opportunistically learn sequences.
Sequence Matching

- Find out which sequences from the database are similar to the currently observed sequence
- Use *Smith-Waterman Algorithm* for sequence matching
  - Local sequence alignment algorithm used in Bioinformatics
    - Suitable for comparing different sequences which may possibly differ significantly in length and have only a short patches of similarity
  - Current (last) cell-ID must be part of the match
  - Modified penalty function

A sequence in sequence DB: [9, 1, 4, 5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10]

Current cell-ID sequence: [9, 1, 4, 5, 6] [4, 5, 6]
Sequence Selection

- Select among the (possibly multiple) matched sequences from the database

<table>
<thead>
<tr>
<th>CURRENT SEQ</th>
<th>1 2 3 4 5</th>
<th>Match</th>
<th>Gap</th>
<th>Mismatch</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB SEQ 1</td>
<td>1 7 3 4 5</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>3.5</td>
</tr>
<tr>
<td>(match)</td>
<td>1 X 3 4 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB SEQ 2</td>
<td>1 2 3 6 4 5</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>4.5</td>
</tr>
<tr>
<td>(match)</td>
<td>1 2 3 – 4 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB SEQ 3</td>
<td>6 7 2 3 4 5 8</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>4.0</td>
</tr>
<tr>
<td>(match)</td>
<td>2 3 4 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB SEQ 4</td>
<td>6 1 3 7 5 9</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2.0</td>
</tr>
<tr>
<td>(match)</td>
<td>1 – 3 X 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Selected sequence is used for position estimation

- Rate-adaptive GPS
  - Turn ON GPS when no good matching exists in the database
  - Turn OFF when position estimation agrees with GPS reading
Implementation

Application

<Position>

Position Estimation

Sequence History Database

Sequence Selection

Matching Alg. SmithWaterman

Sequence Learning

Current Cell-ID Sequence

CAPS

Phone

GPS

Cell-ID
Evaluation

- **Energy savings and accuracy achieved by CAPS**
  - Comparison to periodic GPS strategy
  - **Learning of CAPS**
  - Platform and Carrier Independence
  - Comparison to WiFi-based Positioning (WPS)
  - Effects of Time-of-Day

- **Methodology**
  - **Implemented on Android smartphones**
  - **4 Routes in 3 Cities** – around Los Altos, Sunnyvale, and Los Angeles
  - **2 Transportation** – Bus and car
  - **3 Phones** – Nexus One, MotoDroid, GalaxyS
  - **3 Carriers** – T-Mobile (GSM), AT&T (GSM), Verizon (CDMA)
  - **Each iteration:** < 16.5 miles, < 2 hours
Evaluating the GPS route usage and accuracy:

- **GPS Usage**: 0.9%
- **Accuracy**: 79.0 m

Errors are "on-route". Reasonable accuracy with little GPS usage.
More Evaluation...

- 4 Different Routes, 2 Transportation,
- 3 Phones (Nexus One, DROID, Galaxy S),
- 3 Networks (T-Mobile, AT&T, Verizon (CDMA))

Save more than 90% of the GPS energy, with errors below 20% of the celltower-based scheme.
Runtime Learning

GPS Usage goes down as learning progresses
Remaining Challenge

- Small detour
  - Larger detours, both in **time** and **space**, will be detected.
Where are we?

Accuracy $^{-1}$ (Error)

Celltower-based Localization

Light-weight Positioning Systems

GPS

- EnLoc,
- Entracked,
- SenseLoc,
- RAPS,
- a-Loc,
- CompAcc,
- Escort
- SurroundSense
- etc...

+ CAPS

✓ Accelerometer,
✓ Microphone,
✓ WiFi,
✓ Bluetooth,
✓ Compass,
✓ History,
✓ Context/Activity etc...
CAPS Summary

- CAPS is an *energy-efficient positioning* system for smartphone applications
  - Based on the idea that cell-ID transition points can provide accurate estimate of user position on frequently traveled routes
  - Designed for highly mobile users with consistency in routes traveled
  - Uses *cell-ID sequence matching* and history of GPS coordinates to cleverly estimate current user position without turning on the GPS
  - Reduces energy consumption by more than 90% relative to Always-On GPS while providing reasonable accuracy below 20% of the celltower-based scheme.
QUESTIONS?

Thank you.