Widar: Decimeter Level Passive Tracking via Velocity Monitoring with Commodity Wi-Fi

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Motivation

- Human tracking inspires various applications.
- And tracking with Wi-Fi is superior in
  - Ubiquitous: Almost everywhere installed infrastructure.
  - Low-cost: Off-the-shelf Wi-Fi devices.
  - Non-invasive: not required to wear/carry any devices.

Navigation  
Gait Analysis  
Activity Recognition
Existing Arts

They estimate precise signal parameters, yet rely on specialized hardware!
Existing Arts

Though using COTS Wi-Fi, these solutions focus on training-based activity recognition, yet not tracking.
Problem Statement

- Passive tracking with COTS Wi-Fi devices.
  - Deriving human’s moving velocity and location from Wi-Fi signals without training.
Key Insight

• Modeling interaction between CSI and motion.

• Human movement causes length change of reflecting path.

• Spectrogram of CSI series shows the frequency shift that corresponds to change rate (PLCR).

CARM, Mobicom ’15
Challenges

- PLCR only reflects partial velocity.
- The signs of PLCR are not available.
- Spectrograms containing PLCR are polluted with noises and interferences.

Walking Scenarios

Ideal Spectrograms

Real Spectrograms

We introduce CSI-Mobility model.
From PLCR to Velocity

• From view of geometry,
  – Radial velocity $v_r$ changes the path length and causes Doppler effect, while tangential velocity $v_t$ not.

• From view of algebra,
  – Single links yields one

Single Link is insufficient for tracking!

$$l = (l_x, l_y)^T$$ - Location. $$a_x, a_y$$ - Coefficients decided by $l$. 
CSI-Mobility Model

- By adding more links, velocity can be determined.
- Solving the equation system of all links.
  - \( A \ddot{v} = \ddot{r} \)
  - Where \( A = \begin{pmatrix} a_x^{(1)} & a_x^{(2)} & \cdots & a_x^{(L)} \\ a_y^{(1)} & a_y^{(2)} & \cdots & a_y^{(L)} \end{pmatrix}^T \), \( \ddot{r} = (r^{(1)} \ r^{(2)} \ \cdots \ r^{(L)})^T \)
  - \( \ddot{v} = (A^T A)^{-1} A^T \ddot{r} \)
Two ambiguous solutions always exist, no matter how many links are added.
CSI-Mobility Model

PLCR Signs Identification

- Step I: Opportunistically derive moving directions from subcarriers delay information.

- However, the approach is robust only when,
  - Large moving velocity.
  - Large incident angle between moving direction and link.
CSI-Mobility Model

PLCR Signs Identification

- Step II: consecutiveness of human walking during short time.

\[
\begin{align*}
\dot{v}_k &= (A_k^T A_k)^{-1} A_k^T R_k \hat{s}_k \\
\hat{s}_k &= \text{argmin}(\text{err}_{l,k} + \beta \text{err}_{v,k})
\end{align*}
\]

- Solving the equation system at time \( k \).

- \( \text{err}_{l,k} = ||A_k \dot{v}_k - R_k \hat{s}_k|| \) is the PLCR fit error.

- \( \text{err}_{v,k} = ||A_k \dot{v}_k - A_{k-1} \dot{v}_{k-1}|| \) is the velocity deviation error.
CSI-Mobility Model

PLCR Extraction

• Leveraging acceleration constraints of PLCR.
  
  \[ a(t) = \frac{d}{dt} r(t) \leq 2 \frac{d}{dt} v(t) \]
  
  – PLCR acceleration is bounded by velocity acceleration.

• Manipulation of the spectrogram \( W_{T \times F} \).
  
  – Given the maximum PLCR acceleration,
  
  – By properly decimating the spectrogram,
  
  – PLCR in adjacent time samples is bounded within one bin, i.e. \( \Delta_f = 1 \).

• Thus, global optimal PLCR series is obtained as:
  
  \[ \text{PLCR} = \text{PLCR}(\arg\max_{f_1, ..., f_T} \sum_{i=1}^{T} W_{i,f_i}) \]
  
  \[ s.t. |f_i - f_{i-1}| \leq 1; i = 2, ..., T \]
Implementation Issues

• Initial location estimation.
  – Search through whole tracking space discretely.

• Initial velocity estimation.
  – Set the initial velocity as small disturbance.
  – Values in a pair of symmetric vectors.

• Successive tracking.
  – \( \mathbf{l}_{k+1} = \mathbf{l}_k + \mathbf{v}_k \Delta t \)

• Trace refinement.
  – Reinitiate tracking process at vulnerable moments.

1st Segment  2nd Segment  3rd Segment  4th Segment
Evaluations & Results
Experiment

• Devices
  – 3 mini PC with Intel 5300 NICs.
  – 6 links (3 per receiver).
  – Packet rate: 2000 Hz.
  – Tx power: 15dBm.

• Setup
  – Deployment schemes.
  – Trace shapes.
  – Volunteers.

• Ground truth
  – Video-based tracking

• Basement.
  – CARM (MobiCom ’15)
  – WiDir (UbiComp ’16)
Performance on Velocity

- **Widar** achieves the highest estimation accuracy, with a median error of 13%, for velocity magnitude.
- **Widar** achieves an 80-percentile error of 20° for velocity direction.

![Velocity Magnitude CDF](chart1)

![Velocity Direction CDF](chart2)
Performance on Location

- **Widar** achieves a median tracking error of 25cm and 38cm with and without initial location, and 90-percentile tracking error of 78cm.
- **Decimeter-level Passive Tracking.**
- **Tracking examples**
Impact of Walking Direction

- Evaluation is carried out in Setup 2.
- *Widar* achieves consistently high accuracy through all walking directions.
Impact of Setup

The largest errors emerge at the direction which is the most parallel with all links.

- Setup 1: 135°
- Setup 2: 0°
Impact of Walking Distance

- Due to lack of localization scheme for calibration, tracking errors accumulate at a moderate rate.
Discussion & Future Work

• Model-based passive localization with Wi-Fi.

- LiFS, MobiCom ’16
- DynamicMUSIC, Ubicomp ’16

• These works target at localization, instead of accurate continuous velocity tracking.

• They can complements Widar for initial location and opportunistic calibration.

• Not a easy problem…
Conclusion

• Widar’s CSI-Mobility model
  – Geometrically quantifies the relationships between CSI dynamics and human mobility.
  – Simultaneously estimates human’s moving velocity and locations using COTS Wi-Fi devices.
  – Training-free: extract environment-independent signal feature.

• Decimeter-level passive tracking system.
  – Median location error of 25cm and 38cm with and without initial positions.
  – Median relative velocity error of 13%.
Thanks!

Q&A

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