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

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Motivation

- Human tracking inspires various applications.

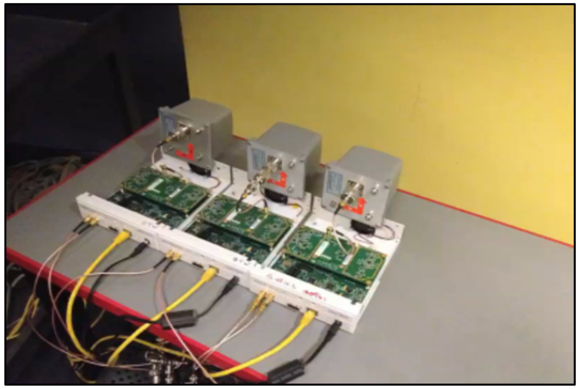
Navigation

Gait Analysis

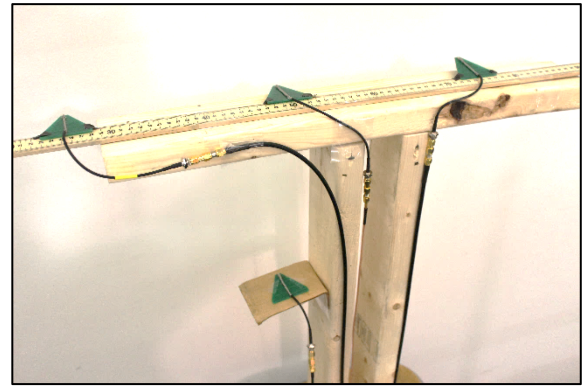
Activity Recognition

- 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.

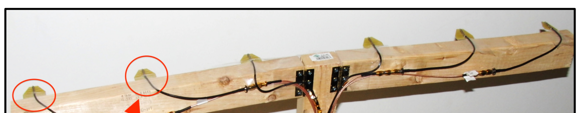
Existing Arts



WiVi, Sigcomm '13

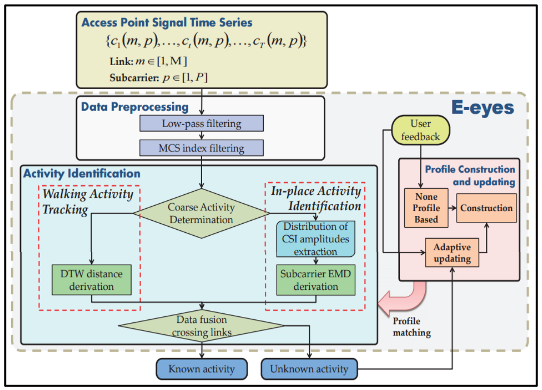


WiTrack, NSDI '14

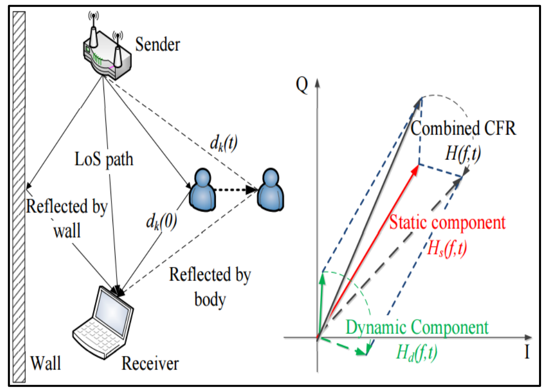


They estimate precise signal parameters, yet rely on specialized hardware!

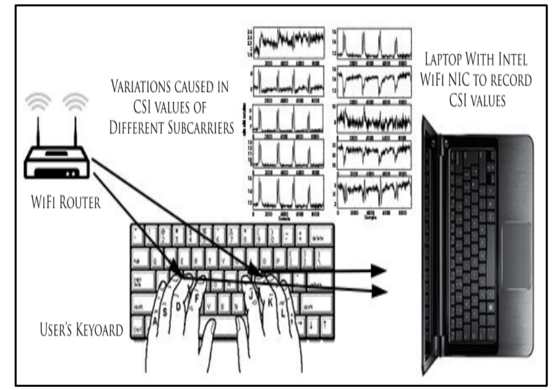
Existing Arts



E-eye, Mobicom '14



CARM, Mobicom '15

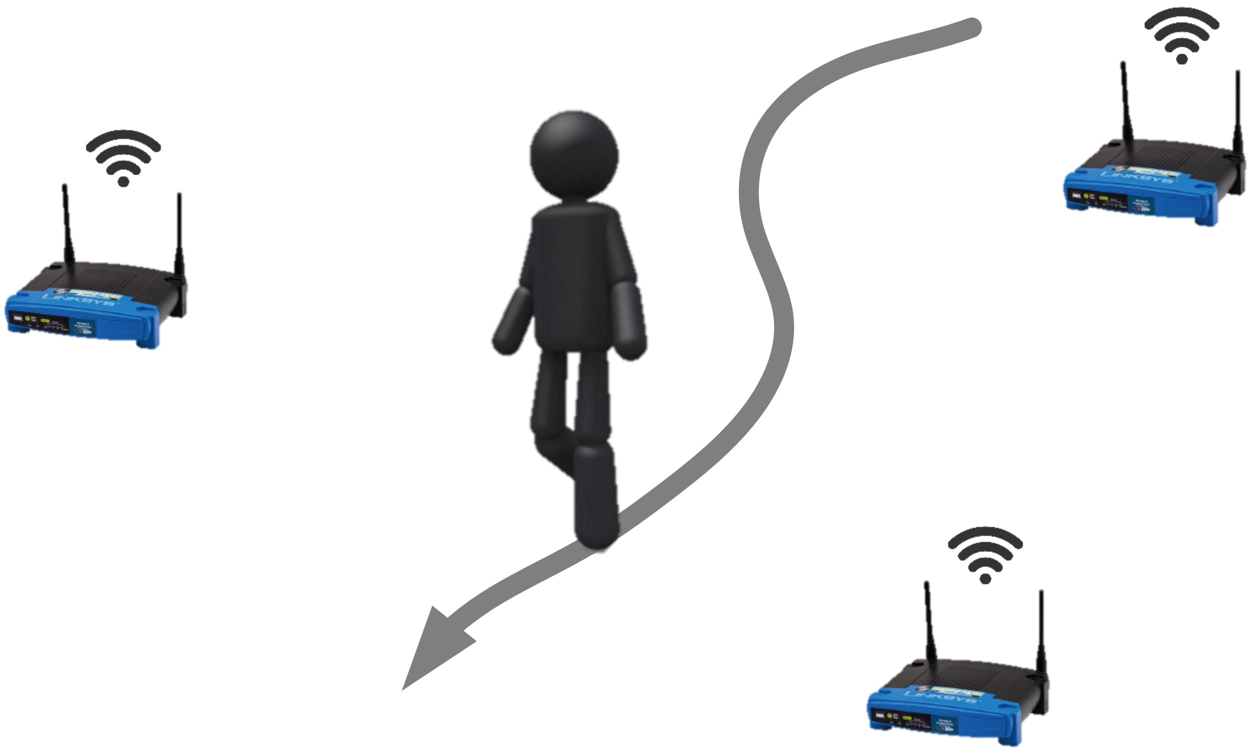


WiKey, Mobicom '15

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

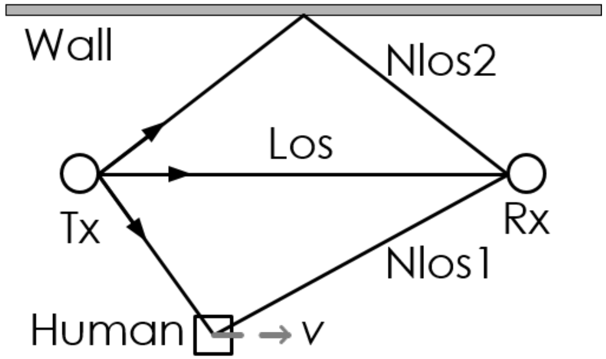
Problem Statement

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

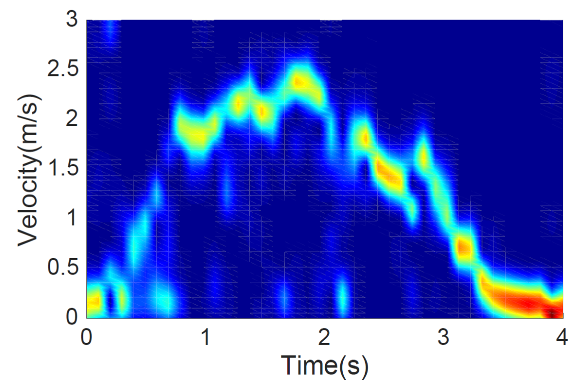


Key Insight

- Modeling interaction between CSI and motion.



Walking Scenario

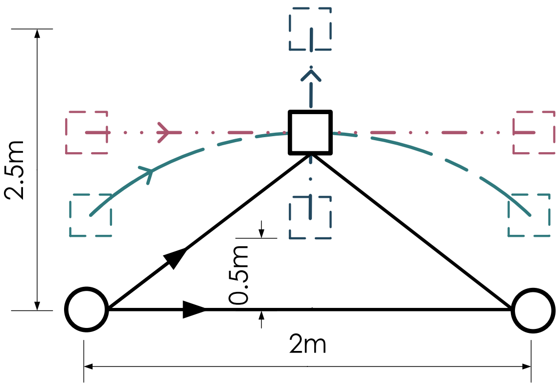


Spectrogram

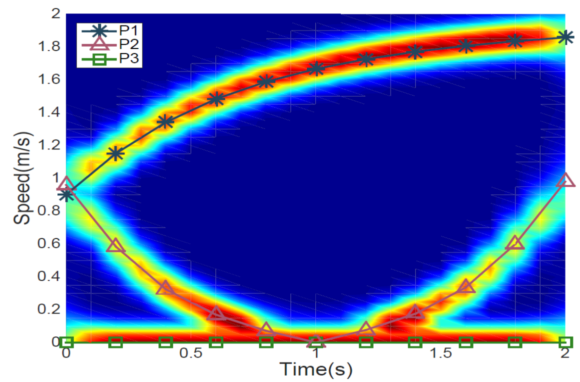
- Human movement causes length change of reflecting path.
- Spectrogram of CSI series shows the frequency shift that corresponds to change rate (PLCR).

CARM, Mobicom '15

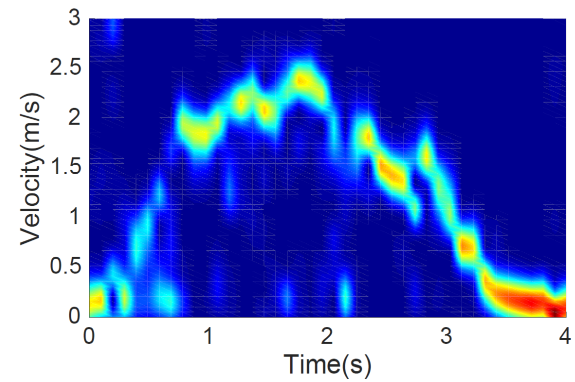
Challenges



Walking Scenarios



Ideal Spectrograms



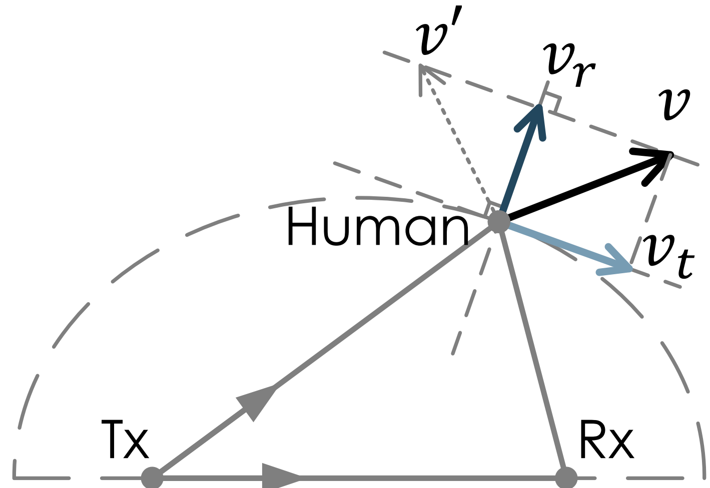
Real Spectrograms

- PLCR only reflects partial velocity

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.

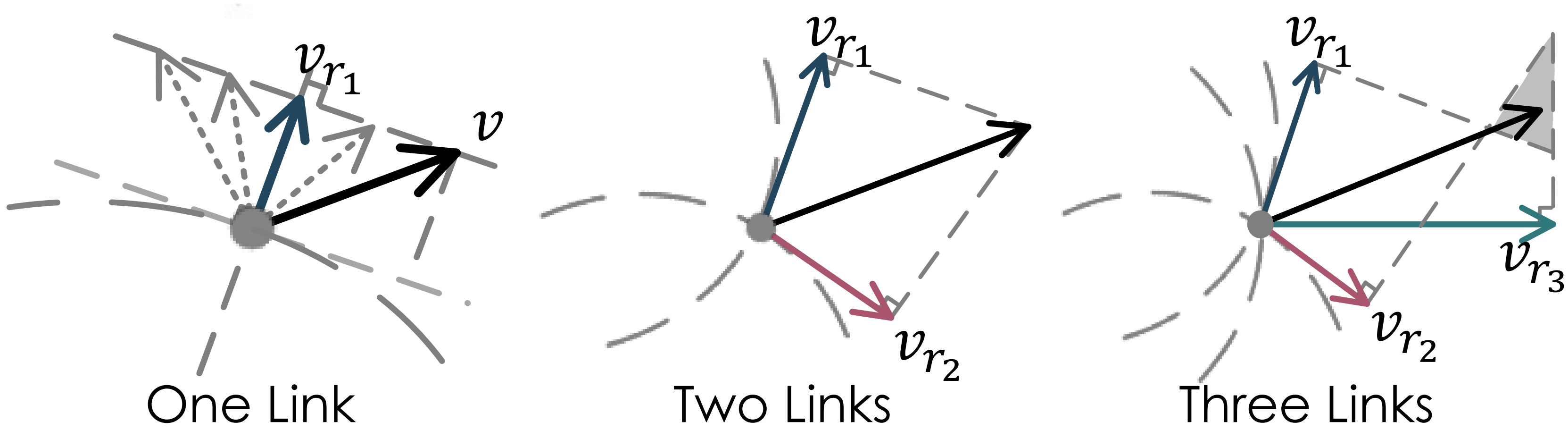


- From view of algebra,
  - Single links yields one

Single Link is insufficient for tracking!

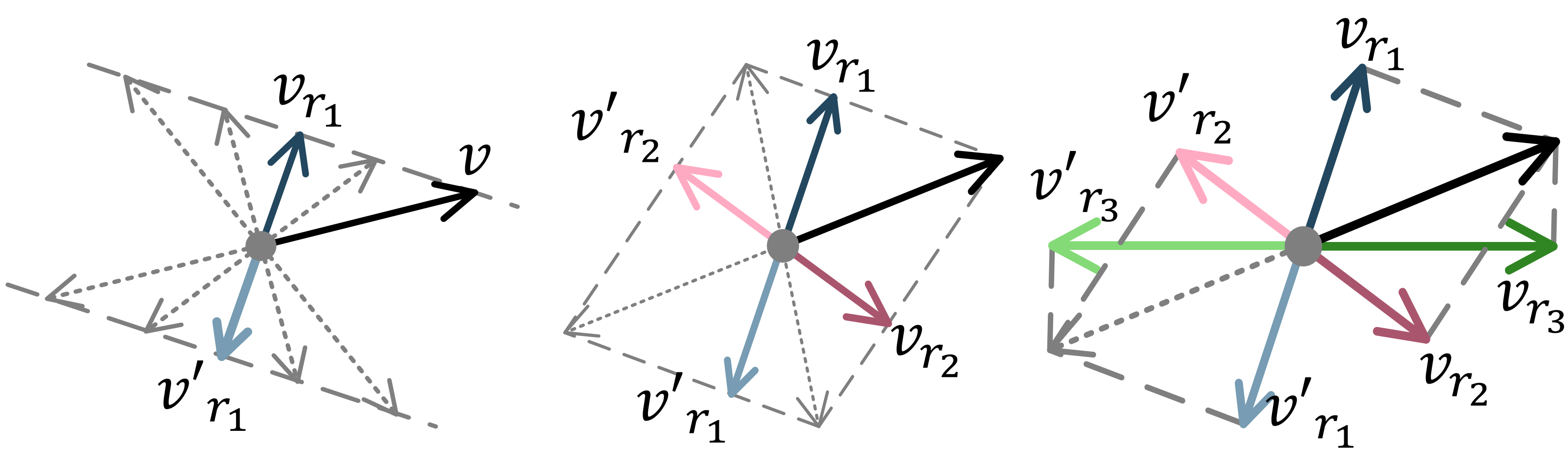
$l = (l_x, l_y)^T$ - Location. a_x, a_y - Coefficients decided by l.

CSI-Mobility Model



- By adding more links, velocity can be determined.
- Solving the equation system of all links.
  - $\mathbf{A}\vec{v} = \vec{r}$
  - Where $\mathbf{A} = \begin{pmatrix} a_x^{(1)} & a_x^{(2)} & \dots & a_x^{(L)} \\ a_y^{(1)} & a_y^{(2)} & \dots & a_y^{(L)} \end{pmatrix}^{\mathrm{T}}$, $\vec{r} = \left(r^{(1)} \quad r^{(2)} \quad \dots \quad r^{(L)}\right)^{\mathrm{T}}$
  - $\vec{v} = \left(\mathbf{A}^{\mathrm{T}}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathrm{T}}\vec{r}$

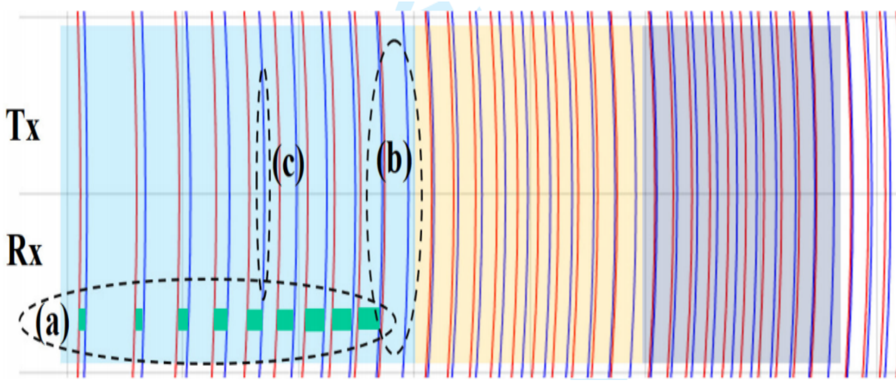
CSI-Mobility Model
Loss of PLCR Signs



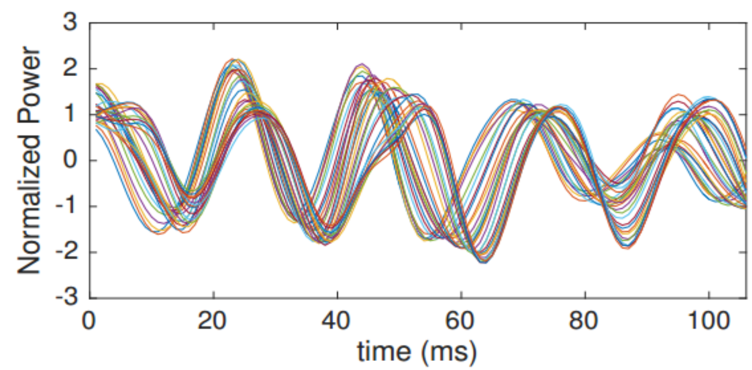
- Two ambiguous solutions always exist, no matter how many links are added.

CSI-Mobility Model
PLCR Signs Identification

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



Geometric relation of two subcarriers



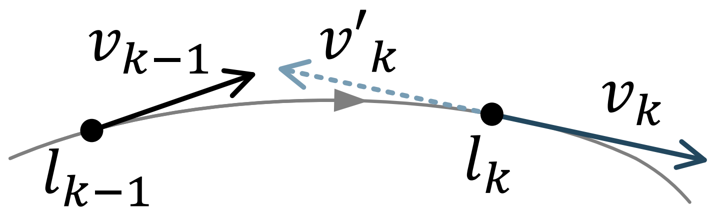
Delayed waveforms of subcarriers

- 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.



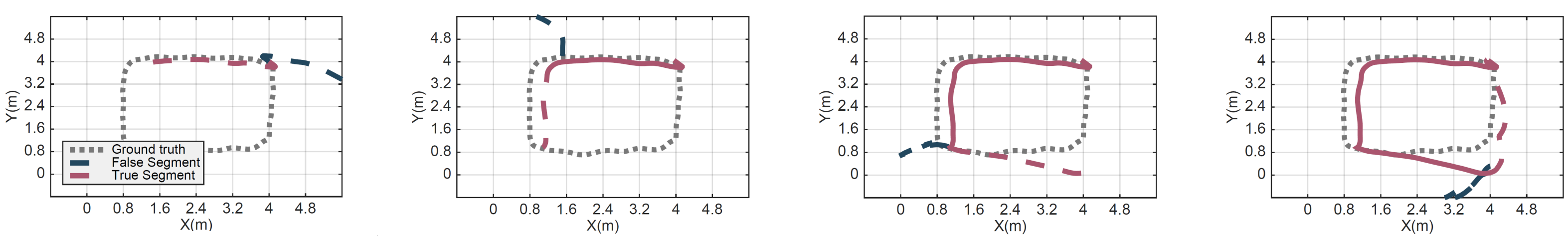
- Solving the equation system at time k.
  - $\mathbf{A}_k \vec{v}_k = \mathbf{R}_k \vec{s}_k$
  - Where $\mathbf{R}_k = \mathrm{diag}\left(|r^{(1)}| \quad |r^{(2)}| \quad \dots \quad |r^{(L)}|\right)^{\mathrm{T}}$, $\vec{s}_k = \left(s_k^{(1)} \quad s_k^{(2)} \quad \dots \quad s_k^{(L)}\right)^{\mathrm{T}}$
  - $\vec{v}_k = \left(\mathbf{A}_k^{\mathrm{T}} \mathbf{A}_k\right)^{-1} \mathbf{A}_k^{\mathrm{T}} R_k \vec{s}_k$
  - $\vec{s}_k = \mathrm{argmin}(\mathrm{err}_{l,k} + \beta \mathrm{err}_{v,k})$
  - $\mathrm{err}_{l,k} = ||\mathbf{A}_k \vec{v}_k - R_k \vec{s}_k||$ is the PLCR fit error.
  - $\mathrm{err}_{v,k} = ||\mathbf{A}_k \vec{v}_k - \mathbf{A}_{k-1} \vec{v}_{k-1}||$ is the velocity deviation error.

CSI-Mobility Model
PLCR Extraction

- Leveraging acceleration constraints of PLCR.
  - $a(t) = \frac{\mathrm{d}}{\mathrm{dt}} r(t) \leq 2 \frac{\mathrm{d}}{\mathrm{dt}} v(t)$
  - 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:
  - $\mathrm{PLCR} = \mathrm{PLCR}(\mathrm{argmax}_{f_1, \ldots, f_T} \sum_{i=1}^{T} W_{i, f_i})$
  - $s.t. |f_i - f_{i-1}| \leq 1; i = 2, \ldots, T$

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.
  - $\vec{l}_{k+1} = \vec{l}_k + \vec{v}_k \Delta t$
- Trace refinement.
  - Reinitiate tracking process at vulnerable moments.

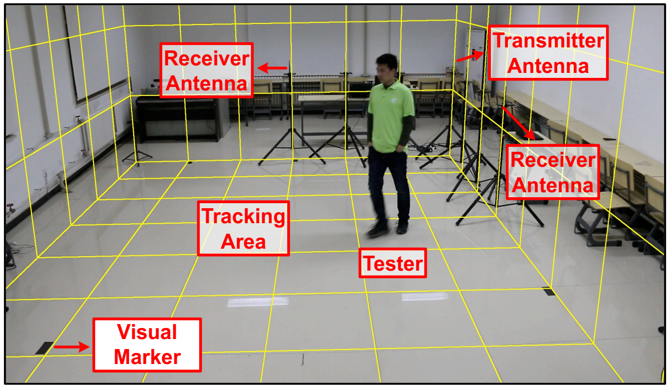


1$^{\text{st}}$ Segment 2$^{\text{nd}}$ Segment 3$^{\text{th}}$ Segment 4$^{\text{th}}$ Segment

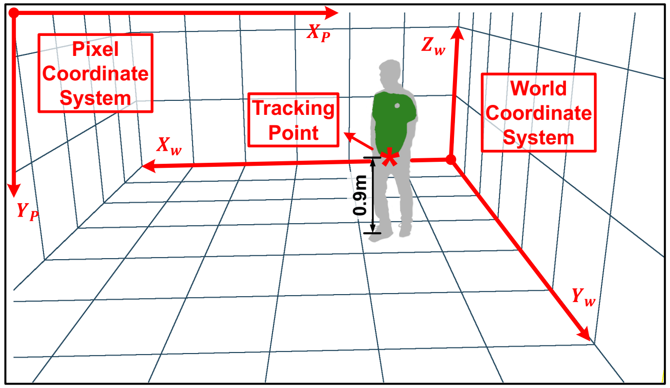
Evaluations & Results

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)

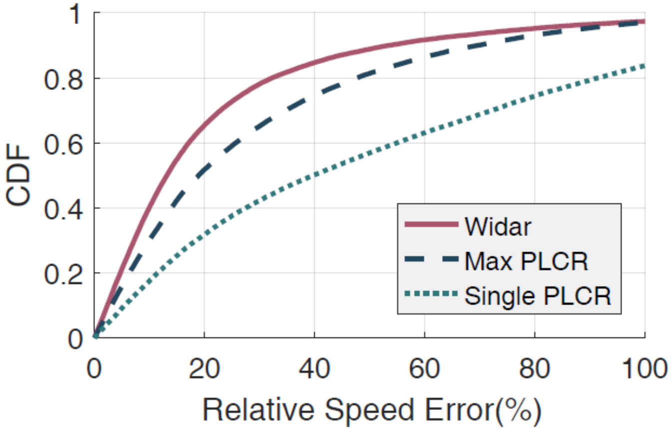


Experimental field

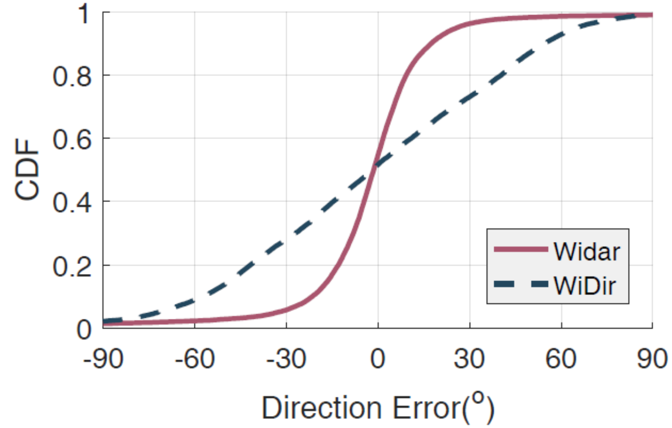


Coordinate transformation

Performance on Velocity



Velocity Magnitude

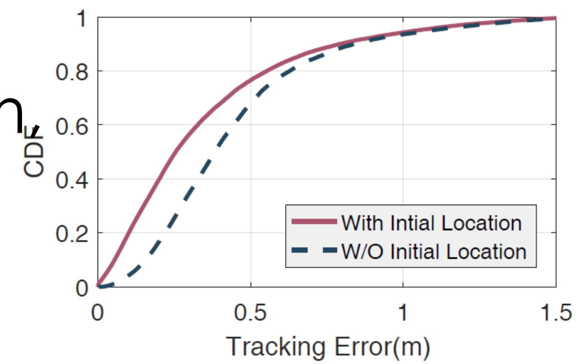


Velocity Direction

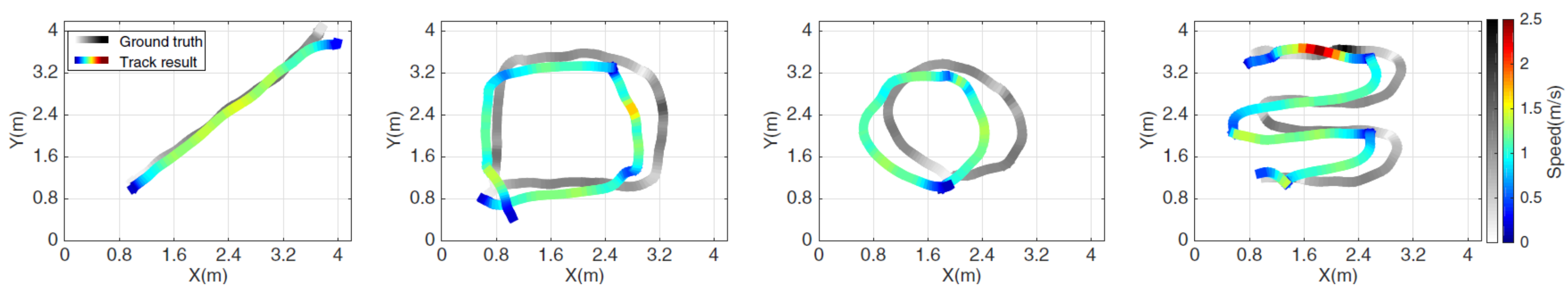
- *Widar* achieves the highest estimation accuracy, with a median error of 13%, for velocity magnitude.
- *Widar* achieves an 80-percentile error of 20° for velocity direction.

Performance on Location

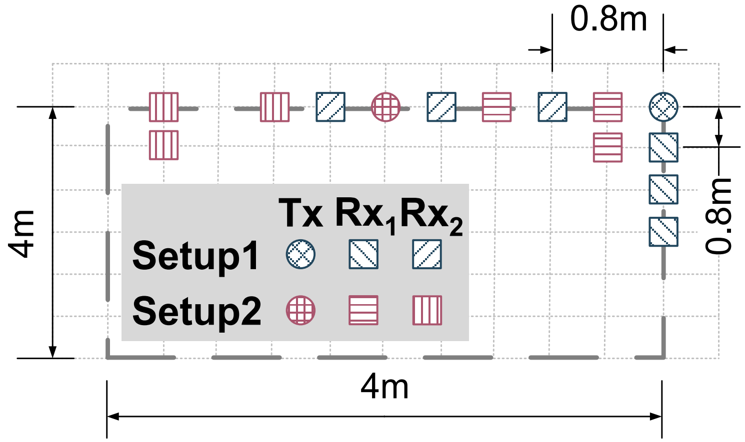
- *Widar* achieves a median tracking error of 25cm and 38cm, with and without initial location, and 90-percentile tracking error of 78cm.
- Decimeter-level Passive Tracking.
- **Tracking examples**



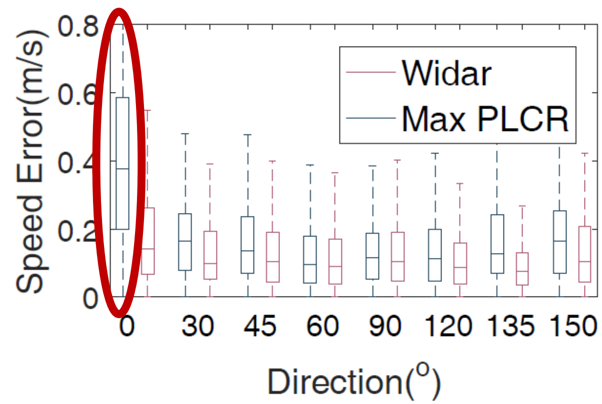
Location Error



Impact of Walking Direction



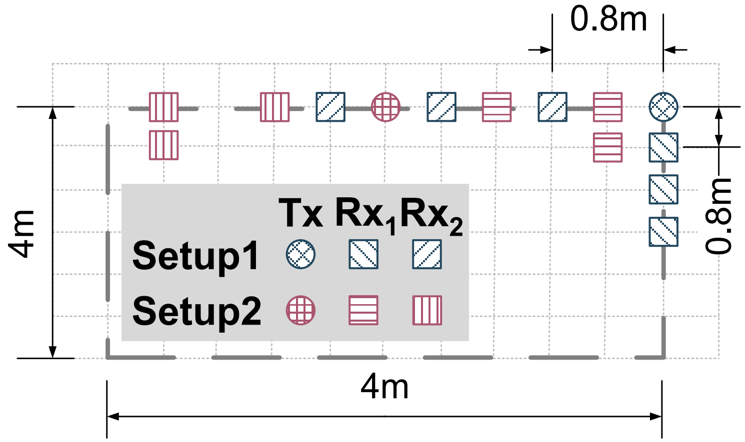
Deployment schemes



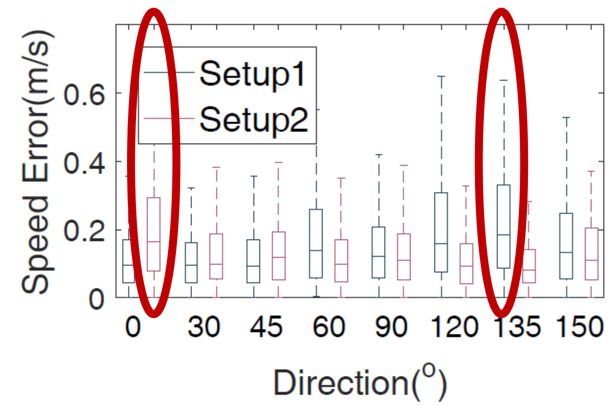
Impact of Direction

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

Impact of Setup



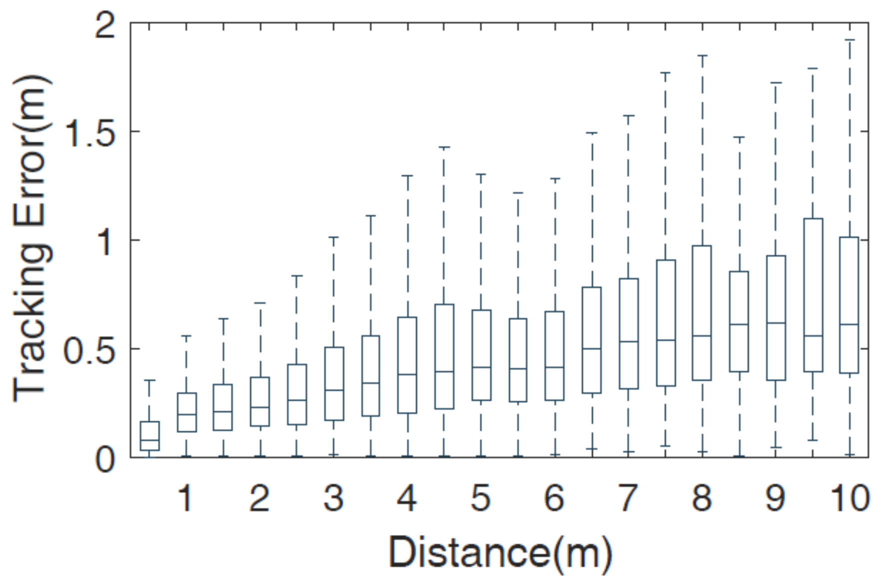
Deployment schemes



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

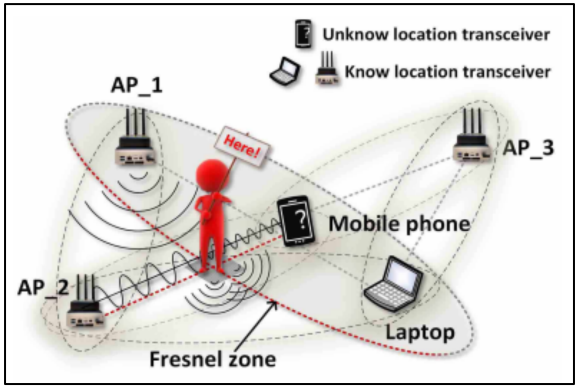


Impact of Distance

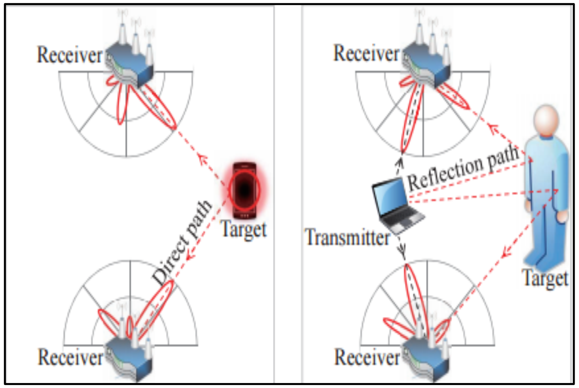
- Due to lack of localization scheme for calibration, tracking errors accumulates at a moderate rate.

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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