清華大學
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Widar2.0

Passive Human Tracking with a Single Wi-Fi Link

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Motivation

- Need for passive localization.

Smart Home

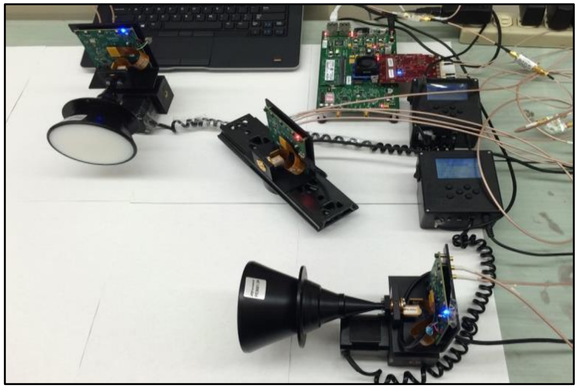
Health Monitoring

Intruder Detection

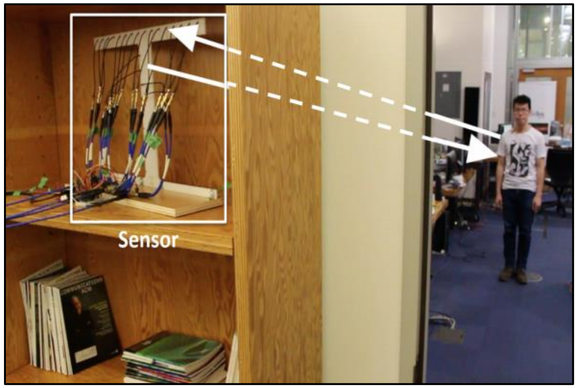
- RF radios VS. Cameras
  - Less privacy concern.
  - Larger surveillance area.
  - More ubiquitous deployment.

Motivation

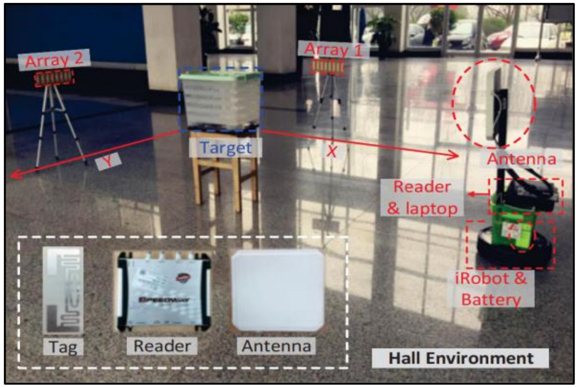
- RF-based tracking thrives with prevail RF devices.



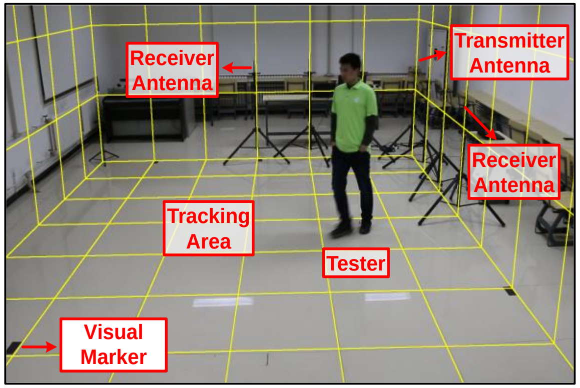
mmWave



FMCW Radar



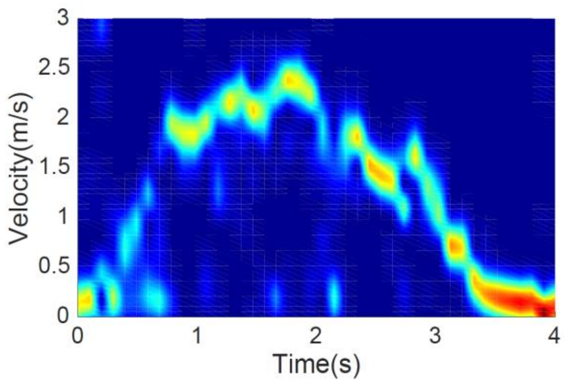
RFID



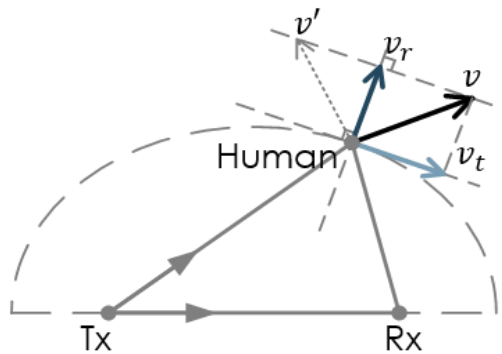
Wi-Fi

Our Early Effort

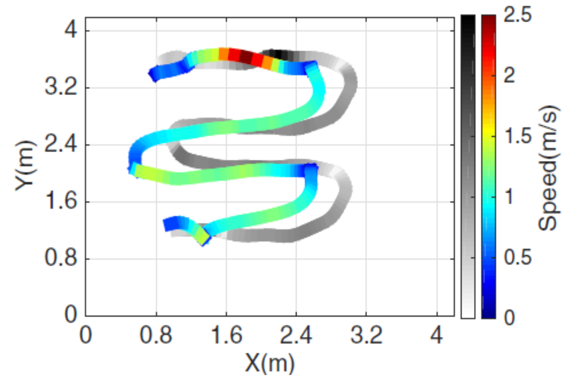
- Widar – Tracking with Doppler Frequency Shifts.



Measurement



Modelling



Localization

- Widar requires,
  - DFS from Multiple links to compute velocity.
  - Trial and error to resolve direction ambiguity.
  - Costly search to spot the initial location.

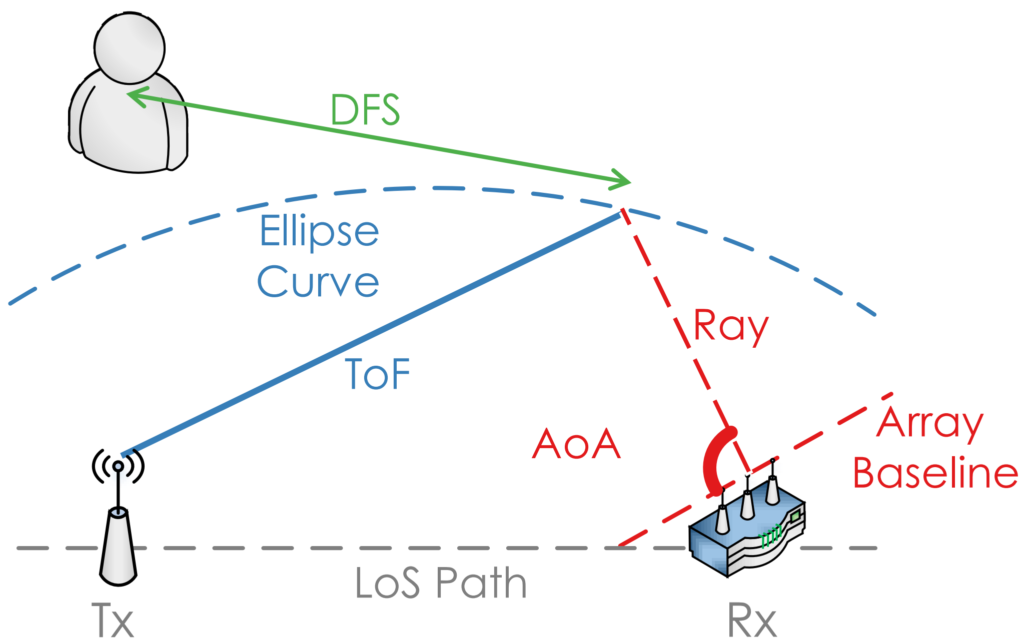
State of the Arts

	WiTrack[1]	WiDeo[2]	Widar[3]	D. Music[4]	IndTrack[5]	LiFS[6]
Technique	FMCW	FD Wi-Fi	Wi-Fi	Wi-Fi	Wi-Fi	Wi-Fi
Parameter	ToF	ToF, AoA	DFS	AoA	AoA, DFS	Attenuation
#Link	(1,1)/2	(1,1)/1	(1,2)/6	(2,2)/4	(1,2)/2	(4,7)/40
#Rx Ant.	1 x 2	4 x 1	6 x 1	3 x 2	3 x 2	-
Range	9 m	10 m	4 m	8 m	6 m	12 m
Accuracy	0.3 m	0.7 m	0.35 m	0.6 m	0.48 m	0.7 m

- Existing approaches either requires,
  - Single link but specialized hardware → less ubiquitous
  - Commercial devices but multiple links → less practical

Key Idea

- Can we achieve both ubiquity and practicality?
  – Yes! Using a single commercial Wi-Fi link.

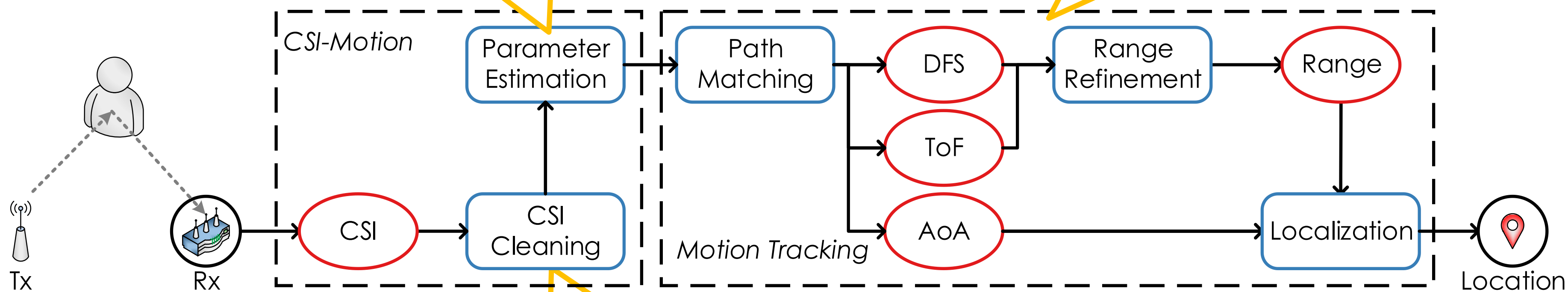


- Widar2.0 – Tracking with ToF, AoA and DFS.

System Overview

C1: How to jointly estimate multipath parameters in CSI?

C3: How to derive locations from un-matched parameters?



C2: How to calibrate CSI phase noises?

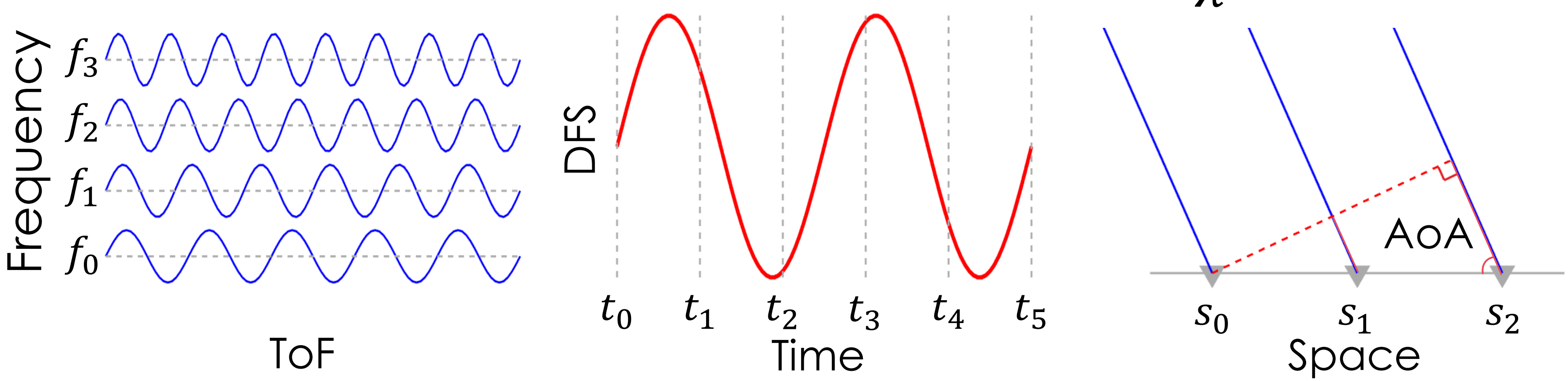
CSI Model

- Due to multipath effect, CSI is modelled as:

$$H(t,f,\boldsymbol{s}) = \sum_{l=1}^{L} P_l(t,f,\boldsymbol{s}) + N(t,f,\boldsymbol{s}) = \sum_{l=1}^{L} \alpha_l(t,f,\boldsymbol{s}) e^{-j2\pi f \tau_l(t,f,\boldsymbol{s})} + N(t,f,s)$$

- The delay of the l-th path $\tau_l(i,j,k)$ is a combination of ToF τ_l, DFS f_{D_l} and AoA $\boldsymbol{\phi}_l = (\cos\phi_l, \sin\phi_l)^{\mathrm{T}}$:

$$\Delta f_j \tau_l \quad + f_{D_l} \Delta t_i \quad - \frac{1}{\lambda} \Delta \boldsymbol{s_k} \cdot \boldsymbol{\phi}_l$$



Parameter Estimation

- The MLE of $\boldsymbol{\theta}_l = (\alpha_l, \tau_l, \phi_l, f_{D_l})$ for all paths,$\boldsymbol{\Theta} = (\boldsymbol{\theta}_l)_{l=1}^{L}$ is formulated as:

$$\Lambda(\Theta; H) = -\sum_{i,j,k} \left| H(i,j,k) - \sum_{l=1}^{L} P_l(i,j,k;\theta_l) \right|^2$$

- L - # of multi path.
  - L should be larger than # of principle multi path.
  - $L = 5$, for sake of computation cost.
- Practical data input.
  - 3 antennas; 30 Subcarriers; 100 Packets (~0.1 s).

SAGE Algorithm

- SAGE algorithm is a general version of EM algorithm.
  - Re-estimate only a subset of parameters in each iteration.
- E – Step.

$$\hat{p}_l(i,j,k;\widehat{\Theta}') = P_l(i,j,k;\hat{\theta}_l') + \beta_l\left(H(i,j,k) - \sum_{l'=1}^{L} P_l(i,j,k;\hat{\theta}_{l'}')\right)$$

- M – Step.

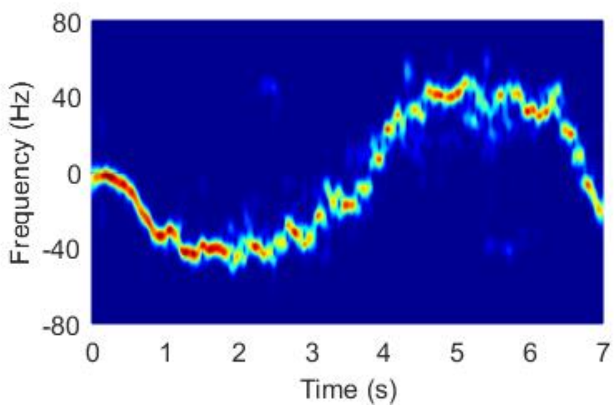
$$\hat{\tau}_l'' = argmax_{\tau}\{|z(\tau, \hat{\phi}_l', \hat{f}_{D_l}'; \hat{p}_l(i,j,k;\widehat{\Theta}')|\}$$
$$\hat{\phi}_l'' = argmax_{\phi}\{|z(\hat{\tau}_l'', \phi, \hat{f}_{D_l}'; \hat{p}_l(i,j,k;\widehat{\Theta}')|\}$$
$$\hat{f}_{D_l}'' = argmax_{f_D}\{|z(\hat{\tau}_l'', \hat{\phi}_l'', f_D; \hat{p}_l(i,j,k;\widehat{\Theta}')|\}$$
$$\hat{\alpha}_l'' = \frac{z(\hat{\tau}_l'', \hat{\phi}_l'', \hat{f}_{D_l}''; \hat{p}_l(i,j,k;\widehat{\Theta}')}{TFA}$$
$$z(\tau, \phi, f_D; P_l) = \sum_{i,j,k} e^{2\pi\Delta f_j \tau_l} e^{2\pi f_c \Delta \boldsymbol{s}_k \cdot \boldsymbol{\phi}_l} e^{-2\pi f_{D_l} \Delta t_i} P_l(i,j,k)$$

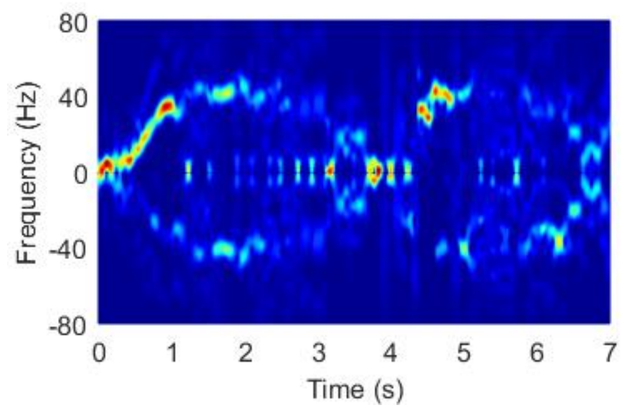
CSI Cleaning

- However, CSI contains not only channel response, but also various unknown phase noises:

$$\widetilde{H}(i,j,k) = H(i,j,k)e^{2\pi\left(\Delta f_j \epsilon_{t_i} + \Delta t_i \epsilon_f\right)}$$

- [SpotFi'15]: The linear regression calibration fails.
  - Weak reflection from human body.





Conjugate Multiplication

- Our Solution: Conjugate multiplication between each antenna and chosen reference antenna.

$$C(i,j,k) = \widetilde{H}(i,j,k) * \widetilde{H}^*(i,j,k_0)$$

- By classifying multipath into static signals P_s $(f_D = 0)$ and dynamic signals P_d $(f_D \neq 0)$, we have:

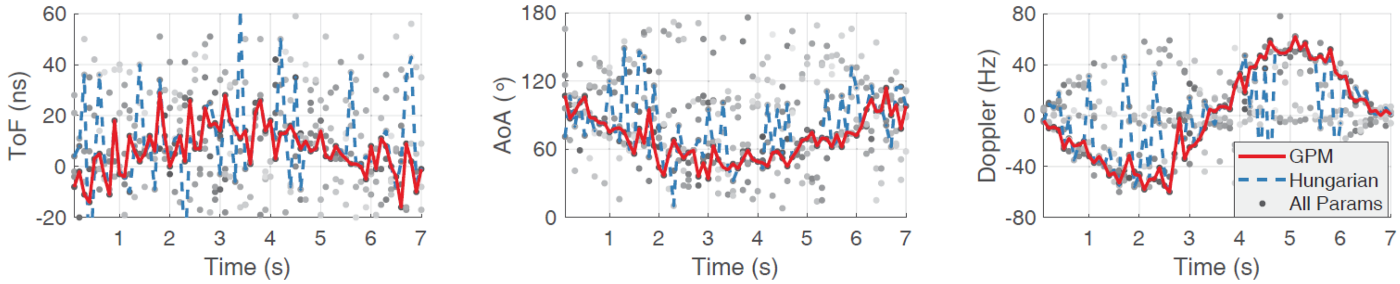
$$\begin{aligned} C(i,j,k) = & \sum_{n_1,n_2 \in P_s} P_{n_1}(i,j,k) P_{n_2}^*(i,j,k_0) \\ & + \sum_{l \in P_d, n \in P_s} \underbrace{P_l(i,j,k) P_n^*(i,j,k_0)}_{\text{Target term}} + P_n(i,j,k) P_l^*(i,j,k_0) \\ & + \sum_{l_1,l_2 \in P_d} P_{l_1}(i,j,k) P_{l_2}^*(i,j,k_0) \end{aligned}$$

- Phase structure is preserved:

$$P_l(i,j,k) P_n^*(i,j,k_0) = \alpha_l \alpha_n^* e^{-2\pi \Delta f_j (\tau_l - \tau_n) - 2\pi f_c \Delta \boldsymbol{s_k} \cdot \boldsymbol{\phi_l} + 2\pi f_{D_l} \Delta t_i}$$

Path Matching

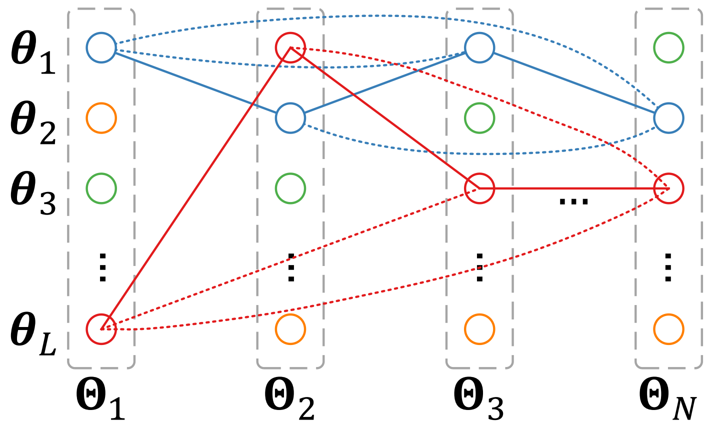
- Multipath parameters are cluttered together.



(a) ToF (b) AoA (c) DFS

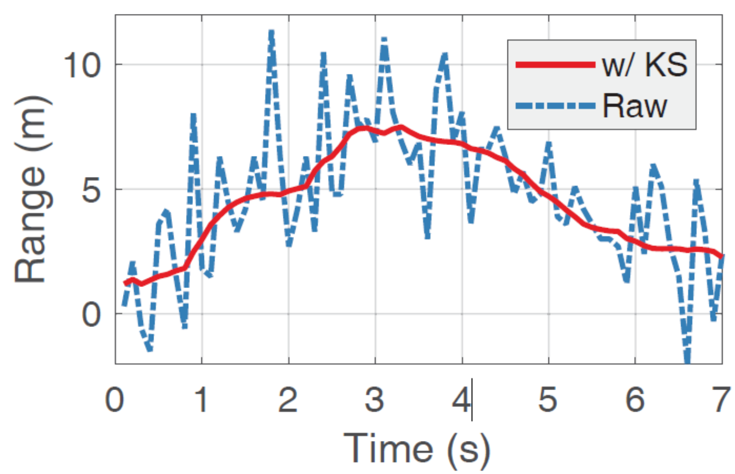
Example of parameter estimates.

- Our approach: Graph-based Path Matching (GPM).



Range Refinement

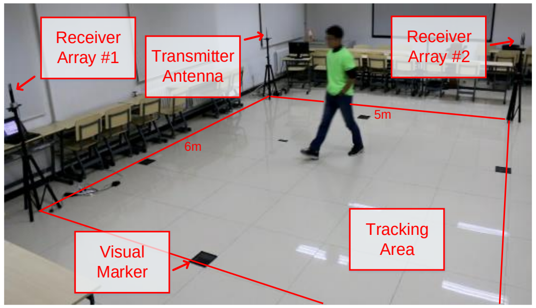
- Range estimation with ToF or DFS
  - ToF → coarse estimate of absolute range.
  - DFS → fine estimate of change rate of range (WiDar).
- We adopt Kalman smoother to refine range with both ToF and DFS.

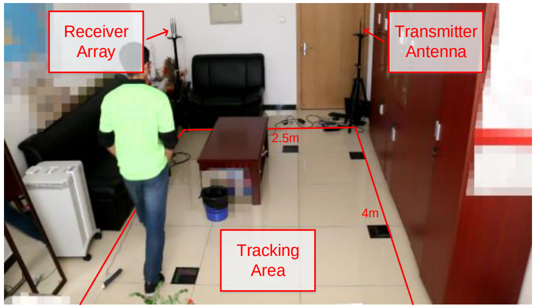


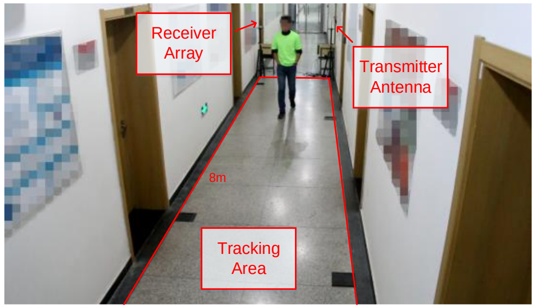
Example of range refinement.

Experiment

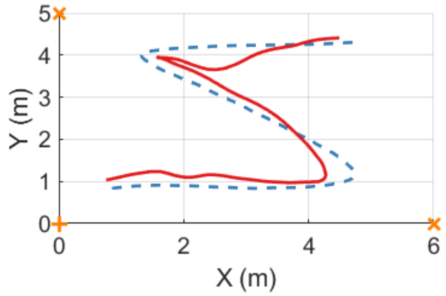
- Implementation
  - Thinkpad laptops with Intel 5300 NIC.
- Setup
  - 3 scenarios: classroom, corridor, office.

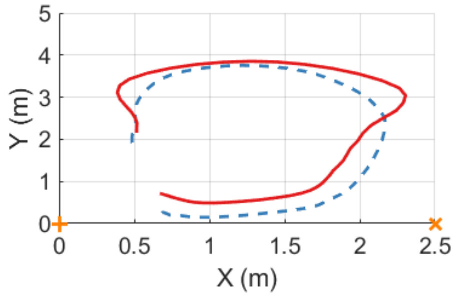


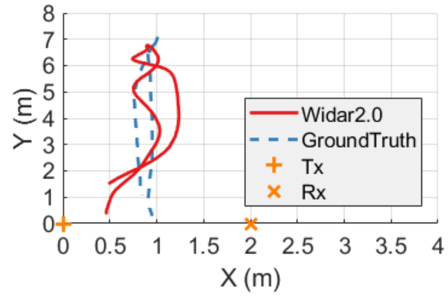




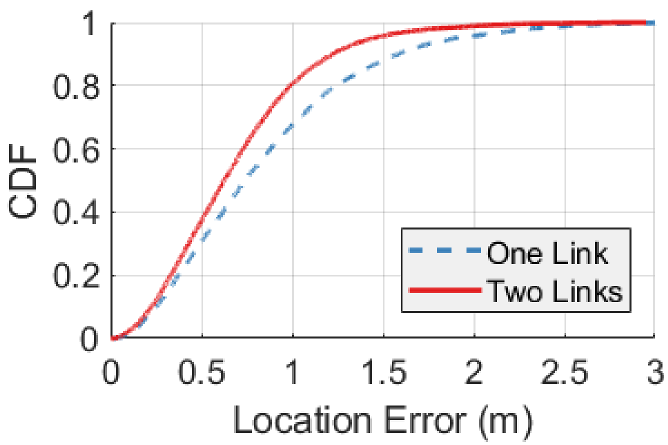
- Tracking samples



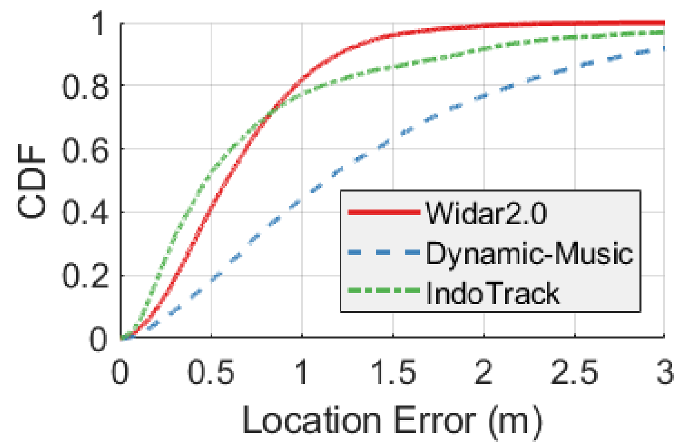




Overall Performance



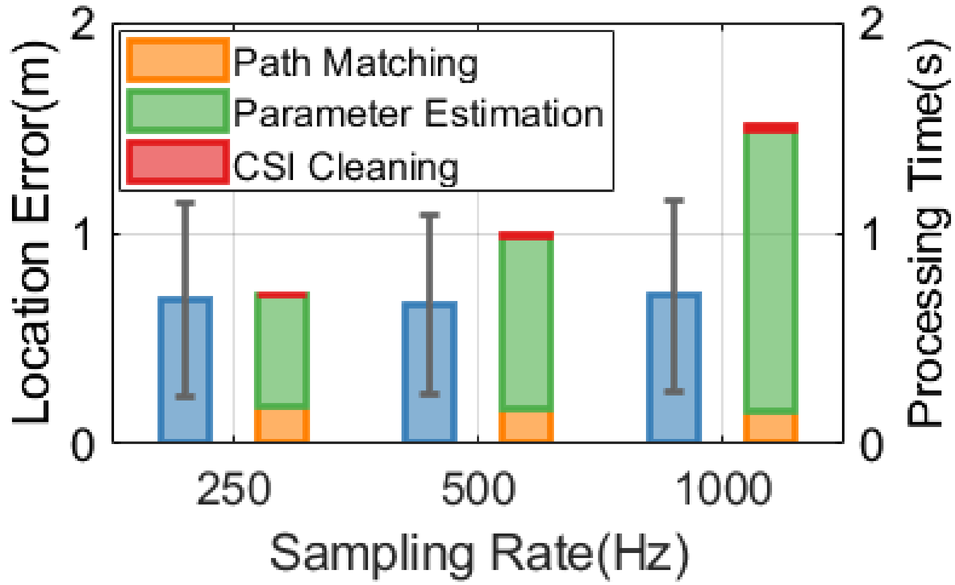
Overall Localization Accuracy



Performance Comparison

- Widar2.0 achieves median tracking errors of 0.75 m and 0.63 m, with one and two links respectively.
- Widar2.0 outperforms [Dynamic-Music'16] , and has a shorter error tail than [IndoTrack'17].

Impact of Sampling Rate



- Widar2.0 works even with 250 pkts/sec.
  - The minimum rate is 200 pkts/sec, for uniqueness of DFS.
- Corresponding per second processing time is 0.7 s.
  - Real-time tracking with Widar2.0.

Conclusion

- From Widar1.0 to Widar2.0
  - From 2 links to 1 single link.
  - A unified model of ToF, AoA and DFS.
  - CSI calibration for weak reflection path.
  - Robust parameter matching and refinement for localization.

- Decimeter-level passive tracking system.
  - Median location error of 75cm with one single link.
  - In a larger 6 m x 5 m area.

Thanks!
Q&A

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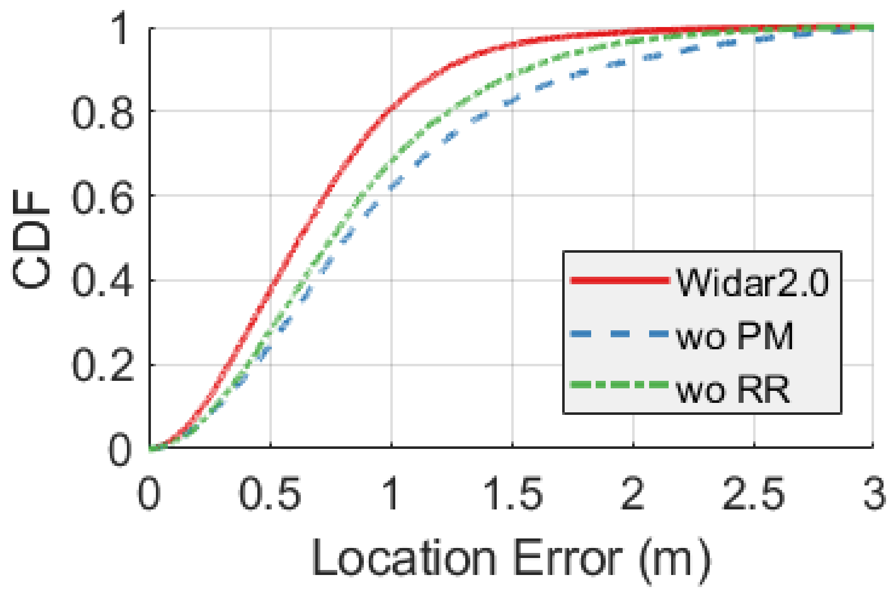
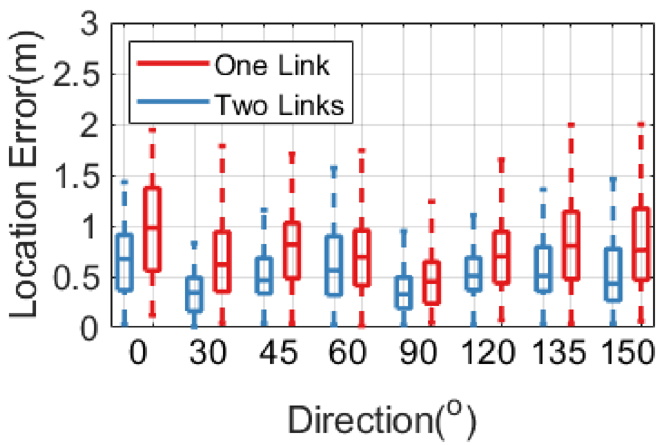
Overall Performance

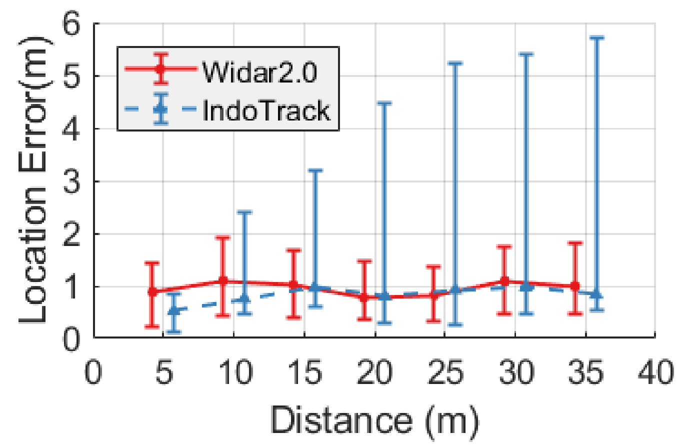


- Contribution of individual modules
  - Path matching – 0.09 m
  - Range refinement – 0.13 m

Impact of Walking Diversity



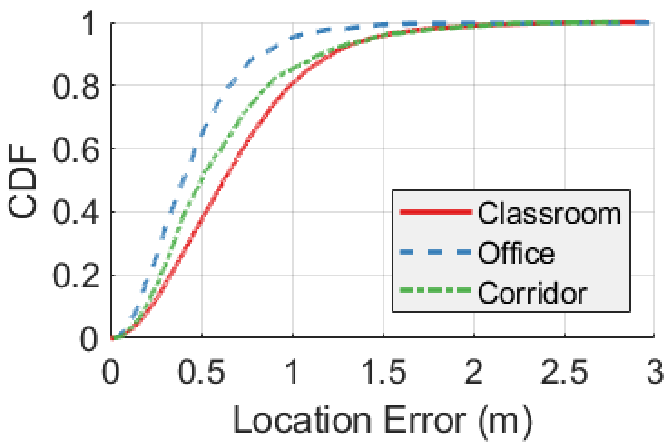
Walking Direction



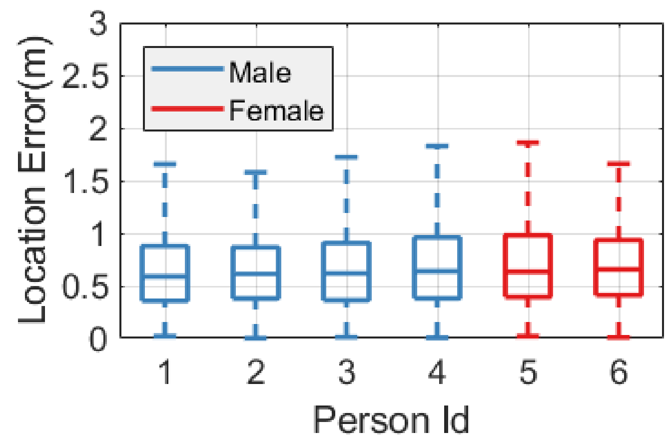
Walking Distance

- Tracking error reduces with more links and larger incident angles between link and walking direction.
- Widar2.0 avoids accumulation error with estimation of absolute ToF.

Impact of Context Diversity



Scenarios



Users

- Tracking error slightly increases with tracking area.
  - Weaker reflection.
  - Smaller DFS.
- Consistent accuracy is achieved with multiple testers.