UNIVERSITY OF MARYLAND

Origin Wireless
A wirelessAI™ company

RIM: RF-based Inertial Measurement

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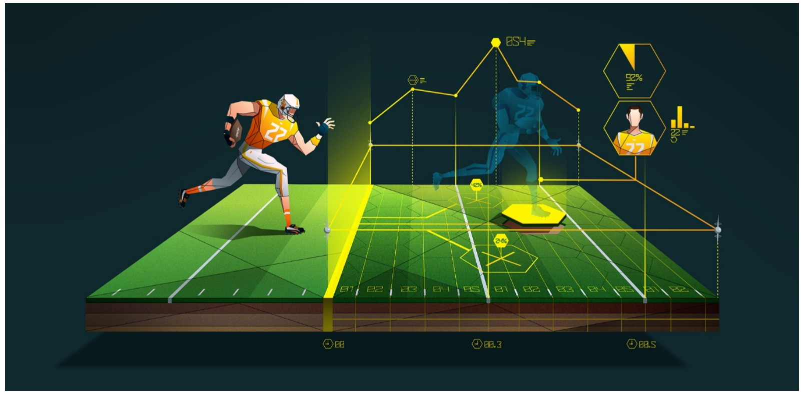
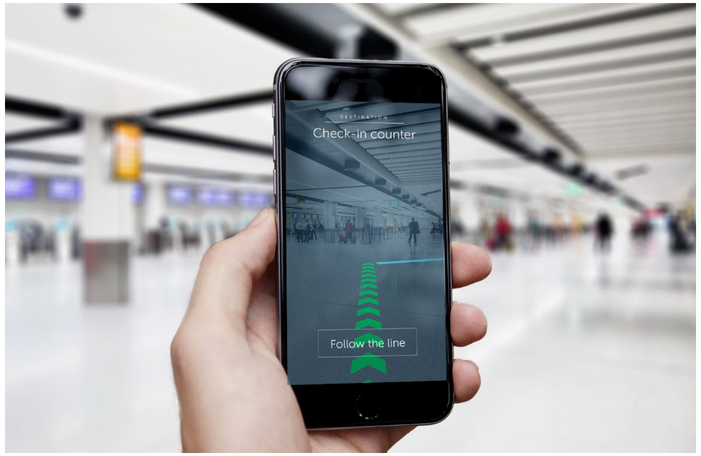
Motion Estimation

Robot Navigation

VR Gaming



Sports Analytics



Mobiles & Wearables

Robots

Drones

Inertial Measurement Unit

Motion Parameters

- Moving Distance
- Heading Direction
- Rotating Angle

IMU

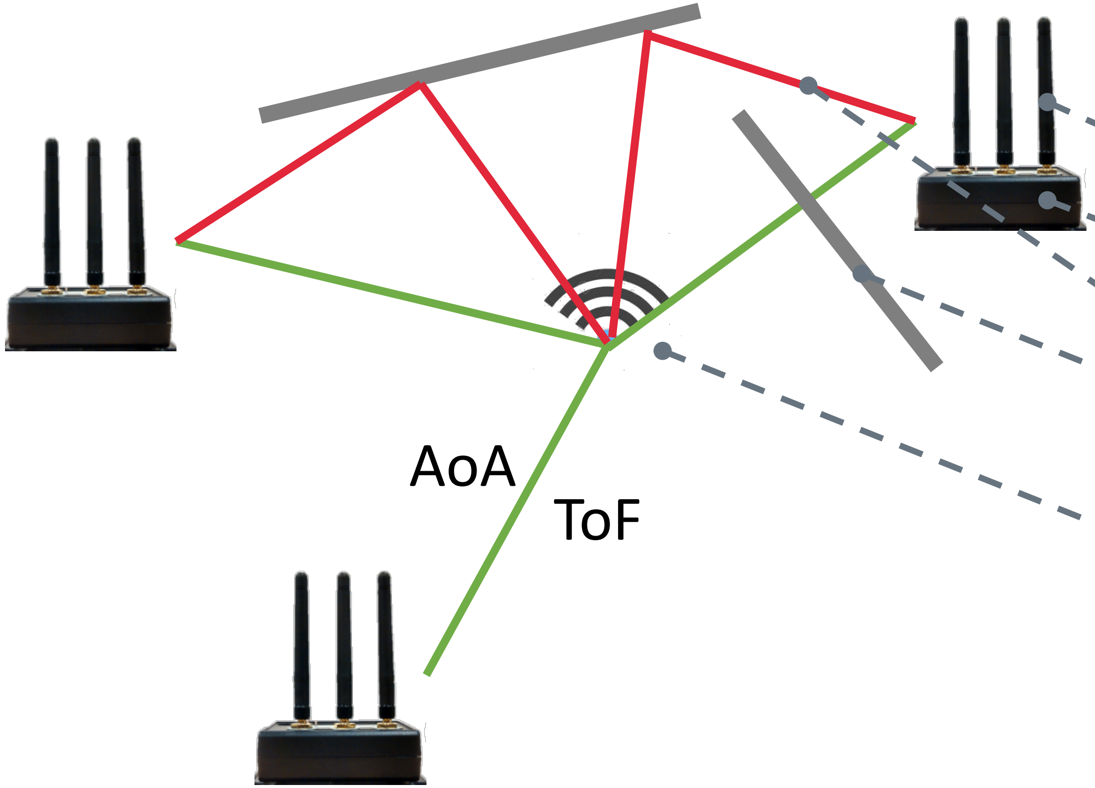
- Accelerometer — Measuring the linear acceleration
- Magnetometer — Reporting the absolute orientation
- Gyroscope — Calculating the angular velocity

$21.74 billion IMU market by 2022!

Significant limitations in precise and robust motion estimation:

- **Accelerometer**: Noisy readings, step counting for distance
- **Gyroscope**: Accumulative errors due to integration
- **Magnetometer**: Environment interference, cannot infer heading direction

Existing Wireless Localization & Tracking



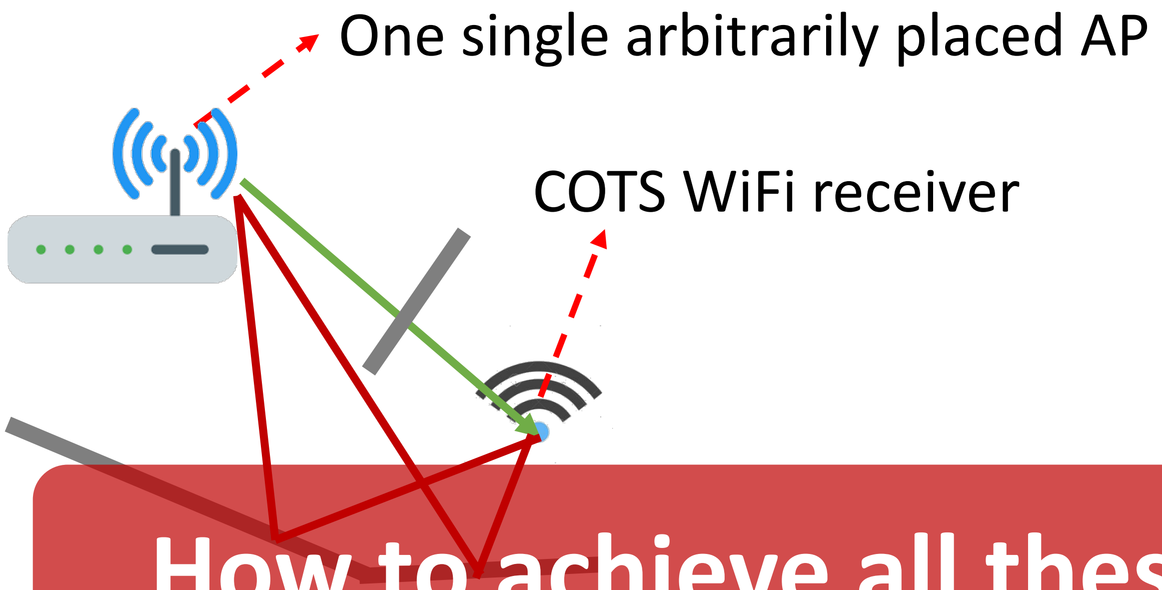
Mainly use geometric channel parameters like AoA, ToF

- Require phased arrays
- Multiple APs with precise location and/or orientation info
- Degenerate or fail in complex multipath scenarios
- Address only locations, but not motion parameters

Multipaths is still enemy!

RIM: RF-based Inertial Measurement

- Turns COTS WiFi radio into precise IMU that measures multiple motion parameters at centimeter accuracy:
  - Moving distance, Heading direction, Rotating angle



- One single arbitrarily placed AP, without knowing its location/orientation
- No additional infrastructure
- Not require large bandwidth or many phased antennas
- No need of a priori calibration
- Works anywhere the AP signal reaches, be there LOS or through multiple walls

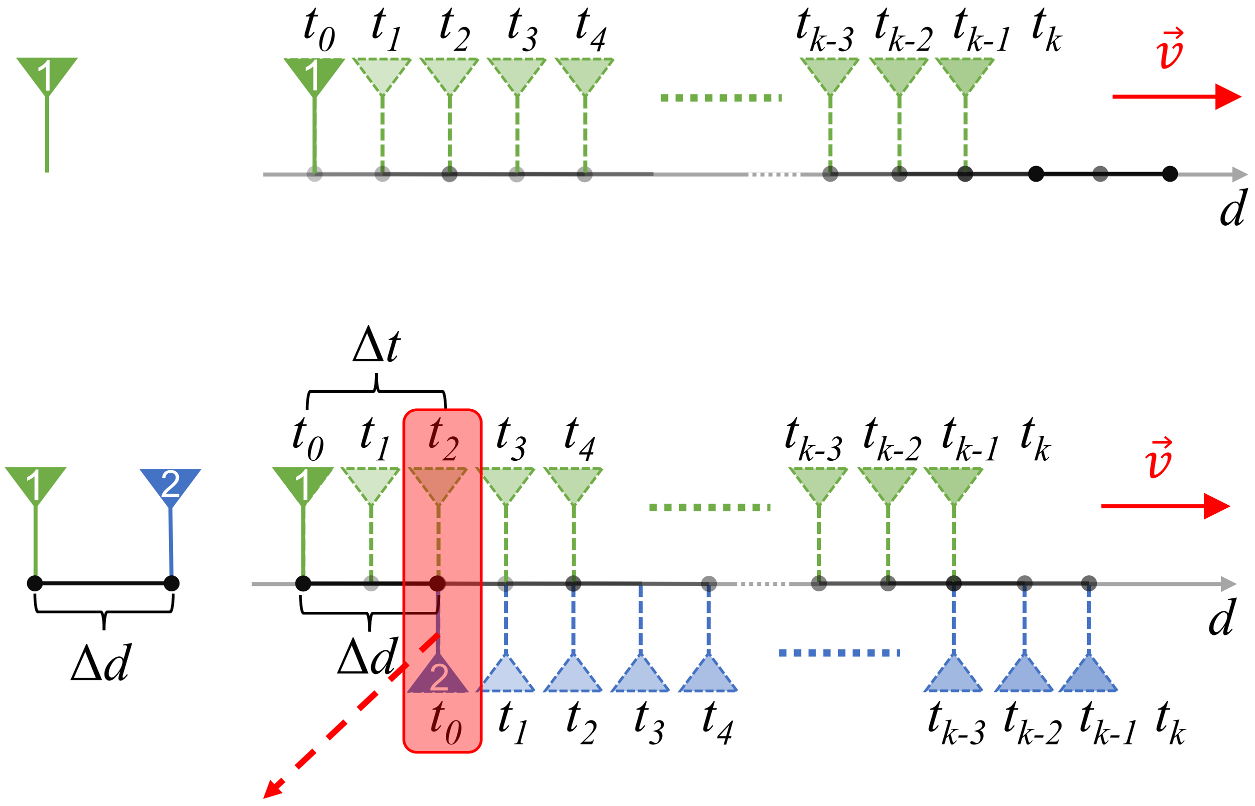
How to achieve all these features in one system?

Spatial-Temporal Virtual Antenna Retracing (STAR)

Multipath Profiles as Virtual Antennas!

1 antenna

1D STAR



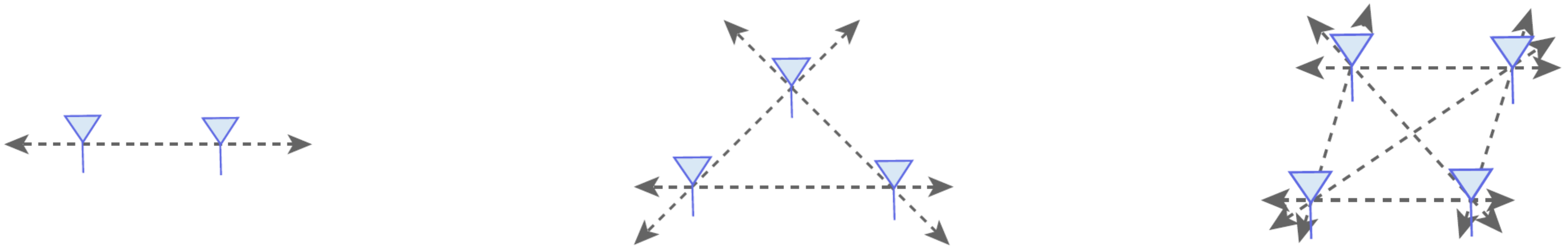
Aligned virtual antennas

$$\hat{v} = \frac{\Delta d}{\Delta t}$$

$$\hat{d} = \int_{t_0}^{t_k} \hat{v}\, dt$$

Moving distance

STAR in 2D space



Line:
2 directions

Triangle:
6 directions

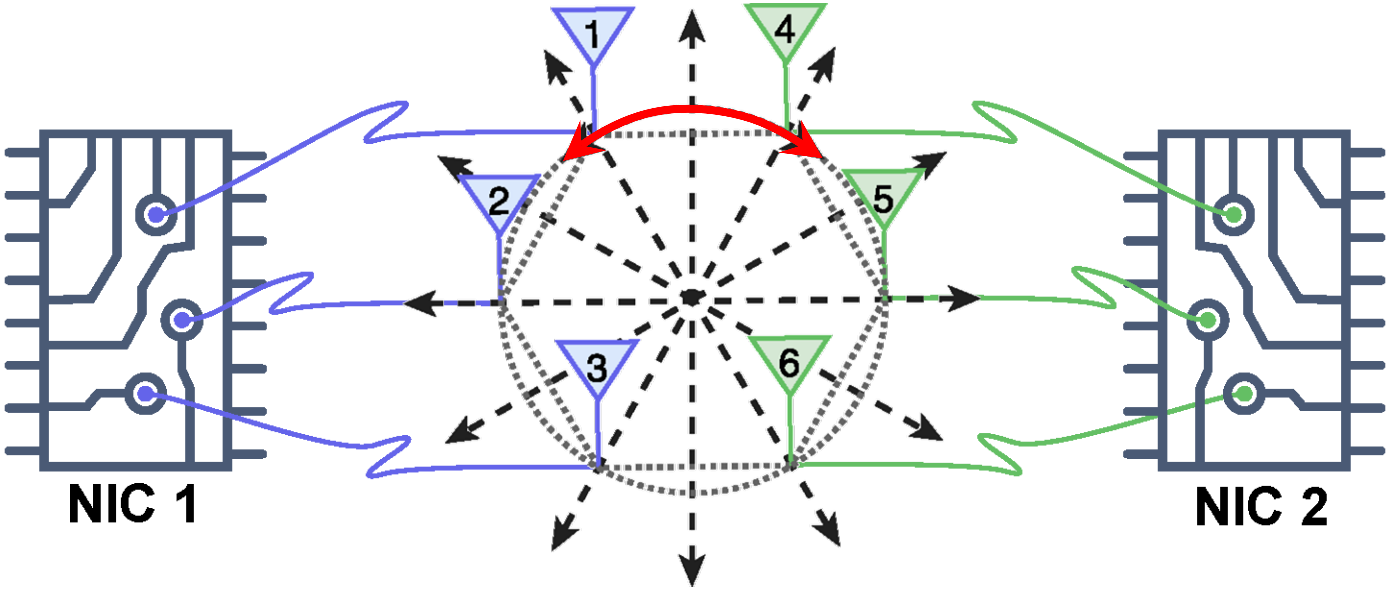
Quadrangle:
12 (6) directions

m antennas → $m*(m-1)/2$ lines → $m*(m-1)$ directions → $2\pi/(m*(m-1))$ orientation resolution

Identifying the aligned antenna pair will give the moving direction

Heading direction ✓

STAR in 2D space



6-element hexagonal array:

- 12 different directions in total and thus an orientation resolution of 30◦
- Build from two COTS WiFi radios without phase synchronization

Translational motion:

- At most three aligned pairs

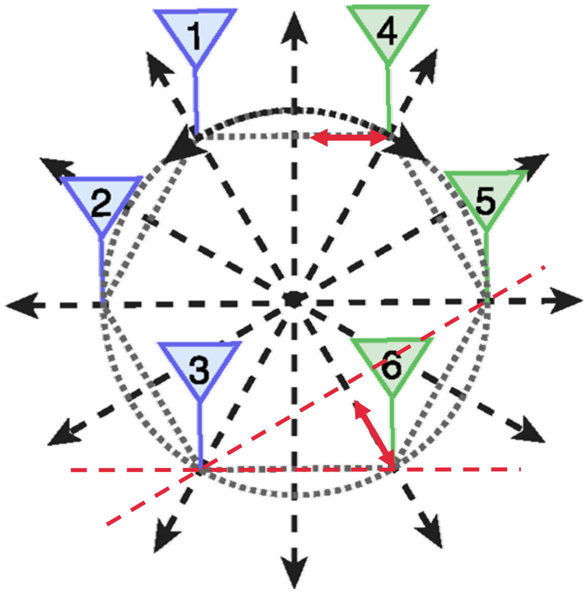
Rotational motion:

- All adjacent pairs will be aligned

Rotating angle ✓

Super-Resolution Virtual Antenna Alignment

How to accurately pinpoint the space-time point that two virtual antennas are aligned with each other, at sub-centimeter resolution?



$\Delta d = \lambda/2$

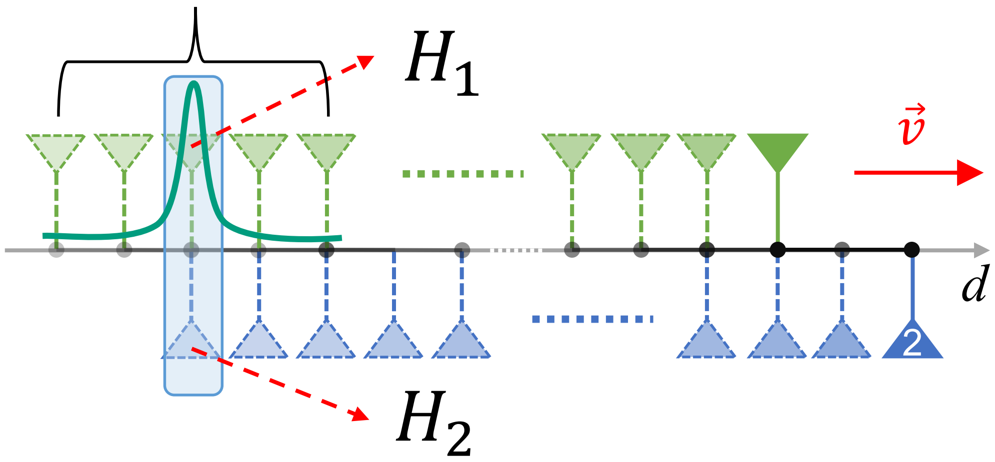
e.g., 1cm error = ~ 50% error in speed
= 30◦ heading error = 22◦ rotation error

Time Reversal Resonating Strength

Virtual Massive Antennas

Time Reversal Resonating Strength (TRRS)

- **Time-Reversal Focusing Effect**: The received CSI, when combined with its time-reversed and conjugated counterpart, will add coherently at the intended location but incoherently at any unintended location, creating a spatial focusing effect



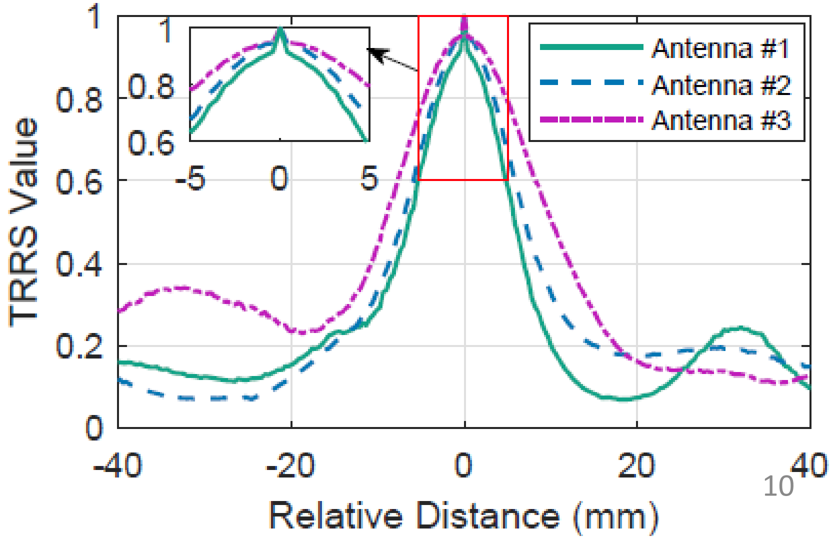
TRRS

$$\kappa(\mathbf{h}_1, \mathbf{h}_2) = \frac{\left(\max_i \left|(\mathbf{h}_1 * \mathbf{g}_2)[i]\right|\right)^2}{\langle \mathbf{h}_1, \mathbf{h}_1 \rangle \langle \mathbf{g}_2, \mathbf{g}_2 \rangle}$$ (CIR)

$$\kappa(H_1, H_2) = \frac{|H_1^{\mathrm{H}} H_2|^2}{\langle H_1, H_1 \rangle \langle H_2, H_2 \rangle}$$ (CFR)

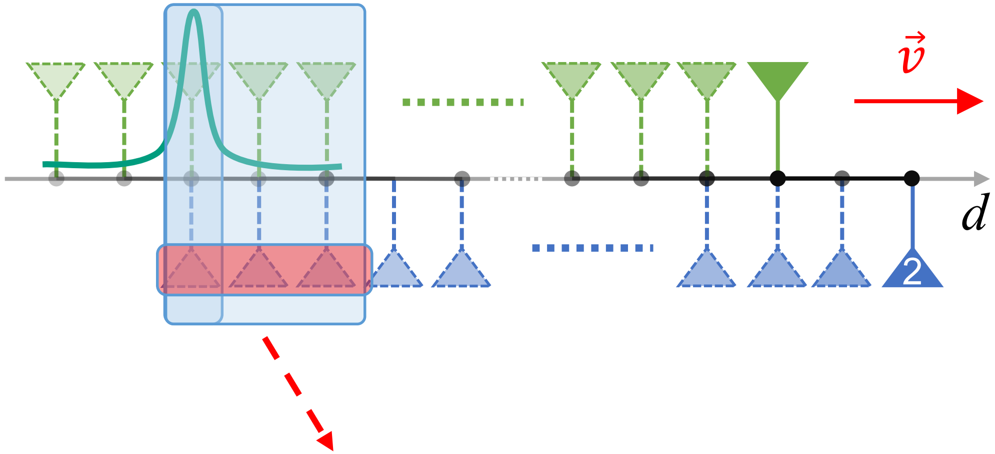
STAR Resolution

- The peak value as high as possible
- The peak width as narrow as possible
- The above two properties as robust as possible



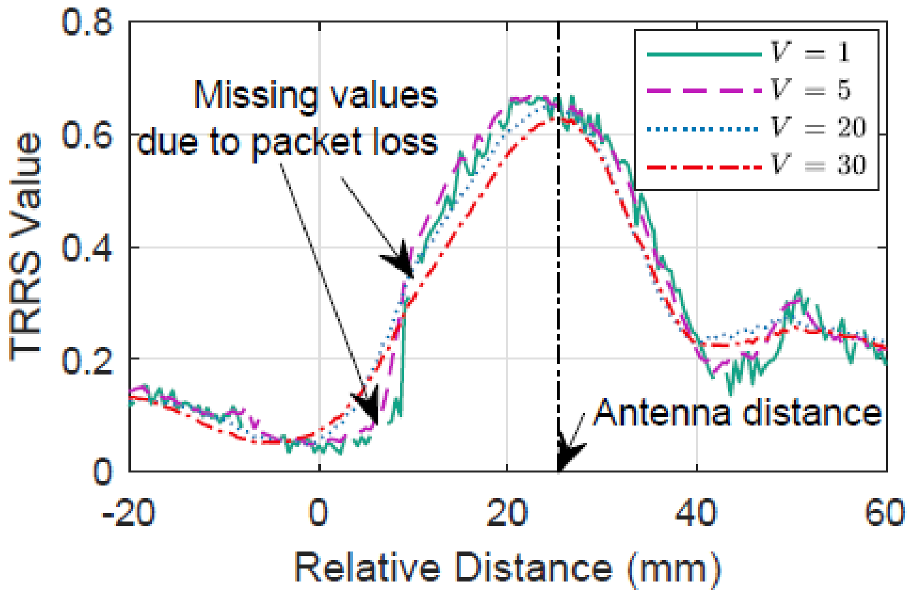
Virtual Massive Antennas

- Overcome distortions in TRRS: Leveraging consecutive multipath profiles as massive virtual antennas



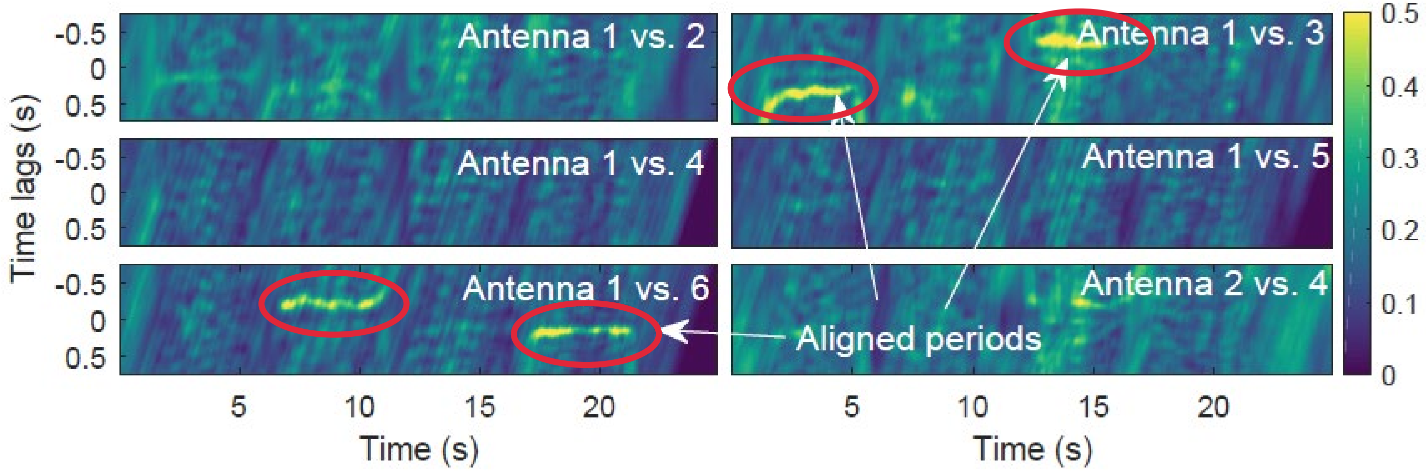
V virtual antennas

$$\kappa\left(P_i(t_i), P_j(t_j)\right) = \frac{1}{V}\sum_{k=-V/2}^{V/2} \bar{\kappa}\left(H_i(t_i+k), H_j(t_j+k)\right)$$

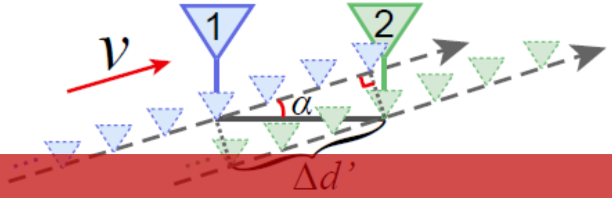


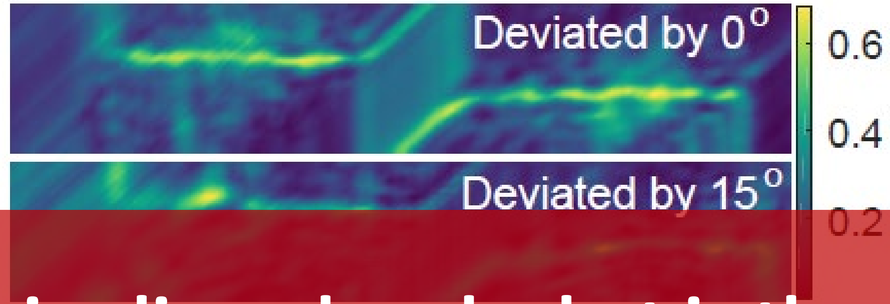
TRRS Matrix

Normal retracing



Deviated retracing





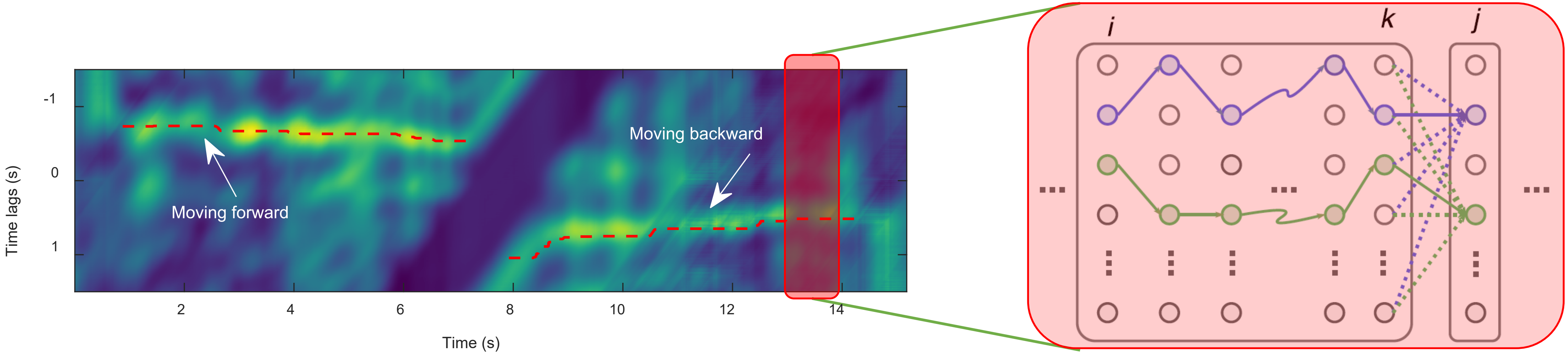
Which antenna pair(s) is aligned and what is the alignment delay?

Noticeable TRRS peaks still exist, albeit weaker:

- Focus on relative TRRS peaks within a window instead of the absolute values

Tracking Alignment Delay

- Continuously track alignment delay via Dynamic Programming



$$S(\boldsymbol{q}_i \rightsquigarrow q_{jn}) = \max_{l \in [-W,W]} \{S(\boldsymbol{q}_i \rightsquigarrow q_{kl}) + S(q_{kl} \rightsquigarrow q_{jn})\}$$

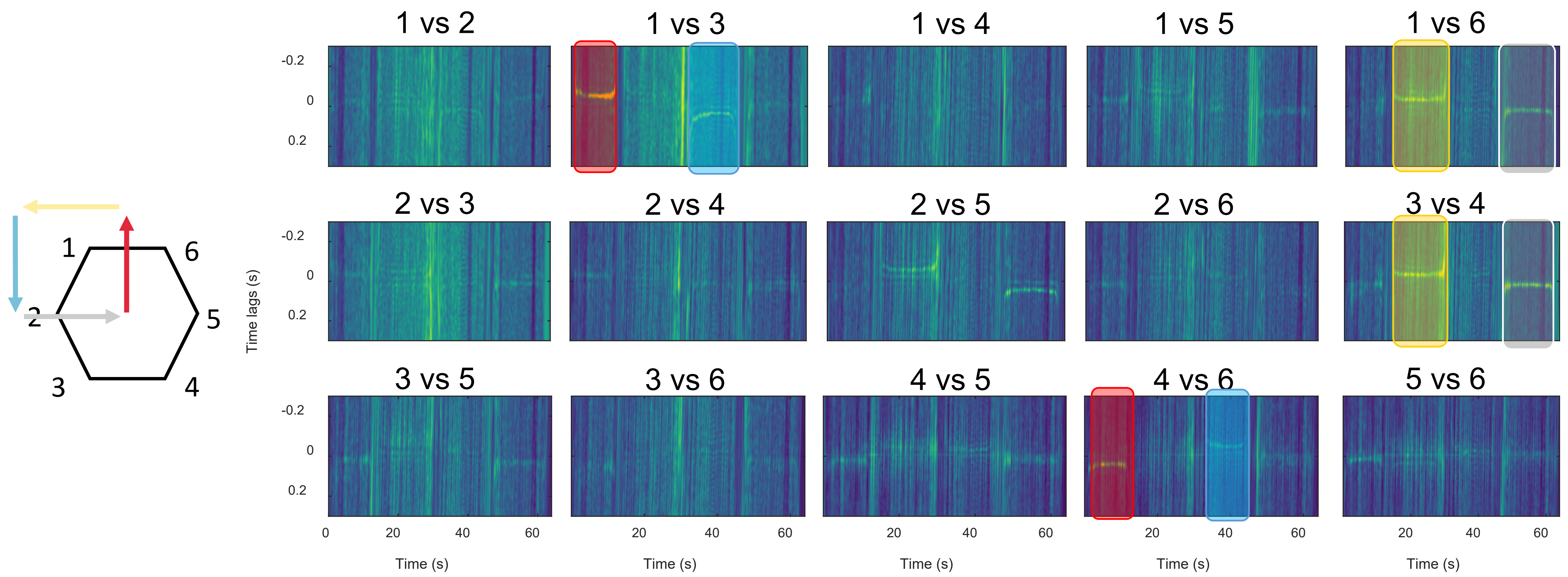
$$S(q_{kl} \rightsquigarrow q_{jn}) = e_{kl} + e_{jn} + \omega C(q_{kl}, q_{jn})$$

Peak value (e_{jn})

(negative) Cost function ($\omega C(q_{kl}, q_{jn})$)

$$n^\star = \arg\max_{n \in [-W,W]} \{S(\boldsymbol{q}_i \rightsquigarrow q_{jn})\}$$

Detecting Aligned Pairs



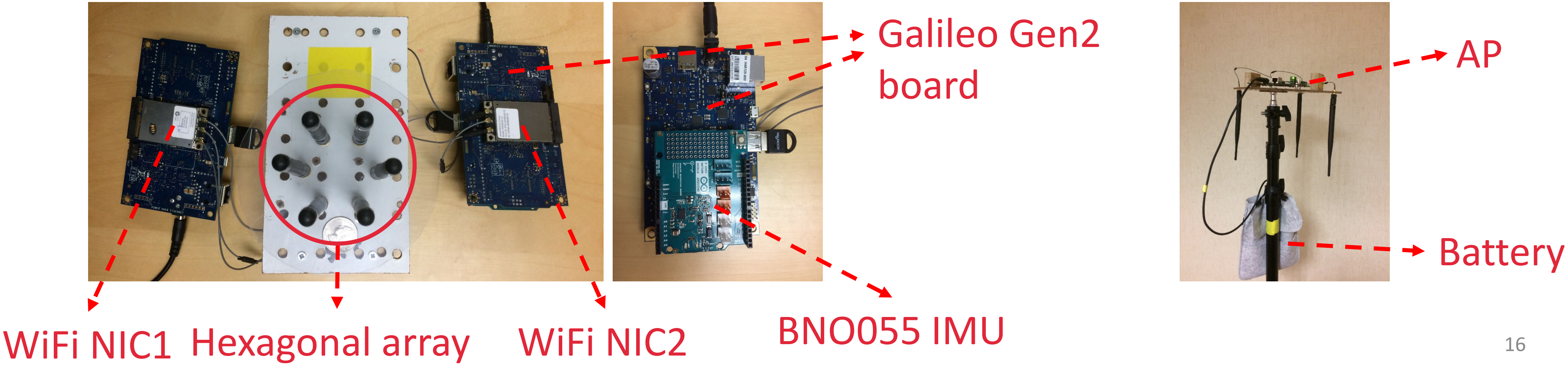
- Detect the top two aligned pairs by TRRS peaks, continuity and smoothness of the peak trace, and the orientations they indicate

Putting It All Together

- Suppose the *i*th and *j*th antennas are detected to be aligned at time *t*, with a separation distance of Δd_{ij} and an alignment delay of $\Delta l_{ij}(t)$:
  - Moving distance: $d(t) = \int_0^t v(\tau)d\tau = \int_0^t \frac{\Delta d_{ij}}{\Delta l_{ij}(\tau)} d\tau$
  - Heading direction: $\theta = \begin{cases} antenna\ i \rightarrow antenna\ j, if\ \Delta l_{ij}(t) \geq 0 \\ antenna\ j \rightarrow antenna\ i, otherwise \end{cases}$
  - Rotating angle: $\Delta\theta = \begin{cases} \frac{R}{r}, if\ rotation\ detected \\ 0, otherwise \end{cases}$

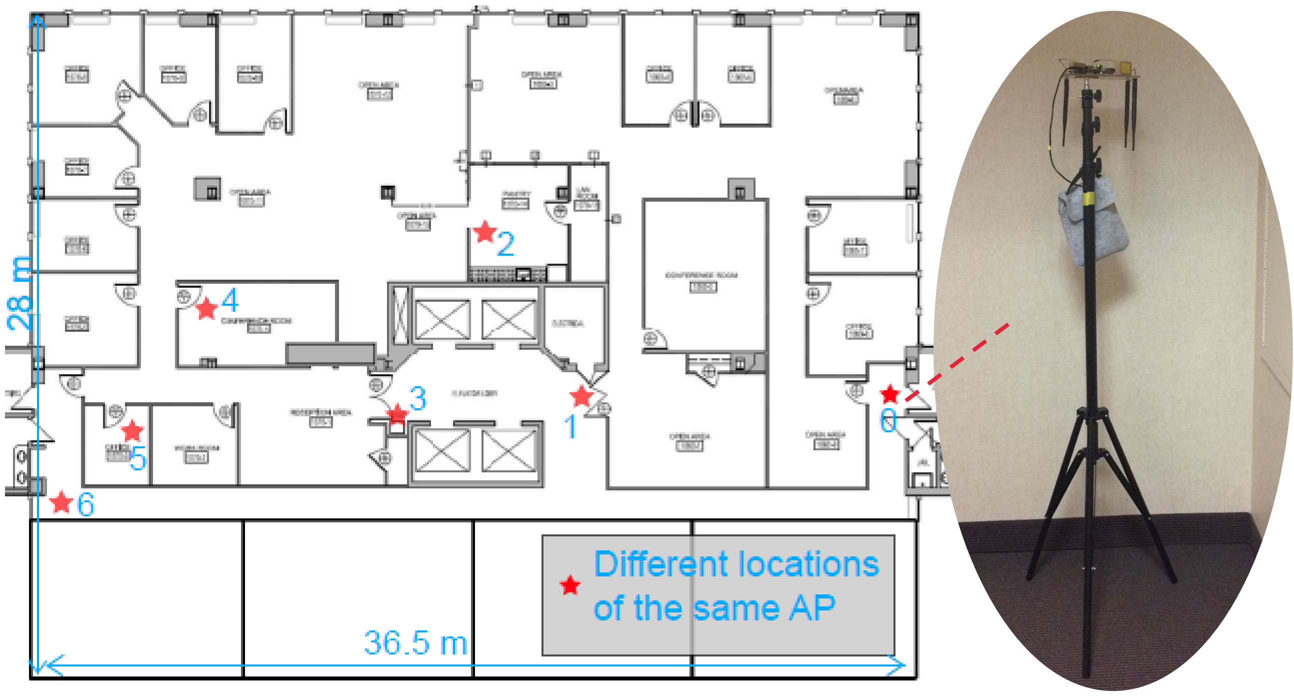
Implementation

- Qualcomm Atheros 9k series chipset
- Running on Intel Galileo Gen2 board (built with an IMU)
- Antennas are spaced at a half wavelength distance (2.58 cm)
- Packet level synchronization (no phase sync required)



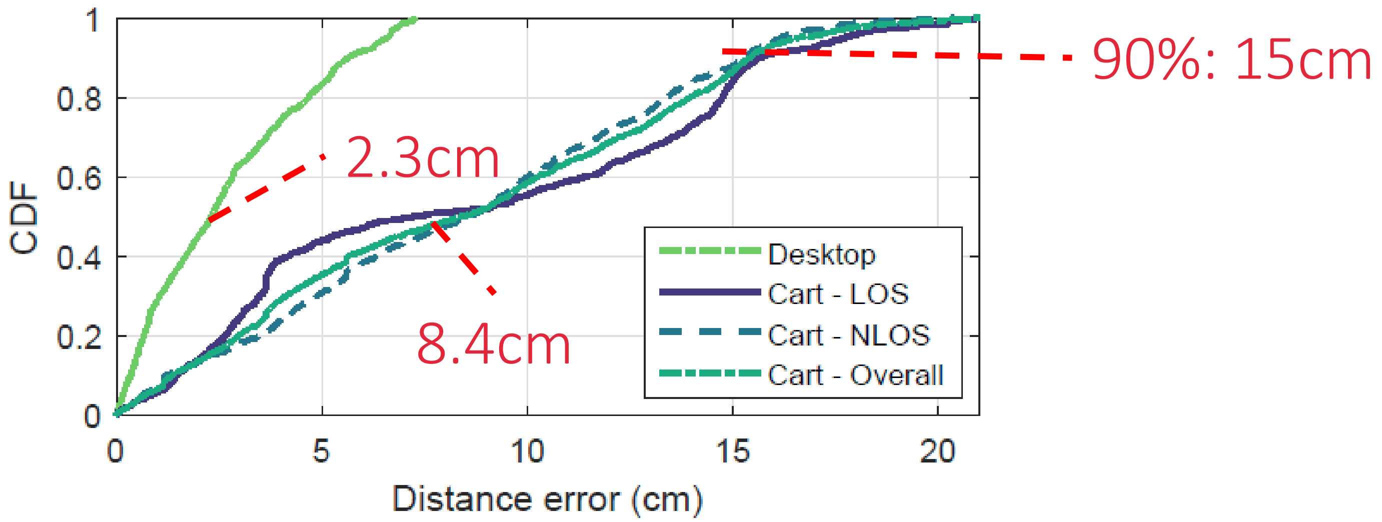
Evaluation

- A single AP, 7 different locations
- Both LOS and NLOS (40m away through multiple walls)
- 200Hz sampling rate on a 40MHz channel in the 5GHz band



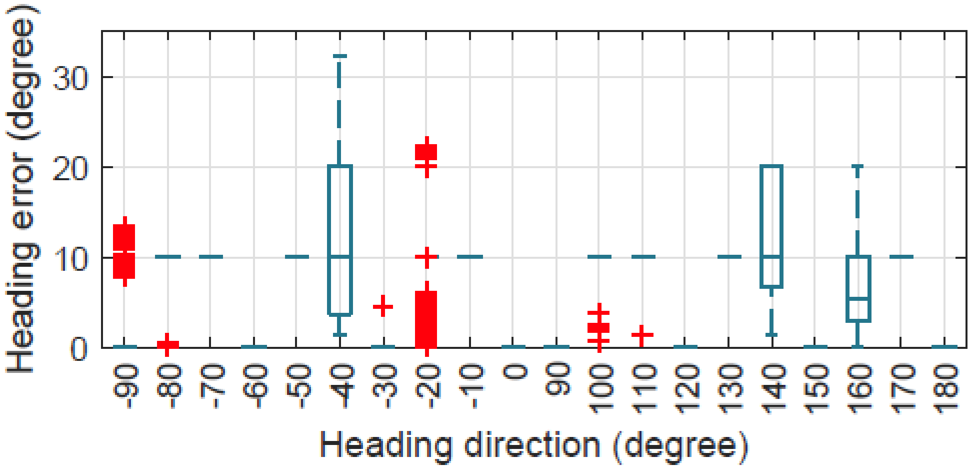
Performance - Moving Distance

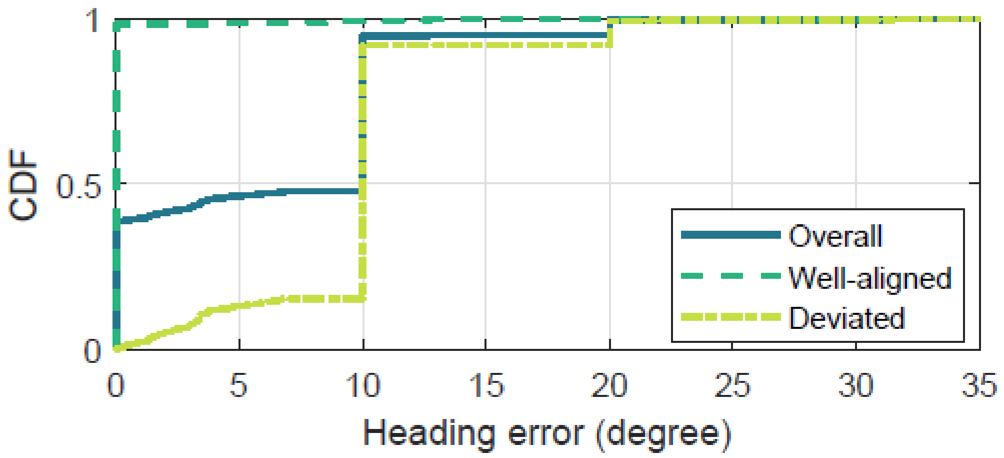
- On desktop: we move the array on a desk surface for traces around 1 m;
- On cart: we put the array on a cart and push it straight forward by more than 10 meters in different areas.



Performance - Heading Direction

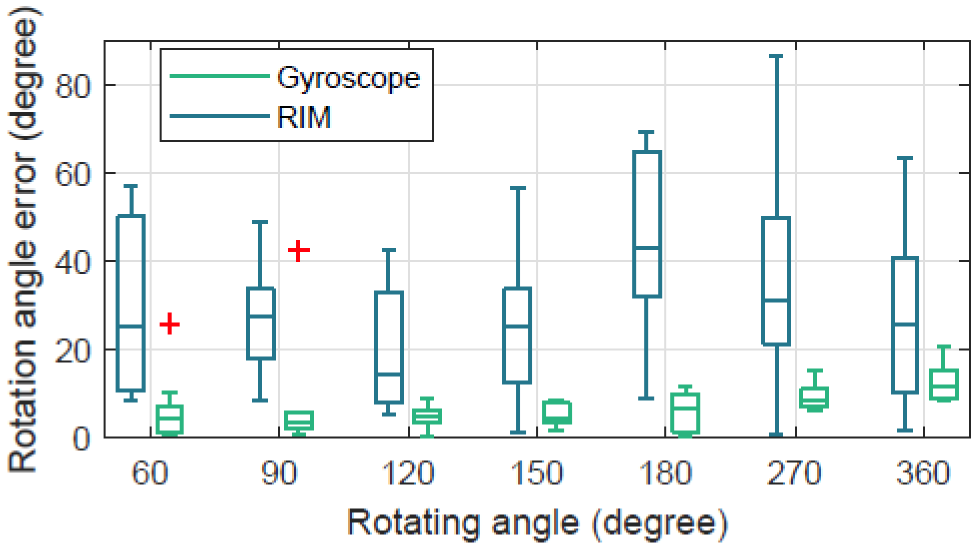
- Traverse a 90◦ range with an increased step of 10◦, together with each of their opposite directions
- >90% of heading errors are within 10◦, with an overall average accuracy of 6.1◦





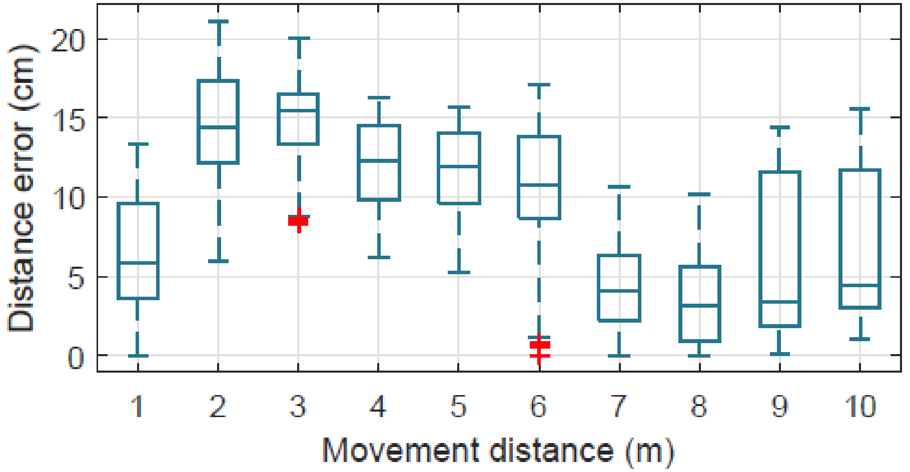
Performance - Rotating Angle

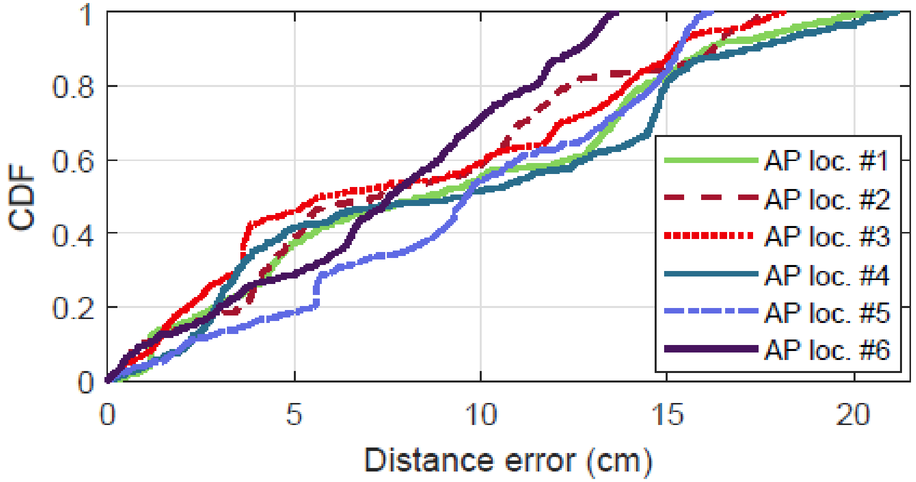
- Median error of 30.1◦, corresponding to an error of merely 1.3 cm in arc lengths (i.e., moving distances)
- Not as good as gyroscope (in short period)



Impacts of Different Factors

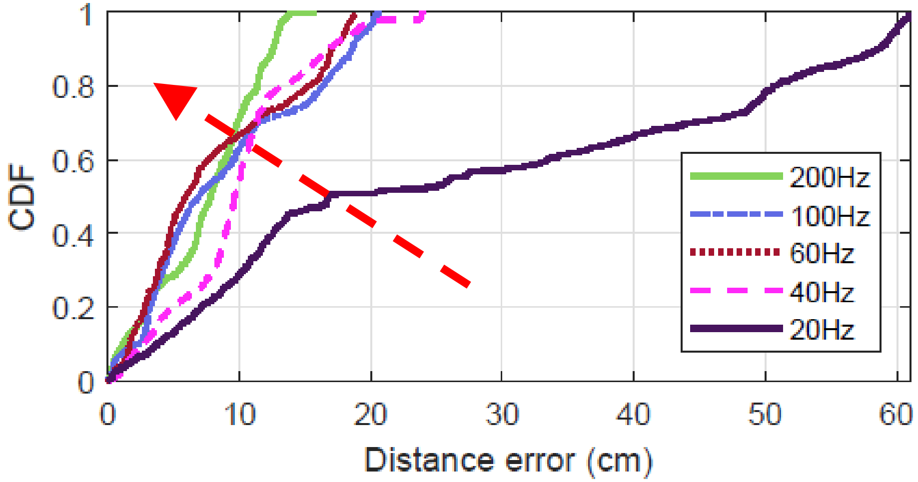
Total distance

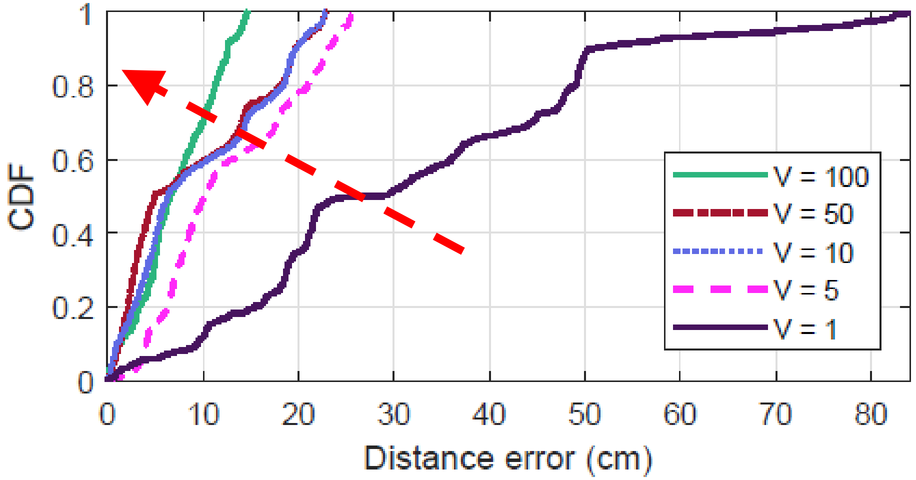




AP locations (coverage)

Sampling rate

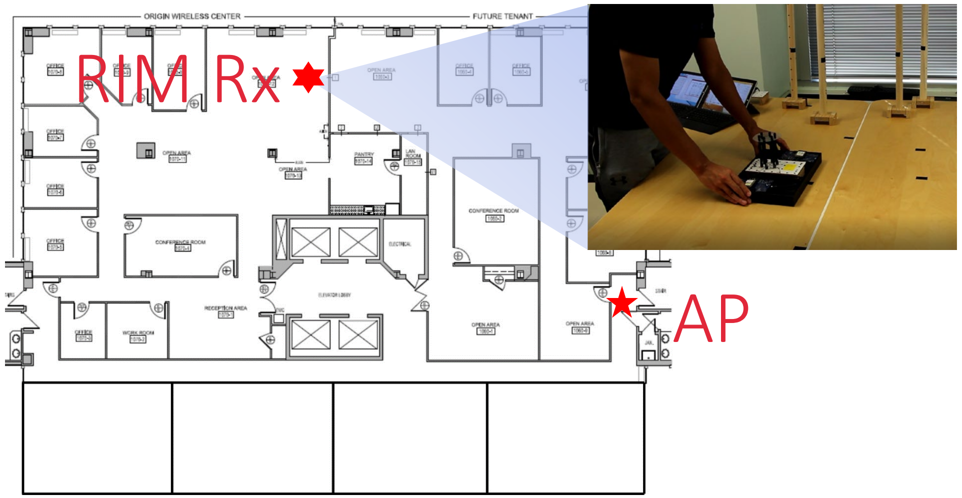




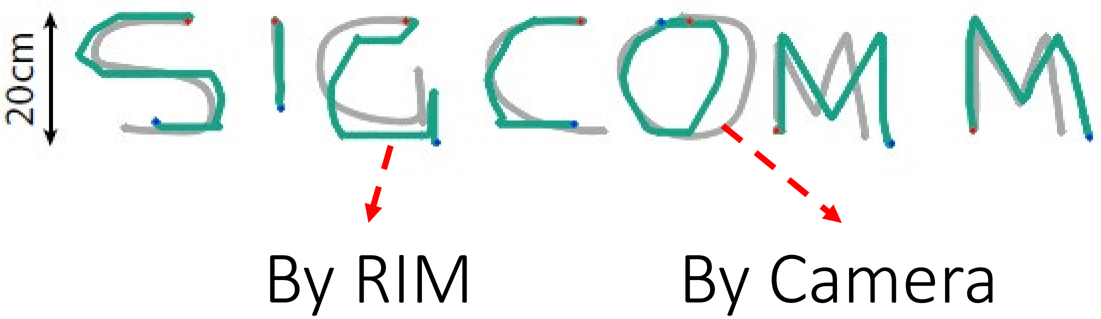
Virtual antennas

Potential Applications - Handwriting

- Move the array by freely writing some letters on a desk surface

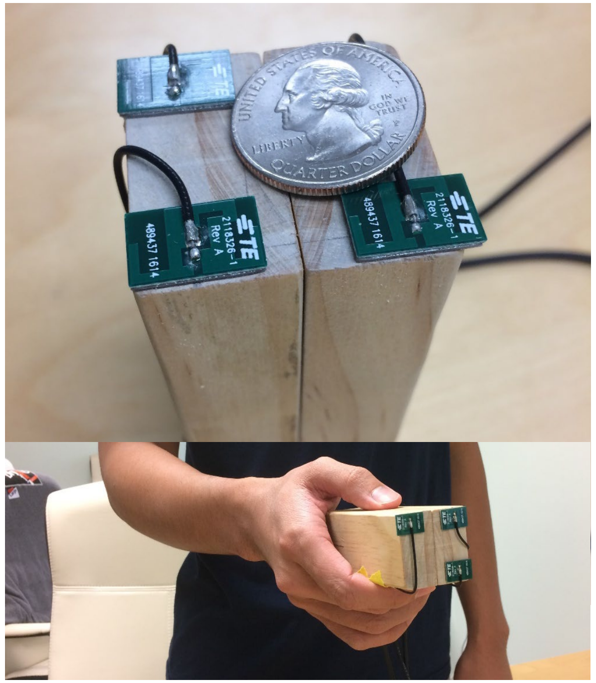


Mean error: 2.4 cm

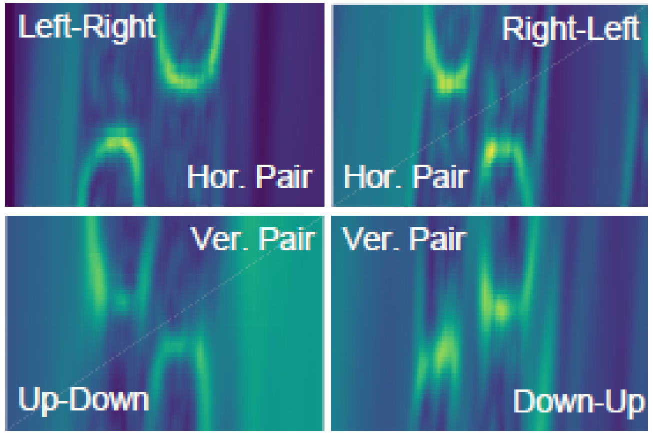


Potential Applications – Gesture Control

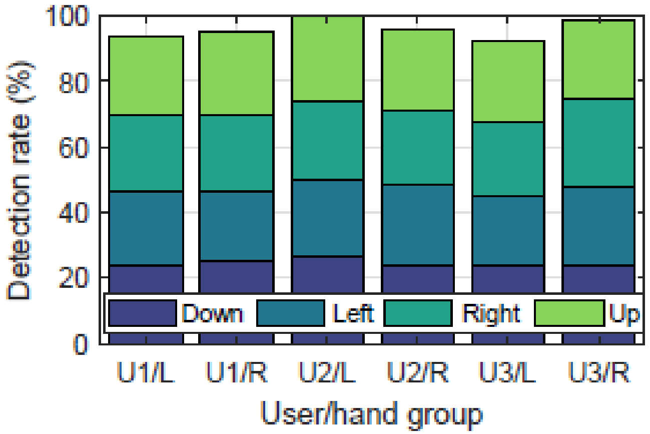
- Integrating RIM into a pointer-like unit
- One WiFi NIC with three small chip antennas arranged in an “L” shape.



96.25% detection rate



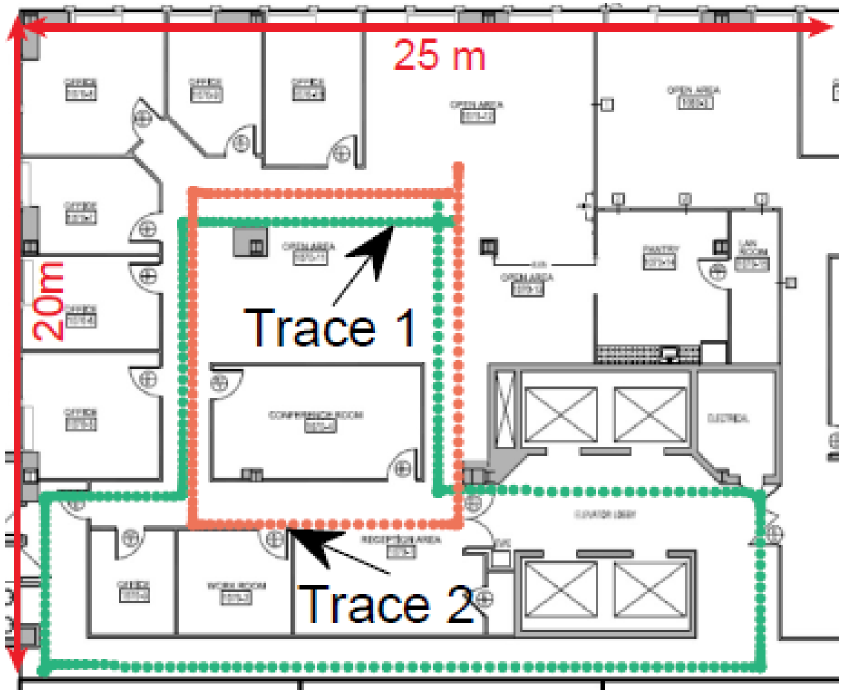
(a) Gesture pattens



(b) Detection rates

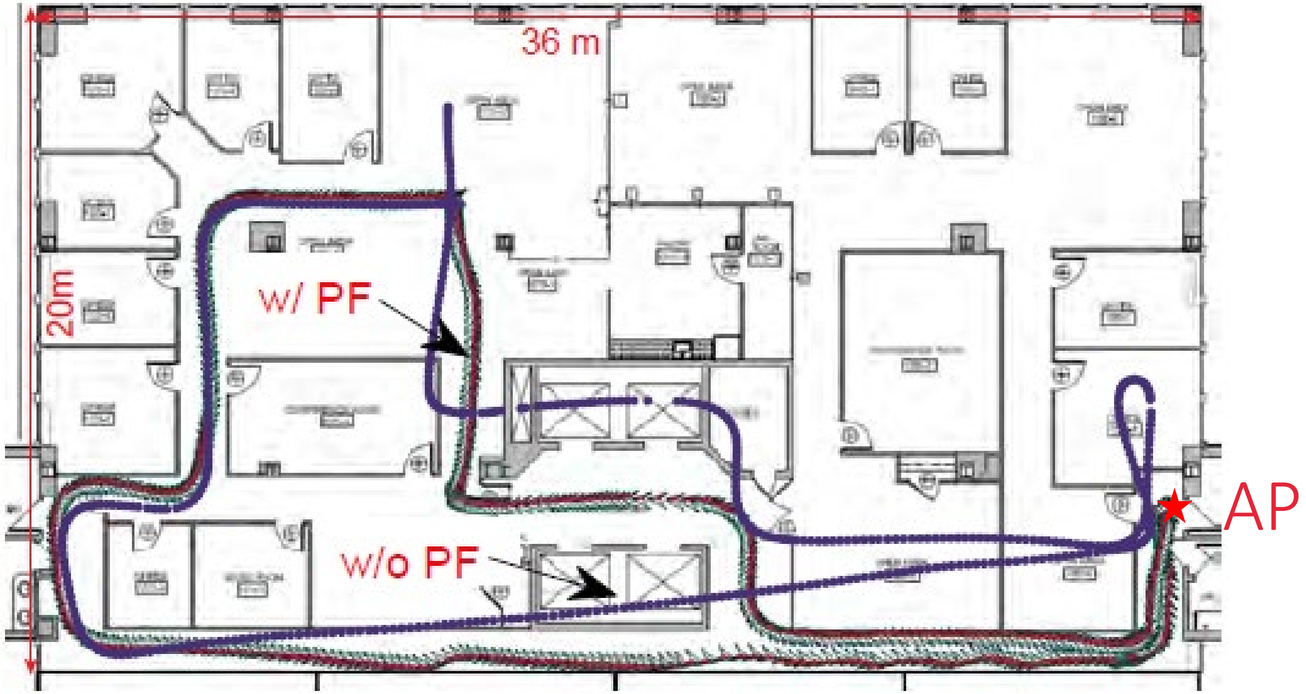
Potential Applications – Indoor Tracking

Tracking by RIM only



2D hexagonal array, resolving sideway movement for AGVs

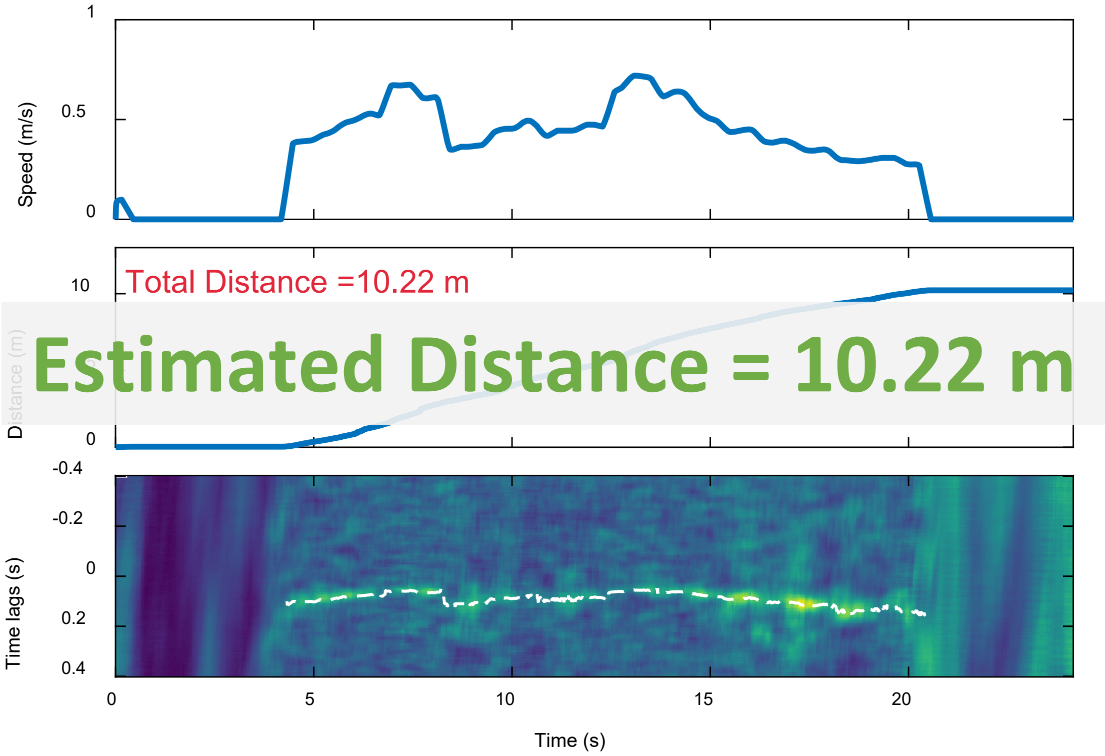
Tracking by RIM integrated with sensors



1D linear array (3 antennas), obtaining direction by IMU, augmented with a particle filter (PF)

Demo: A WiFi Ruler with RIM

Measure the perimeter of a big round table



More interesting videos in our Demo session on Wednesday, August 21!

Discussions and Future Work

- **Angle resolution**: Current RIM only exploits discrete directions defined by the antenna array. On-going work has improved continuous directions with $<10^{o}$ error.
- **Limitation of rotating angle**: It remains open to estimate angular motion more accurately.
- **3D motion**: Current RIM only addresses 2D motion. A 3D array or enhanced solutions is needed for 3D motion.
- **Fusing inertial sensors**: Leverage the complementary advantages of both systems, as demonstrated by our application case of indoor tracking.

Conclusion

- We present RIM, the first RF-based inertial measurement system that estimates centimeter-level moving distance, heading direction, and rotating angle using commercial WiFi radios
- RIM leverages rich multipaths as virtual antennas and contributes a novel super-resolution virtual antenna alignment algorithm.
- RIM works in large area with or without LOS using a single AP that is arbitrarily placed, opening up new directions and new applications of WiFi-based motion sensing

Thanks!

Q&A

http://cswu.me/rim.html

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“We can only see a short distance ahead, but we can see plenty there that needs to be done.”——Alan M. Turing