Indoor Location Sensing: Principals, Potentials, and Practice

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"The light of navigation", Dutch sailing handbook, 1608, showing compass, hourglass, sea astrolabe, terrestrial and celestial globes, divider, Jacob's staff and astrolabe.

Modern Location Sensing Proliferation

June 23, 1977

‘80

‘90

‘00

‘10

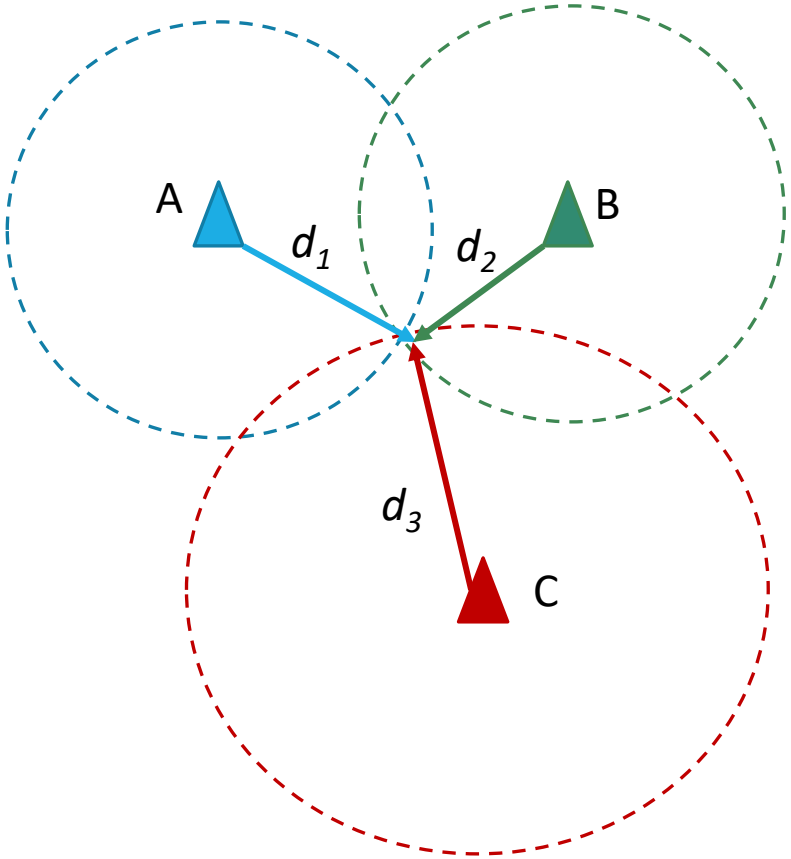
Next Billion Devices

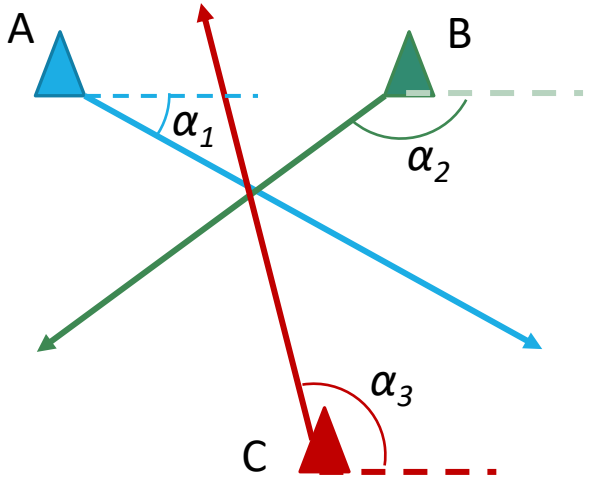
Paradigms of Location Sensing

- Geometric-based: estimate locations directly from geometric measurements
- Experience-based: estimate locations from features collected from the past
- Tracking-based: estimate locations from past locations and motion

1. Geometric Based: “It must be here.”

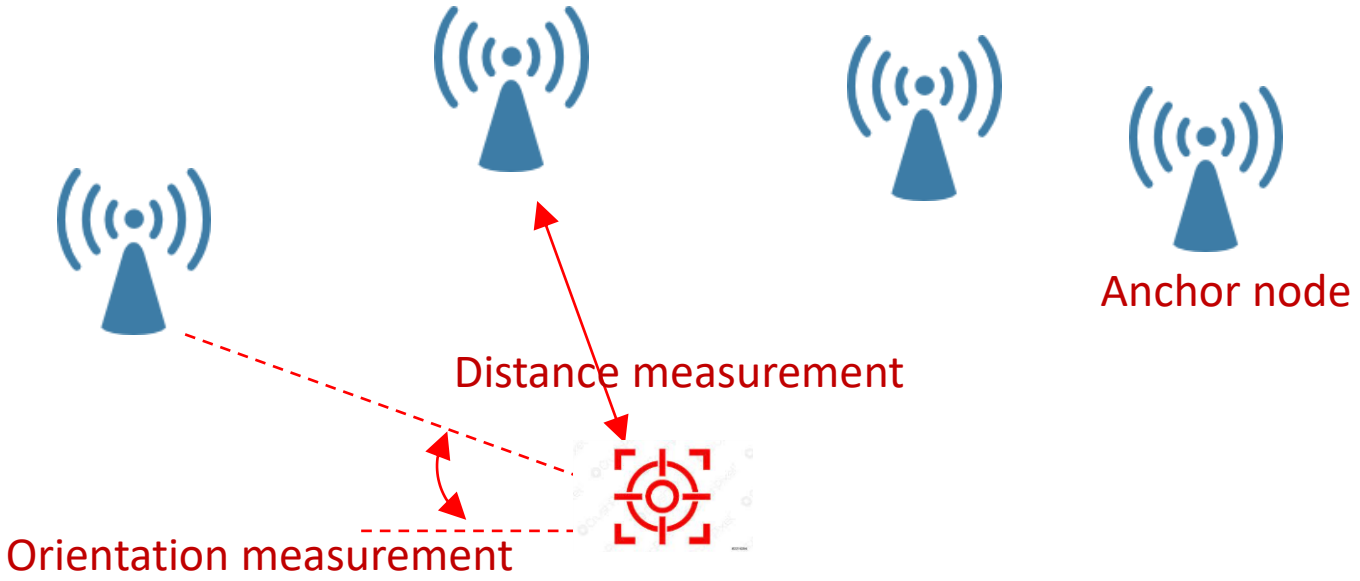
“Determine mobile device location using distance and/or orientation measurements to multiple anchor nodes with known location”





- Distance-Based: Trilateration
- Angle-Based: Triangulation

Measurements

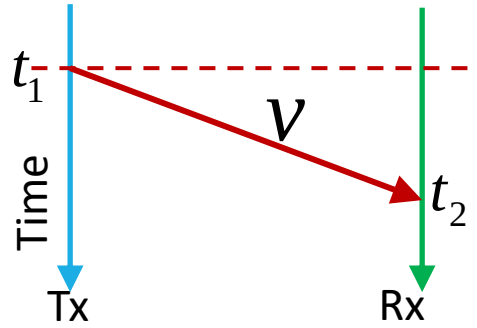


- Questions:
  - What signal to use for measurements?
  - How to measure distances / orientations?
  - How to compute location from these measurements
  - How to determine (configure) anchor node locations?

Distance Measurement Primitives

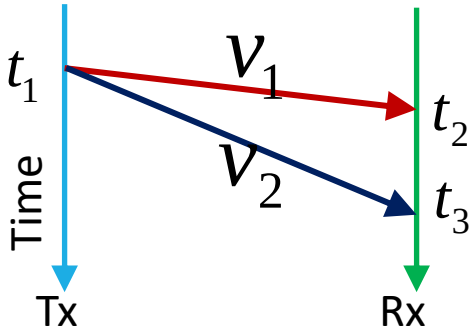
- Time Of Flight (TOF)

$$d = v(t_2 - t_1)$$



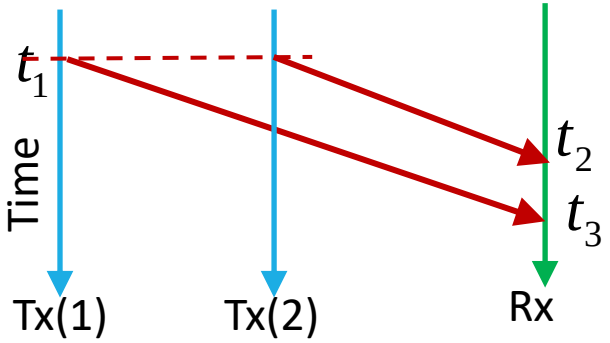
- Time Difference Of Flight (TDOF)

$$d = \frac{(t_3 - t_2)v_1 v_2}{(v_1 - v_2)}$$

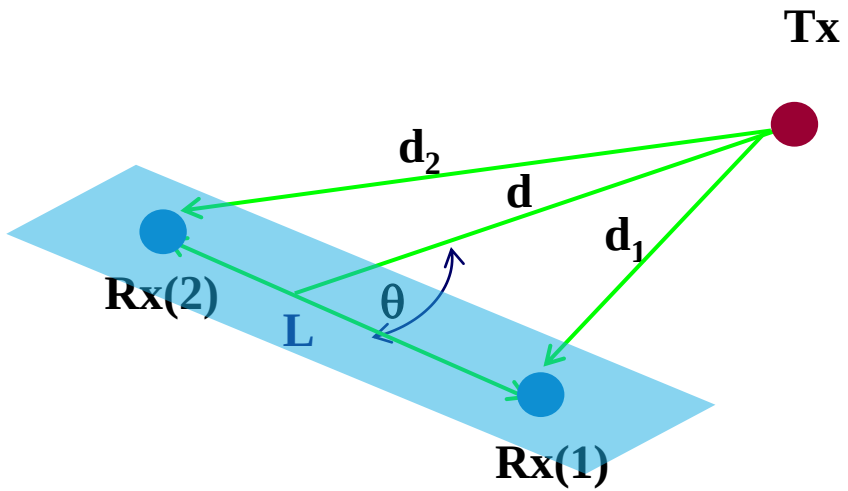


- Time Difference Of Arrival (TDOA)

$$\Delta d = v(t_3 - t_2)$$



Orientation from Difference in Time of Arrival



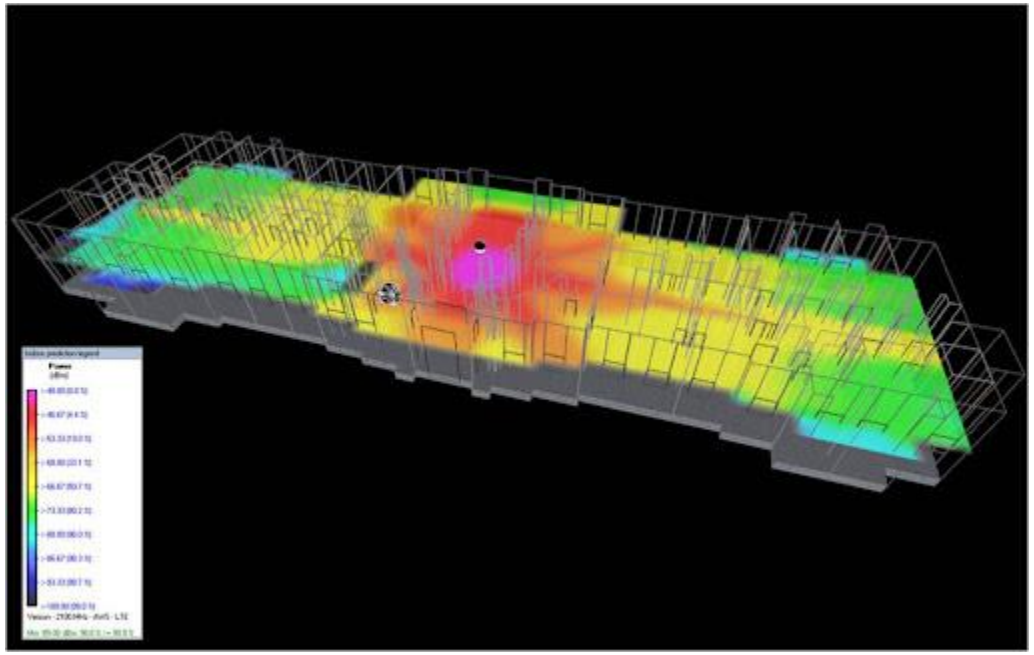
- When d >> L $Cos\theta \approx \frac{d_2 - d_1}{L}$
  - Can be calculated from Time Difference Of Arrival (TDOA) of the signals

Distance Measurement Techniques

- Audio based: audible and ultrasound
  - Advantages
    - Slow speed : easy to measure propagation time
    - Generation and detection using speakers and mics
  - Disadvantages
    - Strict line of sight – blocked by most physical materials
    - Lack of widely deployed infrastructure
    - Interfere with hearing (audible: humans, ultrasound : pets)
- RF based: all kinds of frequencies
  - Advantages
    - Easy to deploy infrastructure
    - Better penetration than audio
  - Disadvantages
    - High propagation speed: difficult to measure time-of-flight
- Active Light based: laser, IR
  - Advantages
    - Can be very accurate using ToF
  - Disadvantages
    - Can be expensive
    - Needs direct line of sight
- Camera based
  - Advantages
    - Can measure distances and angles at once
    - Price is getting cheap
    - Range is limited due to resolutions
  - Disadvantages
    - Need to calibrate
    - Higher computational cost than 1d approaches
    - Needs direct line of sight

2. Experience-based: “I have been (near) here!”

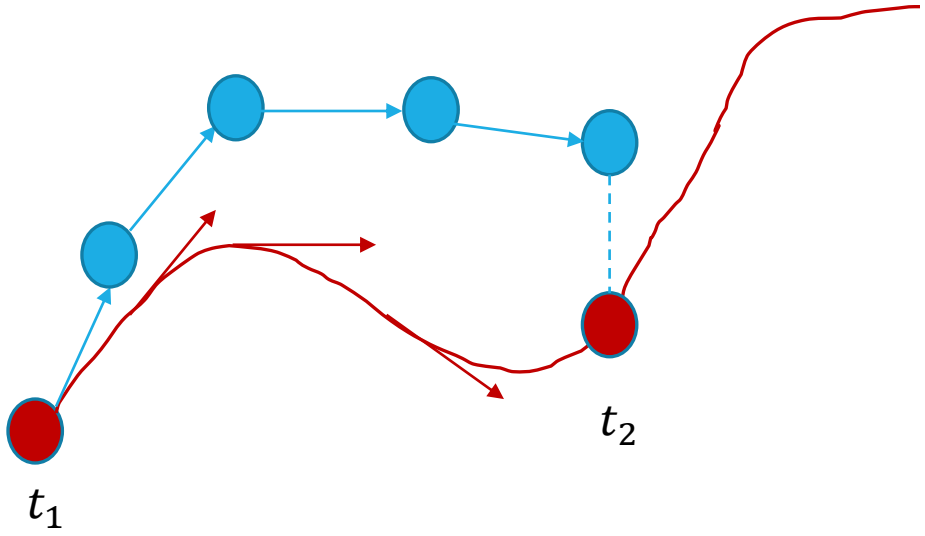
- Fundamentally, it is a signature recall approach.
- Build features mapping $F(V) = L$, that $\min\{D\big(L, F(V)\big)\}$
- Localization: For given measurement $\hat{V}$, find $\hat{L} = \mathrm{F}(\hat{V})$



Indoor Location Dependent Signatures/Features

	Instant	Trajectory
Deployed Infrastructure	**Bluetooth/Zigbee Beacons** **Magnetic Beacons** **RFID** **Modulated Light**	**Ground Vibration** **Sparse Set of Beacons**
(Nearly) Ambient	**Cell Network** **WiFi** **Sound** **FM Radio** **Photos**	**Earth Magnetic Field** **Turns and Stairs** **Video**

3. Tracking-based: “How I have moved”



- Start with a known location (t_1)
- Measure motion over time($t_1 \sim t_2$)
- Estimate new location (t_2)
- Repeat

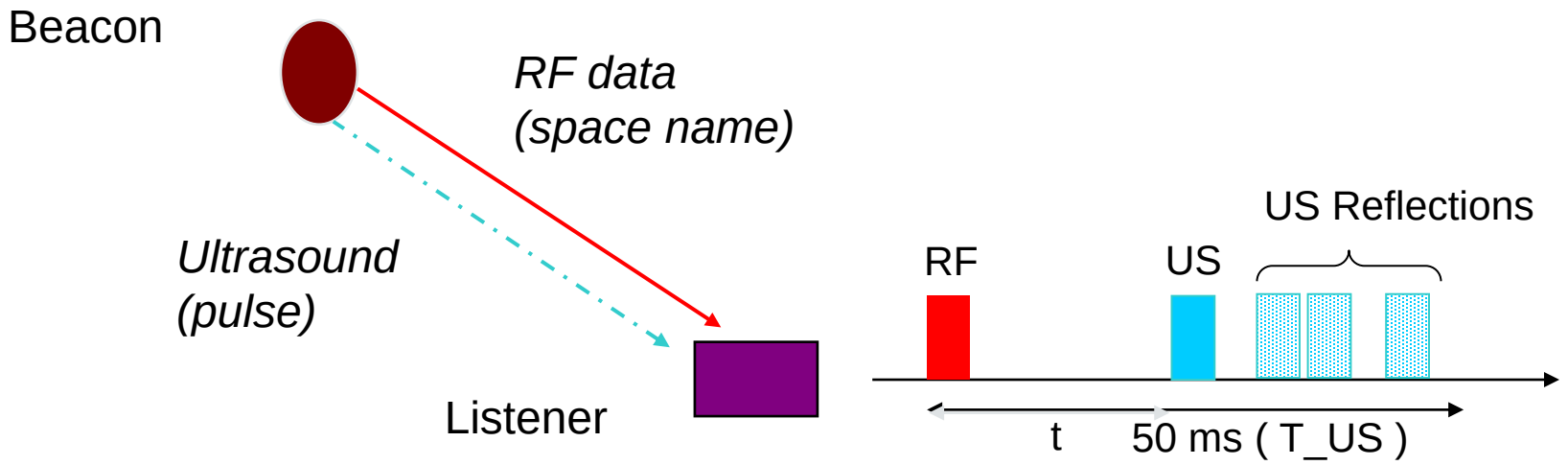
4. Sensor Fusion: Combining Two or More Approaches

- Two or more types of complementary signals (modalities):
  - To measure distances: e.g. Cricket (RF + Ultrasound)
  - To compensate signatures: e.g. FM + WiFi

- Absolute location with motion tracking: E.g.
  - WiFi + step counting
  - Markers + visual odometry

- Location/movement + side knowledge : E.g.
  - Loop closure
  - Map constraints

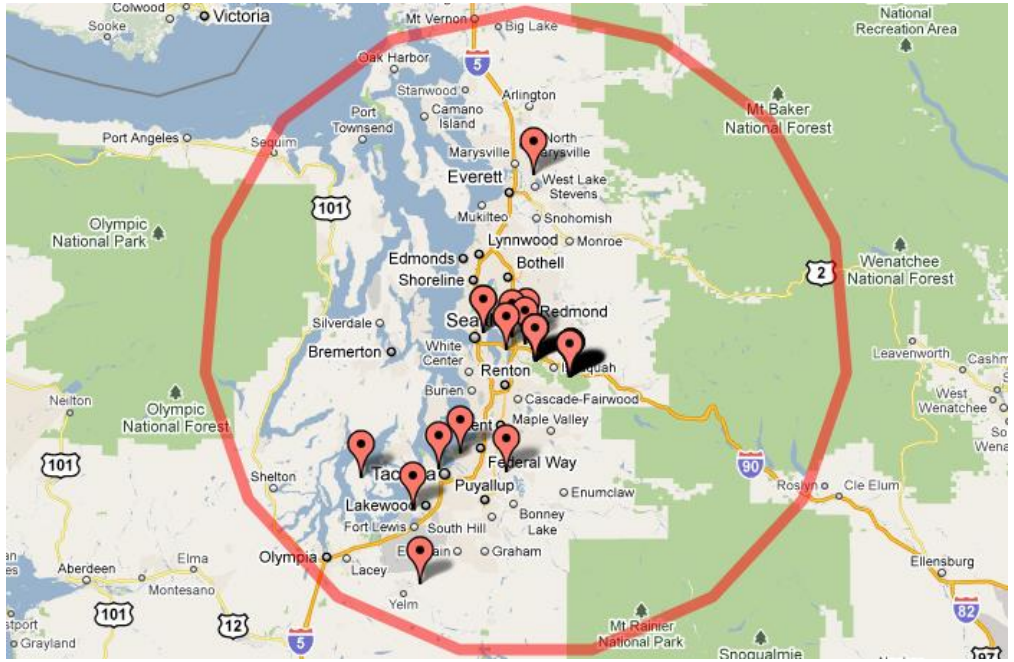
Cricket Indoor Location System

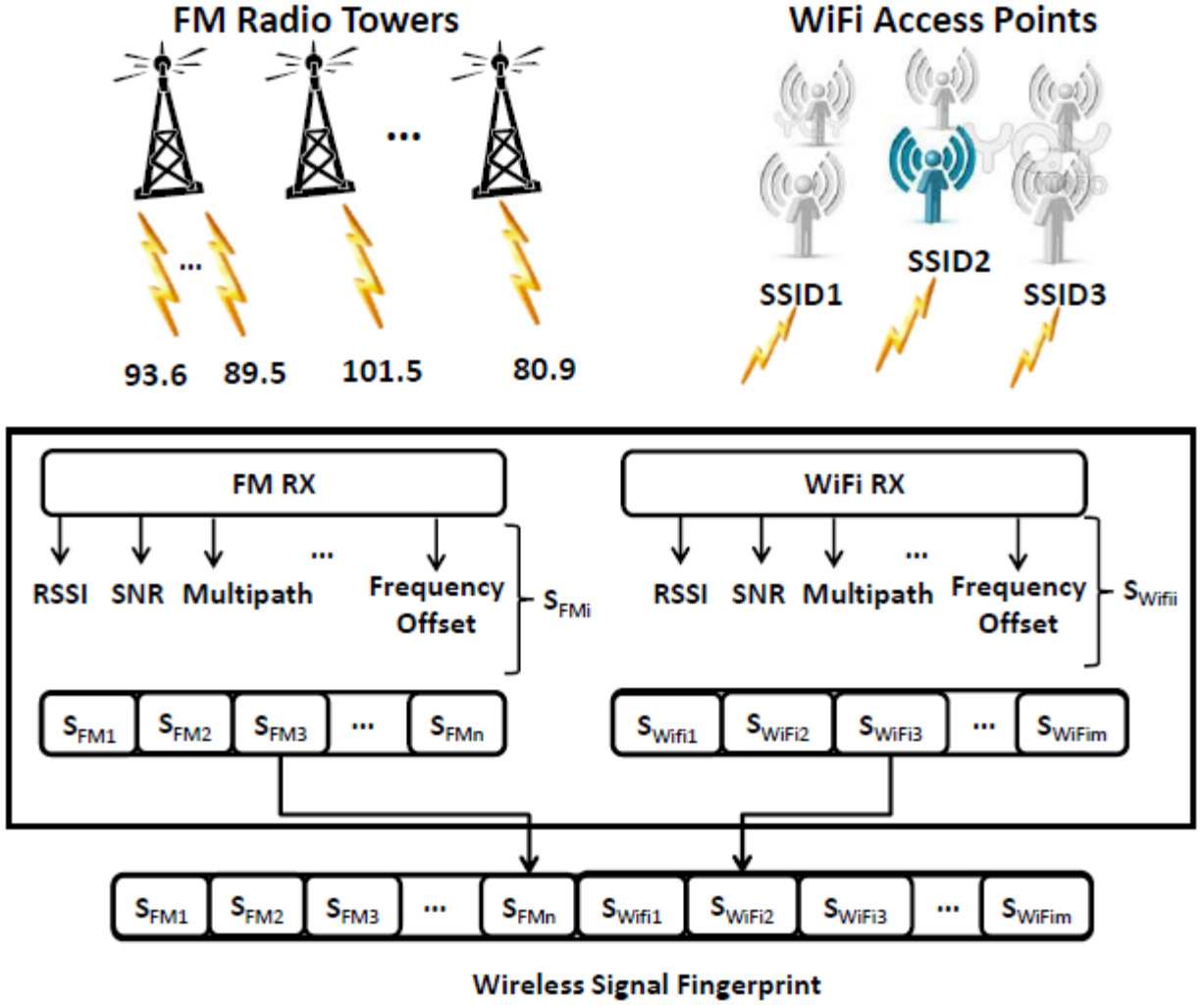


- Cricket:
  - Anchor nodes → beacons
  - Mobile node → Listener
- Computes distance by TDOF of RF and US
- Multipath mitigation: first US pulse to measure distance
  - US signals die down after 50mS

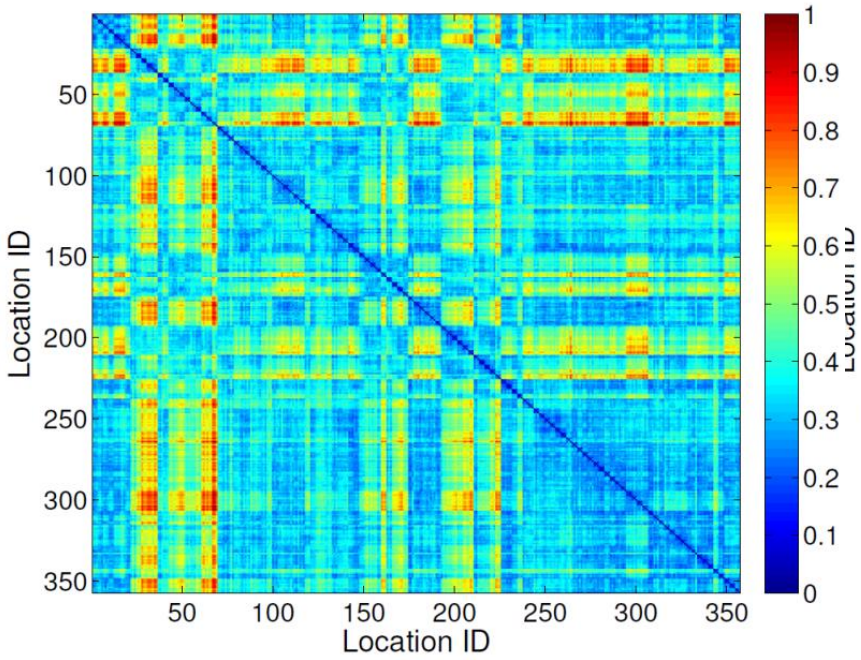
FM+WiFi Based Indoor Localization

FM towers near Seattle

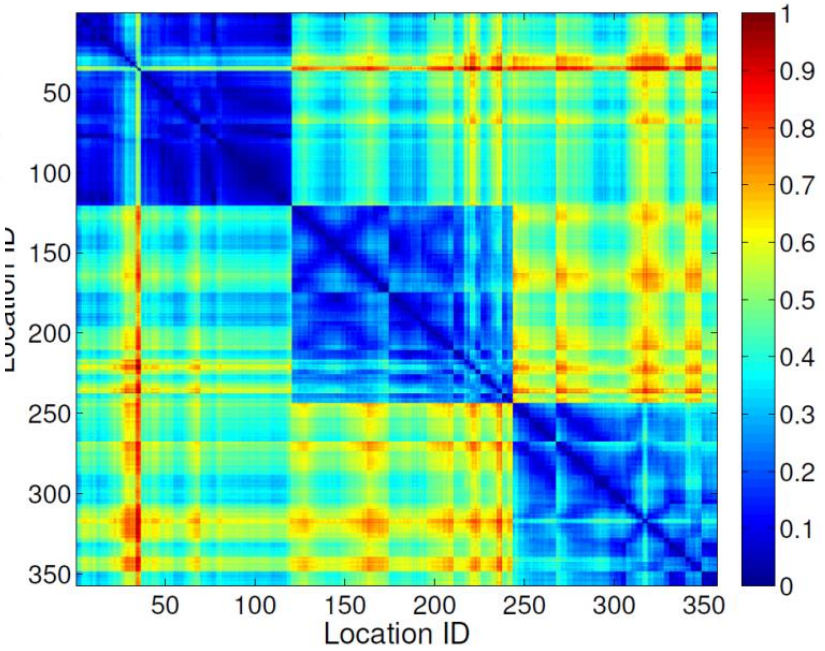




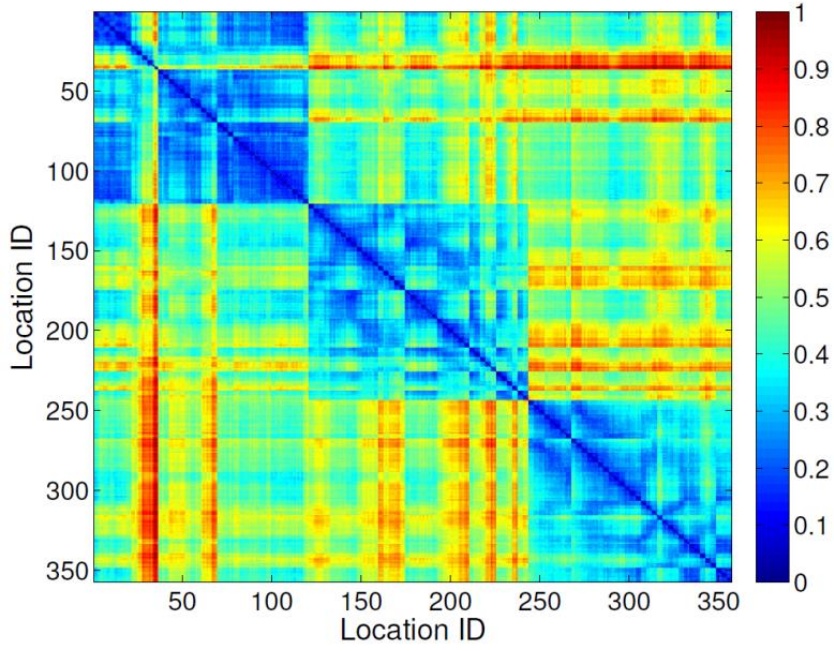
Complementary Roles of WiFi and FM



FM ALL



WiFi RSSI



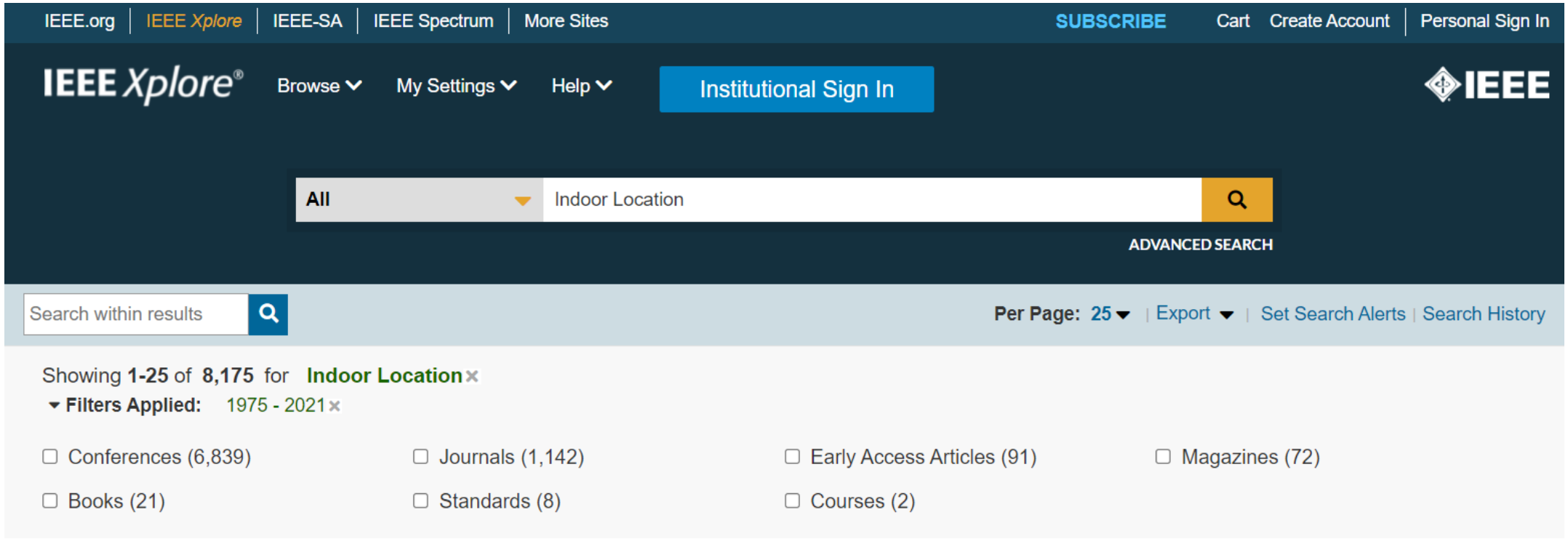
FM ALL + WiFi RSSI

Fusing Motion with Maps

- WiFi Signatures
- IMU based direction & step counting
- Sequential Bayesian updates
- Particle filters
- Map constraints

Potentials: Indoor location examined

Lots of Publications, Very Little Comparison



Which on is better?

System A
3m Location Accuracy

OR

System B
4m Location Accuracy

Microsoft Indoor Location Competitions

- Evaluate and compare technologies from academia and industry in the same, unfamiliar space.
- Bring teams working in this area together in a more effective way.

2014: Berlin

2015: Seattle

2016: Vienna

2017: Pittsburgh

2018: Porto

Microsoft Indoor Location Competitions

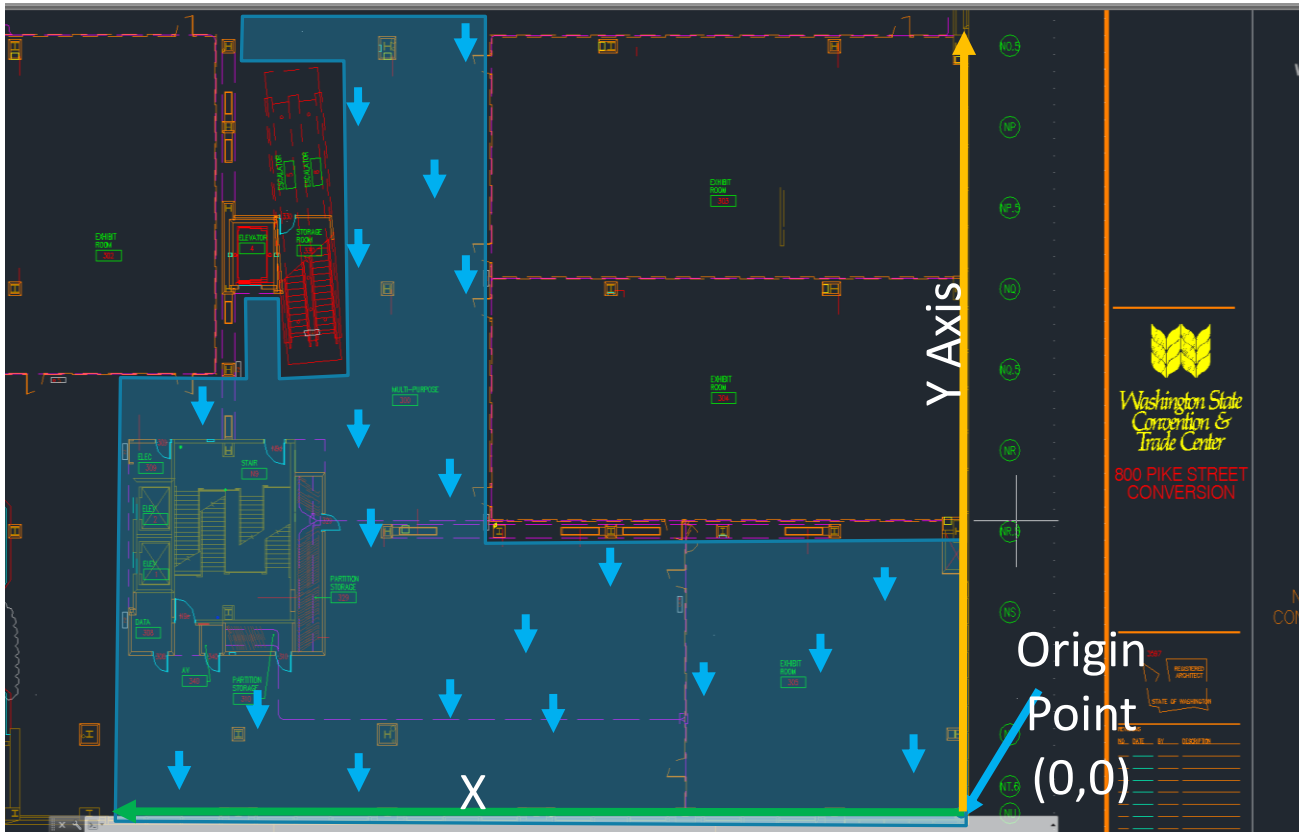
2014

- 36 teams signed up, 22 competed

300 m^2

2015

- 48 teams signed up, 23 competed



2000 m^2

Basic Rules

INFRASTRUCTURE FREE

- Pre-deployed 10 WiFi AP for everyone.

INFRASTRUCTURE ASSISTED

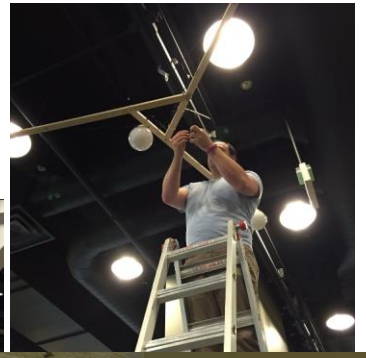
- Allow deployment of up to 10 devices

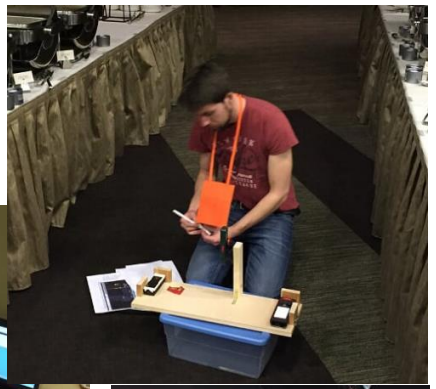
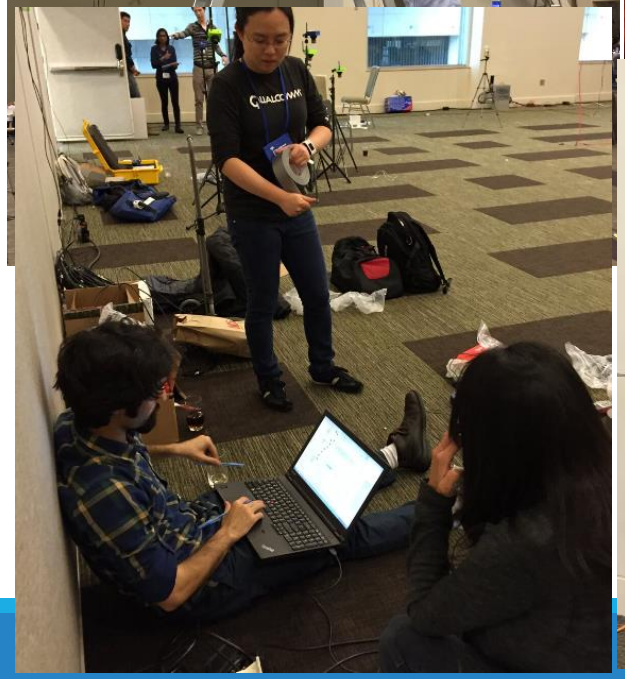
- 8 hours of setup up time
- Unknown evaluation points
- Individually evaluated to prevent interference.

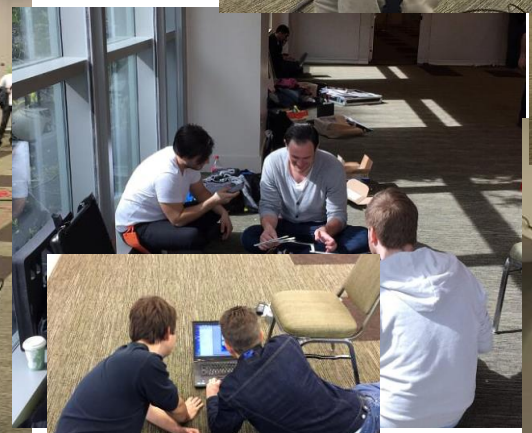
Craziness

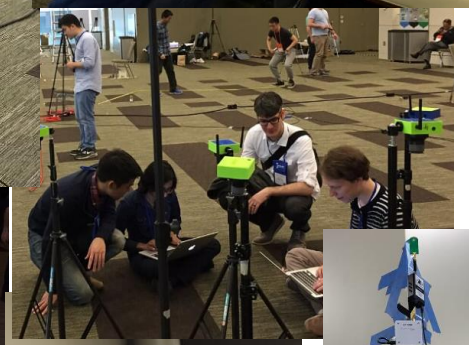




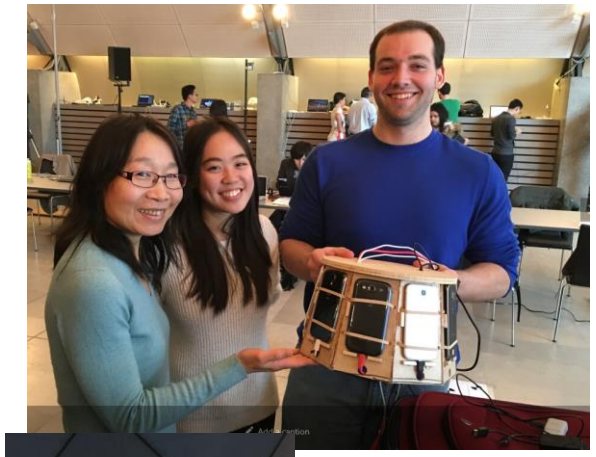
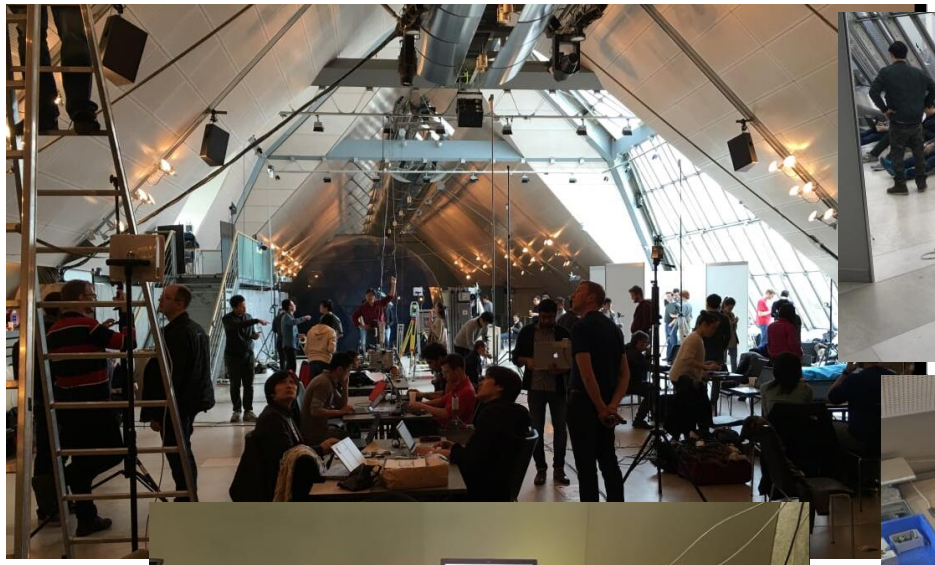




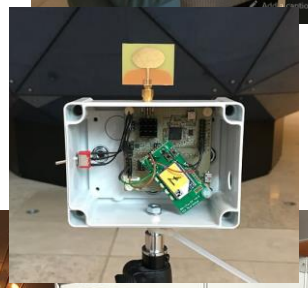



Craziness



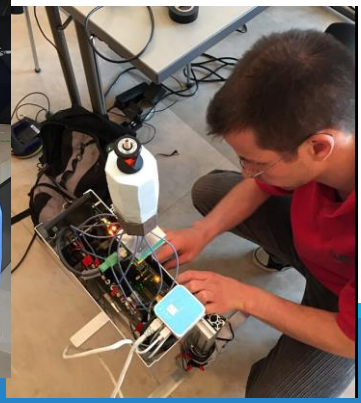






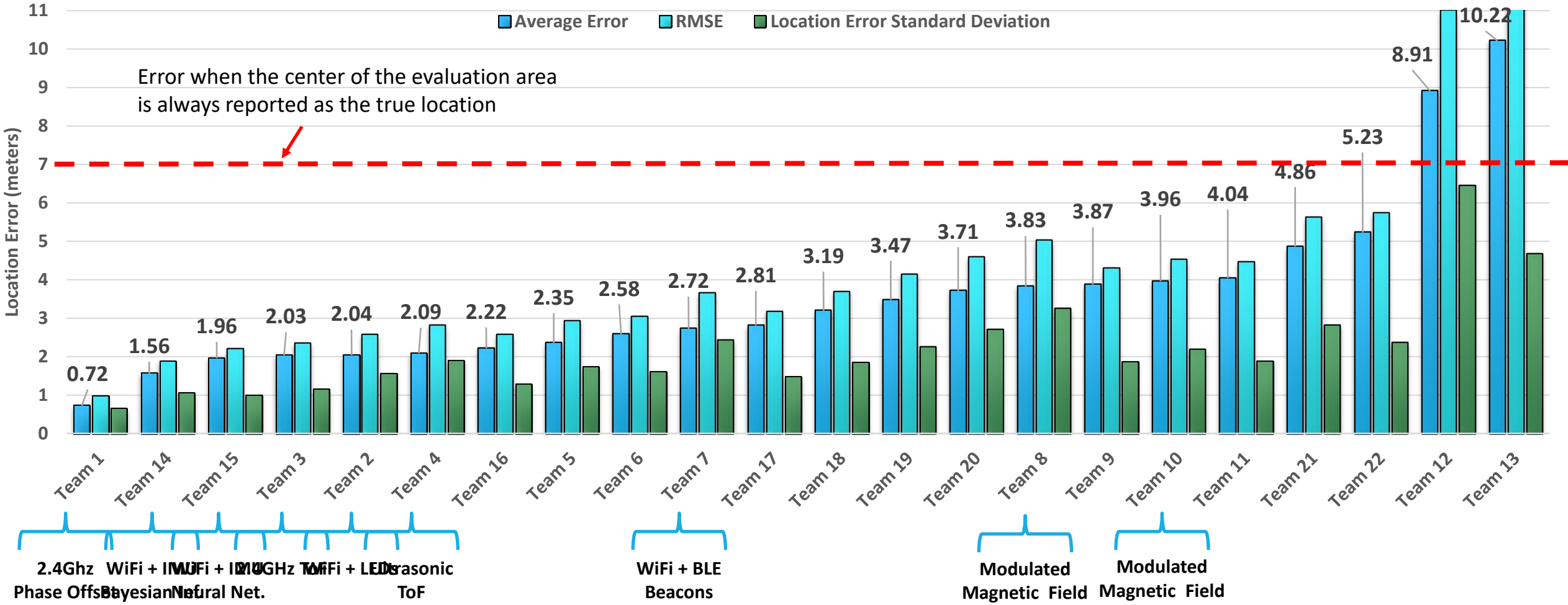




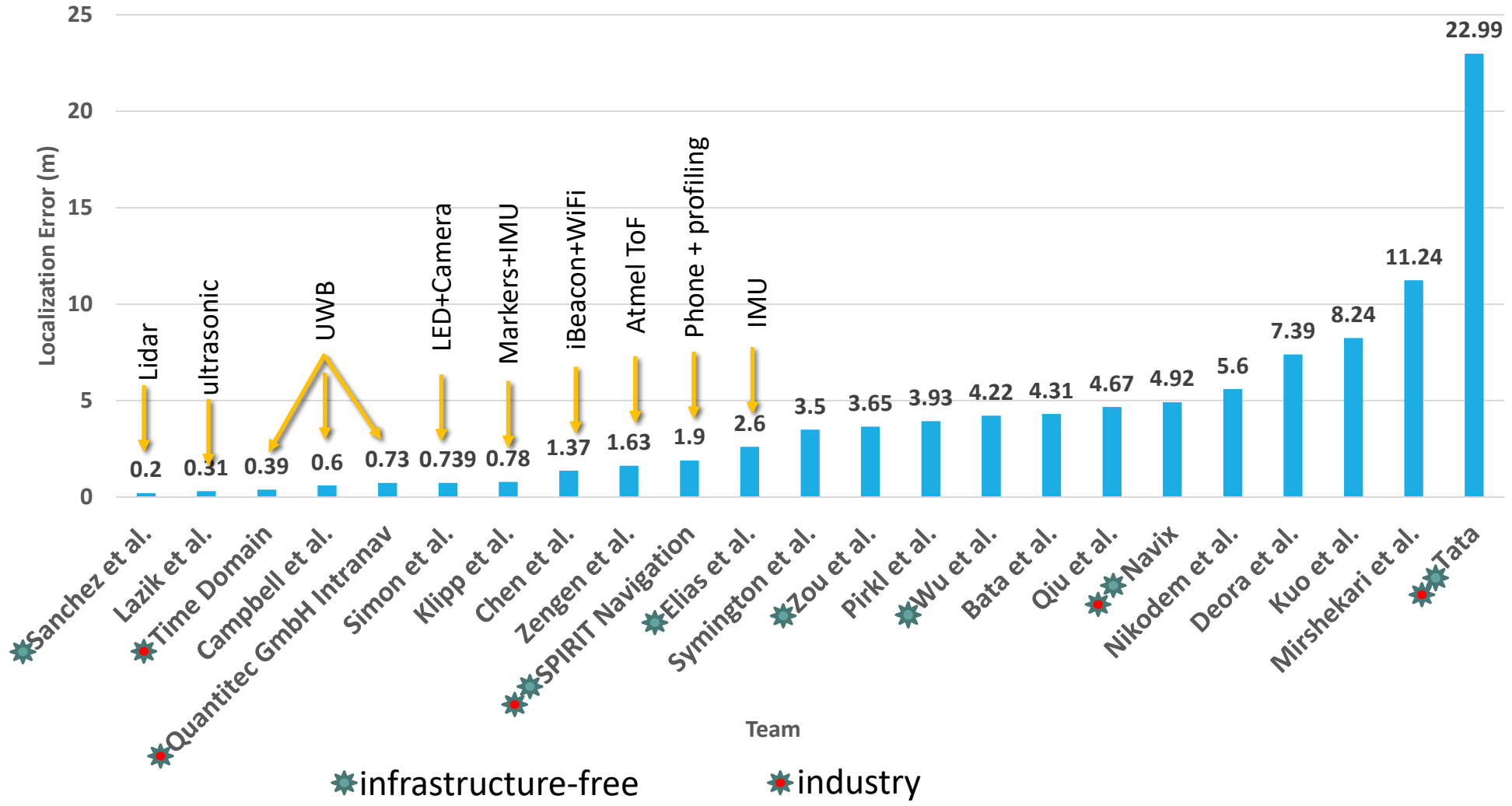


More Craziness

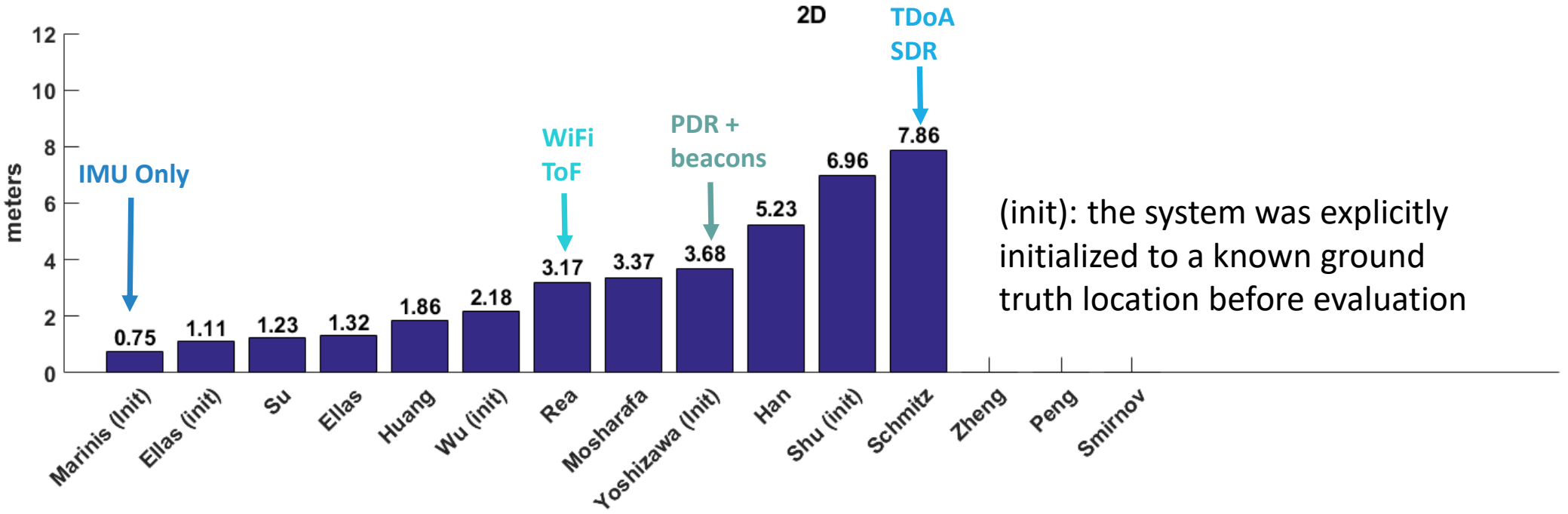
2014 Localization Accuracy



2015 Results

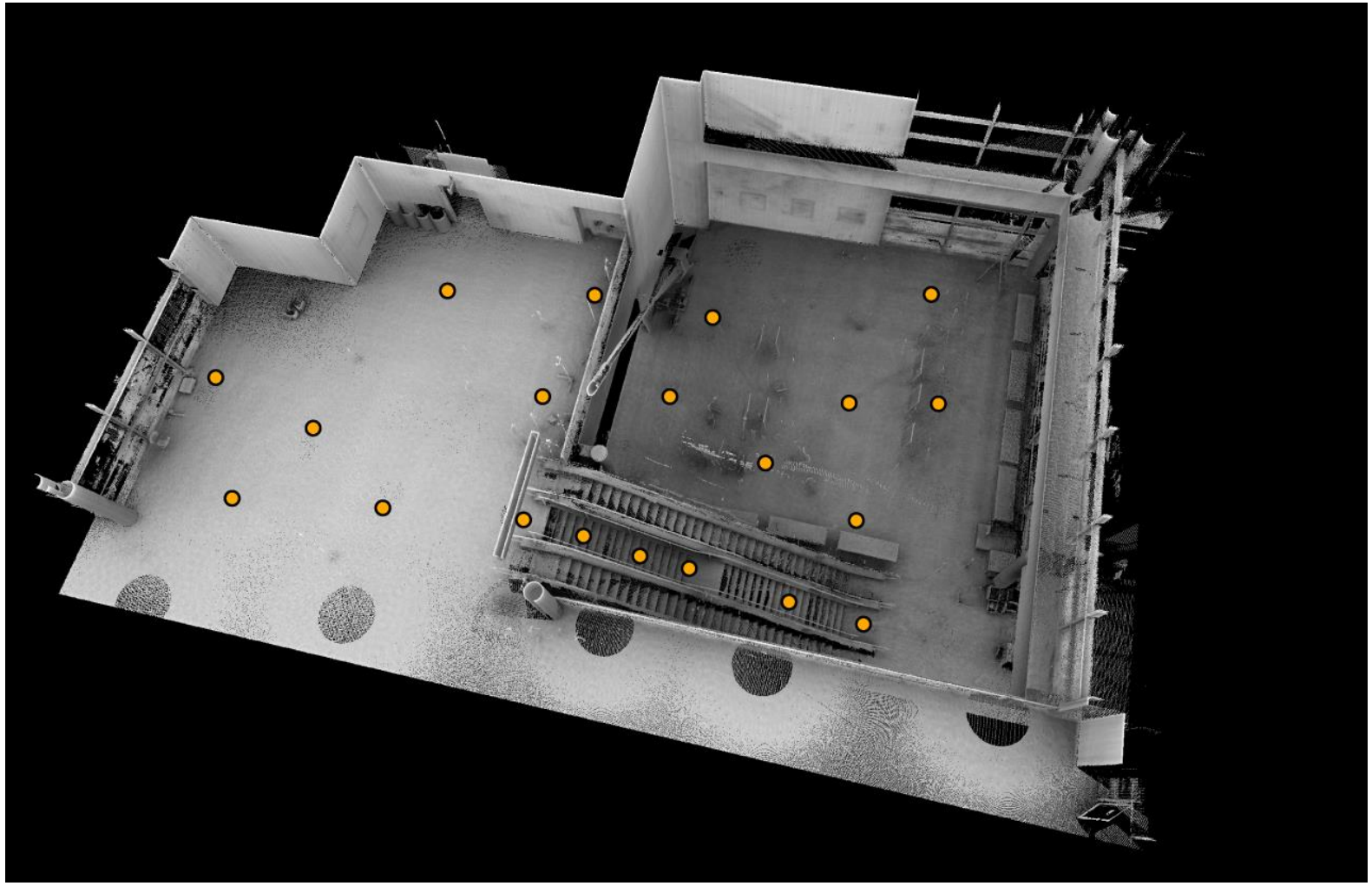


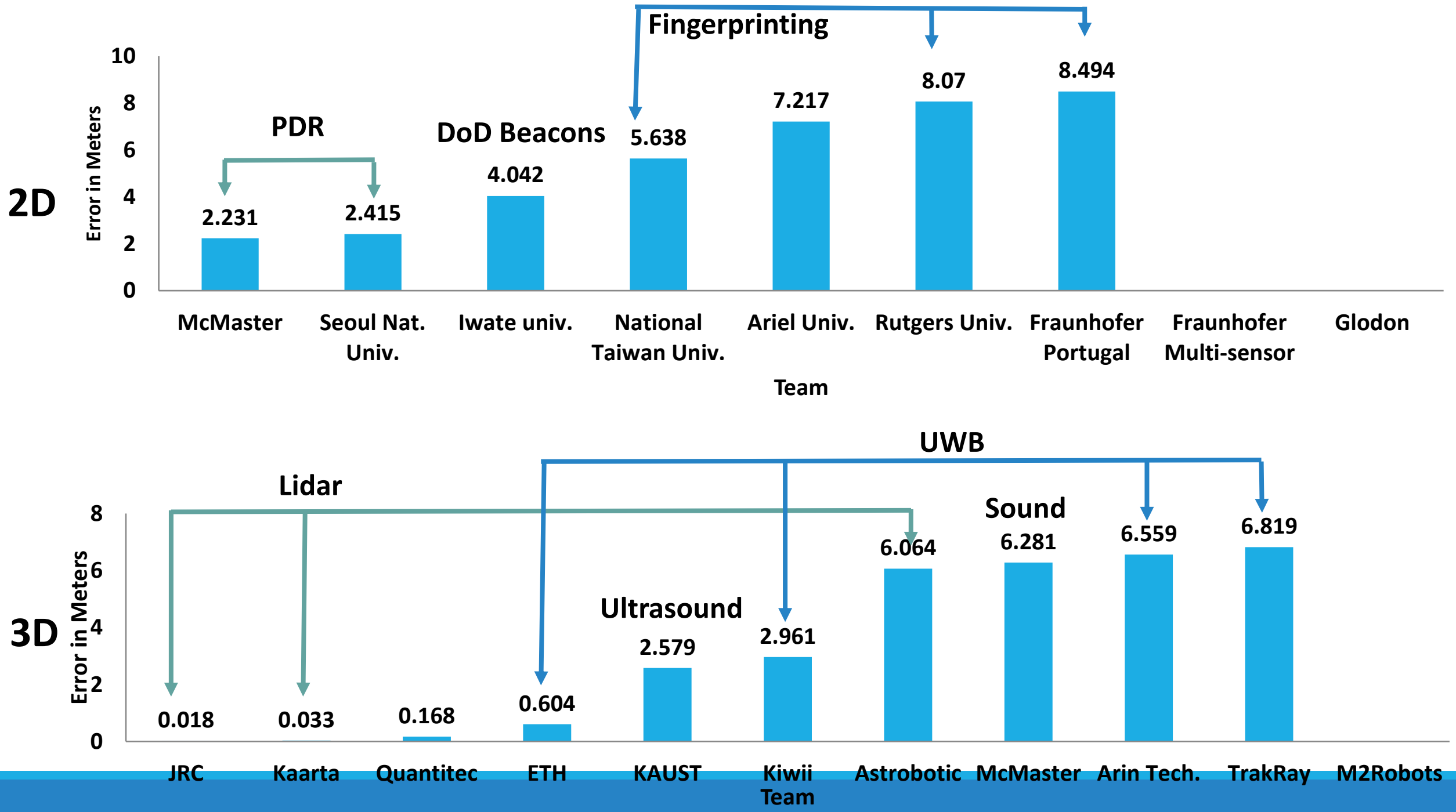
2016: 465m^2 Evaluation Area, Two Levels



(init): the system was explicitly initialized to a known ground truth location before evaluation

2017: 600m^2 Evaluation Area - Two Floors




2D
Error in Meters
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PDR
Fingerprinting
DoD Beacons
2.231
2.415
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5.638
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8.494
McMaster
Seoul Nat. Univ.
Iwate univ.
National Taiwan Univ.
Ariel Univ.
Rutgers Univ.
Fraunhofer Portugal
Fraunhofer Multi-sensor
Glodon
Team
3D
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UWB
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Ultrasound
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JRC
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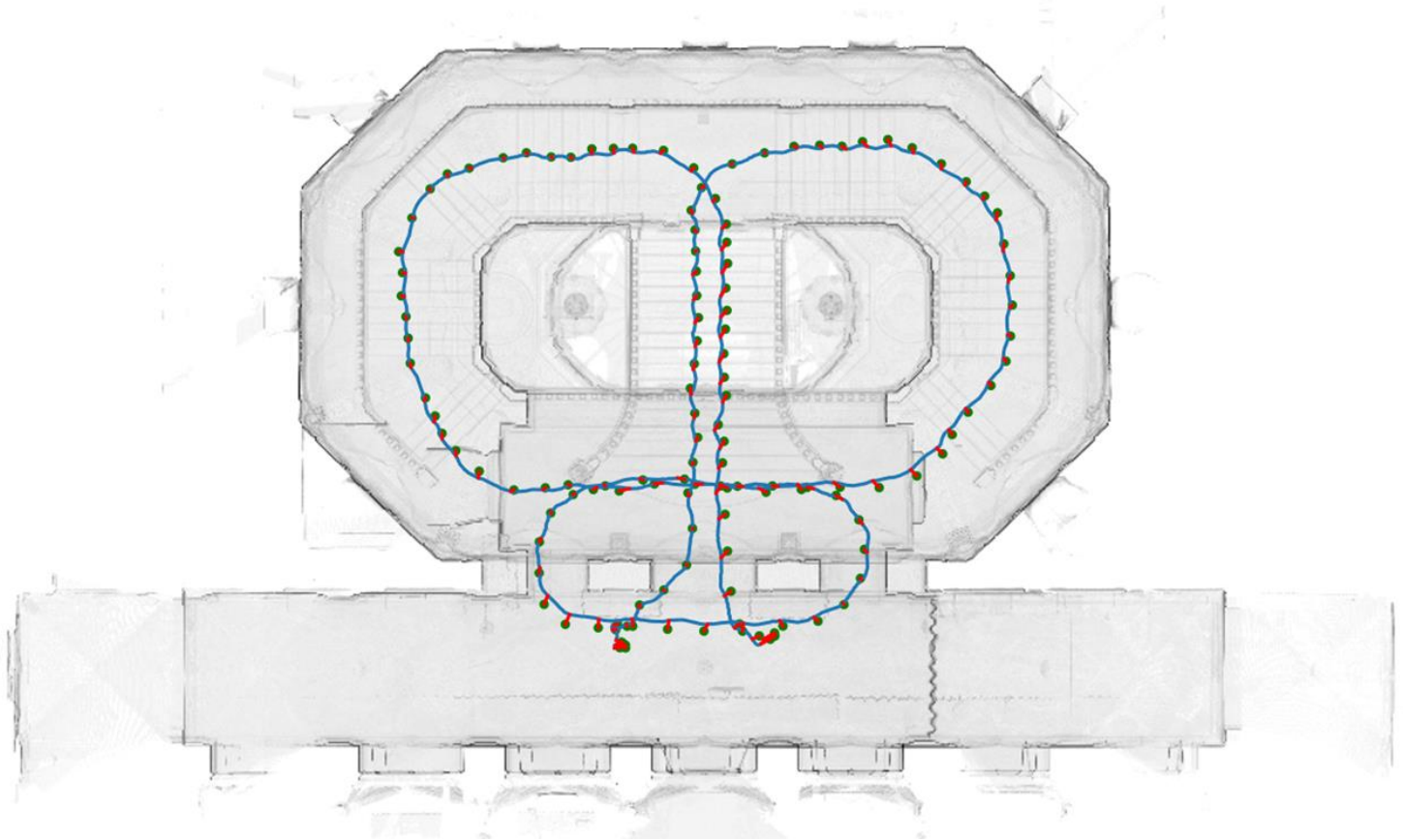
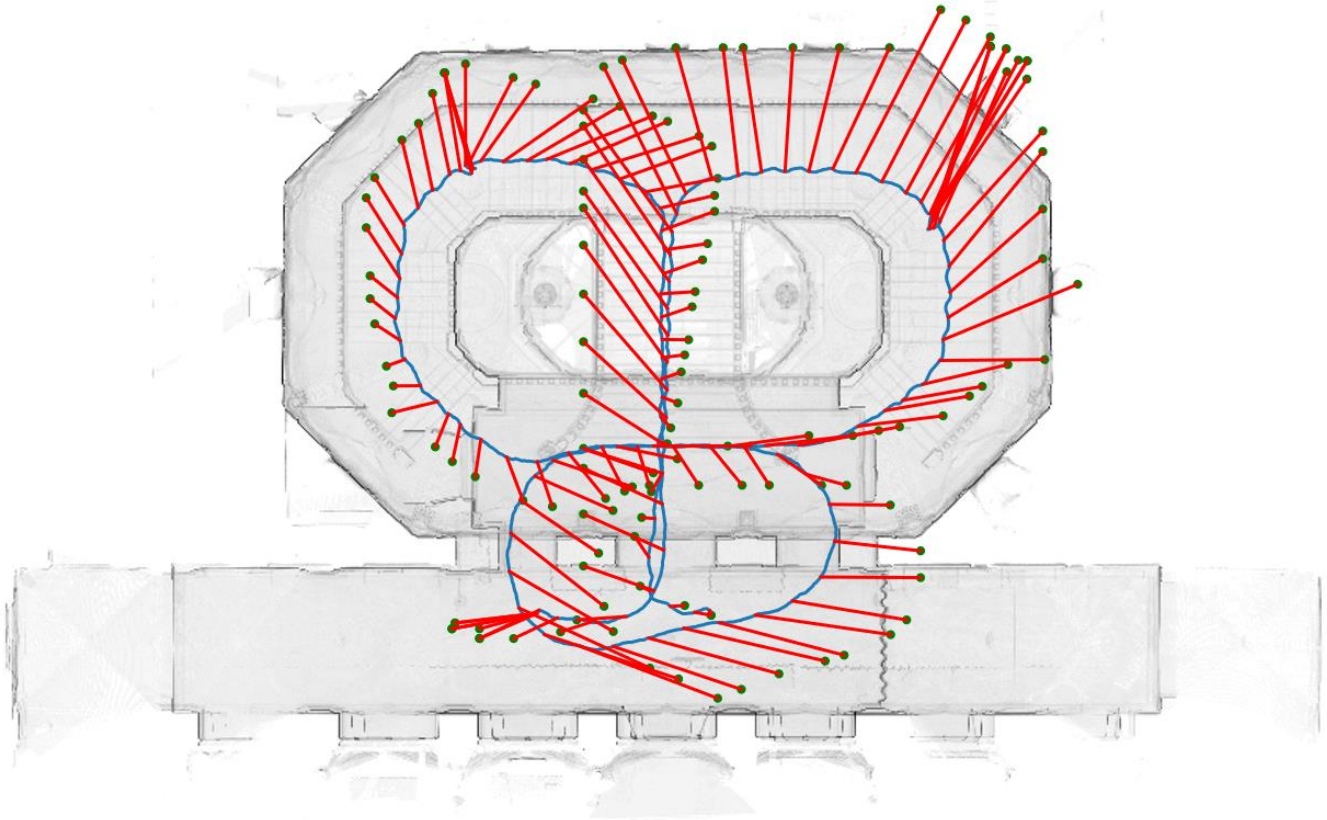
Quantitec
ETH
KAUST
Kiwii Team
Astrobotic
McMaster
Arin Tech.
TrakRay
M2Robots

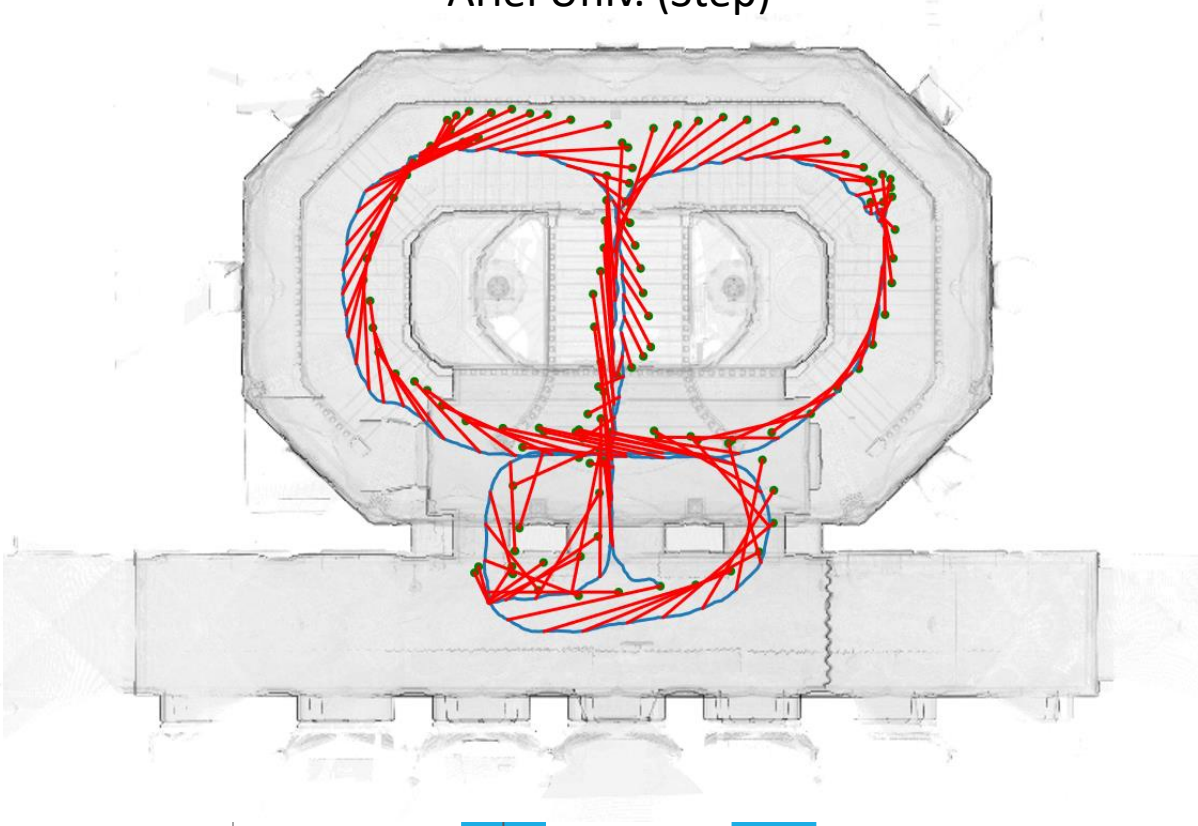
2018: Two Levels

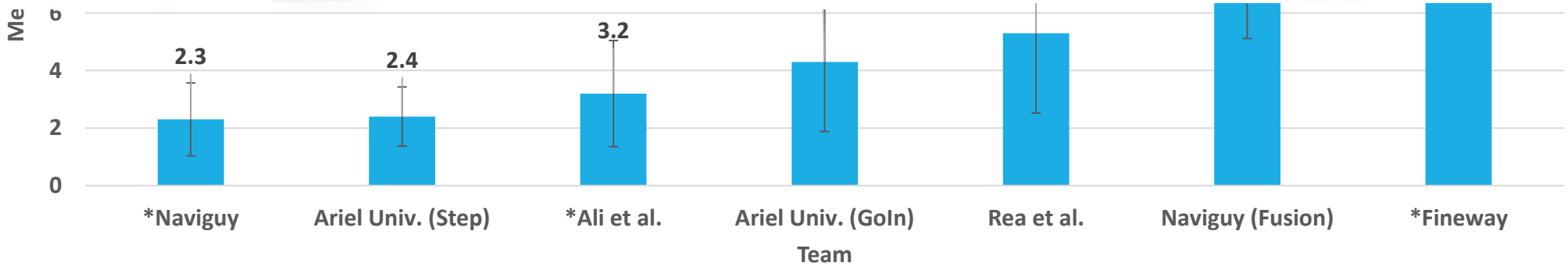


Naviguy



Ariel Univ. (Step)

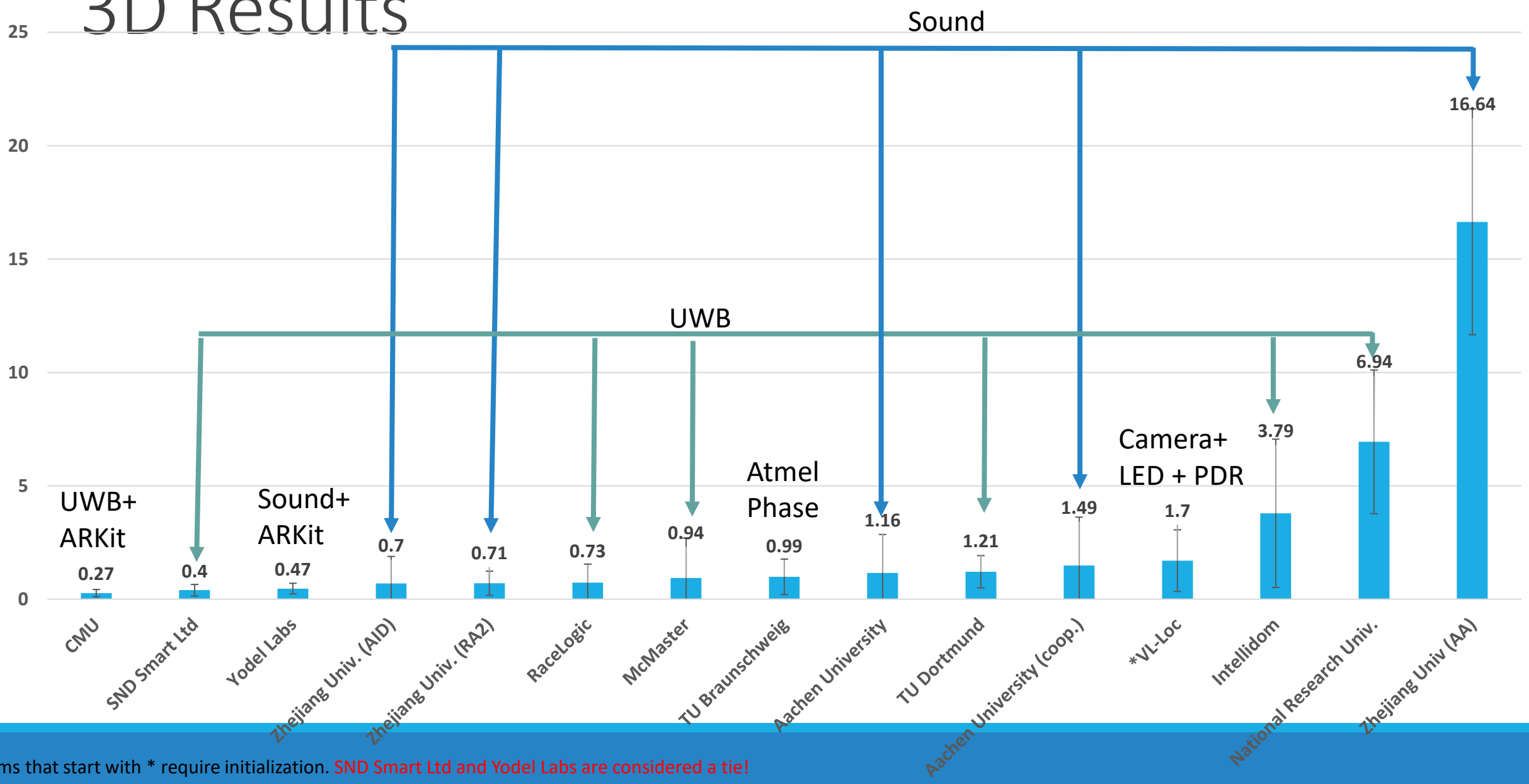




Teams that start with * require initialization.

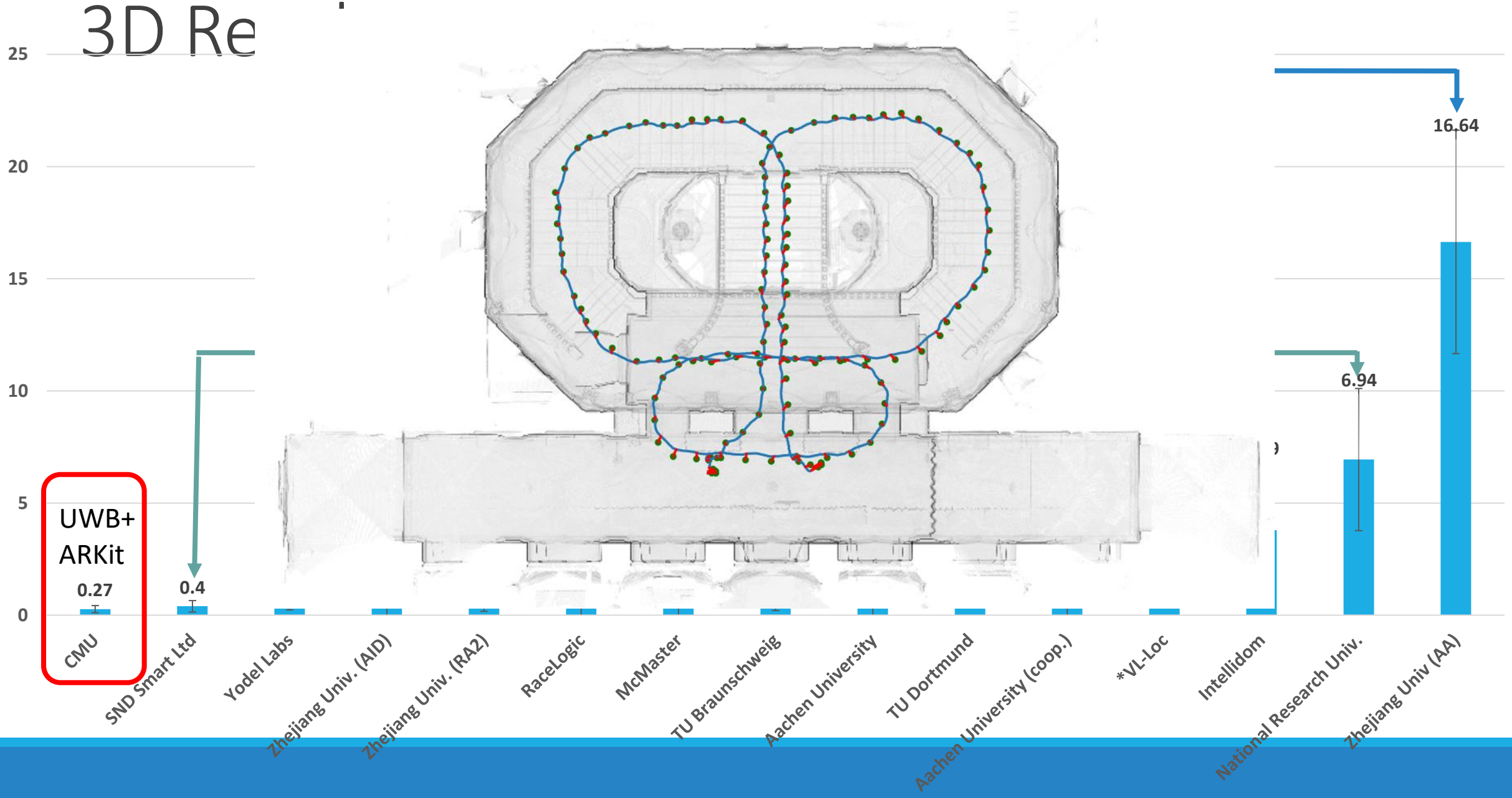
Naviguy and Ariel Univ. were considered a tie! Ariel University is the winner as Naviguy required initialization while Ariel University did not.

3D Results



Teams that start with * require initialization. SND Smart Ltd and Yodel Labs are considered a tie!

3D Re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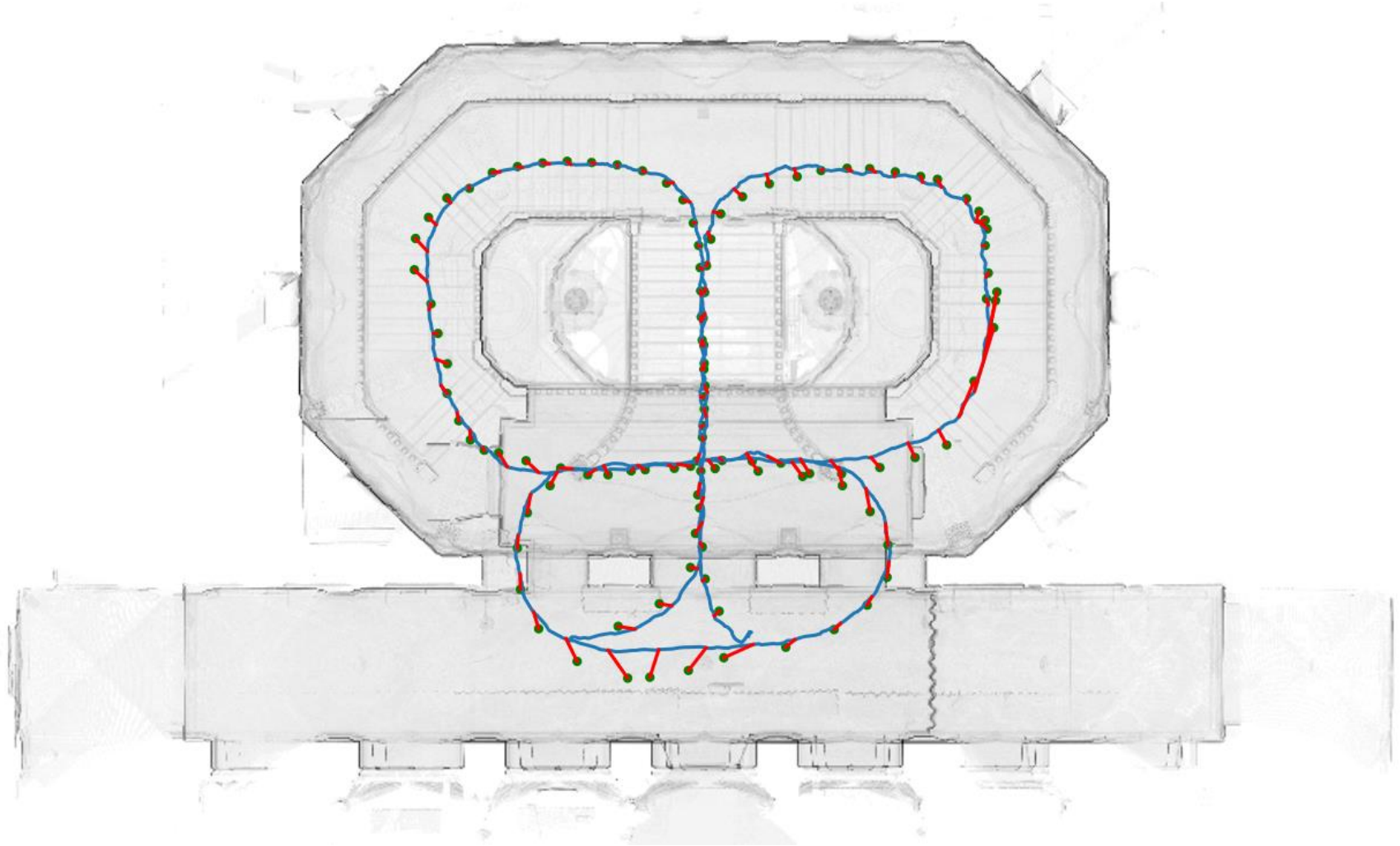
CMU
SND Smart Ltd
Yodel Labs
Zhejiang Univ. (AID)
Zhejiang Univ. (RA2)
RaceLogic
McMaster
TU Braunschweig
Aachen University
TU Dortmund
Aachen University (coop.)
*VL-Loc
Intellidom
National Research Univ.
Zhejiang Univ (AA)

3D Res



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CMU
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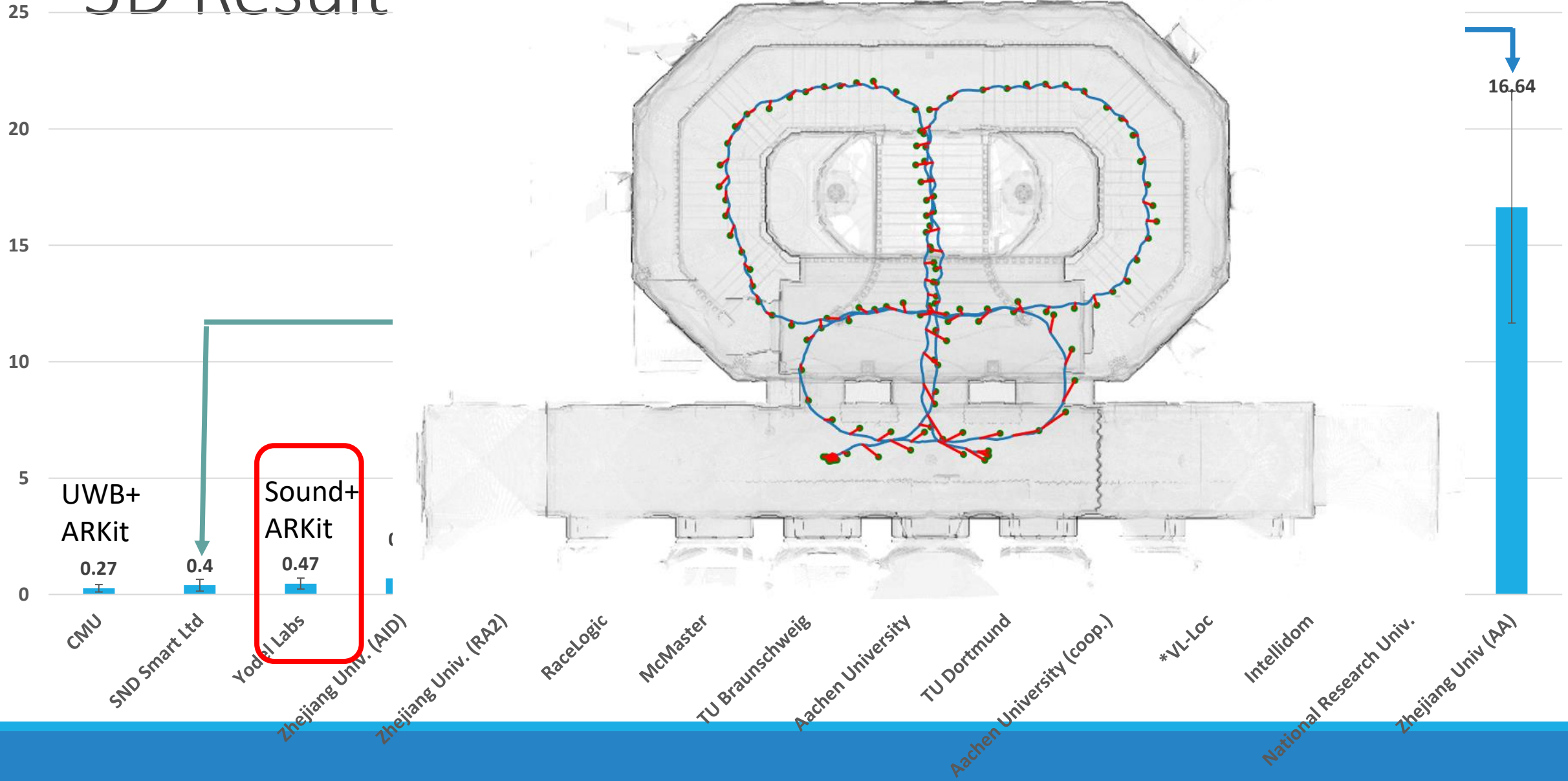
McMaster
TU Braunschweig
Aachen University
TU Dortmund
Aachen University (coop.)
*VL-Loc
Intellidom
National Research Univ.
Zhejiang Univ (AA)

3D Result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CMU
SND Smart Ltd
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McMaster
TU Braunschweig
Aachen University
TU Dortmund
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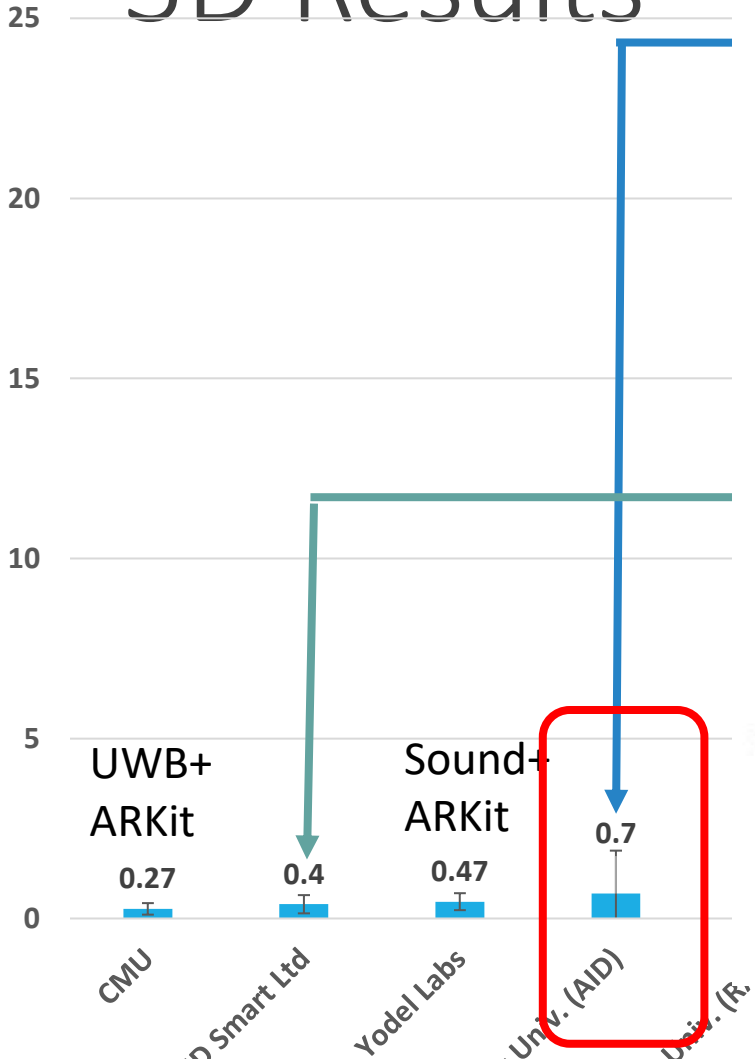
*VL-Loc
Intellidom
National Research Univ.
Zhejiang Univ (AA)

3D Results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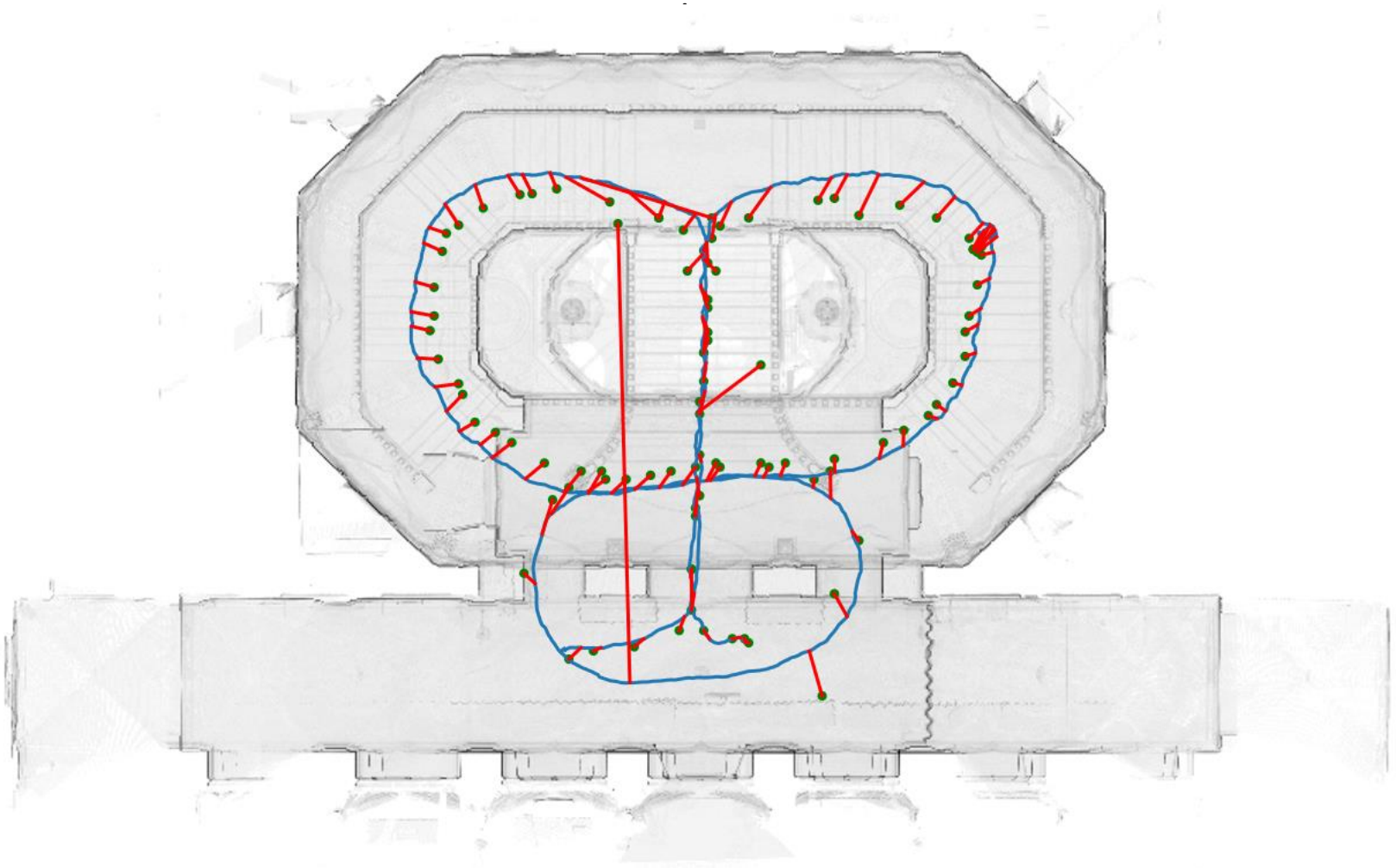
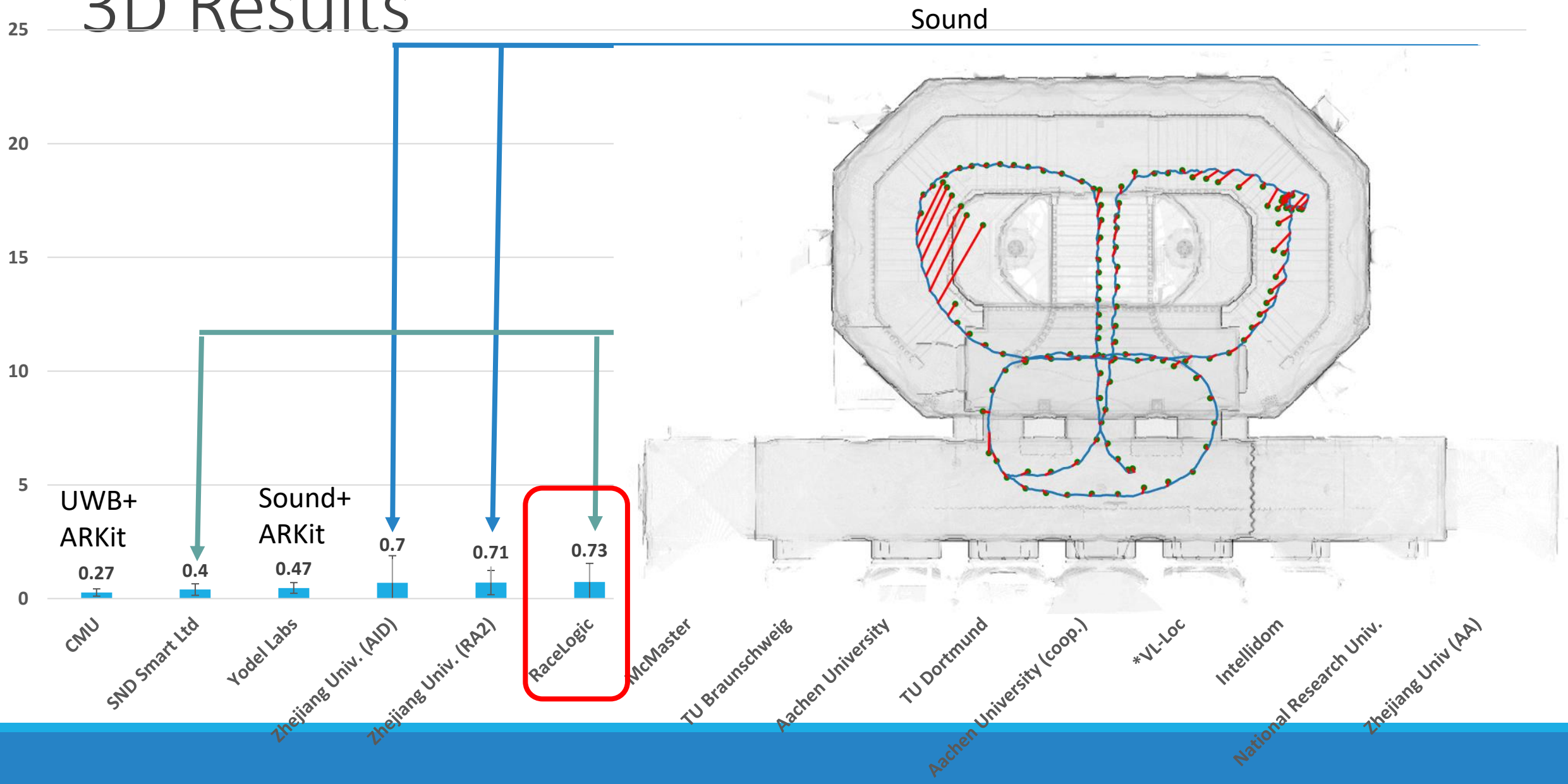
Zhejiang Univ. (AID)



3D Results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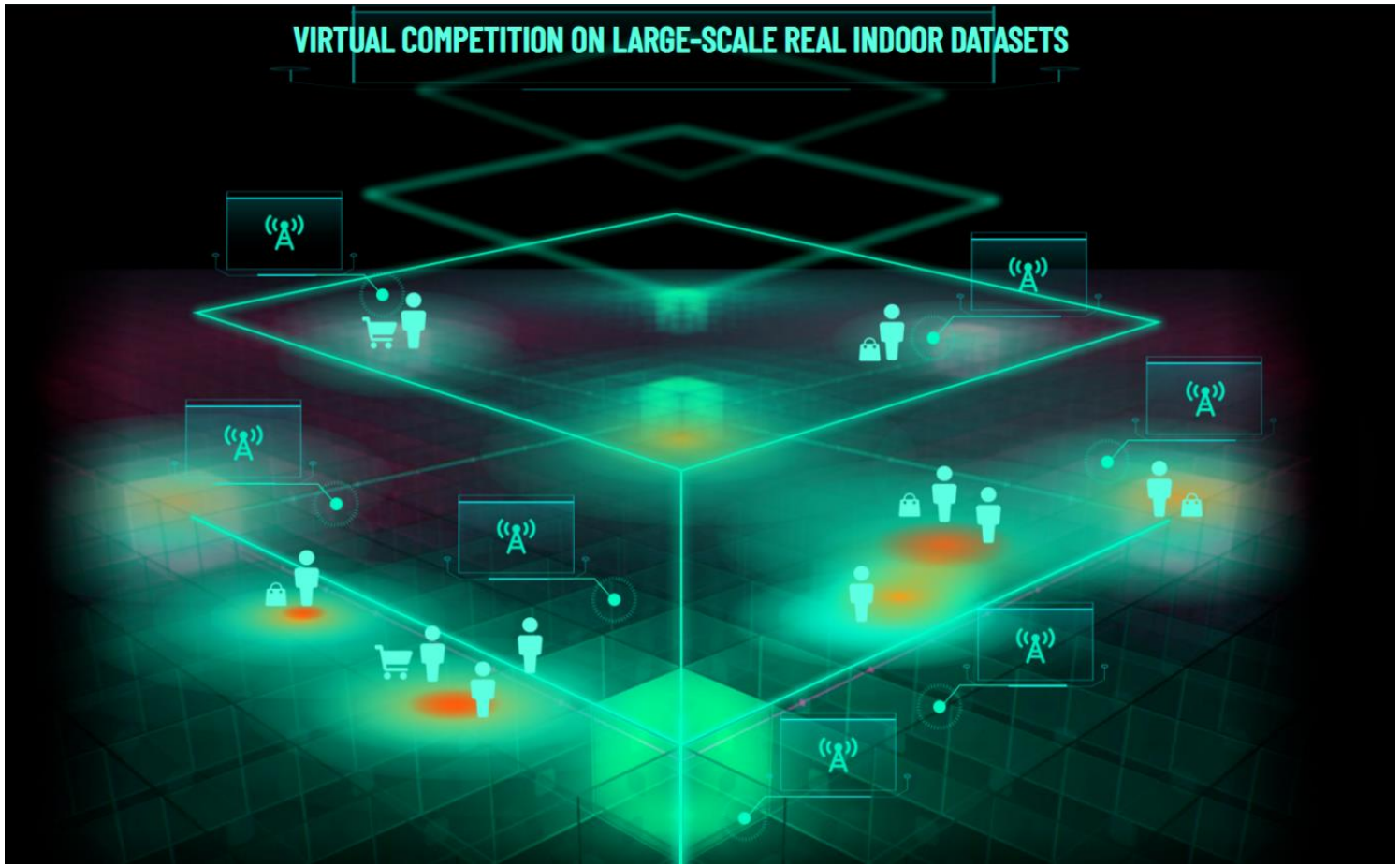
SND Smart Ltd
Yodel Labs
Zhejiang Univ. (AID)
Zhejiang Univ. (RA2)
RaceLogic
McMaster
TU Braunschweig
Aachen University
TU Dortmund
Aachen University (coop.)
*VL-Loc
Intellidom
National Research Univ.
Zhejiang Univ (AA)

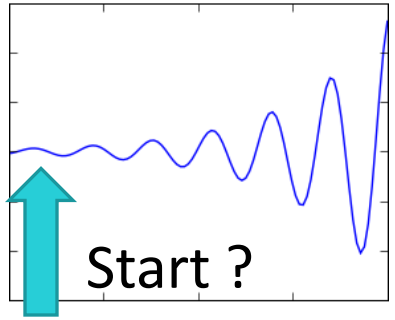
2020: Indoor Location Competition 2.0



- Completely Virtual, Open Competition
- 30,000 traces from over 200 buildings
- $10,000 Award
- 1,170 teams participated!
- Best results:
  Average Location Error < 1.5m

Practice: What's Hard About Indoor Localization

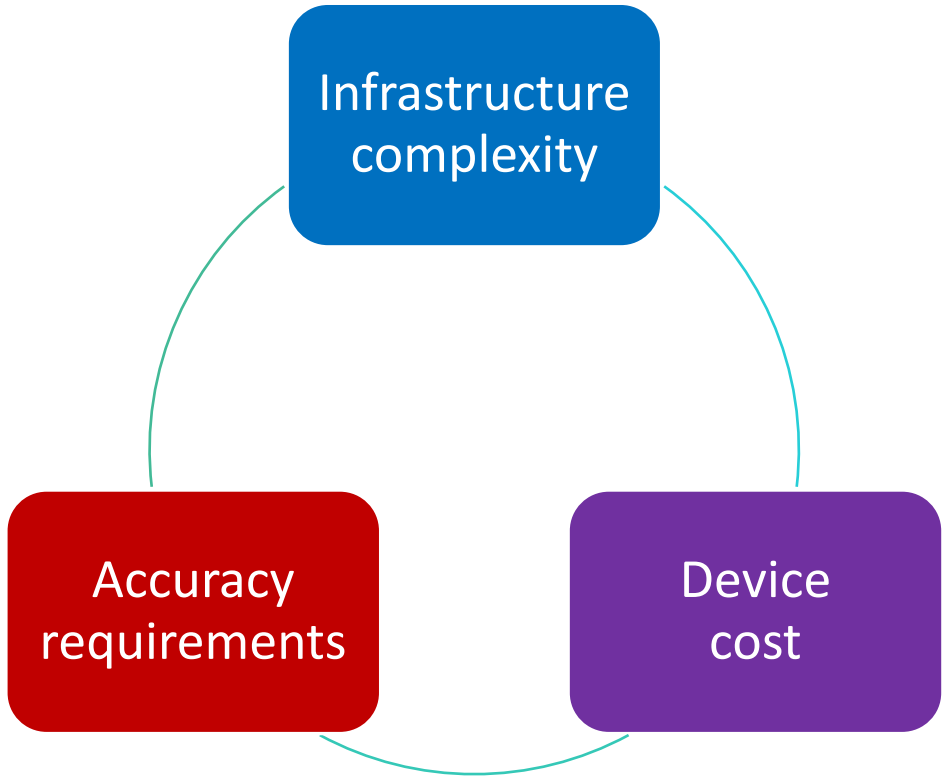
- **Inaccurate measurements**
  - Receiving signal phases and amplitudes (higher frequencies and higher bandwidths are better)
  - Time synchronization
  - Multi-paths fading and reflections
  - Missing line of sight
- **Environments change over time**
  - Setup re-arranged
  - Signal source (beacons) replaced
  - Signal inference
  - Human movements
- **Device variations**
- **Infrastructure cost**



Detecting the start of Rx is hard due to "gradual signal build up"

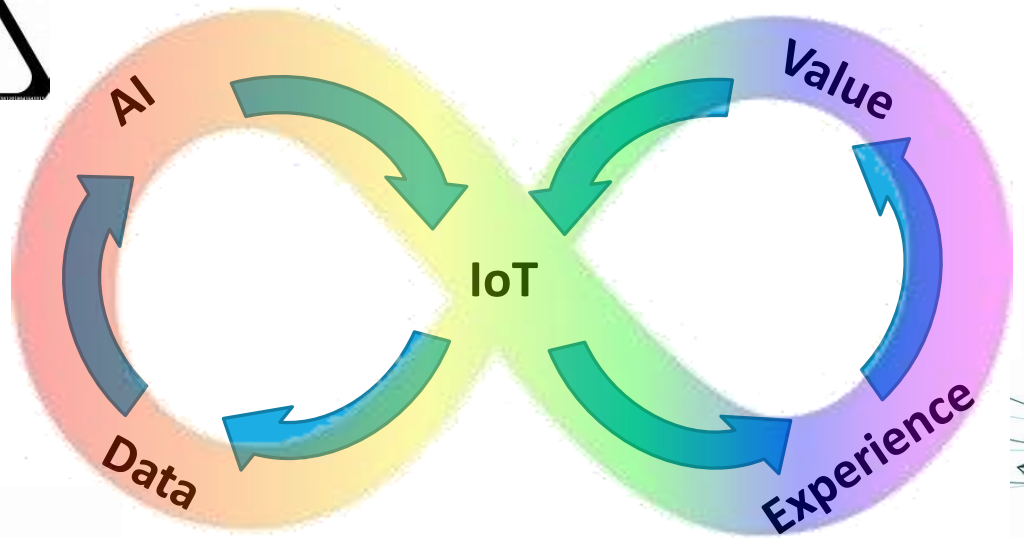
There is NO Single Best Solution

Find the right one, not the best one



- There is a huge variety of signals and techniques for indoor location sensing.
- A pushpin is not the end.
  - Indoor maps
  - Place semantics
  - Adoption paths

Close the Loop with Value Proposition



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