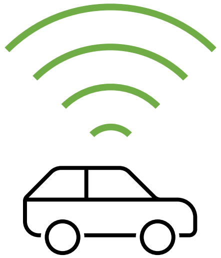
Depth Map Estimation in 6G mmWave systems

Steve Blandino, Raied Caromi, Jelena Senic

National Institute of Standards and Technology
U.S. Department of Commerce

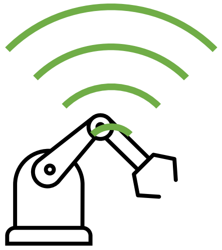
Diversification of applications

Smart Health



Smart Mobility

Smart Home/Cities



Smart Industries

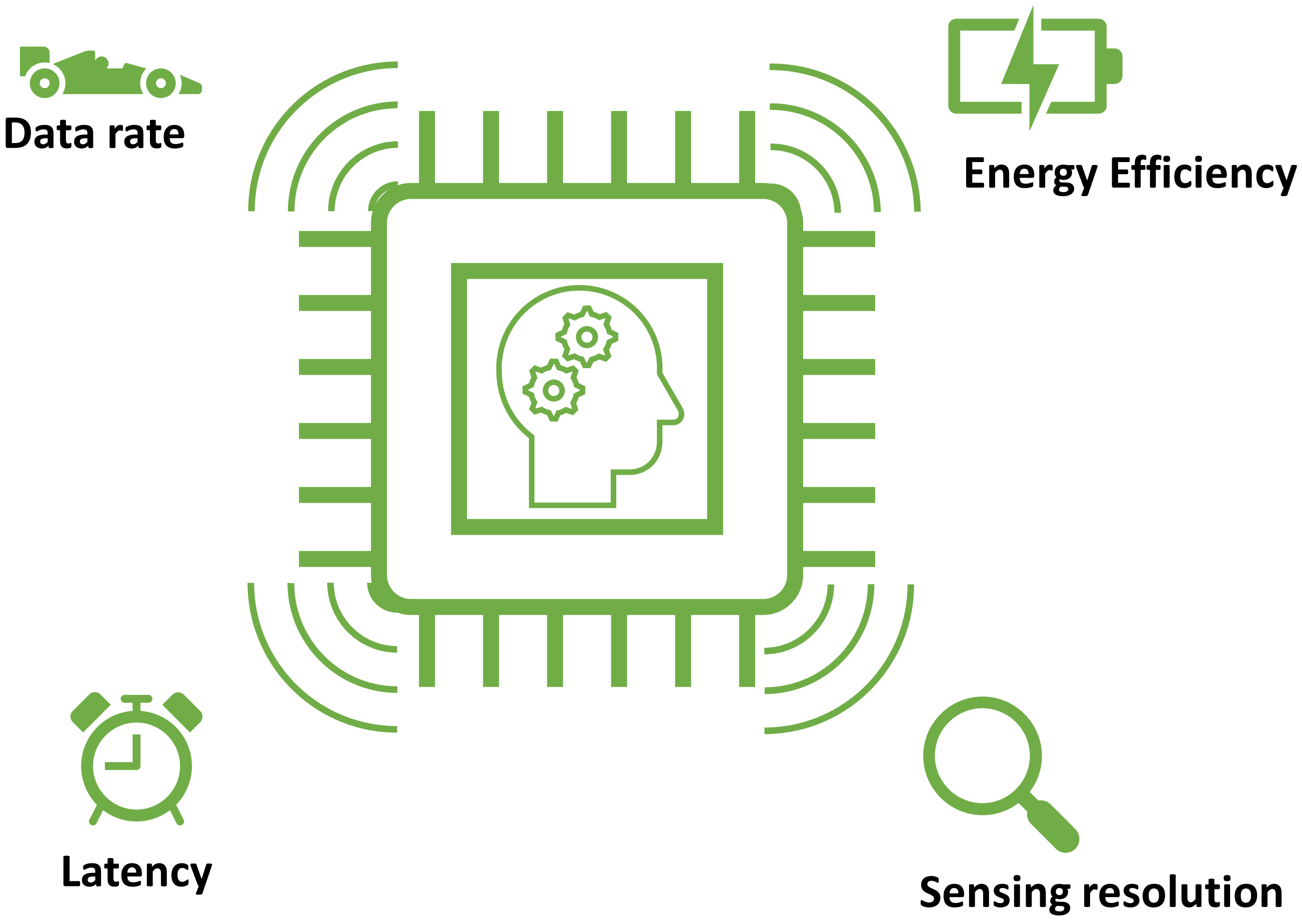
Vital sign monitoring, liveliness detection, fall detection

Traffic monitoring, target classification, autonomous driving, 3D vision, driver sleepiness

Activity/Gesture recognition, 3D vision, presence detection/counting

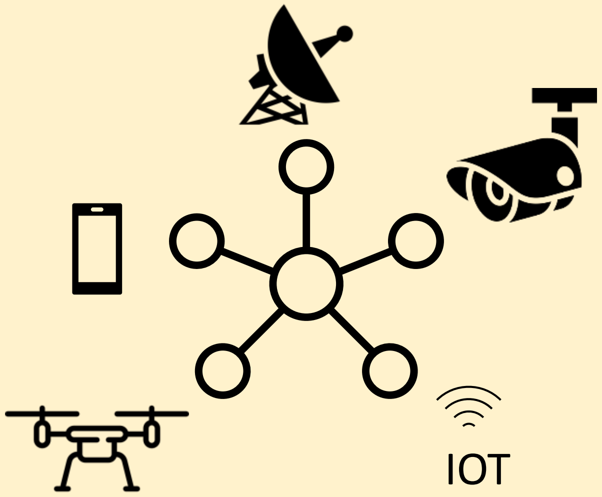
Autonomous robots/drones, 3D vision

Intelligence for adaptive network



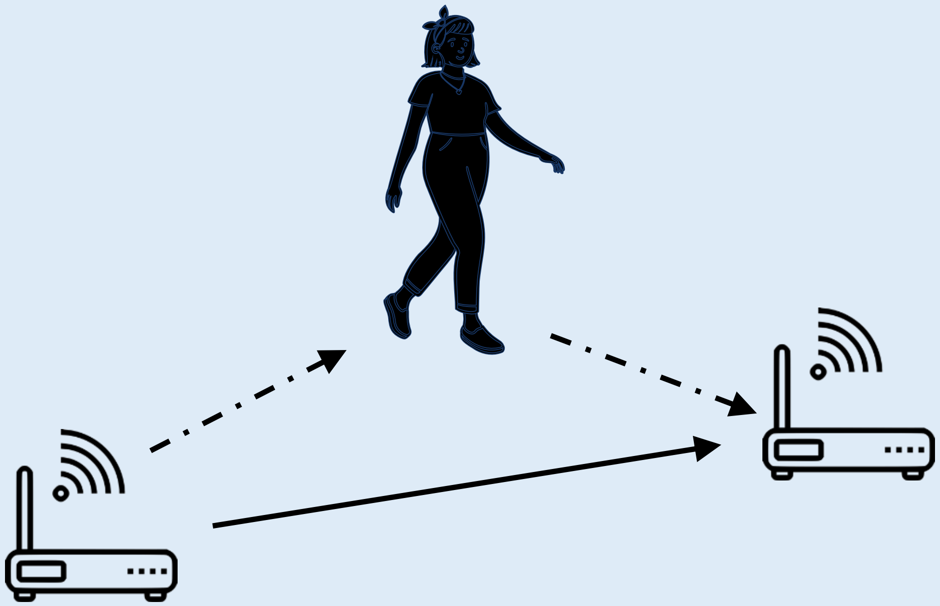
Acquiring multi-dimensional information

Sensor Networks



- Native multi-dimensional data
- Extra hardware investment and power consumption.
- Not scalable over large networks.

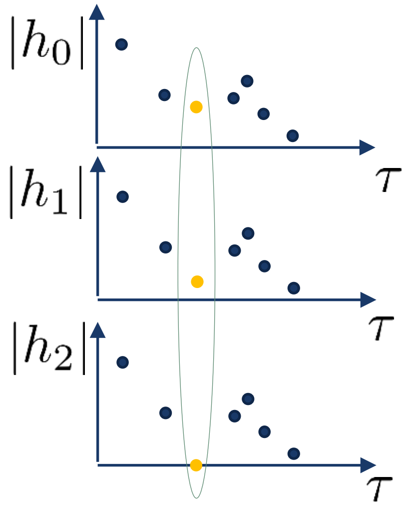
Integrated Sensing And Communication (ISAC)

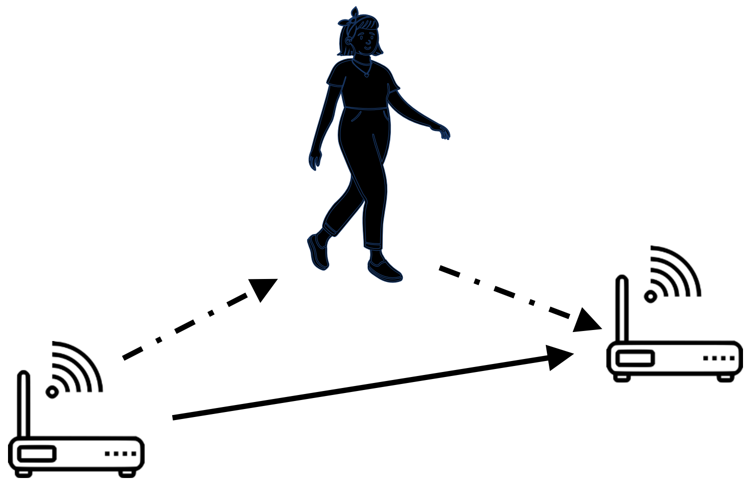


- Source of a massive amount of data
- Re-using same hardware and spectrum
- Extra processing required to acquire multi-dimensional data

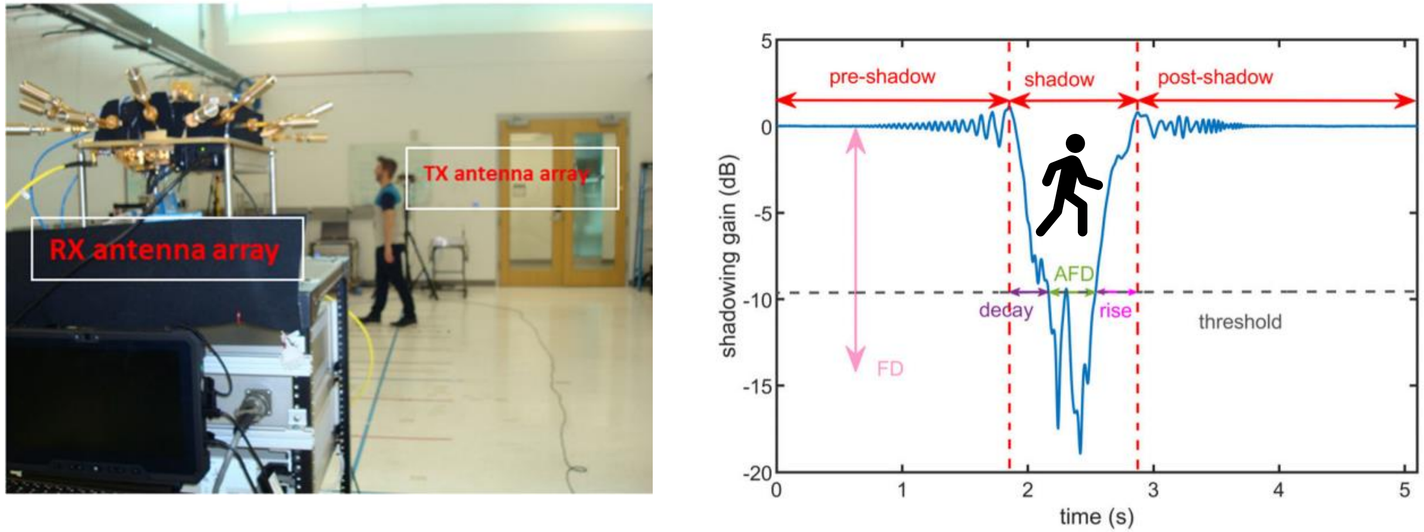
From communication devices to sensors

- Integrated Sensing and Communication:
  - Reuse **spectrum, devices and protocols to perform both communication and sensing.**
  - Keep cost and power of future networks under control
- Sensing can be performed on communication networks by **tracking changes of wireless signals over time.**
  - Time-variations of the wireless signal can be analyzed using signal processing, ML/AI or both.

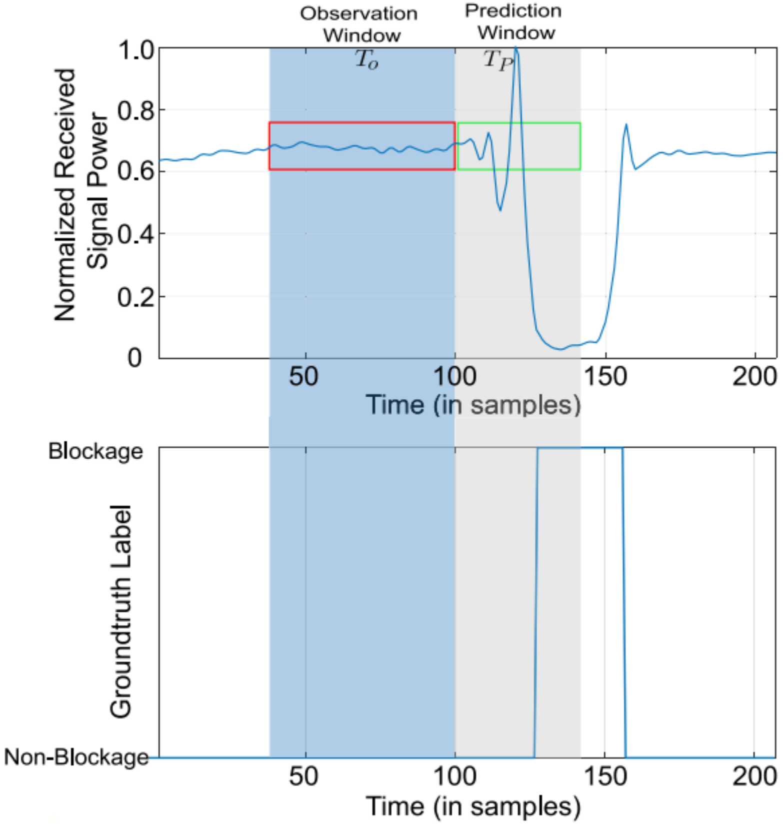




Communication waves to *see the physical world*



Effect of human presence on 60GHz propagation [1]

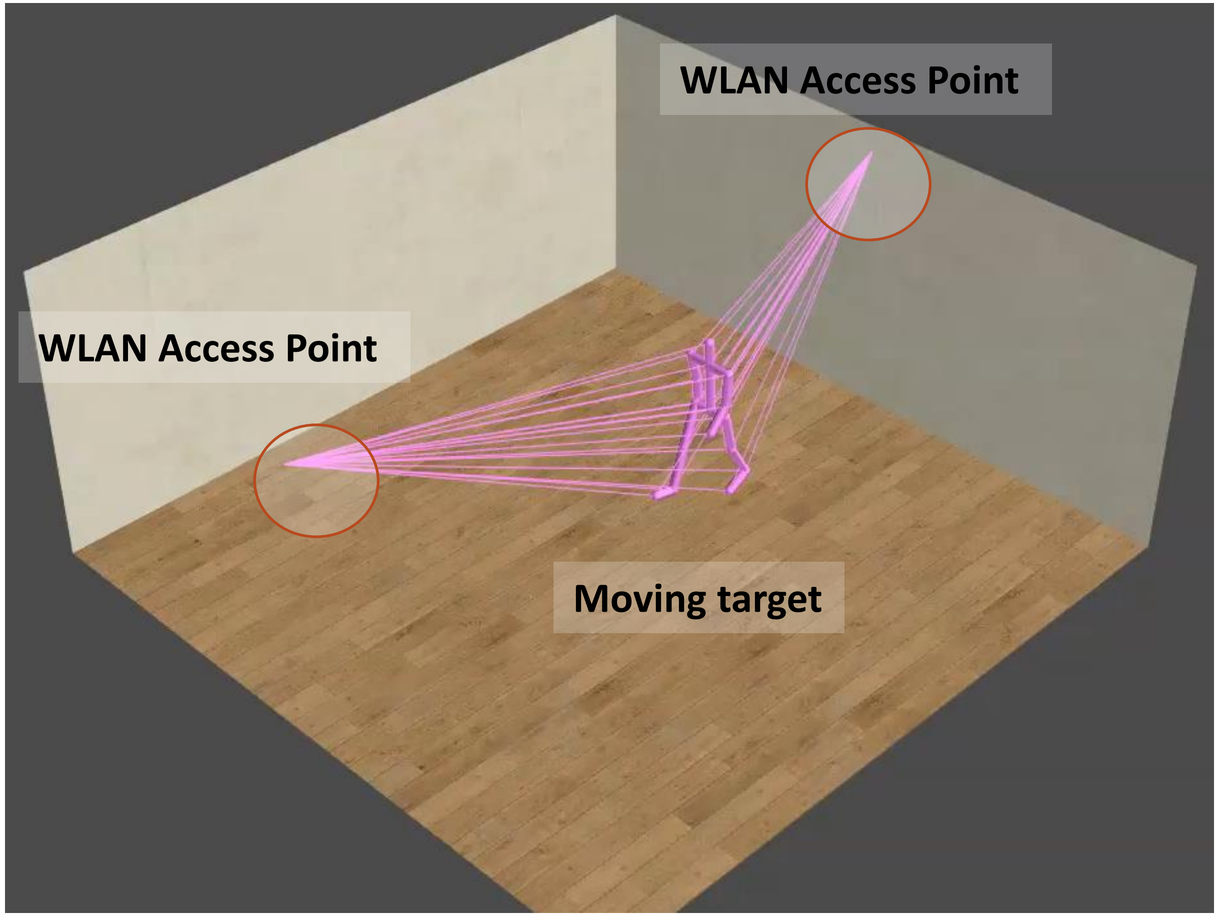


Blockage prediction exploiting RF knowledge [2]

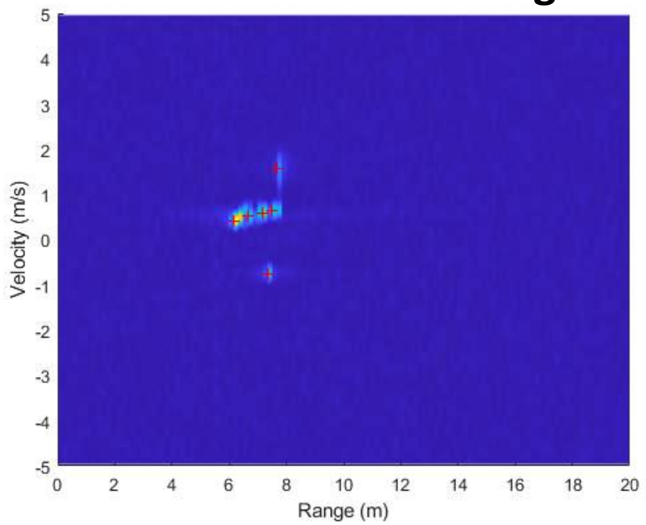
[1] A. Bhardwaj, D. Caudill, C. Gentile, J. Chuang, J. Senic and D. G. Michelson, "Geometrical-Empirical Channel Propagation Model for Human Presence at 60 GHz," in IEEE Access, vol. 9, pp. 38467-38478, 2021, doi: 10.1109/ACCESS.2021.3063655.

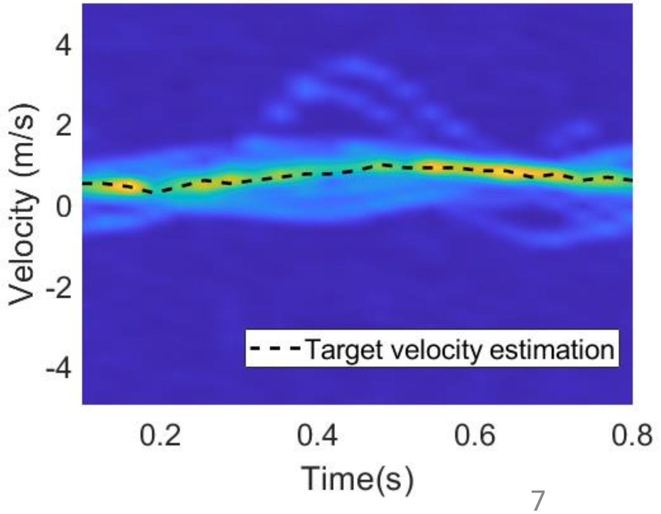
[2] S. Wu, M. Alrabeiah, C. Chakrabarti and A. Alkhateeb, "Blockage Prediction Using Wireless Signatures: Deep Learning Enables Real-World Demonstration," in IEEE Open Journal of the Communications Society, vol. 3, pp. 776-796, 2022, doi: 10.1109/OJCOMS.2022.3162591.

Communication waves to *see the physical world*



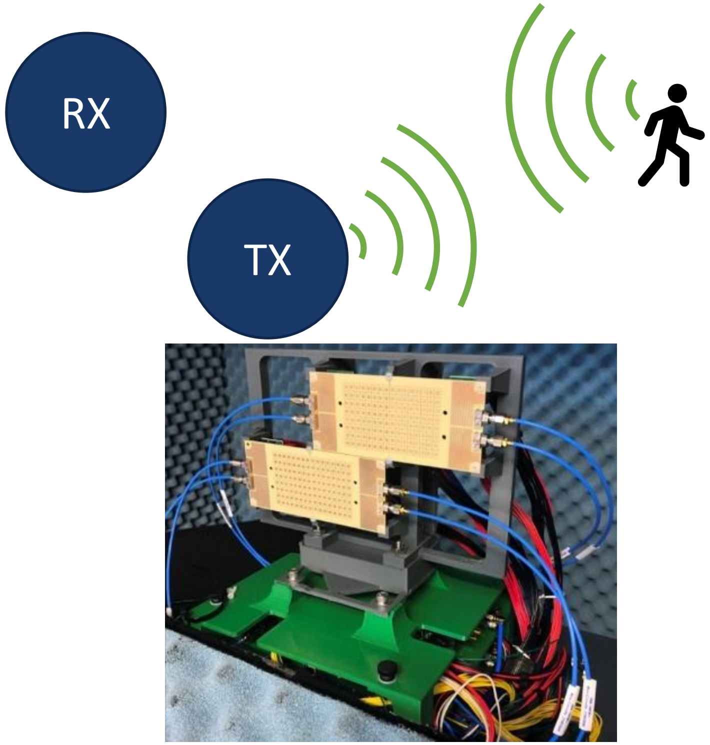
Range/velocity estimation tracking changes of wireless signals over time

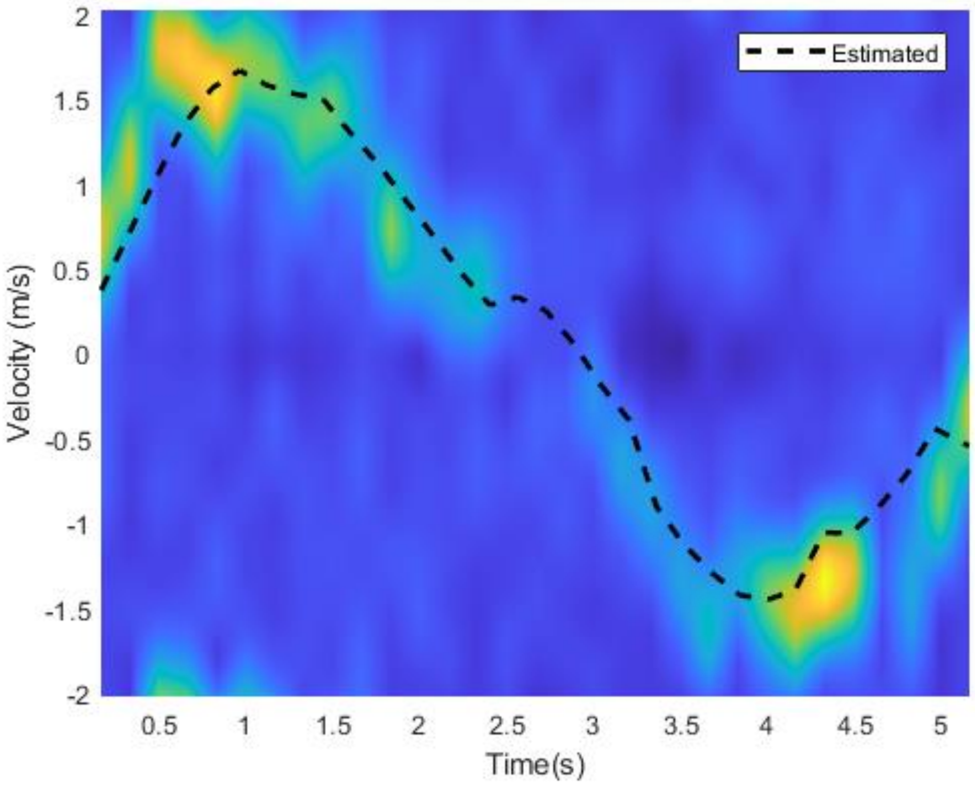




S. Blandino, et al, "Tools, Models and Dataset for IEEE 802.11ay CSI-based Sensing," 2022 IEEE Wireless Communications and Networking Conference (WCNC), https://github.com/wigig-tools

Communication waves to *see the physical world*





S.Y. Jun, J. Chuang, D. Caudill, C. Gentile, S. Blandino, N. Golmie, “NIST mmWave Phased-Array Channel Sounder for Human Sensing,” Document IEEE 802.11-21/1675r0, Oct. 2021. https://mentor.ieee.org/802.11/dcn/21/11-21-1675-00-00bf-mmwave-phased-array-channel-sounder-for-human-sensing.pptx.

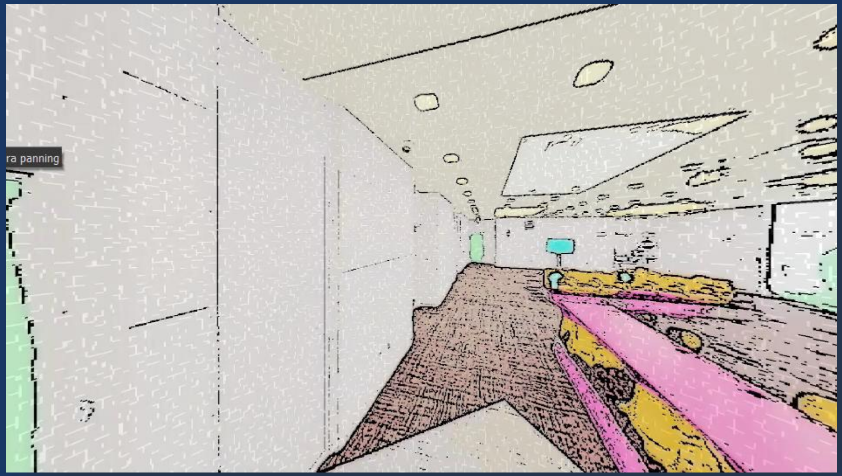
S. Blandino, T. Ropitault, N. Varshney, J. Wang, J. Senic, J. Chuang, C. Gentile, N. Golmie, "DMG/EDMG Link Level Simulation Platform," Document IEEE 802.11-22/0803r0, May 2022. https://mentor.ieee.org/802.11/dcn/22/11-22-0803-00-00bf-dmg-edmg-link-level-simulation-platform.pptx

Communication waves to *create a digital world*

Physical world

ISAC + AI/ML

Digital world

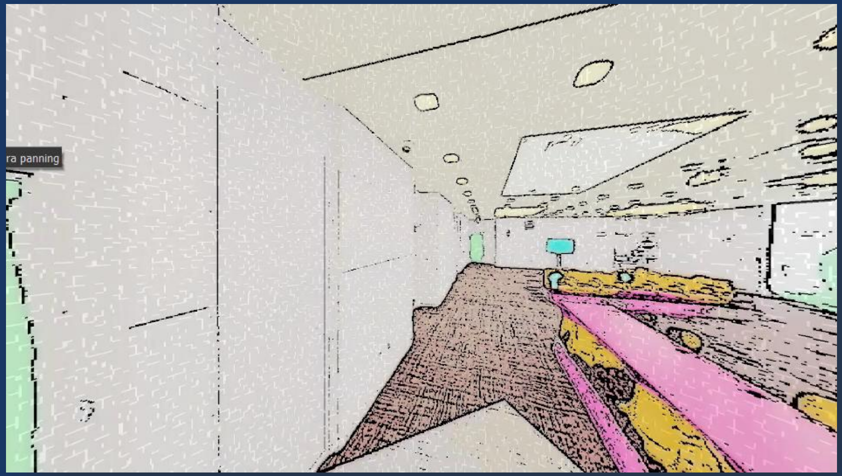


Physical solutions in the digital world

Physical world

ISAC + AI/ML

Digital world

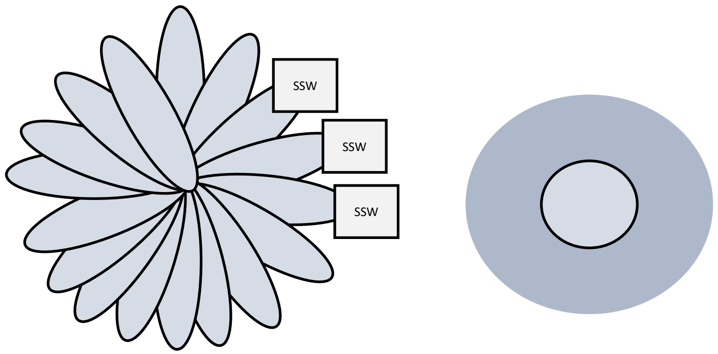


Inference

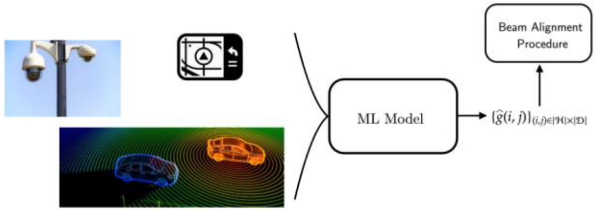
Simulation, verification, prediction, control…

Example: beam selection at millimeter wave

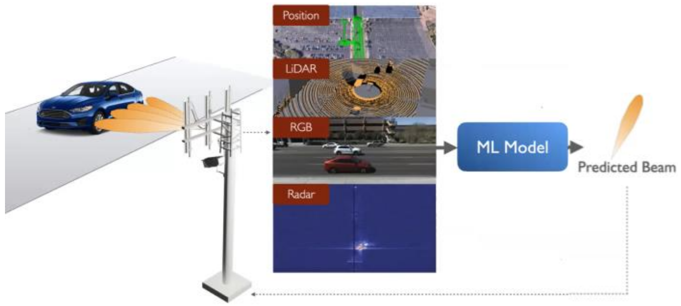
Traditional RF



Sensor Networks + ML/AI

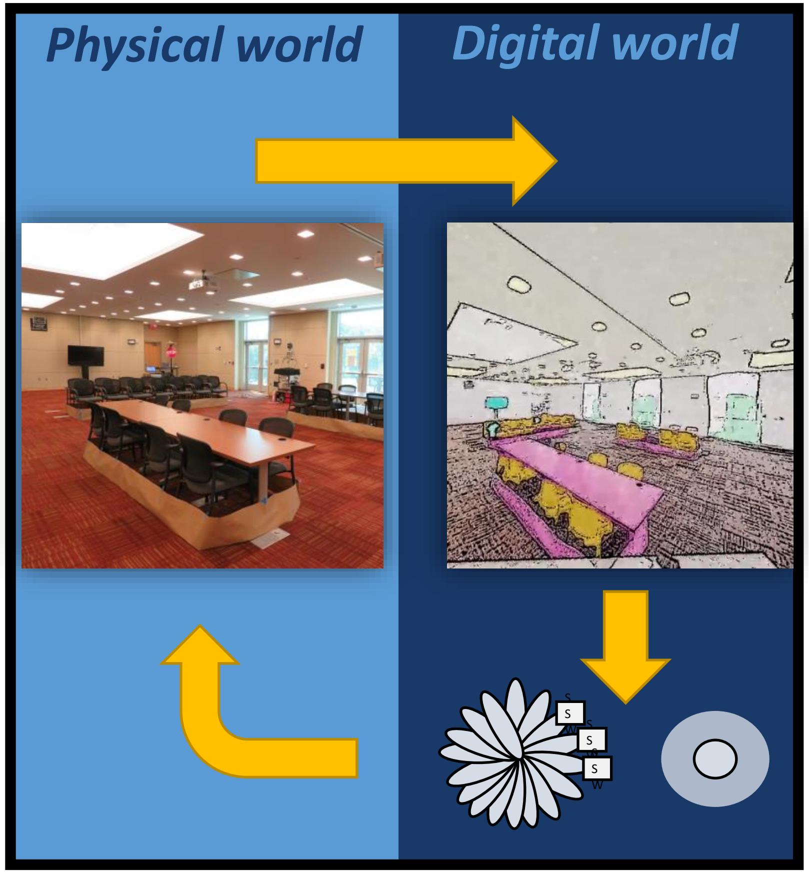


AI-Aided mmWave Beam Selection for Vehicular Communication, ITU ML/AI in 5G 2020

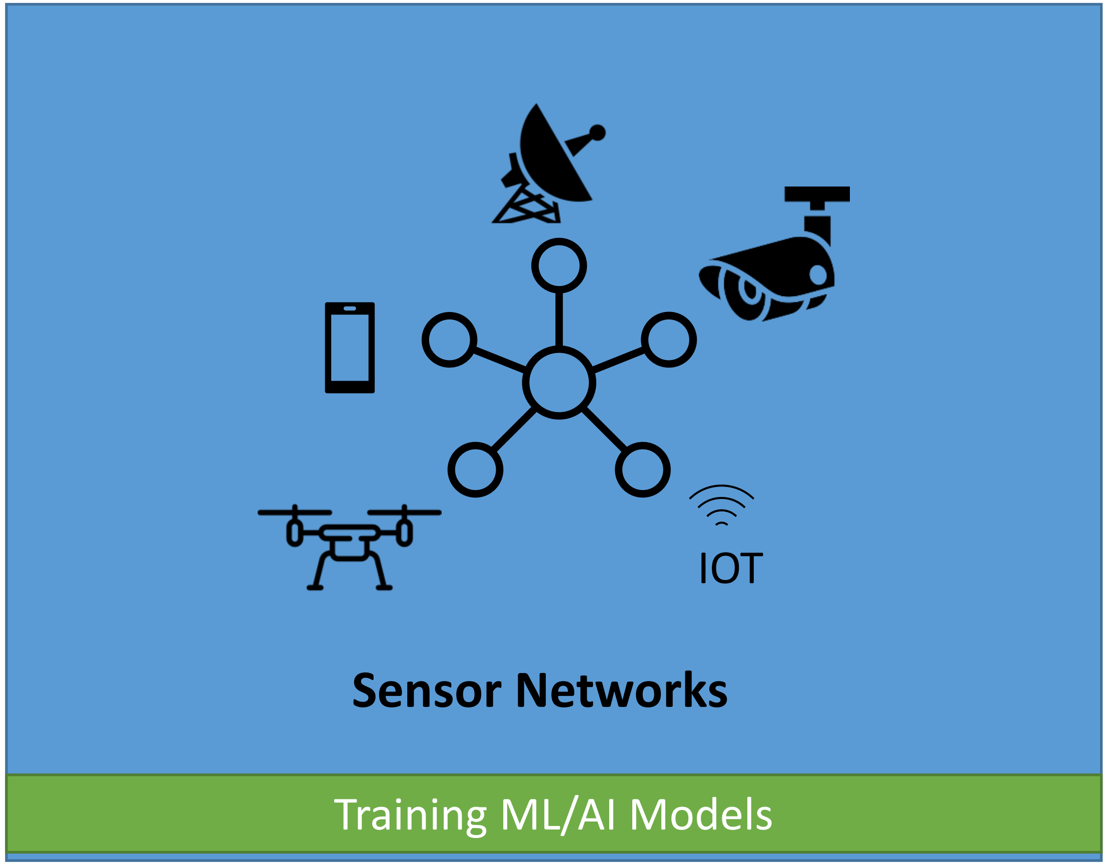


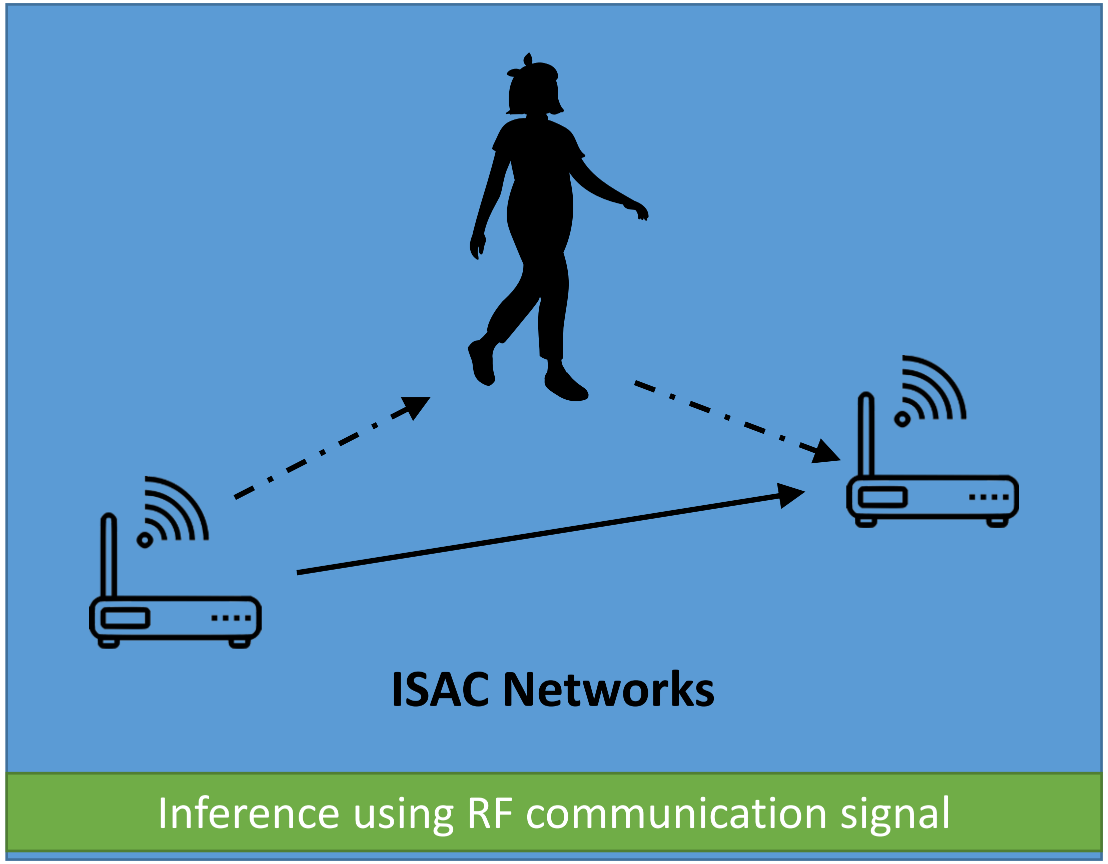
Multi-modal sensing aided beam selection, ITU ML/AI in 5G 2022

ISAC Networks + ML/AI



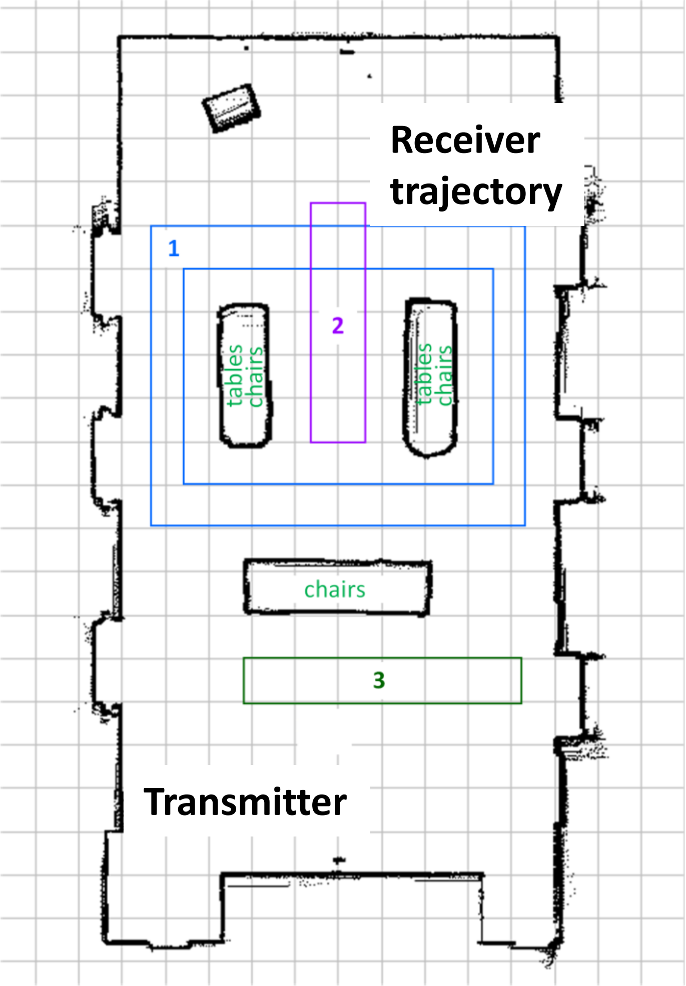
Sensor data to design ML/AI models





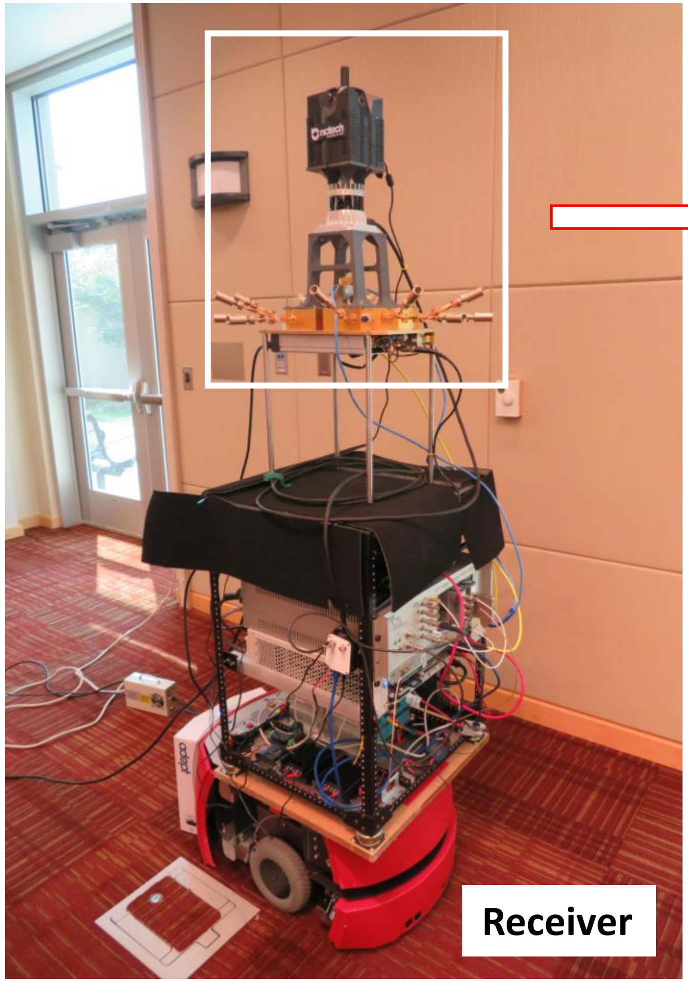
NIST MEASUREMENTS

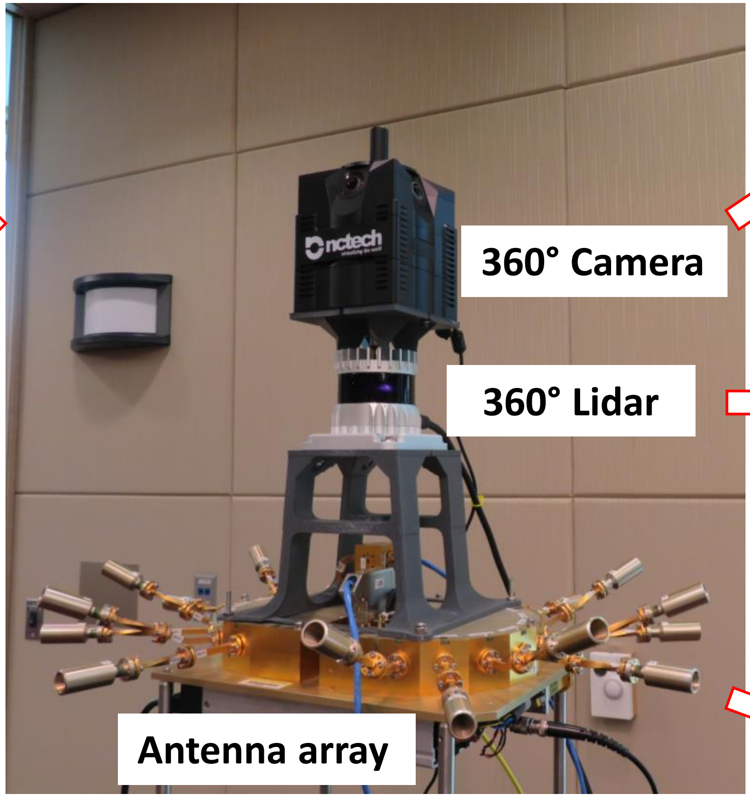
Measurement Environment

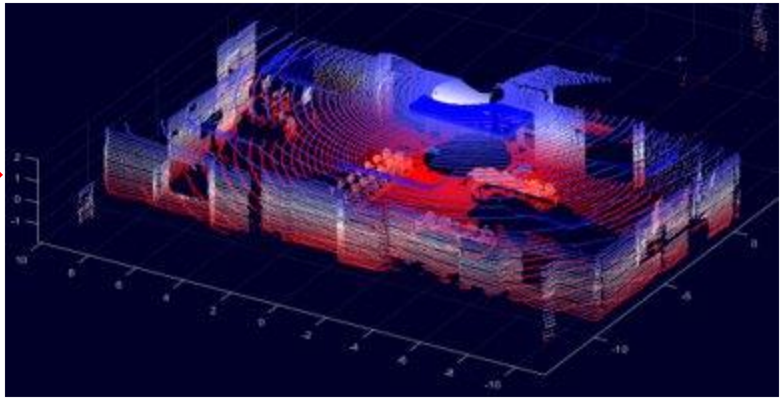


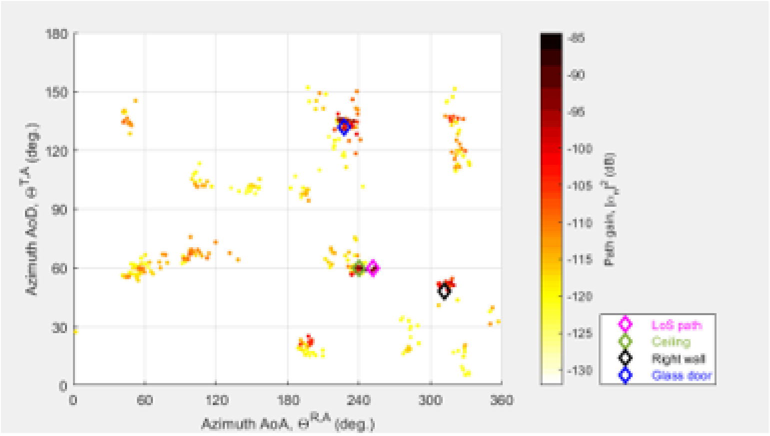
The transmitter was fixed in the corner of the room, while the receiver was moving in three areas across the room.

Measurement System & Data Collection







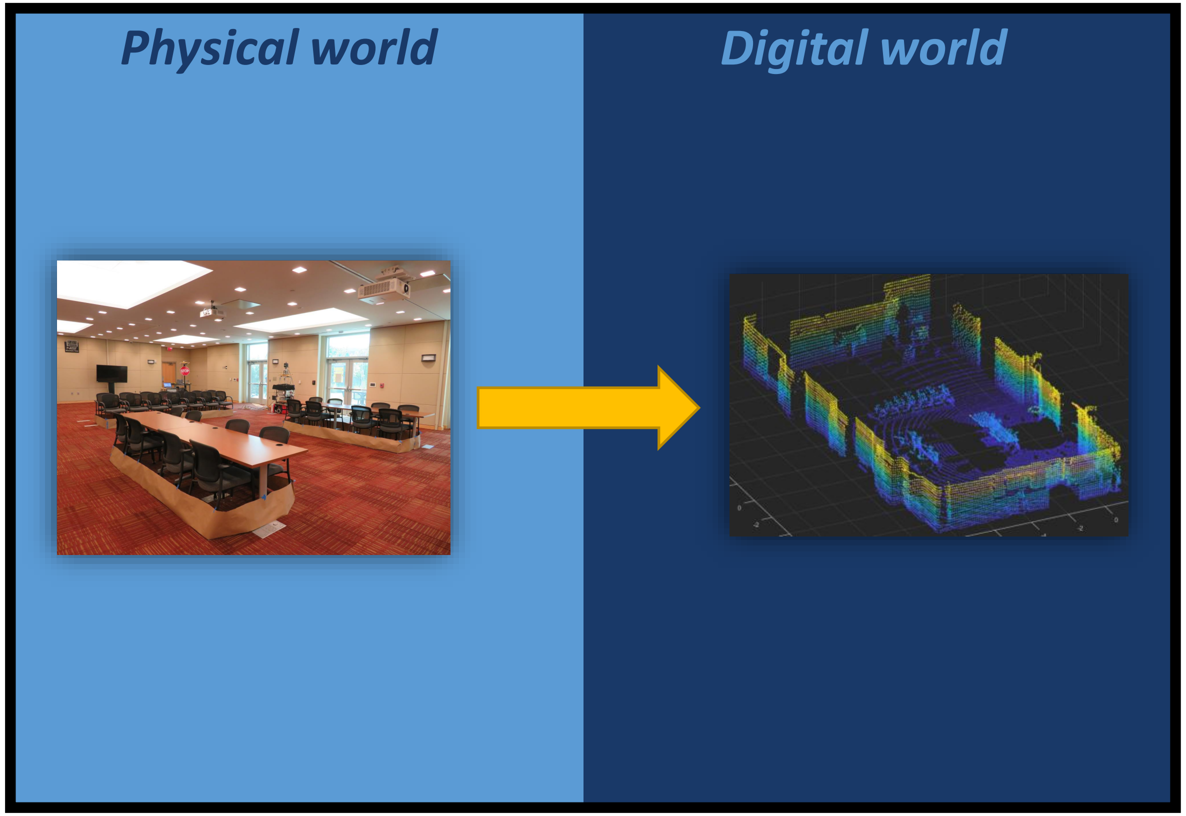


While in motion, the receiver collected: RF data, 360° lidar data, and 360° photos of the environment.

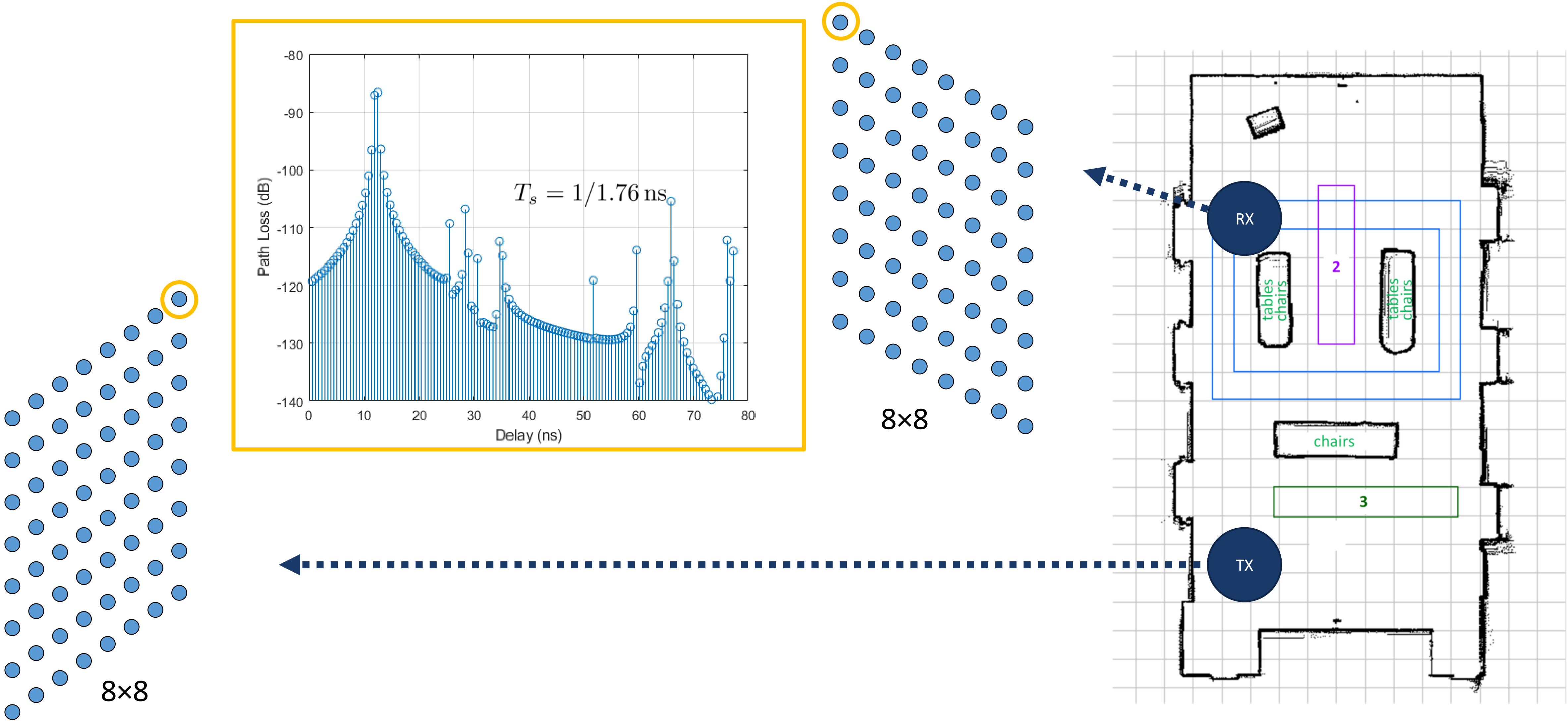
ITU AI/ML IN 5G CHALLENGE

Depth Map estimation using mm-wave+ML

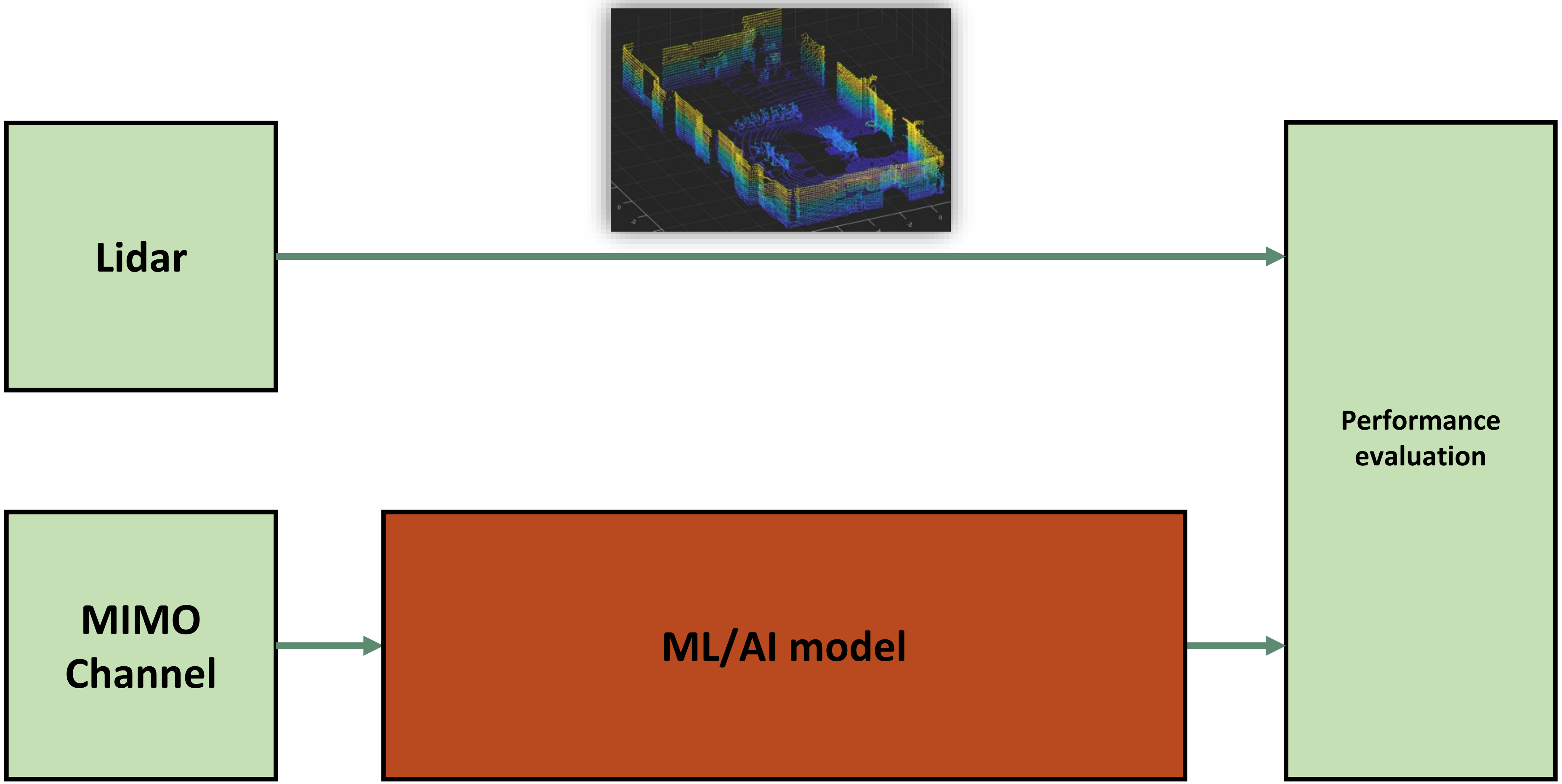
- Two MIMO nodes
  - One fixed transmitter
  - One moving (position and orientation) receiver
- Observation of environment changes over time
  - Relative to position and orientation of the receiver
- **Challenge**: estimate the depth map of the environment at each receiver position, using mm-wave signals.



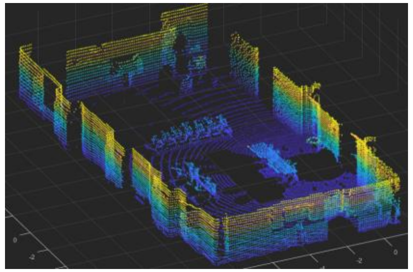
MIMO channel impulse response

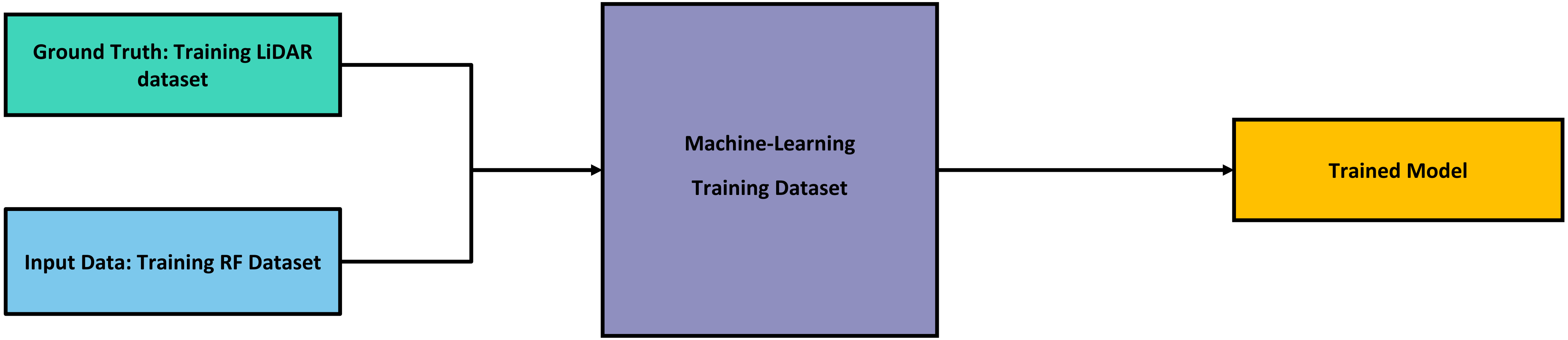


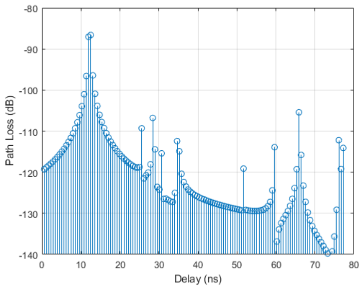
Challenge overview



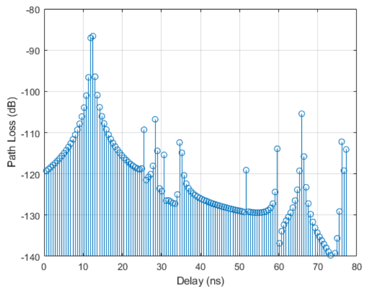
Training the model





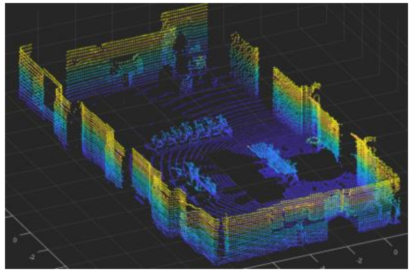


Evaluation of the model

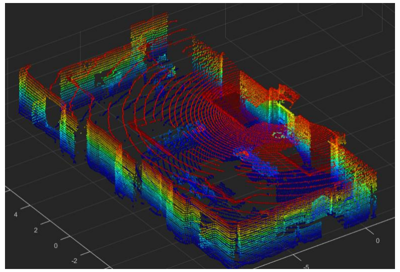


Input Data: RF Data Evaluation Dataset

Trained Model



Output: LiDAR Point Clouds



Ground Truth: LiDAR Evaluation dataset

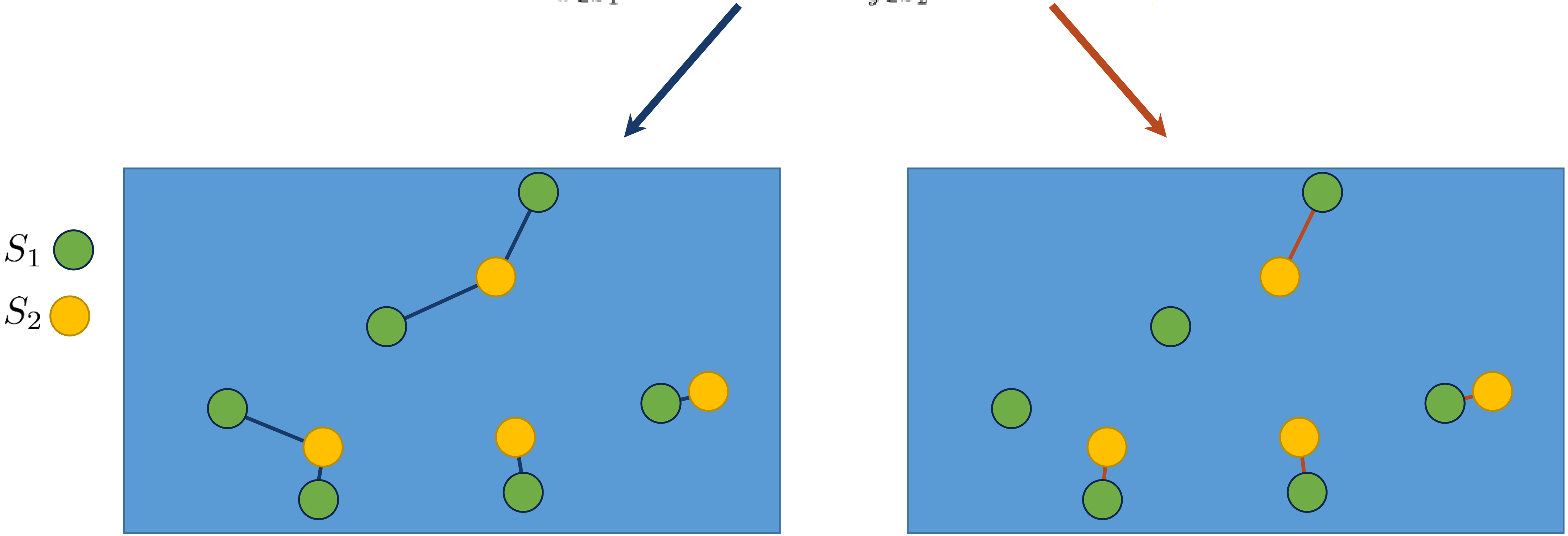
Evaluation

Training and evaluation dataset are collected in different areas of the room

Evaluation metric: Chamfer Distance

Chamfer Distance measures discrepancies between point clouds.

$$d_{CD}(S_1, S_2) = \sum_{x \in S_1} \min_{y \in S_2} \|x - y\|_2^2 + \sum_{y \in S_2} \min_{x \in S_1} \|x - y\|_2^2$$



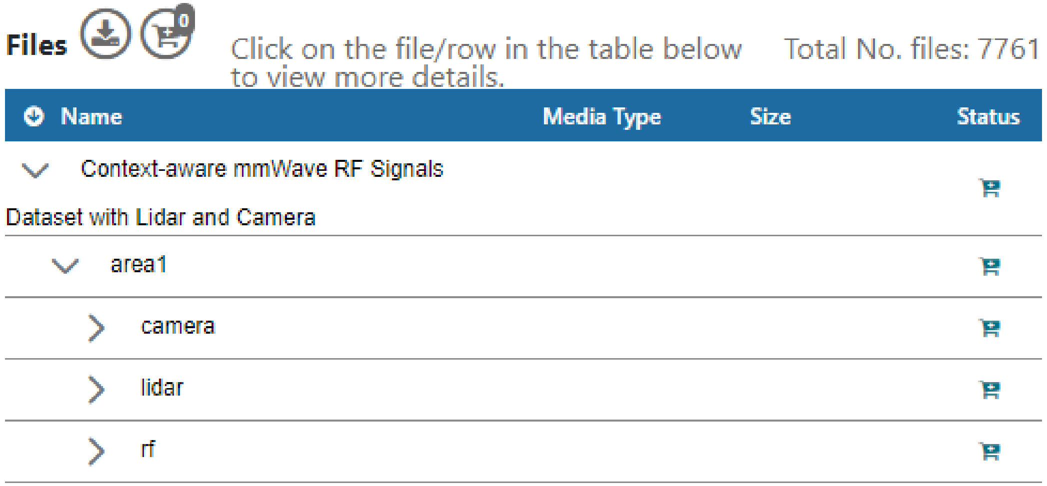
Guest Researcher position at NIST

- **Ranking:** based on average (over different positions) Chamfer Distance
- **Prize**: guest researcher position at NIST

DATASET AND FILE FORMAT

Dataset

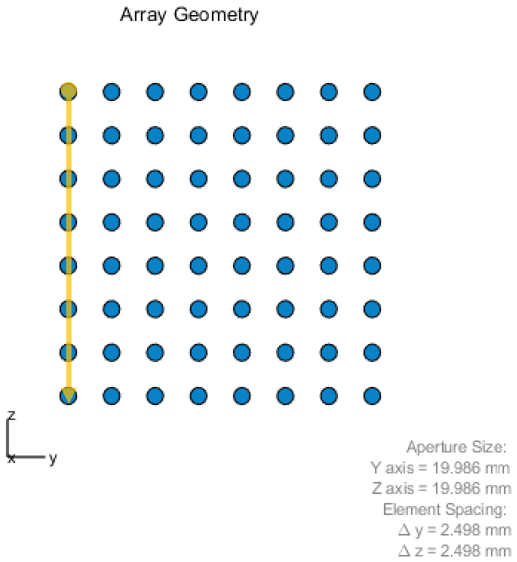
- Training dataset (Area1): "Context-aware mmWave RF Signals Dataset with Lidar and Camera"
  - Dataset website: https://datapub.nist.gov/od/id/mds2-2645

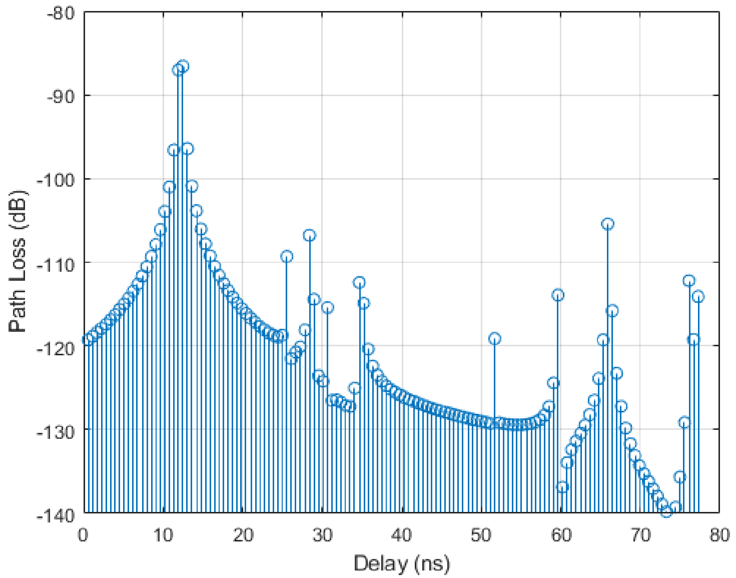


- Challenge and dataset related code @GitHub: https://github.com/usnistgov/ML5G-PS-004
- File Naming:
  - FileTypePrefix_<X*10^6+Index>.ext, where FileTypePrefix refers to the type of the file, X is area number, Index=[0, 1, 2, ….., N-1], N is number of cases, and ext is the file extension (mat, pcd, jpg).

RF data file format

- MIMO CIR format: .mat
- Rx antennas × Tx antennas × Delay taps
- Delay sampled at 1.76GHz

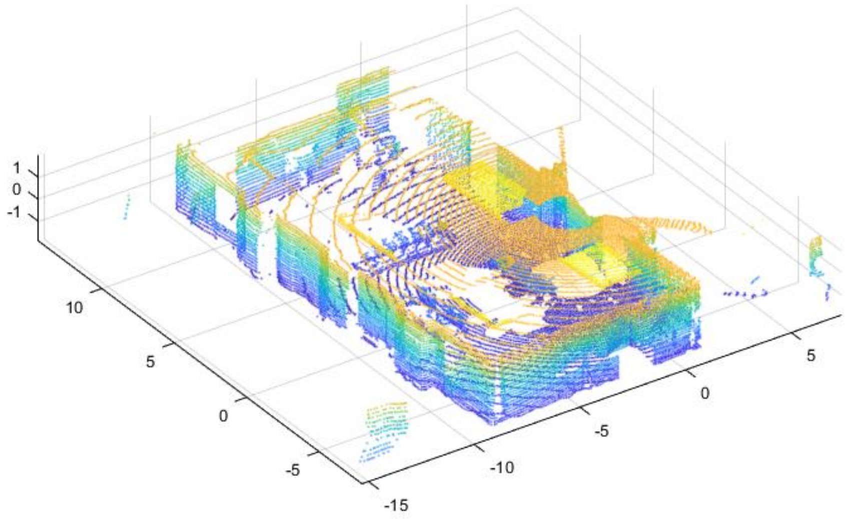





```
struct with fields:

  mimoCir: [64×64×136 double]
```

Lidar file format

- Lidar type: Ouster OS0-128
- Point cloud file format: PCD (binary) https://pointclouds.org/documentation/tutorials/pcd_file_format.html
- Point cloud data format: Unorganized and downsampled
- Datatype: Single (f32)
- How to read point cloud data:
  - MATLAB (recommended 2020b or newer)
  - Python, e.g. `Open3d` and `pyntcloud`
- *Example:*



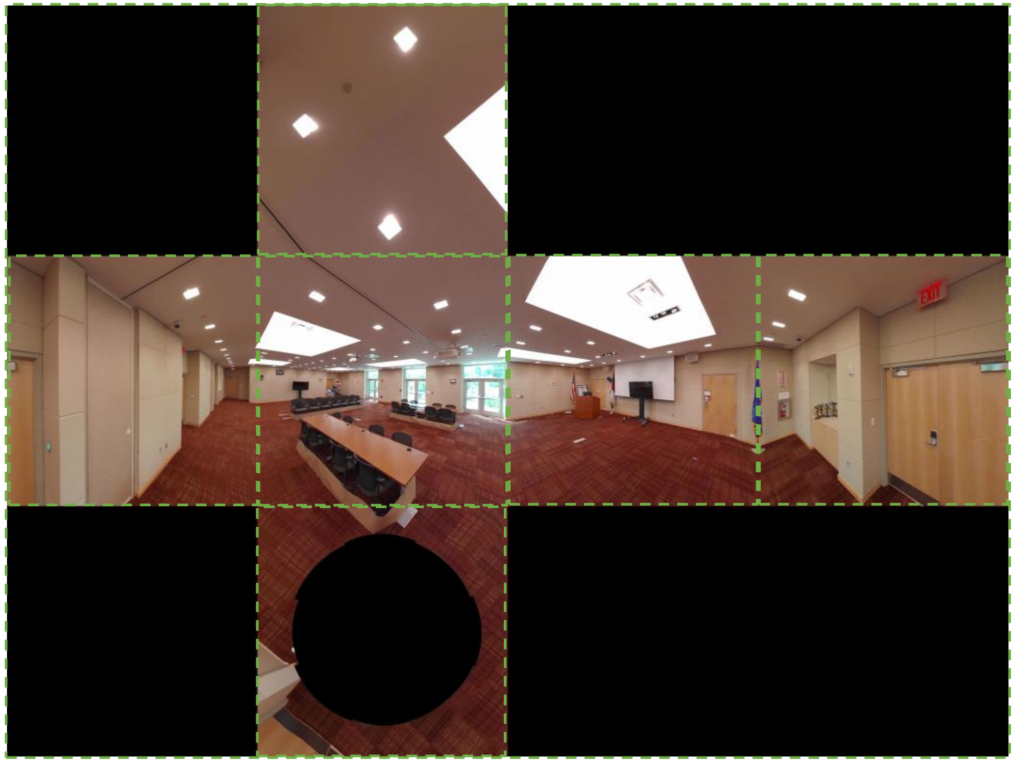

```
pointCloud with properties:

     Location: [32431×3 single]
        Count: 32431
      XLimits: [-15.2894 7.3702]
      YLimits: [-7.9645 14.3672]
      ZLimits: [-1.9031 1.9996]
        Color: []
       Normal: []
    Intensity: []
```

Image file format

- Image resolution: 11000x5500
- File type: JPG
- Projection: 360 image, Equirectangular

Equirectangular projection

Cubemap projection

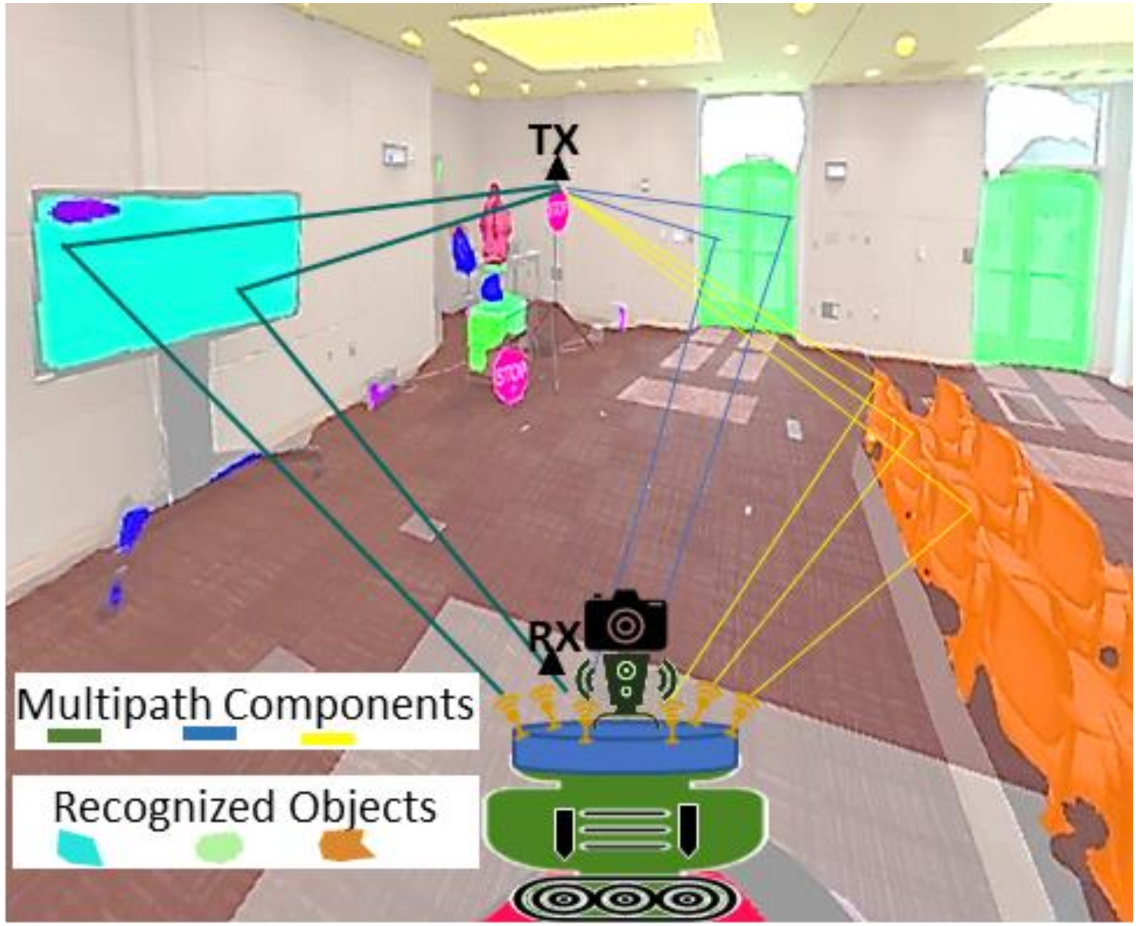


BONUS

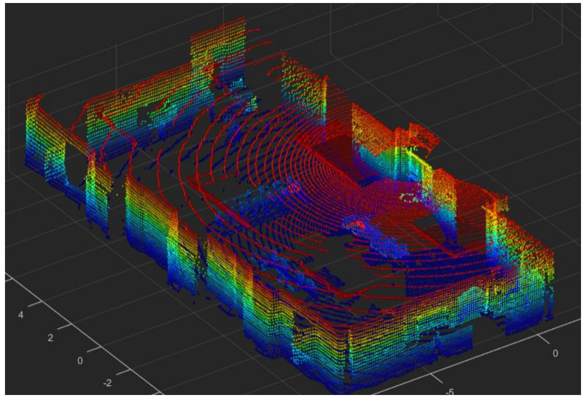
3D ENVIRONMENT PARSING AND RECONSTRUCTION

Channel Modeling

- Context-aware RF measurement system
- Accurate channel models → Reliable designs of wireless systems → Accelerate the deployment of nextG wireless systems
- Machine learning enables fast processing of large volumes of data for accurate channel modeling
- **Environment parsing via object recognition and segmentation**
- **Automated 3d modeling of the environment**
- *Automate the mapping of the multipath components to the objects*
- *Predict channel models of new environment from 3d models*



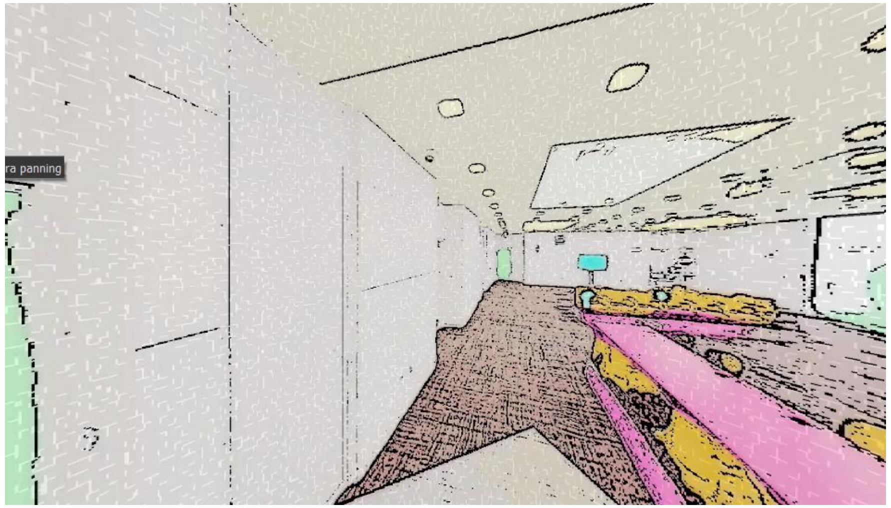
3D Environment Reconstruction: Modeling

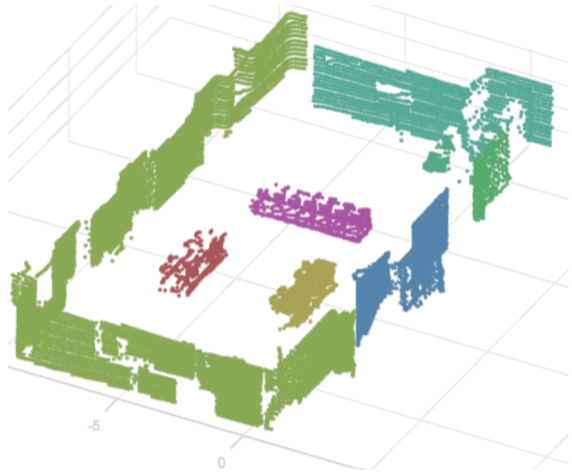


1
- Object Recognition
- Semantic segmentation
- Panoptic segmentation

2
- Point cloud semantic segmentation
- Depth map estimation
- Simultaneous Localization and Mapping (SLAM)

3
- Camera-LiDAR Sensor Fusion
- 3D modeling





Example: B. Pitzer, S. Kammel, C. Duhadway and J. Becker, "Automatic reconstruction of textured 3D models," 2010 IEEE International Conference on Robotics and Automation, 2010, pp. 3486-3493.

3D Environment Reconstruction: Evaluation

NIST

- Point-based qualitative evaluation (30 points Total)
- Ideal solution: Automatic generation of the 3d MAP of the environment with material definition of every object. E.g. Wavefront OBJ and Material Template Library (MTL)
- Subproblem solutions evaluation:

Subproblem solution	Points
1. Image-based machine learning algorithms	0-15
2. Point cloud algorithms	0-10
3. Sensor fusion and 3d Modeling	0-5
Total	0-30

Guest Researcher position at NIST

- **Ranking:** Point-based qualitative ranking
- **Prize**: guest researcher position at NIST

Create a sustainable digital world

NIST

- Future generation network will support unprecedented variety of applications, pervading every aspect of human life.
- Data acquisition and processing, *while keeping low cost and power*, is one of the biggest challenge to overcome
- Exploiting as much as possible the resources that we already have is vital to sustain future networks.
- We challenge participants to contribute to the realization of future sustainable networks:
  - **Leveraging RF signals, estimate the depth map of an environment**
  - **As a bonus, utilize lidar and images to parse and reconstruct the environment**

Team

Steve Blandino

Anuraag Bodi

Raied Caromi

Jack Chuang

Camillo Gentile

Nada Golmie

Chiehping Lai

Tanguy Ropitault

Jelena Senic

QUESTIONS?

steve.blandino@nist.gov