Machine Learning for Joint Sensing and Communication in Future Millimeter Wave IEEE 802.11 WLANs

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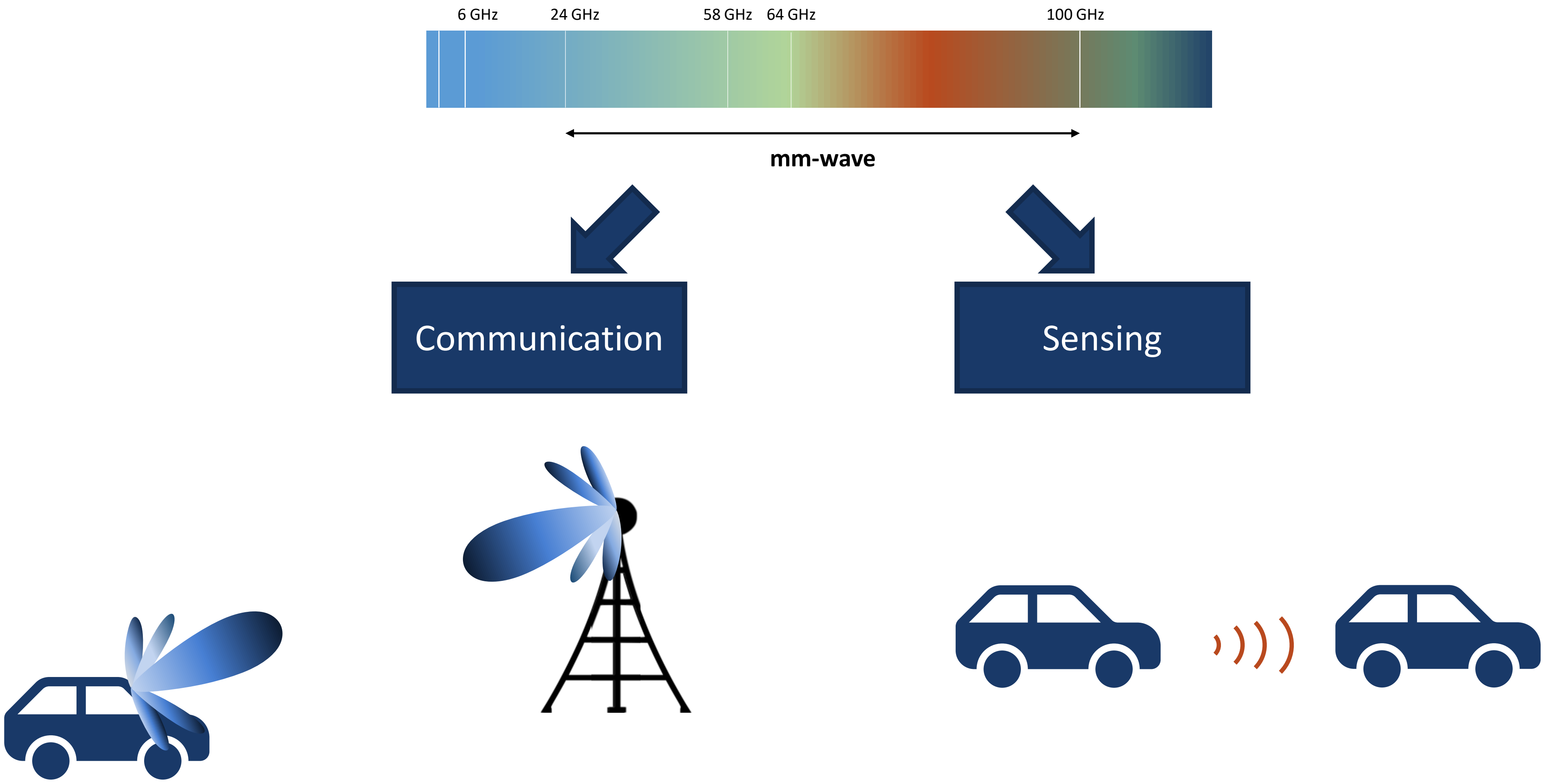
Outline

- Communication and sensing in mm-wave band.
- Turning Wi-Fi devices into motion sensors.
- The NIST Q-D framework.
- ITU AI/ML challenge 2021: sensing with mm-wave communications and ML.

COMMUNICATION AND SENSING IN MM-WAVE BAND

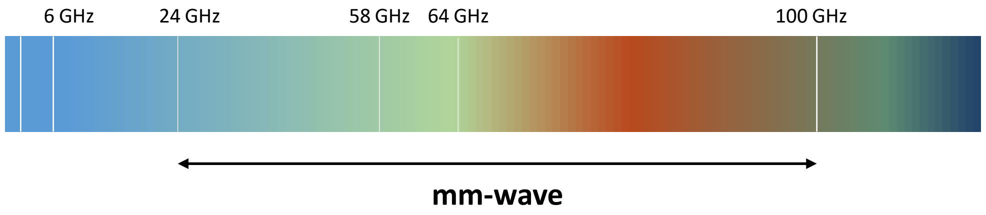
Old paradigm: Communication OR sensing

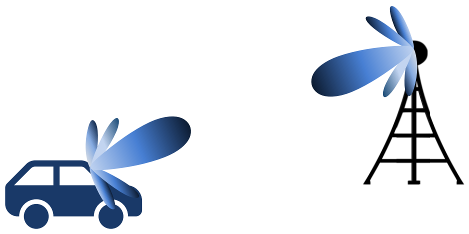


Multi-Gb/s wireless communications.

Cm level sensing resolution.

New paradigm: Communication AND sensing





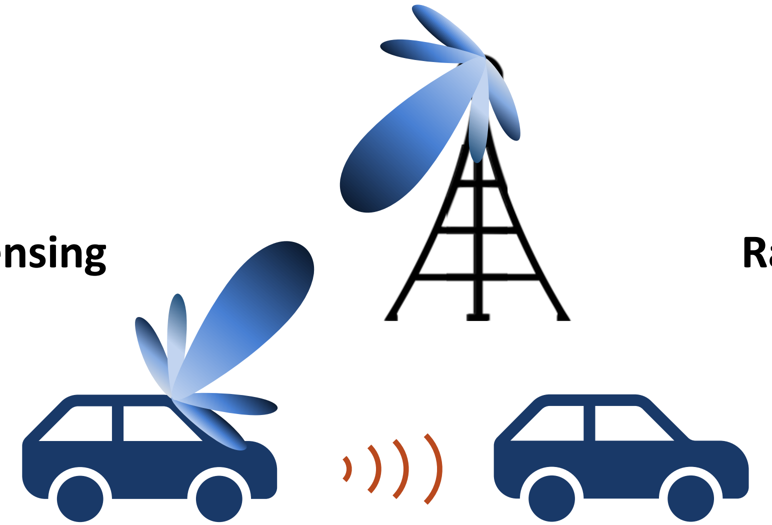
Communication

Sensing

Multi-Gb/s wireless communications.

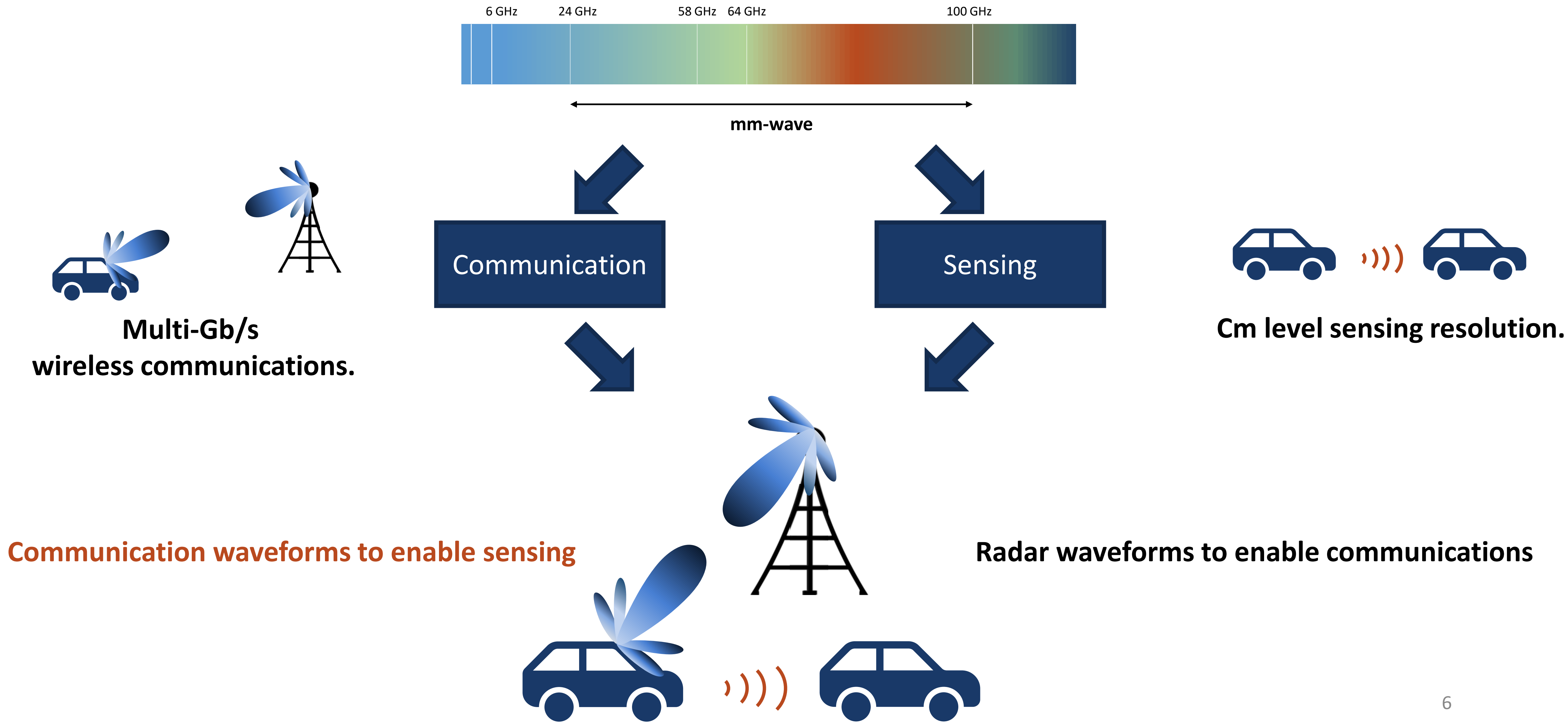
Cm level sensing resolution.

Communication waveforms to enable sensing



Radar waveforms to enable communications

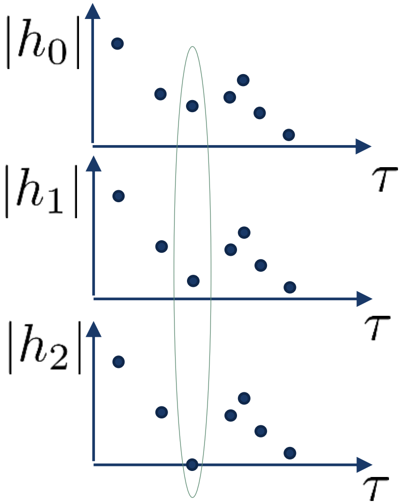
Communication waveforms to enable sensing

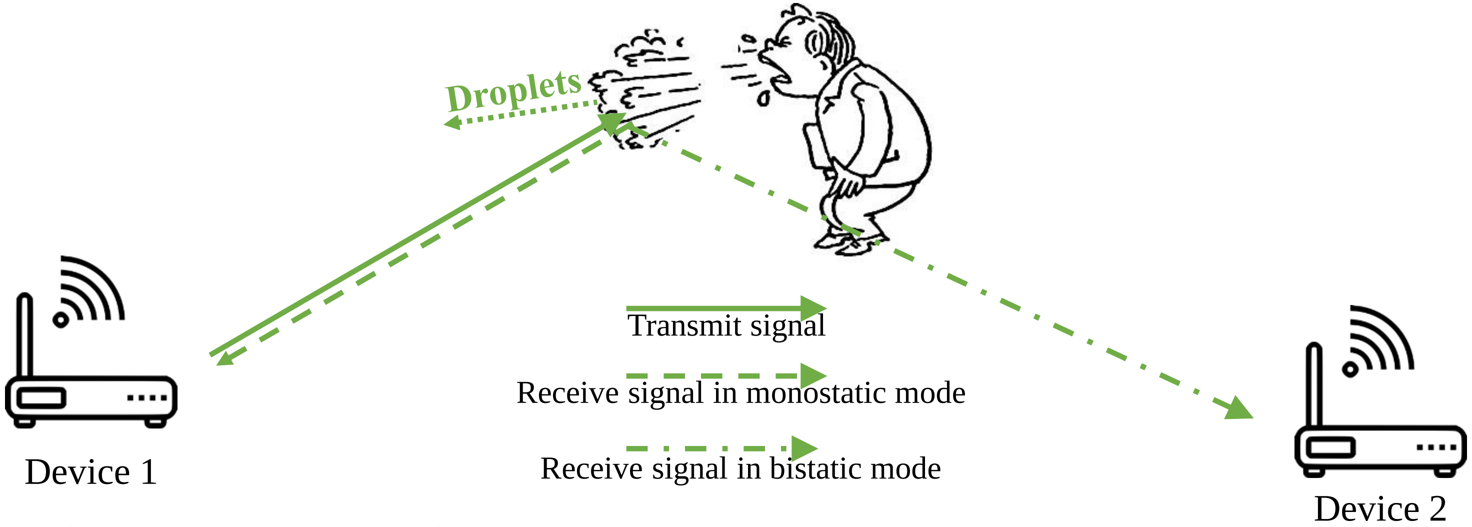


TURNING Wi-Fi DEVICES INTO MOTION SENSORS

Turn Wi-Fi devices into motion sensors

- Ubiquitous WiFi devices:
  - Reuse **communication devices and protocols to perform sensing.**
- Sensing can be performed by **tracking changes on a wireless channel through the reception of multiple packets over time.**
  - Time-variations of the channel can be analyzed using signal processing, ML/AI or both.





https://mentor.ieee.org/802.11/dcn/20/11-20-1640-00-00bf-wlan-sensing-usage-model-sneeze-sensing.pptx

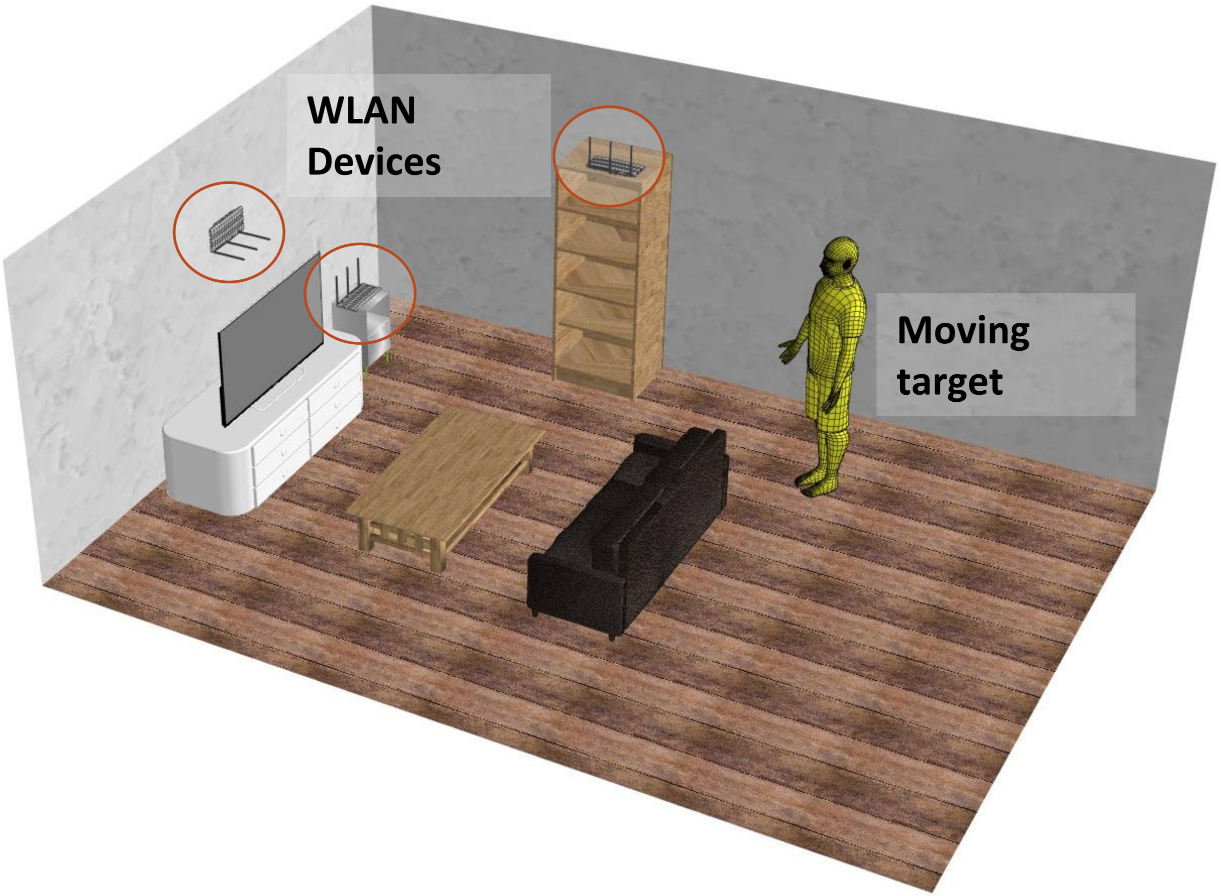
IEEE 802.11bf: WLAN Sensing

- IEEE 802.11bf started in Sep/20
  - Sub 6GHz and mm-wave.
- In mm-wave: use IEEE 802.11ay as a “toolbox” to be used for sensing
  - Re-exploit frame structure to enable sensing
  - Preamble provides sequences repetition to enable radar-like processing
- It will be extended with dedicated procedures for sensing.
- Use cases:
  - Presence detection, counting number of people, track people location, gesture detection recognition, person identification, vital sign monitoring, in car sensing, fast detection of sleeping drivers, etc.

https://mentor.ieee.org/802.11/documents?is_dcn=DCN%2C%20Title%2C%20Author%20or%20Affiliation&is_group=00bf

Use case: sensing human presence

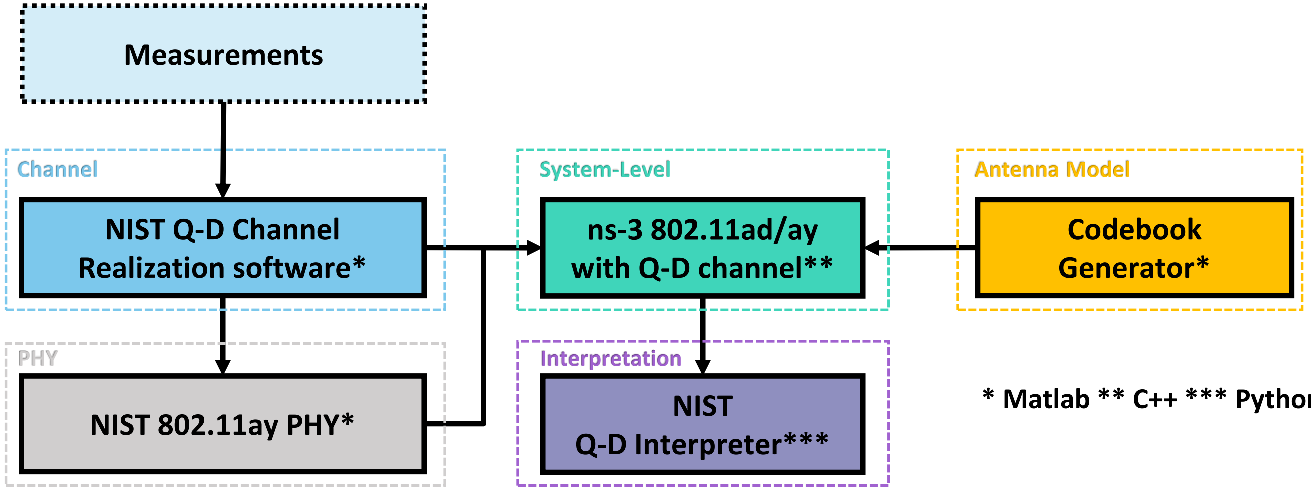
- Multiple mm-wave WLAN devices working as multi-static radar.
- Multiple people moving in an indoor environment.
- Indoor sensing:
  - Presence detection, number of people in the room, localization of active people.
- Application example: audio with user tracking
  - Tracking people in a room and pointing the sound of an audio system at them.



THE NIST Q-D FRAMEWORK

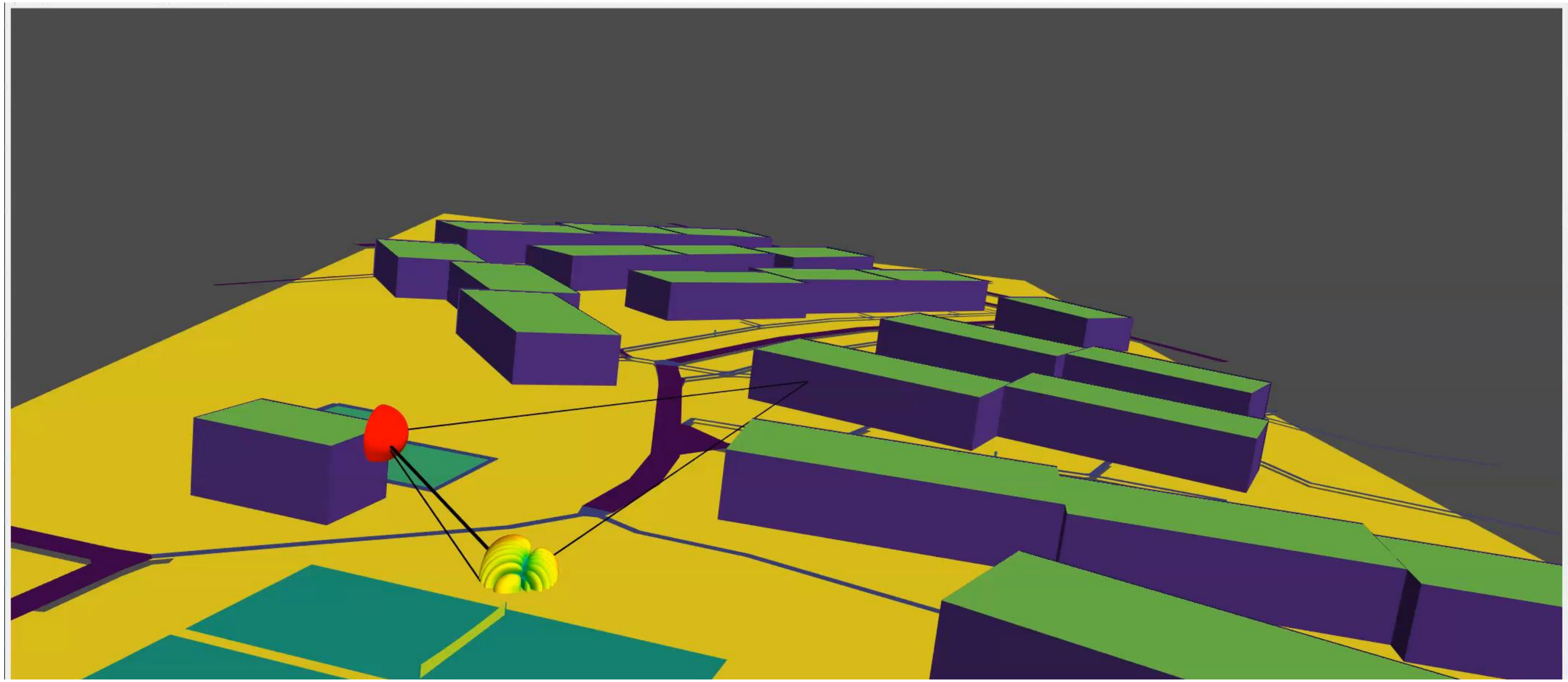
The NIST Q-D framework

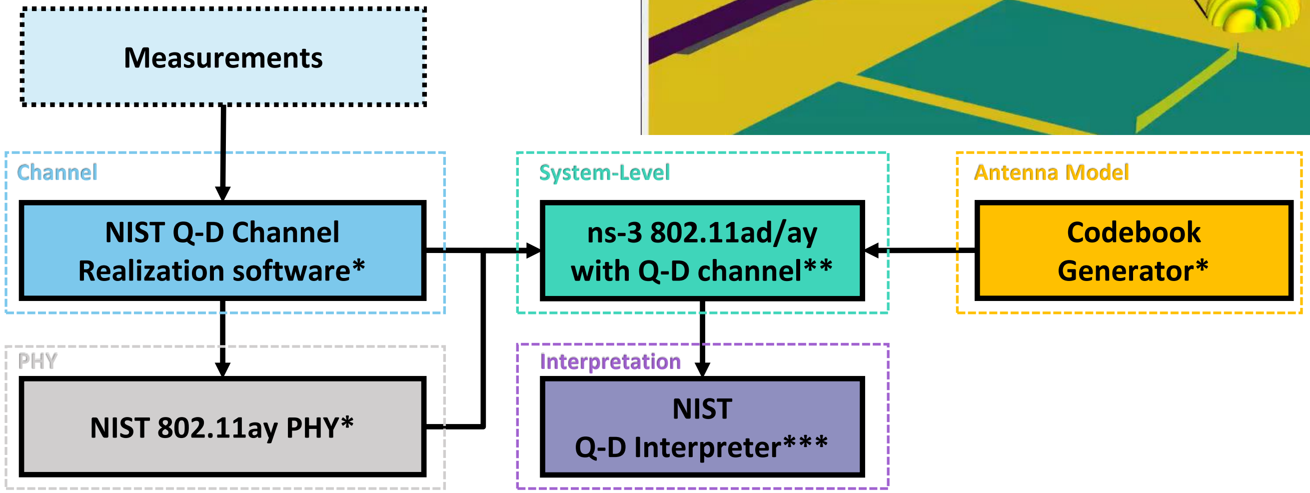
- NIST Quasi-Deterministic (Q-D) framework
  - Develop simulation models to evaluate IEEE 802.11ad/ay end-to-end (communication) performance with high-fidelity channel, antenna model and system-level protocols.
  - Extend the NIST Q-D framework to evaluate IEEE 802.11bf end-to-end performance (**communication and sensing**) with high-fidelity channel, antenna model and system-level protocols.
- 5 software packages *(https://github.com/wigig-tools)*
  - NIST Q-D Channel Realization Software
  - NIST 802.11ay PHY
  - ns-3 802.11ad/ay with Q-D channel
  - Codebook Generator
  - NIST Q-D Interpreter



* Matlab ** C++ *** Python

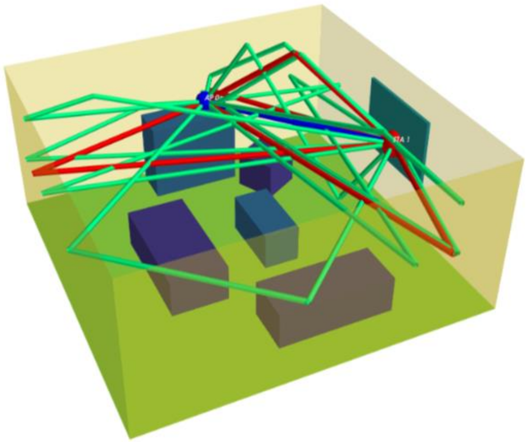
The NIST Q-D framework





The NIST Q-D Channel realization software

- The NIST Q-D Channel Realization software uses the Q-D methodology to generate Multi-Paths Components (MPCs)
  - Specular rays: Deterministic approach – Ray tracing (method of images)
  - Diffuse components: Stochastic approach using a material library (reflectivity, number of pre-post cursors, etc.)
- Channel model for sensing should include:
  - Target(s) to be sensed
    - Location, trajectory, etc.



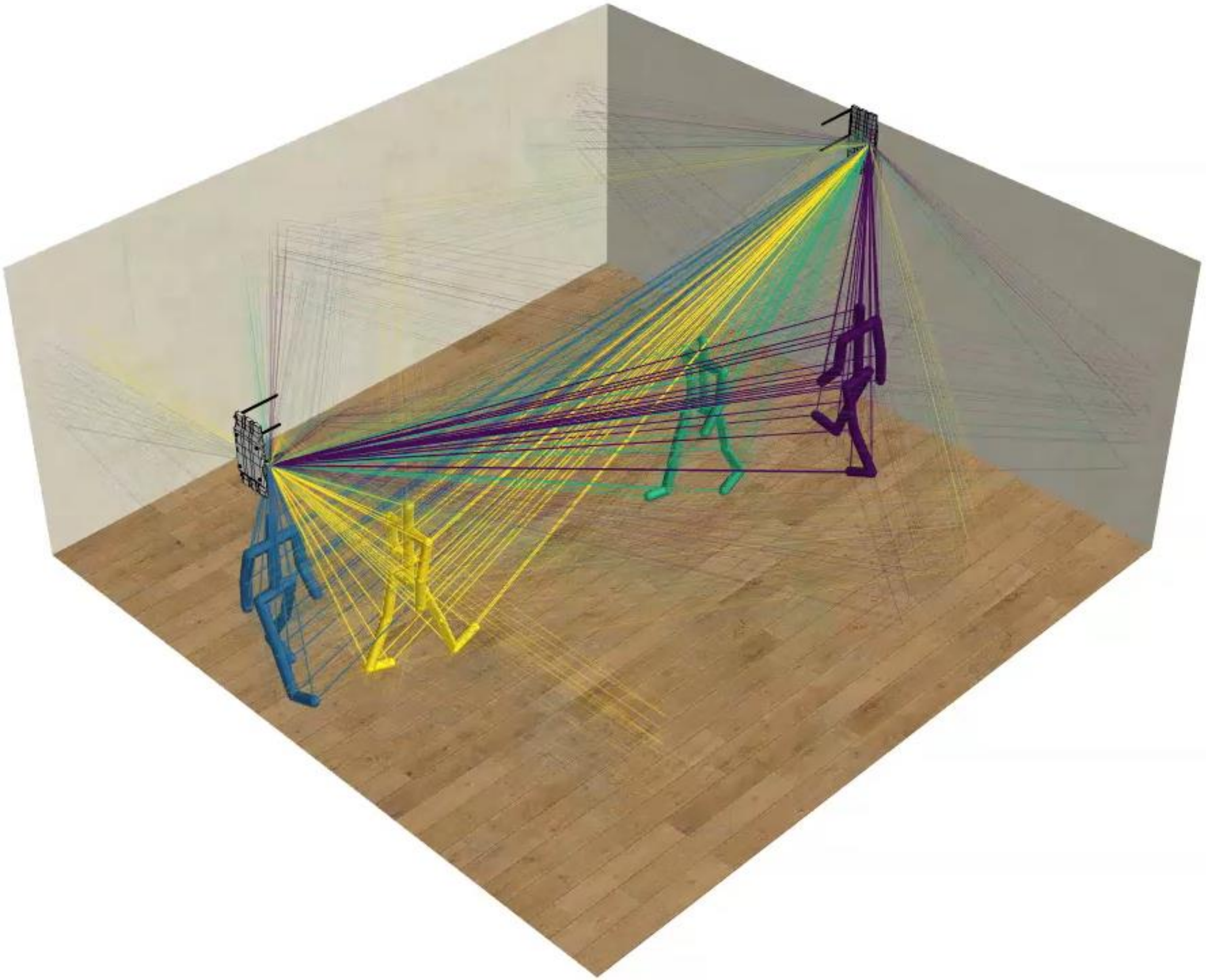
IEEE Living Room Scenario

Target properties

- **Spatial consistency:**
  - Both large-scale and small-scale parameters vary with the position of the WLAN nodes, the targets and the environment.
- **Temporal consistency:**
  - Large-scale and small-scale parameters are correlated over time when WLAN nodes or targets move.
- **Complex targets:**
  - Objects with multiple scattering points: the overall scattering is the sum of all scattering mechanisms from each individual scattering point.

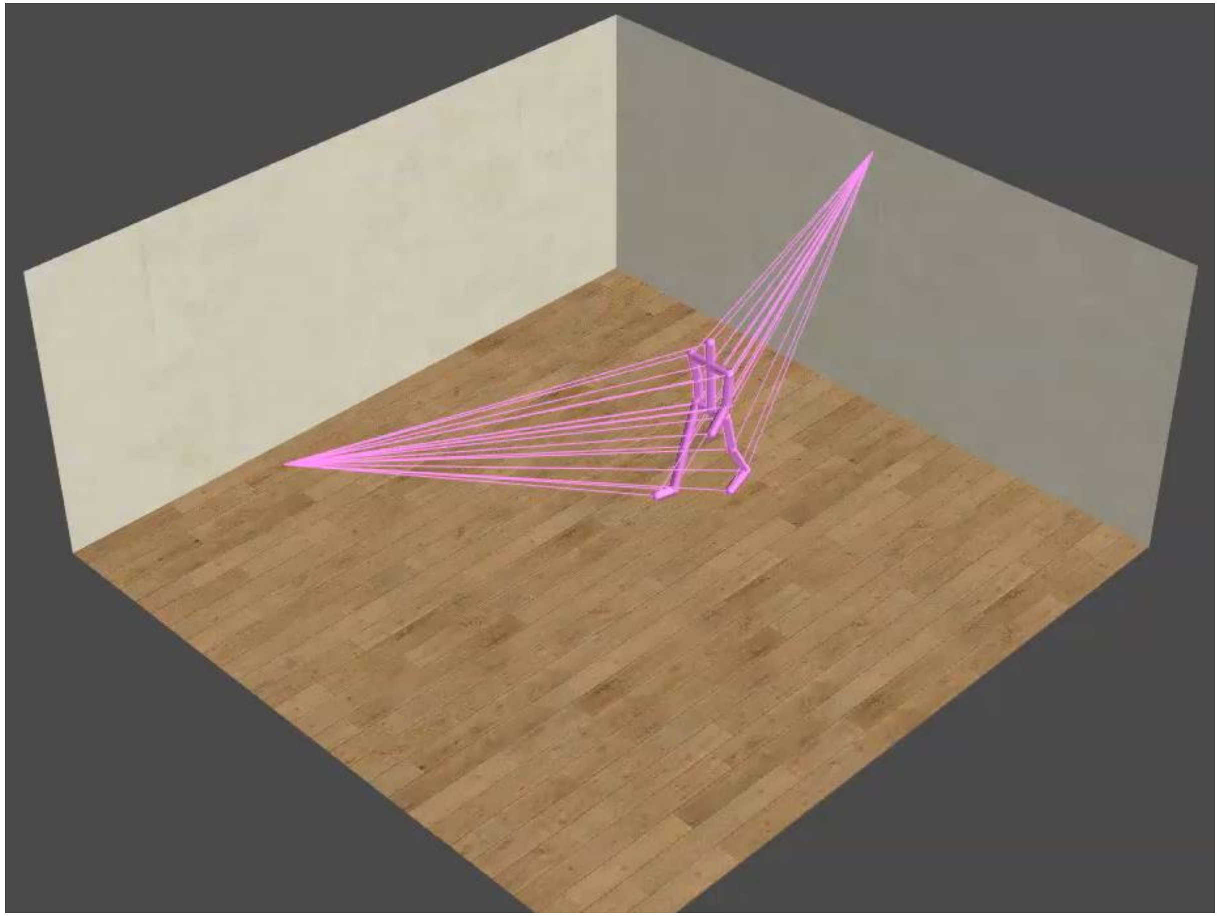
Complex targets: example human motion

- Human micro-doppler signature reflects human motion.
- Human walking is a periodic movement.
- Human body is highly coordinated: when moving, body parts movements are highly correlated.
- Scattering signal from human motion can be modeled as a cluster of scattering points.



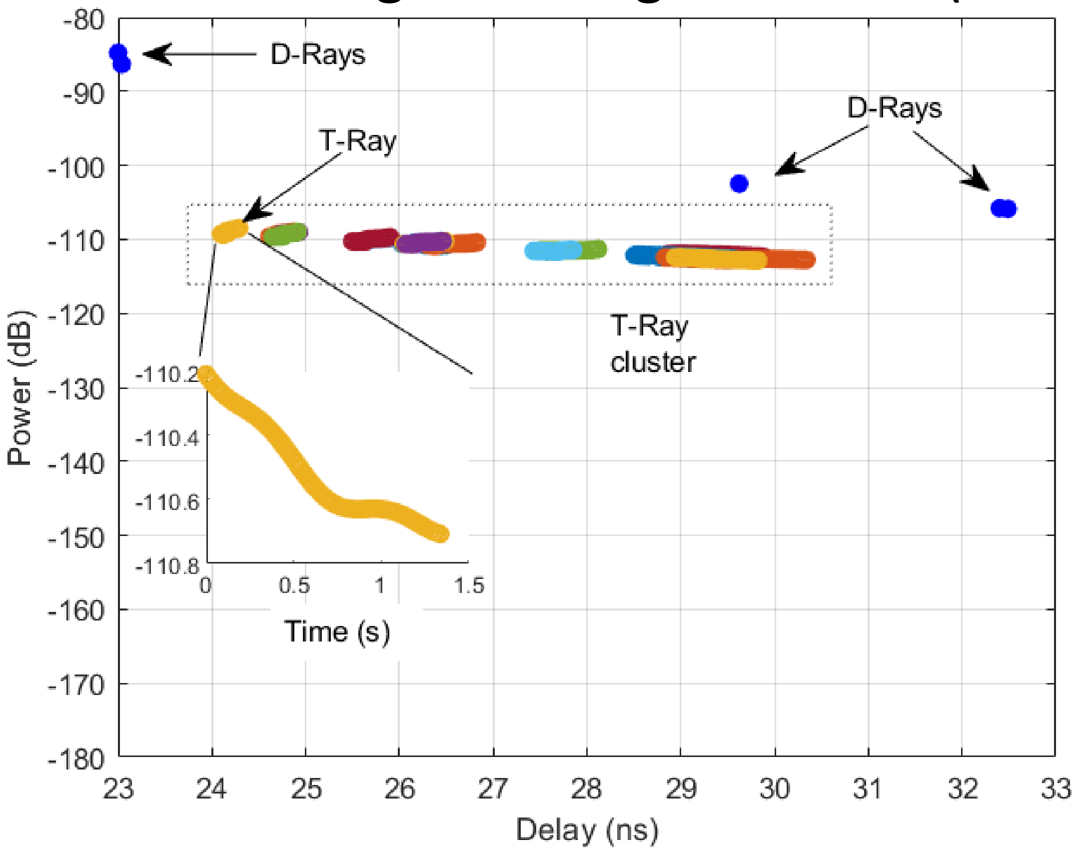
Channel model analysis: human motion scenario

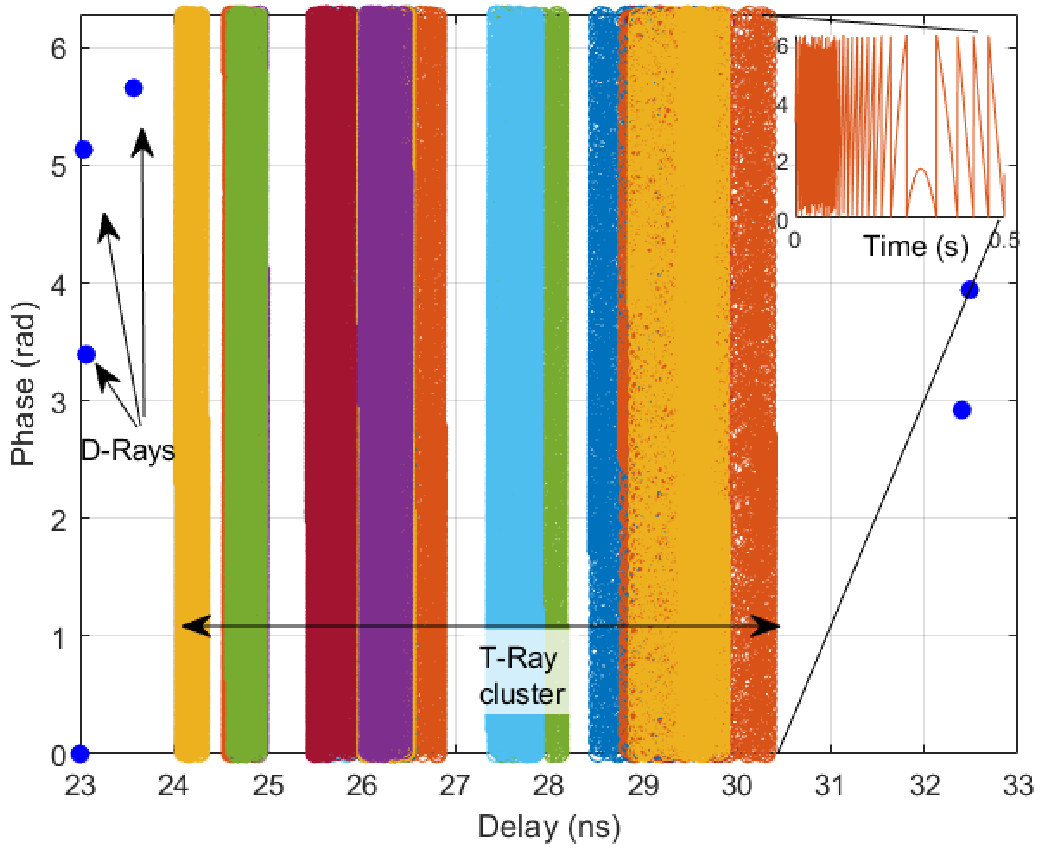
- Living room environment (7m×7m×3m).
- Bi-static system: 1 TX (-3.9m, 0m, 2.8m) and 1 RX (3m, 0m, 2.8m).
- 1 target:
  - 17 centers of scattering (joints).
  - Human walking at ~1m/s.
- Channel realization rate: 1ms.
- Frequency: 60GHz



Ray tracing results: double directional impulse response

- The model captures both the static environment (D-Rays) and the dynamics of the target moving over time (T-Rays).





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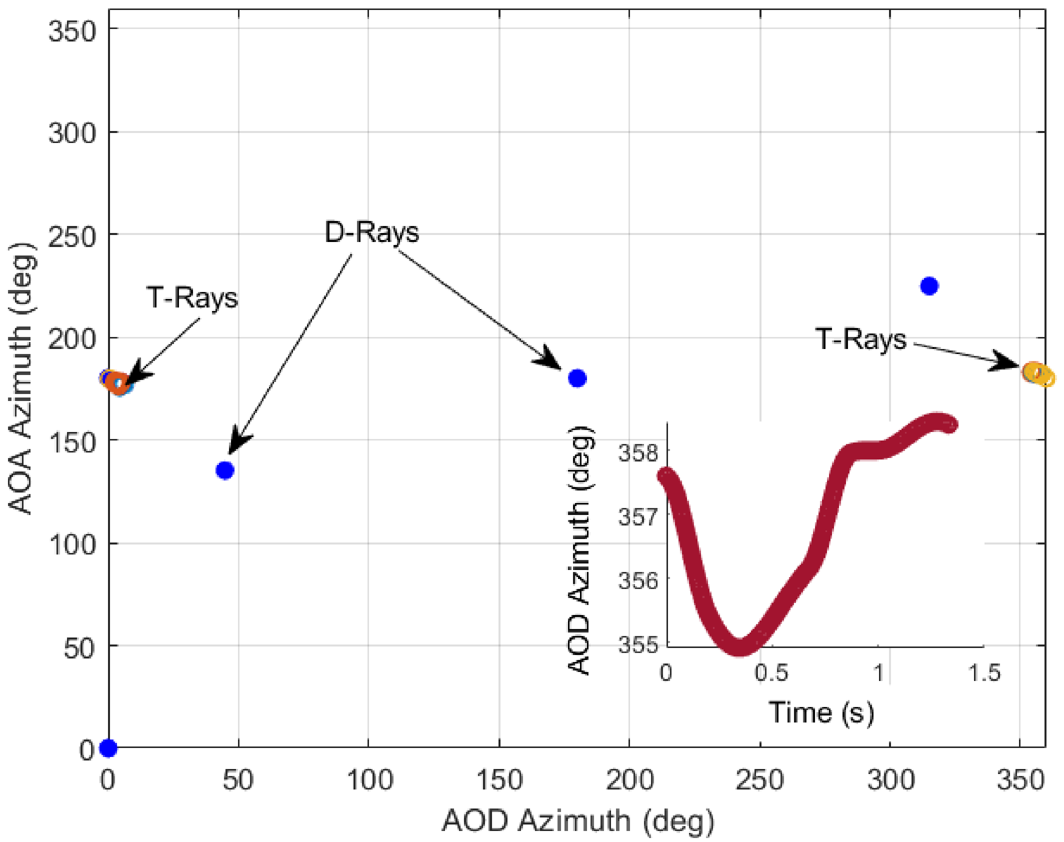
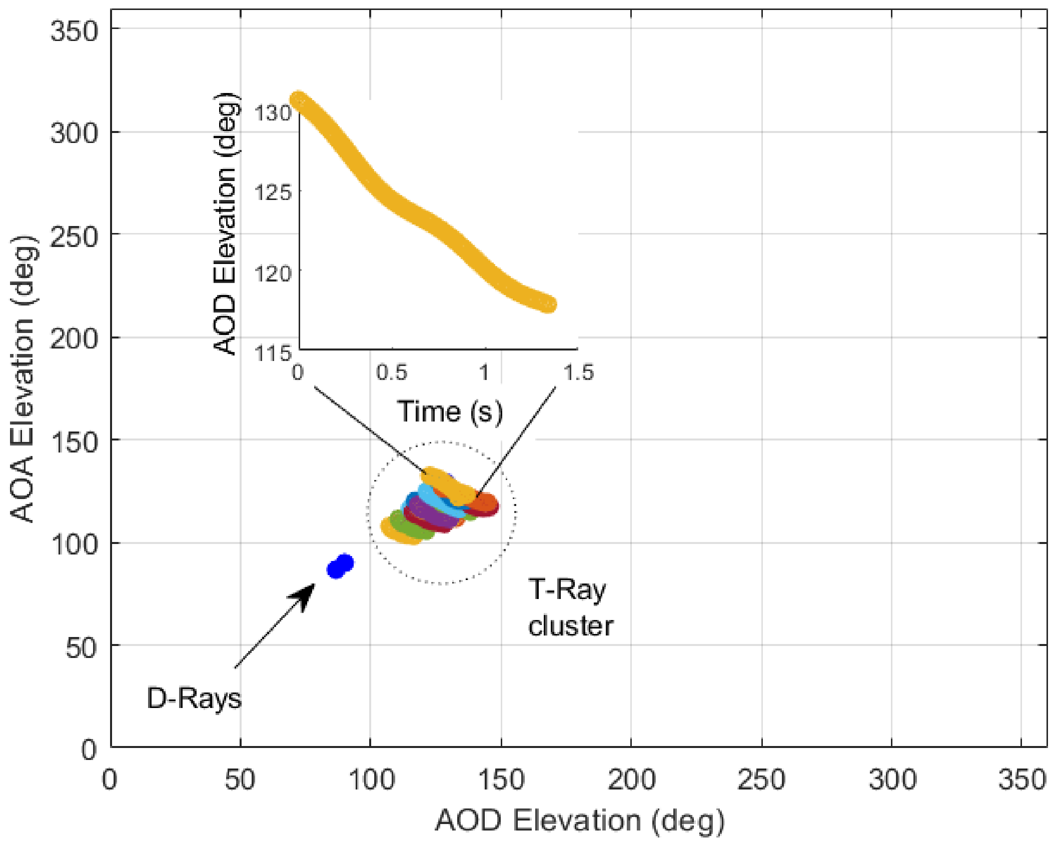
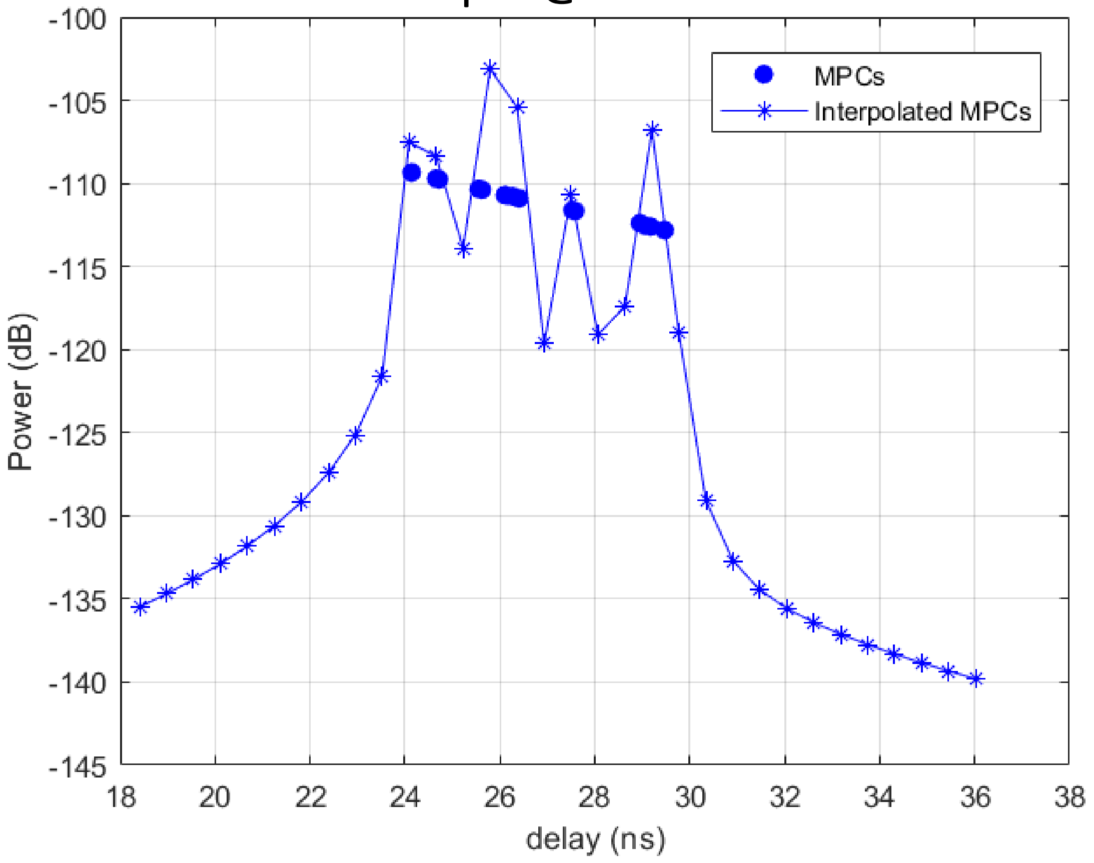




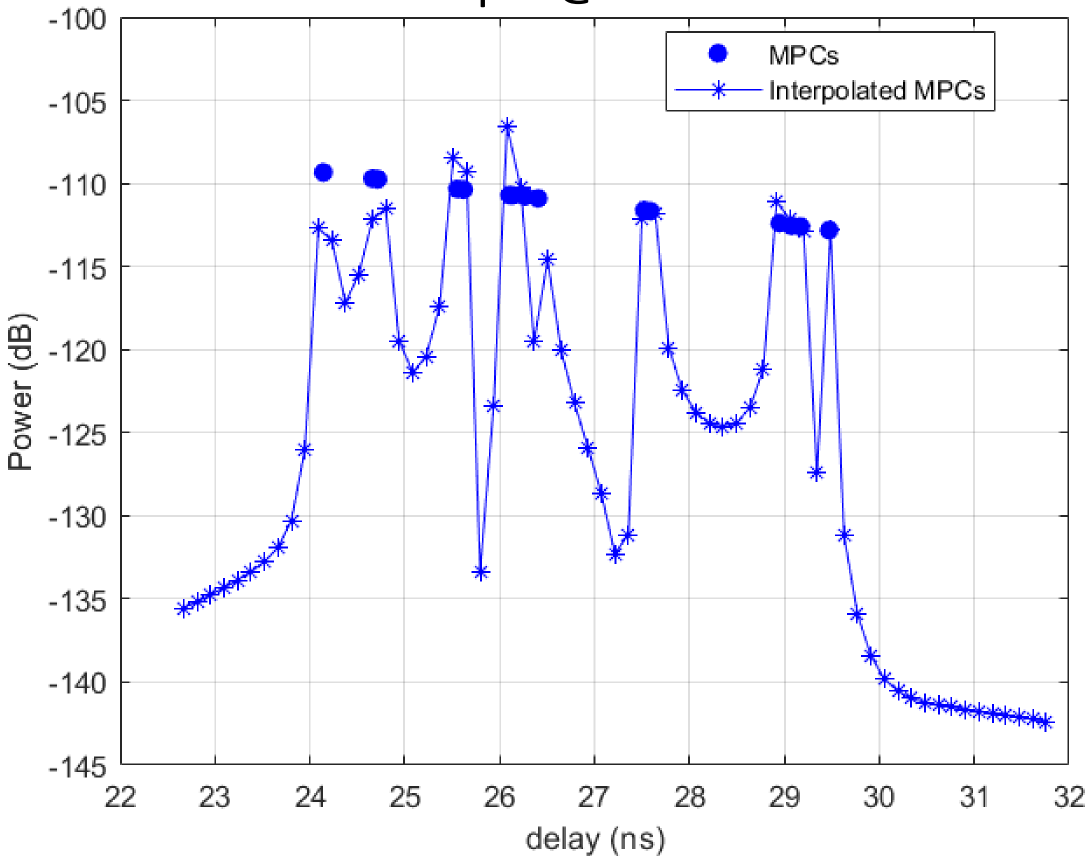
Effect of ideal band limitation

- Multipath components (MPCs) are merged in fewer taps.

Resample @ 1.76GHz



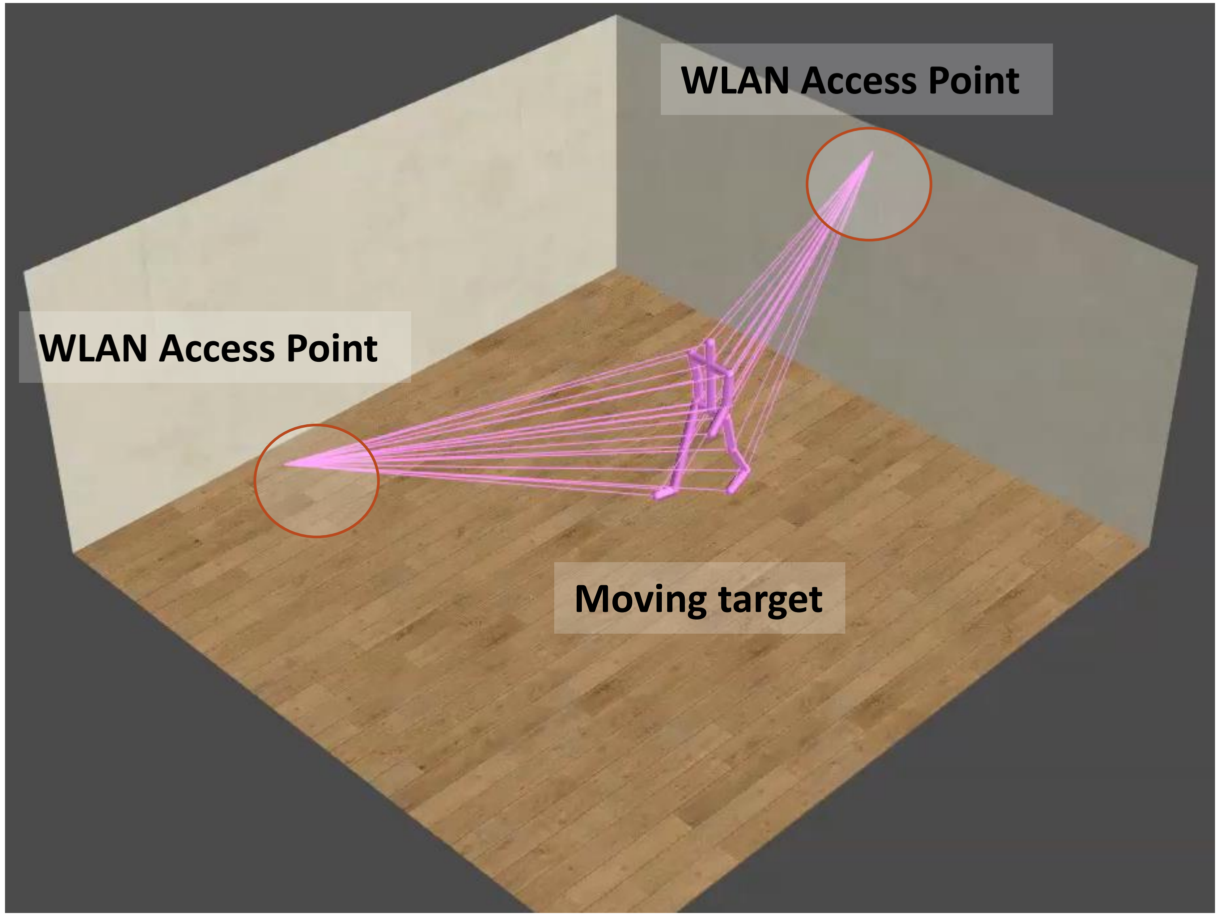
Resample @ 7.04GHz



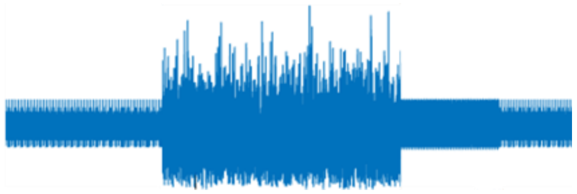
ITU AI/ML 5G CHALLENGE 2.0: WHERE'S WALDO?

Sensing with mm-wave communications and ML

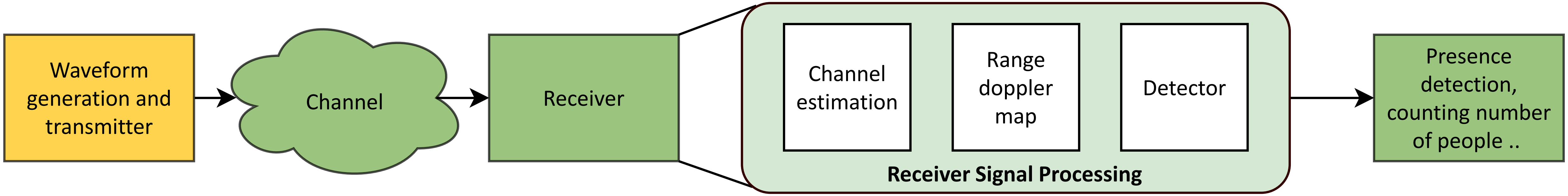
- Two MIMO WLAN Access Points working as a bi-static radar.
- Multiple dynamic people in an indoor environment.
- **WALDO** (**W**ireless **A**rtificial intelligence **L**ocation **D**etecti**O**n): sensing using mmWave communications and ML.
    - Presence detection.
    - Target localization.



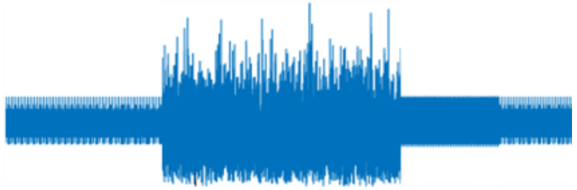
Communication and sensing using signal processing



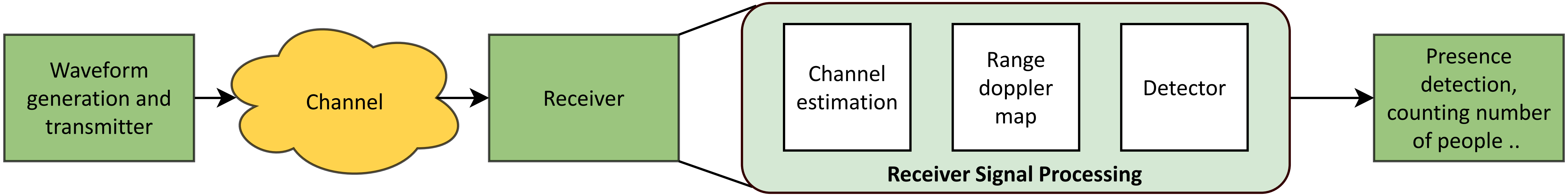
IEEE 802.11ay waveform

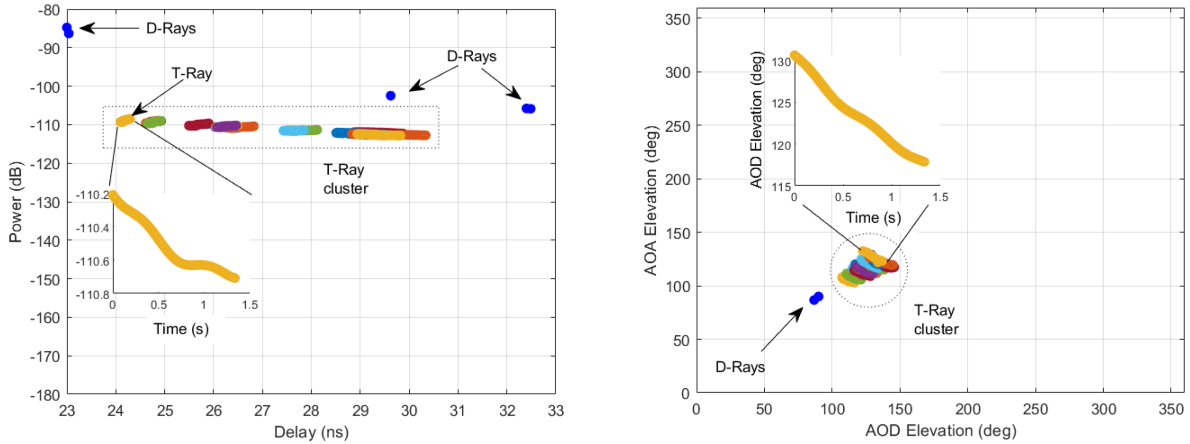


Communication and sensing using signal processing



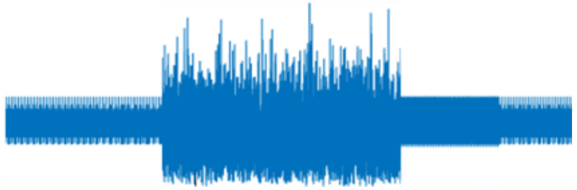
IEEE 802.11ay waveform



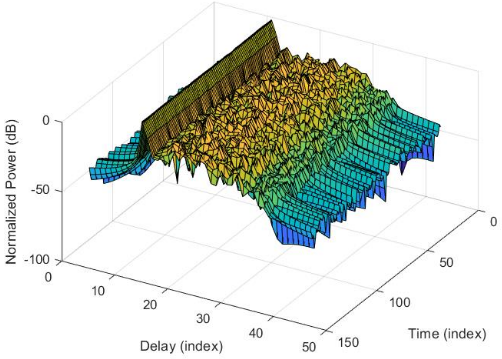


Channel model with spatial and temporal consistency

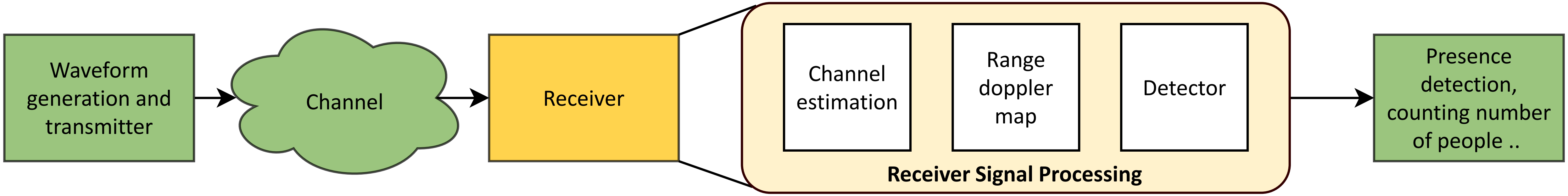
Communication and sensing using signal processing

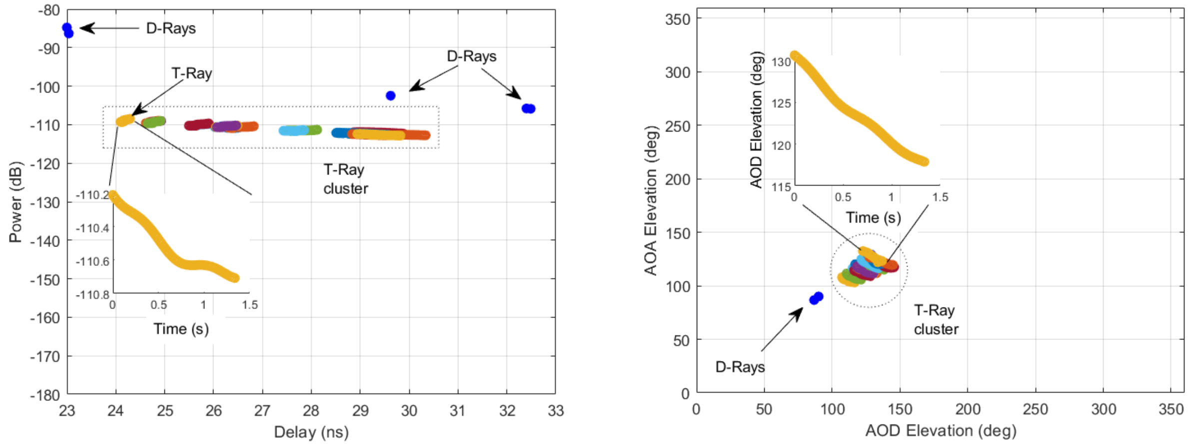


IEEE 802.11ay waveform

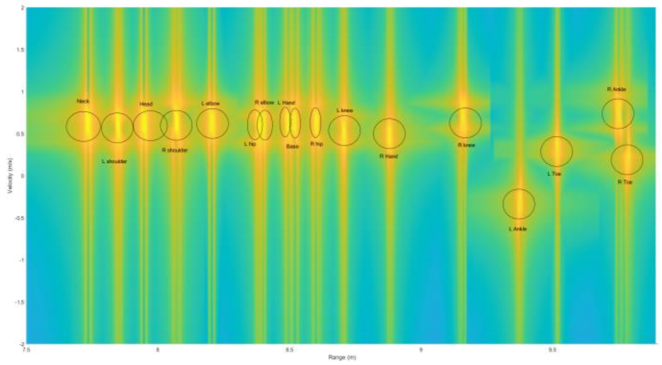


Channel estimation



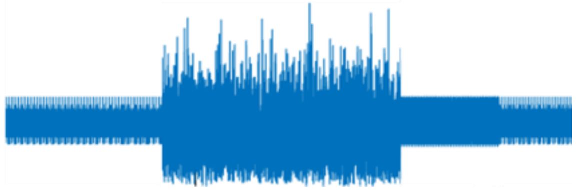


Channel model with spatial and temporal consistency

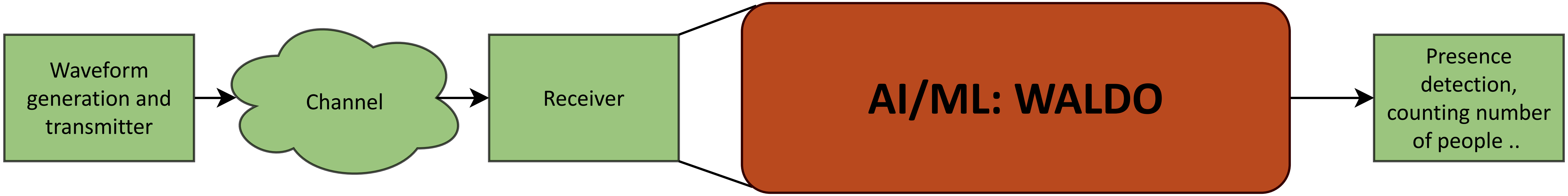


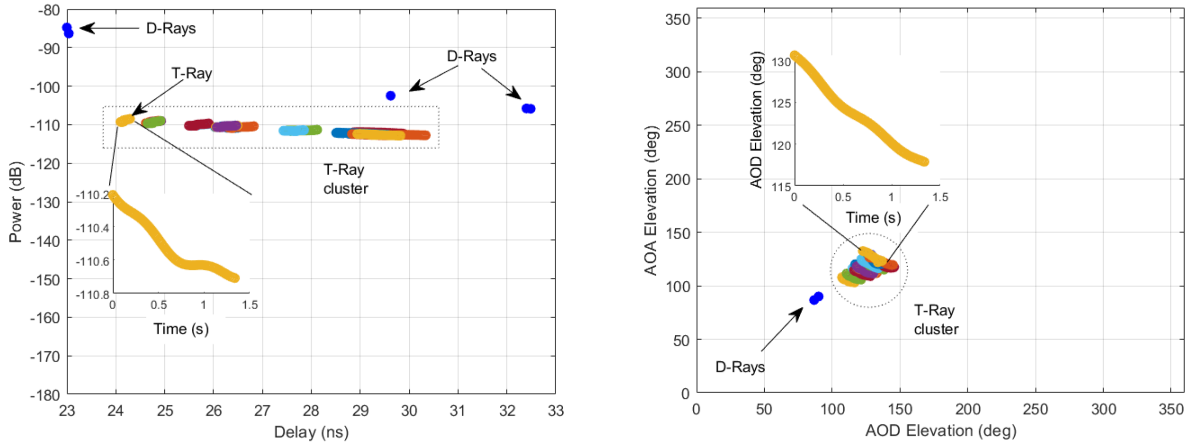
Range-Doppler map

Communication and sensing using ML



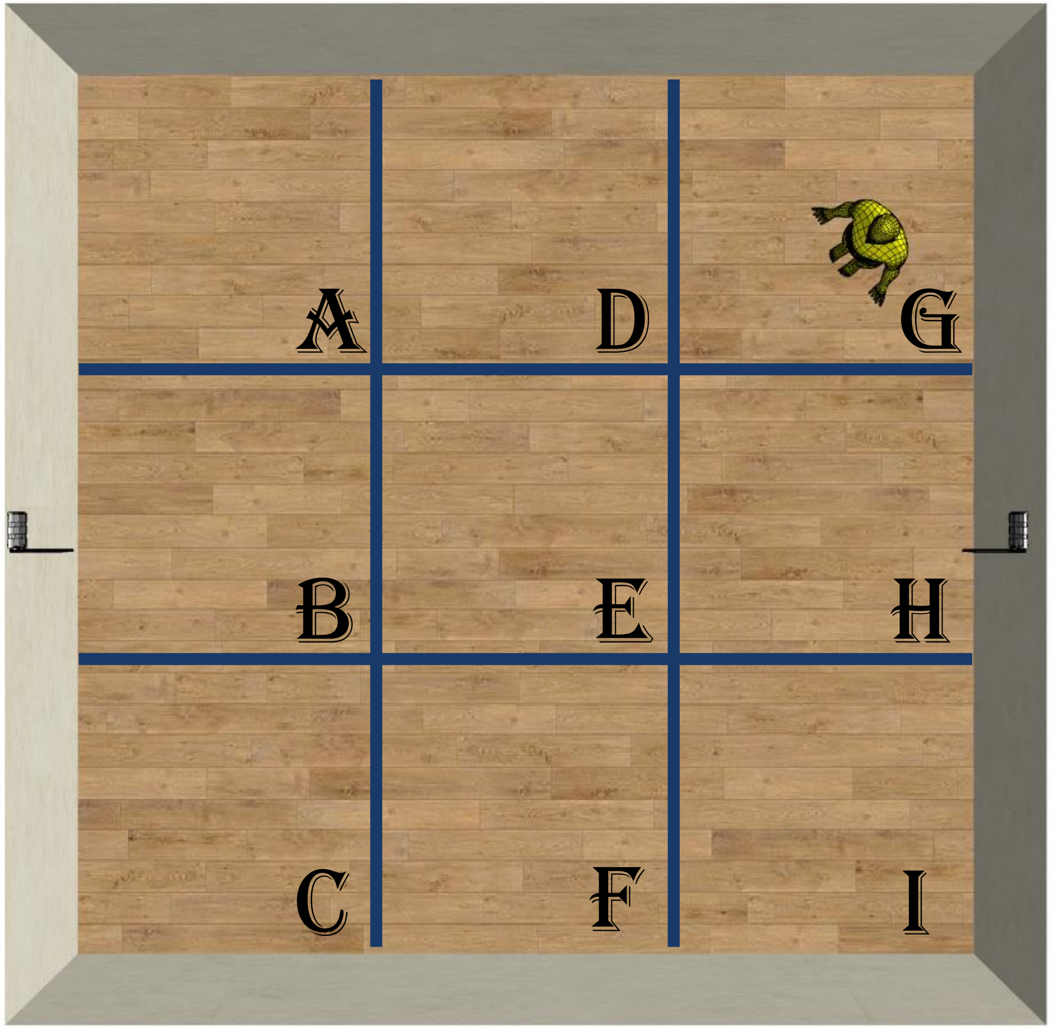
IEEE 802.11ay waveform



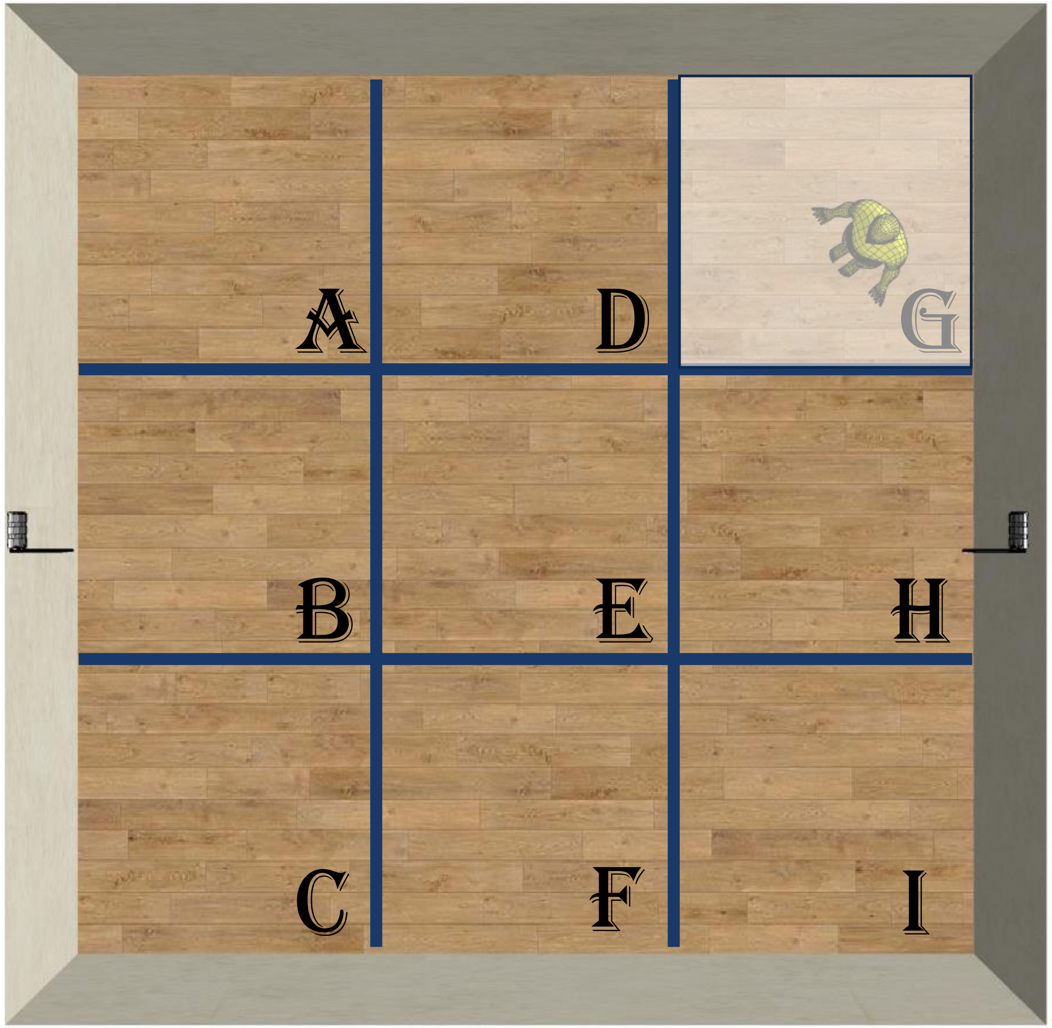


Channel model with spatial and temporal consistency

Where's WALDO?

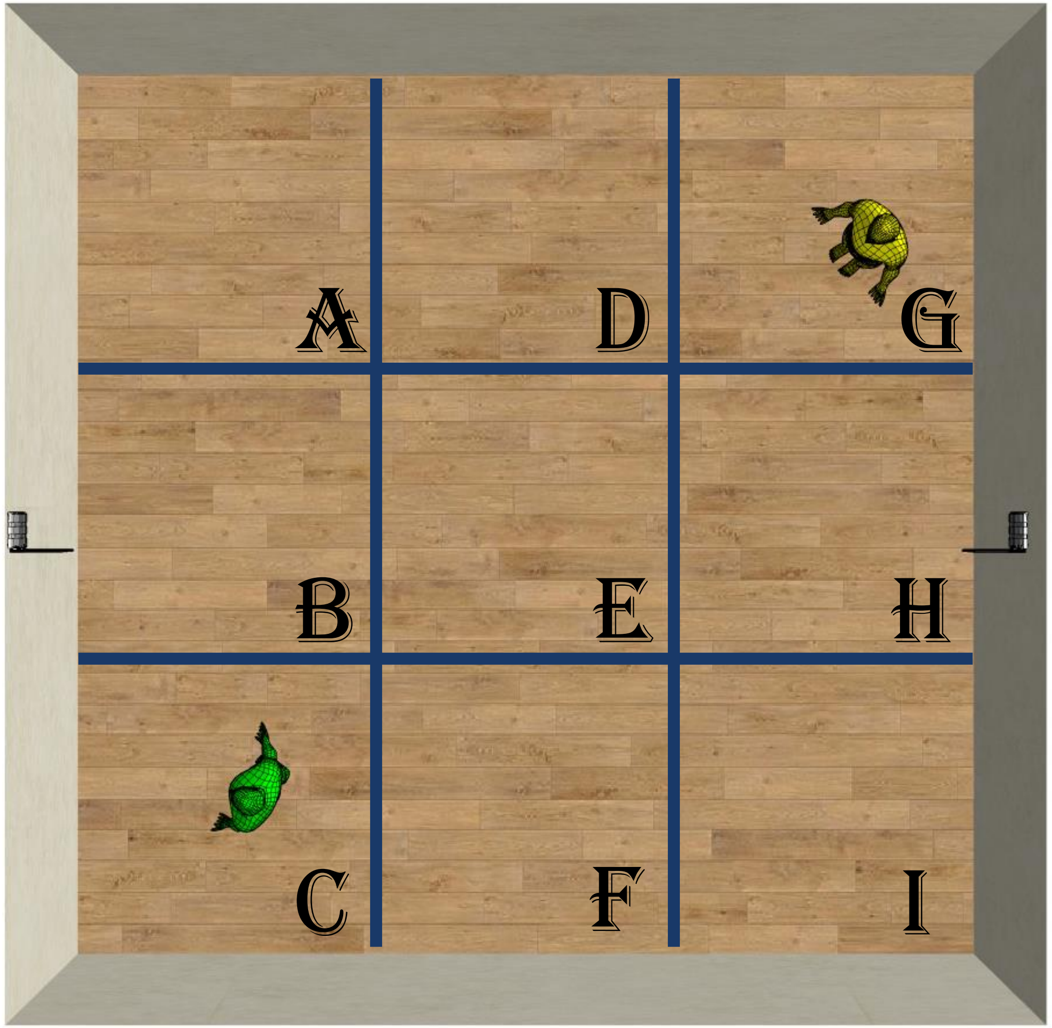


WALDO: we finally found you!



Sector	#people
A	0
B	0
C	0
D	0
E	0
F	0
G	1
H	0
I	0

Where's WALDO?



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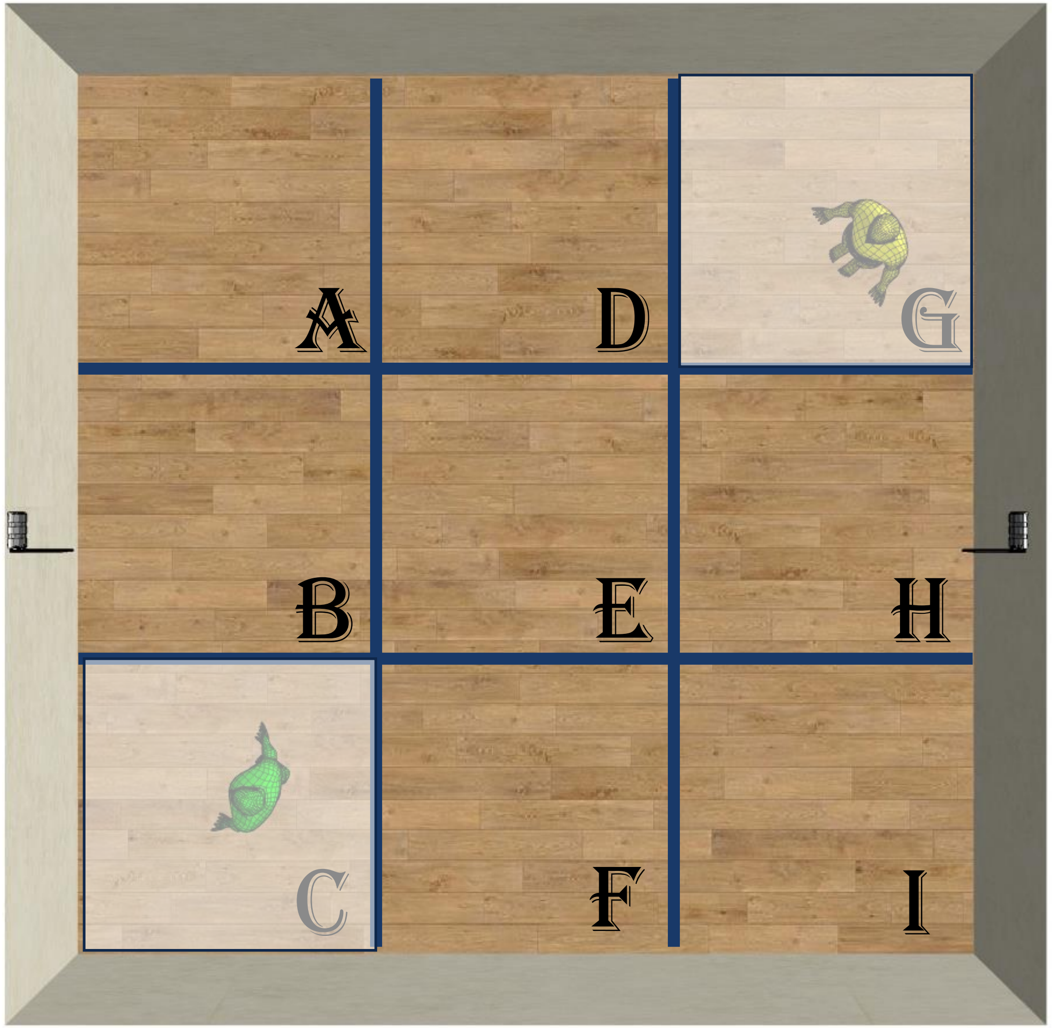
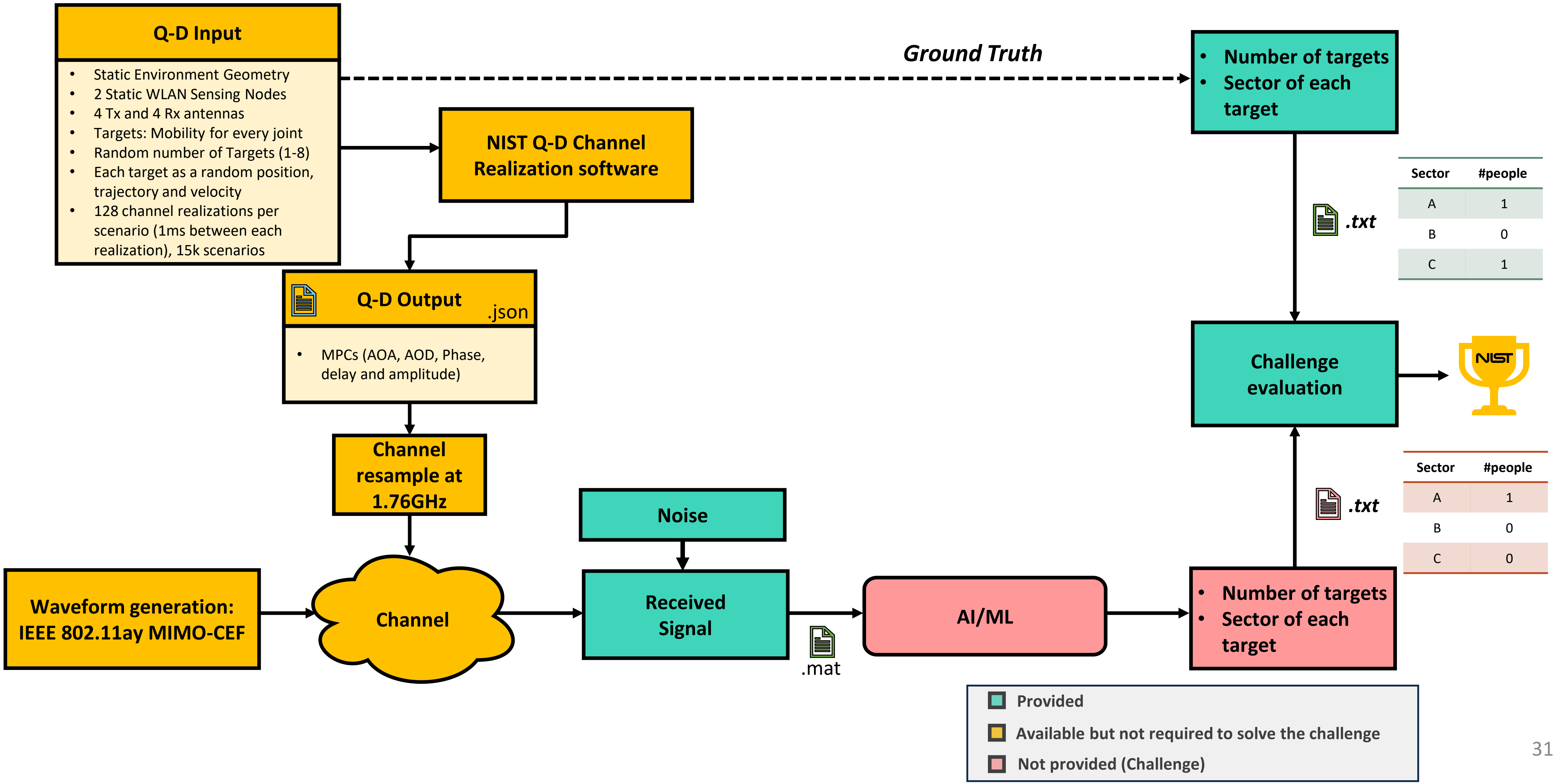


Sector	#people
A	0
B	0
C	1
D	0
E	0
F	0
G	1
H	0
I	0

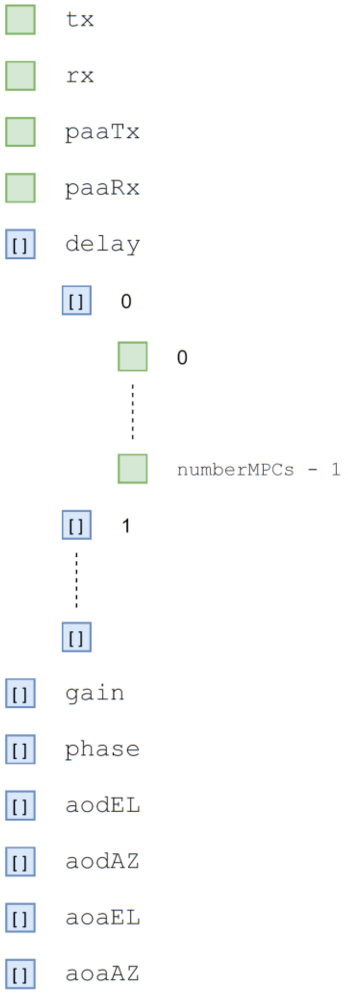
Challenge dataset



Challenge dataset: channel

- Q-D channel output (qdChannel/qdOutput#)
  - Tx index (index from 0)
  - Rx index (index from 0)
  - Antenna tx index (index from 0)
  - Antenna rx index (index from 0)
  - Double directional impulse response
    - Delay (s)
    - Gain (dB)
    - Phase (rad)
    - Angle of arrival/departure, azimuth, elevation (Deg)

Available but not required to solve the challenge



qdOutput.json

Challenge dataset: get receive signal

- Matlab script can be used to generate ML input (receivedSignalGeneration/scriptGenerateRxSig.m) :
  - Generate pilot sequence.
  - Load channel (qdOutput.json), resample at 1.76GHz
  - Transmit pilots on channel.
  - Add noise
  - Save received signals in .mat files

Available but not required to solve the challenge

Received signal

- rxSigCh#.mat file (dataset/snr#/rxSigCh#.mat) :
- Received signal is a 3D matrix Ns × Na × Nc
    - Ns: number of received samples
    - Na: number of antennas (4)
    - Nc: number of channels (128)

Provided

Challenge dataset: ground truth

- .txt file (mlOuput/groundTruth.txt)
  - Each row is a vector of chars. Each entry corresponds to a target position.
  - The length of the vector is the number of people.

Counting: 8 people

Localization

```
DFIC
CACEIB
ACEDCBIG
ABHDDIGE
HEI
EIB
FGBID
DD
EDHHDF
FGGG
EAF
```

Sector	#people
A	1
B	1
C	0
D	2
E	1
F	0
G	1
H	1
I	1

Provided

Challenge evaluation

- Number of targets
- Sector of each target

.txt

Sector	#people
A	1
B	0
C	1

Challenge evaluation

.txt

Sector	#people
A	1
B	0
C	0

- Number of targets
- Sector of each target

Provided

- Counting error:
  - Accuracy in counting the total number of people present in the room.

$$\alpha_c = \frac{\sum_{i=1}^{N} 1_{\hat{y}_i = y}}{N}$$

$\hat{y}$: Counting (estimation)
y: Counting (ground truth)
N: Dataset size

- Localization error:
  - Accuracy in counting the number of people present in each sector.

$$\alpha_l = \frac{\sum_{i=1}^{N} y_i \cdot 1_{\hat{x}_i = x}}{\sum_{i=1}^{N} x_i}$$

$\hat{x}$: Localization (estimation)
x: Localization (ground truth)

Challenge evaluation

- Number of targets
- Sector of each target

.txt

Sector	#people
A	1
B	0
C	1

Challenge evaluation

.txt

Sector	#people
A	1
B	0
C	0

- Number of targets
- Sector of each target

Provided

- Final evaluation:

$$\sum_s w_s \left[w_c \alpha_c(s) + w_l \alpha_l(s)\right]$$

s: snr index
w_s: snr weight
w_c: counting weight
w_l: localization weight

Guest Researcher position at NIST

- **Prize**: guest researcher position at NIST

Communicate and sense at 60GHz

NIST

- Shed light on passive sensing and localization performance re-using current 5G infrastructure.
- Quantify the impact of novel AI/ML techniques with respect to conventional signal processing.
- Provide future directions to IEEE standardization activities.

References

- A collection of open-source tools to simulate IEEE 802.11ad/ay WLAN networks in network simulator ns-3. https://github.com/wigig-tools
- Q-D simulation & Modeling framework for sensing https://mentor.ieee.org/802.11/dcn/21/11-21-0746-01-00bf-q-d-simulation-modeling-framework-for-sensing.pptx
- A preliminary channel model using raytracing to detect human presence https://mentor.ieee.org/802.11/dcn/21/11-21-0747-01-00bf-a-preliminary-channel-model-using-raytracing-to-detect-human-presence.pptx

QUESTIONS?

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