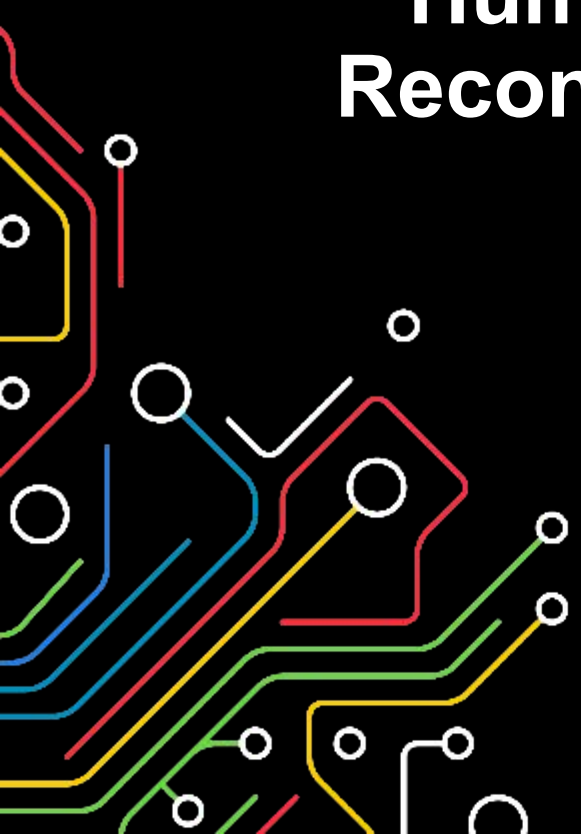
INSTITUTE FOR SYSTEMS
AND COMPUTER ENGINEERING,
TECHNOLOGY AND SCIENCE

INESCTEC

Human Activity Recognition with a 6.5 GHz Reconfigurable Intelligent Surface for Wi-Fi 6E

NOVEMBER 2024



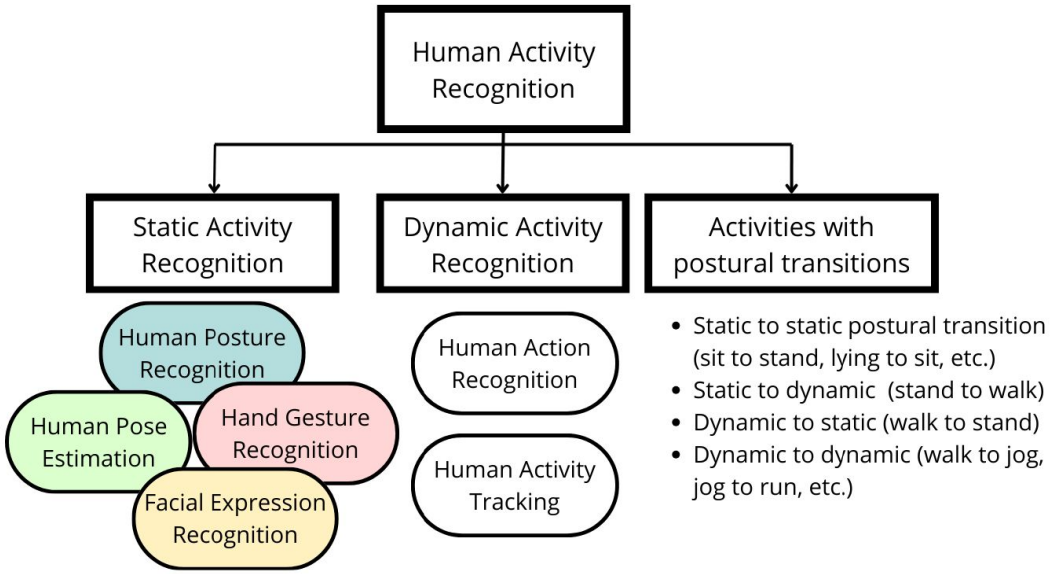
from knowledge generation to science-based innovation

- **Introduction**
- **Human Activity Recognition**
- **Reconfigurable Intelligent Surfaces**
- **HAR via RIS for WiFi-6E**
  - Modeling the Setup
  - Channel Model
  - Unit Cell & 64-element RIS Implementation
- **Experiments**
  - RIS Validation and Beam Steering
  - Human Hand Gesture Recognition

Human Activity Recognition

- **What is HAR?**
  - Identify or classify activities (sitting, walking, falling)
  - Typically done with vision or sensor data

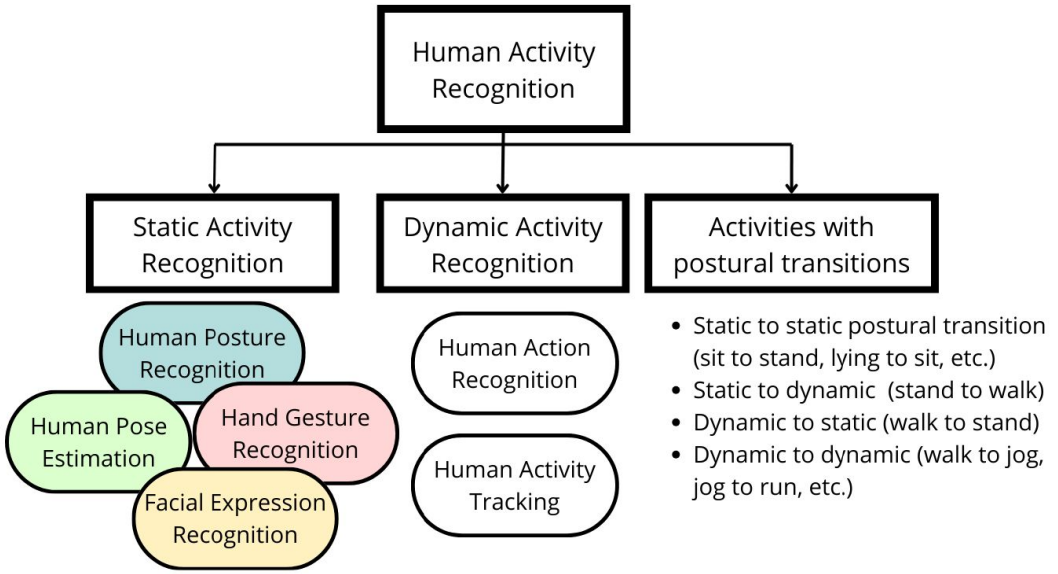
- **Applications**
  - Healthcare (Patient monitoring)
  - Smart Environments (Home assistance)
  - Security (Surveillance systems)
  - HCI (Intuitive interfaces)
  - XR/AR/VR



Human Activity Recognition

- **HAR Challenges?**
  - Data Collection and Fusion
  - Feature extraction
  - Sensor Cost

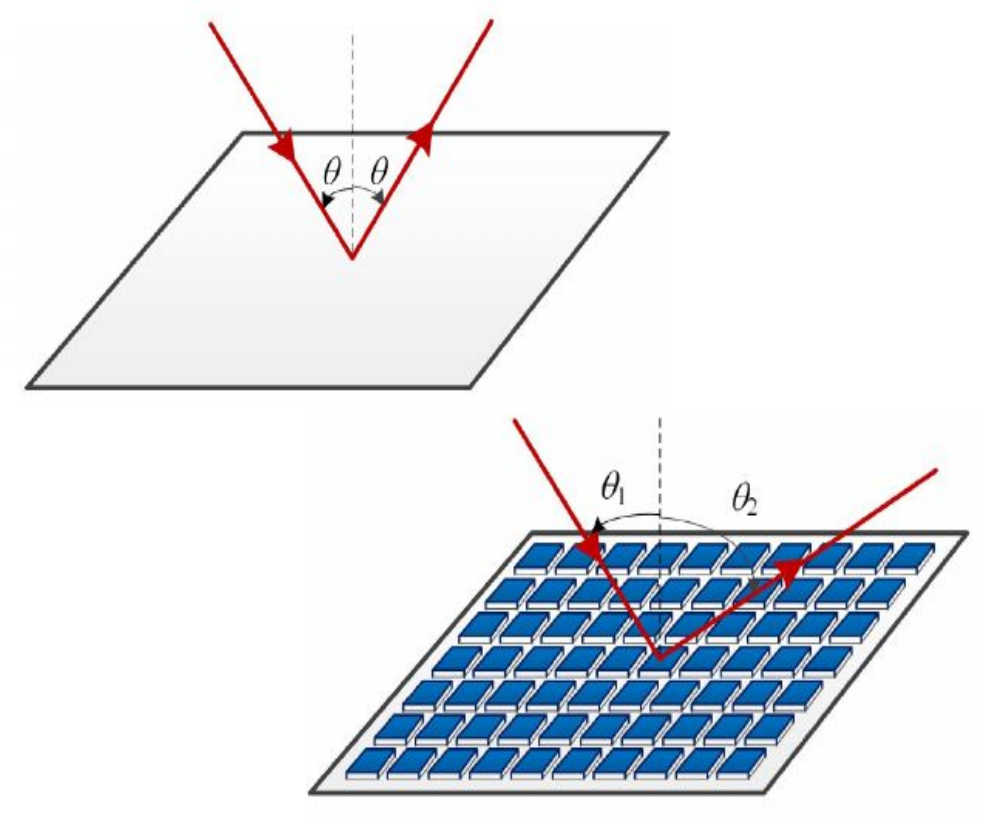
- **RF-Based HAR**
  - Novel approach
  - Exploits stray RF signals in medium
  - Cheaper and privacy capable
  - **But RF medium is generally uncontrollable**



Reconfigurable Intelligent Surfaces

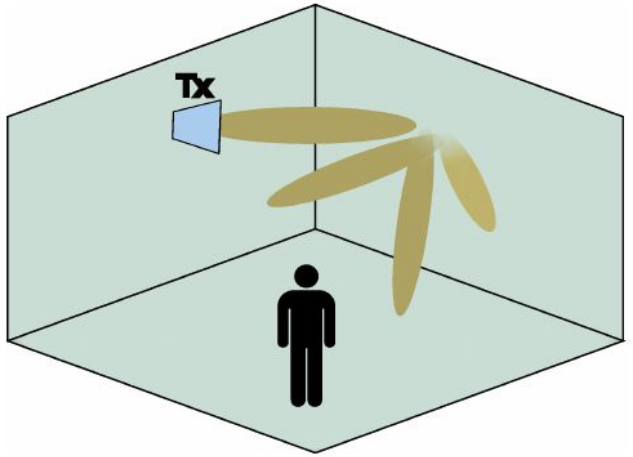
- **RIS**
  - RISs are 2D matrices of passive antenna elements (unit cells) that **reflect** RF signals.
  - Each unit cell adjusts the **reflection coefficient** to control signal **phase** and **direction**.

  - <u>Key Points</u>
    - No active RF chains – low power and cost.
    - Capable of **non-specular** reflections
    - Promising as solution for challenges in 6G and high-frequency band

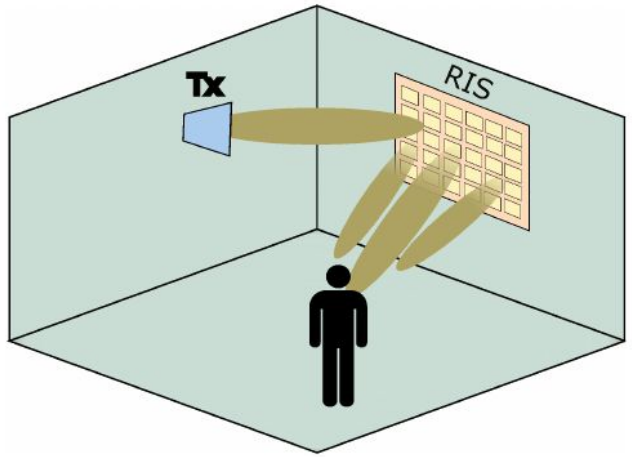


Reconfigurable Intelligent Surfaces

- **Controllable medium**
  - Non-specular reflections
  - NLoS channels
    - Extended coverage
    - Indoor environments
  - Localization
  - Sensing



- **RF-Based HAR with RIS**
  - Medium is controllable through manipulation of reflected signals
  - Associates medium response to control and status of medium → sensing
  - High spatial resolution



Contributions

- Design of a PIN diode based unit cell for 6.5 GHz
- Design of a RIS with 64 elements
- Modeled the environment and channel for an Hand Gesture Recognition
- Implemented RIS configuration for sensing
- Dataset for RF-based classification human gestures
- Classification of gestures for two different CNNs

RIS-Based Hand Gesture Recognition (HGR)

Why 6.5Ghz RIS?

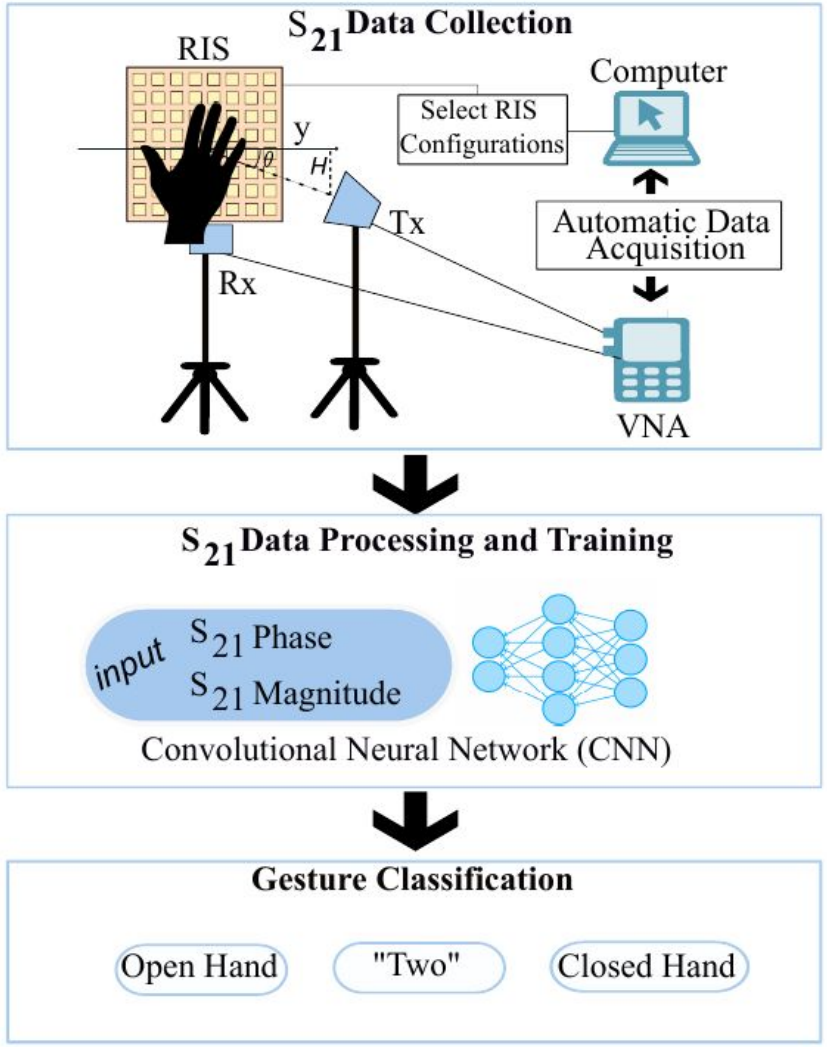
- Leverage ubiquity of WiFi and higher spatial resolution of higher frequency

Why Hand Gesture Recognition?

- Suitable for our RIS size of $18cm^2$

Overall Approach

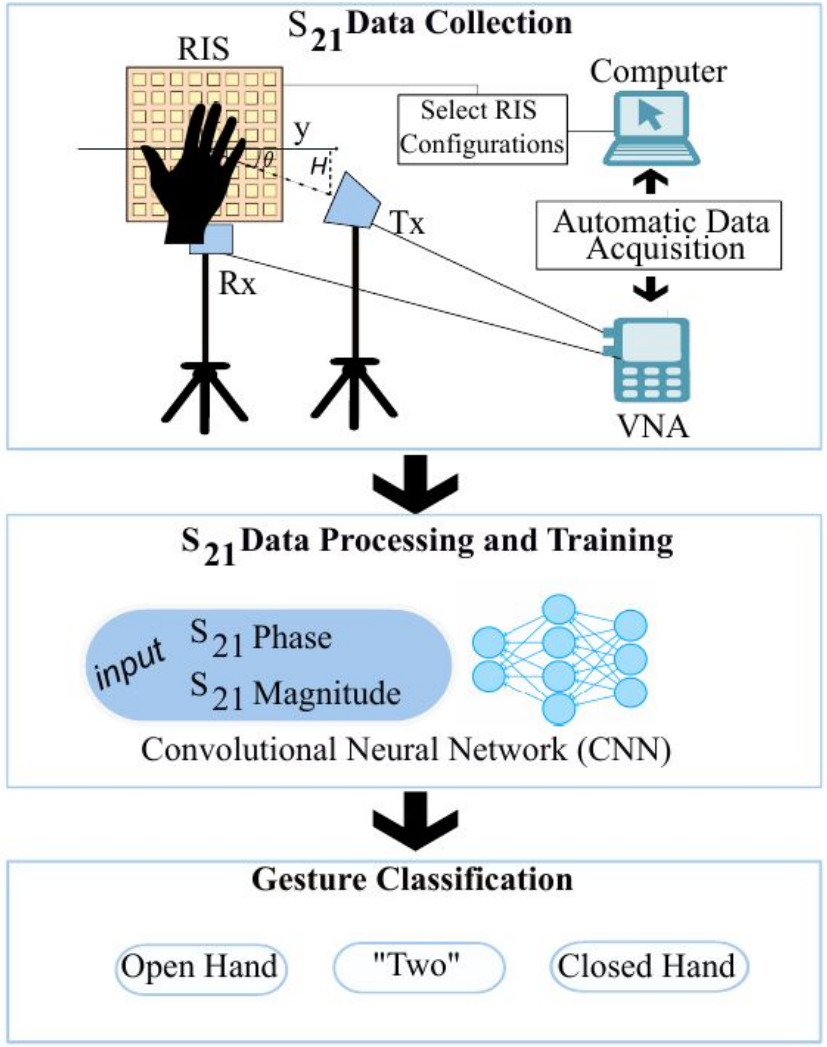
1. Gather S21 parameters in chamber
2. Represent data as image-like tensors
3. Train CNN and classify gestures



RIS-Based Hand Gesture Recognition (HGR)

Gather S21 parameters in chamber

- Anechoic chamber
- Signal path (sequence):
  - Transmitter (Tx).
  - RIS
  - Space of Interest (SoI)
  - Receiver (Rx)

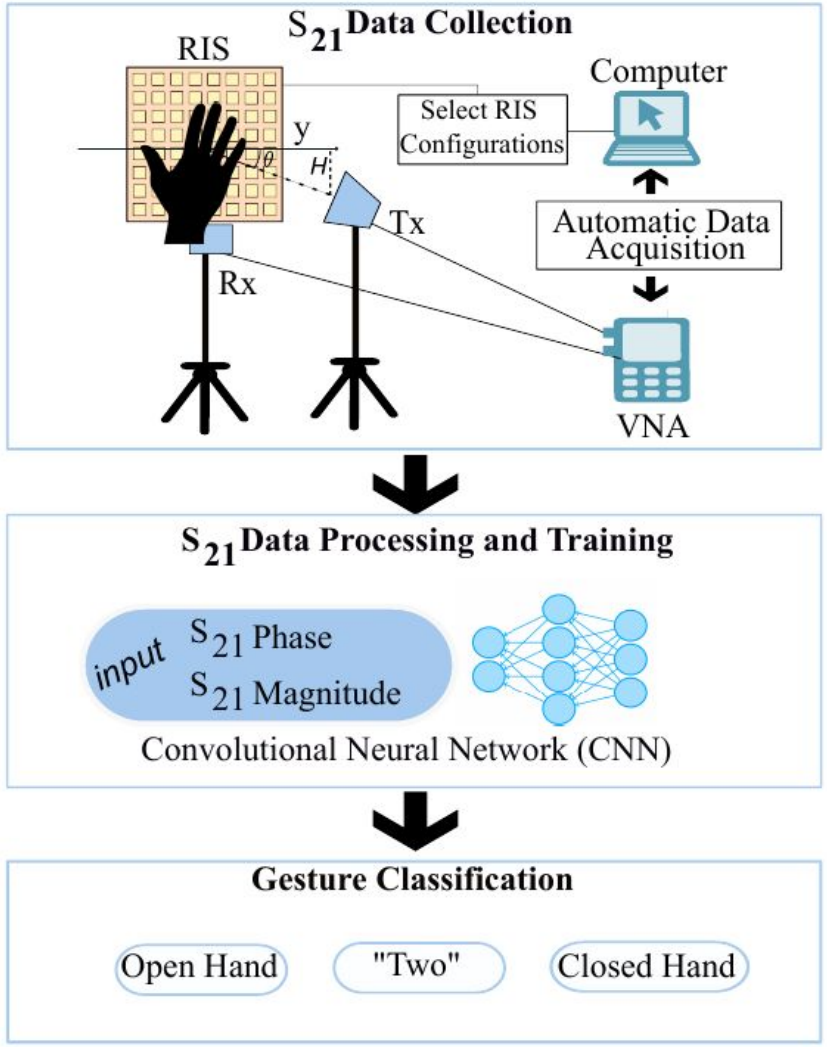


RIS-Based Hand Gesture Recognition (HGR)

Gather S21 parameters in chamber

- SoI (Space-of-Interest) → Hand gestures
- Hand gestures → Different S21 data
- S21 parameters measured with VNA

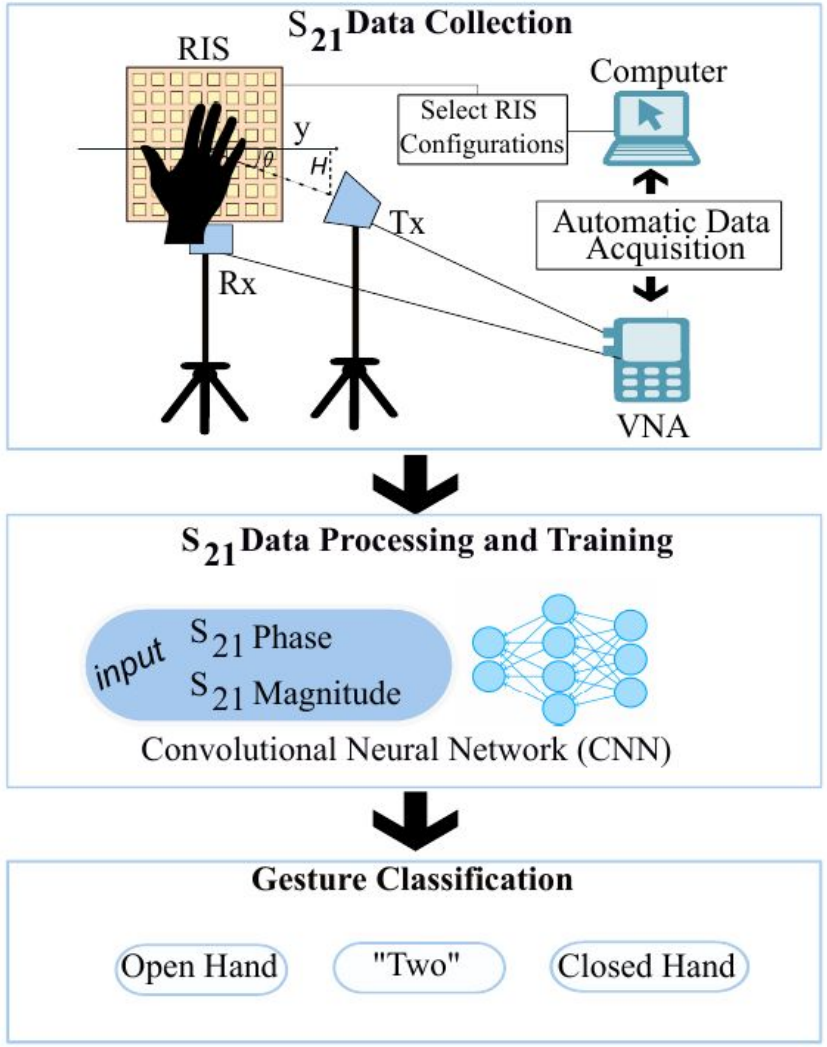
- For two RIS configuration methods:
  - Random sequences
  - Optimized sequences



RIS-Based Hand Gesture Recognition (HGR)

Image representation and classification

- From S21 data:
  - *xx* axis → RIS configuration
  - *yy* axis → Frequency range
  - Color value →
    - 1) Phase or 2) Mag. response
    - → i.e., two channels
- Feed image channels into CNN



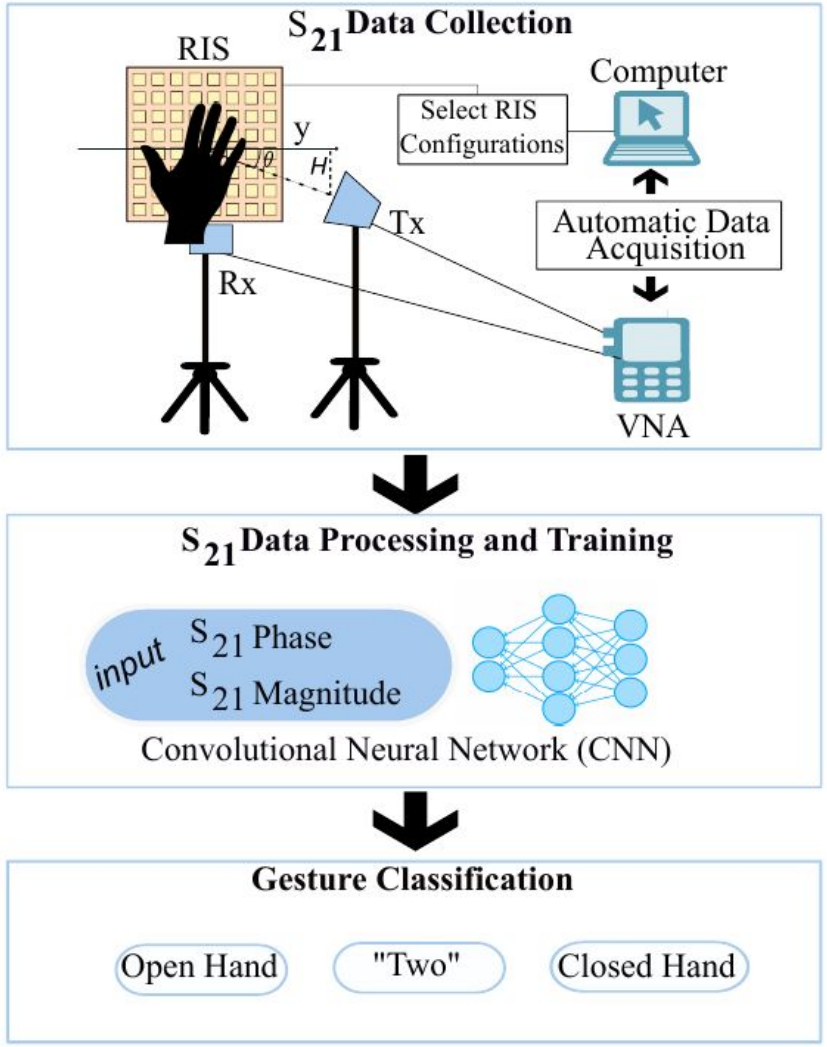
RIS-Based Hand Gesture Recognition (HGR)

Setup

1. Physical setup for HGR
2. Channel model and RIS configuration

Experiments

3. Unit cell characterization
4. RIS steering validation
5. Feasibility study of HGR with RIS
6. RIS-based HGR Classification



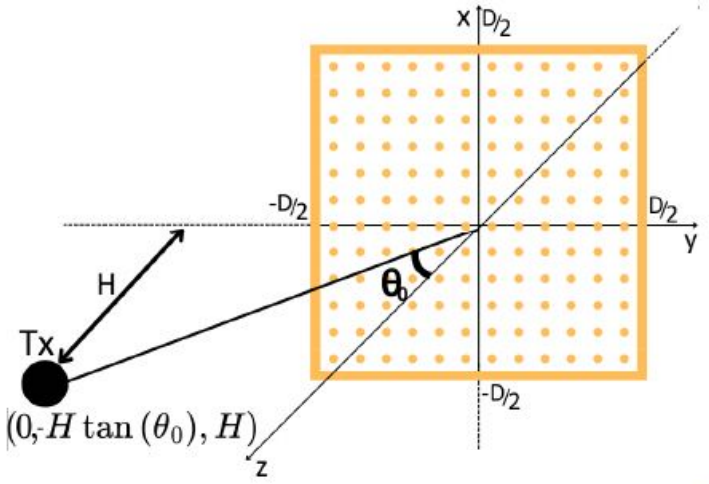
Setup: Physical Setup for HGR

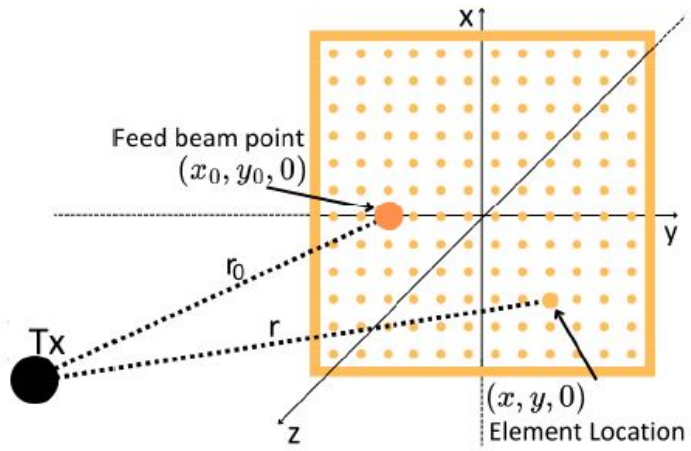
Model

- RIS is coordinate origin
- TX at:
  - Offset angle θ
  - Distance *H*
- Rx and Tx are horn antennas

Issue

- Maximize illumination of RIS by the TX → <u>find **H** and **θ**</u>
- Reduce occlusion of RIS by TX





Setup: Physical Setup for HGR

Maximize illumination

- Spillover Efficiency (ηs)
- Illumination Efficiency (ηi)
- Maximize $\eta_a = \eta_s \times \eta_i$

Swept parameters

- θ_0: 0° to 50°
- H: 20 cm to 180 cm
- y_0: ±15 cm

Results

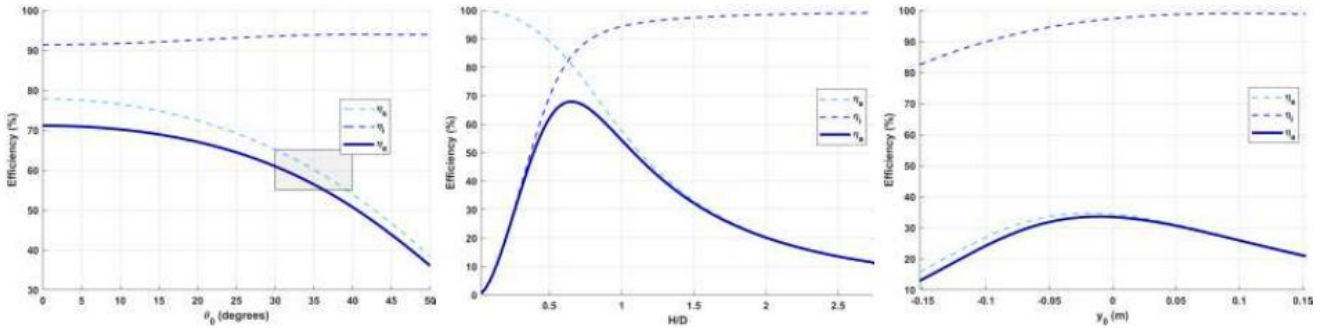
- $\theta_0 = 35°$, H = 33 cm.
- 35% total efficiency (η_a) due to chamber constraints.

$$\eta_s = \frac{\iint_A P(r)\,dA}{\iint_{\text{sphere}} P(r)\,dA} \quad (1)$$

$$P(r)dA = \frac{H}{r^3}\left(\frac{r_0^2 + r^2 - s^2}{2r_0 r}\right)^{2q} dxdy \quad (2)$$

$$\eta_i = \frac{1}{A}\frac{|\iint_A I(x,y)\,dA|^2}{\iint_A |I(x,y)|^2\,dA} \quad (3)$$

$$I(x,y) = \frac{H^{q_e}}{r^{1+q_e}}\left(\frac{r_0^2 + r^2 - s^2}{2r_0 r}\right)^{q} \quad (4)$$



(a) function of θ_0 (b) function of H/D (c) function of y_0

Setup: Physical Setup for HGR

Tx Position → Determined

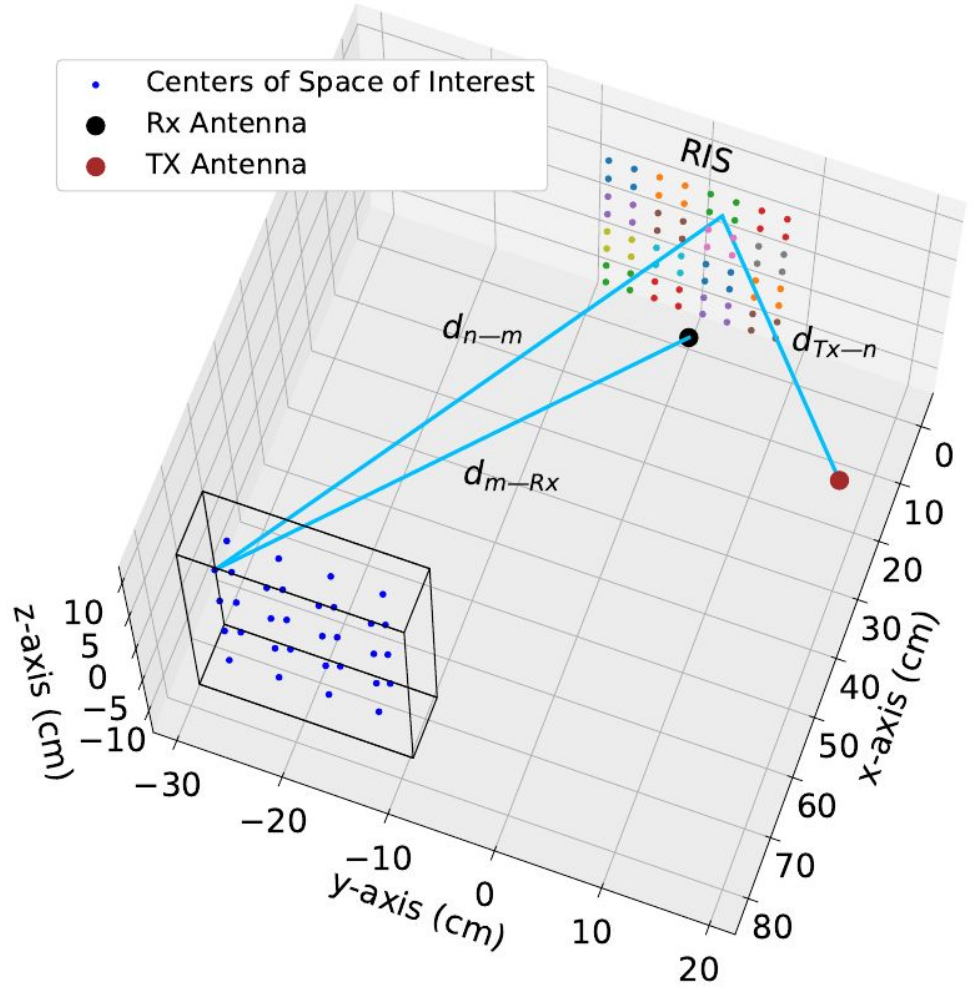
Sol?

- 15° offset to minimize Tx interference
- Divided into M= 32 equal cuboids

Rx Positioning?

- Rx positioned directly below RIS

Effective configuration despite physical limitations of chamber.

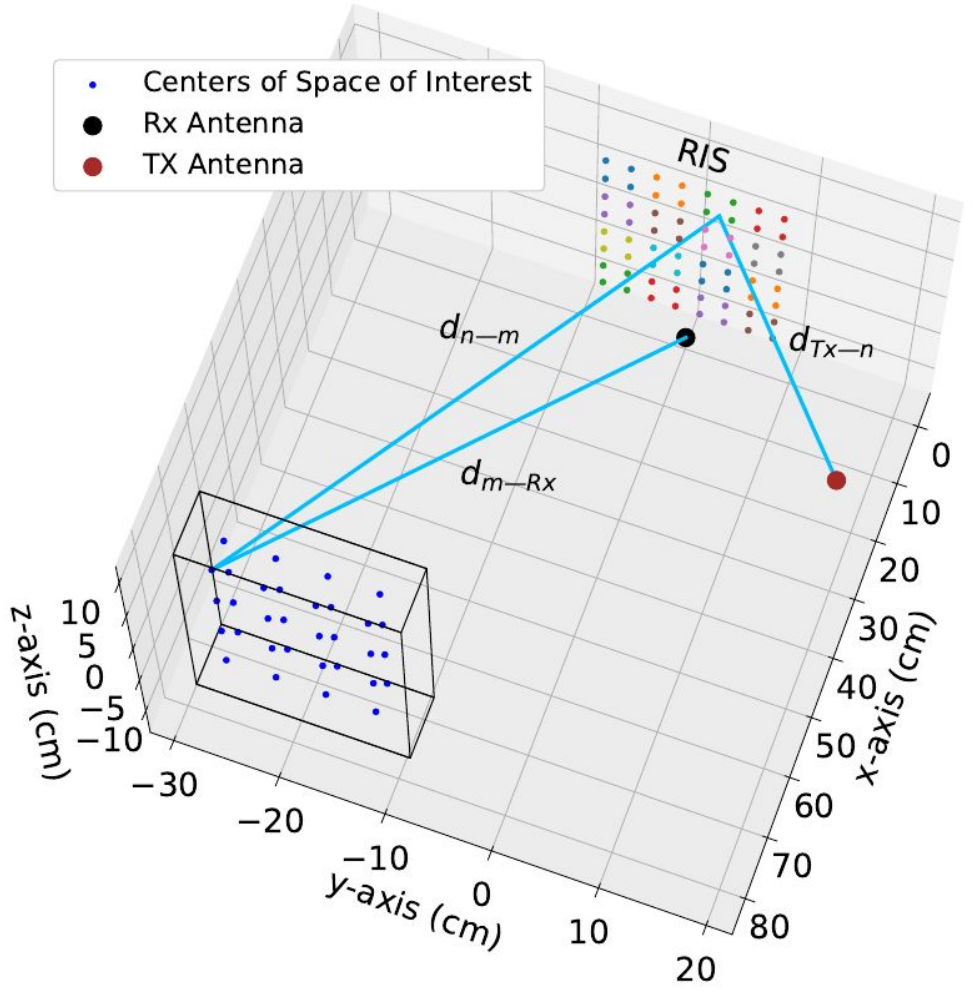


Setup: Channel Model

Components of the Model

- Tx Sends signals to the RIS
- **RIS**
  - 64 elements divided into 16 groups (L = 16)
  - Groups of 4 elements controlled jointly
- **Space-of-Interest (SoI):**
  - Divided into 32 cuboids (M = 32).
  - Gesture→Reflection coefficient $\boldsymbol{\eta_m}$ varies
- **Receiver (Rx)**
  - Captures reflected signals from SoI.

What is the total received Rx signal y_{rx}?
What is the channel gain *h*?
How does RIS configuration change y_{rx}?



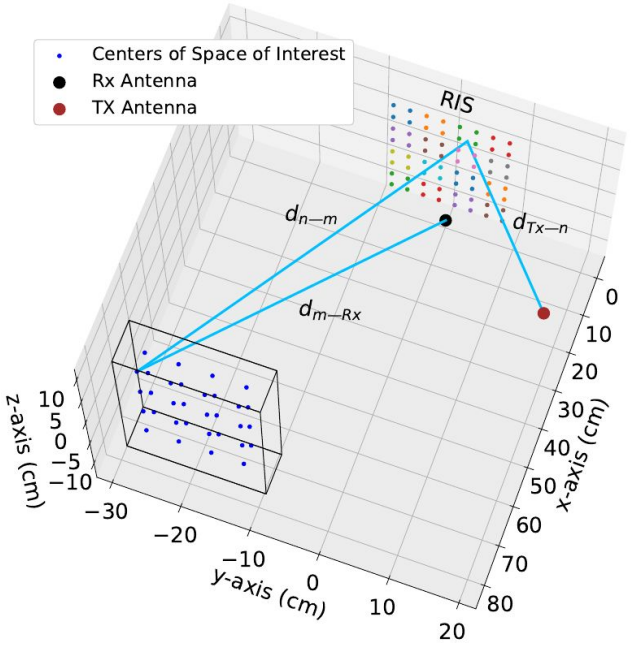
Setup: Channel Model

Total signal y_{rx}

- Reflections from each unit cell to each cuboid
- Reflections from each cuboid to Rx

$$y_{rx} = \sum_{m\in[1,M]} \sum_{l\in[1,L]} \sum_{n\in\mathcal{N}_l} h_{n,m}(s_l, \eta_m) \cdot P_t \cdot x$$

- P_t is Tx power
- x is baseband signal signal at f_c
- h is channel gain
  - η_m depends on SoI state
  - S_l is configuration of group of cells



η_m:	reflection coefficient of each cuboid
rn, m:	RIS's reflection coefficients
gT, gR:	transmitter/receiver gains
d_{nTx}:	Distance from Tx to RIS element nnn.
d_{nm}:	Distance from RIS element **n** to SoI cuboid **m**.
d_{mRx}:	Distance from SoI cuboid mmm to Rx.

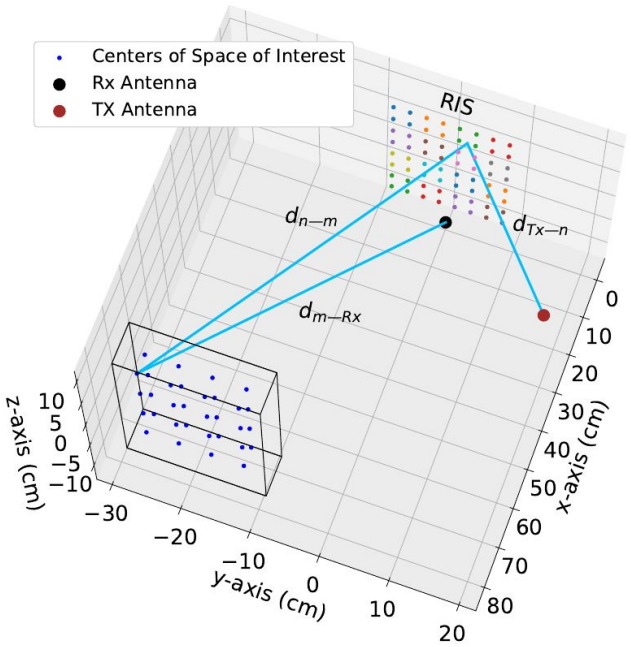
Setup: Channel Model

Modeling channel gain (*h*)

- SoA reflection formula
- Derive distances from physical model layout

$$\phi_{n,m} = e^{-j2\pi(d_{nTx}+d_{nm}+d_{mRx})/\lambda}$$

$$h_{n,m}(s_l, \eta_m) = \frac{\lambda \cdot r_{n,m}(s_l) \cdot \eta_m \cdot \sqrt{gT \cdot gR}}{4\pi \cdot d_{nTx} \cdot d_{nm} \cdot d_{mRx}} \cdot \phi_{n,m}$$



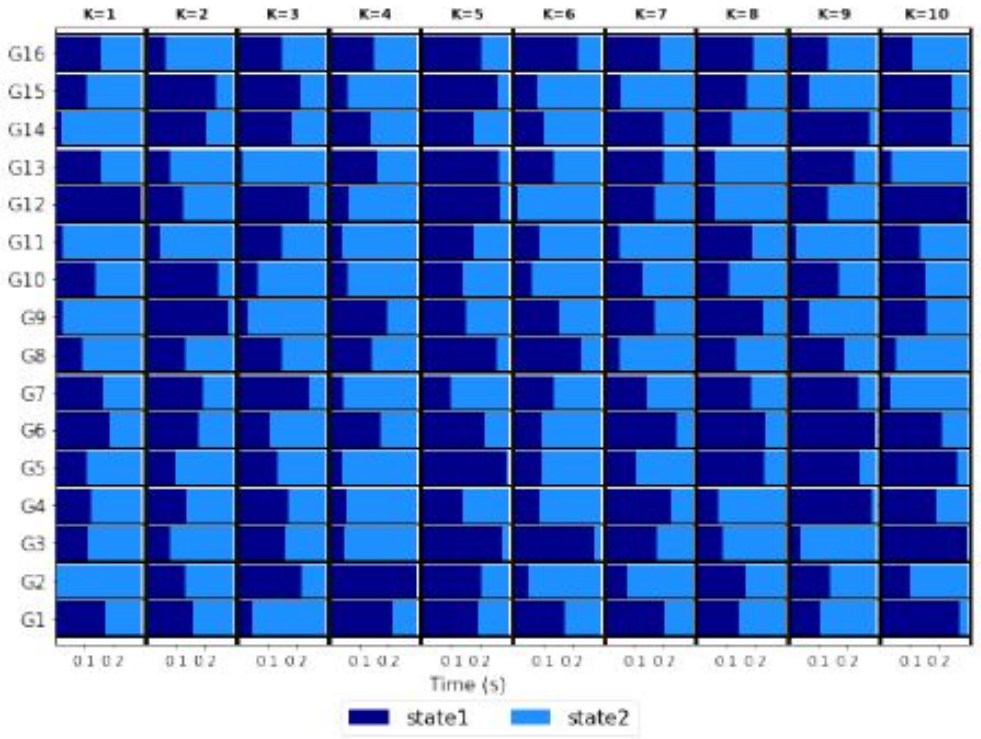
- $r_{n,m}$ is the impedance response of the unit cell at ***n,m***
- Impedance depends on configuration S_l

η_m:	reflection coefficient of each cuboid
rn, m:	RIS's reflection coefficients
gT, gR:	transmitter/receiver gains
d_{nTx}:	Distance from Tx to RIS element nnn.
d_{nm}:	Distance from RIS element **n** to SoI cuboid **m**.
d_{mRx}:	Distance from SoI cuboid mmm to Rx.

Setup: RIS Configuration Sequence

RIS Reconfiguration

- RIS configuration → known
- SoI state → unknown
- Sequences of RIS states produce different S21 responses
  - i.e., we are “observing” the unknown state from several “perspectives”
- We consider 10 “frames” where each of the 16 cells changes state



Time vs. state for 16 cells

Setup: RIS Configuration Sequence

Modeling Config. Sequence

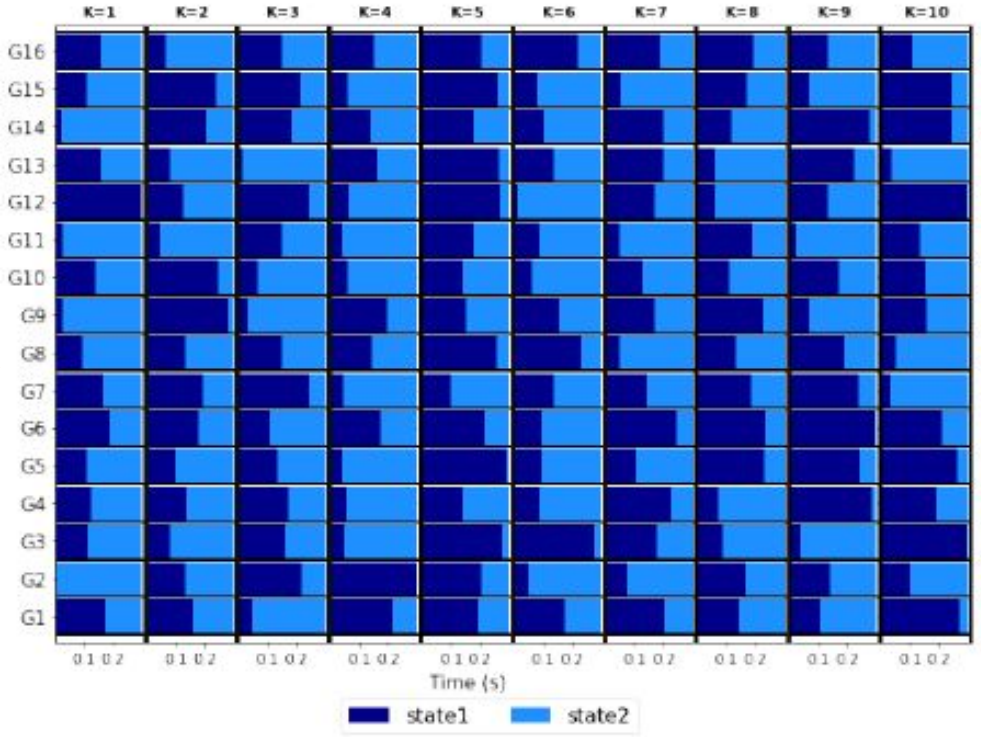
- RIS elements transition between states (s_1,s_{Na}) per time frame (δ).
- **1-bit RIS (2 states)**

$$T = \begin{pmatrix} \mathbf{t_1} & \mathbf{t_2} & \cdots & \mathbf{t_K} \end{pmatrix}^T$$

$$A = [\alpha_1 \ \alpha_2 \ldots \alpha_M]$$

channel gains for cell states

$$y_{rx} = P_t \cdot x \cdot T \cdot A \cdot \eta, \quad \text{with } \Gamma = T \cdot A$$



Time vs. state for 16 cells

Γ = T · A: **Combines RIS configurations and channel gain matrix.**

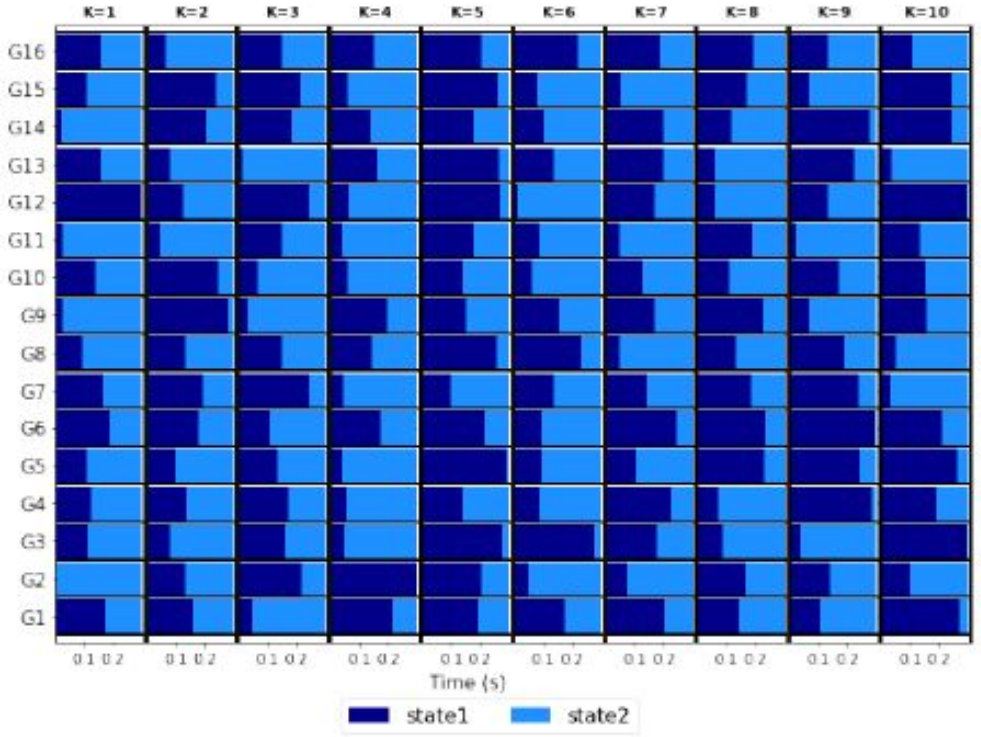
Setup: RIS Configuration Sequence

Determining the Sequence

- Can be random

- However
  - May lead to redundant or insufficient data
  - Ideally, signal paths should carry uncorrelated information
  - Use optimized configurations

→ Optimize for minimum mutual coherence using SoA algorithm



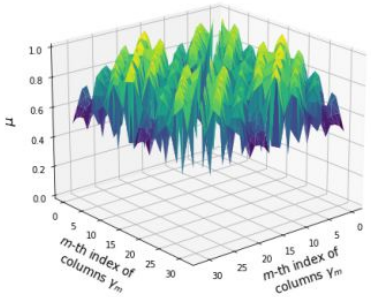
Time vs. state for 16 cells

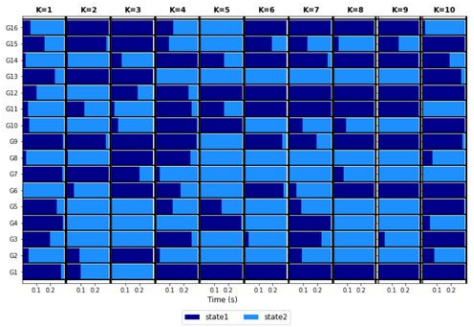
Setup: RIS Configuration Sequence

Optimizing the Sequence

- FCAO Algorithm
- Minimizes mutual coherence
- Sequence gathers more SoI information

Random

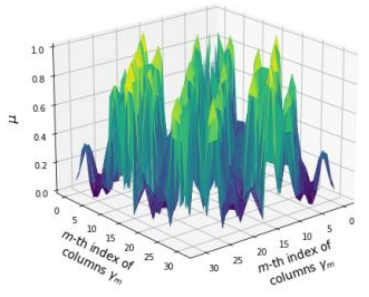


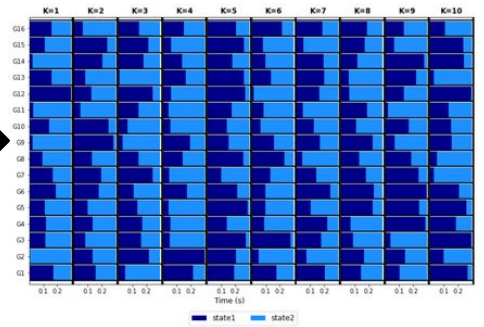


$$
\begin{aligned}
&(\mathrm{P1}) \min_{\boldsymbol{T}} \quad \mu(\boldsymbol{\Gamma}), \\
&\quad with \quad \boldsymbol{\gamma}_m = \boldsymbol{t}_k \boldsymbol{\alpha}_m, \quad \forall m \in [1, M], \\
&\qquad \mathbf{1}^T \tilde{\boldsymbol{t}}_{k,l} = \delta, \quad \forall k \in [1, K],\ l \in [1, L], \\
&\qquad \tilde{t}_{k,l,i} \geq 0, \quad \forall k \in [1, K],\ l \in [1, L],\ i \in [1, N_a].
\end{aligned}
$$

$$
\begin{aligned}
&(\mathrm{P2}) \min_{\boldsymbol{t}_k, \boldsymbol{u}} \quad \|\boldsymbol{u}\|_1, \\
&\quad s.t. \quad u_{m,m'} = \frac{\boldsymbol{\gamma}_m^T \boldsymbol{\gamma}_{m'}}{\|\boldsymbol{\gamma}_m\|_2 \cdot \|\boldsymbol{\gamma}_{m'}\|_2}, \\
&\qquad m,\ m' \in [1, M],\ m \neq m', \\
&\qquad \mathbf{1}^T \tilde{\boldsymbol{t}}_{k,l} = \delta,\ \forall l \in [1, L], \\
&\qquad \tilde{\boldsymbol{t}}_{k,l} \succeq 0,\ \forall l \in [1, L],
\end{aligned}
$$

Optimized





Mutual Coherence

Frame Configuration matrix T

RIS-Based Hand Gesture Recognition (HGR)

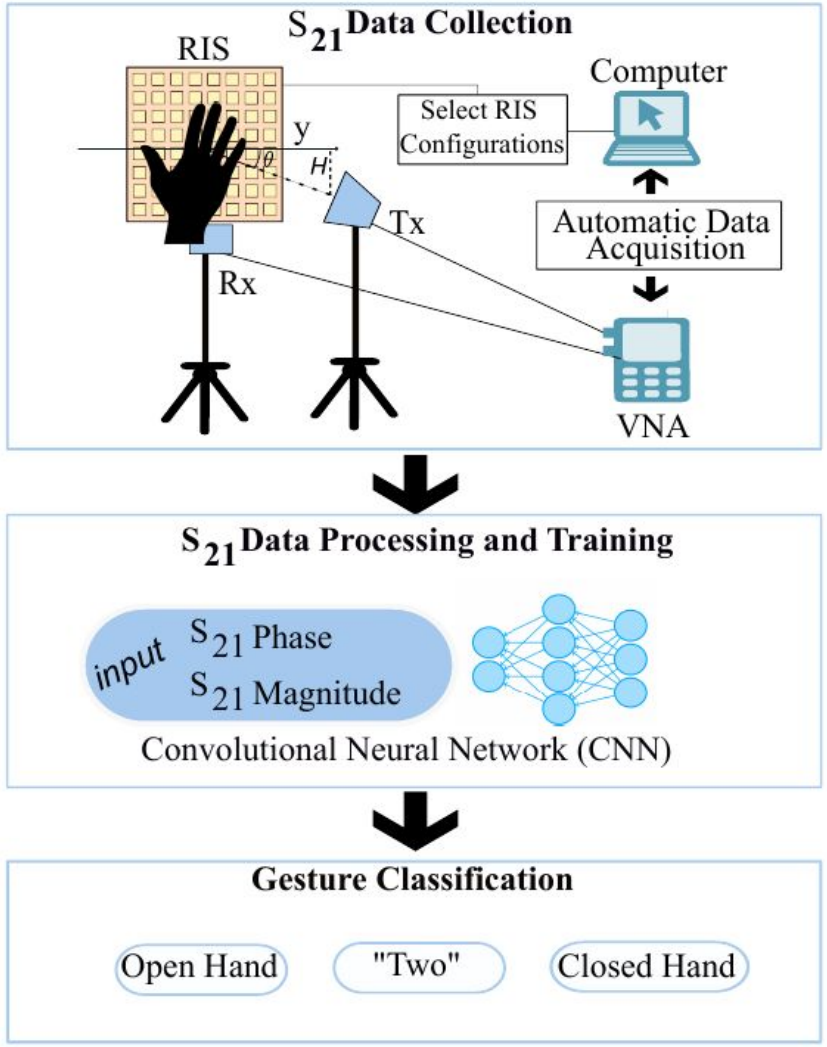
Setup

~~1. Physical setup for HGR~~

~~2. Channel model and RIS configuration~~

Experiments

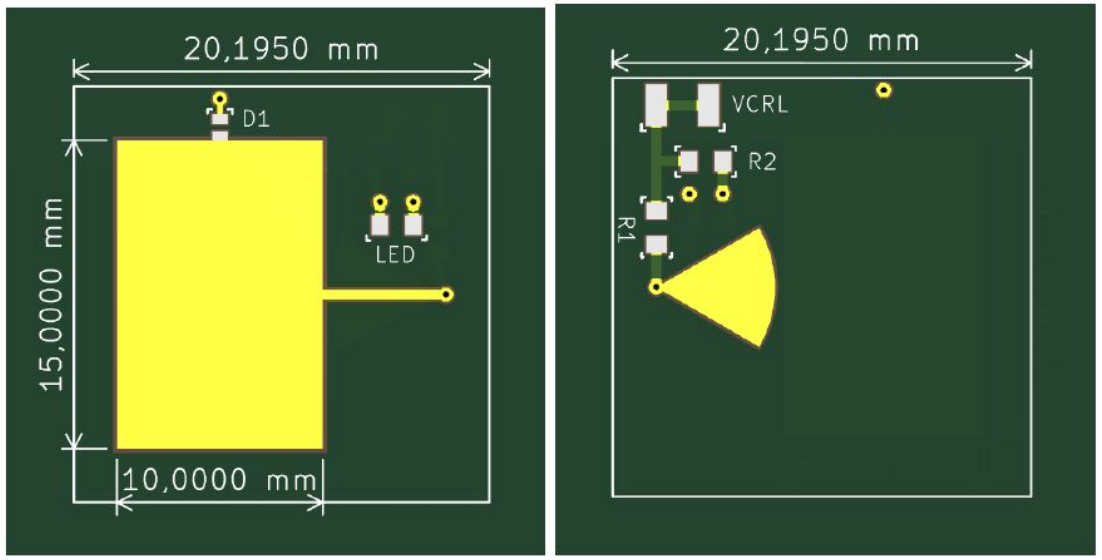
3. **Unit cell characterization**
4. RIS steering validation
5. Feasibility study of HGR with RIS
6. RIS-based HGR Classification



PIN Based Unit Cell Design

Unit Cell for 6.5GHz

- Simple patch antenna
  - f_c = 6.5 GHz, central to the WiFi-6E band
  - 10mm x 15 mm
  - Vertical polarization
  - 4mm F4B + 0.5 FR4 substrate
- Impedance Control
  - PIN diode (SMP1331-079LF)
  - 0.8V forward bias
  - For VCTRL = 3.3V → 15mA draw



(a) top layer (b) bottom layer

PIN Based Unit Cell Design

Objective: Compare fabricated unit cell performance to CST simulation.

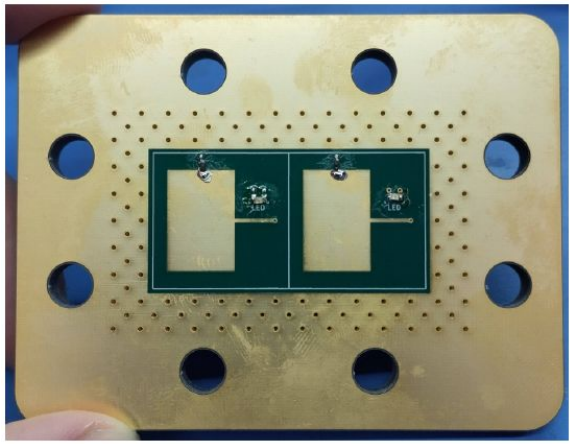
Experimental Setup
PCB with two unit cells in WR159 waveguide. Measure S11 in VNA.

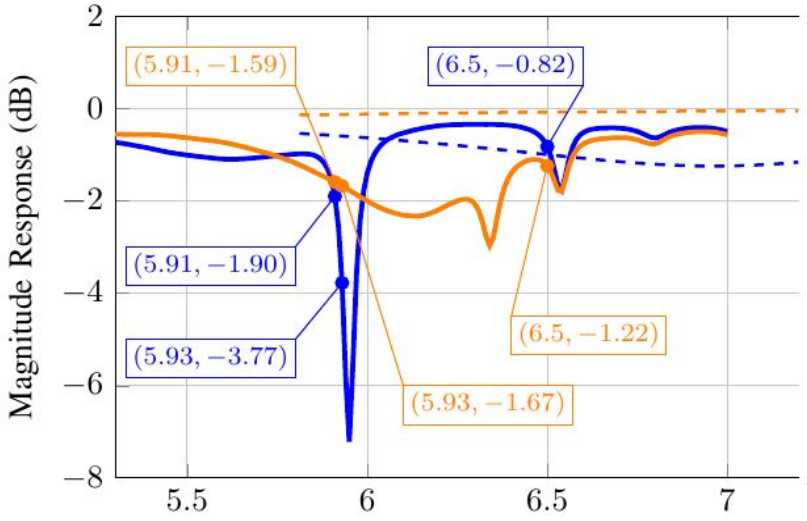
Experimental Results

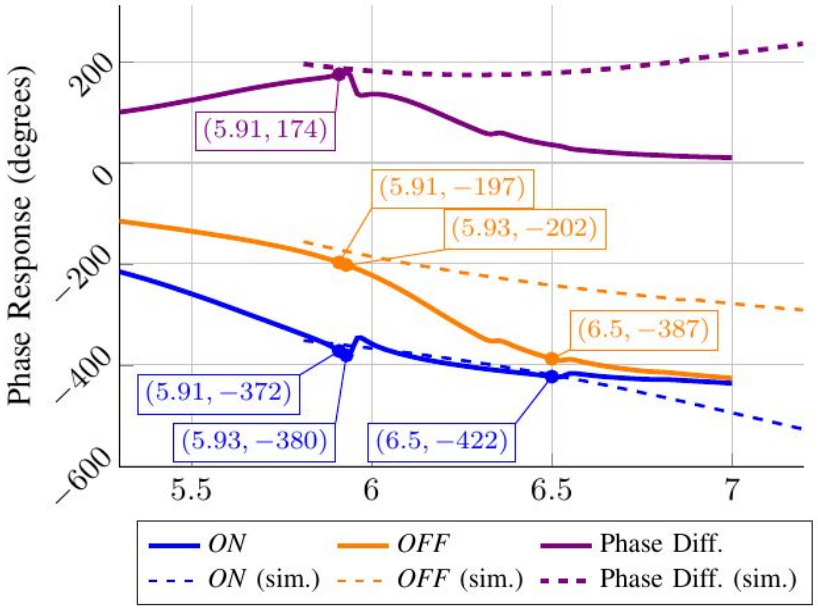
- Simulations predicted 180° phase shift at 6.5 GHz; measured 35°.
- Best trade-off at 5.91 GHz with 174° phase shift and balanced magnitude response.

Conclusion

- Phase difference 35° at 6.5Ghz
- Phase difference 178° at 5.93 GHz but magnitude disparity
- **Use 5.91 GHz** for balanced magnitude response and 174° phase difference.







RIS-Based Hand Gesture Recognition (HGR)

Setup

~~1. Physical setup for HGR~~

~~2. Channel model and RIS configuration~~

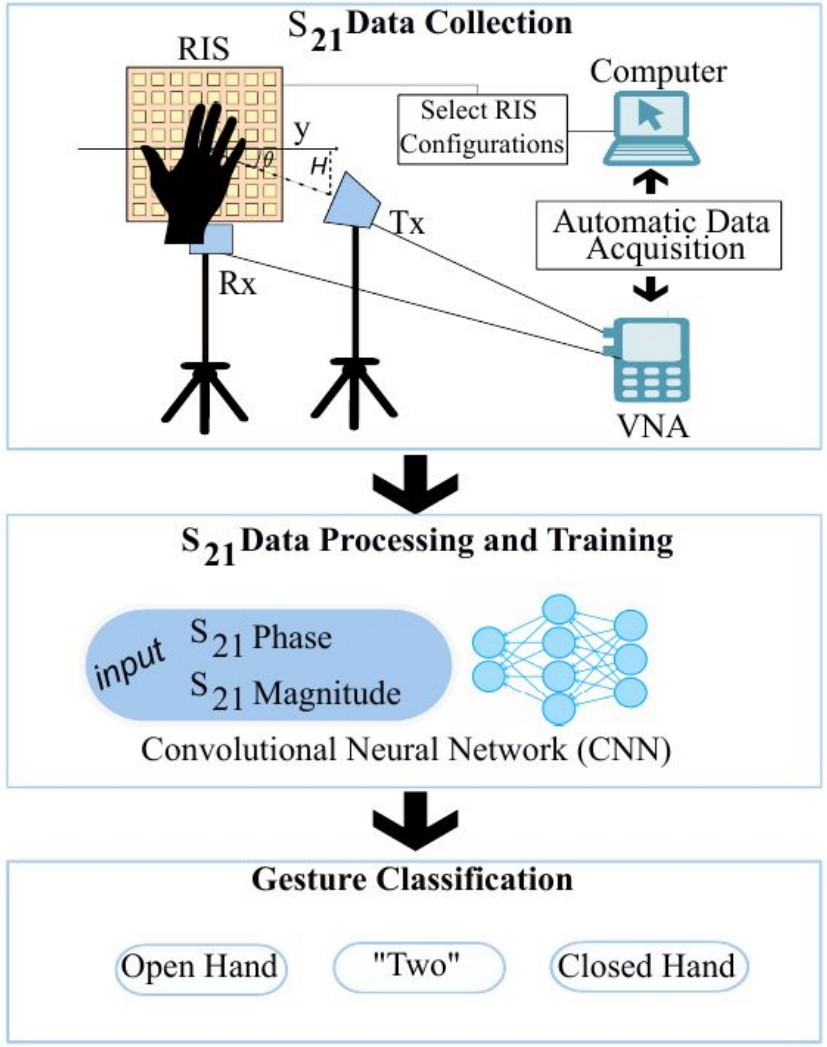
Experiments

~~3. Unit cell characterization~~

4. RIS steering validation

5. Feasibility study of HGR with RIS

6. RIS-based HGR Classification



8×8 RIS Tile Design and Beamforming

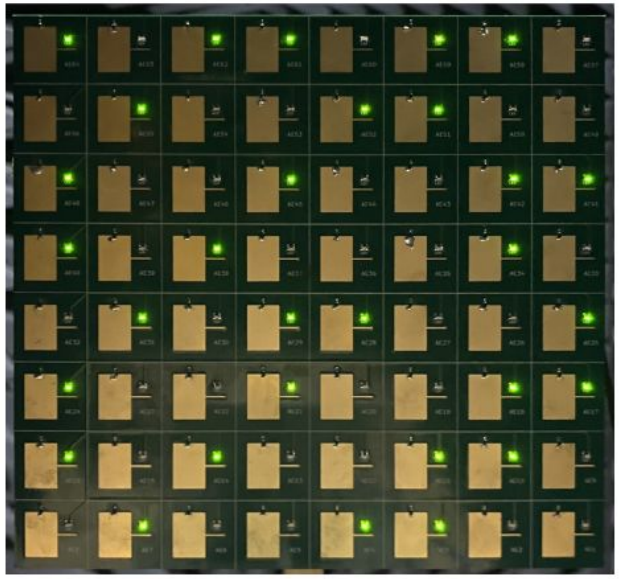
RIS Tile

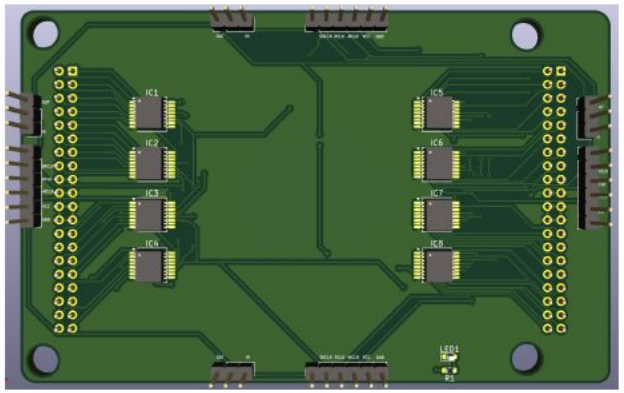
- 8x8 → 64 unit cells
  - Separated by half wavelength
- 18.45cm^2 area
- LEDs indicate ON state
- *"Tile"* ? → align multiple PCBs
  → larger RIS w/o design concerns

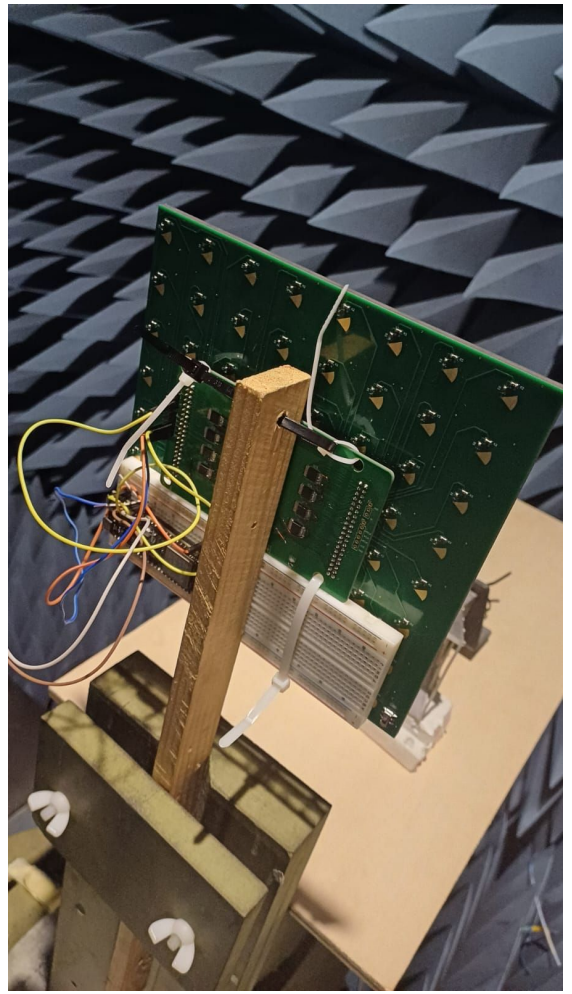
Control Board

- 8 Shift Registers (1 bit per cell)
- SPI interface → ESP32
- Holds tile itself with two 40-pin connectors

Design has contributed to standardization efforts in RIS technology.







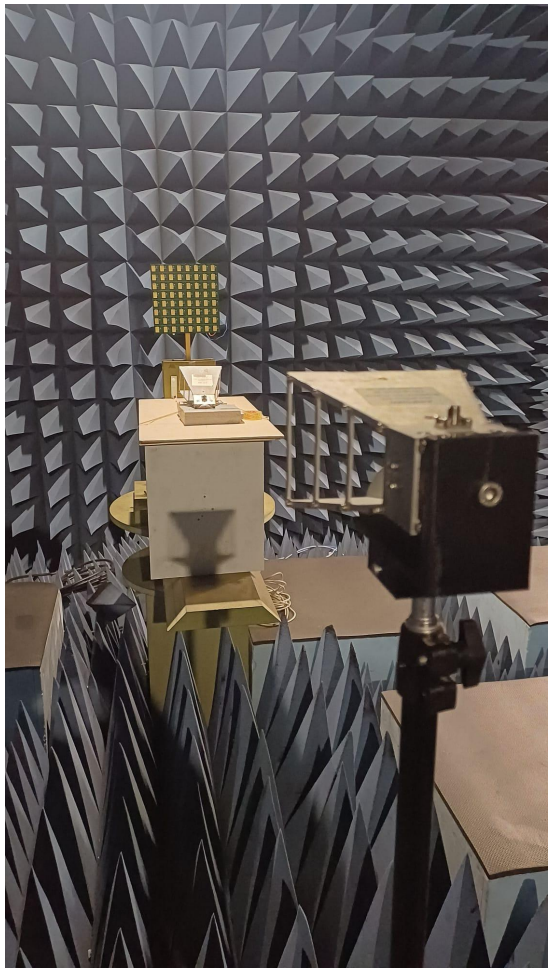
8×8 RIS Tile Design and Beamforming

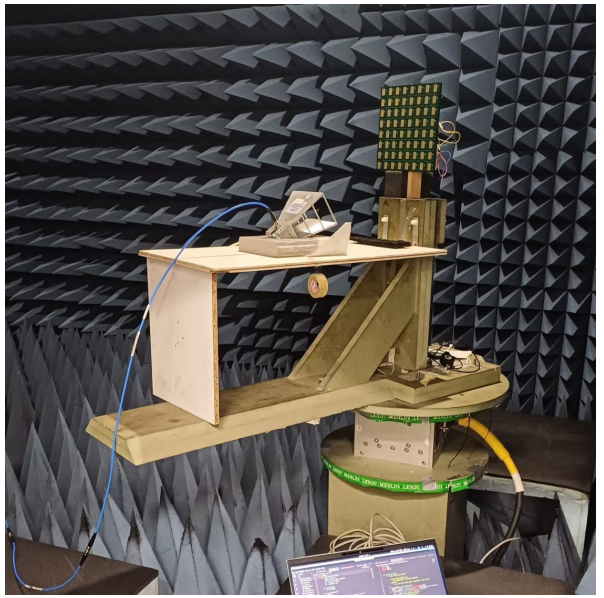
Objective:

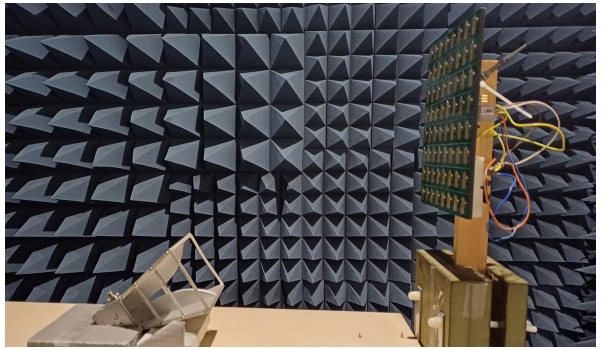
- Measure S21 parameters for various RIS control patterns and orientations.
- Validate **RIS beamforming capabilities** under controlled conditions.

Experimental Setup

- Anechoic chamber (7 m × 7 m × 3 m)
- **RIS:** on rotating platform
- **Tx:** 25.5 cm along X-axis and 36.5 cm along Z-axis (40 cm total distance)
- **Rx:** 170 cm from RIS
- Automated data acquisition:
  - RIS Steering: 0°, ±20°, ±40°
  - Rotor Orientation: ±60°







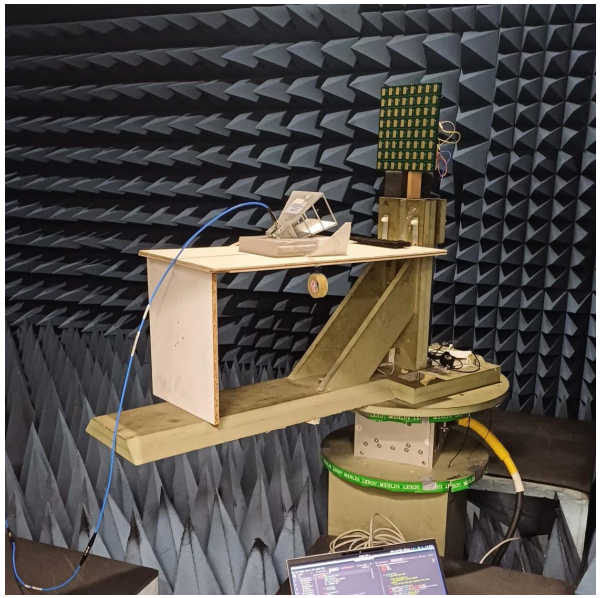
8×8 RIS Tile Design and Beamforming

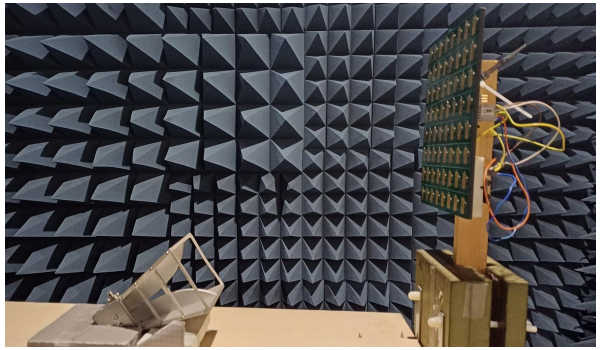
Objective:

- Measure S21 parameters for various RIS control patterns and orientations.
- Validate **RIS beamforming capabilities** under controlled conditions.

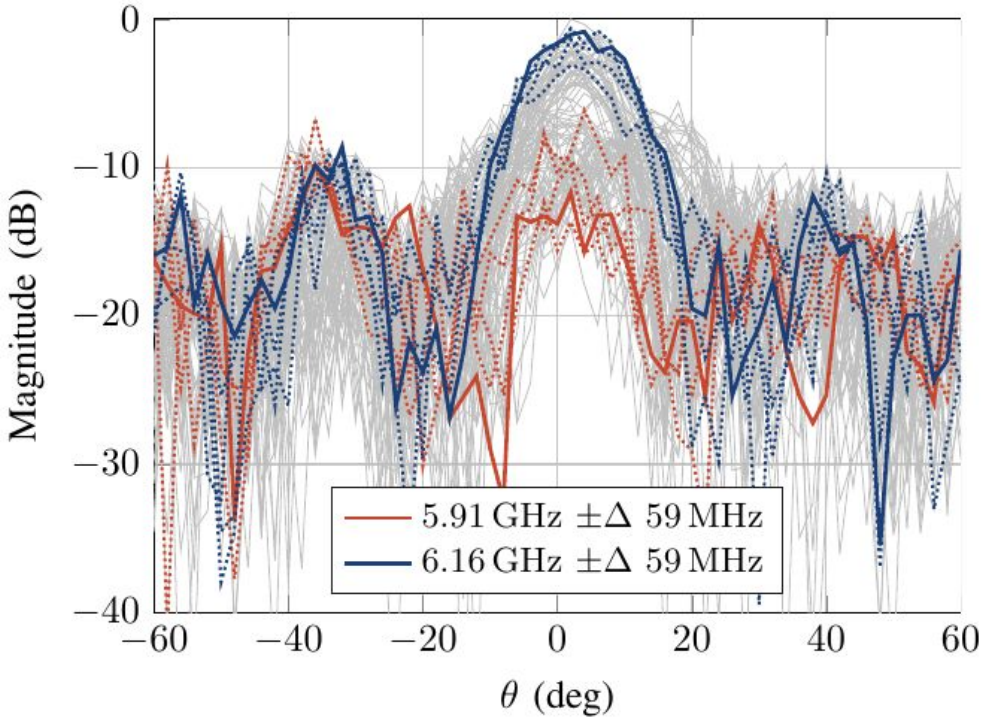
Experimental Setup

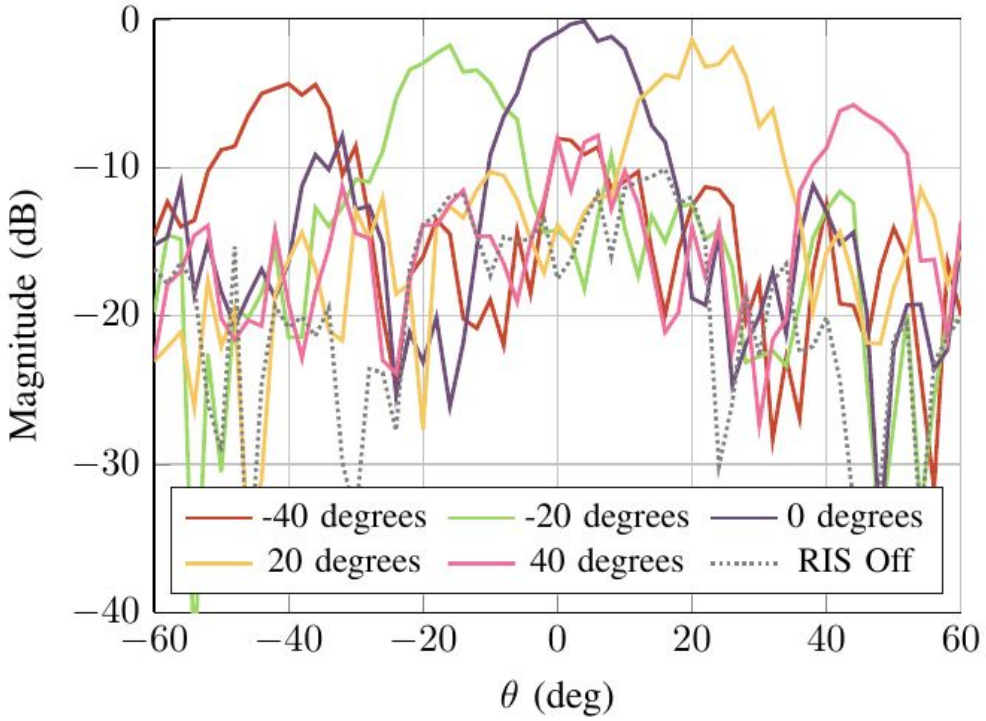
- Anechoic chamber (7 m × 7 m × 3 m)
- **RIS:** on rotating platform
- **Tx:** 25.5 cm along X-axis and 36.5 cm along Z-axis (40 cm total distance)
- **Rx:** 170 cm from RIS
- Automated data acquisition:
  - RIS Steering: 0°, ±20°, ±40°
  - Rotor Orientation: ±60°





8×8 RIS Tile Design and Beamforming





Experimental Results

(left) ±50 MHz bandwidth centered at 6.16 GHz shows the most pronounced steering response, despite chosen frequency of 5.91GHz. Likely due to inaccuracies in physical setup.

(right) Beamsteering patterns clearly observed across the 5.0–6.5 GHz range.

Conclusion

RIS correctly beamforms for 5.0–6.5 GHz, validating capability of controlling medium. Broadband influence of RIS supports application to hand gesture recognition (HGR).

RIS-Based Hand Gesture Recognition (HGR)

Setup

~~1. Physical setup for HGR~~

~~2. Channel model and RIS configuration~~

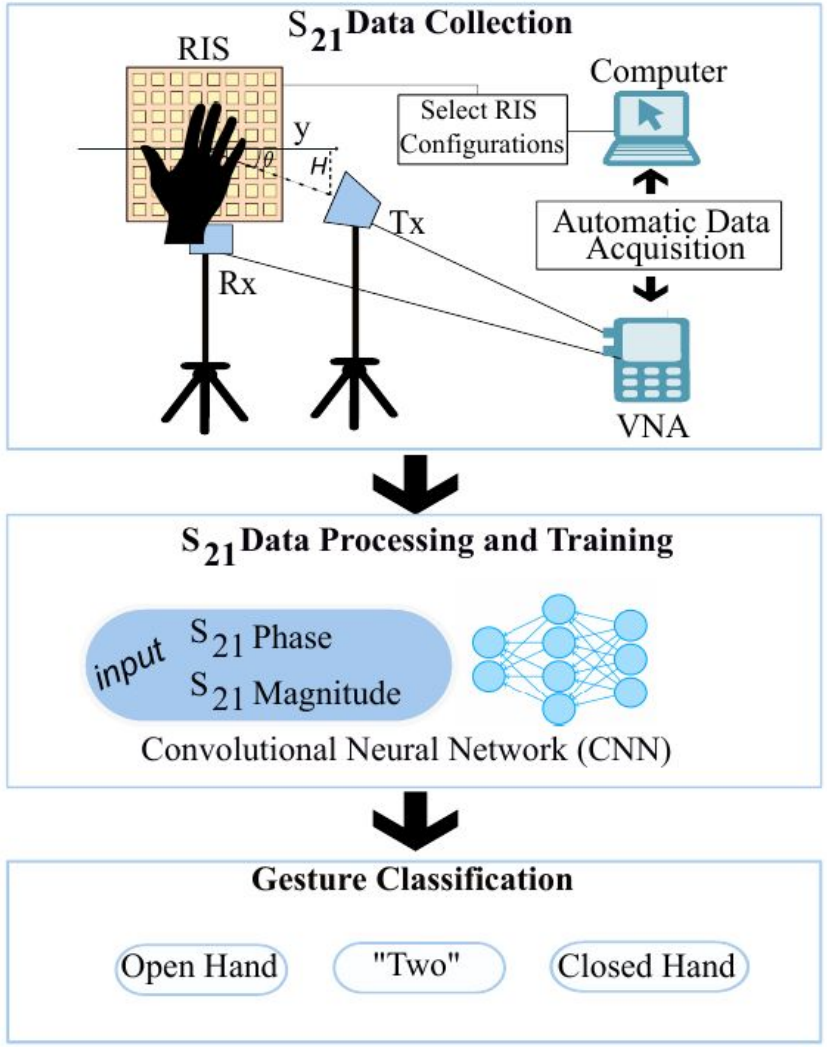
Experiments

~~3. Unit cell characterization~~

~~4. RIS steering validation~~

5. Feasibility study of HGR with RIS

6. RIS-based HGR Classification

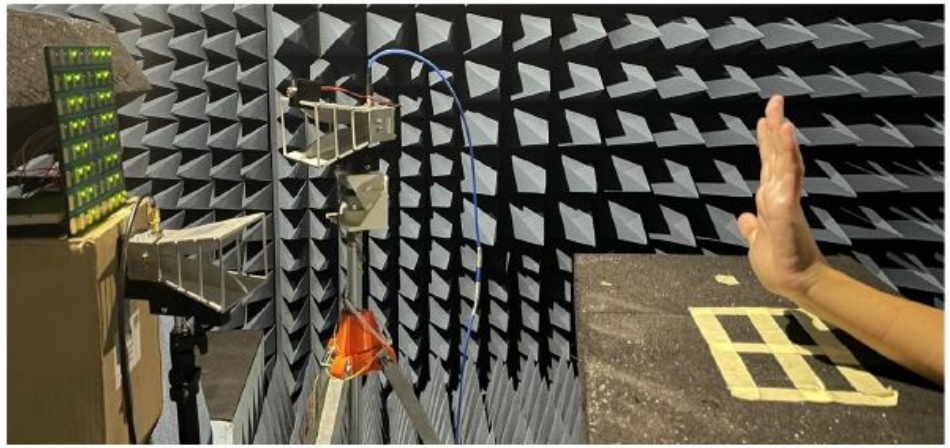


RIS-Based HGR Feasibility

Objective:
Validate the experimental setup and methodology for RIS-based HGR, and test if S21 parameters can distinguish different hand gestures in the SoI.

Experimental Setup

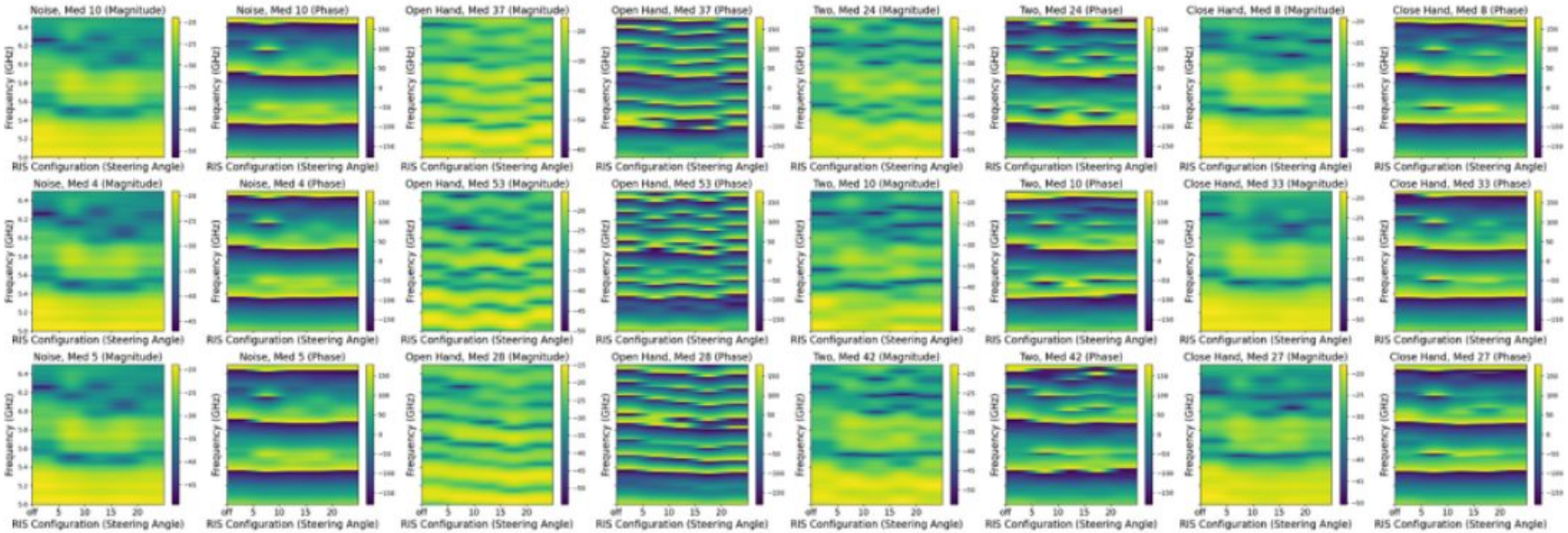
- Anechoic chamber (7 m × 7 m × 3 m)
- Tx and Rx → two pyramidal horns
- Setup according to the model
- RIS: four steering angles (5º, 10º, 15º, 20º)
  - No configuration sequences
- SoI: three different static hand gestures
- Dataset
  - 1 subject × 3 gestures × 5 RIS configs.
  - Frequency range: 5.0 GHz to 6.5 GHz

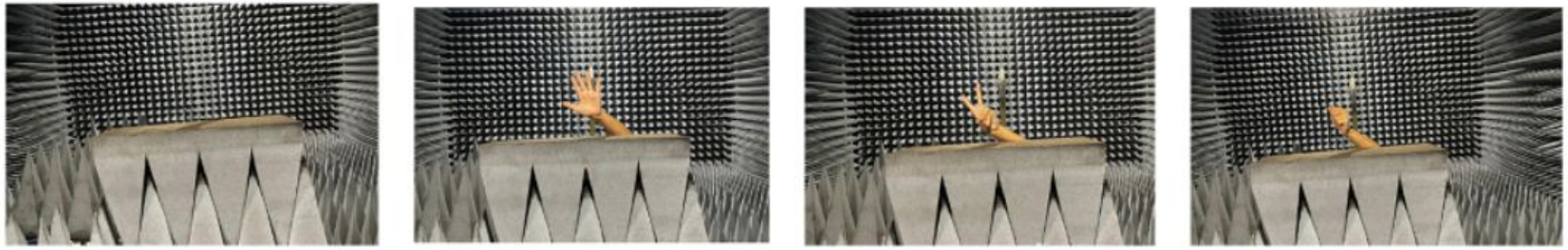


RIS-Based HGR Feasibility

Experimental Results
Consistent S21 response for all measurements of same gesture. Significant differences between gestures in both phase and magnitude responses.

Conclusion
RIS-based HGR is feasible, with clear gesture differentiation in S21 data. Future experiments will use a proxy hand model to streamline data gathering.





RIS-Based Hand Gesture Recognition (HGR)

Setup

~~1. Physical setup for HGR~~

~~2. Channel model and RIS configuration~~

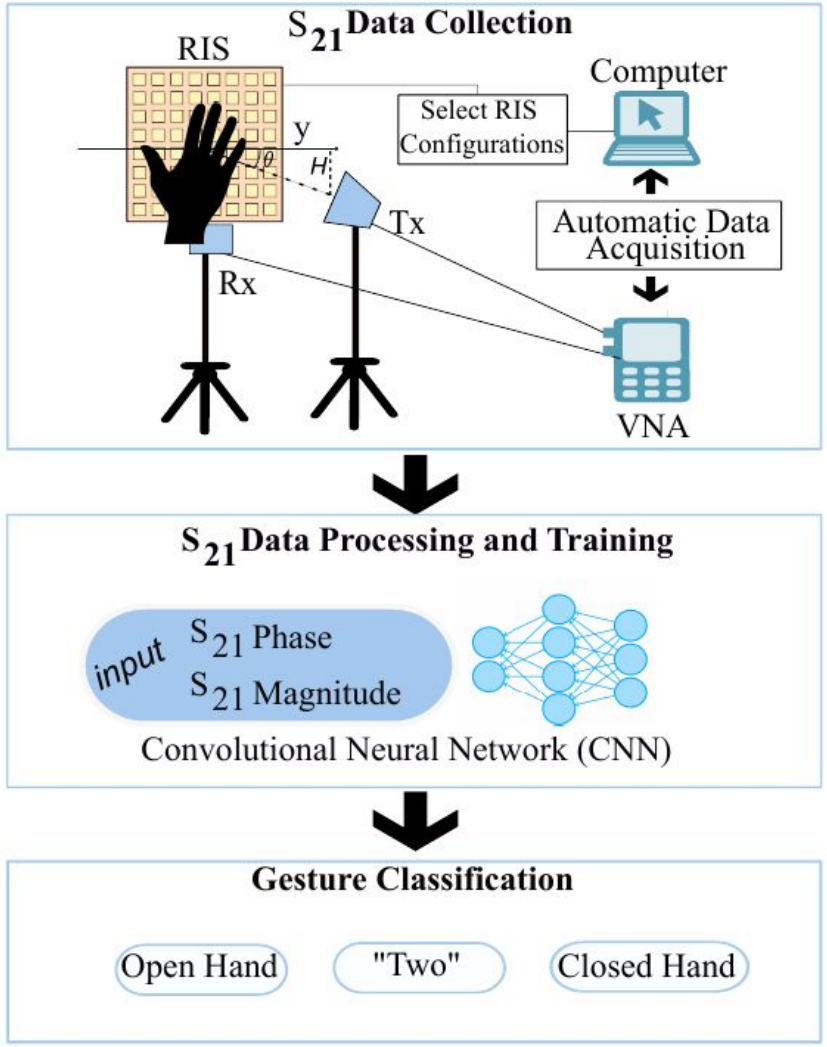
Experiments

~~3. Unit cell characterization~~

~~4. RIS steering validation~~

~~5. Feasibility study of HGR with RIS~~

6. RIS-based HGR Classification

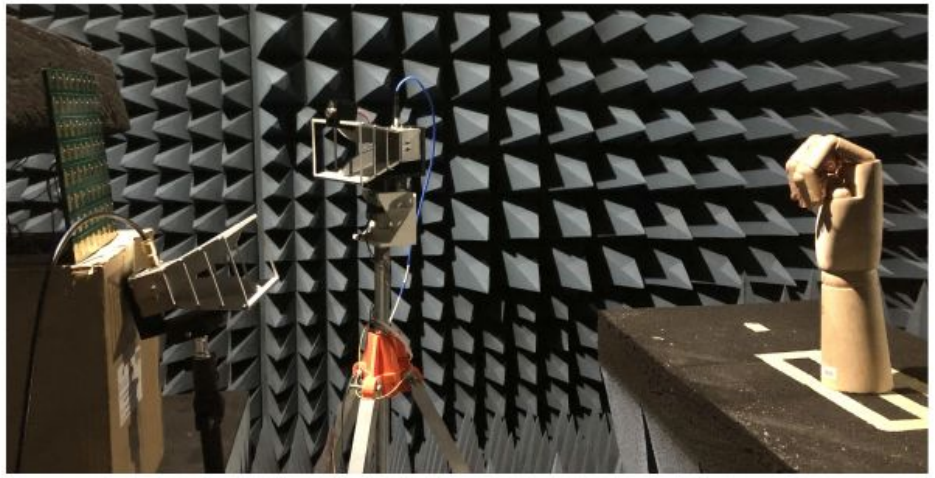


RIS-Based HGR Classification: Data

Objective:
Validate RIS-based hand gesture classification using a large dataset, compare random RIS config. sequences to FCAO-optimized sequences, and classify gestures with S21 data.

Experimental Setup

- Model hand in same 3 gestures
- Applied sequence RIS
  - Random, and FCAO optimized
- Frequency range: 5 GHz to 6.5 GHz
- 115 runs × 10 RIS frames (390 configs./run).
- Total: ~3105 samples per gesture (random and optimized configurations).
- Total data acquisition time: **~39 hours.**

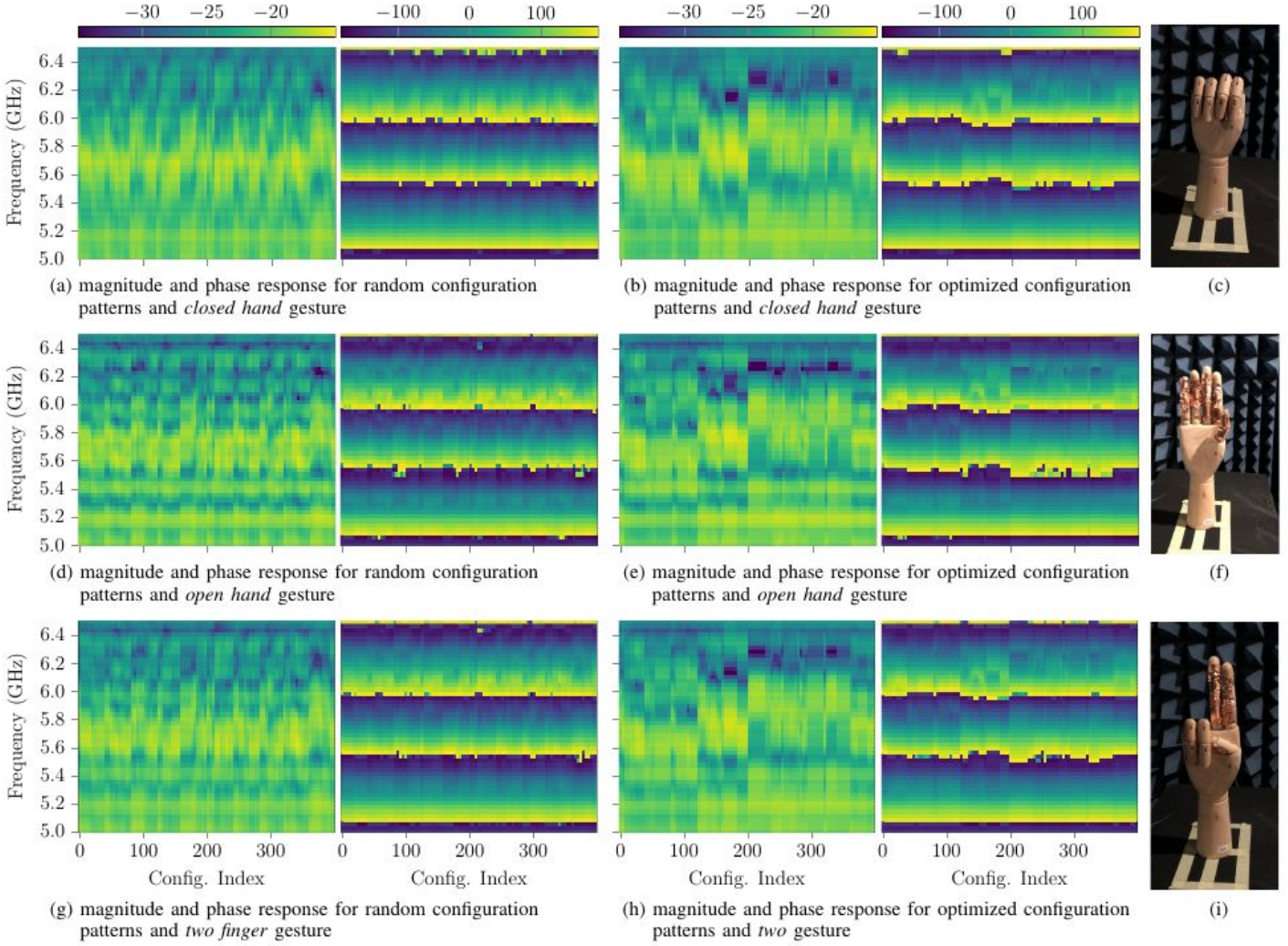


RIS-Based HGR Classification: Data

Optimized vs. Random Configurations:

- Random: Small variability in magnitude across during sequence. Slight phase variability.
- Optimized: captured more distinct S21 responses across gestures.
- Faster CNN learning and improved classification accuracy with optimized data.
- All measurements for same gesture very similar.

Data Augmentation for learning
Hand repositioned in 8 minor orientations for each gesture, and noise was synthetically added to the samples.



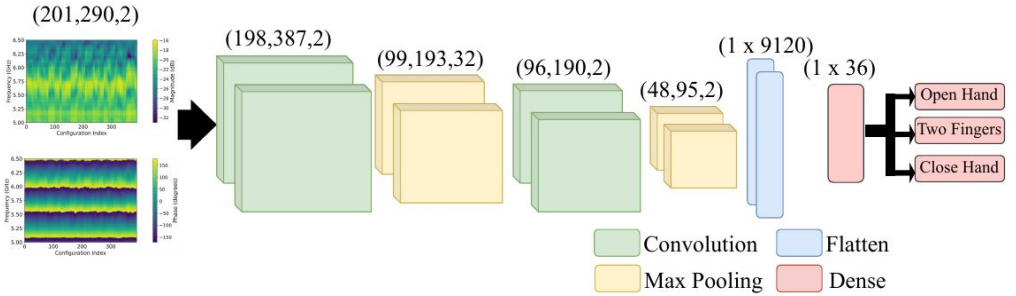
random optimized

RIS-Based HGR Classification: CNN

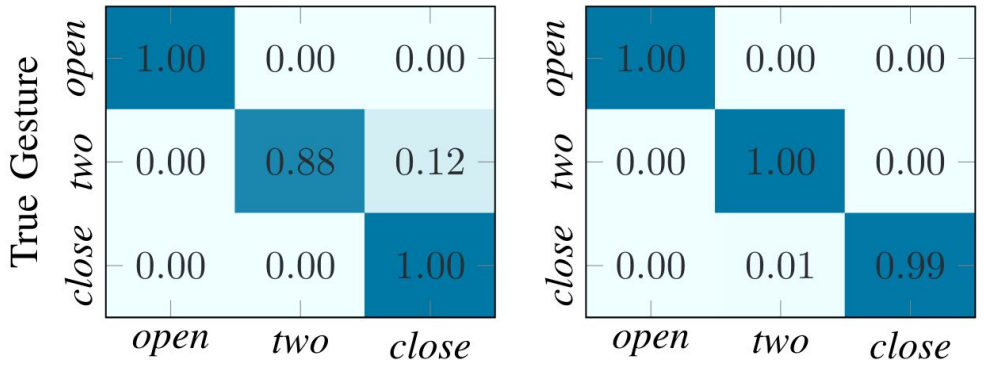
Model 1 (Narrowband):
Input: Average S21 response per frame at 5.91 GHz. Optimized configuration sequences improved accuracy by 3.53%.

Model 2 (Broadband):
Input: Magnitude and phase over 5–6.5 GHz. High accuracy for both configuration sequences (~99%), with minimal gains for optimization.

Conclusion
Successful HGR classification with both models. Narrowband model benefits from from optimized configuration sequences. Broadband model can capture mode information, and benefits less from optimized sequences.

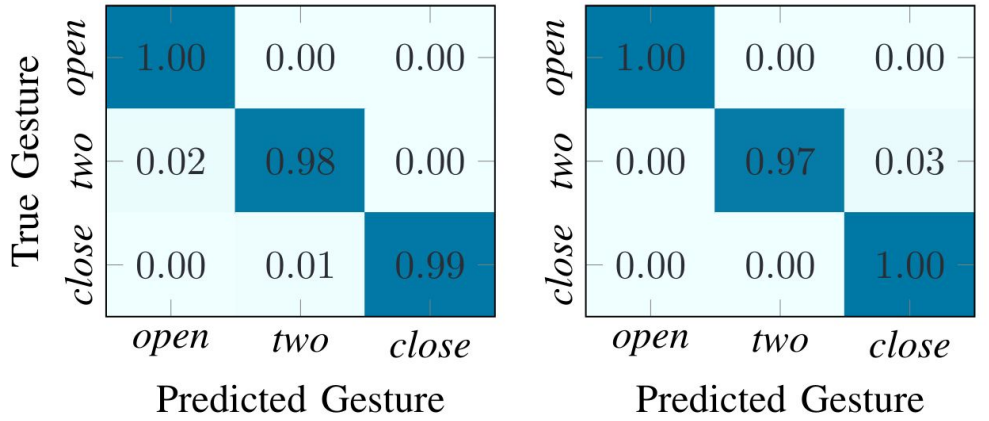


CNN Model #2



(a) CNN #1 and random config. (b) CNN #1 and optimized config.

CNN Model #1 Results



(a) CNN #2 and random config. (b) CNN #2 and optimized config.

CNN Model #2 Results

Conclusions

- **Advancing RF-based Hand Gesture Recognition with RIS**
  - Demonstrated RF-based classification of three distinct gestures using RIS technology
  - Designed and validated an 8×8 RIS tile for the WiFi-6E range, with successful beam steering at 6.16 GHz
  - Published dataset for RF-based HAR

- **Future:**
  - Assemble larger RIS with 4 tiles, and aim for higher frequencies
  - Expand Space-of-Interest for Human Posture Recognition

Campus da Faculdade de
Engenharia da
Universidade do Porto

Rua Dr. Roberto Frias

4200-465 Porto, Portugal

T +351 222 094 000

info@inesctec.pt

www.inesctec.pt