ACTIVE RECONFIGURABLE INTELLIGENT SURFACE FOR MMWAVE

RISING & DEDICATE (Austrian projects)

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AIT AUSTRIAN INSTITUTE OF TECHNOLOGY

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Energy	Health & Bioresources	Digital Safety & Security	Vision, Automation & Control
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- **Employees** 1400+
- **Total revenues** 176 Mio €
- **Business model** 40:30:30

GREEN 6G TECHNOLOGY RESEARCH @ AIT

Distributed Massive MIMO

Distribute radio units (RU) to redcuce transmit power

D-MIMO proof of concept (PoC)

- 100 m aperture
- Vehicular UE nodes
- 32 RU testbed

Main research topics

- Coherent operation for wide aperture
- Reliable channel state acquisition
- Reciprocity callibration

Multiband for Vehicles

Use low frequency bands to setup broadband mmWave links

Multi band PoC for vehicular links

- operation at 3 GHz, 34 GHz & 62 GHz
- V2V and V2I communication

Main research topics

- mmWave beamforming algorithm
- Geometry based radio channel modelling and emulation

Reconfigurable Intelligent Surfaces

Overcome mmWave signals blocking for reliable wireless communication

Active RIS PoC

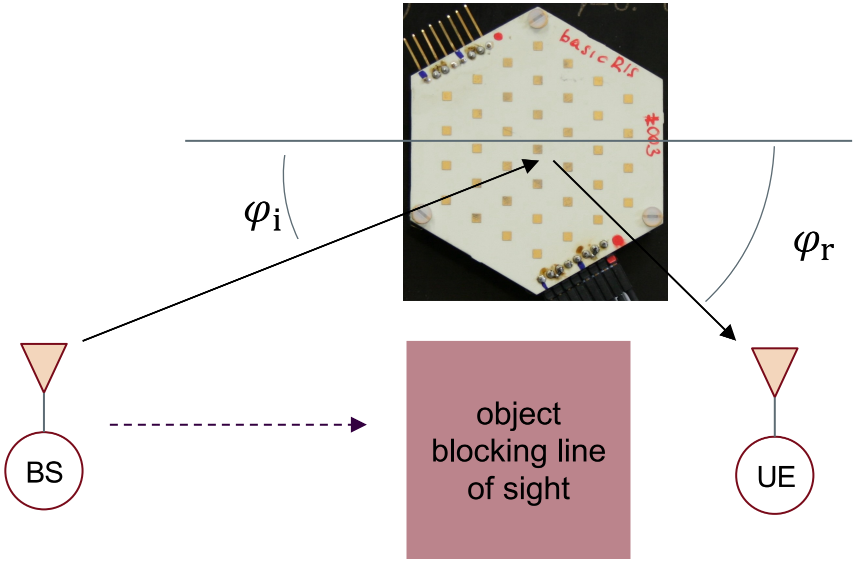
- Fast reconfigurable RIS
- Digital twin for reflective environments

Main research topics

- RIS control using feedback from UE
- Low power BS design

❖ D. Löschenbrand et al., "Towards cell-free massive MIMO: A measurement-based analysis," *IEEE Access*, 2022, doi, arXiv.
❖ M. Hofer et al., „Wireless vehicular multiband measurements in centimeterwave and millimeterwave bands," *PIMRC*, 2021.

RECONFIGURABLE INTELLIGENT SURFACE



- mmWave signal blocked by object
- Reflective intelligent surface (RIS)
  - Semi-passive operation
  - φ_i is given by position of base station (BS) and RIS
  - Adjust φ_r to establish path from source to user euqipment (UE)

➢ **Indoor automation and control use cases**

OUTLINE

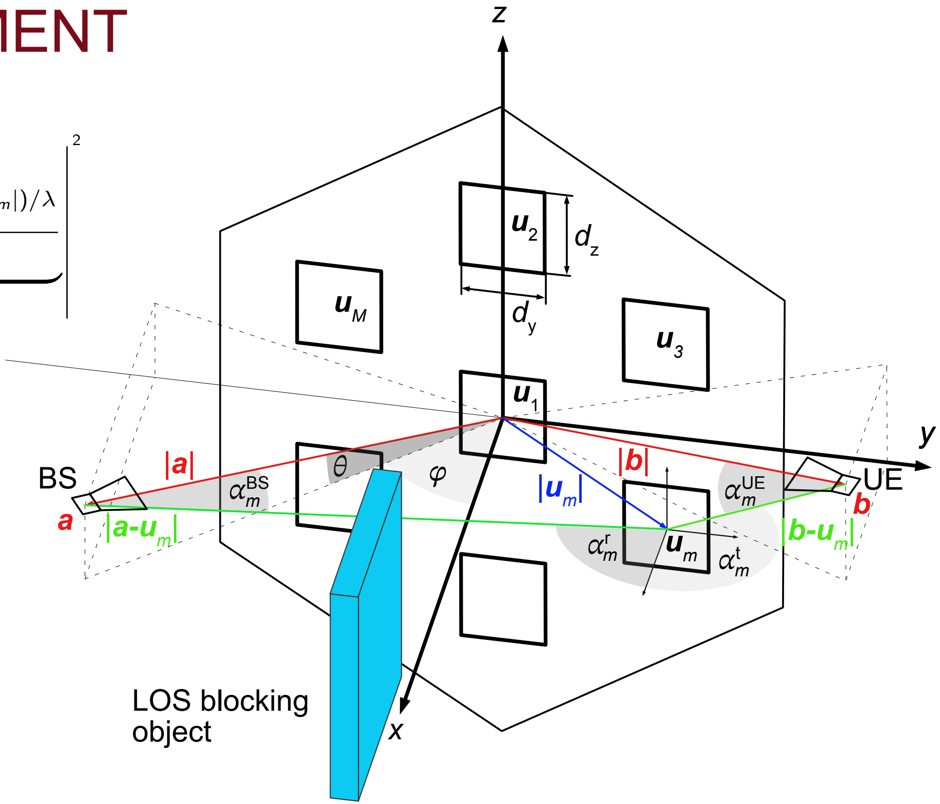
- **RIS design**
  - Loss analysis for RIS reflection coefficient **quantization**
  - **Active RIS** elements using a polarization transform
- Algorithm for **RIS element control** with general reflection coefficient alphabet
- Comparison of **numerical simulation** and empirical result
- **Automation use case**
  - **RIS control** for X-Y plane user-equipment (UE) movement
  - **Ray-tracing based digital twin** for automation use case

RIS IN ANECHOIC ENVIRONMENT

$$P_{\mathrm{UE}} = \underbrace{P_{\mathrm{BS}} \frac{G_{\mathrm{BS}} G_{\mathrm{UE}} (d_{\mathrm{y}} d_{\mathrm{z}})^2}{16\pi^2}}_{C} \times \left| \sum_{m=1}^{M} \Gamma_m \underbrace{\frac{\sqrt{F_m^{\mathrm{c}}} e^{-j2\pi(|\mathbf{a}-\mathbf{u}_m|+|\mathbf{b}-\mathbf{u}_m|)/\lambda}}{|\mathbf{a}-\mathbf{u}_m||\mathbf{b}-\mathbf{u}_m|}}_{D_m} \right|^2$$

P_{BS}	transmit power base station (BS)
P_{UE}	received power at user equipment (UE) position
G_{BS}, G_{UE}	gain BS and UE antenna
d_z, d_x	effective dimension of RIS element
Γ_m	complex reflection coefficient of RIS element *m*
F_m^c	combined beam pattern

$$F_m^{\mathrm{c}} = F^{\mathrm{BS}}(\alpha_m^{\mathrm{BS}}) F(\alpha_m^{\mathrm{r}}) F(\alpha_m^{\mathrm{t}}) F^{\mathrm{UE}}(\alpha_m^{\mathrm{UE}})$$



❖ W. Tang, M. Z. Chen, X. Chen, J. Y. Dai, Y. Han, M. Di Renzo, Y. Zeng, S. Jin, Q. Cheng, and T. J. Cui, “Wireless communications with reconfigurable intelligent surface: Path loss modeling and experimental measurement,” *IEEE Trans. Wireless Com.*, 2021.

REFLECION COEFFICIENT QUANTIZATION

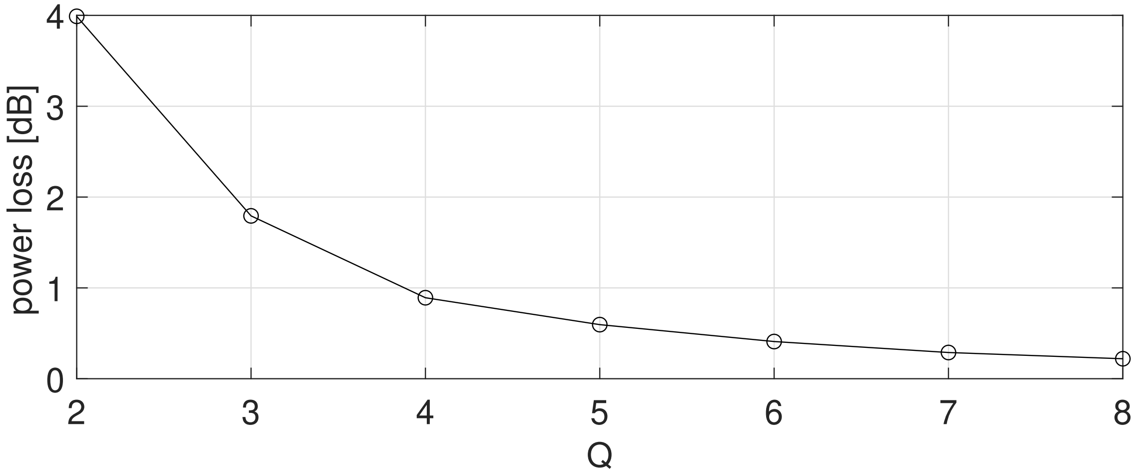
Maximize P_{UE}

$$\Gamma_m = \rho_m e^{j\xi_m} \in \mathbb{C}$$

$$\xi_m = \mod\left(\frac{2\pi(|\mathbf{a}-\mathbf{u}_m| + |\mathbf{b}-\mathbf{u}_m|)}{\lambda}, 2\pi\right) \in \mathbb{R}$$

Quantize ξ_m into Q intervals

$$\xi'_m = \frac{2\pi}{Q}\left(\left\lfloor \frac{\xi_m Q}{2\pi} \right\rfloor + 0.5\right)$$



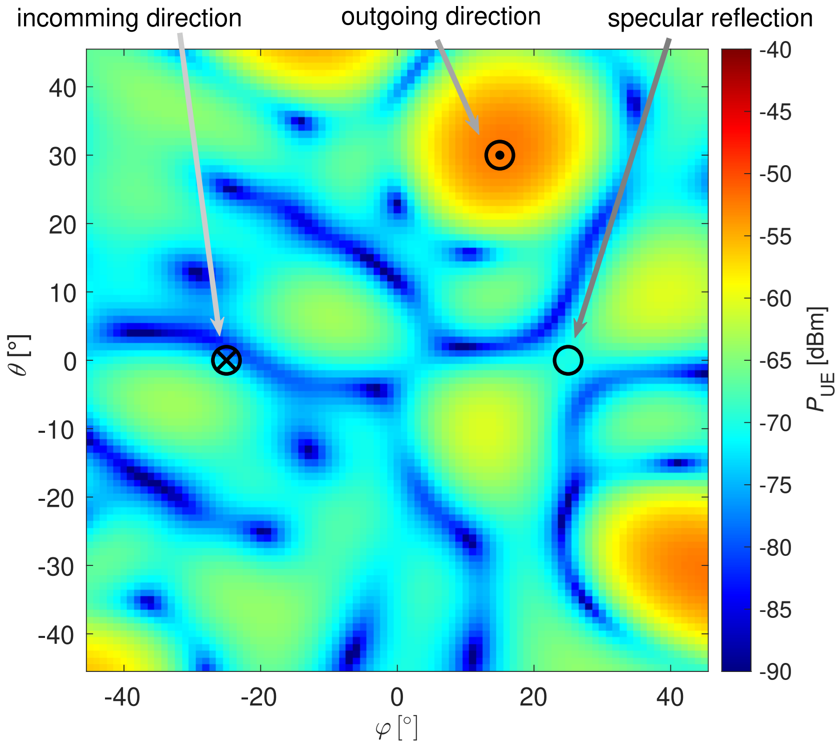
NUMERICAL BEAM PATTERN EVALUATION

Table 1: Active RIS Parameters and Measurement Setup.

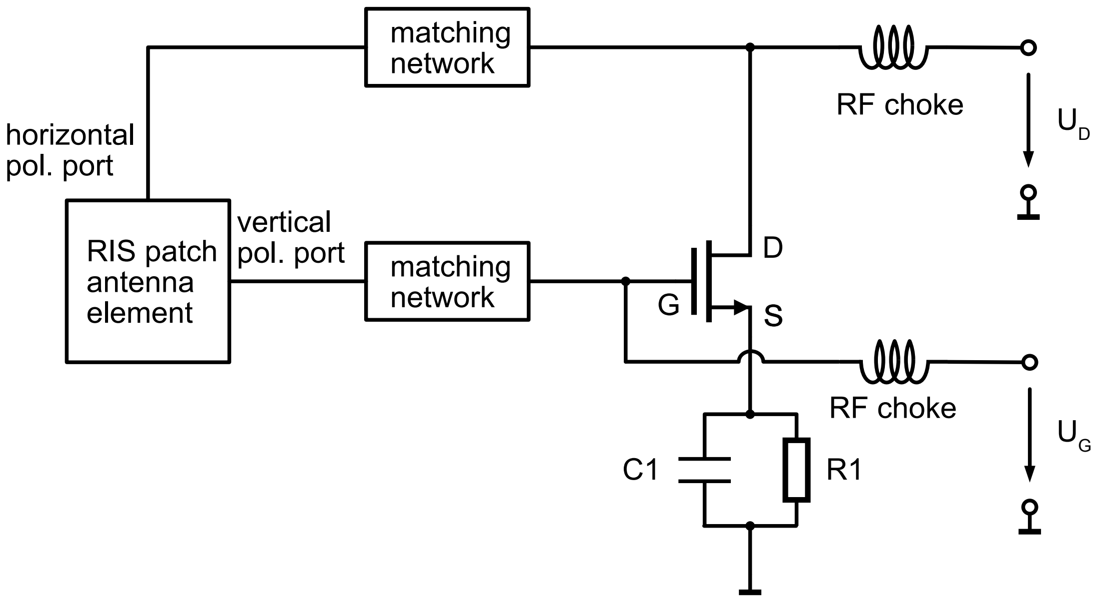
Parameter	Definition
$f = 25.8\,\text{GHz}$	center frequency
$M = 37$	number of RIS elements
$d_z, d_y = 6.6\,\text{mm}$	effective RIS element size
$d = 0.75\lambda = 8.7\,\text{mm}$	smallest RIS element distance
$P_{\text{BS}} = 10\,\text{dBm}$	BS transmit power
$G_{\text{BS}}, G_{\text{UE}} = 19\,\text{dB}$	BS und UE horn antenna gain
$\lvert\mathbf{a}\rvert, \lvert\mathbf{b}\rvert = 1.7\,\text{m}$	distance RIS-BS and RIS-UE
$\tilde{\mathbf{a}} = (1.7\,\text{m}, -25°, 0°)$	BS location
$\tilde{\mathbf{b}} = (1.7\,\text{m}, 15°, 30°)$	UE location

Reflection coefficient alphabet for Q=2

$$\Gamma_m \in \mathcal{A} = \{(0.4, \angle 90°), (0.4, \angle 270°)\}$$



ACTIVE RIS ELEMENT DESIGN



Digital control

- 1 bit for bias voltage U_D
- 1 bit for gate voltage U_G

Two operating modes

- Reflective (R)
- Active (A)

Reflection coefficients of RIS HW

$$\mathcal{A}_{\mathrm{R}} = \{(0.4, \angle 0^\circ), (0.4, \angle 67^\circ)\}$$

$$\mathcal{A}_{\mathrm{A}} = \{(2, \angle 0^\circ), (0, \angle 0^\circ)\}$$

❖ H. Radpour, M. Hofer, L. W. Mayer, A. Hofmann, M. Schiefer, and T. Zemen, „Active reconfigurable intelligent surface for the millimeter-wave frequency band: Design and measurement results,“ in *WCNC*, 2024, arXiv, to be presented.

ALGORITHM FOR GENERAL REFLECTION COEFFICIENTS

- Hardware constraints lead to reflection coefficients with phase difference unqual 360°/Q.

- Joint maximization

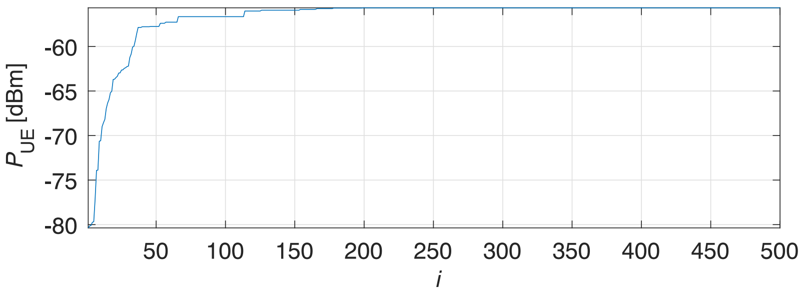
$$\underset{\Gamma_m \in \mathcal{A} \,\forall\, m \in \mathcal{I}_M}{\operatorname{argmax}} \left| \sum_{m=1}^{M} \Gamma_m D_m \right|^2$$

has $|\mathcal{A}|^M$ solutions.

➢ **Simplified Monte Carlo search algorithm** optimizing each RIS element individualy.

Algorithm 1: Maximize received power for finite set of reflection coefficients.

Input: $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{u}_m$, $\mathcal{A}$
$\mathcal{I}_M = \{1, \ldots, M\}$;
$\Gamma_m = 0 \quad \forall \quad m \in \mathcal{I}_M$;
for $i = 1$ **to** 500 **do**
  choose $m' \in \mathcal{I}_M$ randomly;
  $\arg\max_{\Gamma_{m'} \in \mathcal{A}} \left|\sum_{m \in \mathcal{I}_M} \Gamma_m D_m\right|^2$;
end
Output: $\Gamma_m, m \in \mathcal{I}_M$

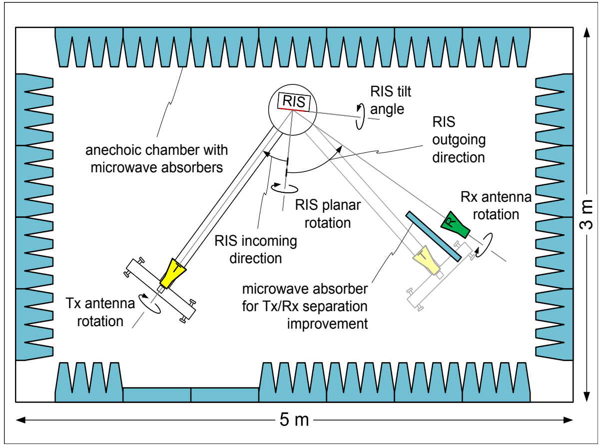


SIMULATION AND MEASUREMENTS

SIEMENS Ingenuity for life | AIT AUSTRIAN INSTITUTE OF TECHNOLOGY

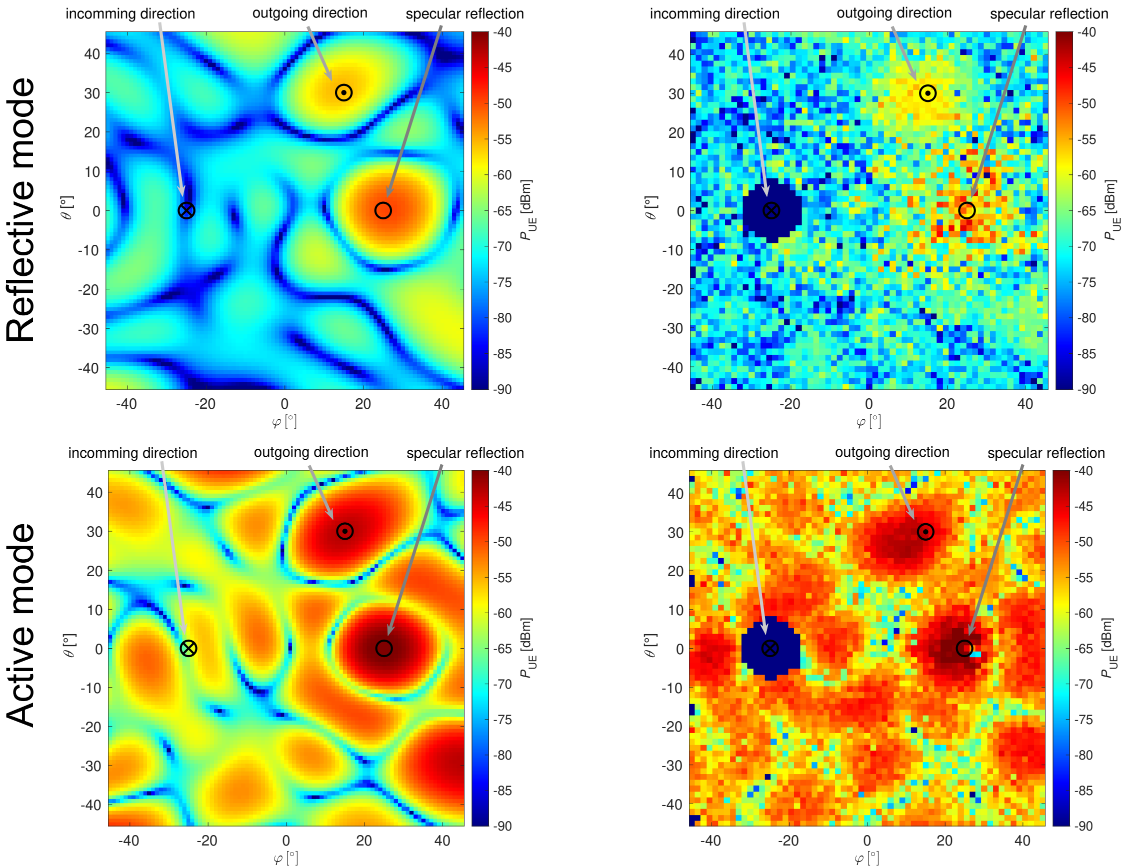
Setup

- BS at (r_i = 1.7 m, φ_{i}= −25°, θ_{i}= 0°)
- UE at (r_i = 1.7 m, φ_{r}= 15°, θ_{r}= 30°)



Reflective mode: $P_{\mathrm{UE}}(15^\circ, 30^\circ) = -55\,\mathrm{dBm}$

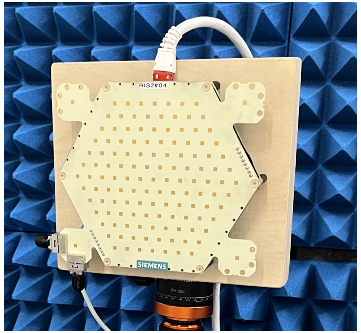
Active mode: $P_{\mathrm{UE}}(15^\circ, 30^\circ) = -43\,\mathrm{dBm}$

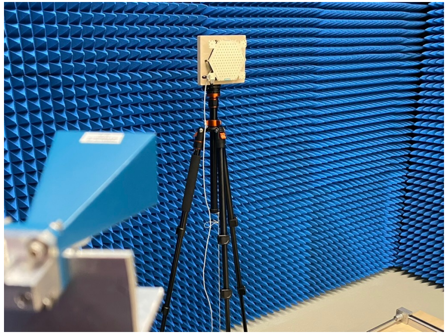


Numerical simulation

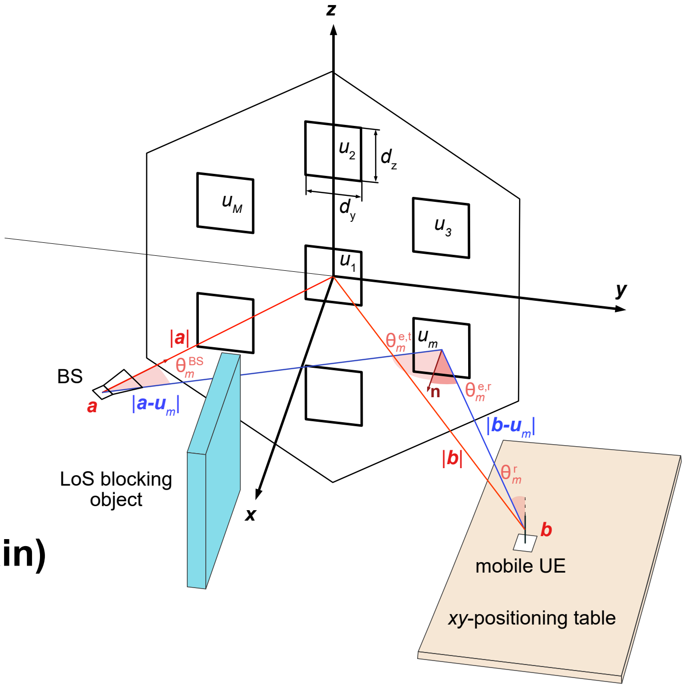
Empirical measurement

127 ELEMENT RIS WITH IMPROVED PROPERTIES





Parameter	Definition
$f = 23.8\,\mathrm{GHz}$	center frequency
$M = 127$	number of RIS elements
$d_z,\, d_y = 6.6\,\mathrm{mm}$	effective RIS element size
$d = 8.7\,\mathrm{mm}$	smallest RIS element distance



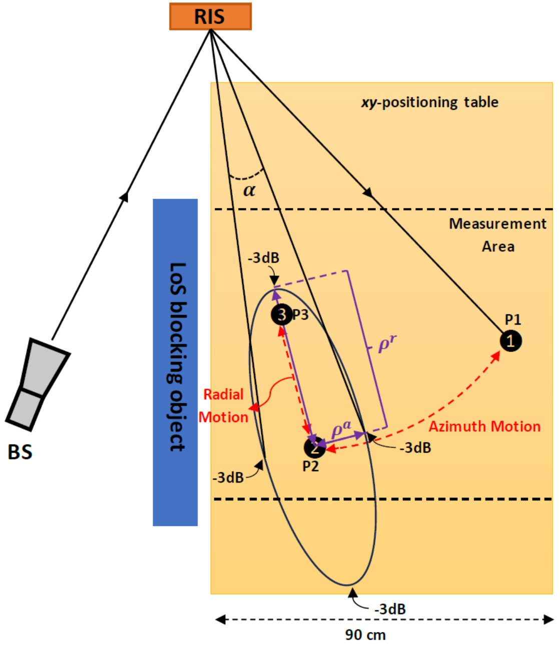
Active RIS with improved matching network (6dB gain)

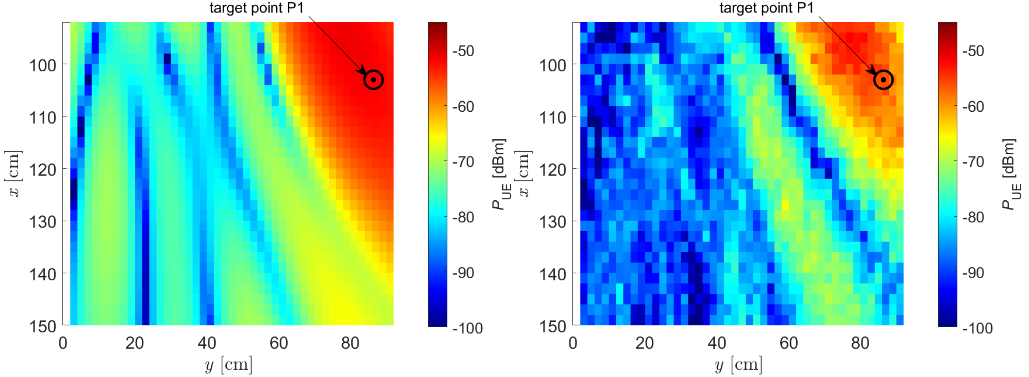
$$\mathcal{A}_{\mathrm{R}} = \{(0.3, \angle -15^\circ), (0.3, \angle 165^\circ)\}$$

$$\mathcal{A}_{\mathrm{A}} = \{(1.25, \angle 0^\circ), (0, \angle 0^\circ)\}$$

❖ H. Radpour, M. Hofer, D. Löschenbrand, L. W. Mayer, A. Hofmann, M. Schiefer, and T. Zemen, "Reconfigurable intelligent surface for indoor industrial automation: mmWave propagation measurement, simulation, and control algorithm requirements," *in PIMRC*, 2024, arXiv, submitted.

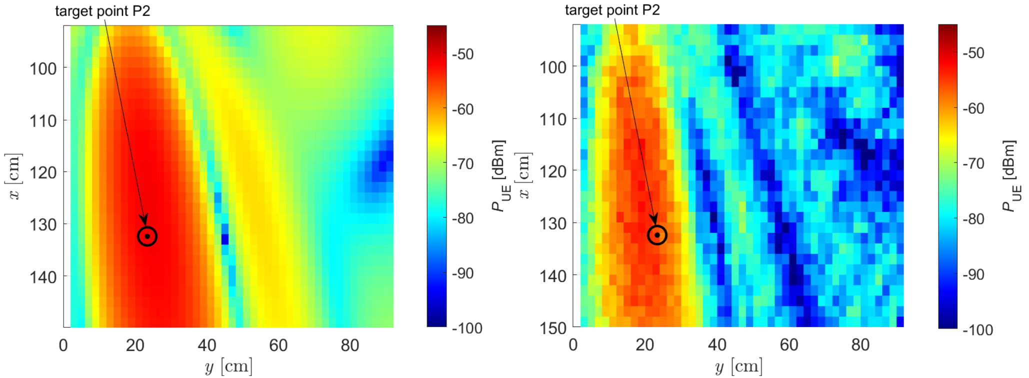
RIS FOR INDUSTRIAL AUTOMATION AND CONTROL





(a) Sim. result for active RIS, focusing radio signal on point P_1.

(b) Meas. result for active RIS, focusing radio signal on point P_1.



Numerical simulation

Empirical measurement

- **RIS update rate for motion in azimuth larger than in radial direction**

DIGITAL TWIN FOR REFLECTIVE SCENARIOS

Two-stage hybrid method

- CPU: Computation of intersection points
- GPU: Ray tracing for potential propagation paths

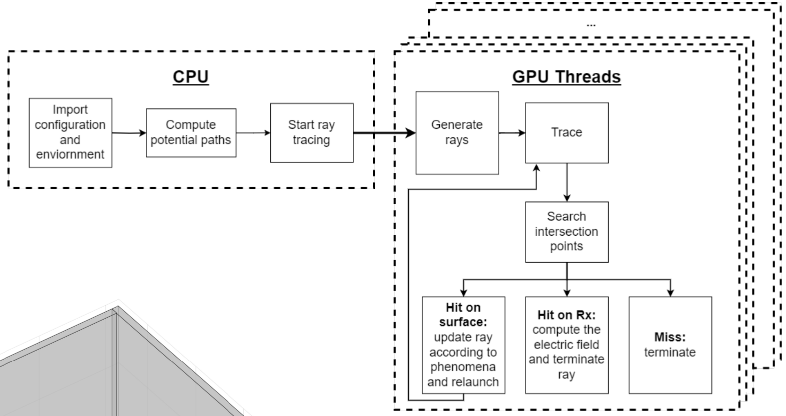
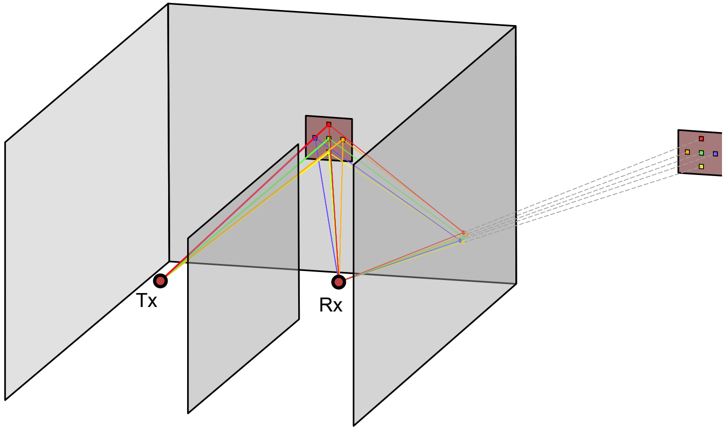
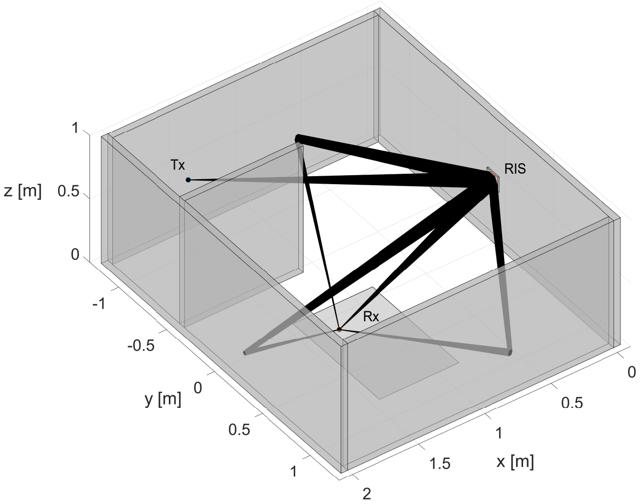
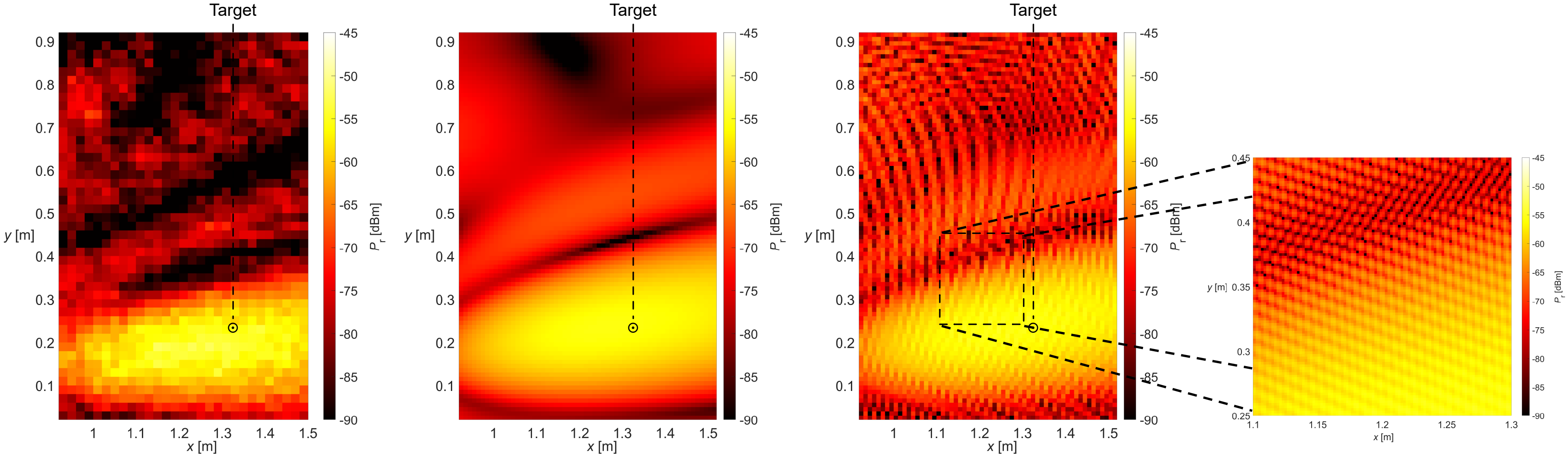


Image method for RIS reflections on environment





SMALL SCALE FADING PATTERN



(a) Measurements from [11]. (b) Simulation in anechoic room. (c) Simulation with higher-order reflections.

➢ **Numerical digital twin is crucial for design/research of RIS control algorithms**

❖ S. Sandh, M. Radpour, B. Rainer, M. Hofer, and T. Zemen, „Ray tracing algorithm for reconfigurable intelligent surfaces,“ *in PIMRC*, 2024, submitted.

CONCLUSION

- **First active RIS** PoC for **mmWave** frequency band
- **Polarization transform** to increase isolation between impinging and reflected wave
- **Coarse quantization** of RIS **reflection state** is sufficient for many applications
- **Digital twin based on RT** allows design of control algorithms for indoor environments
- **RIS is a promissing technology** for **reliable indoor mmWave communication** links.

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