Toward an Electromagnetic Information Theory for Reconfigurable Microwave Systems

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Rennes:	D. González-Ovejero, C. Hammami, C. Monochristou, L. Le Magoarou, H. Prod'homme, J. Tapie, J. Sol
Yale:	A. Alhulaymi, O. D. Miller, A. D. Stone

1) **Multiport-network model formulation** for reconfigurable microwave systems

2) **Prototype-aware model calibration** for reconfigurable microwave systems

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems
   - Bounds on multiplexing gain in backscatter MIMO systems
   - Bounds on information transfer via RIS-parametrized SISO channel
   - Bounds on MIMO operator synthesis

Context

Wireless Communications

Applications of Reconfigurable Microwave Systems

Wireless Sensing

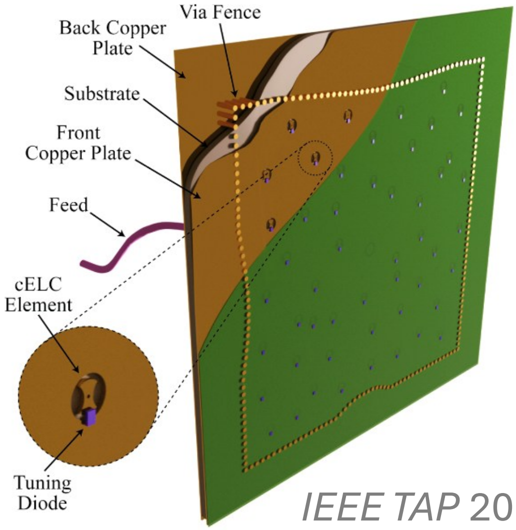
Wave-Domain Computing

Examples of Extremely Reconfigurable Microwave Systems

Smart Radio Environment

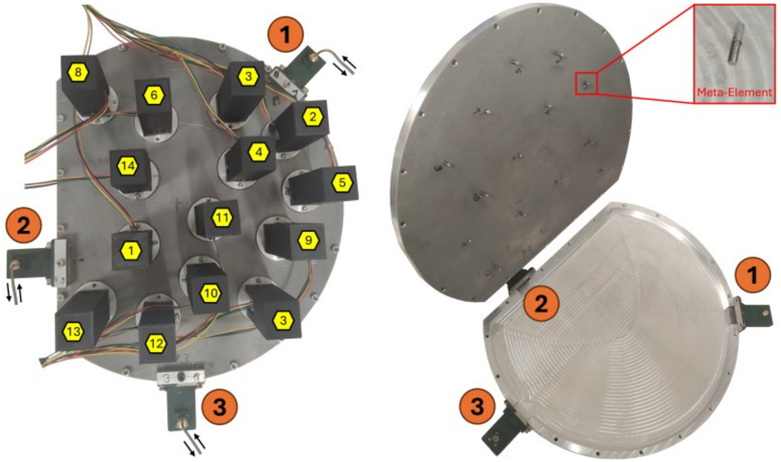
Nat. Commun. 2020

Dynamic Metasurface Antenna



IEEE TAP 2020

Reconfigurable Signal Router



Adv. Sci. 2025

Common features:

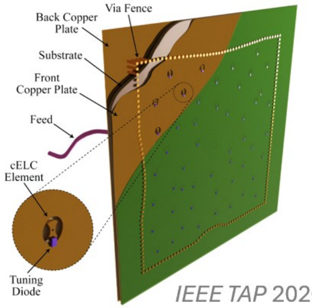
- Linear system transfer function: $\mathbf{y} = \mathbf{H}\mathbf{x}$
- $\mathbf{H}$ is parametrized by the system configuration $\mathbf{c}$

Overarching Questions

Smart Radio Environment

Nat. Commun. 2020

Dynamic Metasurface Antenna



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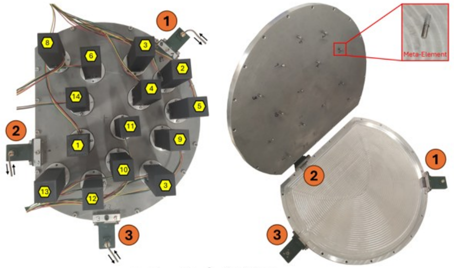

Adv. Sci. 2025

Common features:

- Linear-system transfer function: $\mathbf{y} = \mathbf{H}\mathbf{x}$
- $\mathbf{H}$ is paramaetrized by the system configuration $\mathbf{c}$

Forward Problem:

What is $\mathbf{H}$ for a given $\mathbf{c}$?

Inverse Design Problem:

What $\mathbf{c}$ closely approximates a desired $\mathbf{H}$?

→ How to formulate a model for $\mathbf{H}(\mathbf{c})$?

→ How to calibrate the model for $\mathbf{H}(\mathbf{c})$?

Electromagnetic Information Theory:

What are the (EM-consistent) limits on communications, sensing and computing via deterministically programmable channels?

Hardware Design Principles:

How to maximize the wave-domain flexibility?

(i.e., the ability of $\mathbf{c}$ to shape $\mathbf{H}$)

Outline

1) **Multiport-network model formulation** for reconfigurable microwave systems

2) **Prototype-aware model calibration** for reconfigurable microwave systems

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems
    - Bounds on multiplexing gain in backscatter MIMO systems
    - Bounds on information transfer via RIS-parametrized SISO channel
    - Bounds on MIMO operator synthesis

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1) **Multiport-network model formulation** for reconfigurable microwave systems

At a high abstraction level, most reconfigurable microwave systems are amenable to a **universal** multiport network representation because their reconfigurability relies on tunable lumped elements.

Approach: - Partition system into 3 entities:

1) N_A antenna ports (injection & reception of waves)

2) N_S tunable lumped elements (e.g., PIN diodes)

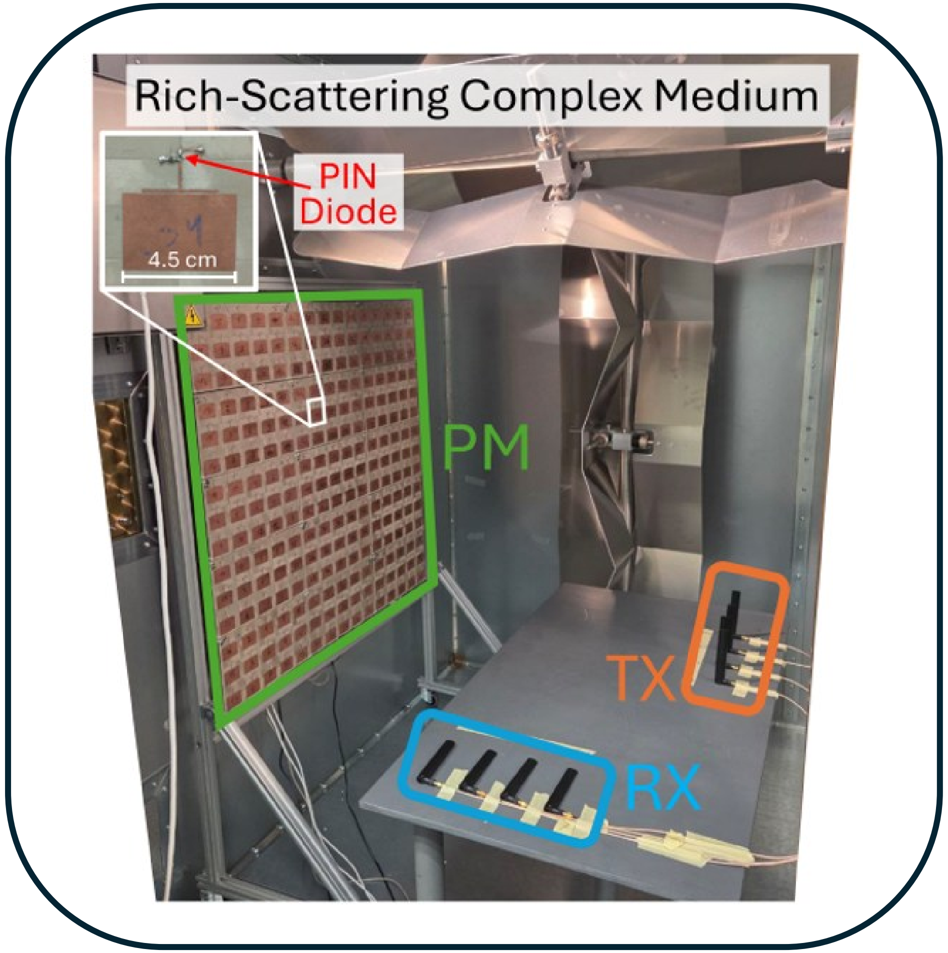
3) Static scattering objects (metallic or dielectric, including all "structural scattering" and all environmental scattering)

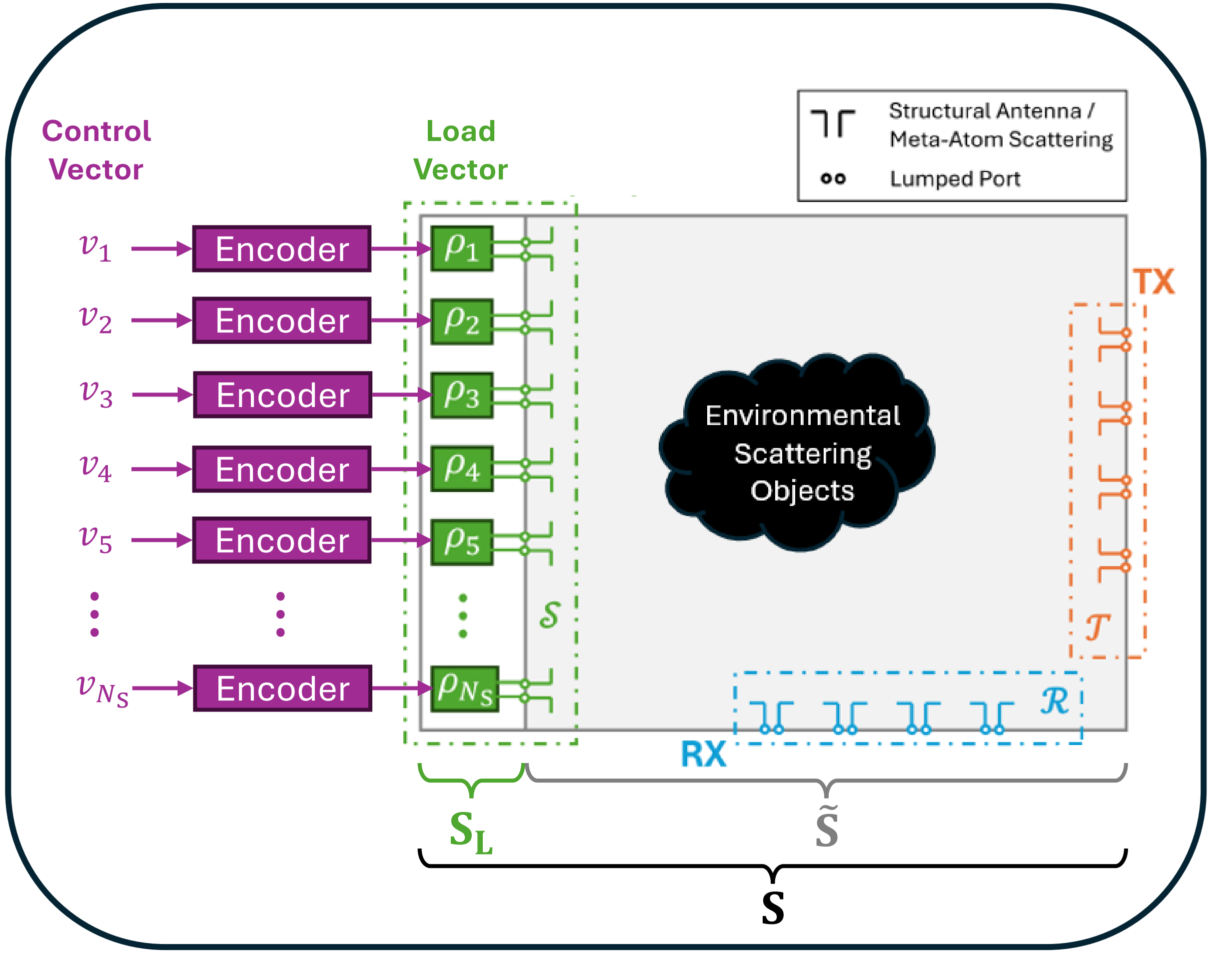
- A tunable lumped element can be viewed as a "virtual" port terminated by tunable load.

Note: This approach can be applied to **any wave system parametrized by tunable lumped elements**, including RISs, DMAs, BD-RISs, BD-DMAs, SIMs, FIMs, etc.

P. del Hougne, M. Di Renzo, A. Alù, T. J. Cui, Y. Eldar, N. Engheta, W. Hu, A. Ozcan, *HAL:05487878* (2026)

1) **Multiport-network model formulation** for reconfigurable microwave systems





P. del Hougne, M. Di Renzo, A. Alù, T. J. Cui, Y. Eldar, N. Engheta, W. Hu, A. Ozcan, *HAL:05487878* (2026)

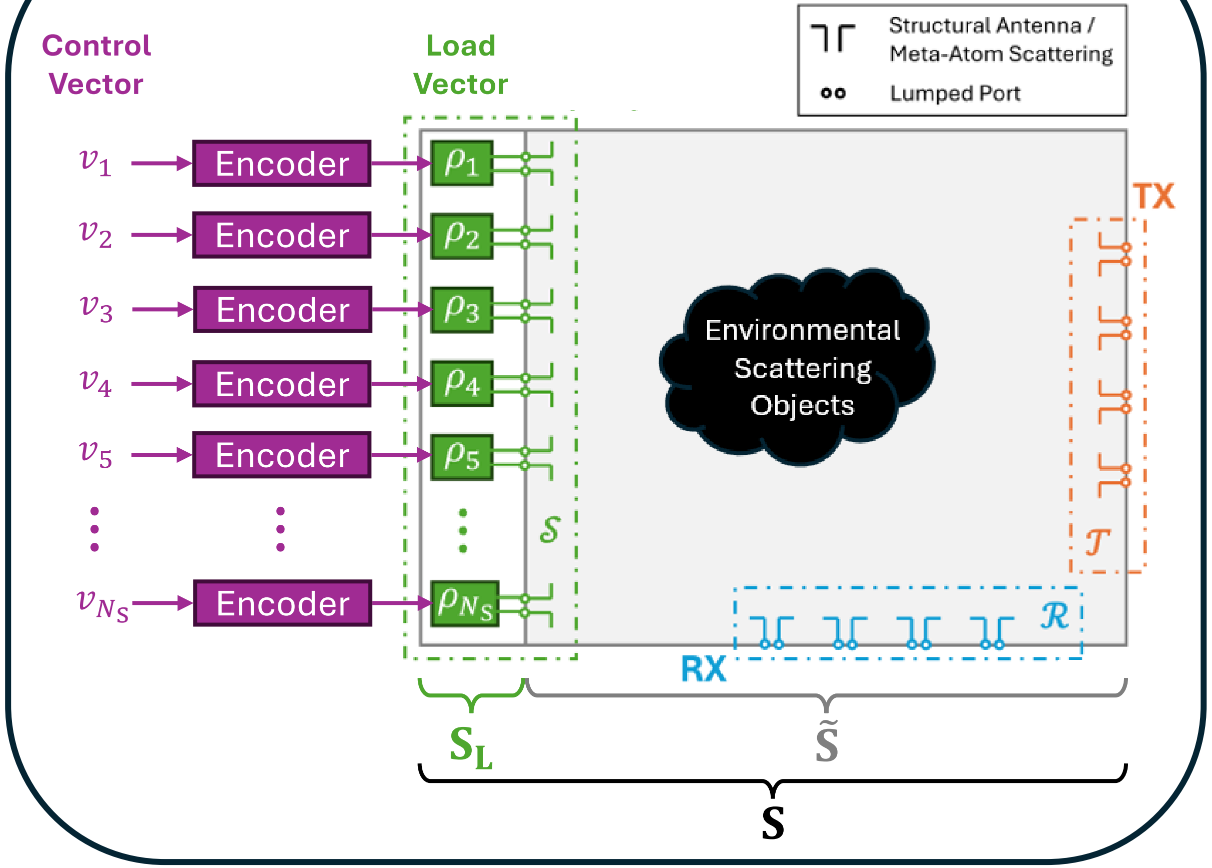
1) **Multiport-network model formulation** for reconfigurable microwave systems

$$\mathbf{S}_\mathrm{L} = \mathrm{diag}\big(f(v_1), f(v_2), \dots, f(v_{N_\mathrm{S}})\big) = \mathrm{diag}(\rho_1, \rho_2, \dots, \rho_{N_\mathrm{S}})$$

$$\mathbf{S} = \tilde{\mathbf{S}}_{\mathcal{AA}} + \tilde{\mathbf{S}}_{\mathcal{AS}}\left(\mathbf{S}_\mathrm{L}^{-1} - \tilde{\mathbf{S}}_{\mathcal{SS}}\right)^{-1}\tilde{\mathbf{S}}_{\mathcal{SA}} = \tilde{\mathbf{S}}_{\mathcal{AA}} + \tilde{\mathbf{S}}_{\mathcal{AS}}\left(\sum_{k=0}^{\infty}\left(\mathbf{S}_\mathrm{L}\tilde{\mathbf{S}}_{\mathcal{SS}}\right)^k\right)\mathbf{S}_\mathrm{L}\tilde{\mathbf{S}}_{\mathcal{SA}}$$

$$\mathbf{H} = \mathbf{S}_{\mathcal{RT}} = \tilde{\mathbf{S}}_{\mathcal{RT}} + \tilde{\mathbf{S}}_{\mathcal{RS}}\left(\mathbf{S}_\mathrm{L}^{-1} - \tilde{\mathbf{S}}_{\mathcal{SS}}\right)^{-1}\tilde{\mathbf{S}}_{\mathcal{ST}}$$

$\mathcal{T}$	Set of transmitting antenna port indices
$\mathcal{R}$	Set of receiving antenna port indices
$\mathcal{A} = \mathcal{T} \cup \mathcal{R}$	Set of antenna port indices
$\mathcal{S}$	Set of meta-atom “virtual” port indices
f	Encoder function



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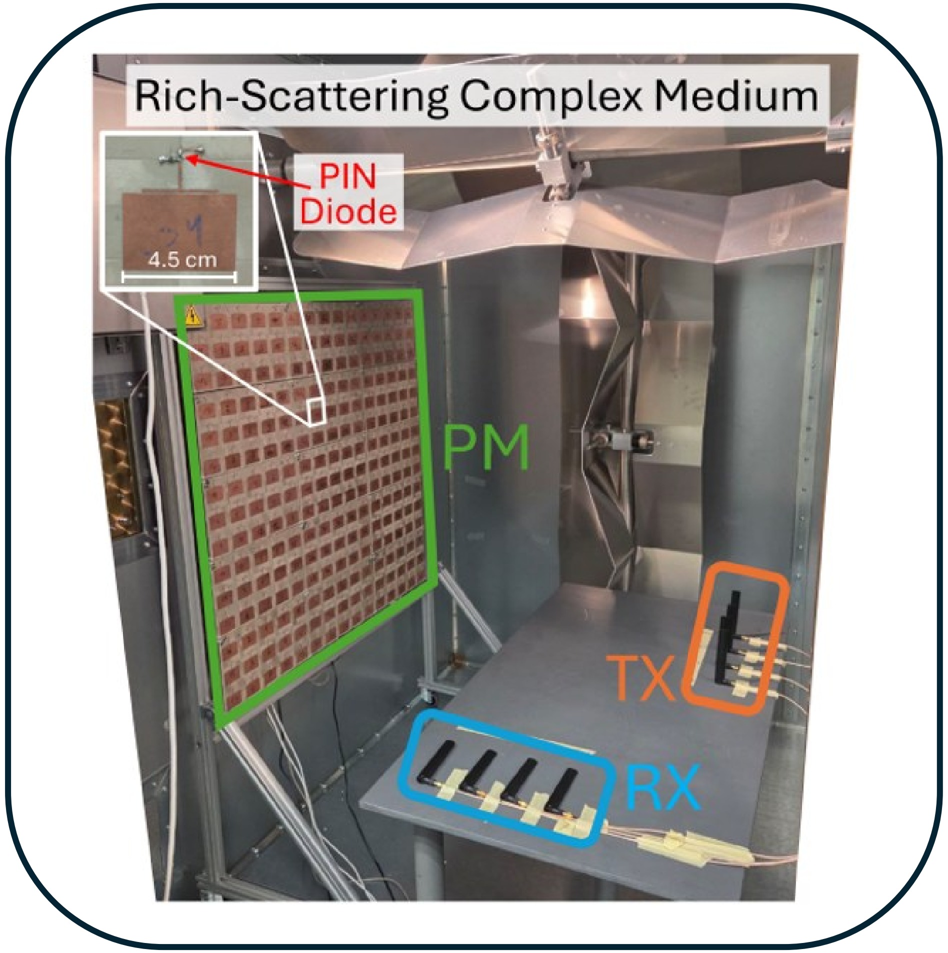

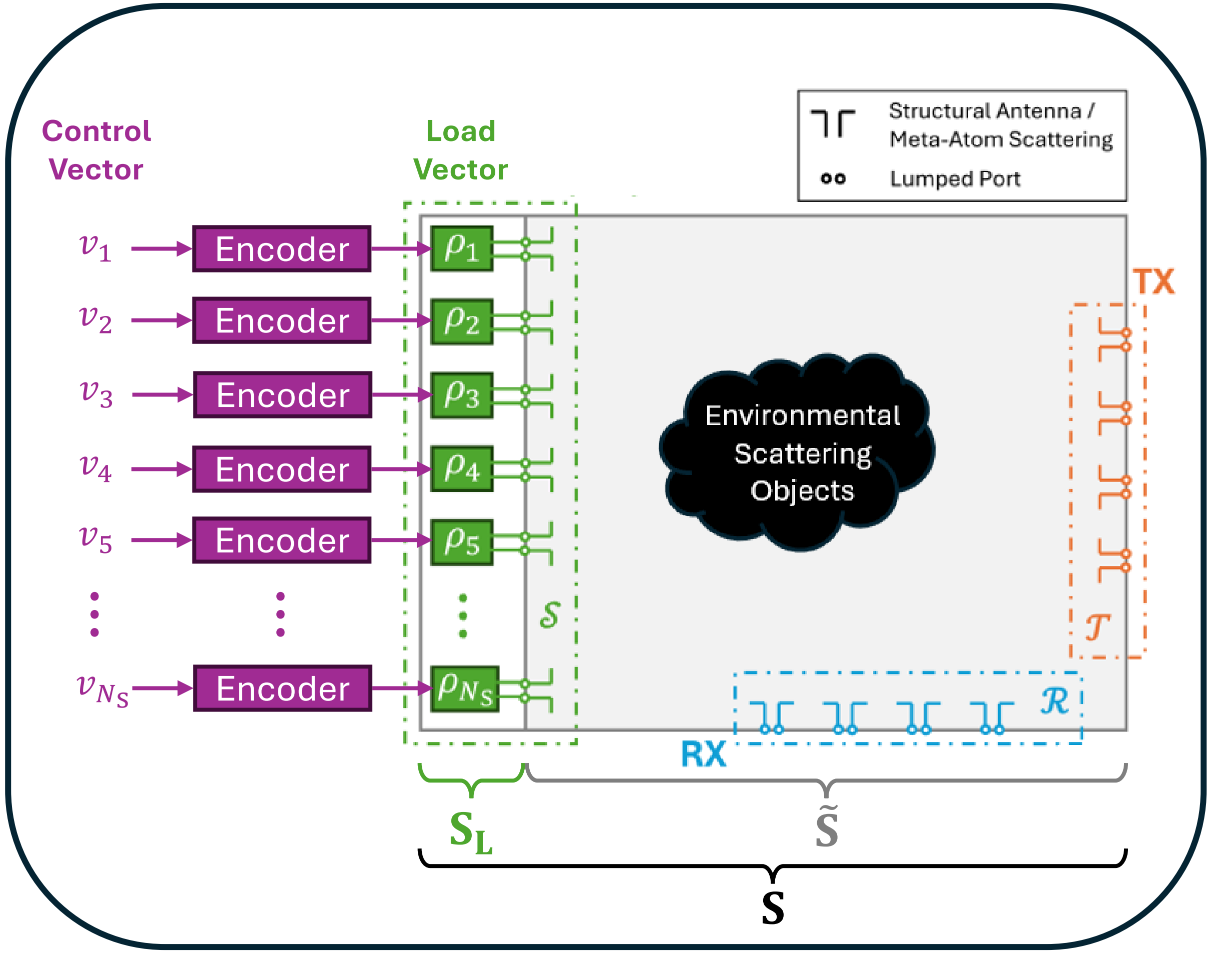

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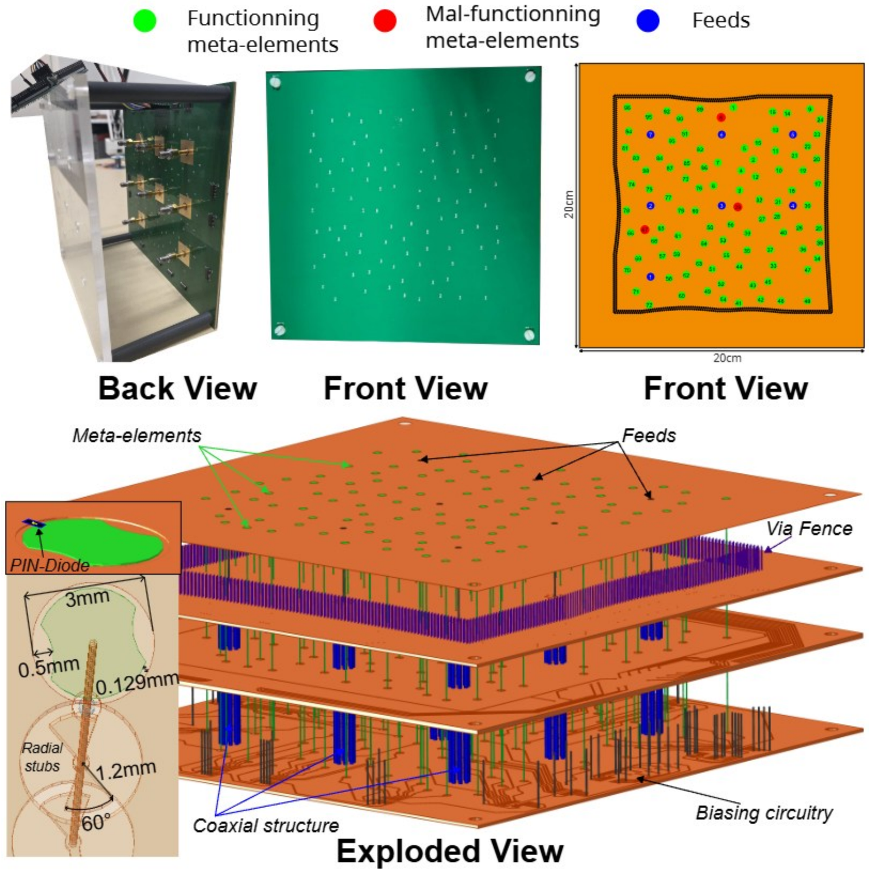
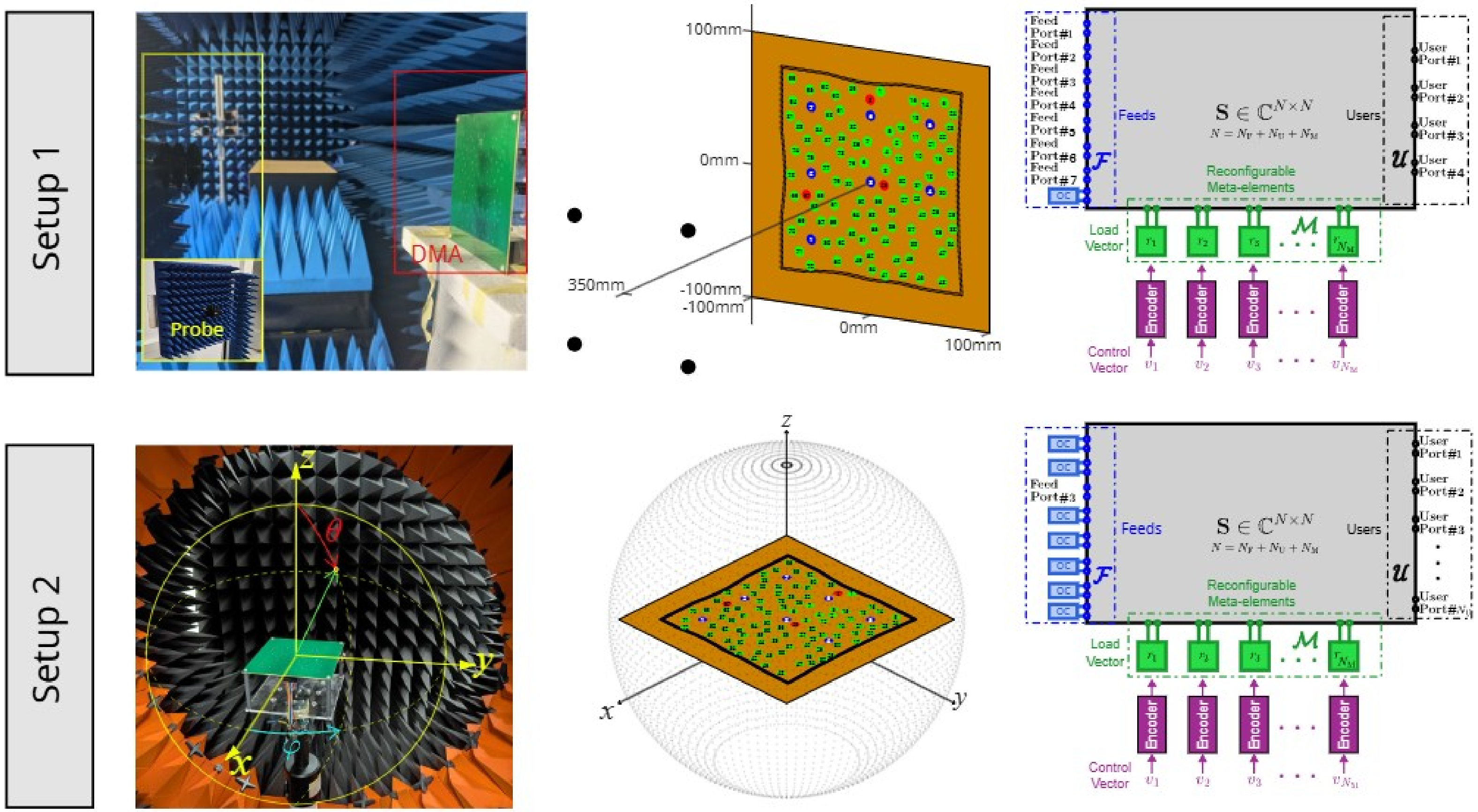
1) **Multiport-network model formulation** for reconfigurable microwave systems

MNT model for a chaotic-cavity-backed dynamic metasurface antenna





J. Tapie, P. del Hougne, *arXiv: 2512.22607* (2025)
J. Tapie, B. Sokal, A. L. F. de Almeida, P. del Hougne, *in preparation* (2026)

Outline

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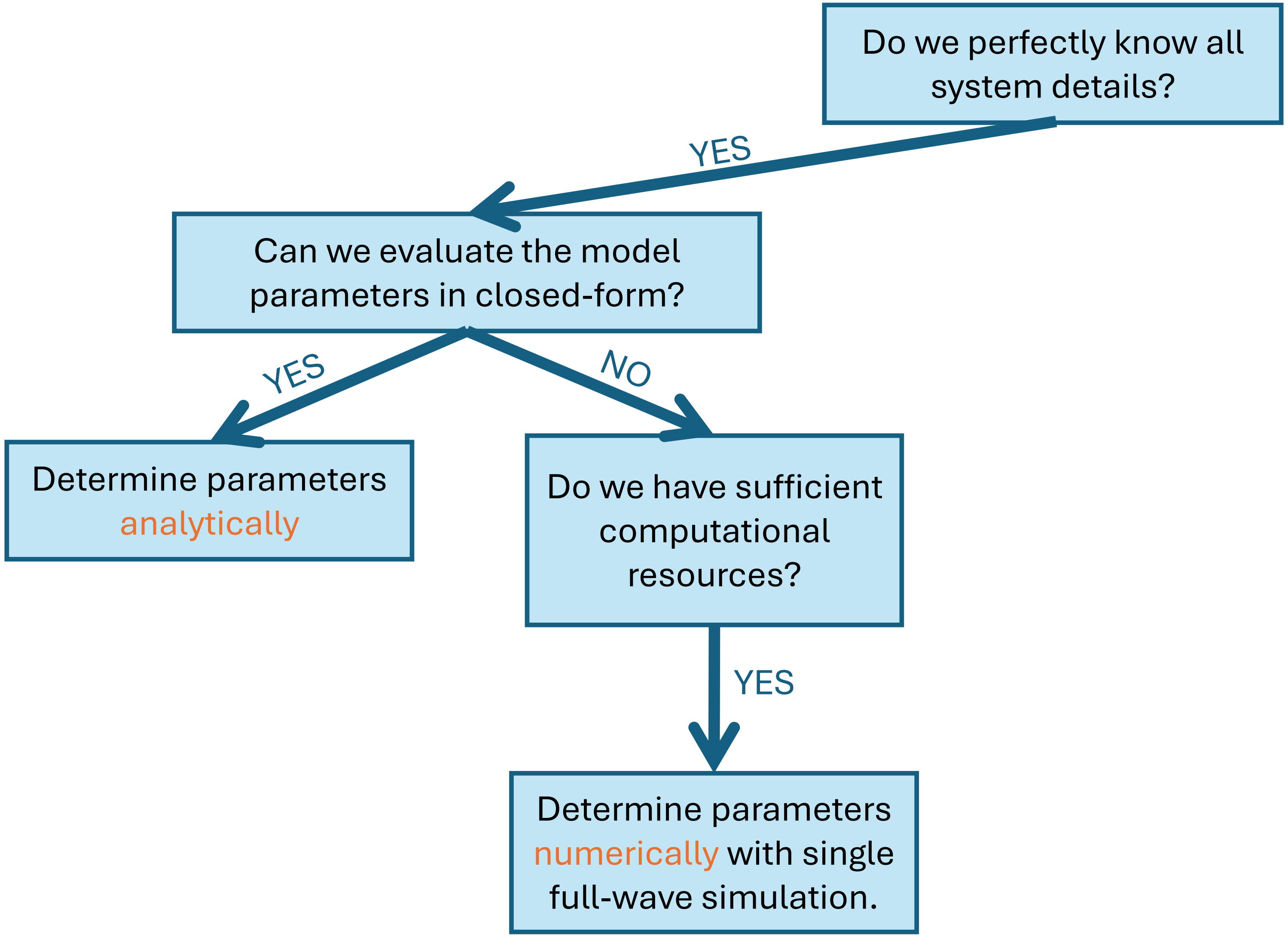
2) **Prototype-aware model calibration** for reconfigurable microwave systems



Do we perfectly know all system details?

YES

Can we evaluate the model parameters in closed-form?

YES

Determine parameters analytically

NO

Do we have sufficient computational resources?

YES

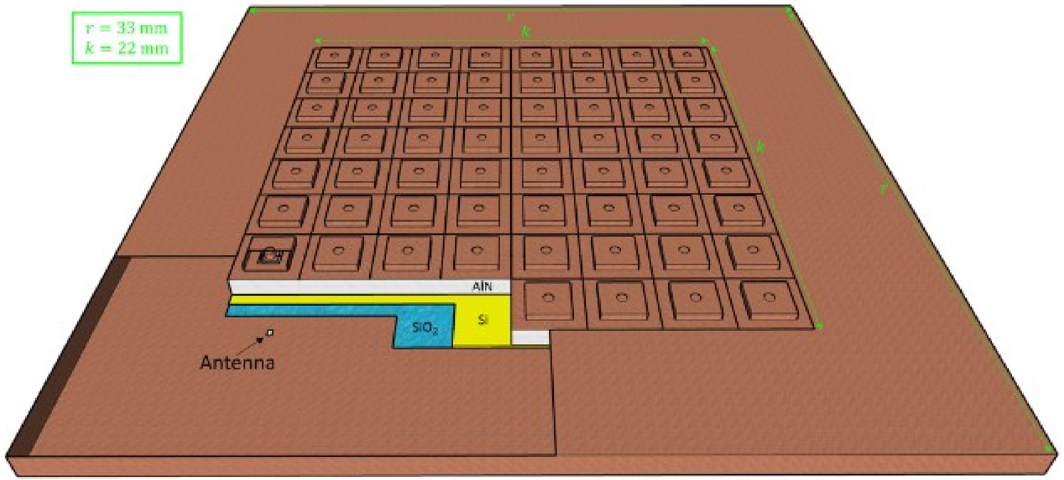
Determine parameters numerically with single full-wave simulation.

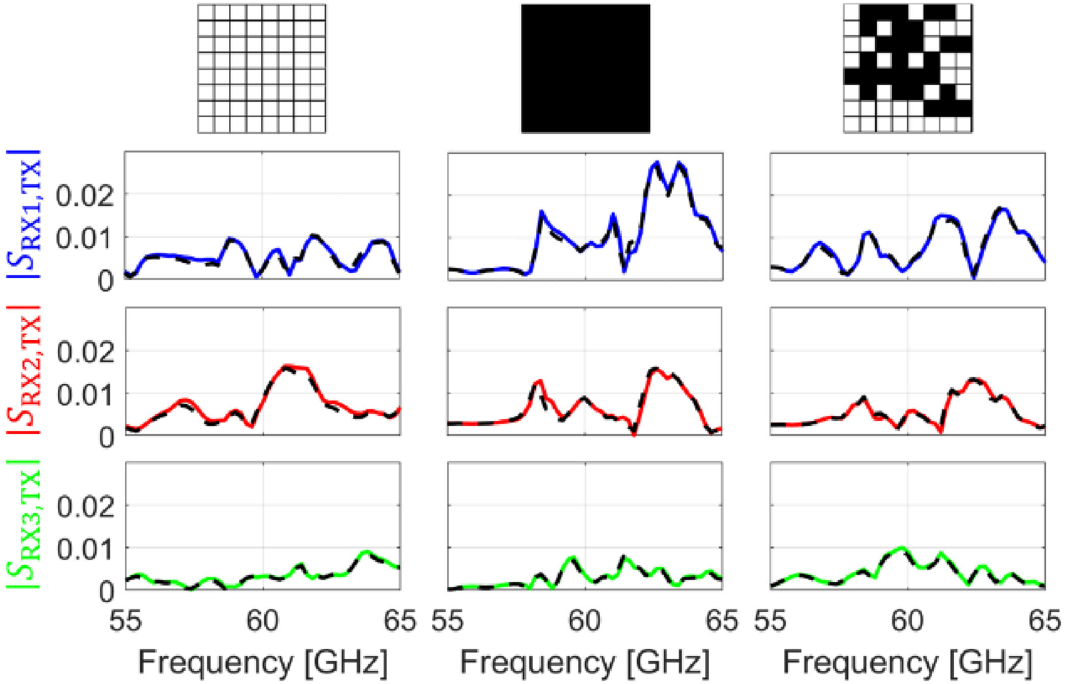
P. del Hougne, M. Di Renzo, A. Alù, T. J. Cui, Y. Eldar, N. Engheta, W. Hu, A. Ozcan, *HAL:05487878* (2026)

2) **Prototype-aware model calibration** for reconfigurable microwave systems

Example: RIS-parametrized Wireless Network-on-Chip

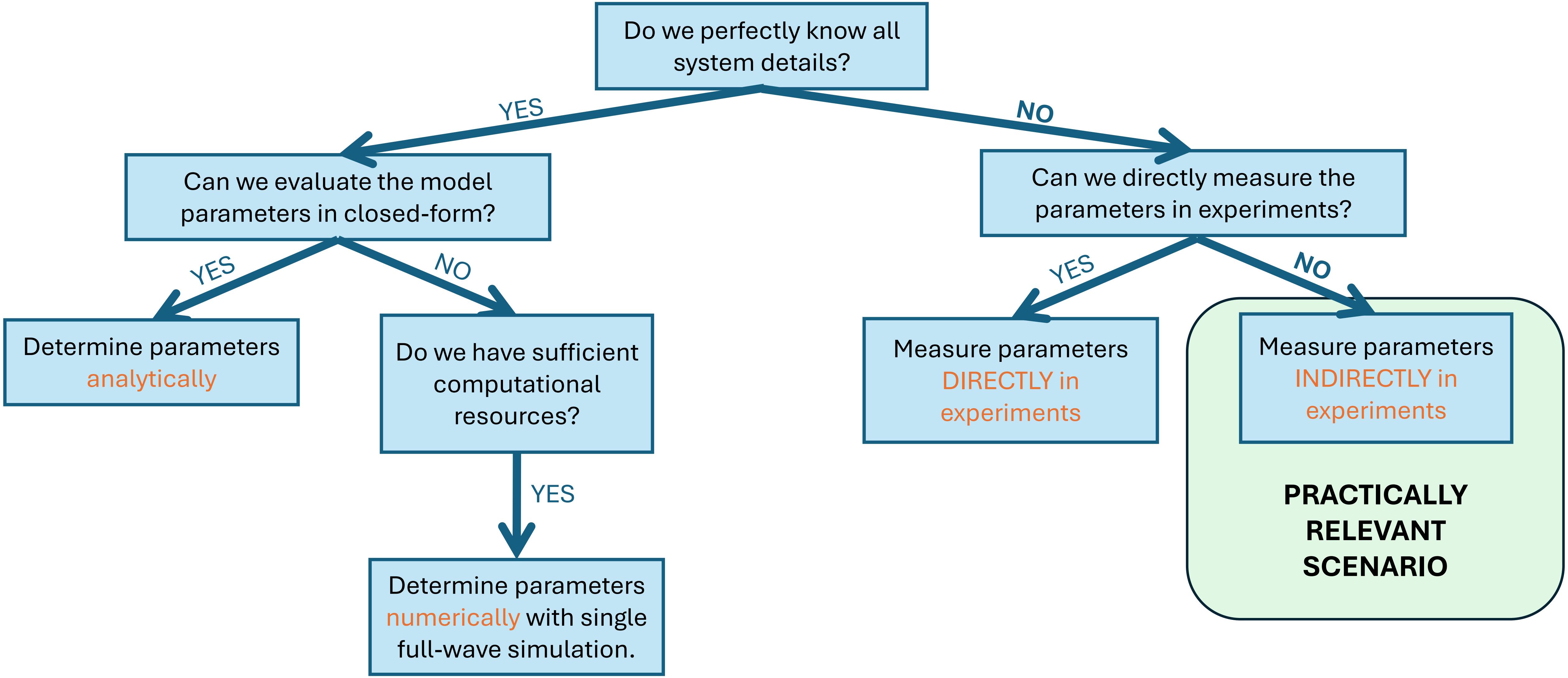
- continuous metallic boundaries
- extended dielectric layers
- structural scattering of RIS elements





J. Tapie, H. Prod’homme, M. F. Imani, P. del Hougne, *J. Sel. Areas Commun.* (2024)

2) **Prototype-aware model calibration** for reconfigurable microwave systems



Do we perfectly know all system details?

Can we evaluate the model parameters in closed-form?

Can we directly measure the parameters in experiments?

Determine parameters analytically

Do we have sufficient computational resources?

Determine parameters numerically with single full-wave simulation.

Measure parameters DIRECTLY in experiments

Measure parameters INDIRECTLY in experiments

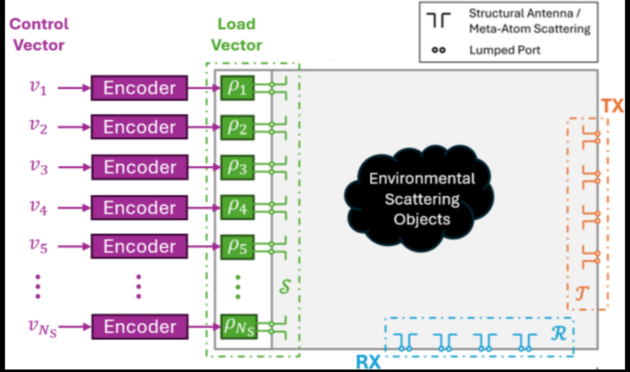
PRACTICALLY RELEVANT SCENARIO

P. del Hougne, M. Di Renzo, A. Alù, T. J. Cui, Y. Eldar, N. Engheta, W. Hu, A. Ozcan, *HAL:05487878* (2026)

2) **Prototype-aware model calibration** for reconfigurable microwave systems

$\mathbf{v}$ →

SYSTEM MODEL



Encoding: $\mathbf{S}_{\mathrm{L}}(\mathbf{v}) = \alpha\mathbf{1} + (\beta - \alpha)\mathbf{v}$

MNT: $\mathbf{H}(\mathbf{v}) = \tilde{\mathbf{S}}_{\mathcal{RT}} + \tilde{\mathbf{S}}_{\mathcal{RS}}\left((\mathbf{S}_{\mathrm{L}}(\mathbf{v}))^{-1} - \tilde{\mathbf{S}}_{\mathcal{SS}}\right)^{-1}\tilde{\mathbf{S}}_{\mathcal{ST}}$

→ $\mathbf{H}(\mathbf{v})$

↑

System parameters:
- Encoding: α, β
- MNT: $\tilde{\mathbf{S}}_{\mathcal{RT}}, \tilde{\mathbf{S}}_{\mathcal{RS}}, \tilde{\mathbf{S}}_{\mathcal{SS}}, \tilde{\mathbf{S}}_{\mathcal{ST}}$

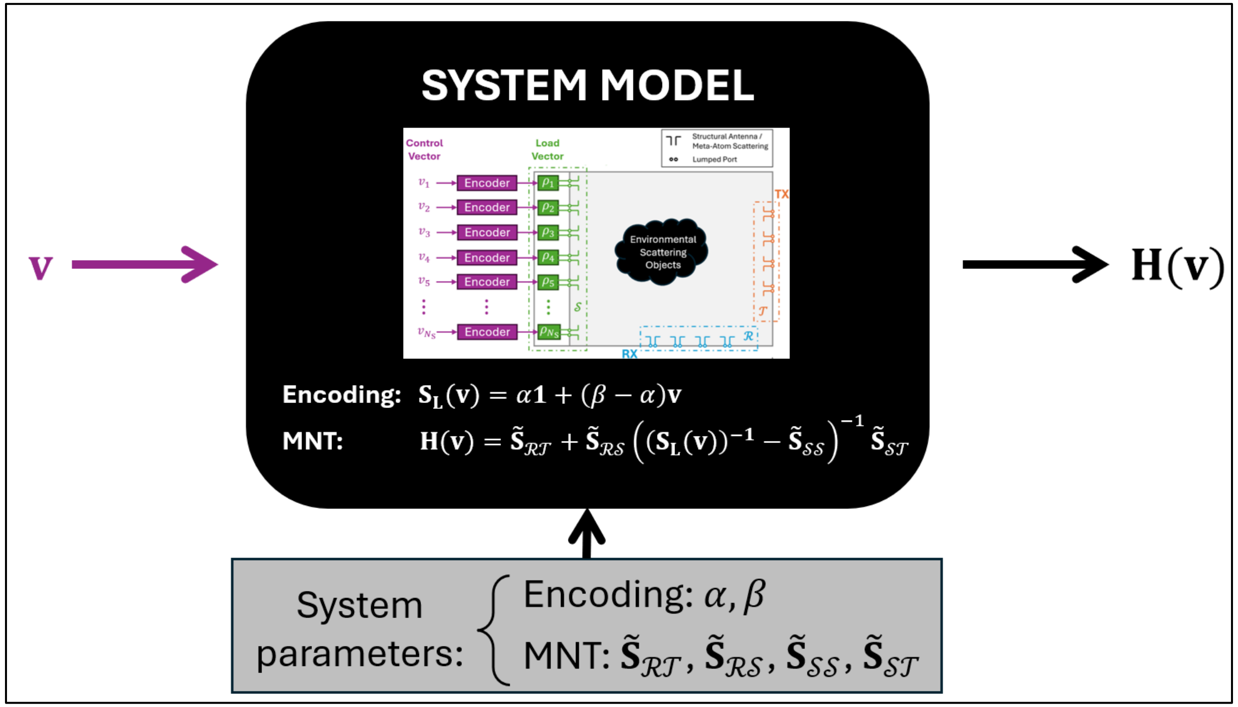
P. del Hougne, M. Di Renzo, A. Alù, T. J. Cui, Y. Eldar, N. Engheta, W. Hu, A. Ozcan, *HAL:05487878* (2026)

2) **Prototype-aware model calibration** for reconfigurable microwave systems

Based on indirect experimental measurements, the model parameters are usually not uniquely identifiable.

Nonetheless, we can estimate a set of proxy parameters that accurately maps any $\mathbf{v}$ to the corresponding $\mathbf{H}(\mathbf{v})$.

J. Sol, ..., P. del Hougne, *Nature Communications* (2024)
P. del Hougne, *IEEE WCL* (2025), *IEEE TCOM* (2026), *IEEE WCL* (2026)
J. Tapie, P. del Hougne, *arXiv: 2512.22607* (2025)



$\mathbf{v}$

SYSTEM MODEL

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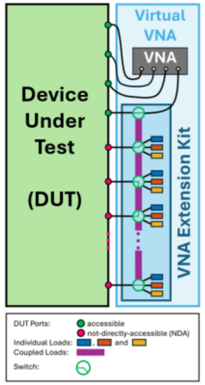
$\mathbf{H}(\mathbf{v})$

System parameters: Encoding: α, β
MNT: $\tilde{\mathbf{S}}_{\mathcal{RT}}, \tilde{\mathbf{S}}_{\mathcal{RS}}, \tilde{\mathbf{S}}_{\mathcal{SS}}, \tilde{\mathbf{S}}_{\mathcal{ST}}$

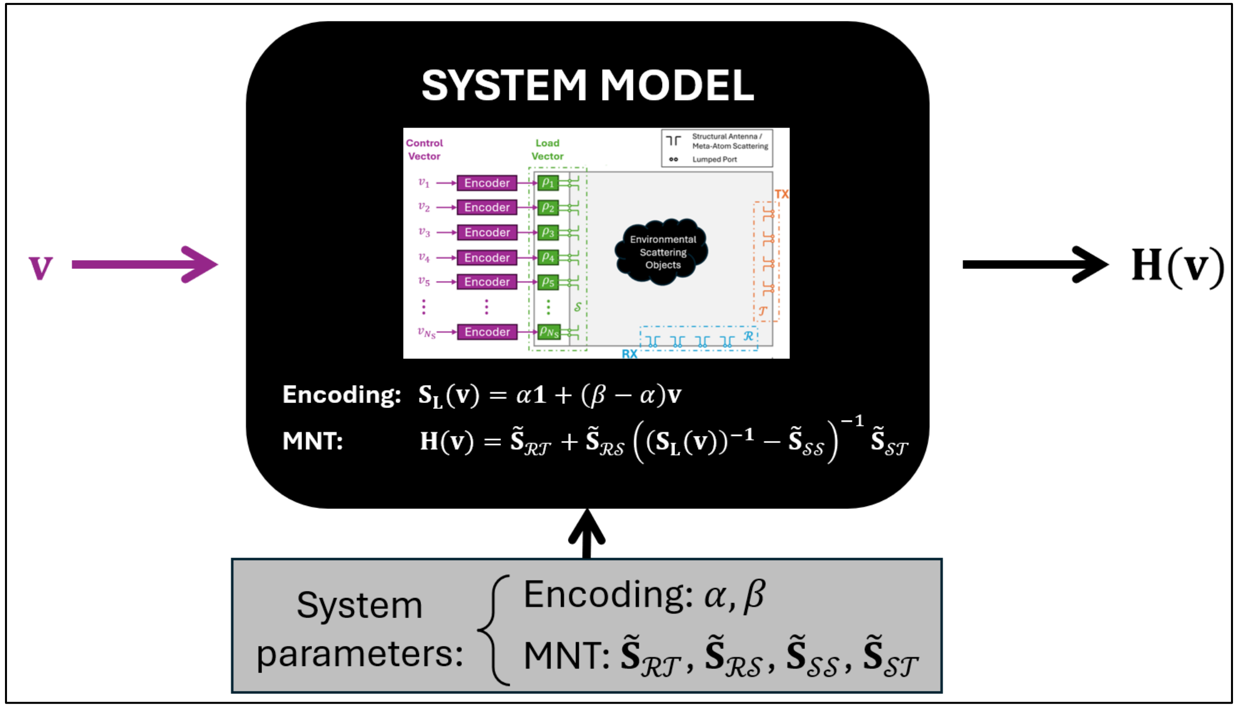
Eliminating all parameter ambiguities is impossible in most prototypes (→ Virtual VNA).

P. del Hougne, *IEEE TIM* (2025) [x3], *IEEE TAP* (2025) [x2]
J. Tapie, P. del Hougne, *IEEE AWPL* (2025)



P. del Hougne, M. Di Renzo, A. Alù, T. J. Cui, Y. Eldar, N. Engheta, W. Hu, A. Ozcan, *HAL:05487878* (2026)

2) **Prototype-aware model calibration** for reconfigurable microwave systems



SYSTEM MODEL

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System parameters: Encoding: α, β
MNT: $\tilde{\mathbf{S}}_{\mathcal{RT}}, \tilde{\mathbf{S}}_{\mathcal{RS}}, \tilde{\mathbf{S}}_{\mathcal{SS}}, \tilde{\mathbf{S}}_{\mathcal{ST}}$

Diagonal-Similarity Gauge:

$\tilde{\mathbf{S}}_{\mathcal{RS}} \to \tilde{\mathbf{S}}_{\mathcal{RS}}\mathbf{D}^{-1}, \tilde{\mathbf{S}}_{\mathcal{SS}} \to \mathbf{D}\tilde{\mathbf{S}}_{\mathcal{SS}}\mathbf{D}^{-1}, \tilde{\mathbf{S}}_{\mathcal{ST}} \to \mathbf{D}\tilde{\mathbf{S}}_{\mathcal{ST}}$
for some invertible, complex-valued $\mathbf{D} = \mathrm{diag}(\mathbf{d})$.

Complex-Scaling Gauge:

$\alpha \to c\alpha, \beta \to c\beta, \tilde{\mathbf{S}}_{\mathcal{RS}} \to \frac{1}{c}\tilde{\mathbf{S}}_{\mathcal{RS}}, \tilde{\mathbf{S}}_{\mathcal{SS}} \to \frac{1}{c}\tilde{\mathbf{S}}_{\mathcal{SS}}$
for some non-zero, complex-valued c.

Möbius Gauge:

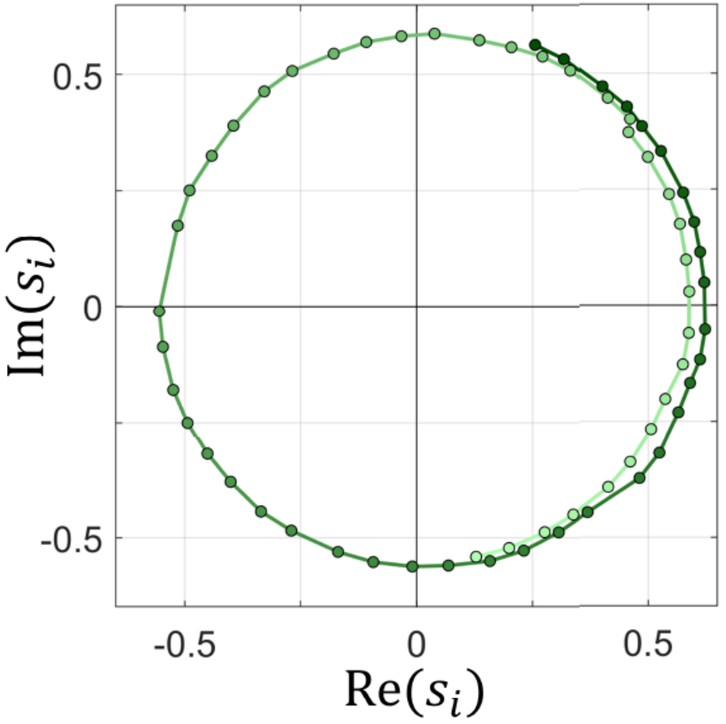
$\alpha \to M_m(\alpha), \beta \to M_m(\beta), \tilde{\mathbf{S}}_{\mathcal{RT}} \to \tilde{\mathbf{S}}_{\mathcal{RT}} + m\,\tilde{\mathbf{S}}_{\mathcal{RS}}\mathbf{F}\tilde{\mathbf{S}}_{\mathcal{ST}}, \tilde{\mathbf{S}}_{\mathcal{RS}} \to k\,\tilde{\mathbf{S}}_{\mathcal{RS}}\mathbf{F}, \tilde{\mathbf{S}}_{\mathcal{ST}} \to k\mathbf{F}\tilde{\mathbf{S}}_{\mathcal{ST}}, \tilde{\mathbf{S}}_{\mathcal{SS}} \to \left(\tilde{\mathbf{S}}_{\mathcal{SS}} - m^*\mathbf{I}\right)\mathbf{F}$
where $\mathbf{F} = \left(\mathbf{I} - m\tilde{\mathbf{S}}_{\mathcal{SS}}\right)^{-1}$, $k = \sqrt{1 - |m|^2}$, and $M_m(r) = \frac{r-m}{1-m^*r}$,
for some non-zero, complex-valued m.

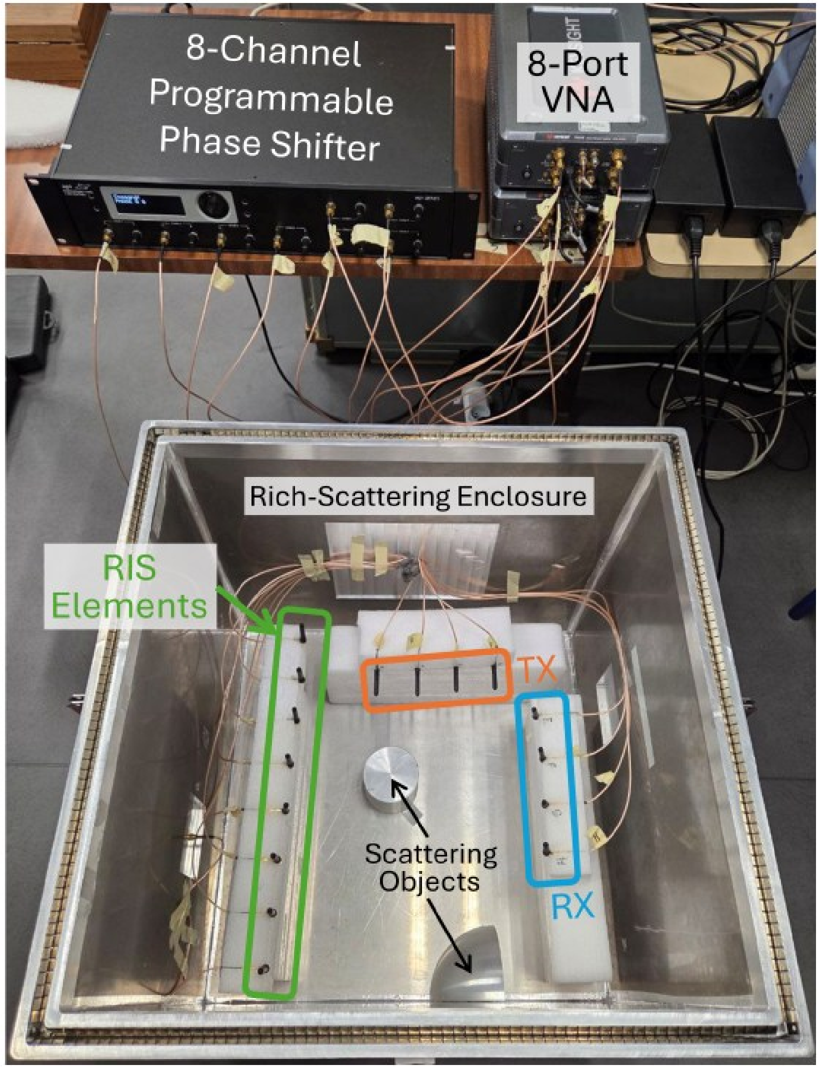
A. Salmi, V. Viikari, P. del Hougne, *arXiv:2601.20017* (2026)

2) **Prototype-aware model calibration** for reconfigurable microwave systems

Modular 6-Bit RIS Prototype

Available load states $\mathbf{s}$



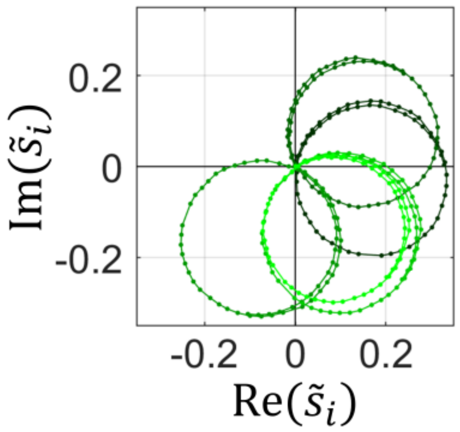


Hybrid Parameter Estimation Approach

1) Fix $s_1 = 0$ and $\tilde{\mathbf{S}}_{\mathcal{RT}}$ to the value of $\mathbf{H}$ in a reference RIS configuration.

2) Fix rows/columns of $\tilde{\mathbf{S}}_{\mathcal{RS}}$ and $\tilde{\mathbf{S}}_{\mathcal{ST}}$ up to scaling factors based on rank-1 changes of reference RIS configuration.

3) Fix remaining parameters via gradient descent based on measurements with random RIS configurations.



Estimates of $\tilde{s}_i$ are Möbius transformations of ground-truth s_i.

P. del Hougne, *IEEE Wireless Communications Letters* (2025)

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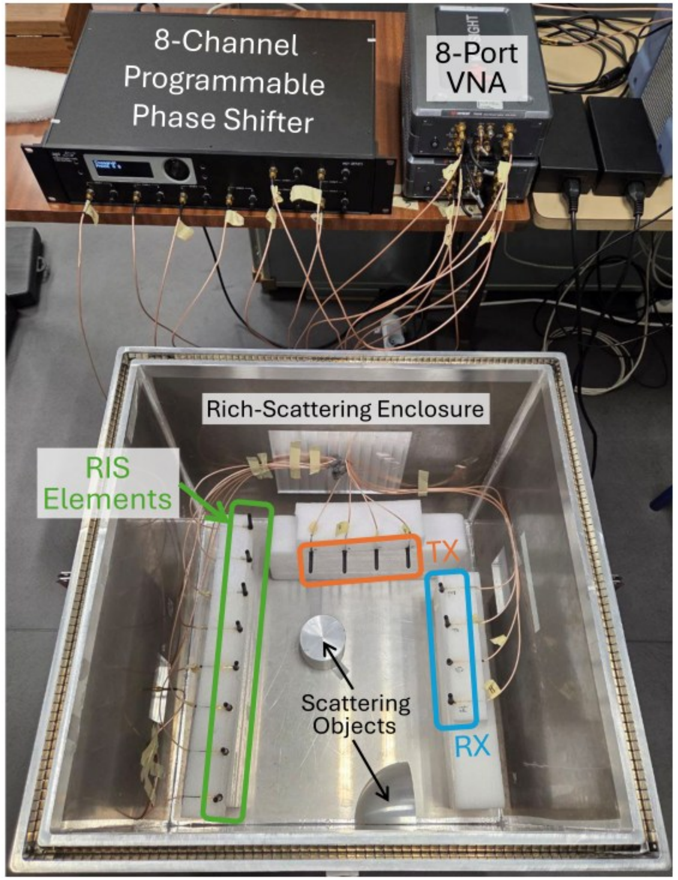
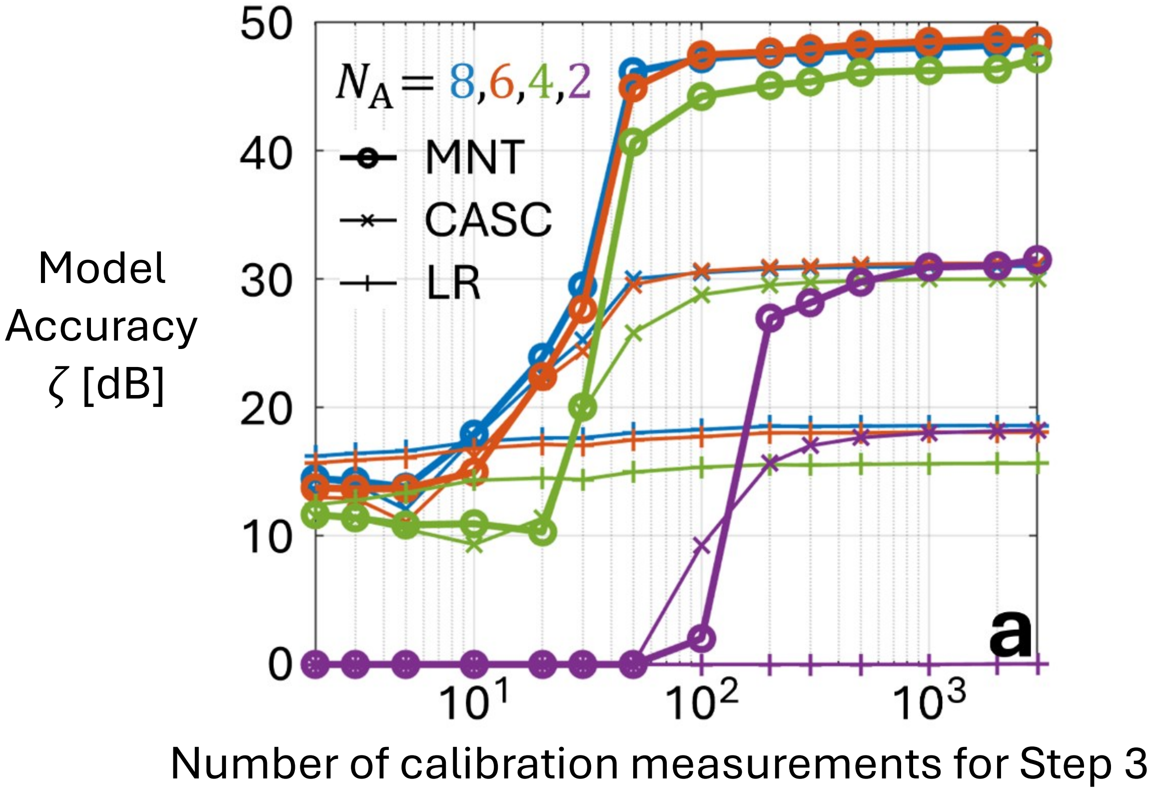
Modular 6-Bit RIS Prototype





P. del Hougne, *IEEE Wireless Communications Letters* (2025)

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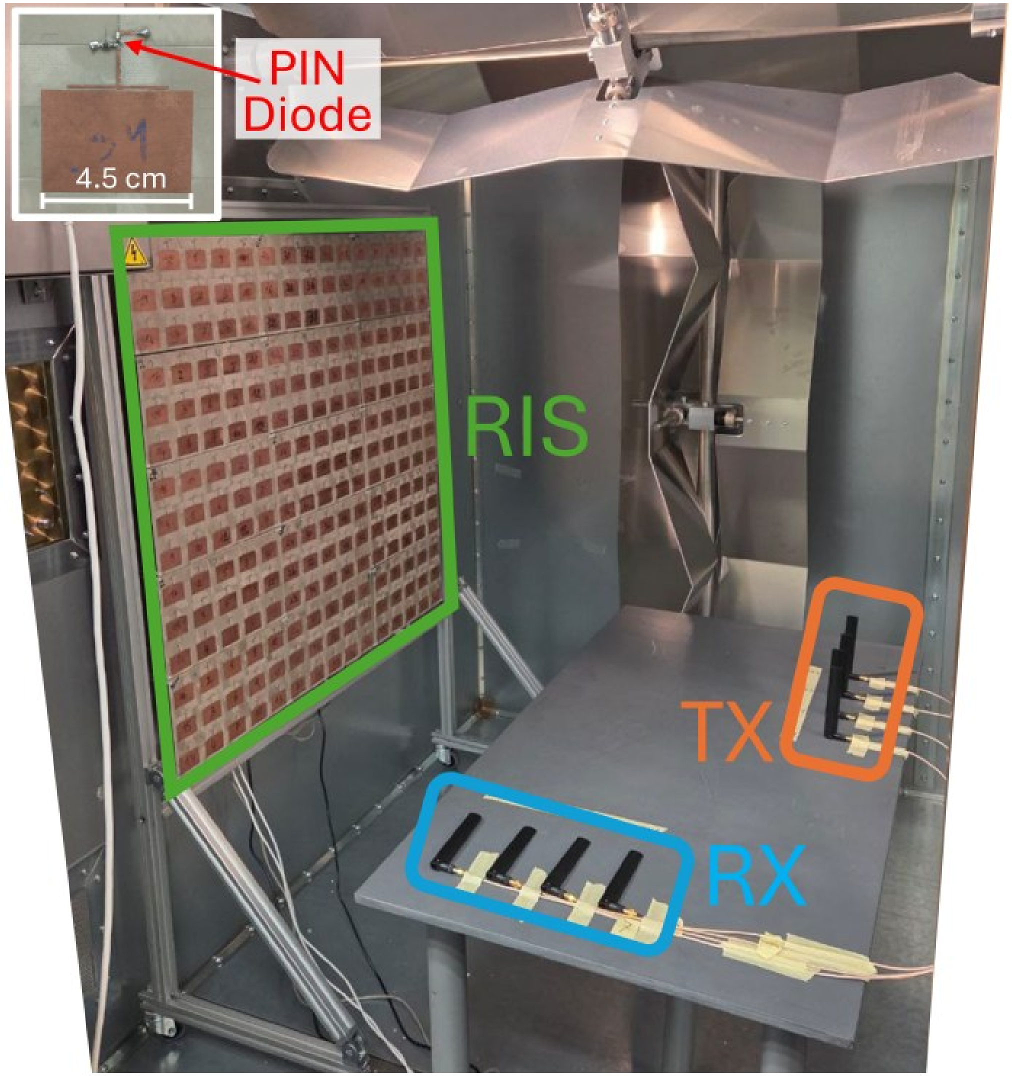

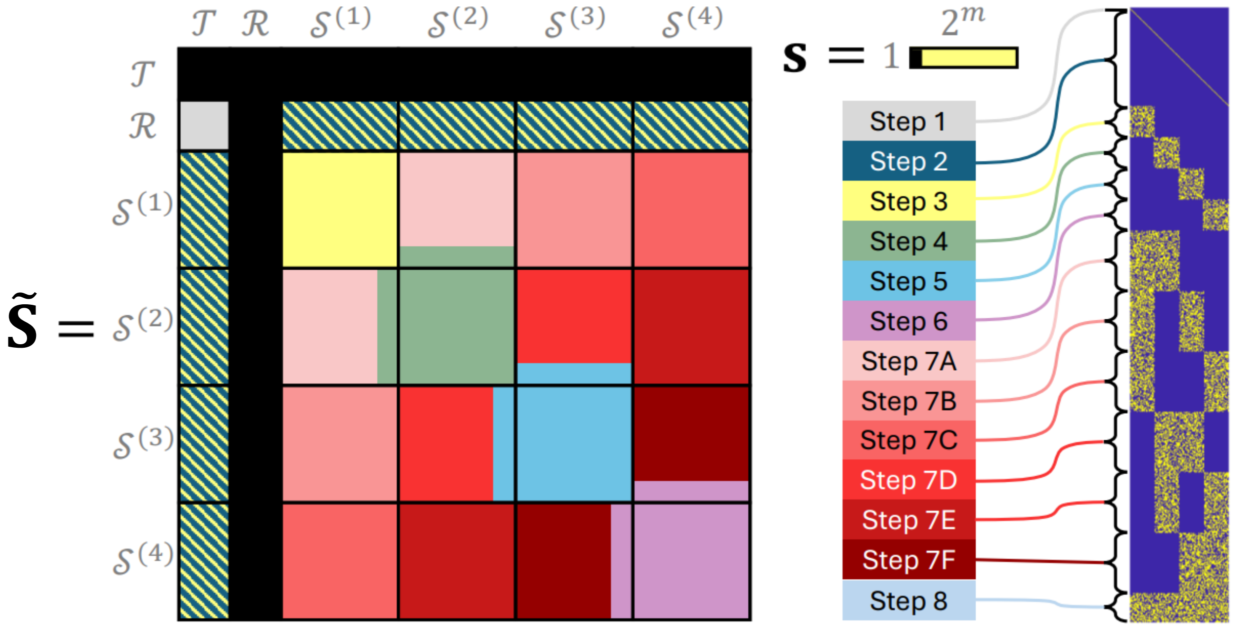

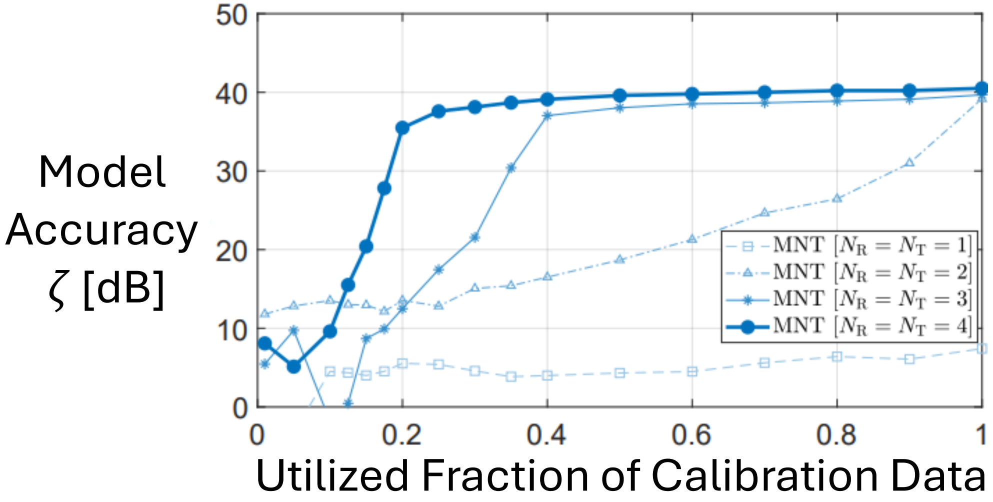

P. del Hougne, *IEEE Transactions on Communications* (2026)

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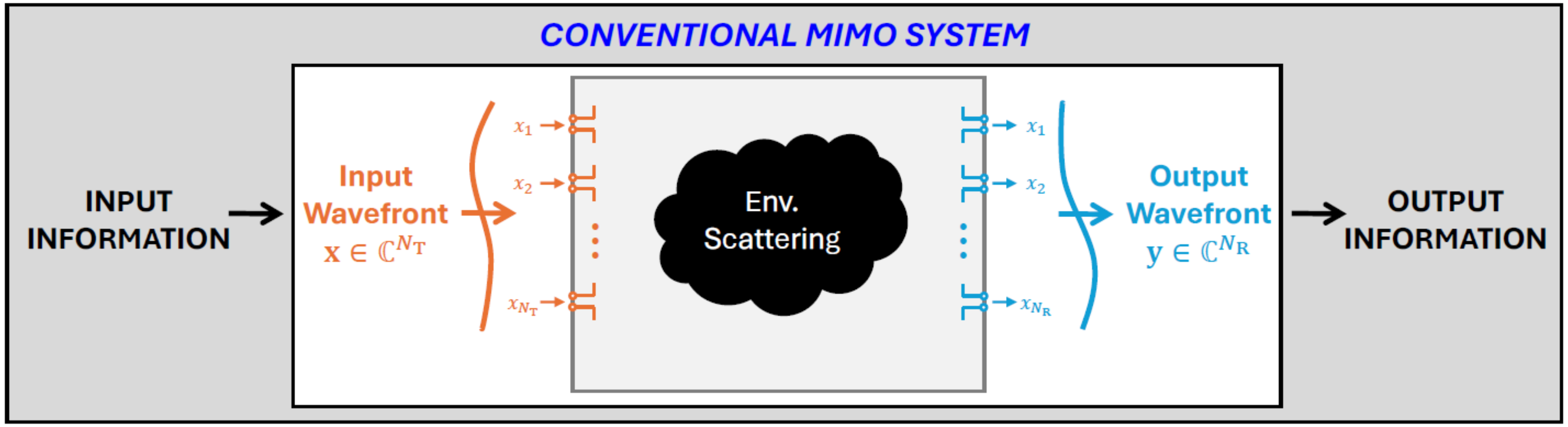
3) Toward a prototype-aware EM information theory for reconfigurable microwave systems

Bounds on multiplexing gain in backscatter MIMO systems

Background on effective EM degrees of freedom (EEMDOFs) in conventional MIMO systems



CONVENTIONAL MIMO SYSTEM

INPUT INFORMATION

Input Wavefront

$\mathbf{x} \in \mathbb{C}^{N_\mathrm{T}}$

Env. Scattering

Output Wavefront

$\mathbf{y} \in \mathbb{C}^{N_\mathrm{R}}$

OUTPUT INFORMATION

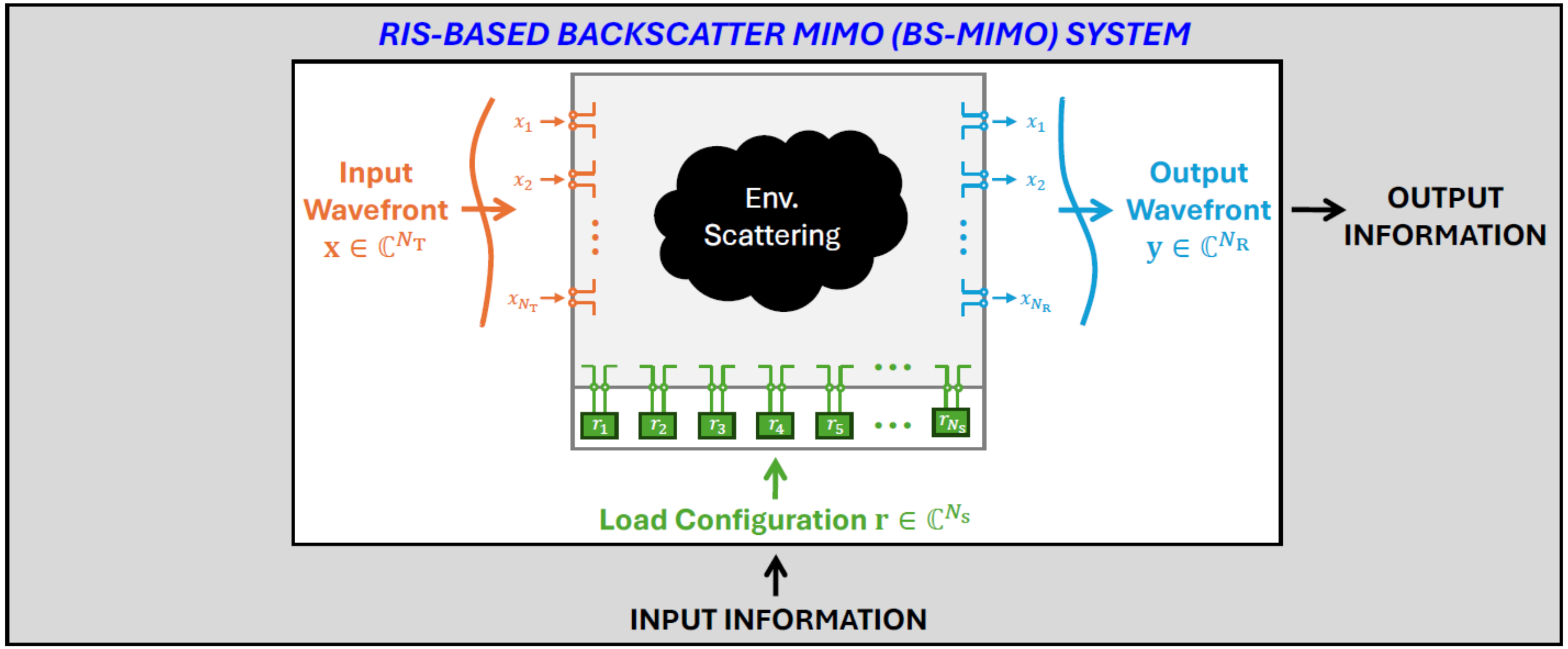
- Effective degrees of freedom quantify how many independent directions in the space of input parameters produce distinguishable changes of the outputs.
- In the high-SNR regime (where multi-eigenmode transmission is applicable), the number of EEMDOFs characterizes the multiplexing gain and the capacity scaling with SNR.
- The number of EEMDOFs is commonly defined as the number of significant singular values of the end-to-end channel matrix characterizing the MIMO system.

P. del Hougne, *IEEE Transactions on Antennas and Propagation* (in press) (2026) *[arXiv:2512.06799]*

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

Bounds on multiplexing gain in backscatter MIMO systems

Massive Backscatter MIMO system



- Mapping from input information to output information is non-linear due to mutual coupling.
- How can we define and evaluate BS-EEMDOFs?

P. del Hougne, *IEEE Transactions on Antennas and Propagation* (in press) (2026) *[arXiv:2512.06799]*

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Bounds on multiplexing gain in backscatter MIMO systems

Generalized definition of effective degrees of freedom

- Input-to-output mapping $\boldsymbol{\theta}_{\mathrm{out}} = f(\boldsymbol{\theta}_{\mathrm{in}})$.
- Local affine approximation around reference point $\boldsymbol{\theta}_{\mathrm{in},0}$:

$$\boldsymbol{\theta}_{\mathrm{out}} \approx \boldsymbol{\theta}_{\mathrm{out},0} + \mathbf{J}(\boldsymbol{\theta}_{\mathrm{in},0})\delta\boldsymbol{\theta}_{\mathrm{in}}, \text{ where } \mathbf{J}(\boldsymbol{\theta}_{\mathrm{in},0}) = \left.\frac{\partial\boldsymbol{\theta}_{\mathrm{out}}}{\partial\boldsymbol{\theta}_{\mathrm{in}}}\right|_{\boldsymbol{\theta}_{\mathrm{in}}=\boldsymbol{\theta}_{\mathrm{in},0}}$$

- Jacobian's participation number quantifies the number of effective DoFs:

$$M(\boldsymbol{\theta}_{\mathrm{in},0}) = PN\left(\mathbf{J}(\boldsymbol{\theta}_{\mathrm{in},0})\right) = \frac{\left(\sum_{i=1}^{\tilde{N}} \sigma_i^2\right)^2}{\sum_{i=1}^{\tilde{N}} \sigma_i^4}$$

- Note: $M(\boldsymbol{\theta}_{\mathrm{in},0})$ depends on $\boldsymbol{\theta}_{\mathrm{in},0}$.

Sanity check on conventional MIMO:

- $\mathbf{y} = f(\mathbf{x}) = \mathbf{H}\mathbf{x}$
- $\mathbf{J}(\mathbf{x}_0) = \left.\frac{\partial\mathbf{y}}{\partial\mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}_0} = \mathbf{H} \ \forall \ \mathbf{x}_0$
- $M(\mathbf{x}_0) = PN(\mathbf{H}) \ \forall \ \mathbf{x}_0$

P. del Hougne, *IEEE Transactions on Antennas and Propagation* (in press) (2026) *[arXiv:2512.06799]*

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

Bounds on multiplexing gain in backscatter MIMO systems

Generalized definition of effective degrees of freedom

- Input-to-output mapping $\boldsymbol{\theta}_{\mathrm{out}} = f(\boldsymbol{\theta}_{\mathrm{in}})$.
- Local affine approximation around reference point $\boldsymbol{\theta}_{\mathrm{in},0}$:

$$\boldsymbol{\theta}_{\mathrm{out}} \approx \boldsymbol{\theta}_{\mathrm{out},0} + \mathbf{J}(\boldsymbol{\theta}_{\mathrm{in},0})\delta\boldsymbol{\theta}_{\mathrm{in}}, \text{ where } \mathbf{J}(\boldsymbol{\theta}_{\mathrm{in},0}) = \left.\frac{\partial\boldsymbol{\theta}_{\mathrm{out}}}{\partial\boldsymbol{\theta}_{\mathrm{in}}}\right|_{\boldsymbol{\theta}_{\mathrm{in}}=\boldsymbol{\theta}_{\mathrm{in},0}}$$

- Jacobian's participation number quantifies the number of effective DoFs:

$$M(\boldsymbol{\theta}_{\mathrm{in},0}) = PN\left(\mathbf{J}(\boldsymbol{\theta}_{\mathrm{in},0})\right) = \frac{\left(\sum_{i=1}^{\tilde{N}} \sigma_i^2\right)^2}{\sum_{i=1}^{\tilde{N}} \sigma_i^4}$$

- Note: $M(\boldsymbol{\theta}_{\mathrm{in},0})$ depends on $\boldsymbol{\theta}_{\mathrm{in},0}$.

Application to Backscatter MIMO:

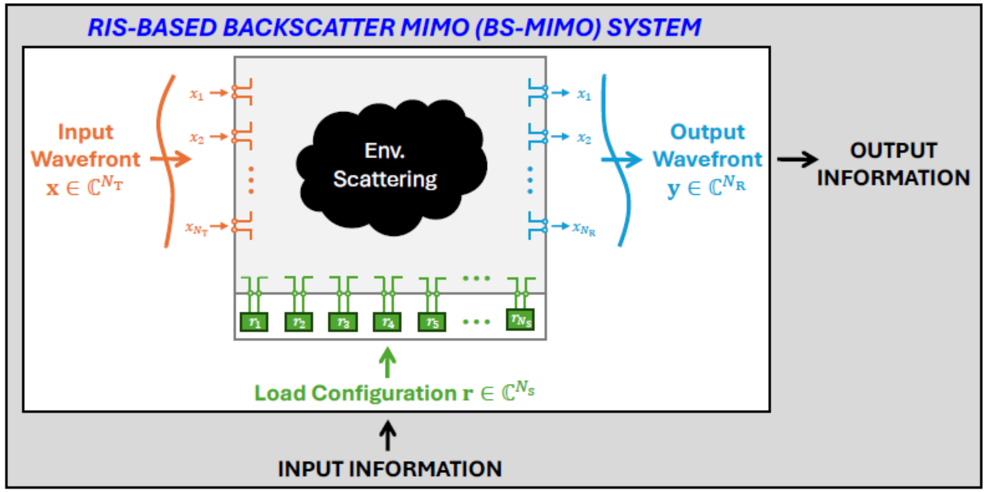
- $\mathbf{y} = f(\mathbf{r},\mathbf{x}) = \left[\tilde{\mathbf{S}}_{\mathcal{RT}} + \tilde{\mathbf{S}}_{\mathcal{RS}}\left(\mathbf{I}_{N_S} - \boldsymbol{\Phi}(\mathbf{r})\,\tilde{\mathbf{S}}_{\mathcal{SS}}\right)^{-\mathbf{1}}\boldsymbol{\Phi}(\mathbf{r})\,\tilde{\mathbf{S}}_{\mathcal{ST}}\right]\mathbf{x}$, where $\boldsymbol{\Phi}(\mathbf{r}) = \mathrm{diag}(\mathbf{r})$.
- $\mathbf{J}(\mathbf{r}_0,\mathbf{x}) = \left.\frac{\partial\mathbf{y}}{\partial\mathbf{r}}\right|_{\mathbf{r}=\mathbf{r}_0} = \tilde{\mathbf{S}}_{\mathcal{RS}}\mathbf{B}(\mathbf{r}_0,\mathbf{x})$.
- $M(\mathbf{r}_0,\mathbf{x}) = PN(\mathbf{J}(\mathbf{r}_0,\mathbf{x}))$
- Note: BS-EEMDOFs depend on $\mathbf{r}_0$ and $\mathbf{x}$.
- If $\tilde{\mathbf{S}}_{\mathcal{SS}} = \mathbf{0}$ (implying no mutual coupling), $\mathbf{J}(\mathbf{r}_0,\mathbf{x}) = \tilde{\mathbf{S}}_{\mathcal{RS}}\mathrm{diag}\left(\tilde{\mathbf{S}}_{\mathcal{ST}}\mathbf{x}\right)\ \forall\ \mathbf{r}_0$.

$$\mathbf{B}(\mathbf{r}_0,\mathbf{x}) = \mathbf{G}(\mathbf{r}_0)\mathrm{diag}(\mathbf{W}(\mathbf{r}_0)\mathbf{x})$$
$$\mathbf{W}(\mathbf{r}) = \tilde{\mathbf{S}}_{\mathcal{SS}}\mathbf{G}(\mathbf{r})\boldsymbol{\Phi}(\mathbf{r})\tilde{\mathbf{S}}_{\mathcal{ST}} + \tilde{\mathbf{S}}_{\mathcal{ST}}$$
$$\mathbf{G}(\mathbf{r}) = \left(\mathbf{I}_{N_S} - \boldsymbol{\Phi}(\mathbf{r})\,\tilde{\mathbf{S}}_{\mathcal{SS}}\right)^{-\mathbf{1}}$$

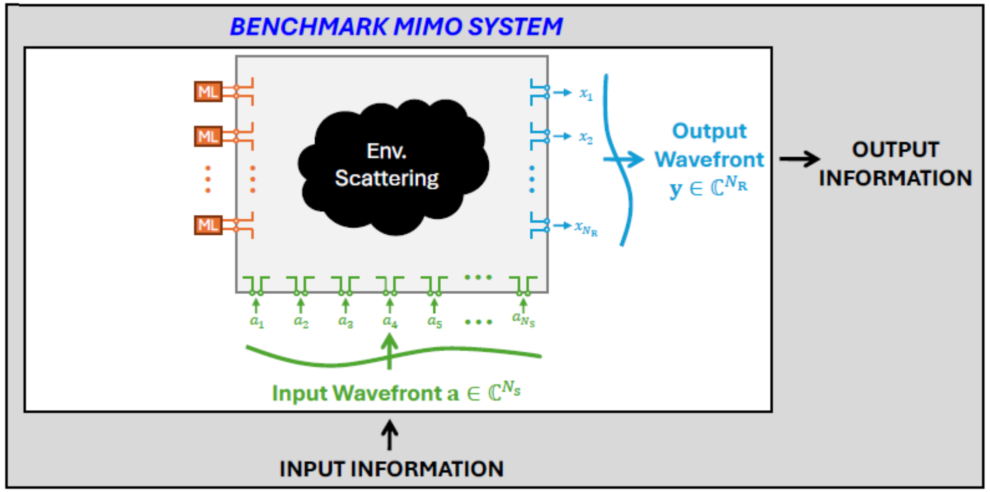
P. del Hougne, *IEEE Transactions on Antennas and Propagation* (in press) (2026) *[arXiv:2512.06799]*

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

Bounds on multiplexing gain in backscatter MIMO systems



Local mapping: $\mathbf{J}(\mathbf{r}_0, \mathbf{x}) = \tilde{\mathbf{S}}_{\mathcal{RS}} \mathbf{B}(\mathbf{r}_0, \mathbf{x})$



Mapping: $\tilde{\mathbf{S}}_{\mathcal{RS}}$

- Modes associated with BS-EEMDOFs lie in the same column space as modes associated with EEMDOFs.
- The number of BS-EEMDOFs generally differs from the number of EEMDOFs.
- The number of BS-EEMDOFs depends on $\mathbf{r}_0$ and $\mathbf{x}$.
- The number of BS-EEMDOFs is generally a random variable (unless MC is negligible and illumination is fixed).
- The distribution of the number of BS-EEMDOFs can be optimized by controlling the illumination.

P. del Hougne, *IEEE Transactions on Antennas and Propagation* (in press) (2026) *[arXiv:2512.06799]*

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

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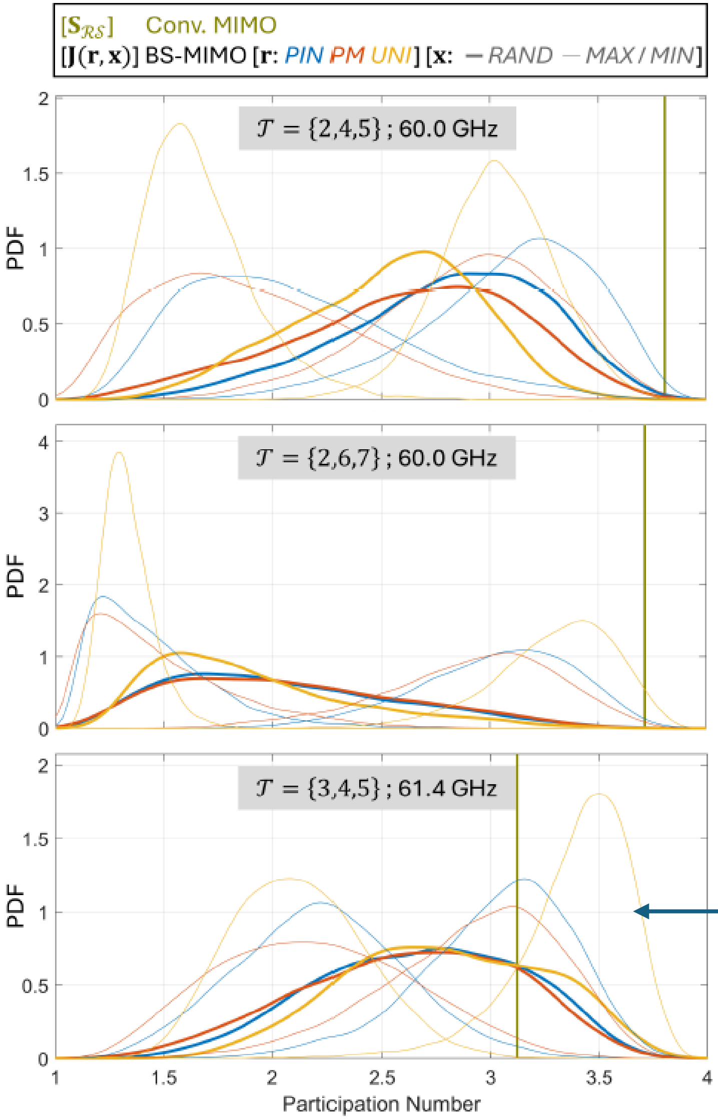
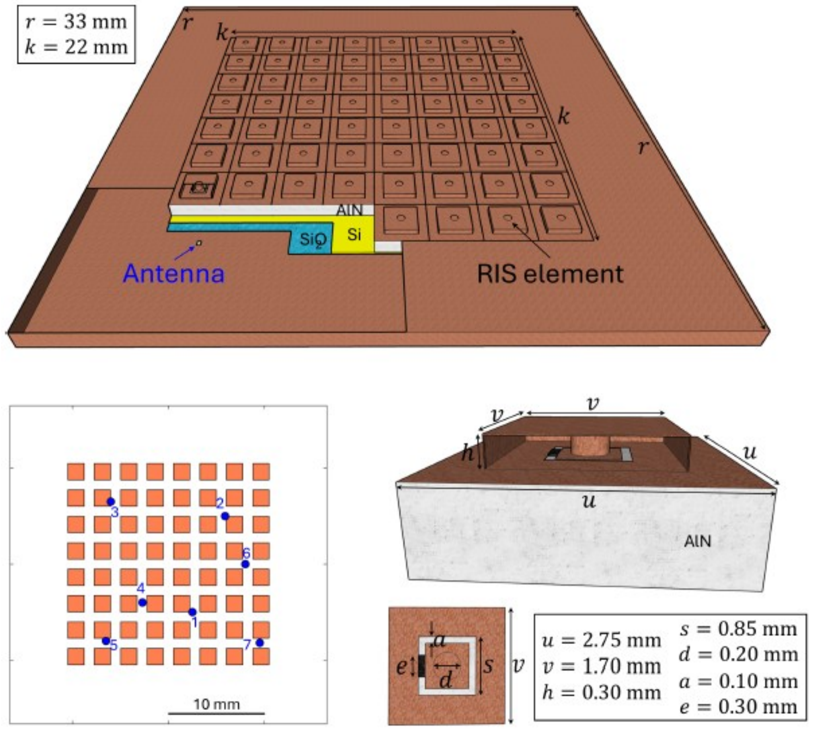




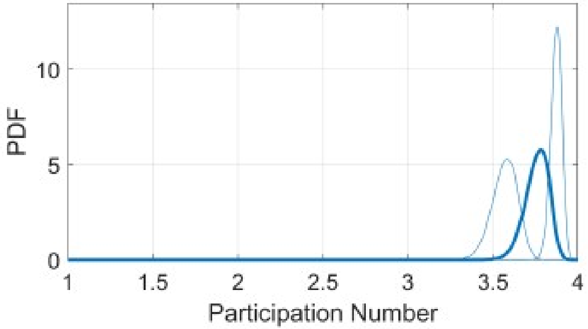
← BS-EEMDOFs clearly exceed EEMDOFs.

P. del Hougne, *IEEE Transactions on Antennas and Propagation* (in press) (2026) *[arXiv:2512.06799]*

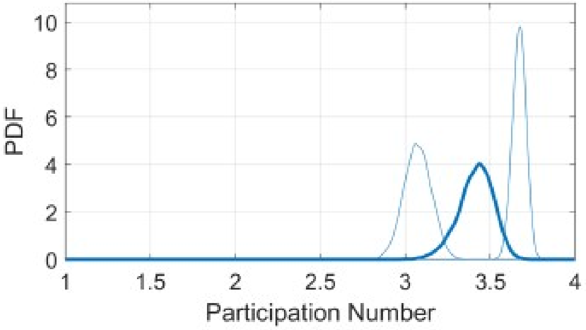
3) Toward a prototype-aware EM information theory for reconfigurable microwave systems

Bounds on multiplexing gain in backscatter MIMO systems

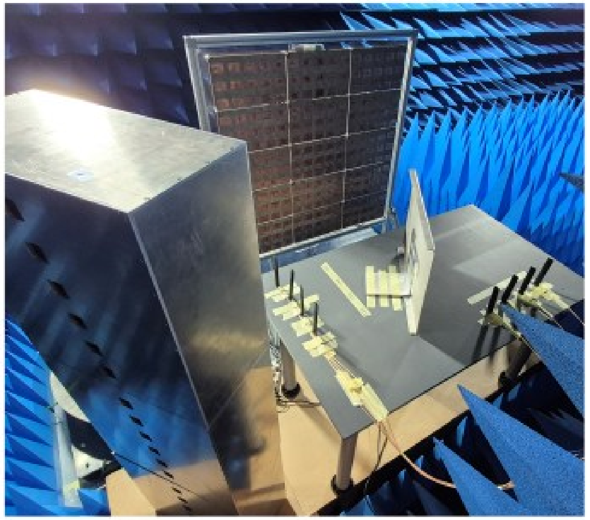
Rich Env. Scattering

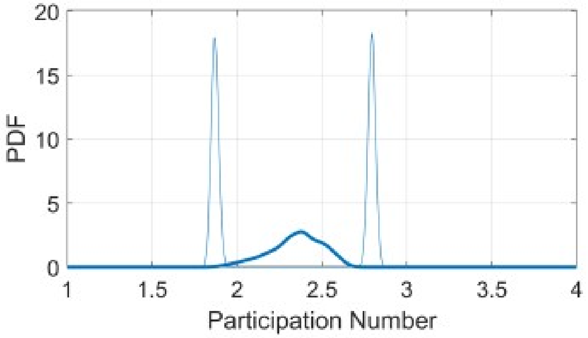


Attenuated Rich Env. Scattering

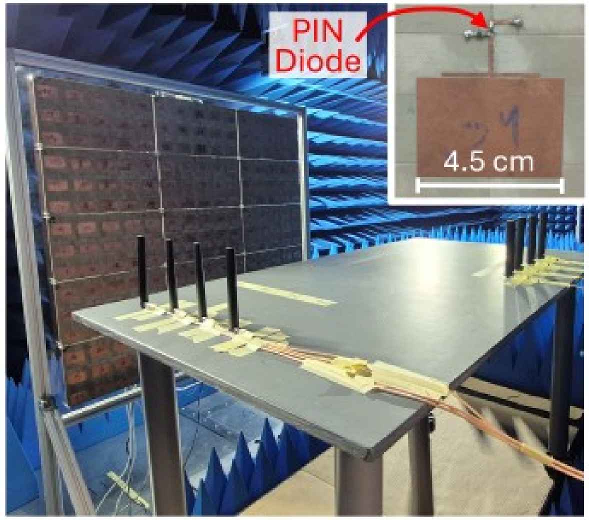


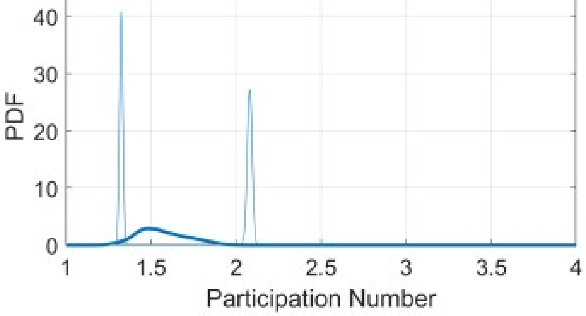
Light Env. Scattering





No Env. Scattering





P. del Hougne, *IEEE Transactions on Antennas and Propagation* (in press) (2026) *[arXiv:2512.06799]*

Outline

1) **Multiport-network model formulation** for reconfigurable microwave systems

2) **Prototype-aware model calibration** for reconfigurable microwave systems

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems
    - Bounds on multiplexing gain in backscatter MIMO systems
    - Bounds on information transfer via RIS-parametrized SISO channel
    - Bounds on MIMO operator synthesis

3) Toward a prototype-aware EM information theory for reconfigurable microwave systems

Bounds on information transfer via RIS-parametrized SISO channel

Shannon’s theorem for achievable reliable information rate on a noisy SISO channel:

$$C = \log_2\left(1 + \frac{P_\mathrm{T}}{\sigma^2}|h|^2\right)$$

Now, we have **deterministically programmable channels**:

$$C(\mathbf{v}) = \log_2\left(1 + \frac{P_\mathrm{T}}{\sigma^2}|h(\mathbf{v})|^2\right)$$

→ What is the bound on the achievable information transfer in a programmable channel subject to the constraints of electromagnetisms and a real-world feasibility set?

In the SISO case, channel gain maps monotonously to Shannon capacity...

→ What is the bound on the channel gain in a programmable channel subject to the constraints of electromagnetisms and a real-world feasibility set?

A. Salmi, V. Viikari, P. del Hougne, *arXiv:2601.20017* (2026)

3) Toward a prototype-aware EM information theory for reconfigurable microwave systems

Bounds on information transfer via RIS-parametrized SISO channel

$$h(\mathbf{r}) = h_0 + \mathbf{a}^\top \left(\mathbf{I}_{N_\mathrm{S}} - \mathbf{\Phi}(\mathbf{r})\,\mathbf{\Gamma}\right)^{-1} \mathbf{\Phi}(\mathbf{r})\,\mathbf{b}$$

$$\mathbf{\Phi}(\mathbf{r}) = \mathrm{diag}(\mathbf{r})$$

$$\mathbf{r}(\mathbf{v}) = \alpha\mathbf{1} + (\beta - \alpha)\mathbf{v}$$

Objective: SISO channel gain maximization.

How can we bound the achievable SISO channel gain $|h|^2$ for a given experimental system?

1) Norm-Inequality Bound

$$|h(\mathbf{r})|^2 \leq B_\mathrm{NI} \triangleq \left(|h_0| + \|\mathbf{a}\|_2 \frac{\gamma}{1-\gamma\|\mathbf{\Gamma}\|_2} \|\mathbf{b}\|_2\right)^2$$

This bound is sensitive to model parameter ambiguities.

→ We can tighten this bound by optimizing over model parameter ambiguities.

$$\begin{aligned} B_\mathrm{NIO}(\boldsymbol{\theta}) \triangleq \min_{\mathbf{d},\, m} \quad & B_\mathrm{NI}\left(\hat{g}(\boldsymbol{\theta}; [\mathbf{d}^\top, c_0, m]^\top)\right) \\ \text{s.t.} \quad & \tilde{\gamma}\left\|\tilde{\mathbf{\Gamma}}\right\|_2 < 1, \quad d_i \neq 0 \;\forall\, i, \quad \text{all inverses in } \hat{g}(\cdot) \text{ exist} \end{aligned}$$

A. Salmi, V. Viikari, P. del Hougne, *arXiv:2601.20017* (2026)

3) Toward a prototype-aware EM information theory for reconfigurable microwave systems

Bounds on information transfer via RIS-parametrized SISO channel

$$h(\mathbf{r}) = h_0 + \mathbf{a}^\top \left(\mathbf{I}_{N_\mathrm{S}} - \mathbf{\Phi}(\mathbf{r})\,\mathbf{\Gamma}\right)^{-1} \mathbf{\Phi}(\mathbf{r})\,\mathbf{b}$$
$$\mathbf{\Phi}(\mathbf{r}) = \mathrm{diag}(\mathbf{r})$$
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Objective: SISO channel gain maximization.

How can we bound the achievable SISO channel gain $|h|^2$ for a given experimental system?

2) Idealized-BD-RIS Bound

If $|\alpha| = |\beta| = 1$ and $\|\mathbf{\Gamma}\|_2 < 1$,

then the closed-form global solution for the case in which $\mathbf{\Phi}$ can be any unitary matrix is a bound.

Using the auxiliary variable $\mathbf{x} \triangleq \left(\mathbf{I}_{N_\mathrm{S}} - \mathbf{\Phi}\,\mathbf{\Gamma}\right)^{-1} \mathbf{\Phi}\,\mathbf{b}$,

the problem can be reframed as maximizing an affine functional over an ellipsoid,

for which a closed-form solution via Cauchy-Schwarz alignment exists.

See also:

Z. Wu, M. Nerini, and B. Clerckx, *arXiv:2510.12366* (2025)

Being a global solution, this bound B_{IBD} is by construction insensitive to model parameter ambiguities.

A. Salmi, V. Viikari, P. del Hougne, *arXiv:2601.20017* (2026)

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

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Objective: SISO channel gain maximization.

How can we bound the achievable SISO channel gain $|h|^2$ for a given experimental system?

3) Semidefinite Relaxation Bound

Introducing the auxiliary variable $\mathbf{x} \triangleq \left(\mathbf{I}_{N_\mathrm{S}} - \mathbf{\Phi}\,\mathbf{\Gamma}\right)^{-1} \mathbf{\Phi}\,\mathbf{b}$,

we can formulate our problem as QCQP:

$$\begin{aligned} \max_{\mathbf{x} \in \mathbb{C}^{N_\mathrm{S}}} \quad & \mathbf{x}^\dagger\,\mathbf{R}_0\,\mathbf{x} + 2\,\Re\{\mathbf{q}_0^\top\,\mathbf{x}\} + t_0 \\ \text{s.t.} \quad & \mathbf{x}^\dagger \mathbf{R}_i \mathbf{x} + \mathbf{x}^\dagger \mathbf{q}_{1,i} + \mathbf{q}_{2,i}^\top \mathbf{x} + t_i = 0, \qquad i = 1, \ldots, N_\mathrm{S}. \end{aligned}$$

By introducing $\mathbf{X} = \mathbf{x}\mathbf{x}^\dagger$, a semidefinite relaxation yields an SDP

that can be solved with standard convex solvers:

$$\begin{aligned} \max_{\mathbf{x}, \mathbf{X}} \quad & \mathrm{tr}(\mathbf{R}_0 \mathbf{X}) + 2\,\Re\{\mathbf{q}_0^\top\,\mathbf{x}\} + t_0 \\ \text{s.t.} \quad & \mathrm{tr}(\mathbf{R}_i \mathbf{X}) + \mathbf{x}^\dagger \mathbf{q}_{1,i} + \mathbf{q}_{2,i}^\top \mathbf{x} + t_i = 0, \qquad i = 1, \ldots, N_\mathrm{S}, \\ & \begin{bmatrix} \mathbf{X} & \mathbf{x} \\ \mathbf{x}^\dagger & 1 \end{bmatrix} \succeq \mathbf{0}. \end{aligned}$$

Any feasible point for QCQP is also feasible for SDP, hence

$B_\mathrm{SDR} \triangleq \mathrm{tr}(\mathbf{R}_0\,\check{\mathbf{X}}) + 2\,\Re\{\mathbf{q}_0^\top\,\check{\mathbf{x}}\} + t_0$ (which we can show to be ambiguity-insensitive).

A. Salmi, V. Viikari, P. del Hougne, *arXiv:2601.20017* (2026)

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

Bounds on information transfer via RIS-parametrized SISO channel

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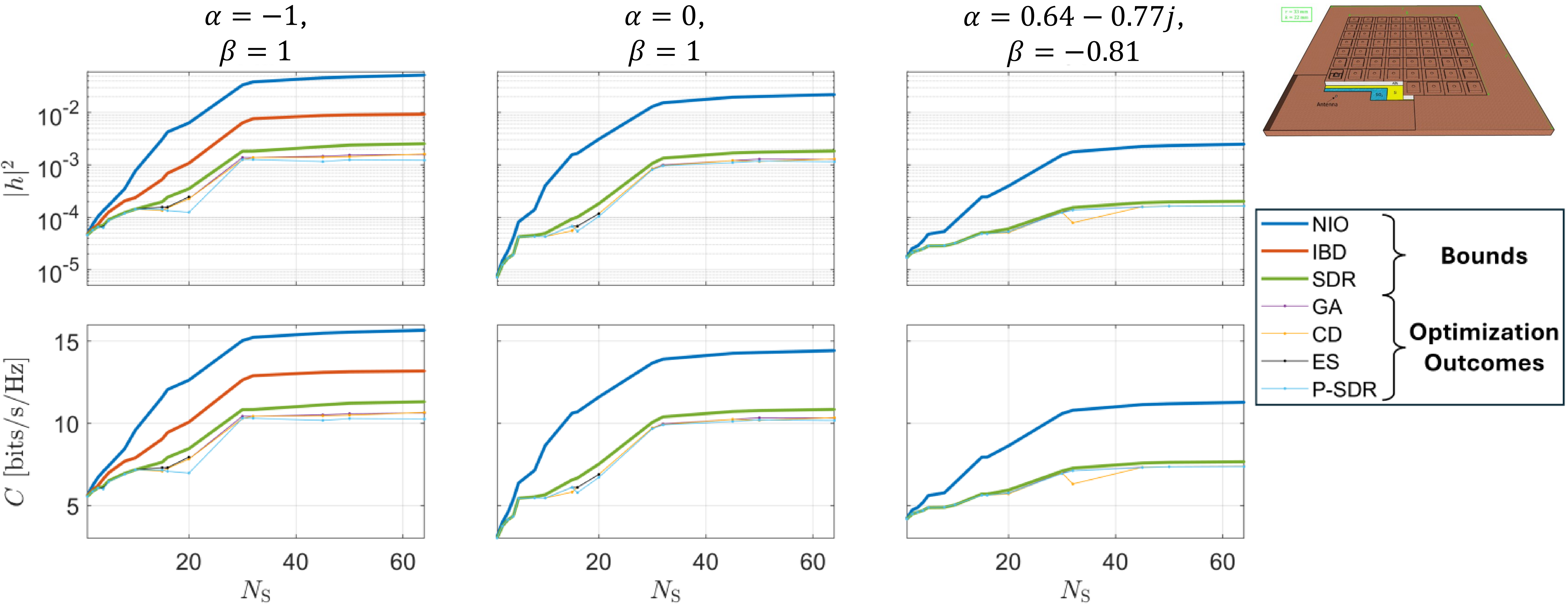
$$\mathbf{\Phi}(\mathbf{r}) = \mathrm{diag}(\mathbf{r})$$

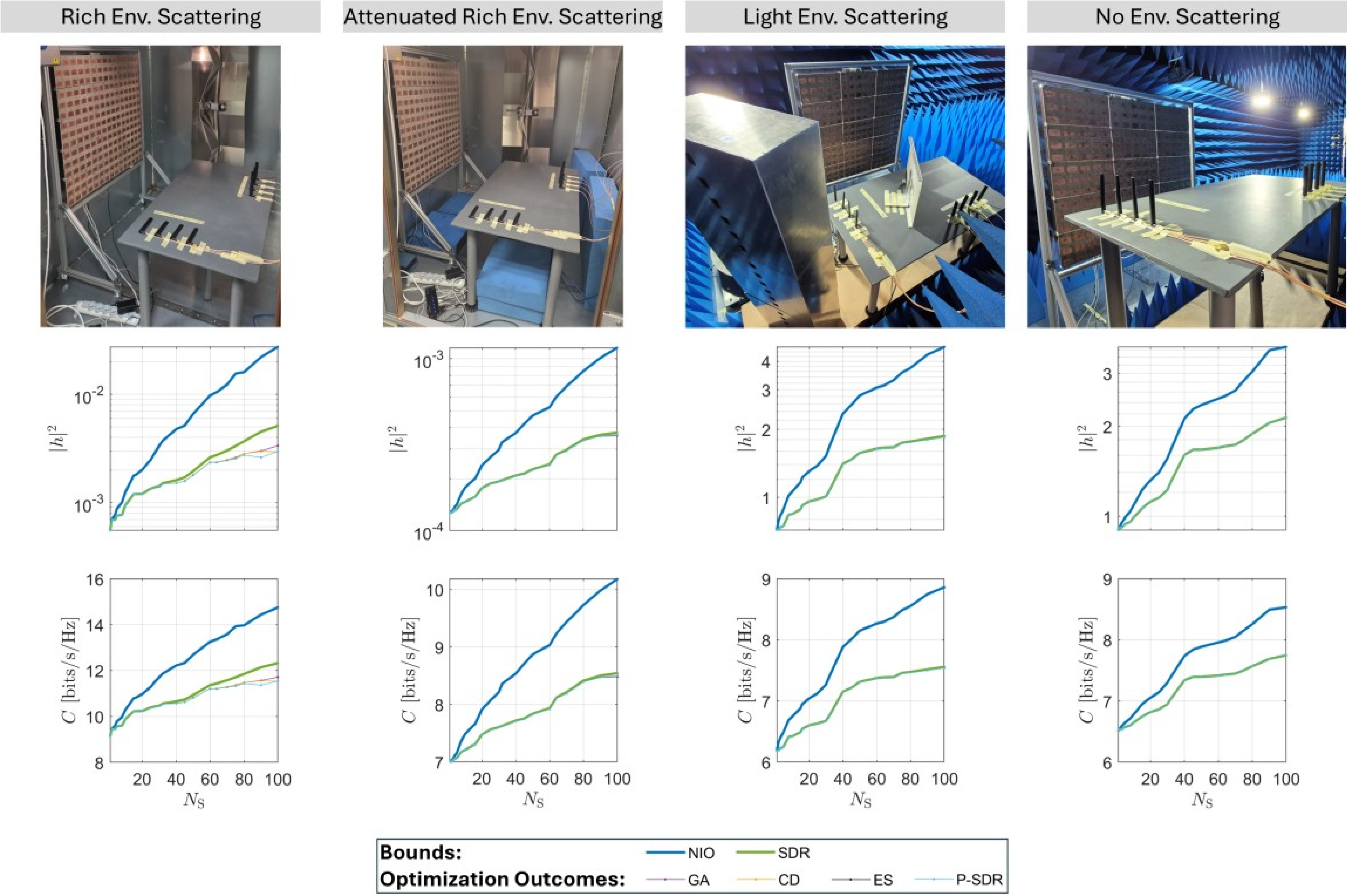
$$\mathbf{r}(\mathbf{v}) = \alpha\mathbf{1} + (\beta - \alpha)\mathbf{v}$$



A. Salmi, V. Viikari, P. del Hougne, *arXiv:2601.20017* (2026)

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

Bounds on information transfer via RIS-parametrized SISO channel



A. Salmi, V. Viikari, P. del Hougne, *arXiv:2601.20017* (2026)

Outline

1) **Multiport-network model formulation** for reconfigurable microwave systems

2) **Prototype-aware model calibration** for reconfigurable microwave systems

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems
    - Bounds on multiplexing gain in backscatter MIMO systems
    - Bounds on information transfer via RIS-parametrized SISO channel
    - Bounds on MIMO operator synthesis

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

Bounds on MIMO operator synthesis

How well can a reconfigurable MIMO system's transfer function approximate a desired linear operator?

Relevance:

- hybrid-MIMO analog combining
- computational meta-imaging with illuminations based on principal scene components
- programmable wave-domain signal processing

P. del Hougne, *arXiv:2602.14152* (2026)

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

Bounds on MIMO aggregate channel gain

$$\begin{aligned}
\mathbf{H}(\mathbf{r}) &= \mathbf{H}_0 + \mathbf{A}\left(\mathbf{I}_{N_\mathrm{S}} - \boldsymbol{\Phi}(\mathbf{r})\,\boldsymbol{\Gamma}\right)^{-1}\boldsymbol{\Phi}(\mathbf{r})\,\mathbf{B}\\
\boldsymbol{\Phi}(\mathbf{r}) &= \mathrm{diag}(\mathbf{r})\\
\mathbf{r}(\mathbf{v}) &= \alpha\mathbf{1} + (\beta - \alpha)\mathbf{v}
\end{aligned}$$

Let us first consider a simpler intermediate goal:

MIMO aggregate channel gain maximization.

Upon introducing the auxiliary variable $\mathbf{X} \triangleq \left(\mathbf{I}_{N_\mathrm{S}} - \boldsymbol{\Phi}(\mathbf{r})\,\boldsymbol{\Gamma}\right)^{-1}\boldsymbol{\Phi}(\mathbf{r})\,\mathbf{B}$ and vectorizing it with $\mathbf{y} \triangleq \mathrm{vec}(\mathbf{X})$,

we can formulate our problem as QCQP:

$$\begin{aligned}
\max_{\mathbf{y}\in\mathbb{C}^{N_\mathrm{S}N_\mathrm{T}}} \quad & \mathbf{y}^\dagger\mathbf{R}_0\mathbf{y} + 2\,\Re\left\{\mathbf{q}_0^\dagger\mathbf{y}\right\} + \tau_0\\
\text{s.t.} \quad & \mathbf{y}^\dagger\mathbf{R}_{s,t}\mathbf{y} + \mathbf{y}^\dagger\mathbf{p}_{s,t} + \mathbf{q}_{s,t}^\dagger\mathbf{y} + \tau_{s,t} = 0, \\
& \quad \forall\, s\in\{1,\ldots,N_\mathrm{S}\},\ \forall\, t\in\{1,\ldots,N_\mathrm{T}\},\\
& \mathbf{y}^\dagger\mathbf{R}_{s,t}^{(i)}\mathbf{y} + \mathbf{y}^\dagger\mathbf{p}_{s,t}^{(i)} + \left(\mathbf{q}_{s,t}^{(i)}\right)^\dagger\mathbf{y} + \tau_{s,t}^{(i)} = 0,\\
& \quad \forall\, s\in\{1,\ldots,N_\mathrm{S}\},\ \forall\, t\in\{2,\ldots,N_\mathrm{T}\},\ \forall\, i\in\{1,2\}.
\end{aligned}$$

Quadratic objective

Quadratic binary-programmability constraint

Quadratic repetition constraint

See also:

H. Shim et al., *Nanophotonics* (2024)
A. Salmi et al., *IEEE TAP* (2025)

P. del Hougne, *arXiv:2602.14152* (2026)

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

Bounds on MIMO aggregate channel gain

$$\begin{aligned}\mathbf{H}(\mathbf{r}) &= \mathbf{H}_0 + \mathbf{A}\left(\mathbf{I}_{N_\mathrm{S}} - \mathbf{\Phi}(\mathbf{r})\,\mathbf{\Gamma}\right)^{-1}\mathbf{\Phi}(\mathbf{r})\,\mathbf{B}\\ \mathbf{\Phi}(\mathbf{r}) &= \mathrm{diag}(\mathbf{r})\\ \mathbf{r}(\mathbf{v}) &= \alpha\mathbf{1} + (\beta-\alpha)\mathbf{v}\end{aligned}$$

Let us first consider a simpler intermediate goal:

MIMO aggregate channel gain maximization.

Upon introducing the auxiliary variable $\mathbf{X} \triangleq \left(\mathbf{I}_{N_\mathrm{S}} - \mathbf{\Phi}(\mathbf{r})\,\mathbf{\Gamma}\right)^{-1}\mathbf{\Phi}(\mathbf{r})\,\mathbf{B}$ and vectorizing it with $\mathbf{y} \triangleq \mathrm{vec}(\mathbf{X})$,

we can formulate our problem as QCQP:

$$\begin{aligned}\max_{\mathbf{y}\in\mathbb{C}^{N_\mathrm{S}N_\mathrm{T}}}\quad & \mathbf{y}^\dagger\mathbf{R}_0\mathbf{y} + 2\,\Re\left\{\mathbf{q}_0^\dagger\mathbf{y}\right\} + \tau_0\\ \text{s.t.}\quad & \mathbf{y}^\dagger\mathbf{R}_{s,t}\mathbf{y} + \mathbf{y}^\dagger\mathbf{p}_{s,t} + \mathbf{q}_{s,t}^\dagger\mathbf{y} + \tau_{s,t} = 0,\\ & \quad \forall\, s\in\{1,\ldots,N_\mathrm{S}\},\ \forall\, t\in\{1,\ldots,N_\mathrm{T}\},\\ & \mathbf{y}^\dagger\mathbf{R}^{(i)}_{s,t}\mathbf{y} + \mathbf{y}^\dagger\mathbf{p}^{(i)}_{s,t} + \left(\mathbf{q}^{(i)}_{s,t}\right)^\dagger\mathbf{y} + \tau^{(i)}_{s,t} = 0,\\ & \quad \forall\, s\in\{1,\ldots,N_\mathrm{S}\},\ \forall\, t\in\{2,\ldots,N_\mathrm{T}\},\ \forall\, i\in\{1,2\}.\end{aligned}$$

Introduce $\mathbf{Y} = \mathbf{y}\mathbf{y}^\dagger$

and apply SDR

$$\begin{aligned}\max_{\mathbf{y},\mathbf{Y}}\quad & \mathrm{tr}(\mathbf{R}_0\mathbf{Y}) + 2\,\Re\left\{\mathbf{q}_0^\dagger\mathbf{y}\right\} + \tau_0\\ \text{s.t.}\quad & \mathrm{tr}(\mathbf{R}_{s,t}\mathbf{Y}) + \mathbf{y}^\dagger\mathbf{p}_{s,t} + \mathbf{q}_{s,t}^\dagger\mathbf{y} + \tau_{s,t} = 0,\\ & \quad \forall\, s\in\{1,\ldots,N_\mathrm{S}\},\ \forall\, t\in\{1,\ldots,N_\mathrm{T}\},\\ & \mathrm{tr}(\mathbf{R}^{(i)}_{s,t}\mathbf{Y}) + \mathbf{y}^\dagger\mathbf{p}^{(i)}_{s,t} + \left(\mathbf{q}^{(i)}_{s,t}\right)^\dagger\mathbf{y} + \tau^{(i)}_{s,t} = 0,\\ & \quad \forall\, s\in\{1,\ldots,N_\mathrm{S}\},\ \forall\, t\in\{2,\ldots,N_\mathrm{T}\},\ \forall\, i\in\{1,2\},\\ & \begin{bmatrix}\mathbf{Y} & \mathbf{y}\\ \mathbf{y}^\dagger & 1\end{bmatrix} \succeq \mathbf{0}.\end{aligned}$$

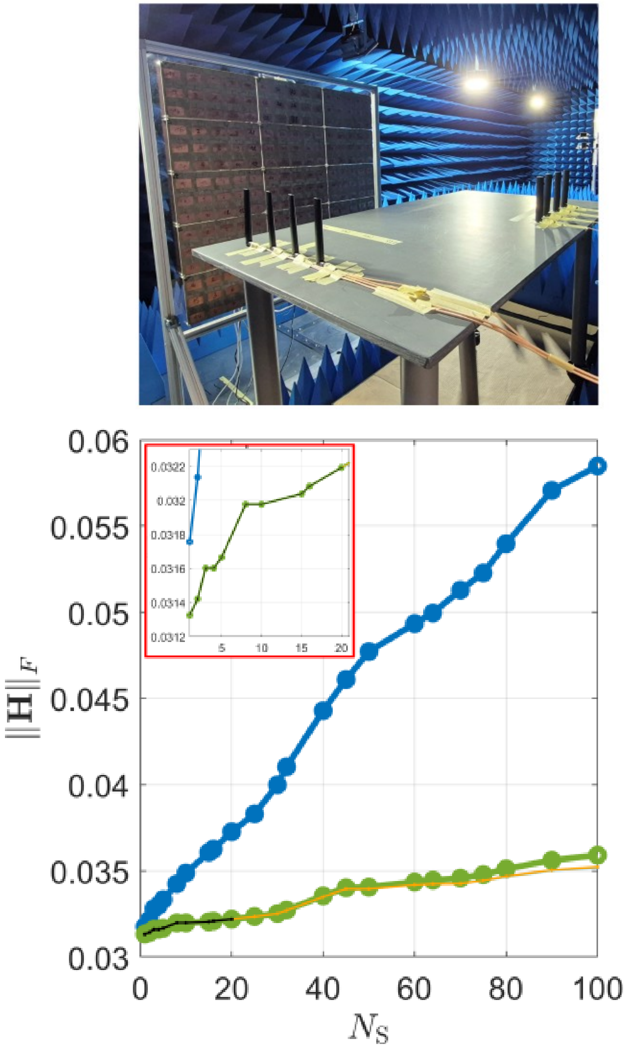
Any feasible point for QCQP is also feasible for SDP, hence $B^{\mathrm{Fro}}_{\mathrm{SDR}} \triangleq \mathrm{tr}(\mathbf{R}_0\,\check{\mathbf{Y}}) + 2\,\Re\left\{\mathbf{q}_0^\dagger\,\check{\mathbf{y}}\right\} + \tau_0$.

P. del Hougne, *arXiv:2602.14152* (2026)

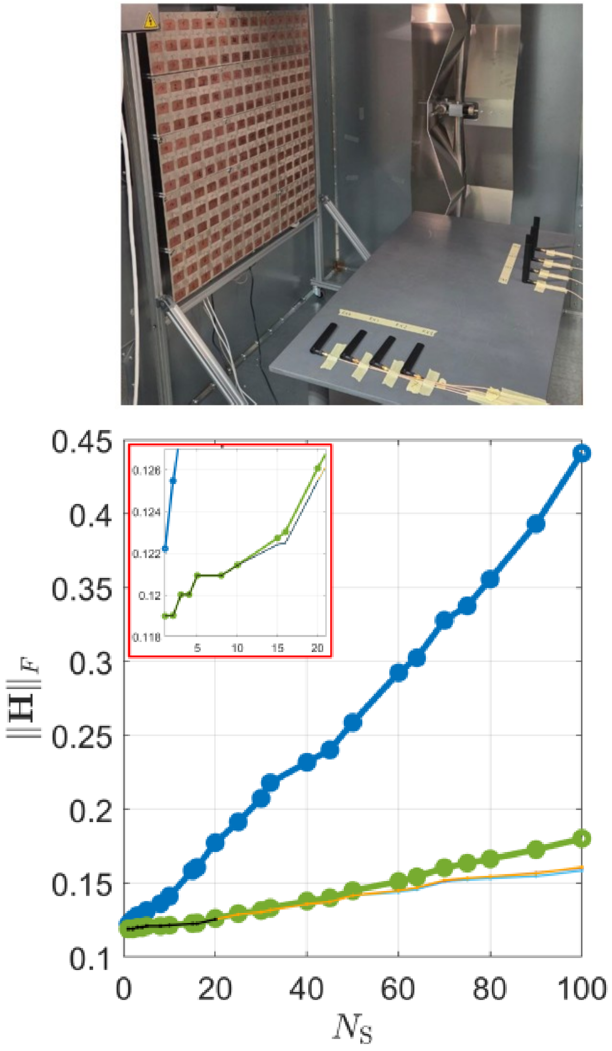
3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems

Bounds on MIMO aggregate channel gain

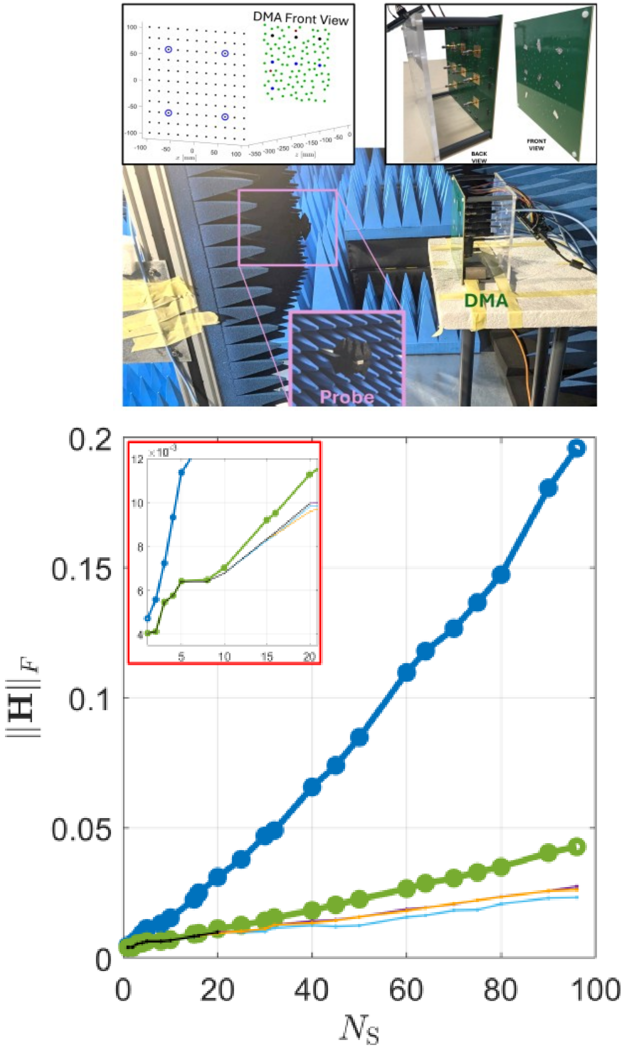
(a) RIS-Parametrized Free-Space MIMO Channel



(b) RIS-Parametrized Rich-Scattering MIMO Channel



(c) Multi-Feed-DMA Multi-User MIMO Channel



NIO
SDR
} **Bounds**

P-SDR
GA
CD
ES
} **Optimization Outcomes**

P. del Hougne, *arXiv:2602.14152* (2026)

3) Toward a prototype-aware EM information theory for reconfigurable microwave systems

Bounds on MIMO operator synthesis

Goal: Maximize operator-synthesis fidelity $F(\mathbf{H}(\mathbf{r}),\mathbf{H}_{\mathrm{des}}) \triangleq \dfrac{\left|\mathrm{tr}\left(\mathbf{H}_{\mathrm{des}}^{\dagger}\mathbf{H}(\mathbf{r})\right)\right|^2}{\|\mathbf{H}_{\mathrm{des}}\|_F^2\ \|\mathbf{H}(\mathbf{r})\|_F^2} \in [0,1].$

$$\boxed{\begin{aligned} &\mathbf{H}(\mathbf{r}) = \mathbf{H}_0 + \mathbf{A}\left(\mathbf{I}_{N_\mathrm{S}} - \boldsymbol{\Phi}(\mathbf{r})\boldsymbol{\Gamma}\right)^{-1}\boldsymbol{\Phi}(\mathbf{r})\mathbf{B} \\ &\boldsymbol{\Phi}(\mathbf{r}) = \mathrm{diag}(\mathbf{r}) \\ &\mathbf{r}(\mathbf{v}) = \alpha\mathbf{1} + (\beta-\alpha)\mathbf{v} \end{aligned}}$$

This objective is fractional-quadratic.

$$\boxed{\begin{aligned} \max_{\mathbf{y},\mathbf{Y}}\quad & \frac{\mathrm{tr}(\mathbf{R}_1\mathbf{Y}) + 2\,\Re\left\{\mathbf{q}_1^{\dagger}\mathbf{y}\right\} + \tau_1}{h\,\mathrm{tr}(\mathbf{R}_0\mathbf{Y}) + 2\,h\,\Re\left\{\mathbf{q}_0^{\dagger}\mathbf{y}\right\} + h\,\tau_0} = \frac{f_\mathrm{n}(\mathbf{y})}{f_\mathrm{d}(\mathbf{y})} \\ \text{s.t.}\quad & \mathrm{tr}(\mathbf{R}_{s,t}\mathbf{Y}) + \mathbf{y}^{\dagger}\mathbf{p}_{s,t} + \mathbf{q}_{s,t}^{\dagger}\mathbf{y} + \tau_{s,t} = 0, \\ & \quad \forall\, s\in\{1,\ldots,N_\mathrm{S}\}, \\ & \quad \forall\, t\in\{1,\ldots,N_\mathrm{T}\}, \\ & \mathrm{tr}(\mathbf{R}_{s,t}^{(i)}\mathbf{Y}) + \mathbf{y}^{\dagger}\mathbf{p}_{s,t}^{(i)} + \left(\mathbf{q}_{s,t}^{(i)}\right)^{\dagger}\mathbf{y} + \tau_{s,t}^{(i)} = 0, \\ & \quad \forall\, s\in\{1,\ldots,N_\mathrm{S}\}, \\ & \quad \forall\, t\in\{2,\ldots,N_\mathrm{T}\}, \\ & \quad \forall\, i\in\{1,2\}, \\ & \mathbf{Y} = \mathbf{y}\mathbf{y}^{\dagger}. \end{aligned}}$$

$$\xrightarrow[\substack{\text{where } \sigma = \frac{1}{f_\mathrm{d}(\mathbf{y})} \\ \text{(“Charnes–Cooper transformation”)}}]{\text{Introduce } \tilde{\mathbf{y}} = \sigma\mathbf{y} \text{ and } \tilde{\mathbf{Y}} = \sigma\mathbf{Y},}$$

$$\boxed{\begin{aligned} \max_{\tilde{\mathbf{y}},\tilde{\mathbf{Y}},\sigma}\quad & \mathrm{tr}(\mathbf{R}_1\tilde{\mathbf{Y}}) + 2\,\Re\left\{\mathbf{q}_1^{\dagger}\tilde{\mathbf{y}}\right\} + \tau_1\,\sigma \\ \text{s.t.}\quad & h\,\mathrm{tr}(\mathbf{R}_0\tilde{\mathbf{Y}}) + 2h\,\Re\left\{\mathbf{q}_0^{\dagger}\tilde{\mathbf{y}}\right\} + h\,\tau_0\,\sigma = 1, \\ & \mathrm{tr}(\mathbf{R}_{s,t}\tilde{\mathbf{Y}}) + \tilde{\mathbf{y}}^{\dagger}\mathbf{p}_{s,t} + \mathbf{q}_{s,t}^{\dagger}\tilde{\mathbf{y}} + \tau_{s,t}\,\sigma = 0, \\ & \quad \forall\, s\in\{1,\ldots,N_\mathrm{S}\}, \\ & \quad \forall\, t\in\{1,\ldots,N_\mathrm{T}\}, \\ & \mathrm{tr}(\mathbf{R}_{s,t}^{(i)}\tilde{\mathbf{Y}}) + \tilde{\mathbf{y}}^{\dagger}\mathbf{p}_{s,t}^{(i)} + \left(\mathbf{q}_{s,t}^{(i)}\right)^{\dagger}\tilde{\mathbf{y}} + \tau_{s,t}^{(i)}\,\sigma = 0, \\ & \quad \forall\, s\in\{1,\ldots,N_\mathrm{S}\}, \\ & \quad \forall\, t\in\{2,\ldots,N_\mathrm{T}\}, \\ & \quad \forall\, i\in\{1,2\}, \\ & \tilde{\mathbf{Y}} = \frac{1}{\sigma}\,\tilde{\mathbf{y}}\tilde{\mathbf{y}}^{\dagger}, \\ & \sigma > 0. \end{aligned}}$$

Then, the usual SDR procedure yields an SDP, and ultimately

$$B_{\mathrm{SDR}}^{\mathrm{Fid}} \triangleq \mathrm{tr}(\mathbf{R}_1\,\check{\tilde{\mathbf{Y}}}) + 2\,\Re\left\{\mathbf{q}_1^{\dagger}\,\check{\tilde{\mathbf{y}}}\right\} + \tau_1\,\check{\sigma}.$$

P. del Hougne, *arXiv:2602.14152* (2026)

3) Toward a prototype-aware EM information theory for reconfigurable microwave systems

Bounds on MIMO operator synthesis

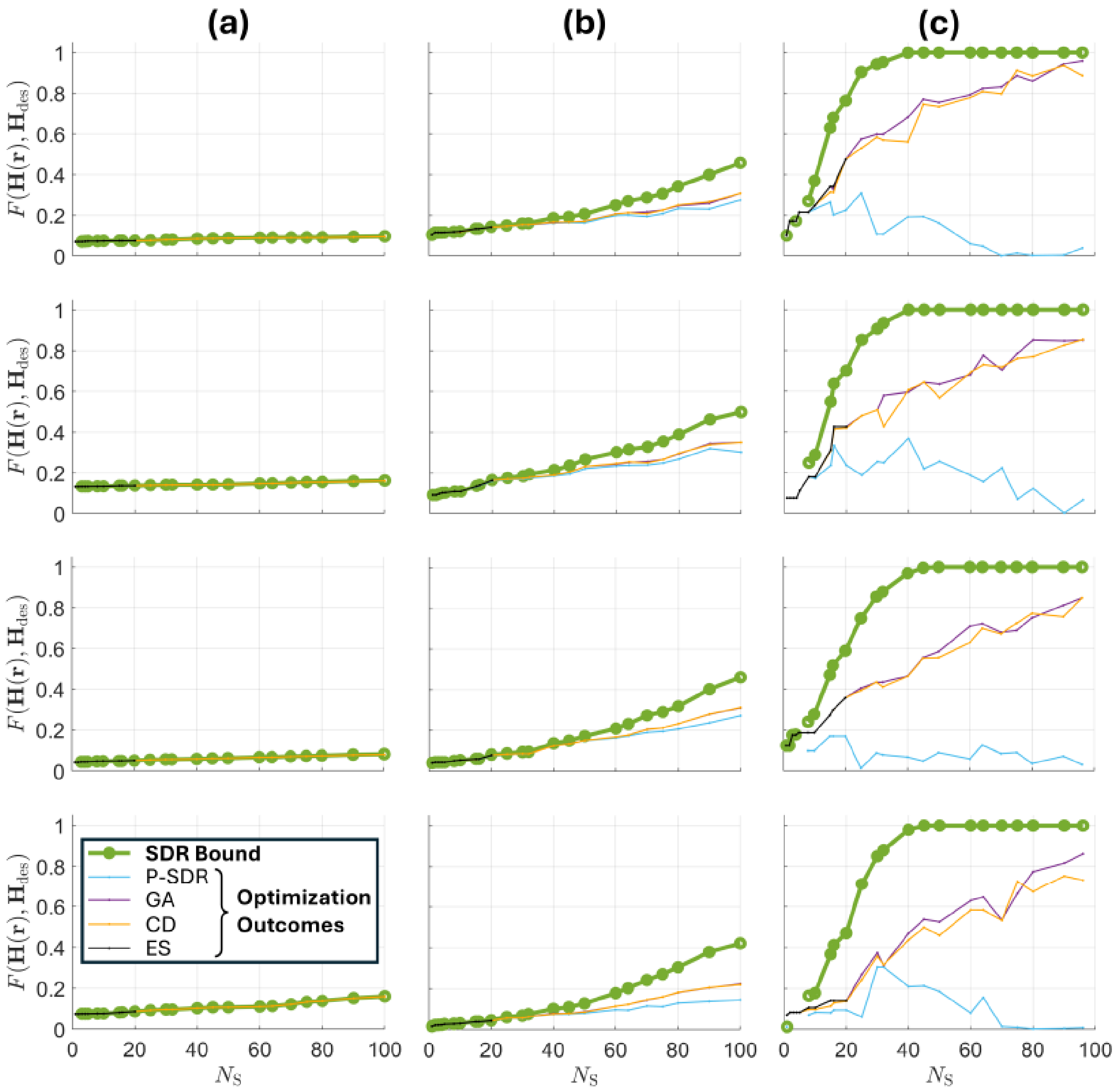
$\mathbf{H}_{\text{des}}$

$$\begin{bmatrix} 0.50+0.00\jmath & 0.00+0.00\jmath & 0.00+0.00\jmath & 0.00+0.00\jmath \\ 0.00+0.00\jmath & 0.50+0.00\jmath & 0.00+0.00\jmath & 0.00+0.00\jmath \\ 0.00+0.00\jmath & 0.00+0.00\jmath & 0.50+0.00\jmath & 0.00+0.00\jmath \\ 0.00+0.00\jmath & 0.00+0.00\jmath & 0.00+0.00\jmath & 0.50+0.00\jmath \end{bmatrix}$$

$$\begin{bmatrix} 0.00+0.00\jmath & 0.50+0.00\jmath & 0.00+0.00\jmath & 0.00+0.00\jmath \\ 0.00+0.00\jmath & 0.00+0.00\jmath & 0.50+0.00\jmath & 0.00+0.00\jmath \\ 0.00+0.00\jmath & 0.00+0.00\jmath & 0.00+0.00\jmath & 0.50+0.00\jmath \\ 0.50+0.00\jmath & 0.00+0.00\jmath & 0.00+0.00\jmath & 0.00+0.00\jmath \end{bmatrix}$$

$$\begin{bmatrix} 0.25+0.00\jmath & 0.25+0.00\jmath & 0.25+0.00\jmath & 0.25+0.00\jmath \\ 0.25+0.00\jmath & 0.00-0.25\jmath & -0.25+0.00\jmath & 0.00+0.25\jmath \\ 0.25+0.00\jmath & -0.25+0.00\jmath & 0.25+0.00\jmath & -0.25+0.00\jmath \\ 0.25+0.00\jmath & 0.00+0.25\jmath & -0.25+0.00\jmath & 0.00-0.25\jmath \end{bmatrix}$$

$$\begin{bmatrix} 0.08+0.15\jmath & 0.17-0.28\jmath & 0.22-0.06\jmath & 0.03-0.09\jmath \\ 0.08-0.21\jmath & 0.00+0.43\jmath & -0.11+0.28\jmath & -0.27+0.11\jmath \\ 0.02+0.15\jmath & -0.01-0.12\jmath & -0.10+0.06\jmath & -0.09+0.04\jmath \\ -0.04-0.06\jmath & -0.03+0.17\jmath & 0.37+0.38\jmath & -0.01-0.13\jmath \end{bmatrix}$$



P. del Hougne, *arXiv:2602.14152* (2026)

Toward an Electromagnetic Information Theory for Reconfigurable Microwave Systems

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1) **Multiport-network model formulation** for reconfigurable microwave systems

2) **Prototype-aware model calibration** for reconfigurable microwave systems

3) **Toward a prototype-aware EM information theory** for reconfigurable microwave systems
   - Bounds on multiplexing gain in backscatter MIMO systems
   - Bounds on information transfer via RIS-parametrized SISO channel
   - Bounds on MIMO operator synthesis