An Adaptive Algorithm for Fully Automated Extraction of Passive Parameterized Macromodels

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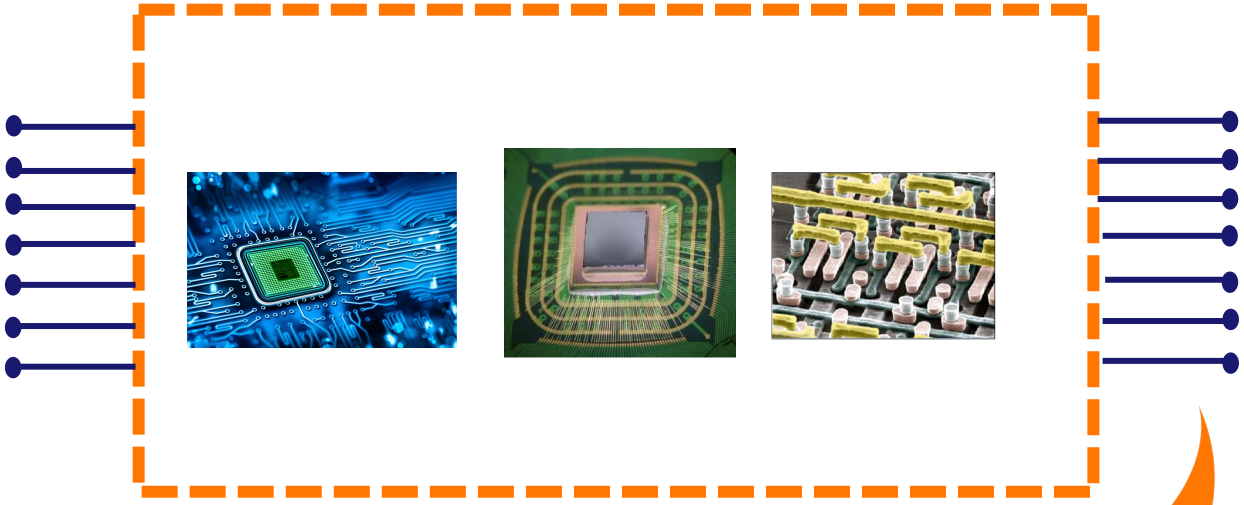
POLITECNICO DI TORINO

Background: Macromodeling

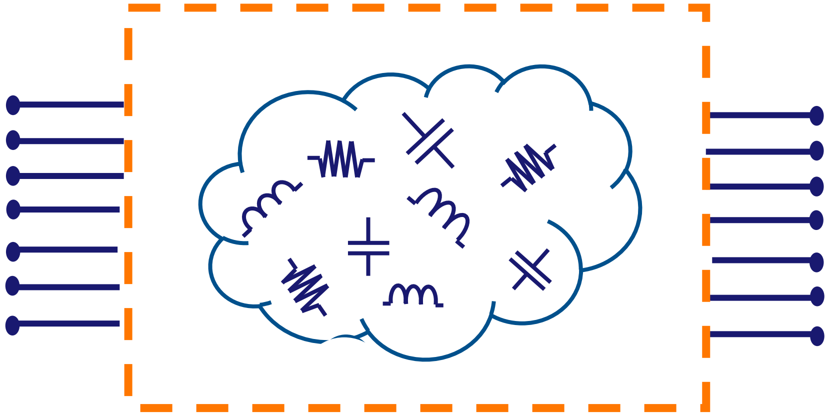


Complex EM structure

Field solutions = hours

Macromodel

Model solution = seconds

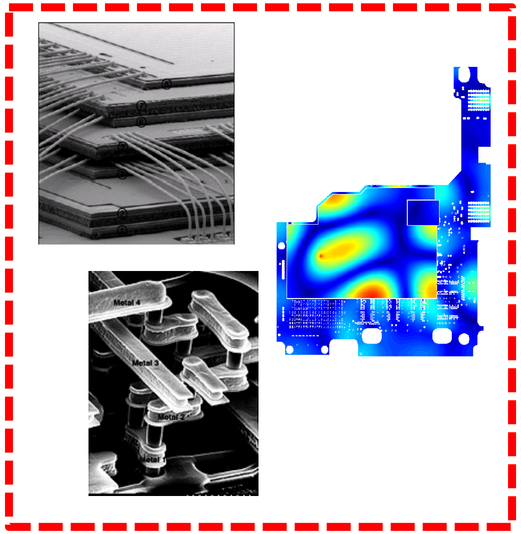


Advantages:

- Compact
- Accurate
- Reduced-order
- SPICE-compatible

- Reused many times
- Ideal for ***optimization***

Background: Data-driven macromodeling flow



Extraction

EM simulation

(Measurement)

IN

$$\breve{\mathbf{H}}_k = \breve{\mathbf{H}}(j\omega_k)$$
$$k = 1, \dots, K$$

.snp

Rational Fitting

Passivity Enforcement

$$\mathbf{H}(s) = \frac{\mathbf{N}(s)}{\mathrm{D}(s)}$$

State-space realization

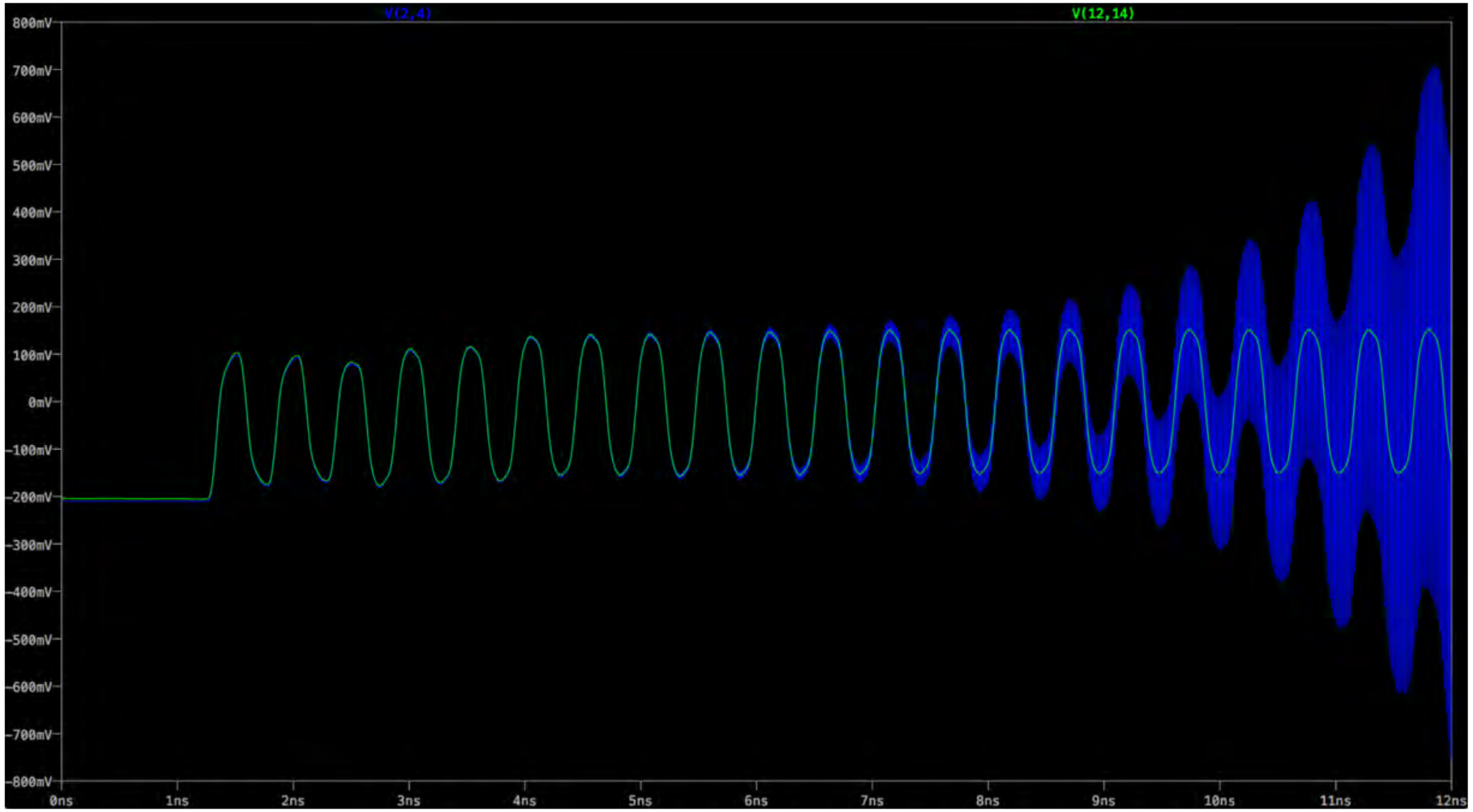
OUT

SPICE netlist

$$\dot{\boldsymbol{w}} = \boldsymbol{A}\boldsymbol{w} + \boldsymbol{B}\boldsymbol{u}$$
$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{w} + \boldsymbol{D}\boldsymbol{u}$$

Background: Macromodeling

Why a ***passive*** model?



A passive model is ***guaranteed stable***

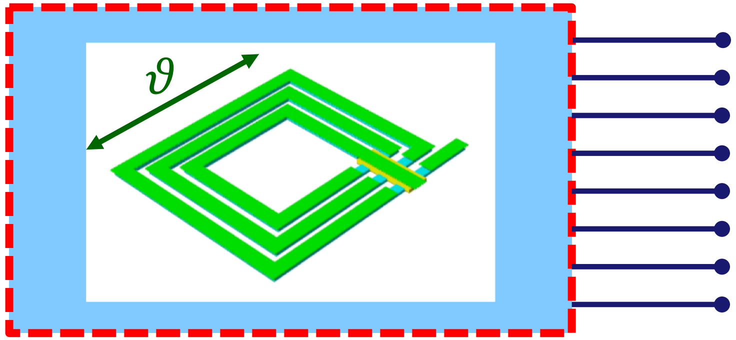
Background: Parameterized Macromodeling

Pre-layout, structure is not fixed but can be parameterized

Input: sets of S-params from field solver (as few as possible)

Objective: optimization, what-if, DOE, minimize solver runs

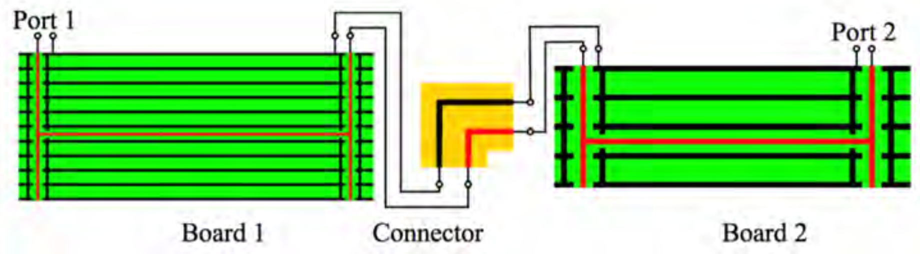
Requirement: parameterized model (SPICE if possible)



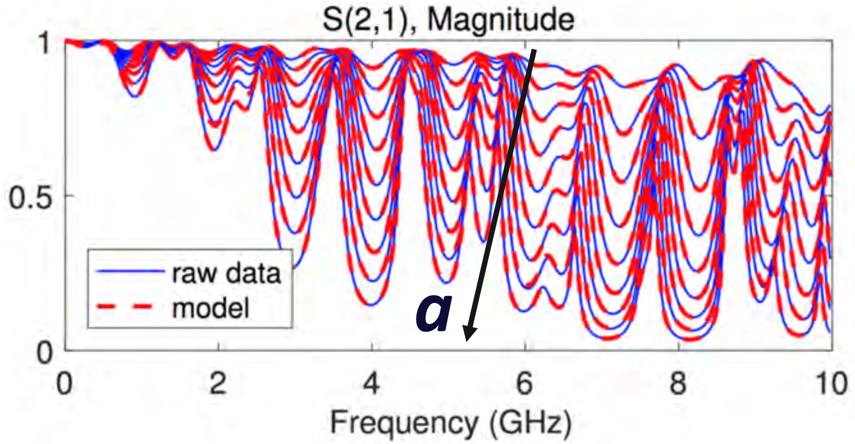
$$\begin{aligned} \dot{w} &= A(\vartheta)w + B(\vartheta)u \\ y &= C(\vartheta)w + D(\vartheta)u \end{aligned}$$

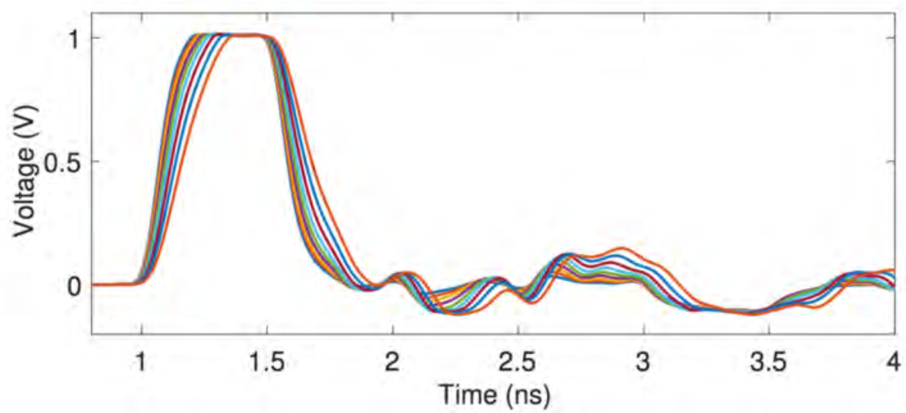
Parameterized Macromodeling: an example

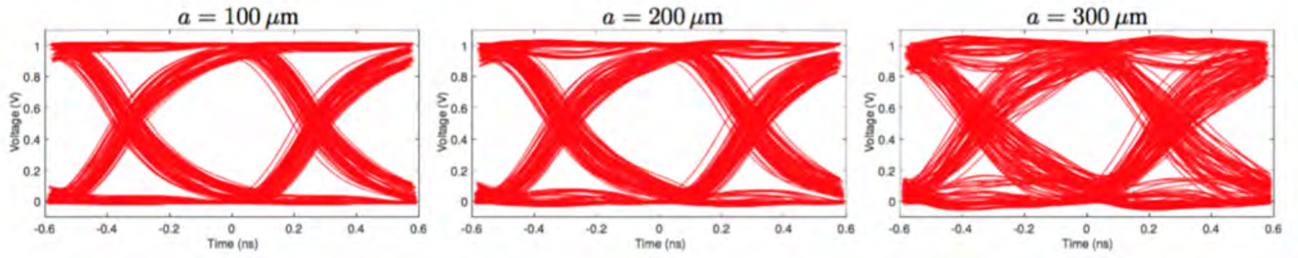
Multiboard PCB link
parameter: via radius a



[Courtesy: J. B. Preibisch and C. Schuster, Technische Universität Hamburg-Harburg, Hamburg, Germany]

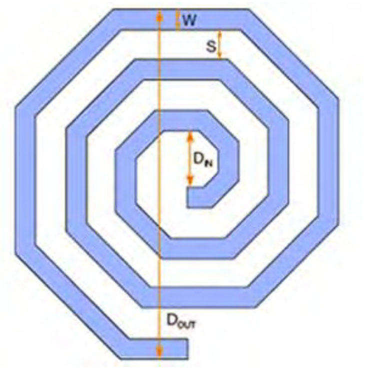






SPICE transient simulations
with NL terminations

Parameterized Macromodeling Flow



Parametric sweep

Simulation or Measurement

Multiple S-parameters

$$\breve{\mathbf{H}}_{k;m} = \breve{\mathbf{H}}(j\omega_k; \vartheta_m)$$
$$k = 1, \dots, K; \; m = 1, \dots, M$$

IN

.snp

Multivariate Rational Fitting

Stability, Passivity Enforcement

$$\mathbf{H}(s; \boldsymbol{\vartheta}) = \frac{\mathrm{N}(s; \boldsymbol{\vartheta})}{\mathrm{D}(s; \boldsymbol{\vartheta})}$$

Parameterized model

State-space realization

Circuit synthesis

OUT

SPICE netlist

$$\dot{\boldsymbol{w}} = \boldsymbol{A}(\boldsymbol{\vartheta})\boldsymbol{w} + \boldsymbol{B}(\boldsymbol{\vartheta})\boldsymbol{u}$$
$$\boldsymbol{y} = \boldsymbol{C}(\boldsymbol{\vartheta})\boldsymbol{w} + \boldsymbol{D}(\boldsymbol{\vartheta})\boldsymbol{u}$$

Fitting data with a parameterized model

$$\mathbf{H}(s_k; \boldsymbol{\vartheta}_m) \approx \breve{\mathbf{H}}(s_k; \boldsymbol{\vartheta}_m)$$

Model

Fitting

Frequency responses from field solver

Frequency sweep

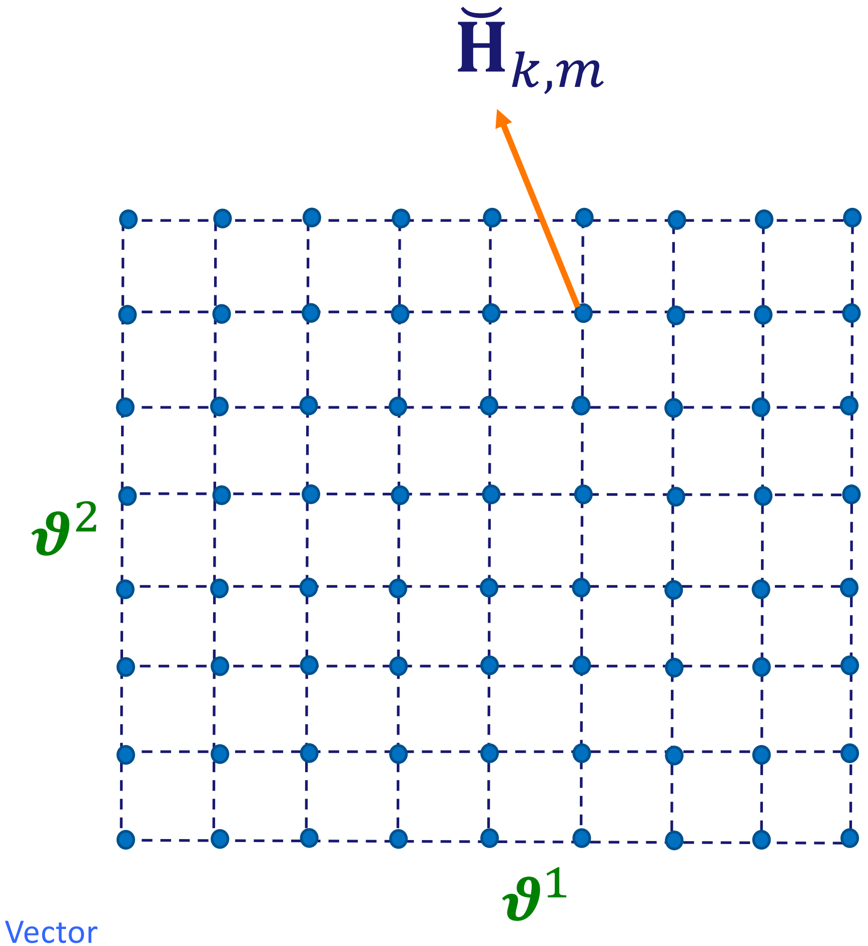
$s_k = j\,2\pi f_k$: $k = 1, \ldots, K$

Parameter sweep

$\boldsymbol{\vartheta}_m$: $m = 1, \ldots, M$

PROBLEMS

- Large number of simulations
- Expensive in terms of time and resources
- Not feasible for large number of parameters



D. Deschrijver, T. Dhaene and D. De Zutter, "Robust Parametric Macromodeling Using Multivariate Orthonormal Vector Fitting," in IEEE Trans. MTT, vol. 56, no. 7, pp. 1661-1667, July 2008

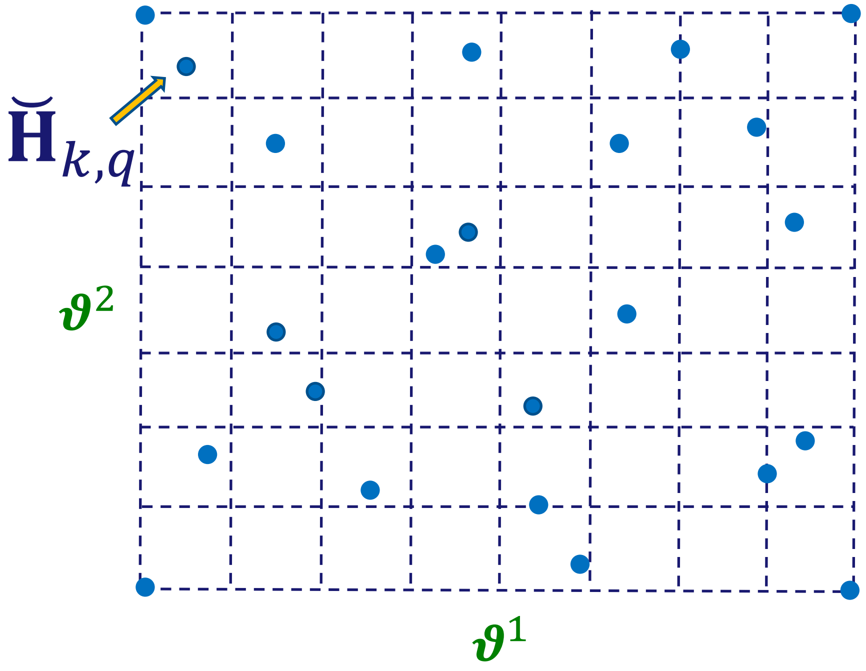
P. Triverio, S. Grivet-Talocia and M. S. Nakhla, "A Parameterized Macromodeling Strategy With Uniform Stability Test," in IEEE Transactions on Advanced Packaging, vol. 32, no. 1, pp. 205-215, Feb. 2009

Proposed Approach

Adaptive sampling scheme for point selection

GOALS:

- Minimal number Q of responses
- Optimal parameter configurations $\boldsymbol{\vartheta}_q$
- Final stable and passive model $\mathbf{H}(s;\boldsymbol{\vartheta})$



D. Deschrijver, K. Crombeq, H.M. Nguyen, T. Dhaene," Adaptive Sampling Algorithm for Macromodeling of Parameterized S-Parameter Responses," in IEEE Trans. MTT, vol. 59, no. 1, pp. 39-45, 2011

MODEL-DRIVEN

Adaptive Point Selection

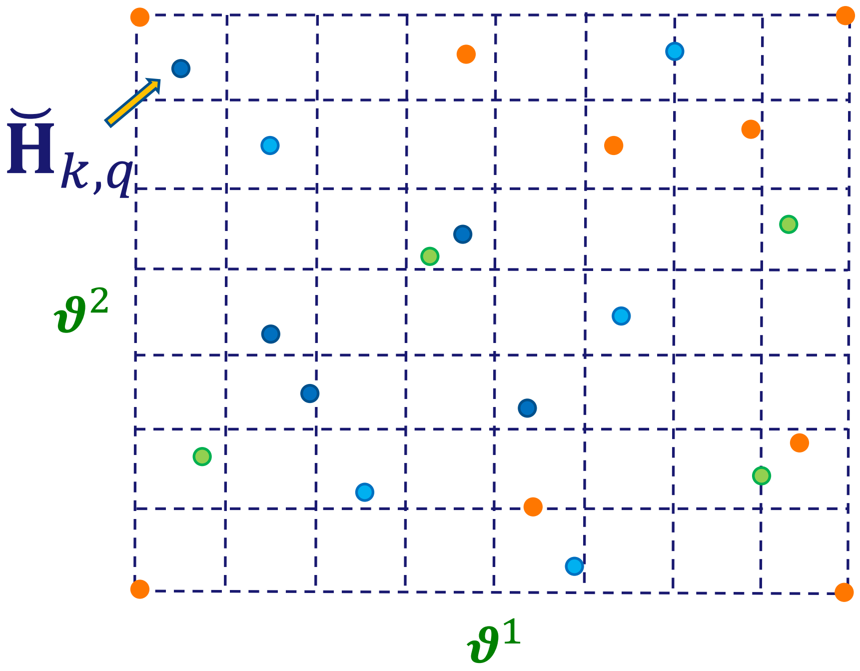
Initial set of points

Evaluate metrics:
- Exploration
- Model-Data error
- Passivity violations

New set of points

Model creation

Final passive model



Exploration

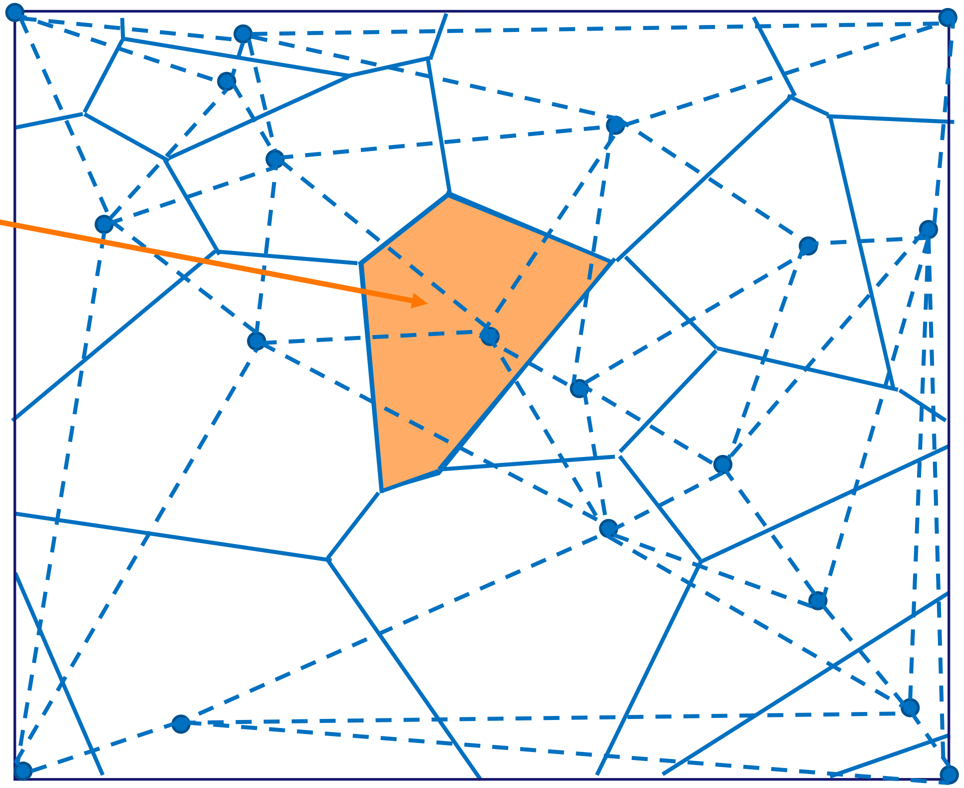
Identify regions with **fewer** data points

Volume of Voronoi cells $V(C_q)$

EXPLORATION METRIC

$$\Lambda_1(\boldsymbol{\vartheta}_q) = \frac{V(C_q)}{\sum_{q=1}^{Q} V(C_q)}$$

Voronoi Tessellation



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Model-Data error

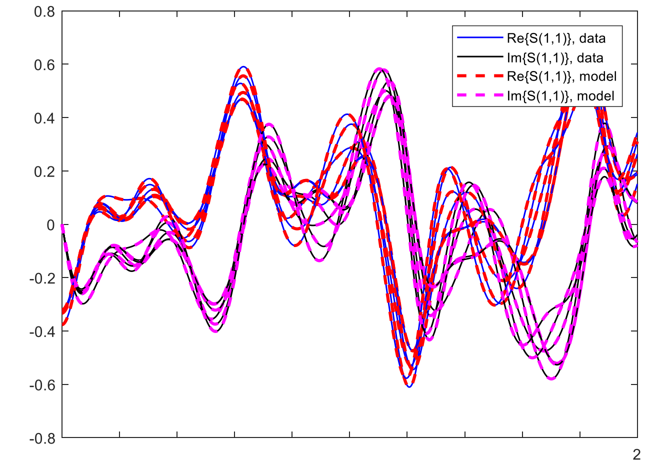
Identify regions where model is **less accurate**

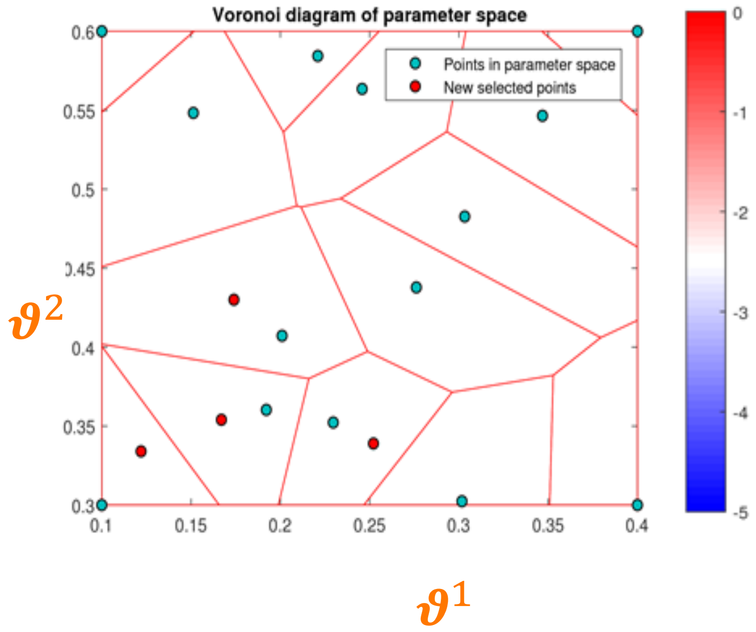
Error between data and intermediate model:

$$R^2(\boldsymbol{\vartheta}_q) = \frac{\sum_k \left\| \mathbf{H}(s_k, \boldsymbol{\vartheta}_q) - \breve{\mathbf{H}}(s_k, \boldsymbol{\vartheta}_q) \right\|^2}{\sum_k \left\| \breve{\mathbf{H}}(s_k, \boldsymbol{\vartheta}_q) \right\|^2}$$

MODEL ERROR METRIC

$$\Lambda_2(\boldsymbol{\vartheta}_q) = \frac{R(\boldsymbol{\vartheta}_q)}{\sum_{q=1}^{Q} R(\boldsymbol{\vartheta}_q)}$$





Passivity Violations

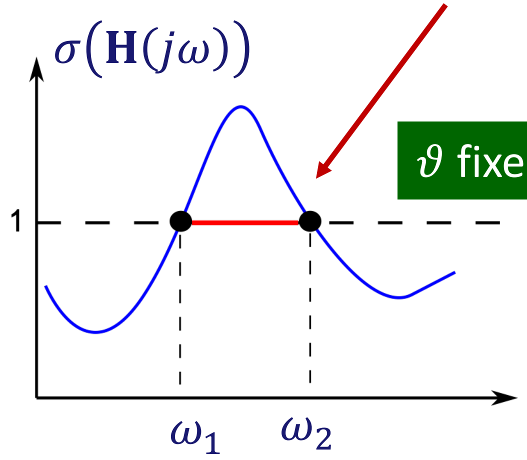
Passivity condition - Scattering

$$\sigma_{\max}\{\mathbf{H}(j\omega;\boldsymbol{\vartheta})\} \leq 1 \ \forall \omega, \boldsymbol{\vartheta}$$

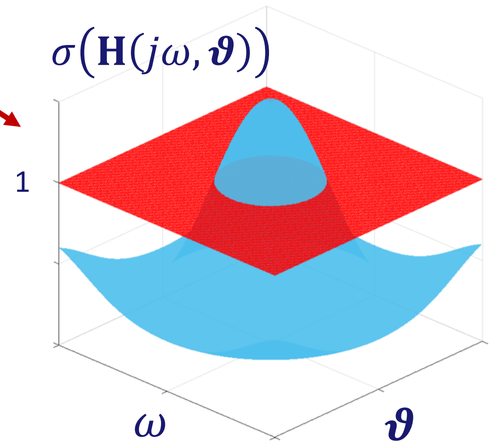
⇕

No energy gain

Passivity violations



ϑ fixed

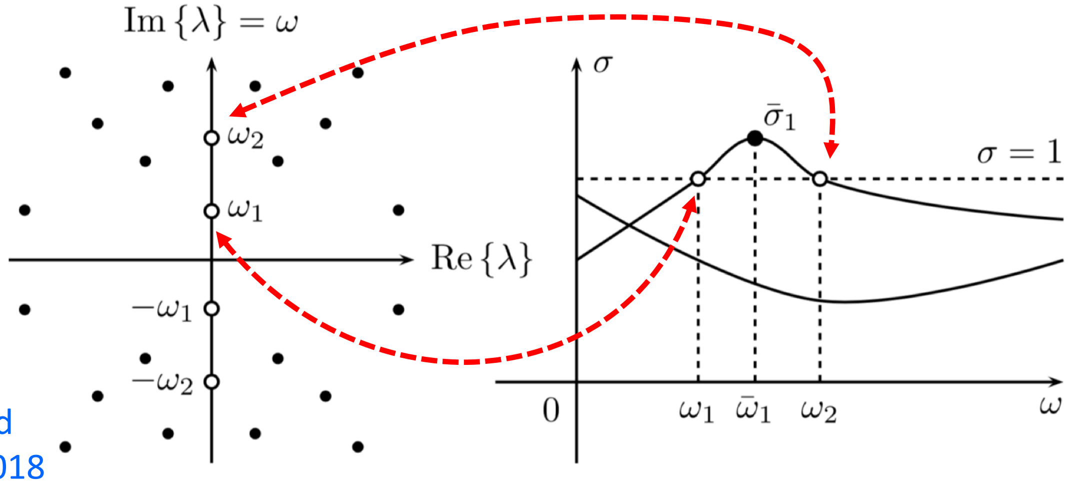


How to detect violations? → ***Hamiltonian Based approach***

$$\mathbf{H}(s) \longrightarrow \begin{cases} \mathbf{E}\,\dot{x} = \mathbf{A}\,x + \mathbf{B}u \\ y = \mathbf{C}\,x \end{cases}$$

ϑ fixed

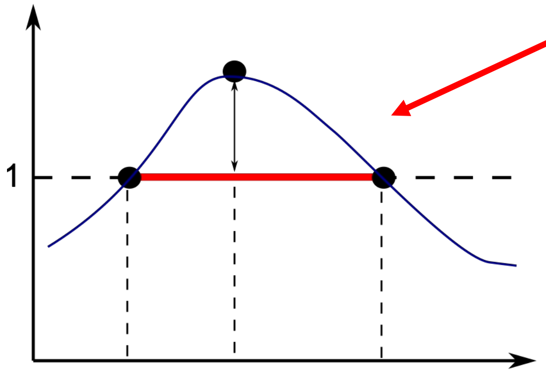
$$\mathcal{M} = \begin{pmatrix} \mathbf{A}^T & \mathbf{B}\mathbf{B}^T \\ -\mathbf{C}^T\mathbf{C} & -\mathbf{A}^T \end{pmatrix}, \quad \mathcal{K} = \begin{pmatrix} \mathbf{E} & \mathbf{0} \\ \mathbf{0} & \mathbf{E}^T \end{pmatrix}$$

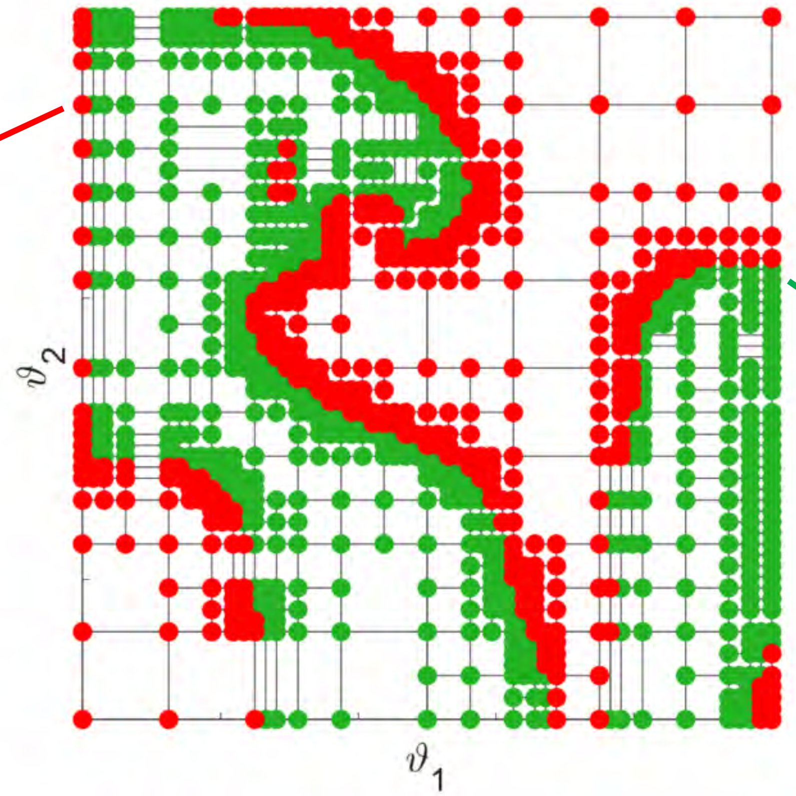


A. Zanco, S. Grivet-Talocia, T. Bradde, M. De Stefano, " Enforcing passivity of parameterized LTI macromodels via Hamiltonian-driven multivariate adaptive sampling", in IEEE TCAD, 2018

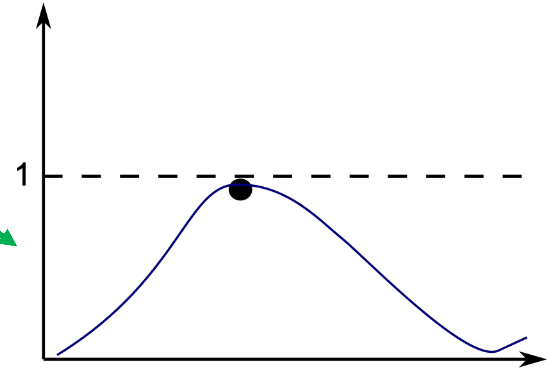
Passivity check

non-passive point





passive point



Finding all Passivity Violations of parameterized models

Why a passivity metric?

- In-band passivity violations → Bad model accuracy
- ***Predictive capabilities*** of Hamiltonian-based approach

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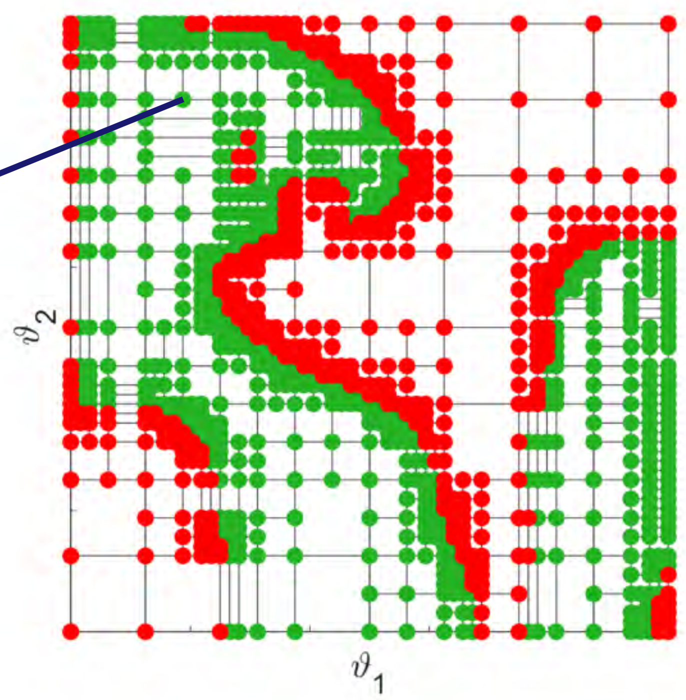
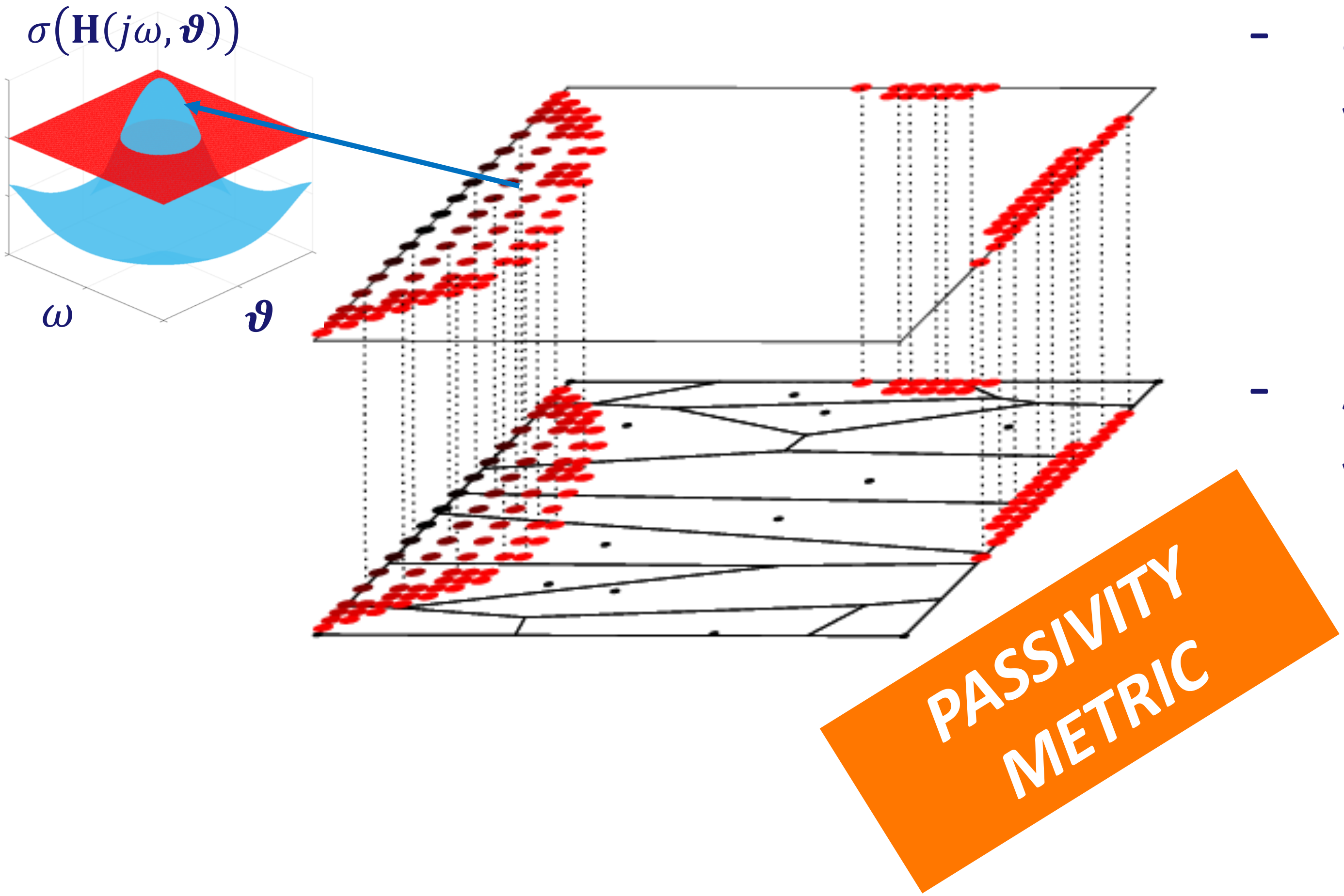
PROXY FOR MODEL-DATA ERROR

model responses, NOT simulation points



Passivity Violations Metric



- Superimpose in-band passivity violations to Voronoi cells

$$S(\boldsymbol{\vartheta}_q) = \ max_{\omega\in\Omega}\sigma_{max}(\mathbf{H}(s;\boldsymbol{\vartheta}))$$

- Associate to each cell the largest violation

$$\Lambda_3(\boldsymbol{\vartheta}_q) = \frac{S(\boldsymbol{\vartheta}_q)}{\sum_{q=1}^{Q} S(\boldsymbol{\vartheta}_q)}$$

E. Fevola, A. Zanco, S. Grivet-Talocia, T. Bradde, M. De Stefano, "An Adaptive Sampling Process for Automated Multivariate Modeling Based on Hamiltonian-Based Passivity Metric," to appear in IEEE Trans. CPMT, 2019

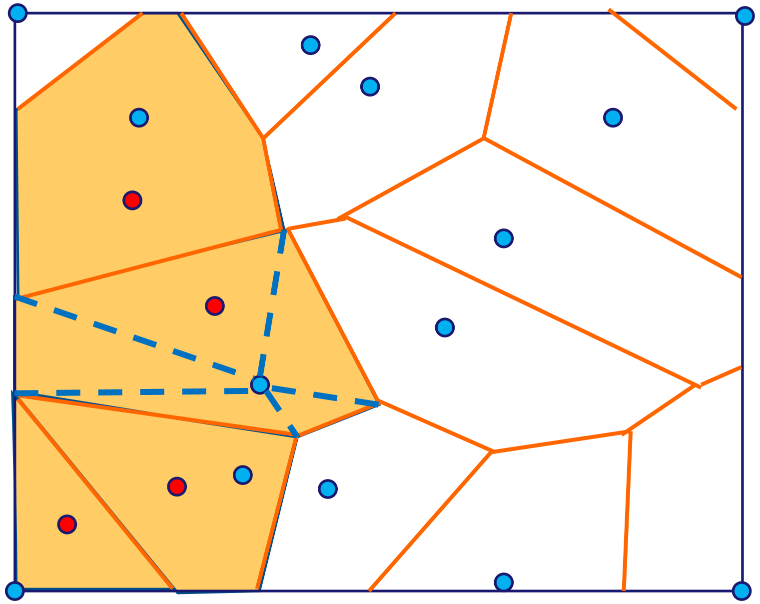
Adaptive Selection of New Points

Final metric

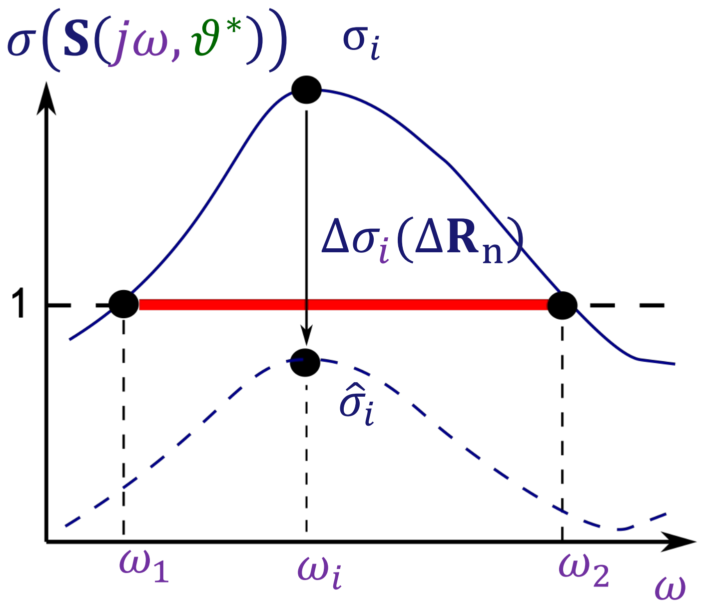
$$\Lambda(\boldsymbol{\vartheta}_q) = w'\Lambda_1(\boldsymbol{\vartheta}_q) + w''\Lambda_2(\boldsymbol{\vartheta}_q) + w'''\Lambda_3(\boldsymbol{\vartheta}_q)$$

weights to tune metrics

- Rank the **Voronoi cells** on the basis of the final metric
- Take 1/3 of cells with **higher ranking**
- Place the new points inside these cells



Passivity Enforcement



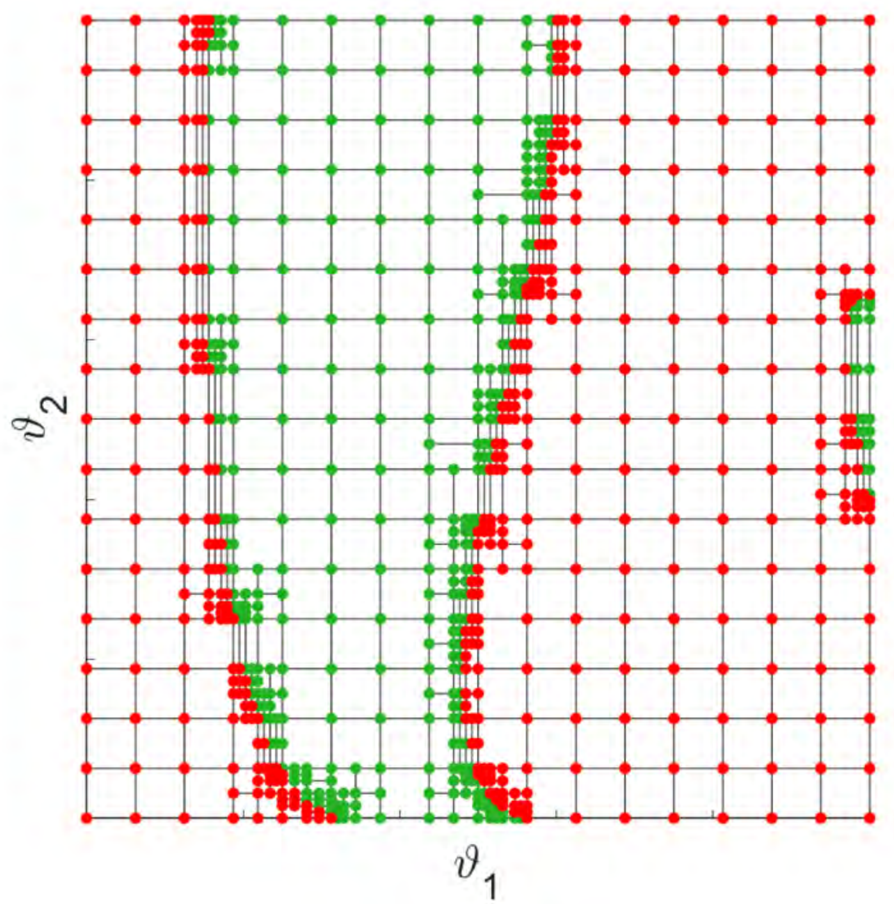
Why do we need an enforcement?

↓

out - of band violations

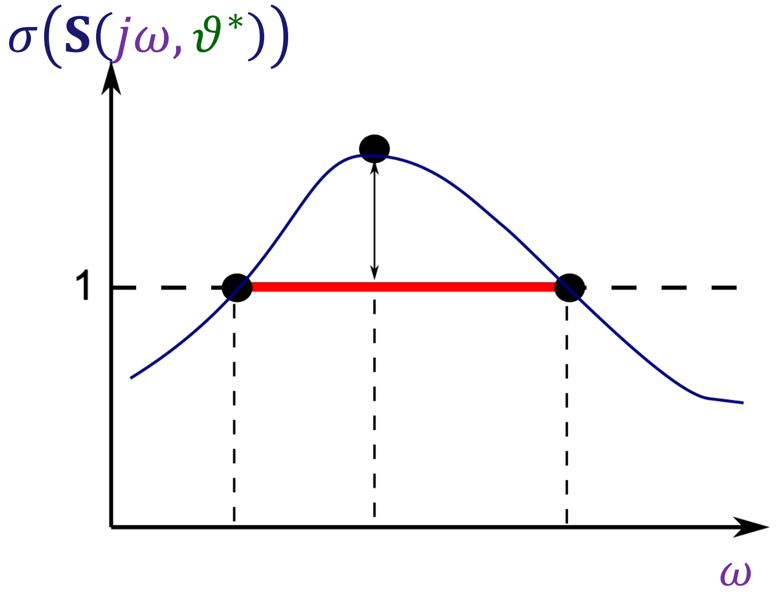
Perturbation of model coefficients $(\Delta\mathbf{R}_n)$

Iterative process



S. Grivet-Talocia, "A Perturbation Scheme for Passivity Verification and Enforcement of Parameterized Macromodels," *IEEE Transactions on Components, Packaging and Manufacturing Technology, 2017*

Passivity Enforcement



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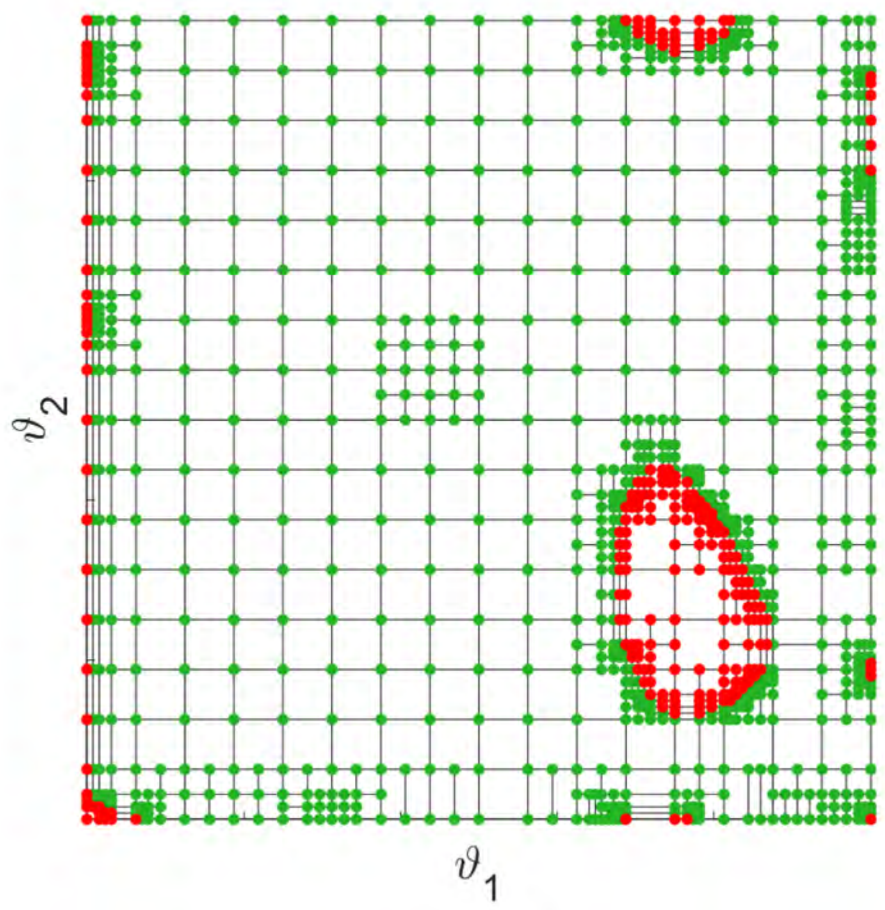

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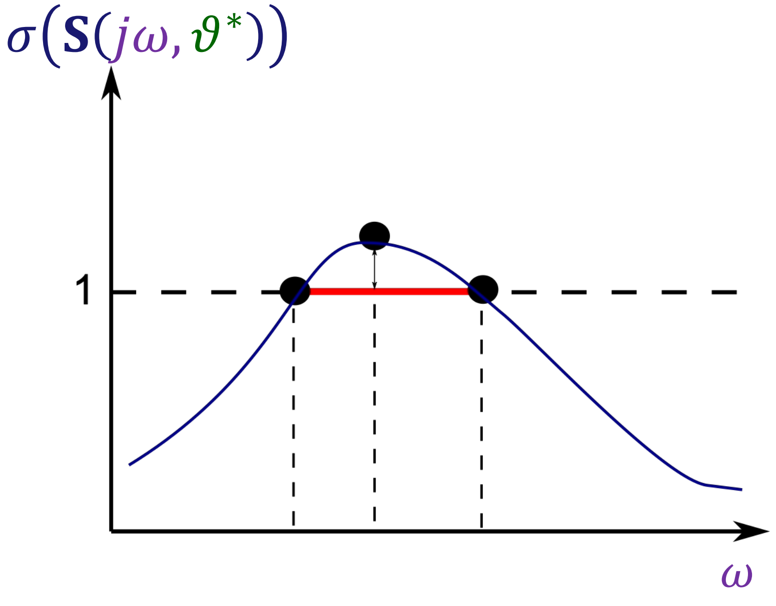

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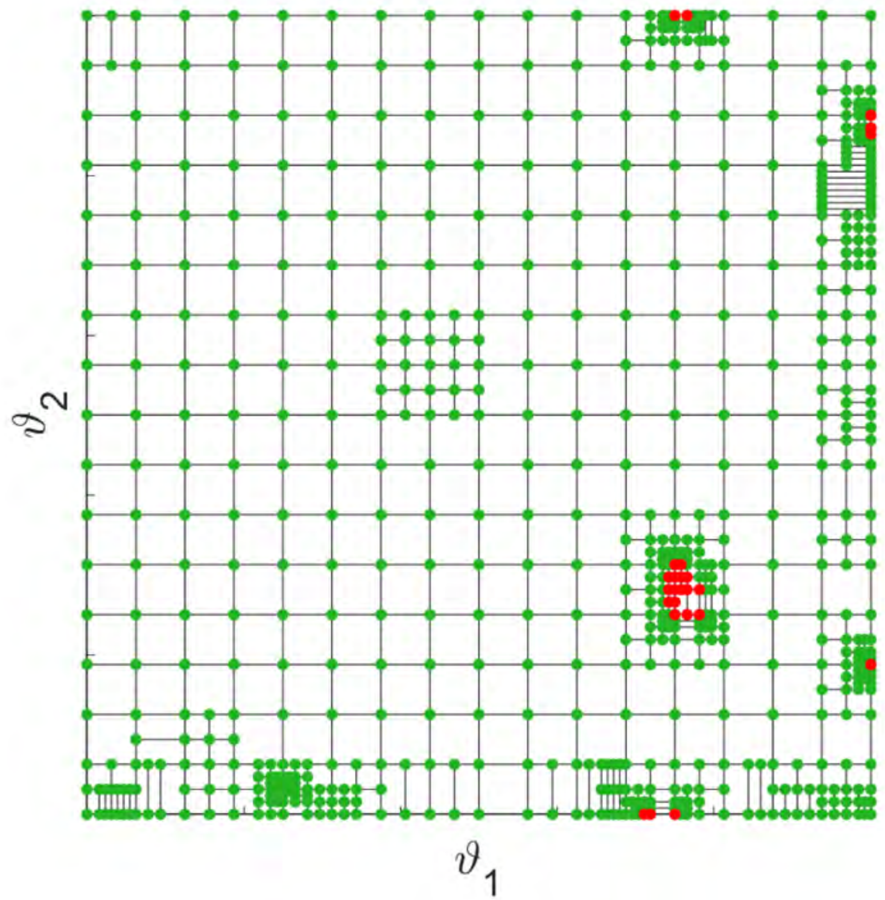

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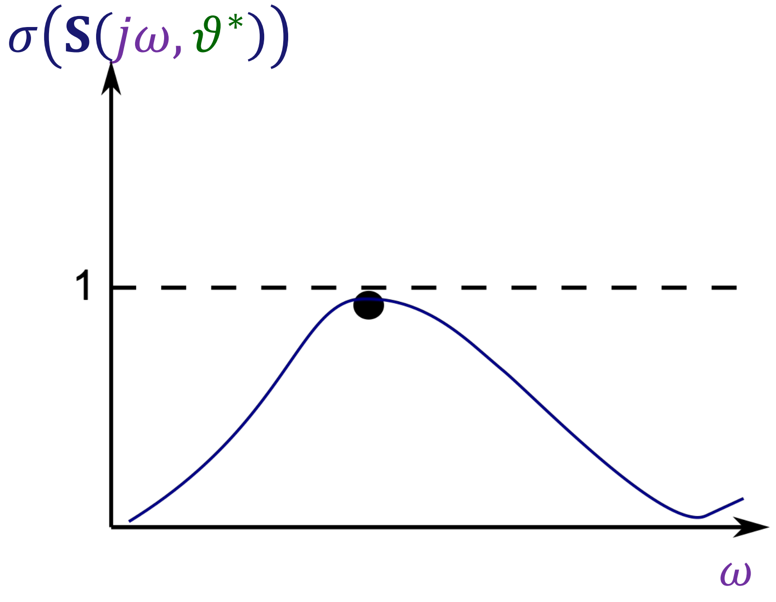
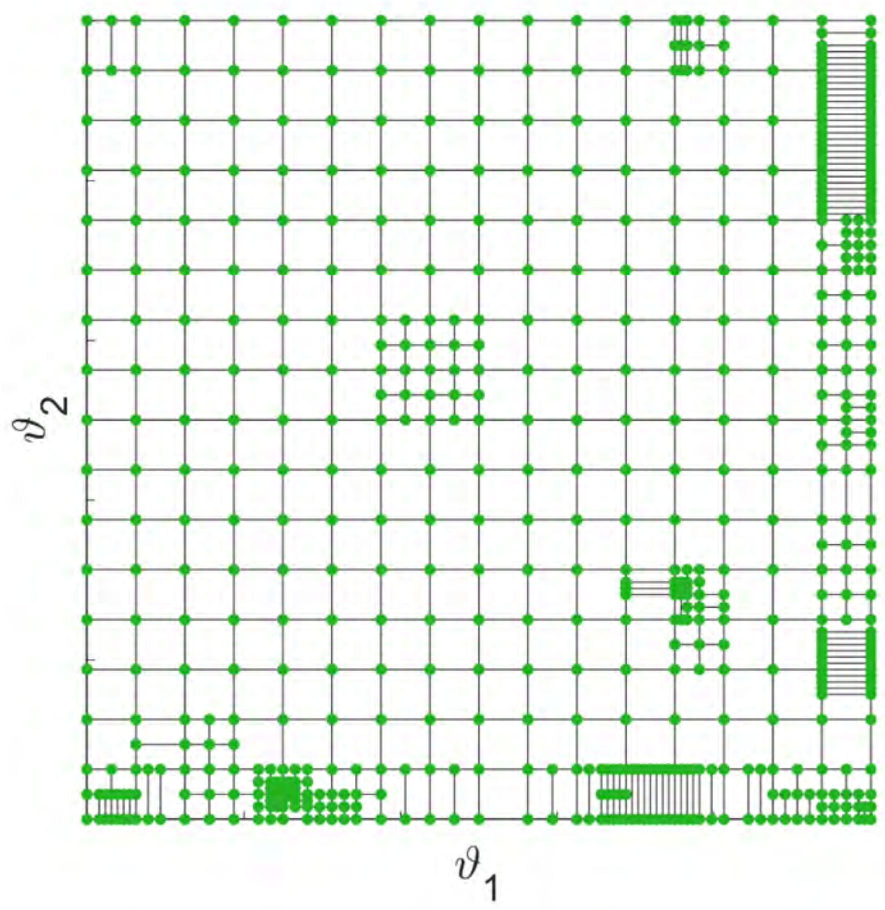


Iterative process



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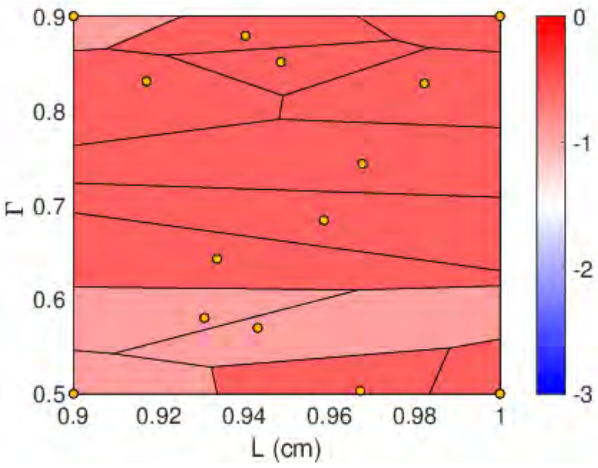
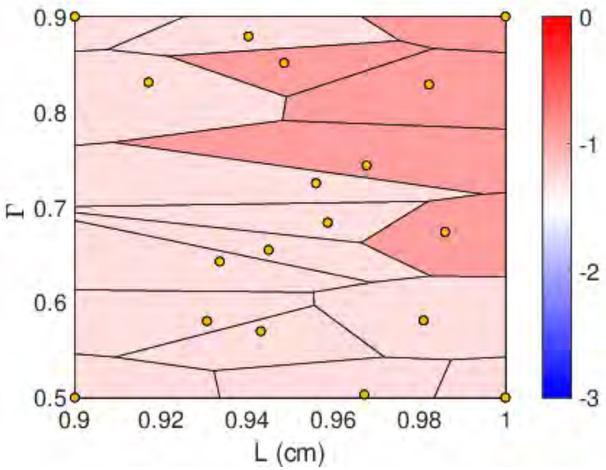
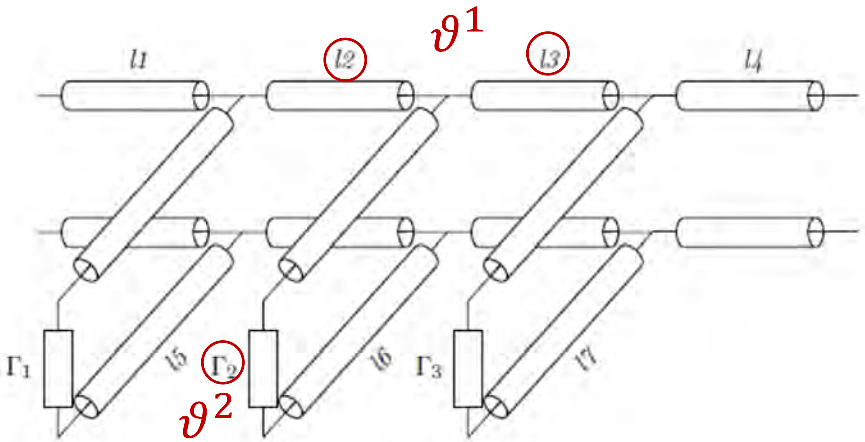
Examples – Transmission Line Network

Iteration 0

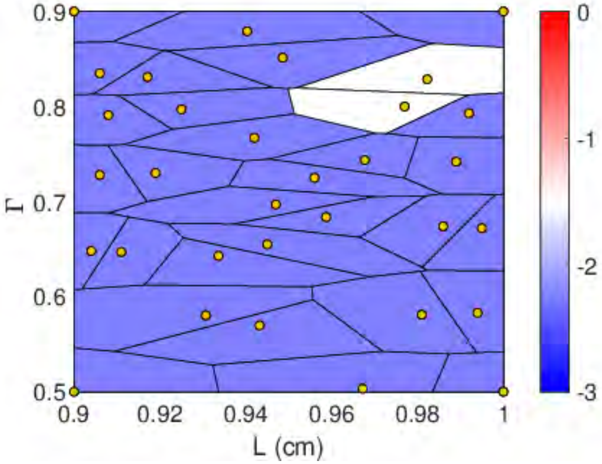


Iteration 2

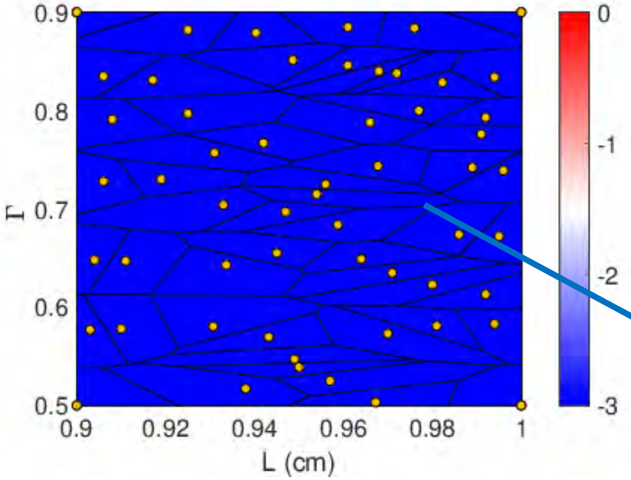




Iteration 3



Iteration 5



Parameters:

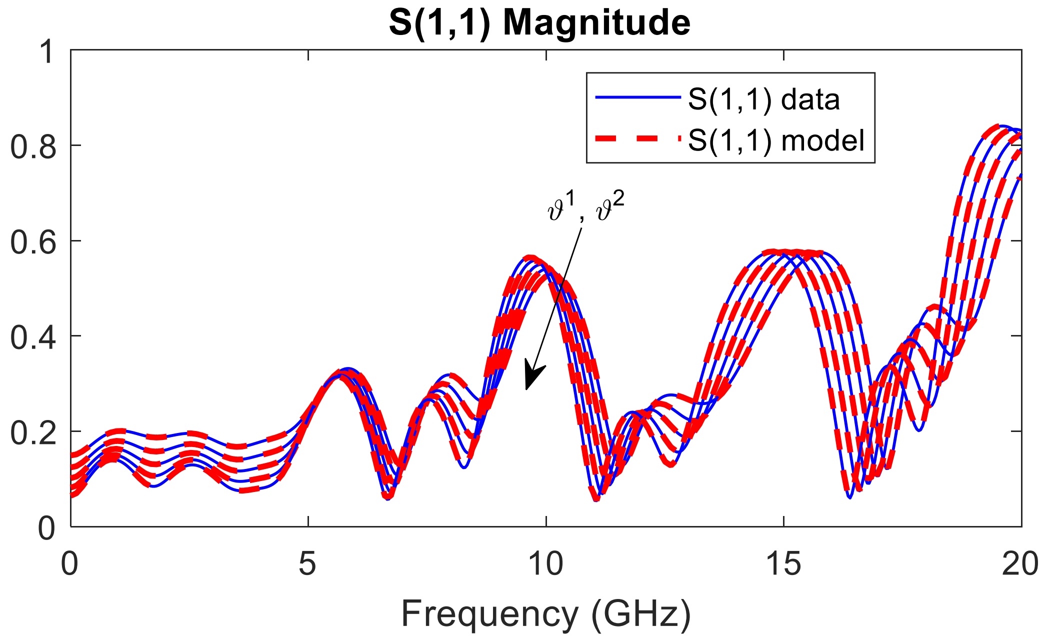
$\vartheta^1 = L \in [9 \; - 10]$ mm

$\vartheta^2 = \; \Gamma \; \in [0.5 \; - 0.9]$

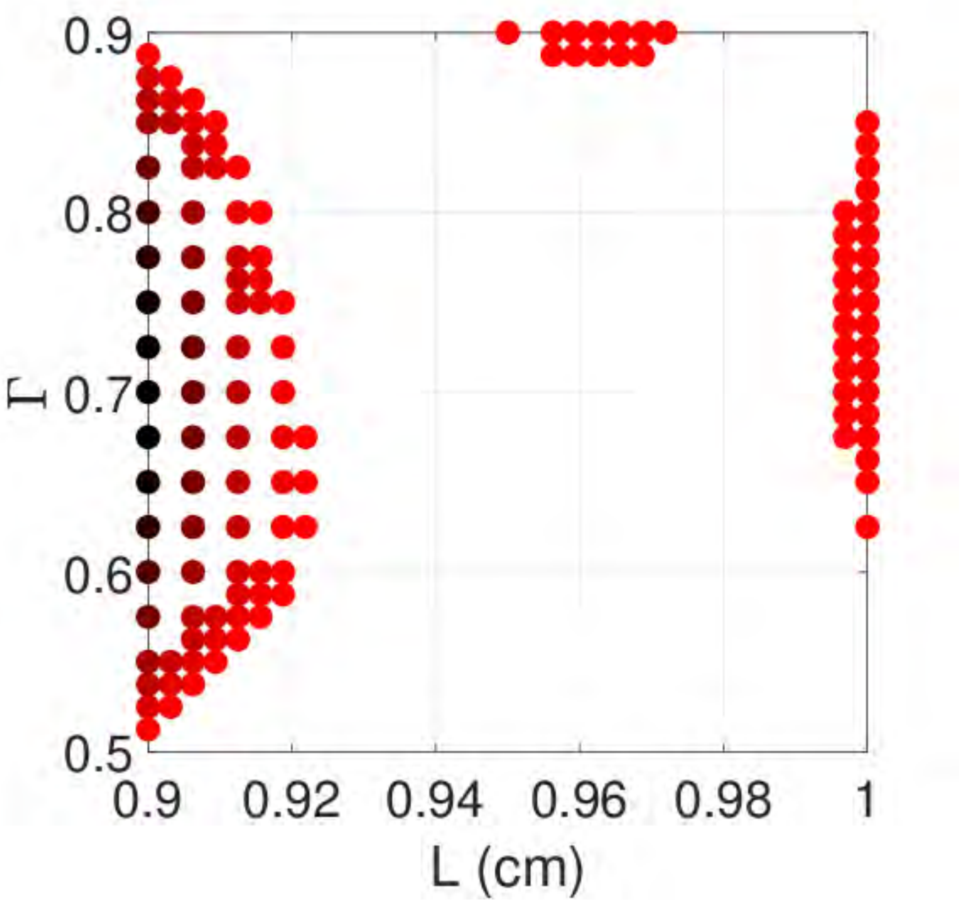
Q = 56 points

Examples – Transmission Line Network

Model vs data responses

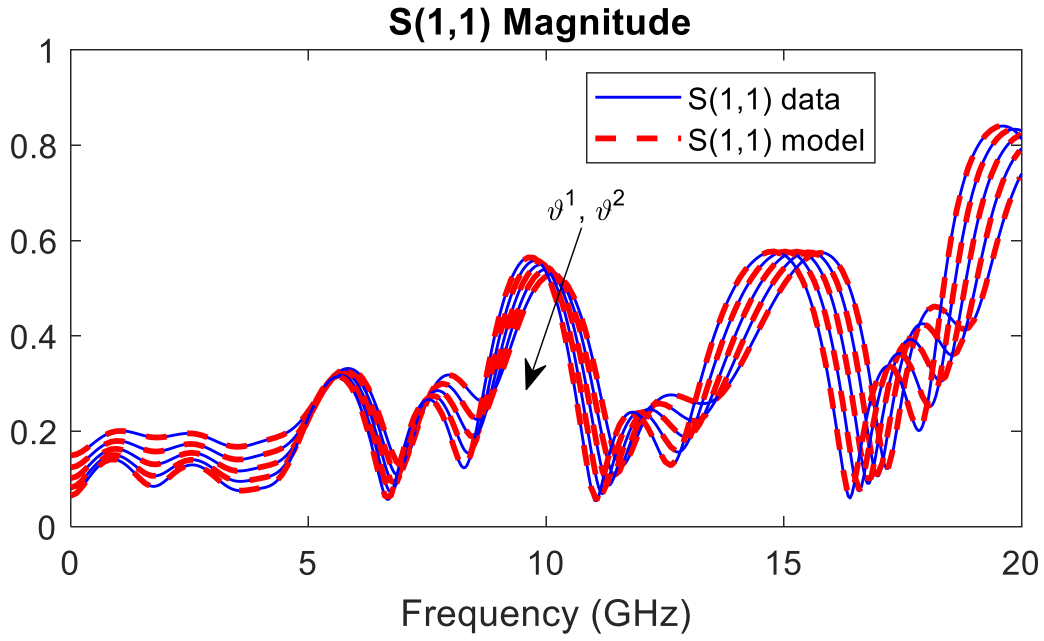


Passivity metric – Iteration 1

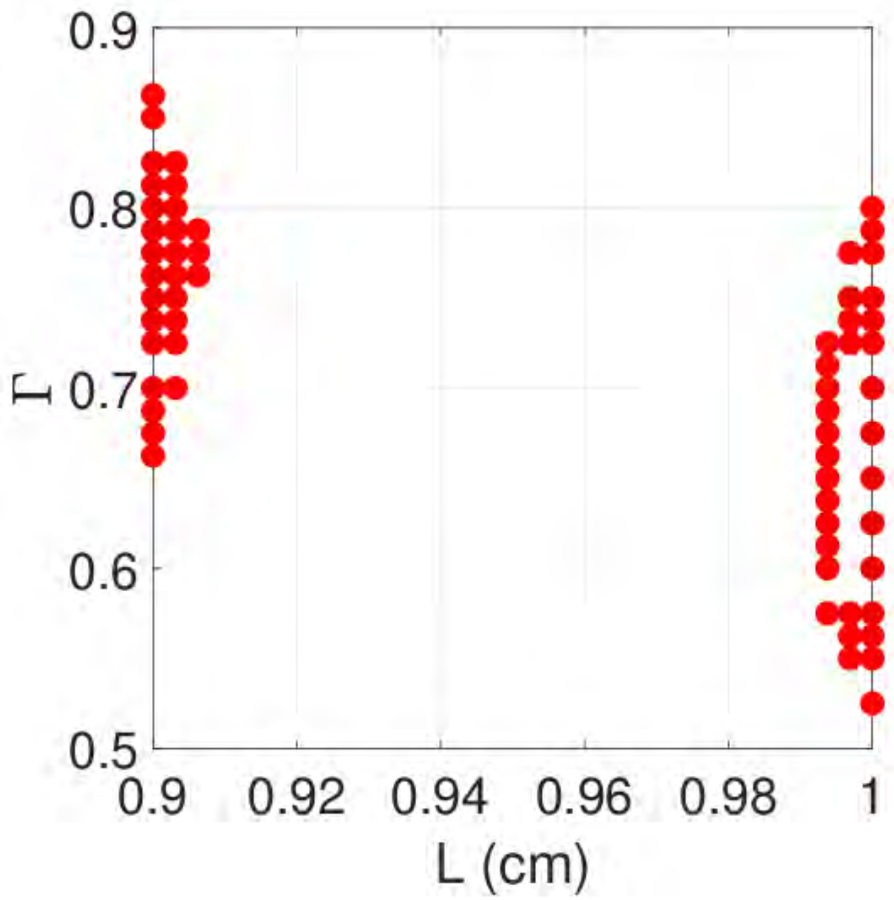


Examples – Transmission Line Network

Model vs data responses

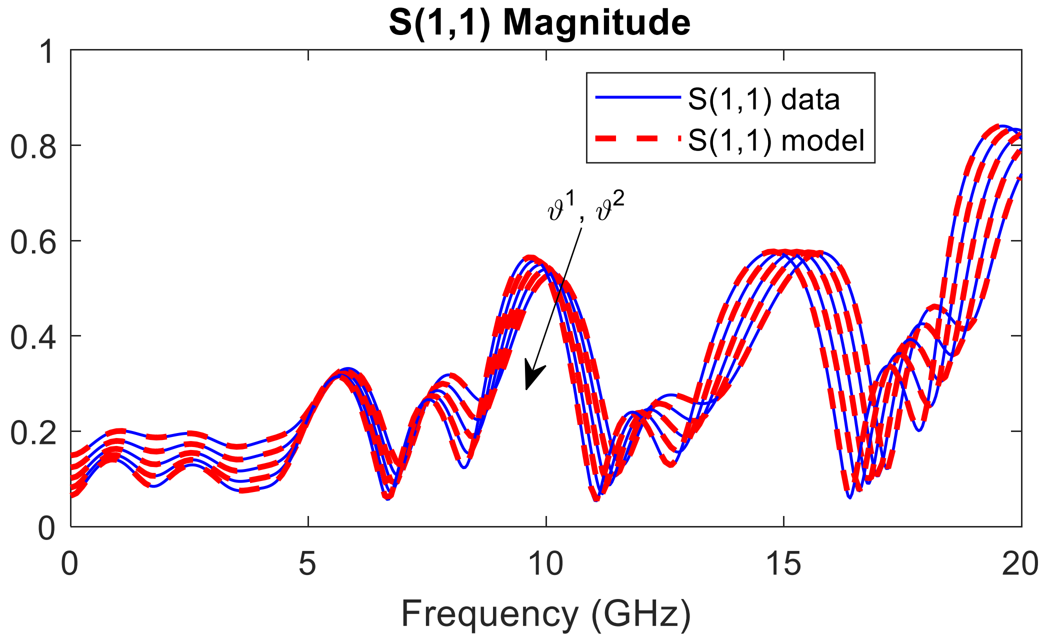


Passivity metric – Iteration 2

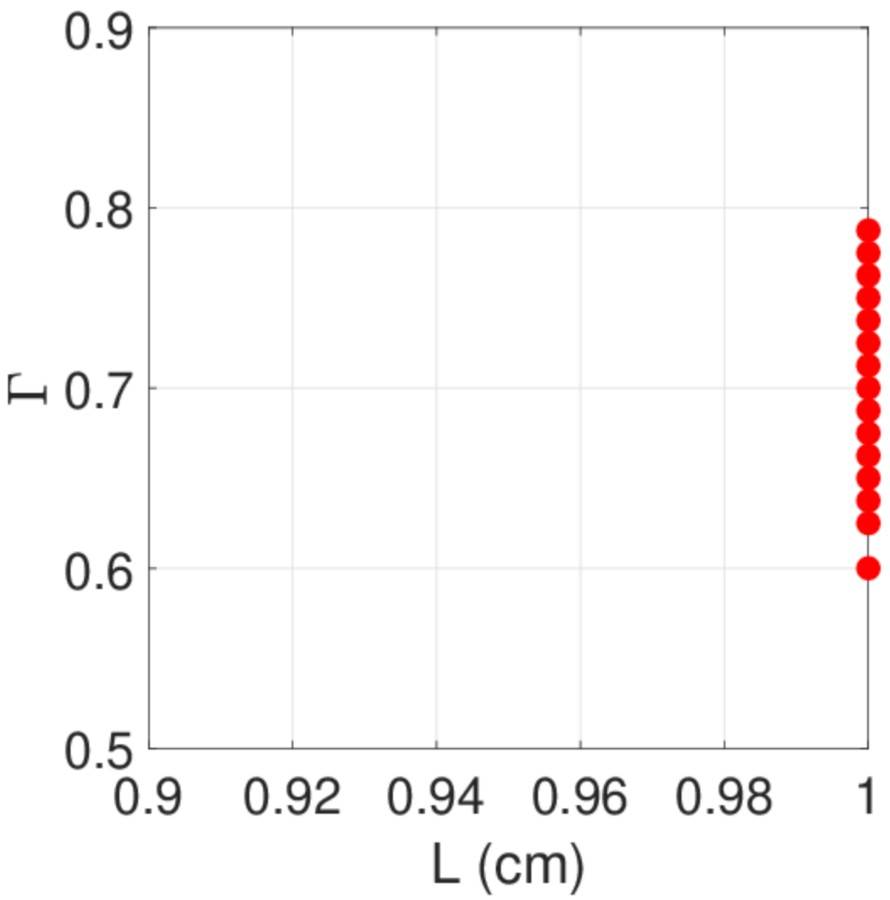


Examples – Transmission Line Network

Model vs data responses

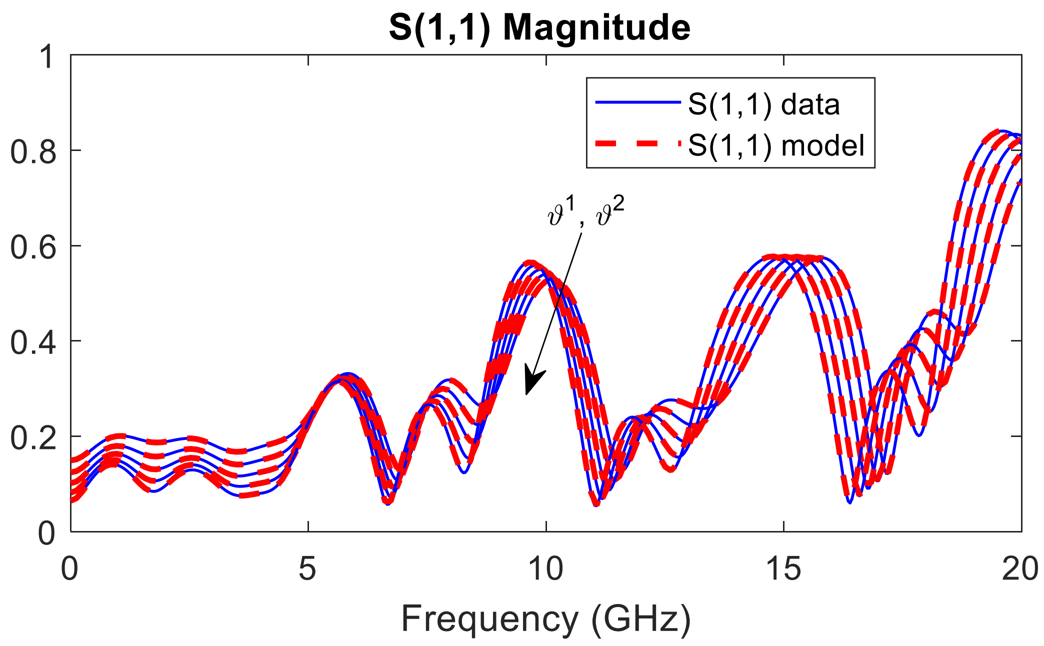


Passivity metric – Iteration 3

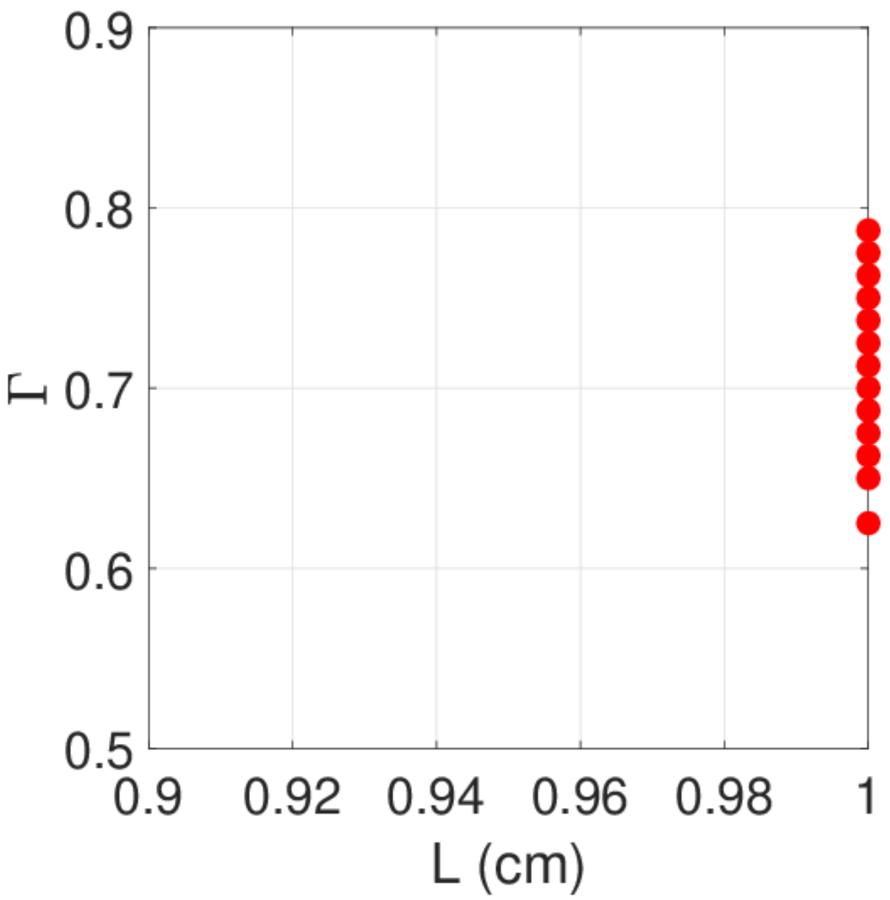


Examples – Transmission Line Network

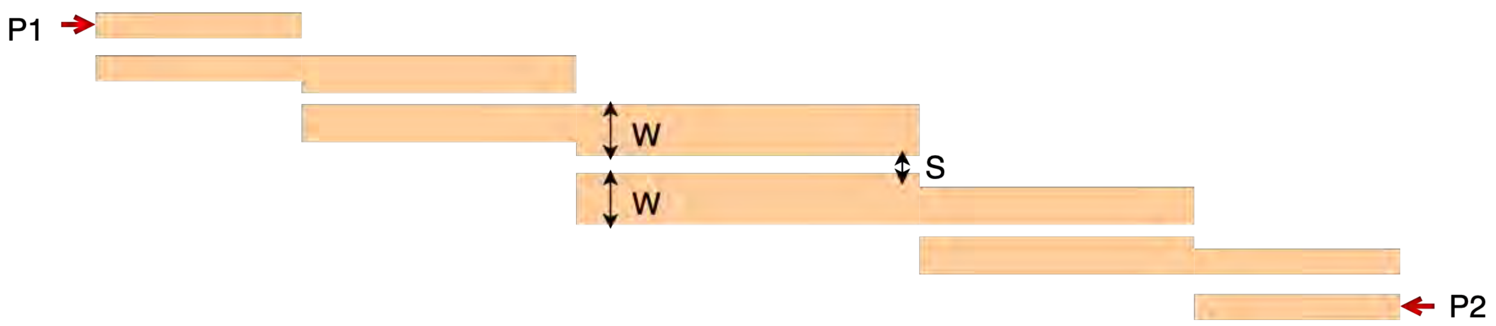
Model vs data responses



Passivity metric – Iteration 4



Examples – Coupled Line Bandpass filter



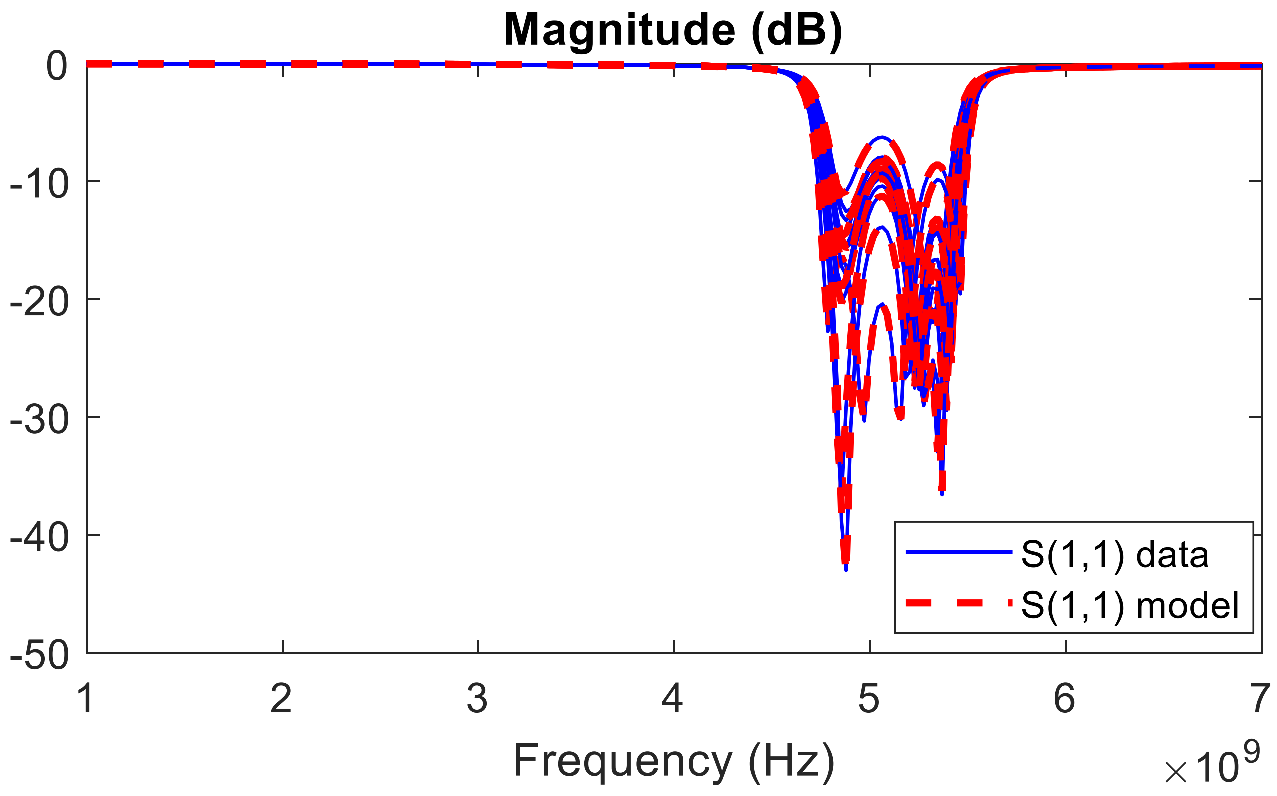
Parameters:

$\vartheta^1 = \mathrm{W} \in [25 - 35]$ mil

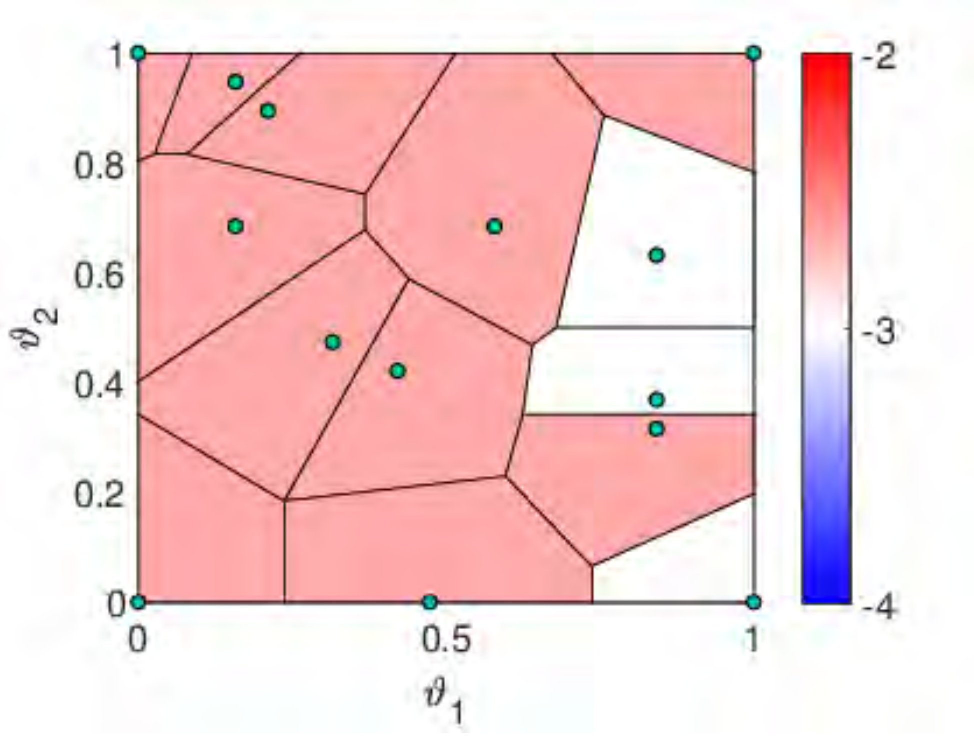
$\vartheta^2 = \mathrm{S} \in [25 - 35]$ mil

Examples – Coupled Line Bandpass Filter

Model vs data responses

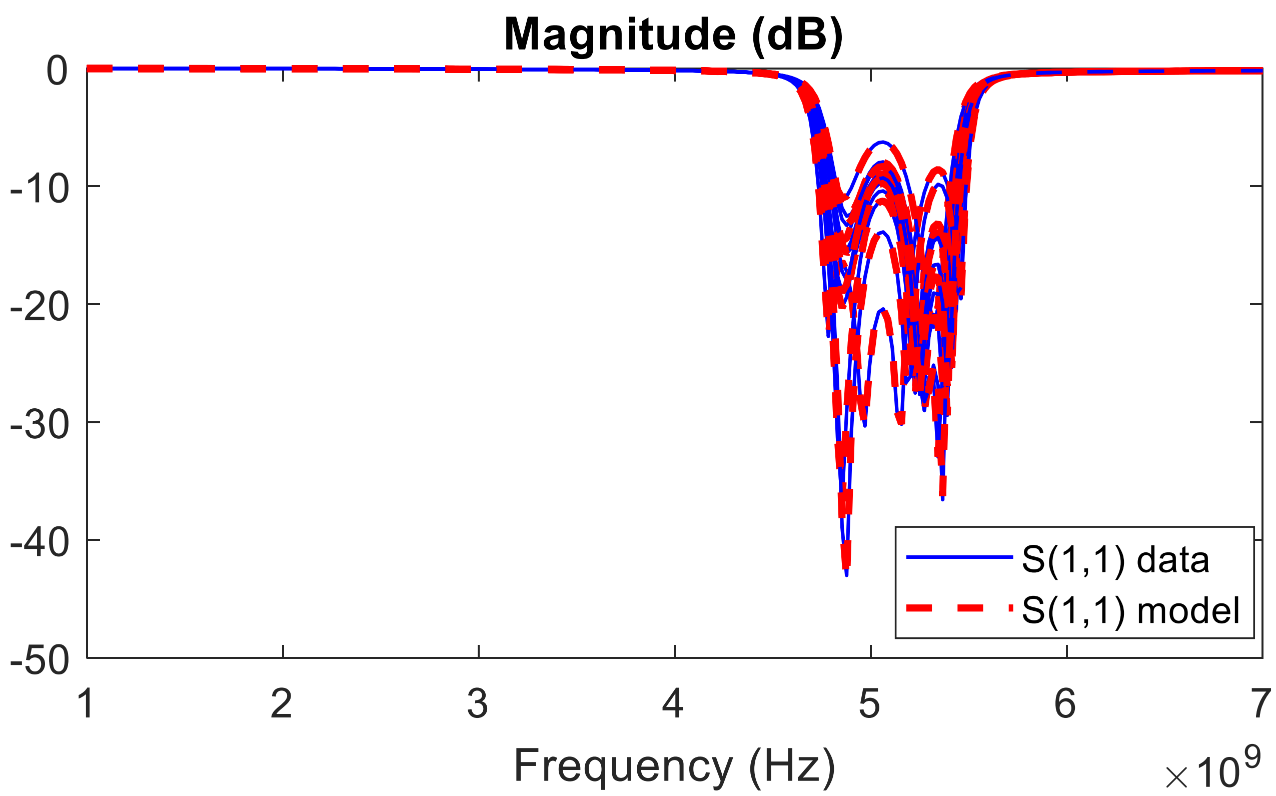


Iteration 0

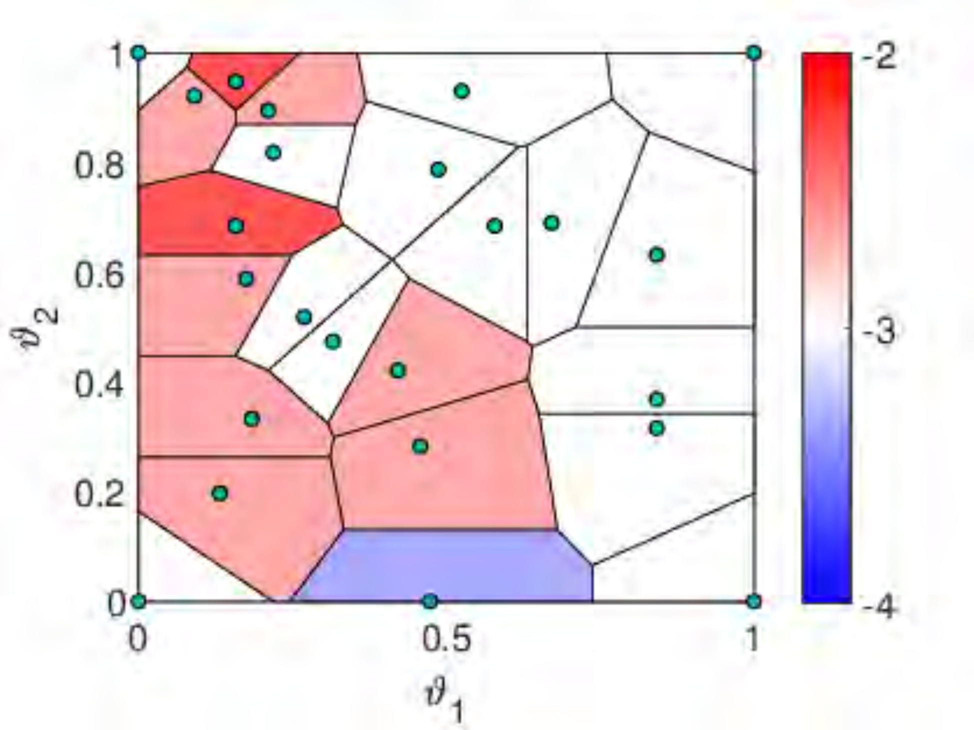


Examples – Coupled Line Bandpass Filter

Model vs data responses

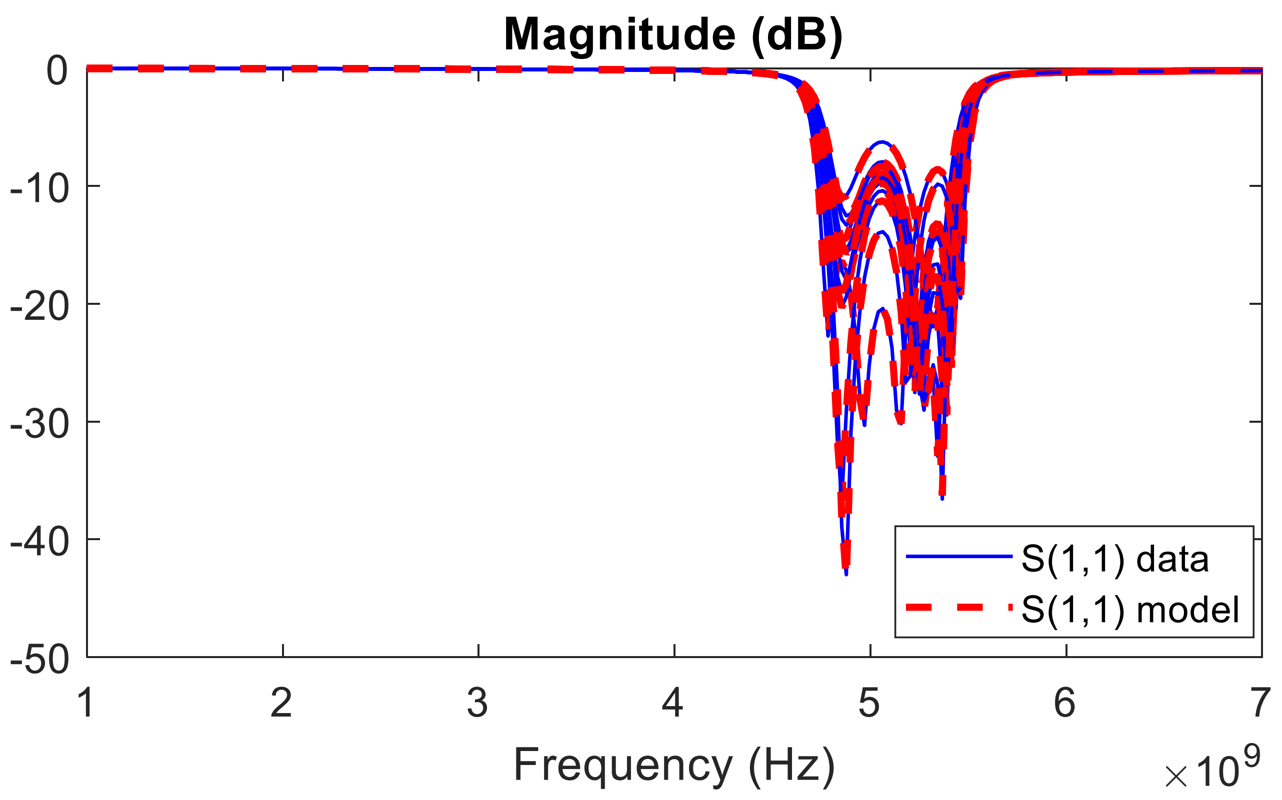


Iteration 2

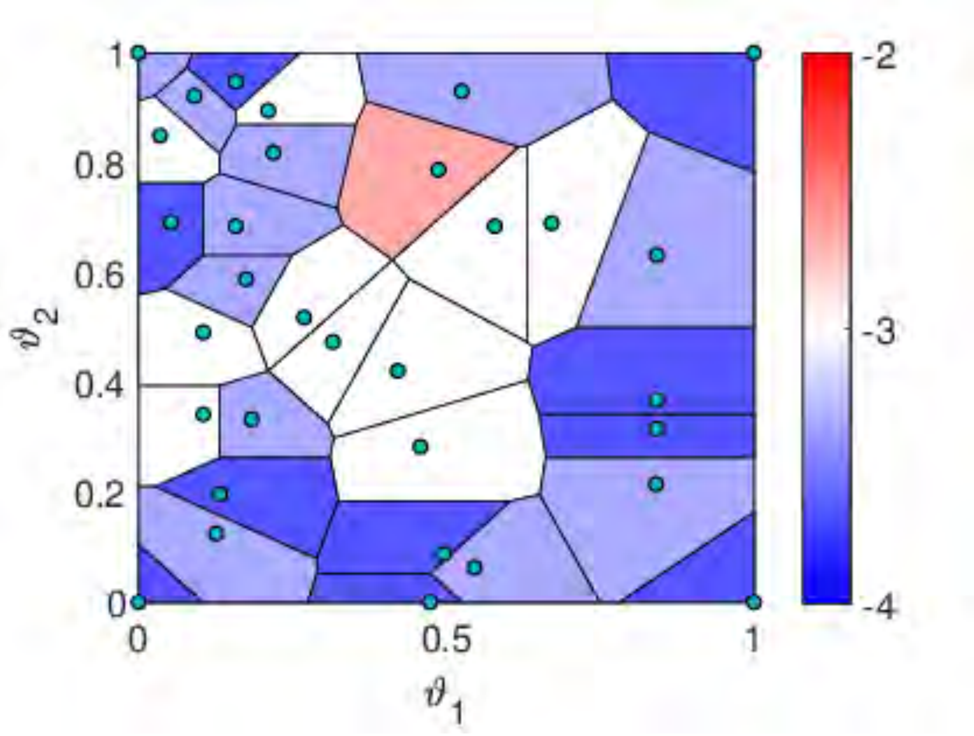


Examples – Coupled Line Bandpass Filter

Model vs data responses



Iteration 3



Examples – Coupled Line Bandpass Filter

Runtime

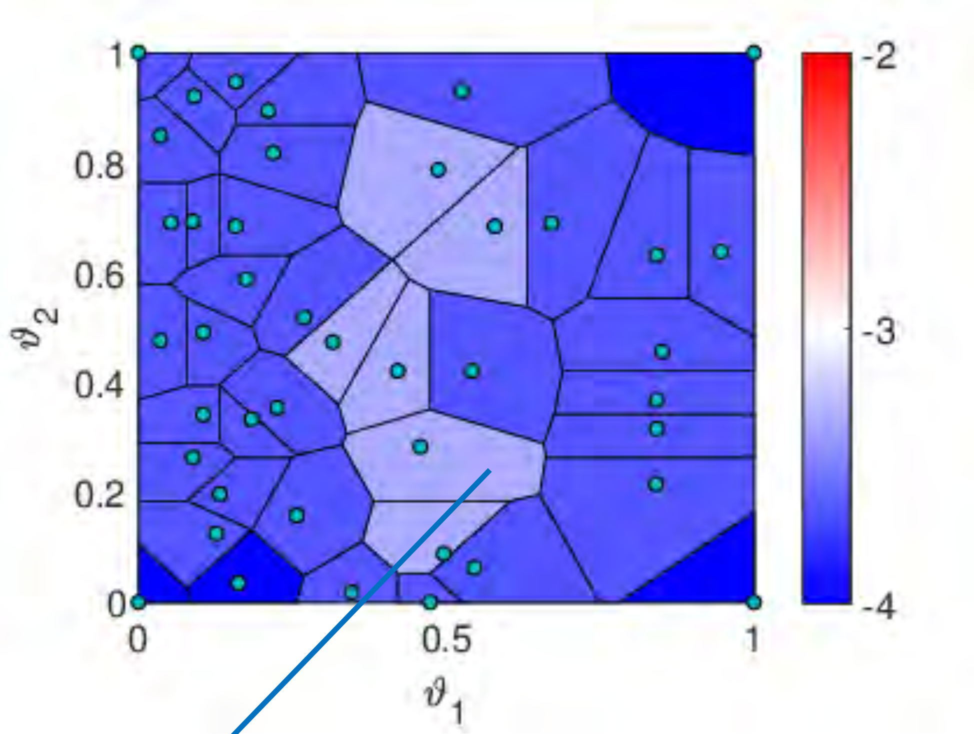
42 field solver responses → **1.2 hours**

Proposed algorithm → **417 s**

↓

Less than 9% of total time

Iteration 4



Q = 42 points

Conclusions

- Fully automated algorithm for the generation of stable and passive parameterized macromodels.

- Identification of a quasi minimal set of simulation points.

- Enforcement of passivity and stability on the final model using perturbation approach.