Recent Developments on Advanced Macromodeling by Politecnico di Torino

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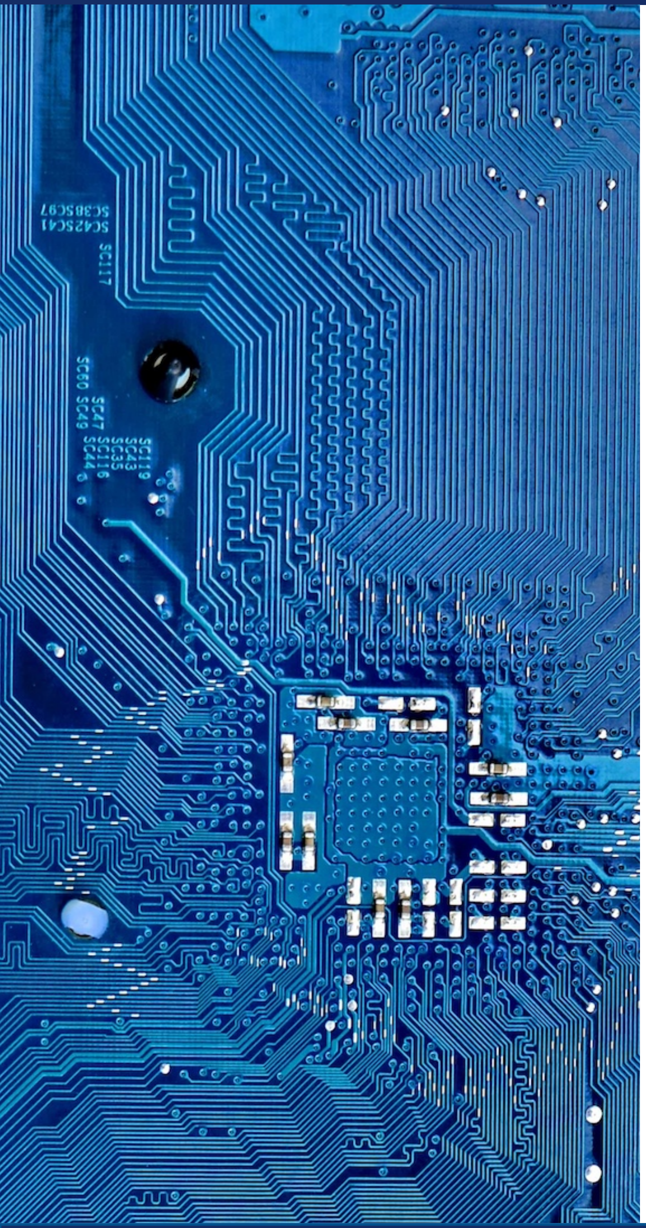
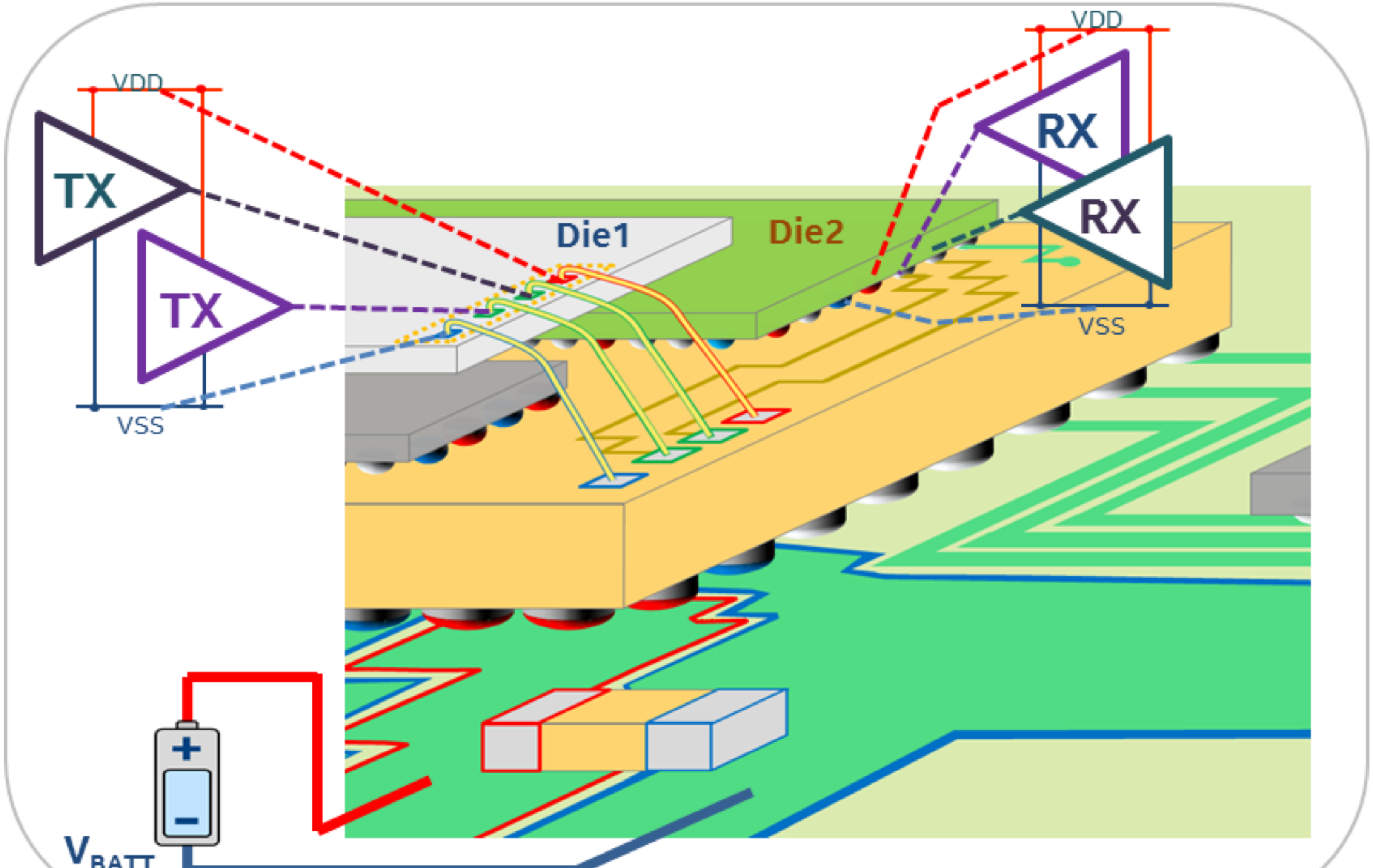
POLITECNICO DI TORINO

EMC Group

Signal and Power Integrity

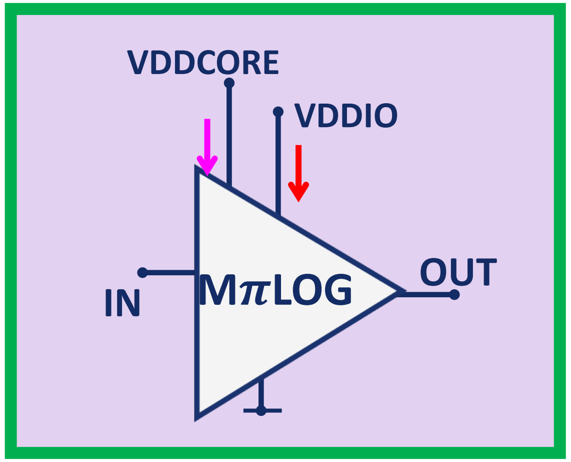




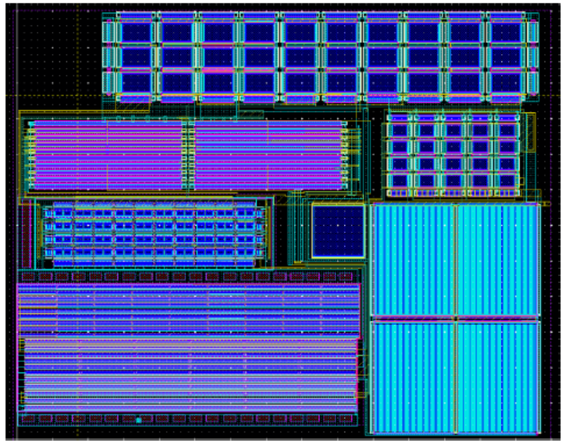
Courtesy: Dr. Gianni Signorini, (formerly) Intel

The objective: behavioral models

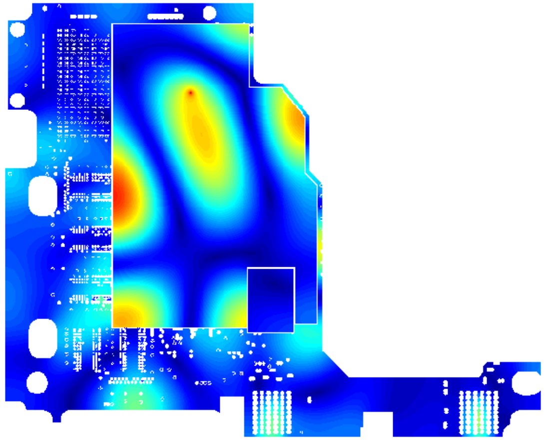
Behavioral models: used extensively and successfully to approximate…



I/O Buffers



Analog Devices



Passive Structures

Many different modeling techniques (such as IBIS standards) are available

The most appropriate approach is application-dependent

We will focus here on passive structures and partially on analog devices

Features of behavioral models

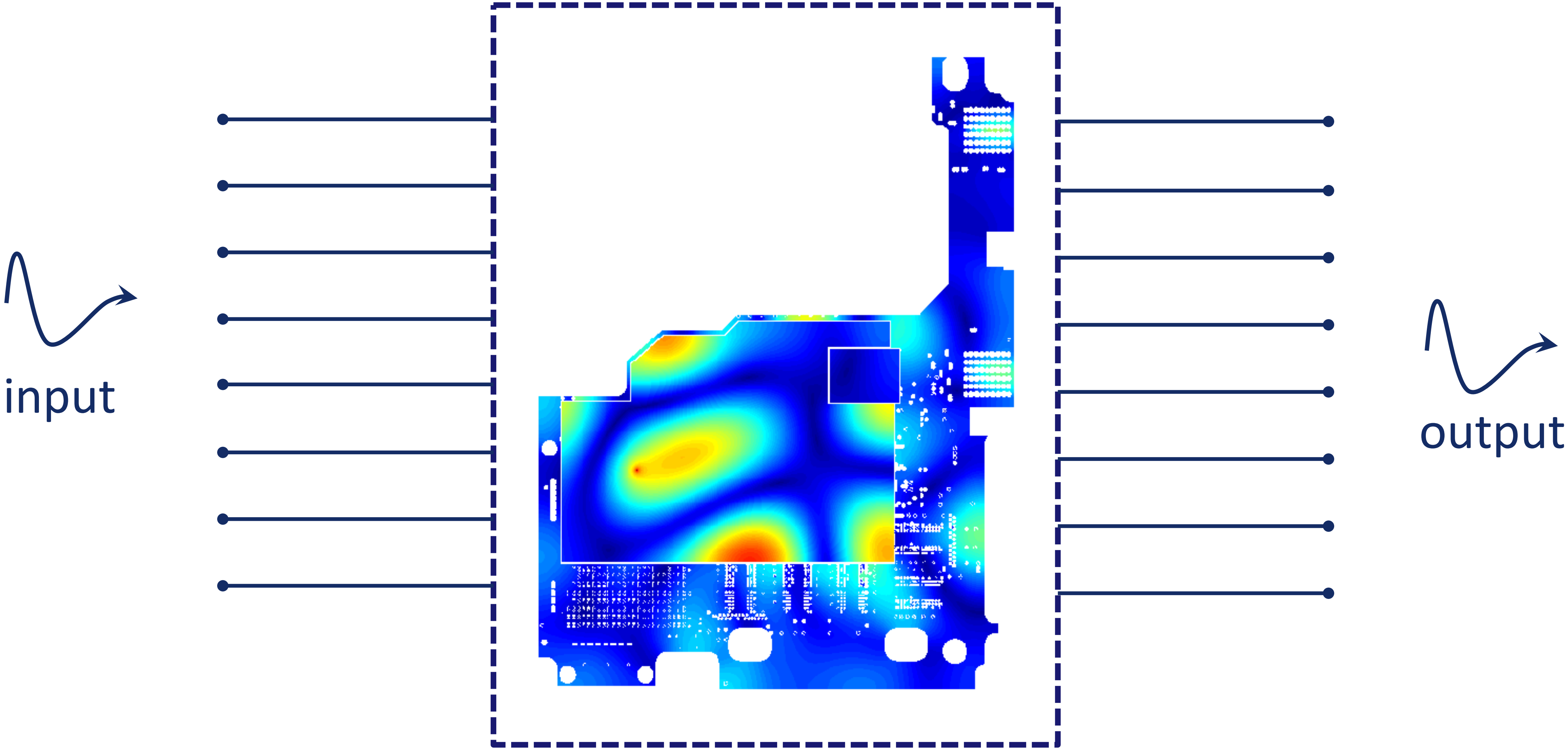
Behavioral models are intrinsically:

- Simplified and accurate descriptions
- Very general and design-independent
  - black-box: do not unveil details of the underlying design

Additional desirable features:

- Compliance with spice-like circuit solvers or other common simulation environments
- Compliance with fundamental properties of the reference system (e.g. stability and passivity)
- Generated automatically by non-expert users

Macromodels of passive structures

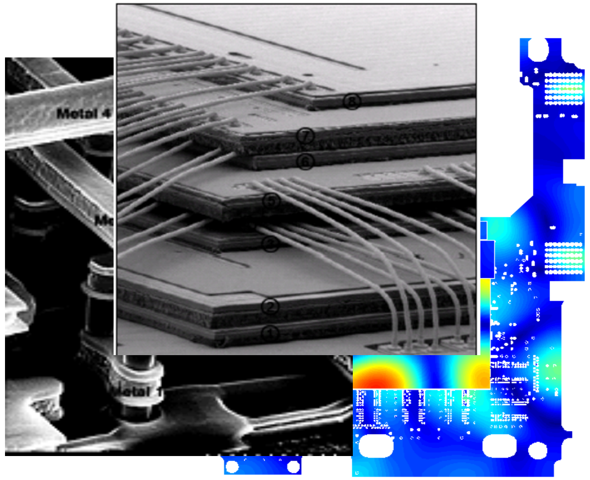


Courtesy Prof. Swaminathan, GA Tech

Macromodels of passive structures

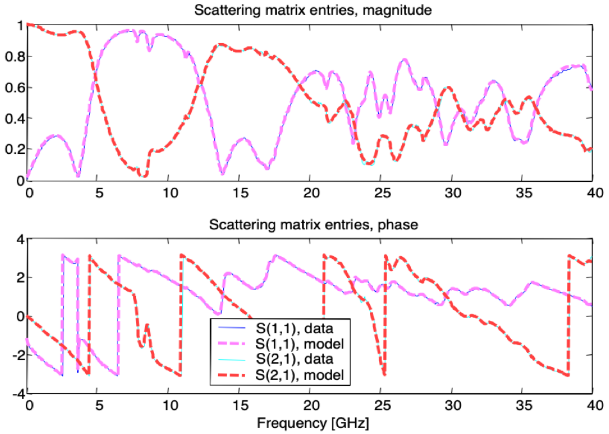
Passive structures dynamics are properly described by linear ODEs or PDEs

Geometry, materials



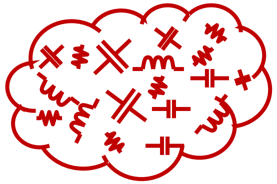
Extraction
EM simulation
Ckt simulation

Scattering data $\hat{S}_k = \hat{S}(j\omega_k)$



Macromodel

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$



LTI systems are best represented by rational transfer functions

Rational fitting
Passivity enforcement

Realization or synthesis

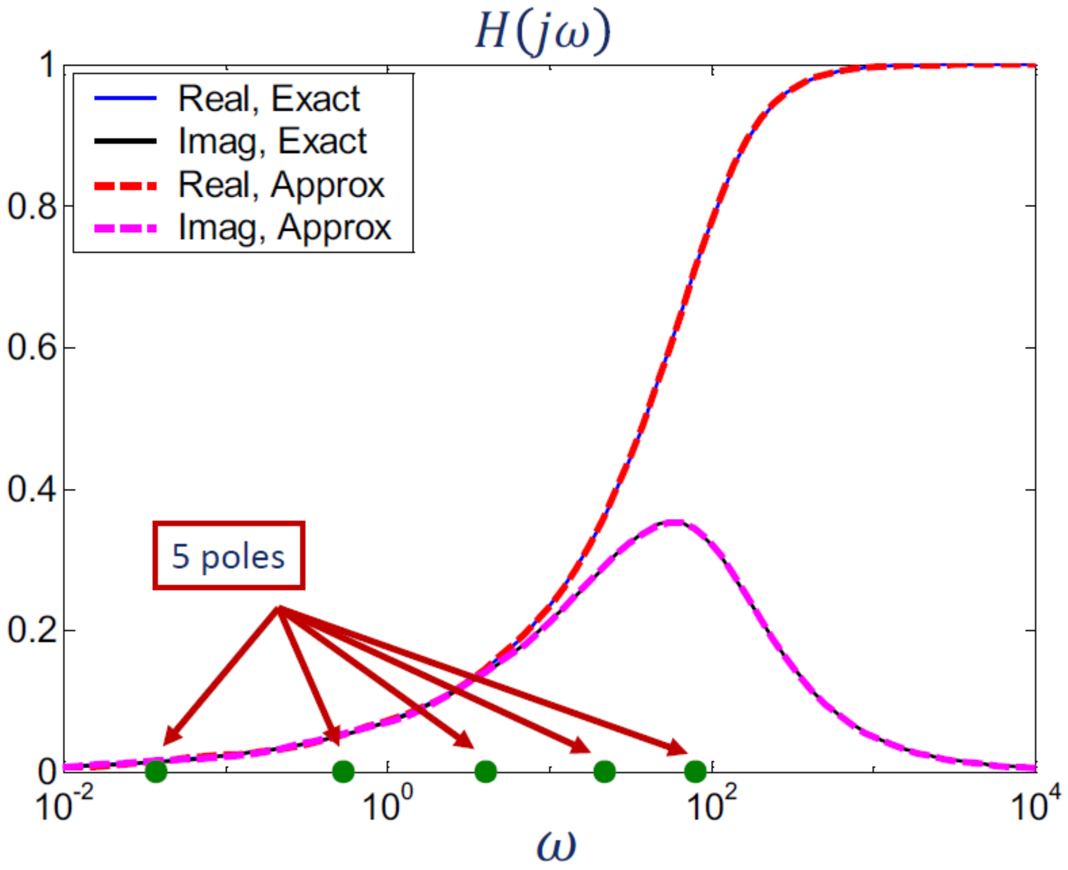
$$S(s) = \sum_{n=1}^{N} \frac{R_n}{s - p_n} + S_\infty$$

A very general approach

The approximations are topology-free and can potentially reproduce a variety of behaviors typical of distributed-parameter systems

Non-rational smooth function

$$H(s) = \sqrt{\frac{s+0.001}{s+100}}$$



Outline

- Recent advancements on macromodeling by Politecnico di Torino
  - Macromodeling of large-scale systems (hundreds of I/O ports)
    - Speaker: Marco De Stefano, PhD candidate
    - Compression strategies
    - Fast passivity verification and enforcement
  - Parameterized (multivariate) macromodels
    - Speaker: Alessandro Zanco, PhD candidate
    - Model structure and enhanced scalability (Radial Basis Functions – RBF)
    - Stability enforcement
  - Small-signal modeling of (nonlinear) analog circuit blocks
    - Speaker: Tommaso Bradde, PhD candidate
    - Embedding bias-dependence through parameterized macromodels
    - Theoretical assessment of dissipativity

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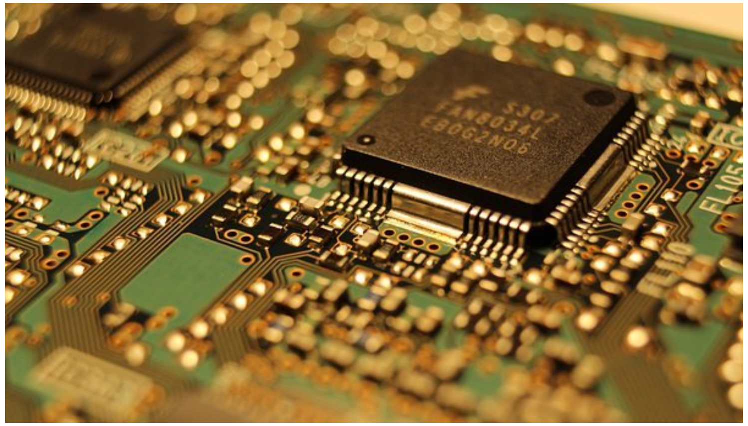
Handling large-scale LTI systems

Large-Scale LTI Systems

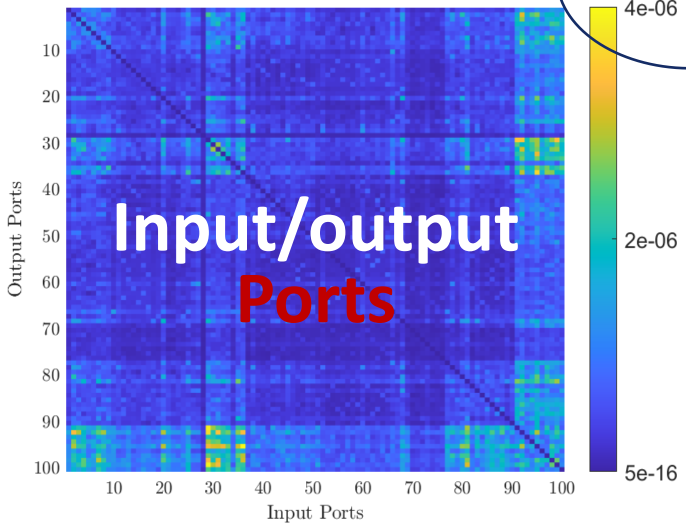


Shielding enclosures

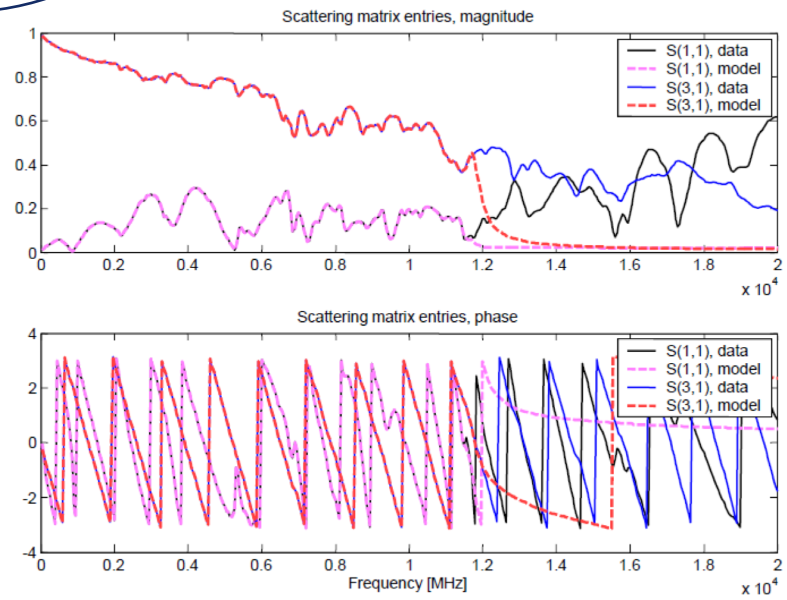
PCBs

TLs

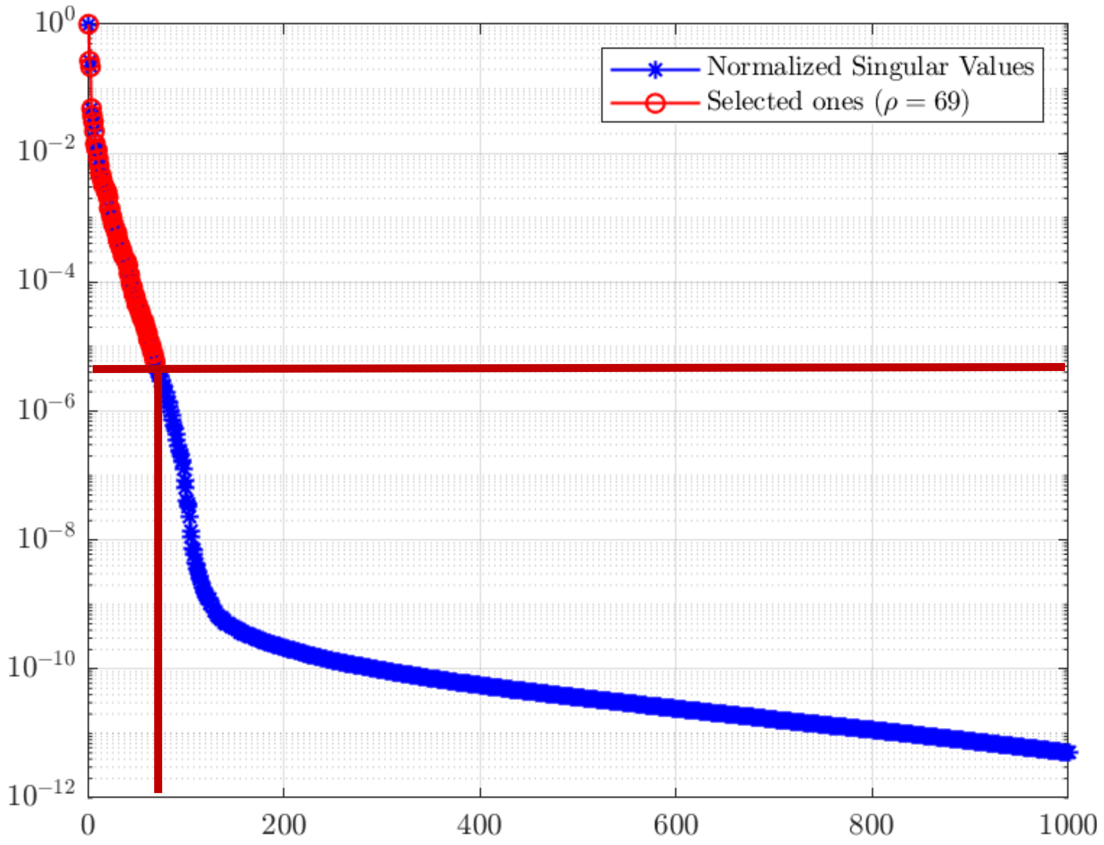
PDNs



Dynamic Order



Handling large-scale LTI systems



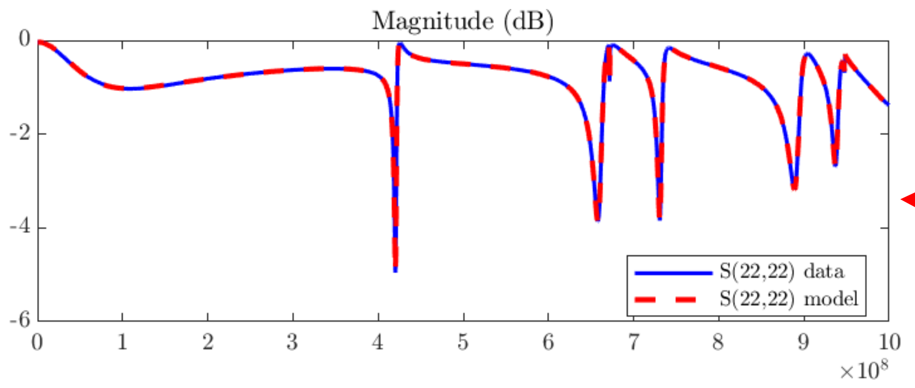
For structures with **many electrical ports**, the behavior can be recovered as a linear combination of a **reduced number** of case-dependent basis functions obtained from a **data-compression technique** (e.g. truncated SVD)

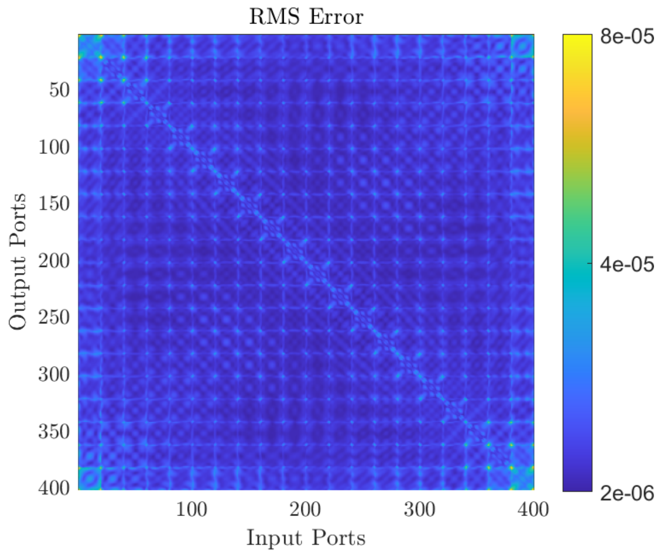
69 out of 160000 !!!

S. B. Olivadese and S. Grivet-Talocia, "Compressed Passive Macromodeling“, IEEE Trans. CPMT, vol. 2, no. 8, pp. 1378-1388, Aug. 2012

Surrogate Macromodeling → Data Compression Technique + Vector Fitting

- ✚ Accurate and Fast
- ✚ Data compression based on Singular Value Decomposition (SVD)
- ✚ Robust and reliable: full control over accuracy





Accuracy **OK**, Stability **OK**, Passivity **???**

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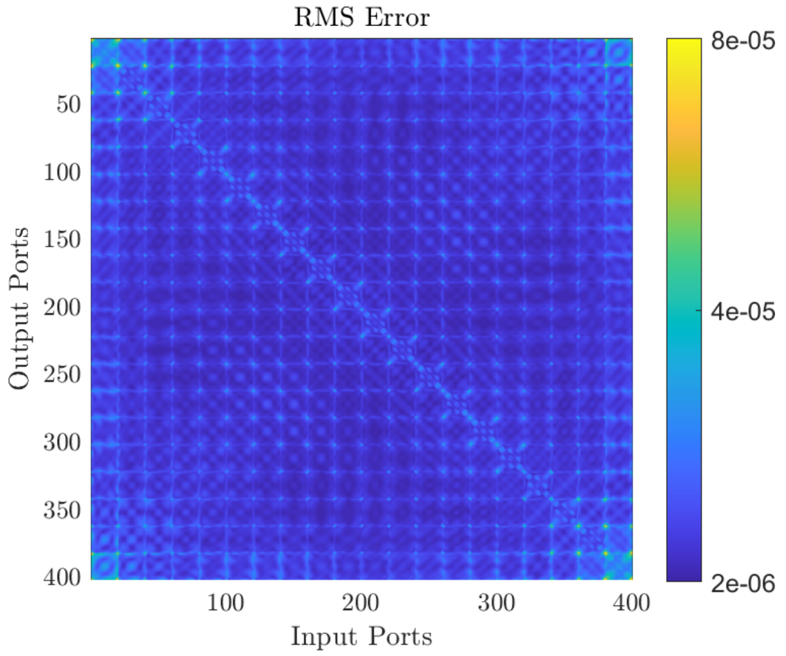
Handling large-scale LTI systems: passivity

- Passivity check based on a **Hamiltonian matrix eigenvalues** computation **is the state-of-the-art**
- Such technique becomes **infeasible** when the model **complexity grows**, in terms of
  - P: **Ports**
  - N: Number of **Poles**
- **Computational cost scales as $O((kPN)^3)$**



64 GB of RAM necessary to check passivity of 400-port, 90-pole model

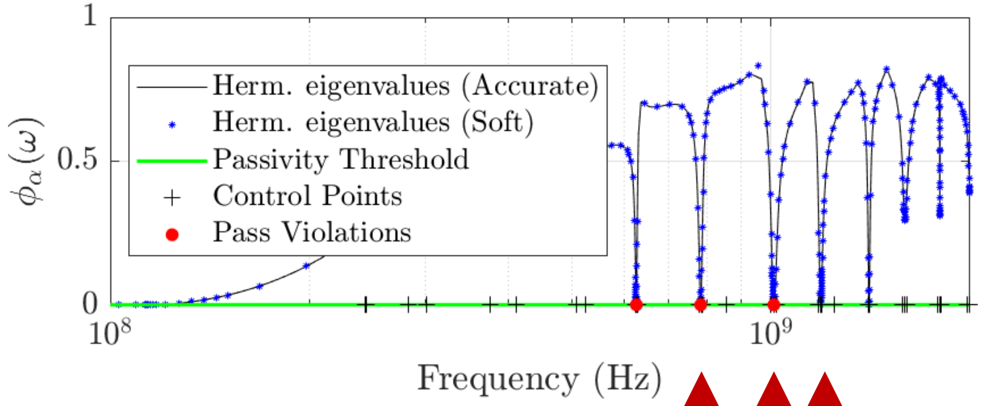
A **new procedure** to address large-size macromodels is **required**
→ adaptive sampling in the frequency domain may be sufficient…

Handling large-scale LTI systems: passivity

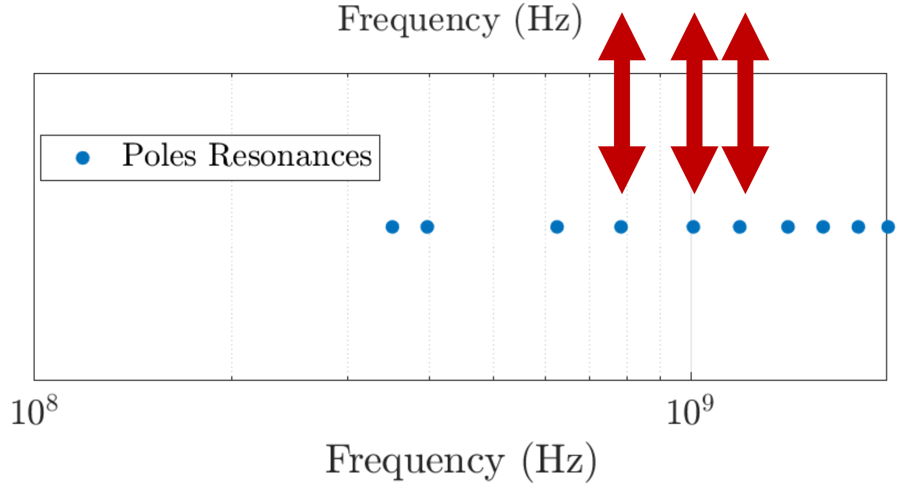
Adaptive-sampling-based passivity checking scheme developed to overcome the complexity of Hamiltonian checks

Based on a **2-stage** approach

1. **Pole-based** adaptive **frequency warping**
2. A passivity-driven **tree-search divide-and-conquer strategy**



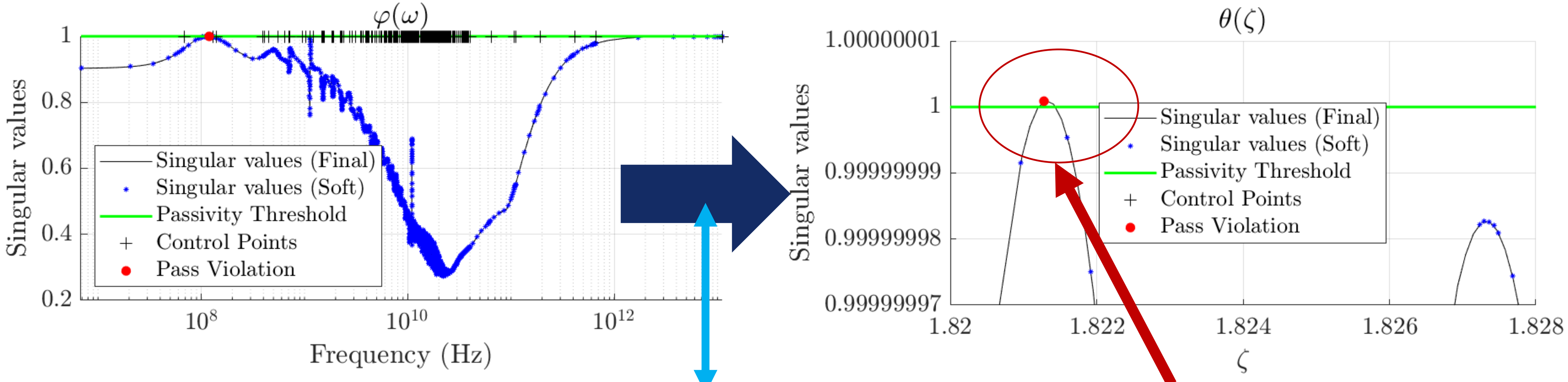
Fast variations of eigenvalues (or singular values) trajectories are mostly induced by the model **poles resonances**



M. De Stefano, S. Grivet-Talocia, W. Torben, C. Yang, C. Schuster, “A Multistage Adaptive Sampling Scheme for Passivity Characterization of Large-Scale Macromodels”, IEEE Trans. CPMT, vol. 11, no. 3, pp. 471–484, March 2021

Handling large-scale LTI systems: passivity

The result is a **fast** and **reliable** strategy for the **passivity characterization** of **large-scale macromodels**



Frequency Warping = Change of variable

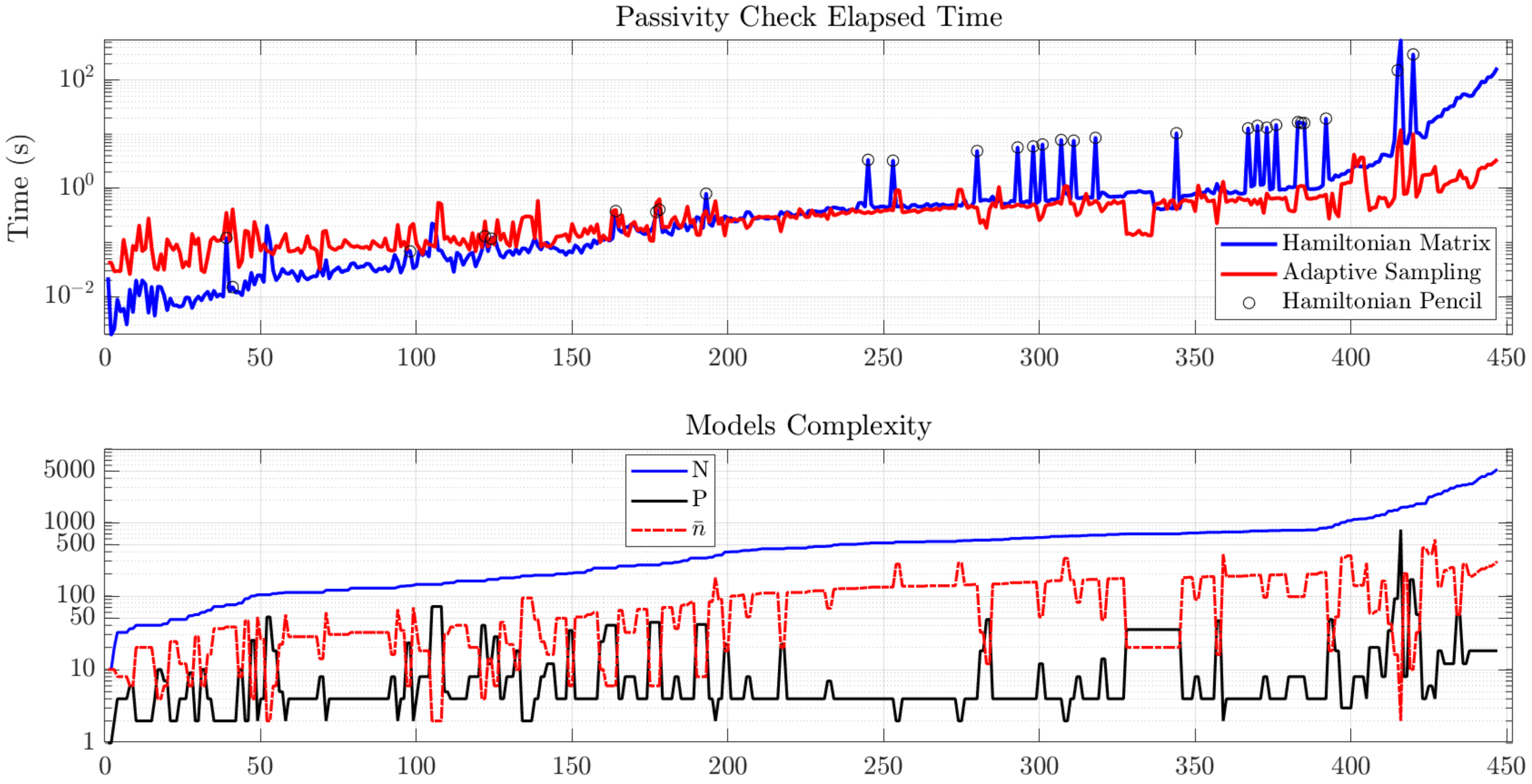
$$\zeta = \mathcal{W}(f)$$

Very **small passivity violations** can be effectively detected!

M. De Stefano, S. Grivet-Talocia, W. Torben, C. Yang, C. Schuster, "A Multistage Adaptive Sampling Scheme for Passivity Characterization of Large-Scale Macromodels", IEEE Trans. CPMT, vol. 11, no. 3, pp. 471–484, March 2021

Handling large-scale LTI systems: passivity

Massive testing campaign to assess the algorithm reliability



- All examples run on **8GB of RAM** laptop (64GB are required for the Hamiltonian Check)
- **large** size cases **speed-up from 10 to 100X**
- small and medium size performances are comparable

M. De Stefano, S. Grivet-Talocia, W. Torben, C. Yang, C. Schuster, "A Multistage Adaptive Sampling Scheme for Passivity Characterization of Large-Scale Macromodels", IEEE Trans. CPMT, vol. 11, no. 3, pp. 471–484, March 2021

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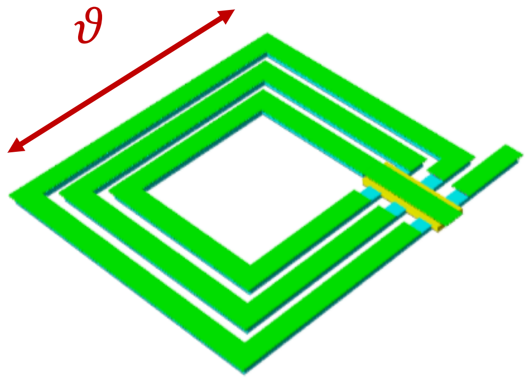
Parameterizing macromodels



Parametric sweep

Simulation or Measurement

IN

.snp

Multiple S-parameters

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

Model construction

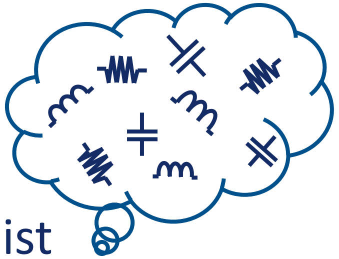
$$\mathbf{H}(s, \boldsymbol{\vartheta})$$

Parameterized model

Circuit synthesis

State-space realization

OUT

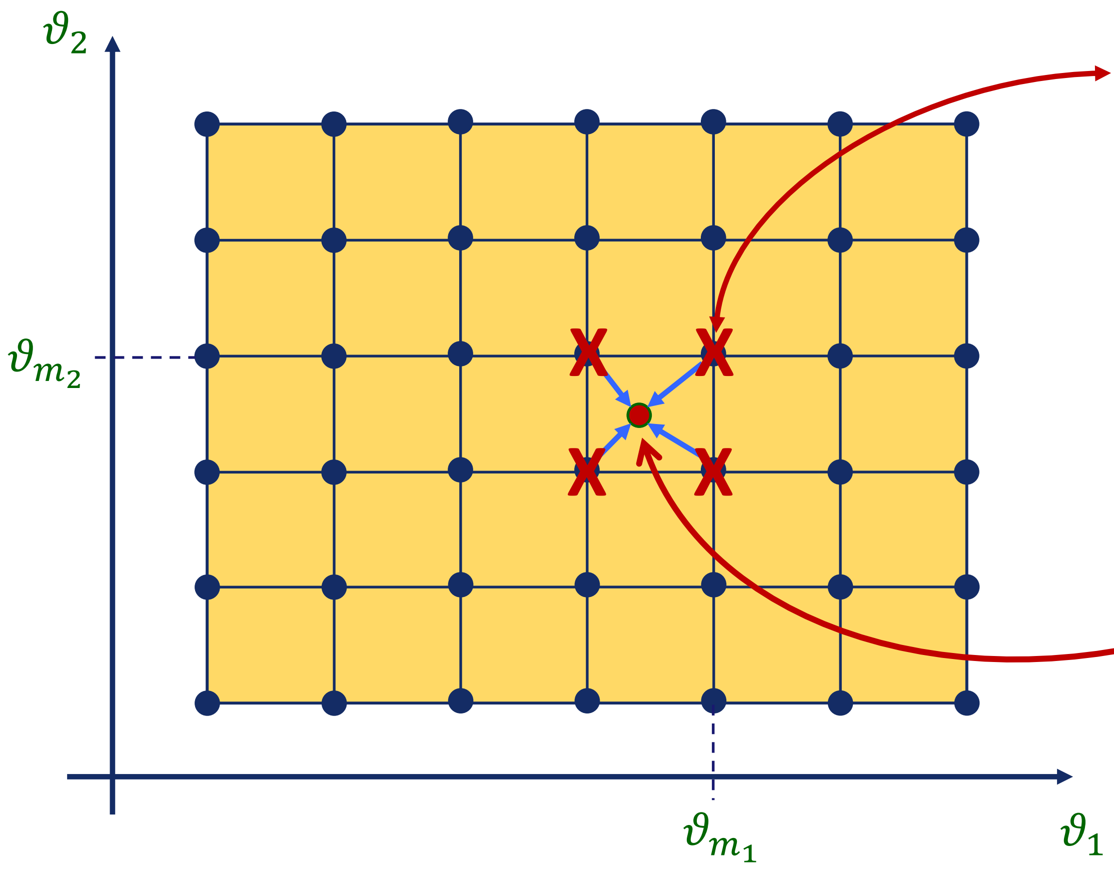


SPICE netlist

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

Possible parameterization approaches

Approach #1: interpolate independent non-parametric "root" macromodels



$$\mathbf{H}(s, \boldsymbol{\vartheta}_m) = \sum_{n=1}^{N} \frac{\mathbf{R}_n^{\boldsymbol{m}}}{s - p_n^{\boldsymbol{m}}} + \mathbf{H}_\infty^{\boldsymbol{m}}$$

"Root" models in pole-residue form (each with individual poles and residues)

$$\mathbf{H}(s, \boldsymbol{\vartheta})$$

Obtained by **interpolating** the closest "root" models

Pros:

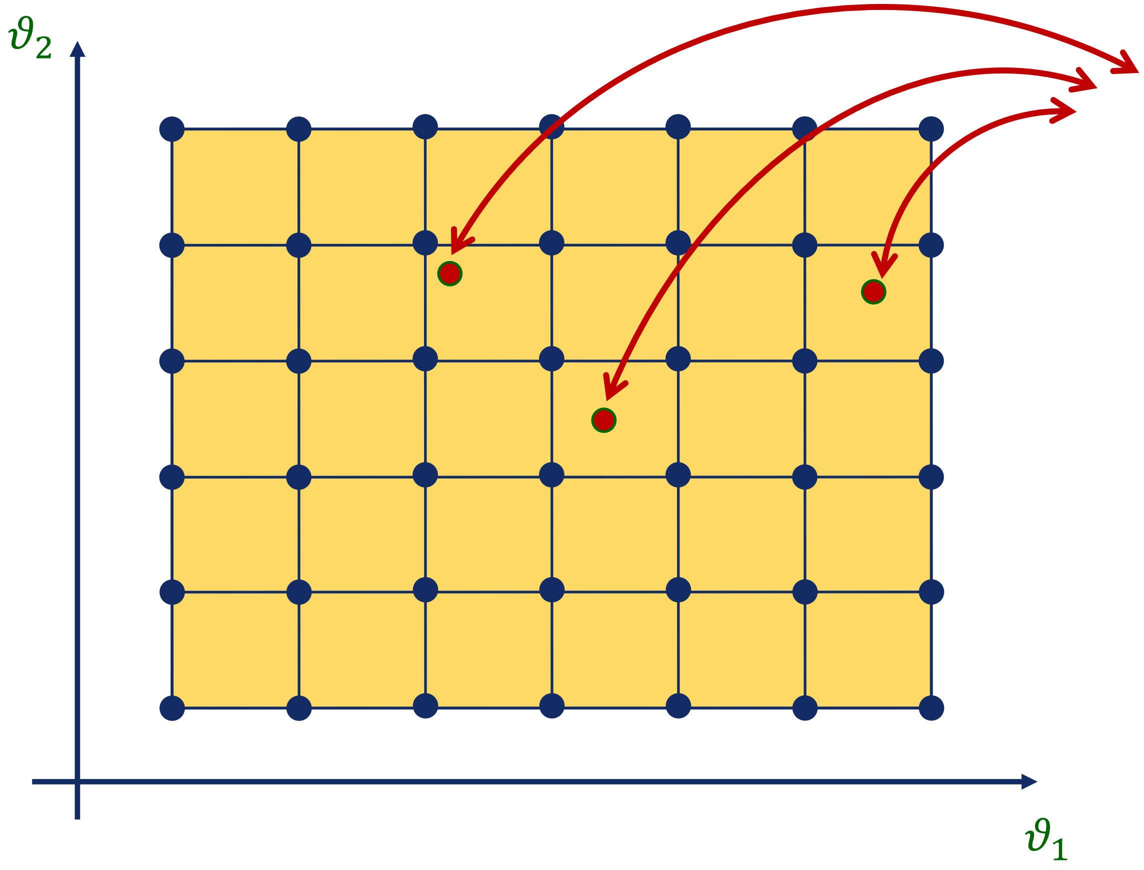
- Very simple scheme
- Interpolation schemes exist that guarantee passivity

Cons:

- Model is fully defined only by including a large set of "root" macromodels
- Poles are usually many more than required

Possible parameterization approaches

Approach #2: embed in closed the parameter variability in the model



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

Rational **parametric** model

Pros:

- Compact parametric model (few kB)
- No need to generate a possible large number of ''root'' models
- SPICE - compatible

Cons:

- Advanced techniques are required to guarantee stability and passivity

One general model strcuture

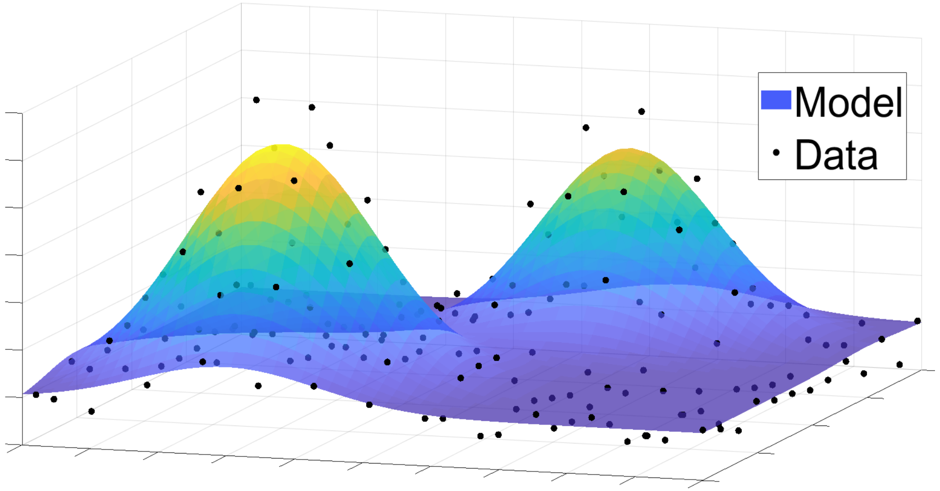
Rational model structure

$$\mathbf{H}(s;\boldsymbol{\vartheta}) = \frac{\mathbf{N}(s;\boldsymbol{\vartheta})}{\mathrm{D}(s;\boldsymbol{\vartheta})} = \frac{\sum_n \sum_\ell \mathbf{R}_{n,\ell}\, \xi_\ell(\boldsymbol{\vartheta}) \varphi_n(s)}{\sum_n \sum_\ell r_{n,\ell}\, \xi_\ell(\boldsymbol{\vartheta}) \varphi_n(s)}$$

To be estimated

$$\frac{\mathbf{N}(s;\boldsymbol{\vartheta})}{\mathrm{D}(s;\boldsymbol{\vartheta})} \approx \breve{\mathbf{H}}(j\omega_k;\boldsymbol{\vartheta}_m)$$

Partial Fractions $\varphi_n(s): \frac{1}{s-q_n}$



Parameter basis function $\xi_\ell(\boldsymbol{\vartheta})$:

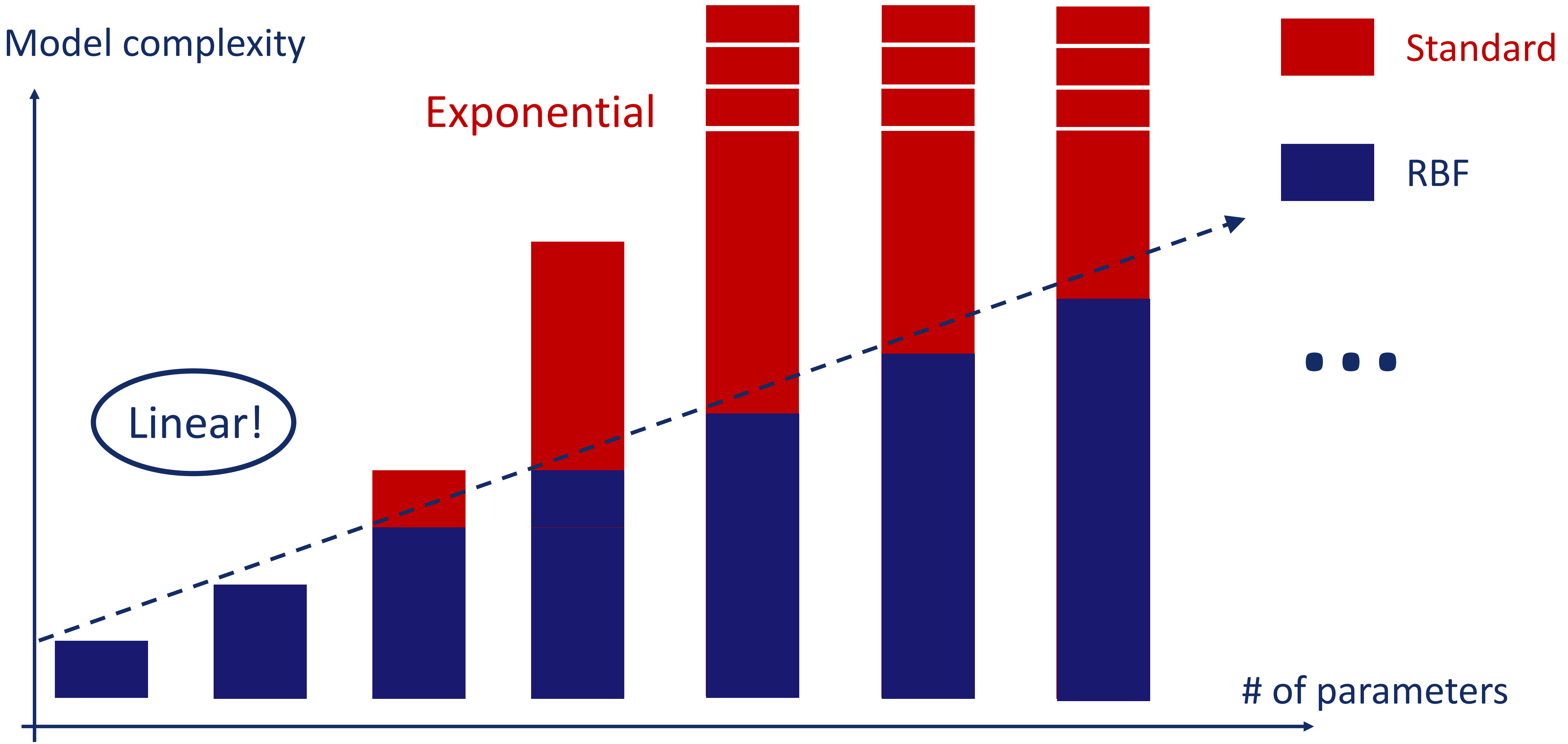
High-dimensional **kernel (RBF)** expansion

Gaussian kernel $\xi_\ell(\boldsymbol{\vartheta}) = e^{-\varepsilon\|\boldsymbol{\vartheta}-\vartheta_\ell\|^2}$

PRO:
Good scalability in high-dimensions

A. Zanco, S. Grivet-Talocia, “High-dimensional parameterized macromodeling with guaranteed stability,” in in Proc. IEEE 29th Conf. Electr. Perform. Electron. Packag. Syst. (EPEPS), Montreal, CA, Oct. 2020, pp. 1–3.

Handling many parameters



Handling many parameters

The model $\mathbf{H}(s; \boldsymbol{\vartheta})$ depends upon some free hyper-parameters, whose number:

STANDARD

Scales exponentially

RBF

Fixed!!!

Gaussian kernel

$$\xi_\ell(\boldsymbol{\vartheta}) = e^{-\varepsilon \|\boldsymbol{\vartheta} - \boldsymbol{\vartheta}_\ell\|^2}$$

Shape parameter

# of RBFs
RBF's centers

There exists techniques to optimize these hyper-parameters for model compactness and accuracy

A. Zanco and S. Grivet-Talocia, "Hyperparameter determination in multivariate macromodeling based on radial basis functions," in Proc. IEEE 29th Conf. Electr. Perform. Electron. Packag. Syst. (EPEPS), San Jose, CA, USA, Oct. 2020, pp. 1–3.
A. Zanco, S. Grivet-Talocia, "A mesh-free adaptive parametric macromodeling strategy with guaranteed stability," in Proc. International Symposium on Electromagnetic Compatibility 2020 - EMC Europe 2020 , Rome, Italy, Sept. 2020, pp. 1-6.

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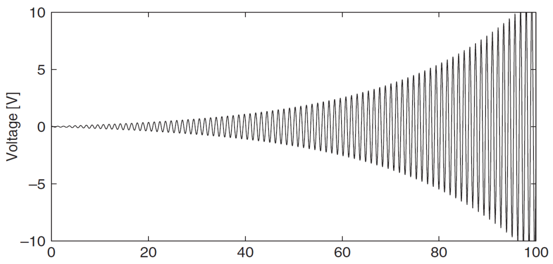
Multivariate models: fast stability enforcement

$$\mathbf{H}(s;\boldsymbol{\vartheta}) = \frac{\mathbf{N}(s;\boldsymbol{\vartheta})}{\mathrm{D}(s;\boldsymbol{\vartheta})} = \frac{\sum_n \sum_l \mathbf{R}_{n,l}\, \xi_l(\boldsymbol{\vartheta})\varphi_n(s)}{\sum_n \sum_l r_{n,l}\, \xi_l(\boldsymbol{\vartheta})\varphi_n(s)} = \sum_n \frac{\mathbf{R}_n(\boldsymbol{\vartheta})}{s - p_n(\boldsymbol{\vartheta})}$$

Implicit poles parameterization

NO CONTROL ON POLES LOCATIONS!

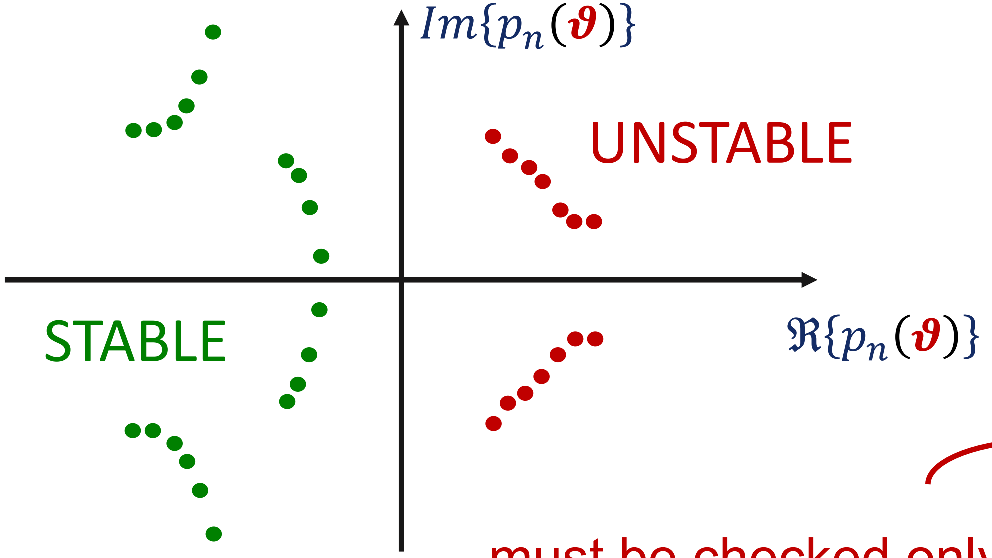


For uniform stability

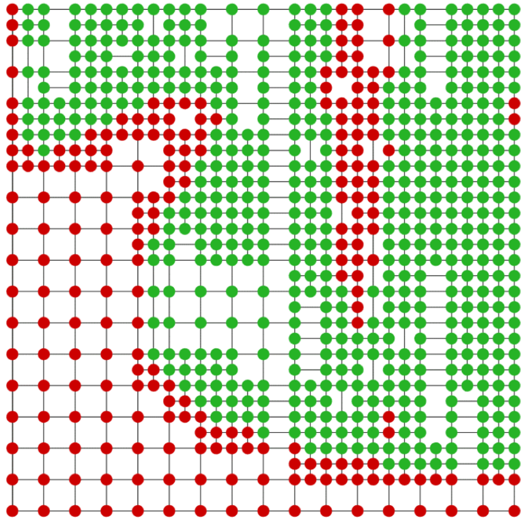
$\Re\{\mathrm{D}(s;\boldsymbol{\vartheta})\} > 0,\ \forall\, s, \boldsymbol{\vartheta}$

$\Downarrow$

$\Re\{p_n(\boldsymbol{\vartheta})\} < 0,$ for **all** $\boldsymbol{\vartheta}$



Parameter space sampling



must be checked only for $s = j\omega$ but for **all** $\boldsymbol{\vartheta}$

Stefano Grivet-Talocia, Riccardo Trinchero. "Behavioral, parameterized, and broadband modeling of wired interconnects with internal discontinuities." *IEEE Transactions on Electromagnetic Compatibility* 60.1 (2017): 77-85.

Multivariate models: fast stability enforcement

… but, with positive-definite kernels …

$$\varphi_n(s) : \frac{1}{s - q_n}$$

$$\Re\{\mathrm{D}(s;\boldsymbol{\vartheta})\} = \Re\{\textstyle\sum_n \sum_l r_{n,l}\ \underbrace{\xi_l(\boldsymbol{\vartheta})}_{> 0,\ \forall \boldsymbol{\vartheta}}\varphi_n(s)\} > 0$$

$$\Updownarrow$$

$$\Re\{\textstyle\sum_n \sum_l r_{n,l}\ \varphi_n(s)\} > 0$$

$$\Updownarrow$$

$$\begin{cases} r_{n,l} > 0 & \text{for real poles } q_n \\ -\alpha_n r'_{n,l} \pm \beta_n r''_{n,l} > 0 & \text{for complex poles } \alpha_n \pm j\beta_n \end{cases}$$

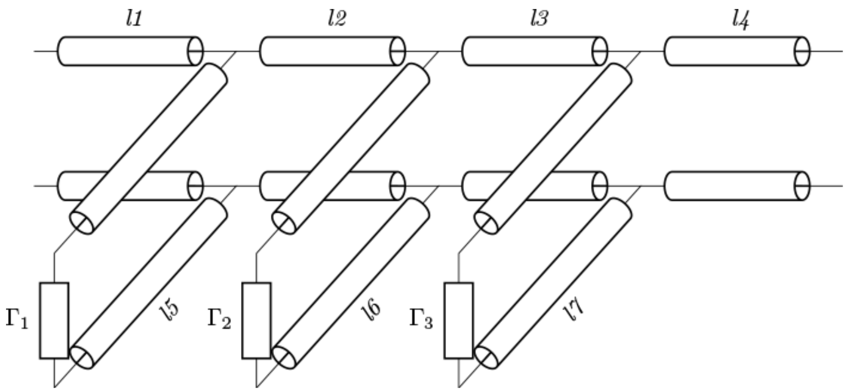
No parameter-space sampling!

Few constraints in few variables!

Analytic stability constraints!

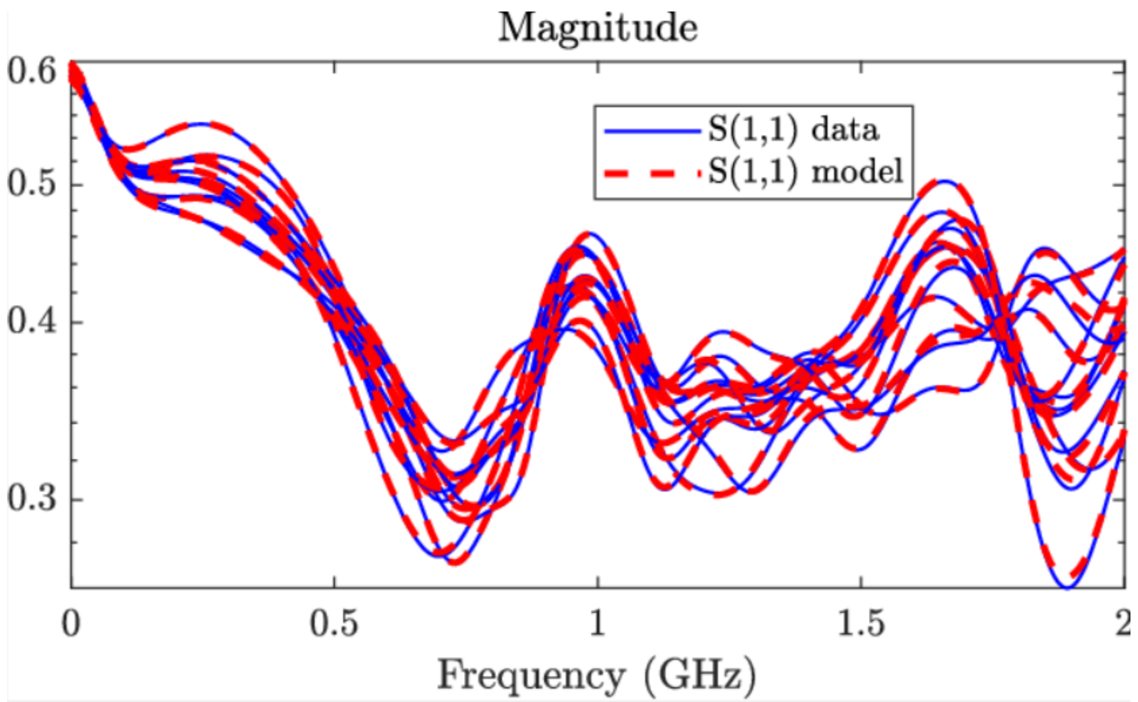
Multivariate models: fast stability enforcement

A parameterized microstrip transmission line



10-independent parameters

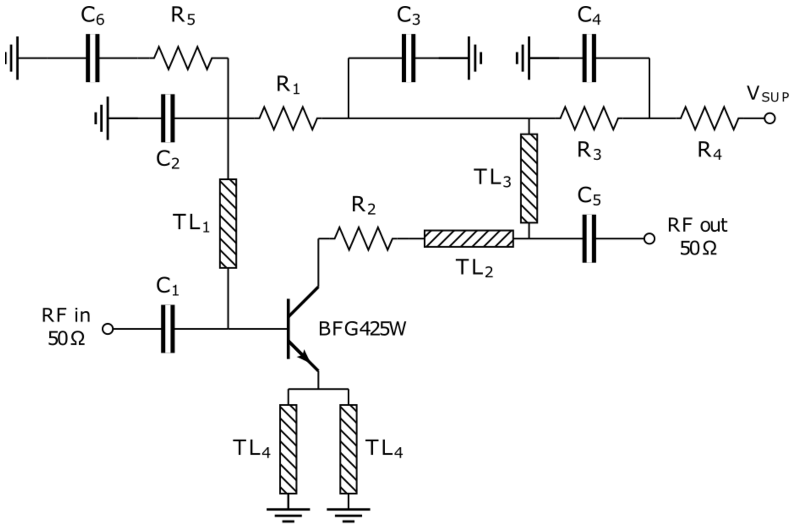
- Inner lines length
- Stubs length
- Load resistances
- Substrate electrical parameters



It required 14 minutes to extract a STABLE model, with accuracy 11×10^{-3}

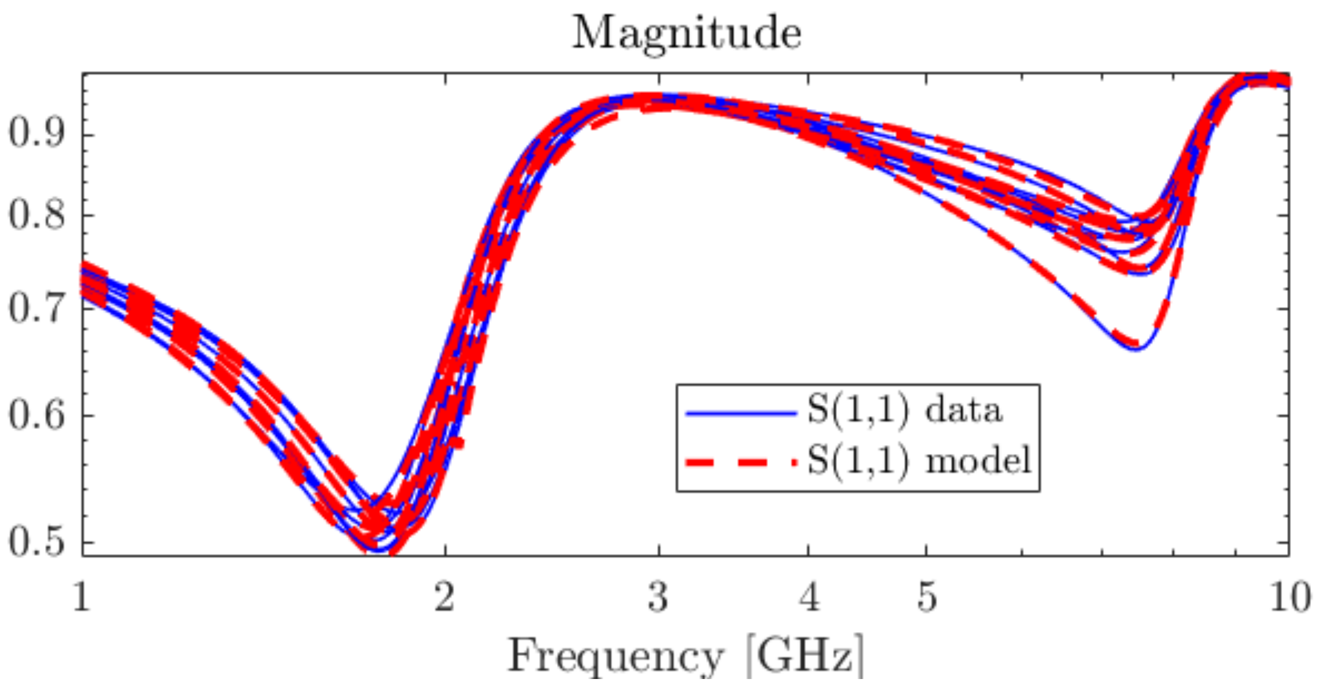
A 10-parameters example

Low Noise Amplifier



#	Parameter ϑ_i	$\vartheta_{i,\min}$	$\vartheta_{i,\max}$
1	L_b (nH)	0.88	1.32
2	L_c (nH)	0.88	1.32
3	L_e (nH)	0.20	0.30
4	C_{cb} (pF)	0.0016	0.0024
5	C_{be} (pF)	0.064	0.096
6	C_{ce} (pF)	0.064	0.096
7	h (mm)	0.45	0.55
8	t_k (μm)	1.8	2.2
9	$w_{1,2,3}$ (mm)	0.225	0.275
10	w_4 (mm)	0.72	0.88

Automatic generation of a STABLE parameterized model: 6 minutes!



Model vs Data error: $9.2 \cdot 10^{-3}$

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Affine linearized models of NL analog blocks

Nonlinear equations

$$\dot{w} = F(w,u)$$
$$y = G(w,u)$$

Small signal analysis

→

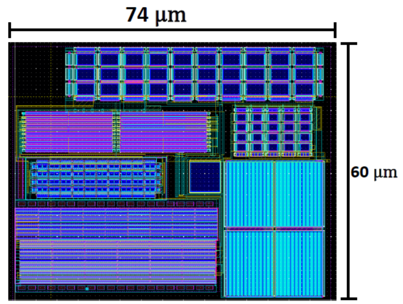
Linearization around the operating point

Local model

$$\dot{w} = Aw + Bu$$
$$y = Cw + Du$$

PROBLEM: post-layout circuit equations are unavailable (hidden)

SOLUTION: data driven modeling approach based on AC analysis



AC DATA

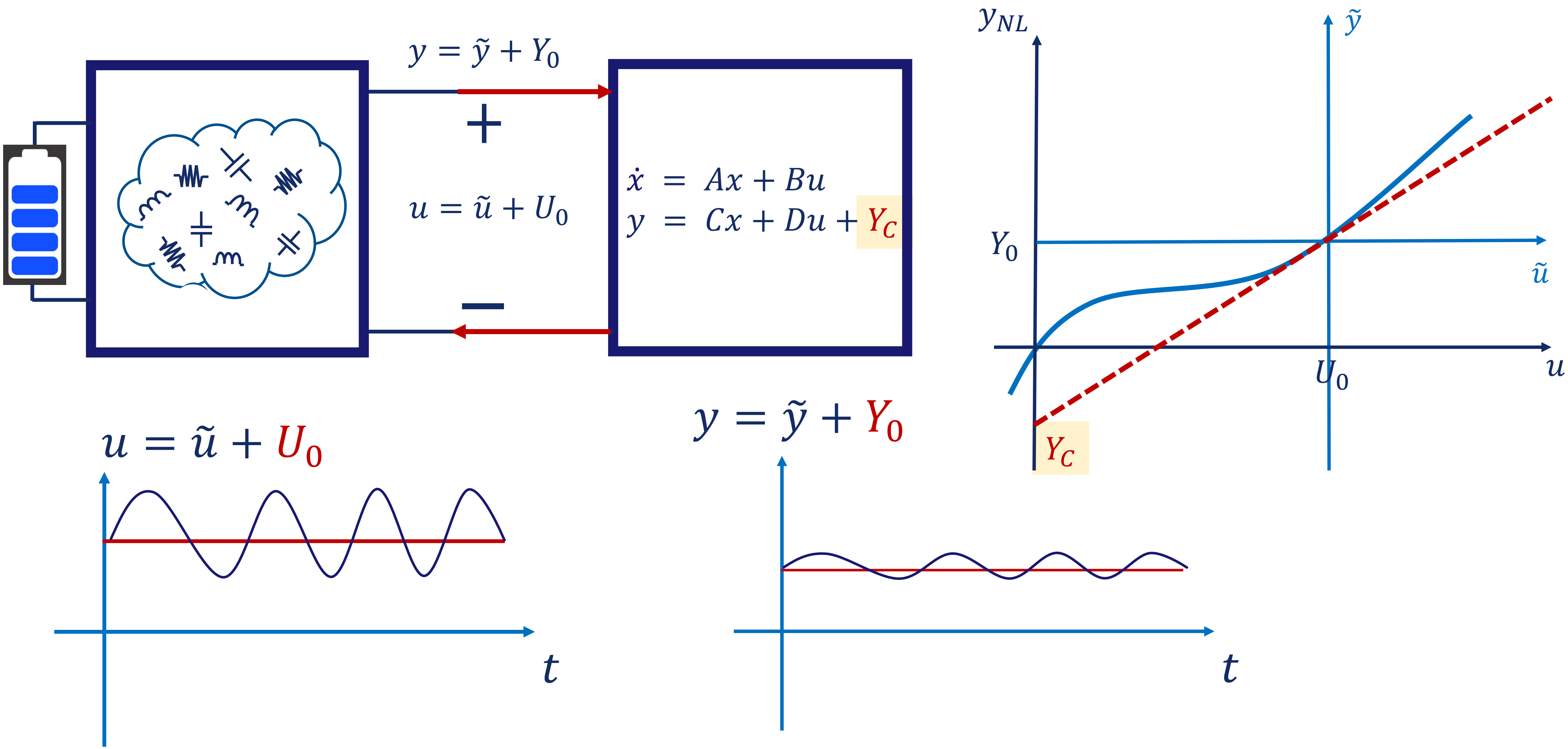
→

Rational Approximation (Vector Fitting)

Reduced order local model

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

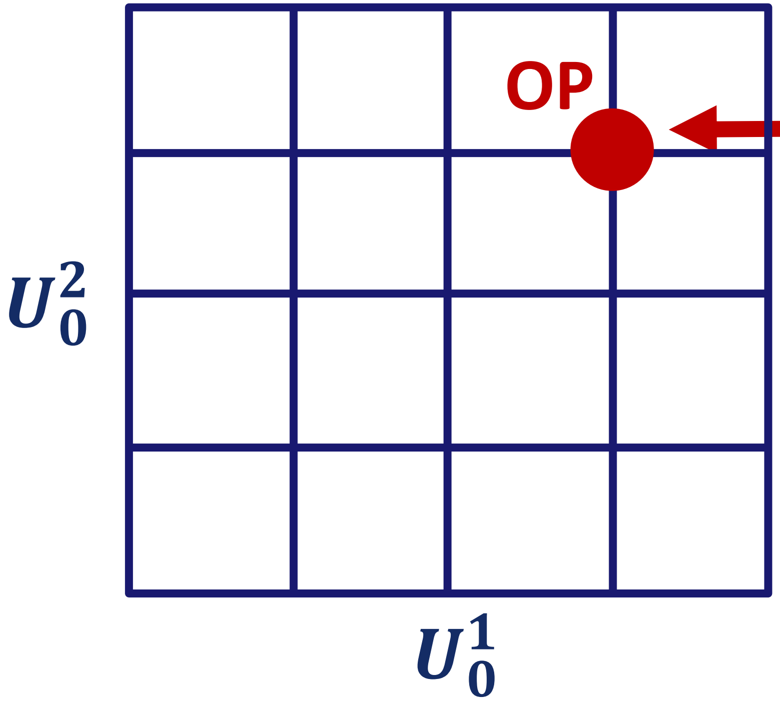
Affine linearized models of NL analog blocks



Operating point parameterization

P electrical ports → P DC inputs set the operating point

$$U_0 = \begin{bmatrix} U_0^1 \\ \dots \\ U_0^P \end{bmatrix}$$



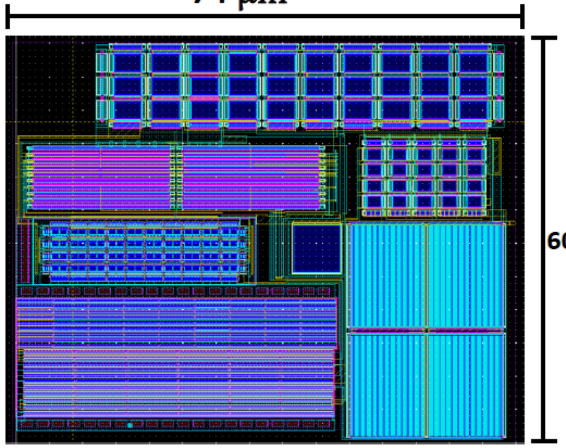
Standard rational fitting techniques return models for each single OP

The **bias space** of interest

model for the entire bias space ↔ model for all the U_0 values of interest

Bradde, T., et al. Enabling fast power integrity transient analysis through parameterized small-signal macromodels. In: *2019 International Symposium on Electromagnetic Compatibility-EMC EUROPE*. IEEE, 2019. p. 759-764.

For active circuit blocks: $\boldsymbol{\vartheta} \equiv \boldsymbol{U_0}$



Parametric sweep

Simulation or Measurement

IN

Frequency response data

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

Multivariate Rational Fitting

Stability

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

Parameterized model

State-space realization

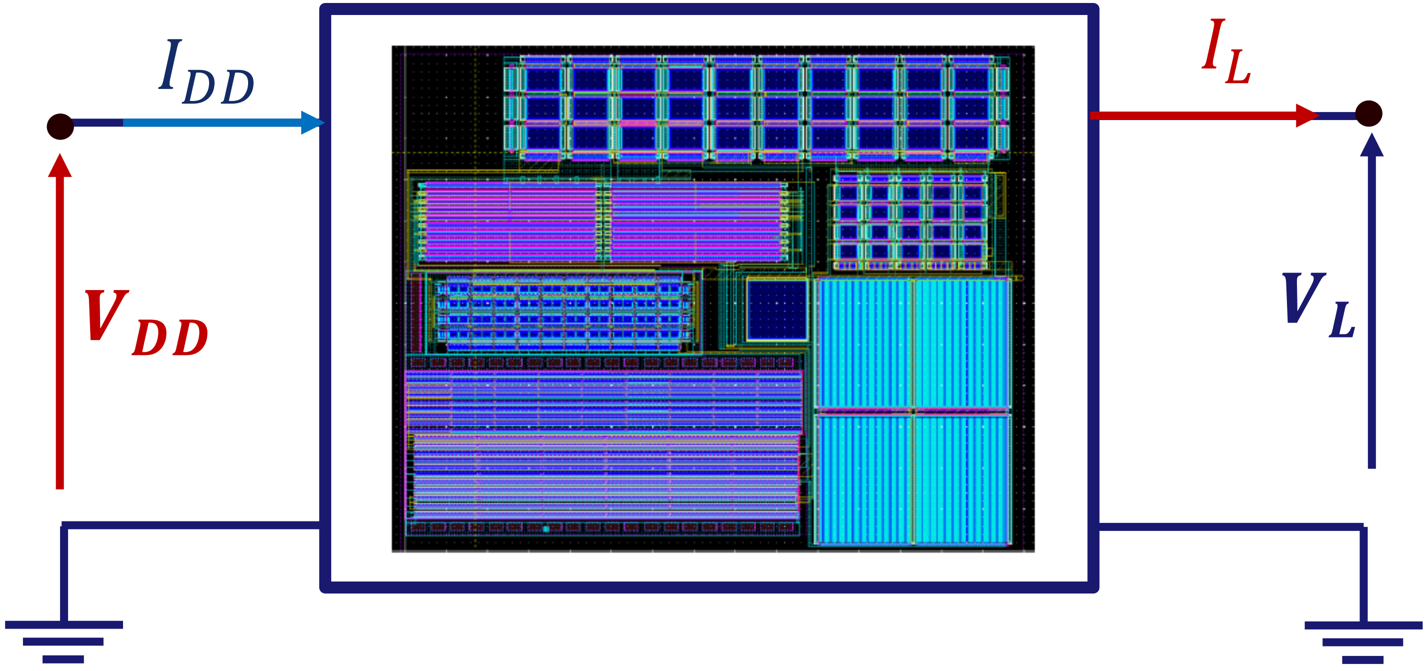
Circuit synthesis

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

OUT

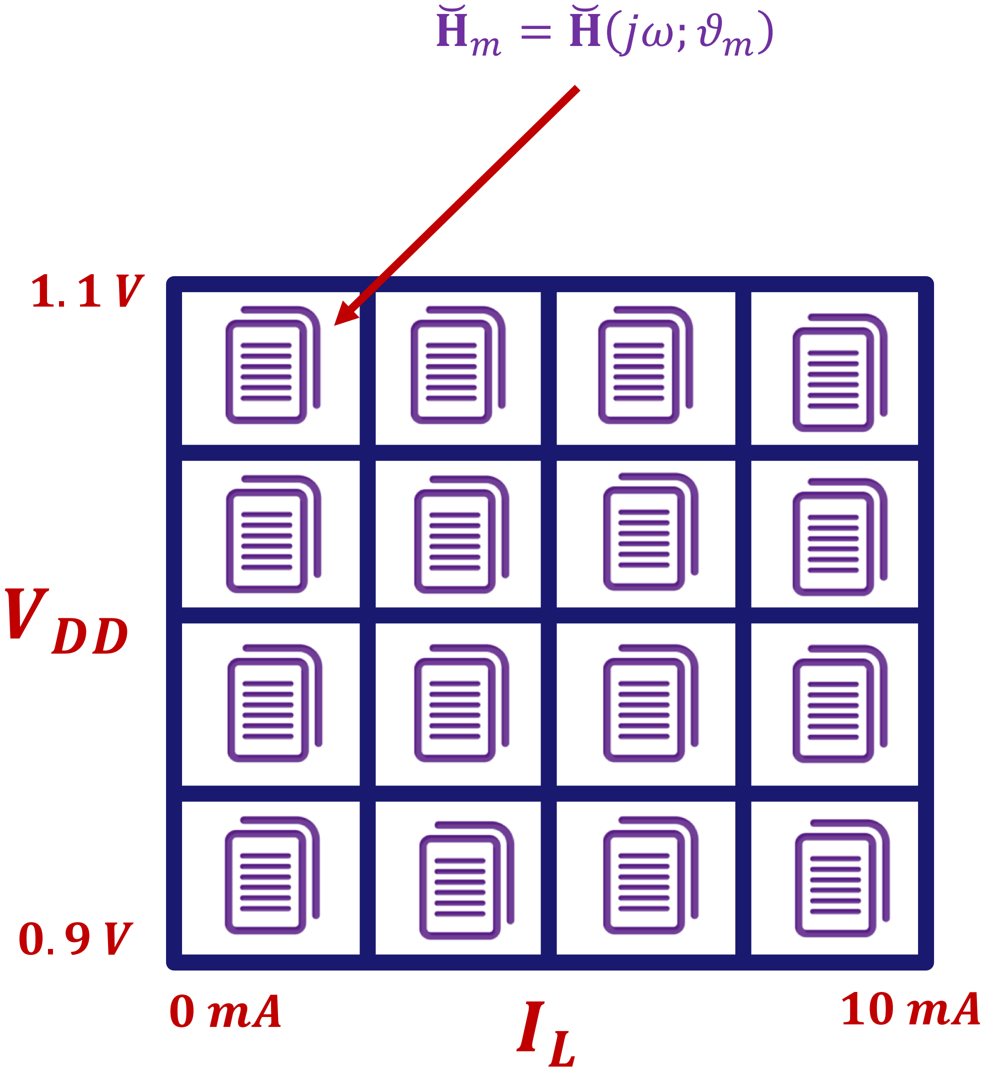
SPICE netlist

Example: a post-layout voltage regulator



$V_{DD} \in [0.9, 1.1]\ V$ $\quad I_L \in [0, 10] mA$

$U_0 = \begin{bmatrix} V_{DD} \\ I_L \end{bmatrix}$ Induce the parameterization



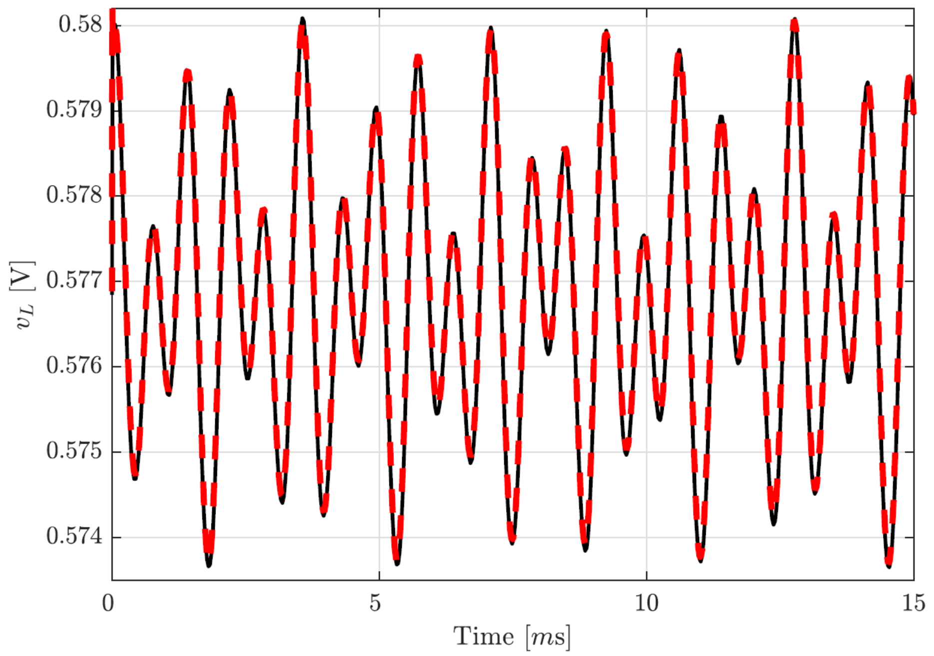
Transient simulation results: multitone signal

Bias point: $V_{DD} = 1V,\ I_L = 5mA$

Computed time span: $100ms$

Small-signal: multitone noise of amplitude $120mV$ overimposed to V_{DD}

Regulated Voltage



Dashed Red Lines : Model

Black lines: post layout LDO

Model time requirements: 363 ms

Transistor level post Layout: 258 s

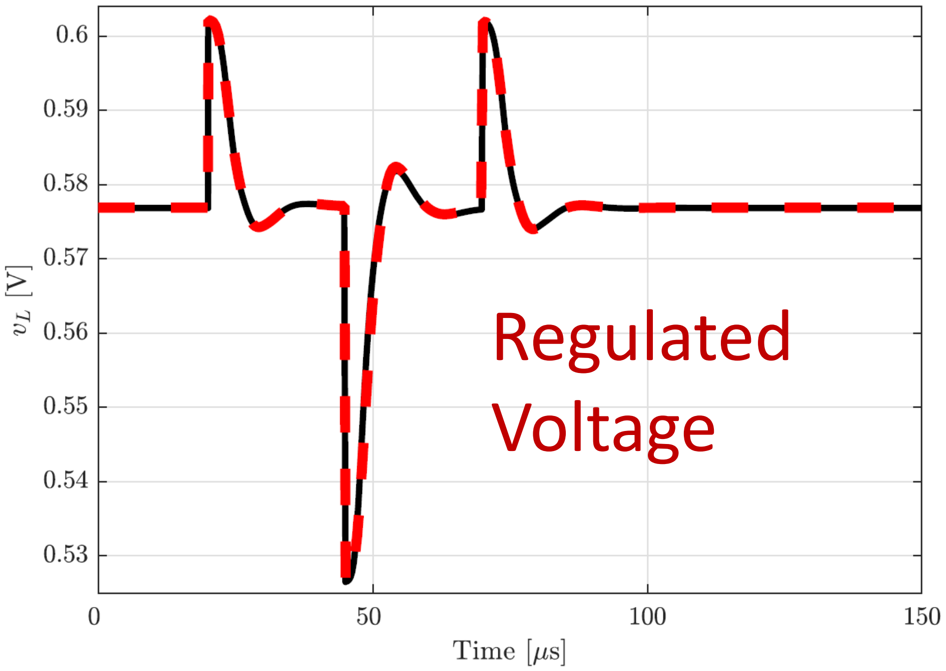
SPEED UP FACTOR: 700X

Transient simulation results: sequential pulses

Bias point: $V_{DD} = 1V,\ I_L = 5mA$

Computed time span: $100\mu s$

Small-signal: Sequential square pulses of amplitude $\pm 25mV$ over V_{DD}



Dashed Red Lines : Model

Black lines: post layout LDO

Model time requirements: 93 ms

Transistor level post Layout: 63 s

SPEED UP FACTOR: 675X

Outline

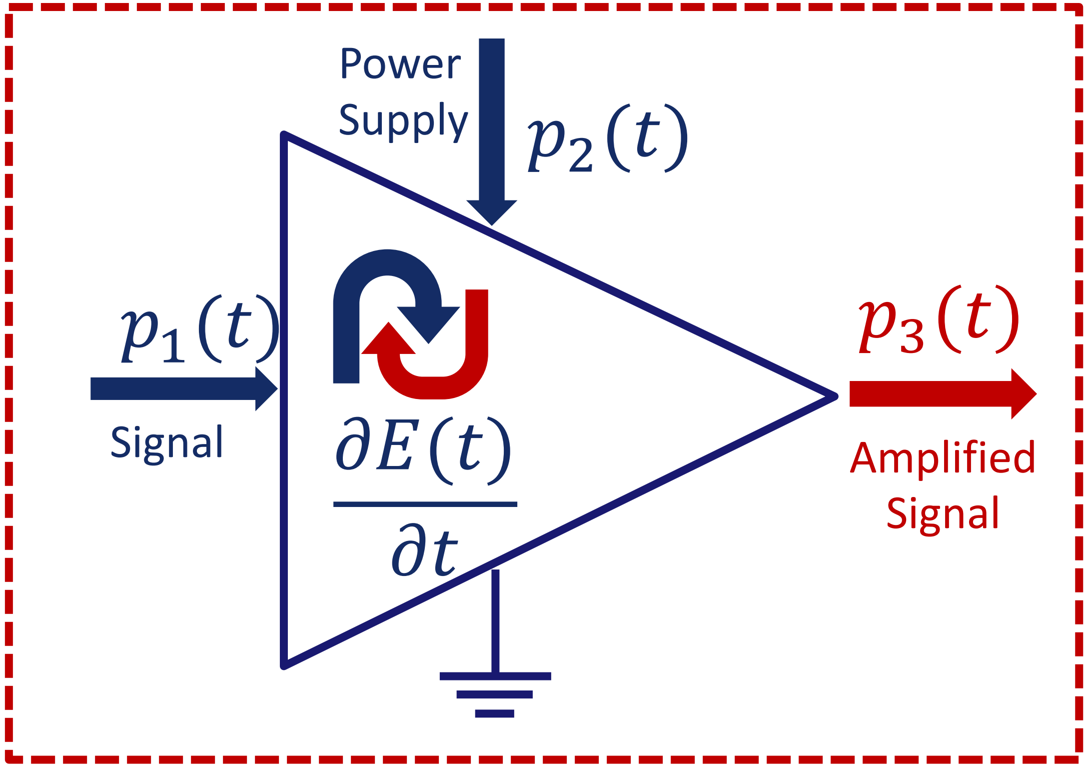
- Recent advancements on macromodeling by Politecnico di Torino
  - Macromodeling of large-scale systems (hundreds of I/O ports)
    - Speaker: Marco De Stefano, PhD candidate
    - Compression strategies
    - Fast passivity verification and enforcement
  - Parameterized (multivariate) macromodels
    - Speaker: Alessandro Zanco, PhD candidate
    - Model structure and enhanced scalability (Radial Basis Functions – RBF)
    - Stability enforcement
  - Small-signal modeling of (nonlinear) analog circuit blocks
    - Speaker: Tommaso Bradde, PhD candidate
    - Embedding bias-dependence through parameterized macromodels
    - **Theoretical assessment of dissipativity**

Remark on dissipativity of active circuits

Any integrated circuit is not able to generate energy on its own

Proper circuit functioning is allowed by external power supply

Illustrative Example: 3-P Amplifier



The amplifier fullfils the dissipation inequality:

$$\frac{\partial E(t)}{\partial t} \leq p_1(t) + p_2(t) - p_3(t)$$

$E(t)$: Stored energy

$p_i(t)$: i-th power flow

Energetic contraints reflects into NL dynamics (e.g.saturation)

Dissipativity of linear affine systems

For linear affine systems we have:

$$p(t) = (U_0 + \tilde{u})^T (Y_0 + \tilde{y}) \qquad \text{AND} \qquad E(x) = \frac{1}{2} x^T P x + q^T x + c, \qquad P = P^T$$

NEW RESULT: DISSIPATIVITY OF LINEAR AFFINE SYSTEMS

$$\exists P, q: \ \tilde{z}^T \Sigma(P) \tilde{z} + 2\theta_0(P, q, U_0, Y_0)^T \tilde{z} - 2U_0^T Y_0 \leq 0$$

Additional terms due to different input power

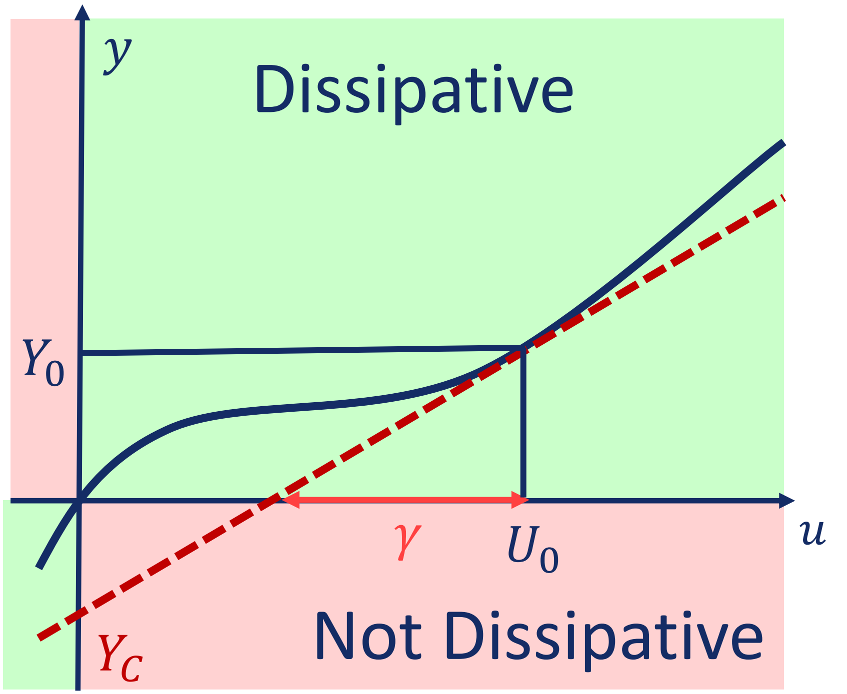
$$p(t) = U_0^T Y_0 + U_0^T \tilde{y} + \tilde{u}^T Y_0 + \tilde{u}^T \tilde{y}$$

DC power: $U_0^T Y_0$ } **Positive**

Small signal power: $\tilde{u}^T \tilde{y}$

Cross-power: $U_0^T \tilde{y} + \tilde{u}^T Y_0$

} **Undefined sign**



Bradde, T., et al. Bounded input dissipativity of linearized circuit models. *IEEE Trans. CAS-I*, 2020, 67.6: 2064-2077.

EMC Group

Conclusions

- Recent advancements on macromodeling by Politecnico di Torino
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    - Fast passivity verification and enforcement
  - **Parameterized (multivariate) macromodels**
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