Electrical Modeling and Simulation Challenges for High-end Microprocessor Systems

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Acknowledgement: Intel Strategic Research Segment (SRS) Grant 2022-24

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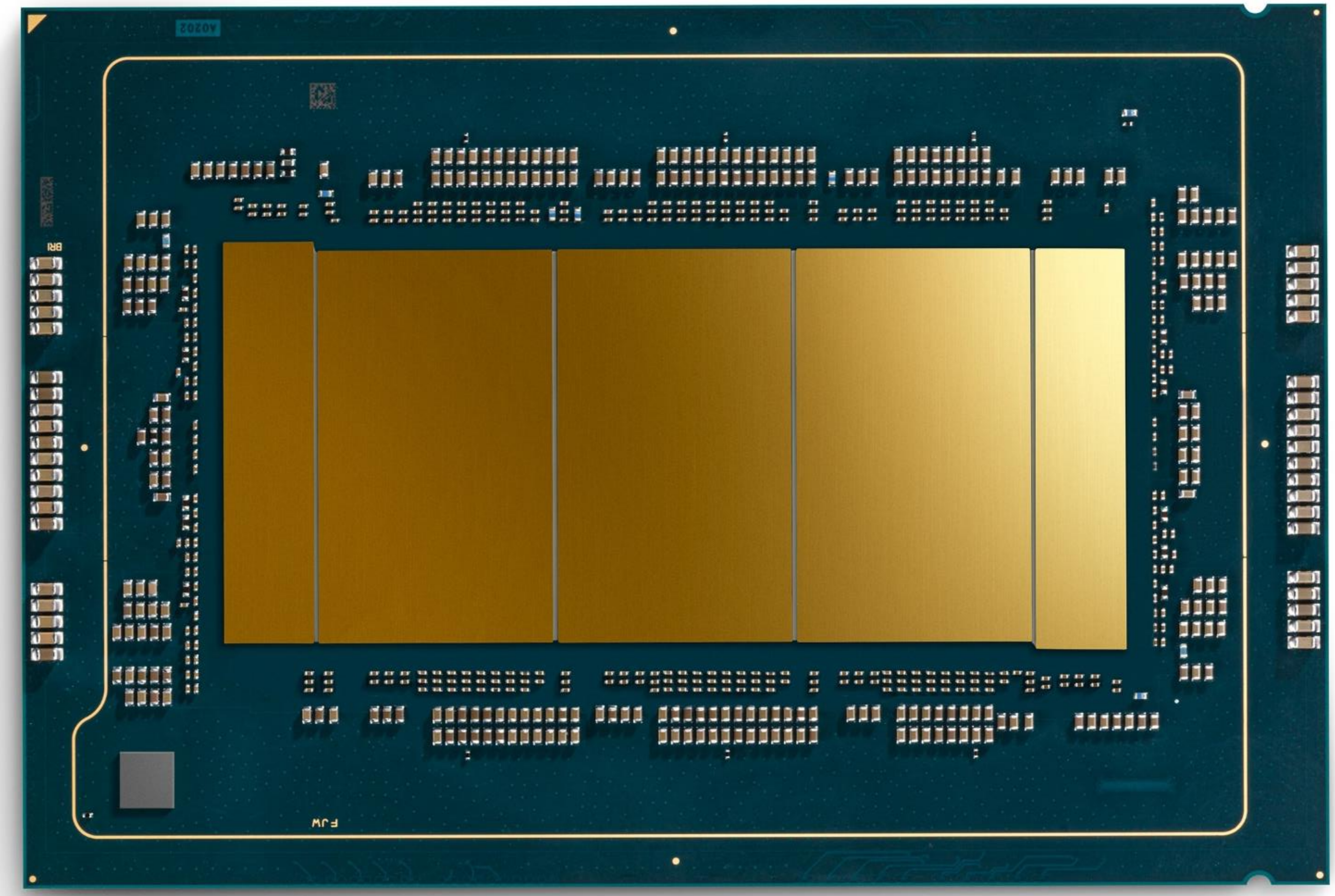
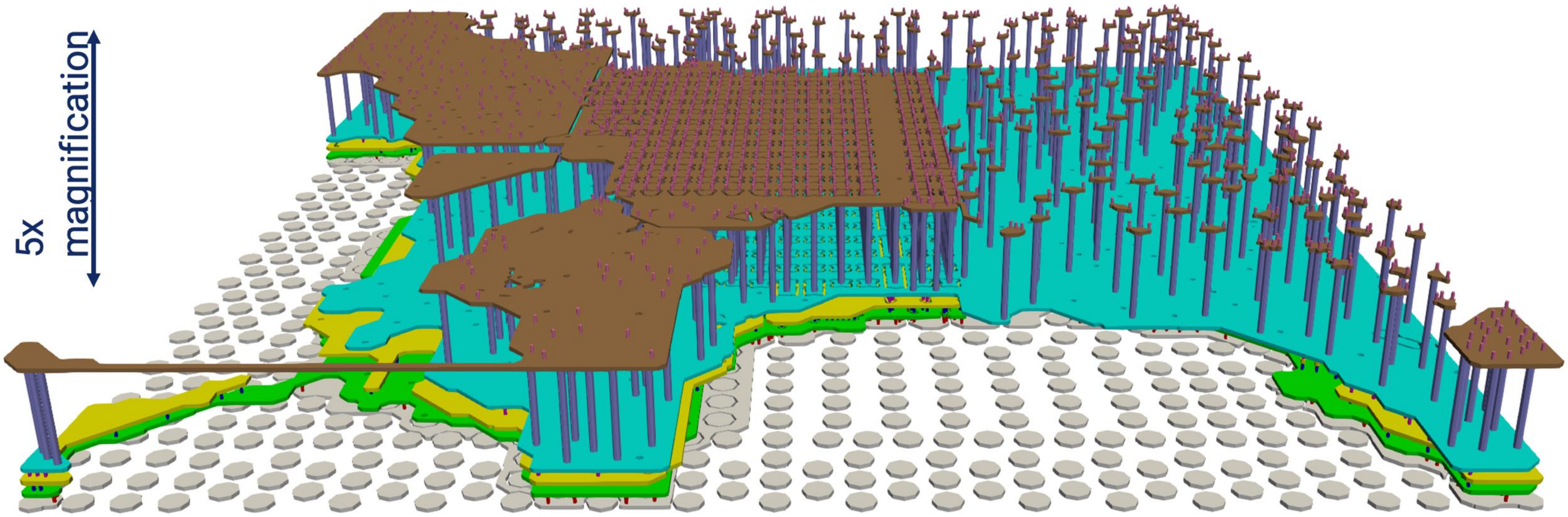
The context



6th generation Intel Xeon processor (2024)

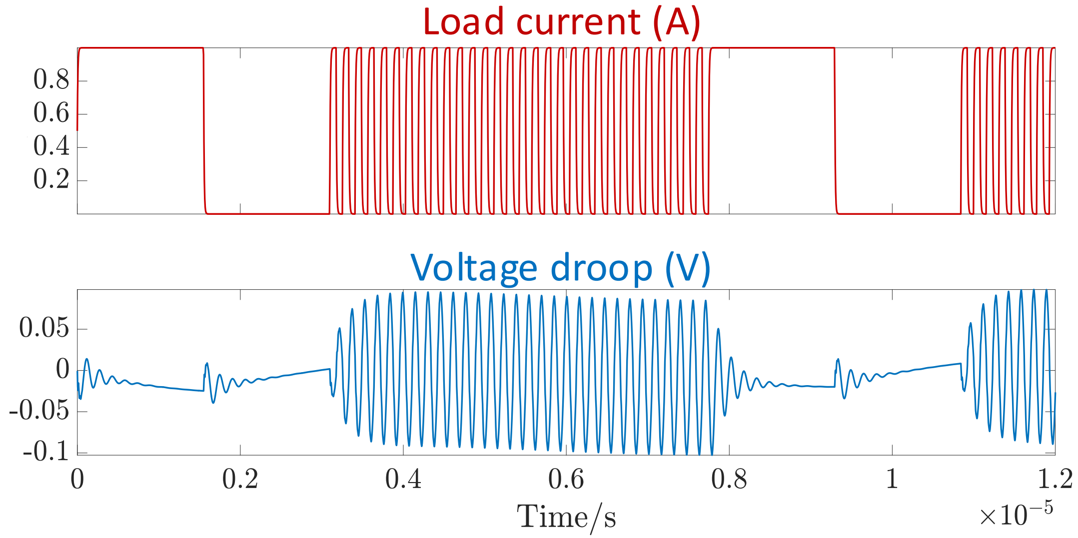
The context

IC package from AMD, see packaging-benchmarks.org/



Electrical modeling: the Power Integrity problem

Power Delivery Network: system level view



Voltage droops must be kept within limits

PI verification:

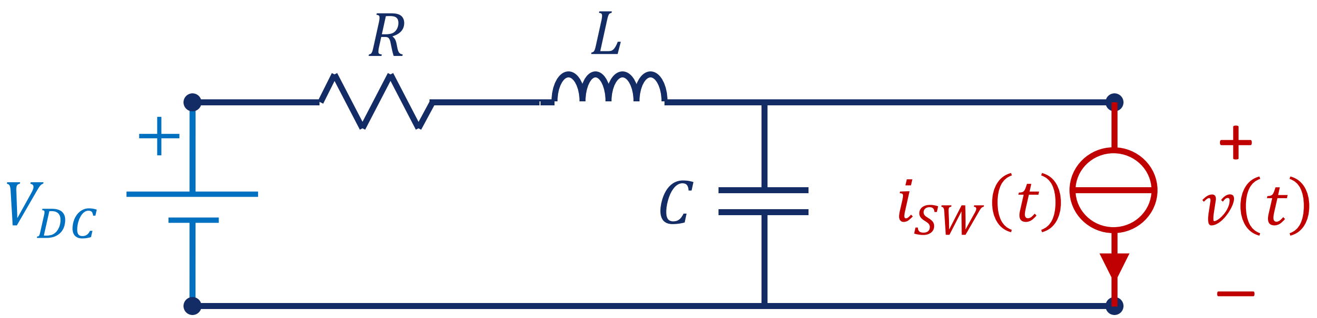
Very long transient simulations

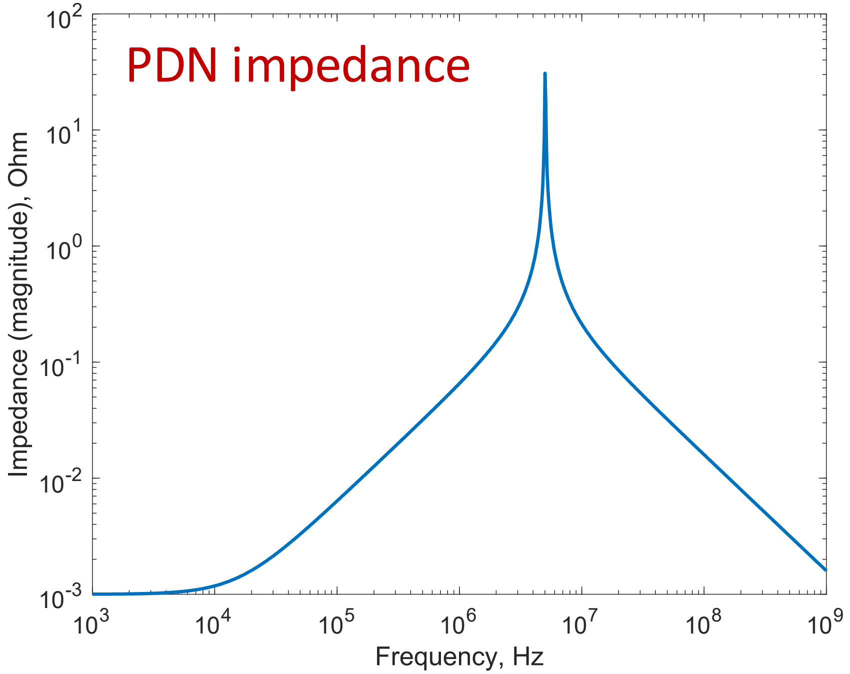
System-level, all parts must be considered

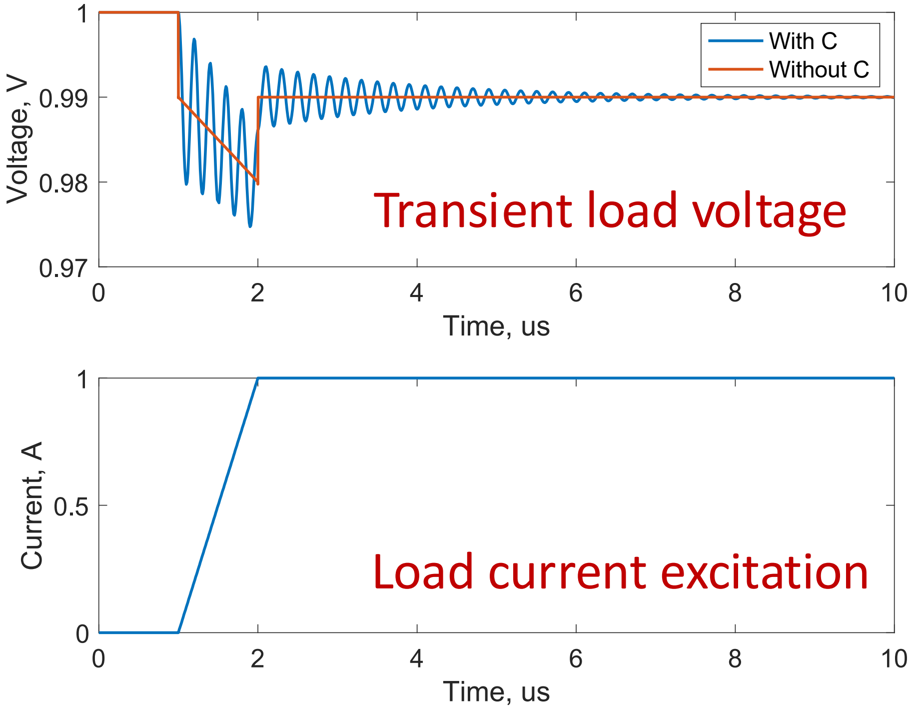
Different excitation patterns (chip activity)

Electrical modeling: the Power Integrity problem

A simplistic PDN model…

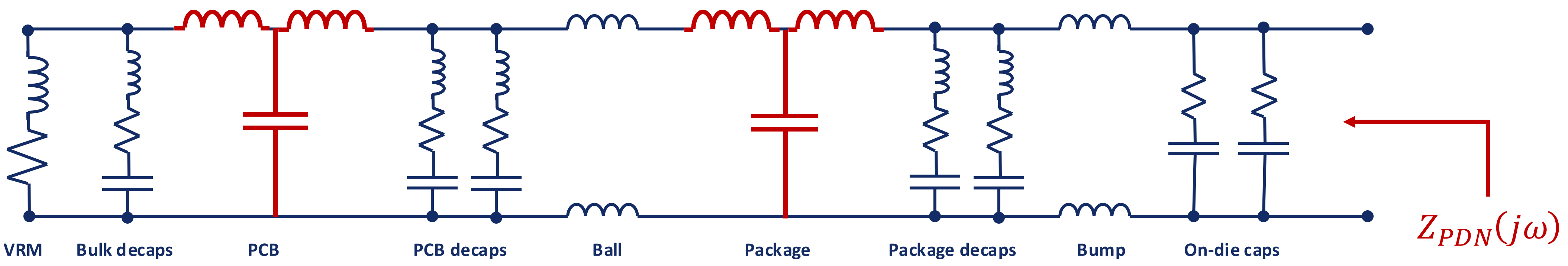






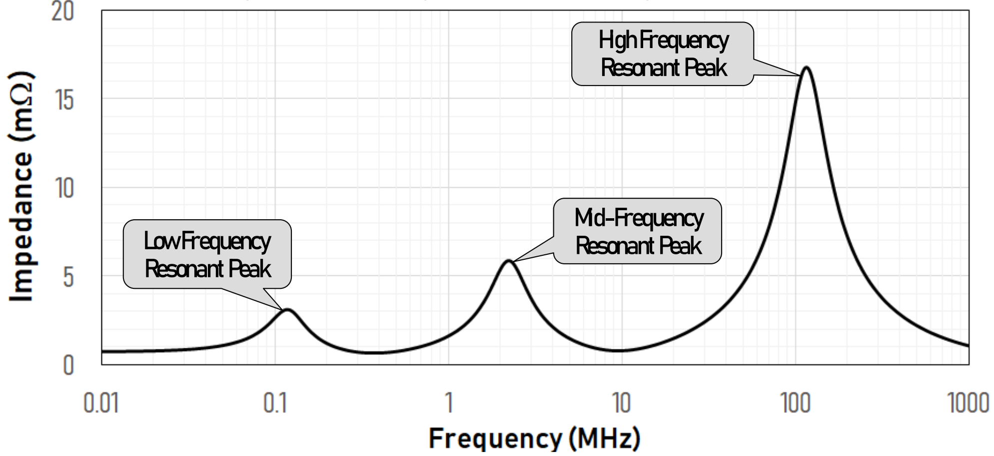
Electrical modeling: the Power Integrity problem

~50 cm — Feature size — 5 nm



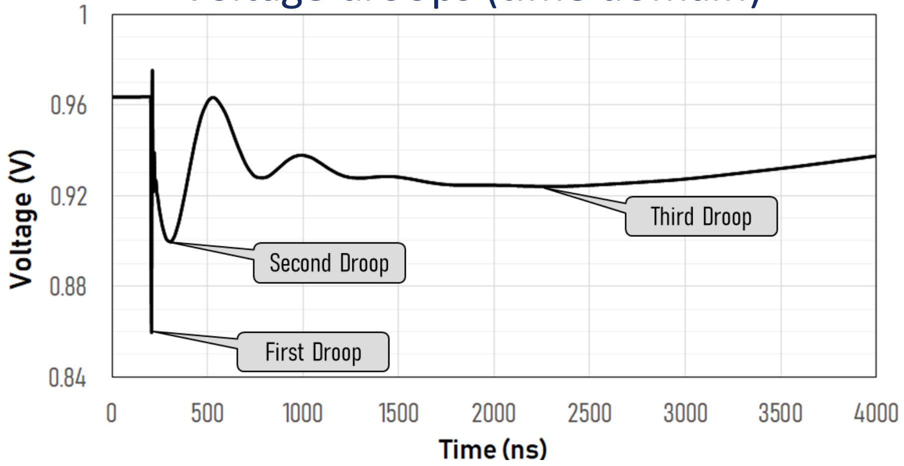
Lumped PDN model

Impedance profile (freq. domain)



Board only   Board+Package   Chip+Package

Voltage droops (time domain)



Electrical modeling: the Power Integrity problem

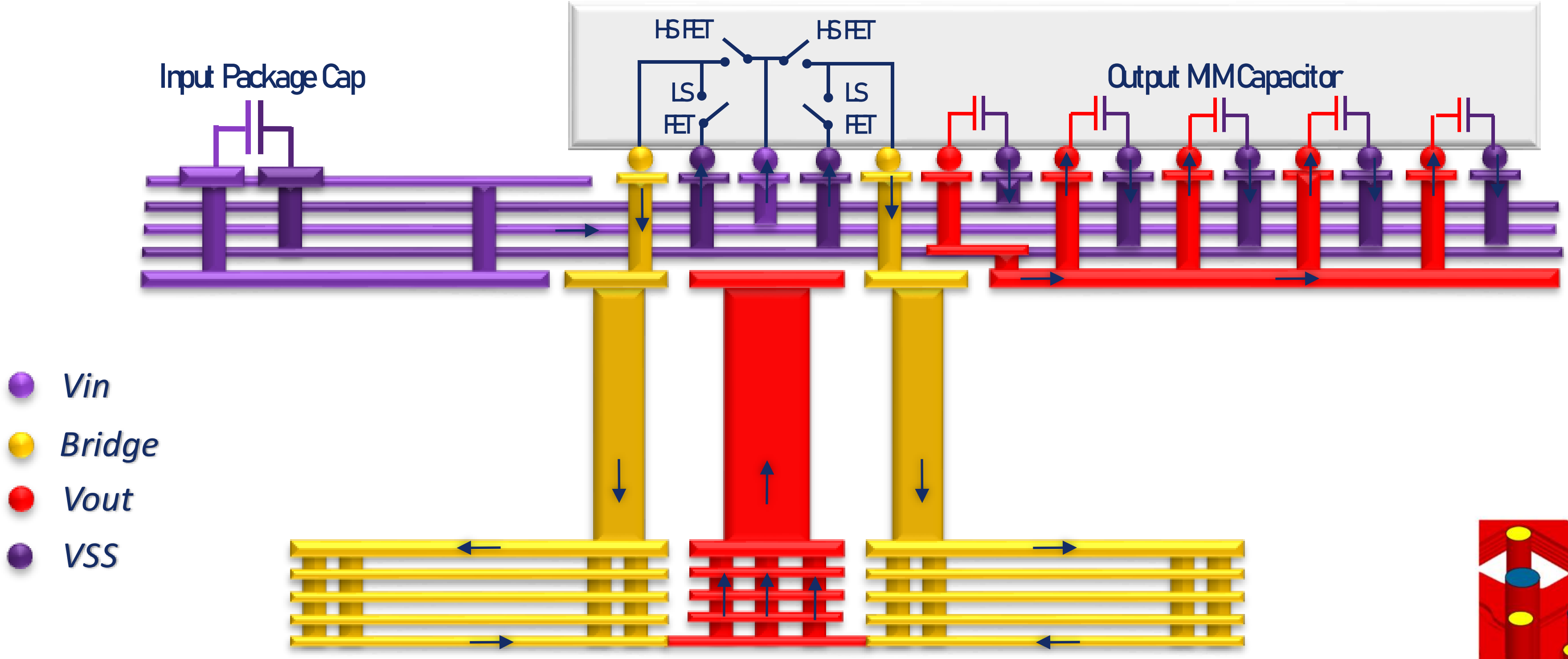
Power Delivery Network: the real structure

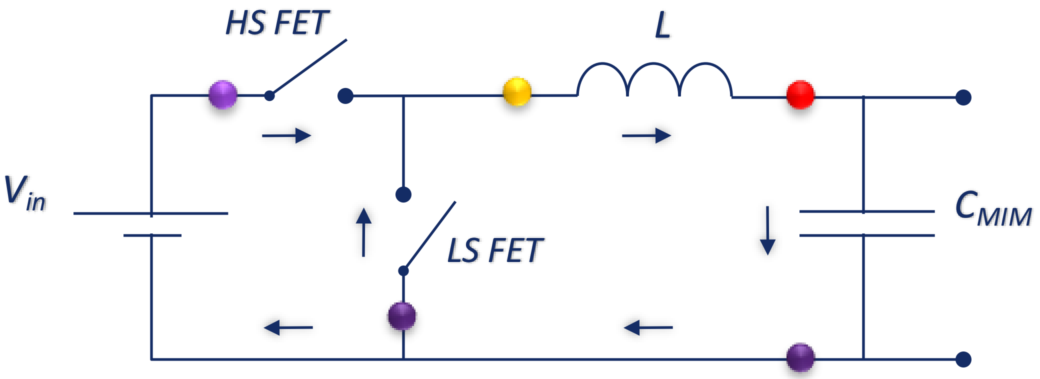
~50 cm 8 orders of magnitude 5 nm

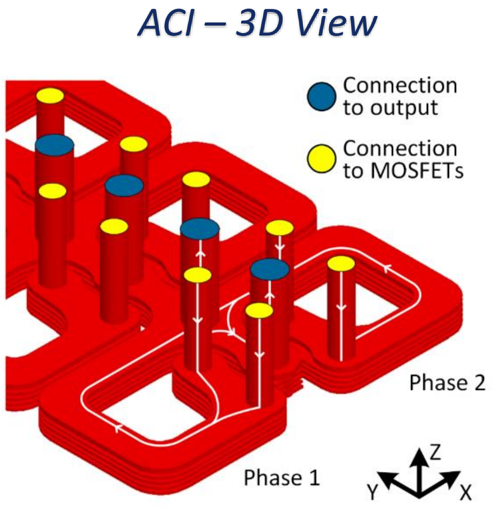
Feature size

Modeling challenges:
multiscale, huge complexity, heterogeneous, interconnected, linear?

Fully Integrated Voltage Regulators (FIVRs)

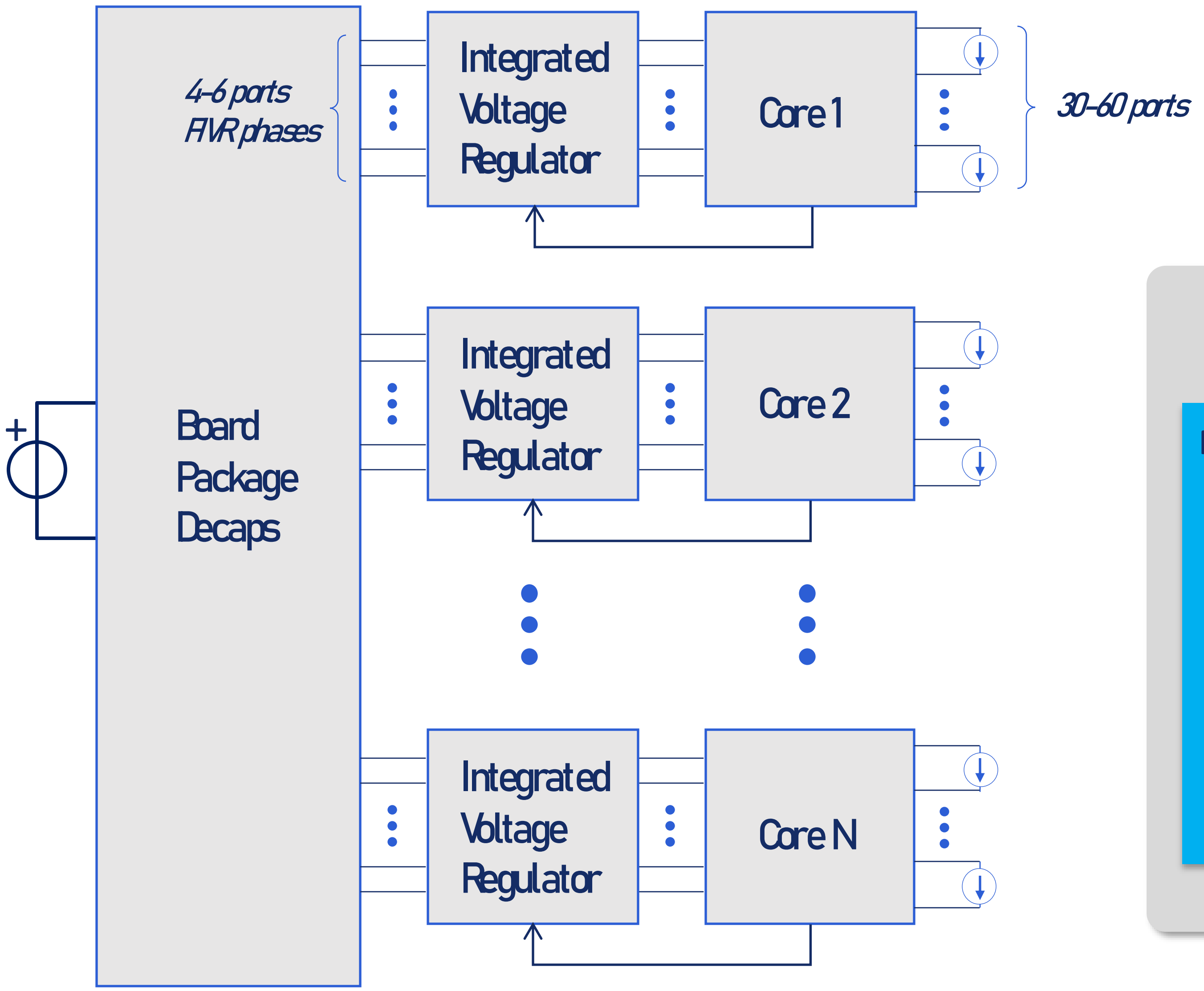






Courtesy: Kaladhar Radhakrishnan, Intel

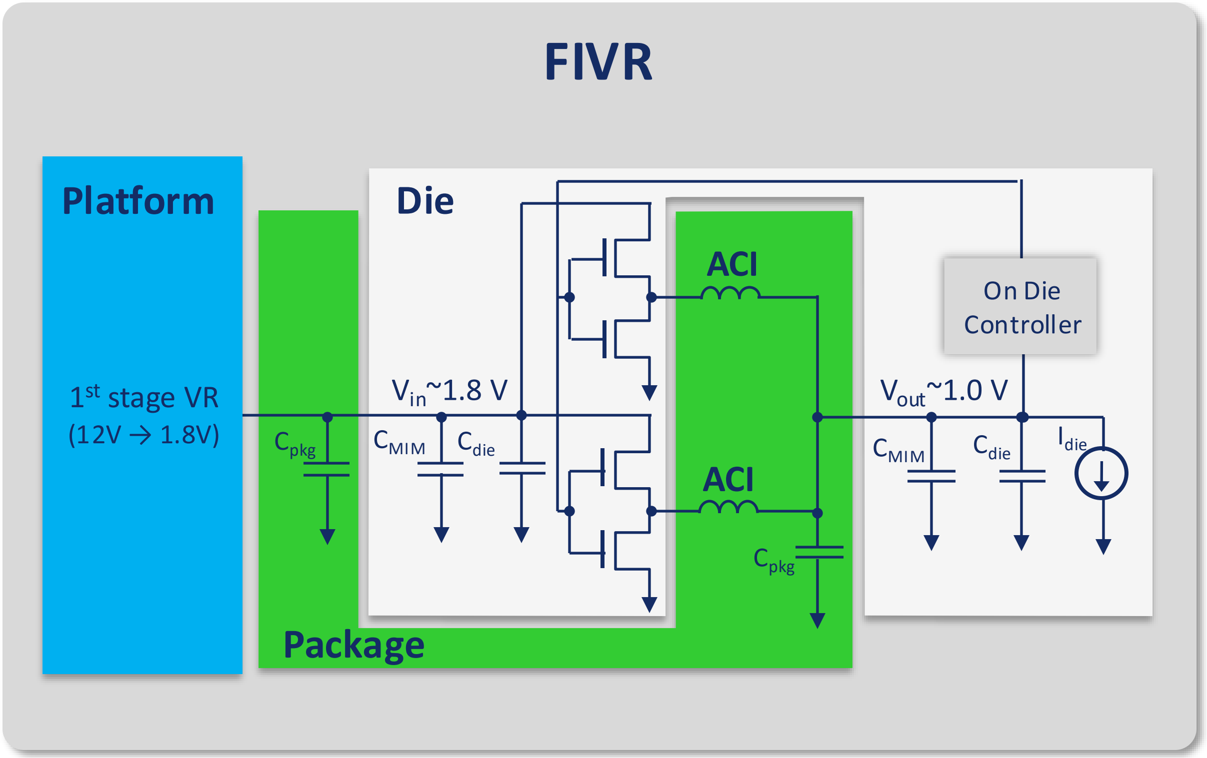
Fully Integrated Voltage Regulators (FIVRs)



Multiphase buck converters

At the chip-package interface

One for each CPU core

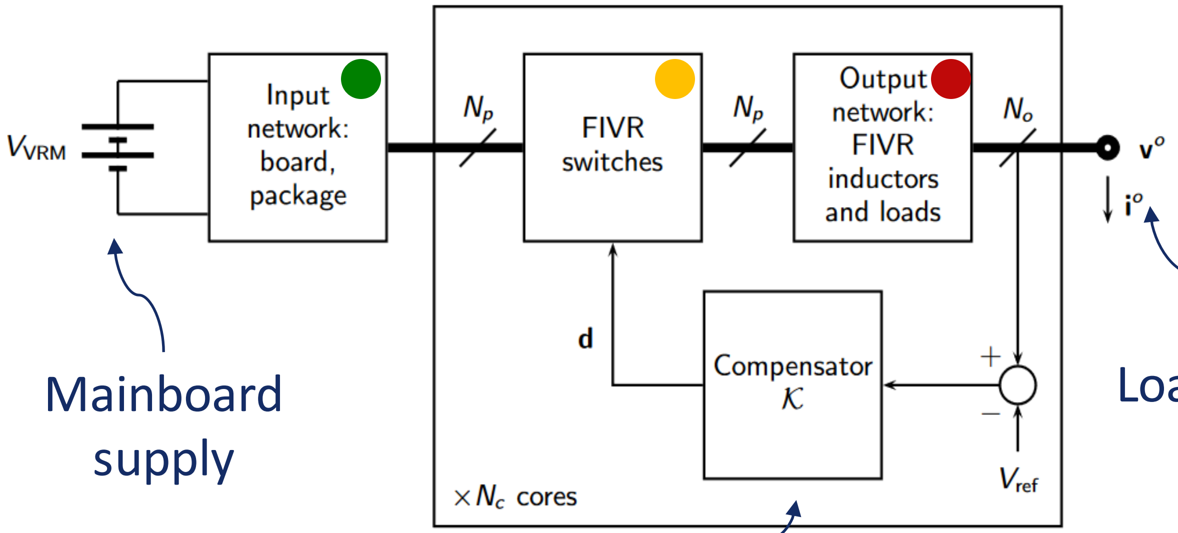


Courtesy: Kaladhar Radhakrishnan, Intel

System-level PDN with FIVRs

Structure

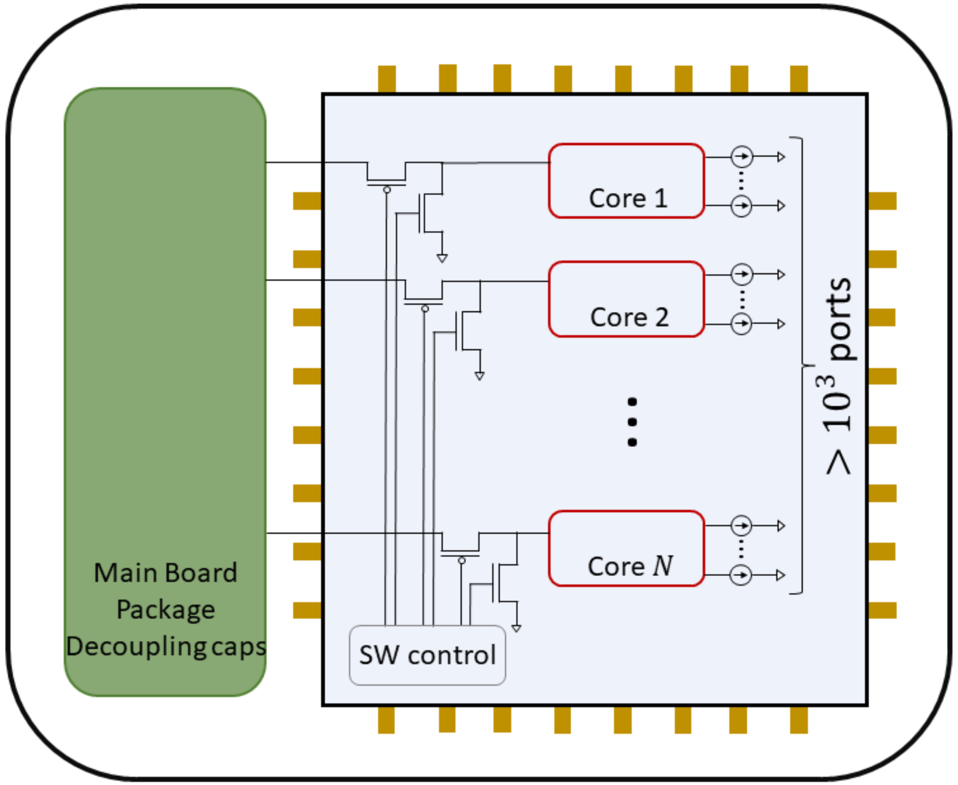
- **Board/package PDN:** large-scale LTI subsystem
- **Die subsystem** (+inductors): many identical models
- **FIVR switches:** one (multiphase block) per core

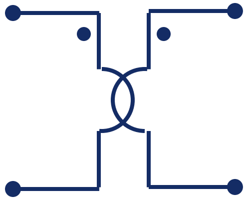


Mainboard supply

Load ports

Compensator steers duty cycle d to regulate load voltage v^o





Averaged switch model OK for system-level

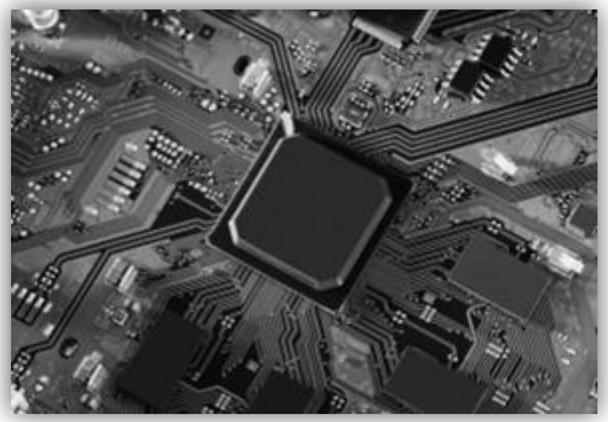
Nonlinear: d is a variable

Challenges

- Problem 1: generate simulation models for all system parts
  - Linear interconnect subsystems, fully coupled, many ports
  - Require Maxwell equation solvers, full-wave, frequency-domain → S-parameters
  - S-parameters → simulation models (SPICE): Vector Fitting + Passivity Enforcement
  - Issue: scalability with number of ports, inconsistency of field solver results
- Problem 2: interconnection of linear macromodels. Simple?
  - Interconnected system still too large (HSPICE fails)
  - Loading conditions may trigger sensitivity and error magnification
- Problem 3: multiple feedback with controllers and FIVR switches
  - Combined with overall complexity, leads to intractable system

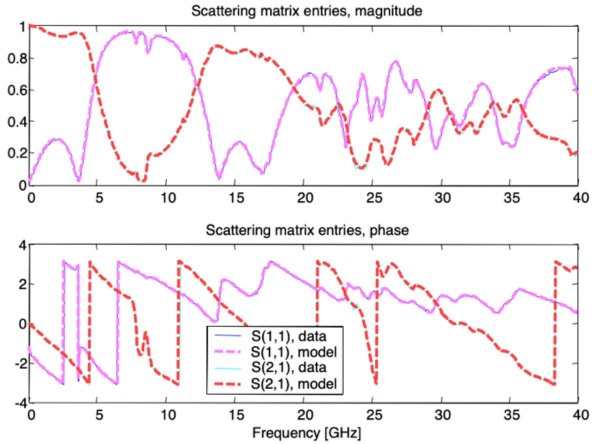
Building individual models: Vector Fitting

Geometry, materials



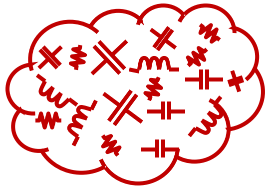
Extraction
EM simulation
Ckt simulation

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



Macromodel

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

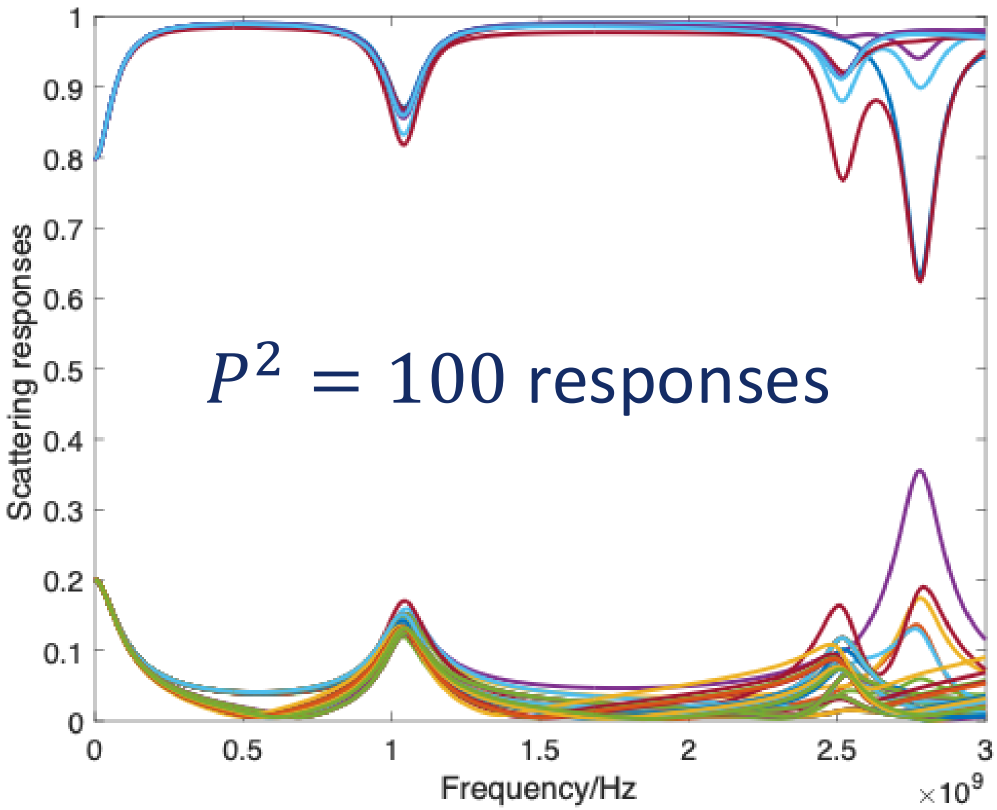


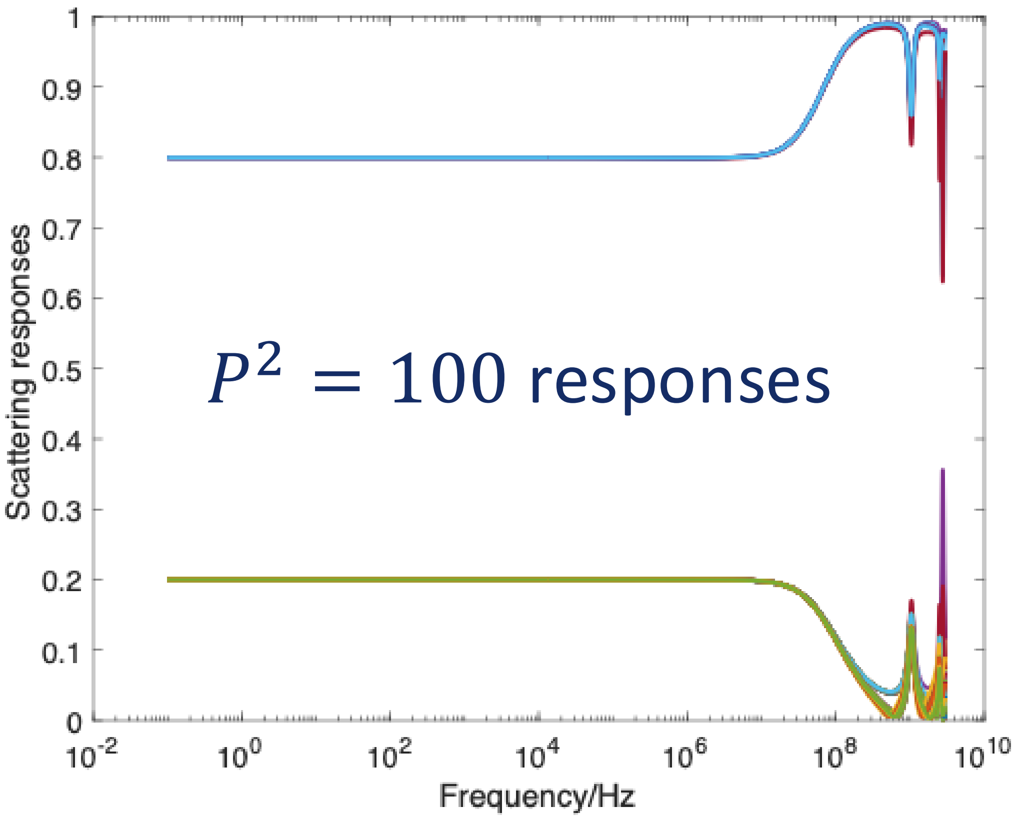
Rational fitting
Passivity enforcement

Realization
or synthesis

$$S(s) = R_0 + \sum_{i=1}^{\nu} \frac{R_i}{s - p_i}$$

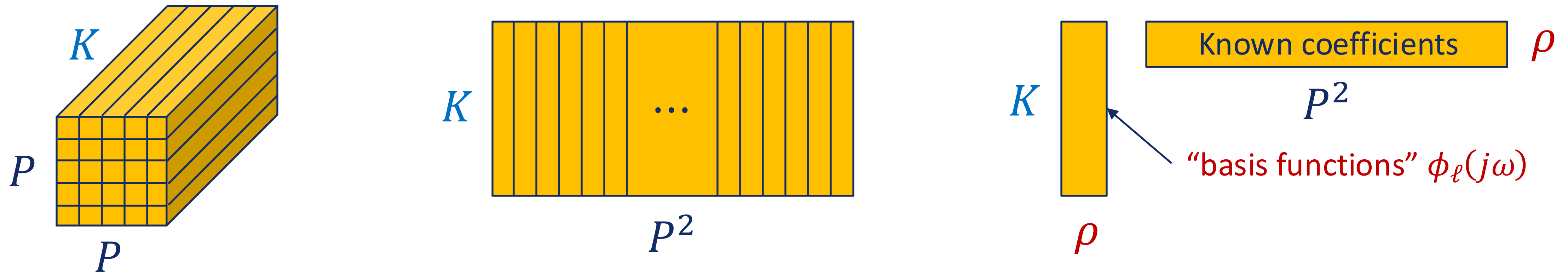
A simple 10-port PDN example





Compressed macromodeling

Scattering tensor from solver | Reshaped tensor | SVD (randomized, constrained real)



Ports: $P \sim 10^3$
Freqs: $K \sim 10^4$
Basis: $\rho \sim 100$

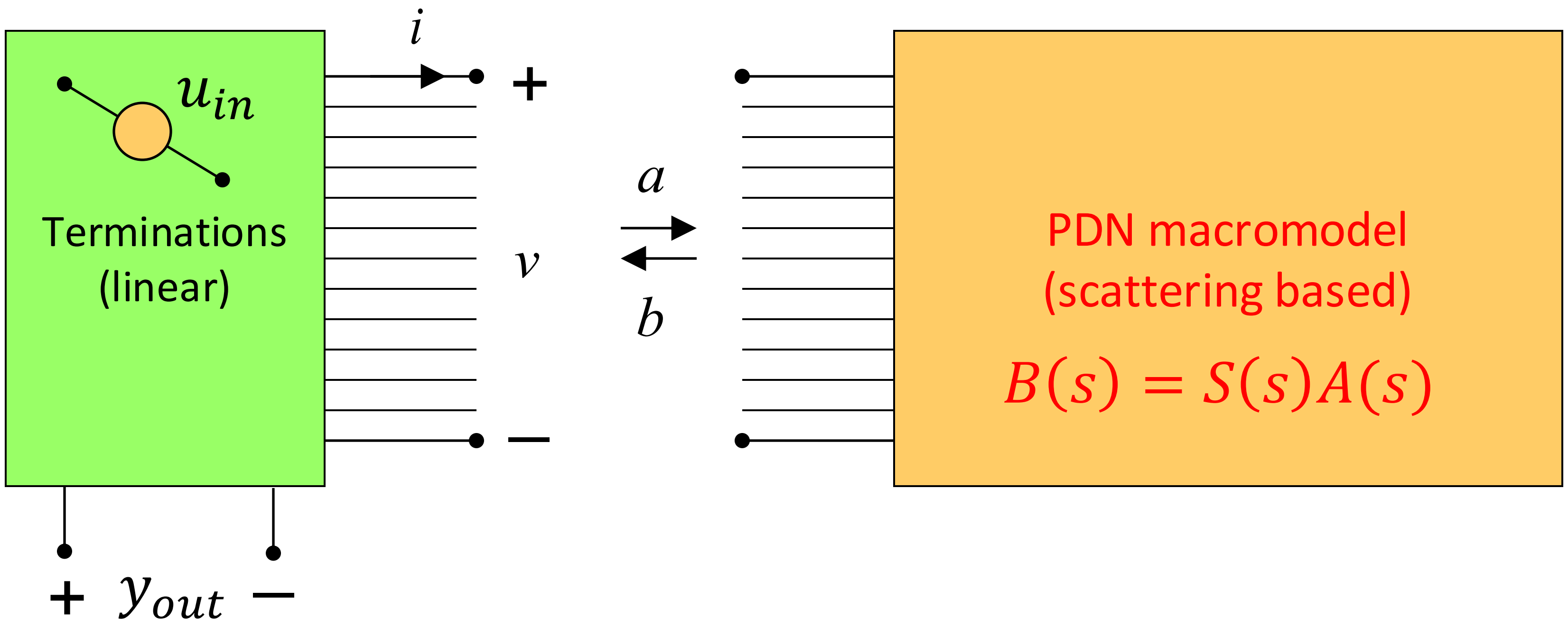
$$S_{ij}(s) \approx \sum_{\ell} \alpha_{ij;\ell}\phi_\ell(s)$$

← Vector Fitting applied only to $\phi_\ell(j\omega)$

A-priori error bounds!

S. B. Olivadese and S. Grivet-Talocia, "Compressed passive macromodeling," IEEE Transactions on Components, Packaging, and Manufacturing Technology, vol. 2, pp. 1378–1388, August 2012.
M. De Stefano, T. Wendt, C. Yang, S. Grivet-Talocia, and C. Schuster, "Regularized and compressed large-scale rational macromodeling: Theory and application to energy-selective shielding enclosures," IEEE Transactions on Electromagnetic Compatibility, vol. 64, pp. 1365–1379, Oct. 2022.

Sensitivity



Standard VF flow

Input data (from solver)

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

Rational macromodel

$$S(s) = R_0 + \sum_{i=1}^{\nu} \frac{R_i}{s - p_i} = \frac{n(s)}{d(s)}$$

Fitting condition

$$S(j\omega_k) \approx \hat{S}_k$$

Target transfer function

$$Y_{out}(s) = H(s)U_{in}(s)$$

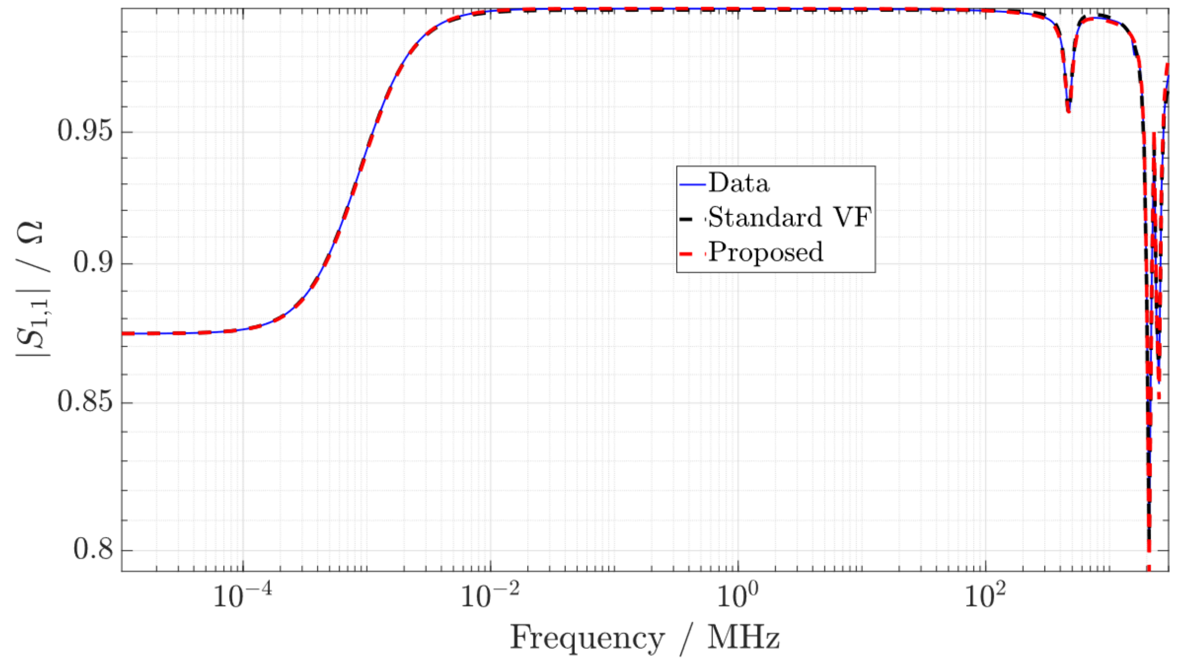
This should be accurate!

Solution: modified VF cost function

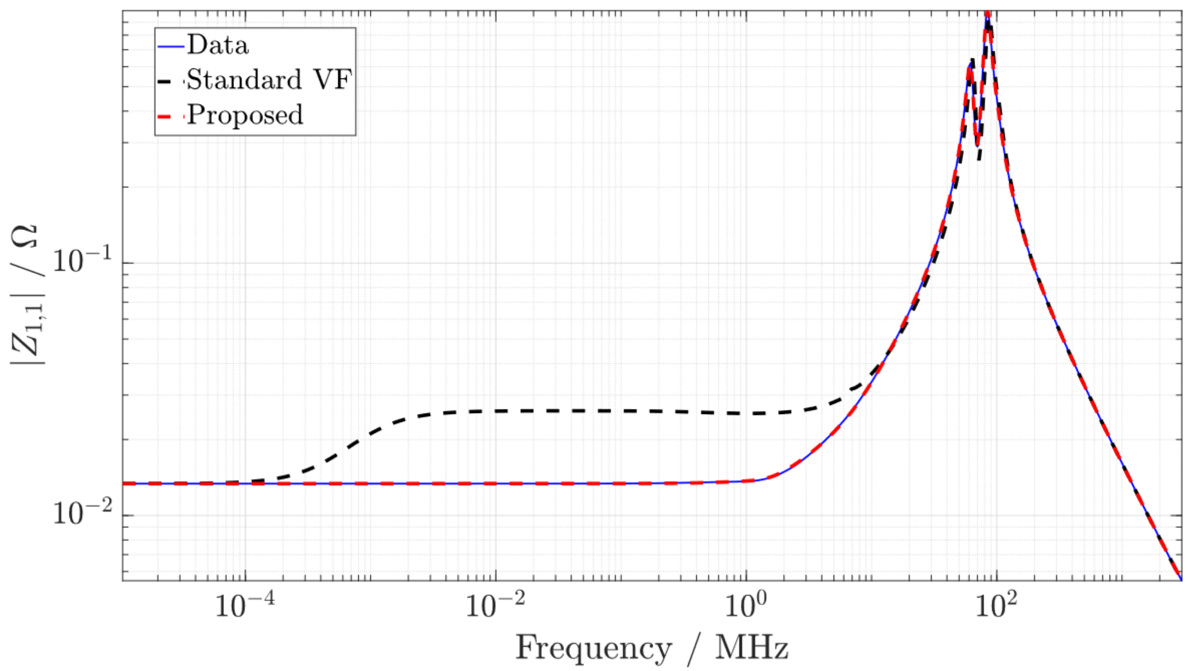
$$\sum_{k=1}^{K} \left\| n(j\omega_k) - d(j\omega_k)\hat{S}(j\omega_k) \right\|^2 + \lambda \cdot \sum_{k=1}^{K} \left\| n(j\omega_k)\hat{U}(j\omega_k) - d(j\omega_k)\hat{Y}(j\omega_k) \right\|^2$$

Sensitivity: an example

Accurate S-parameter model…

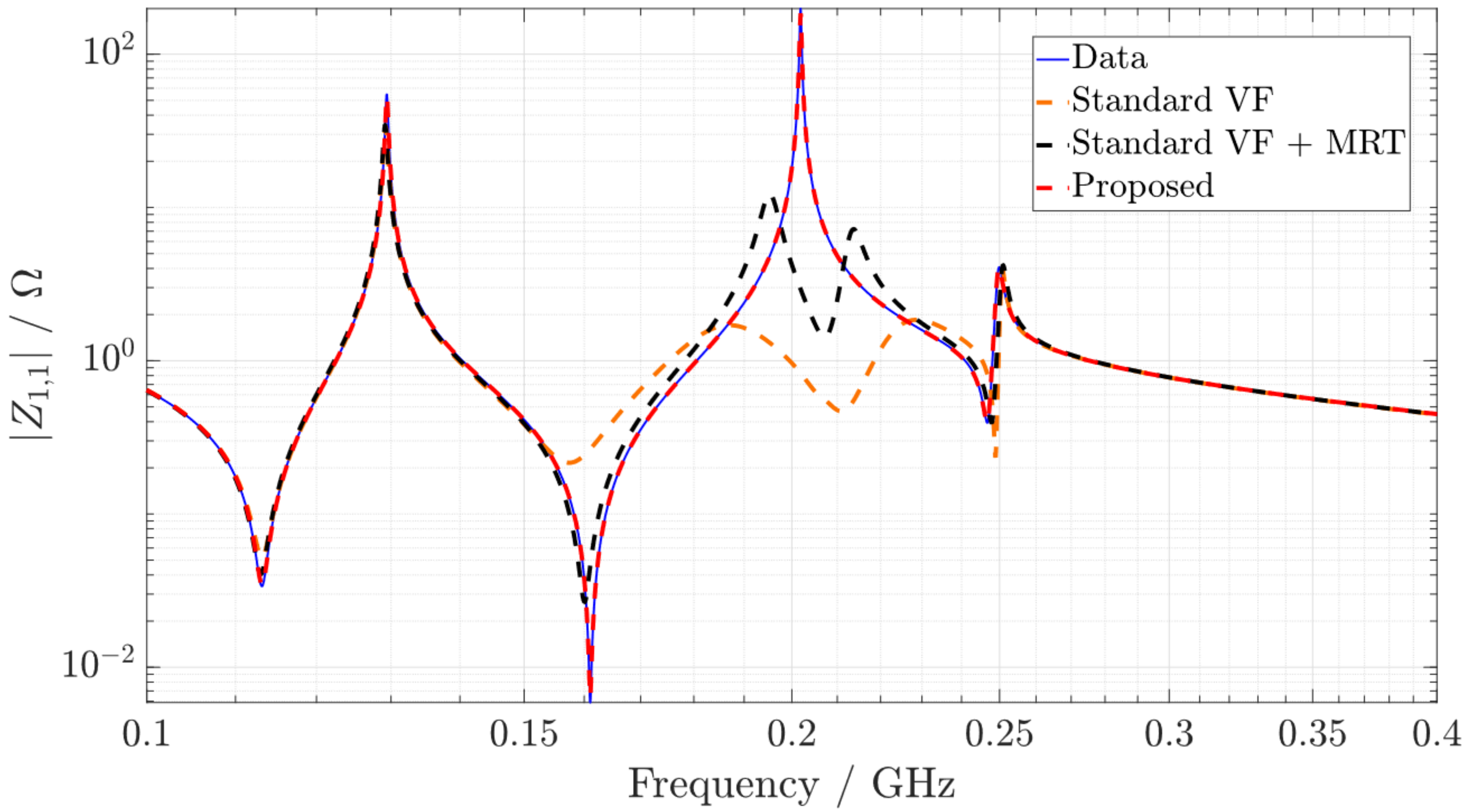


…but error magnification occurs in basic VF



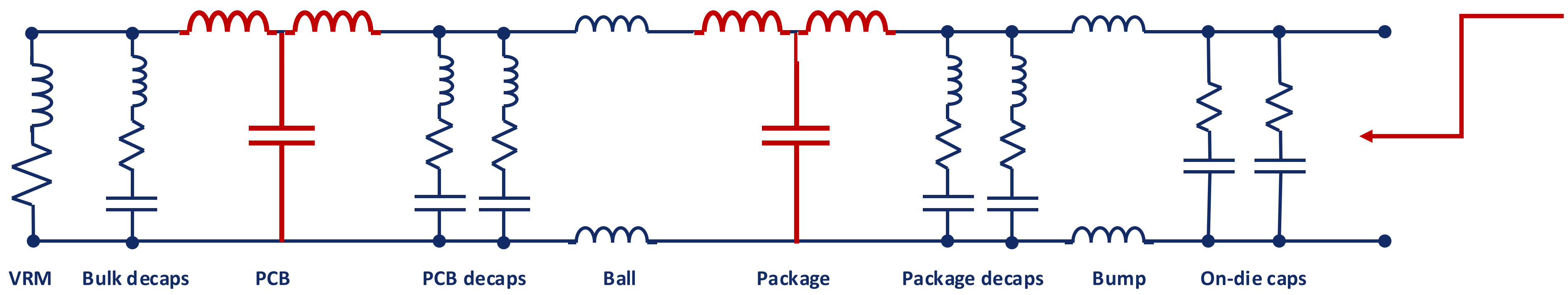
A. Carlucci, T. Bradde, and S. Grivet-Talocia, "Addressing load sensitivity of rational macromodels," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 13, pp. 1591–1602, Oct 2023.

Sensitivity: another example



A. Carlucci, T. Bradde, and S. Grivet-Talocia, “Addressing load sensitivity of rational macromodels,” *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 13, pp. 1591–1602, Oct 2023.

More on sensitivity…



Ideally…

$Z_{PDN}(j\omega) \approx 0$

$|S_{PDN}(j\omega)| \approx 1$

$$Z = R_0^{\frac{1}{2}}(I - S)^{-1}(I + S)R_0^{\frac{1}{2}}$$

$$Y = R_0^{-\frac{1}{2}}(I - S)(I + S)^{-1}R_0^{-\frac{1}{2}}$$

For low-loss and resonant interconnects…

$$\sigma\big(S(j\omega)\big) \lesssim 1$$

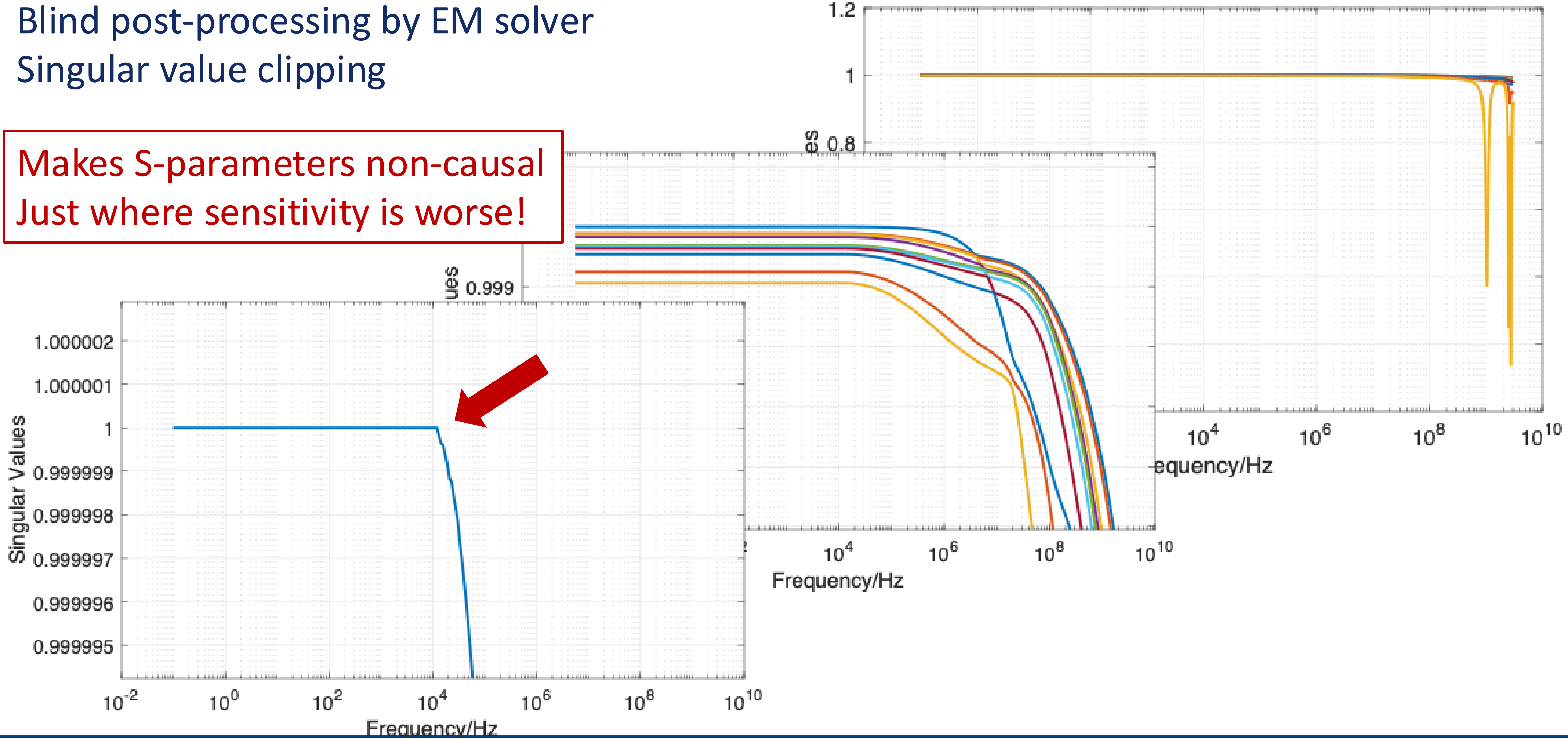
singular values

This condition triggers sensitivity: small error on S leads to large error on Z

More on sensitivity… and non-causal data from solvers

Blind post-processing by EM solver
Singular value clipping

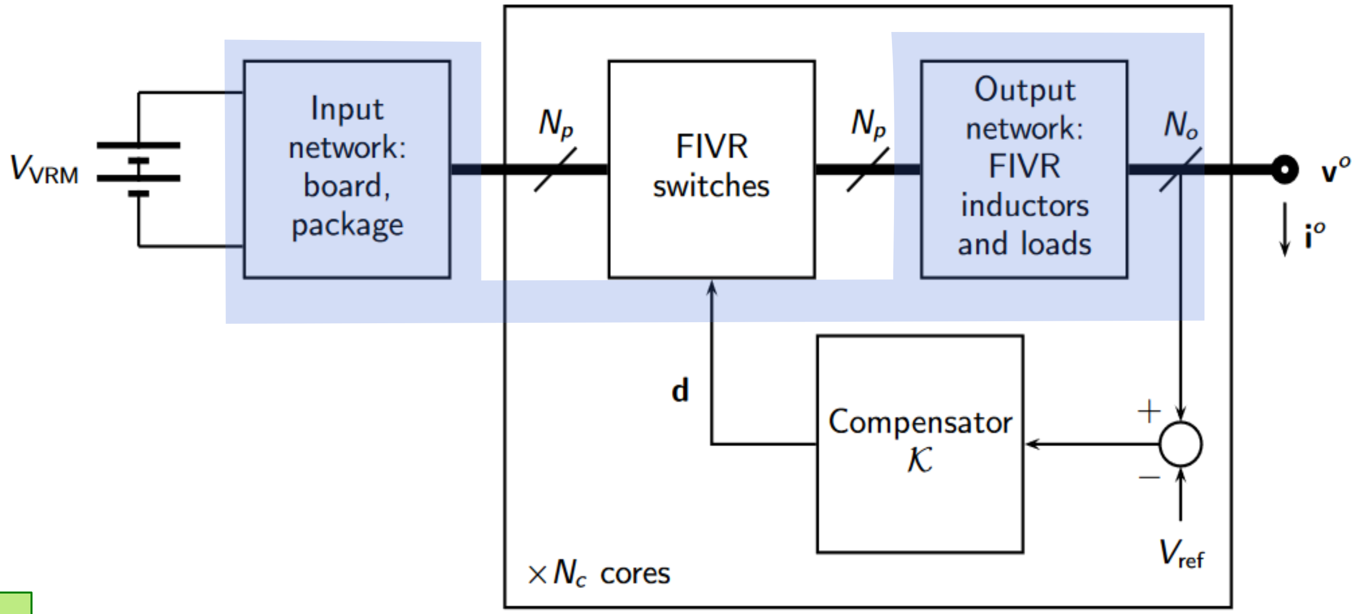
Makes S-parameters non-causal
Just where sensitivity is worse!



Handling Complexity: Structured Model Order Reduction

Collect all LTI blocks

$$\begin{cases} E\,\dot{x} = A\,x + B\,u \\ y = C\,x + D\,u \end{cases}$$



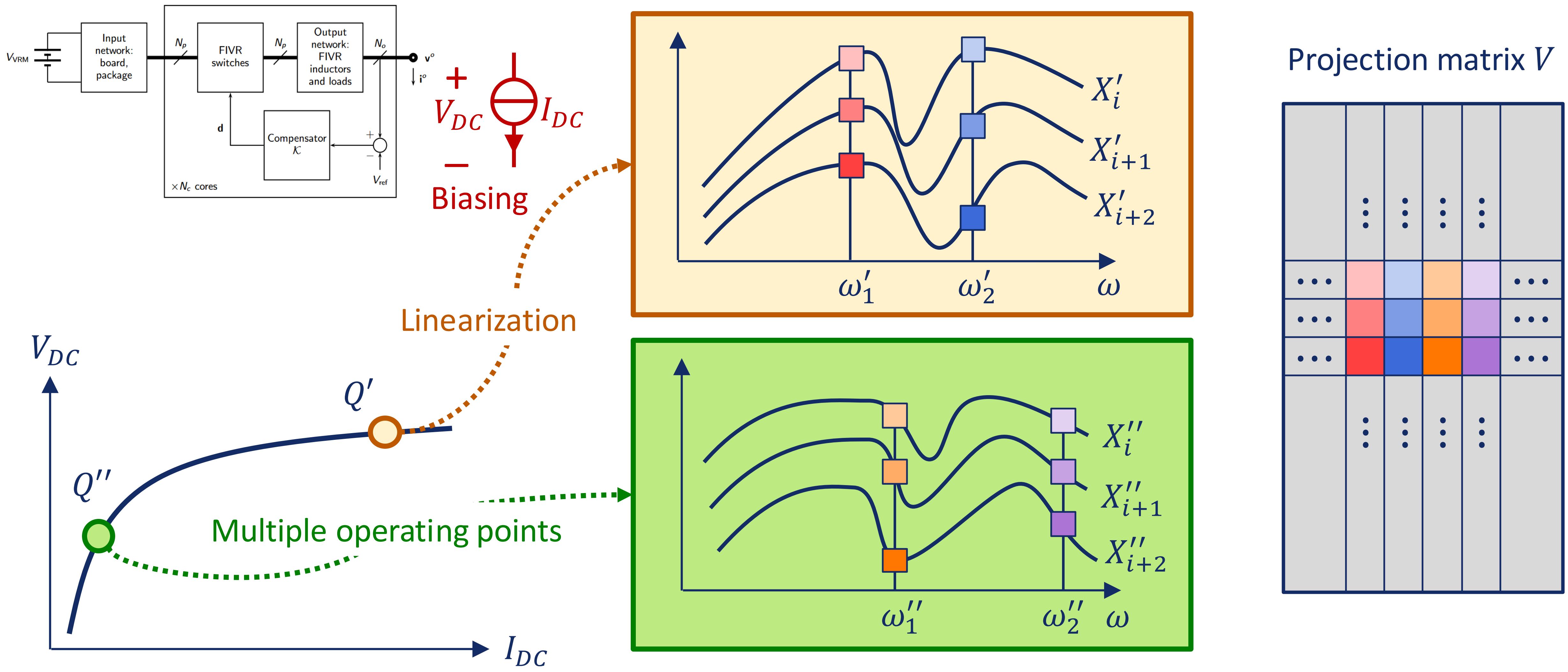
Petrov-Galerkin projection

$$\hat{A} = W^T \, A \, V$$

Typical compression ratio $\sim 100:1$

A. Carlucci, S. Grivet-Talocia, S. Kulasekaran, and K. Radhakrishnan, “Structured model order reduction of system-level power delivery networks,” IEEE Access, vol. 12, pp. 18198–18214, 2024.

Building projection matrices



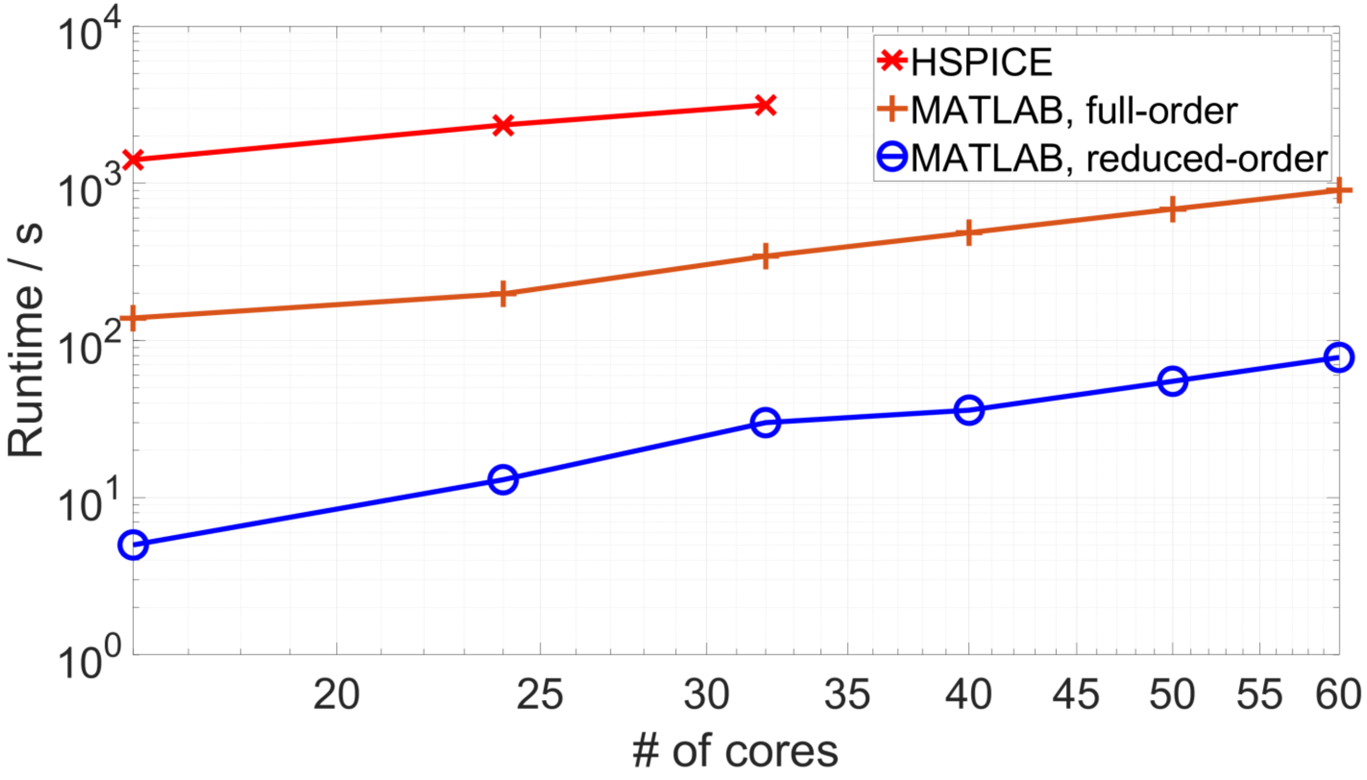
Small-signal state responses

Structured Model Order Reduction

HSPICE fails here!

Speedup

$10^2 - 10^3$



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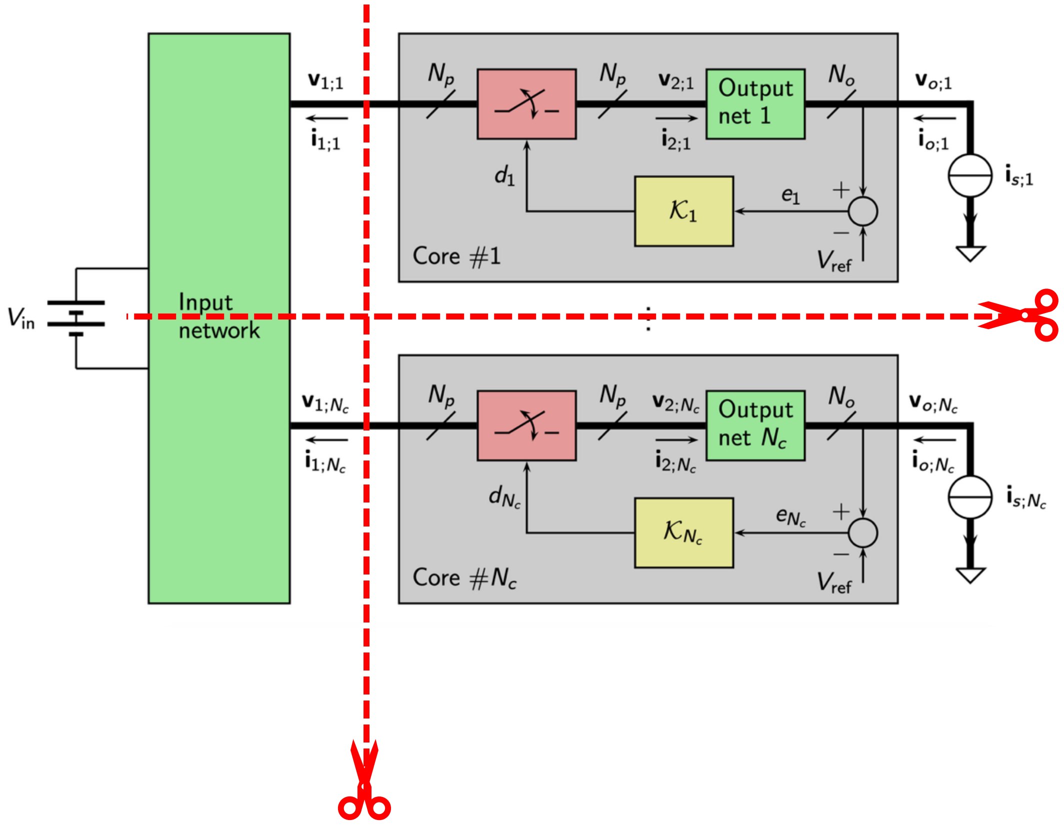
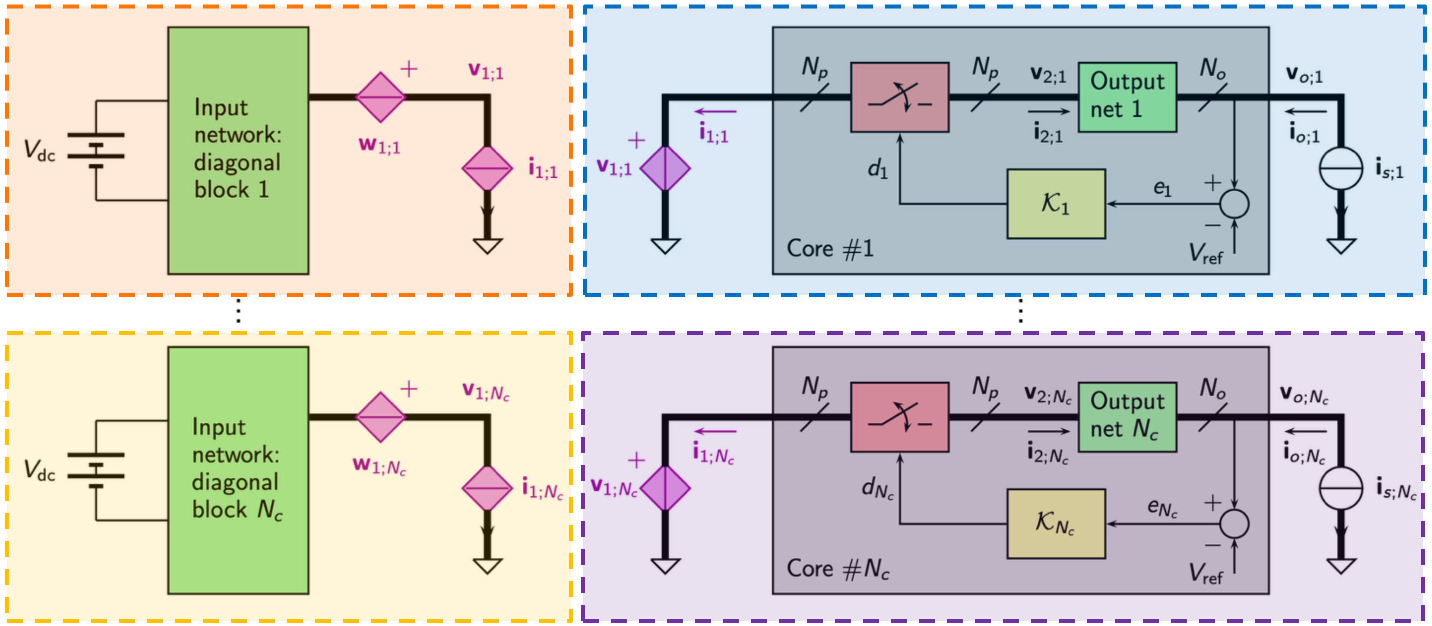
Parallel transient simulation

Fully coupled simulation



Domain decomposition with local (weak) coupling

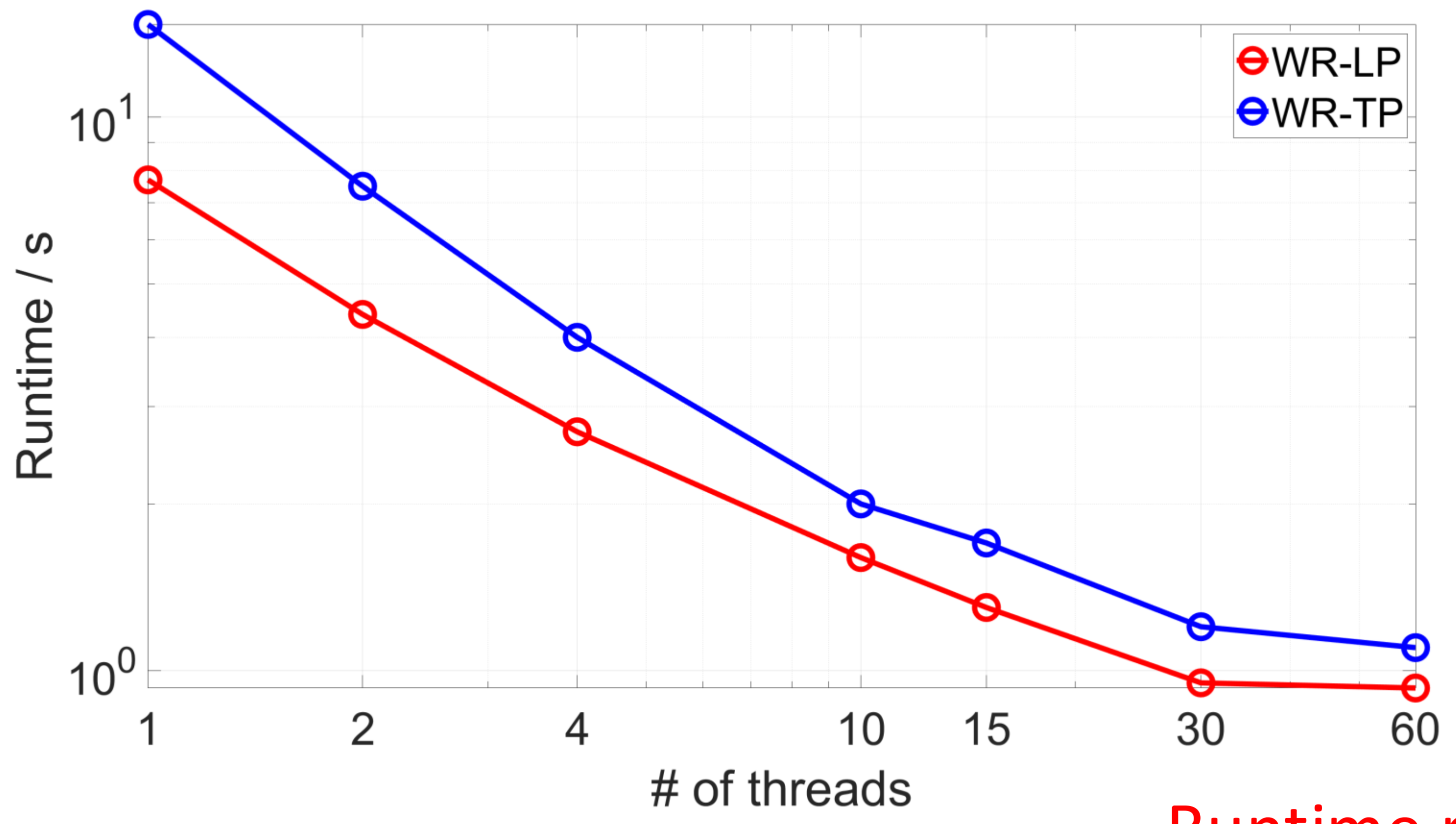


WR Iteration

- Solved by parallel threads
- Update of coupling sources

Parallel transient simulation

Optimized serial solver: <10s



Runtime reduced to < 1s

A. Moglia, A. Carlucci, S. Grivet-Talocia, S. Kulasekaran, and K. Radhakrishnan, “Fast transient simulation of system-level power delivery networks via parallel waveform relaxation,” IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 15, pp. 39–53, Jan 2025.

Thank you

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