Towards real-time S-parameter qualification and macromodeling

Towards real-time S-parameter qualification and macromodeling

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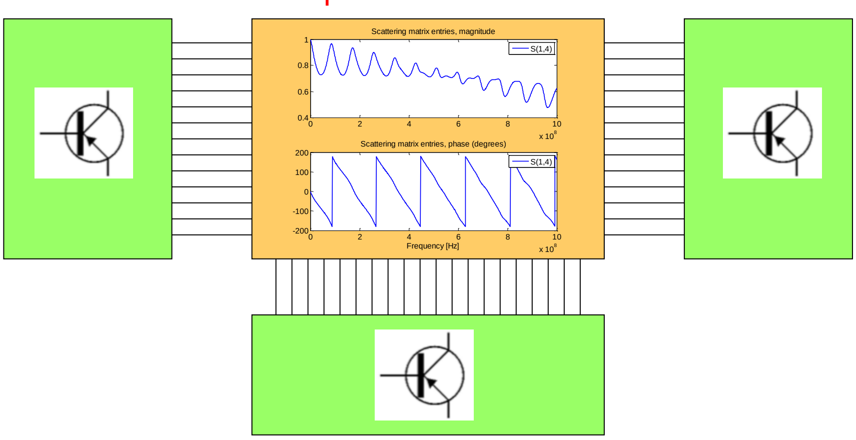
IBIS Summit, 16 May 2012, Sorrento, Italy

S.Grivet-Talocia, “Real-time S-parameter qualification and macromodeling”, IBIS Summit, 16 May 2012, Sorrento, Italy

The objective

S-parameter block



Why S-parameters

- S-parameters are always defined
  - Impedance or admittance may not
- S-parameters are normalized
  - Good numerical properties in simulation
- S-parameters are easily measured
  - Even at very high frequency, good reliability
- Standard format for S-parameters
  - Touchstone files from measurement hardware
  - All field solvers provide S-parameters on output
- Tabulated frequency data
  - Intrinsic IP protection for vendors
  - Do not disclose design details, but only I/O electrical properties
- Best way to represent broadband EM/circuit interactions
  - The essence of Signal and Power Integrity

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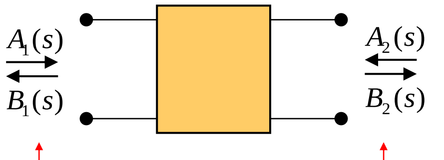
Scattering network functions

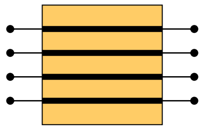


power waves

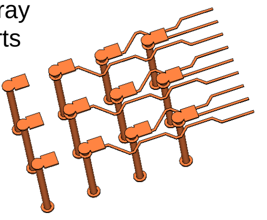
complex frequency

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \underbrace{\begin{bmatrix} S_{11}(s) & S_{12}(s) \\ S_{21}(s) & S_{22}(s) \end{bmatrix}}_{\text{Scattering matrix}} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}$$

Examples of S-parameter data

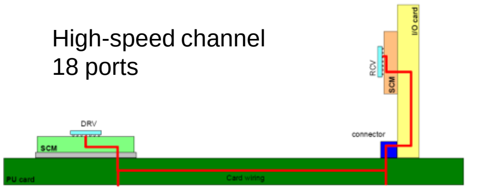


Via array
12 ports



Wiring harness
8 ports

High-speed channel
18 ports



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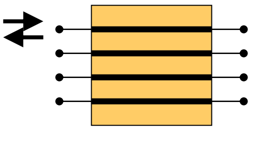
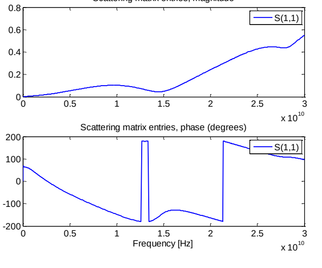
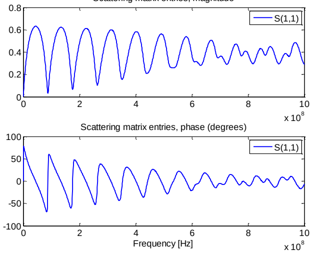
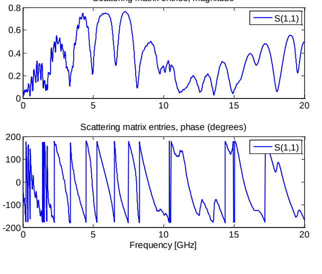
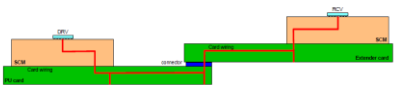








S-parameter modeling flow



Measurement

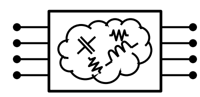
Simulation

Frequency response

Data qualification
Rational approximation
Passivity enforcement
Synthesis

Passive Causal

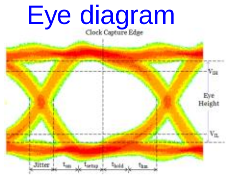
Macromodel



Circuit solver

Time domain simulation

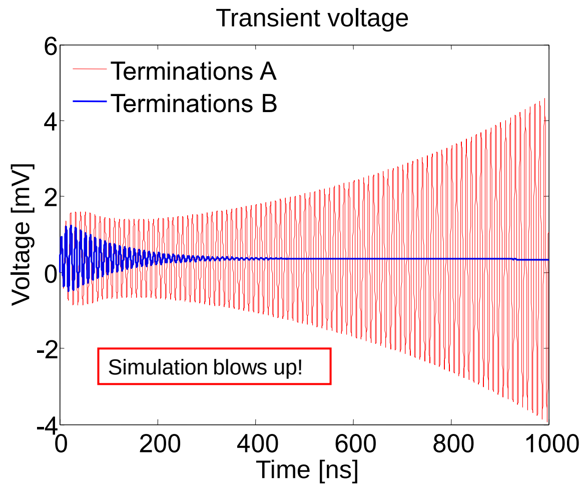
Eye diagram

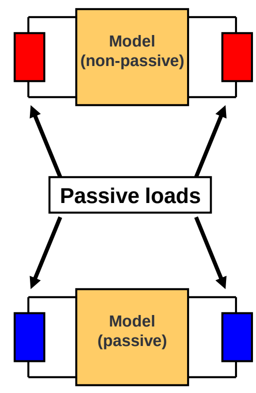


Part I: qualification

A quick overview

Passivity: why?





Passivity

$$\mathbf{S}(-j\omega) = \mathbf{S}^*(j\omega)$$

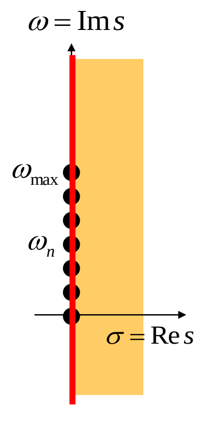
Guarantees real-valued impulse response.
Always assumed by construction

$$\|\mathbf{S}(j\omega)\| \le 1 \quad \text{or} \quad \max_i \sigma_i\{\mathbf{S}(j\omega)\} \le 1$$

Energy condition: structure must not amplify signals.
Sometimes called simply “passivity” condition

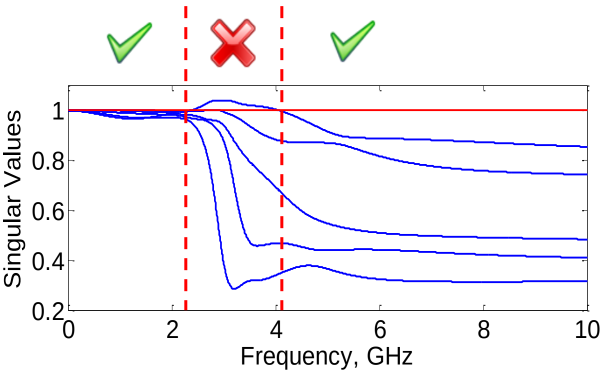
$$\mathbf{S}(j\omega) \text{ is causal}$$

No anticipatory behavior in time-domain.
Note: causality is a prerequisite for passivity!

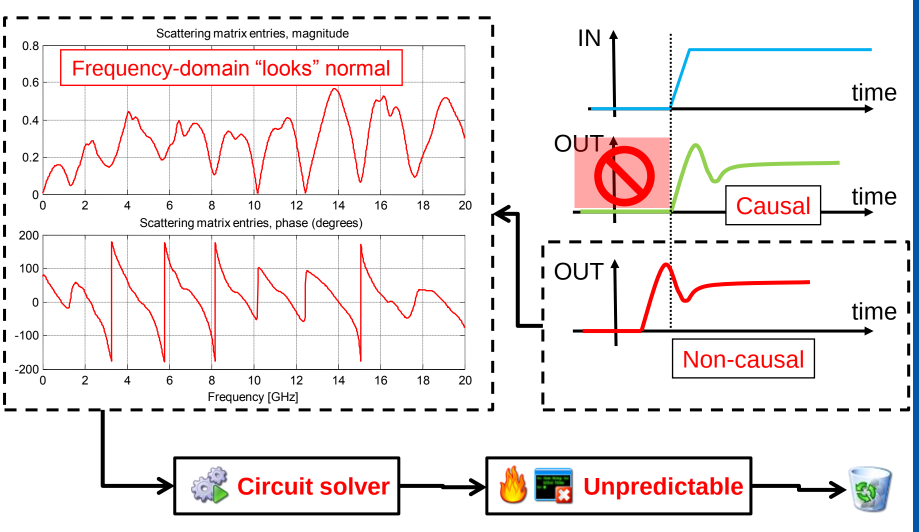


Passivity

$$\mathbf{S}(s) \text{ is passive} \Rightarrow \{\text{singular values of } \mathbf{S}(j\omega)\} \le \mathbf{1},\ \forall\omega$$



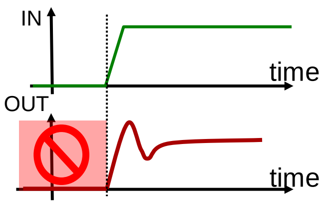
Causality



Causality: definitions

Time-domain

IN $\rightarrow$ $\boxed{\mathbf{H}(j\omega)}$ $\rightarrow$ OUT



Note: no delay extraction here

Frequency-domain

Hilbert transform

Kramers-Krönig dispersion relations

$$\boxed{H(j\omega) = \frac{1}{j\pi}\,\mathrm{pv}\int_{-\infty}^{+\infty} H(j\omega')\,\frac{d\omega'}{\omega-\omega'}}$$

Self-consistency

All samples are strongly related

Causality check

$\mathbf{H}(j\omega)$ $\rightarrow$ **Generalized** Hilbert transform $\rightarrow$ $\mathbf{H}_{\mathrm{REC}}(j\omega)$

$\rightarrow$ $\boldsymbol{\Delta}(j\omega)$

“Error bar”

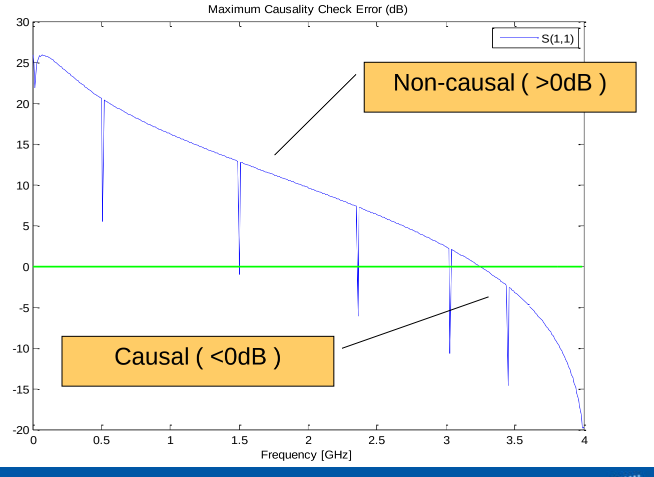
Causal $\quad \left|\mathbf{H}_{\mathrm{REC}}(j\omega) - \mathbf{H}(j\omega)\right| < \boldsymbol{\Delta}(j\omega)$

Non-causal $\quad \left|\mathbf{H}_{\mathrm{REC}}(j\omega) - \mathbf{H}(j\omega)\right| > \boldsymbol{\Delta}(j\omega)$

Causality check error

$$E_{dB}(j\omega) = 20\log_{10}\frac{|H_{\mathrm{REC}}(j\omega) - H(j\omega)|}{\Delta(j\omega)}$$

Computed (parallel) for each scattering response



Part II: macromodeling

An update on recent developments

Rational function fitting: why?

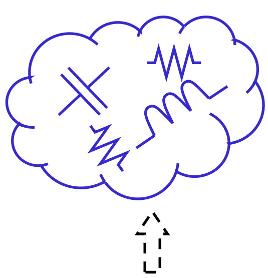
Circuit solvers understand circuits

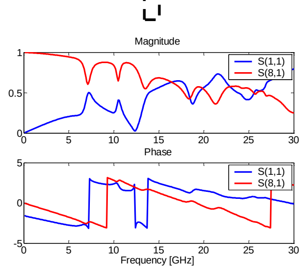
Any lumped circuit has rational frequency responses (poles-residues, poles-zeros, ratio of polynomials)

$$\mathbf{S}(s) \approx \sum_{n=1}^{N} \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty$$

Impedance, admittance, scattering

Rational function fitting: why?





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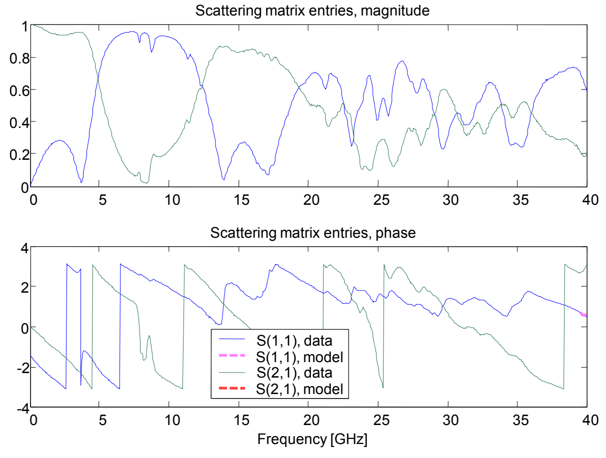
$$\mathbf{S}(s) \approx \sum_{n=1}^{N} \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty$$

Impedance, admittance, scattering

Extraction of an equivalent circuit is an inverse problem (two-step)

Stripline + launches

Data: measured S-parameters



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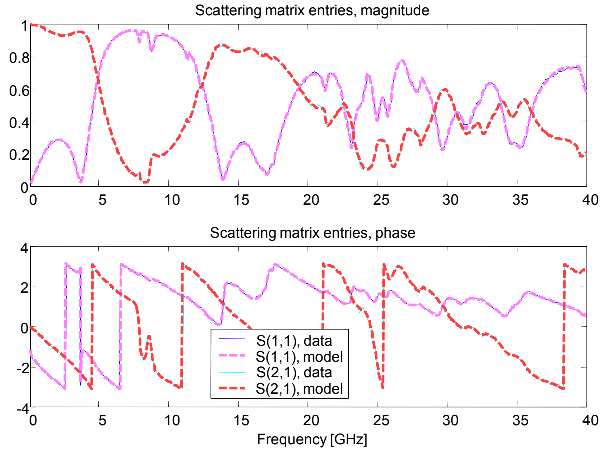
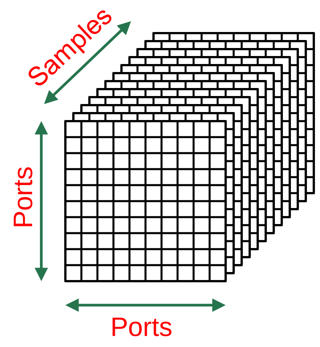
Stripline + launches

Macromodel: 60 poles



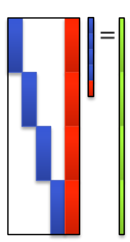
Handling many ports



$$\hat{S}_{i,j}(s) \approx \sum_{n=1}^{N} \frac{R_n^{i,j}}{s - p_n} + S_\infty^{i,j}$$

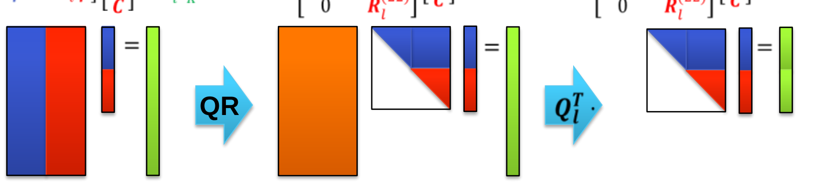
Processing **all** responses may lead to a **large** system!

Parallel Vector Fitting



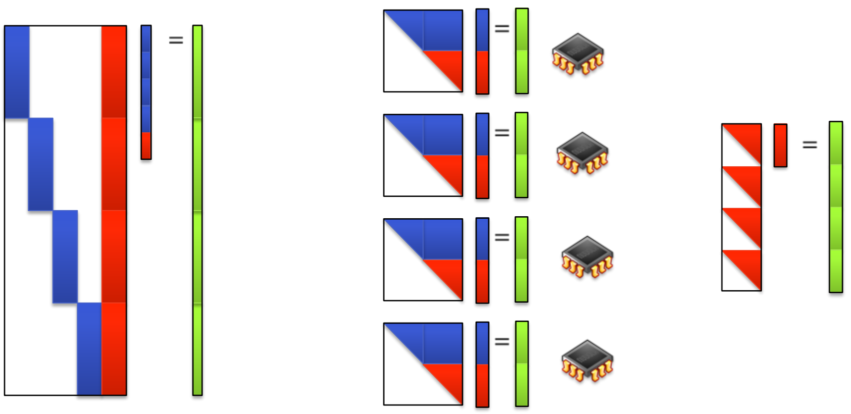
$$\begin{bmatrix} I_K & \varphi & 0 & 0 & \cdots & 0 & 0 & -S_1\varphi \\ 0 & 0 & I_K & \varphi & \cdots & 0 & 0 & -S_2\varphi \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & I_K & \varphi & -S_{p^2}\varphi \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_{p^2} \\ C \end{bmatrix} = \begin{bmatrix} S_1 I_K \\ S_2 I_K \\ \vdots \\ S_{p^2} I_K \end{bmatrix}$$

$$\begin{bmatrix} I_K & \varphi & -S_l\varphi \end{bmatrix} \begin{bmatrix} R_l \\ C \end{bmatrix} = S_l I_K \qquad Q_l \begin{bmatrix} R_l^{(11)} & R_l^{(12)} \\ 0 & R_l^{(22)} \end{bmatrix} \begin{bmatrix} R_l \\ C \end{bmatrix} = S_l I_K \qquad \begin{bmatrix} R_l^{(11)} & R_l^{(12)} \\ 0 & R_l^{(22)} \end{bmatrix} \begin{bmatrix} R_l \\ C \end{bmatrix} = Q_l^T S_l I_K$$



Parallel Vector Fitting

Original LSP — QR decompositions — New LSP



1 GB — $P = 83 \quad K = 1228 \quad N = 30$ — 12 MB

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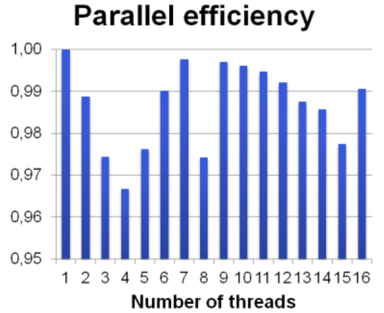
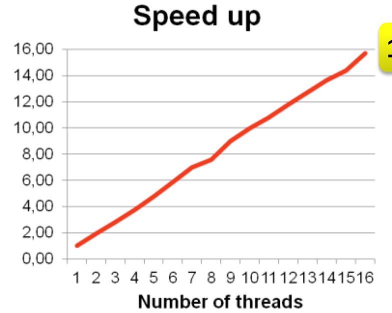
Parallel Vector Fitting

$P = 83 \quad K = 1228 \quad N = 30$





15.7 x

From 193.33 to 12.23 seconds

State-space macromodel realization

$\mathbf{a}(t)$ $\rightleftarrows$ $\mathbf{b}(t)$

$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{B}\ \mathbf{a}(t) \\ \mathbf{b}(t) = \mathbf{C}\,\mathbf{x}(t) + \mathbf{D}\ \mathbf{a}(t) \end{cases}$$

$$\mathbf{S}(s) \approx \sum_{n=1}^{N} \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty = \mathbf{D} + \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

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Checking macromodel passivity

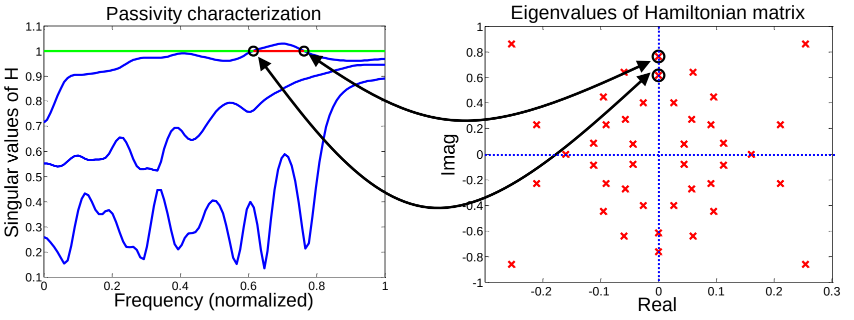
$$\boxed{\{\text{singular values of } \mathbf{S}(j\omega)\} \le \mathbf{1}, \quad \forall \omega}$$

Eigenvalues of Hamiltonian matrix

$$\mathbf{M} = \begin{pmatrix} \mathbf{A} - \mathbf{B}\left(\mathbf{D}^T\mathbf{D} - \mathbf{I}\right)^{-1}\mathbf{D}^T\mathbf{C} & -\mathbf{B}\left(\mathbf{D}^T\mathbf{D} - \mathbf{I}\right)^{-1}\mathbf{B}^T \\ \mathbf{C}^T\left(\mathbf{D}\mathbf{D}^T - \mathbf{I}\right)^{-1}\mathbf{C} & -\mathbf{A}^T + \mathbf{C}^T\mathbf{D}\left(\mathbf{D}^T\mathbf{D} - \mathbf{I}\right)^{-1}\mathbf{B}^T \end{pmatrix}$$

Real matrix $\mathbf{M}$ must have no imaginary eigenvalues

Checking macromodel passivity



Theorem

$j\omega_0$ is an eigenvalue of $\mathbf{M} \Leftrightarrow \sigma = 1$ is a singular value of $\mathbf{S}(j\omega_0)$

Passivity enforcement

- Generate a new passive macromodel
- Apply small correction to preserve accuracy through
  - iterative passivity check
  - solution of small-size optimization problems

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\,\mathbf{x} + \mathbf{B}\,\mathbf{a} \\ \mathbf{b} = \mathbf{C}\,\mathbf{x} + \mathbf{D}\,\mathbf{a} \end{cases} \Rightarrow \begin{cases} \dot{\mathbf{x}} = \mathbf{A}\,\mathbf{x} + \mathbf{B}\,\mathbf{a} \\ \mathbf{b} = (\mathbf{C} + \Delta\mathbf{C})\,\mathbf{x} + \mathbf{D}\,\mathbf{a} \end{cases}$$

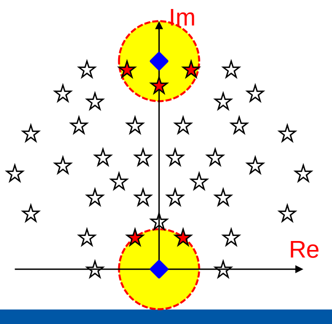
$$\Delta\mathbf{S} = \Delta\mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

Passivity check: computing few eigenvalues

We need only all purely imaginary eigenvalues of **M**

Iterative single-shift Arnoldi iterations to find few eigenvalues "close" to imaginary "shift points".

Pick initial shifts at ends of spectrum



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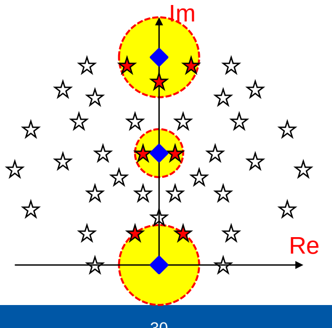

Bisection on imaginary axis

Passivity check: computing few eigenvalues

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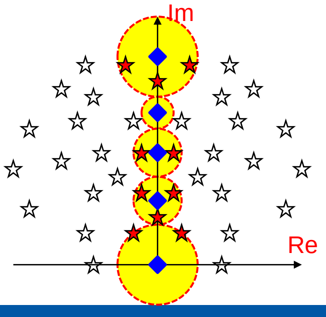
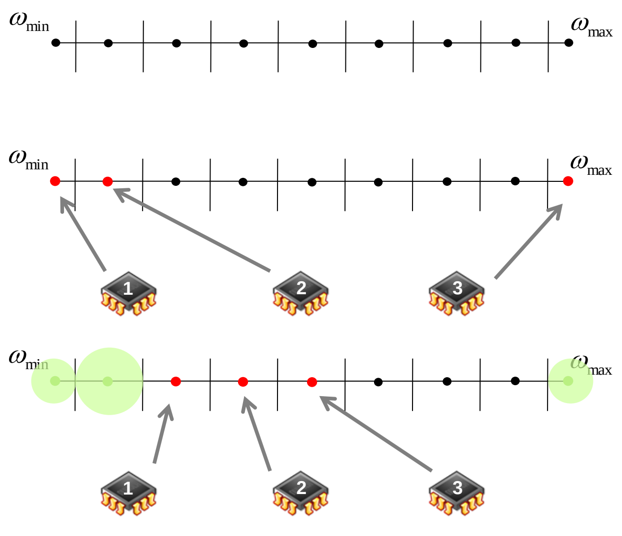


Bisection on imaginary axis

The union of all disks must have no “gaps”!

Basic idea: single-shift ↔ single-thread

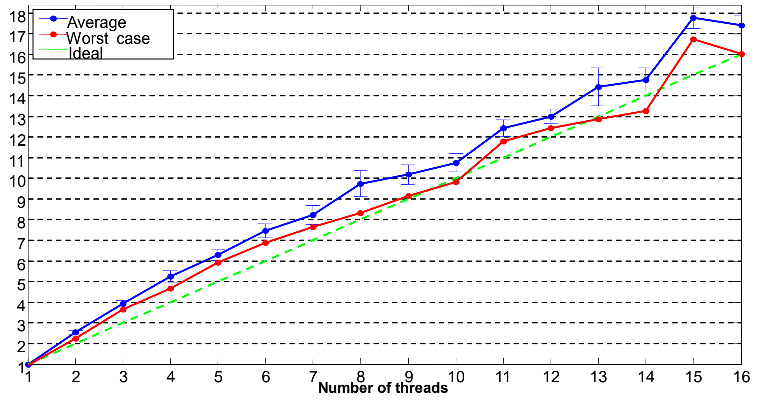


Split bandwidth into N subbands
N = F(T)
T= threads

Startup phase

Ready
In execution
Completed

Speedup (high-speed connector model)



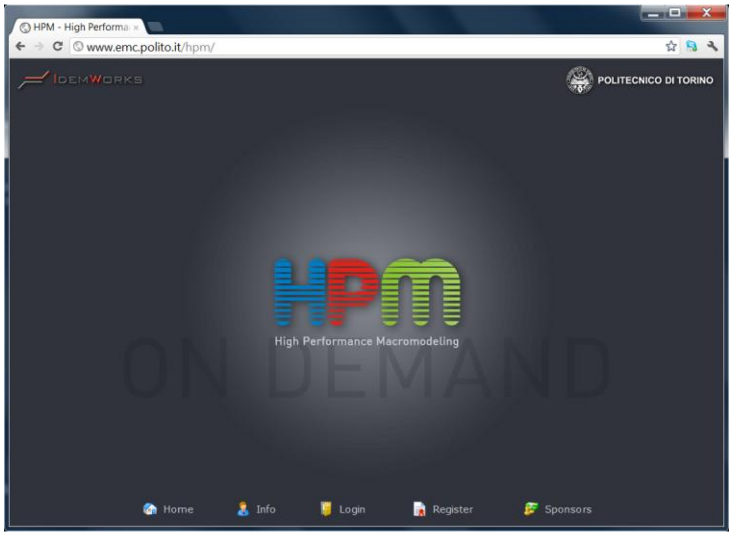
Order	2240
Ports	56
f_{min}	0 GHz
f_{max}	21 GHz
α	5
N λ_{imag}	22

Number of threads	1	2	8	16
Number of λ	90	110	86	84
Analysis time [s]	33.778	13.259	3.369	1.830
Refine time[s]	0.096	0.039	0.021	0.019
Total time [s]	33.972	13.398	3.487	1.950
Speedup		2.5 X	9.7 X	17.4 X

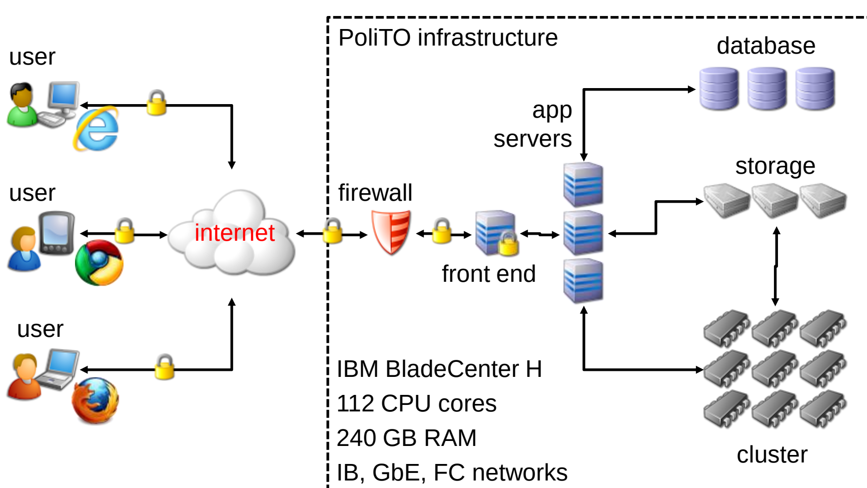
S-parameter modeling flow: a summary

- Input
  - Tabulated frequency responses (“numbers”, “S-parameters”)
    - From EM simulations (in-house or external tools)
    - From measurements
    - From vendors (connectors, filters, etc…)
  - Standardized (Touchstone format)
  - Small-size, compact files
  - Hides IP (behavioral data)
- Output
  - System-level simulation model (“equation”, “netlist”)
  - Qualification certificate (WHY?)
    - Physical self-consistency (stability, causality, passivity)
    - Guaranteed performance in system-level analysis

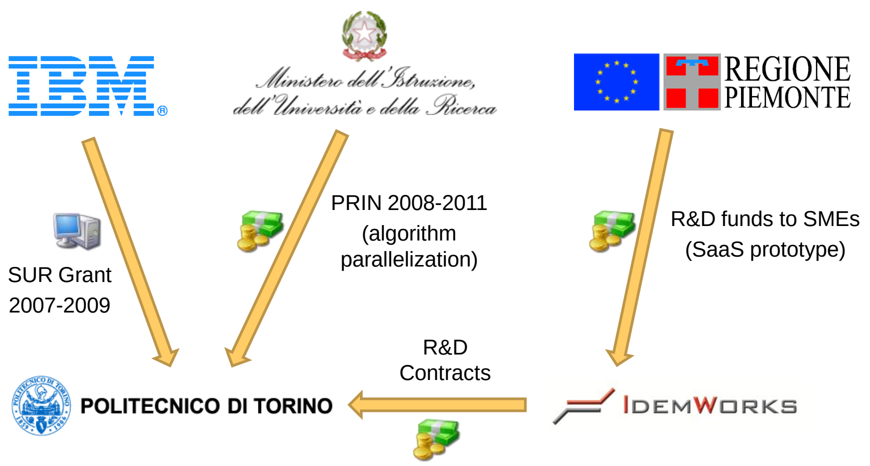
The HPM Service

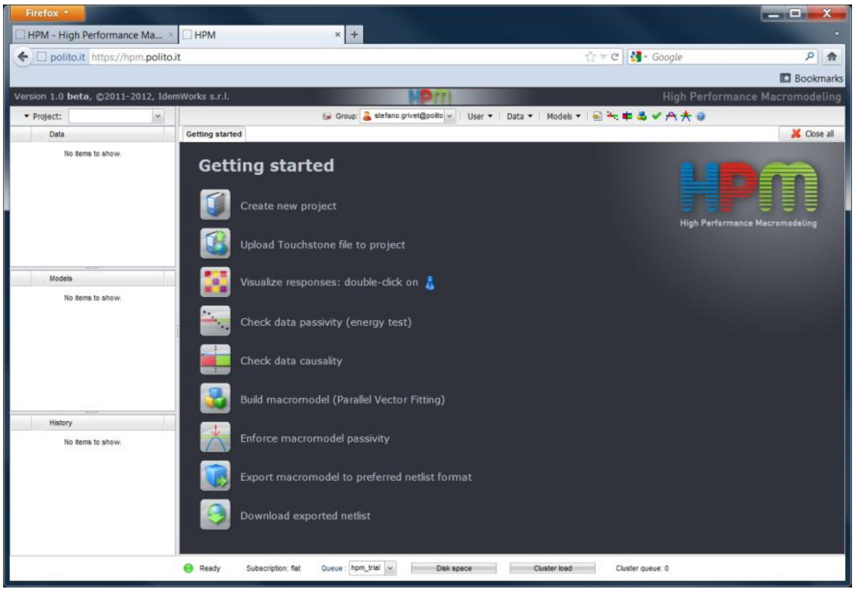


The HPM Service



Sponsors


IBM
Ministero dell'Istruzione, dell'Università e della Ricerca
REGIONE PIEMONTE
SUR Grant
2007-2009
PRIN 2008-2011
(algorithm
parallelization)
R&D funds to SMEs
(SaaS prototype)
R&D
Contracts
POLITECNICO DI TORINO
IDEMWORKS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High Performance Macromodeling
Getting started
Create new project
Upload Touchstone file to project
Visualize responses: double-click on
Check data passivity (energy test)
Check data causality
Build macromodel (Parallel Vector Fitting)
Enforce macromodel passivity
Export macromodel to preferred netlist format
Download exported netlist
HPM
High Performance Macromodeling

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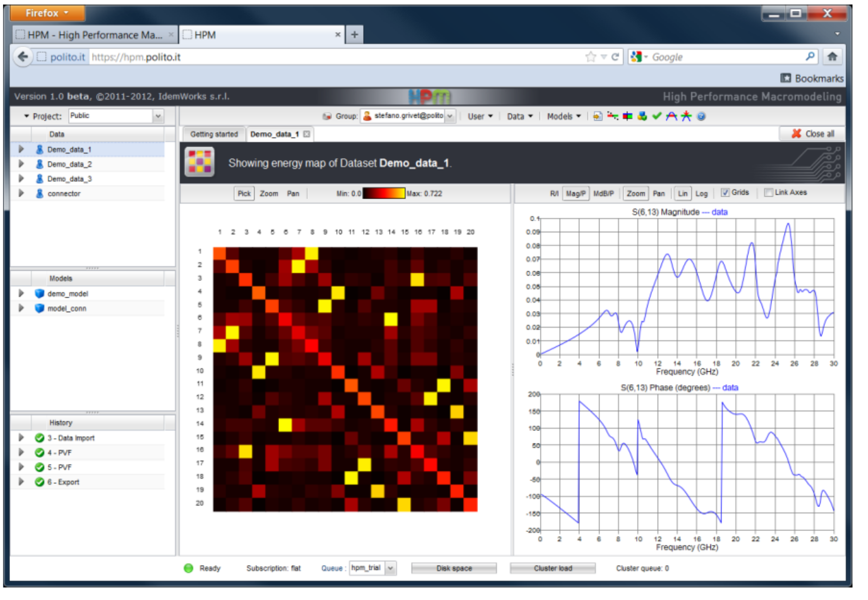

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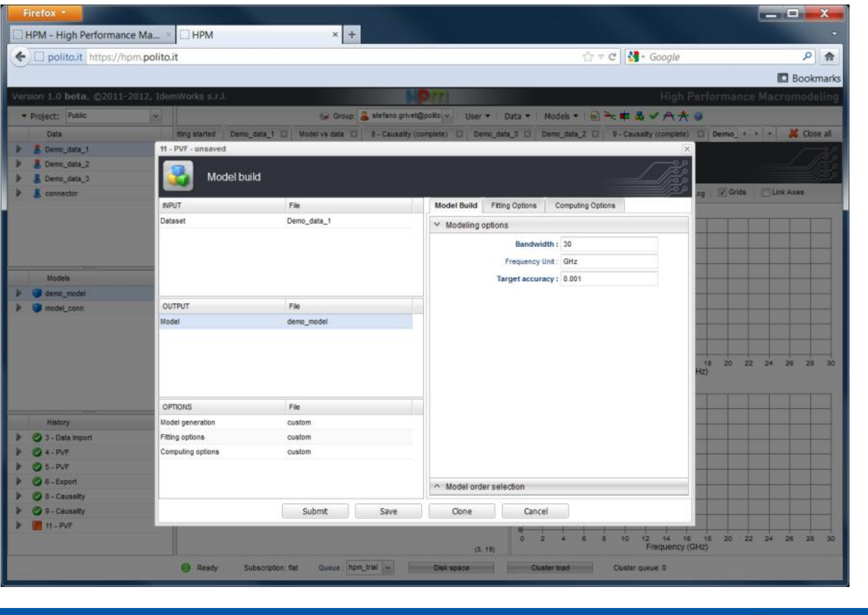

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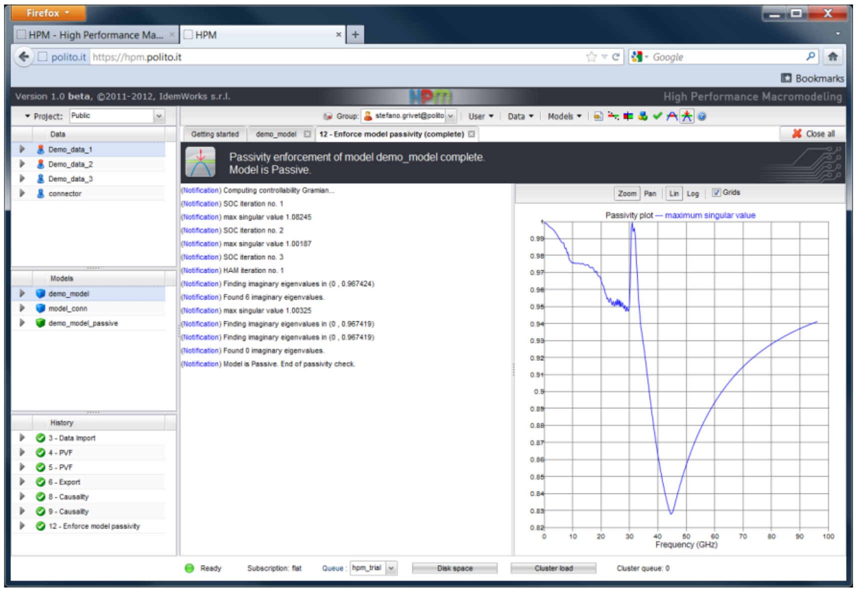
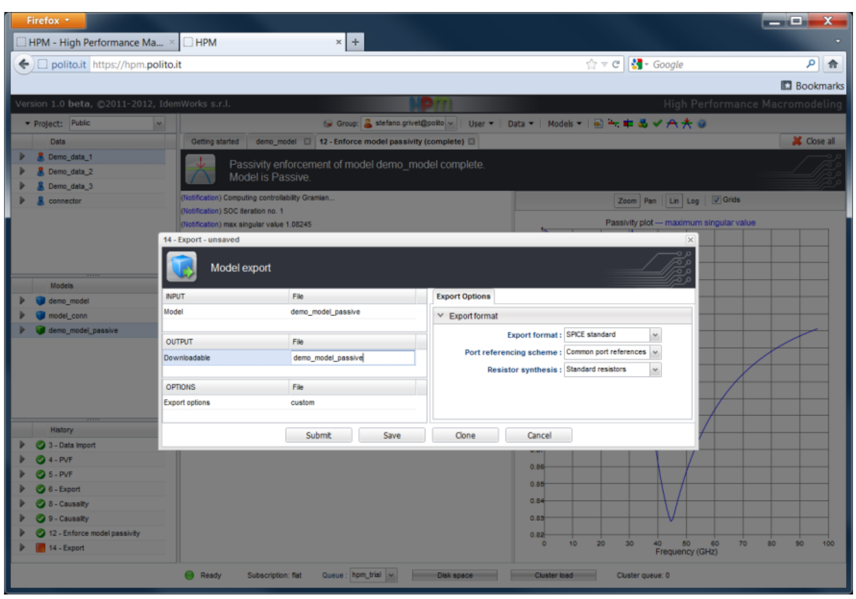
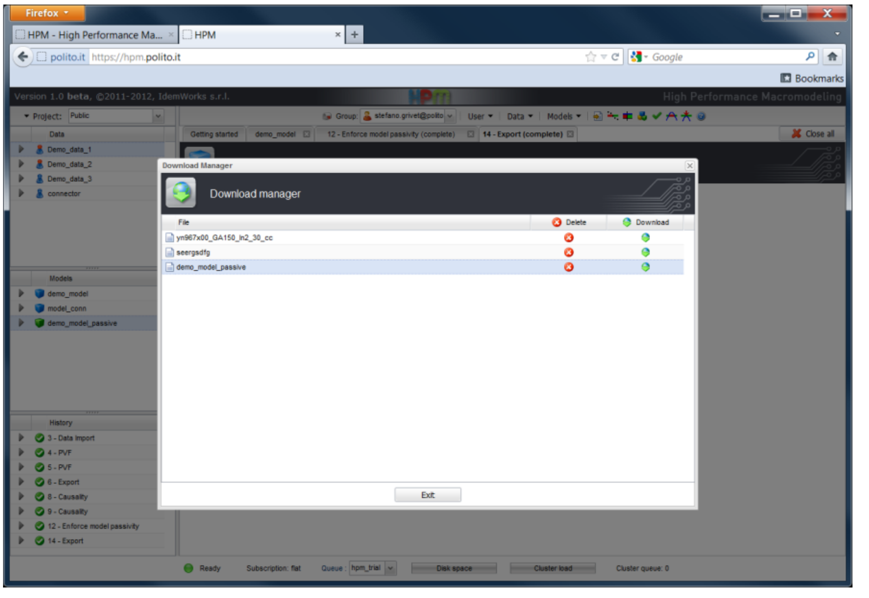
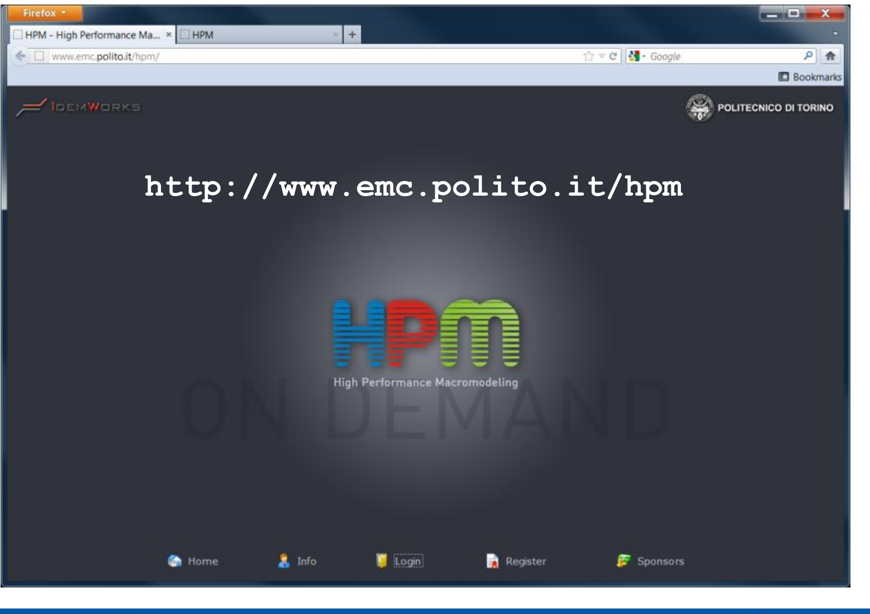

Version 1.0 beta, ©2011-2012, IdemWorks s.r.l.
High Performance Macromodeling
12 - Enforce model passivity (complete)
Passivity enforcement of model demo_model complete.
Model is Passive.
(Notification) Computing controllability Gramian...
(Notification) SOC iteration no. 1
(Notification) max singular value 1.08245
(Notification) SOC iteration no. 2
(Notification) max singular value 1.00187
(Notification) SOC iteration no. 3
(Notification) HAM iteration no. 1
(Notification) Finding imaginary eigenvalues in (0 , 0.967424)
(Notification) Found 6 imaginary eigenvalues.
(Notification) max singular value 1.00325
(Notification) Finding imaginary eigenvalues in (0 , 0.967419)
(Notification) Finding imaginary eigenvalues in (0 , 0.967419)
(Notification) Found 0 imaginary eigenvalues.
(Notification) Model is Passive. End of passivity check.
Passivity plot — maximum singular value
Frequency (GHz)
History
3 - Data import
4 - PVF
5 - PVF
6 - Export
8 - Causality
9 - Causality
12 - Enforce model passivity


14 - Export - unsaved
Model export
INPUT File
Model demo_model_passive
OUTPUT File
Downloadable demo_model_passive
OPTIONS File
Export options custom
Export Options
Export format
Export format : SPICE standard
Port referencing scheme : Common port references
Resistor synthesis : Standard resistors
Submit
Save
Clone
Cancel


Firefox
HPM - High Performance Ma...
HPM
https://hpm.polito.it
Google
Bookmarks
Version 1.0 beta, ©2011-2012, IdemWorks s.r.l.
High Performance Macromodeling
Project: Public
Data
Demo_data_1
Demo_data_2
Demo_data_3
connector
Models
demo_model
model_conn
demo_model_passive
History
3 - Data import
4 - PVF
5 - PVF
6 - Export
8 - Causality
9 - Causality
12 - Enforce model passivity
14 - Export
Getting started
demo_model
12 - Enforce model passivity (complete)
14 - Export (complete)
Close all
Download Manager
Download manager
File
Delete
Download
seergsdfg
demo_model_passive
Exit
Ready
Subscription: flat
Queue
hpm_trial
Disk space
Cluster load
Cluster queue: 0


Firefox
HPM - High Performance Ma...
HPM
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IDEMWORKS

http://www.idemworks.com

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