

Towards real-time S-parameter qualification and macromodeling

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# Towards real-time S-parameter qualification and macromodeling

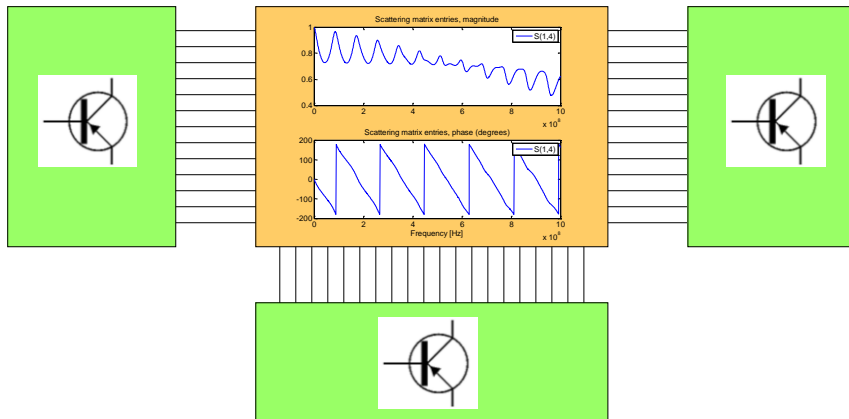
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16<sup>th</sup> IEEE Workshop on Signal and Power Integrity  
IBIS Summit, 16 May 2012, Sorrento, Italy

## The objective

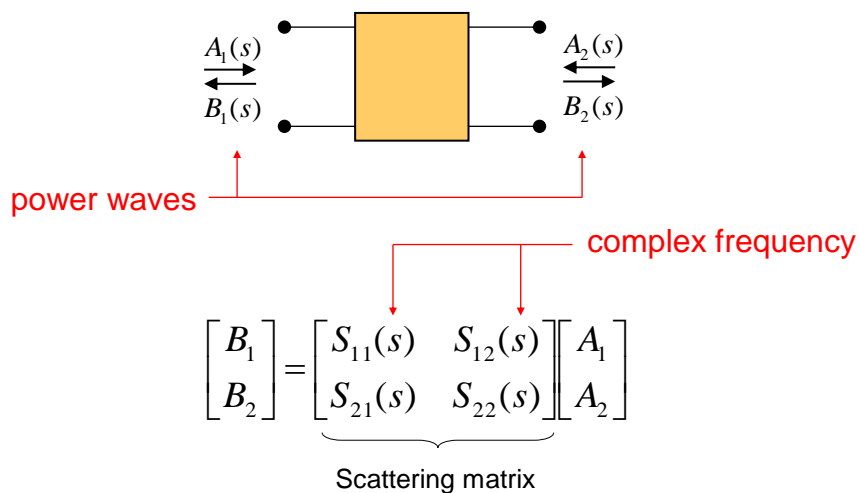
### S-parameter block



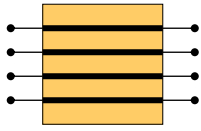
## Why S-parameters

- 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

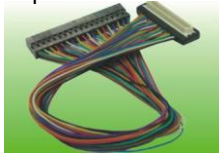
## Scattering network functions



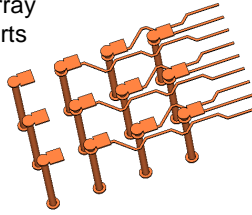
## Examples of S-parameter data



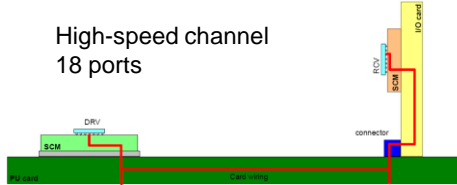
Wiring harness  
8 ports



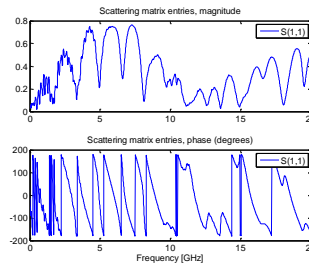
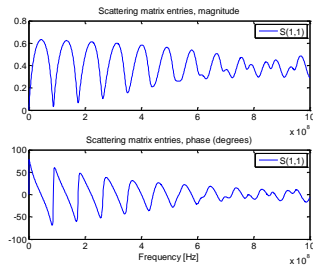
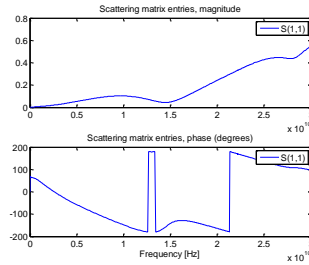
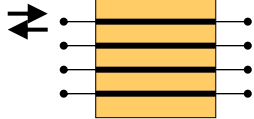
Via array  
12 ports



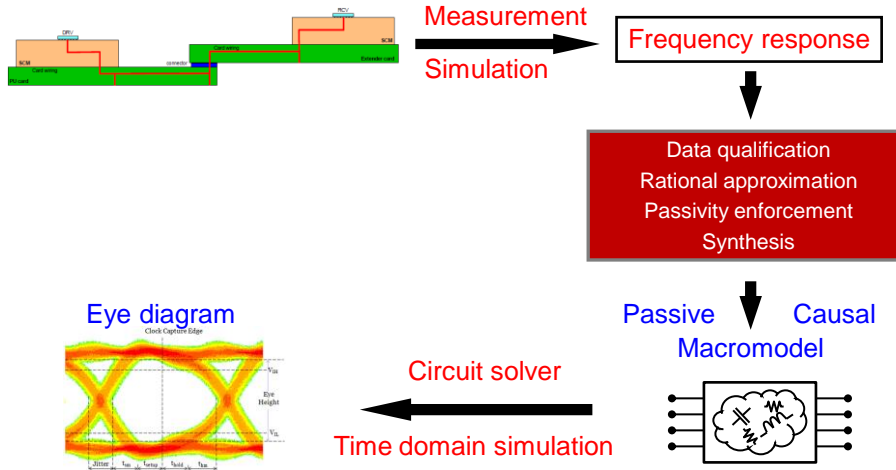
High-speed channel  
18 ports



## Examples of S-parameter data



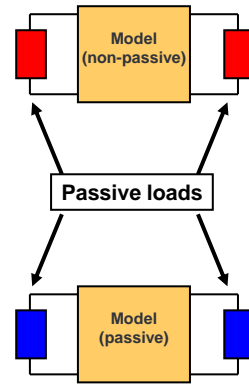
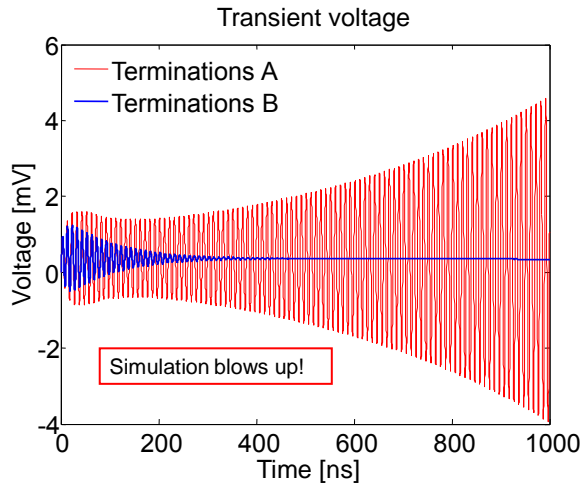
## S-parameter modeling flow



## Part I: qualification

A quick overview

## Passivity: why?



## Passivity

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

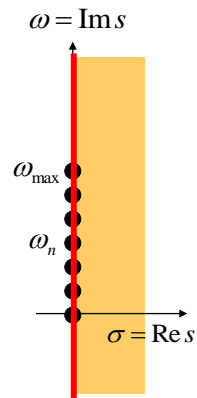
Guarantees real-valued impulse response.  
Always assumed by construction

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

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

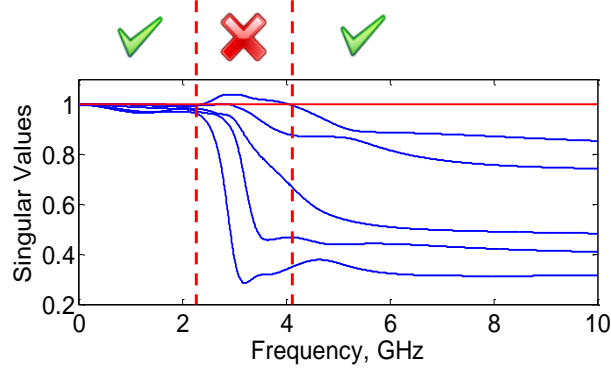
$\mathbf{S}(j\omega)$  is causal

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

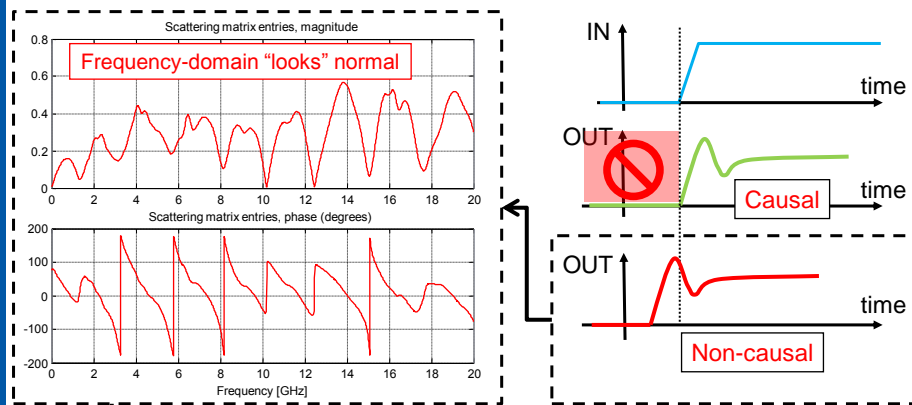


## Passivity

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



## Causality



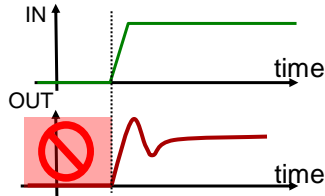
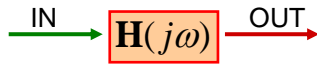
**Circuit solver**

**Unpredictable**



## Causality: definitions

### Time-domain



Note: no delay extraction here

### Frequency-domain

Hilbert transform

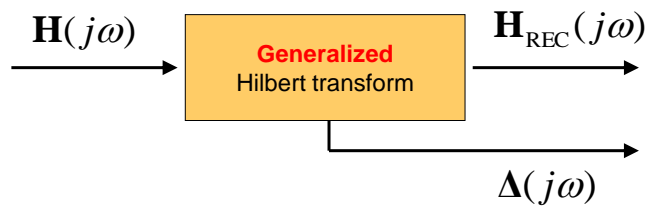
Kramers-Krönig dispersion relations

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

Self-consistency

All samples are strongly related

## Causality check



"Error bar"

Causal  $|\mathbf{H}_{\text{REC}}(j\omega) - \mathbf{H}(j\omega)| < \Delta(j\omega)$

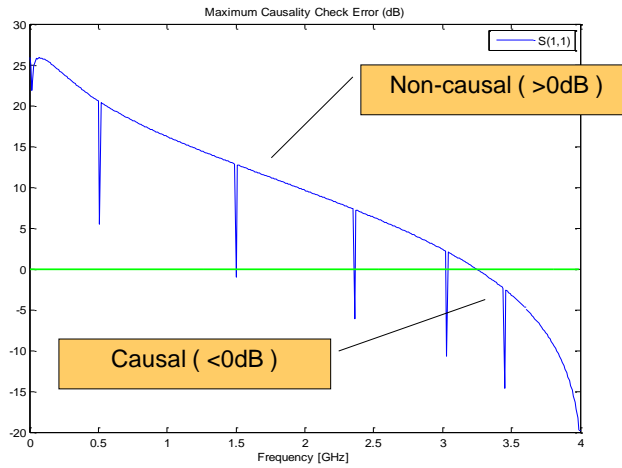
Non-causal  $|\mathbf{H}_{\text{REC}}(j\omega) - \mathbf{H}(j\omega)| > \Delta(j\omega)$



## Causality check error

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

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?



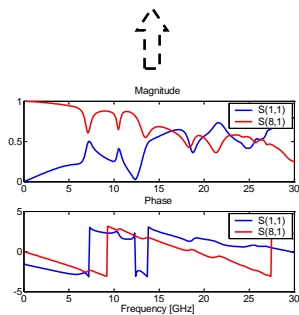
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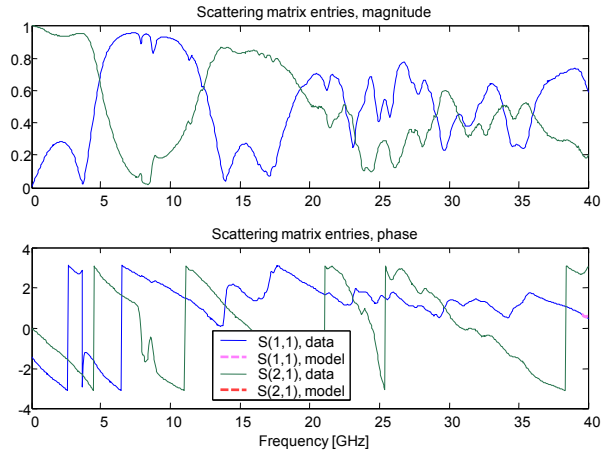
Impedance, admittance, scattering

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



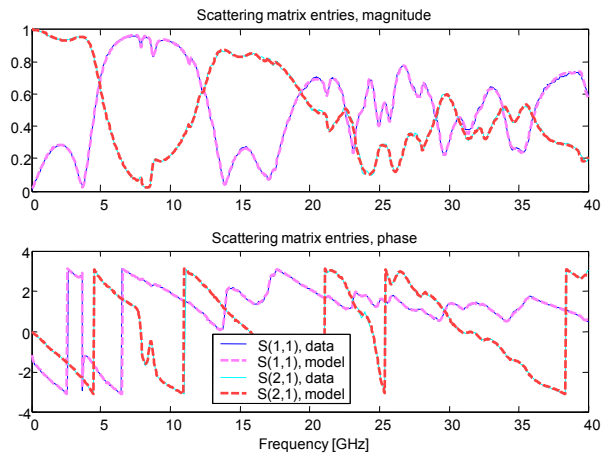
## Stripline + launches

Data: measured S-parameters

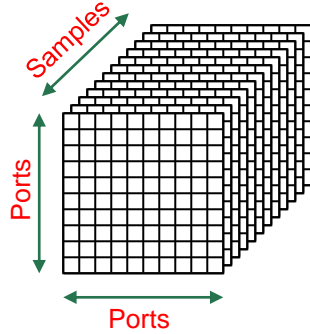


## Stripline + launches

Macromodel: 60 poles



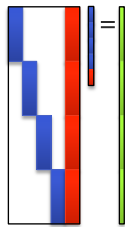
## Handling many ports



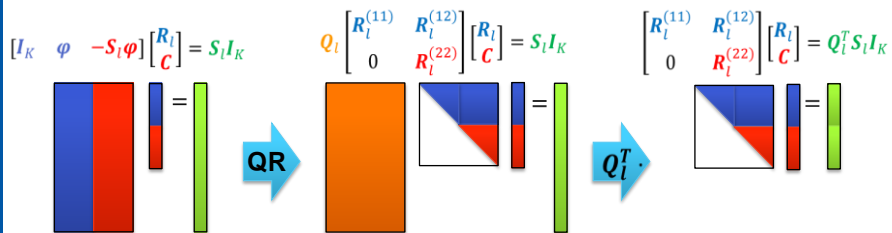
$$\hat{S}_{i,j}(s) \approx \sum_{n=1}^N \frac{R_n^{i,j}}{s - p_n} + S_\infty^{i,j}$$

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

## Parallel Vector Fitting

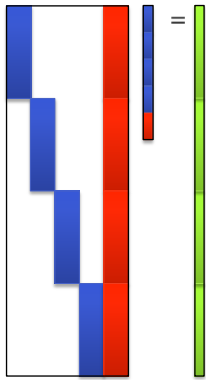


$$\begin{bmatrix} I_K & \varphi & 0 & 0 & \dots & 0 & 0 & -S_1\varphi \\ 0 & 0 & I_K & \varphi & \dots & 0 & 0 & -S_2\varphi \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \dots & I_K & \varphi & -S_{p^2}\varphi \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\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



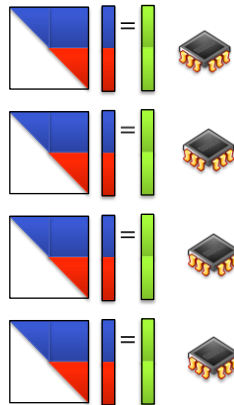
## Parallel Vector Fitting

Original LSP



1 GB

QR decompositions



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

New LSP

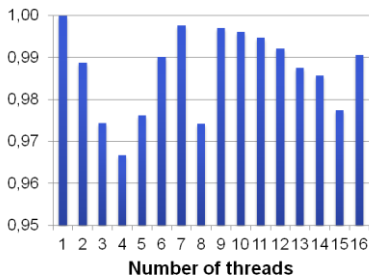


12 MB

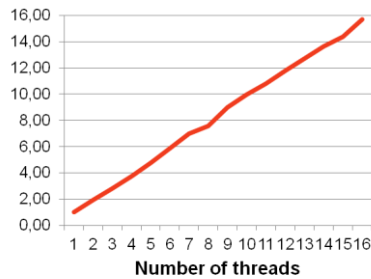
## Parallel Vector Fitting

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

Parallel efficiency



Speed up

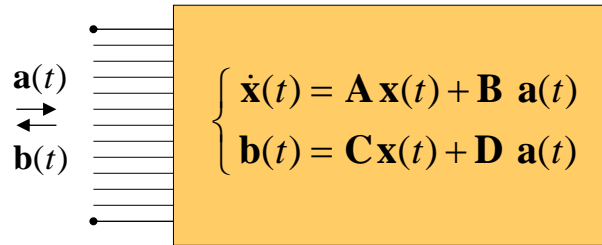


15.7 x



From 193.33 to 12.23 seconds

## State-space macromodel realization



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

## Checking macromodel passivity

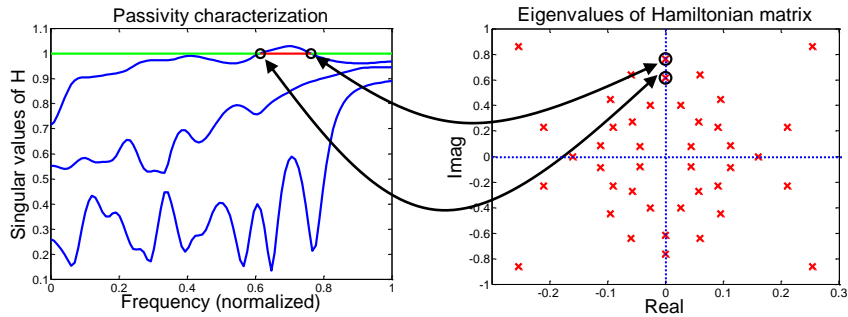
$$\{\text{singular values of } \mathbf{S}(j\omega)\} \leq \mathbf{1}, \quad \forall \omega$$

### Eigenvalues of Hamiltonian matrix

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

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

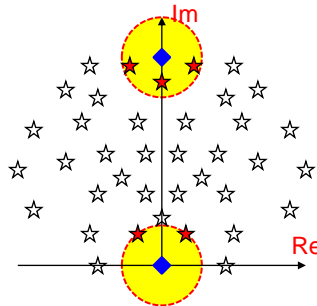
$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{a} \\ \mathbf{b} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{a} \end{cases} \quad \longrightarrow \quad \begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{a} \\ \mathbf{b} = (\mathbf{C} + \Delta\mathbf{C})\mathbf{x}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

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

## Passivity check: computing few eigenvalues

We need only all purely imaginary eigenvalues of  $\mathbf{M}$   
Iterative single-shift Arnoldi iterations to find few eigenvalues "close" to imaginary "shift points".

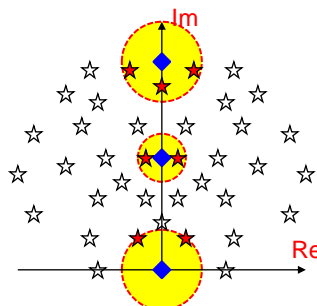
Pick initial shifts at ends of spectrum



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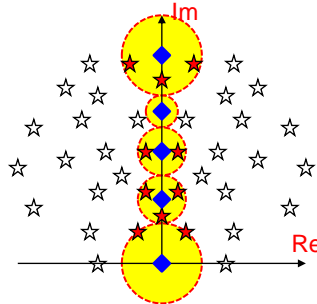
Bisection on imaginary axis



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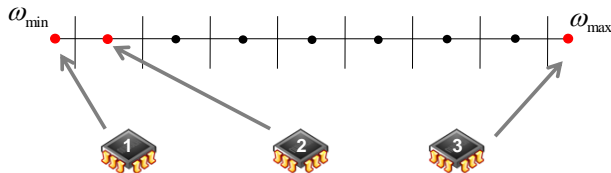
Bisection on imaginary axis

The union of all disks must have no "gaps"!

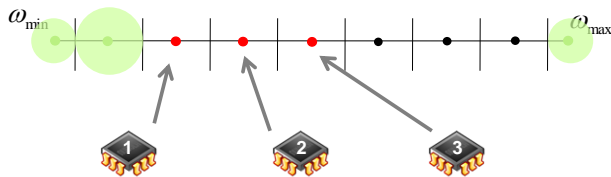
## Basic idea: single-shift $\leftrightarrow$ single-thread



Split bandwidth into N subbands  
 $N = F(T)$   
 $T = \text{threads}$

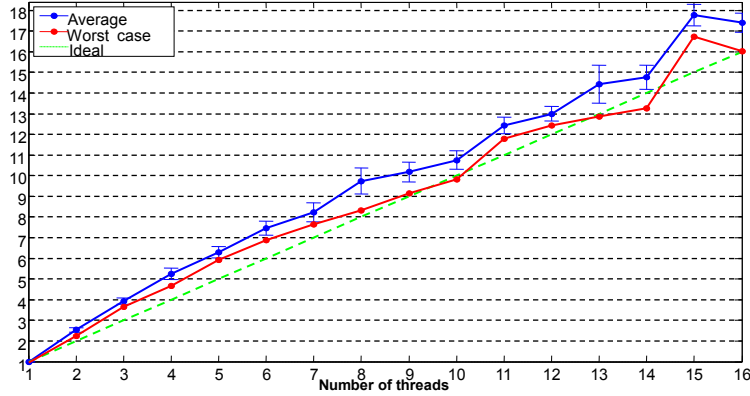


Startup phase



● Ready  
 ● In execution  
 ● Completed

## Speedup (high-speed connector model)



Order	2240
Ports	56
f <sub>min</sub>	0 GHz
f <sub>max</sub>	21 GHz
α	5
N λ <sub>imag</sub>	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

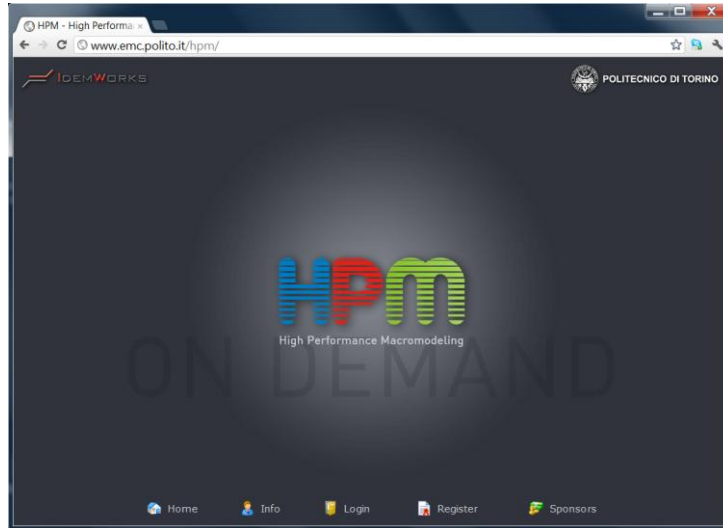
- Tabulated frequency responses ("numbers", "S-parameters")
  - From EM simulations (in-house or external tools)
  - From measurements
  - From vendors (connectors, filters, etc...)
- Standardized (Touchstone format)
- Small-size, compact files
- Hides IP (behavioral data)



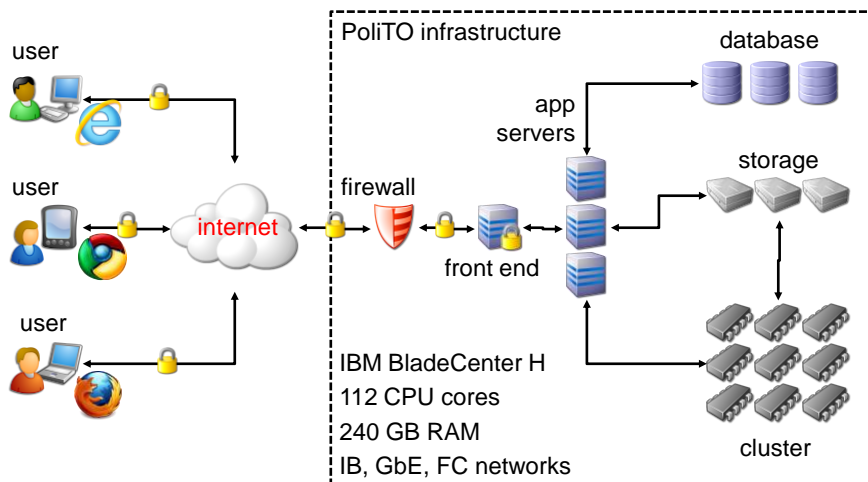
### Output

- System-level simulation model ("equation", "netlist")
- Qualification certificate (WHY?)
  - Physical self-consistency (stability, causality, passivity)
  - Guaranteed performance in system-level analysis

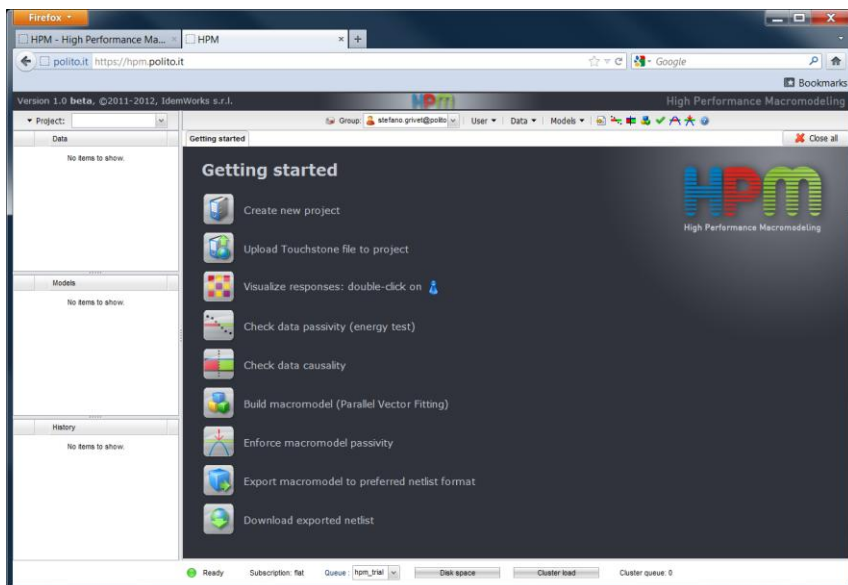
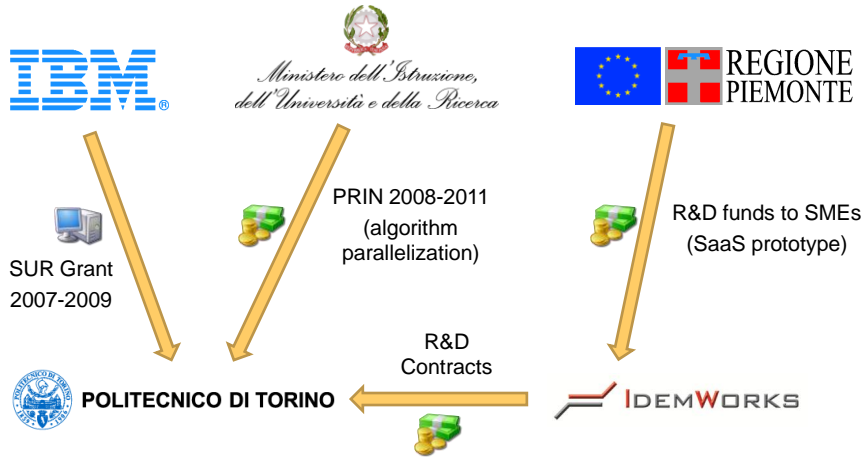
## The HPM Service

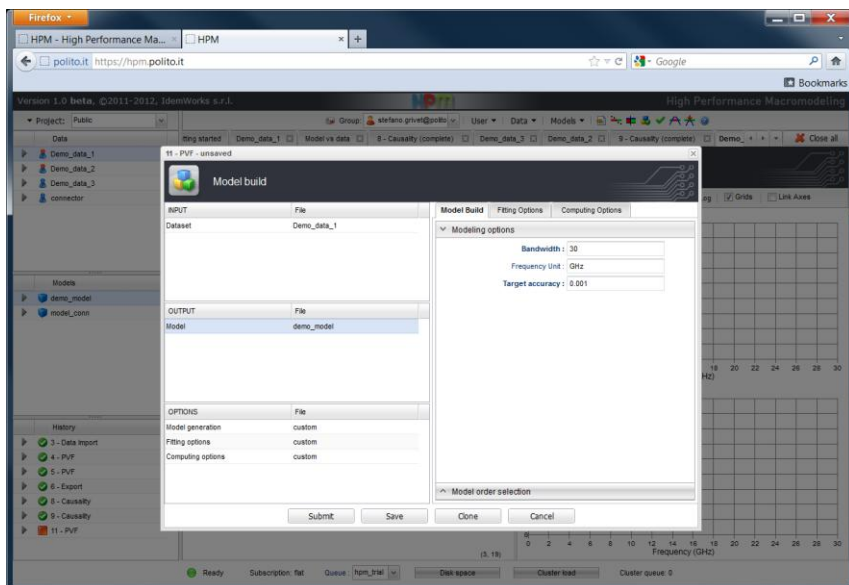
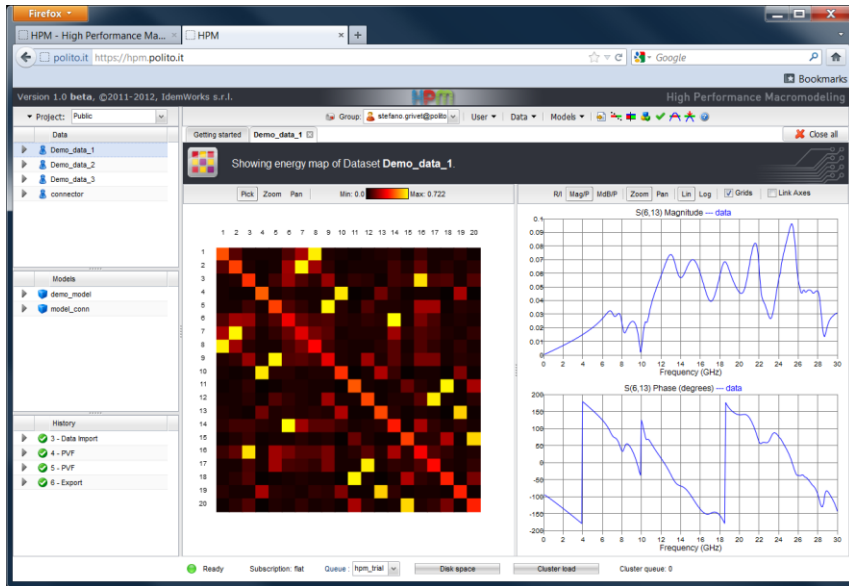


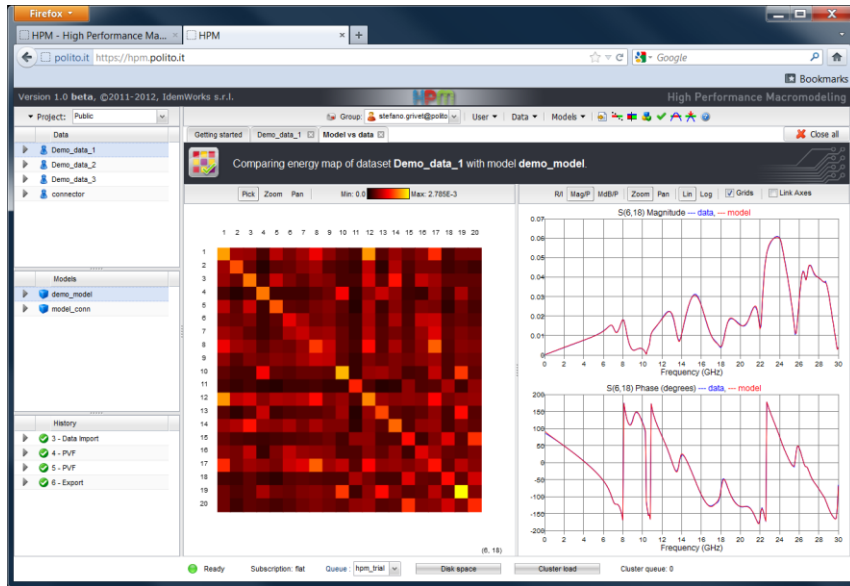
## The HPM Service

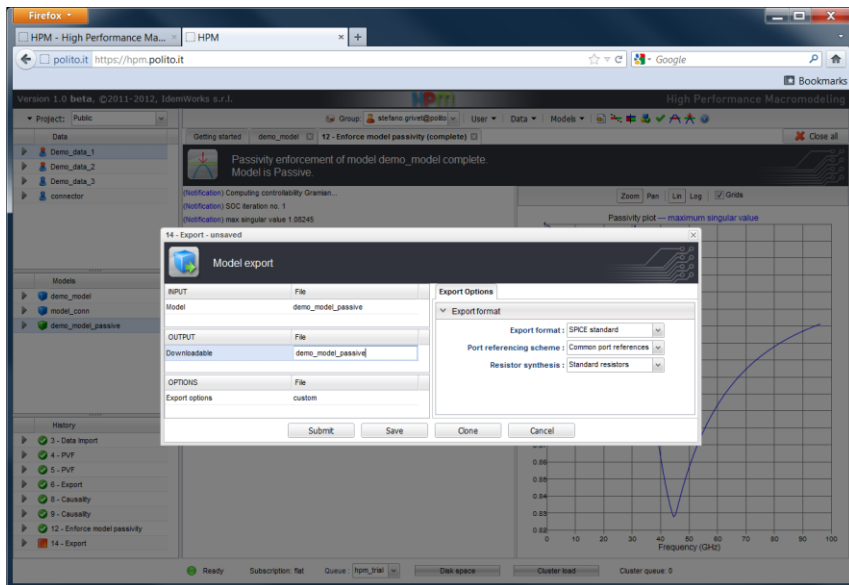
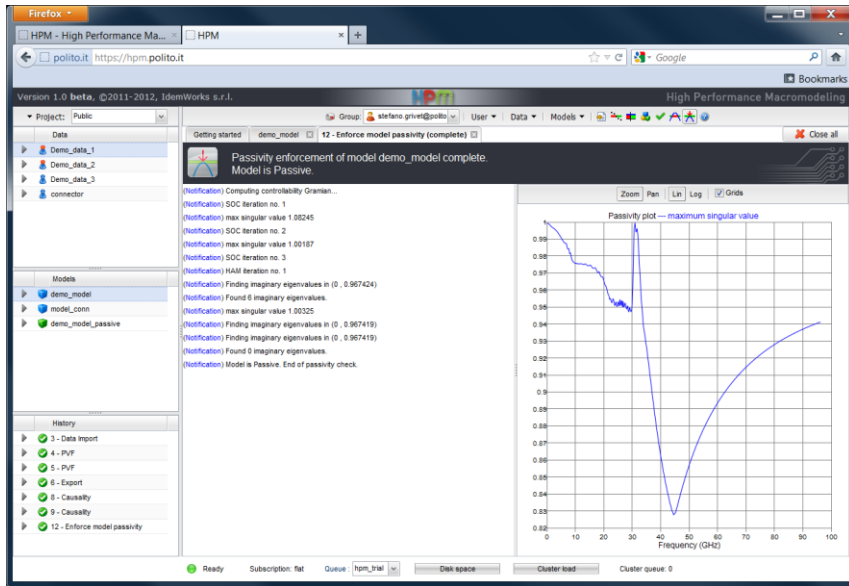


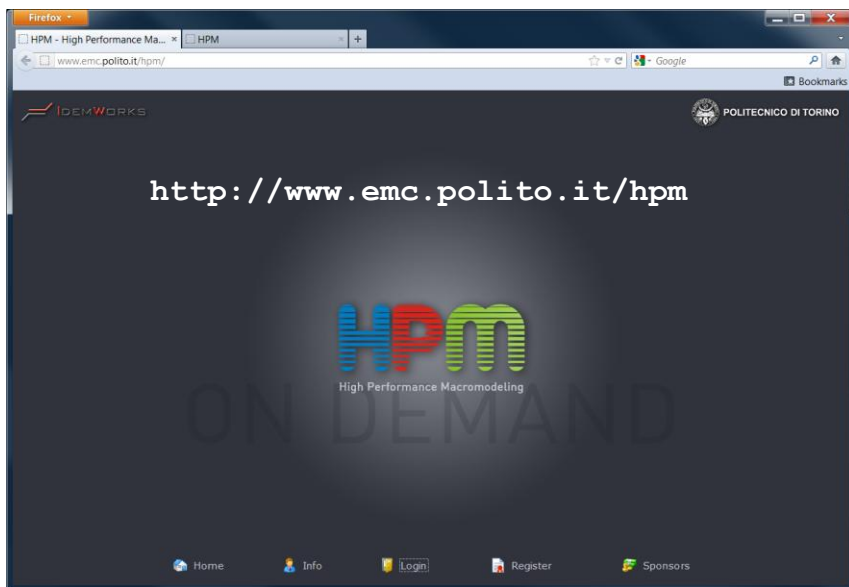
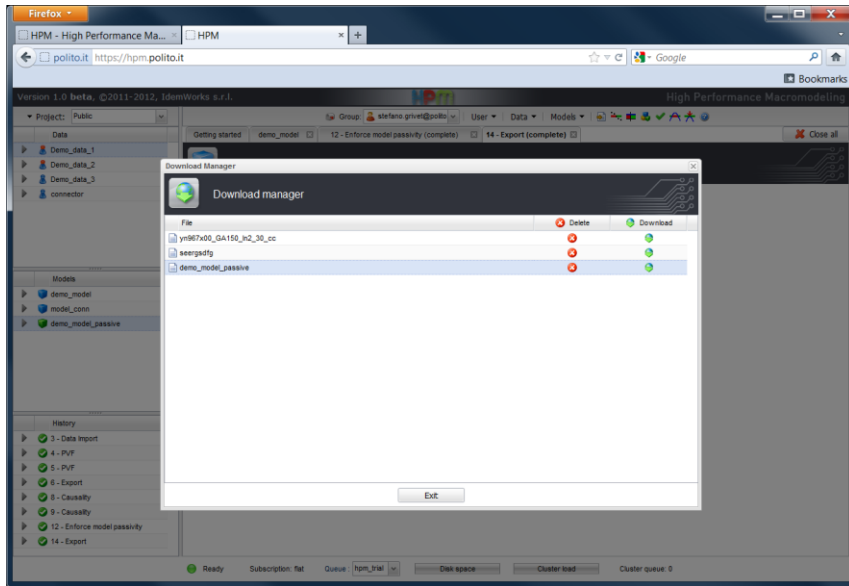
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Thank you



<http://www.emc.polito.it>



<http://www.idemworks.com>

## References

1. S. Grivet-Talocia, HPM: an interactive web service for high-performance macromodeling of passive interconnects in system-level verification flows, *University Booth, Design Automation and Test in Europe Conference (DATE12), Dresden (Germany)*, March 12-16, 2012.
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4. A. Chinae, S. Grivet-Talocia, "On the Parallelization of Vector Fitting Algorithms" , *IEEE Transactions on Components, Packaging, and Manufacturing Technology*, Vol. 1, n. 11, pp. 1761-1773, November 2011, 2011
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