SPACE MAPPING TECHNOLOGY:
A NEW APPROACH TO ENGINEERING OPTIMIZATION

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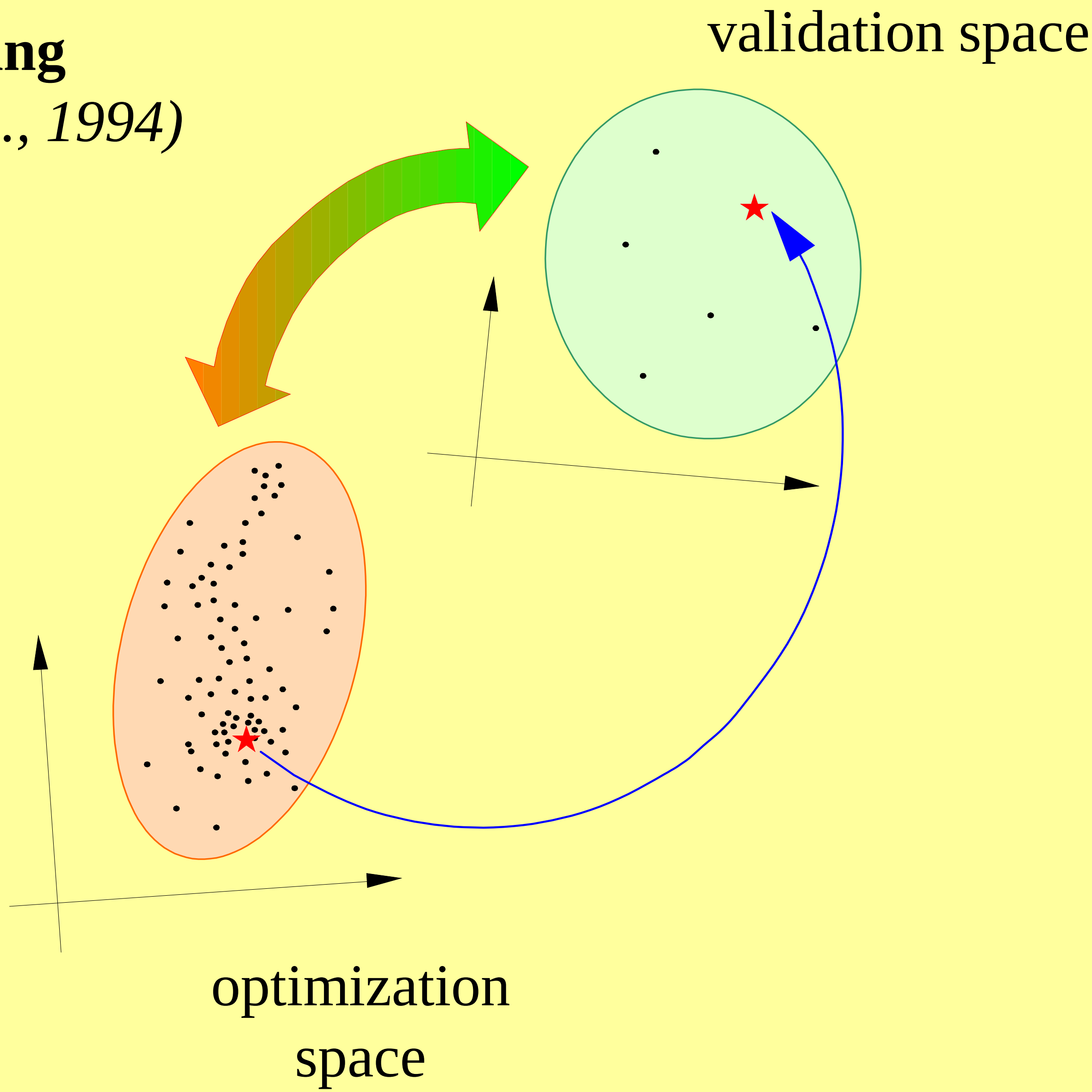
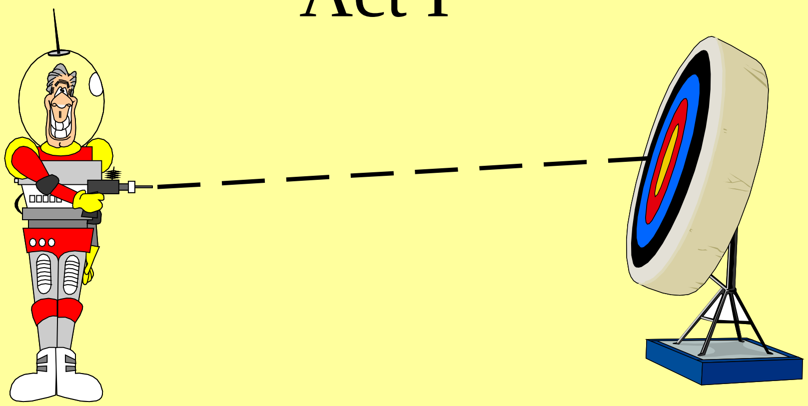
University of Victoria, February 12, 2001

Space Mapping

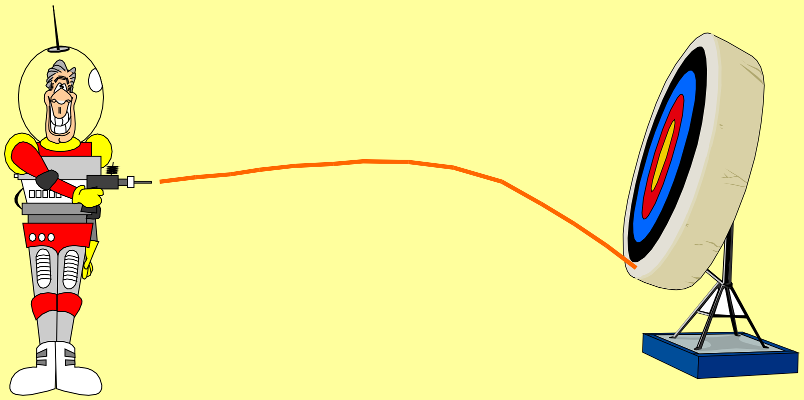
(Bandler et al., 1994)



Space Mapping
Act I

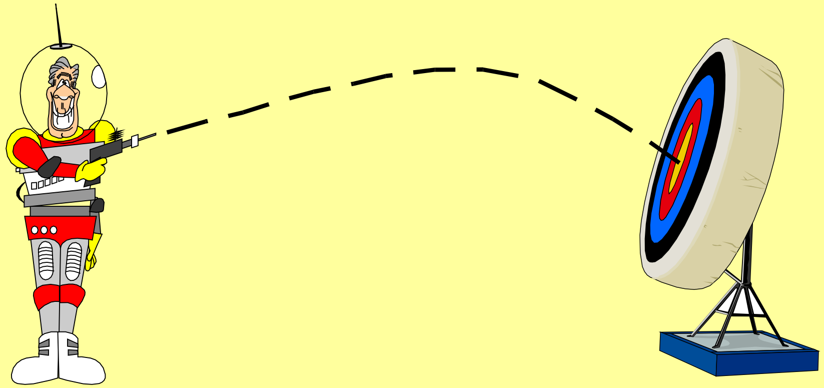


ideal aim

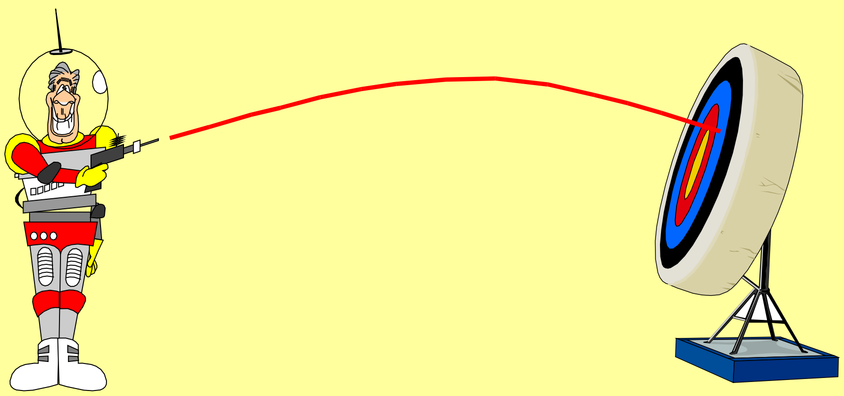


reality check…oops

Space Mapping
Act II

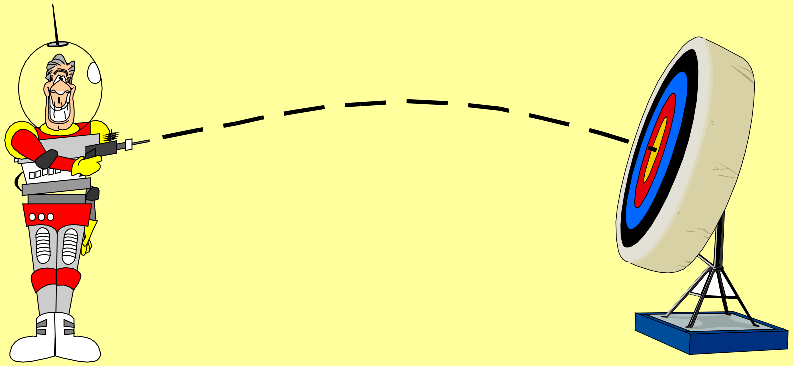


first iteration

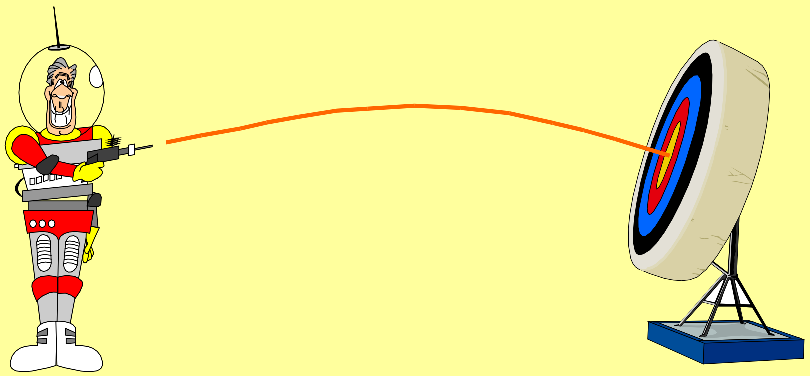


almost there

Space Mapping
Act III



second iteration



hey, SM works!

Outline

Generalized Space Mapping (GSM) tableau approach *(Bandler et al., 1999)* to engineering device modeling exploiting Frequency Space Mapping (FSM) *(Bandler et al., 1995)* and the Multiple Space Mapping (MSM) *(Bandler et al., 1998)*

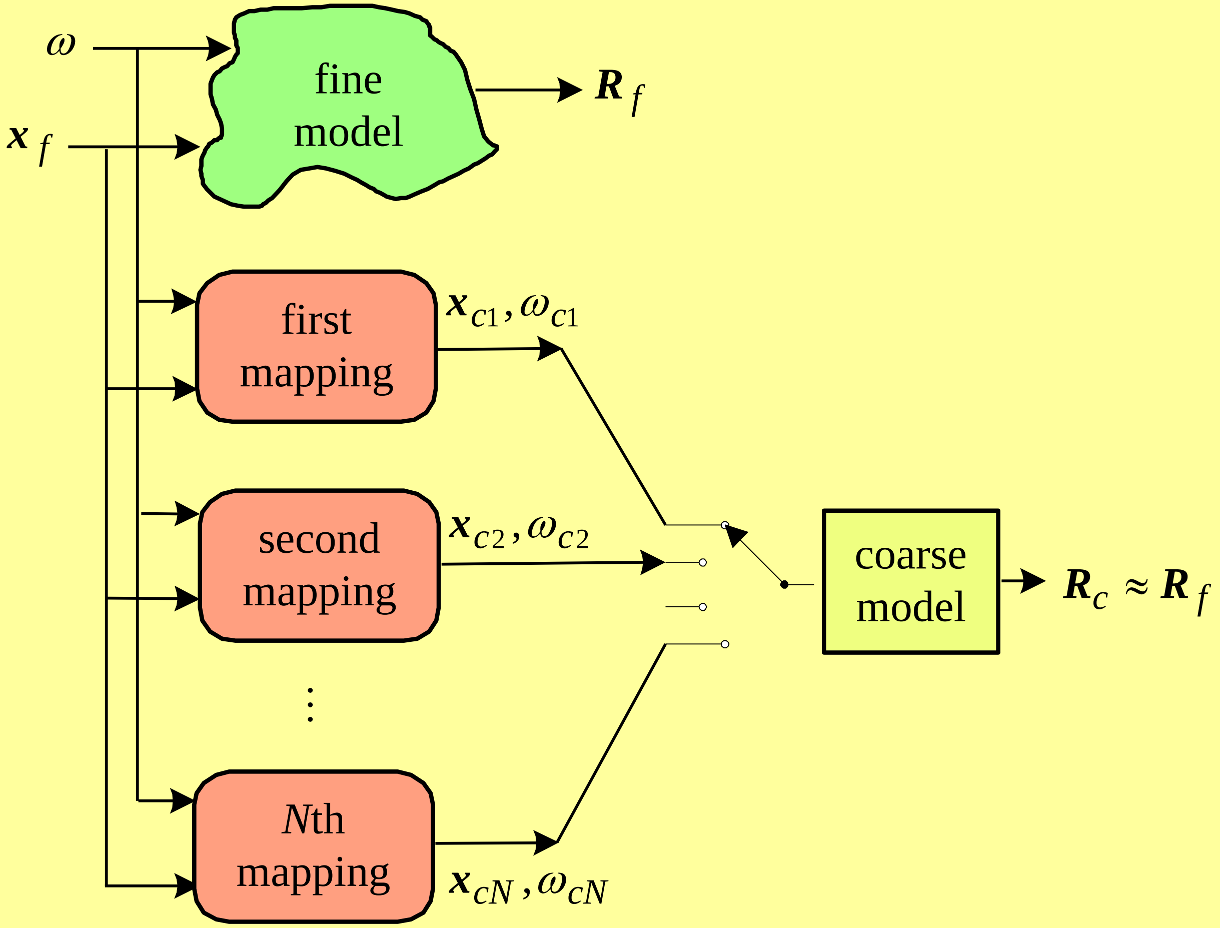
Neural Space Mapping (NSM) optimization approach exploiting SM-based neuromodeling techniques *(Bakr et al., 2000)*

Space Mapping optimization exploiting surrogate models
(Bakr et al., 2000)

state-of-the-art SMX system
(Bandler et al., 2000)

Multiple Space Mapping (MSM) Concept

MSM for Frequency Intervals (MSMFI)



Mathematical Formulation for GSM

(Bandler et al., 1999)

the *k*th mapping targeting the sub-response or the response $\boldsymbol{R}$ in the *k*th frequency sub-range is given by

$$(\boldsymbol{x}_{ck}, \omega_{ck}) = \boldsymbol{P}_k(\boldsymbol{x}_f, \omega)$$

or, in matrix form, assuming a linear mapping

$$\begin{bmatrix} \boldsymbol{x}_{ck} \\ \omega_{ck} \end{bmatrix} = \begin{bmatrix} \boldsymbol{c}_k \\ \delta_k \end{bmatrix} + \begin{bmatrix} \boldsymbol{B}_k & \boldsymbol{s}_k \\ \boldsymbol{t}_k^T & \sigma_k \end{bmatrix} \begin{bmatrix} \boldsymbol{x}_f \\ \omega \end{bmatrix}$$

the mapping parameters $\{\boldsymbol{c}_k, \boldsymbol{B}_k, s_k, t_k, \sigma_k, \delta_k\}$ can be evaluated, directly or indirectly, by solving the optimization problem

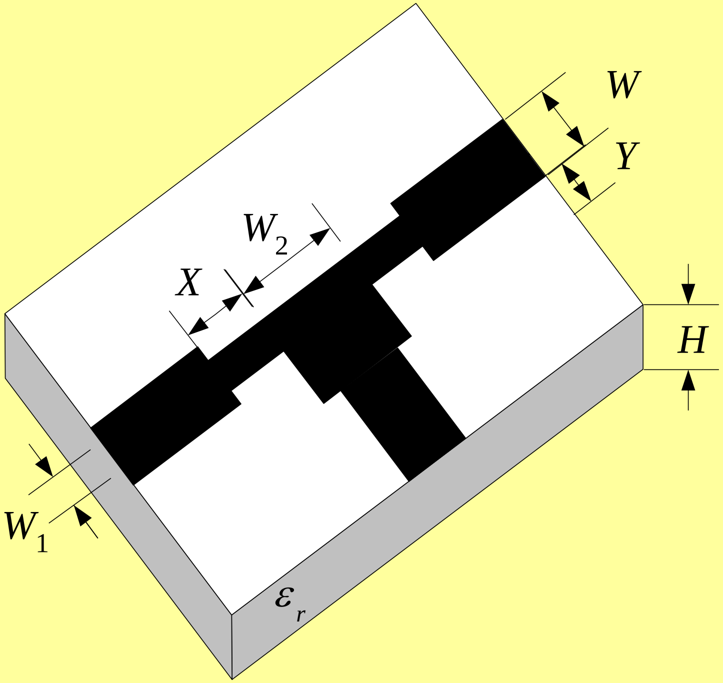
$$\min_{\boldsymbol{c}_k, \boldsymbol{B}_k, \boldsymbol{s}_k, \boldsymbol{t}_k, \sigma_k, \delta_k} \left\| \begin{bmatrix} \boldsymbol{e}_{k1}^{\ T} & \boldsymbol{e}_{k2}^{\ T} & \cdots & \boldsymbol{e}_{km}^{\ T} \end{bmatrix}^T \right\|$$

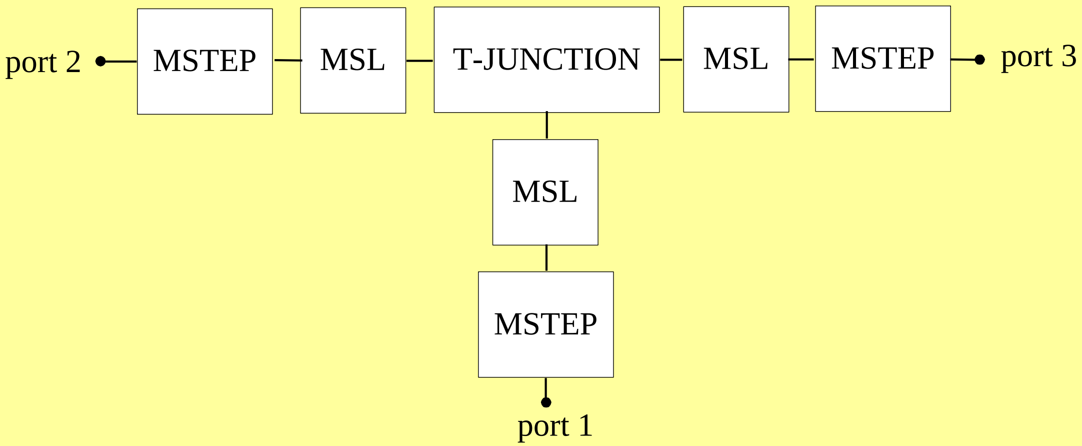
where m is the number of base points selected in the fine model space and $\boldsymbol{e}_{kj}$ is an error vector given by

$$\boldsymbol{e}_{kj} = \boldsymbol{R}_f(\boldsymbol{x}_f^{(j)}, \omega) - \boldsymbol{R}_c(\boldsymbol{x}_{ck}^{(j)}, \omega_{ck}), \quad j = 1,2,\ldots,m$$

Microstrip Shaped T-Junction

the fine and coarse models





Microstrip Shaped T-Junction

the region of interest

$$15 \text{ mil} \leq H \leq 25 \text{ mil}$$
$$5 \text{ mil} \leq X \leq 15 \text{ mil}$$
$$5 \text{ mil} \leq Y \leq 15 \text{ mil}$$
$$8 \leq \varepsilon_r \leq 10$$

the frequency range is 2 GHz to 20 GHz with a step of 2 GHz

the number of base points is 9 and the number of test points is 50

the width W of the input lines is determined in terms of H and so that the characteristic impedance of the input lines is 50 ohm

the width W_1 is taken as 1/3 of the width W

the width W_2 is obtained so that the characteristic impedance of the microstrip line after the step connected to port 2 is twice that of the microstrip line after the step connected to port 1

Microstrip Shaped T-Junction

MSM for Frequency Intervals (MSMFI) was developed to enhance the accuracy of the T-Junction coarse model

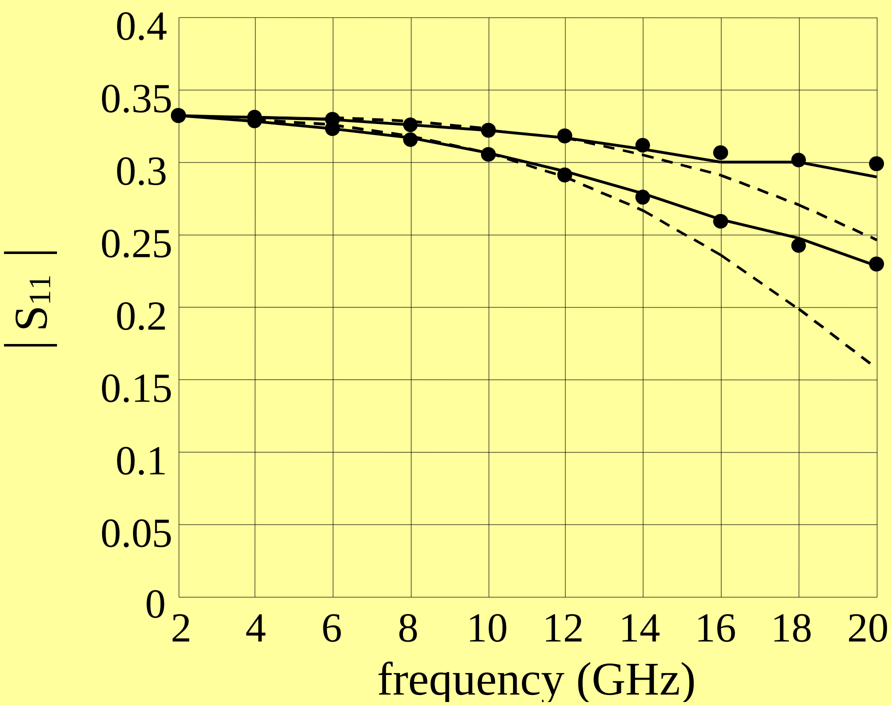
the total frequency range was divided into two intervals: 2-16 GHz and 16-20 GHz

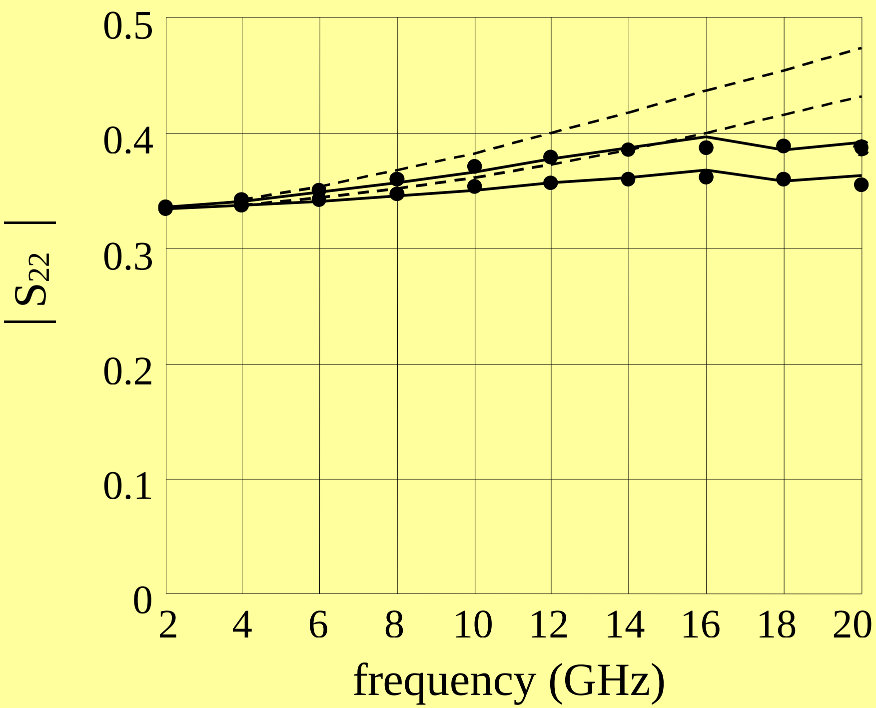
the mapping parameters are

	2 GHz to 16 GHz	16 GHz to 20 GHz
$\boldsymbol{B}$	$\begin{bmatrix} 1.04 & 0.07 & 0.01 & 0.08 & -0.06 & 0.00 & 0.22 \\ 0.00 & 0.89 & 0.00 & -0.07 & -0.20 & 0.06 & -0.03 \\ -0.00 & 0.07 & 0.99 & 0.04 & -0.12 & 0.01 & -0.06 \\ -0.04 & 0.00 & -0.01 & 0.97 & 0.10 & -0.06 & -0.27 \\ 0.01 & 0.04 & 0.00 & 0.03 & 0.99 & -0.05 & -0.03 \\ -0.13 & -0.05 & -0.04 & -0.16 & 0.12 & 0.99 & 0.62 \\ -0.08 & 0.12 & -0.03 & 0.00 & -0.07 & 0.03 & 0.83 \end{bmatrix}$	$\begin{bmatrix} 0.99 & 0.02 & -0.00 & 0.01 & -0.09 & -0.01 & 0.13 \\ 0.05 & 0.85 & 0.01 & -0.07 & -0.28 & 0.01 & -0.01 \\ -0.06 & 0.15 & 0.98 & 0.04 & -0.25 & 0.00 & 0.02 \\ -0.10 & -0.06 & -0.03 & 0.88 & 0.13 & -0.09 & -0.27 \\ 0.08 & 0.04 & 0.03 & 0.11 & 1.07 & -0.04 & -0.12 \\ -0.14 & -0.02 & -0.05 & -0.15 & 0.23 & 1.03 & 0.51 \\ -0.13 & 0.22 & -0.04 & 0.02 & -0.07 & 0.03 & 0.87 \end{bmatrix}$
$\boldsymbol{c}$	$[0.02 \quad 0.01 \quad -0.01 \quad -0.03 \quad -0.01 \quad 0.07 \quad -0.03]^T$	$[0.01 \quad 0.01 \quad -0.01 \quad -0.03 \quad -0.01 \quad 0.05 \quad -0.03]^T$
$\boldsymbol{s}$	$[-0.01 \quad 0.09 \quad -0.10 \quad -0.02 \quad 0.00 \quad -0.02 \quad -0.20]^T$	$[0.00 \quad 0.01 \quad -0.01 \quad 0.00 \quad 0.00 \quad 0.00 \quad -0.02]^T$
$\boldsymbol{t}$	$\mathbf{0}$	$[0.01 \quad 0.00 \quad -0.02 \quad 0.00 \quad 0.00 \quad 0.00 \quad 0.00]^T$
σ	0.851	0.957
δ	–0.003	0.008

Microstrip Shaped T-Junction

the responses of the shaped T-Junction at two test points in the region of interest by Sonnet's ***em*** (•), by the coarse model (---) and by the enhanced coarse model (—)





Microstrip Shaped T-Junction

the enhanced coarse model for the shaped T-Junction can be utilized in optimization

the optimization variables are X and Y

the other parameters are kept fixed (W = 24 mil, H = 25 mil and ε_r = 9.9)

the design specifications are

$$|S_{11}| \leq 1/3, \quad |S_{22}| \leq 1/3$$

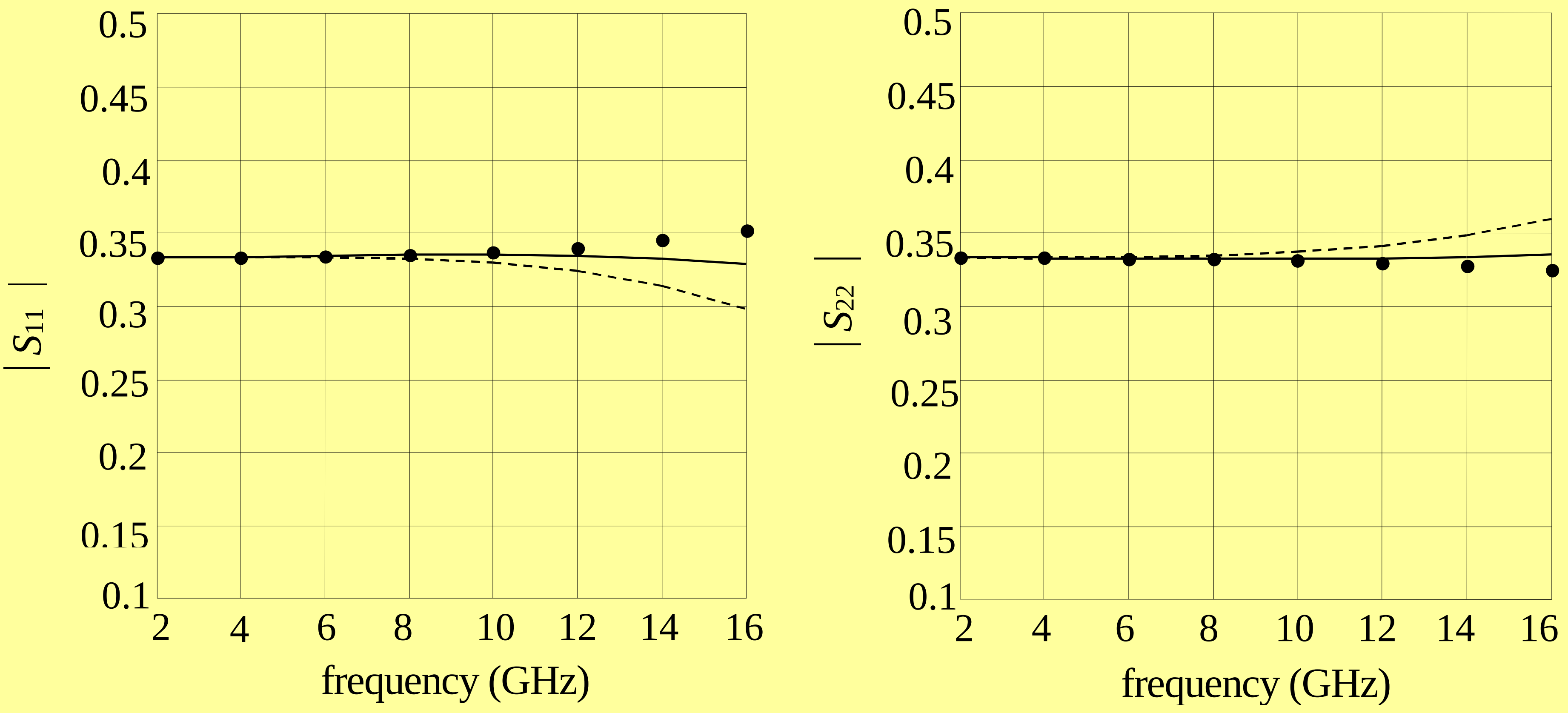
in the frequency range 2 GHz to 16 GHz

the minimax optimizer in OSA90/hope reached the solution

$$X = 2.1 \text{ mil and } Y = 21.1 \text{ mil}$$

Microstrip Shaped T-Junction

responses of the optimal shaped T-Junction by Sonnet's ***em*** (•), by the coarse model (---) and by the enhanced coarse model (—)



Neural Space Mapping (NSM) Optimization
(Bakr et al., 2000)

exploits the SM-based neuromodeling techniques
(Bandler et al., 1999)

coarse models provide knowledge to reduce the amount of learning data and improve generalization and extrapolation performance

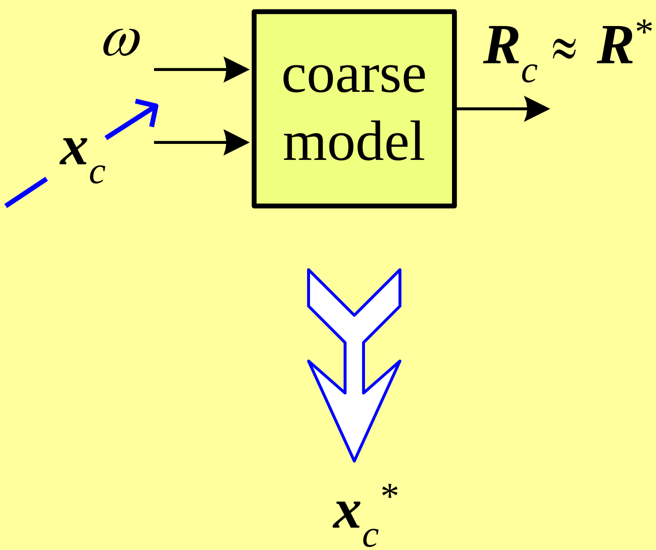
NSM requires a reduced set of upfront learning base points

initial learning base points are selected through sensitivity analysis using the coarse model

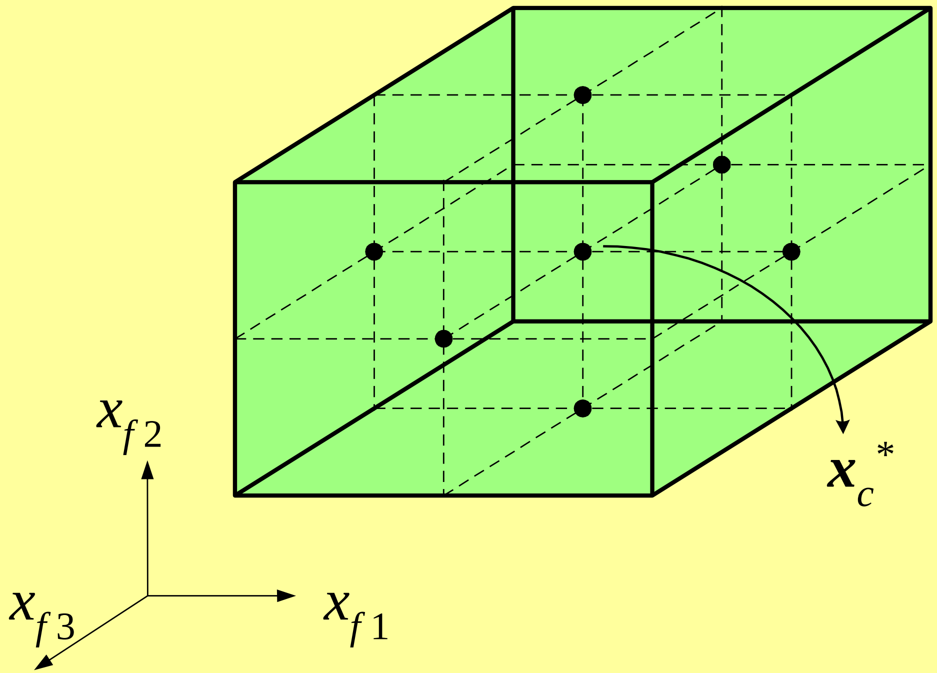
neuromappings are developed iteratively: their generalization performance is controlled by gradually increasing their complexity starting with a 3-layer perceptron with 0 hidden neurons

Neural Space Mapping (NSM) Optimization Concept

step 1



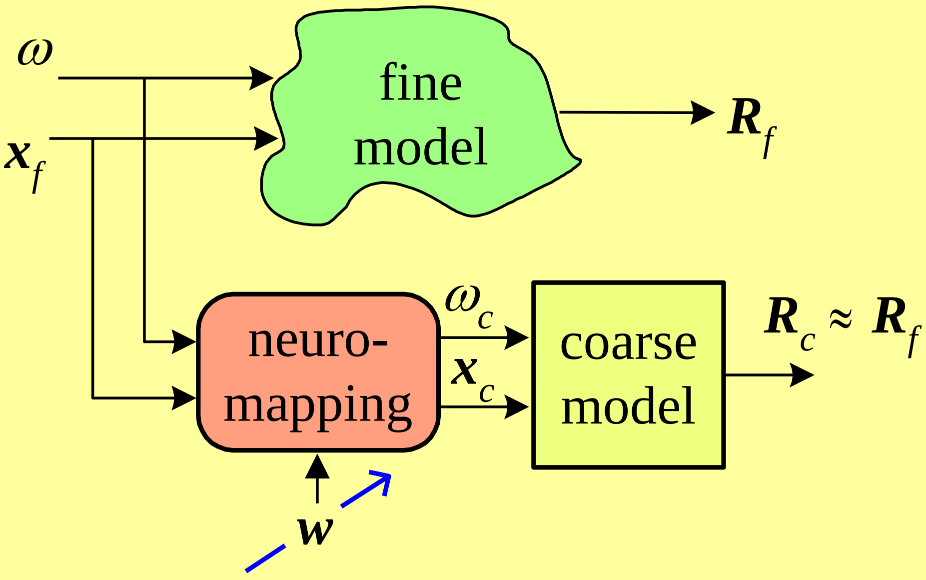
step 2



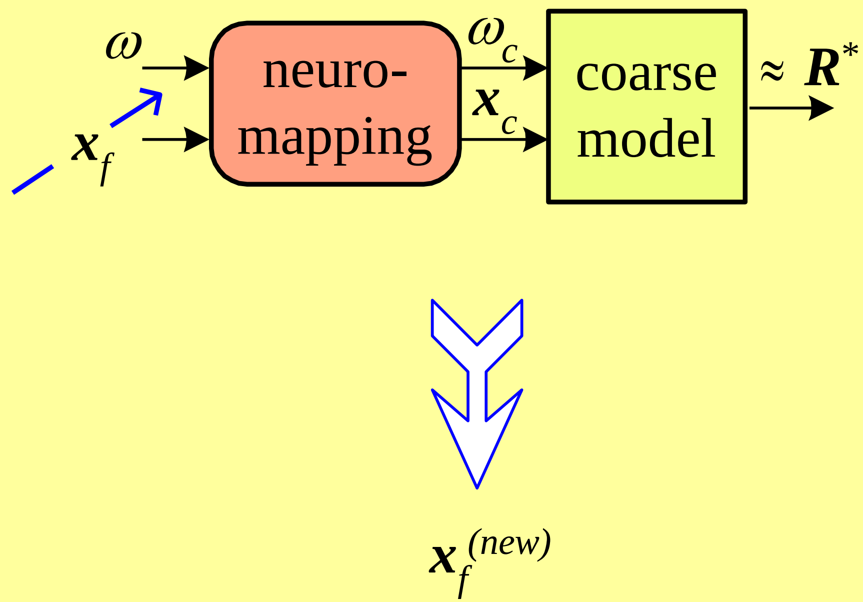
(2*n* + 1 learning base points for a microwave circuit with *n* design parameters)

Neural Space Mapping (NSM) Optimization Concept (continued)

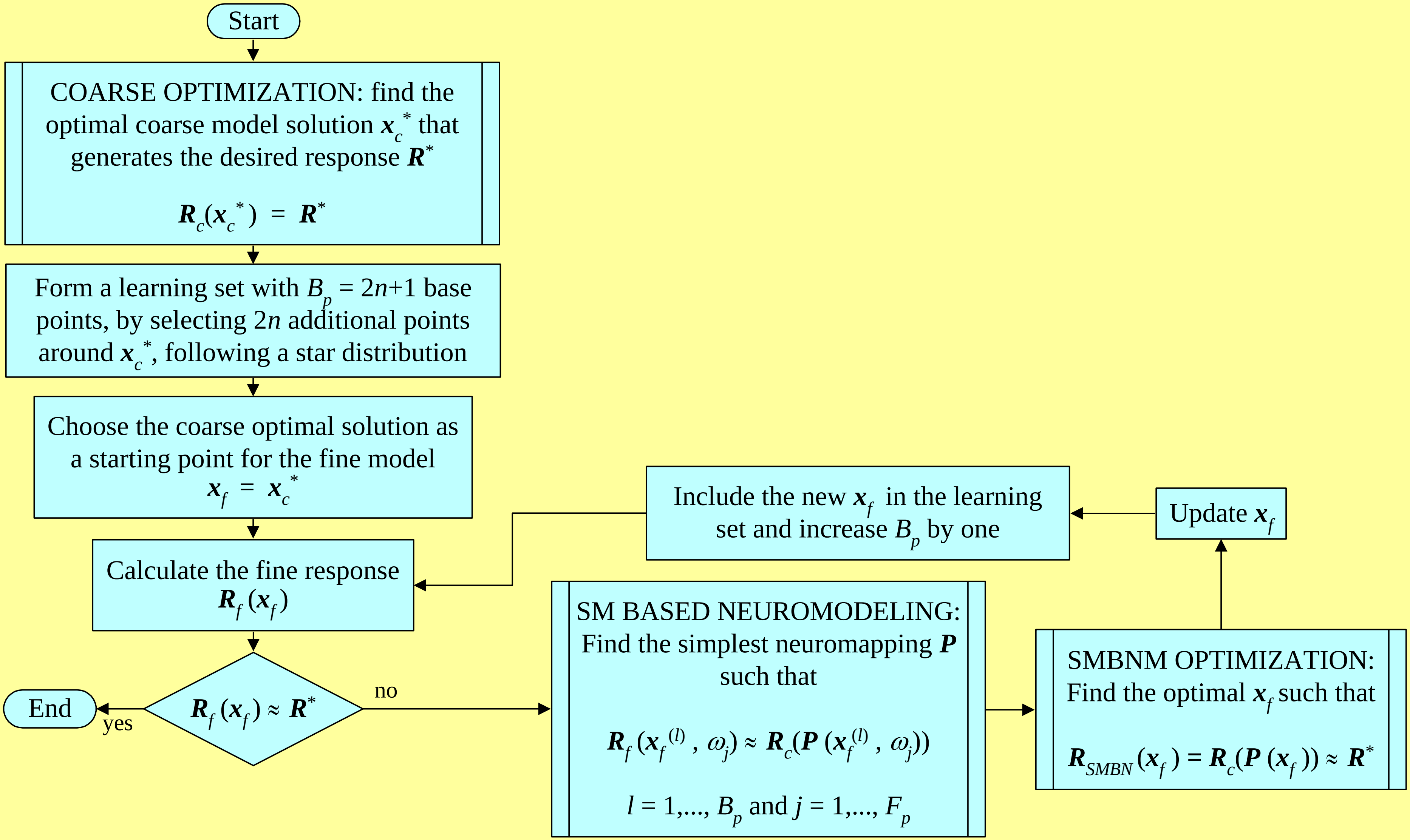
step 3



step 4

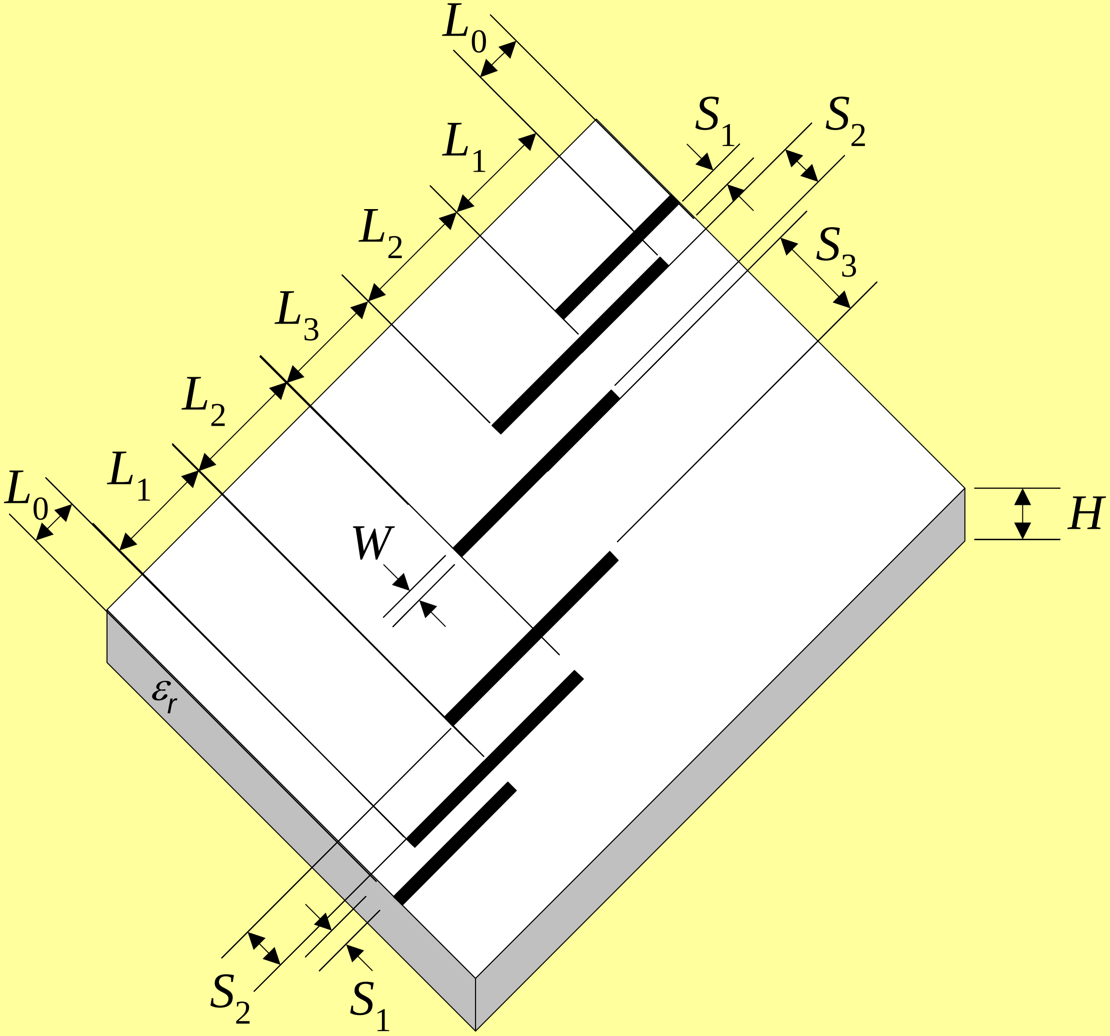


Neural Space Mapping (NSM) Optimization Algorithm



HTS Quarter-Wave Parallel Coupled-Line Microstrip Filter

(Westinghouse, 1993)



we take L_0 = 50 mil, H = 20 mil, W = 7 mil, ε_r = 23.425, loss tangent = 3×10^{-5}; the metalization is considered lossless

the design parameters are $\boldsymbol{x}_f = [L_1\ L_2\ L_3\ S_1\ S_2\ S_3]^T$

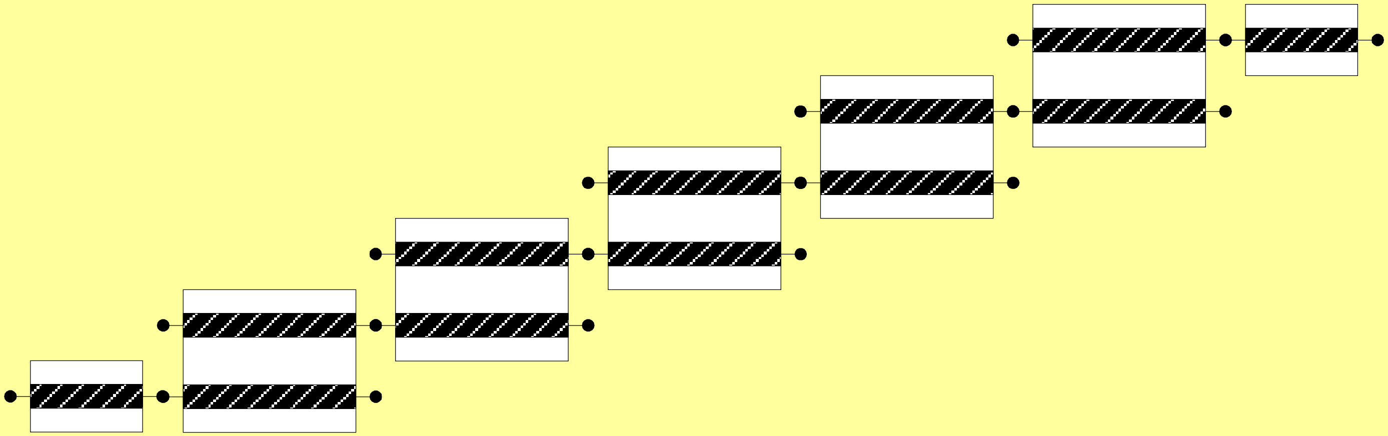
NSM Optimization of the HTS Microstrip Filter

specifications

$|S_{21}| \geq 0.95$ for 4.008 GHz $\leq f \leq$ 4.058 GHz
$|S_{21}| \leq 0.05$ for $f \leq$ 3.967 GHz and $f \geq$ 4.099 GHz

"fine" model: Sonnet's ***em***™ with high resolution grid

"coarse" model: OSA90/hope™ built-in models of open circuits, microstrip lines and coupled microstrip lines

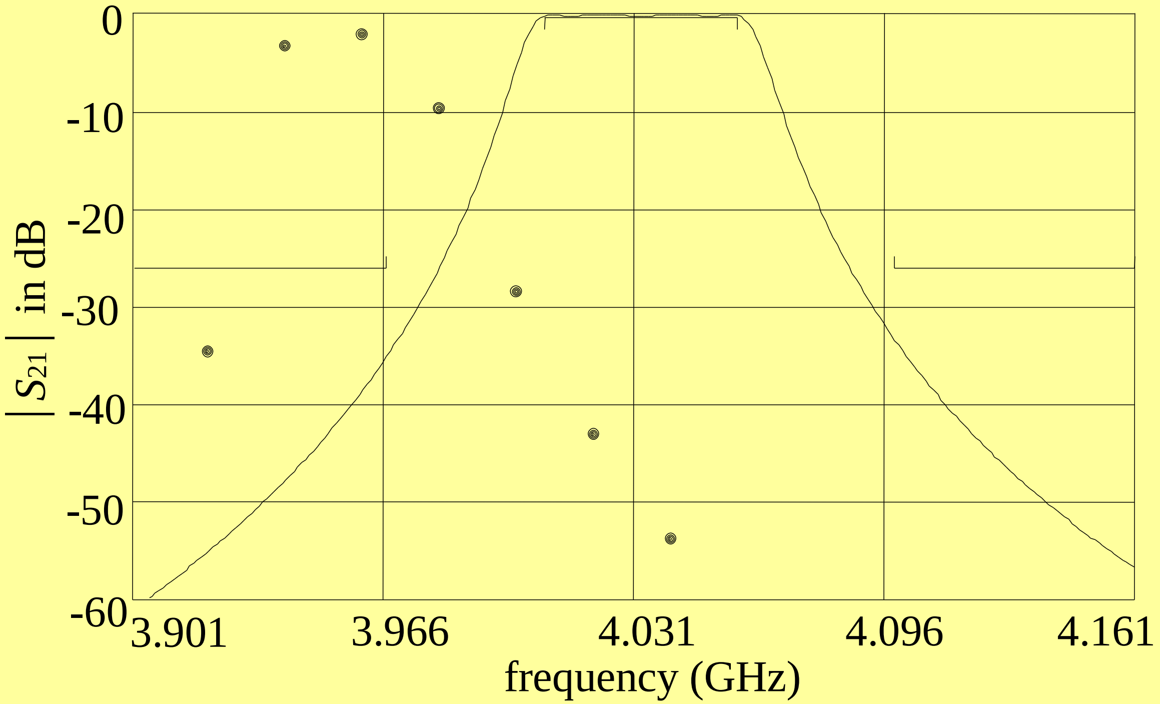


NSM Optimization of the HTS Filter (continued)

coarse and fine model responses at the optimal coarse solution

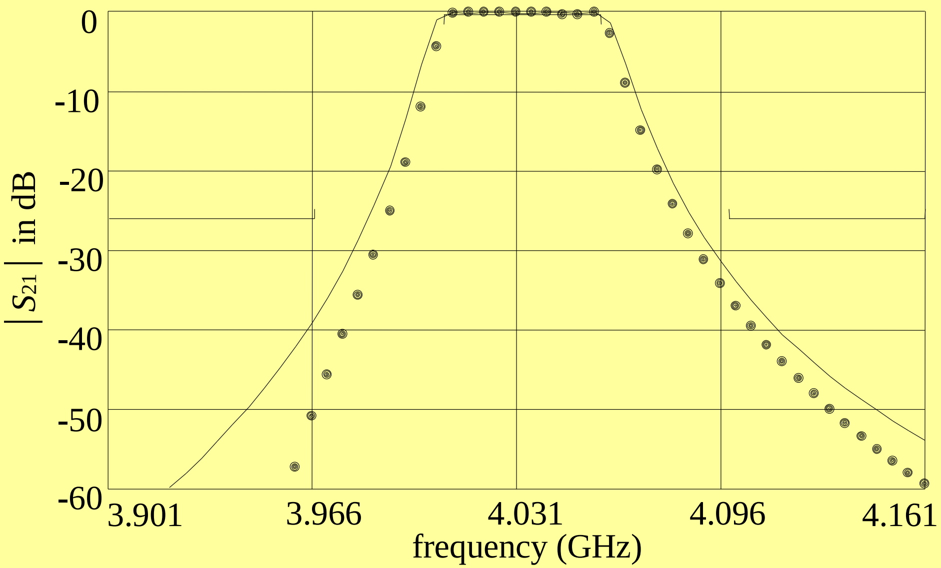
$$x_c^* = [188.33 \;\; 197.98 \;\; 188.58 \;\; 21.97 \;\; 99.12 \;\; 111.67]^T \text{ (mils)}$$

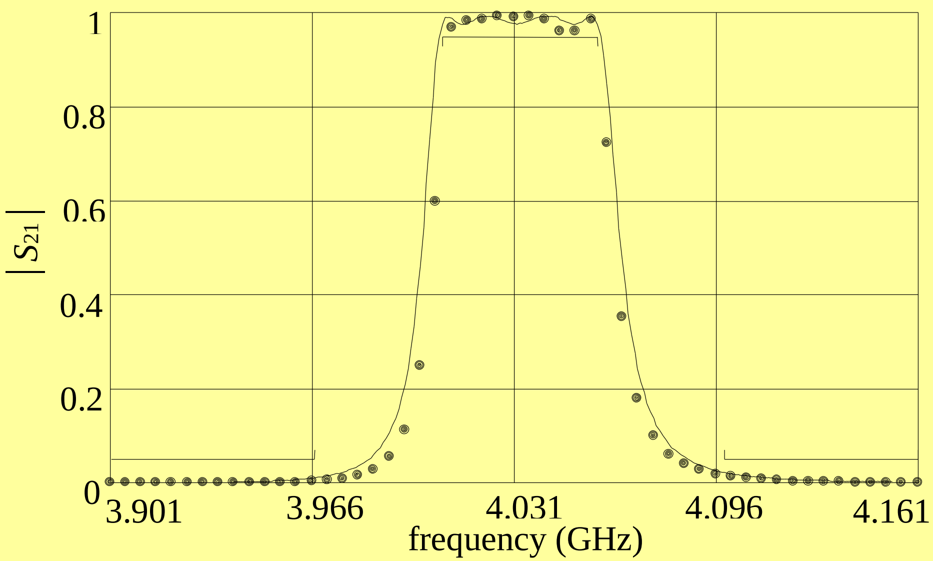
OSA90/hope™ (–) and ***em***™ (•)



NSM Optimization of the HTS Filter (continued)

em™ (•) and FPSM 7-5-3 (–) model responses at the NSM solution using a fine frequency sweep





Space Mapping Optimization Exploiting Surrogates
(Bakr et al., 2000)

a powerful new Space Mapping (SM) optimization algorithm

draws upon recent developments in both surrogate model-based optimization
and modeling of microwave devices

SM optimization is formulated as a general optimization problem of a surrogate model

this model is a convex combination of a mapped coarse model and a linearized fine model

it exploits a linear frequency-sensitive mapping

during the optimization iterates, the coarse and fine models are simulated at different sets of frequencies.

this approach is especially powerful if a significant response shift exists

The Surrogate Model

our surrogate model is a convex combination of a mapped coarse model and a linearized fine model

the ith iteration surrogate model is

$$\boldsymbol{R}_s^{(i)}(\boldsymbol{x}_f) = \lambda^{(i)}\boldsymbol{R}_m^{(i)}(\boldsymbol{x}_f) + (1-\lambda^{(i)})(\boldsymbol{R}_f(\boldsymbol{x}_f^{(i)}) + \boldsymbol{J}_f^{(i)}\Delta\boldsymbol{x}_f), \quad \lambda^{(i)} \in [0,1]$$

the mapped coarse model utilizes the frequency-sensitive mapping

$$\boldsymbol{R}_f(\boldsymbol{x}_f,\omega_j) \approx \boldsymbol{R}_m^{(i)}(\boldsymbol{x}_f,\omega_j) = \boldsymbol{R}_c(\boldsymbol{P}^{(i)}(\boldsymbol{x}_f,\omega_j), \boldsymbol{P}_\omega^{(i)}(\boldsymbol{x}_f,\omega_j))$$

where

$$\begin{bmatrix} \boldsymbol{P}^{(i)}(\boldsymbol{x}_f,\omega_j) \\ \boldsymbol{P}_\omega^{(i)}(\boldsymbol{x}_f,\omega_j) \end{bmatrix} = \begin{bmatrix} \boldsymbol{B}^{(i)} & \boldsymbol{s}^{(i)} \\ \boldsymbol{t}^{(i)T} & \sigma^{(i)} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{x}_f \\ \omega_j \end{bmatrix} + \begin{bmatrix} \boldsymbol{c}^{(i)} \\ \gamma^{(i)} \end{bmatrix}$$

the parameters $\boldsymbol{B}^{(i)} \in \Re^{n\times n}$, $\boldsymbol{s}^{(i)} \in \Re^{n\times 1}$, $\boldsymbol{t}^{(i)} \in \Re^{n\times 1}$, $\boldsymbol{c}^{(i)} \in \Re^{n\times 1}$, $\sigma^{(i)} \in \Re^{1\times 1}$ and $\gamma^{(i)} \in \Re^{1\times 1}$ are obtained such that the mapped coarse model approximates the fine model over a given set of fine model points $V^{(i)}$ and frequencies $\boldsymbol{\omega}$

The Surrogate Model (continued)

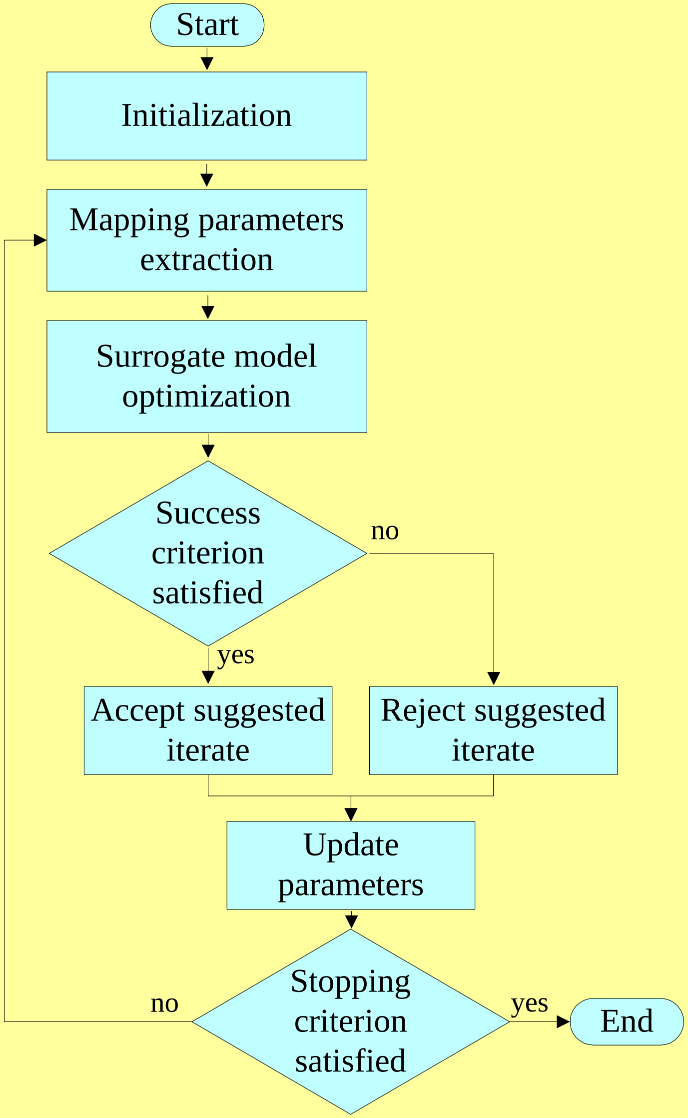
the mapping parameters are obtained through the optimization process

$$[\boldsymbol{B}^{(i)}, \boldsymbol{s}^{(i)}, \boldsymbol{t}^{(i)}, \sigma^{(i)}, \boldsymbol{c}^{(i)}, \gamma^{(i)}] = \arg\left\{ \min_{\boldsymbol{B}, \boldsymbol{s}, \boldsymbol{t}, \sigma, \boldsymbol{c}, \gamma} \left\| \begin{bmatrix} \boldsymbol{e}_1^T & \boldsymbol{e}_2^T & \cdots & \boldsymbol{e}_{N_p}^T \end{bmatrix}^T \right\| \right\}$$

where

$$\boldsymbol{e}_k = \boldsymbol{R}_m^{(i)}(\boldsymbol{x}_f^{(k)}) - \boldsymbol{R}_f(\boldsymbol{x}_f^{(k)}) \qquad \forall\, \boldsymbol{x}_f^{(k)} \in V^{(i)}$$

The Algorithm Flowchart



The SMX System
(Bandler et al., 2000)

SMX is a new generation engineering optimization system

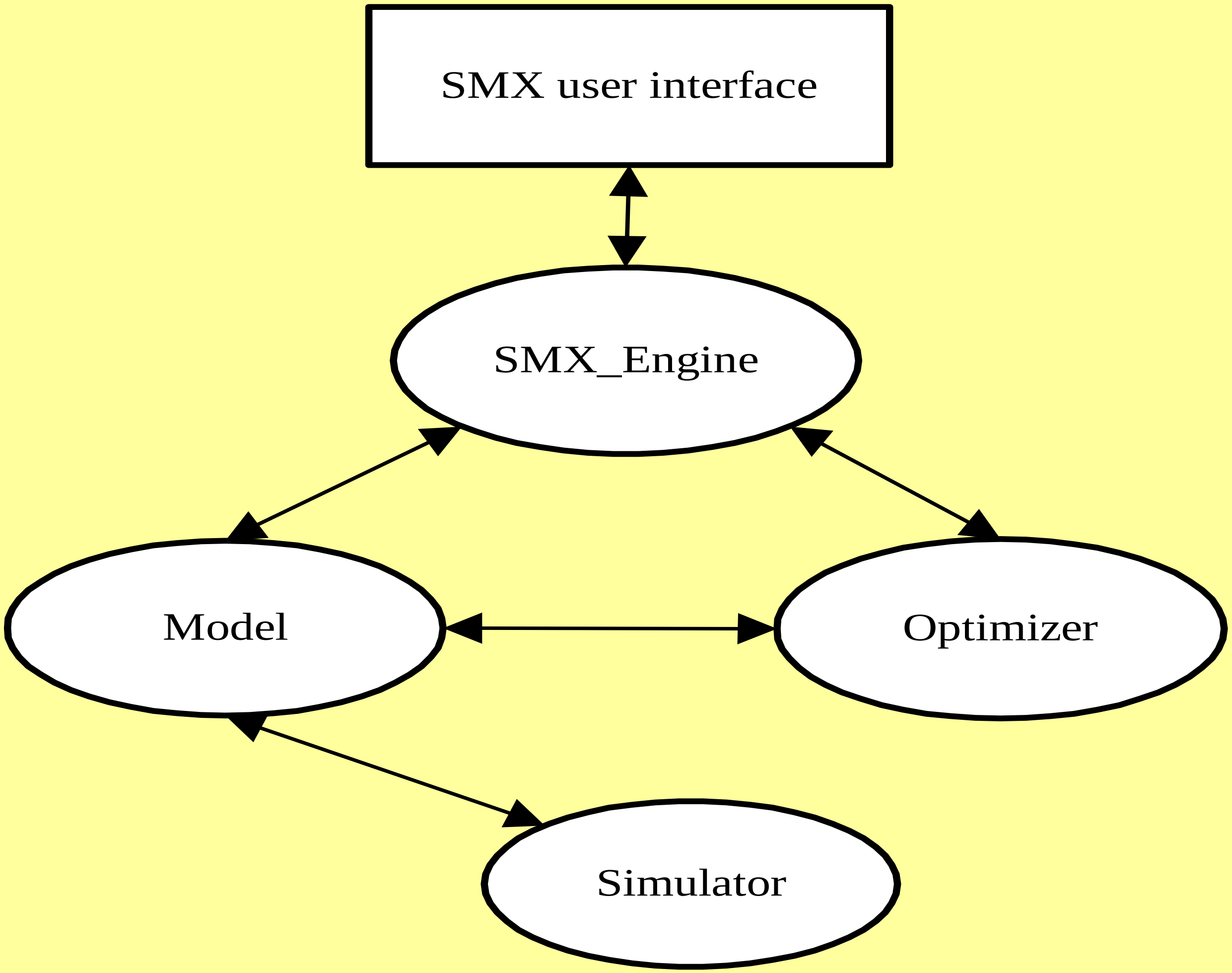
it currently provides the following optimization capabilities

minimax
Huber
Space Mapping using Surrogate Models

it can be interfaced to

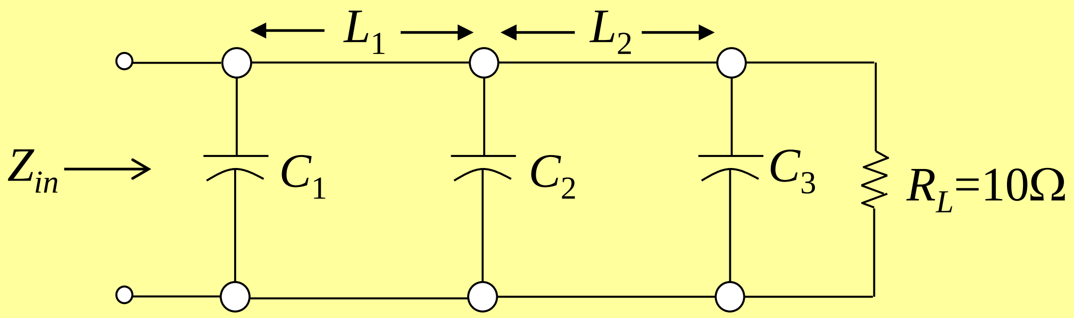
OSA90/hope *(Optimization Systems Associates, 1997)*
Momentum *(Agilent EEsof EDA)*
user supplied executable programs

Object Oriented SMX System Design: Data Flow Between Modules

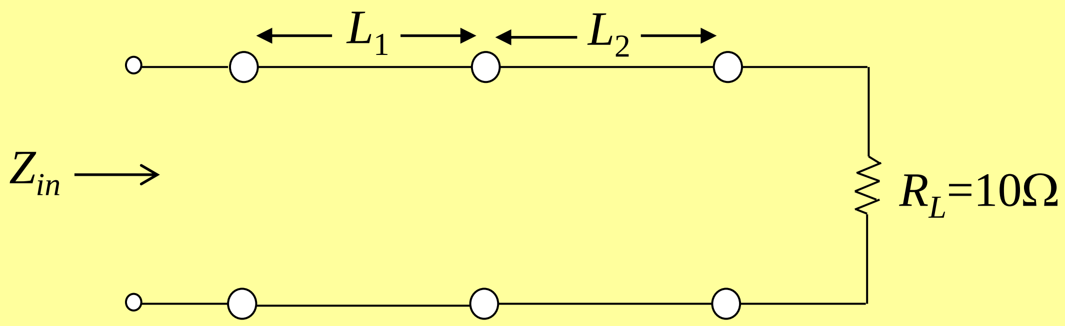


SMX Example: A Two-section 10:1 Capacitively-loaded Impedance Transformer Design

fine model



coarse model

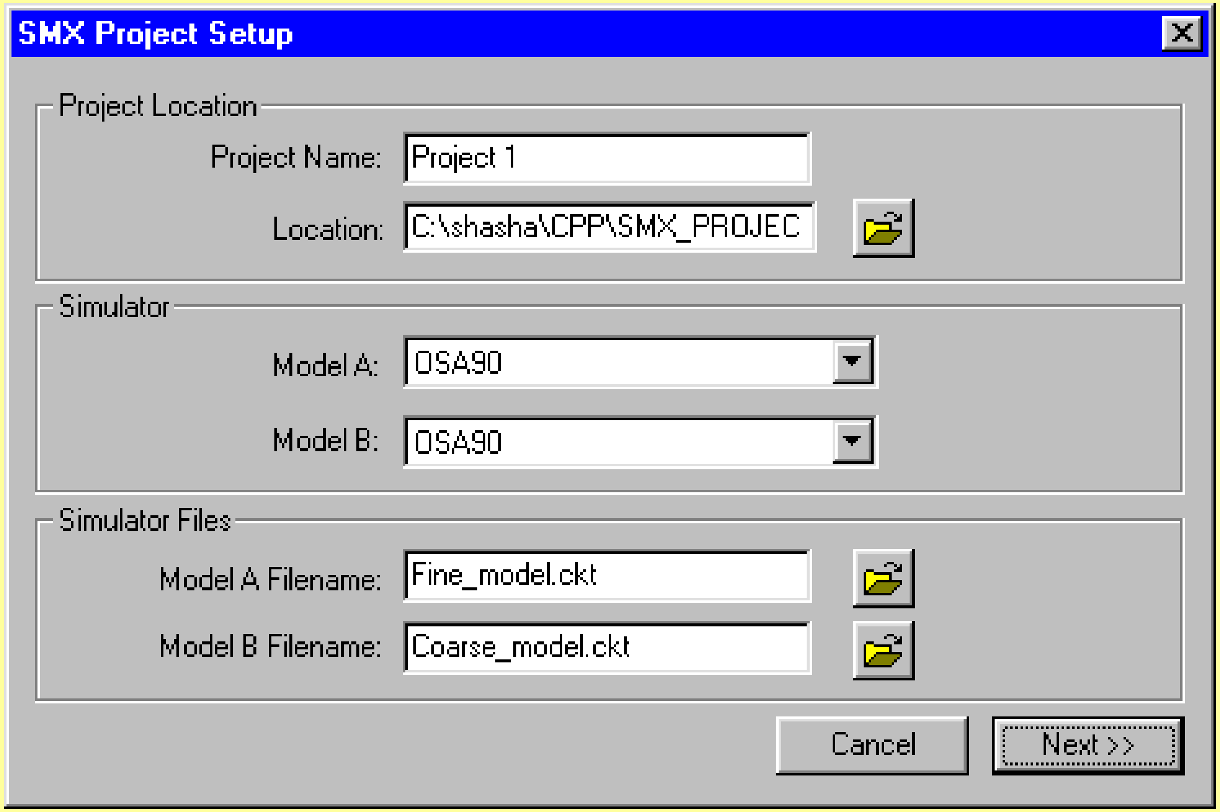


specifications

$$|S_{11}| \leq 0.50 \text{ for } 0.5 \text{ GHz} \leq \omega \leq 1.5 \text{ GHz}$$

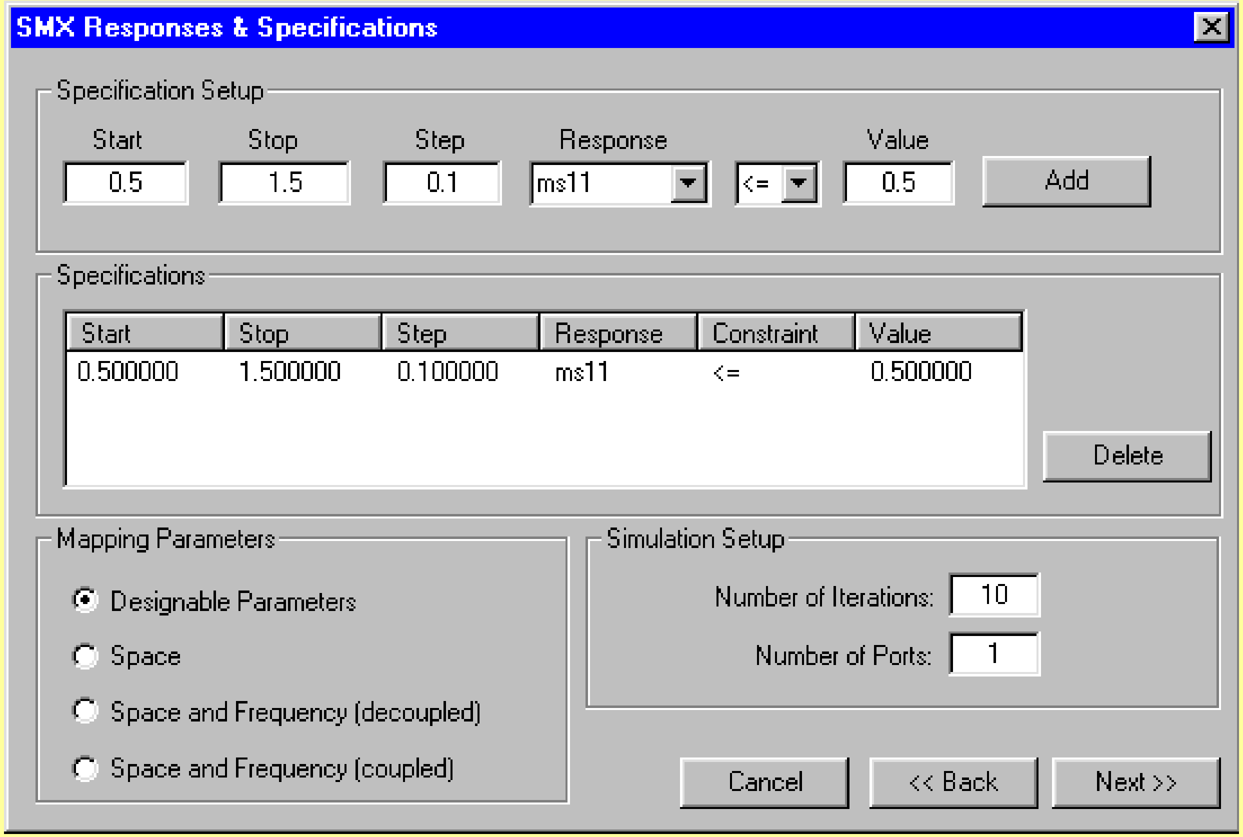
Object Oriented SMX System Example: Problem Setup Wizard

step 1: project setup



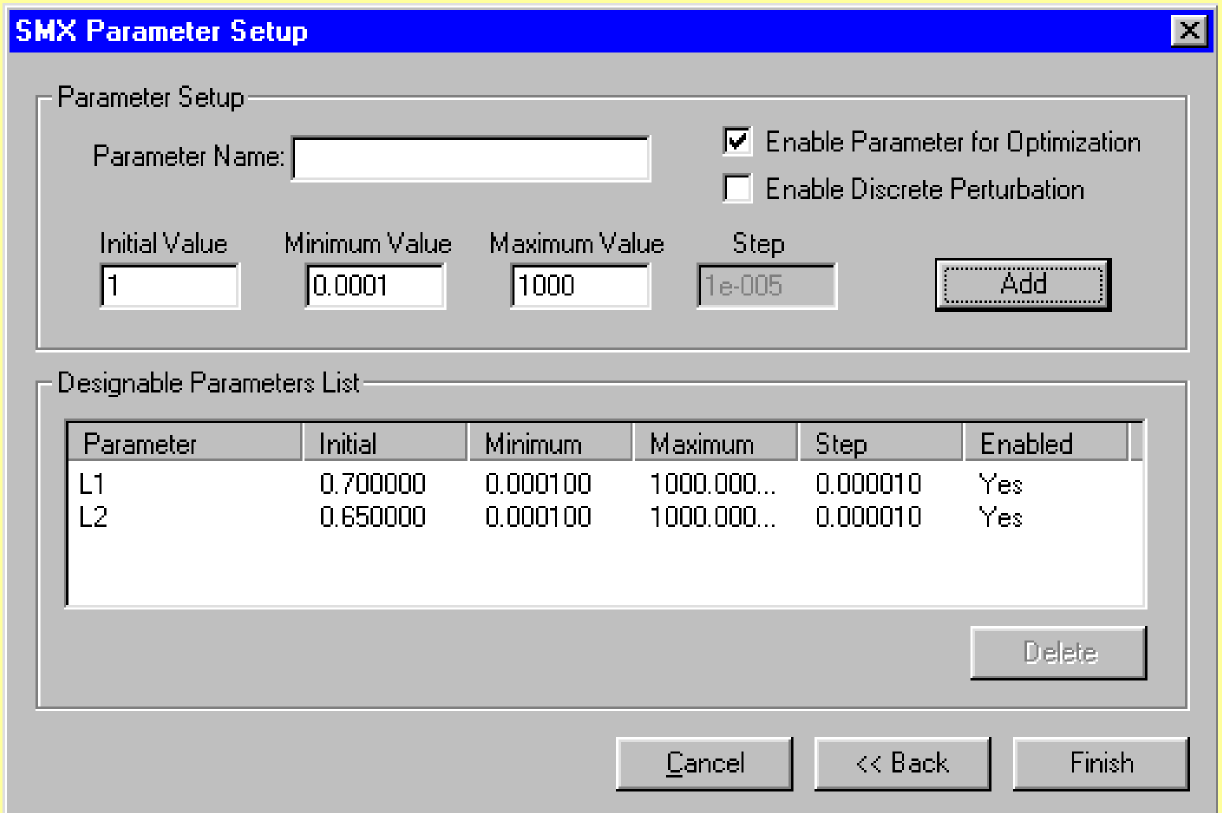
Object Oriented SMX System Example: Problem Setup Wizard

step 2: responses and specifications

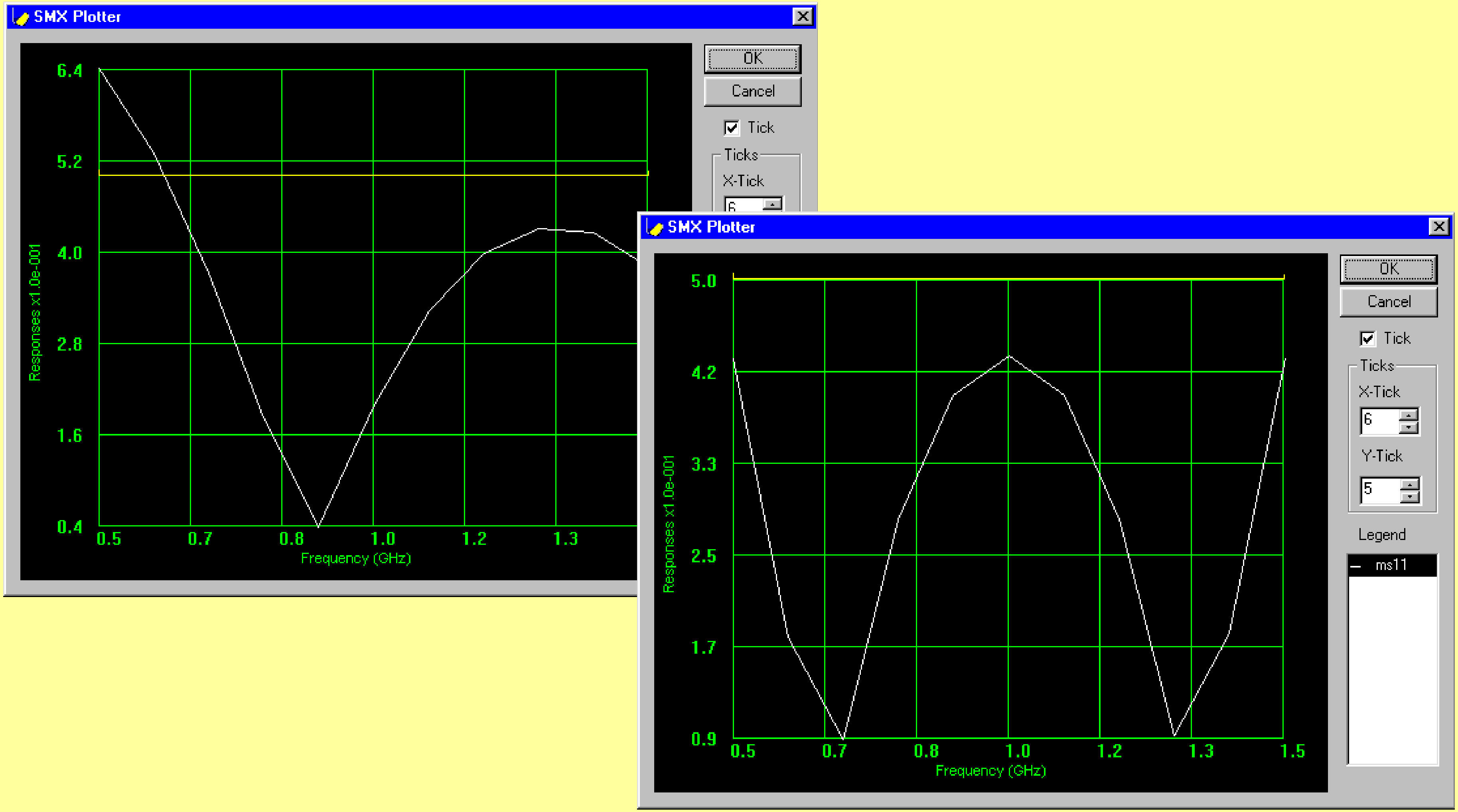


Object Oriented SMX System Example: Problem Setup Wizard

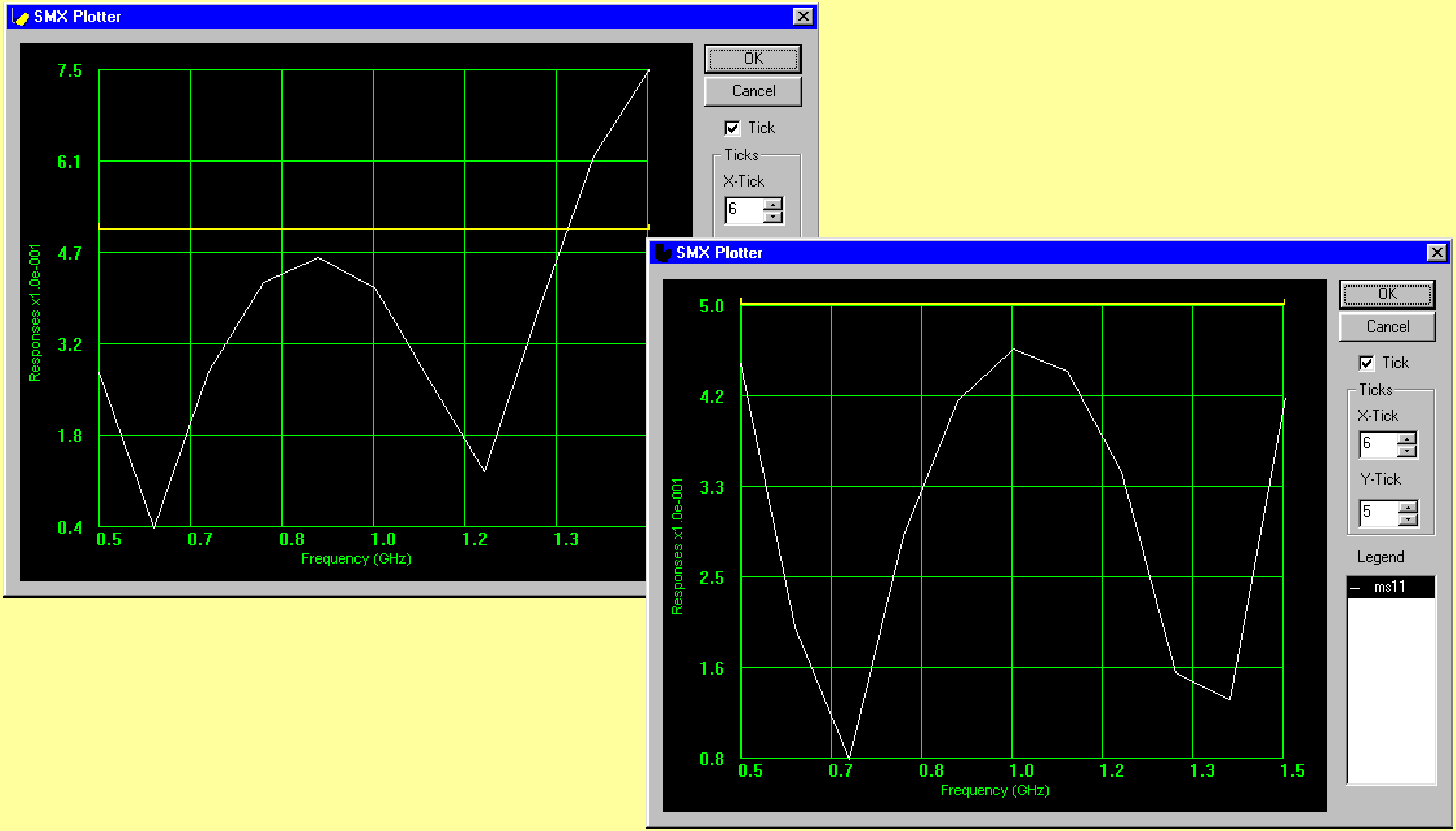
step 3: parameter setup



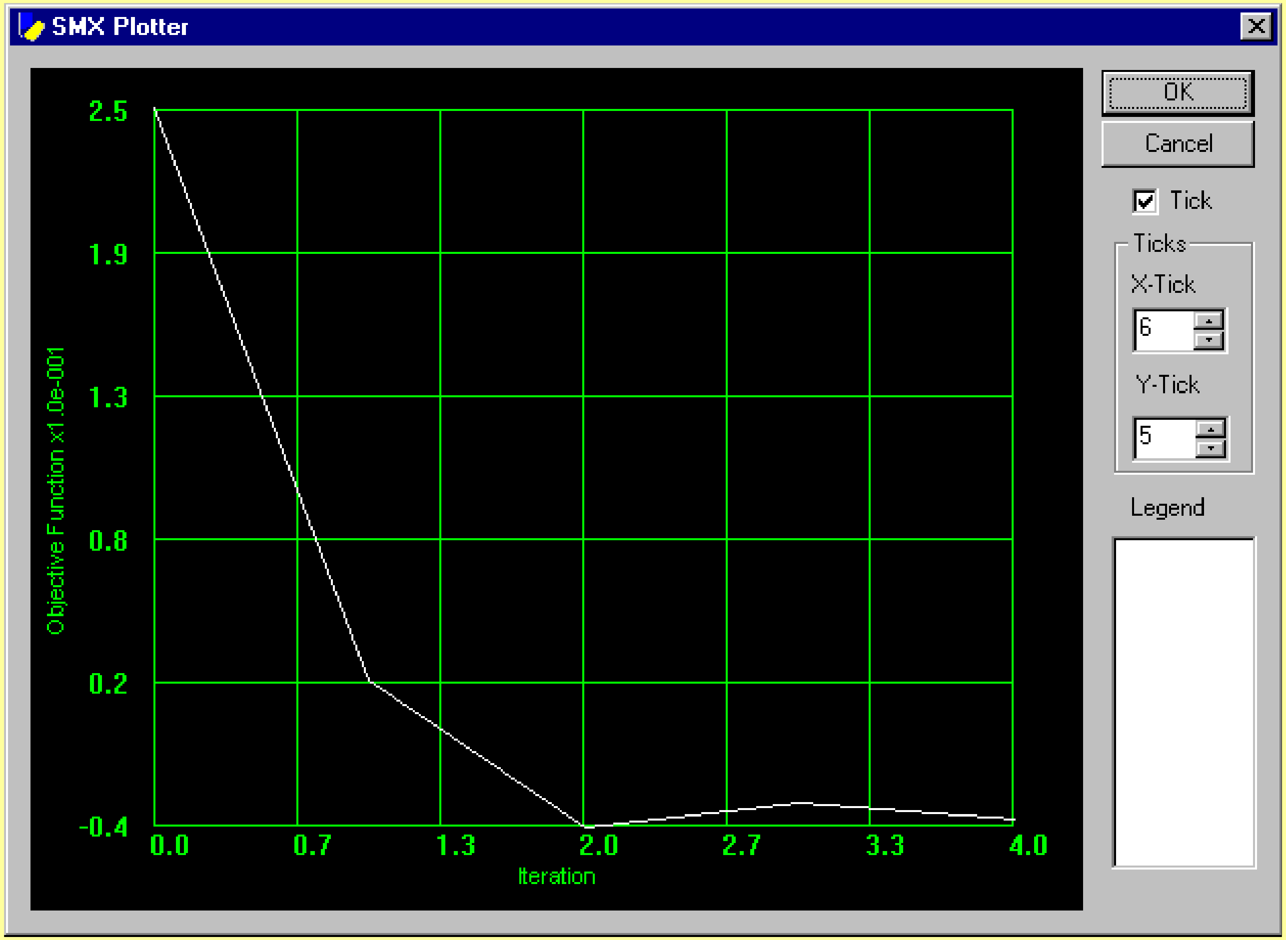
Object Oriented SMX System Example: Initial and Optimal Coarse Model Responses

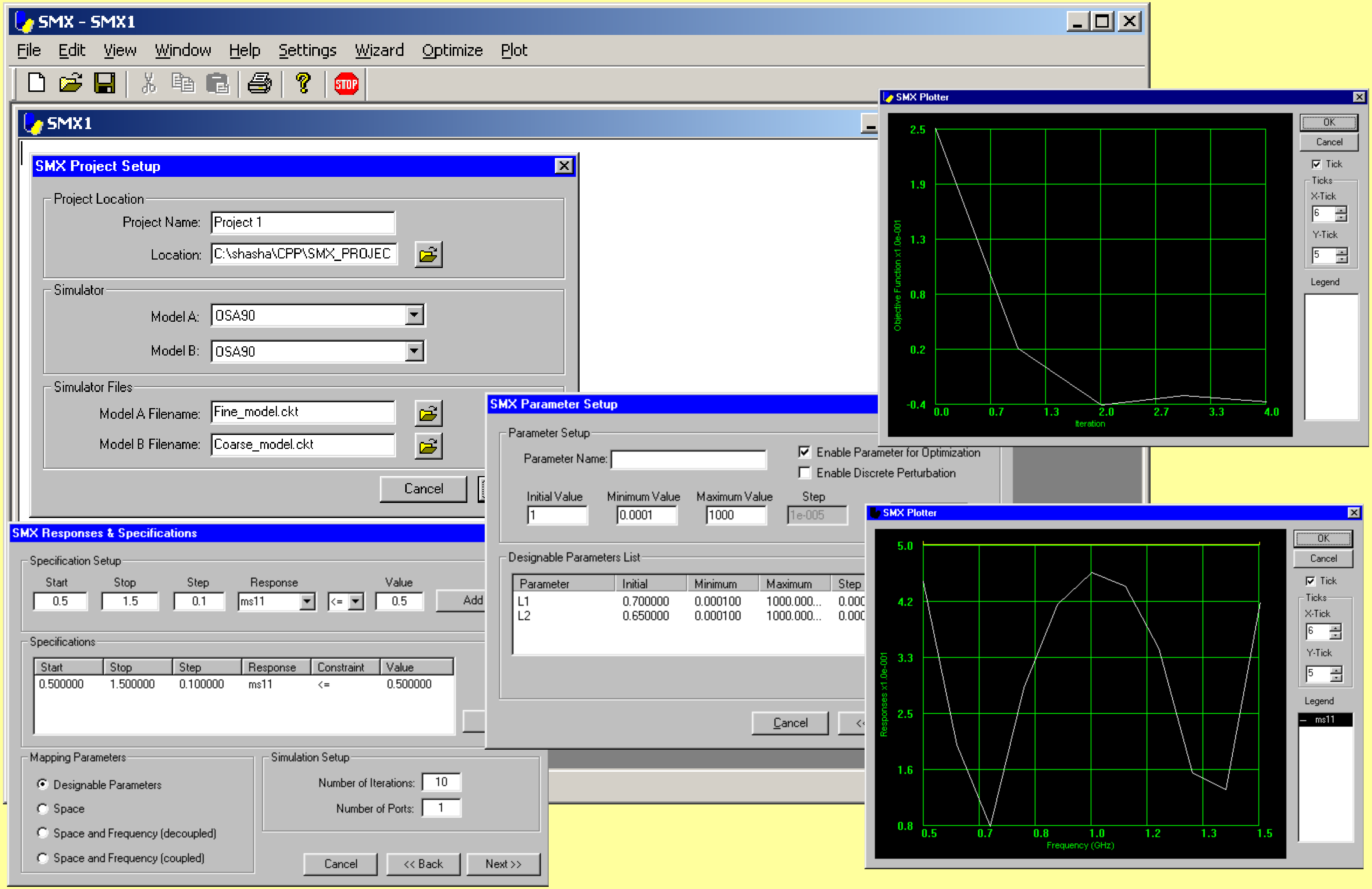


Object Oriented SMX System Example: Initial and Optimal Fine Model Responses



Object Oriented SMX System Example: Objective Function Value




SMX - SMX1
File Edit View Window Help Settings Wizard Optimize Plot
SMX1
SMX Project Setup
Project Location
Project Name: Project 1
Location: C:\shasha\CPP\SMX_PROJEC
Simulator
Model A: OSA90
Model B: OSA90
Simulator Files
Model A Filename: Fine_model.ckt
Model B Filename: Coarse_model.ckt
Cancel
SMX Responses & Specifications
Specification Setup
Start Stop Step Response Value
0.5 1.5 0.1 ms11 <= 0.5
Add
Specifications
Start Stop Step Response Constraint Value
0.500000 1.500000 0.100000 ms11 <= 0.500000
Mapping Parameters
Designable Parameters
Space
Space and Frequency (decoupled)
Space and Frequency (coupled)
Simulation Setup
Number of Iterations: 10
Number of Ports: 1
Cancel << Back Next >>
SMX Parameter Setup
Parameter Setup
Parameter Name:
Enable Parameter for Optimization
Enable Discrete Perturbation
Initial Value Minimum Value Maximum Value Step
1 0.0001 1000 1e-005
Designable Parameters List
Parameter Initial Minimum Maximum Step
L1 0.700000 0.000100 1000.000... 0.000
L2 0.650000 0.000100 1000.000... 0.000
Cancel
SMX Plotter
OK
Cancel
Tick
Ticks
X-Tick
Y-Tick
Legend
Objective Function x1.0e-001
Iteration
2.5 1.9 1.3 0.8 0.2 -0.4
0.0 0.7 1.3 2.0 2.7 3.3 4.0
SMX Plotter
Responses x1.0e-001
Frequency (GHz)
5.0 4.2 3.3 2.5 1.6 0.8
0.5 0.7 0.8 1.0 1.2 1.3 1.5
ms11

Conclusions

we review the Space Mapping concept and the Aggressive Space Mapping concept

we review Generalized Space Mapping, a new engineering device modeling framework, that exploits Frequency Space Mapping and Multiple Space Mapping

we review EM optimization based on Space Mapping technology and Artificial Neural Networks

Neural Space Mapping optimization exploits our SM-based neuromodeling techniques

we review a new SM optimization algorithm based on surrogate models

the surrogate model is a convex combination of a mapped coarse model and a linearized fine model

we briefly review the state-of-the-art SMX engineering optimization system including Space Mapping technology

References

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