Inverse Design Algorithm for Arbitrary Microwave Circuits

Caleb Brown, Gabriel Santamaria-Botello, Peter Aaen

Colorado School of Mines, Microwave Photonics Lab

Github Repository

Introduction and Motivation

- As high frequency electronic devices become more common, it becomes difficult to design optimal circuits to operate at these frequencies.
- Inverse design can synthesize an electromagnetic structure to achieve a desired response.
- Inverse design avoids lengthy parameter tuning steps.
- Arbitrary geometries can greatly expand the available solution space.

High Level Overview of the Algorithm

A multilayer process is used to divide the problem into simpler parts, greatly speeding up computation.

Layer 1: The desired input response as S-parameters. This can represent many microwave circuits like filters, power dividers, or couplers. The input can also be entirely arbitrary.

Layer 2: The input response is divided into a 2D grid of lower complexity black-box networks.

Layer 3: An inverse design process creates a 2D geometry for each black-box network in layer 2.

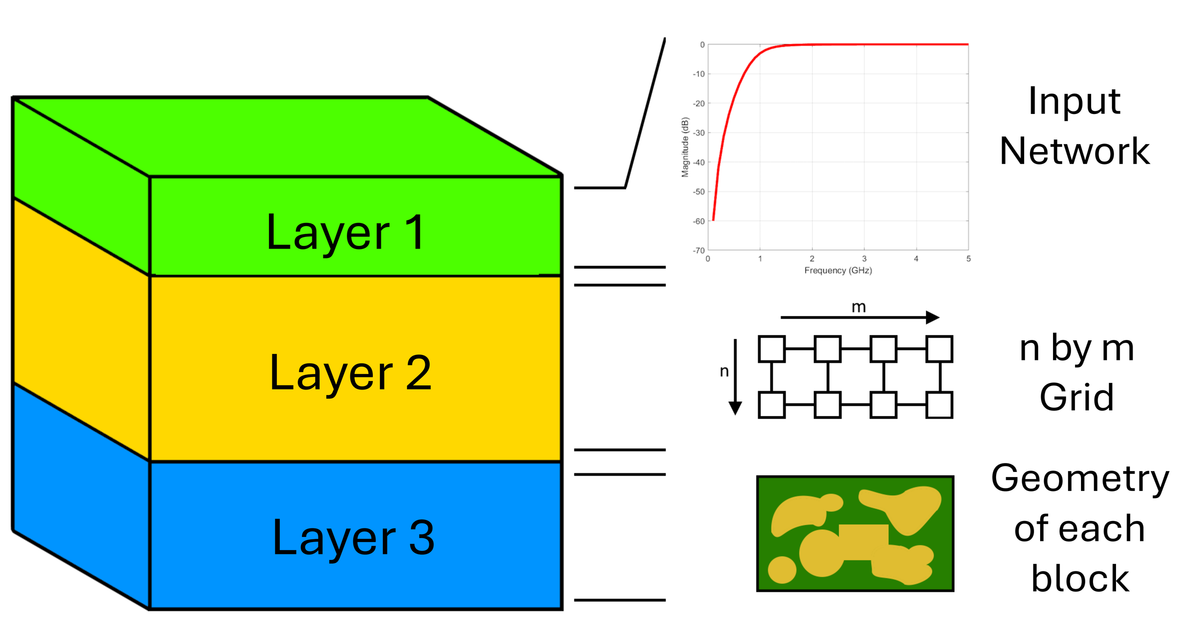

Figure 1: The algorithm has 3 layers to recreate the input

Layer 2 Math

An arbitrary cascade of S-parameter networks can be computer using method described in [1].

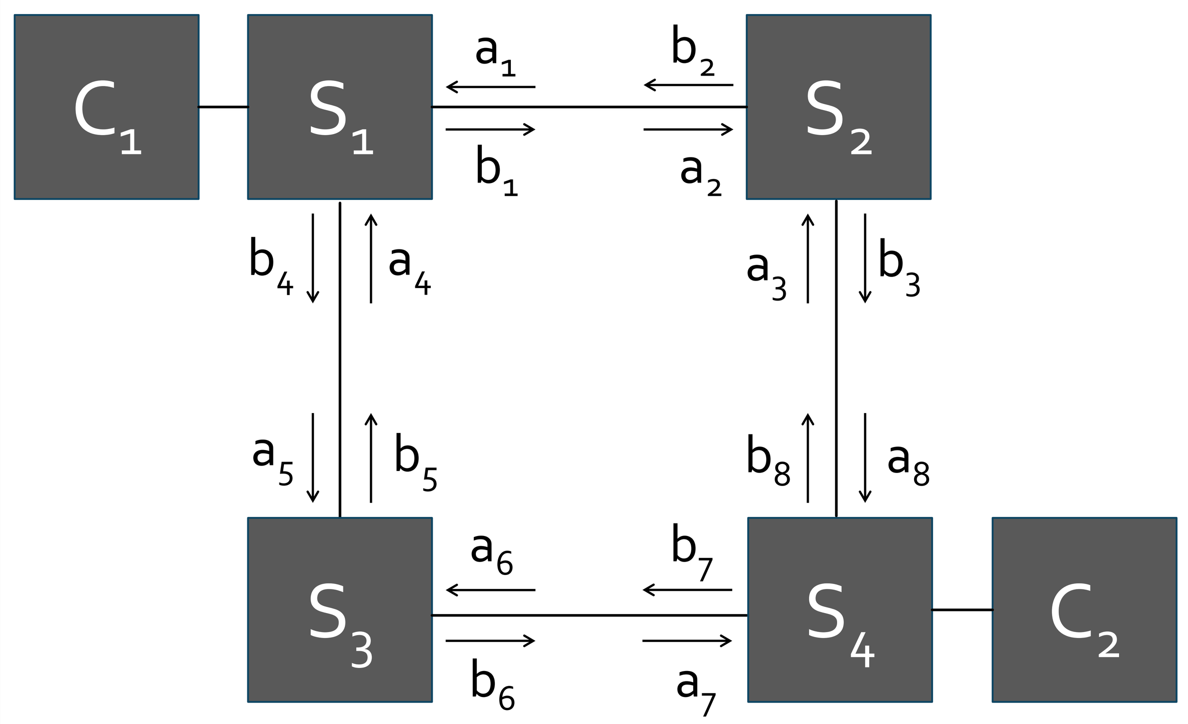

Figure 2: Arbitrary interconnection of four networks

The grid can be represented by the following equations. The variable $\vec{c}$ is the vector of excitation ports. $\vec{a}$ and $\vec{b}$ are the wave variables from figure 2 for each network.

$$\vec{b} = \mathbf{S}\vec{a} + \vec{c}$$

$$\vec{a} = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_{n \times m} \end{bmatrix}, \quad \vec{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_{n \times m} \end{bmatrix}, \quad \vec{c} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_{n \times m} \end{bmatrix}$$

$$\mathbf{S} = \begin{bmatrix} S_1 & \dots & 0 & \dots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \dots & S_i & \dots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & \dots & S_{n \times m} \end{bmatrix}$$

We can define a matrix Γ that represents the interconnection of all wave variables where $\vec{a}_k = \vec{b}_j$. Then we can solve for $\vec{a}$ and $\vec{b}$.

$$\vec{b} = \mathbf{\Gamma}\vec{a}$$

$$\vec{a} = (\mathbf{\Gamma} - \mathbf{S})^{-1}\vec{c}$$

Implementation

The connection scattering method was created using the *Transfer System Cascade* algorithm, a custom MATLAB algorithm which implements the math of layer 2. We represent each black-box network in Laplace domain. Each parameter (S11, S12, ...) is a first order function in terms of s.

$$\mathbf{S}_{k,ij}(s, \vec{x}) = x_1 + \frac{x_2}{s + |x_3|}$$

The following constraints are placed on each network to increase speed and to generate physical realizable systems [2].

$$\mathbf{S}_{k,ij} = \mathbf{S}_{k,ji} \quad (Reciprocity)$$
$$||\mathbf{S}_{k,ij}||_\infty \leq 1 \quad (Passivity)$$

The network can then be optimized. The optimizer attempts to minimize the error between the input X and synthesized output Y at each frequency point, producing a cascaded network which closely resembles the desired response. The cost function is equation 1. The optimization is run twice: once with a quick curve fitting algorithm, and a second, longer optimization using gradient descent.

$$\min_{\vec{x}} \sqrt{\sum_k \frac{|X(f_k, \vec{x}) - Y(f_k, \vec{x})|^2}{N}} \quad (1)$$

Results

Three test cases were used to validate the algorithm: A lowpass filter, a bandpass filter, and a noise matching network. Each optimization was done with a Microsoft Surface 4 with four cores running in parallel. No GPU acceleration was used.

Test Case	Time Taken	#Interations
Lowpass	5 min, 26 sec	208
Bandpass	8 min, 06 sec	355
BFP540	4 min, 30 sec	195

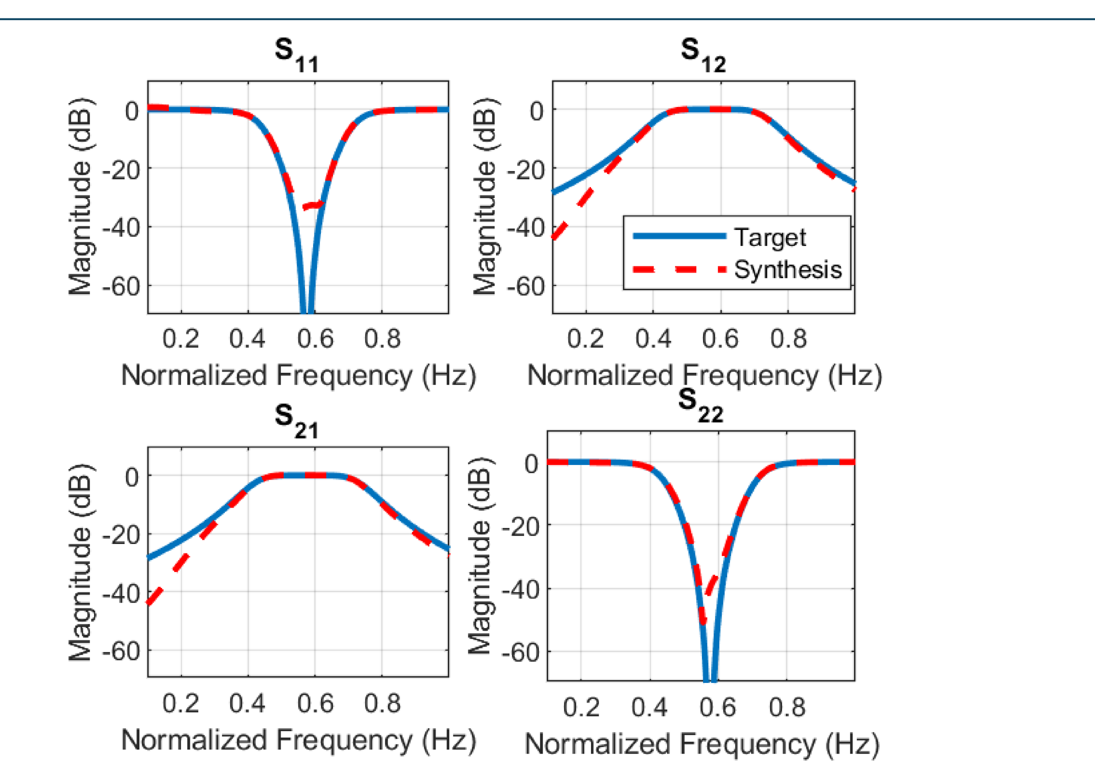

Figure 3: 3rd order bandpass filter. Network Size: 3x3

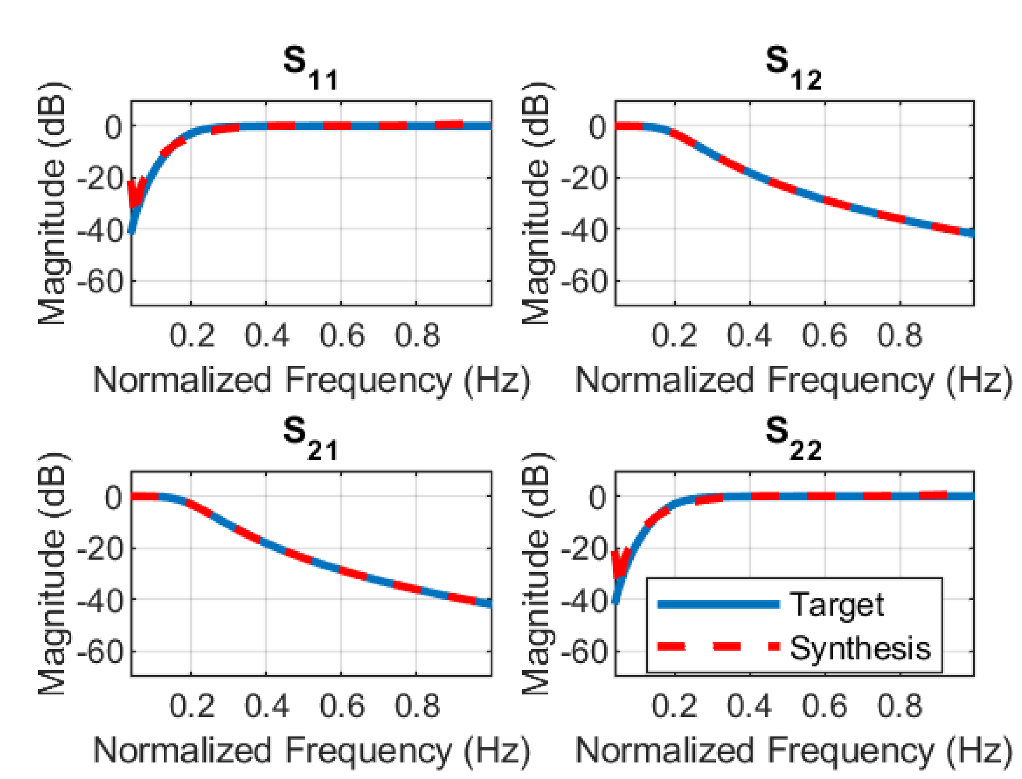

Figure 4: 3rd order lowpass filter. Network Size: 1x4

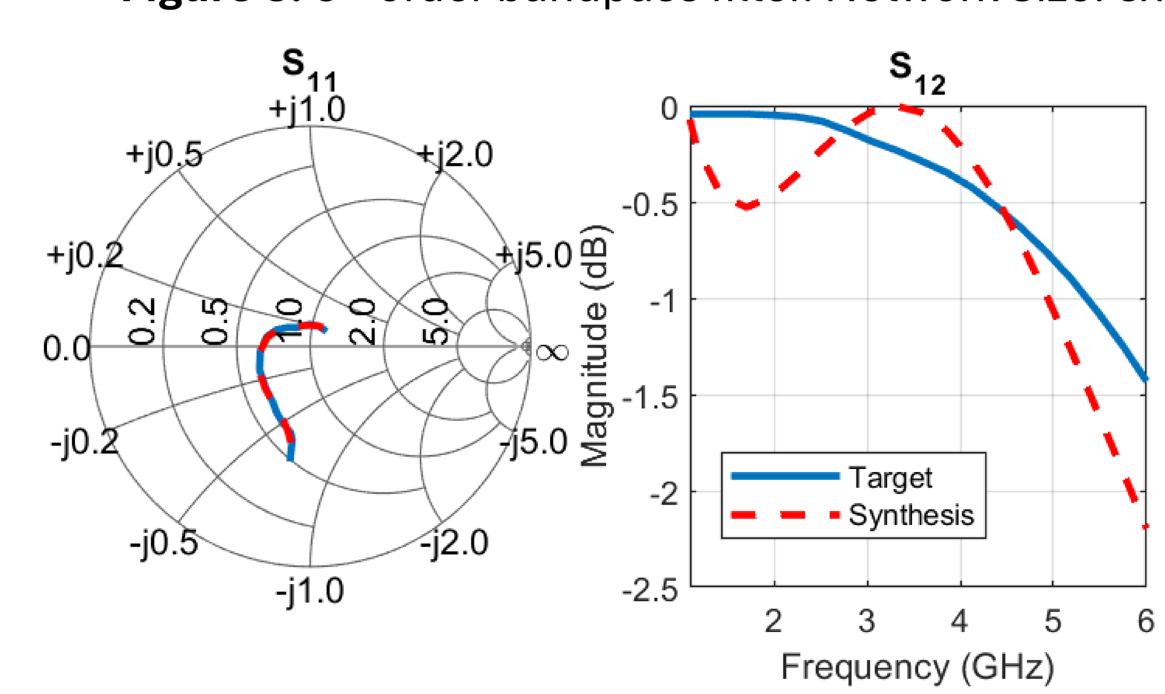

Figure 5: BFP540 transistor noise optimizing input network. Network Size: 2x4

References

[1] K. C. Gupta, R. Garg, and R. Chadha, *Computer-aided design of microwave circuits*. Dedham, Mass: Artech, 1981.

[2] R. E. Collin, *Foundations for microwave engineering*, Second edition, Reissued edition. in IEEE Press series on electromagnetic wave theory. New York: IEEE Press, 2001.