A Linear Inverse Space Mapping Algorithm for Microwave Design in the Frequency and Transient Domains

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Introduction

Space Mapping (SM) techniques have been proposed in many innovative ways to efficiently design microwave circuits using very accurate but computationally expensive models.

All of the algorithmic SM approaches to RF and microwave engineering design have been illustrated with linear frequency domain design problems.

In the present work, a Linear Inverse Space Mapping (LISM) algorithm is described. The LISM formulation is directly applicable to frequency domain problems, to nonlinear time domain steady-state problems and to nonlinear transient-state problems. An example of high-speed digital design is shown.

Linear Inverse Space Mapping (LISM)

A fine model is assumed to be a high-fidelity (or high-accuracy) representation whose evaluations are expensive.

A coarse model is a low-fidelity representation that can be intensively evaluated with no significant cost.

$\boldsymbol{x}_c$ and $\boldsymbol{x}_f$ contain n design variables of the coarse and fine models, respectively. The corresponding responses are in $\boldsymbol{R}_c$ and $\boldsymbol{R}_f$.

LISM starts by optimizing the coarse model,

$$\boldsymbol{x}_c^* = \arg\min_{\boldsymbol{x}_c} U(\boldsymbol{R}_c(\boldsymbol{x}_c, \boldsymbol{\psi}))$$

where U is the objective function expressed in terms of the design specifications, $\boldsymbol{x}_c^*$ is the optimal coarse model design, $\boldsymbol{\psi}$ contains the operating conditions.

LISM algorithm aims at finding a fine model solution $\boldsymbol{x}_f^{SM}$ such that $\boldsymbol{R}(\boldsymbol{x}_f^{SM}) \approx \boldsymbol{R}(\boldsymbol{x}_c^*)$. This is realized by iteratively solving the system of nonlinear equations

$$\boldsymbol{f}(\boldsymbol{x}_f) = \boldsymbol{P}(\boldsymbol{x}_f) - \boldsymbol{x}_c^*$$

where $\boldsymbol{P}(\boldsymbol{x}_f)$ is the mapping function obtained from a parameter extraction process

$$\boldsymbol{P}(\boldsymbol{x}_f) = \arg\min_{\boldsymbol{x}_c} \left\| \boldsymbol{R}_f(\boldsymbol{x}_f, \boldsymbol{\psi}) - \boldsymbol{R}_c(\boldsymbol{x}_c, \boldsymbol{\psi}) \right\|_2^2$$

Approximating the inverse of the mapping function at the i-th iteration is realized by linearly interpolating the last n+1 pairs of designs, i.e., by solving the optimization problem

$$\min_{\boldsymbol{A},\boldsymbol{b}} \left\| \begin{bmatrix} \boldsymbol{e}_{i-n}^T & \cdots & \boldsymbol{e}_i^T \end{bmatrix} \right\|_2^2$$

where $\boldsymbol{A} \in \Re^{n \times n}$, $\boldsymbol{b} \in \Re^n$ are the inverse mapping parameters and the k-th error vector is given by

$$\boldsymbol{e}_k = \boldsymbol{A}\boldsymbol{x}_c^{(k)} + \boldsymbol{b} - \boldsymbol{x}_f^{(k)}$$

LISM optimization algorithm can be summarized as follows:

Algorithm: LISM

begin

$\boldsymbol{x}_c^* = \arg\min_{\boldsymbol{x}_c} U(\boldsymbol{R}_c(\boldsymbol{x}_c, \boldsymbol{\psi}))$

$i = 0$

$\boldsymbol{x}_f^{(i)} = \boldsymbol{x}_c^*,\ \boldsymbol{A}^{(i)} = \boldsymbol{I}, \boldsymbol{b}^{(i)} = \boldsymbol{0}$

do until *stopping_criterion*

$\boldsymbol{x}_c^{(i)} = \boldsymbol{P}(\boldsymbol{x}_f^{(i)})$

$\boldsymbol{A}^{(i)}, \boldsymbol{b}^{(i)} = \min_{\boldsymbol{A},\boldsymbol{b}} \left\| \begin{bmatrix} \boldsymbol{e}_{i-n}^T & \cdots & \boldsymbol{e}_i^T \end{bmatrix} \right\|_2^2$

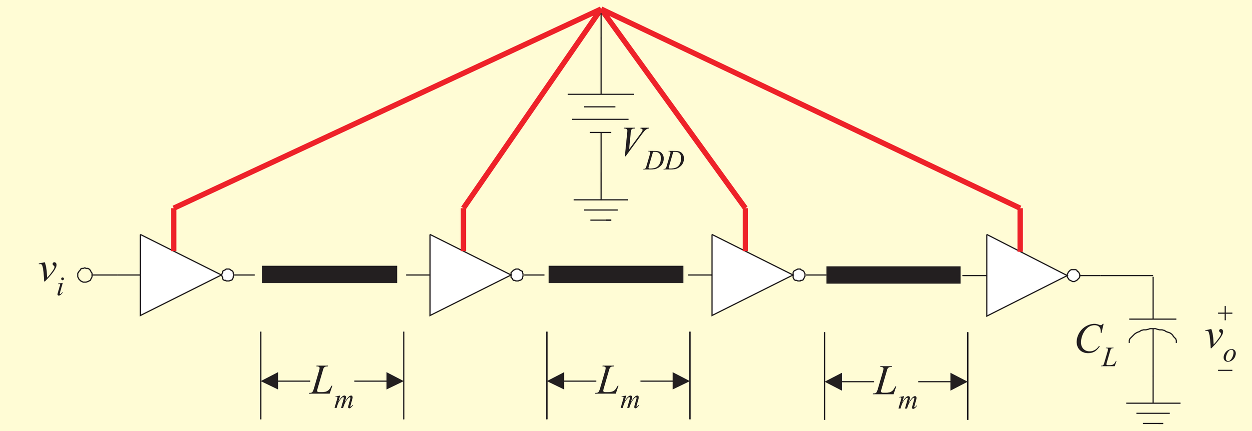
$\boldsymbol{x}_f^{(i+1)} = \boldsymbol{A}^{(i)}\boldsymbol{x}_c^* + \boldsymbol{b}^{(i)}$

$i = i + 1$

end

Example: CMOS Drivers for a Long Microstrip Line

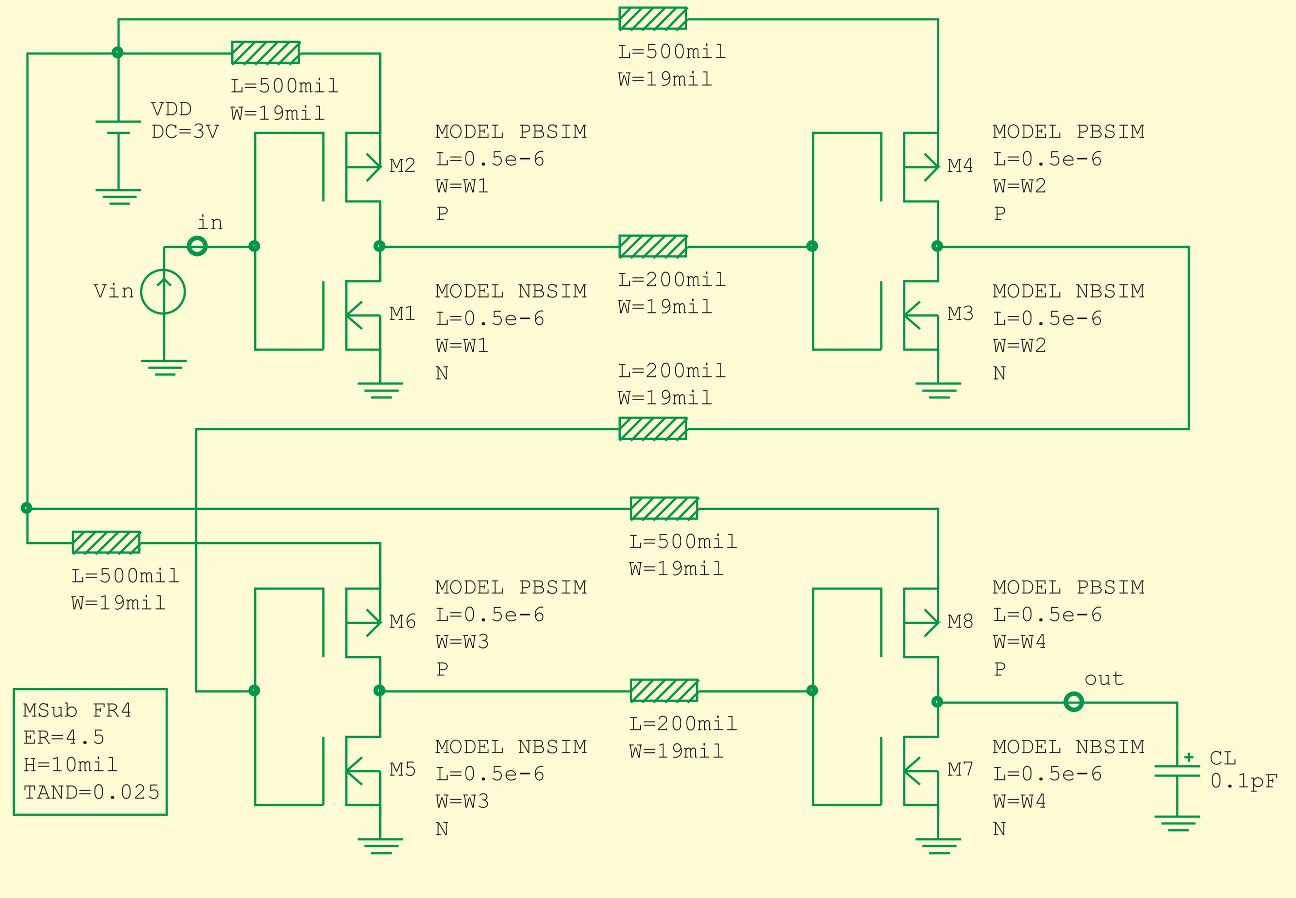
Consider the problem of designing a set of four CMOS inverters driving a 600-mil microstrip line:



The microstrip lines are on a FR4 half epoxy half glass substrate with thickness H = 10 mil, width W = 19 mil, loss tangent 0.025 and dielectric constant ε_r = 4.5. L_m = 200 mil. A typical 0.5 μm CMOS process technology is assumed.

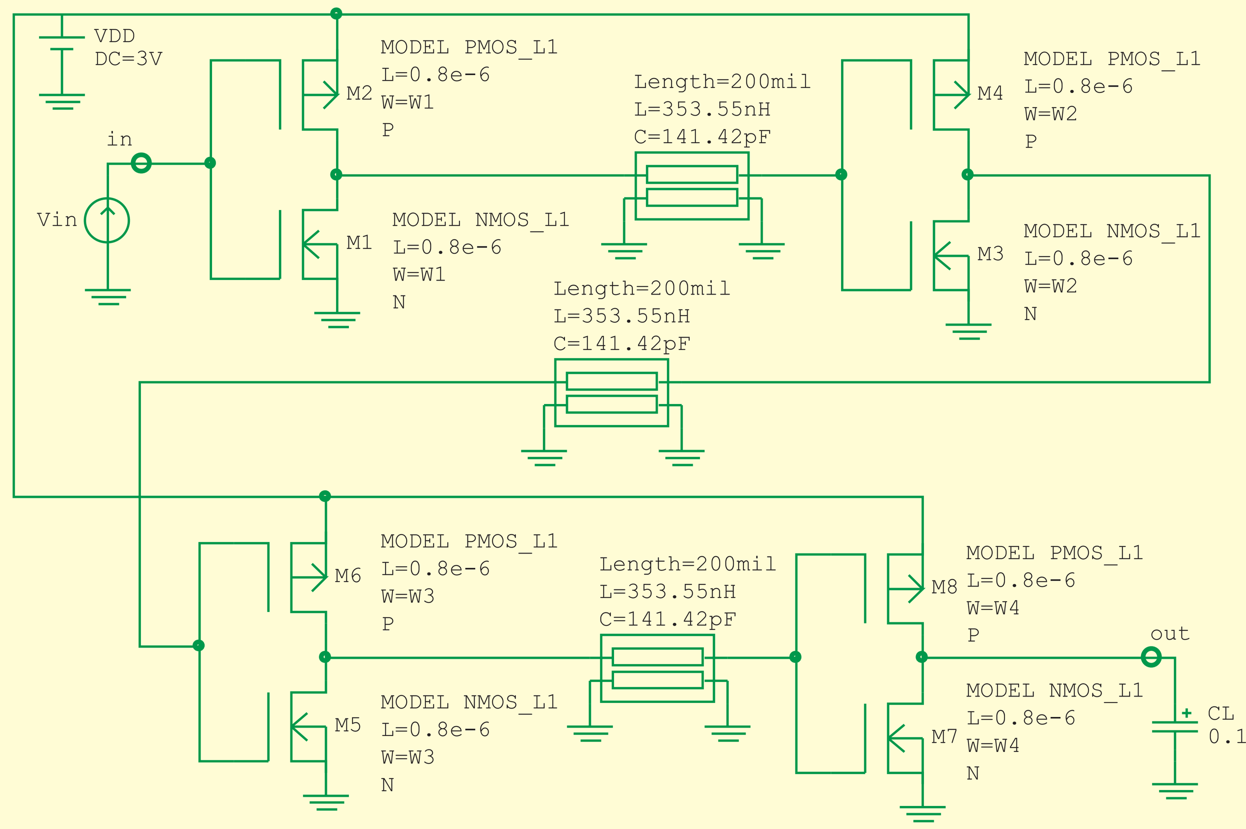
Both the coarse and fine models are implemented in APLAC®.

Fine Model



All the MOSFETs use the BSIM (Level 4) model. The built-in component *Mlin* available in APLAC is used for all the microstrip line segments. The DC power line biasing each inverter is also modeled (assuming it follows a completely different path).

Coarse Model

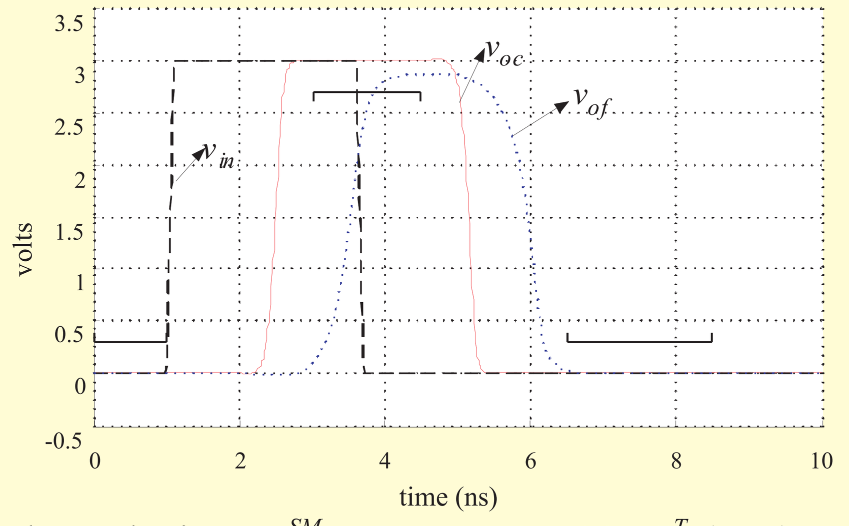


All the MOSFETs use the Shichman and Hodges (Level 1) model, the microstrip lines are modeled by segments of ideal lossless transmission lines using the built-in component *Tlin* available in APLAC, and the effects of the DC power line are neglected.

The design specifications are: v_{out} < 0.3V from 0 to 1ns, v_{out} > 2.7V from 3ns to 4.5ns, and v_{out} < 0.3V from 6.5ns to 8.5ns.

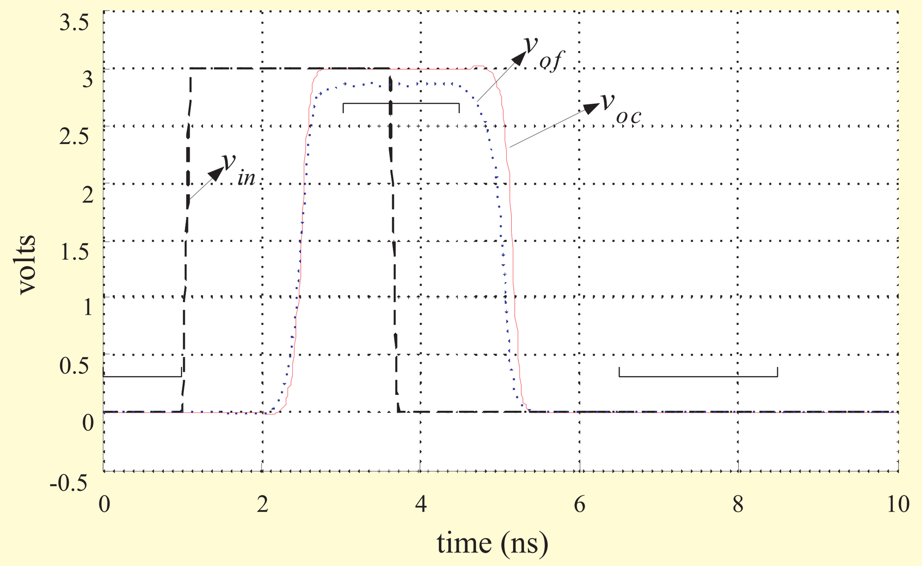
The design parameters are the channel widths for all the MOSFETs, assuming symmetric inverters, $\boldsymbol{x}_f = [W_1\ W_2\ W_3\ W_4]^T$.

The following optimal coarse model solution is found: $\boldsymbol{x}_c^*$ = [11.0 11.5 11.0 10.5] ^{T} (μm).



Input voltage (v_{in}), coarse model (v_{oc}) and fine model (v_{of}) responses at $\boldsymbol{x}_c^*$

After 6 LISM iterations the solution $\boldsymbol{x}_f^{SM}$ = [23 18 21 19.5]^T (μm) is found.



Input voltage (v_{in}), coarse model (v_{oc}) response at $\boldsymbol{x}_c^*$ and fine model (v_{of}) response at $\boldsymbol{x}_f^{SM}$

Conclusion

An inverse space mapping optimization algorithm for designing linear and nonlinear microwave circuits is presented in this work for the first time. The inverse mapping function follows a piece-wise linear formulation, avoiding the use of neural networks. The physical design of a set of CMOS buffers driving an electrically long microstrip line on FR4 illustrates our algorithm.

Selected References

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