

A Novel Parametric Macromodeling Technique for Electromagnetic Structures with Propagation Delays

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Abstract — This work addresses the problem of building accurate and stable parametric macromodels for distributed electronic structures with propagation delays. First, reduced root macromodels are calculated by means of Delayed Vector Fitting technique at estimation points of the design space grid. Then, a suitable interpolation scheme for the delay trends and rational terms is proposed, preserving the model stability over the entire design space. The fundamentals of the identification scheme are discussed, and some insight on basic robustness and accuracy problems is provided. A couple of significant case studies are reported to demonstrate the accuracy and efficiency of the presented technique.

Keywords — high-speed interconnects, interpolation, parametric macromodeling, scattering parameters, delays.

I. INTRODUCTION

Propagation affects electrical systems when their physical size and signal bandwidth increase. Therefore, it must be properly taken into account when numerical simulations are performed in high-speed VLSI design. This can be pursued efficiently by means of the macromodeling approach [1]. In this context, it is well known that a standard approach to macromodel identification as the Vector Fitting (VF) algorithm [2] is inadequate for electrically long interconnects, since an excessive number of pole/residue terms is needed to achieve a sufficient accuracy. Significant improvements in model efficiency for structures with propagation have been demonstrated by Delayed Vector Fitting (DVF) algorithm [3], which is based on a combination of delay extraction [4,5] and rational approximation in the frequency domain. Moreover, the identified delay-less terms are possibly realized with passive circuits [6].

In the last years, several parametric macromodeling techniques have been introduced, in order to provide an efficient design space exploration and design optimization [7]–[10]. In [7] a strategy is described for the construction of parameterized linear macromodels with a highly efficient combination of rational identification and piecewise linear interpolation, based on a barycentric state-space form. Unfortunately, this technique does not guarantee the stability of the computed macromodel over the entire design space. The technique presented in [8] overcomes this limitation and enforces stability and passivity by means of direct interpolation of the system transfer function. However, this may result in a poor accuracy of the parametric macromodel and an increase of the model order. State-space interpolation techniques are able to solve these issues: in [9] a technique is

introduced, based on the solution of the Sylvester equation, which provides inherently passive multivariate macromodels. In [10], a technique based on amplitude scaling and frequency shifting coefficients, computed by means of optimization, is described, which is characterized by a very good robustness and modeling capability, although at the price of some additional computational effort.

The aim of the present work is to study the extension of the parametric macromodeling approach to the case of electrically long interconnects, in a way able to guarantee high model accuracy with reduced complexity. It is based on the interpolation of the estimated time delays and a modification of the DVF pole relocation procedure necessary to build stable root macromodels. It represents a first attempt to interpolate the time delays within the parameters space, while dealing with possible inaccuracies of the macromodel that originate from errors in the estimate.

The paper is organized as follows: in Section II the novel parametric macromodeling technique is discussed in detail, with reference to delay trends evaluation, rational functions interpolation, and the main accuracy issues; in Section III two representative case studies are provided to demonstrate the basic consistency of the proposed technique.

II. DELAY-BASED PARAMETRIC MACROMODELING

A. Parametric Macromodels with Delays

Parametric macromodels of linear microwave structures with delays are considered, which can be described in general as multiport systems in the frequency domain. For the sake of simplicity, a single element of the transfer matrix is considered and denoted as $H(s, \mathbf{g})$. The element depends on the frequency $s = j\omega$ and some design parameters vector \mathbf{g} , related to material properties or layout. The classical mathematical expression for such element is given as [3]:

$$H(s; \mathbf{g}) \approx \sum_{m=0}^{M-1} Q_m(s; \mathbf{g}) e^{-s\tau_m(\mathbf{g})}, \quad (1)$$

$$Q_m(s; \mathbf{g}) = R_{0m}(\mathbf{g}) + \sum_{j=1}^n \frac{R_{jm}(\mathbf{g})}{s - p_j(\mathbf{g})} \quad (2)$$

where the $Q_m(s, \mathbf{g})$ terms are recognized as smooth functions of the complex frequency s , so they can be approximated by rational functions, n is the model order of each $Q_m(s, \mathbf{g})$ term and $\{\tau_m(\mathbf{g})\}_{m=0}^{M-1}$ are the M most significant delay terms. Note that the p_j terms do not depend on m , so a common set of

poles is used to model each $Q_m(s, \mathbf{g})$ term. The model order of the delay-based macromodel is defined as $N = n \times M$. In this contribution, we focus on a 2D design space, with parameters λ and μ . It is assumed that the frequency response of the transfer function elements are available for a set of frequency points $\{s_k\}_{k=1}^K$ and for different parameters values $\{\lambda_{p_e}\}_{p_e=1}^{P_e}, \{\mu_{q_e}\}_{q_e=1}^{Q_e}$ which define a regular *estimation grid* over the design space. The corresponding tabulated data are denoted as $\{\tilde{H}(s_k; \lambda_{p_e}, \mu_{q_e})\}$. A second grid, denoted as *validation grid*, is defined by the parameters values $\{\lambda_{p_v}\}_{p_v=1}^{P_v}, \{\mu_{q_v}\}_{q_v=1}^{Q_v}$. In each *estimation grid* point a *root macromodel* $\tilde{H}(s; \lambda, \mu)$, with $\lambda \in \{\lambda_{p_e}\}_{p_e=1}^{P_e}, \mu \in \{\mu_{q_e}\}_{q_e=1}^{Q_e}$ is identified by means of DVF. Then, in each *validation grid* point a parametric delay-based macromodel in the form (1) is computed, and its accuracy is measured according to the metric:

$$MAX_{err} = \max\{20 \log_{10}(|H(s; \lambda, \mu) - \tilde{H}(s; \lambda, \mu)|)\} \quad (3)$$

$$\text{with } \lambda \in \{\lambda_{p_v}\}_{p_v=1}^{P_v}, \mu \in \{\mu_{q_v}\}_{q_v=1}^{Q_v}, s \in \{s_k\}_{k=1}^K.$$

B. Delays Trend Evaluation

Any delayed macromodel is characterized by one or more delays related to the propagation paths of the structure under analysis. In a parametric macromodel, each delay becomes a function of the varying parameters $\tau_m(\mathbf{g})$. Hence, it is necessary to firstly extract the dominant delay terms in every point of the estimation grid (for which a modification of the so-called Gabor transform is adopted [3]) and then identify the delay trends over the entire design space. The aforementioned algorithm provides the amplitude spectrogram and, after an averaging process on the frequency variable, a time function with local maxima that represent a good estimation of the delays, as shown in Fig. 1.

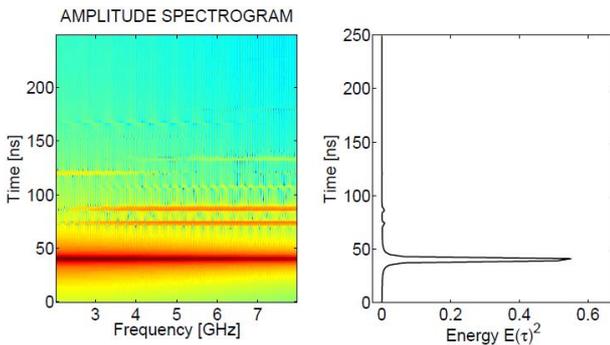


Fig. 1 - Time-Frequency spectrogram (left) and frequency-averaged plot (right)

A correct time delay trends parameterization must take into account two main problems:

- *Time Delays Shadowing*, which consists in the overlapping of two or more energy peaks associated to different delays that could be confused in the identification process;

- *Time Delays Interleaving*, which occurs when two different trends, associated to different propagation modes, cross at some point in the parameter space, causing unacceptable interpolation error.

Furthermore, such effects can appear as combined, as shown in Fig. 2, which reports an example of the change in the estimated delays with respect to the chosen design parameters. In particular, Fig. 2(c) shows the shadowing effect, while Fig. 2(b) and 2(d) shows the interleaving phenomenon, when the parameters \mathbf{g} gradually change from the value shown in 2(a).

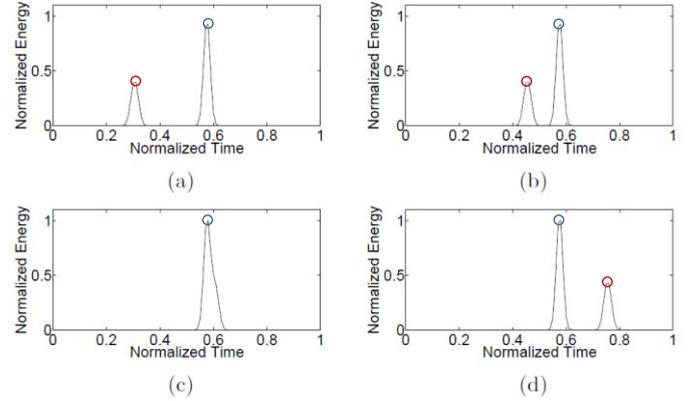


Fig. 2 - Example of shadowing (c) and interleaving (b)-(d) effects

As a possible solution for both problems, a post processing step on the estimated time delays is proposed, which is based on two main assumptions: (i) there are always (at least) 3 consecutive estimation points for each trend that are not affected by any problem (such as shadowing or interleaving): the corresponding delays associated to these points are named here “guide delays”; (ii) the delay trends can be approximated as linear through the entire design space. Assumption (i) is easily accomplished since, when it is not originally satisfied, the density of the mesh can be refined. Assumption (ii) is theoretically more questionable, however one can consider to properly restrict the parameter range. In the authors’ experience, many experiments with different structures with propagation have showed that, in the usual variation ranges of the design parameters, the delay trends can be considered as almost linear.

The post-processing step proceeds then as follows: starting from the three guide delays, a linear prediction of the current trend is generated. If there is an estimated delay similar (within a certain threshold) to the predicted one, then it is considered as part of the trend (*true delay*). Otherwise, the delay of the prediction is taken as next delay in the currently analyzed trend (*artificial delay*). This iterative procedure can overcome both the delays shadowing and interleaving issues, producing as output an ordered set of delay trends. Since the first delay cannot get confused with others, because it is not associated with any reflection, it is used for the identification of thresholds necessary for the algorithm to perform the post-processing properly. Figure 3 reports an example of a scenario after the first estimation of the delays, and its post-processing for a 1D parameterization example: the delays are colored as

blue (*guide delay*), red (*true delay*), green (*artificial delay*) or black (*neglected delay*, not used in the parameterization process). The developed algorithm has been also extended for 2D cases, while further work will be required for cases with 3 or more varying parameters.

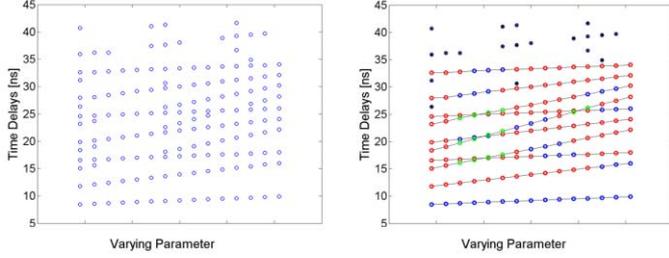


Fig. 3 - Estimated (left) and post-processed (right) delays

C. Rational Functions Interpolation

The estimation grid can be divided in rectangular cells Ω_i , whose vertices are estimation points. We restrict our analysis to a single cell $\bar{\Omega}$. Starting from the set of data samples $\{\hat{H}(s_k; \lambda_{p_e}, \mu_{q_e})\}_{k=1}^{\bar{N}}$ and the estimated delays $\{\tilde{\tau}_m(\lambda_{p_e}, \mu_{q_e})\}_{m=1}^{\bar{M}}$, root macromodels $\{\tilde{H}(s; \lambda, \mu)\}_{\lambda, \mu}^{\bar{N}}$ are built using a set of poles $\{p\}_j^{\bar{N}}$, denoted as *reference poles*, which are common to both each cell vertex, as well as the different $\{\tilde{Q}_m(s; \lambda_{p_e}, \mu_{q_e})\}_{m=1}^{\bar{M}}$ terms. This can be accomplished by collecting the tabulated data $\{\hat{H}(s_k; \lambda_{p_e}, \mu_{q_e})\}_{k=1}^{\bar{N}}$ in a column vector and performing a pole relocation process based on the least-squares solution of an over determined linear problem, with the same structure as the multiport VF formulation. Stability is enforced by means of pole flipping [3].

Once the *reference poles* are available, the residues and the constant terms, collected respectively in the matrices $\{\tilde{\mathbf{R}}(\lambda_{p_e}, \mu_{q_e})\}_{p_e, q_e}^{\bar{N}}$ and $\{\tilde{\mathbf{R}}_0(\lambda_{p_e}, \mu_{q_e})\}_{p_e, q_e}^{\bar{N}}$ can be independently computed in each cell vertex just as they are computed in the DVF scheme. The parametric representation within each cell is then given via piecewise linear interpolation:

$$\mathbf{R}(\bar{\lambda}, \bar{\mu}) = \sum_{p_e=1}^{P_e} \sum_{q_e=1}^{Q_e} \mathbf{R}(\lambda_{p_e}, \mu_{q_e}) \varphi_{p_e}(\bar{\lambda}) \xi_{q_e}(\bar{\mu}) \quad (4)$$

where

$$\varphi_{p_e} = \begin{cases} \frac{\lambda - \lambda_{p_e-1}}{\lambda_{p_e} - \lambda_{p_e-1}}, & \lambda \in [\lambda_{p_e-1}, \lambda_{p_e}), \quad p_e = 2, \dots, P_e \\ \frac{\lambda_{p_e+1} - \lambda}{\lambda_{p_e+1} - \lambda_{p_e}}, & \lambda \in [\lambda_{p_e}, \lambda_{p_e+1}], \quad p_e = 1, \dots, P_e - 1 \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

and a similar definition can be applied to $\xi_{q_e}(\mu)$.

At this point, a parameterized delay-based macromodel in the form (1) can be built relying on the *reference poles*, the constant terms and the residues computed in (4) and the delays estimated in II.B. The stability is guaranteed over the entire design space since the *reference poles* are enforced to be stable. It is important to note that, while the delays interpolation scheme is global, the constant terms and the

residues are locally interpolated. In addition, according to (4), if a validation grid point is located on the cell edge, then the interpolation is solely based on the vertices related to that edge. The technique avoids a direct interpolation of the *reference poles*, as this could lead to possible bifurcation effects and consequent irregular variations.

D. Reliability and accuracy issues

Some difficulties may arise in the procedure described above for the identification of the rational terms. First, even small errors on the delay estimation result in a very poor accuracy of the identified delay-based macromodels [3], which cannot be solved by increasing the order of each rational approximation (2). A second significant problem is raised when two delays, corresponding to different trends in the parameter space, are very close to each other: in fact, residues and constant terms associated to those delays might exhibit a strong non-smooth variation, resulting in very inaccurate interpolation results. To solve this, a further post processing step of the previously identified delays is introduced. To this end, a *delay distance* is defined as the non-negative, dimensionless quantity:

$$d_m(\lambda, \mu) = \frac{|\tau_{m+1}(\lambda, \mu) - \tau_m(\lambda, \mu)|}{\tau_m(\lambda, \mu)} \quad (6)$$

with $0 \leq m < M$, $\lambda \in \{\lambda_{p_e}\}_{p_e=1}^{P_e}$, $\mu \in \{\mu_{q_e}\}_{q_e=1}^{Q_e}$. Then an estimation grid point is denoted as *critical* if in that point:

$$\exists m : d_m(\lambda_{p_e}, \mu_{q_e}) < \alpha, \quad \text{with } 0 \leq m < M \quad (7)$$

The m value satisfying equation (6) identifies the *critical delays* (those associated to subscripts m and $m+1$). For cells where at least one of the vertices is a critical point, the critical delays corresponding to the lowest energy are neglected when the root macromodels are built. Eventually, in these cells, the model order of the rational terms of the expansion (1) can be increased so that the model order N remains constant. Based on a large number of test cases, the optimal value for threshold α in (6) is chosen as $\alpha = 0.035$. This value is used for the following examples.

III. CASE STUDIES

A. Interconnected Transmission Lines

The first case study is depicted in Fig.4. Each line segment is characterized by a $10 \Omega/m$ p.u.l. resistance. We focus our attention on the $S_{12}(s)$ scattering parameter, evaluated over the frequency range $[1kHz, 10GHz]$. A 2D design space has been set up by assuming $l_1 \in [0.9m \pm 5\%]$ and $l_2 \in [1.4m \pm 8\%]$. An estimation grid of $5000 \times 3 \times 8$ (f, l_1, l_2) samples is defined. For this structure 10 delay planes have been detected and 12 poles have been selected: for the sake of readability,

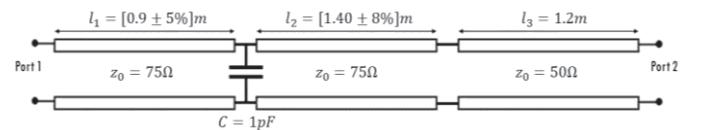


Fig. 4 - Three interconnected transmission lines

Fig. 5 reports the post-processed delay trends for a fixed l_1 to show the interleaving issue between 2 out of 10 delays. The validation points are located in the center of each cell of the rectangular estimation grids. Figure 6(a) reports the design space grid, while Fig. 6(b) shows the error analysis in the form of absolute error histogram. The accuracy appears as satisfactory over the entire design space, being bounded to -40.5 dB . This shows how the shadowing and the interleaving effects are correctly handled by this technique.

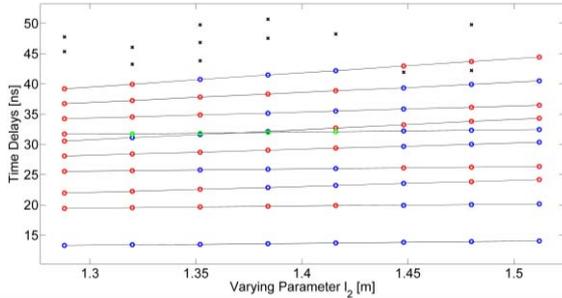


Fig. 5 - Delay trends for $l_1 = 0.915\text{m}$ and varying l_2

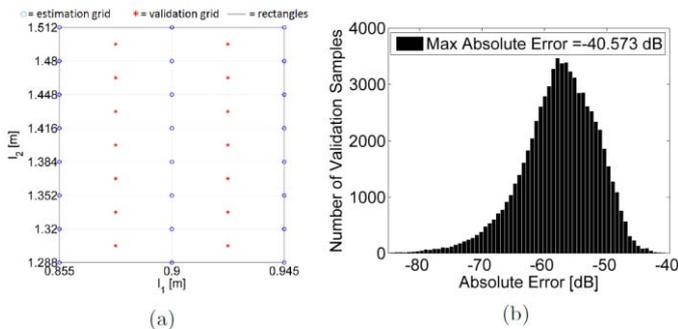


Fig. 6 - Study case design space grid (a) and absolute error histogram (b)

B. Three Coupled Transmission Lines

The second example is reported in Fig. 7(a) and consists of three coupled transmission lines characterized by a common width of $700\mu\text{m}$, a spacing of $350\mu\text{m}$ and a FR4 substrate with a $300\mu\text{m}$ thickness, characterized by means of the ADS (Advanced Design System) software. The design parameters are the length $l \in [19.5\text{cm} \pm 2.5\%]$ and relative permittivity $\epsilon_r \in [4.6 \pm 10\%]$, chosen over a $1001 \times 9 \times 9$ (f, l, ϵ_r) estimation grid within a $[0, 20]\text{GHz}$ frequency range. Again, the validation points are in the center of each cell of the rectangular estimation grids, see Fig. 7(b). For this structure, different scattering parameter elements have been analyzed and the main modeling results are shown in Table I.

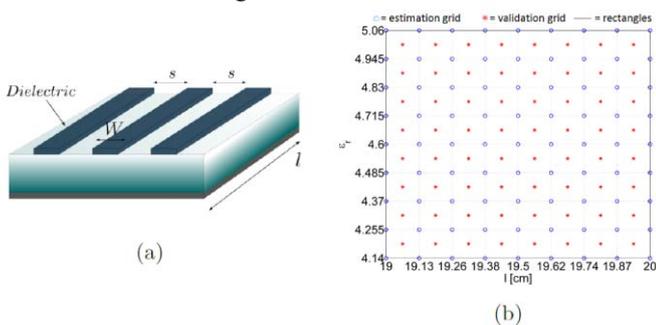


Fig. 7 - Three coupled microstrips structure (a) and its design space grid (b)

Scattering Parameter	Number of Poles	Number of Delays	Max Absolute Error
$S_{1,5}$	10	2	$-40,56\text{ dB}$
$S_{2,5}$	12	2	$-40,10\text{ dB}$
$S_{3,4}$	12	1	$-41,32\text{ dB}$

Table I - Validation results for different scattering parameters elements

Also in this case, a satisfying accuracy is achieved within the parameters space, as compared to full 3-D simulations: in fact, the maximum error never exceeds -40 dB , with a relatively low model order.

IV. CONCLUSIONS

The technique presented and discussed in the paper demonstrates the efficient and reliable combination of delay estimation and processing, as well as rational identification of the rational part of the transfer matrix elements. The parameterization of the delays guarantees a high modeling capability, allowing the use of a common set of stable poles for a specific area of the design space. A direct interpolation of the system poles is avoided, so that bifurcation effects do not affect the accuracy of interpolated models. Many analyzed case-studies, well exceeding those explicitly reported in the paper, have demonstrated the reliability of the technique, with good accuracy results over the entire design space.

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