Behavioral Modeling of IC Ports Including Temperature Effects

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Abstract: The development of temperature-dependent macromodels for digital IC ports is addressed. The proposed modeling approach is based on the theory of discrete-time parametric models and allows to estimate the model parameters from voltage and current waveforms observed at the ports and to implement the model as a SPICE subcircuit. The proposed technique is validated by applying it to commercial devices described by detailed transistor-level models. The obtained models perform at a good accuracy level and are more efficient than the original transistor-level models.

1 Introduction

Nowadays the development of high performance digital systems requires the assessment of Signal Integrity (SI) and ElectroMagnetic Compatibility (EMC) effects at an early stage of the design process. This is mainly achieved by representing the parts of the interconnection systems in a circuit simulation environment by suitable macromodels and by simulating the evolution of signals sent on interconnections.

In these simulations, a dominant role is played by the macromodels for the ports of digital Integrated Circuits (IC), that act as receivers or signal pattern generators loading the interconnects. These macromodels should represent the port constitutive relations for a known internal logical activity of the ICs. It has been demonstrated that the use of nonlinear parametric models and system identification methods are useful resources for the development of such behavioral macromodels of IC ports [1, 2, 3]. This modeling approach has interesting advantages, that make it a useful alternative to the traditional approach based on simplified equivalent circuits of IC ports [4]. In the parametric approach, the model parameters are estimated from the transient port current and voltage waveforms and the obtained models automatically take into account any electrical effect significantly influencing the port behavior. Besides, the accuracy of the obtained models is weakly sensitive to the driven loads.

In this paper, we extend a parametric model for IC output ports [2], in order to take into account the influence of the device operating temperature. The proposed extension preserves the structure and the advantages of the model, allowing the description of the device behavior over a wide temperature range for a small increase of the number of model parameters.

2 Output port macromodel

The aim of this Section is to briefly introduce the parametric macromodeling technique for the output ports of digital ICs. The parametric model that is going to be presented was developed and described in [2]. It concerns the functional part of the devices, and assumes constant all other variables influencing their behavior. Here, we mainly focus on the definition of such parametric model representation and on the estimation of its parameters from port transient waveforms. The model is of discrete-time type and involves the samples of the port electric voltage $v(k) = v(kt_s)$ and current $i(k) = i(kt_s)$, where t_s is the sampling time used to sample the time axis.

For output ports, the following model representation is exploited

$$i(k) = w_1(k)i_1(k) + w_2(k)i_2(k) \tag{1}$$

where w_1 and w_2 are time varying weight sequences accounting for state switchings in (1). Submodels i_1 and i_2 are parametric representations defined by Radial Basis Function (RBF) expansions approximating both the nonlinear static and dynamic $i - v$ port behavior in the High and in the Low fixed logic states, respectively.

RBF parametric models are suitable for the characterization of the external behavior of many nonlinear dynamic systems [5]. They approximate the input-output system behavior, *i.e.*, for the problem at hand the $i - v$ port relation, through a finite weighted sum of scalar basis functions (*e.g.*, Gaussian) with a suitable width and proper position. In particular, the submodels $i_n(k)$, $n = 1, 2$ of (1) are defined by

$$i_n(k) = \sum_j \alpha_{nj}\phi_j(x_n(k)) \tag{2}$$

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where x_n is the regressor vector

$$x_n(k) = [i_n(k-1), \ldots, i_n(k-r), v(k), \ldots, v(k-r)]^T$$

collecting the present sample of the port voltage v and past r samples of v and i, r being the dynamic order of the model. ϕ_j is the j-th Gaussian basis function

$$\phi_j(x_n(k)) = \exp\{-||x_n(k) - c_{nj}||^2/(2\beta_n^2)\}$$

defined by a position (center c_{nj}) in the space of the regressor vector x_n and by a width (spreading parameter β_n). The complete set of unknown parameters defining the model are the linear parameters $\alpha_n = [\alpha_{n1}, \alpha_{n2}, \ldots]^T$ and the nonlinear parameters, *i.e.*, the center and the spreading of each basis function. The above time-variant two-piece model arises systematically from the property of output port structures and of RBFs and inherits most of strengths of RBF parametric models in approximating nonlinear dynamic systems.

The parameters of submodels i_n are computed from a set of transient voltage and current waveforms (named *identification signals*) by means of the application of estimation algorithms matching the model response to the port reference response [6, 7]. The identification signals are obtained by forcing the port in the High and in the Low logic state, respectively, and by recording the port current response to a multilevel voltage signal applied to the output of the port and spanning the range of operating voltages. Then, the weight coefficients w_1 and w_2 are obtained from a set of switching experiments by linear inversion of equation (1). In these experiments the port is driven to produce complete state switchings for two different load conditions and the port voltage and current waveforms are recorded. Finally, as the last step of the modeling process, the estimated output port model is implemented as a SPICE subcircuit in order to allow the use of such model for circuit simulation. This is done by converting the discrete-time model (1) into a continuous-time state-space representation and by synthesizing it into an equivalent circuit. A more detailed discussion of the derivation of model (1) together with guidelines for the estimation of its parameters and the implementation of the model in a circuit simulation environment can be found in [2], where the modeling approach has already been applied to commercial devices defined by transistor-level models. Besides, it has been demonstrated that such modeling technique is equally applicable to the characterization of real devices from direct measurements taken on the external pins of the device [1].

3 Inclusion of temperature dependence

In this Section, the model representation defined by (1) is suitably modified to include the extra dependence on the temperature variable T. For typical output ports, the temperature has a weak influence on the port dynamic behavior, even for large variations of T. As an example, Fig. 1 shows the set of responses of a commercial high-speed driver connected to a transmission line load. The responses are computed via SPICE-type simulations of a detailed transistor-level model of the driver, for different values of T in the range $[-10, 100]\,°C$.

The regular behavior highlighted in Fig. 1 suggests to look for a model representation defined by

$$i(k;T) = w_1(k;T)i_1(k;T) + w_2(k;T)i_2(k;T) \quad (3)$$

where both the weight coefficients w_1 and w_2 and the RBF submodels i_1 and i_2 depend on the extra input T.

Besides, since the submodels defined by (2) are weakly sensitive to the position of centers and spreading parameters [6, 7], the temperature dependence of submodels $i_n(k;T)$ can be confined to the linear parameters α_n. Therefore, for the RBF submodels, this means to estimate the complete set of parameters from the transient identification curves recorded at a nominal temperature value and to obtain the parameters for other possible temperature values by re-estimating the linear parameters only. It is ought to remark that, when the centers and the spreading parameters are fixed, the estimation of the linear parameters α_n can be easily done by solving a standard linear least square problem as suggested in [6].

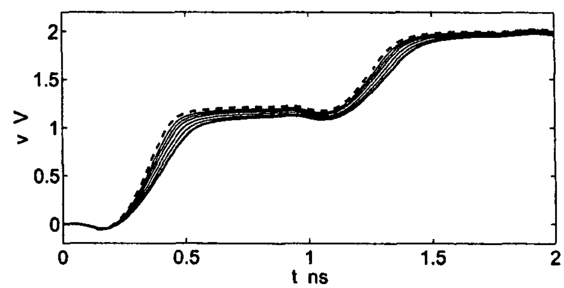

Figure 1: Example of the output port voltage response $v(t)$ of a commercial high-speed IBM CMOS driver feeding a 12 cm long transmission line. The driver performs a Low-to-High transition. The different curves refer to various operating temperatures, *i.e.*, $T = -10\,°C$ (dashed thick line), $T = 100\,°C$ (solid tick line) and $T = 10, 25, 40, 60, 80\,°C$ (solid thin lines).

In order to derive dependency of α_n from T, we estimated the linear parameters of submodels $i_n(k)$ for several transistor-level models of commercial drivers and for different temperature values. As an example, Fig. 2 shows the entries of the linear parameter vector α_1 computed at $T = 10, 25, 40, 60, 80\,°C$ for a common driver. In this example, the linear parameters are obtained by assuming constant the centers and the spreading parameter estimated at $T = 40\,°C$.

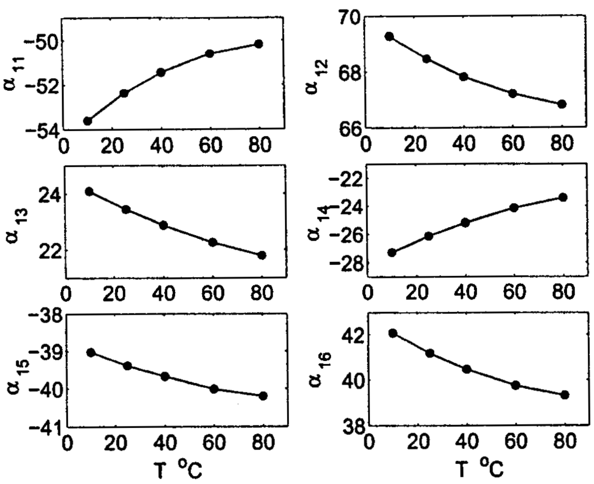

Figure 2: Example of dependency of the linear parameters α_1 from temperature. Dots indicate the computed values for $T = 10, 25, 40, 60, 80\,°C$.

The curves of Fig. 2 show that a linear or a piecewise linear function can be an accurate approximation of $\alpha_n(T)$, *i.e.*, for any T_1, T_2 and $T \in [T_1, T_2]$

$$\alpha_n(T) \approx \bar{\alpha}_n(T) = \left(\frac{T-T_2}{T_1-T_2}\right)\alpha_n(T_1) + \left(\frac{T-T_1}{T_2-T_1}\right)\alpha_n(T_2) \tag{4}$$

where $\alpha_n(T_1)$ and $\alpha_n(T_2)$ are the linear parameters of (1) computed at $T = T_1$ and $T = T_2$, respectively. It is ought to remark that, for any point of the regressor space, submodels defined by $\bar{\alpha}_n(T)$ are monotonous functions of T as those defined by the exact $\alpha_n(T)$.

In a similar way, the relation defining the weight coefficients $w_n(k;T)$ can be represented by

$$w_n(k;T) \approx \bar{w}_n(k;T) = \left(\frac{T-T_2}{T_1-T_2}\right)w_n(k;T_1) + \left(\frac{T-T_1}{T_2-T_1}\right)w_n(k;T_2) \tag{5}$$

where $w_n(k;T_1)$ and $w_n(k;T_2)$ are the weight coefficients of (1) computed at $T = T_1$ and $T = T_2$, respectively.

The accuracy required in common simulation problems can be easily achieved by two-piece linear representations $\bar{\alpha}_n(T)$ and $\bar{w}_n(k;T)$ defined by three temperature values, *i.e.*, the minimum, the nominal and the maximum values of the IC operating temperature.

4 Application example

In this Section, we apply the proposed modeling approach to the output port of a high-speed CMOS driver used in IBM mainframe products. The reference responses for the estimation and validation of the sought parametric model are obtained from a detailed transistor-level model of the driver via SPICE-type simulations (PowerSPICE [8]).

As outlined in Section 3, we approximate the temperature-dependent parameters of the model by two-pieces linear relations interpolating the exact values at the minimum, nominal and maximum device operating temperatures. For this example, the values of the three temperatures are $T_1 = 10\,°C$ (minimum), $T_2 = 40\,°C$ (nominal) and $T_3 = 80\,°C$ (maximum).

The model parameters and their temperature-dependent approximations are obtained as follows. Three sets of identification signals are recorded while the device is at the three temperature values T_j, $j = 1,2,3$. Submodels $i_n(k;T_2)$, $n = 1,2$ for the nominal temperature value are estimated from the identification signal recorded at T_2, obtaining $\alpha_n(T_2)$, the centers and the spreading parameters for the temperature value T_2. The centers and spreading parameters defining these submodels are used to estimate the linear parameters $\alpha_n(T_j)$ of submodels $i_n(k;T_j)$ at T_j, $j = 1,3$ from the identification signal recorded at T_1 and T_3, respectively. Then $\bar{\alpha}(T)$ of (4) is obtained by interpolating $\alpha_n(T_j)$, $j = 1,2,3$. Once submodels $i_n(k;T_j)$, $n = 1,2$ and $j = 1,2,3$ are known, the weight coefficients $w_n(k;T_j)$ describing state switchings at T_j are computed, and the

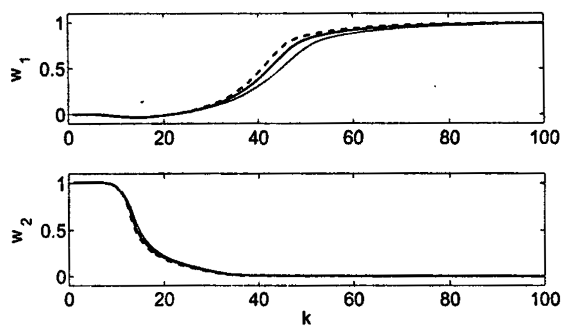

Figure 3: Weight coefficients $w_n(k;T_j)$ driving the model to produce a Low-to-High state transition. The above curves are computed at the three different temperatures T_1 (dashed line), T_2 (solid thick line) and T_3 (solid thin line).

weight coefficients for the other temperatures $w_n(k;T)$ are approximated by two-piece linear relations interpolating $w_n(k;T_j)$. Finally the obtained temperature-dependent parametric model (3) is implemented as a subcircuit of the same SPICE environment used to run the transistor-level model of the driver.

For this example, the estimated submodels $i_1(k;T)$ and $i_2(k;T)$ turn out to be composed of seven Gaussian basis function and to have dynamic order $r = 1$.

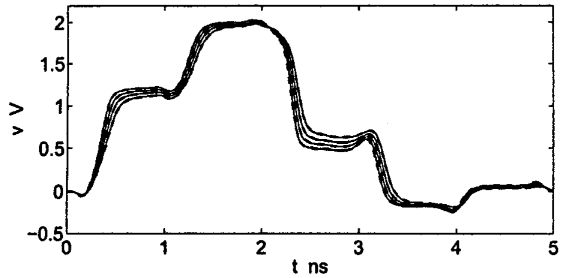

Figure 4: Far-end voltage waveforms on a ideal transmission line (See text). The curves are computed for the temperature values $T = -10, 25, 60, 100\,°C$. Solid curves: reference responses; dashed curves: model responses.

Figure 3 shows the weight coefficients $w_n(k;T_j)$, $n = 1,2$ and $j = 1,2,3$ describing a Low-to-High state transition for the minimum, nominal and maximum temperatures. In this example the two reference loads used to generate the reference switching responses and to compute $w_n(k;T_j)$ are a simple $50\,\Omega$ resistor and the series connection of a $50\,\Omega$ resistor and a V_{dd} battery.

In order to verify the accuracy of the obtained model, its responses are compared to the responses of the original transistor-level model for test loads different from the reference loads. As an example, Figure 4 shows the responses of the parametric model and of the reference transistor-level model when they drive a test load composed of an ideal transmission line with characteristic impedance $Z_0 = 50\,\Omega$ and delay $T_d = 40$ ps terminated by a 1 pF capacitor. The far-end voltage waveforms for a single pulse excitation and for $T = -10, 25, 60, 100\,°C$ are shown. This Figure demonstrate the correct operation of the model for a realistic test load and for temperature values different from those used for the interpolation of the temperature-dependent model parameters. For all these temperatures, including $T = -10$ and $T = 100$ that are outside the approximation interval $[T_1, T_2]$, the estimated model still reproduces the port reference behavior very well. The timing errors produced by the model are always less that $5 \div 10$ ps, $t_s = 10$ ps being the sampling time used in the estimation process. Besides, since the temperature-dependent model has the same structure of the parent temperature-independent model, it fully benefits of the simplicity and efficiency of the RBF parametric approach. In terms of figures, this means that the temperature-dependent models can be estimated in some tens seconds by a desktop PC and that they are some tens times faster than the original transistor-level models.

5 Conclusions

In this paper, a macromodeling technique for the development of a temperature-dependent parametric macromodel suitable for the output ports of a digital IC is presented. The parameters defining the model are estimated from port transient voltage and current waveforms by means of a simple and efficient procedure. The obtained models, implemented as SPICE subcircuits, hold over a wide temperature range and perform at an accuracy and efficiency level suitable for system-level SI and EMC simulations.

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