Versatile surrogate models for IC buffers

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Abstract

In previous papers [1, 2] the authors have investigated the use of Volterra series in the identification of IC buffer macro-models. While the approach benefited from some of the inherent qualities of Volterra series it preserved the two-state paradigm of earlier methods (see [3] and its references) and was thus limited in its versatility. In the current paper the authors tackle the challenge of going beyond an application or device-oriented approach and build versatile surrogate models that mimic the behavior of IC buffers over a wide frequency band and for a variety of loads thus achieving an unprecedented degree of generality. This requires the use of a more general system identification paradigm.

Introduction

Volterra series [4-6] are one of the best known tools for identifying nonlinear systems and are quite popular in various fields of science. They constitute an elegant generalization of the impulse response function and as such are theoretically appealing for the construction of behavioral models. From a practical point of view, as soon as one deals with strong nonlinearities, building a suitable Volterra model amounts to solving huge parametric problems. Difficulties, mostly numerical, often outmatch the theoretical advantages of the approach. This is arguably one of the reasons that made Volterra unpopular with buffer modelers. Another reason may be a lack of control over the static behavior of the Volterra model, but this issue was addressed by the authors in a previous paper [2] and a practical solution was proposed.

The current paper attempts to deal with the larger road-blocks and shows that very high order Volterra-Laguerre models may be built without unbearable computational cost and that a well-devised identification sequence allows the accurate identification of an IC driver. Using a very straightforward approach the technique yields a unique, general surrogate model that accurately reproduces the behavior of the original system for both a wide range of input frequencies and a wide range of output loads.

Description of the test vehicle

Using a large-enough number of real-life drivers would have proven cumbersome and the authors needed a configurable test vehicle allowing the new approach to be tested for a wide range of devices. A synthetic nonlinear system was thus designed Its general behavior reproduces from a both static and a dynamic point of view, that of a single-ended driver while the various parameters allow tuning according to the user's wishes.

Figure 1 shows the schematic design of the test vehicle. The input port is characterized by a capacitance C_{in}. The voltage controlled current source $i = f(v_1, v)$ is the key feature of the system. This memory-less nonlinear circuit element is mathematically defined by

$$f(v_1, v) = [1 - g(v_1)]i_H(v) + g(v_1)i_L(v) \qquad (1)$$

where $i_H(v)$ and $i_L(v)$ represent the static characteristics of the system locked in high and low state respectively. They were designed as third order polynomials and are quite similar to what one would expect in a real driver (see figure 2).

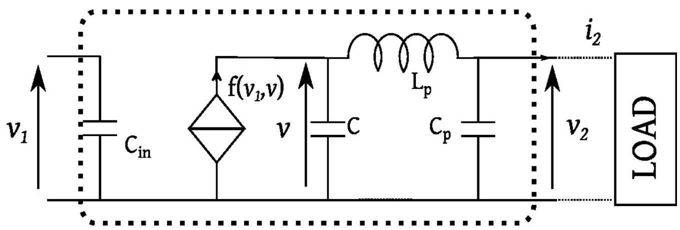

Fig. 1. Synthetic test-system designed to behave like a single-ended driver

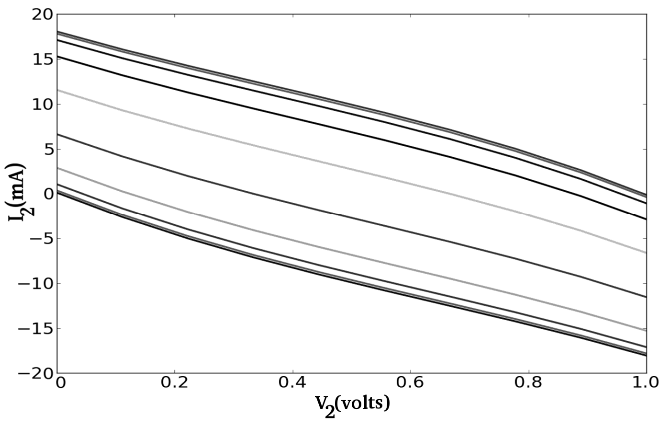

Fig. 2. Output port static characteristic for different values of the input voltage v_1

The nonlinear function $g(v_1)$ was designed to induce the expected switching behavior of a driver and is largely responsible for the realistic input/output characteristic (Fig.3). It is defined as:

$$g(v_1) = \frac{1 + \tanh[A \cdot (v_1 - 0.5)]}{2} \qquad (2)$$

Parameter A was set to 5 for all examples presented in this paper, modifying it induces a smoother or steeper switching behavior.

The influence of a hypothetical package is simulated by an inductance L_p and a capacitance C_p which, along with capacitance C, dictate the system's dynamic behavior.

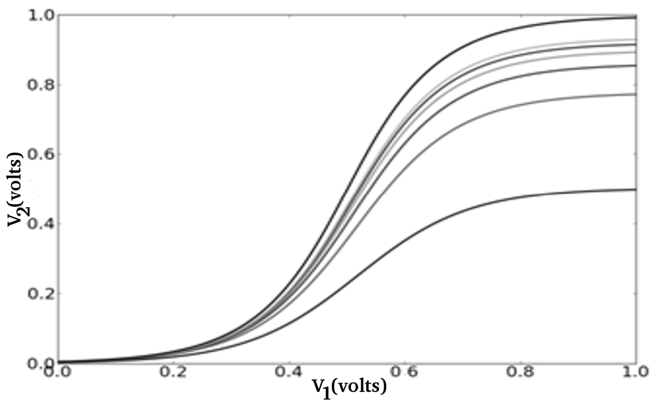

Fig.3. Input/output of the test vehicle for different resistive loads.

The test vehicle was thus far assumed to work at a fixed V_{dd} voltage therefore neither it nor any of the models subsequently presented include V_{dd} variation. Generic operating voltages have been set between 0V and 1V but like most parameters of the test vehicle they may be easily modified for a closer match of a given technology.

Such a synthetic driver proves very useful when one experiments with novel techniques of macromodeling. It allows one to easily generate a whole library of examples by directly modifying static and dynamic parameters. It is easily implemented in both Matlab and SPICE and allows a researcher to easily validate or invalidate a new macro-modeling method.

Model structure

The main idea of the macromodeling technique proposed in this paper supposes the identification of a surrogate driver model implemented as a simple controlled nonlinear current source $i_2[k]$ where k denotes discrete time (see Fig. 4).

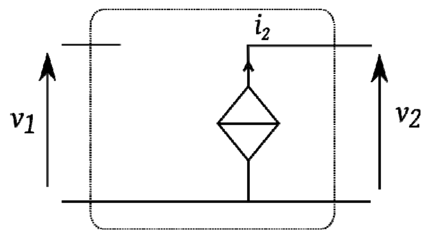

Fig. 4. Surrogate model structure

The relation binding the output current to the port voltages is a high order multivariable Volterra-Laguerre series given by

$$i_2[k]=\sum_{m=1}^{M}\sum_{n_1=1}^{2}\cdots\sum_{n_m=1}^{2}\sum_{i_1=0}^{I_m-1}\cdots\sum_{i_m=0}^{I_m-1}C_{m,n_1,\ldots,n_m,i_1,\ldots,i_m}\prod_{l=1}^{m}\bar{v}_{n_l,i_l}(k). \quad (3)$$

Equation (3) can be developed as follows:

$$\begin{aligned}i_2[k]&=\sum_{i_1=0}^{I_1-1}C_{1,1,i_1}\bar{v}_{1,i_1}[k]+\sum_{i_1=0}^{I_1-1}C_{1,2,i_1}\bar{v}_{2,i_1}[k]\\&+\sum_{i_1=0}^{I_2-1}\sum_{i_2=0}^{I_2-1}C_{2,1,1,i_1,i_2}\bar{v}_{1,i_1}[k]\bar{v}_{1,i_1}[k]+\sum_{i_1=0}^{I_2-1}\sum_{i_2=0}^{I_2-1}C_{2,1,2,i_1,i_2}\bar{v}_{1,i_1}[k]\bar{v}_{2,i_1}[k]\\&+\sum_{i_1=0}^{I_2-1}\sum_{i_2=0}^{I_2-1}C_{2,2,1,i_1,i_2}\bar{v}_{2,i_1}[k]\bar{v}_{1,i_1}[k]+\sum_{i_1=0}^{I_2-1}\sum_{i_2=0}^{I_2-1}C_{2,2,2,i_1,i_2}\bar{v}_{2,i_1}[k]\bar{v}_{2,i_1}[k]\\&+\ldots\end{aligned}$$

where $\bar{v}_{n_l,i_l}[k]$ denotes the convolution of the respective voltages with discrete-time Laguerre functions:

$\bar{v}_{n_l,i}[k]=(v_1*\phi_{1,i_l})[k]$ for $n_l=1$ and

$\bar{v}_{n_l,i}[k]=(v_2*\phi_{2,i_l})[k]$ for $n_l=2$.

One notes the straight-forward generalization of the single-variable Volterra-Laguerre expansion [4-5]. Discrete-time Laguerre functions (see [7] for a detailed analysis) are conveniently defined by their z -transform:

$$\Phi_{n_l,i_l}(z)=\sqrt{1-a_{n_l}^2}\,\frac{z}{z-a_{n_l}}\left(\frac{1-a_{n_l}z}{z-a_{n_l}}\right)^{i_l},\ i_l=0,1,\ldots I_m-1 .$$

Note that each voltage is associated to a specific Laguerre orthogonal basis $\phi_{n_l,i_l}[k]$ identified by a distinct parameter a_{n_l} . M represents the order of the Volterra series, i.e. the highest order kernel. The expansion of each Volterra kernel is truncated, a finite number I_m of Laguerre functions being used.

Using a discrete-time paradigm is numerically convenient; once an adequate model has been identified a simple bilinear transform may be used to switch back to continuous time and easily implement the model in a SPICE tool.

Identification

The identification problem at hand basically boils down to the computation of the Volterra-Laguerre spectrum $C_{m,n_1,\ldots,n_m,i_1,\ldots,i_m}$.(for basic Volterra-Laguerre identification problems see [4] and the references therein). This can be achieved by performing an initial simulation of the original device. With knowledge of both port voltages and of the output port current the Volterra-Laguerre spectrum may be computed using (3).

In practice, the problem is far from trivial. The approach has the objective of building a "true" surrogate model valid for a predefined, relatively large range of loads and for spectrally diverse input signals. Furthermore the very nature of the driver will require the Volterra-Laguerre system to reproduce a switching behavior with respect to v_1 , therefore the order of non-linearity M will have to be very large and numerically problematic unless handled properly. The following setting and the considerations presented in this section are vital for the procedure to work and constitute one of the main contributions of the paper.

The identification signal v_1 (Fig. 5) has to explore the behavior of the modeled system both spectrally and in terms of amplitude and include large enough steady states to allow a good identification of the static characteristic.

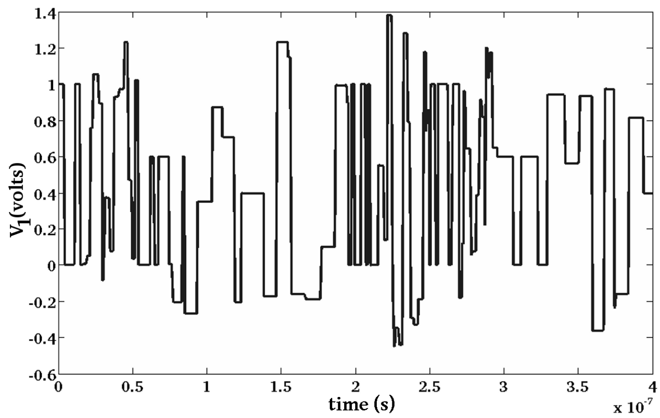

Fig. 5. Part of the excitation signal v_1 used during the identification sequence

A dynamic load model shown in figure 6, was designed for identification purposes. Load elements vary in quasi random fashion within predefined limits. The purpose of the procedure is to perform a thorough exploration of the (v_1, v_2) surface along a large number of possible trajectories. The explored area is further extended by varying the v_0 voltage.

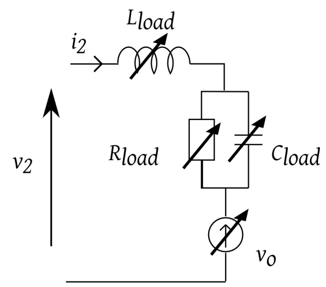

Fig. 6. Dynamic load used during identification

It should be noted that while high order Volterra kernels are often needed to correctly identify the driver (the authors have gone as far as an order 15) computational problems are reduced by drastic truncation of the upper kernel expansions. Indeed beyond an order 3 the Laguerre expansions are reduced to no more than two functions. Only in these terms Volterra-Laguerre spectrum that will not introduce spurious dynamics or static aberrations may be determined.

Validation

In this section we show that the model identified according to the procedure described above accurately reproduces the behavior of the original system. The same model is tested in configurations involving different loads. The order of the Volterra series is 14 and a total amount of 325 coefficients are computed for the Volterra-Laguerre expansion. Validation signal v_1 visible in figure 7 is used as an input for both the synthetic driver and the model, it was chosen to demonstrate the wide band characteristic of the approach. All simulations were performed using a non-commercial SPICE tool.

The first load we used for validation (Fig. 8) is a transmission line with capacitor at its far-end. The time delay of the line $Td = 10ps$ and the characteristic impedance is $Z_0 = 50\Omega$. The system and model output voltage are plotted in figure 9.

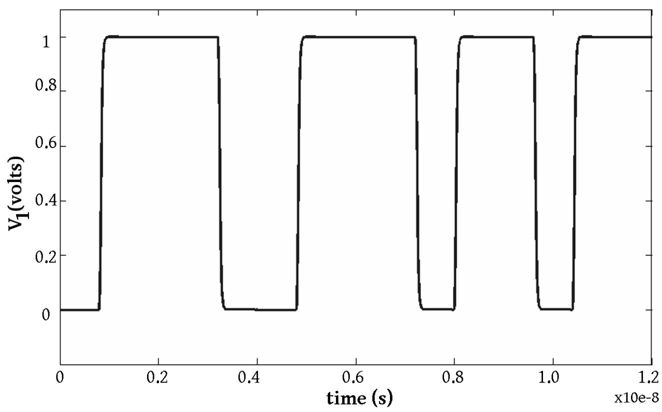

Fig. 7. Validation signal v_1

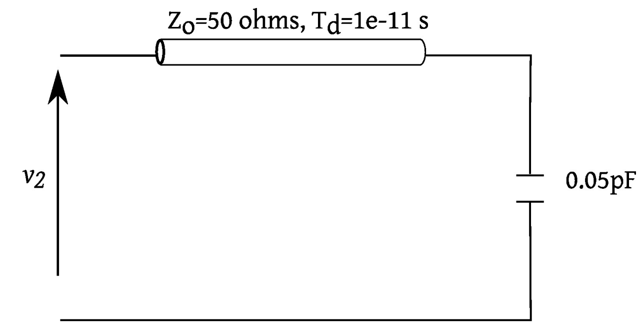

Fig. 8. First load configuration

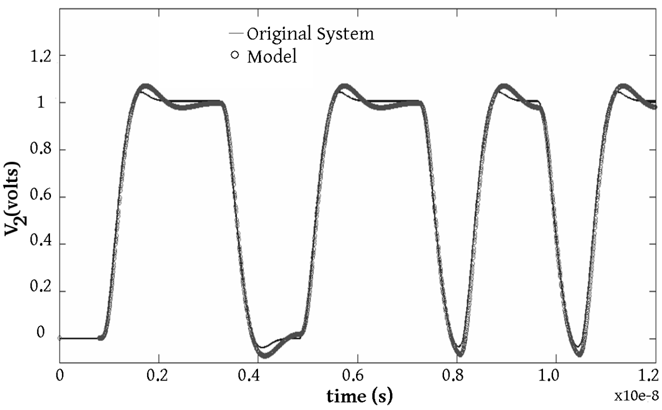

Fig. 9. Output voltage v_2 for the driver and the macromodel (first configuration)

Note the good convergence of the output responses, both from a static and dynamic point of view.

Another configuration is then tested (Fig. 10). It includes an inductor purposefully dimensioned to induce a large overshoot and longer transmission line load ($Z_0 = 50\Omega$ and $Td = 9ns$). As it can be seen from figure 11 the model response continues to match the original despite a radical change in the loading conditions. This is a remarkable property, not shared by IBIS-like tools.

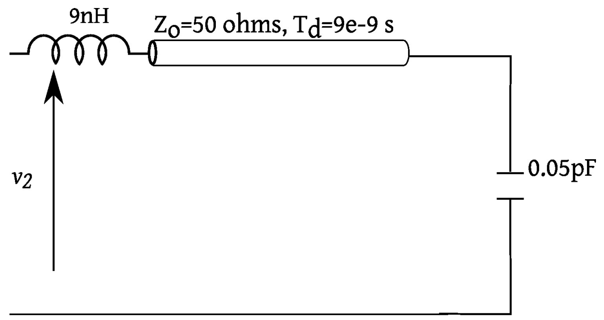

Fig. 10. Second load configuration

The simulation time was approximately 2 seconds for both configurations on a standard laptop computer equipped with a 2.53 GHz Intel core i5. Since real driver transistor models usually take several tens of seconds to simulate in similar conditions, the method appears remarkably time-saving.

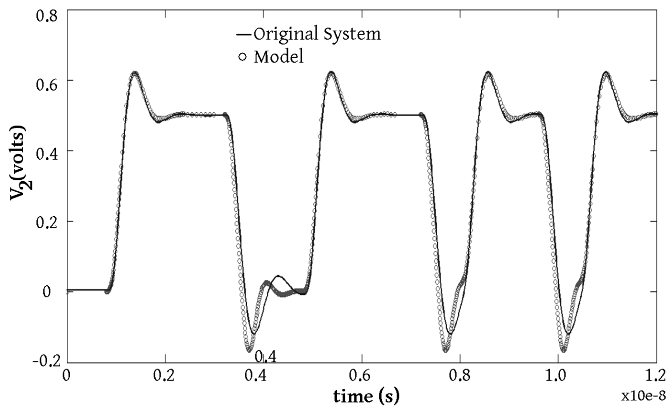

Fig. 11. Output voltage v_2 for the driver and the macromodel (second configuration).

Conclusion

The paper describes a novel approach to buffer modeling using high order Volterra-Laguerre expansions. The authors show how a unique model may accurately mimic the behavior of a driver in very different load configurations, the strength of the approach thus residing in the versatility of the surrogate models it produces. It should further be noted that the approach is computationally efficient and doesn't disclose in anyway the physical structure of the original circuits.

References

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