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(Article begins on next page)

Scattering-based nonlinear macromodels of high-speed differential drivers

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Abstract—**This paper introduces a scattering-based nonlinear macromodeling framework for high-speed differential drivers. Using an industrial test case, we show that the proposed scattering formulation enables more accurate and robust model identification with respect to standard voltage-current representations. The combination of proposed driver models with a Waveform Relaxation solver allows accurate and efficient transient channel simulation, including nonlinear and dynamic termination effects.**

I. INTRODUCTION

Data transmission on high-speed links is one of the fundamental bottlenecks in the overall performance of computing and networking platforms. Parasitic effects of high-speed channels such as losses, dispersion, discontinuities and couplings inevitably set an upper limit to the data rate that is supported by the link, due to signal degradation effects that accumulate at the receiver. Analog transient simulations are therefore a key step for link qualification during the design process.

Since electrical interconnects are linear and time-invariant structures, their characterization can be performed in the frequency domain, in order to simplify the representation of inherently frequency-dependent phenomena such as metal and dielectric losses. Tabulated scattering parameters have thus become the standard format to specify channel responses. Any numerical simulation of a transmission link requires in addition proper models for drivers and receivers loading the channel at its terminations. Such models should represent all the features of these transceivers that are relevant to signal quality, which may include dynamic and nonlinear effects.

The class of adopted driver and receiver models dictates the type of transient analysis that can be supported. Full transistor-level models support comprehensive analyses, but only for very short bit patterns due to excessive complexity. Eye diagram simulations for Bit Error Rate (BER) determination are ruled out. Simpler behavioral models have been proposed in the past to cope with this complexity. Examples are the various IBIS models [1], MπLog models [2], [3], Volterra-Laguerre models [4], Neural Network models [5], and more recently X-parameter-based models [6]. All these approaches provide a compromise between accuracy and complexity, with accuracy being very critical especially for highly nonlinear structures. Due to this fact, robustness and speed requirements in numerical simulations led to the recent adoption in the industrial community of the IBIS-AMI paradigm [7], which completely neglects the nonlinear driver/receiver effects. The

question remains on how such simulation results are representative, given that important phenomena are not included in the models by construction.

This paper proposes a new modelling approach for high-speed differential drivers. The model structure belongs to the MπLog class [2], [3]. As such, nonlinear and dynamic effects are implicitly included in the model parametric equations. The main novelty of our approach lies in the adoption of the scattering wave variables as the basis for the representation of the model characteristics. We show that this representation is more reliable than the standard voltage-current representation both in robustness of the model identification and in the resulting accuracy. A second advantage of the proposed driver structure is the compatibility with a recently-developed solver based on the Waveform Relaxation (WR) concept [8], which is also based on transient scattering waves. The combination of proposed driver model with this WR solver leads to a complete link simulation platform, that enables transient simulation of bit patterns of moderate lengths with a speedup of 2-3 orders of magnitude with respect to transistor-level models. The proposed framework can thus be applied both as a direct channel simulation tool by itself, but also as a validation tool for eye diagram patterns and BER calculations obtained by faster by less accurate (linear) solvers.

II. BACKGROUND

The goal of device macromodeling is to find a mathematical relation that can reproduce the electrical behavior at the device ports without any assumption on the device internal structure. Such an approach has been successfully exploited for the modeling of both single-ended [2] and differential [3] drivers, leading to the so-called Mπlog technique. This approach is briefly reviewed below.

Referring to the differential driver shown in Fig. 1, the macromodel that describes the output port currents $i_{1,2}(t)$ depending on the corresponding output voltages $v_{1,2}(t)$ is defined by the following two-piece relations [3]

$$\begin{cases} i_1(t) &= w_{1H}^i(t) i_{1H}(v_1(t), v_2(t), d/dt) \\ &+ w_{1L}^i(t) i_{1L}(v_1(t), v_2(t), d/dt) \\ i_2(t) &= w_{2H}^i(t) i_{2H}(v_1(t), v_2(t), d/dt) \\ &+ w_{2L}^i(t) i_{2L}(v_1(t), v_2(t), d/dt) \end{cases} \quad (1)$$

where i_{nH} and i_{nL} for $n = 1, 2$ are parametric submodels describing the nonlinear dynamic behavior of the output port
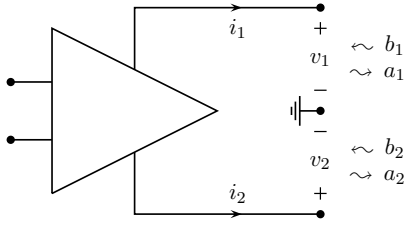
Fig. 1. Differential driver: definition of output ports and signals

in the fixed High (H) and Low (L) logic states, respectively, and w^i_{nH} and w^i_{nL} are time-dependent weights accounting for logic state transitions. We remark that the model expressions are natively formulated in discrete-time $t_k = k\,\delta t$, such that the output currents at a given time step t_k can be computed directly from (1) knowing their past samples, as well as present and past voltage samples.

The estimation process of model (1) amounts to selecting a parametric model representation for submodels i_{nH} and i_{nL} and to computing the parameters by matching the response of the submodels to the reference current responses obtained by applying suitable voltage stimuli to the driver forced in a fixed high and low logic state, respectively [2]. Once the submodels are completely defined, the computation of the time-dependent weights w^i_{nH} and w^i_{nL} is carried out by a simple linear inversion of (1). This is performed starting from switching voltage and current waveforms recorded during state transitions events, as suggested in [2]. The last step of the modeling process addresses the coding of the model equations in a simulation environment.

III. SCATTERING-BASED MπLOG MACROMODELING

As we will see in Sec. IV, the application of the above identification process to real industrial testcases may not lead to satisfactory results in terms of model accuracy. Therefore, we considered restating the model equations in terms of transient (discrete-time) scattering waves. This is motivated by the fact that differential drivers are designed to launch signals into controlled-impedance (often 50Ω) channels. Since scattering wave variables normalized to this impedance best represent the physical propagation of pulses (and power) along the channel, we argue that this representation will perform well also for modeling drivers that are optimally matched to the channel. These assumptions will be confirmed later.

We define the transient scattering waves at the output ports of the driver as $a_n = (v_n + R_0 i_n)/(2\sqrt{R_0})$ and $b_n = (v_n - R_0 i_n)/(2\sqrt{R_0})$ for $n = 1, 2$ (see Fig. 1) with R_0 reference resistance *e.g.,* $R_0 = 50\Omega$. Note that, considering the interconnection of the driver with its channel, the waves $b_{1,2}(t)$ are considered as incident into the driver output (hence outgoing from the channel), whereas $a_{1,2}(t)$ are the scattered (launched) waves form the driver into the channel. Further, we define the common and differential incident waves, respectively, as $b_c(t) = (b_1(t) + b_2(t))/2$ and $b_d(t) = b_1(t) - b_2(t)$, and we use them as controlling inputs of our proposed scattering-based

Mπlog model

$$\begin{cases} a_1(t) & = & w^a_{1H}(t)a_{1H}(b_c(t), b_d(t), d/dt) \\ & + & w^a_{1L}(t)a_{1L}(b_c(t), b_d(t), d/dt) \\ a_2(t) & = & w^a_{2H}(t)a_{2H}(b_c(t), b_d(t), d/dt) \\ & + & w^a_{2L}(t)a_{2L}(b_c(t), b_d(t), d/dt) \end{cases} \quad (2)$$

We choose $b_{c,d}$ as model inputs because under ideal conditions, i.e., when connecting the driver model to a pair of perfectly matched transmission lines with line impedance R_0, we obtain $b_d = 0$ independent on the driver logic state. Arguing that under realistic operations the equivalent channel impedance will not be far from R_0 (a condition that is targeted in the design), the range of values that will be spanned by b_d will be a small neighborhood of 0, thus making the model outputs $a_{1,2}$ very insensitive to its differential input.

The estimation process of (2) is standard. In particular, as discussed in [3], in order to facilitate model estimation and to make the modelling procedure more robust, each submodel $a_{n\nu}$ for $n = 1, 2$ and $\nu = H, L$ is further split into the sum of a nonlinear static and linear dynamic contribution

$$a_{n\nu}(b_c, b_d) = a_{ns\nu}(b_c, b_d) + a_{nd\nu}(b_c, b_d, d/dt) \quad (3)$$

Each contribution is identified independently: for the static part (or static characteristic) $a_{ns\nu}$, low order multidimensional polynomials are used, while a simple linear state-space model (with one or two poles) is used to model the dynamic part $a_{nd\nu}$ by means of standard techniques [10]. The circuit setup represented in Fig. 2 is used to collect the data for the various submodels identification through the following set of transistor-level circuit analyses.

1) Static part identification *i.e.,* construction of four bivariate polynomials for $a_{ns\nu}(b_c, b_d)$ for $n = 1, 2$ and $\nu = H, L$. The data for the fitting are obtained by running a double DC sweep of the $b_{c,d}$ sources in Fig. 2.
2) Dynamic part identification *i.e.,* extraction of four low-order dynamic models for $a_{nd\nu}(b_c, b_d, d/dt)$ for $n = 1, 2$ and $\nu = H, L$. In this case the setup in Fig. 2 is used by setting the $b_{c,d}$ sources as time-varying multilevel stimuli [2] and by running transient circuit analyses.
3) Identification of the time-dependent weights $w^a_{n\nu}$ accounting for the switching behaviour of the driver. The switching curves $a_{1,2}(t)$ are recorded for a simple 010 bit sequence with the driver terminated by resistive reference loads, and the single-switching weighting functions are computed by a linear inversion of (2), followed by time-gating. A simple concatenation leads to the weighting sequences for any arbitrary bit stream.

IV. AN INDUSTRIAL DRIVER TESTCASE

We illustrate the proposed macromodeling technique on a real production level driver used for differential signaling on high speed buses (courtesy of IBM). This driver has a nominal supply voltage $V_{dd} = 1.1$ V, with a swiching time of 100 ps.

We start by illustrating the static characteristics $a_{1sH}(b_c, b_d)$ in Fig. 3, where the transistor-level DC results are compared
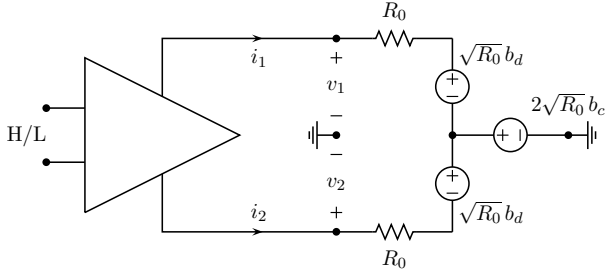
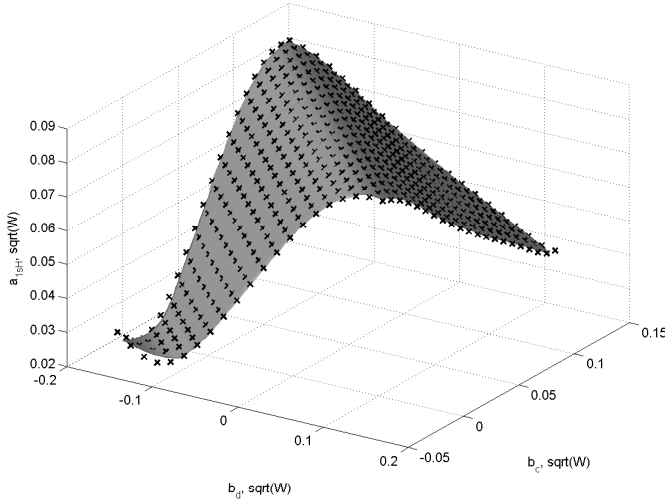Fig. 2. Setup for driver model identification.

Fig. 3. Static response $a_{1sH}(b_c, b_d)$ from a DC sweep of the transistor-level driver schematic (surfaces) and corresponding polynomial fit (markers).

to the model polynomial fit. A 9-th order polynomial was used to ensure accuracy throughout the domain, although a smaller order might be sufficient (see later). The same accuracy level was obtained for all other static surfaces (not shown).

Figure 4 shows a comparison between transient results of model and reference netlists for the dynamic submodel $a_{1dH}(t)$. A similar accuracy was obtained for the other three dynamic submodels. The corresponding linear state-space submodels were identified by enforcing a (low) dynamic order 2 in all cases. The accuracy is excellent, taking into account that the reference simulation includes all nonlinear effects detrended of the static characteristics, whereas the dynamic macromodel part is forced to be linear.

We now turn to the reconstructed time-dependent weights for time-dependent switching modeling. Figure 5 shows the rising and falling transitions of $w_{1\nu}^a$ (top panel) of the proposed scattering-based macromodel, compared with the corresponding weights $w_{1\nu}^i$ of the standard voltage-current $M\pi\log$ model (1). The weighting functions for the scattering-based model result smooth and monotonic between 0 and 1, while those of the standard model are affected by spurious ringing. This ringing implies that when the driver should be in a fixed H (resp. L) state, the response of the model is still a combination of both H and L submodels. This behavior
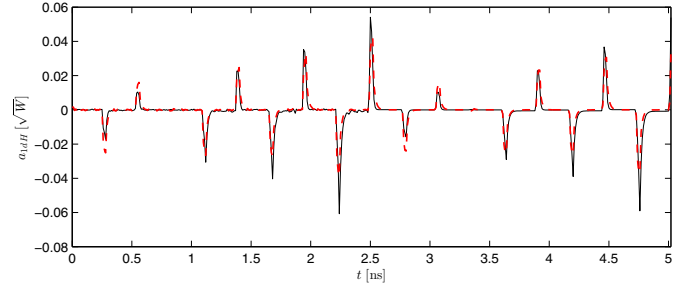

Fig. 4. Linear dynamic submodel $a_{1dH}(t)$ response (red dashed line), compared to reference transistor-level response (black solid line).

is of course incorrect. This different transition behavior has a dramatic effect on the quality of the model prediction. In fact, Fig. 6 collects the responses for a short validation setup, obtained by terminating the driver into a pair of mismatched transmission lines (40Ω and 60Ω, respectively). It is evident that the scattering-based model provides more accurate predictions even if the terminations are different from the nominal identification loads.

A more compelling validation is now illustrated on a more realistic setup. An 18-port channel consisting of 9 coupled interconnects and characterized by its tabulated scattering matrix is processed by a delayed rational fitting engine to obtain a time-domain macromodel [9], which returns the transient scattered waves at the channel ports $b_n(t)$ by means of delayed recursive convolutions applied to the incident waves $a_n(t)$. The proposed driver model is connected to a differential pair and launches a pseudo-random bit sequence at 1 Gbps. The other coupled channels are terminated by synchronous aggressor signals. A reference simulation is obtained by synthesizing a circuit netlist for the channel which, combined with the transistor-level driver schematic, is run in a circuit
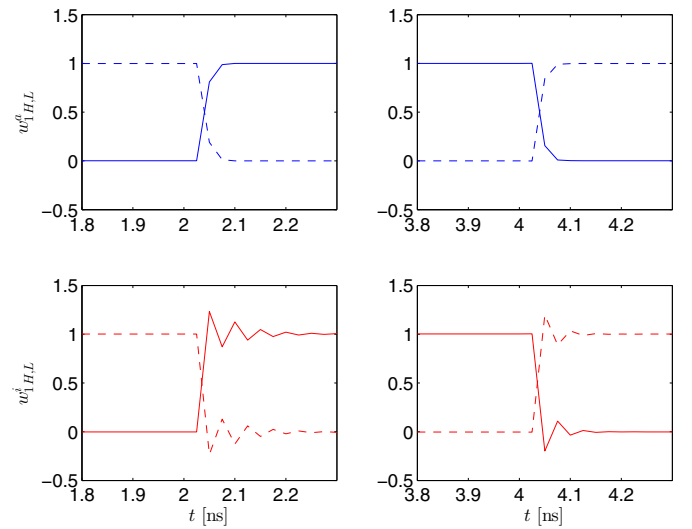

Fig. 5. Switching weights of the scattering-based model $w_{1H,L}^a$ (top panel) and the voltage-current model $w_{1H,L}^i$ (bottom panel).
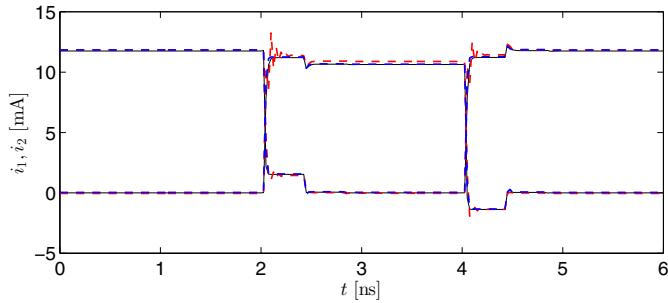
Fig. 6. Validation of the driver model loaded by a mismatched transmission line load. Reference (solid black line), scattering-based model (blue dashed line) and voltage-current based model (red dashed line).
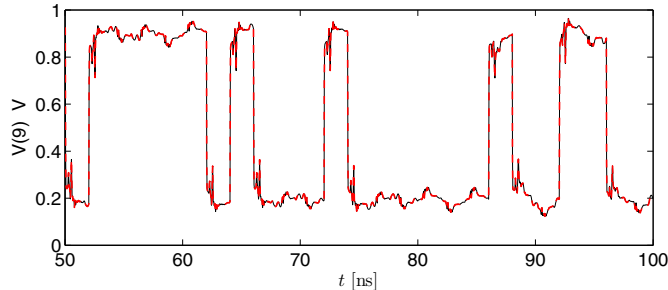

Fig. 7. Full channel/driver combined simulation (see text). Model response (dashed red line) is compared to a full transistor-level reference simulation (black solid line).

solver (Spectre). The WR solver presented in [8] exploiting both channel and driver macromodels is then used to verify accuracy and speedup. Figure 7 compares the voltage at a selected port for both simulations. The accuracy is excellent, considering that the transistor level simulation took 2h 30min, where the macromodel simulation took only 1 min, with a corresponding speedup of 150×.

Figure 8 reports a very interesting result, which is one of the motivations for using scattering-based driver macromodels in our investigation. The figure reports the trajectory of the scattering wave $a_1(t)$ at the driver output, computed in the full channel/driver simulation. The trajectory is superimposed to the static characteristics a_{1sH} and a_{1sL}. We see that the driver responses "jump" from the static submodels corresponding to the static H and L states during switching (the vertical lines), but during non-switching periods the dynamic behavior of the structure appears to span only a small region of the (b_c, b_d) plane. This fact could be used to fine-tune the accuracy of the driver macromodel around this region, thus avoiding large polynomial orders to fit all regions of the static characteristic that are never reached during operation (this will be the subject of a future investigation). In other words, the driver exploits a weak dependence on the mixed-mode scattering signals that are incident into its output ports. This fact renders the mixed-mode scattering representation upon which the driver model is constructed very robust and realible for channel simulation.
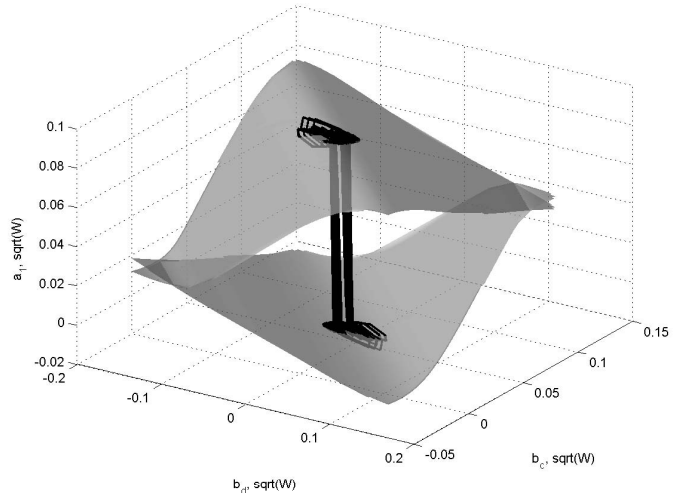

Fig. 8. Trajectory of $a_1(t)$ at the driver output during the validation run, superimposed to the static a_{1sH} and a_{1sL} characteristics of the driver model.

V. CONCLUSIONS

This paper presented a systematic approach for high-speed differential driver macromodeling. It was shown on a production driver that casting the nonlinear and dynamic characteristics of the model in the scattering domain leads to improved robustness with respect to standard voltage-current representations. The resulting macromodel allows fast and accurate simulation of loaded channels, including nonlinear and dynamic driver effects. A systematic analysis to a large set of benchmark drivers is in order to assess the generality of the approach. This will be the subject of our future investigations.

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