Signal Prediction for Digital Circuits by Sigmoidal Approximations using Neural Networks

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***Abstract*—Investigating the temporal behavior of digital circuits is a crucial step in system design, usually done via analog or digital simulation. Analog simulators like SPICE iteratively solve the differential equations characterizing the circuits' components numerically. Although unrivaled in accuracy, this is only feasible for small designs, due to the high computational effort even for short signal traces. Digital simulators use digital abstractions for predicting the timing behavior of a circuit. We advocate a novel approach, which generalizes digital traces to traces consisting of sigmoids, each parameterized by threshold crossing time and slope. For a given gate, we use an artificial neural network for implementing the transfer function that predicts, for any trace of input sigmoids, the parameters of the generated output sigmoids. By means of a prototype simulator, which can handle circuits consisting of inverters and `NOR` gates, we demonstrate that our approach operates substantially faster than an analog simulator, while offering a much better accuracy than a digital simulator.**

I. Introduction and Overview

The golden standard for accurate dynamic timing analysis of digital circuits are analog simulators like SPICE [1]. In contrast to static timing analysis, which conducts corner-case analysis of critical path delays in a circuit only, dynamic timing analysis provides per-transition timing information in digital signal traces. By iteratively solving the differential equations that govern the electrical behavior of the transistors of a circuit numerically, highly accurate traces of the output signal waveforms are computed. The drawback of this kind of analysis is the high computational effort and, hence, the low scalability in terms of the circuit size, which makes it feasible for small designs and short traces only. By contrast, digital timing simulators completely abstract away analog waveforms, by discretizing those via zero-time (Heaviside) transitions generated at threshold crossing times. Instead of solving differential equations at simulation time, digital timing analysis tools like ModelSim use pre-computed delay models to parameterize pure or inertial delay channels [2], which ultimately determine the digital output signal traces.

Given the inability of pure and inertial delays to model pulse degradation, which severely limits the achievable accuracy, alternative delay models have been proposed in the past. All of these are single history models, where the input-to-output delay $\delta(T)$ of a given input transition depends on the time difference T of the input to the previous output transition. By choosing a suitable function for $\delta(.)$, pulse degradation (up to complete canceling) can be modeled. For example, the authors of the *Delay Degradation Model* (DDM) [3], [4] proposed a suitably parametrized exponential function for $\delta(.)$. However, in [5], it has been shown that all the existing delay models, including the DDM, do not match reality in some situations. This problem has been avoided by the *Involution Delay Model* (IDM) proposed in [6] later on, which is based on delay functions that are self-inverse, more specifically, negative involutions satisfying $-\delta(-\delta(T)) = T$. And indeed, it has been shown in [7], [8] that this model surpasses all popular alternative models also in terms of accuracy.

Inherently, however, digital models, including the IDM, cannot express and utilize slope information: a Heaviside transition does not reveal whether the corresponding analog waveform has crossed the threshold voltage steeply or not. Still, this might severely affect the gate delay. In this paper,[1] we propose an approach that mitigates this shortcoming, by replacing traces consisting of sequences of Heaviside transitions by traces consisting of sequences of sigmoids (subsequently called *sigmoidal approximations*). Given that a single sigmoid is parametrized with a threshold crossing time, analogous to a Heaviside transition, but also by a slope parameter, this is a very natural generalization.

Our approach primarily requires a *transfer function*, for every gate, which, given the sigmoidal approximations of the inputs, allows to determine the sigmoidal approximation of the output. We developed a prototype of a simulator for circuits composed of inverters and `NOR` gates, which implements all transfer functions by means of relatively simple *Artificial Neural Networks* (ANNs) trained by sigmoidal approximations of SPICE-generated analog sample traces; Fig. 1 depicts the gist of our approach. A number of experiments using our simulator confirm that it operates substantially faster than an analog simulator, while offering considerably better accuracy than any digital simulator.

II. Signal Prediction via Sigmoidal Approximation

In contrast to digital simulators that represent signals as sequences of transition times, and to analog simulators that

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[1]The full version of this extended abstract can found in [9].

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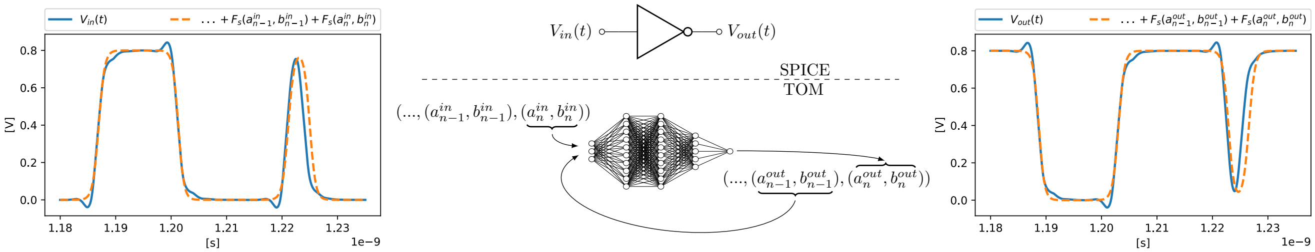

Fig. 1. An example of the prediction of our third-order model (TOM) compared to SPICE for a single inverter.

represent signals as time-dependent voltage or current values, our approach represent signals as sequences of sigmoid parameters. A sigmoid being a bounded differentiable real function that is defined for all input values, with a positive derivative everywhere. Since a single sigmoid $F_S(a, b)$ is characterized by two parameters, representing the zero-crossing time a and the slope b, the sigmoidal approximation of a signal is given by a list of parameter tuples $((a_1, b_1), (a_2, b_2), ...)$ [10], see Fig. 1 for two examples. Practically, this list can be obtained from the analog signal by means of a fitting algorithm.

The goal of the transfer function of a gate G is to predict the current output transition parameter tuple $(a_{n-1}^{out}, b_{n-1}^{out})$, given the parameter tuples of the current input transition (a_n^{in}, b_n^{in}) and the previous output transition $(a_{n-1}^{out}, b_{n-1}^{out})$. We accomplish this by a function F_G that relates these parameters such that $(a_n^{out}, b_n^{out} - b_n^{in}) = F_G(b_n^{in} - b_{n-1}^{out}, a_n^{in}, a_{n-1}^{out})$. Note carefully that, unlike a digital ("first order") model that only takes into account the time difference $T = b_n^{in} - b_{n-1}^{out}$ between the current input and the previous output transition for predicting the gate delay $\delta(T)$, our *third order model* (TOM) also considers the slope a_n^{in} of the current input and the slope a_{n-1}^{out} of the previous output.

As an analytical solution for F_G seemed out of reach, whereas splines, polynomials and look-up-tables turned out to be inappropriate, we implemented our transfer functions via ANNs. We split F_G into four separate ANNs, which predict the output slope (a_i^{out}) and output delay (b_i^{out}) for the rising and falling case separately. Note that no systematic search for the optimal ANN architecture was performed, as our architecture (multilayer perceptron with 3 inputs, two internal layers with 10 neurons, third internal layer with 5 neurons and one output, with each neuron using a ReLU activation function) depicted in Fig. 1 was found to be sufficient for our purposes. The training data for these ANNs were generated via SPICE simulations of the corresponding gates (`NOR` and inverters), using specifically tailored input stimuli.

III. Results

In order to demonstrate the principal feasibility of our approach, we simulated the instances c17, c499 and c1355 of the ISCAS-85 Benchmark [11] in SPICE, in ModelSim, and in our simple prototype implementation of the TOM. In order to be consistent across all three simulators, we converted the ISCAS-85 circuits (which consist of gates of any type) to equivalent circuits consisting of just `NOR` gates. We applied randomized sets of stimuli in all three simulators and compared the average simulation accuracy and simulation time. Overall, our simulator provides a much better accuracy than Modelsim while, at the same time, requiring less simulation time than SPICE.

Whereas the results of our experiments are of course by no means meant to be representative, they nevertheless demonstrate the potential of our approach.

IV. Conclusion

We advocated a generalization of dynamic digital timing analysis, which relies on signal traces consisting of a sequence of time-shifted sigmoids. Gates are described by means of transfer functions, which describe how the output sigmoid parameters, namely, occurrence time and slope, depend on the input sigmoid parameters.

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