ABCD: Accurate Booleanization of Continuous Dynamics for Analog/Mixed-Signal Design and Verification

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I. Abstract

We propose a new approach (called "Booleanization"), and a suite of related computational modelling techniques (collectively dubbed ABCD[1]) to the longstanding problem of effectively modelling, efficiently analyzing, and formally/pseudo-formally verifying and validating analog/mixed-signal (AMS) systems that play a key role in today's high-consequence control (HCC) systems.

A. The increasing importance of AMS systems

AMS systems are those that contain both analog and digital components. Examples include Analog to Digital (A/D) and Digital to Analog (D/A) converters, high-speed communications sub-systems, Phase Locked Loops (PLLs), *etc.* AMS modules have come to play an increasingly important role in modern HCC systems. A variety of critical components (*e.g.*, the USB interface, I/O, memory, high-speed communications modules, *etc.*) that traditionally used to be predominantly digital are now being implemented using AMS blocks instead. As a result, the AMS components in such designs have become key bottlenecks that have an outsize impact on important system-level performance metrics such as data-rate/throughput, power consumption, noise margins, *etc.*

B. The need for accurate AMS modelling

Due to the increasing importance of AMS components, "effective, bug-free AMS design" has become a key problem in the design of HCC systems. However, this is a large and challenging problem that spans many dimensions and sub-problems, including (a) high-speed AMS simulation, (b) effective and scalable formal AMS verification and validation, (c) comprehensive AMS test-generation and debugging, and (d) a variety of circuit-specific algorithms and analyses needed to ensure the correctness of critical AMS blocks in a design (these include, for example, eye-diagram analysis, bit error rate analysis, noise margin analysis, uncertainty quantification and variability analysis, *etc.*).

Each of the above sub-problems and analysis procedures requires *accurate modelling of the underlying AMS components*. For example, successful verification of AMS sub-systems requires accurately modelling their behaviour in a form that verification tools can scalably analyze; otherwise, the proofs and guarantees produced by verification tools will not be trustworthy, and critical bugs could be missed.

C. Our approach: "Booleanizing" AMS systems

We propose to approximate the discrete and continuous dynamics of AMS systems using purely Boolean models (*e.g.*, Finite State Machines or FSMs). In these models, the important state variables and signals in these systems (*e.g.*, voltages and currents) are discretized both in time and in space, and the evolution of these quantities over time, in response to the system's inputs, is represented using purely Boolean constructs such as counters, state machines, latches and flip-flops, combinational logic gates, *etc.*

We find that even though these systems exhibit continuous dynamics (*e.g.*, as predicted by SPICE using transistor-level models for the components), we are able to represent such continuous dynamics with a high degree of accuracy using only purely Boolean models. Indeed, we have developed a suite of computational techniques, ABCD, to automatically abstract SPICE-level netlists into Boolean form.

The Boolean models produced by ABCD have several advantages. For example, they can be simulated very efficiently (ideally, in $O(1)$ time per simulation time-step) compared to SPICE-level simulation. Furthermore, they enable the use of modern cutting-edge formal verification and model checking tools and techniques (*e.g.*, ABC) for proving that the underlying components and interfaces are bug-free.

We have applied ABCD to a variety of AMS systems such as charge pumps, filters, equalizers, A/D and D/A converters, power grids, high-speed communications and signaling systems, *etc.*, and in each case we have been able to capture the continuous dynamics of these systems to high accuracy using only purely Boolean models – paving the road to accurate high-speed simulation and scalable formal verification and property checking of AMS systems.

[1]ABCD stands for **A**ccurate **B**ooleanization of **C**ontinuous **D**ynamics.

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