Advantage of Black-Box Modeling of Mixed-Signal Integrated Circuits

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Abstract—**The modeling techniques of mixed-signal integrated circuits are gaining attention in industry and research community due to the low speed of time-domain SPICE transistor level simulations. The black-box approach to behavioral modeling, although very challenging, is particularly interesting due to its broad spectrum of possible applications and high simulation speed. The goal of this paper is to explore possibilities for the future research in the area of black-box behavioral modeling of mixed-signal integrated circuits.**

I. Introduction

This work will focus on the modeling aspect of mixed signal integrated circuit CAD and emphasis will be on black box behavioral modeling. Behavioral modeling, in general, tries to describe circuit, subsystem or system based on recorded responses to well-selected excitation signals. Behavioral modeling has become a critical step in designs of large circuit systems. Today billion transistor microprocessors or high level DSP integrated circuits simply could not be designed at the transistor level of circuit description their design is heavily based on behavioral descriptions of the circuits used in the overall designs. Black box is a technical term for a device, circuit or a system that is observed in terms of its input, output or transfer characteristics without any knowledge of its internal workings. Black-box modeling usually refers to behavioral modeling of such devices, circuits or systems. The specific aspects of black-box modeling are discussed in section II-A.

For linear systems, broadband S-parameters can provide an essentially good black-box, measurement based, behavioral model of the component [1] .The linear circuit can therefore, be adequately replaced by S-parameter simulation block (if the mentioned limitations are observed, understood and taken into account). Unfortunately, nonlinear systems and circuits are more common than linear and are much harder to model. The main reason for that is the fact that there are so many types of nonlinear systems with extremely complex dynamical behavior that is far from being exhaustively investigated Nonlinear modeling methods, in general, are highly interdisciplinary, from (device) physics to mathematics and computer science.

One should also note that circuit terminations or loads have no impact on the modeling process of the linear circuit. When dealing with nonlinear circuits, the choice of terminations chosen in the training process, directly affects the quality of the model. This work focuses on the behavioral modeling of nonlinear ear systems, in particular, the mixed signal integrated circuits. Several aspects make modeling of the mixed-signal integrated circuits especially difficult.

* Large number and wide choice of passive and particularly active components in case of integrated circuits, one comes across a variety of passive and active components. Passive components include a variety of transmission line structures, resistors, capacitors, inductors and other. Furthermore, there is a vast number of active components, e.g. semiconductor devices like MOSFET (Metal-Oxide- Semiconductor Field- Effect Transistor), MESFET (Metal Semiconductor Field-Effect Transistor), BJT (Bipolar Junction Transistor), HBT (Hetero junction bipolar transistor), HEMT (High Electron Mobility Transistor) and many other. The modeling process of each of these components is a complex matter and therefore, it is even more complex to model circuits that consist of many such components.

* high nonlinearity of active components as mentioned in the last paragraph, there is a broad spectrum of active component types, especially semiconductor transistors and their models (just to name a few, BSIM (Berkeley Shortchannel IGFET Model), EKV (Enz, Krummenacher and Vittoz transistor model), PSP (Penn State Phillips transistor model), HICUM (High Current Model), MEXTRAM (Most Exquisite transistor Model) and many more). None of these models are adoptable for full gamma of transistors, mainly because the behavior of transistors is highly nonlinear and dynamic and highly dependent on the transistor type and technology it is built on.

* it is often found that both digital and analog circuits are placed on the same die, e.g. it is very common to find systems with embedded digital, analog and radio frequency RF/microwave blocks in a single die with a mixed technology. The Domenech Asensietal. in accent that such complex circuits impose to reconsider and replace traditional design methods.

 there are several constraints on the model which are difficult to satisfy:

! The models have to be accurate - in order to be practically useful, the models have to be accurate enough. The demand for accuracy varies from application to application and usually conflicts with simulation speed of the model.
! The models have to simulate fast (especially at the system level) - if models are not fast enough, IC and system designers cannot use them.

! Model development resides in finding a good compromise between accuracy and complexity higher complexity usually implies lower simulation speed. The optimal tradeoff between those two parameters depends on the particular application and therefore, it is very hard to extract general guidelines.
! The model should be effectively implementable in modern integrated circuit simulation tools if the models are not includable into the standard simulation environment, they are practically useless.
! The models have to be stable and robust if the models are not stable and robust enough, they are not usable. Extraction principle of the model should be simple enough to be implementable and usable.

A. Inspiration

Large circuits, if simulated in time-domain, contain a very large number of nonlinear equations to be solved. Such a task is difficult, in terms of simulation time and memory, for typical computer workstations available to most designers. Even modern simulation algorithms such as harmonic balance and transient envelope analysis do not solve this problem completely, although they are more efficient than traditional methods used by time-domain SPICE-like simulators. The black-box approach to behavioral modeling, although very challenging, is particularly interesting due to its broad spectrum of possible applications and fast simulation speed. One of the advantages of black-box models is that they can be derived from both measurements and simulations. The measured circuit that can be modeled in the behavioral way, is probably the most accurate representation of this circuit because it includes all parasitic effects (from packaging, bonding, PCB and other sources) which could have been overlooked in SPICE simulation.

In the second, simulation based approach; the circuit simulator is used as a virtual instrument to generate needed data to build a behavioral model. The behavioral modeling methods presented in this work are generally targeted and applicable to both simulations based and measurement- based cases.

From system designer perspective, behavioral models are critical for system design. Wood and Root in went even further in stressing the behavioral modeling importance stating that “good behavioral model is perhaps the best specification of the IC performance” in system design. One should also note that in most cases the time-domain simulation of the whole integrated circuit is impossible for large designs.

One interesting feature of behavioral models is that they can be built for components for which “classical” model has not been built yet or even for components that have not been built yet at all. Using black-box modeling techniques, a model could be developed even based on the desired or estimated input-output relations. In that way, system designer can design several aspects of the system based on general specifications of components and reduce overall time to market. Good behavioral models can be a competitive advantage for both circuit and system design houses. Circuit design house can send a behavioral model to system design houses without revealing any inside information about how they have built the circuit, thus protecting their intellectual property. If the models are fast and accurate, system design house might be interested to use the services of that particular circuit design house, rather than the other, because they provide good models, and in spite of the hypothetical difference in price, which can generate additional revenues to circuit design house. Good behavioral models enable system design houses to be effective and cut the design time. Also, sys- tem design house capable of creating their own behavioral models can design systems more easily than competitions who must wait for hardware or built costly prototypes.

For analog and mixed signal design, behavioral modeling is even more difficult, especially at high frequencies. At high frequencies, a behavioral model has to be able to directly or indirectly describe the influence of the circuit parasites (which are, in general, difficult to extract and model). The behavioral modeling techniques that can accomplish that are especially sought after. There is especially big interest for suitable behavioral models in a wireless communications market, due to its commercial significance.

Another key issue in behavioral modeling is the fact that today’s most prevalent approach for creating models is a man- ual abstraction. Manual abstraction is heuristic, inconvenient, computationally expensive and error prone. Automated abstraction has many benefits, but is very difficult to develop, because it has to cover a wide choice of circuits and devices. The strategies and methodologies that are developed with- in the scope of this work, can be considered on a path to the full automated abstraction of models.

The lack of fast and accurate enough system simulation methods leads to costly and time-consuming design iterations including expensive prototype cycles. Two basic solutions are almost obvious. The first solution is to divide the system in separate blocks and circuits and with simplified, but suffi- ciently accurate behavioral models. This would enable the full system simulation. The second solution would be to build the behavioral model out of the measurements of the full sys- tem (or simulations if possible at all). Unfortunately, the path to the realization of these deceivingly simple solutions is not clear and therefore, this work will try to be one definite step in the realization of that goal.

B. Scope

The main goal of this paper is to propose several approach- es for black-box modeling based on global approximation techniques. Based on current research status we will try to give guidelines for the future research.

The main emphasis will be on the modeling aspects that require least information about the model .(The goal is also that all models built from proposed behavioral modeling proce- dures should be effectively implementable in common simula- tion tools. This goal has proven to be an extraordinary chal- lenge because there is always a discrepancy between “cutting -edge” academic research and industrial application, which has to be robust, stable and “mature”. The “ideal” behavioral model that this work aspires to, has these properties.

- accurate,
- fast,
- robust,
- stable,
- built with least amount of information (i.e. black-box),
- built with least amount of user interaction (i.e. automat ed abstraction),
- implementable in modern circuit simulators.

The actual model implementation is always a compromise between mentioned properties.

II.BEH AVIOUR AL M ODELLING OF INTEGR AT ED ELECT RONIC CIRCUIT S

This section will give a brief overview of the common terms in behavioral modeling approaches and procedures. Also, a brief overview of the current state-of-the-art in black-box modeling will be presented.

A. Comparison of basic modeling approaches

Models can be classified according to the level of physical information used in model extraction in three categories:

- white-box models,
- grey-box models,
- black-box models.

White-box models require detailed knowledge about circuit (or device) structure and processing technology, which is of- ten difficult to obtain. White-box models are detailed models that (usually) have the advantage of being scalable. Black- box models have the advantage that no physical information is needed to build them. These models are fast but (usually) not scalable. Changes in circuit or device properties ne- cessitate a complete reconstruction of the model. The characteristics of grey-box models are (as the name sug- gests) somewhere between the characteristics of black- and white-box models. The emphasis of this work is on black-box models and modeling procedures. Table I presents the com- parison (by the list of advantages and disadvantages) of white- and black- box modeling approach. Some characteris- tics of white- and black- box models depend on the circum- stances, e.g. the execution speed of white-box and black- box models depends on the modeling procedure, model type and system, circuit or device signal complexity. The same conclusion stands for the overall model complexity.

B. Procedure of behavioral modeling

Behavioral modeling tries to describe circuit, subsystem or system based on recorded responses to well-selected excitation signals. Such a behavioral modeling procedure consists of several stages:

- selection of the excitation signals and acquirement of the training data - the excitation signals have to be well selected in order to capture the full behavior (or just behav- ior of interest) of the modeled system, circuit or device. The excitation signals should cover frequency range of interest.
- data analysis and processing in this stage, the data obtained from stimulating the integrated circuit with well- selected excitation signals is analyzed and processed. The analysis and processing usually include signal selection and applying various algorithms to them (including scal- ing and normalization).
- Selection of the model and its parameters - after selection and processing of the model inputs, a specific model type should be selected. Several types of current state- of-the art behavioral models are briefly described and dis- cussed in section II-C.
- Modeling - the actual modeling is the last part of be- havioral modeling procedure. It tries to apply the modeling procedure suitable for the specific se- lected model type and its parameters.

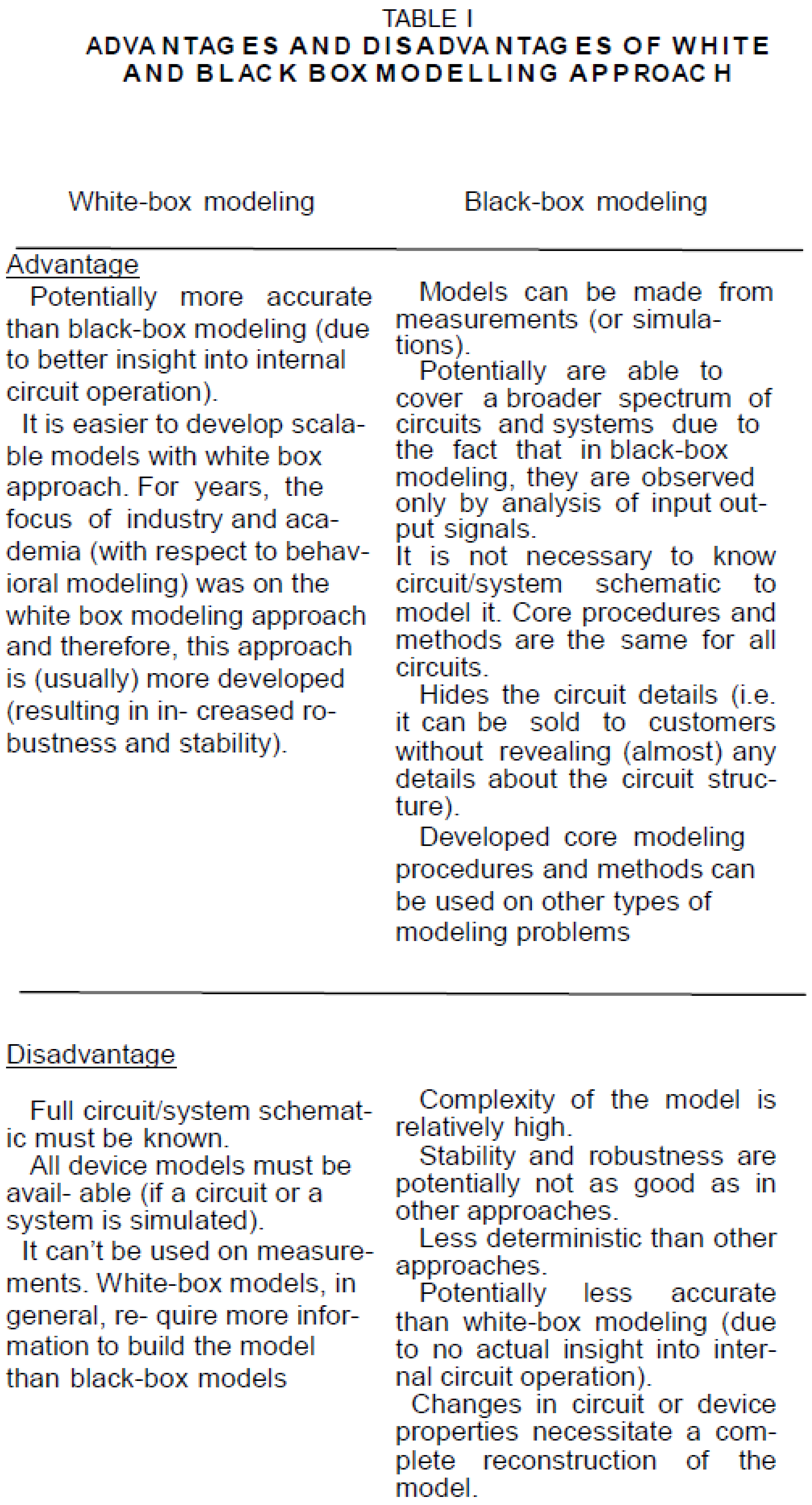

TABLE I
ADVANTAGES AND DISADVANTAGES OF WHITE AND BLACK BOX MODELLING APPROACH

	White-box modeling	Black-box modeling
Advantage	Potentially more accurate than black-box modeling (due to better insight into internal circuit operation). It is easier to develop scalable models with white box approach. For years, the focus of industry and academia (with respect to behavioral modeling) was on the white box modeling approach and therefore, this approach is (usually) more developed (resulting in increased robustness and stability).	Models can be made from measurements (or simulations). Potentially are able to cover a broader spectrum of circuits and systems due to the fact that in black-box modeling, they are observed only by analysis of input output signals. It is not necessary to know circuit/system schematic to model it. Core procedures and methods are the same for all circuits. Hides the circuit details (i.e. it can be sold to customers without revealing (almost) any details about the circuit structure). Developed core modeling procedures and methods can be used on other types of modeling problems
Disadvantage	Full circuit/system schematic must be known. All device models must be available (if a circuit or a system is simulated). It can't be used on measurements. White-box models, in general, require more information to build the model than black-box models	Complexity of the model is relatively high. Stability and robustness are potentially not as good as in other approaches. Less deterministic than other approaches. Potentially less accurate than white-box modeling (due to no actual insight into internal circuit operation). Changes in circuit or device properties necessitate a complete reconstruction of the model.

III. FRAMEWORK FOR MODELLING OF INTEGRATED CIRCUITS

In this section, the framework for behavioral modeling of integrated electronic circuits is proposed. The framework facilitates easier creation of behavioral models that are integrated in the modern IC simulators.
To enable easier research, development and building of black-box behavioral models, several requirements are met:
- New methods and procedures can be added in a "simple" way to facilitate easier research and development.
- Connects to modern circuit simulators (Cadence) for testing and validation of the models or obtaining training data. Framework facilitates easy incorporation of other integrated circuits simulators that can be controlled by command line.
- The resulting model is implemented in Verilog A which facilitates easier dispatch to different circuit simulators. The details about Verilog A implementation will be discussed in section III-B.

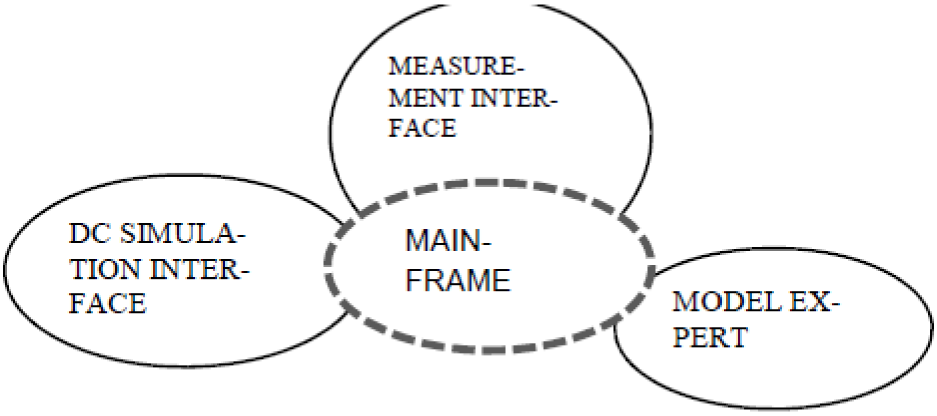

Fig. 1. Basic schematic of the modeling framework

The basic parts of the framework are:

- Mainframe this is the main part of the framework. The mainframe controls all parts of the framework. This part contains core black-box modeling procedures and methods.
- Measurement interface if the modeling is based on measurements, then we need an interface to the measurement data (or devices).
- IC simulation interface - there are two main reasons why we need an interface to the modern IC simulators. First, if the modeling is based on simulations, we need an interface to them. Second, we need an interface to the simulator to test the framework's model.
- Model export module - model must be exported to the format suitable for the use in most modern circuit simulators. The details about actual implementation will be dis- cussed in section III-B.

Figure 2 presents the mainframe part of the pro- posed framework. The basic parts of the mainframe are:

- data acquisition :this part connects to either the IC simulator or measurement setup (as shown in Figure 1).
- Selection of the input-output variables - this step per- forms selection of the model inputs and outputs. This stage is interconnected with the data acquisition stage.
- data processing - in this stage, the data from the last step is processed. Several steps are applied, e.g. splitting data in the training, validation and testing data sets, normalization, scaling, adding delay, differentiating etc.

- Selection of the model type: e.g. two-stage model as presented in section IV.
- Selection of the modeling method three approximation techniques are proposed to be used for black-box model- ing: artificial neural networks, support vector machines and k-nearest neighbor regression. The selection criteria is proposed in section III-A. This stage interacts with data processing stage because different modeling methods might require different preprocessing of the model inputs and outputs
- core modeling stage : this is the part where actual modeling is done .
- evaluation of the model - finally the model is evaluated. As arrows in Figure 2 point out, the stages can be re- cursive and iterative, e.g. if in the model accuracy is not satisfying, different model type should be selected and the process repeated.
- The framework is implemented in Math works Matlab software package using object oriented programming. To improve reliability and robustness, automated unit testing is used

The implementation details are more development than research topic and therefore, will not be discussed in detail.

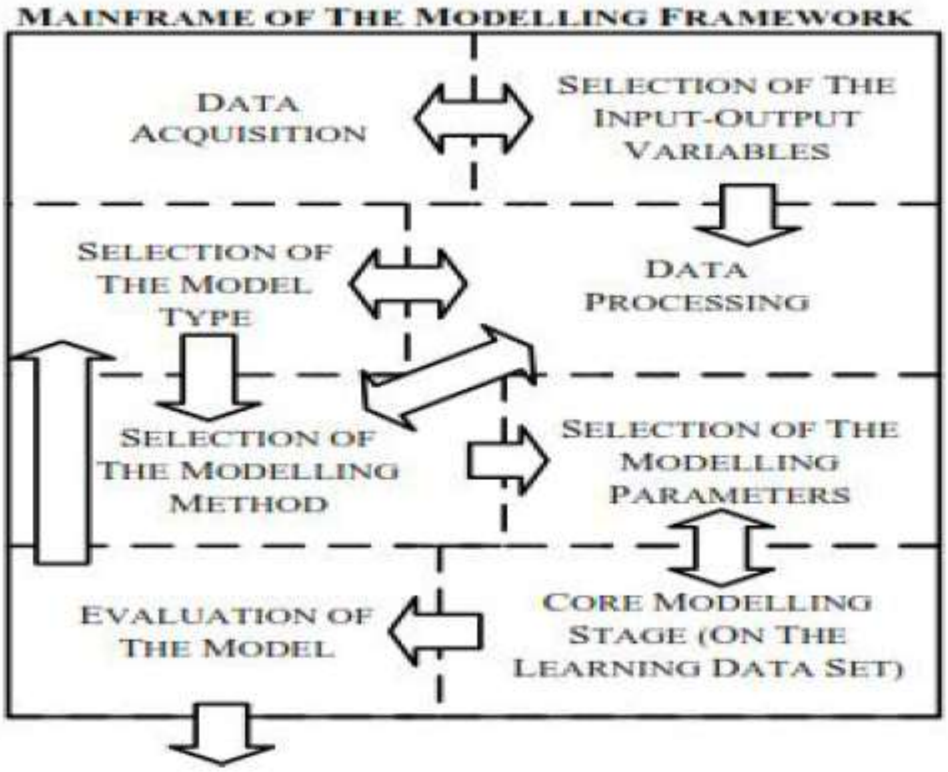

Fig.2.Modelling framework

A. Selection of the appropriate approximation method

A choice of particular approximation method is proposed to depend on two basic factors:
- Signal complexity - ICs with higher complexity will require usage of approximation techniques that are “better than average” in accuracy (i.e. low training and testing er- ror) and generalization.
- number of IC pins the higher number of IC pins that we would like to model, the higher dimensionality of the problem is. The higher dimensionality increases susceptibility to the curse-of-dimensionality13.

Table II presents the selection of the approximation method in the core module, based on model complexity and number of IC pins. Three different cores approximates are selected among wealth of methods:

- Artificial neural networks,
- support vector machines,
- K-nearest neighbor algorithm.

The artificial neural networks and support vector machines are selected as universal approximates based on current “state- of-the-art” in the field of black-box modeling of electronic circuits .

The k-NN regression is selected due to its very good handling of the high dimensional regression problems as a potential candidate for modeling ICs with a high number of pins. Each of these core modules has different properties (sets of advantages and disadvantages). All three together cover (or adjust to) a wide range of behavioral modeling needs for modeling of electronic circuits. The artificial neural networks are suitable for fast modeling of low to medium complex circuits with a low to a medium number of pins. Support vector machines, due to the better generalization and resistance to so called curse-of-dimensionality and potentially slower learning (because “optimal” parameters for learning have to be chosen are more suitable for medium to highly complex circuits with medium number of pins. k-NN regression, due to worse generalization and modeling properties when compared with support vector machines and neural networks, but higher resistance to curse- of-dimensionality, is suitable for a low to complex circuits with a higher number of pins

B. Exporting the model to the modern circuit simulators.

When implementing behavioral models into circuit simulators, several aspects are important:
- ease of implementation,
- Possibility of use of different OS platforms,
- Possibility of implementation of the same model in (at least several) modern circuit simulators,

- Simplicity of use and installation.

The main benefits of using Verilog-A(MS) or VHDL-A(MS) for compact modeling over general-purpose programming languages is that it frees the model developer from handling the simulator interface. When implementing models in Verilog- A and VHDL-A, one needs not be concerned with circuit simulator details. Also, they are considerably simpler then implementations of models in C language where one had to worry about symbolic partial derivatives of the currents and charges in a compact model and deter- mine the proper insertion of these values into the Jacobian matrix for Newtons method . In this work, Verilog-A is chosen as an implementation platform for behavioral models. Some of the specific benefits of using VerilogA(MS) are.

- Some modern circuit simulators internally compile Veri- log A code to fast C code (e.g. Cadence, Spectre),
- Verilog-AMS runs in the same AMS simulators as VHDL-AMS,
- can be easily converted to VHDL-AMS.

A good overview of Verilog A advantages can be found in.

IV. PRELIMINARY EXPERIMENT

Local Interconnect Network (LIN) interface circuit is selected as a fist test case for the proposed methodology. In this section, fist preliminary experiment are shown.
The basic LIN Schematic circuit interface is shown
in Figure 3. Table III shows the circuit inventory of the LIN interface under test. The circuit contains 253 transistors and 124 diodes and therefore, can be considered as a highly nonlinear circuit

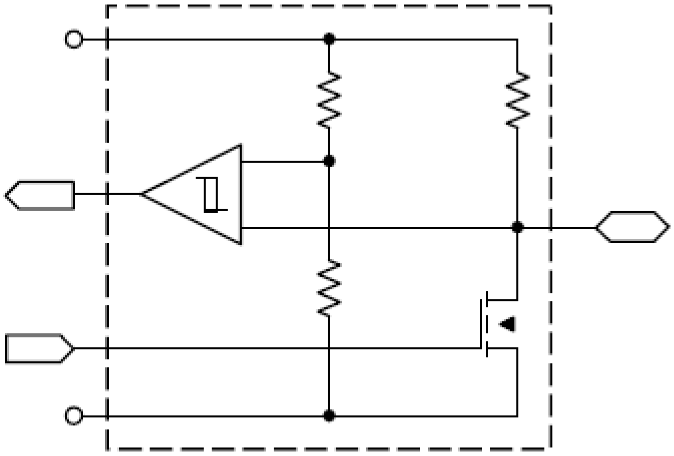

Fig. 3. Basic schematic of the LIN interface

TABLE II
INVENTORY OF THE LIN INTERFACE TEST CIRCUIT

Circuits parts	Total Number
nodes	365
transistor	253
capacitor	132
delay	24
diodes	124
jfet	15
resistor	156
vcvs	4

In order to test the proposed framework, full signal path from transmit pin RxD to receive pin TxD is modeled. In order to obtain the training data, a frequency modulated (FM) sinusoid is applied to the transmit pin with maximum frequency of f = 100 kHz. For the validation and test data set, a digital signal was applied with frequency f = 10 kHz. The rise and fall time in the validation set is equal to 15 µs, while in testing data set it is equal to 10 µs. The frequencies and shapes of the validation and testing data sets can be considered as standard operation mode of the LIN interface [31]. The training data interval lasts for 100 µs, the same as validation and testing interval. The model is in this case based on SPICE simulations (in Cadence Spectre). The receive pin RxD is loaded with resistor R = 106 Ω and capacitor C = 1 pF which are varied by 10% with frequency f = 0.1 MHz. By using variable loads, more cases are covered in less time.

The proposed model consists of two stages:
- input stage for the input stage, and for this particular case, ANN are chosen as the universal approximation method.
- output stage approximation of the output stage. This stage deals with the load of the circuits, decreases the complexity that first stage has to "learn". Preliminary tests show that this output stage increases stability and robustness of the full model.

The proposed model is presented in Figure 4. The voltage VIN is the voltage at the TxD pin. The inputs of the ANN are the voltage VIN (t) and its delayed variants VIN (t), VIN (t − 0.1us), VIN (t − 0.2us), VIN (t − 0.3us), VIN (t−0.4us), VIN (t−0.5us), VIN (t−1us), VIN (t−1.5us), VIN (t− 2us), VIN (t− 2.5us), VIN (t− 3us), VIN (t−3.5us), VIN (t− 4us), VIN (t− 4.5us), VIN (t− 5us), VIN (t− 5.5us), VIN (t− 6us), VIN (t− 6.5us), VI N (t− 7us), VIN (t− 7.5us), VIN (t− 8us), VIN (t− 8.5us), VIN (t− 9us), VIN (t− 9.5us), VIN (t− 10us). The output of the ANN is the voltage VCONT ROL, the control (input) voltage of the output stage.

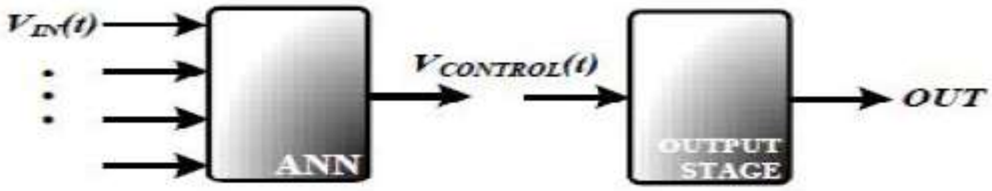

Fig. 4. Basic topology of the proposed model.

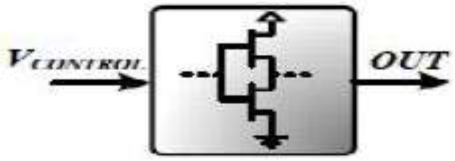

Fig. 5. Output stage consisting of two transistors.

Figure 5 shows the two-transistor output stage. Parameters of the transistors are optimized.

The first problem is how to extract signal VCONT ROL that drives the output stage without knowing the actual schematics (i.e. in blackbox way). The proposed solution is to generate the control voltage.

VCONT ROL(t) = 3.3 − VOUT (t − tDELAY), (1)
Where tDELAY is the parameter which value is optimized among the values of two transistors in Figure 5.

The figure 6 shows the preliminary modeling results of the LIN interface transmit-to-receive path (pin TxD to pin RxD). The figure shows the voltage at the RxD (receiver) pin of the LIN interface. The blue line is the result of the SPICE simulations and the dotted red line the result of proposed model simulation. The proposed model is about ten times faster than the time-domain simulation.

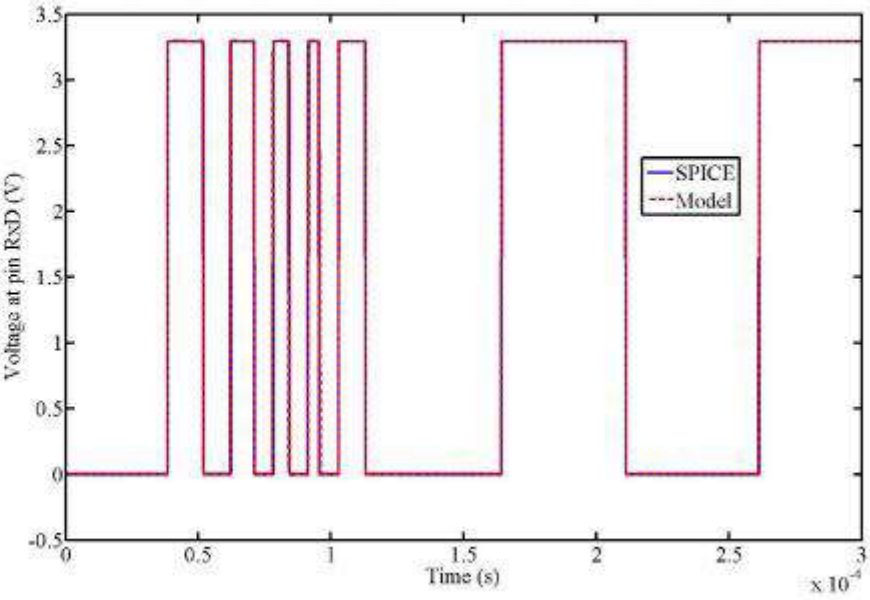

Fig 6: The voltage at the RxD (receiver) pin of the LIN interface

V. CONCLUSION

In this work, an overview of the state-of-the-art in behavioral modeling of integrated circuits is given together with pointers were future research should go. One of the goals is that all models built from proposed behavioral modeling procedures should be effectively implementable in common simulation tools. This goal has proven to be an extraordinary challenge. The preliminary modeling results are promising and show that a medium complex circuit can be efficiently replaced by faster blackbox based behavioral model within the standard integrated circuit simulator.

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