Implementation of Behavioral Models in System level environements and RF circuit-system Co-simulation

A. Bennadji, E. Ngoya, R. Quéré.

Abstract— **The verification of the system performances becomes of prime importance and notably with the emergence of the soc, in which, the spurious couplings between the functional circuits can be critical. the needs in terms of system simulation tools become thus very important. This paper is divided into two parts, the first part presents a method to implement the volterra and nonlinear impulse response models in matlab/simulink environment. The second part presents a co-simulation interface between Matlab/Simulink and Goldengate (Agilent Technologie) circuit simulator.**

Index Terms— **System simulation environment, Volterra Model, Nonlinear impulse response.**

I. Introduction

The applications of modern wireless communications require the reduction of the cost and the time of the design process in order to answer to the demand of the commercial marketplace. If nowadays, the top-down process is suitable, the verification of the full system performances suffers from a lack of system simulation tools able to predict the nonlinear effects. The accuracy of the simulations of communication systems and nonlinear circuits is in general dependent on the availability of models able to describe the behavior of the different components with a high level of precision. These models must be able to predict the influence of nonlinear effects (saturation, memory effects, mismatches phenomena and noise). Moreover, they must be associated to simulation algorithms able to handle the information contained in these models. These two points are nowadays an important research subject in order to calculate reliable link budgets.

In this context, this paper presents a methodology for the implementation of the models based on nonlinear convolution integrals in system environment. These models have proven to be accurate for all types of signals and their extraction is affordable in common circuit simulators and measurement benches.

In an effort to improve modeling accuracy, we have developed a co-simulation interface that allows the system simulator to access a circuit simulator for each time sample. In our example we have considered co-simulation between Matlab/Simulink and Goldengate (Agilent technologie) circuit simulator.

The paper is structured as follows, in a first section, we will briefly present the numerical implementation of Volterra and nonlinear impulse model in system-level environment. The section III describes the numerical implementation of these models in Matlab/Simulink environment. The co-simulation interface between system simulator and circuit simulator is described in section IV. Some practical results will be presented in section V.

II. Nummerical Implementation of Volterra Model and Nonleaner Impulse Response Model

Some works have been reported in last years about several modeling approaches based on Volterra-Wiener theory [1-5], on nonlinear time series [6] or on empirical structures. In particular, behavioral models based on Volterra series showed their excellent capacities to reproduce the effects of short-term memory (Volterra model) [7] and long-term memory (nonlinear impulse response model) [8]. The constitutive equations of these two models are expressed respectively as follows (1) and (2) :

$$\tilde{Y}(t) = \frac{1}{2\pi}.\int_{-BW/2}^{BW/2} H_V\left(\left|\tilde{X}(t)\right|,\Omega\right).\tilde{X}(\Omega).e^{j\Omega t}.d\Omega \quad (1)$$

$$\tilde{Y}(t) = \int_{0}^{Tm} h_R\left\{\left|\tilde{X}(t-\tau)\right|,\tau\right\}.\tilde{X}(t-\tau).d\tau \quad (2)$$

Where $\tilde{X}(t)$ and $\tilde{Y}(t)$ refer to the complex envelope representation of the band pass input and output signals. *BW* is the signal bandwidth, $H_V(\cdots)$ is the Volterra kernel and $h_R(\cdots)$ is the impulse response.

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The computation of the integrals in Eq. (1) and Eq (2) can't be based on the classical integration formulas like Newton-Côtes formulas. Indeed, the use of such techniques can lead to a large consumption of CPU time and memory resources. The basic idea, to circumvent this problem, is to expand the impulse response $h_R(\cdots)$ and the Volterra kernel $H_V(\cdots)$ in series of functions, like below:

$$H_V\left\{\left|\tilde{X}(t)\right|,\Omega\right\}=\sum_{k=0}^{K}\alpha_k(\Omega).f_k\left(\left|\tilde{X}(t)\right|\right) \qquad (3)$$

$$h_R\left\{\left|\tilde{X}(\lambda)\right|,t\right\}=\sum_{k=0}^{K}\beta_k(t).f_k\left(\left|\tilde{X}(\lambda)\right|\right) \qquad (4)$$

Where $f_k(\cdots)$ are well chosen basis function, we have chosen in our example the simplest case of $f_k(\cdots)=|X|^{2.k}$.

Inserting (3) into (1) and (4) into (2), we find respectively the expression (5) and (6).

$$\tilde{Y}(t)=\frac{1}{2.\pi}\sum_{k=0}^{K}\cdot f_k\left\{\left|\tilde{X}(t)\right|\right\}\cdot\int_{-BW/2}^{+BW/2}\alpha_k(\Omega).\tilde{X}(\Omega).e^{j.\Omega.t}.d\tau \qquad (5)$$

$$\tilde{Y}(t)=\sum_{k=0}^{K}\int_{0}^{Tm}\beta_k(\tau).f_k\left\{\left|\tilde{X}(t-\tau)\right|\right\}.\tilde{X}(t-\tau).d\tau \qquad (6)$$

The figure 1 and 2 illustrate respectively the representation of the Volterra model and the nonlinear impulse response model. The models' structures become basic cells called Wiener (linear filters $\alpha_i(\cdots)$ follow-up by static nonlinearity $f_i(\cdots)$) or Hammerstein (static nonlinearity $f_i(\cdots)$ follow-up by linear filters $\beta_i(\cdots)$).

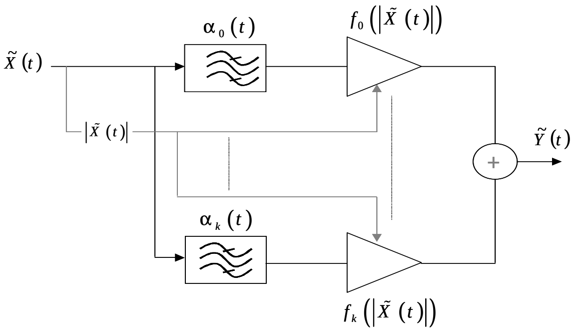

Fig. 1. Volterra model.

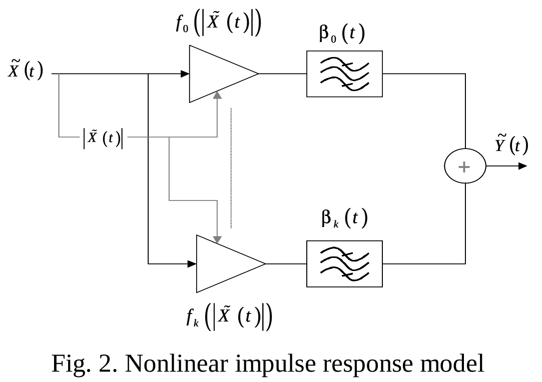

Fig. 2. Nonlinear impulse response model

The coefficients of the linear filters are synthesized by the Padé approximation [9].

III. SIMULINK IMPLEMENTATION

Simulink is a graphical extension to MATLAB for modeling, simulating, and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two [10].

The Volterra and nonlinear response impulse models are written in C++ language and are then interfaced using the Simulink C MEX S-Function [11].

The figure 3 shows the flowchart which recalls the advance of our principle of modeling. We have developed two data processing modules; a module which carries out the calculation of the filters' coefficients and a module which carries out the execution of the model in Simulink.

The files resulting from measurement or simulation must have a standard format (.dat). They contain all information of the extracted data of the model (Volterra or nonlinear impulse response). Following data processing with the extraction module, the model is completely defined by a header file (.head) containing information on the linear filters. During simulation, the execution module reads these header files.

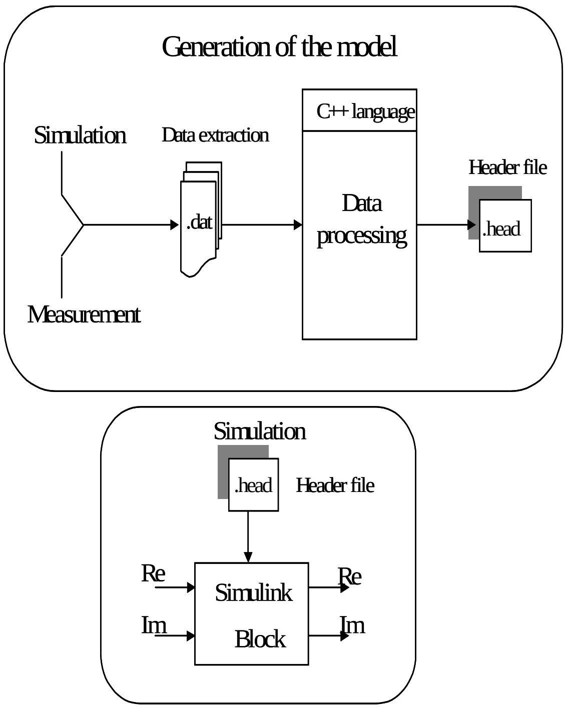

Fig. 3. Principle of modeling.

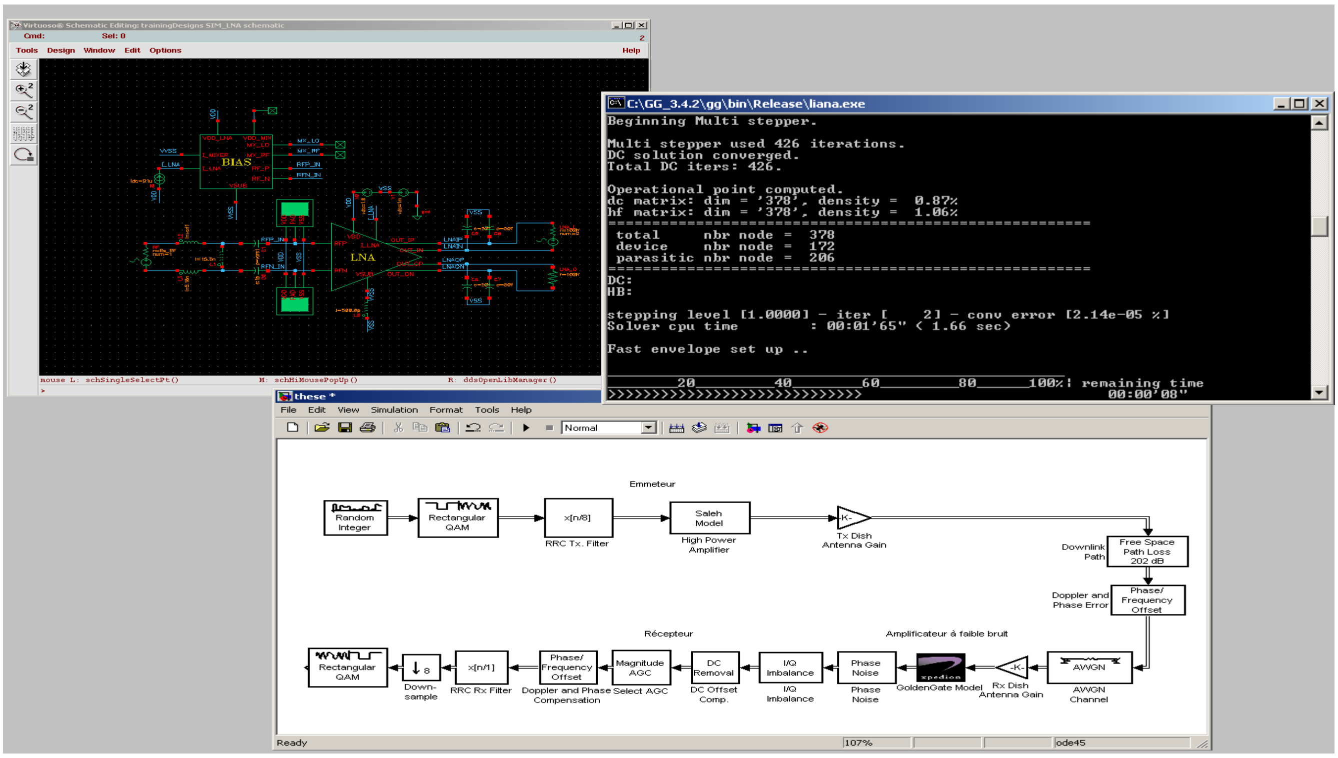

Fig. 4. Communication Chain (Satellite Link)

In co-simulation, the system simulator instantiates an or several Envelope Transient [12] circuit engines to compute the output signals of the critical parts of the system. The interface between the two simulators is based on a parent/child interaction (figure 5). Simulink acts as the parent simulator, which calls GoldenGate (Agilent technologie) at the beginning of the simulation as its child. The co-simulated amplifier block is instantiated into Simulink model thanks to a bloc based on a C MEX S-Function, during the simulation, the two simulation kernels are synchronized and share data on their I/O. On the Simulink side, a special S-Function block acts as the coupling element and it is configured for shared memory communication between Simulink and GoldenGat (Agilent technologie), running on a single computerNumber equations consecutively with equation numbers in parentheses flush with the right margin, as in (1). First use the equation editor to create the equation.

We have run a Simulink simulation using alternatively the models presented above and the co-simulation interface for a satellite communication chain. This chain represents a satellite link composed by a Satellite Downlink Transmitter, Downlink Path, and Ground Station Downlink Receiver (figure 4). The signal transmitted over the channel is 16-QAM waveform flows with speed of 5 Mbits/s, the carrier frequency of the link equal to 8 GHz. The Volterra kernel and the impulse response of the LNA (operating at 1.96 GHz) located after the reception antenna were extracted from GoldenGate™ simulations.

Figure 6 shows the ACPR comparison between the AM/AM AM/PM, Volterra and response impulse models with the results obtained from a co-simulation. The agreement between the response impulse model and the co-simulation is fairly good, the AM/AM AM/PM and the Volterra models give predictions that are 4 to 7 dB off. This figure shows also that the Volterra model dedicated to take into account short term memory effects is not able to predict accurately the ACPR, because, in this case the QAM signal is stimulating mainly long term memory effects.

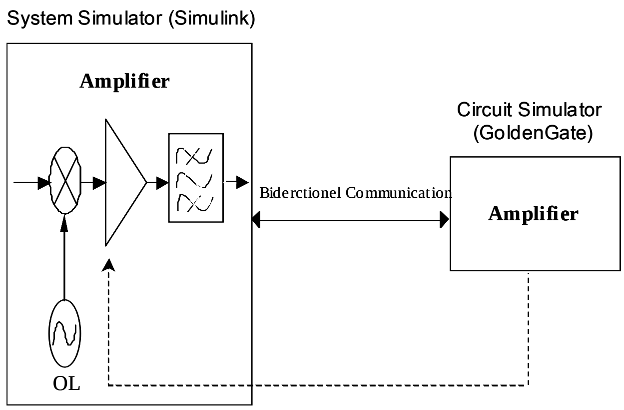

Fig. 5. Co-simulation principle

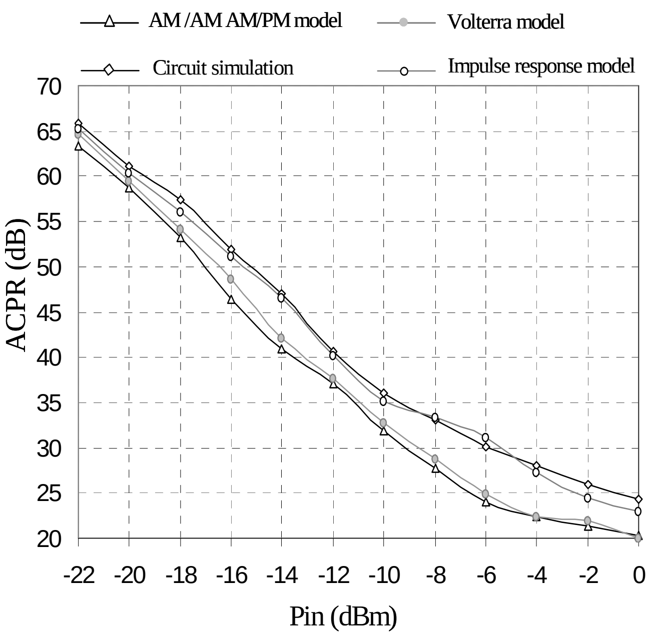

Fig. 6. ACPR=f(Pin) 16-QAM @ 5 Mbits/s.

The simulation performances (CPU) are summarized in table 1. We observe that using the Volterra and nonlinear impulse response models has reduced the CPU time. The performance of nonlinear impulse response model shows a simulation speed up without sacrificing accuracy.

Complete chain simulation time	Co-simulation	AM/AM AM/PM model
	1 h.12 min	14 sec
	Volterra model	Nonlinear impulse model
	2 min. 18 sec	2 min. 23 sec

Table. 1. Simulation performances.

We have shown that nonlinear convolution integral based model can be efficiently implemented in system simulators, guarantying both simulation speed and higher accuracy. Combining a DSP behavioral Simulink simulator in a cosimulation environment with a time domain nonlinear circuit simulator in the complex envelope domain increases simulation flexibility and improves accuracy

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