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# Implementation of Behavioral Models for Amplifiers in System Level Simulation and RF Circuit-System Co-Simulation

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***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.

Recently, the model order reduction techniques (MOR) [1-4] received a significant attention by the circuits CAD communities. These techniques have found a first application in the issue of the simulation of the interconnects in the high speed digital communications. Unfortunately, these techniques based on projection methods like Krylov subspace projection, are nowadays only applicable to weakly-nonlinear systems (such as classical Volterra series or polynomial expansion methods).

Behavioral models are a convenient means to predict system level performances without the computational complexity of full circuit model simulation. The "black-box" modeling consists to simplify the description of the different circuits, and more precisely to identify the input/output functional, keeping in mind the fact that this identification must not cause a too large loss of information about the internal dynamic and the fundamental nonlinear effects.

Some works have been reported in last years about several modeling approaches based on Volterra-Wiener theory [5-8], on nonlinear time series [9] or on empirical structures. In particular, behavioral models based on Volterra series showed their excellent capacities to reproduce the effects of short-term memory (one Volterra kernel model) [10] and long-term memory (nonlinear impulse response model) [11].

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. Section II provides a brief overview of nonlinear memory effects in the amplifiers. In the third section, we will briefly present the one Volterra kernel model and nonlinear impulse response model. We will present in the section IV, the numerical implementation of Volterra and nonlinear impulse model in system-level environment. The section V 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 VI. Some practical results will be presented in section VII.

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## II. MEMORY EFFECTS STUDY

This section is dedicated to the presentation of nonlinear memory effects involved in the amplifiers. Memory effects are defined as changes in the amplitude and phase of distortion response components according to the excitation signal speed. It is well known that most RF and microwave amplifiers hold two basic nonlinear dynamics with widely separated time constants, Short-Term Memory (STM) effects (also designated as high-frequency memory) and Long-Term Memory (LTM) effects (also designated as low-frequency memory).
Figure 1 illustrates the origins of the two memory mechanisms in an integrated circuit structure.

The STM effects can arise from short time constants, usually lower than a nanosecond, related to the microwave cutoff frequency of transistors and group delay in matching network and filters. This kind of memory can be visualized by driving the circuit with a single tone (sinusoid) signal. The LTM effects can arise from large time constants of the order a fraction of microsecond and more, related to the bias network [6], the presence of traps in the semiconductor material [7] or from electrothermal coupling [8]. It is possible to visualize the LTM effects only with a multi-tone, typically a two-tone excitation. STM and LTM phenomena are tightly coupled.

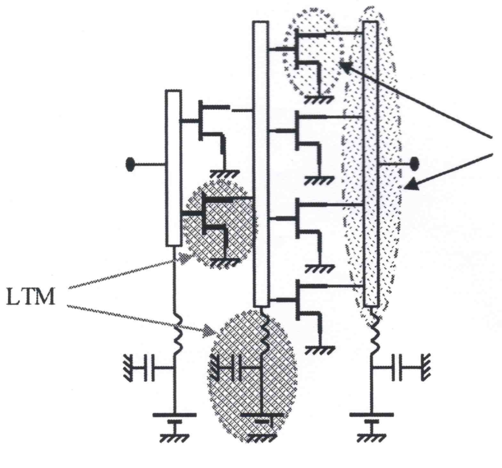


Fig. 1. Memory effects in integrated circuits

## III. VOLTERRA AND NONLINEAR IMPULSE RESPONSE MODELS

At system level low pass equivalent signals are used and real signals are replaced by associated input/output complex envelopes $\tilde{X}(t)$ and $\tilde{Y}(t)$ (Fig 2).

$$x(t) = \Re e\left[\tilde{X}(t)e^{j\omega_0 t}\right] \qquad y(t) = \Re e\left[\tilde{Y}(t)e^{j\omega_0 t}\right]$$

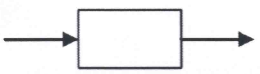

Fig. 2. Nonlinear system with memory

### A. *One Volterra kernel Model principal*

As formerly described in [10] the output of a nonlinear system with short-term memory (STM) could be expressed with sufficient accuracy as the first order development as following:

$$\tilde{Y}(t) = Y_{dc}\left(\left|\tilde{X}(t)\right|\right)e^{j\phi_{x(t)}} + \frac{1}{2\pi}\cdot\int_{-BW/2}^{BW/2} H_{ST}\left(\left|\tilde{X}(t)\right|,\Omega\right).\tilde{X}(\Omega).e^{j\Omega t}.d\Omega \qquad (1)$$

where : $BW$ is the modulation bandwidth, $\tilde{X}(\Omega)$ the spectrum of input signal.
$Y_{dc}\left(\left|\tilde{X}(t)\right|\right)e^{j\phi_{x(t)}}$ represents the purely static response of the system : this is the response calculated with Memoryless Model. $H_{ST}\left(\left|\tilde{X}(t)\right|,\Omega\right)$ is the Volterra Kernel accounting for nonlinear short-term memory effects, expressing the distance from the real response to the purely static one (without memory).
Measurement of static part of the model $Y_{dc}\left(\left|\tilde{X}(t)\right|\right)$ is easily done with classical AM/AM and AM/PM measurements performed on a nonlinear vector network analyzer at the center frequency $\omega_0$ of amplifier, with an input swept-power.

Nonlinear transfer function $H_{ST}$ is unambiguously extracted, by driving the amplifier with a single tone signal $\tilde{X}(t) = X_0 e^{j\Omega_0 t}$,

as the ratio $\hat{H}_{ST}\left(\left|\hat{X}_0\right|,\Omega_0\right) = \dfrac{\hat{Y}_0}{\hat{X}_0}$.

This is illustrated in Figure 3.

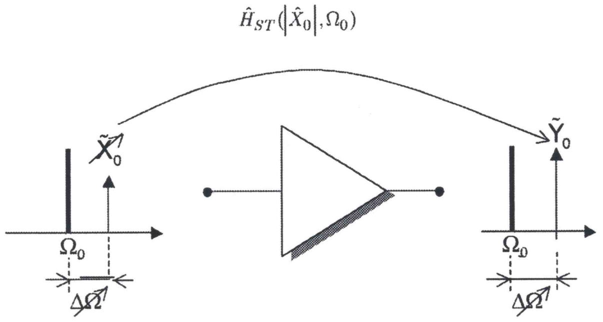


Fig. 3. One Volterra kernel extraction set-up

### B. *Nonlinear Impulse response model principal*

As described in the original work [11], the nonlinear impulse response model equation is expressed as follows:

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

Where $\tilde{X}(t)$ and $\tilde{Y}(t)$ refer to the complex envelope representation of the band pass input and output signals. $T_m$ is the memory duration, $h_{LT}(\cdots)$ is the nonlinear impulse response.

The observation of equation (2) shows that the nonlinear impulse response can be obtained by driving the system with a unit step function $x(t)=\left[X_0.U(t)e^{j(\omega_0+\Omega)t}\right]$, where $\omega_0$ (reference frequency) will be set to the center frequency of the system bandwidth as depicted in figure 4.

The nonlinear impulse response $h_{LT}(\cdots)$ can thus be readily obtained considering the time derivative of the device response to a step function excitation. The magnitude $X_0$ and the carrier $\Omega$ of the step function are swept to cover the system input power range and frequency bandwidth. The memory duration $T_m$ will correspond on the time for which the response to the step function reaches steady state, all over the input power range and frequency bandwidth.

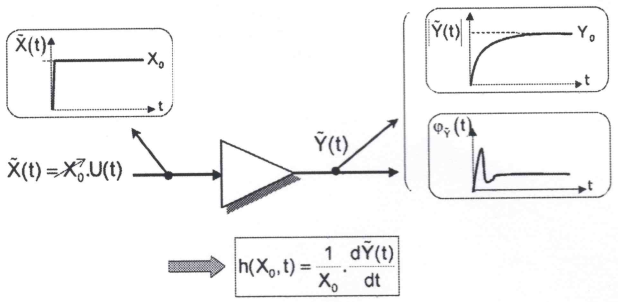


Fig. 4. Impulse Response Extraction Principle

This type of impulse characterization is nowadays easily carried out using envelope transient analysis, available in commercial CAD tools.

## IV. Numerical Implementation of Volterra Model and Nonlinear Impulse Model

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 $H_{ST}(\cdots)$ and the Volterra kernel in $h_{LT}(\cdots)$ series of functions, like below:

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

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

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

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

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

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

The figure 5 and 6 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 $\beta_i(\cdots)$).

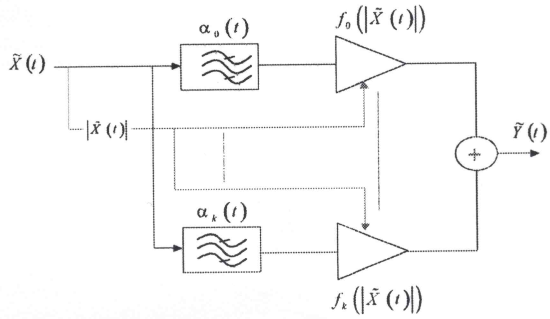


Fig. 5. One kernel Volterra model

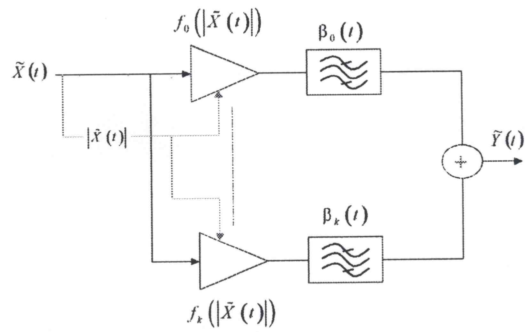


Fig. 6. Nonlinear impulse response model

The coefficients of the linear filters are synthesized by the Padé approximation [12].

## V. 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 [13].

The Volterra and nonlinear response impulse models are written in C++ language and are then interfaced using the Simulink C MEX S-Function [14].

The figure 7 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 (one Volterra kernel or nonlinear impulse response). Following data processing with the extraction module, the model is completely defined by header file (.head) containing information on the linear filters. During simulation, the execution module reads these header files.

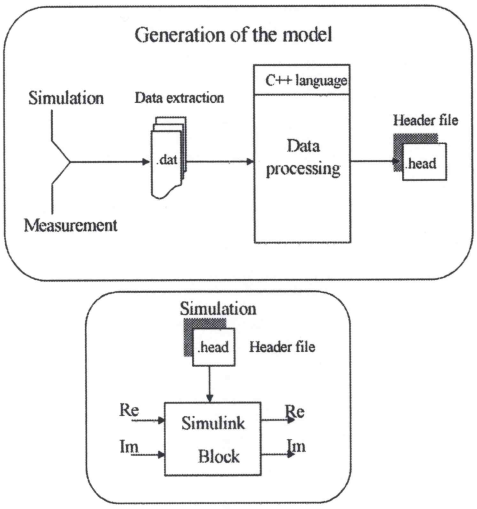


Fig. 7. Principle of modeling.

## VI. CO-SIMULATION PRINCIPAL

In co-simulation, the system simulator instantiates an or several Envelope Transient [15] 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 8). 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 GoldenGate (Agilent technologie), running on a single computer.

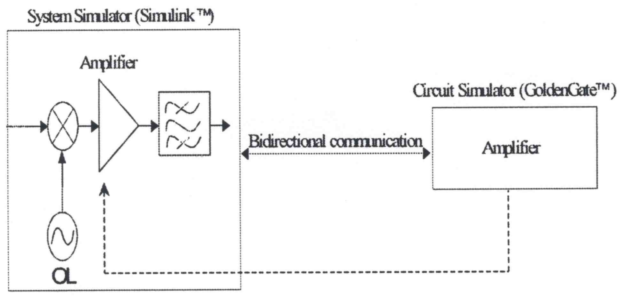


Fig. 8. Co-simulation principle

## VII. APPLICATION

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 11). 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 BiCMOS LNA (operating at 1.96 GHz) located after the reception antenna were extracted by Harmonic Balance simulation using the Agilent GoldenGate™ simulator. This amplifier implements a gain control loop responsible for important long term memory.

The gain as function of input power and frequency is showed in figure 9. Compression and wrapping or gain curves indicate the presence of nonlinear short term memory.

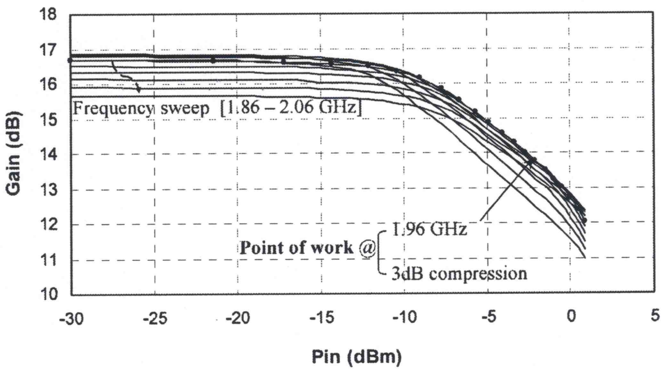


Fig. 9. Amplifier gain compression

This amplifier also exhibits important long term memory that can be observed in C/IM3 asymmetries and deep ringing with varying two-tone spacing, as illustrated in figure 10.

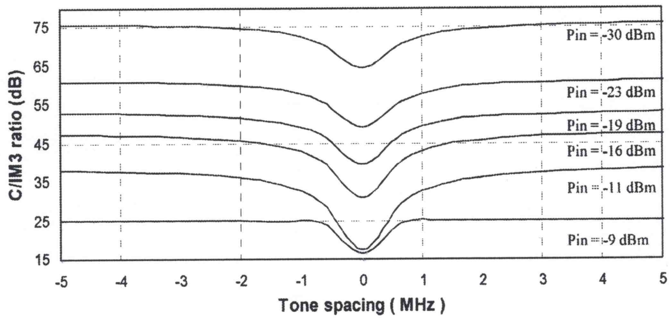


Fig. 10. Two-tone C/IM3 curves versus two-tone frequency spacing for several input powers.

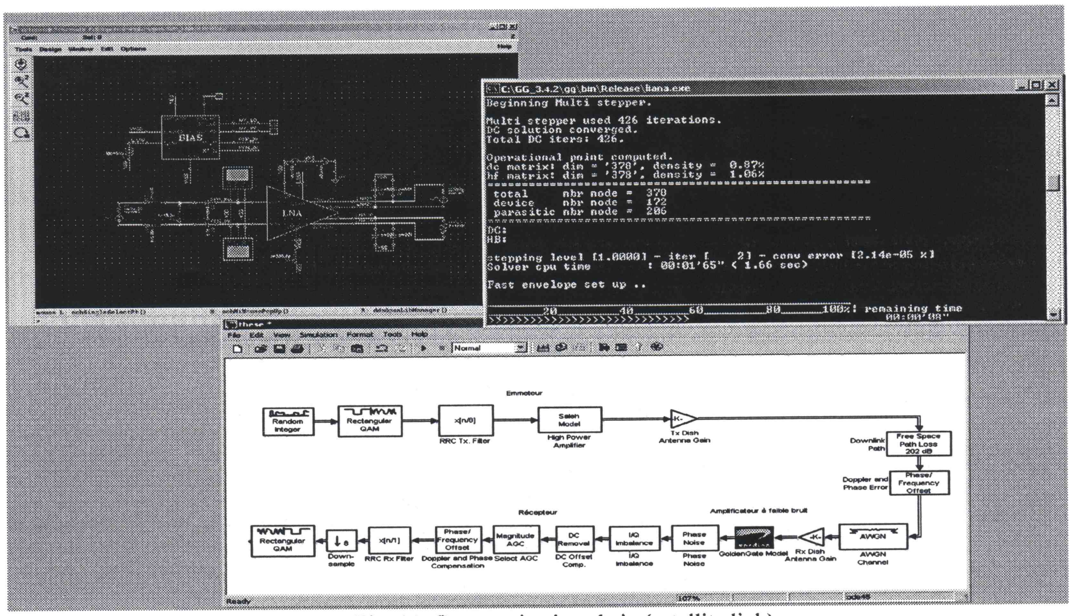

Fig. 11. Communication chain (satellite link)

We have extracted the STM and the LTM kernels by Harmonic Balance. Figure 12 shows the real and the imaginary parts of the STM kernel as a function of frequency ranging from 1.86 to 2.06 GHz and input power ranging from -22 to -2 dBm.

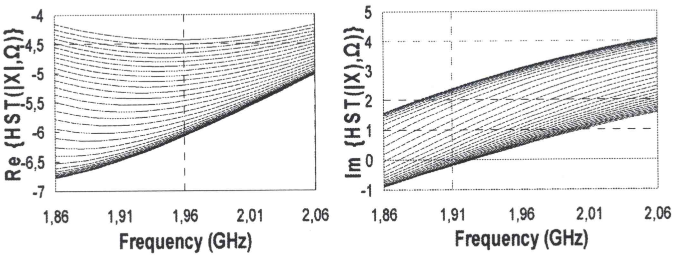


Fig. 12. Extracted STM kernel.

Figure 13 shows the real and the imaginary parts of the extracted LTM kernel as a function of time. We may observe a long transient duration of about 16 μs.

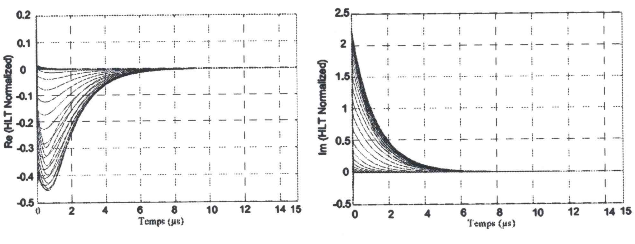


Fig. 13. Extracted LTM kernel

We have then tested the extracted models on a 16-QAM modulated signal with 5 Mbits/s bit rate. Figure 14 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.

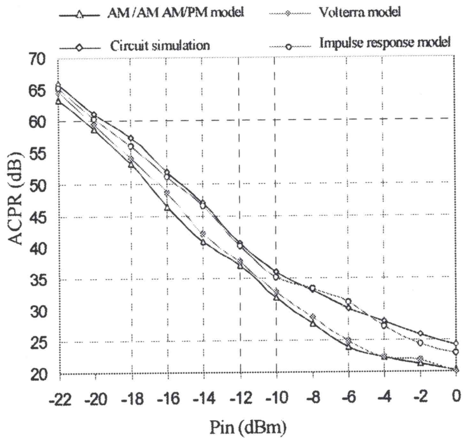


Fig. 14. ACPR=f(Pin) 16-QAM @ 5 Mbits/s.

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.

Table. 1. Simulation performances.

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

Figure 15 compares a sample of the time domain waveform of the output from the behavioral models, and the co-simulation. This figure confirms the excellent accuracy of the nonlinear impulse response model.

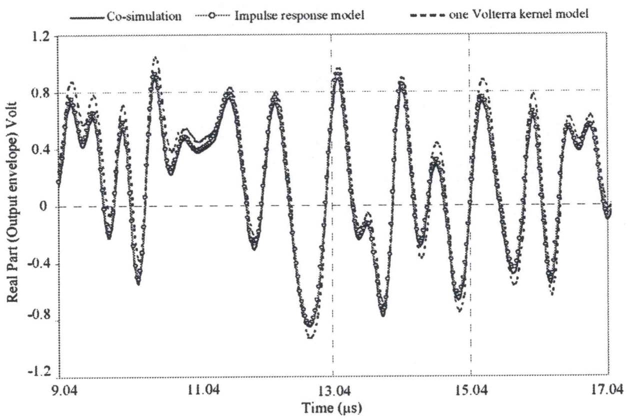


Fig. 15. Time domain waveform output signal with 16-QAM input signal @ Input Power = -3 dBm , Bite Rate = 2 MB/s.

## VIII. CONCLUSION

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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