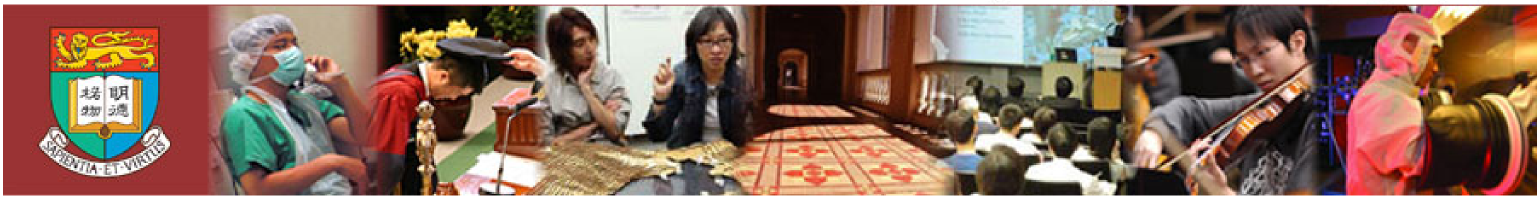

Title	Simulations of pulse signals with X-parameters
Author(s)	Huang, NKH; Jiang, L
Citation	The IEEE 20th Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS 2011), San Jose, CA., 23-26 October 2011. In Proceedings of the IEEE 20th EPEPS, 2011, p. 129-132
Issued Date	2011
URL	http://hdl.handle.net/10722/158768
Rights	IEEE Topical Meeting on Electrical Performance of Electronic Packaging Proceedings. Copyright © IEEE.

Simulations of Pulse Signals with X-Parameters

Nick K. H. Huang and Lijun Jiang
Department of Electrical and Electronic Engineering,
The University of Hong Kong, Pokfulam, Hong Kong
Email: khhuang@eee.hku.hk and jianglj@hku.hk

***Abstract*—Nonlinearity is becoming increasingly important to IC technologies. From the PHD formalism, X-parameter models provide an accurate frequency-domain method under large-signal operating points to characterize their nonlinear behaviors. In this work, X-parameter models are investigated to handle time-domain pulse signals which is critical to IC signal integrity but was not studied before. Two representative circuits, an analog LNA and a digital CMOS buffer, were employed to characterize the X-parameter performance. The results obtained in this paper provide the first hand data for pulse signal responses of X-parameters in signal integrity modelings.**

***Index Terms*—Nonlinearity, polyharmonic distortion, pulse signal, X-parameters.**

I. INTRODUCTION

Over the past decades, the behavioral modeling of IC and RF/microwave circuits became increasingly important [1]. As the operating frequencies and bandwidth continue to rise in modern technologies, most devices exhibit nonlinear behaviors. This fact causes a surge demand for powerful nonlinear simulation and measurement techniques to characterize, describe mathematically, and validate the efficient numerical solutions to RF/microwave and IC components. S-parameter is the network parameter that has been used widely in signal integrity and RF/microwave frequency domain. But it has been limited to small signals and linear behaviors. X-parameter concept was developed by Root and Wood [1], [2]. Mathematically it can be treated as an nonlinear extension of S-parameters to large signal conditions for analyzing the nonlinear behavior in a robust manner. It was first introduced from polyharmonic distortion (PHD) modeling [2], [3]. According to it, the construction of nonlinear electronic systems could be implemented through a framework.

Responses of X-parameter models to single or several continuous waves (CW) have been properly discussed [4]. In this paper, we investigate the X-parameter model response to pulse signals, which was never studied before. It is an interesting issue because it explores the possibility of using X-parameters for the characterization of digital circuits. It has deeper impact since digital circuits such as ICs have broader applications.

The remainder of this paper is organized as follows. The PHD models represented along with X-parameters are described first. Next, the methodologies of building X-parameter models and processing pulse signals for X-parameter simulations are introduced. Then, simulation studies using the representative analogy LNA and the digital CMOS buffer are presented to discuss the performance of X-parameter models for pulse signals in signal integrity.

II. PHD AND X-PARAMETER FORMULATION

The basic concept of X-parameters is proposed on the PHD model, which is based on the principle of harmonic superposition. In this section, the PHD and X-parameter formalisms are to be discussed.

A. PHD

One of the first papers introducing PHD behavioral models can be found in [2]. PHD framework is a black-box, frequency-domain modeling techniques. The annotation *black-box* indicates all needed information is acquired externally to make it technology independent [3]. The PHD modeling approach can be considered as an nonlinear extension of S-parameters under large signal conditions.

$$B_{pk}(|A_{11}|, f) = \sum_{q} \sum_{l=1,\ldots,M} S_{pq,kl}(|A_{11}|, f) \cdot P^{k-l} \cdot A_{ql} + \sum_{q} \sum_{l=1,\ldots,M} T_{pq,kl}(|A_{11}|, f) \cdot P^{k+l} \cdot A_{ql}^{*} \tag{1}$$

$$T_{p1,k1} = 0 \tag{2}$$

$$P = e^{jArg(A_{11})} \tag{3}$$

where A_{ql} is the l^{th} harmonic of the incident wave into port q and B_{pk} is the k^{th} harmonic of the scattered wave at port p. $S_{pq,kl}$ is a S-type scattering parameter that accounts for the contribution to the k^{th} harmonic at port p due to the l^{th} harmonic of the incident wave in port q. $T_{pq,kl}$ is a T-type scattering parameter that accounts for the contribution to the k^{th} harmonic at port p due to the l^{th} harmonic of the conjugated incident wave in port q. In (3), P is a pure phase that, along with the magnitude-only dependence on A_{11} by convention [2]. The S and T functions describe a full set of parameters to completely characterize the nonlinearities.

B. X-Parameter

A full matrix representation of X-parameters could be found in [4]. It is shown that not only harmonics and ports but also real and imaginary components must be separated in an X-parameter matrix formulation. $X_{pqri}^{(kl)}$ is the contribution to the real part of the k^{th} harmonic of the wave scattered at the

978-1-4244-9401-9/11/$26.00©2011 IEEE

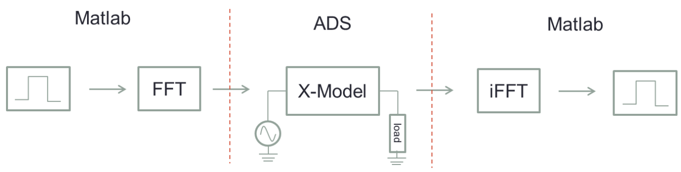

Fig. 1. The X-parameter simulation setup for pulse signals.

p^{th} port due to the imaginary part of the l^{th} harmonic of the incident port at the q^{th} port [4].

III. X-Parameter Simulation Setup

In Agilent ADS, the X-parameter models are generated by using the ADS X-parameter generator. Then the resultant X-parameter model can be used with other circuit components to perform the X-parameter model simulation.

Since the X-parameter model in ADS only works with power input sources, it is difficult to input the pulse signal into the model. To overcome this issue, we input a pulse signal generated in a Matlab program. Then the Fourier Transform is employed to extract the frequency domain harmonics of the pulse signal. Then, a sequence of power input sources, based on the spectral components of the pulse signal in the unit of either W or dBm, are generated along with phases in ADS.

The simulation comparisons between the X-parameter models and the direct circuits were studied. Next, the output data in frequency domain was sent to a simulation program which does the Inverse Fourier Transform to recover the time domain data for comparison. Fig. 1 displays the X-parameter simulation setup for pulse signals.

IV. Results with LNA and CMOS

In order to find out the performance of X-parameter models for pulse signals, simulations were performed with two cases: an LNA and a CMOS buffer. The results are shown as follows.

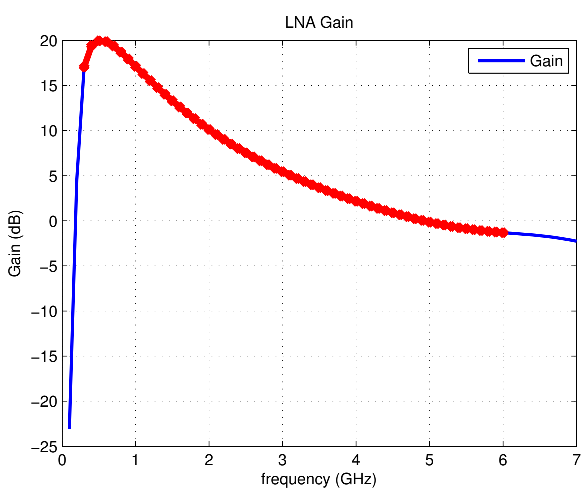

Fig. 2. The gain of LNA.

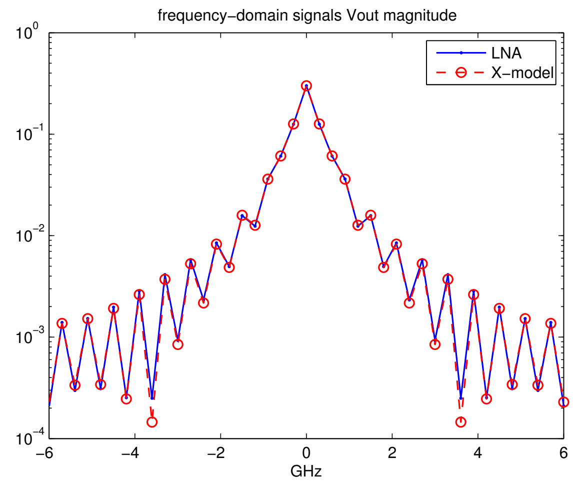

Fig. 3. LNA output magnitude in the frequency domain.

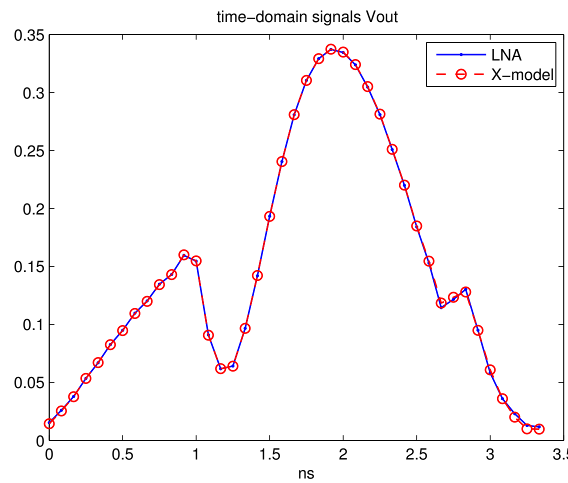

Fig. 4. LNA output signal in the time domain.

A. LNA

LNA is a representative analog device primarily working in its linear region to amplify weak signals. Because of limited bandwidth of LNA, when a pulse signal is used as the input, the high order harmonics of the input signal will suffer sharp drops through LNA. Hence, non-linear effects are expected when the pulse signal is the applied.

The amplifier schematic used in this work was from the example directory of *ADS 2009 Update 1*. Its X-parameter model is generated with the ADS X-parameter generator. An X-parameter data file is created and used in X-parameter model simulations with the comparable setups as that for direct LNA simulations. The comparison results of both circuits with 20 harmonics have been investigated.

The input is a 70-mV pulse signal as the saturation limit of LNA input and output occurs beyond 70 mV. Fig. 2 shows the LNA gain vs frequency. The highlighted portion from 0.3 GHz to 6 GHz is chosen for the reasonable gain range. Fig. 3 shows the output magnitudes of both direct LNA and X-parameter models. The solid line represents the direct LNA result, and the dash line with circle points is the result using the X-parameter model. Fig. 4 reveals the Inverse Fourier Transform of Fig. 3 in the time domain. It is obvious to see that both simulations match correspondingly well.

The reason for the distorted output from the pulse input signal is due to the limited bandwidth of the LNA. Its gain at higher frequencies (such as above 5 GHz) becomes relatively small, which distorts the signal.

B. CMOS Buffer

The CMOS buffer, used in this work, is constructed with a couple of identical CMOS inverters in 0.8 μm technology. To validate the buffer, one fundamental frequency in the Harmonic Balance simulator was first performed.

The generation of the X-parameter model for the CMOS buffer follows the same procedure as described before. The input pulse signal and its spectral components are shown in Fig. 5 for both time and frequency domains. The pulse signal is designed to have a 5-Volt amplitude and the sampling rate is $40/ns$. The average magnitude DC point is observed at 2.5 voltages.

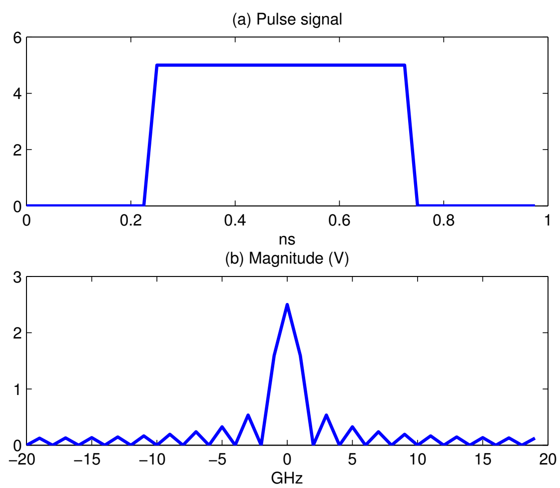

Fig. 5. Input pulse signal in (a) the time-domain and (b) the frequency domain.

A 1-GHz large signal was first used to excite the CMOS buffer at the fundamental frequency. Small signal tones are then sent to the input port at the harmonic frequencies of the fundamental. X-parameter models are defined according to the different combinations of excitation at the input port. Next, the results with selected harmonic numbers (1, 3, 5, 10, and 20) of harmonics for comparison between the direct buffer and the X-parameter model from Fig. 6 to Fig. 10, respectively.

The ADS X-parameter generation only works with AC simulations. As a consequence, simulating DC condition separately is needed to complete a full simulation. Then both X-parameter model and the DC component are combined to make it comparable with the original circuit.

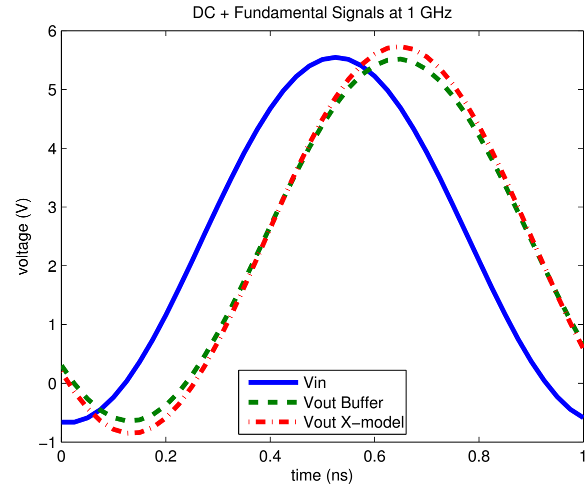

Fig. 6. DC + Fundamental signals at 1 GHz.

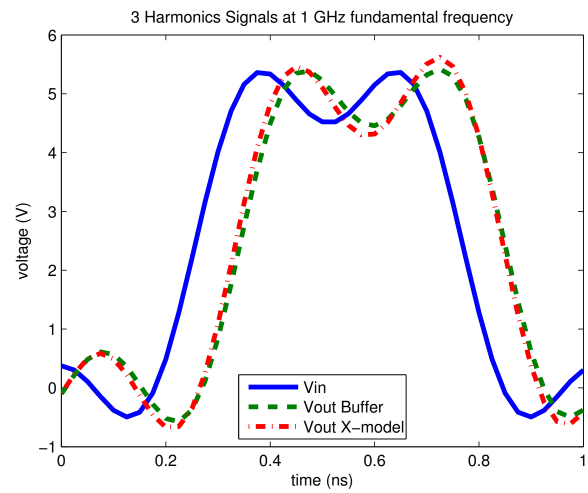

Fig. 7. 3 Harmonics signals with 1 GHz fundamental frequency.

Fig. 6 shows the DC and 1-GHz fundamental frequency results of the buffer. As more harmonic frequencies are added, the outputs of the pulse signals have the ringing artifacts due to Gibbs phenomenon in signal processing for the buffer circuit. When the number of harmonics rises, the error of approximation is reduced in width and energy (amplitude). A convergence to a fixed height is also observed in Fig. 10.

As observed in the X-parameter results, there is an undesired short pulse, or referred as *glitch*, on the output signal when it switches to the high state in Fig. 10. Its reason might be that transistors in X-parameter models are not fast enough when switched on and along with another cause of ringing oscillations in square waves. However, another case with 0.1-GHz fundamental frequency and 20 harmonics shows the correlation without a certain delay and a glitch effect (see Fig. 11).

In spite of the Gibbs ringing phenomenon and the glitch, the X-parameters models (the dash-dot lines from Fig. 6 to

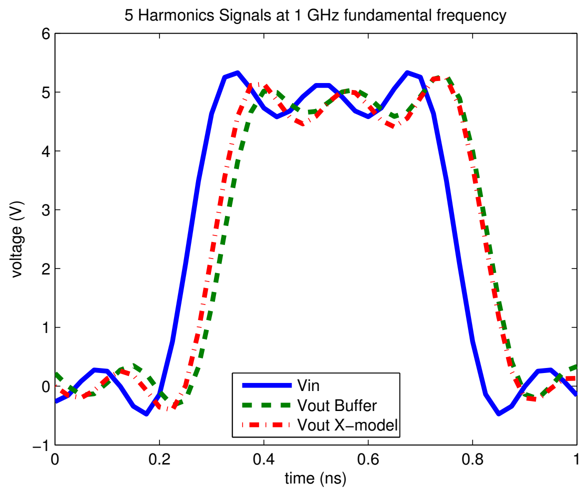

Fig. 8. 5 Harmonics signals with 1 GHz fundamental frequency.

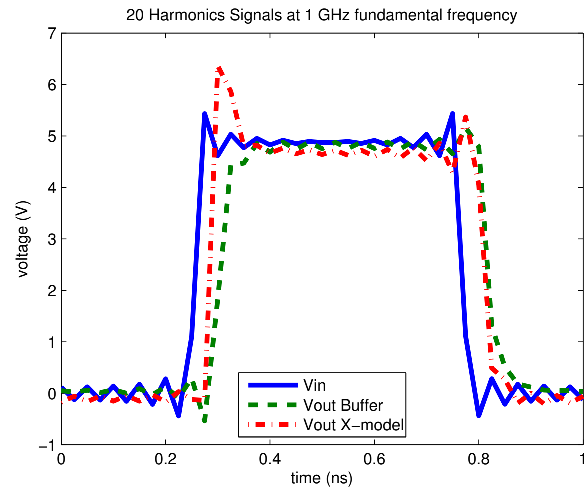

Fig. 10. 20 Harmonics signals with 1 GHz fundamental frequency.

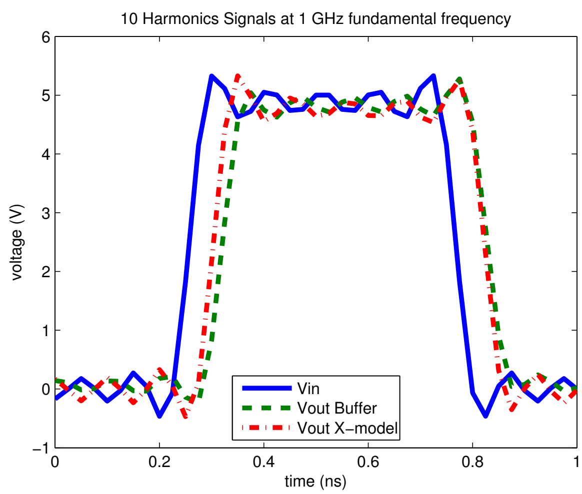

Fig. 9. 10 Harmonics signals with 1 GHz fundamental frequency.

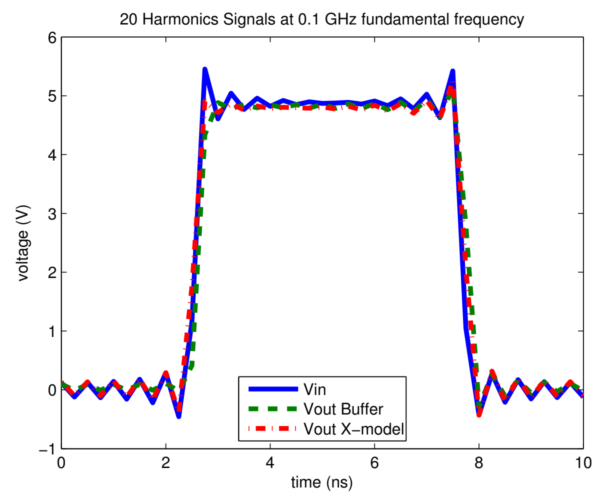

Fig. 11. 20 Harmonics signals with 0.1 GHz fundamental frequency.

Fig. 10) showed reasonable results compared with the standard ADS simulator results (the dash lines) under a CMOS buffer. Hence a further investigation on CMOS circuits with X-parameters models could be a potential study subject.

V. Conclusion

This paper studied pulse signal responses of X-parameter models. It is interesting to digital circuits but was never addressed before. The benchmarks demonstrated that X-parameters/PHD formulations with the assumption of the harmonic superposition can produce satisfactory results. Compared to direct solving, the X-parameter models can obtain good agreement in the simulated data regarding to the nonlinear property of both analog and digital circuits. Hence, X-parameters could be a novel ways to handle signal integrity issues in IC interconnect and packaging modeling.

Acknowledgment

We would like to thank Professor Jose Schutt-Aine and his student for the help in providing X-parameter models for our comparison studies. This work was supported by the research grant 201007176196 and 201001159006 at the University of Hong Kong.

References

[1] J. Wood and D. E. Root, *Fundamental of Nonlinear Behavioral Modeling for RF and Microwave Design*. Norwood, MA: Artech House, 2005.

[2] D. Root, J. Verspecht, D. Sharrit, J. Wood, and A. Cognata, "Broad-band poly-harmonic distortion (phd) behavioral models from fast automated simulations and large-signal vectorial network measurements," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 53, no. 11, pp. 3656 – 3664, Nov. 2005.

[3] Verspecht and D. Root, "Polyharmonic distortion modeling," *Microwave Magazine, IEEE*, vol. 7, no. 3, pp. 44 –57, June 2006.

[4] J. Schutt-Aine, P. Milosevic, and W. Beyene, "Modeling and simulation of high speed i/o links using x parameters," in *Electrical Performance of Electronic Packaging and Systems (EPEPS), 2010 IEEE 19th Conference on*, Oct. 2010, pp. 29 –32.