VHDL-AMS Models of Millimeter-wave Oscillators for Simulations of System-on-Chip Behavior

M. Kraemer[1,2], D. Dragomirescu[1,2], R. Plana[1,3]

LAAS-CNRS[1], INSA[2], UPS[3]

University of Toulouse, 7 Avenue de Colonel Roche, 31077 Toulouse, France

Email: {mkraemer, daniela, plana}@laas.fr

I. Introduction

For future high-data rate communication systems the ultra-large frequency band around 60 GHz represents a promising alternative to the overcrowded spectra available at lower frequencies [1]. To avoid connection losses and achieve small system size and very low cost, the transceivers will typically be designed as System on Chip (SoC) in a low cost silicon technology or as System in Package (SiP) where sub-micron CMOS technologies with high f_{max} can be combined with high quality antenna arrays.

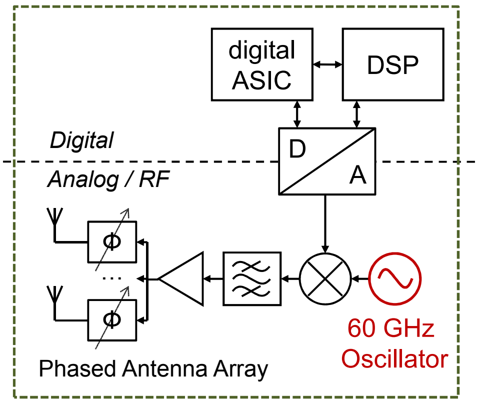

Fig. 1: Simplified block diagram of a single chip 60 GHz Transmitter containing both digital and analog parts.

In Fig. 1 the block diagram of such a receiver working at 60 GHz is presented. It contains both the digital, baseband part of the circuit and the analog part working at millimeter-wave frequencies, connected by an analog-to-digital converter. Note that at 60 GHz due to small size and high directivity of the antennas integrated phased arrays are used.

A current research topic is the behavioral modeling of such entire systems. A hardware description language ideally suited for this task is VHDL-AMS because of its capability to describe analog and mixed signal systems [2]. While for the digital part, the VHDL code used in the design process can be directly employed, for the analog part behavioral models need to be created that are less complex than the circuit level schematics.

Different aspects need to be taken into account when approaching the task of modeling the analog part: At millimeter wave frequencies, coupling between different circuit components becomes a major issue and needs also be taken into account on the system level. The behavior of new technologies employed, for example micro electro-mechanical systems (MEMS) used in the design of the phase shifters, needs to be properly described as well.

While for microwave two-ports like amplifiers, filters or mixers behavioral modeling techniques employing artificial neural networks (ANNs) where presented [3], the technique described in this paper focuses on the oscillator [4].

The novel model takes into account start-up, steady state behavior and phase noise. To describe the nonlinearities, an ANN is employed. The dynamic behavior of the oscillator is described by a system of differential equations that are solved in VHDL-AMS. As opposed to input-output models of microwave devices, the described technique simulates a self sustaining oscillation, which starts from a small injected excitation (e.g. noise) and ends in a stable limit cycle. Additionally, the phase noise characteristics of the oscillator in the $1/f^2$ and flat region are emulated.

II. Model Structure

The present model uses a state space representation to describe the oscillator. While the order of the oscillator circuit equals the nuber of all of its independent energy storages, which can be quite high if all parasictics are taken into account, the order of the model is reduced to $N = 2$, which is sufficient to represent the trajectory of the oscillation in state space.

The state vector of size two can thus be defined as

$$\boldsymbol{x}(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} v(t) \\ \dot{v}(t) \end{bmatrix} \quad (1)$$

with the oscillator voltage and its derivatives as state variables. The state space equation, consisting of the differenital equation with the velocity vector, is represented by

$$\dot{\boldsymbol{x}}(t) = \begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} x_2(t) \\ f\left(x_1(t), x_2(t), u(t)\right) \end{bmatrix}. \quad (2)$$

While the advancement of the system states depend mainly on the former states, the input $u(t)$ is used to inject noise to start the oscillation. If the position in the circuit where this noise is injected is wisely choosen, it can also be used to generate phase noise in the $1/f^2$ region. A second, additive noise source completes the phase noise characteristics reproduced by the VHDL-AMS model.

The function *f( )* in (2) describes the nonlinear behavior of the oscillator. In the model it is generated by a multilayer preceptron neural network [5]. The parameters of this ANN are found by training it with trajectories of the oscillator startup obtained from ciruit level simulations, e.g. done in ADS. Fig. 2 shows the plot of a function produced by such a trained ANN versus a ADS startup trajectory used in the training process. Excellent agreement can be observed.

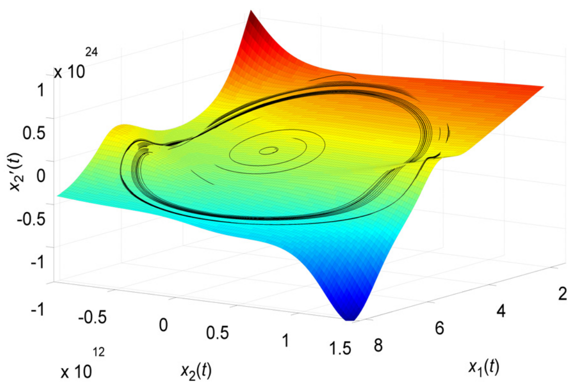

Fig. 2 function *f( )* reproduced by the ANN (plane) versus trajectory of the oscillator used as reference.

To implement the model in VHDL-AMS, the state space equations and the equations constituting the ANN are entered in VHDL-AMS. To represent the derivatives, the `'dot` – directive is used. The unique feature of the SMASH – VHDL-AMS interpreter to specify different tolerances for a quantity and its derivative is essential for the model to work properly.

III. Modeling Results

In Fig. 5 the output waveform achieved by a VHDL-AMS model of a 60 GHz Colpitts oscillator is compared to the original ADS output. The DC operation point of 5.0 V corresponds exactly to the original. The two signals differ in the transient region. The steady state is

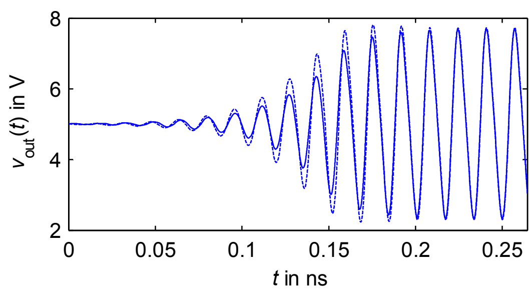

Fig. 5. Solid line: VHDL-AMS response, dashed line: ADS response (original circuit)

reproduced very accurately: The frequency is 61.08 GHz instead of 61.22 GHz in the original circuit and the voltage range is 2.32 V to 7.71 V instead of 2.30 V to 7.73 V.

The phase noise generated by the VHDL-AMS model is shown in Fig. 6. One can clearly distinguish between the flat region and the $1/f^2$ region. The two asymptotes of Fig. 6 can be shifted by adjusting the variances of the two Gaussian noise sources employed in the VHDL-AMS model.

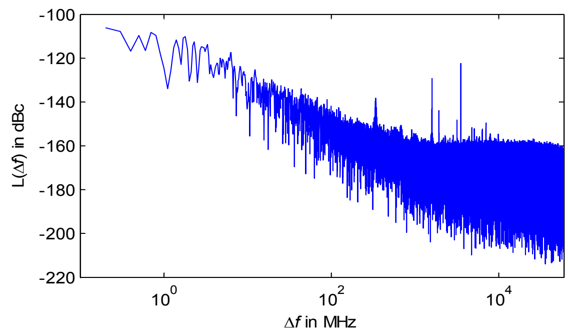

Fig. 6. Phase noise spectrum of VHDL-AMS model

IV. Conclusion

This paper presented a methodology to model a nonlinear oscillator in VHDL-AMS using an ANN, including the capability of simulating phase noise. The output reproduces faithfully the behavior of the original circuit. The presented example models a very basic oscillator, but can be enhanced by also taking into account other properties of the circuit like the voltage controlled variation of the frequency.

Acknowledgement

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References

[1] N. Guo, R.C. Qiu et al.: ”60-GHz Millimeter-Wave Radio: Principle, Technology and New results”, EURASIP Journal on Wireless Communications and Networking, 2007

[2] “IEEE standard VHDL analog and mixed-signal extensions: Std. 1076.1-1999,” 1999.

[3] J. Wood, D. Root, and N. Tufillaro, “A behavioral modeling approach to nonlinear model-order reduction for RF/microwave ICs and systems,” IEEE Trans. Microwave Theory & Techn., Vol. 52, pp. 2274–2284, 2004.

[4] Kraemer, M.; Dragomirescu, D., Plana, R., “Nonlinear Behavioral Modeling of Oscillators using Artificial Neural Networks”, IEEE Radio Frequency Integrated Circuits Symposium, 2008

[5] S. Haykin, “Neural Networks - A Comprehensive Foundation”, 2nd ed. Upper Saddle River, New Jersey: Prentice-Hall, Inc., 1999.