GENERATION OF MULTICARRIER COMPLEX LOWPASS MODELS OF RF ICs

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Abstract - **The design of transceivers for wireless digital telecommunications is subject to severe requirements on cost and power consumption. This is a challenge for the design of RF front-end blocks that degrade the bit-error-rate of a telecommunication link. This paper describes a technique to generate accurate high-level models for the RF front-end blocks. The models take into account the nonlinear behavior as a function of frequency. The accuracy of the models is higher than classical complex equivalent models since out-of-band distortion is taken into account. The technique, that is verified with a low-noise amplifier design for 5 GHz WLAN, yields an important gain in simulation efficiency of RF ICs, compared to circuit-level simulations.**

I. INTRODUCTION

The design of today's digital wireless communication systems is driven by requirements for miniaturization, lower power consumption and high flexibility. Meeting these demands means a serious challenge for the design of the analog front-ends in the transceivers. The signal degradation caused by these front-ends (noise, nonlinear distortion…) should be kept as low as possible. The total effect of signal degradations of the complete transceiver, including both the analog and the digital part, can be quantified by means of the bit-error-rate (BER). A prediction of the BER requires a simulation where many symbols are transmitted from the transmitter to the receiver, leading to large CPU times. Therefore it is very important that the inclusion of the RF front-end nonidealities in BER simulations does not slow down the computations too much. A co-simulation of the digital parts, described at a high abstraction level, with the analog parts described at the circuit level, is therefore not feasible. Instead, the analog front-end blocks could be modeled at a high level and simulated with a dataflow simulator, which is also used for the simulation of the digital part. Examples of such simulators are SPW [1], COSSAP [2], or Hptolemy in ADS [3]. For a high simulation efficiency the RF blocks are often represented by a complex lowpass representation, which models the linear behavior of an RF circuit together with its in-band distortion around DC instead of around the RF carrier. Such complex lowpass equivalent circuits, however, only consider the modulation of one carrier. In this way, out-of-band distortion that is folded back inside the band of interest by a subsequent nonlinear block is not modeled. This folding effect is more and more important in highly integrated RF front-end architectures such as zero-IF [4] or low-IF configurations. In these architectures, many RF bandpass filters are eliminated, resulting in a cascade of active, i.e. nonlinear, blocks.

In this paper a modeling technique is presented that generates a high-level model from a nonlinear RF circuit, starting from a circuit netlist description e.g. in SPICE format or in APLAC [5] format. The circuit can contain active elements and both lumped and distributed elements. The high-level model represents both the linear and weakly nonlinear behavior up to order three, and takes into account frequency dependence of this nonlinear behavior. The generated high-level models are more accurate than the classical complex lowpass representations since they take into account out-of-band distortion. This is accomplished by the use of a multicarrier representation that is also used in [6]. With this multicarrier representation the modulation of every harmonic is represented at baseband.

The modeling approach has been implemented in a program called DISHARMONY. This program, written in C++, starts from a circuit netlist and generates a high-level model with a user-defined accuracy. The use of DISHARMONY is illustrated with an integrated low-noise amplifier that has been designed for a 5 GHz WLAN application.

The outline of the paper is as follows. In Section II., the generation of a bandpass high-level model is discussed. This model consists of the most important contributions to the second- and third-order Volterra kernels of the input-output relationship of the circuit under consideration. The approximation of the Volterra kernel is user definable. A useful side effect of this approach is that it reveals the most important nonlinearities in the circuit operation. In this way, insight in the circuit operation can be gained.

The generated models consist of combinations of static nonlinearities and linear transfer functions.

Section III. discusses the translation of this representation into a multiple complex lowpass representation, in which linear transfer functions are replaced by digital filters, in order to speed up the high-level simulations.

The modelling approach is applied to the 5 GHz low-noise amplifier in Section IV.

II. Nonlinear Analysis And Modeling

The starting point for the generation of the high-level models described in this work, is the theory of Volterra series [7, 8]. For the modeling of weakly nonlinear behavior including frequency dependence, the multidimensional Fourier transforms of Volterra kernels can be used. The first-order kernel transform describes the linear behavior of the circuit. The second-order and third-order kernel transforms, which are functions of two and three frequency variables, respectively, describe the second- and third-order nonlinear behavior. Using these kernel transforms, the modeling approach described in [9], generates high-level models for low-frequency analog circuits. The high-level models are suitable for use with digitally modulated signals. This paper describes an extension of this approach to RF circuits. The problem of these circuits is that they operate at RF circuits and not as baseband. A co-simulation of these circuits with baseband circuits or with digital circuits with a wideband input signal such as an OFDM signal for HIPERLAN, is not efficient with classical approaches such as transient analysis or harmonic balance analysis. The inefficiency of the first approach is due to the large difference in operating frequency, requiring simulations with a very small timestep over a number of periods of the baseband frequencies. The second approach is not efficient when the excitation is a wideband signal that cannot be represented by a small number of sinusoidal signals.

For the modeling approach described here, the nonlinear devices of the circuit have to be described using power series expansion of their modeling equations, which are usually described in admittance form. For example, a power series approximation of the collector current of a bipolar transistor, without taking into account the Early effect, can be described as

$$i_c = gm \cdot v_{be} + K2_{gm} v_{be}^2 + K3_{gm} v_{be}^3 + \ldots \quad (1)$$

in which $K2_{gm}$ and $K3_{gm}$ are referred to as nonlinearity coefficients. These coefficients are proportional to the second- and third-order derivative of the current with respect to the base-emitter voltage v_{BE}. With the inclusion of the Early effect, the power series for i_C is two-dimensional, defining two extra second-order and three third-order nonlinearity coefficients.

Next, the multidimensional Fourier transforms of second- and third-order Volterra kernels of the output of interest are computed. These kernel transforms contain many contributions, namely one for each second- or third-order nonlinearity coefficient of the power series description of the different nonlinearities in the circuit. Each contribution consists of a combination of the nonlinearity coefficient and linear transfer functions [9].

With this information we can construct a high-level model of each kernel in the form of a block diagram (see Fig.1). It comprises many parallel paths, one for each nonlinearity coefficient. The structure of each path can be different depending on the type of nonlinearity (conductance, transconductance, capacitance), but generally each path consists of nonlinearity coefficients, linear transfer functions and a static nonlinearity (e.g. x^2, x^3 or an ideal multiplier).

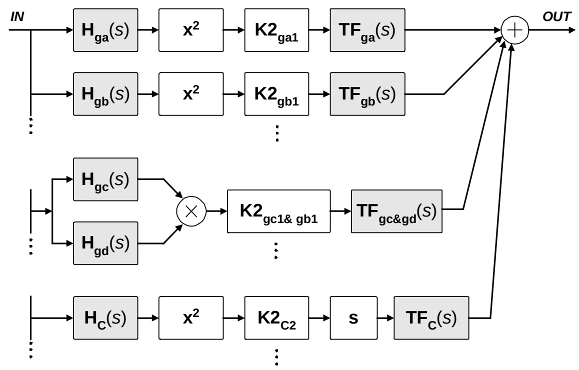

Fig.1. Block diagram of a general second-order Volterra kernel.

Due to the large number of nonlinearities in a circuit of a practical size, the complete high-level models of Volterra kernels are quite complex. Fortunately, in most practical cases many nonlinearity coefficients give a negligible contribution to the overall second- or third-order nonlinear behavior. This is exploited in an algorithm that eliminates all negligible contributions up to a user-definable error on the magnitude and phase of the kernel transforms in a given frequency band of interest.

Finally a translation of the dominant contributions into a block diagram yields the final model in the form of relatively simple block diagram that comprises only a limited number of static nonlinearities, scale factors and transfer functions. Because many blocks are identical in different parallel paths, the approximated high-level models can be further simplified in its structure by grouping identical parts and by using elementary mathematics. The simplified block diagram exhibits exactly the same accuracy as the original approximated model but with less complexity and therefore can be evaluated in more effective way.

III. Translation To Multicarrier Complex Lowpass Equivalent High-Level Models

The signals that we deal with in communication systems are often carrier-modulated signals that are processed in bandpass systems. In simulation these signals have to be sampled at a rate that is at least twice the highest frequency in the signal spectrum. In the case of RF analog blocks this could cause high simulation inefficiency. This can be overcome with the complex envelope method [10], which uses complex lowpass equivalent signals: if the signal spectrum around a carrier at frequency f_c is contained in the band <f_c-B/2, f_c+B/2>, then with a complex lowpass representation the sampling frequency only needs to be on the order of B.

The procedure of the nonlinear analysis and modeling described in the previous section leads directly to the approximated high-level model in the analog *s*-domain. The complex envelope simulation technique requires the transformation of the original high-level model described in passband to its complex lowpass equivalent. To this purpose, the linear transfer functions in the model and the modulated signals are translated to baseband. This results into an efficient simulation model that takes into account in-band distortion only.

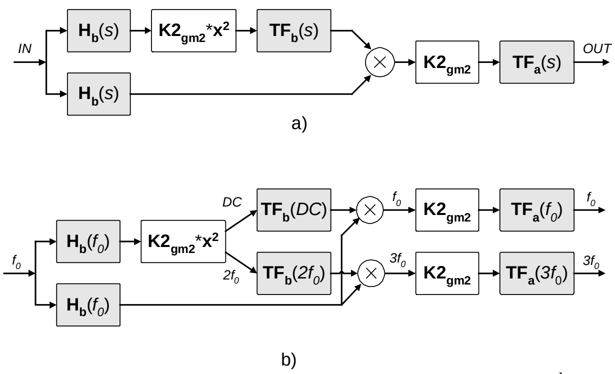

Fig. 2. High-level model of the contributions to the 3rd order nonlinear behavior of a one-dimensional second-order coefficient $K_2 g_m$. (a) bandpass representation (b) complex lowpass equivalent with multi-carrier signal representation. The frequency in the parenthesis reflects the carrier frequency to which the particular complex lowpass equivalent model of the transfer function was derived.

A model with in-band distortion only, is not accurate in the case of highly integrated RF frond-end architectures where cascade connections of active RF blocks without any intermediate frequency-selective blocks often occur. A practical signal often consists of different bandpass signals, e.g. the modulated carrier of interest and its (modulated) harmonics, or an interfering signal. These out-of-band signals can cause in-band distortion due to nonlinear behavior of a subsequent front-end block. In order to take into account out-of-band distortion with the simulation efficiency of a complex lowpass representation we use this representation for each carrier. This requires the translation of each transfer function to the several complex lowpass equivalents in accordance with all possible bandpass signals in the place of the signal path of interest. This is illustrated in Fig. 2 for the contribution of a one-dimensional nonlinearity to the third-order nonlinear behavior of the complete circuit.

If the resulting model is used in a digital dataflow simulator, then, as a last step, the s-domain representations of the linear transfer functions are translated into digital filters.

IV. Example

The modeling approach described above is implemented in a program called DISHARMONY. This program starts from a netlist and generates an approximate high-level model with a user-definable error. In this way, only the most relevant nonlinearities are considered in the high-level model. The use of DISHARMONY is illustrated with the analysis of a 5 GHz low-noise amplifier (see Fig. 3).

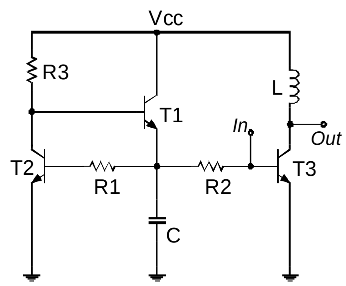

Fig. 3. A 5 GHz low noise amplifier.

In this circuit transistor T3 is the amplifying transistor. The rest of the circuit provides the necessary bias. It is found by DISHARMONY that the largest contribution to the second-order nonlinear behavior originates from the second-order nonlinearity coefficient of the collector current power series expansion (see equation (1)). For the third-order nonlinear behavior, the second- and third-order derivatives with respect to i_C yield the most important contributions. These three contributions

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suffice for an accurate high-level model. A further simplification based on elementary mathematics in the block diagram, leads to the final complex lowpass, multicarrier model. (see Fig. 4).

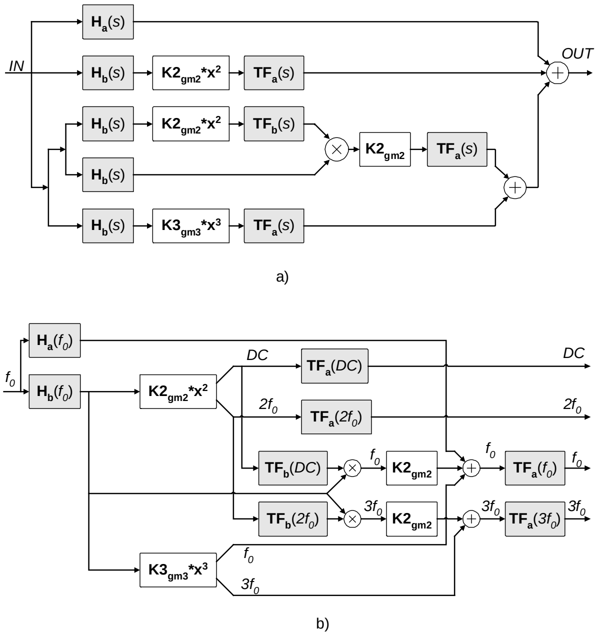

Fig. 4. High-level model after simplification: a) general model b) and its multicarrier complex low-pass equivalent. With a classical complex lowpass representation only the paths of "f_0" would be present.

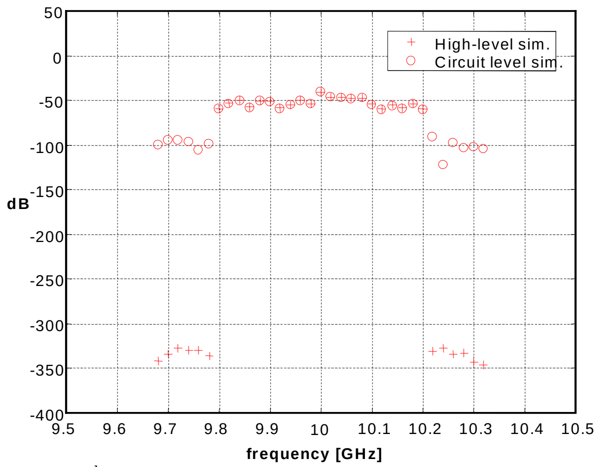

Fig. 5. 2nd order distortion computed by circuit simulation in comparison with high-level simulation performed by Aplac harmonic balance analysis

The accuracy of our modeling approach is verified by comparing the results of the circuit level and the high-level simulation. The input of the low noise amplifier is excited by digitally modulated signal around the carrier frequency 5 GHz with bandwidth of 200 MHz.

A comparison of the high-level model with a circuit-level description is made using the harmonic balance analysis of APLAC [5]. For a 5 GHz multicarrier input signal, the maximum deviation on the magnitude is only 0.8 dB (see Fig. 5 for a comparison of the 2nd order nonlinear distortion). The difference in CPU time is a factor 5. This difference will be more pronounced for larger circuit netlists.

V. Conclusions

A prediction of the BER of wireless transceivers requires accurate high-level models for the RF front-end blocks. In this paper a technique is described for the generation of models that take into account the frequency-dependent nonlinear behavior of the RF blocks. The models are generated starting from a circuit netlist. The resulting models contain a multicarrier equivalent lowpass representation of the most important contributions to the circuit's nonlinear behavior. The simulation accuracy is higher than classical complex lowpass models, since out-of-band distortion is taken into account. The simulation efficiency on the other hand is comparable to the use of classical complex lowpass models. Apart from a compact high-level model that can be used in BER simulations, e.g. with a digital dataflow simulator, knowledge of the most important contributions yields insight in the nonlinear operation of an RF circuit.

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