RF and Microwave Mixer Behavioural Modelling

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Abstract: - Efficient models based on behavioural modelling techniques are needed for RF and microwave mixers in order to check the performances of communication systems. Here, we propose a model consisting on the cascade connection of an input equivalent filter, characterising the linear transmission and reflection memory effects, and an ideal nonlinear mixer model, providing the frequency translation and also the nonlinear amplitude and phase distortion for the central frequency. Model parameters can be obtained either from measurements or simulations of the mixer circuit. The reported models can be implemented in any commercial simulator by using standard library components and can be employed both in frequency and time-domain simulations, demonstrating good agreement and significant reduction of simulation time with respect to the simulation of detailed electrical circuit models. The modelling technique is illustrated through two WLAN IEEE 802.11a mixer examples: an up-converter and a down-converter.

Key-Words: - Behavioural Modelling, RF and Microwave Mixers, System Simulation, Linear Memory Effects, Nonlinear Memory-less Distortion.

1 Introduction

The growing complexity of analogue and mixed-signal systems requires analysis and verification efforts at different hierarchical levels. Behavioural models of the different system components are able to capture, to a given accuracy, the input-output behaviour by abstraction of the circuit operation, providing the required simulation agility to check-up the system performances. The high integration levels and the complexity of actual and future RF and microwave systems make necessary the system performance analysis at a high level of abstraction in order to avoid unnecessary and costly redesigns and prototyping. Behavioural modelling techniques are efficient methods in order to provide accurate and suitable models for system level simulation.

Different works can be found in the literature, concerning different mixer behavioural modelling approaches, such as, for instance, [1-2]. In this paper, a different behavioural modelling technique for RF and microwave mixers is described. The model consists in the cascade connection of an input LTI block that characterise the linear memory effects related to linear transmission and reflection coefficients and an ideal mixer function that provides the frequency translation and also the nonlinear amplitude and phase distortion for the central frequency of operation. The input LTI block is build-up with the help of system identification techniques in frequency domain [3]. The behavioural model is able to reproduce transmission and mismatch effects at the input and output ports. This is extremely important when performing system level simulations involving several blocks. The model provides accurate results both in time and frequency domain simulations, with a significant reduction in terms of simulation time. The modeling method has been illustrated through two WLAN IEEE 802.11a mixer examples. The first is an up-converter and the second is a down-converter. Their behavioral models have been extracted from simulations of electrical detailed models.

2 Mixer Modelling Method

This section deals with the behavioural modelling of RF and microwave mixers. The topology of the proposed model is presented in Fig. 1.

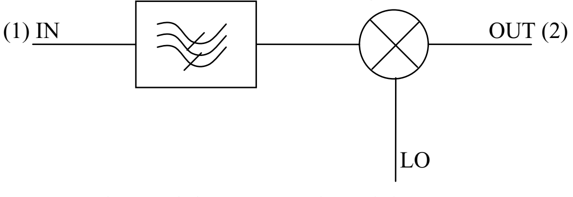


Fig. 1. Topology of the proposed model.

As it can be observed in the figure, the proposed model is composed by an input equivalent filter followed by an ideal mixer. The input filter serves to model the linear memory of the mixer [4], both in transmission and reflection. On the other hand, the output ideal mixer, characterises the nonlinear and memory-less amplitude and phase input-output distortion, and also serves to provide the required frequency translation of the mixer. The equivalent LTI filter corresponding to the linear memory of the circuit is computed and modelled as described in section 2.1. On the other hand, the non-linear mixer can be implemented by means of typical library elements, available in commercial simulation tools.

2.1 Linear Memory Effects Characterisation

The linear memory of the mixer is a function of the LO signal and can be represented by means of a "conversion admittance matrix" [$Y_{ij}(j\omega,LO)$]. In the case of a mixer with an input port numbered as 1 and an output port numbered as 2, and for a given LO signal, the equivalent linear admittance parameters are defined as follows:

$$\begin{aligned}
Y_{11} &= \left.\frac{I_1(f_{IN})}{V_1(f_{IN})}\right|_{V_2(f_{IN})=0} \\
Y_{12} &= \left.\frac{I_1(f_{IN})}{V_2(f_{OUT})}\right|_{V_1(f_{OUT})=0} \\
Y_{21} &= \left.\frac{I_2(f_{OUT})}{V_1(f_{IN})}\right|_{V_2(f_{IN})=0} \\
Y_{22} &= \left.\frac{I_2(f_{OUT})}{V_2(f_{OUT})}\right|_{V_1(f_{OUT})=0}
\end{aligned} \tag{1}$$

The admittance parameters of (1) can be obtained from simulations of the circuit schematic by two different methods. In the first case, HB (Harmonic Balance) simulations are used in presence of the LO nominal signal and RF-IF signals small enough, in order to guarantee the linear operation of the mixer. The second option is the typical "mixer-mode" simulation in which the simulator calculates the equivalent LTV system of the mixer, in order to obtain the required information. After obtaining the equivalent admittance parameters in the frequency domain, it's possible to deal with following theory of typical LTI systems. The next paragraph presents a method that serves to obtain a simplified model, providing us simulation ability both in frequency and time-domain. Note that the linear matrix characterising the linear memory effects can also be obtained from Large-Signal Vector-Network-Analyser measurements.

2.2 Modelling of LTI Systems by System Identification Methods in Frequency Domain

Distributed linear continuous-time systems, such it's the general case of RF and microwave LTI circuits, are physically described by partial differential equations with constant coefficients which can be expanded in an infinite series of partial fractions in the Laplace-domain. Frequency domain is the natural way in which the linear RF and microwaves circuits are handled in measurement or simulation. The transfer function of a distributed linear continuous-time system can be approximated, within the working frequency band, by a rational transfer function of finite order. Frequency domain identification techniques of LTI systems rely on the estimation of a transfer function model H(s) in the Laplace-domain from its frequency response H(jω) [3]:

$$H(s) = K\frac{\prod_{j=1}^{Nz}\left(s-z_j\right)}{\prod_{j=1}^{Np}\left(s-p_j\right)} \tag{2}$$

A particular efficient modelling approach can be achieved by computing a linear multi-port matrix describing the circuit response in frequency domain in the band of interest and, then, identifying, for each matrix element, the minimum-order transfer function (transfer function having the minimum number of poles) fitting the associated frequency response in the frequency band of interest. The main drawback of the identification of LTI models in frequency domain is related to the presence of noise and nonlinear distortion in the data, which can lead to extensive computation requirements, inaccuracy and the instability of the identified transfer function. Note that the data obtained from the mixer-mode or HB simulations, by applying small enough input signal in order to guarantee the linear operation of the circuit, are free of noise and nonlinear distortion in such a way that the major problems of the frequency domain identification are circumvented. This is very useful when extracting a behavioural model from the detailed electrical description of the circuit, in order to speed-up the simulations at system level.

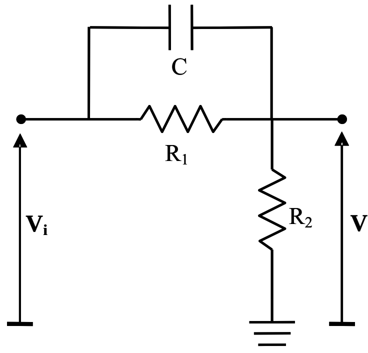
2.2.1 Implementation of the LTI block

In case of using a typical time-domain system simulators, usually it is possible to introduce directly the identified transfer functions in order to simulate the LTI system. But when using an electrical type simulator the implementation of transfer function's equivalent circuits can be very useful. In this work, ADS from Agilent Technologies has been used as electrical simulator.

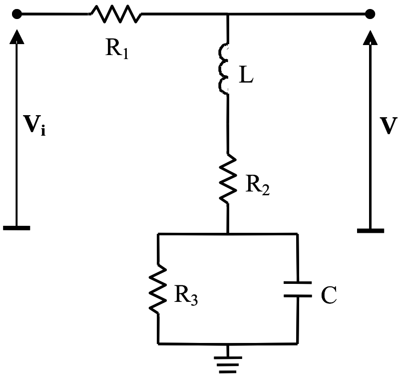
If I_i is the output current for the i-node and V_j is the input voltage for the j-node of the LTI system, in the Laplace domain we have:

$$I_i = Y_{ij} V_j \tag{3}$$

The elements $Y_{ij}(s)$ can be implemented in any commercial simulator using standard library components, such as ideal voltage-controlled current sources (VCCS) connected to the equivalent circuits of transfer functions $Y_{ij}(s)$. In a general case, when the number of poles of the reduced model is high, the implementation of the equivalent circuits can be performed by decomposition of each transfer function in the product of several simpler ones. In this way, the equivalent circuit is made up of a cascade of different simple sub-circuits, interconnected through buffers (ideal voltage-controlled voltage sources (VCVS) having unity gain) [5]. For instance, Figure 2 shows basic equivalent building blocks for order 1 and 2 cases, as well as the associated transfer functions.



$$\frac{V_o}{V_i} = \frac{s + \dfrac{1}{R_1 \cdot C}}{s + \dfrac{R_1 + R_2}{R_1 \cdot R_2 \cdot C}}$$



$$\frac{V_o}{V_i} = \frac{s^2 + s \cdot \dfrac{R_2 \cdot R_3 \cdot C + L}{R_3 \cdot L \cdot C} + \dfrac{R_2 + R_3}{R_3 \cdot L \cdot C}}{s^2 + s \cdot \dfrac{R_1 \cdot R_3 \cdot C + R_2 \cdot R_3 \cdot C + L}{R_3 \cdot L \cdot C} + \dfrac{R_1 + R_2 + R_3}{R_3 \cdot L \cdot C}}$$

Fig. 2. Order-1 and -2 equivalent circuits and associated transfer functions.

Drastic order reductions can be obtained in the particular case of RF and microwave LTI circuits, which usually involve a large number of distributed elements. This results in significant reduction of simulation time of such efficient models respect to the simulation of the complete original circuit. This is particularly true in time-domain simulations, in which the linear RF and microwave circuits or sub-circuits are responsible for long transients. The simplified model can be implemented as a lumped equivalent circuit using standard library elements, which makes possible to use it in any frequency or time domain simulation environment.

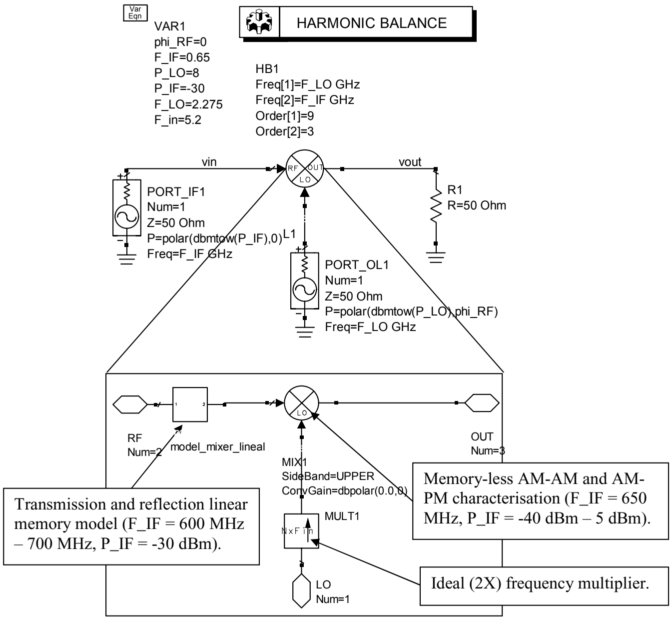
2.3 Nonlinear Memory-less Distortion Characterisation

In order to characterise the memory-less nonlinear distortion of a mixer, HB simulations are very useful. In this case a simulation involving the nominal LO signal and an input tone at the central frequency of the bandwidth of interest is required. Sweeping the power level of the input tone in a certain range and retaining the information concerning to the power level and the phase of the output tone, the memory-less nonlinear behaviour of the mixer will be characterised, in a similar way as is generally assumed for the PAs (Power Amplifiers) case [6]. This information can also be obtained from measurements.

The implementation of the nonlinear compression and phase distortion characteristics depends on the specific simulator, but in general, the commercial simulation tools offer design libraries with elements that provide the implementation capabilities for the required nonlinear characteristics.

3 WLAN IEEE802.11a Up-Converter Application

In this section, the modelling methodology previously detailed is applied to a mixer designed for its application to the standard WLAN IEEE 802.11a. Figure 3 shows the implementation of the mixer behavioural model. In this case, the mixer is an up-converter. The input frequency band is centred at 650 MHz and the nominal LO signal has a frequency of 2275 MHz and a power of 8 dBm. The output of the mixer is located around the second harmonic of the LO frequency, so the output frequency band is centred at 5200 MHz.



Transmission and reflection linear memory model (F_IF = 600 MHz – 700 MHz, P_IF = -30 dBm).

Memory-less AM-AM and AM-PM characterisation (F_IF = 650 MHz, P_IF = -40 dBm – 5 dBm).

Ideal (2X) frequency multiplier.

Fig. 3. Implementation of the behavioural mixer model.

3.1 Linear Memory and Nonlinear Distortion Characterisation

Following the method detailed in the previous section, the first step has been the linear memory and nonlinear distortion characterisation.

Figures 4 and 5 show the schematics used to extract the linear memory of the system. As we can observe there, we follow strictly the definition of the Y_{ij} parameters reported in Equation 1. In particular, Figure 4 shows the extraction of the Y_{11} and Y_{21} parameters, and Figure 5 shows the extraction of the Y_{22} and Y_{12} parameters. By sweeping the frequency of the small signal generator (P=-30 dBm) in the frequency band of interest, it's possible to obtain the frequency response of the mentioned admittance parameters.

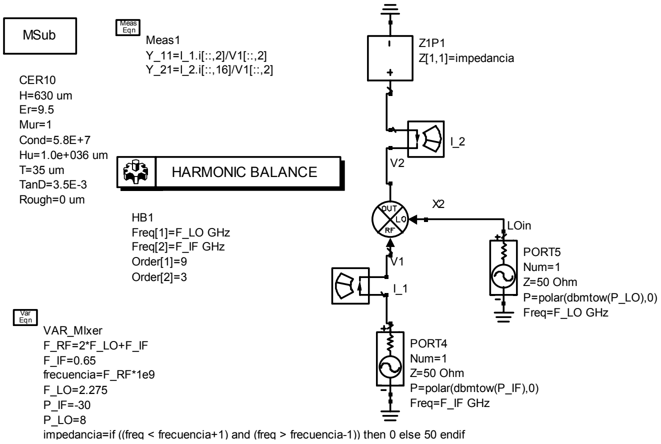


Fig. 4. Extraction of the Y_{11} and Y_{21} frequency response.

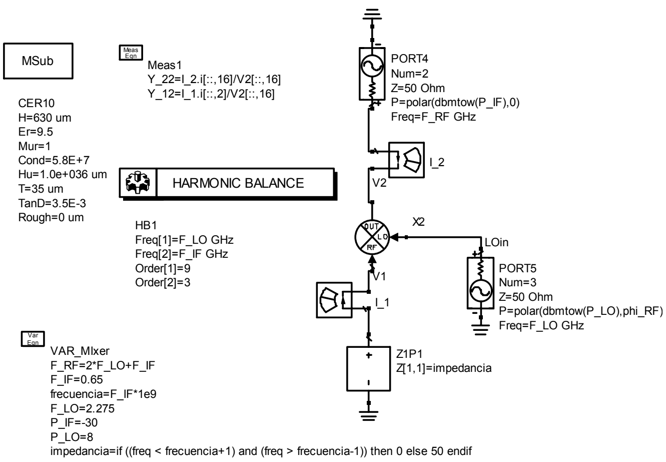


Fig. 5. Extraction of the Y_{22} and Y_{12} frequency response.

Figure 6 shows the comparison between the Y_{ij} equivalent admittance parameters extracted from the original circuit and the behavioural model. These parameters have been characterised for an input frequency bandwidth from 600 to 700 MHz. The resulting transfer functions have 4 poles for each of the Y_{ij} parameters. Due to the perfect match of the Y parameters, we can conclude that the linear transmission and reflection memory effects are well characterised by the behavioural model in the frequency band of interest.

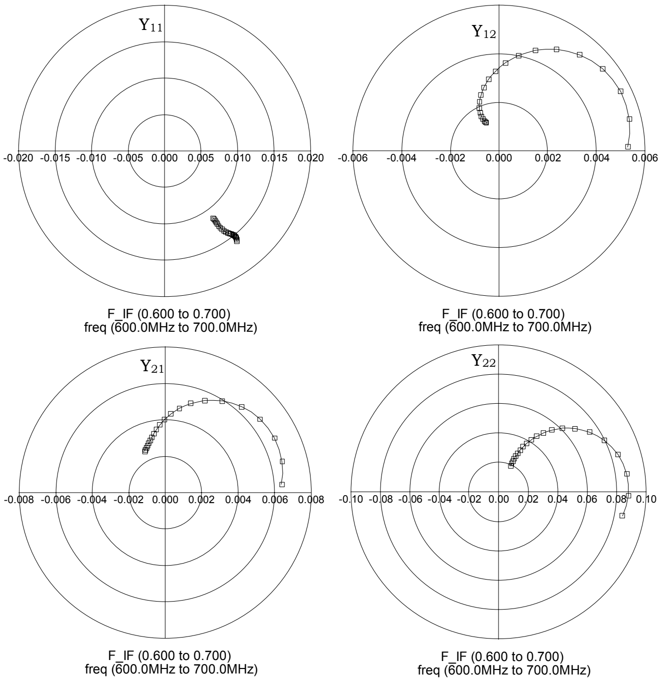


Fig. 6. Equivalent admittance parameters. Squares: data obtained from the original circuit (P_IF = -30 dBm in order to ensure small-signal operation mode). Solid line: data obtained from the behavioural model.

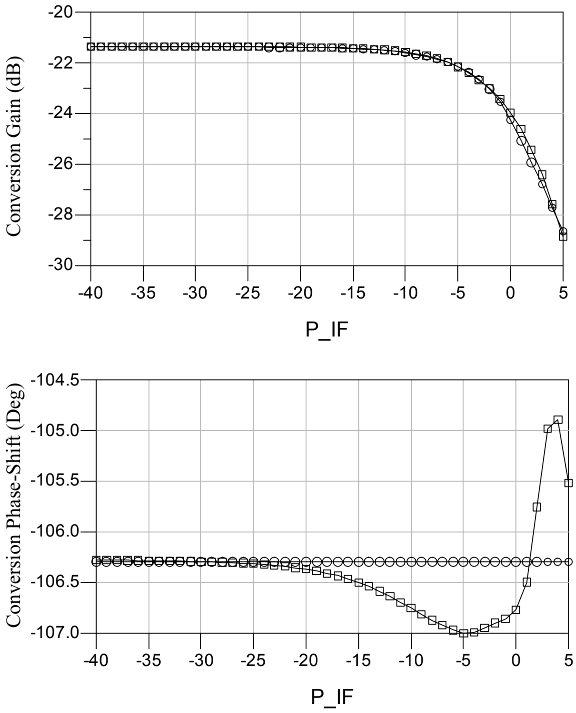


Fig. 7. Amplitude and phase memory-less nonlinear distortion. Squares: data from the original circuit. Circles: data from the behavioural model. F_IF = 650 MHz (F_RF = 5.2 GHz).

On the other hand the amplitude and phase nonlinear distortion has been also characterised for the central frequency of the bandwidth of interest (650 MHz) from HB simulations. Figure 7 shows the comparison between the conversion gain and phase-shift corresponding to the original circuit and the behavioural model. The error has been considered small enough both in amplitude and phase. In this particular case the phase distortion has been neglected but, in general, it can be implemented if necessary in an equivalent way as the amplitude distortion.

3.2 Model Validation

In this section the model validation by means of one and two tone HB simulations is presented.

Figure 8 shows the superposition of the amplitude and phase of the output signal of the mixer, for one input tone with a frequency that has been swept from 600 to 700 MHz and a power level of -30 dBm. In this figure the results of the original circuit, the nonlinear behavioural model and the linear memory model are compared. Due to the small signal operation of the circuit, an absolute match is achieved.

As it can be observed in Figure 9, by increasing the input tone power level the error between the results provided by the circuit and the behavioural model is also increased. Nevertheless, the nonlinear behavioural model presents a good agreement with the results provided by the original circuit.

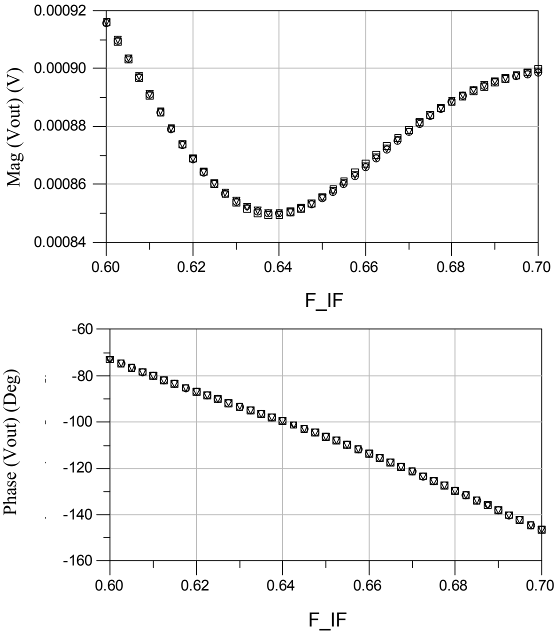


Fig. 8. One tone test for a -30 dBm input tone. Squares: original circuit. Circles: non-linear behavioural model. Triangles: linear memory model (LTV). Vin frequency = F_IF, Vout frequency = 2*F_OL + F_IF

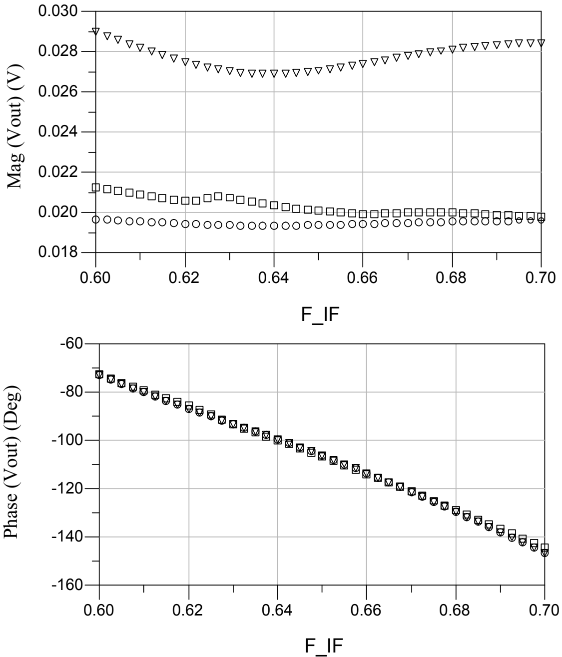


Fig. 9. One tone test for a 0 dBm input tone. Squares: original circuit. Circles: non-linear behavioural model. Triangles: linear memory model (LTV). Vin frequency = F_IF, Vout frequency = 2*F_OL + F_IF.

Another important experiment in order to validate the behavioural model is the two tones test. Figure 10 shows the comparison between the results provided by the original circuit and the behavioural model for two tones at frequencies 645 and 655 MHz and a power of 0 dBm each.

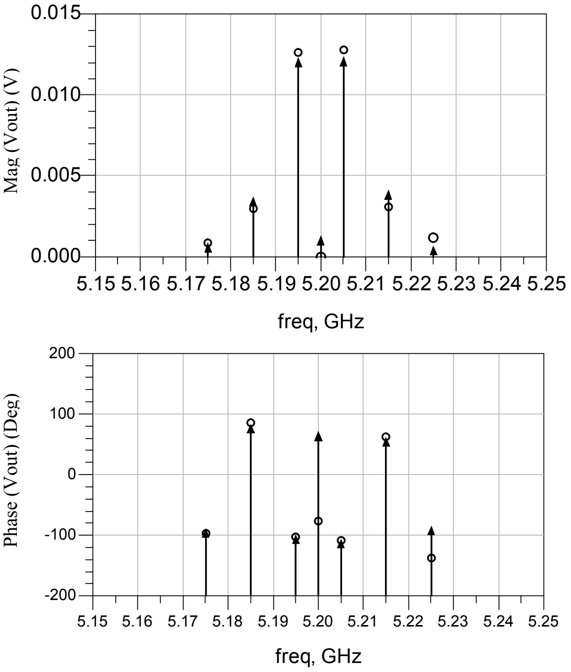


Fig. 10. Two tones test for two 0 dBm input tones. Arrows: original circuit. Circles: behavioural model. F_IF1 = 645 MHz, F_IF2 = 655 MHz.

It can be observed a good agreement between the results both in amplitude and phase of the output signal. The more significant error in the phase of the signal corresponds to the smallest intermodulation tone in the amplitude, so its effect on the overall resulting error is low.

3.3 Model Application: Time-Domain Simulations

Due to the signal complex formats employed in actual communication applications, time-domain simulations are well suited for system-level analysis. Figure 11 shows the result of the time-domain one tone simulation of the original mixer circuit description. These results have not physical sense, probably, due to a convergence problem in the integration process. This kind of problem can appear when simulating circuits including distributed elements, such as transmission lines, defined in the frequency domain and signals involving very different time scales.

Simulation results obtained by using the reported behavioural model under one-tone excitation are reported in Figure 12.

Identical results to those of Fig. 12 are obtained from HB simulations. So, the behavioural model works well under, both, time- and frequency-domain simulations.

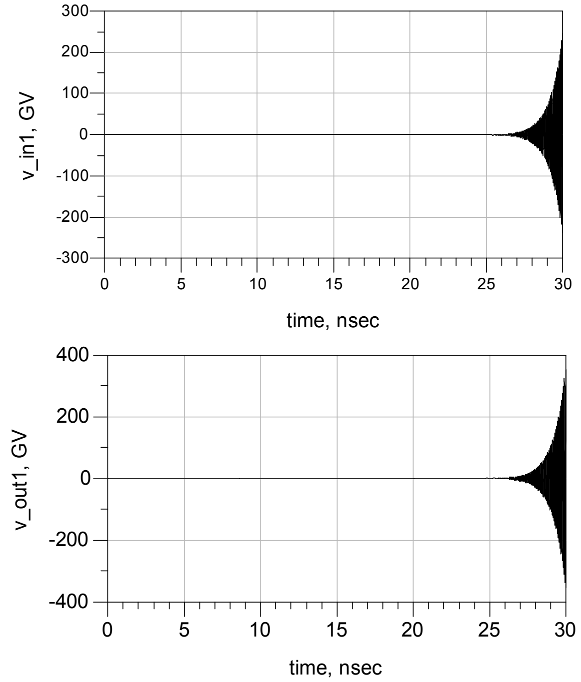


Fig. 11. One-tone time-domain simulation result by using the original circuit. V_IF frequency = 650 MHz, P_IF = -30 dBm. Simulation Time = 94.8 Sec.

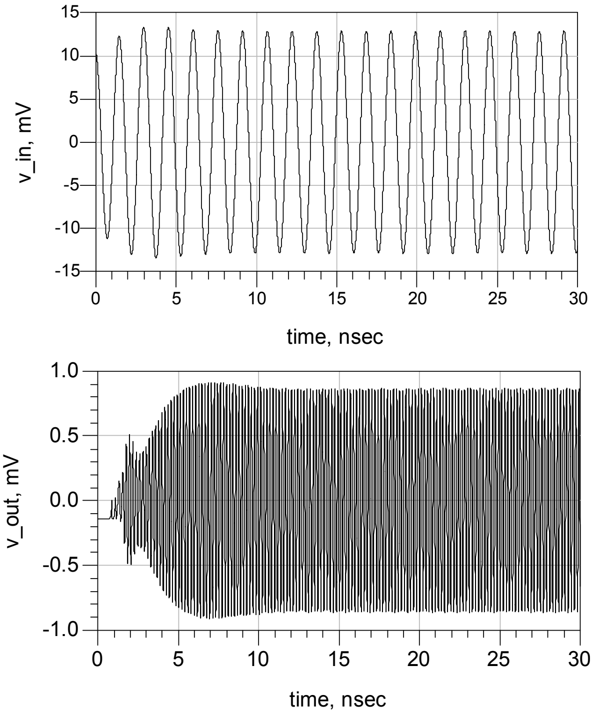


Fig. 12. One-tone time-domain simulation result by using the behavioural model. V_IF frequency = 650 MHz, P_IF = -30 dBm. Simulation Time = 6.2 Sec.

As an example, Figure 13 shows input and output mixer OFDM modulated signals, performed by means of time-domain simulations (standard IEEE 802.11.a). It is possible to observe, in the successive zooms, that the frequency of the input carrier is 650

MHz and the frequency of the output carrier is 5.2 GHz.

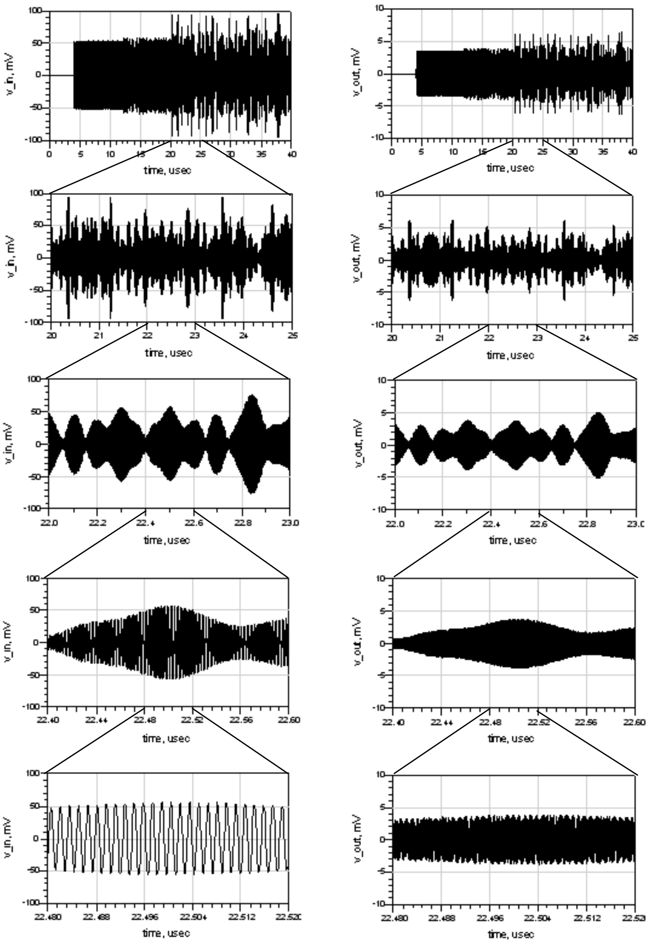


Fig. 13. Time domain simulation results: Mixer input (left) and output (right) OFDM modulated signals.

Figure 14 shows input and output spectra. As it was already mentioned, the spectral complexity of this kind of signals makes difficult the simulation of the real circuit, described through a detailed electrical model. However, the reported behavioural model is well conditioned for time- or frequency-domain simulations, providing accurate results together with shorter simulation time.

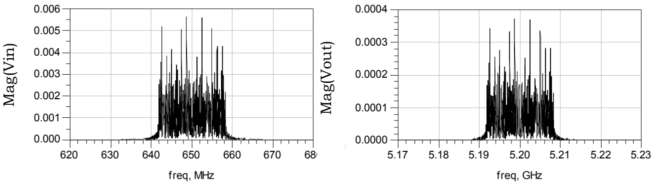


Fig. 14. Mixer input and output spectra for an OFDM modulated input signal.

4 WLAN IEEE802.11a Down-Converter Application

In this section, the modeling methodology has been applied to a simple balanced diode mixer design for the WLAN standard IEEE 802.11a [7]. The mixer is a down-converter and has been designed and implemented using hybrid technology (see Fig. 15). The input frequency band is centered at 5200 MHz and the nominal LO signal is a 0 dBm power tone at 4550 MHz. The output frequency band of the mixer is centered at 650 MHz by the direct conversion with the LO signal. In this case, the behavioral model has also been obtained from the equivalent circuit representation of the mixer.

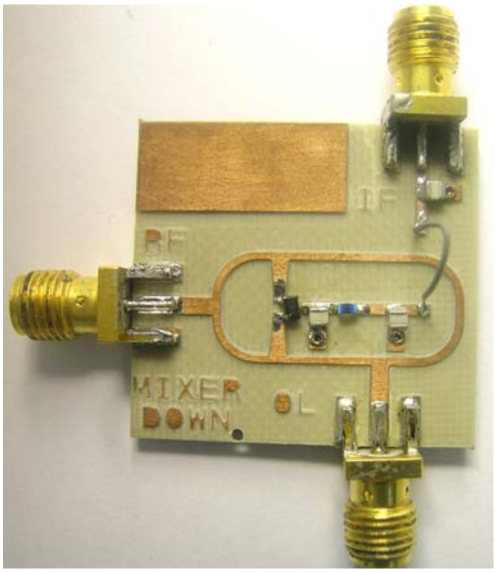


Fig. 15. Simple balanced diode down-converter.

4.1 Linear Memory and Nonlinear Distortion Characterisation

Figure 16 shows the AM-AM characteristics obtained with an input tone at the central frequency of the operating bandwidth (5200 MHz) from HB simulations of the behavioral and circuital model, as well as from measurements.

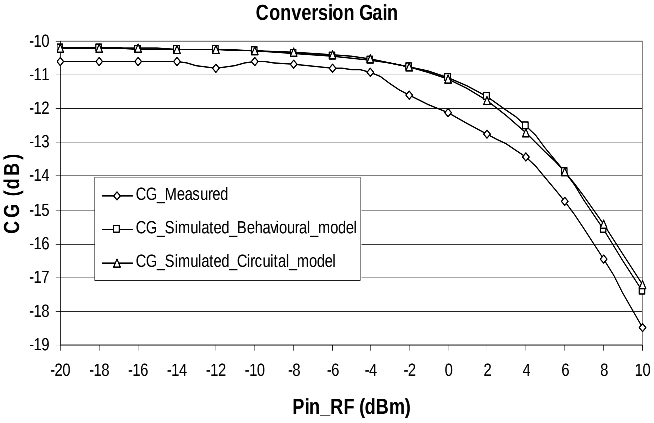


Fig. 16. Conversion gain curves obtained from simulation and measurement of the mixer.

Figure 17 shows the comparison between the conversion admittance parameters [Y] obtained from simulation of the circuital representation (circles) and the behavioral model (continuous line), for a frequency band of 100 MHz around the input central frequency of 5200 MHz. In the same way as in the up-converter case, the resulting transfer functions have 4 poles. Due to the good agreement observed, we conclude that the linear transmission and reflection memory effects and also the nonlinear distortion are well characterized by the behavioral model in the bandwidth of interest.

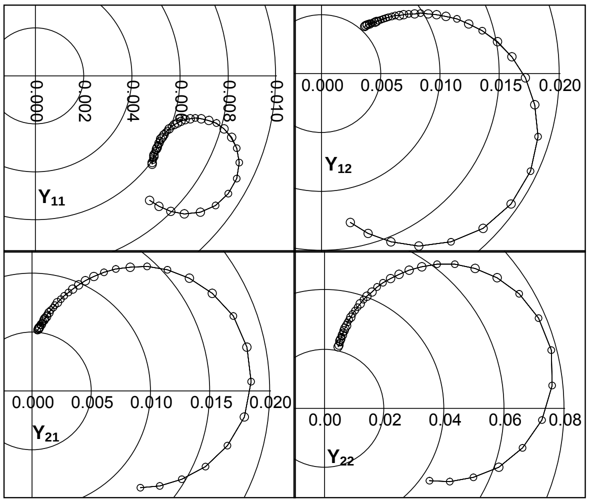


Fig. 17. [Y] parameters comparison.

4.2 Model Validation

In this section the model validation by means of one and two tone HB simulations is presented. Figure 18 shows the superposition of the amplitude and phase of the output signal provided by the original circuit, the nonlinear behavioral model and the linear memory equivalent representation of the mixer.

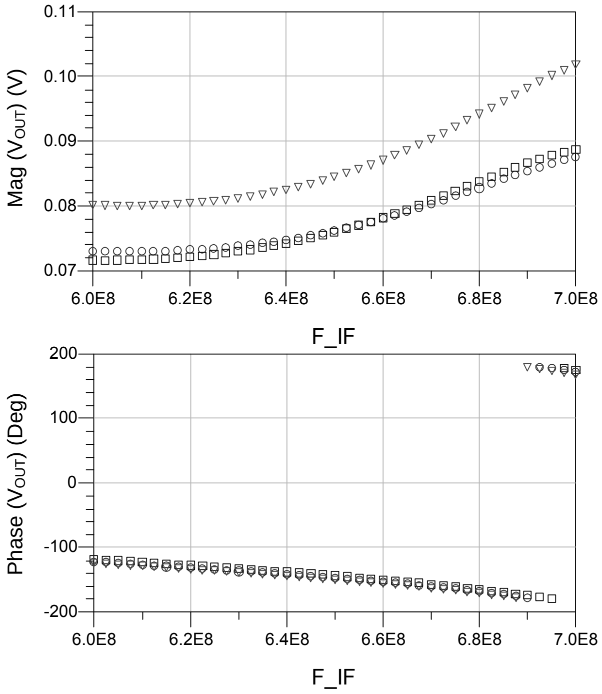


Fig. 18. One tone test for a 0 dBm input tone. Squares: original circuit. Circles: non-linear behavioural model. Triangles: linear memory model (LTV).Vout frequency = F_RF – F_LO.

The frequency of the input tone has been swept from 5150 to 5250 MHz presenting a power level of 0 dBm.

Figure 19 shows the comparison between the two-tone test results provided by the original circuit and the behavioral model. The input tones at frequencies 5195 and 5205 MHz have a power of 0 dBm each.

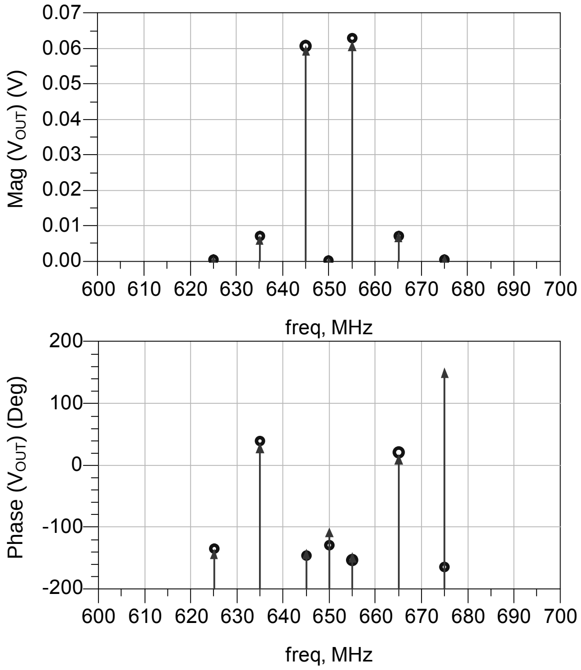


Fig. 19. Two tones test for two 0 dBm input tones. Arrows: original circuit. Circles: behavioural model. F_IF1 = 5195 MHz, F_IF2 = 5205 MHz.

In both cases, it can be observed good agreement between the results both in amplitude and phase of the output signal. In the two-tone test case, the more significant error in the phase of the signal corresponds to the smallest intermodulation tone in the amplitude, so its effect on the overall resulting error is low.

4.3 Model Application: Time-Domain Simulations

In the same way as in the section 3.3, time-domain simulation of the original circuit has presented drastic convergence problems (see Figure 11).

Nevertheless, the down-converter behavioral model works also well performing time-domain integration processes. Figure 20 shows the output mixer OFDM modulated signal and its corresponding spectra, developed by means of time-domain simulations (standard IEEE 802.11.a). Clearly, the reported behavioral models are well conditioned for time- and frequency-domain simulations, providing accurate results and short simulation time.

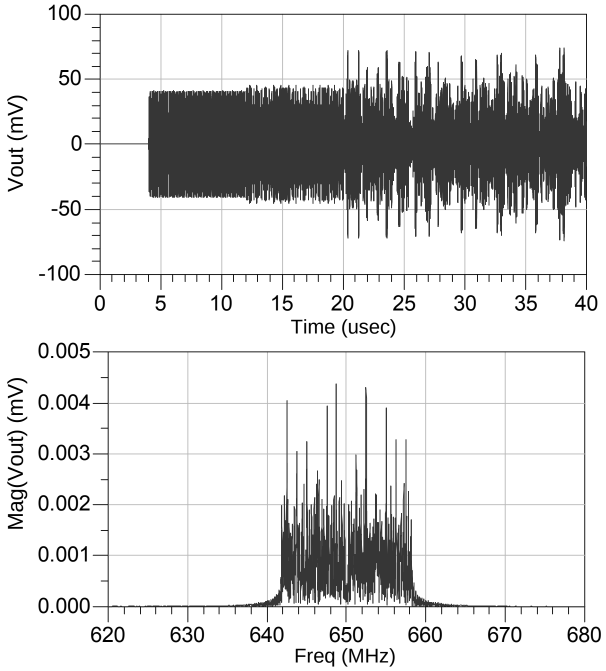


Fig. 20. OFDM modulated output mixer signal.

5 Conclusion

An efficient behavioural modelling technique has been reported and applied to microwave up- and down-conversion mixers. The models are able to capture the linear memory and the input-output memory-less nonlinear circuit behaviour. It can also reproduce the matching conditions at the model ports. The simulation results using the behavioural models demonstrate good accuracy when compared to the simulations of the overall electrical model of the circuit. Moreover, significant reduction in terms of simulation time with respect to the simulation of the detailed circuit description is achieved. The resulting behavioural models can be implemented in any simulation environment and employed both in frequency and time-domain simulations. The reported modelling technique has been illustrated through its application to up- and down-converter mixers for WLAN IEEE 802.11.a applications.

Acknowledgments

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