A Novel Calibrated Time Domain Envelope Measurement Setup for the NPR Characterization and the Behavioral Modeling of Power Amplifiers

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INTRODUCTION

Characterization of the nonlinear microwave power devices has been considerably enhanced during the last decades. CW stimuli enable to provide valuable and very useful information for the validation of transistor nonlinear models for CAD. They provide also experimental confirmations of the optimum operating conditions of active cells in terms of power, gain and efficiency [1] [2] [3]. Additive characterization and test signal configurations (like two tone – multitone) using vector network analyzers, or spectrum analyzers provide additive information concerning linearity / efficiency trade-offs. Looking at the subsystem or system levels (50 Ω or closed to 50 Ω matched modules) calibrated measurement systems are required for the accurate characterization of modulated signal distorsions due to non linear devices [4].
As a matter of fact, CW tests only provide information on non linear static aspects (through the well known AM/AM and AM/PM conversion characteristics). CW measurements performed on a frequency grid within the device operating bandwidth provide additive information on AM/AM and AM/PM dispersions. If the characterization and the modeling of such non linear dispersive effects are commonly assumed to be sufficient for TWTAs [5], they are not for SSPAs.
Hence, when SSPAs are used for the amplification of non envelope constant modulated signals, they exibit low frequency (rather long time constants) non linear dispersion associated to slow variations of the envelope compared to RF carrier variations. Thermal as well as dynamic envelope spurious in transistors biasing circuits are obviously responsible of this [6]. This paper presents a measurement system which enables the generation and the time domain measurements of complex envelopes of modulated signals at both ports of nonlinear microwave power amplifier. The first goal of the setup presented hereafter is to perform an accurate calibrated large bandwidth (250 MHz) NPR measurements up to Ka band. A second application consist on characterizing power amplifiers under test to make out an associated behavioral model taking into account nonlinear memory effects.

MEASUREMENT SETUP

Measurement setup diagram

A block diagram of the measurement set-up that we have developed is given in figure 1 (L-S bands).
Baseband modulation schemes are achieved by using a computer controlled arbitrary waveform generator (12 bits – 250 Ms/s). The corresponding baseband envelope is then up-converted to the microwave domain using an I/Q modulator and linearly amplified to drive the input of the amplifier under test (AUT). A programmable step attenuator is used to enable average power sweeps.
The RF output signal of the AUT is then down converted to baseband using and I/Q demodulator and the corresponding complex envelope including distorsions is measured using a sampling scope (1 Gs/s, 500 MHz bandwidth, 8 bits). A calibrated ([S] parameters) step attenuator connected at the RF port of the I/Q demodulator is used to keep it working in its linear operation regime. In the emitter part of the set-up a specific circuit arrangement is used to improve LO leakage rejection at the RF output of the I/Q modulator.
A bandpass filter is also used to improve image rejection. The receiver part of the set-up consists of a RF block (couplers and attenuators) and a frequency translating and measurement block (I/Q demodulator and sampling scope).

This receiver part must be calibrated in order to get error corrected time domain envelopes (analytic signals) associated to the real RF modulated signals at AUT reference planes.

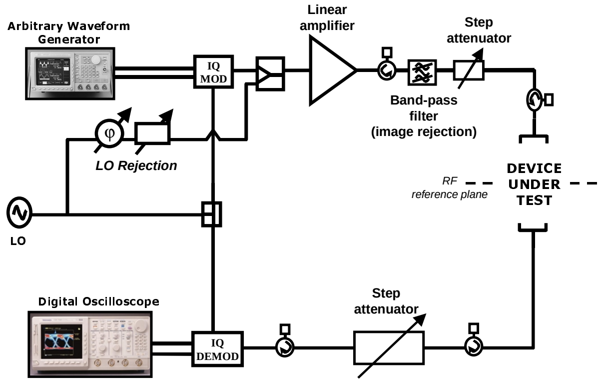


Fig. 1. The measurement setup block diagram

Calibration procedure

The calibration procedure of the receiver part is divided in two steps. The first step consists in measurements of the [S] parameters of the linear RF bloc : the step attenuator.
The second step consists in the characterization of the frequency translating block witch is composed with the I/Q demodulator and the digital scope as sketched in figure 2. Conversion losses, group delay and phase imbalance of the I/Q demodulator are determined as the function of the frequency each side away from the LO frequency. Theses parameters, which depend on the envelope frequency, are the calibration parameters.

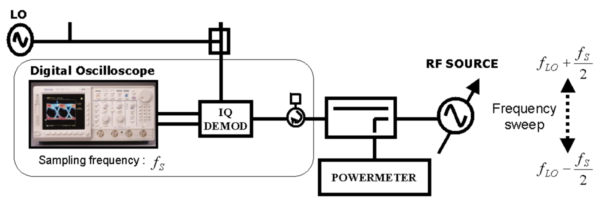


Fig. 2. IQ demodulator calibration principle

To characterize a device under test, the non corrected complex envelope is recorded with the digital oscilloscope. The correction to get the complex envelope at the AUT reference plane consist on weighting calibration parameters on the recording waveform in the envelope frequency domain. Thus, the measurement setup and the calibration procedure enable to get the corrected input and output envelopes at the DUT reference planes.

APPLICATION FOR THE NPR CHARACTERIZATION

The presented setup can be used as NPR measurement system in L/S band based on digital signal generation [7]. The aim of the proposed system is to extend this technique up to Ka-band with higher bandwidths.

Overall structure

To content the objectives, especially in terms of bandwidth, frequency ranges and evolutions, the measurement system is based on :

- numerical generation of signals based on Arbitrary Waveform Generator (AWG 520 - Tecktronix. Its main characteristics are the sample frequency (1Gech/s) and the vertical resolution (10 bits).
  The key advantages of digital techniques [8] over analog ones [9] are now well-known for NPR determination [10] : the shape of the noise is not imposed by a rejecter filter, it exhibits better repeatability ; and as the generated signal is pseudo-noise, the averaging of signals along several periods reduce the thermal noise.

Moreover, the numerical technique has been specially selected according to the wide variety of signals that can be generated thanks to the high degree of flexibility of the system.

- A frequency plan with two level of frequencies translation. The determination of the intermediate frequency (3.875 GHz) results from trade-off between modulator/demodulator performances and the facility to reject spurious frequencies after RF frequency translation. The generic part delivers signals around 3,875 GHz. This frequency plan enable a very wide range of available frequencies for characterization. In each case, specific elements are the power driver and the filter. For example, the overall architecture is given Fig. 3 for 17-21GHz measurements.
- The output envelope of the D.U.T. is recorded with the digital oscilloscope and corrected. A FFT is performed to compute NPR.

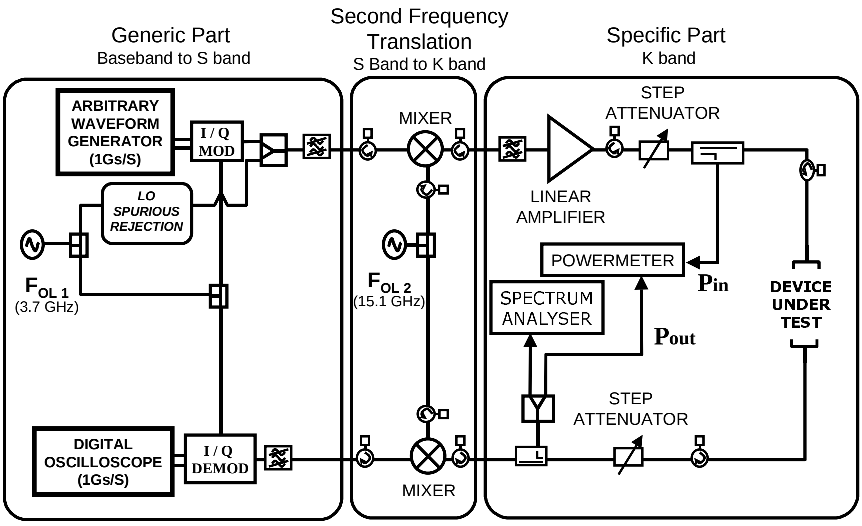


Fig. 3. Architecture in 17-21 GHz configuration

Numerical signal calculation

The pseudo-noise signal is created by combining a large number of discrete spectral lines equally spaced with the same amplitude and random phases. The number of the spectral lines and her phase drawing are the signal key parameters. The notch width determination issued from trade-off. Too wide, the signal properties are significantly changed ; too tight, the low number of tones inside the notch is not sufficient to determine accurately the noise power.
A good configuration is obtained with Matlab software considering 25000 signal tones and 5% relative notch width. The right and left side bands have to be uncorralated in order to excite phase and magnitude noises. If not [13], the RF signal is magnitude modulated and do not represent multicarrier loading. It gives pessimistic results compare to NPR.

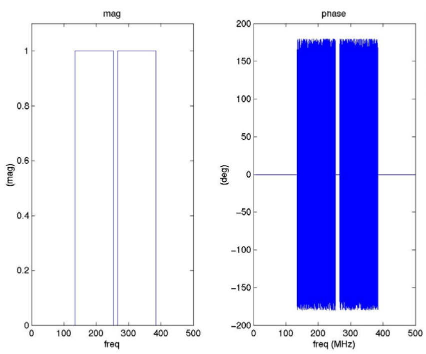


Fig. 4. Magnitude and Phase of the signal spectrum

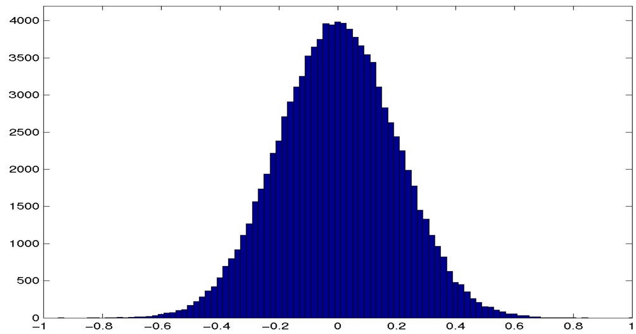


Fig. 5. Temporal signal magnitude distribution

NPR measurements system performances

- The shape of the signal at the D.U.T. input is shown in figure 6. The shape observed demonstrate a very flat profile and a notch with sloping sides.

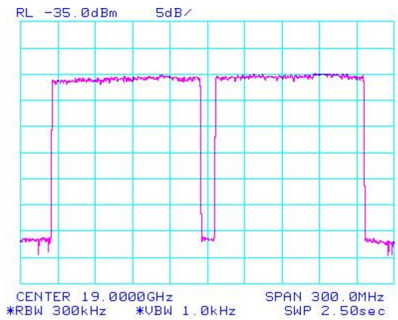


Fig. 6. 19GHz/250MHz signal shape

- Validation of the signal calculation. In order to determine the variance of the NPR due to the limited number of tones and the associated phases distribution ; ten different signals are generated and applied to the D.U.T. (1W/17-21GHz SSPA from ADVANCED MICROWAVE). We can note the 35dB NPR at low output power level that ensure high dynamic NPR measurement. A low dispersion of 0,4dB typically is obtained.

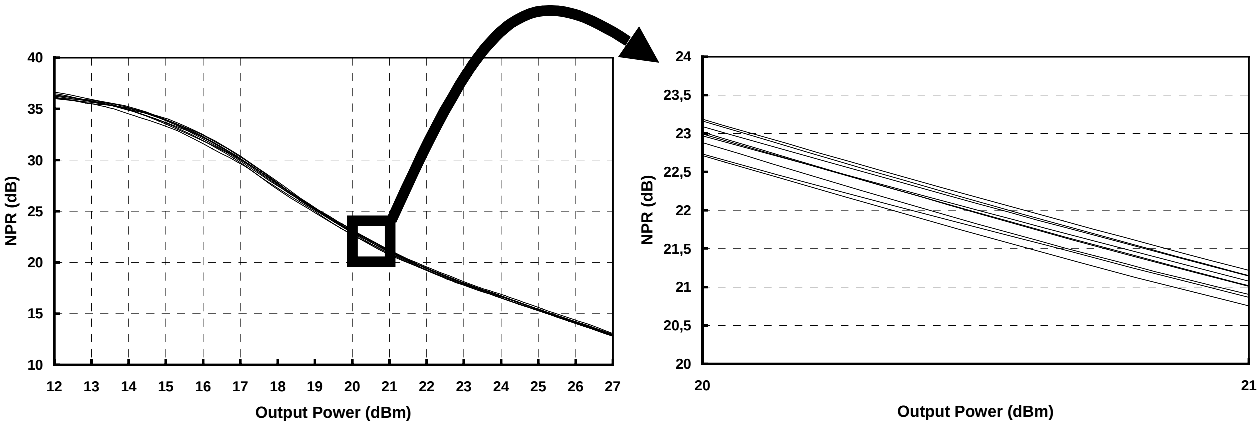


Fig. 7. NPR dispersion for nine different signals

- Level of reproducibility. Different measurements of the same device have been performed now and then over a 15 days period. The figure below illustrates the high level of NPR measurements reproducibility.

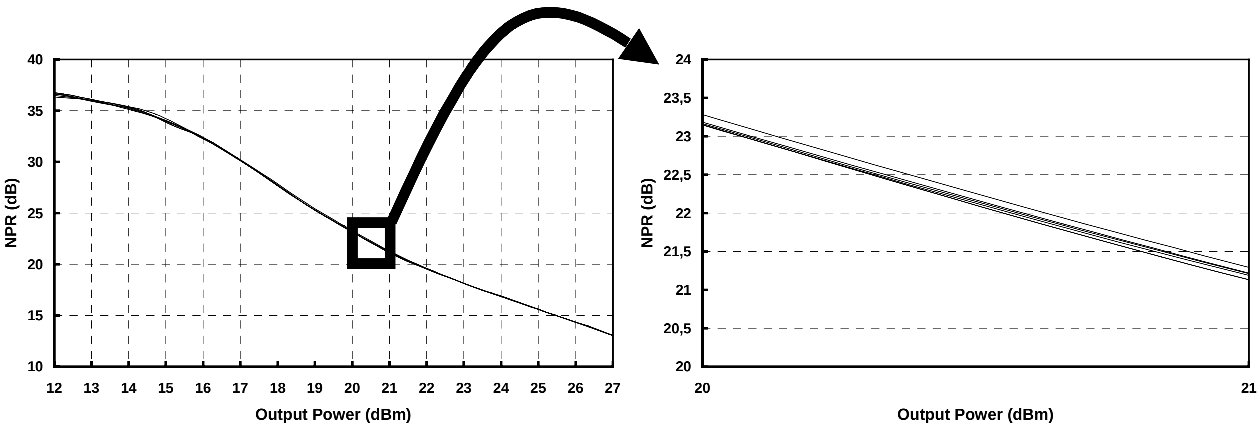


Fig. 8. NPR measurements reproducibility illustration

APPLICATION FOR THE BEHAVIORAL MODELING OF POWER AMPLIFIERS

A 36 dBm output power, 30 dB gain SSPA has been measured at 1.5 GHz for several baseband modulation schemes. A sinusoïdal baseband generation provide two tone (C/I) measurements. Multitone CW format as well as QPSK modulation were also performed.

Experimental visualization of memory effects

Figure 9 sketches an intantaneous output power of the AUT when the input signal is a 2 tones with a 250 kHz beat frequency. Notice the hyteresis for high envelope instantaneous output power value : this memory effect event can be linked to trapping effects [14] or the bias circuits [15] in the AUT.

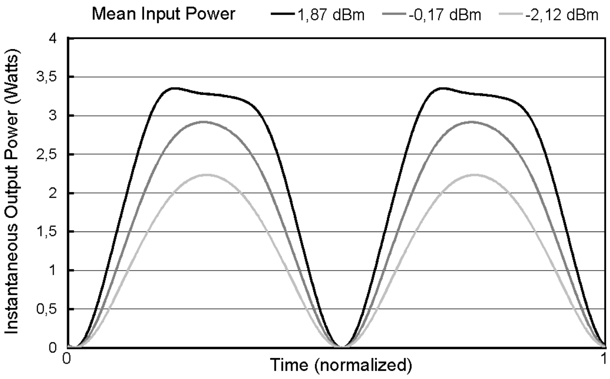


Fig. 9. Instantaneous envelope at the output of the SSPA driven by a 2 tones modulation

Figure 10 shows dynamic AM/AM conversion characteristics. The three case corresponds to a same +2 dBm average input power driving the AUT. For each cases the peak to average ratio, the modulation bandwidth and the statistic distribution of the envelope are different thus leading to different, non linear dynamic behavior of the AUT.

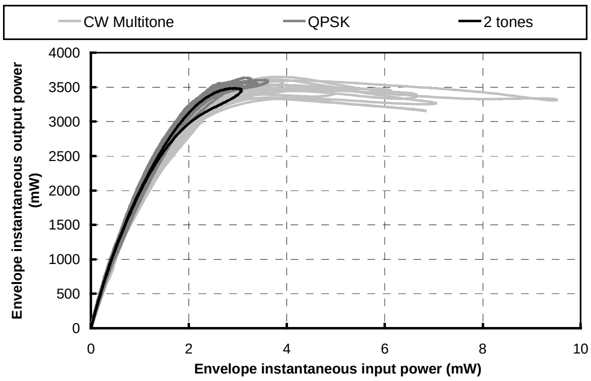


Fig. 10. Dynamic AM/AM measurements for different kind of modulation

A novel approach of dynamic behavioral modeling of power amplifiers

Using the versatility offered by our measurement system concerning modulation schemes, vector corrected envelopes were recorded and processed for the identification of the dynamic non linear behavior of the AUT. The input complex envelope is named $\tilde{x}(t) = A(t)e^{j\varphi(t)}$. The distorted output complex envelope is named $\tilde{y}(t)$.
Assuming an explicit first order behavioral function linking $\tilde{x}(t)$ and $\tilde{y}(t)$, one can write :

$$\tilde{y}(t) = f_{NL}\left(\tilde{x}(t), \frac{\partial \tilde{x}(t)}{\partial t}\right) \tag{1}$$

however,

$$\frac{\partial \tilde{x}(t)}{\partial t} = \tilde{x}(t).\left(\frac{\frac{\partial A(t)}{\partial t}}{A(t)} + j.\frac{\partial \varphi(t)}{\partial t} \right) \tag{2}$$

thus, equation (1) can also be written as :

$$\tilde{y}(t) = f_{NL}\left(A(t), \varphi(t), \frac{\partial A(t)}{\partial t}, \frac{\partial \varphi(t)}{\partial t} \right) \tag{3}$$

By applying this type of formulation to a complex gain expression, one define a new function independent of the input envelope phase such as:

$$\tilde{y}(t) = g_{NL}\left(A(t), \frac{\partial A(t)}{\partial t}, \frac{\partial \varphi(t)}{\partial t} \right) \tilde{x}(t) \tag{4}$$

This "dynamic" complex gain constitutes a enhancement of the complex gain used in system simulation and obtained with CW measurements.
A(t) is the instantaneous magnitude of the input envelope. If we use only this parameter in the previous relationship, we have only a static non linear behavioral description of the AUT.
The first derivatives $\frac{\partial A(t)}{\partial t}, \frac{\partial \varphi(t)}{\partial t}$ provide first order dependence of $\tilde{y}(t)$ to the low frequency dynamic variations of $\tilde{x}(t)$ including both high frequency and low frequency non linear memories (group delay, thermal dependence, envelope spurious within the DC biasing circuits).
The functional g_{NL} was chosen to be represented by using a neural network [16].
The behavioral model topology is sketched in figure 11.
A multitone test envelope (64 carriers) was used for the training procedure of the neural network. This envelope was synthesized by performing an appropriate loading of the baseband signals into the AWG (similar than the one that can be used for NPR tests) [17]. Input and output envelopes of the corresponding pseudo-noise modulated signal at both RF ports of the AUT were recorded using the sampling scope.

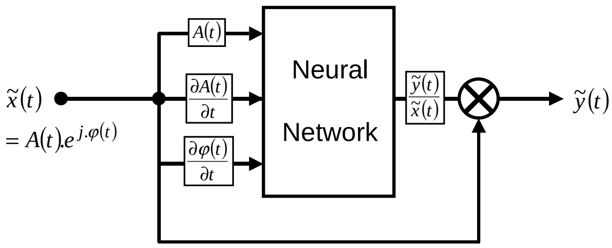


Fig. 11. Behavioral model topology

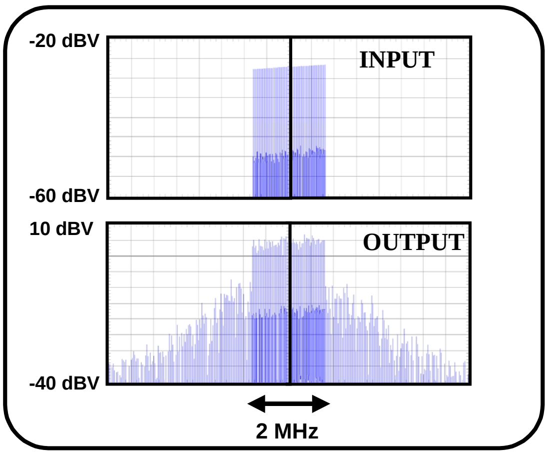
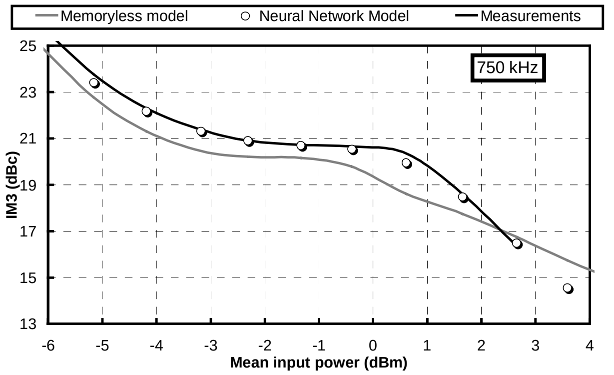
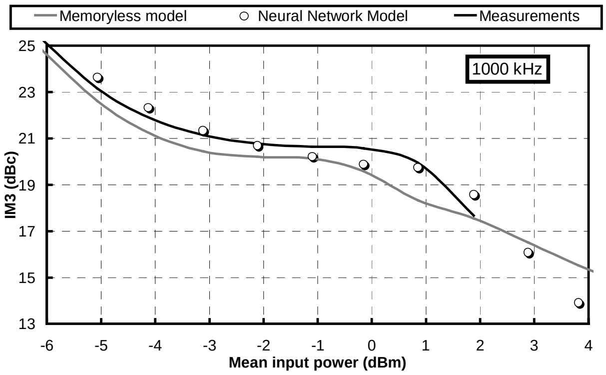


Fig. 12. Spectral shape of the test signals used for the neural network training

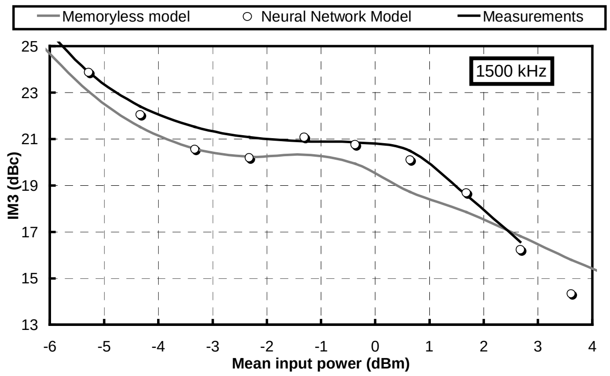
Once the behavioral model is built, it is used for the prediction of the envelope response of the AUT to other modulations. For example, we have performed predictions of third order intermodulation (two tone tests) at different carrier spacing. Two tone envelope measurements were performed and compared to simulation results obtained with our behavioral model. They have been also compared to the purely static response obtained with the well-known memoryless complex gain method derivated from center frequency AM/AM, AM/PM characteristics. Figures 13a, 13b and 13c show the set of curves superimposed on the same plot for different frequency distance between the two tones of the excitation RF signal.



(a)



(b)



(c)

Fig. 13.(a), (b) and (c) : IM3 of New Model / Measurement /AM/AM AM/PM Model for different beat frequencies

These curves demonstrate the significant enhancement of our dynamic behavioral modeling approach for the predictions of non linear envelope distorsions caused by microwave solid state power devices.

CONCLUSION

This paper has proposed a calibrated time domain envelope measurement system for the characterization of non linear equipment driven by microwave modulated signals. The architecture of the set-up (digital baseband modulation synthesis by using an AWG) offers the versatility required for in depth investigations. Two applications examples have been demonstrated : the NPR characterization and the dynamic behavioral modeling of power amplifiers. A hardware extension of the setup is quite easy to investigate different frequency band. 2 exemples have been presented in L and K bands. Thus, this new measurement setup is very useful to investigate deeply nonlinear memory effects when amplifiers are driven by complex modulations and to validate nonlinear models.
The very accurate NPR characterization enable to determine precisely nominal power and operating point of power amplifiers. This leads to decrease the power consumption of satellite payloads.
Furthermore, a novel behavioral model approach has been presented. Results obtained with a dynamic complex envelope gain (taking into account a first order nonlinear memory effects) improve considerably the usually memoryless method (AM/AM – AM/PM model).

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