History of Nonlinear Microwave Measurements.

Alain Barel
Vrije Universiteit Brussel (Dept. ELEC); Pleinlaan 2; B-1050 Brussels (Belgium)
Phone: +32.2.629.29.49; Fax: +32.2.629.28.50; Email: Alain.Barel@vub.ac.be

Vectorial network analyzers (VNA) are a key-part of any RF and microwave laboratory equipment since more than 30 years. These "S-parameters"-meters are ideal tools for linear time-invariant system analysis (or simply linear transfer functions), and were for a long time considered to be sufficient to solve all RF and microwave network analysis problems.
However, the increasing need for power-efficient high performance components and systems has pushed operating points closer to- and even in- the nonlinear operation regimes, these regimes are also called the large-signal operation regimes.
To characterize, model and verify such nonlinear systems, the linear VNA is no longer the panacea.
The following introductory lines make a short historical overview of the development of microwave vectorial network analyzers for nonlinear devices.

Historical evolution.
In an anticipation of current needs, some precursors started to explore the possibility to expand the VNA capability to nonlinear systems. A microwave measurement instrument able to characterize part of the nonlinear behavior of microwave devices was already realized back in 1990.
Indeed, the very first prototypes of microwave network analyzers for nonlinear (large-signal) circuits go back to the period 1988-1990 when Urs Lott [Ref 1] developed a frequency domain based "nonlinear" network analyzer.

From VNA to "Nonlinear" VNA: some theoretical considerations.
The basic idea of the VNA is that the output spectrum of the DUT at one frequency is only influenced by the input spectrum at the same frequency. On the other hand the nonlinear DUT creates additional spectral components different from those applied at the input of the device and can combine a number of spectral contributions at different frequencies to obtain the output components.
Characterizing a nonlinear device therefore requests that the instrument is able to measure the complete spectrum in a single measurement take.
This is not possible with the "heterodyne" measurement principle applied in linear frequency domain based network analyzers where the device response is obtained through successive excitation of the DUT at one single spectral line.
Consequently, the narrow banded "heterodyne" instrument must be abandoned in favor of a broadband instrument able to measure simultaneously the scattered and the incident wave spectra at the device ports in one take.
A fast way to reuse the "heterodyne" principle was proposed by Urs Lott [Ref 1]. The instrument measures successively each harmonic generated by the nonlinear DUT (excited by a pure sine wave) by synchronizing the linear VNA on the corresponding harmonics generated by an auxiliary generator that is phase coherent with the exciting source. Finally a known diode is used as phase reference to calibrate phase errors.
The major drawback of this approach is the assumption that the input signal is a spectrally pure sinewave, while nonlinear microwave systems often distort the input

signal through source pull. This results in the presence of harmonic excitation components on the incident wave of the DUT.

The first technology to measure simultaneously several spectra in one take relies on the availability of microwave digitizers, called DSO's (digitizing sampling oscilloscopes), which measure the fast RF time domain waveforms by an equivalent time sampling.
The "nonlinear" network analyzer proposed by the groups of Sipila-Lethinen-Porra [Ref 2] and Kompa-Van Raay [Ref 3] use both this instrument. The instrument proposed by Kompa et al. improved on the calibration accuracy through the use of a VNA. However, these instruments suffer from the poor dynamic range and the time base distorsion problems that are inherent to the DSO's.
The second brand of devices was built based on the availability of microwave samplers which perform harmonic sampling.
Harmonic sampling uses the spectral folding of an equidistant slowly sampled signal to cut the whole spectrum of the microwave signal to be measured in periodic sheets that are superposed as pages of a map (in zig-zag) at baseband. This yields a downconverted signal in baseband that contains all spectral contributions present in the original spectrum.
The further processing consists of applying the downconverted signal to an anti-aliasing low-pass filter and finally to digitize it with at least 14 bits. Special care must also be taken to synchronize carefully the sampling heads of the four channels to guarantee the coherence of the four signals.

Harmonic sampling is able to measure simultaneously the harmonics and the intermodulation terms generated by the nonlinear DUT. Even if the excitation signals consists of several spectral tones as like is the case for modulated signals (CDMA, ODFM, etc), the instrument still cleans the job.

The group Demmler-Tasker-Schlechtweg [Ref 4] in 1994 followed by the group Clark-Chrisikos-Moulthrop-Muha-Silva in 1998 [Ref 5], developed an instrument where the sampling scope is replaced by a MTA (Microwave Transition Analyzer) that uses a harmonic sampling downconvertor.
Simultaneously, a co-operation between the Agilent-NMDG group (at that time still called Hewlett-Packard) and the department ELEC/VUB of the Vrije Universiteit Brussel [Ref 6 to 10] developed a "Large-Signal Network Analyzer" (LSNA) based on MTA-technology, but with full control on the frequency down conversion mechanism.
The contribution of the Agilent-NMDG group was the key to benefit from the internal expertise of the MTA by which the instrument is able to perform versatile harmonic sampling [Ref 11 and 12].
A second challenge was to make a quantum leap towards the full calibration of the microwave nonlinear network analyzer for nonlinear circuits.
At this stage already six different names have been given to this new measurement instrument: NonLinear Network Analyzer (NLNA), Nonlinear Vectorial Network Analyzer (NVNA), Vectorial NonLinear Network Analyzer (VNLNA), Nonlinear Network Analyzer System (NNAS), Nonlinear Network Measurement System (NNMS) and Large-Signal Network Analyzer (LSNA).
Because all these names have been used in the literature, and avoiding the reader to get confused, we decided that all contributions to this special issue of the Revue HF use the same name: Large-Signal Network Analyzer (LSNA).

The collaborative goal of Agilent-NMDG and ELEC/VUB have been reached: the new instrument is born in 1994: The obtained LSNA operates as an absolute wave meter that captures the whole wave spectrum of a two-port device (4 waves) in a single measurement. The instrument measures the absolute magnitude of the waves as well as the absolute phase relations between harmonic components of the spectrum. Or in other words, the LSNA can be seen as a "Fourier analyzer for microwaves".

Restriction of the class on nonlinearities that can be measured.

The LSNA is seemingly capable to extend the capability of the VNA. But, to characterize a nonlinear system is in itself a major challenge, as the nonlinear system is at least one order of magnitude more complex than it's linear time invariant counterpart.

The first problem to consider is to restrict the class of nonlinear systems to a subclass that is wide enough to contain major applications and narrow enough to rule out excessive complexity.

Since the LSNA is based on harmonic sampling, it can only characterize periodic signals. Therefore, assuming that the periodicity at the input and the output must be the same, is a natural hypothesis.

Microwave systems which show a chaotic behavior or are presenting hysteresis do not obey this rule. As a consequence, they can not be measured by the present versions of the nonlinear network analyzer.

This restriction allows nevertheless to characterize an extremely wide range of devices among which the devices that show saturation with increasing input signal are the most common case.

Up to now, no specific name has been given to this category of devices. Rolain [Ref 29] proposes to call them NICE; this is not an acronym, it just express that the devices are well-behaved nonlinear devices unlike the "ugly" chaotic and hysteretic are.

Applying the right excitation signal.

Even in the restricted class of NICE systems, it is no longer possible to describe a nonlinear system in general for an arbitrary input based on measurements belonging to another class of excitation signals.

Putting it another way, a sinewave test on a nonlinear device will never allow you to characterize the spectral regrowth for an OFDM signal.

Instead of just characterizing a device, we will need to restrict our goal to the characterization of a device for a certain class of excitation signals.

This explains the present quest to more complex generators.

As for today, the LSNA instrument designed at Brussels handles fully absolute calibrated two port measurements in CW and in modulated regime.

How to describe the measured nonlinearity? Need of data-processing.

Nonlinear characterization tends to present an awful lot of data. At least two dimensions need to be scanned (frequency and power) and each measured couple results in a full set of four measured spectra.

To present this data in an informative format to the user hence is a major challenge.

If there is no, or if the user doesn't want to implement a model, the measured results can only be presented on a non-parametric way.

This consists of just producing the classical plots of the AM/AM and the AM/PM curves. Note that these data can be measured with a linear network analyzer, provide it can operate in amplitude sweep mode.
Belonging to the same family are the “energy transport” plots where the amplitude (and phase) of the higher order harmonics or of the intermodulation terms “grow” as function of the input signal power. Remark that this presentation of the measured results has the advantage to make a soft transition with the classical linear measurements.
If the following hypothesis holds, by which there is a dominant term in the spectrum of the measured waves, then the large-signal S-parameters can be used as black-box descriptors of the microwave devices.

When the user is not afraid of a model, then we call it a parametric approach of the problem.
It consists of using a nonlinear mathematical model to describe the behavior of the device. That formalism replaces quite efficiently all the non-parametric plots.
Different mathematical formalisms can be considered: it goes from the device physical models to the pure black-box models.
Device models of transistors are in direct relation with the foundry chip process parameters and should be scalable to the layout parameters of the transistor.
On the other hand, a black-box model is able to describe any circuit going from the single transistor to a complete microwave system.
Between the white and the black box models, a whole class of measurement based transistor device models exists which are extremely useful equivalent circuits in simulations, but not related to the chip process parameters.

<u>R&D-activities in nonlinear microwave measurements worldwide.</u>
The research on nonlinear microwave measurements splits at least in two parts: the measurement instrument itself, and the characterization of microwave nonlinear devices, as transistor models and black-box models.
Research on the first topic is one of the main activities of the Agilent NMDG group for support of the development of the commercial nonlinear vectorial network analyzer [Ref 8 to 10 and 13, 14].
Yves Rolain and Wendy Van Moer (VUB/Dept ELEC) developed research on the same topic but with an academic finality [Ref 15 to 30].
Research on the second topic covers the modelling of transistors for large signals but also the characterization of microwave nonlinear devices as a black-box model.
Dominique Schreurs (K.U.Leuven/ESAT-TELEMIC), Paul Tasker (University of Cardiff, UK), Jean-Pierre Raskin (UCL/EMIC) and Don DeGroot (NIST) are active on this topic.

The group of Limoges (Quéré and Nébus) concentrates it’s activities on the nonlinear PAE and Load-Pull measurement techniques.
The group of the Aerospace Corporation (Silva) [Ref 5] uses their time domain nonlinear network analyzer for the measurement and the modeling of Travelling Wave Tube amplifiers as a generalized Wiener-Hammerstein cascade of black-boxes.

<u>Some philosophical conclusions about nonlinear measurements:</u>
The experimentor who wants to describe nonlinear devices has to restrict himself to a certain class of nonlinearities, has to choose a class of nonlinear models and

has to select a class of excitation signals; finally he has to live within these constrains.
When choosing a class of excitation signals, the experimentor should mimic the real world operation conditions of the device (Multisine spectral engineering).

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