NVNA Users' Forum: Mission and Overview*

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Abstract — **This paper introduces readers to the NVNA Users' Forum, an informal discussion group devoted to sharing information and issues related to instrumentation utilized in vector large-signal network analysis of microwave circuits and systems that contain nonlinear elements. The Forum was initiated by the Automatic RF Techniques Group (ARFTG) in 2002 [1], and is now organized for the first time in Europe as a Focused Session of the European Microwave Conference. We outline the typical agenda of this Forum, and illustrate this with some highlights of past meetings.**

I. INTRODUCTION

During the 1990s, technological and theoretical advances greatly simplified the direct measurement of the complex large-signal response of devices, circuits, and systems containing nonlinear elements. Tools for performing large-signal measurements include [2] load-pull systems, vector-signal analyzers, real-time analyzers, and oscilloscopes. Recent additions to this collection of tools include instruments capable of direct large-signal network analysis, such as the microwave transition analyzer (MTA) [3, 4], and its two-port extension that includes an external phase calibration, the large-signal network analyzer (LSNA) [5, 6]. These last instruments were enabled through development of special calibration techniques, including calibration of the phase of harmonic components of a signal relative to its fundamental frequency [7-11].

For the purposes of the Users' Forum discussion group, all of the instruments described above are lumped together under the general classification of Nonlinear Vector Network Analyzers (NVNAs), even though certain instruments are not directly capable of network analysis.

Over the last few years, technical papers on large-signal measurement methods have become more and more prevalent in the literature. Many of these papers have been presented at the semi-annual Automatic RF Techniques Group (ARFTG) Microwave Measurements Conference in the United States. As indicated by the name, this conference is devoted entirely to the topic of microwave measurement techniques. Its relatively small size (typically ~100 attendees) and informal atmosphere facilitates discussion with like-minded engineers on many topics of interest.

Three years ago, ARFTG introduced the half-day Nonlinear Measurements Workshop at its fall meeting. This workshop is organized each year by an expert in some aspect of nonlinear measurement with a different emphasis each time.

A natural outgrowth of this workshop was the NVNA Users' Forum [1], whose initial meeting occurred two years ago. A group of ARFTG members, including the authors of this paper, decided that it might be of interest to engineers who use or are interested in learning more about vector large-signal measurements to gather together and discuss issues unique to this new technology. Because ARFTG was originally formed as a Vector Network Analyzer (VNA) users' group, the organization seemed like a natural sponsor.

The NVNA Users' Forum is: "an informal discussion group devoted to sharing information and issues related to instrumentation utilized in vector large-signal network analysis of microwave circuits and systems that contain nonlinear elements."

To date, four meetings have taken place; the first was held in Washington, D.C. in the fall of 2002, where about 25 attendees introduced themselves, their research projects, and their interest in nonlinear vector network analysis to each other. The group decided that the forum was of interest and decided to meet again at the next ARFTG conference. The second meeting was held in Philadelphia, PA, in conjunction with the spring 2003 ARFTG conference and the IEEE International Microwave Symposium (IMS). This meeting was attended by about 30 participants. Attendance during the spring forums is typically higher since many engineers interested in nonlinear measurements and modeling regularly attend the IMS meeting. At this second meeting the concept of moderated discussions on topics of interest to the participants was successfully tried out. It was decided to continue these discussions at future meetings.

The third meeting, held in Boulder, CO, again saw a high-level of interaction between the 30 or so participants through the moderated discussion format. The fourth meeting was held in conjunction with the 2004 spring ARFTG conference and IMS in Fort Worth, TX. More than 35 participated. At this meeting, we included brief research updates from a small number of institutions, as well a presentation and discussion of the Ph.D. work of a student whose research might benefit from discussion with engineers involved in the complicated technical area of nonlinear network analysis. Notes from the first four meetings have been summarized, and are presented in Ref. [1].

Based on the first four NVNA Users' Forums, a typical agenda follows in the next section. One of the unique aspects of the Users' Forum is the moderated discussion segment of each meeting. Summaries of some of these discussions follows in Section III. Section IV is devoted to an overview of current research in the field of NVNA measurement technology. New work on several of these topics has been introduced in the research updates from past and present meetings. Note that additional papers in the NVNA Users' Forum Focused Session segment of the European Microwave Conference Proceedings are based on research updates first presented at the NVNA Users' Forum.

II. Typical Agenda

The outline of a typical agenda is as follows:

- 05 mins: Introductions
- 25 mins: Discussion topic 1
- 25 mins: Discussion topic 2
- 25 mins: Research updates
- 15 mins: Discussion of Ph.D. research in one area
- 25 mins: Demos, announcements, and open discussion

Total: 2 hours

After a welcoming introduction, two interactive discussions follow. The topics are proposed by the participants in advance. Some examples are summarized in Section III. Next, we offer the opportunity for short research updates from 3 to 5 labs with new results (see Section IV). The next item on the agenda is to involve more young researchers in this Users' Forum. A Ph.D. student then introduces his/her research in the nonlinear field and asks for help with problems and suggestions from the "senior" (more experienced) researchers. Thereafter, participants are given the opportunity to show demonstrations of in-house developed applications, which are mostly software tools. The Forum is ended by making some final announcements.

III. Discussion Topics

As the objective of this Users' Forum is to exchange experiences and share knowledge, interactive discussions are an important part of the meeting. We selected four of the topics already covered and give a flavour of the discussion results below.

- *"Are current large-signal measurement hardware set-ups adequate to support the needs of behavioural modelling techniques?"*

A first aspect is the bandwidth of the instrumentation. In the case of the Large Signal Network Analyzer (LSNA) instrument, for example, the lower frequency of the measurement bandwidth is 600 MHz, due to the bandwidth of the phase reference standard. The attendees feel that this seriously restricts multi-tone characterizations, and consequently the modelling. On the other hand, the 40 GHz (MTA & LSNA) upper frequency of the measurement bandwidth is considered high enough for most nonlinear applications that participants are working on.

A second aspect is the importance of load-pull. For device modelling, the load conditions of the device under test are often critical. Participants have noted that there is a need for not only passive but also active loadpull.

A third aspect is the observation that the need for three-port and multi-port measurements is growing very fast. There already exists a prototype implementation in an academic research group that allows for three-port (mixer characterizations and differential measurements [12], but this is not commercially available yet.

- *"Software: What do users want their large-signal measurement control software to do?"*

A discussion point was the User Interface (UI). For academic researchers, it is not essential to have a nice GUI (Graphic User Interface), but it is for an industrial environment. It was also felt that researchers prefer having access to the in-depth controls of the hardware, and that the software should not implicitly make decisions such as fixing values of instrument parameters. A suggestion was to have a "power user" button on the instrument that would give users who so desired more access to settings, while allowing general users to rely more on the UI for set-up.

- *"Phase calibrations—how necessary are they?"*

The opening statement is that phase calibrations are not essential as long as the measurement bandwidth is small as compared to the bandwidth of the samplers, e.g., a 20 GHz LSNA using 40 GHz samplers. However, a phase calibration is necessary to assess which level of error is made. The whole point is to have a traceable standard, and this standard has to be better than what users use in practice. In this regard, NIST researchers briefly described their on-going activities.

- *"What is the status of research on measurement-based behavioural modelling? Is it still academic or are these techniques being used on a large scale? What is missing to further deploy these techniques?"*

It was pointed out that the bottleneck is not directly the measurements, but the difficulty of implementing models in CAD software, because this is often not well documented and supported. For example, it should be possible to include warnings to inform users when models get extrapolated, as an inherent drawback of behavioural models is their limited validity, usually restricted to a class of signals and/or operating space. Also, as these models are measurement based, it requires expertise to collect the appropriate set of data.

IV. RESEARCH UPDATES

Most of the topics that are discussed during the ARFTG NVNA Users' Forum can be split up into three main categories:

- Measurement of nonlinear systems
- Calibration of nonlinear measurements
- Modelling of nonlinear systems

The latest developments in these areas are summarized in the following paragraphs:

- ***Measurement of nonlinear systems***

Load- and source-pull measurements [13]

For many years, calibration techniques and measurement accuracy have been studied in depth for S-parameter measurements using VNAs. Today, Large-Signal Network Analyzers are used to characterize the nonlinear behavior of components. In contrast to VNAs the stimulus cannot be switched from input to output and vice versa. Also LSNAs need to characterize components with source and load impedances different from 50 ohms. These requirements demand special calibration care, even for the relative portion of the calibration process. Techniques have been developed that allow a user to perform accurate large-signal measurements with impedances different from ohms. A properly adapted SOLT calibration technique and de-embedding of the characteristics of the tuners makes it possible to perform accurate large-signal measurements in a non-50-ohm environment.

Differential measurements

A hot topic these days is differential measurement! However most measurement instruments are designed to measure single-input-single-output devices and so they need to be adapted to be able to perform differential measurements. To that extend, new coaxial-to-differential adapters were designed and fabricated [14].

Furthermore, the classical two-port LSNA has been extended to three ports. This allows a user to do nonlinear differential measurements as well as mixer measurements.

To be able to do precise differential measurement, one also needs a differential signal source. A new measurement procedure for the nonlinear baseband response of a differential amplifier has been developed. The setup uses only one single-ended RF generator. A simplified nonparametric model for the frequency response of the device and its nonlinear contributions over a wide power range has been proposed, measured and validated experimentally [12].

- ***Calibration of nonlinear measurements***

Repeatability of commercial Harmonic Phase Standards [15]

In the first published repeatability study of commercial harmonic phase standards (HPS) measured by a Large-Signal Network Analyzer, two harmonic phase standards were measured. One is specified to 20 GHz and the other to 50 GHz. By performing five calibrations and making 100 measurements from 600 MHz to 19.8 GHz for each calibration, the repeatability bounds for the complex wave-variable vectors and associated phases and magnitudes of each harmonic component could be determined. The mean phase values were then compared to those supplied by the manufacturer. Although the standard uncertainties were no greater than 0.73 degrees, significant variations were found in the mean values with changing HPS conditions and show evidence of a substantial thermal contribution.

- ***Modelling of nonlinear systems***

Extraction of conversion matrices for PHEMTs based on Vector Large-Signal Measurements [16]

The objective of this research work is to provide a behavioral frequency-domain description of a nonlinear device suitable for mixer design starting from large-signal vector measurements. The conversion matrix is evaluated directly from LSNA measurements eliminating the need for accurate device models and large-signal analysis in mixer design. The validation of the developed method is obtained through circuit-level comparison and by VNA measurements.

State-space modelling of slow-memory effects based on multisine vector measurements [17]

Nonlinear microwave devices and circuits often exhibit slow-memory effects. When subjected to two-tone or more general multisine excitations, the characteristics of these devices and circuits depend on the offset frequency between the tones. Since modulated excitations are an integral part of telecommunication systems, models aimed for circuit and system design should be able to accurately represent slow-memory behavior. A modelling procedure was developed based on the state-space modelling approach to accurately incorporate these slow-memory effects. The state-space procedure relies on large-signal measurements for model extraction.

V. CONCLUSION

This paper has presented an overview of the ARFTG NVNA Users' Forum. The forum serves both as a discussion group and as an opportunity for labs to present their latest research in the area of vector large-signal measurements to an audience of like-minded engineers. An important aspect of the forum is its interactivity. Whether one is an experienced NVNA user or someone just starting out, the forum encourages participation and interaction.

This fall, the ARFTG NVNA Users' Forum will be co-sponsored by the European Network of Excellence TARGET and will occur as a Focused Session at the European Microwave Conference. Papers based on extensions of research updates first given at the Users' Forum appear in the proceedings of the European Microwave Conference under the sponsorship of the Users' Forum Focused Session. Anyone interested in finding out more about large-signal measurements is

encouraged to read these papers and attend the special session.

ACKNOWLEDGEMENT

The authors acknowledge and thank all attendees in the Users' Forums for their constructive input in the discussions and for sharing their latest research results. This Users' Forum is supported by the ARFTG organization and the European Network of Excellence TARGET.

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