Introduction for the draft reviewers

This document was drafted through an effort initiated by Anritsu and with the help of AWR, NMDG, HFE, and Mesuro. It is offered as a document for broader OWF consideration for the purposes stated within as an aid to the industry as a whole. Those who've worked on it thank you in advance for your time and effort in providing your constructive feedback so that the OWF can bring to fruition the aims of this work.

Kind regards,

The OWF Compatibility working group.

Note to Document Reviewers:

Various references are provided at the end of this document in section 10 as a general guide to initial recommendations for documented references; this is not meant as an exhaustive list or even a list that should be in the final version of the document. In reviewing the text "[ref]" appears where it may be appropriate to include an external reference as a service and/or aid to the eventual end-users of this document. In both cases, please make recommendations for both.

Comments from reviewers are marked with an asterisk (*) and can be found in the Addendum "Reviewers Comments'

OpenWave Forum

(www.openwaveforum.org)

Nonlinear Measurement-Based Modelling

Compatibility Document

Draft Proposal

May 31, 2011

1. Overview

The OpenWave Forum (OWF) exists to further RF/microwave industry-wide interaction on measurement-based modelling as a means for discussing support for, and compliance with, end-users needs in this area.

The purpose of this document is to define OWF compatibility for the simulation of nonlinear behavioural model from nonlinear vector network analyser measurements.

While this document defines the OWF capability for nonlinear measurement-based behavioural models (NMBM), it cannot be defined apart from considering the end-users' use of the capability as well as their needs. It is not possible to define NMBM as a single relationship among user, measurement and model: there are unique user-communities each with a finite number of issues which need to be considered regarding both measurement and model if a useful representation of the DUT is be achieved. Indeed "useful" is defined by the user.

End-users want models directly from measurement without the need to "fit" parameters or worry about extractions. Measurement-based behavioural models theoretically enable this. The overall aim, therefore, is to allow a user to go directly from measurement to simulation by simply moving a data file from the test and measurement system to the simulation software. Similar, a nonlinear circuit in a simulator should be able to create a NMBM that represents the essential performance of the circuit without the schematic details which would otherwise reveal the designer's IP.

No post-processing of the NMBM data file should be required if appropriate attention is given to the measurement set-up (be it from a hardware test or a simulation analysis): all the measurement data taken will allow for the complete elaboration of the behavioural model needed for the desired simulated behaviour. Conversely, if the appropriate hardware test or simulation analysis has been done, then the NMBM should capture the essentially feature desired. This document defines how to formulate such tests and simulations and the issues which must be considered to do so.

The structure of the document is as follows. Background information (section 4) as to motivation for the move to NMBM and the purpose for this document (section 5) precede requirements (section 6) and a general specification for the measurement, extraction, formatting, and simulation associated with these models (section 7). Examples (section 8), exceptions and expanded information for specific models (section 9) is also provided.

2. Revision History

Revision	Date	Who	Description
0.1	September 2010	Anritsu	Initial draft outline
0.2	December 2010	Anritsu	Complete initial draft
0.2.1	January 2011	Anritsu	NMDG file format proposal, AWR edits
0.3	March 2011	Working Group	Draft for initial OWF review
0.3.1	May 2011	Working Group	Response to April 2011 Reviewers Comments

0.3.2	May 2011	Working Group	Format changes, TM modifications

3. Definitions

Note to Document Reviewers: Please recommend terms to be included as well as definitions for those terms.

Cardiff Model

Compact model – parameter based model where model parameters defining a set of analytical equations are used to mimic essential device performance.

DUT – Device Under Test

Measurement point – combination of input signal characteristics and terminations defining one single measurement.

NMBM – Nonlinear Measurement-based Behavioural Model

PHD – Poly-Harmonic Distortion.

NMDG's S-Functions

Agilent's X-Parameters®

Note: X-Parameters are a registered trademark of Agilent Technologies.

4. Background

4.1. Introduction

The facility provided by S-parameters has underpinned the success of the RF/microwave industry for more than half a century. Product development has recently seen a push toward design performance where linear s-parameters are insufficient and there is a desire for more and more need nonlinear simulation prior to hardware prototyping:

- system level and/or concurrent design,
- design complexity driven by more complex modulation schemes and denser circuits, and
- aggressive design goals with associated shrinking design margins.

A nonlinear version of S-parameters is clearly needed as component vendors are unable to satisfy end-users simulation requirements with parameter-based "compact" models. At one extreme, compact models are difficult to develop if they are to capture the necessary behaviour of the device. While individually, the input-output characteristics of a component are simple to represent (i.e. Pin vs. Pout as a function of frequency), it is much more difficult to capture all the interlocking dependent behaviours one would like to have in a model. Second, the parameter space necessary to support such models can be exhaustive and parameter extraction from measured data is not analytical or even intuitive.

The overall aim, therefore, is to allow a user to go directly from measurement to simulation by simply moving a data file from the test and measurement system to the simulation software. A nonlinear analogy, or extension, to S-parameters would in theory eliminating many short-comings of compact models. There would be no need to develop behavioural or physical equations describing the input-output relationships for the device. Extraction would be a turn-key process solely determined at each measurement and just like an s-parameter file, a larger measurement-based file representing the NMBM would be a direct consequence of more measurement and operating points for the model.

A measurement-based model is a simple matter for linear, small-signal measurement based behavioural models (i.e. S-parameters) owing to the very nature of the behaviour that is trying to be captured: it is linear. S-parameters can be used to fulfil this objective by choosing a sufficiently low input power to assure that the linearity requirements are met over the frequencies of interest. The only care aside from "low" input power is that a frequency sweep plan must be developed which is sufficiently dense to capture the necessary phenomena given the frequency characteristics of the DUT and the overall circuit. Overly dense frequency sweep plans create unnecessarily large data files while insufficient ones miss resonances and other essential features.

Nonlinear measurement based behavioural models are even more difficult to design measurement or simulation plans for. In addition to the frequency range as an independent variable determining the model, there are several other factors. And in actuality, if frequency conversion is involved, then frequencies need to be planned very carefully. NMBM require consideration of three key areas to assure accurate representation of DUT performance.

First, the input signal characteristics need to be defined. Primarily, for nonlinear characterization, this would require definition of the input power levels over which the model is valid. Keeping strictly to the notion of behavioural model, this should be determined by the behaviour trying to be modelled. Additionally, the number of measurement tones and how measurement and simulation stimulus are related needs to be considered.. Second, and on a related note, the device operation itself needs to be considered. The behaviour of the DUT can be linear, weakly nonlinear or (highly) nonlinear. Third, the impedance environment needs to be considered, especially if the DUT is not impedance matched, not just at the fundamental for the primary tone, but at all harmonics of sufficient power of all tones involved. Appropriate calibration of tonal harmonics at the input cannot be underestimated [6] especially because relative phase is so critical to measurement accuracy [10].

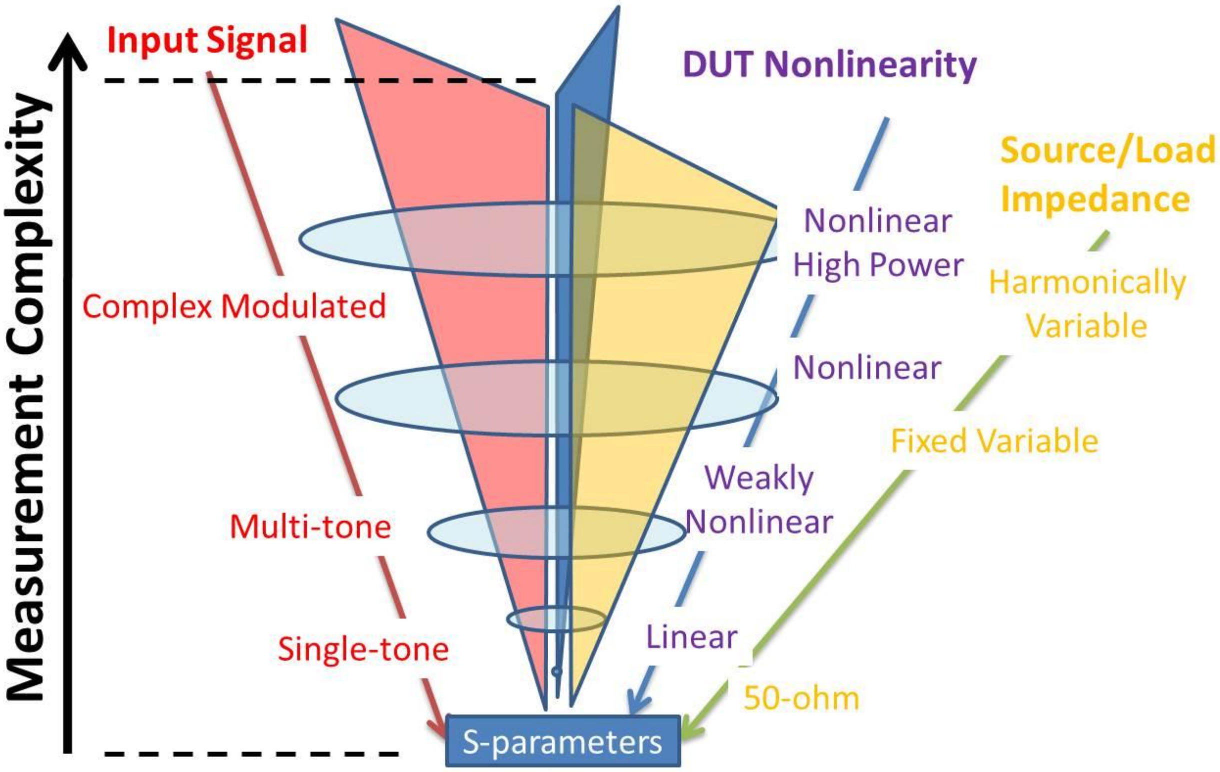

Figure 1 – Input signal composition, DUT behaviour and the measurement impedance environment all contribute to the ease or complexity of both measurement, and model, complexity.

4.2. NMBM representations

Three representations of NMBM are currently enjoying popular following. X-Parameters™, S-Functions, and the Cardiff model all represent approaches to reproducing behaviour of nonlinear devices without the need for a detailed schematic representation or parameter-fitting to a compact model. An excellent treatment at an overview level can be found in [1].

As a working example, Agilent X-Parameters are considered to discuss issues with measurement and simulation planning discussed in section 5.1, above.

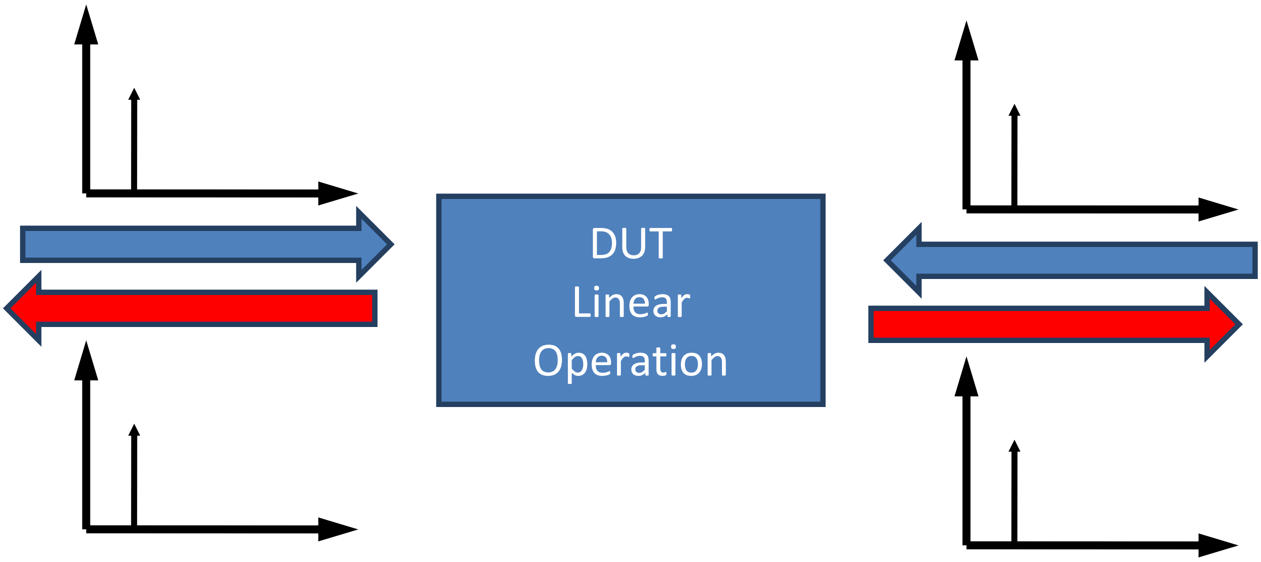

Figure 2 – DUT under linear operation. Only the fundamental is considered during the linear measurement as there is no harmonic generation when the DUT is linear. For an excitation at the input, the power is measured at the input (as a reflected power) and at the output.

Agilent X-Parameters offer a generalized representation and extension from S-parameters aimed at capturing nonlinear behaviour. The S-parameter notion of incident and reflected waves is extended to harmonics and power levels. So a set of X-Parameters are not just defined for a given input frequency, but for power levels of that input frequency. For simplicity, we assume a single tone excitation where that single tone is a large-signal so that it induces nonlinear behaviour; X-Parameters are then swept over the frequency and power level of the fundamental of this tonal input. The “measured” X-Parameters are comprised of several components. First, there will be a reflected wave at the port where the input tone is applied. Similar to the operation of a VNA but for large-signal, the (large-signal) A wave going into this port produces large-signal reflected, or B-waves, but since this is a large-signal excitation, we expect to see B-waves not just at the fundamental but also at the harmonics of the tone. The combination of the A-wave and the B-waves at the driving port completely defines the behaviour at that port. For the other ports of the DUT, we have a B-wave representing the direct effect of driving fundamental appearing at each of the non-driven ports at each of the desired harmonics. So B22 represents the large-signal reflected wave from port 2 at the second harmonic. Additionally, there are S terms which correspond to a small signal wave appearing at a port a given harmonic that are caused by a small-signal excitation input at some port at some harmonic: S22,13 would be a small-signal component appearing at port 2 at the second harmonic due to an excitation at port 1 of the third harmonic.

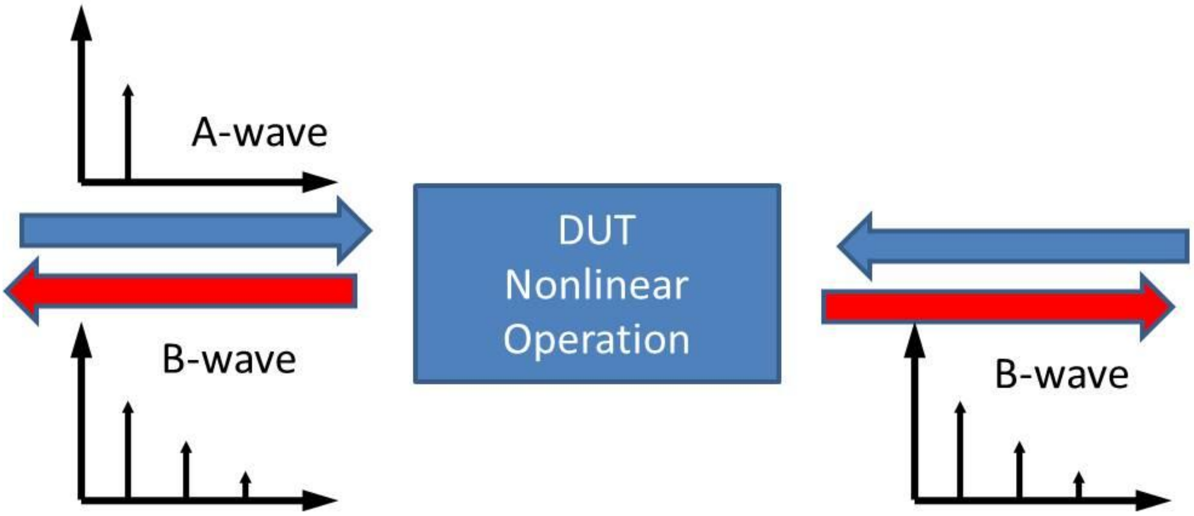

Figure 3 – Fundamental excitation at the input by the A-wave results in B-waves with harmonic content at the other ports.

Direct measurement of the A- and B- waves at each port due to each excitation and all the necessary harmonics is the most straightforward method. Separating out the individual contributions can be difficult, especially if ports are not terminated at precisely 50 ohms for each and every harmonic that is being tracked. This makes obvious and imperative that for DUTs of any complexity, harmonic load-pull is almost an essential extension to the use of NVNAs when accurate NMBM are sought.

Another method of measuring the effect of the large-signal drive tone is to use an offset, or tickle tone. Using the notion of small-signal mixer analysis the offset tone is chosen within 1 KHz of the presumably GHz drive-tone. In addition to the S term—which reduces to the S-parameter in the absence of the large-signal and for the offset going to zero--a T term provides a phase conjugate representation of the S term that results from using the small-signal as a “probing”. The presence of the S and T components also contribute to the ability to include nonideal and varying harmonic terminations. In practice the phase of the offset tone is known but cannot be specified, so several measurements are required to determine S and T.

A more complete description of Agilent X-Parameters can be found in [10].

From this brief description it is obvious that certain aspects of the X-parameter dataset need to be planned prior to its creation even for a simple single tone large-signal drive. First, the input signal planning must include not just a frequency sweep, but a power sweep and consideration of the number of harmonics to track. Second, the small-signal effects will be captured through the use of a tone slightly offset from this fundamental.

4.3. Customer motivation – measurement-based behavioural modelling

It would be much simpler if there was one driving requirement from end-users for NMBMs. In reality, there are many. In this section, the end-users’ requirements are discussed. Moreover, it is apparent that there are three classes of end-user: those taking the measurements, those responsible for turning the measurements into models, and those using the models.

4.3.1.DUT complexity

If the DUT and/or its behaviour are very complicated, then a behavioural model is easier to develop than a compact model because there is no need to determine the analytical relationship among the developed parameter set.

Many DUTs have analog or digital controls specifying its behaviour. Turn-down modes, digital tuning, external AGC loops are all examples. Even a single transistor is a good example as when S-parameters are measured, a wide range of bias conditions are used. Careful planning of these is required.

DUT's can be linear, weakly nonlinear or strongly nonlinear. Users of NMBM require assurance that the model can be used for these different conditions. In the limit of linear capability, the models should revert to S-parameter equivalent behaviour in both test and simulation.

DUT behaviour can be difficult to test and measure but this impacts models of all types. Notwithstanding the desire to have NMBM some behaviour and DUTs are naturally difficult to measure. The availability of NMBM does not eliminate this. NVNAs naturally make nonlinear measurement easier by providing COTS solution rather than a custom solution, but this does not change the fact that some DUTs and DUT behaviours require complex test and measurement.

With this in mind, this specification does not include the following:

Frequency-conversion DUTs are not handled in this revision. This also includes oscillators and synthesizers.

Three- and higher port counts are not handled in this revision except as an obvious extension to their two-port counterparts defined herein.

4.3.2.Compact model complexity

Compact models can be simple or difficult. From the end-user perspective, complexity creeps in when no analytical solution exists for parameter extraction based on measurements. Progress in compact modelling has associated with parameter extraction and, sometimes, the need for custom software. Both of these are undesirable from the perspective of those providing the model and those using the model. The latter group wants simply to have their EDA software, get a file from the component vendor, and start designing. There are normally installation and debugging issues, if not extra costs, associated with custom models which act as a barrier to using the model and therefore the component. The former group would prefer to eliminate the need for parameter extraction procedures as this requires additional infrastructure (automated systems), consultants, or highly-specialized employees.

4.3.3.Input signal complexity

Input signal can be swept in frequency. Knowing the sweep range and the step size is not always obvious when needing to use measurements in simulation. An NMBM can be developed directly from the same input signal seen by the DUT in the actual product if the team creating the NMBM is aware of how the designer intends to use the DUT. This may not always be the case if the component provider is also providing the model. That being said, components are often (but not always) targeted at specific applications, e.g. GSM/EDGE handset PAs, WiMAX basestation receivers, etc.

Input signals must also be swept in power. This is the whole point of the nonlinear modelling exercise. Since DUTs behaviour can be characterized as linear, weakly nonlinear, or strongly nonlinear, the input signal sweep plan should include those aspects of DUT behaviour required for the NMBM

Input signals can be single, multi-tone, and complex modulated. One potential benefit for the NMBM is that under some DUT conditions and with certain simulators, the NBMB can be used in ways that go beyond how the measurement was taken. Different NMBMs by their nature will do this for some cases better than others; in some instances the NMBM should not be used in this manner. For example, the use of the tickle tone with X-Parameters™ and S-functions mean that a traditional two-tone measurement should be fairly well represented. .

4.3.4.Design of test and measurement plan

The measurement must be designed to appropriately represent all the independent measurement variables required to accurately model the device. Sweep plans for frequency and power at each tone or waveform, and the varying input/output impedance(s), if any, need to be designed relative to the desired simulation environment of the DUT. Of particular importance here is measurement density [6] and the trade-off between measurement time and model accuracy.

In short the input signal construction for measurement needs and the load-pull needs to be designed based on how the device is to be simulated.

A simple T&M plan may suffice for a simple use of a DUT. More complex DUT applications will suffer if a model developed from a simple T&M plan provides insufficient coverage and accuracy.

4.3.5. IP protection

NMBM allows component manufacturers to provide high levels of model functionality (assuming appropriate measurement point density) without the need to release any IP beyond that afforded someone with the related DUT.

4.4. Nonlinearity

Nonlinear is anything “not linear”. Since linear implies a single tone input yielding a single tone response (i.e. just the fundamental) *and* superposition of signals, anything violating this is nonlinear. This section discusses different sources of DUT behaviour where linear approximations breakdown. Working definitions for quantifying nonlinear are provided in section 8.2

4.4.1.Trapping

Time-constants associated with trapping can induce asymmetries in two-tone and multi-tone measurements. Trapping effects can range over the full spectrum of frequency. Trapping effects can be excited in pulsed operation but they can also be seen in steady-state multi-tone measurements.

4.4.2. Impact Ionization

Impact ionization can complicate trapping-related effects. Impact-ionization effects are steady-state and can be seen in S-parameter data taken over multiple bias conditions. [ref]. Changes in drive levels associated with nonlinear behaviour can push a device into and out of operational areas where impact ionization is a factor.

4.4.3. Thermal heating

Thermal effects can cause a rebiasing of the device and has a time-constant that can be significantly different than trapping effects. Thermal heating can also lead to memory effects [3]. As the thermal conditions are directly related to the overall system, the drive tone can contribute to observed thermal behaviour or even dominate it relative to the effect of the steady-state operating conditions. Modern DUTs, with external controls and power turn-down capabilities may operate under non-ideal thermal conditions as part of their regular operation.

4.4.4. Memory effects

Complex DUTs with active and passive circuitry can exhibit long-term, non-steady state effects. These effects can be due to semiconductor self-heating, trapping as well as bias networks and can be exacerbated by impedance termination at tonal harmonics as well as at baseband [4]. It is not uncommon for memory to be induced by a circuit's DC network...

4.5. Source/Load terminations

The difference between the impedance at the input of the DUT and the impedance at the source creates additional reflected power which can significantly alter the operation of the device. The same is true for the output of the DUT and the load. Significant amounts of reflected power effectively rebias the device but even at small signal conditions, the reflected signal mixes the all the other tones/harmonics in the DUT.

The reflection due to termination mismatch occurs dynamically as well. As the DUT's operation changes, the equivalent impedances it presents at the output and input will vary. With nonlinear drive, higher drive levels will change these equivalent impedances.

Even more complicating is that both these effects—reflected power and DUT equivalent input/output impedance—are concerns for both fundamental and harmonics of each input tone. With significantly nonlinear systems, it might be desirable to track 5 harmonics.

In practice, "load pull" systems are used to alter the impedance presented to the DUT. Despite the name, a load-pull arrangement can be used on the source as well to provide a desired impedance to the input. Harmonic load-pull is very complicated but is necessary in highly nonlinear systems to extend the operational range or performance of the DUT. Automated harmonic load-pull systems are challenging to implement while single tone systems are generally simple and easy to use.

4.6. Interpolation effects

Interpolation of NMBM performance in between measured or simulated data points can cause significant departures from actual DUT behaviour if the measurement plan is not appropriately matched to the DUT's performance. Resonance can be missed in frequency sweeps. Optimal positions in bias points can be overlooked. Local IM3 minima may not appear when they actually exist in real devices/components. [ref]

4.7. Extrapolation Effects

NMBMs created over measurement plans limited in frequency, power, harmonics, impedance variation, harmonic impedance matching, are subject to extrapolation when used by the simulator. Such extrapolations, while mathematically sound or justified, may not represent real device performance.

5. Problem Statement and Purpose

In light of the general complexities of the measurement and modelling of, and of designing with, nonlinear devices, the user community is confronted by the problem of how to assess NMBM solutions and usage. For example, it is unclear to the user community the nature of the correspondence among DUT behaviour, measurement system capability/limitation, and model accuracy/extensibility. Furthermore, the industry lacks a consistent vocabulary for a discussion of this issue.

The purpose of this document is to define NMBM capability so that end-users can determine their NMBM need against a consistent set of criteria. Harmony and consistency among measurement, modelling, and simulation solutions is specified in terms of tiered sets of expanding capability along the lines of input signal complexity, DUT nonlinearity, and impedance environment. Terminology is defined to specifically address the need for a consistent dialogue.

6. Requirements Overview*

Summarizing the details discussed in previous sections it is clear that there are three distinct models to be supported: X-Parameters, S-functions, and the Cardiff model.

Not as obvious is that there are three distinct users with diverse needs: test and measurement(TM), modelling, and design. The TM user needs an easy setup despite the added complexity of nonlinear versus linear measurements. There is a trade-off for the TM user between this ease of use and accuracy; the data file that is created should accurately convey the measurements made on the actual device. The modelling user needs to protect the intellectual property of the DUT, have no explicit parameter extraction, and no custom modelling effort. The first and third of these requirements are inherent in all three models. The latter two can be summarized by saying that the NMBM capability should be part of the commercial off-the-shelf capability of the test equipment and EDA tool, respectively. The design user needs the same EDA requirement as the modelling user but also has an accuracy requirement somewhat different than the TM user. This accuracy requirement is of the simulated device to the designed component both under operational conditions.

OWF support for 3 different users:

a. T&M user requirements – 1) easy to setup measurement (apart from calibration) + 2) reasonable accuracy (data file relative to actual device as measured)
b. Model creator user requirements – hides IP, no parameter extraction (available in COTS T&M tool), no custom modelling (available in COTS EDA tools).
c. Designer user requirements – easy to use in COTS EDA tool, reasonable accuracy (simulation under expected drive signal relative to measured performance with same drive signal).

OWF capabilities should be discussed in the context of three independent criteria: input signal, DUT complexity, and impedance environment. Input signals are traditionally specified in terms of swept frequency and power, but now also require knowledge of the harmonic content and any additional tones. Input signals can be single-tone, multi-tone, or complex-modulated. DUT complexity needs to be specified in terms of nonlinearity. Traditionally, operating point conditions for control and bias are specified but here it must be extended to whether the device is being operated as linear, weakly nonlinear, or (strongly) nonlinear. Impedance environment is typically 50-ohms at the fundamental, but now we care not only about load-pull, but impedance and load-pull at potentially several harmonics.

The overall specification for testing should be rational in the sense that each one of these independent criteria reflects every increasing tiers of complexity. Models developed at the higher tiers should incorporate the performance at the lower tiers such that as the input signal, DUT operation, and impedance environment approach their S-parameter equivalent operation, the NMBM should exhibit a commensurate relaxation to S-parameter performance. Conversely, models derived from more complex criteria should provide proper harmonic content when driven by traditional two-tone, P1dB, Psat, AM/AM and AM/PM, and spectral mask simulations that is similar to what would be seen if that measurement or simulation was performed.

7. General Specification

7.1. Introduction

This section provides the general specification for classification of compatibility with OWF NMBM. An OWF-compatible NMBM is defined by three dimensions of classification: input signal, DUT nonlinearity, and impedance environment. Each dimension is divided into tiers of performance with each higher tier encompassing the relevant lower tiers' performance.

7.2. Definitions

7.2.1. Input Signal

7.2.1.1. Multi-tone signal

A multi-tone drive signal is comprised of more than one discretely generated tone from a unique source. Multi-tone drive signals are completely specified by the frequency of the tone and by the phase relative to each other: one tone can be arbitrarily chosen as the reference for purposes of determining phase.

7.2.1.2. Complex-modulated signal

A complex-modulated signal is a multi-tone signal that is described by a carrier tone and bandwidth about that carrier tone which may contain measureable signal content. Complex-modulated signals may not be identifiable by unique tonal content.

7.2.2. DUT Nonlinearities

*7.2.2.1. Harmonic test – linear to weak nonlinearity**

For measurement, if there are no measured harmonics of the drive tone at a specified drive level than the measurement is linear. For simulation, all harmonics of the drive tone should be at -100 dBc and at -40 dBc of any other signals in a 1% bandwidth for the (nonlinear) simulation to be linear (in its results).

7.2.2.2. Gain test – weak to strong nonlinearity

If the relationship between Pout and Pin cannot be characterized by a single value, gain, to within 0.1 dB as a function of frequency and source/termination impedance, then the system is nonlinear.

7.2.2.3. OIP3 test – weak to strong nonlinearity

Transition from weakly nonlinear to nonlinear occurs where OIP3 changes by 1 dBm.

7.2.3. Impedance Environment

7.2.3.1. 50 ohms

Termination or measured impedance is within ±1 ohm of 50 ohms at all measured or simulated harmonics. User may specify number of measured/simulated harmonics.

7.2.4.2. Non-50 ohm fixed

Terminations or measured impedance is as specified at all measured or simulated harmonics. It is assumed that within measurement/simulation accuracy, the termination impedance is as-specified. User may specify number of measured/simulated harmonics.

7.2.4.3. Harmonically variable

Termination or measured impedance is as specified in terms of impedance and harmonic relative to the specified input signal tone(s). It is assumed that within measurement/simulation accuracy, the termination impedance is as-specified. Harmonics not listed are assumed to be not supported in the measurement or simulation.

7.3. Classification matrix

The classification matrix is defined by three classes: input signal, DUT behaviour, and impedance environment. The value of these classes is referred to as the model state. An NMBM is uniquely defined by the model state and the DUT operating point (DC bias and control signal state(s)).

The 2D representations of this matrix are shown in Appendix 1 with each 2D matrix corresponding to fixed values of the DUT behaviour.

(Appendix 1.1 shows 2D matrix of input signal vs. impedance environment for linear DUT)

(Appendix 1.2 shows 2D matrix of input signal vs. impedance environment for weakly nonlinear DUT)

(Appendix 1.3 shows 2D matrix of input signal vs. impedance environment for strongly nonlinear DUT)

7.3.1. Input Signal

NMBM model simulation and simulation accuracy will depend upon the nature of the input signal. Input signal is classified in terms of the richness of the harmonic content.

In all cases the input signal must be defined in terms of its frequency and power sweep. Sweep range and density will determine model accuracy to the extent that resonances, nulls, and other such features in the dependent performance of the DUT are a function of frequency and/or power.

The measured data and generated model file will appropriately document frequency and power sweep.

All power sweep measurements must accurately reproduce small-signal S-parameters in the limit of lower input power. This condition will vary from DUT to DUT

Note to Document Reviewers: Please make recommendations for Complex modulated (input tier 3) and Multi-ton Multi-port (input tier 4) test regimes in section 7.4.x. They have not been considered in this release of the document

7.3.1.1. Input Signal Tier 1 - Single tone

Small or Large-signal driving tone is applied to one port only. Small-signal tone corresponds to linear test condition for DUT. Large-signal tone corresponds to weakly nonlinear or nonlinear DUT test. All tones at driving port and other ports are defined for harmonics of this tone only.

Power sweep is defined to exhibit desired DUT characteristics: linear, weakly nonlinear, or nonlinear.

7.3.1.2. Input Signal Tier 2 – Multi-tone

Small- or large-signal tone is applied to one port and is comprised of two or more tones. Small-signal multiple tones, as in linear two-tone testing, corresponds to weakly nonlinear test conditions. Large-signal multi-tone, single-port can be weakly nonlinear or nonlinear.

Power sweeps for the defined input tones are defined to exhibit desired DUT characteristics: linear, weakly nonlinear, or nonlinear.

7.3.1.3. Input Signal Tier 3 – Complex-modulated, single port

Input signal is best characterized in the time-domain either as an envelope or complex-modulated signal. Tests defined with this input signal will always exhibit weakly nonlinear or nonlinear DUT performance.

Power sweep for this signal is defined in terms of a time-average power and is selected to exhibit the desired DUT characteristics: weakly nonlinear or nonlinear

7.3.1.4. Input Signal Tier 4 - Multi-tone, multi- port

Large-signal tone or tones can be applied to multiple ports. This input signal corresponds to weakly nonlinear or nonlinear DUT behaviour.

Power sweeps for the input tones are defined to exhibit desired DUT characteristics: weakly nonlinear or nonlinear

7.3.2. DUT behaviour

7.3.2.1. Linear

The linear region must agree with S-parameter measurements. Dataset must have single tone input and reflected waves at ports of interest. No harmonic content and no small-signal additive terms.

Dataset will adhere to standards for particular model implementation used (X-parameter, S-Function, Cardiff, etc.), but its simulated performance will be identical to an s-parameter file for the same device under the same frequency and power level.

Dataset will simulate and give results independent of power level.

7.3.2.2. Weakly nonlinear

DUT behaviour can be characterized by weak harmonics relative to power-level(s) found in the fundamental spectrum of the drive signal. This behaviour would be similar to that captured by a volterra series representation or analysis. Behaviour conforms to “weakly nonlinear” by at least one of the criteria specified in section 7.2.2. A single driving tone is used with harmonics of that tone and, optional, small-signal components from other tones. Total power at the output should be defined by device gain to within the measurement/simulation accuracy of the system.

For measurement, if there are no measured harmonics of the drive tone at a specified drive level than the measurement is linear and if harmonics are visible the measurement is weakly nonlinear. For simulation, all harmonics of the drive tone should be at -100 dBc and at -40 dBc of any other signals in a 1% bandwidth for the (nonlinear) simulation to be linear (in its results).

In the limit of low input signal power level, the model will reproduce similar s-parameters. Multiple tones under low large-signal drive levels will give results compatible with classic small-signal mixer theory [ref Steve Maas’s mixer book]

7.3.2.3. Nonlinear

DUT behaviour is complex in power and or harmonic content. DUT can exhibit nonlinear behaviour for several distinct reasons. Amplifiers will become nonlinear for two distinct reasons. First, the DUT contains nonlinear components which generate harmonics and gets to sufficiently high power levels that the harmonics no longer scale linearly, as would be expected with the weakly nonlinear conditions. Second, the power being supplied to the DUT, through linear components, can no longer supply the power sufficient for weakly nonlinear conditions. Other devices, like oscillators and mixers are inherently nonlinear as they generate harmonic content as part of their normal functionality, but even here these devices exhibit behaviour that transitions from weakly nonlinear (scalable harmonic content) to nonlinear (breakdown of scalable harmonic content).

Harmonics are within -20dBc of driving tone or of the order of the fundamental tone at the port of interest. DUT may include signal generation and or complex modulation inherently in its operation (i.e. oscillator or complex modulator). Behaviour may not be compatible with steady-state analysis and may include memory or hysteresis.

At sufficiently low power-levels DUT should reduce to behaviour equivalent to S-parameters measured under similar frequency plan. At weakly nonlinear levels the NMBM should display weakly nonlinear behaviour with linear “small-signal mixer” harmonic growth.

The transition from weakly nonlinear to nonlinear for both measurement and simulation occurs at P1dB.

7.3.3. Impedance Environment

7.3.3.1. 50 ohm fixed

All ports terminated in 50 ohms at all relevant harmonics being measured

7.3.3.2. Non-50 ohm fixed

At least one port is not terminated in 50-ohms. All ports are considered constant fixed impedance, as specified, over all harmonics being measured.

7.3.3.3. Harmonically variable

At least one port is not terminated in a broadband fixed impedance. This port is specified by different impedance for each harmonic of the tones/harmonics of interest. All remaining ports are considered fixed impedance, as specified, over all harmonics measured.

7.4. Classification of regimes

7.4.1. Single-tone, linear, 50-ohm termination

A single drive tone is provided under conditions where the DUT is operating linearly and all ports are terminated in 50 ohms.

This corresponds to S-parameters

7.4.2. Single-tone, Linear non 50-ohm termination

A single drive tone is provided under conditions where the DUT is operating linearly and all ports are terminations are as-specified, with at least one not at 50 ohms. Terminations are assumed to be constant at all relevant harmonics.

This corresponds to S-parameters into non -50 ohm loads.

7.4.3. Single-tone, Linear harmonically variable termination

This model condition is not possible since there should be no harmonics under linear DUT operation.

7.4.4. Single-tone, weakly nonlinear, 50-ohm termination

A single large-signal drive tone is provided which causes the DUT to operate under weakly nonlinear conditions per the definitions in section 7.3.2. Terminations at all ports for all harmonics are at 50 ohms.

This test corresponds to an NVNA with no load-pull system.

7.4.5. Single-tone, weakly nonlinear, non 50-ohm termination

A single large-signal drive tone is provided which causes the DUT to operate under weakly nonlinear conditions per the definitions in section 7.3.2. Terminations for at least 1 port are different than 50-ohms for all harmonics at that port.

This test corresponds to an NVNA with a load-pull system.

7.4.6. Single-tone, weakly nonlinear, harmonically variable termination

A single large-signal drive tone is provided which causes the DUT to operate under weakly nonlinear conditions per the definitions in section 7.3.2. Termination for at least 1 port is different than 50-ohms and specified for all relevant harmonics at ports with variable termination. All other ports are as specified.

This test corresponds to an NVNA with a harmonic load-pull system.

7.4.7. Single-tone, nonlinear 50-ohm termination

A single large-signal drive tone is provided which causes the DUT to operate under nonlinear conditions per the definitions in section 7.3.2. Terminations at all parts are 50 ohms for all harmonics.

7.4.8. Single-tone, nonlinear non-50 ohm termination

A single large-signal drive tone is provided which causes the DUT to operate under weakly nonlinear conditions per the definitions in section 7.3.2. Termination for at least 1 port is different than 50-ohms for all harmonics at that port.

This test corresponds to an NVNA with a load-pull system.

7.4.9. Single-tone, nonlinear, harmonically variable termination

A single large-signal drive tone is provided which causes the DUT to operate under nonlinear conditions per the definitions in section 7.3.2. Terminations for at least 1 port are different than 50-ohms and specified for all relevant harmonics at ports with variable termination. All other ports are as specified.

This test corresponds to an NVNA with a harmonic load-pull system

7.4.10. Multi-tone, Linear, 50-ohm termination

This model condition is not possible as a multi-tone drive signal will produce mixing products.

7.4.11. Multi-tone, Linear, non 50-ohm termination

This model condition is not possible as a multi-tone drive signal will produce mixing products.

7.4.12. Multi-tone, Linear, harmonically variable load

This model condition is not possible as a multi-tone drive signal will produce mixing products.

7.4.13. Multi-tone, weakly nonlinear, 50-ohm termination

A drive signal comprised of at least two distinct tones is provided under conditions where the DUT is operating weakly linearly per section 7.3.2 and all ports are terminated in 50 ohms.

For the case of two sinusoidal tones, this corresponds to the classic CW two-tone. Only four tones should be present for linear DUT behaviour.

7.4.14. Multi-tone, weakly nonlinear, non 50-ohm termination

A drive signal comprised of at least two distinct tones is provided under conditions where the DUT is operating weakly linearly per section 7.3.2 and all ports are terminations are as-specified, with at least one not at 50 ohms. Terminations are assumed to be constant at all relevant harmonics.

For the case of two sinusoidal tones, this corresponds to the classic CW two-tone. Only four tones should be present for linear DUT behaviour.

7.4.15. Multi-tone, weakly nonlinear, harmonically variable termination

A drive signal comprised of at least two distinct tones is provided under conditions where the DUT is operating weakly linearly per section 7.3.2. Terminations for at least 1 port are different than 50-

ohms and specified for all relevant harmonics at ports with variable termination. All other ports are as specified.

For the case of two sinusoidal tones, this corresponds to the classic CW two-tone. Only 4 tones should be present for linear DUT behaviour.

7.4.16. Multi-tone, nonlinear, 50-ohm termination

A drive signal comprised of at least two distinct tones is provided under conditions which causes the DUT to operate under nonlinear conditions per the definitions in section 7.3.2. Terminations at all ports for all harmonics are at 50 ohms.

This test corresponds to an NVNA with multiple sources with no load-pull system.

7.4.17. Multi-tone, nonlinear, non 50-ohm termination

A drive signal comprised of at least two distinct tones is provided under conditions which causes the DUT to operate under nonlinear conditions per the definitions in section 7.3.2. Terminations for at least 1 port are different than 50-ohms for all harmonics at that port.

This test corresponds to an NVNA with multiple sources and a load-pull system.

7.4.18. Mutlti-tone, weakly nonlinear, harmonically variable termination

A single large-signal drive tone is provided which causes the DUT to operate under weakly nonlinear conditions per the definitions in section 7.3.2. Termination for at least 1 port is different than 50-ohms and specified for all relevant harmonics at ports with variable termination. All other ports are as specified.

This test corresponds to an NVNA with multiple sources and a harmonic load-pull system.

> Note to Document Reviewers: Please make recommendations for Complex modulated (input tier 3) and Multi-ton Multi-port (input tier 4) test regimes. They have not been considered in this release of the document

7.5. Compliance flow

The compatibility flow defines a process for demonstrating agreement with this compliant document. This step is carried out under two different circumstances. First, an NMBM may need to be created for a given DUT or, second, the measurement setup relative to the simulation environment may need to be qualified. It is composed of 4 primary sections as shown in Figure 7.5.1.

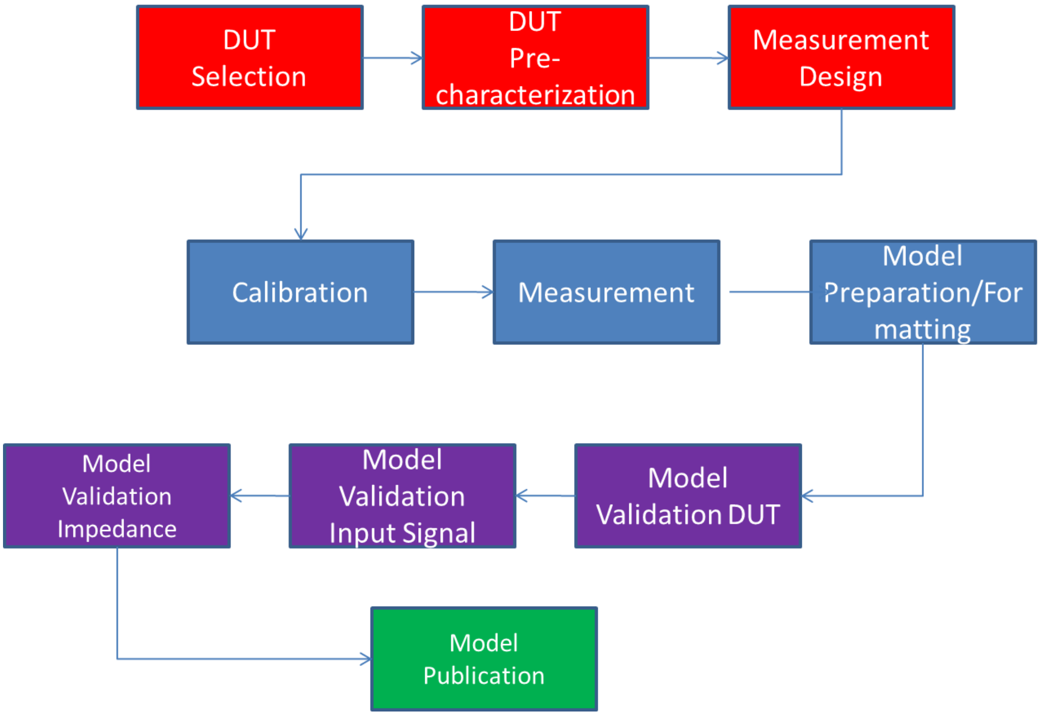

Figure 7.5.1 – Compliance Flow

1. Measurement preparation (red blocks) –The aim of this step is to create an experiment design to minimize measurement time and complexity while providing a high level of assurance that the model will be accurate and/or the measurement-simulation results correlated.

   DUT selection should focus on a DUT which is close to nominal based on the manufacturer's datasheet. Furthermore, if the measurement-simulation environments are being validated, the selected DUT should exercise those aspects of the measurement system which will be exercised by the simulation environment according to the classification matrix in section 7.3, above.

   DUT pre-characterization follows. This step is necessary to gain a proper understanding of the DUTs power and frequency characteristics so as to design a sweep plan of appropriate density. If load/source pull or high-power sources external to the NVNA are to be used, then these domains should be explored as well.

   The last step of measurement preparation is to design the actual measurement plan. Besides power, frequency, and impedance sweeps, if bias, turn-down voltages or other independent controlling parameters/variables need to be included these should be done so relative to actual usage and application. In regard to bias, however, proper care should be taken not to over-stress the DUT in high voltage or high current situations prior to the majority of the data being taken. This may require, for example in the case of power devices, that high Vds values near threshold be taken after all other Vgs-Vds combinations below positive gate bias so as to limit irreversible or long time constant effects associated with high fields and charge injection.

2. Measurement Execution (blue blocks) – This series of tasks is related to the actual measurement of the device. There are three tasks in this step: Calibration, Measurement, and Model Preparation/Formatting.

   Calibration should be done not only to the NVNA manufacturer's instructions but should also be designed relative to the DUT being measured (connecterized standards vs. Waveguide standards vs. Wafer-probe standards) and must include proper calibration of the measurement system at all harmonics at all impedance and at all power levels and frequencies being measured [ref]. Failure to do so will undermine the integrity of the entire compliance flow.

   Measurement should proceed immediately after calibration. Owing to the enormous number of data points needed to span the measurement domain, attention must be paid to the calibration drift associated with each component of the measurement system. All measured data should be taken within the time span that the calibration is still valid based on the overall stability of the measurement system, not just the NVNA.

   Model Preparation/formatting are the final step. This step assumes that the measurement system is able to directly create from the measurements a) the model parameters in the b) format required by the simulation environment. Consult section 9 for the appropriate file format for each model.

3. Model Validation (purple blocks) – Prior to release and use of the model in a design, it is necessary to validate the model relative to a circuit designer's expectations of its performance in limiting conditions and its intended application as well as against measured data. Validation levels are NMBM-dependent and occur along the three axes of the classification matrix in section 7.3: DUT nonlinearity, input signal, and impedance environment

4. Model Publication (green blocks) – the Final step packages the NMBM with all the data necessary to install it into the simulation environment. This can be, for example, a software installer which automatically adds the part to simulation environment's parts library.

7.5.1.DUT selection

The DUT should be selected based on the model variability to be considered. If the model is meant to be a nominal model, then the DUT should be selected so as to be representative of the typical behaviour expected. Corner models for manufacturing variance or semiconductor processing windows and models with variable temperature can also influence DUT selection.

7.5.2.DUT pre-characterization

In all cases, the DUT should be pre-characterized to determine areas of interest with regard to the independent test variables. Frequency, impedance (where it is considered) and power are swept for the NMBM and so to develop these sweep plans, the device should be assessed experimentally prior to the nonlinear measurement run to identify measurement density in terms of these sweep plans.

Linear measurements can be used as a guide for frequency planning. S-parameter analysis over bias or control features on the DUT can identify resonances and areas of potential (nonlinear) instability. An impedance plan can also be nominally inferred from gain and noise figure circles (if available).

A Pin/Pout sweep at nominal frequencies can be used as a guide for the power plan. Attention should be paid to strongly nonlinear transition points of interest: places where the onset of gain compression, rapid changes in AM-PM, Psat, etc. are observed.

7.5.3. Measurement Design

Given the data from section 7.5.1 and 7.5.2 the measurement should be designed with regard to frequency, power, and impedance (where it is considered) and any other independent measurement variables, like power, supply voltage, or temperature.

7.5.4. Calibration

This should be done with regard to the NVNA and other equipment manufacturers' specifications.

Total measurement time between calibrations should be recorded and reported relative to the manufacturers' specification for calibration validity.

7.5.5. Measurement

Measurement time should be recorded so that any calibration derating can be considered.

7.5.6. Model Formatting

Upon completion of measurement, the test equipment should format the measured data into the model format specified for that NMBM. This model format will vary from model to model. See the model information in section 9 for the proper format for the model of interest.

7.5.7. Model Validation DUT

7.5.7.1. Linear Harmonic Validation

This test can be used to verify weakly nonlinear behaviour. This is not necessary for linear DUTs but should be carried out for weakly nonlinear and (strongly) nonlinear DUTs. The model should exhibit this behaviour if it is to capture the DUT's transition from linear to weakly nonlinear behaviour.

1. Carry out the S-parameter validation test, section 7.5.8.1 below.
2. Start with power of drive tone well-backed off from P1dB, OIP3, and Psat. Increase output power of drive tone(s) until 2nd harmonic at the DUT output port(s) is approximately 60 dBc below the fundamental. Reduce drive tone by 2-5 dB and confirm that 2nd harmonic decreases by 4-10 dB, respectively.

7.5.7.2. Compression Validation

This test verifies that typical first-order strongly nonlinear behaviour is manifested as gain compression. The model should exhibit such behaviour if it is to be useful for gauging the transition from weakly to strongly nonlinear regimes.

1. Carry out the Linear Harmonic Validation, section 7.5.7.1, above.

2. Note small-signal gain during Linear Harmonic Validation testing.
3. Increase power of drive tone until gain is 1dB below value noted in step 2.

7.5.7.3. Saturation Validation

This test verifies that more detailed strongly nonlinear behaviour is manifested as saturated power output: the DUT should be limited in the output power it is capable of delivering.

1. Carry out the Compression Validation, section 7.5.7.2, above.
2. Start with the power drive-tone well-backed off from P1dB and measure output power as the input power of the drive-tone is increased.
3. Increase power of the drive tone until the output power reaches a maximum and then starts to decrease.

7.5.8.Model Validation Input Signal

7.5.8.1. S-parameter validation

This test validates that the NMBM reduces to S-parameters at low drive levels. It can be carried out with single-tone and multi-tone simulations, the latter since a multi-tone simulation at sufficiently low powers should have a response which reduces to a linear superposition of signals.

1. Import the part into the simulator’s schematic capture environment
2. Instantiate the part on a schematic within the simulation environment.
3. Embed the schematic containing the part in a nonlinear test bench corresponding to the input signal used to create the NMBM and with the ability to vary at least the input power seen by the fundamental of the drive tone(s).
4. Reduce the input power of the simulation until the simulated data agrees with the measured s-parameter data.
5. Validate that this power level for the simulation agrees with measured data for linear performance and that it is not too high and not too low given the components specification for performance parameters such as P1dB or OIP3 (e.g. 10-20 dB back off).

7.5.8.2. Harmonic generation

This test validates that the NMBM generates harmonics only associated with the drive tone. It requires either a transient simulator or a two-tone harmonic balance measurement where the second tone is swept over frequency at a very low power level to probe for erroneous tone generation. It assumes that the device is stable at the bias and impedance environment specified by the test.

1. Import the part into the simulator’s schematic capture environment
2. Instantiate the part on a schematic within the simulation environment
3. Embed the schematic containing the part in a nonlinear test bench corresponding to the input signal used to create the NMBM and with the ability to vary the frequency and power level of the drive tone. If harmonic balance analysis is being used, then a two-tone

measurement should be set up where the second tone is used as a probe tone at very low levels simply to get the analysis to look at off-drive tone frequencies.

4. Set the power level of the drive-tone sufficiently high to generate harmonics of the fundamental drive tone but well-below P1dB (section 7.5.7.2). At least 3 harmonics, including the fundamental, should be used.
5. Confirm that only harmonics of the fundamental are found and that no atonal signals are found.

7.5.8.3. Multi-tone linearity validation

This test validates that NMBM is able to accept and operate in a linear fashion with a multi-tone. It can be done with a complex-modulated waveform as well as a classic CW two-tone. At sufficiently low total input power levels, the DUT should exhibit linear, frequency-dependent behaviour.

1. Import the part into the simulator’s schematic capture environment
2. Instantiate the part on a schematic within the simulation environment
3. Embed the schematic containing the part in a nonlinear test bench corresponding to a single tone input signal used to create the NMBM and with the ability to change the input signal from a single tone, variable power level signal to a multi-tone signal.
4. Simulate with the power level set below the threshold for weakly nonlinear behaviour defined by section 7.5.7.1.
5. Substitute the multi-tone input signal for the single tone input signal, making certain that the total input power of the multi-tone signal corresponds to the power of the single tone input signal.
6. Decrease the total power level and validate that the DUT exhibits linear behaviour relative to the multi-tone signal.
7. Increase the power level above and beyond the threshold for weakly nonlinear behaviour (section 7.5.7.1) and confirm that either:
    a. The signal remains linear, or
    b. Gain compression (section 7.5.7.2) or power saturation (section 7.5.7.3) does not occur.

7.5.9.Model Validation Impedance

Validation of the model within the simulation environment should be done with regard to impedance variation and carried out in the following manner.

7.5.9.1. 50-ohm fixed

1. Proper importation of the part into the simulator’s schematic capture environment
2. Instantiation of the part on a schematic within the simulation environment.
3. Embed the schematic containing the part in a nonlinear test bench corresponding to the input signal used to create the NMBM and with the ability to vary at least the impedance seen by the fundamental of the drive tone(s).

4. Complete test for S-parameter compliance, section 7.5.7.1, and linear harmonic performance, section 7.5.8.1 if applicable, with source and load termination impedance set to 50 ohms and proceed if tests are positive.
5. Vary source impedance ±10% from 50-ohms checking for smooth and continuous variation in S-parameters for linear DUT, harmonics for weakly nonlinear DUT, and P1dB, PAE and gain at P1dB for strongly nonlinear DUT. Proceed if tests are positive. If test is negative, compare any sudden jumps in data to measurements and check for oscillations.

5.5.9.2. Non 50-ohm fixed

1. Carry out procedure in section 7.5.9.1, above, except in step 5, use ±10% variation from the impedance(s) used in the measurement.

7.5.9.3. Harmonically variable

1. Carry out procedure in section 7.5.9.1, above.
2. Repeat at impedances closest to edge of Smith Chart and then at half the distance between these measured points and the edge of the Smith Chart.

7.5.10. Model Publication

The model publication step packages the model with the other necessary information to make a complete, functional part in the EDA environment. This will include, but it is not limited to:

- The NMBM in the format specified in section 7.5.6.
- A graphical symbol with a logical pin count corresponding to the number of ports in the NMBM and a physical pin count corresponding to the number of ports/pins/leads on the physical package.
- A library definition for the part in the vendor or related library (may be optional)
- A footprint or package definition for the physical package (optional).
- Element/Component help information for use with the part (optional).

7.6. Measurement density

Measurement density must be chosen to capture all relevant DUT behaviour given input signal and impedance test conditions.

See [6] for some guidelines.

7.7. Accuracy*

Accuracy is based on current techniques for calibration and model generation. It is expected that this metric can be improved upon as familiarity with NVNAs and NMBMs matures. Current values are reported based on what is available in peer-reviewed published literature.

Simulated versus measured accuracy should be within 1 dB for Pin/Pout curves for weakly nonlinear systems.

S-parameters should be reproduced within 0.1 dB magnitude and 3 degree of phase.

7.8. Calibration

Calibration will be according to test & measurement equipment provider.

Careful note must be taken of harmonic levels, especially reflected waves from DUT, at drive ports. These harmonic levels can change with device bias conditions and the nature of small-signal tones [6, ref brinkhoff baseband paper].

7.9. Portability

Portability of datasets from one simulation environment to another is not currently supported.

7.10. Repeatability

Measurements should be reproducible to within the limits determined by the test and measurement equipment. Reproducibility is limited by the duration that the calibration is valid, and is therefore a function of the measurement complexity and measurement sweep (frequency, power, load impedance, etc.) density.

8. Example Implementations

Note to Document Reviewers: This section is reserved for any recommendation on components proposed as the equivalent of a “reference design”. Please make recommendations for which you can share measured data.

8.1. Introduction

This section reports on measured and simulated data for selected components. The purpose of including this information is purely for validation of NMBM measurement and model validation across different test equipment and simulator vendors. These data are not meant as an endorsement of the respective component, equipment, or software vendors.

8.2. Cree 10W FET

8.3. XYZ part

8.4. ABC Component

9. NMDG Nonlinear Neutral File Format

Note to Document Reviewers: This file format has been proposed by NMDG as a format neutral to all NMBM implementations. Please include an NMDG representative on all broader OWF discussions regarding this proposed file format.

9.1. Introduction

This file format is proposed as a means for transferring measured data from one tool to another.

9.2. File Format

It has been agreed that this file format is only used to "export" to another tool.
As such there is no need to be able to add on the fly additional measurements to the sweep plan. Mesuro presently has that capability using 1 file for sweep plan and another file for the data. This was considered as "too complex" to be used for standard

(*): indicates that this has not been discussed but it came up while making this concrete proposal

9.3. Comments

A comment is indicated by “!” in the first position of a row

9.4. Version

(*) I propose that we introduce a version nbr for format control
Version: 1.0

9.5. Preamble

Need for a preamble where in ASCII format any descriptive info can be stored
Example:
Date: 9 October 2010 Performed by: Pipo

9.6. Units

Setup: ....

(*) To avoid Unit parsing I propose to use everywhere MKSA units

9.7. Device description

Description of device, number of ports and purpose of ports
(*) Cardinal sensitive
(*) Format : <Agreed type token>:<user selectable name> _n1 _n2 ... [node definition] <Agreed parameter token>=<variable or fix value>...

(*) We need to agree on how to store complex numbers ... any proposal?

Component:mycomponent _n1 _n2 _n3 _n4 _n5

9.8. Port Definitions

9.8.1. Power Port

P_Source:mypsource _n1 0 Z=50.+I*0. Pwr=Pin Freq=Freqs

9.8.2. Current Port

I_Source:myidcgate _n3 0 I=Igate Freq=0

9.8.3. Voltage Port

V_Source:myvdcdrain _n4 0 V=Vdrain Freq=0

9.8.4. Control Voltage port

V_Source:myvcontrol _n5 0 V=1.0 Freq=0

9.8.5. Impedance Port

G_Tuner:myfundtuner _n2 0 Z=50. Gamma=Refl1 Freq=Freqs
G_Tuner:mysectuner _n2 0 Z=50. Gamma=Refl2 Freq=2.0*Freqs
G_Tuner:mythirdtuner _n2 0 Z=50 Gamma=0.3+I*0.4 Freq=3.0*Freqs

9.9. Sweep Plan

Definition of sweepplan
It has been agreed to decouple the frequencies in the sweep plan from the frequencies at which the receivers will measure
As such there will be a frequency list for the sources and ONE frequency list for all the receivers
(*) This could be a problem if one sweeps the source frequencies of the setup. Maybe we need to define some base frequencies
(*) from which all the other frequencies need to be derived. I can imagine that the common list of receiver frequencies is
(*) dependant on the frequency of the sources

(*) It is possible to maintain the structure of how certain sweeps were done or one can use a flattened list
complex Refl1[5]={{0.0+I0.5},{-0.25+I 0.25,0.25+I 0.25},{-0.5,0,0.5},{-0.25-I 0.25,0.25-I 0.25},{0.0-I0.5}}
complex Refl2[3]={0.3 -I 0.2,0.9 - I 0.3,1.0}

9.9.1.Frequency

double Freqs[5]={1.0 10^9, 2.0 10^9,3.3 10^9,5. 10^9,6.0 10^9}

9.9.2.Power

double Pin[Freq1] = {{1. 10^-4,1.2589 10^-4,1.5849 10^-4},{1. 10^-4,5.0119 10^-4},{1. 10^-5,1.5849 10^-5,5.0119 10^-4},{1.0 10^-5},{1.99526 10^-4,1.58489 10^-4,1.25893 10^-4}}

9.9.3.Dc

double Igate[5] = {10. 10^-3,15. 10^-3, 25. 10^-3}
double Vdrain[3]={1.,2.,3.}

9.9.4.Impedance

9.9.5.Sweep Plan Sequence

(*) There is a need to define the sweep sequence. As far as I remember this was not discussed
Sweepsequence: {Freqs,Refl1,Refl2,Igate,Vdrain,Pin}

9.10. Measured Data

Description of the measured data

9.10.1. Deembedding information

Deembedding information
Per port of DUT one defines the reference planes. We discussed three tokens: IGEN, COAX, DUT
IGEN: deembedded up to intrinsic nonlinearity
DUT: deembedded up to the DUT planes
COAX: in the calibration plane
(*) PLEASE CHECK THE TOKENS .. I am not sure anymore and it is not 100% clear. Can one of you adapt and clarify the definition?
(*) I would add 1 token "NONE" for ports where it is not relevant, e.g. control ports
RefPlanes: {COAX, IGEN, DUT, DUT, NONE}

9.10.2. Interpolation

There was a discussion related to mentioning whether the data could be interpolated
Two tokens: YES or NO
Interpolation: NO

9.10.3. Characteristic Impedance

When waves are stored, the characteristic impedance is needed per port
CharacteristicImped: {50., 10+0.3I, -10.,-10.,-10.}

9.10.4. Measurement

(*) A negative double is used to indicate irrelevance for port
(*) We can also explicitly describe what to store per port.
We decided to store only the basic frequency domain data (most compact), either V,I or A/B
(*) Possibly there is only 1 variable or no variable at a port
(*) Possibly we need to define the format or we choose for 1 format
Measurements: {{A,B},{A,B},{V,I},{V,I},{V}}
Format: RI or MA

(*) Should we use CharacteristicImped to decide what data is saved? When NO char. imped defined -> V and I for that port?

9.11. Receiver Frequency

Definition of the receiver freq list

(*) What is we have a sweep of different frequencies of sources in the setup and the receiver freq list needs to track it?

(*) I think we should track the receiver freq list as function of the indexing of the frequency settings of the sources in

(*) the sweep plan

ReceiverFreqList:{0., 1.0 10^9, 1.1 10^9. 2.3 10^9,.....}

9.13. Other Comments

(*) The data will be at the end of the file and will be stored with a record indicator to minimize the overhead. The order of the records

is preferred to be conforming the sweep sequence to simplify the reading of the data from the file. Or should we not worry about it?

(*) Maybe we need to figure a more compact format here and possibly allowing to save this as binary format ?

(*) We store the data as indicated in "Measurements" using the "FORMAT" in rows. Each row corresponds to the respective frequency in

(*) in ReceiverFreqList. Possibly when needed one can add the frequency also to the record indicator in combination with dropping a

(*) variable for which there is no measurement at that frequency

.....

{3,{2,2},2,3,2,1}

<A at port 1> <B at port 1> <A at port 2> <B at port 2> <V at port 3> <I at port 3> <V at port 4> <I at port 4> <V at port 5>

.....

10.Special Specifications Models

Note to Document Reviewers: This section is reserved for any issues specific to the various NMBM implementations

10.1. Agilent X-Parameters

Xnp format

10.2. NMDG S-Functions

S-function citifile.

10.3. Cardiff Model

Cardiff MDIF file

11. Reference

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[11] J. Verspect and D.E. Root, 2010 ARFTG

[12] D.E. Root, 2010 INMMIC

Appendix 1.1 –

(Appendix 1.1 shows 2D matrix of input signal vs. impedance environment for linear DUT)

	Sin gle-Tone **tier 1**	**Multi-tone Single-port** **tier 2**	**Complex** **Modulated** **tier 3**	**Multi-tone Multi-port** **tier 4**
50 Ω fixed	7.4.1 S-parameters	7.4.10 S-parameters with linear superposition	X	X
Non 50 Ω fixed	7.4.2	7.4.11	X	X
Harmonically variable	X	X	X	X

Appendix 1.2

(Appendix 1.2 shows 2D matrix of input signal vs. impedance environment for weakly nonlinear DUT)

	Sin gle-Tone tier 1	**Multi-tone Single-port tier 2**	**Complex Modulated tier 3**	**Multi-tone Multi-port tier 4**
50 Ω fixed	7.4.4 S-parameters	7.4.13 S-parameters with linear superposition	**TBD**	**TBD**
Non 50 Ω fixed	7.4.5	7.4.14	**TBD**	**TBD**
Harmonically variable	7.4.6	7.4.15	**TBD**	**TBD**

Appendix 1.3

(Appendix 1.3 shows 2D matrix of input signal vs. impedance environment for strongly nonlinear DUT)

	Sin gle-Tone **tier 1**	**Multi-tone Single-port** **tier 2**	**Complex Modulated** **tier 3**	**Multi-tone Multi-port** **tier 4**
50 Ω fixed	7.4.7 S-parameters	7.4.16 S-parameters with linear superposition	**TBD**	**TBD**
Non 50 Ω fixed	7.4.8	7.4.17	**TBD**	**TBD**
Harmonically variable	7.4.9	7.4.18	**TBD**	**TBD**

Addendum – Reviewers’ Comments

1. Comments from Jon, Anritsu. Received April 2011.

Section 6.0

The tests mentioned in terms of deltas may make sense but in a more complete grid of powers, one will not see 2:1 2nd harmonic behaviors in general.

> *Draft Committee Response – please make recommendations either for a global set of tests for all DUTS or a set of tests per DUT type. DUT type could be a nonlinearity classification (linear, weakly nonlinear, strongly nonlinear) or it could be a device class (low noise amplifier, linear amplifier, power amplifier), keeping in mind that the current revision of this spec does not include frequency conversion.*

Section 7.2.2.1

The DUT non-linearity tests (7.2.2 and 7.5.7 mainly) could cause some concern. It starts off categorizing harmonic behavior in terms of simulation parameters but then, presumably in a measurement context, makes comments about 'no harmonic content' and -60 dBc numbers. Since even the best synthesizers are usually in the -50 dBc spec ranges and VNAs usually worse, these criteria could be problematic from a measurement point of view. I'm not sure if something along the lines of 'negligible harmonic content in excess of the residuals in the stimulus (in relative terms)' would work?

> *Draft Committee Response – Since the models are generated by measurement equipment but used by simulation it is desirable to capture the limitation of test equipment (which one might expect to change over time) while exhibiting desired behaviour in simulation. Would it be desirable to have all harmonics below the test equipment limits to scale “linearly” and then expect that any nonlinear behaviour would be represented above this level? If so, then models must either report the source floor or a global value (like -50 dBc) should be specified by this document.*

Section 7.7

0.1 dB mag and 3 degree phase may be too optimistic given the possible conditions. Can this be opened up?

> *Draft Committee Response – what would be reasonable reproducibility Sparameters being measured by an NVNA for the test and measurement community?*