Greener wireless: Non-linear analysis applied to wireless device characterization

By Darren McCarthy, Tektronix and Wally Arceneaux, Mesuro

A critical design goal for wireless is more efficient or greener devices, whether it's reducing power consumption in base stations or boosting battery life across several billion handsets. Using active devices in their nonlinear region improves operating efficiency of wireless products.

Traditionally, characterizing nonlinear device behavior has involved the use of measurements and modeling to achieve optimum results. On the measurement side, existing products have been expanded with application software and hardware in an attempted to address this market and assist with the creation of behavioral models. However, these power amplifier (PA) measurement techniques can lack a coherent integration with a harmonic source/load pull system resulting in device and amplifiers being characterized at impedances that are different from their final application making it challenging to (1) translate the measured device performance into a PA design or (2) achieve the potential performance available from the device or the employed PA architecture.

New approaches in extrapolating the measured waveform data into a fundamental and harmonic space have been developed recently. These approaches are mostly based on PHD models that have been developed[1] and form a coherent and mathematically robust way to expand s-parameters into a nonlinear domain. However, further investigation is required to determine how well this approach extrapolates beyond the measured impedance space at the fundamental and harmonic frequencies.

An alternative approach is an integrated measurement system that supports simultaneous measurement of device's actual current and voltage waveforms while offering control of the harmonic source/load impedance over the entire Smith chart. For the harmonic impedance control and active load pull it is necessary to compensate for any losses between the device under test and the source/load pull. Such an integrated system enables a genuine and coherent link between the nonlinear device characterization and PA design. For instance, the harmonic source/load pull enables the generation of RF waveforms that boost the efficient operation of the device and the direct translation of the obtained impedances ensures the accurate replication of this performance within a PA design. Also, the inverse is possible as the impedances that are present within a PA can be readily emulated by the system and the resulting RF current and voltage waveforms can be utilized to obtain detailed information as to how close the device is operating to its maximum efficiency or what impact the resulting current and voltage swings might have on the device reliability.

Designing a highly efficient PA is coupled to the precise control of the fundamental and harmonic impedances that are presented to the device. It is therefore critical that the designer be able to measure what is needed at relevant power levels and frequencies, with the signal complexity that is required for a given application.

In this article, we explore the evolution of non-linear measurement solutions and then detail an emerging approach that greatly reduces design iterations even for complex power amplifier modes while achieving performance closely matching theory.

A variety of approaches to non-linear measurement have been attempted and each faces a number of challenges that have made it difficult to obtain maximum PA efficiency. These include passive source/load pull, closed loop active load pull and, more recently, open loop active load pull.

Passive source, load pull

A power sensor, VNA or sampling scope can be used for non-linear measurements as shown in Figure 1. Tuners allow for tuning impedance values of the harmonics at the device under test (DUT) input and output. This provides impedance values for designing matching circuits and power levels.

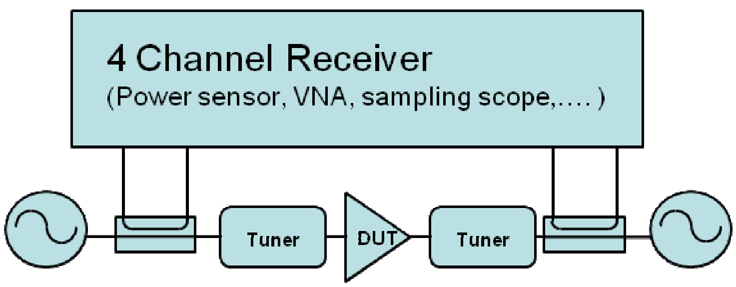

Figure 1. Passive source, load pull test set up.

The biggest disadvantage of these systems is that they generate impedances over a large frequency range but can control the impedance at only one single frequency. The impedance control is achieved by positioning the slug, which physically affects all remaining frequencies over which the tuner can be operated. Consequently, all harmonic impedances are not only uncontrollable but also change their value with every new position resulting in measurement artifacts that are not reproducible in real circuits. This can lead to significant performance variations between the load-pull measurements and the realized power amplifier.

The same disadvantage is valid for harmonic tuners (passive tuners with multiple slugs and sliding shorts) that allow a limited control of harmonic impedances as the higher harmonics (above 3rd harmonic) are not controlled and still vary largely. For instance, a small current coming from the DUT can be transformed, due to ohm's law, into a very large voltage with harmonic impedances (above 3rd harmonic) that are easily generated by the tuners. The uncontrolled load variations make it impossible to achieve clean waveforms as required for waveform engineering as they will introduce significant capacitive and inductive loading making the waveforms highly distorted.

Another significant problem, especially with today's compressed design cycles, is that the correct operation of passive tuners requires a highly accurate calibration procedure that can take an extensive amount of time, resulting in significant down times.
High reflection loads present another challenge. The readings of the power sensor can be severely affected by the set reflection coefficient of the output tuner. This is especially true at harmonic frequencies at which high reflection coefficients (short or open) are desirable with the result that almost all harmonic power is reflected back to the device. In this situation, a meaningful reading at the power sensor is difficult due to their finite dynamic range. This can be compensated by using a more expensive network analyzer with more dynamic range.

The position of the passive tuner between the DUT and the measuring receiver (as shown in Figure 1) makes it difficult to distinguish artefacts from the tuner and the DUT itself. This effect then has potential impact on the input or output matching network in a PA (power amplifier) design. The increased length will produce a larger phase variation and introduce measurement artifacts that differ from real circuits. For instance, it has been shown that a phase difference of only a few degrees can introduce artifacts that resemble memory effects. Even more, these impedance artefacts are changing with each impedance setting (due to the varying positioning of the slug) and it is therefore very challenging to account for them. Such phase variations can readily occur when utilizing wideband modulated signals such as in W-CDMA or LTE systems or narrowband systems with multiple channels.

Close loop active load pull
The closed loop architecture shown in Figure 2 uses the DUT itself as the stimulus for the closed loop technique. Closed loop active load pull compensates for any losses by taking the signal from the DUT, modulating its magnitude and phase, and boosting the signal before being injected back into the DUT. The resulting control of the ratio between the signal that is generated by the DUT and the signal that is send back allows for the generation of any impedance on the Smith chart including negative impedances with reflection coefficient magnitudes larger than unity.

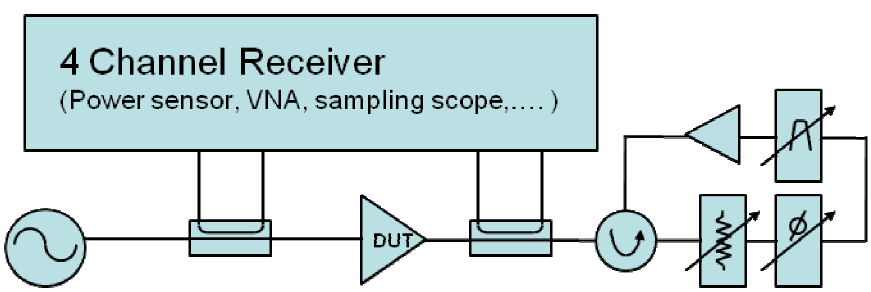

Figure 2. Closed loop, active load pull test set up

The product $\Gamma_{DUT}{\cdot}\Gamma_{LP}\leq1$ that is formed from the reflection coefficients generated by the device under test (DUT) and the load pull (LP) at any frequency is required to guarantee its stability. To reduce this interaction between the two coefficients and to minimize the risk of uncontrolled power build-up a tuneable narrowband filter is introduced into the loop.

For devices that require high reflection coefficients for their optimum operation as demanded by high power devices such as Si LDMOS, GaAs HBTs or GaN pHEMT, oscillations and uncontrolled power build-ups are a challenge. Consequently, the active loop operates close to the $\Gamma_{DUT} \cdot \Gamma_{LP}=1$ oscillation condition as the device reflection coefficients Γ_{DUT} tend to be close to unity. In other words, the active loop system operate at the edge of any oscillations and any small deviation of the reflection coefficient at neighbouring frequencies can send the entire system into an oscillation and an uncontrolled power build-up with the potential to destroy the DUT and the measurement instrumentation.

To keep the loop as stable as possible the required bandpass filters must be narrowband and exclude the application of the active loops to modulated signals with bandwidth in excess of 1MHz such as W-CDMA, LTE.

In case of multi-tone signals the closed-loop architecture does not allow for an independent control of the impedances over the modulation bandwidth as both the magnitude and phase control elements remain constant over the modulation bandwidth.

Open loop, active load pull

A newer approach to non-linear measurements is open loop, active load pull, as shown in Figure 3. This technique uses a separate signal source to stimulate either the source or load side of the DUT thus removing any uncontrolled interaction between the DUT and load pull system. This removes the power build up concerns in the closed loop technique. Interestingly, the open-loop architectures can be even safely used to generate reflection coefficients larger than unity. This allows for unique investigations of the interaction between a driver and main PA stage. Due to the unconditional stability of the open-loop architecture, it can be easily used in measurement systems.

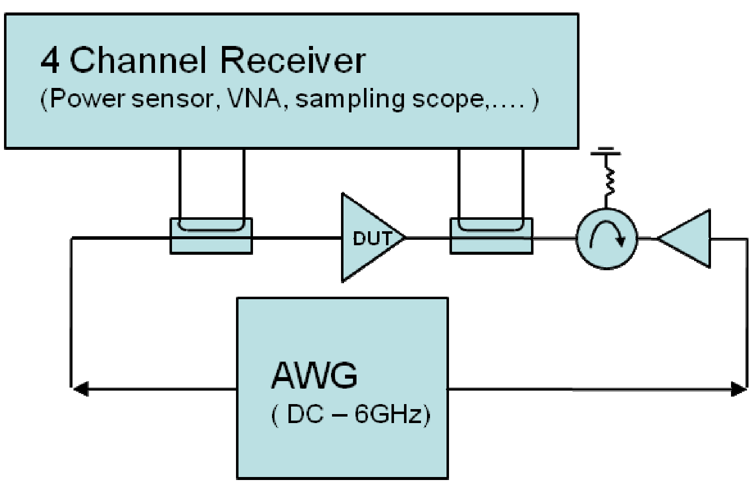

Figure 3. Open loop, active load pull test configuration

The fact that the active load pull system is positioned further away than an impedance network within a real circuit design can be readily compensated by controlling the phase and magnitude of each frequency component within the signal that is generated by the arbitrary waveform generator (AWG). As the active load-pull system is placed outside the calibrated path (comprised of couplers and their connection to the sampling scope) the load-pull can be reconfigured without the need to re-calibrate the measurement system. When no signal is output by the AWG, the active source/load pull architecture presents a broadband 50ohm impedance environment and therefore a reflection coefficient that is nearly zero over the entire bandwidth of the system. This 50ohm environment is changed only at the frequencies that the AWG produces. Consequently, this load pull architecture also eliminates the artifacts that were discussed previously with the passive tuner technique.

The active load-pull system is controlled electronically and does not include any moving mechanical elements. This makes it ideal for on-wafer measurement. Maximum reliability of the probe contact is achieved as no mechanical vibrations are generated during load-pull measurements.

The AWG can also generate pulsed signals and as such enables the use of the open-loop architecture for pulsed measurements. Moreover, the AWG allows an accurate control of all spectral components that constitute the pulsed signal thus making it possible to investigate the dependence of the device behaviour on the reflected pulsed signals. The frequency bandwidth of the AWG starts at the DC frequency making it possible to use the same load-pull system for the impedance control at baseband frequencies. Finally, modern synthesisers are capable of covering frequencies from sub-Hertz to Gigahertz frequencies thus allowing the use of the open-loop architecture at baseband, fundamental and higher harmonic frequencies.

At present, available AWGs are capable of generating any signal within a 6GHz bandwidth enabling the control at all frequency components in their phase and magnitude whether it is a CW or a complex multi-tone signal, hence, covering a large range of fundamental and harmonic frequencies that are utilised within wireless communication systems.

The open loop approach does have some minor disadvantages. For instance iterative search of the correct power level is required to achieve the desired reflection coefficient. Since there is a fundamental load pull, no iterations are needed in the linear region of the DUT. However, iterations are required within the nonlinear region of the DUT during a power sweep or to take into account the nonlinear relationship between the harmonic loads.

In addition, there is a need for additional PAs for the characterization of high-power devices to overcome the difference between the characteristic system impedance and the optimum load. This is only the case at the fundamental frequency as no need for power dissipation at the harmonics. It should be noted that narrowband PAs are readily available at most companies.

Next generation non-linear measurement capabilities
Given the demand for greener wireless devices, more advanced measurement solutions are needed to enable designers to characterize non-linear device behaviour more quickly and efficiently. The open-loop active load pull is a promising new approach offering unique set of advantages.
This load pull technique can be in principle combined with any nonlinear receiver that is capable to measure all 4 waveforms present at the device input and output. An attractive solution is to combine the open loop architecture with commercially available sampling oscilloscopes as shows in Figure 4.

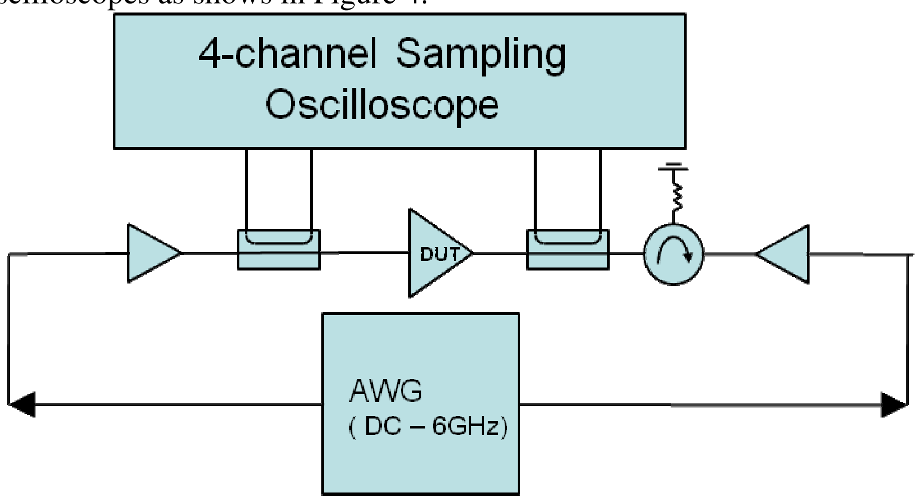

Figure 4. Test configuration for open loop, active source/load pull.

The use of sampling scopes enables phase coherent wideband measurements to be made. The advantages of using the sampling scope are the coherent alignment of all spectral components of multiple signals that are measured simultaneously. The sampling scope can acquire up 8 signals simultaneously making it readily expandable for measurements of devices with up to 4 single-ended or 2 differential ports. In addition, the acquisition units measures all relevant spectral components within the signal including the fundamental and multiple higher order harmonics, as well as the DC and baseband response which are essential in capturing the often seen memory effects in devices. As a result genuine voltage and current waveforms are obtained that represent the actual physical properties of the device.

Waveform engineering
For improved designer efficiency, the next logical step is to use the test configuration just described to create an integrated system that provides for signal conditioning coupled with waveform engineering software for performing the non-linear calibration, measurements and analysis. Textbooks have described the theoretical voltage and current waveforms for specific power amplifiers, such as Class-F and Class-J designs. Waveform engineering describes the designer's ability to optimize their design to achieve these

theoretical waveforms. A totally integrated system allows the measurement of nonlinear parameters via genuine current and voltage waveforms in order to obtain an accurate picture of the DUT behavior. The measured results enable insight into the investigation and development of efficient PA modes of operation[2] and for advanced characterization of memory effects[3,4]. Commonality of voltage and current data allows for easy interchangeability between measurement and simulation, resulting in faster time-to-market[6]. This workflow is show in Figure 5.

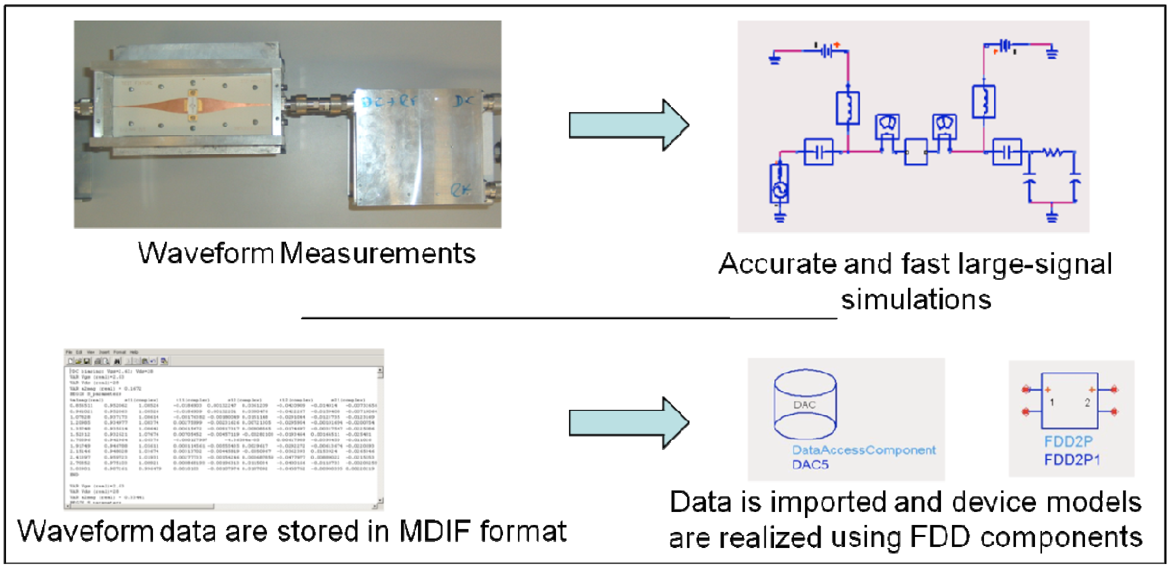

Figure 5. Workflow for exporting waveforms to EDA software tools.

The user can now determine whether a given device is better represented within the simulator through a set of non-linear measurements or a non-linear model. These capabilities make such an approach relevant to the semiconductor industry as specific waveforms can be generated to test and investigate particular properties of a transistor, such as its knee-walk-out or voltage breakdown characteristics[7]. This measurement approach, in essence, is a practical realization of a harmonic balance or envelope simulator and offers the capability for a seamless integration with any nonlinear EDA software.

Conclusion

The use of a sampling oscilloscope and an AWG offers a new alternative to traditional VNA based measurement techniques which measure only a single frequency component at a time. The solution takes fully into account that non-linear devices and systems produce spectrally rich signals at baseband, fundamental and harmonic frequencies and enables their simultaneous control to obtain maximum performance from a given technology. Its modular approach takes fully into account the diversity of the market spanning small, medium and large power applications offering solutions for markets operating up to 20W and 150W. The technology is not limited to tonal stimulus, response techniques, but can be adapted for modulated or pulsed stimulus, response measurements with software. This approach offers significant advantages for the design of more efficient – and greener – wireless devices.

Darren McCarthy

RF Technical Marketing Manager
Darren is the Worldwide RF Technical Marketing Manager for Tektronix. He has worked extensively in various Test and Measurement positions for the over 20+ years including R&D engineer, R&D project manager, Product Planning, Business and Market Development.
During his career, he has also represented the US as a Technical Advisor and Working Group Member for eight years on several IEC Technical Committees and Working Groups for international EMC standards, and currently represents Tektronix on several industry standard working groups and forums.
His recent published contributions include a wide variety of subjects from non-linear device characterization to Ultra-wideband measurement challenges.
He holds a BSEE from Northwestern University in Evanston, Illinois.

Wally Arceneaux

Wally Arceneaux is the Sales and Marketing Manager at Mesuro Ltd., leading the commercial introduction of new measurement solutions that enable systematic waveform engineering at RF and microwave frequencies.
During his 25 year career, he has worked as an R&D engineer in the defense industry and as a marketing specialist in the test and measurement business. Through his career he has focused in several areas including: antenna/radome design, radar, stealth technologies, component testing, and commercial wireless applications.
He holds a BSEE from West Virginia University and an MSEE from the University of Central Florida.

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