Unleashing UHF Nonlinear Measurements Using Active Load Pull and Waveform Engineering Techniques

Technical Brief

The drive for more efficient and lower cost designs is increasing for all wireless communications at all frequency ranges. As this trend relates to power amplifier design, an improvement in Power Added Efficiency (PAE) across a wider fractional band of operation can enable fewer components for multi-band designs. Existing tools have been sufficient to date, but often require multiple design cycles due to poor correlation between expected and actual results. For complex wireless radio formats, optimum efficiency is realized by operating devices in their nonlinear regions where the natural device distortion products can be represented by their harmonic components. In order to achieve the desired performance, next generation tools are needed to more accurately understand the higher order harmonics.

Commercial wireless applications have driven much of the power amplifier market at fundamental frequencies ranging from 0.8 GHz to 2.7 GHz. In the lower part of the UHF band most of the commercial opportunities had long been held by the broadcasters of analog television. With the move to digital television and the subsequent reallocation of UHF band frequencies, some very attractive spectrum is being opened up. There are new opportunities for extending commercial wireless technologies and applications in the 200 MHz to 800 MHz frequency bands.

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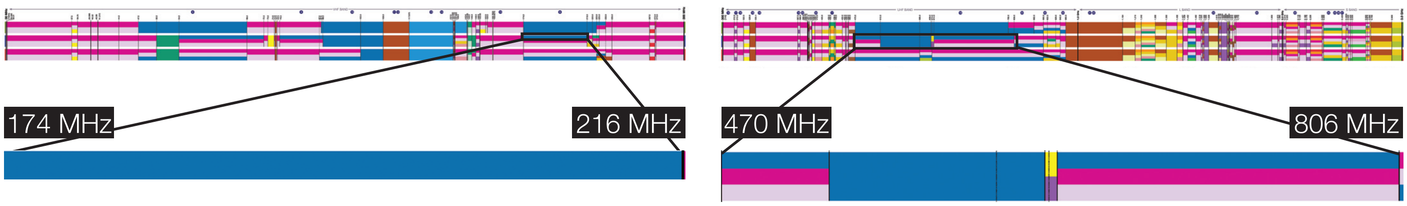

Figure 1. The move from analog to digital television has created “white spaces” of unused spectrum in the UHF band.

In the aerospace and defense market, satellite communications (SATCOM) systems have long operated in the UHF band. However today, just like the commercial smart phones, the need for instant communication across more troops and including voice, video, and data is driving the next generation system specifications.

An expanding need for high efficiency UHF power amplifiers creates some interesting challenges for traditional measurement solutions. Mesuro and Tektronix have recently introduced a new active load pull technology that not only simplifies UHF testing, but also removes several of the limitations and inaccuracies common to passive load pull measurements. The solution is a result of over a decade of technology advances from Cardiff University in Wales, UK. Cardiff’s Centre for High Frequency Engineering has been researching time domain techniques and load pull measurement technologies in close cooperation with industry leaders in the mobile wireless area. The need for a practical design methodology for optimizing power amplifier designs lead to the development of the open loop active load pull techniques.

This paper provides an overview of some emerging UHF power amplifier markets and provides a discussion regarding the evolution of nonlinear measurements. A brief overview is provided on Mesuro’s MB series active load pull measurement solutions and how the Tektronix AWG7000 Series Arbitrary Waveform Generator and DSA8200 Series Sampling Oscilloscope enable a new approach to non-linear device characterization and amplifier development.

Modern Technologies Expanding into UHF Band

The UHF band represents a very valuable spectrum due to some of the physical propagation properties at these frequencies. Traditional analog television broadcasts have long operated in the UHF band. Most people are familiar with the good in building penetration of their TV signals. When compared with more modern wireless applications, such as WiFi, UHF signals have both better penetration and range. In this section we will talk about two growing areas in the UHF band that are creating opportunities for both commercial wireless and aerospace and defense applications.

Expanding to Broadband Everywhere

Today, less than twenty percent of the world population has internet access. Studies have shown that higher levels of broadband usage are a key driver in internet activity growth. Some of the largest companies today have built their success on business closely tied to the internet. Expanding the internet to include another 5-10% of the world’s population represents a huge commercial opportunity.

The recent move from analog to digital television in the US and other countries has created an unusual opportunity of some prime spectrum, which had not been available before (see Figure 1). The US National Broadband Plan calls for the freeing up of 120 MHz of bandwidth in this new “white space”. White Space is the new term being used to describe the old analog TV bands that have been freed up by the move to digital TV.

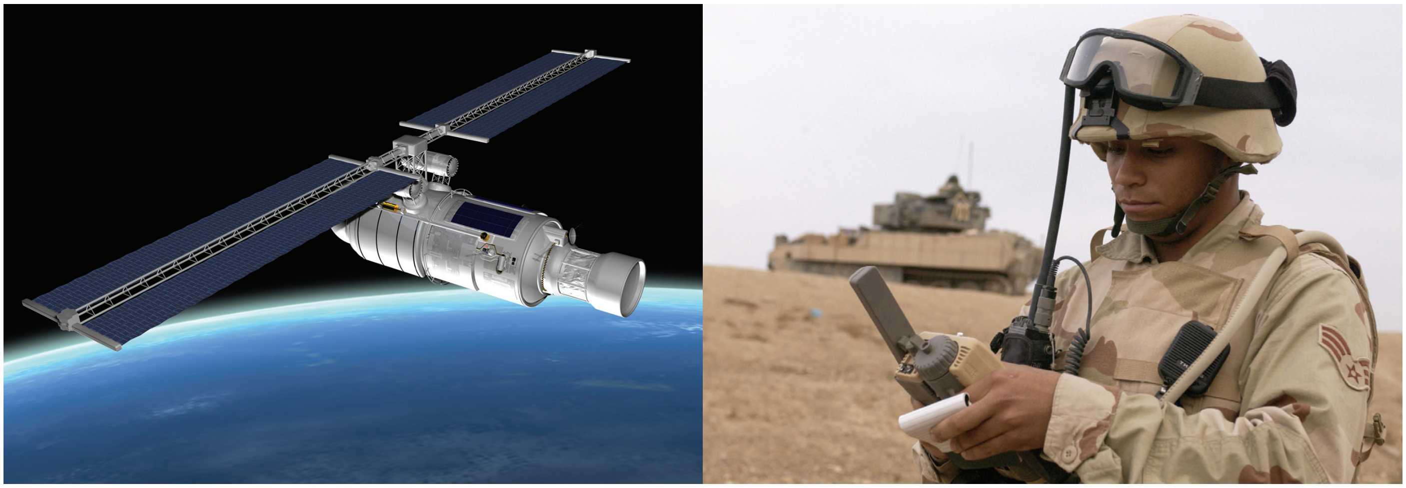

Figure 2. The need for increased data and instant communication is driving the development of next generation UHF SATCOM.

A “White Spaces Coalition” has been formed by 8 major companies to influence the regulations to enable a new high speed internet technology in this white space (Microsoft, Google, Dell, HP, Intel, Philips, Samsung, Earthlink). One option being considered is creating a new White Space Network based on establishing a WLAN technology at UHF. Potential uses would be for:

- Extending broadband to rural areas
- In-home multimedia
- Open neighborhood access
- Public safety
- Backhaul operations
- Public enterprise

This new White Space Network would have the ability to extend the signal range by a factor of 3 without increasing required power levels. The influence of weather is greatly reduced while in-building signal penetration is dramatically improved. The commercial opportunity of this application has been estimated to be $100 Billion over the next 15 years.

Next Generation UHF Satellite Communication

Similar to the growing use of smart phones in the commercial space, the need for data by deployed soldiers is also rapidly increasing. In rough terrain areas, the ability for instant communication can provide a distinct advantage. In satellite communication (SATCOM) networks, satellites play a similar role as base stations in commercial cellular networks. Existing UHF satellite networks are being used and plans are underway to expand their functionality.

One such program is the Mobile User Objective System or MUOS. MUOS plans to utilize WCDMA technologies into the UHF SATCOM band. The goal is to use the commercial technologies to provide a 16-fold increase in number and capacity over the legacy system.

There are a few interesting challenges for amplifier designers as they implement WCDMA at UHF. MUOS operates over the 240-270 MHz frequency band for the downlink and 290-320 MHz frequency band for the uplink while the current commercial systems operate over the 1920-1980 MHz band. The user terminal power amps must operate over a larger fractional bandwidth (~10% vs. 3.6%). Higher efficiency and linearity performance will be two required primary improvements. Improving efficiency is critical to meet the goal of reducing combat load, such as reducing spare battery weight. Higher efficiency will be critical for battery life and thermal considerations. The goal is to achieve power efficiencies of >50%. The maximum output power is expected to be 8 W versus 800 mW for a typical commercial amplifier. In addition, MUOS must amplify a frequency "notched" WCDMA signal to allow for simultaneous legacy users. The notched WCDMA signal has a 2-3 dB larger peak-to-average ratio (PAR) than the WCDMA signal amplified by a commercial phone.

The technical needs and potential commercial opportunity for improving PA performance in UHF SATCOM radios represent an interesting new challenge for R&D engineers.

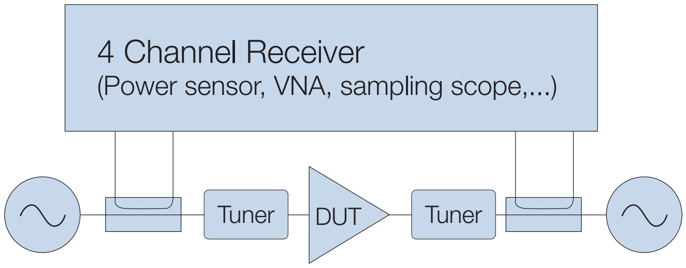

Figure 3. Typical configuration for passive source/load pull configuration.

Evolution of Nonlinear Measurement Techniques

Network analyzers and s-parameter theory have long been available for testing both passive and active components. No matter the frequency, as long as active components are kept in the linear region, s-parameter measurements are the accepted standard for CW testing. Network analyzers are commonly available at frequencies as low as 9 kHz and up to 100 GHz and beyond. However, as active components move into their nonlinear regions, the theory and measurements become more complex. Typical network analyzers are swept frequency instruments and the need for accurate phase correlation across the harmonics has been a challenge. Recent advances in calibration techniques have been developed and a new X-parameter™ capability has been introduced into a network analyzer family. While X-parameters can now measure an accurate harmonic response for a repetitive signal, many device and PA designers still need the load pull capability to test under a variety of impedances.

Passive Source/Load Pull

Passive load pull solutions have been a valuable tool for device and PA designers over the years. A power sensor, VNA or sampling scope can be used for nonlinear measurements (see Figure 3). 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. A typical configuration consists of one tuner at the input, to reduce the mismatch between the input source and the device under test, and one tuner at the output to generate the required loading condition. Tuner positioning is highly accurate and repeatable and this allows them to be calibrated. During the calibration an accurate relationship is established between the position of the slug and the sliding short. Based on this calibration stage, the power inserted into the DUT can be determined from the power level set by the input source while the output power can be then calculated from the power sensor reading. To look at multiple harmonics tuners can be concatenated to allow for the additional control of harmonic impedances. Today, passive tuners are also available that can handle multiple harmonics in a single tuner.

The biggest disadvantage of these systems is that they generate impedances over a large frequency range not just the harmonic impedances, 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 representative of real circuits. This can lead to significant performance variations between the load-pull measurements and the realized power amplifier performance.

Passive Load Pull Challenges:

- Losses reduce practical tuning range at fundamental and more so at harmonic frequencies.
- Control at single or finite set of frequencies can create measurement artifacts for wideband or harmonic signals.
- High reflections at the tuners limit the signals that can be detected at the receivers/sensors requiring high dynamic range receivers.
- As tuners are inside the calibration path, error coefficients must be determined for all utilized fundamental and harmonic impedances.
- Tuner size introduces new challenges at UHF frequencies – over 3 feet in length per tuner!

	Single Harmonic	Multi Harmonic
Frequency Range	250 – 2500 MHz	400 – 3000 MHz
# of Harmonics	1	3
Size (h x w x l)	12" x 10" x 36.9" .31 x .25 x .94 m	12.6" x 13" x 51" .33 x .32 x 1.30 m

Table 1. Passive tuner size creates challenges at UHF frequencies.

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 have large variance from real circuits. For instance, a small current coming from the device under test, 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 time-domain waveforms highly distorted.

The position of the passive tuner between the DUT and the measuring receiver (as shown in Figure 3) makes it difficult to distinguish artifacts 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. Due to the losses between the DUT and the tuners only part of the Smith Chart can be covered. At lower frequencies this effect is mitigated by the relatively low losses however can increase significantly for higher frequencies such as the harmonics of a signal.

For UHF applications passive tuners represent a physical challenge as their size is proportional to wavelength (as shown in Table 1). The control of the reflection coefficients at lower frequencies is limited by the prohibitive length requirements for the coaxial line for the respective wavelength. Passive tuners that operate in the several hundreds of megahertz can be three feet long or more! Adding these tuners to either side of the DUT creates a number of challenges. For on wafer applications, the tuner size and weight can add to the cost and complexity of the probe station. In addition there are vibration concerns as impedances on these large tuners are varied. The move to increase PA performance at UHF frequencies creates a unique problem for passive load pull.

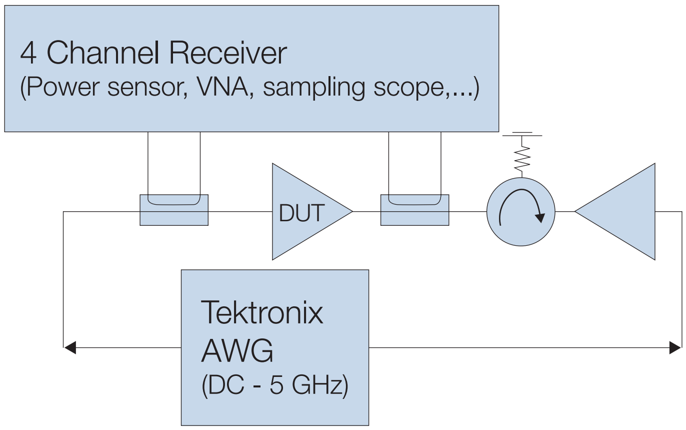

Figure 4. Typical configuration for open loop active source/load pull configuration.

Open Loop Active Load Pull

A new approach to nonlinear measurements has been developed and it is called open loop active load pull, or Active Load Pull for short. 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 (see Figure 4). The open loop system absorbs the signal that is generated by the device under test (DUT) and injects back into the device a signal that is generated by an independent source. The amplifier bandwidth is large enough to cover all harmonic frequencies at which the impedance control is required.

For UHF applications the need for passive tuners and their physical size challenges disappears. With active load pull all impedance variations are created electronically. Eliminating the need for passive tuners removes the physical constraints for performing load pull measurements at low frequencies. Whether you are measuring at 2 GHz, 200 MHz, or 200 kHz becomes a function of your source and is no longer limited by wavelength.

Within the open-loop architecture all in-band and out-of-band impedances are tightly controlled. All the frequencies at which the active load pull is operating are absolutely controlled by the load source while all other frequencies are terminated into 50Ω. When no signal is output by the AWG, the active source/load pull architecture presents a broadband 50Ω impedance environment and therefore a reflection coefficient that is nearly zero over the entire bandwidth of the system. The 50Ω environment is changed only at the frequencies that the AWG produces. As a consequence, the open loop active load pull architecture also eliminates the artifacts that were discussed previously with the passive tuner technique.

Active Load Pull Advantages:

- Unconditional stability.
- Complete control of all load/source impedances.
- Allows for source/load pull at high power levels.
- No need for large passive tuners at UHF frequencies.
- All electronic solution ideal for on-wafer measurements.
- Generate any load/source impedance inside or outside of the Smith Chart at fundamental and harmonic frequencies.
- High measurement accuracy for source/load reflection coefficients.
- Simple calibration process based on traditional reference standards.

Each channel of the Tektronix AWG is capable of generating any signal within a > 5 GHz bandwidth on each channel. It is possible to control and modulate all frequency components in phase and magnitude irrespective of whether it is a CW or a complex multi-tone signal. Interestingly, the open-loop architectures can even be 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.

An interesting new area emerges related to load pull measurements at baseband frequencies. Electrical memory effects are a resultant hysteresis of a rapidly changing modulation envelope signal due to the parasitic capacitance across the surface of the transistor. The phenomena and effect are represented in the baseband measurement of the modulated signal. The impedance control at baseband (below 50 MHz for most modulated signals) is an important part of being able to accurately predict the memory behavior.

The basic instruments used for stimulus and response, the Tektronix AWG7000 Series Arbitrary Waveform Generator, and the DSA8200 Series Sampling Oscilloscope, have generation and measurement capabilities that cover DC operation.

Figure 5. Mesuro's MB Series solution utilizes the unique function and performance of Tektronix equipment for the simultaneous utilization of its waveform measurement and harmonic active load pull capability.

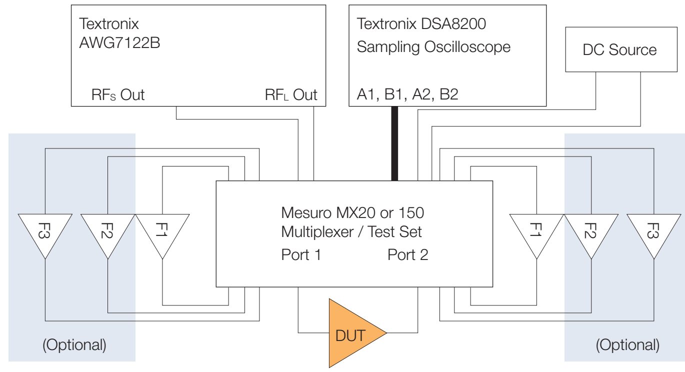

Figure 6. The MB Series can be configured for multiple harmonics on both source/load pull.

Commercial Active Load Pull Solution using Waveform Engineering

The new open loop active load pull technique was developed over the last ten years at Cardiff University and commercialized by Mesuro LLC, a spin out from the University. The MB20 and MB150 series offer 20W or 150W solutions respectively (see Figure 5). The solution replaces the passive tuners with amplified RF sources. By varying the amplitude, and phase any impedance can be created at the DUT interface. With advances made in the Tektronix Arbitrary Waveform Generator (AWG), these signals can be very stable, repeatable and changed very quickly. This allows load pull measurements to be performed much faster and may broaden the application of these measurements.

As mentioned, for UHF applications (or lower), the frequency bandwidth of the AWG and the DSA series sampling scope both start at the DC frequency making it possible to perform very low frequency load-pull measurements. With > 5 GHz of bandwidth, the AWG is 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. The use of the sampling scope as the nonlinear receiver also removes the restriction on lower frequency as the RF modules are available covering DC to 20 GHz (with optional electrical modules available up to 70 GHz). The operational frequency range is therefore defined by the Mesuro multiplexer and RF test set, which can be defined by the frequency ranges of interest.

At higher power levels it is often more cost efficient to implement the amplification over the required number of harmonics through use of narrowband PA with center frequencies located around the fundamental and harmonic frequencies. The separation of the harmonic frequencies can be readily obtained by means of a multiplexer (see Figure 6). The same multiplexer can then be used re-combine the harmonic signals.

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 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.

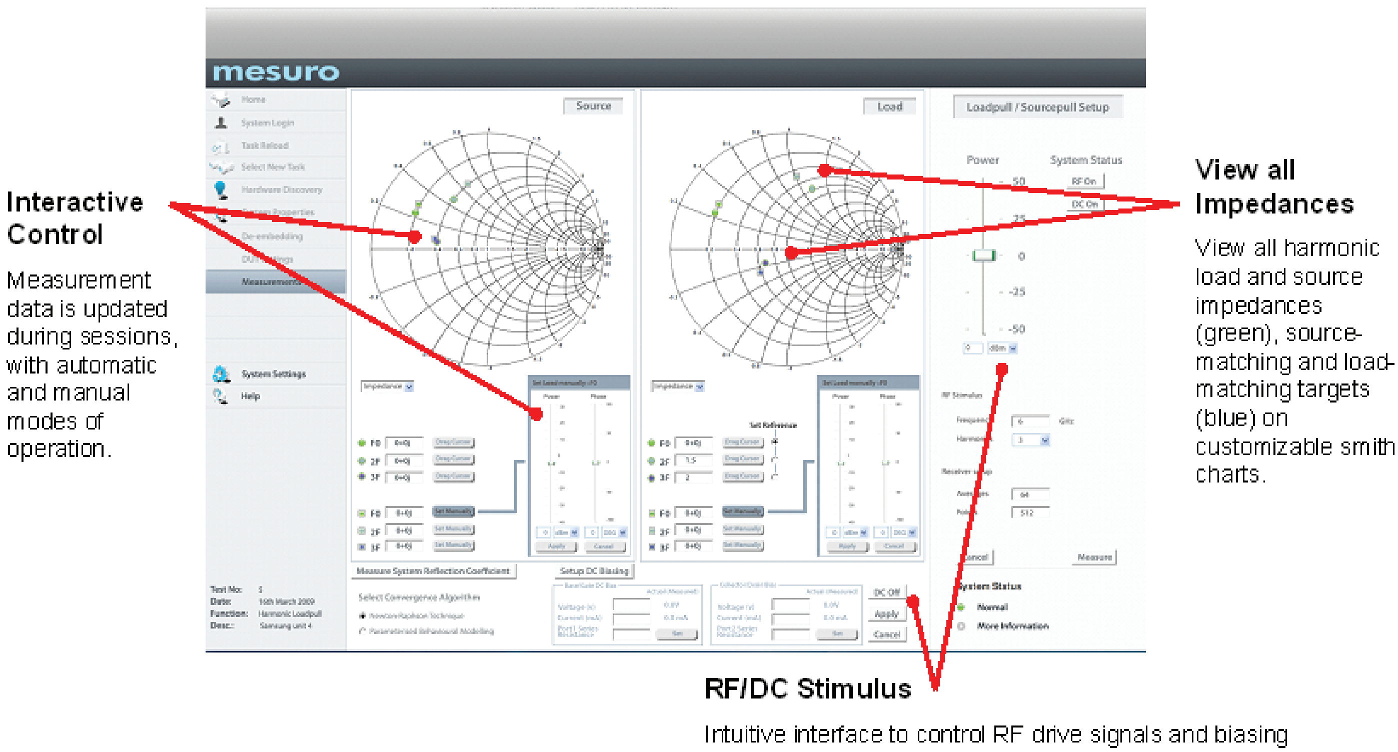

Figure 7. The MB Series software provides complete control automation for performing measurements and setting source/load impedances.

Fully Automated Measurement Solution

The MB Series solution includes system level software with a user interface that has been streamlined to automatically configure and control all instruments and allow the user to focus on his measurements. The graphic user interface is split into two primary displays: measurement control and measured results. The measurement control display (see Figure 7) allows for:

- Automatic detection, initialization, and calibration of the attached instrumentation and measurement set-up.
- Easy access to all relevant measurement parameters such as the control of the DC and RF input signal.
- Concurrent control of harmonic source and load pull impedances.
- Allows for a macro-based automation of the measurement system to maximize its utilization.

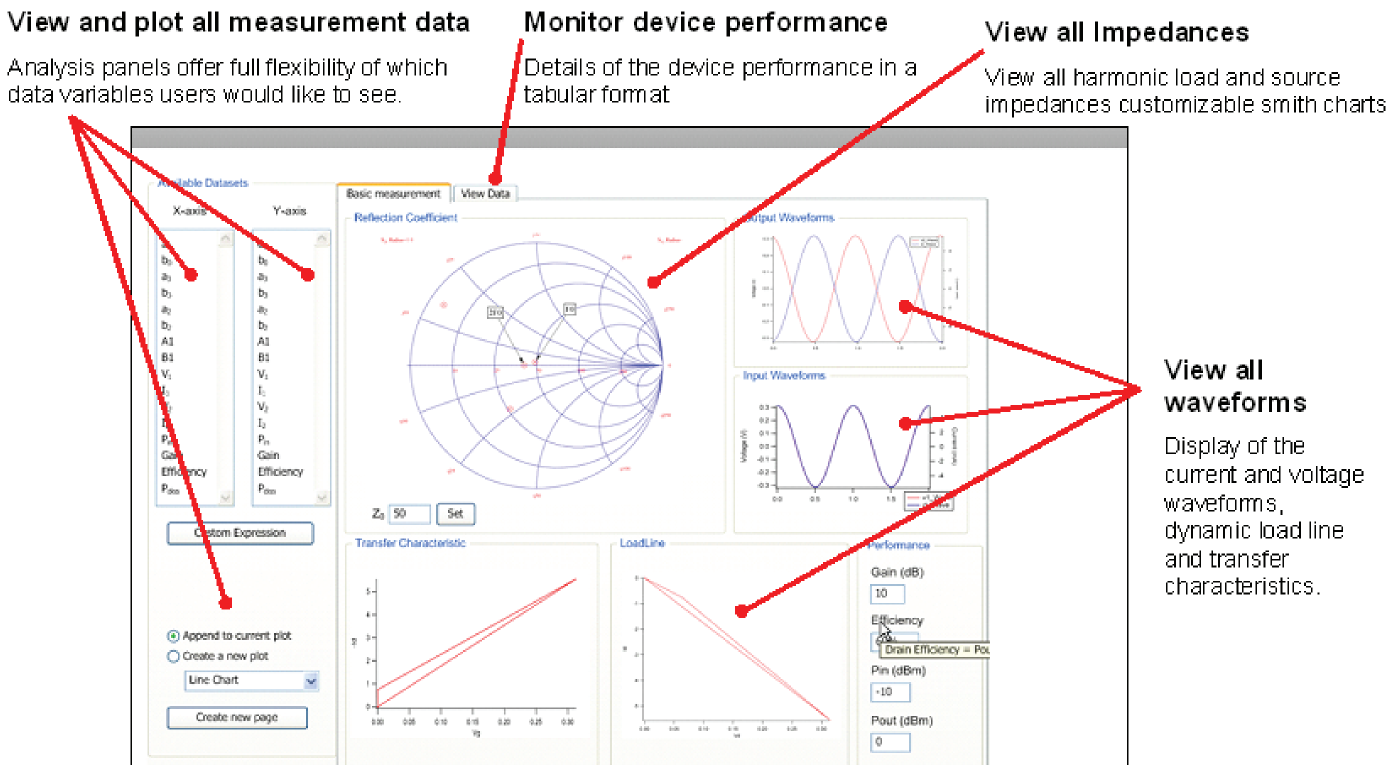

Figure 8. Easily define and display waveforms and measured results in a wide variety of convenient formats.

The measured results display shown in Figure 8 allows for:

- Display of all the measured data with user-defined data variables.
- Large viewing area for plotting the information that is contained within the measured waveforms.
- Supports multiple tabs to organize the displayed data.
- Facilitates the creation of user-defined variables the screen has an in-build equation generator.

Create Accurate and Fast Large-Signal Simulations

Designers have been challenged over the years from the discrepancies observed between simulations and measured performance. This can result in the need for multiple design cycles thus increasing development costs and often adding months in development cycle time. 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 often lack a coherent integration with a harmonic source/load pull system resulting in devices and amplifiers being characterized at impedances that are different from their final application making it challenging to translate the measured device performance into a PA design, or achieve the potential performance available from the device or the employed PA architecture.

Mesuro's MB Series test system allows for accurate and fast large signal simulations, including both high power and non-50Ω applications. The system measures basic voltage and current waveform data which provides the full information required for harmonic balance and envelope simulations. The time domain data collected by the sampling scope is transformed into the frequency domain and stored in an MDIF format which can be imported into today's popular CAD tools. Once the data is imported it can be used for spot-analysis and the authentic recreation of the device behavior with the look-and-feel of a behavioral model. This allows for complete characterization of nonlinear devices and amplifiers and their use in common nonlinear simulation engines. These behavioral models can be used by designers in complex component or system level simulations.

Summary

New applications and technologies are being developed at UHF frequency bands for both commercial and aerospace and defense uses. When used to help optimize power amplifier designs, traditional passive load pull solutions have both limitations as well as challenges at these low frequencies. R&D engineers need next generation tools to best optimize their RF device and PA designs. The Mesuro MB series active load pull technology not only simplifies UHF testing, but also removes several of the limitations common to passive load pull measurements. Active load pull and waveform engineering enable the designer to more accurately understand the higher order source/load harmonics and thus achieve near theoretical performance. Improving the correlation between design tools and measured results will reduce the number of design cycles and accelerate time to market.

For more information on the Mesuro MB series please visit their website at www.mesuro.com

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