# Performing Accurate Nonlinear Device Measurements Using Active Tuners

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With continued pressure for broader 3G coverage for smart phones, increased Internet connection for Wi-Fi and WiMAX, and the imminent introduction of 4G/LTE systems, design activity for digital communication RF components has never been greater. At the forefront is the development of power amplifiers (PA). At the top of the list of concerns for PA design engineers is power added efficiency (PAE). High PAE in a power amplifier provides:

- Increased battery life for mobile devices
- Maximum antenna coverage for base stations with lower electricity bills for network providers
- The opportunity for manufacturers to charge increased prices for higher performing devices and consequently, generate higher revenue return per wafer.

Digital modulation schemes such as PSK, QAM and OFDM result in modulated RF carriers with high Peak-to-Average Ratios (PAR). PA design engineers must consider the consequences of amplifying a communication signal with high PAR, yet maintain linearity and acceptable Error Vector Magnitude (EVM) rates. A linear vector network analyzer (VNA) provides essential information regarding the performance of small signal amplifiers operating under linear conditions. However, when high-power amplifiers are designed for compressed nonlinear operation, VNAs must provide additional data to help engineers optimize their designs.

VNAs can measure S parameters of active and passive devices and systems. When measuring active devices, these measurements are made on small signal devices where gain is linear. When measuring a device operating nonlinearly, the VNA must include the fact that the device is generating multiple harmonics as well as the fundamental frequency. So, a critical aspect of a nonlinear VNA is the ability to measure harmonic content as well as the fundamental signal, and provide the performance data to facilitate optimum nonlinear PA design. In addition, a critical element of nonlinear analysis is the ability to provide a wide range of impedance loads to the device, especially at the harmonics, using load pull measurement techniques.

PAE is an important concern for all communication power devices. Power efficiency provides the highest power output possible while maintaining long battery life. Amplifiers operating in a compressed nonlinear state offer high-power efficiency ratings reaching PAE levels of 70% or higher.

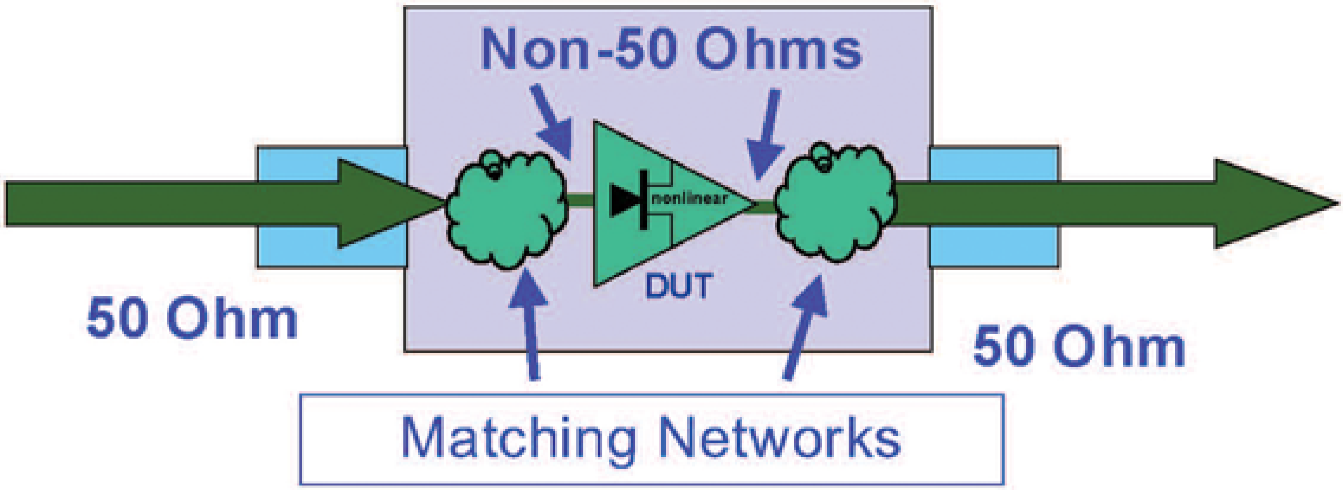


**Figure 1. On-wafer active devices need matching networks to optimize performance in 50 chm system.**

Design of a nonlinear power amplifier begins at the wafer level. The on-wafer device ultimately will be embedded into a 50 ohm system. However, the input impedance of on-wafer active devices is not 50 ohms and the output impedance of most high-power devices normally operate in the 1 to 2 ohm range. A matching network is necessary to transition the input and output of the on-wafer device to a 50 ohm system (Figure 1). Since the device is rich in harmonics, the matching network must also include the optimum match for both fundamental and harmonic components.

Providing information on the performance of the device relative to the source and load impedances is the primary objective of a nonlinear VNA measurement system. The wider the range of load impedances a nonlinear NVNA system can present to the device, the more accurately the optimum performance can be realized. Since the load impedance requirements are in the 1-2 ohm range an active loop tuner is ideal for overcoming insertion losses in the measurement system. As will be discussed, an active loop tuner provides the best nonlinear measurement solution for device optimization.

**A New, Improved Test System**
A new nonlinear measurement system provides a unique method of providing load pull measurements for nonlinear device characterization (Figure 2). Load pull tuners provide different impedance loads to the device under test (DUT) in order to evaluate the potential performance of nonlinear devices. The primary difference between the new system and traditional load pull systems is the location of the tuners and monitoring couplers.

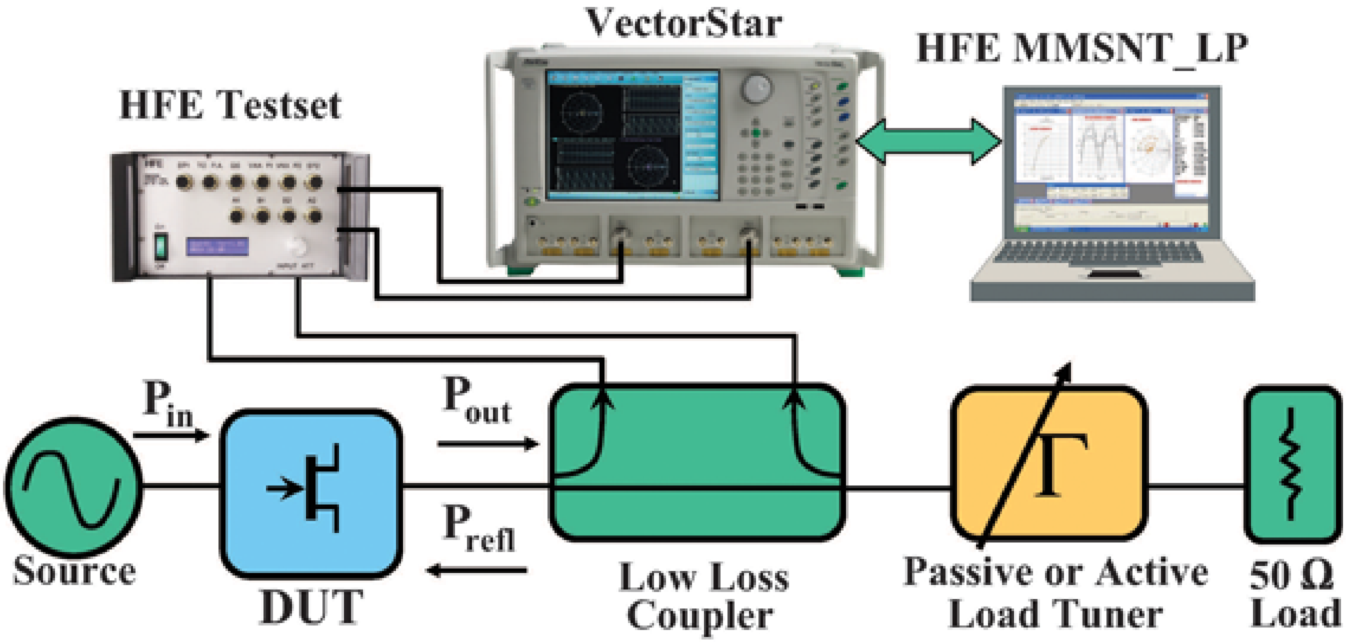


**Figure 2. Simplified block diagram (showing output only) of the Anritsu VectorStar and HFE Nonlinear load pull system.**

A typical load pull system locates the coupler outside the tuner and monitors the power output of the device as the tuner is varied in impedance. This method requires that the tuner be pre-calibrated. The accuracy of the measurement is determined by the repeatability of the tuner, cables, and connectors after calibration. The tuner in this traditional configuration is controlled by vendor software for both calibration and control, and creates a complex relationship between the tuner software and nonlinear VNA software. Since many devices need to be tuned over a large area of the Smith Chart, the calibration table of this traditional load pull system will be very large. Calibration time will run into hours.

The new system inserts an ultra low loss coupler between the DUT and tuner. Because the system locates the coupler next to the DUT, high measurement accuracy of the source and load impedance at the DUT is achieved. In addition, this method provides a method to simultaneously monitor the impedance and performance of the DUT in real time. This provides immediate display of the response and the ability to perform real-time tuning. It also means the tuner no longer needs to be pre-calibrated.

**Measuring PAE**

A typical plot of PAE performance relative to harmonic load impedance is shown in figure 3. Note that as the second harmonic is terminated at a specific phase angle, PAE is optimized, and that the optimum PAE and minimum PAE can be quite close to each other. This is another reason why accurate harmonic load pull is critical to optimum design. It is not only desirable to accurately find the location for best PAE, gain, max power, etc., it is also important to accurately identify areas to avoid. In this case, if design constraints result in a matching network variance of up to 50°, it would be prudent to design the network far enough away from the Imax point to ensure acceptable performance.

During analysis, the effects of the second and third harmonic need to be considered since they are significant contributors to amplifier performance. Thus, at least three frequencies must be tuned simultaneously while performing nonlinear analysis. The result is that a properly configured nonlinear measurement system will have three or more separate tuners as part of the configuration.

One of the design requirements of nonlinear classes of operation is the need to fully reflect harmonics back to the DUT to minimize harmonic content at the output and maximize PAE performance. This means that during the analysis portion of the load pull process, the harmonics must see a full reflection (maximum gamma of 1) at the device output. When the load pull tuner is set for maximum reflection, any insertion loss between the tuner and the device will result in less reflection at the device. These measurements are typically taken on-wafer using probe stations and probe tips. The insertion losses in these systems, with long RF cables and lossy probe tips, can be substantial, resulting in less than ideal reflection at the device.

With traditional load pull systems, the monitoring VNA is located after the tuner and susceptible to mismatch loss errors, which degrades power output measurement accuracy. At high gammas, the mismatch loss error in the traditional system is substantial. Using the new technique, mismatch loss errors are minimized since the coupler is located next to the DUT and monitors power output of the device before the tuner. Note that this new technique only works if the couplers are ultra low loss since. A normal coupler would attenuate the reflected signal and diminish the accuracy of the analysis. In the system described in Figure 2, the low loss couplers provide a maximum insertion loss of 0.05 dB at 2 GHz thereby ensuring best measurement.

Active tuners are critical for optimum load pull analysis because passive tuners cannot overcome system losses to provide the high gammas needed to fully evaluate a nonlinear device. Active tuners provide amplification of the reflected signal and can overcome system losses. Passive tuners by their nature cannot provide a gamma higher than 1 and in many cases will be in the 0.9 range before system losses. Active tuners are designed to provide gammas that can overcome losses between the tuner and the DUT and provide sub-ohm loads at the DUT.

**Active Loop Tuner Configuration**
Although the optimum choice is active loop tuners, the new nonlinear system can be installed using passive or active tuners. If the user already owns passive tuners, the system will still provide real-time tuning without the need for the tuner control software or pre-calibrating the passive tuner. When configured with the appropriate active loop tuner, optimum reflection at the DUT port can be delivered. Figure 3 is an example of an active loop tuner configuration.

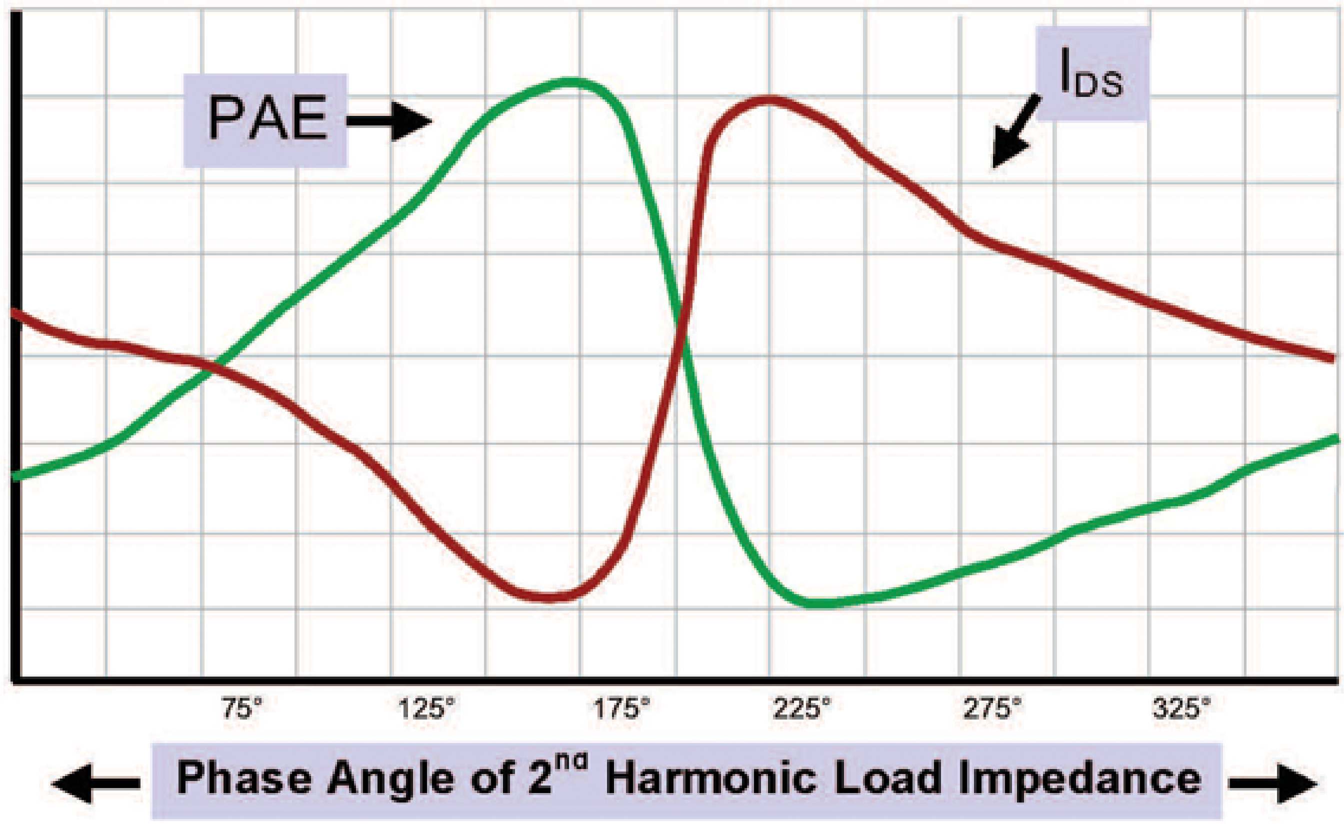


**Figure 3. Example of the effect of harmonic load impedance on PAE.**

Active tuners make it possible to configure the test system for load pull measurements of differential devices. Since it is possible to actively monitor the real-time impedance presented to the device, it is also possible to actively and independently tune the input of the device to specific phase positions. In the case of a differential device, this means it is now possible to actively control the differential input, and tune the device under varying source and load conditions by adding a second leg to the device. This configuration provides a true balanced load pull differential measurement of differential devices.

Because of the large quantity of data acquired during nonlinear measurements, it should be formatted in a way that is easy to store, convenient to open and view, organized in a flexible manner, and easy to share. The OpenWave Forum (OWF) is an alliance of RF and microwave firms formed to collaborate, create and promote a unified and transparent data exchange format for large-signal nonlinear simulations, measurements and models. An open standard ensures that any system adhering to the standard will be compatible and transportable to an EDA environment that recognizes the standard. Thus, a data set using an open standard can be shared with other measurement systems adhering to the standard. This method reduces risk by providing flexible, non-proprietary data format files that can be shared.

**Conclusion**
A new nonlinear VNA measurement system incorporates a different method of conducting load pull measurements on nonlinear devices. This new method allows

for true differential measurements to be made on PAs, and allows engineers to have greater confidence that their designs will meet the demands of today's digitally modulated systems.