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Mixed-Signal System Speeds Load-Pull Testing

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Tracing The Evolution Of Load-Pull Methods

The evolution of load-pull tuning has led to hybrid and mixed-signal approaches that use the best features of mechanical and active tuners to speed measurements on nonlinear devices.

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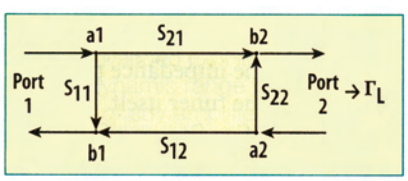
Amplifier designers have long appreciated the capabilities of load-pull systems to develop impedance matching networks for a transistor of choice. In a linear system, it is enough to simply use the complex conjugate of the small signal input impedance as the source matching network, and the complex conjugate of the small signal output impedance as the load matching network.[1] But for power devices and their nonlinear characteristics, load-pull systems can provide the information needed to maximize power transfer and output power over a broad range of frequencies.

Load-pull techniques rely on studying the response of an active device, such as a power transistor, to changes in source and load impedance. A load-pull system provides the means to change impedances while characterizing a device for its optimum large-signal conditions.[2]

Harmonic load-pull techniques represent an extension of fundamental-frequency load-pull measurements, studying the response of a device under test (DUT) for combinations of load impedance, Z_L, with a fundamental test tone and one or more harmonic frequencies of the fundamental. The approach is often used to increase the efficiency of a highly compressed amplifier[3] or to lower the error vector magnitude (EVM) of an amplifier operating in backed-off conditions.



1. This diagram shows the familiar two-port model for deriving the four scattering parameters.

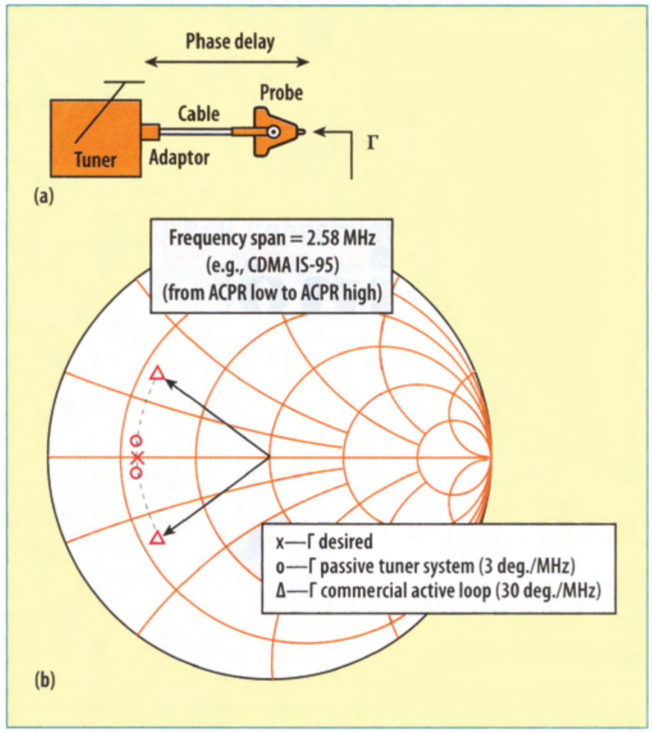
The impedance presented to the DUT can be stated in various formats: impedance, Z_L (consisting of R + jX), voltage standing wave ratio, VSWR (as a complex number in magnitude and phase), and reflection coefficient, Γ_L (as a complex number in magnitude and phase). Considering the DUT as a two-port device (***Fig. 1***), the magnitude of reflection presented to the DUT, Γ_L, is nothing more than a_2/b_2, or the ratio between the reflected and forward traveling waves. The generalized formula can be written as

$$\Gamma_{x,n}(f_n) = a_{x,n}(f_n)/b_{x,n}(f_n)$$

In a traditional passive mechanical tuner system, reflection occurs by partially interrupting the electric field of an airline using a metallic probe (also referred to as a tuning slug). The probe is inserted into the airline at some variable depth; the further the probe penetrates into the airline and interrupts the electric field, the greater the magnitude of reflection, or Γ_L. The phase of reflection is varied by sliding the probe along the length of the slabline. Therefore, any impedance on the Smith Chart can be presented to the DUT by selecting the appropriate vertical and horizontal positions of the probe with respect to the airline.

Fundamental load-pull tuning is achieved with a single tuning probe, or a combination of tuning probes, with regard only to the fundamental frequency impedance. Harmonic load-pull tuning is achieved using a combination of two, three, or more probes in cascaded[4] or filtered[5] configurations.

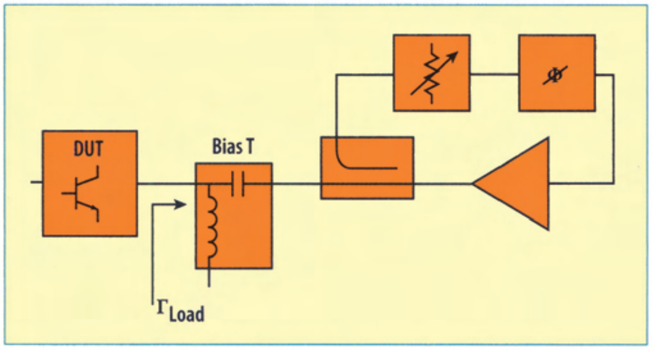
With a passive mechanical tuner, it is clear that a_2 will always be lower than b_2 due to the reflection limitations of the tuner (not all the energy can be reflected) as well as the losses between the DUT and the tuner (energy is dissipated before reaching the tuner, lowering the amount of energy that can be reflected). Assuming a theoretical ideal termination for harmonic impedances of around $\Gamma_L = 1$, typical achievable values using mechanical tuners range between $\Gamma_L = 0.8$ and $\Gamma_L = 0.92$ at the DUT's reference plane.



2. These depictions show the phase delay caused by (a) the electrical lengths of cables, adapters, and probes, and (b) the phase delay of a 2.58-MHz wideband signal for a typical load-pull system.

The growing use of modulated wideband signals in communications and other systems poses challenges for traditional load-pull systems. Traditional load-pull systems are designed to work at discrete frequencies, whereas wideband signals occupy segments of spectrum often 10 MHz or wider. Yet, the load-pull system is also presenting impedances, for example across a 10-MHz-wide bandwidth, albeit not all with the same value as that of the tuned center frequency. Vastly different impedances may be presented across the wideband signal's bandwidth, due to the phase delays between the DUT and the impedance tuner, including probes, cables, fixtures, and the tuner itself. This can result in misleading values for amplifier figures of merit, such as power-added efficiency (PAE) and adjacent-channel power ratio (ACPR), resulting in misleading results for power amplifier performance. ***Figure 2*** demonstrates the effect of phase delay on tuned impedances. In this example, a wideband signal of 2.58 MHz bandwidth is used with a standard non-optimized load-pull system, which yields a phase shift of 3 deg./MHz, or 7.74 deg. over the signal bandwidth. For a multichannel WCDMA signal with a 40-MHz bandwidth, the phase shift would be 120 deg.[6]

Active closed-loop load-pull methods have been referenced in IEEE publications since the late 1970s. The methodology uses an amplified version of b_2 as the reflected signal a_2. To accomplish this, a coupler or circulator is used to direct the signal from the DUT, b_2, through a variable amplification



3. This block diagram shows a typical tuning loop in a closed-loop active load-pull system.

stage with control of both magnitude and phase, and re-inject the signal as a_2 back into the device.[7] ***Figure 3*** shows the block diagram for a typical closed-loop system.

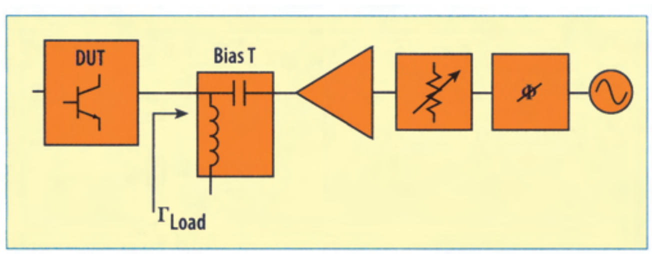
There are several advantages to this technique over traditional mechanical load-pull tuners including speed, control of gamma, and ease of integration especially in on-wafer measurement systems. Since the system relies on electrical tuning with no moving mechanical parts, tuning can be quite fast. Amplifiers in the closed-loop configuration can be used to increase a_2 so that Γ_L can approach unity at the DUT's reference plane. On the negative side, oscillations can occur in an active closed-loop load-pull system due to leakage from passive components. Significant filtering is needed to reduce the chance of oscillation that typically makes this system approach narrowband. Nor does the active approach solve the phase-delay problems of mechanical load-pull systems. In fact, the added length of the tuning loop can cause an increase phase delay with respect to the DUT reference plane. A commercial closed-loop active load pull system has phase shift of 30 deg./MHz, or 77.4 deg. over the signal bandwidth. For the 40-MHz WCDMA signal mentioned earlier, the phase shift would be 1200 deg. Finally, the use of high-power linear amplifiers in the active closed-loop load-pull approach can add considerably to the cost of the system.

A closer examination of the formula $\Gamma_L = a_2/b_2$ reveals that there is no limitation on separating the sources of a_2 and b_2. It is obvious that b_2 is the wave coming from the device, of which we have no direct control; however a_2 need not be a reflected version of b_2 but can be a new signal entirely.[8] Open-loop active load pull relies on external sources to inject a signal into the output of the DUT, thereby creating a_2. The simple active tuning chain consists of a signal source, a variable phase shifter, and a variable gain stage (***Fig. 4***). Commercial signal generators with built-in amplitude and phase control of the injected signal are ideal for active load pull.

With active load-pull techniques, harmonic load-pull tuning is simplified since a multiplexer can be used to merge multiple active tuning paths, one per frequency, so that the condition $\Gamma_{x,n}(f_n) = a_{x,n}(f_n)/b_{x,n}(f_n)$ is satisfied. Any losses inherent to multiplexers are easily overcome by the amplifiers used in each active tuning chain. The benefits of active open-loop systems are similar to those of closed-loop systems: fast tuning, high-gamma tuning, and ease of integration with on-wafer measurement systems. But open-loop systems also have an advantage over closed-loop systems: there is no feedback path and therefore no chance of tuning-loop oscillation.

A negative aspect of the open-loop load-pull approach is the expense of having multiple signal generators for each impedance-controlled frequency of interest, limiting the functionality of practical open-loop systems to single-tone signals and their harmonics. Open-loop systems also require high-power amplifiers to achieve the desired reflection coefficients when testing a high-power device. However, unlike the closed-loop system, these amplifiers do not have to be linear since the user-specified reflection coefficient is reached by successive software iterations.

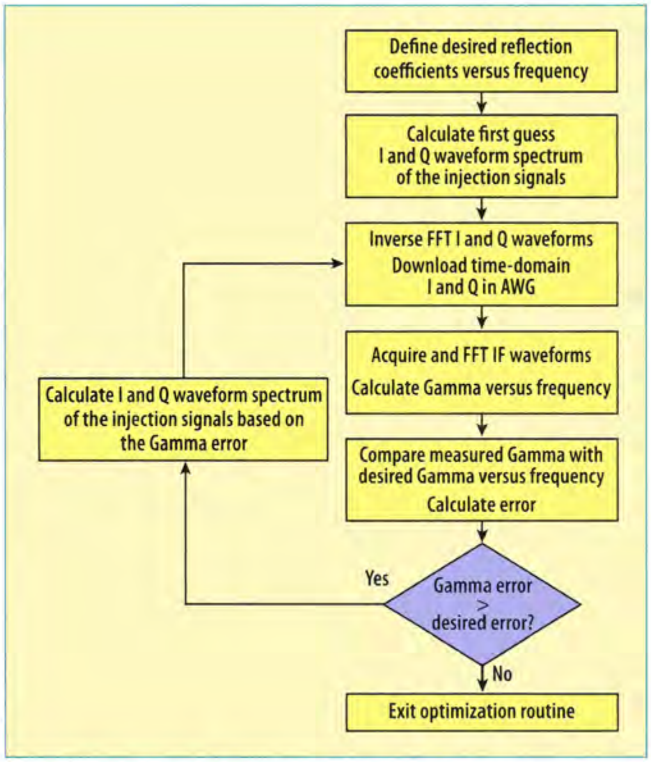
While mechanical tuners are simple, less expensive and can handle high power, there is no physical way to overcome the losses involved with the system that limit obtainable Γ_L.[9] While open-loop active load pull systems tune quickly, are capable of $\Gamma_L = 1$, and offer



4. This block diagram shows a typical tuning loop in an open-loop active load-pull system.

ease of integration, they require expensive band-limited amplifiers. Fortunately, a technique called the hybrid load-pull approach offers the advantages of passive and active load-pull approaches while minimizing the disadvantages of both. Hybrid load pull refers to a combination of active and passive tuning in the same system. Traditional passive mechanical tuners can be used to reflect high power at the fundamental frequency allowing a much smaller active injection signal, using much smaller amplifiers, to overcome losses and achieve $\Gamma_L = 1$. Since the power levels of harmonic frequencies are often well below the power of the fundamental signal, less-expensive wideband amplifiers can be used with active tuning to accomplish active harmonic load pull with $\Gamma_{L,nf} = 1$. Both cases require only low power levels for active tuning.

Maury Microwave Corp. (***www.maurymw.com***) and partners Agilent Technologies (***www.agilent.com***) and AMCAD Engineering (***www.amcad-engineering.fr***) provide turnkey open-loop active and hybrid passive active load pull systems based on the Agilent PNA-X nonlinear vector network analyzer and Maury's impedance tuners and ATS and IVCAD software platforms. AMCAD's family of PIV pulsers add pulsed-bias capabilities. The PNA-X nonlinear VNA provides the required a_2 for the active load pull as well as the receivers to measure the applied and transmitted power. It offers frequency coverage of 10 MHz to 50 GHz or greater and a flexible test set for adding external components such as amplifiers. The PNA-X monitors the tuned impedance by measuring the a_1, b_1, a_2, and b_2 waves at desired frequencies and making corrections as required. Even without tuning the source, the knowledge of a_1 and b_1 allows a calculation of the DUT input impedance and results in the determination of delivered power to the DUT.



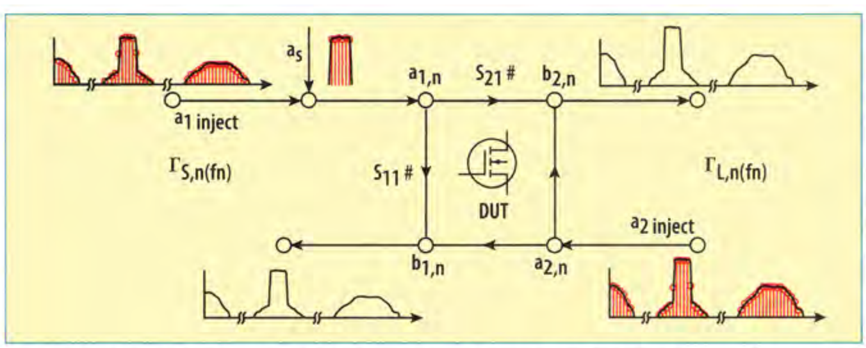
5. This diagram shows the signal synthesis and analysis process used in a mixed-signal active load pull system.

Mixed-signal active load pull is a unique form of open-loop active load pull invented and patented by Anteverta Microwave (***www.anteverta-mw.com***) and available exclusively through Maury Microwave in its MT2000 series product offering. Instead of direct-frequency signal synthesis and analysis, it makes use of frequency upconverters and downconverters along with wideband analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) to create and analyze waveforms at baseband.[10] Because of the wideband nature of the arbitrary waveform generators (DACs), wideband modulated signals to 120 MHz can be created, upconverted, and presented to a DUT, allowing an almost unlimited number of a_1, b_1, a_2, and b_2 waves with a bandwidth of interest.

In the mixed-signal approach, the errors rising from phase delays for wideband modulated signals can be eliminated, since the impedances can be synthesized without restriction over the entire signal bandwidth. Such a system has the capability to put every frequency component within the signal to a single impedance point, or to an arbitrary pattern, or even to the realistic frequency-response of a typical matching network. ***Figure 5*** shows the signal synthesis and analysis process for the mixed-signal approach.

First, the single-tone, multitone, or modulated signal (a_S) is defined in the frequency domain, together with user-defined reflection coefficients as a function of frequency. An inverse Fast Fourier Transform (FFT) is used to convert the signal to the time domain, after which it is loaded into the DAC at baseband. The signal is then upconverted from baseband by the RF test set to the desired frequency and injected into the DUT.

Second, the injected (a_n) and reflected



6. This is a simplified algorithm of the mixed-signal-based active load pull system for controlling the reflection coefficient within the modulation bandwidth.

(b_n) waves are sampled by directional couplers and downconverted by the RF test set to a low intermediate frequency (IF) representation where each signal is captured in the time domain by the ADCs. FFTs are applied to convert the signal to the frequency domain and calculated the measured reflection coefficients versus the modulation bandwidth.

Third, the measured reflection coefficients are compared with user-predefined values for each frequency component of the signal. The original injection signals $(a_{1,n},\ a_{2,n})$ are then adjusted in the frequency domain to converge to the user-defined values. An inverse FFT is applied to convert the new injection signals to time-domain, which are uploaded to the DACs to generate new baseband signals. These signals are upconverted by the RF test set to the desired frequency and presented back to the DUT. As in the original open-loop approach, an iteration process is used to compare the created waveforms with the desired waveforms, and make successive corrections as needed. The flow-chart describing the process is shown in ***Fig. 6.***

The innovative MT2000 series mixed-signal active load-pull system offers broadband capabilities from 0.4 to 26.5 GHz. It supports load-pull measurements with wideband modulated signals at standard bandwidths to 120 MHz (and available bandwidths to 240 MHz).

Single-tone measurements with an MT2000 series load-pull system can be performed in real time, at test speeds accommodating more than 1000 power and impedance load states per minute. The systems have executed independent fully controlled multidimensional load-pull parameter sweeps and captured over 5000 measurement points in less than 5 minutes, using 90 fundamental load states, swept load and source harmonic terminations, and 16 power levels.

The advantages of the mixed-signal open-loop technique are numerous: high-speed single-tone device characterization, high gammas, wideband control for realistic communications-standard compliant modulated signals, resulting in a far more realistic characterization of the DUT, while its active nature allows easy integration with on-wafer measurement systems.

Unlike the closed-loop technique, there is no feedback path and therefore no chance of tuning-loop oscillation. While compared to the traditional open-loop active load pull approach, higher measurement speeds are achieved and there is no longer the need to have individual synthesizers for each impedance-controlled frequency. Furthermore, the open-loop nature of the system results in injection amplifiers that can be used up to their saturated power levels, as the signals synthesis and analysis will identify nonlinear imperfections caused by the power amplifiers and compensate automatically by modifying the injected signals.

Finally, since active load pull systems control impedances at only the desired frequencies, the DUT will see a system characteristic impedance of 50 Ohms even for out-of-band frequencies. This reduces the out-of-band oscillations that can occur when using passive load-pull techniques. Maury Microwave Corp., 2900 Inland Empire Blvd., Ontario, CA 91764-4804; (909) 987-4715, FAX: (909) 987-1112, Internet: www.maurymw.com.

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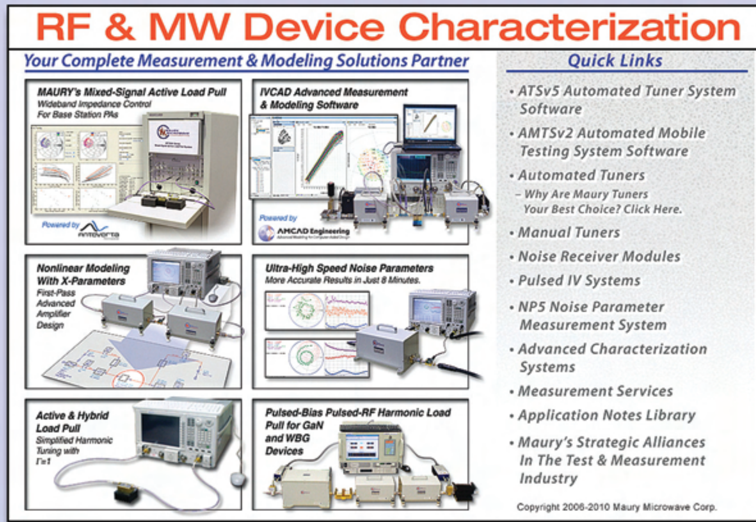

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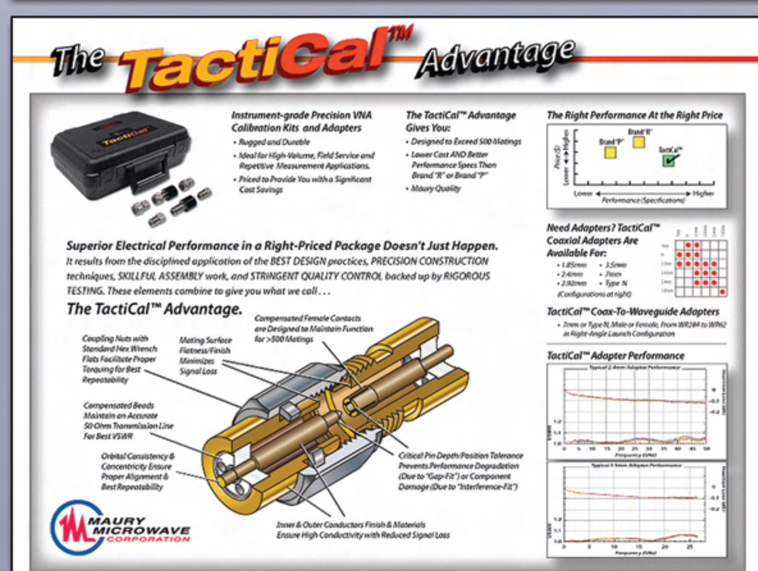

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