

MT1000 and MT2000 – Mixed-Signal Active Load Pull System (1.0 MHz to 40.0 GHz) And MT2001 System Software

DATA SHEET / 4T-097

U.S. Patent No. 8,456,175 B2
Several international patents also available





Introduction

The MT1000 and MT2000 mixed-signal active load pull systems are the only commercially-proven solutions¹ capable of performing load pull at high speeds of up to 1000 impedance/power states per minute with no limitation on Smith Chart coverage, under the following conditions:

- > Single-tone CW and pulsed-CW RF signal
- > DC and pulsed-DC bias
- > Time-domain NVNA voltage and current waveforms and load lines
- > Fundamental and harmonic impedance control on the source and/or load
- > Frequencies between 1 MHz and 40 GHz²

High-speed load pull with high magnitudes of reflection coefficients under the above conditions are ideal for:

- > Reducing time-to-market due to quicker measurement speed
- > Reducing bottlenecks caused by traditional passive mechanical load pull systems without a loss of accuracy
- > Validating nonlinear compact models
- > Extracting nonlinear behavioral models
- > Research and development, design validation test, and on-wafer production test

In addition, the MT2000 is the only commercially-proven solution¹ capable of wideband impedance control of up to 500 MHz bandwidth at the fundamental, harmonic and baseband frequencies² and is ideal for

- > Using ACPR and EVM measurement data in the design of wideband PA circuits
- > Improving PA linearity based on controlled baseband terminations
- > Evaluating the performance of a DUT under realistic antenna load conditions
- > Evaluating the performance of DUT under different matching network topologies

The MT1000 and MT2000 are turnkey one-box solutions that replace the functions typically performed by passive fundamental and/or harmonic impedance tuners, VNAs and/or NVNAs, analog signal generators, vector signal generators, vector signal analyzers and oscilloscopes, and add the capabilities of high-speed load pull measurements and wideband impedance control for modulated signals.

¹ as of the publish date of this document

² see Available Models on page 8

What is load pull?

Load Pull is the act of presenting a set of controlled impedances to a device under test (DUT) and measuring a set of parameters at each point. By varying the impedance, it is possible to fully characterize the performance of a DUT and use the data to:

- > Verify simulation results of a transistor model (model validation)
- > Gather characterization data for model extraction (behavioral model extraction)
- > Design amplifier matching networks for optimum performance (amplifier design)
- > Ensure a microwave circuit's ability to perform after being exposed to high mismatch conditions (ruggedness test)
- > Confirm the stability or performance of a microwave circuit or consumer product under non-ideal VSWR conditions (stability/performance/conformance/antenna test)

Figure 1a—Example of load pull measurements with Output Power (P_{out}) contours plotted on a Smith Chart.

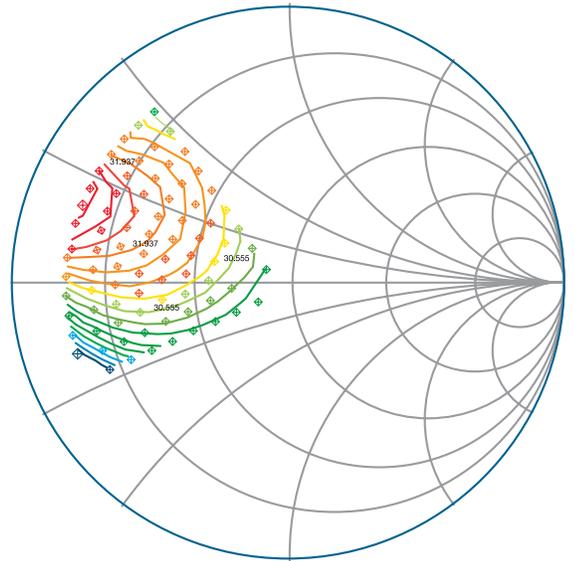


Figure 1b—Iso P_{out} Contours Measured @ 1.85 GHz

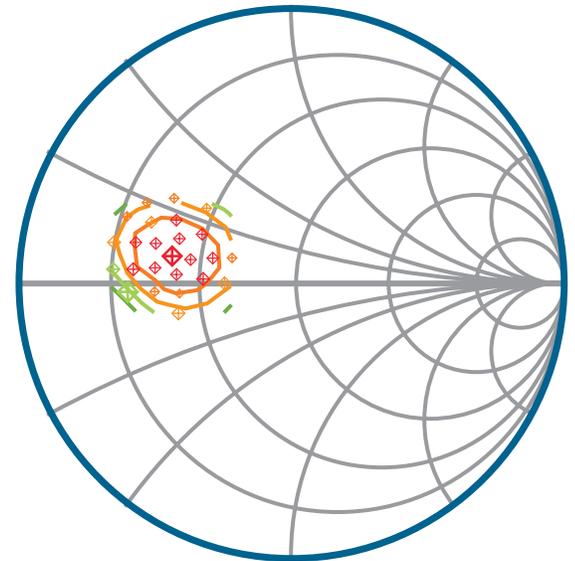
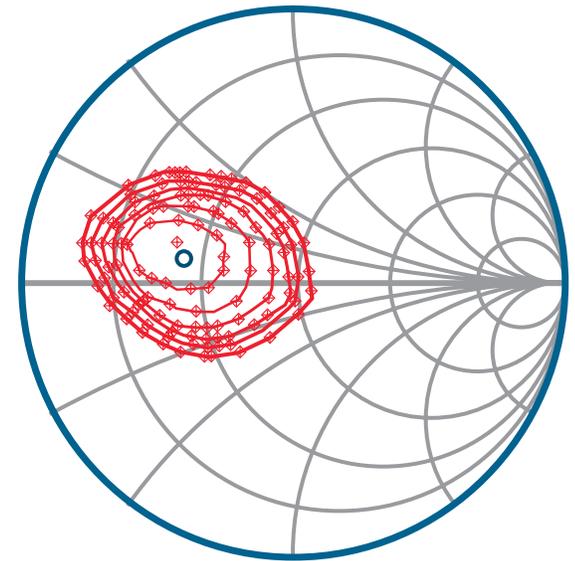


Figure 1c—Iso P_{out} Contours Simulated @ 1.85 GHz



Active Load Pull

In order to understand how the impedance presented to a DUT is varied, we must first consider the DUT as a two-port network shown in Figure 2.

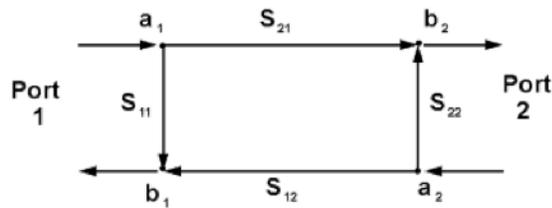


Figure 2. Two-port representation of DUT

The two-port network consists of four waves, a_1 , b_1 , b_2 and a_2 .

- > a_1 is the input signal which is injected into port 1 of the DUT
- > b_1 is the input signal which is reflected from the input of the DUT due to the mismatch between the DUT's input impedance and the load impedance of the input network
- > b_2 is the signal which emerges from port 2 of the DUT
- > a_2 is the output signal which is reflected from the output of the DUT due to the mismatch between the DUT's output impedance and the load impedance of the output network

The magnitude of reflection presented to the DUT is calculated as $\Gamma_L = \frac{a_2}{b_2}$. The magnitude and phase of the reflection presented to the load of the DUT can be varied by changing the magnitude and phase of the signal a_2 . In other words, any load impedance $Z = Z_0 \left(\frac{1+\Gamma_L}{1-\Gamma_L} \right)$ can be presented to the DUT as long as the signal a_2 can be achieved.

With regards to active load pull, the signal a_2 is a vector combination of the reflected portion of b_2 due to the mismatch between the DUT's output impedance and the load impedance of the output network, and a new signal created by a signal generator with magnitude and phase variability (referred to as an active tuning loop). An example block diagram of an active tuning loop is shown in Figure 3.

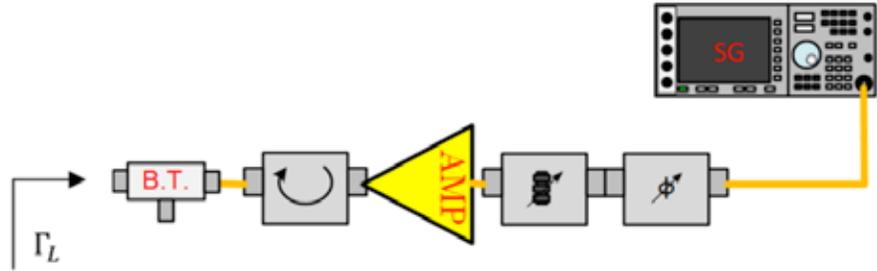


Figure 3. Output network of a simple active load pull setup

In order to perform active load pull, it is necessary to have a vector-receiver capable of accurately measuring the a- and b-waves, as well as signal generator(s) capable of generating output tuning signals.

Mixed-signal active load pull system architecture

A typical mixed-signal active load pull system architecture is shown in Figure 4. Signal analysis of the a1, b1, b2 and a2 waves is achieved by using mixers and local oscillators to down-convert the RF signal to baseband and processed using wideband analog-to-digital converters (ADCs). Signal synthesis of the input drive signal as well as the active tuning signals is achieved by generating signals at baseband frequencies using wideband arbitrary waveform generators (AWGs) and upconverting to RF using mixers and local oscillators.

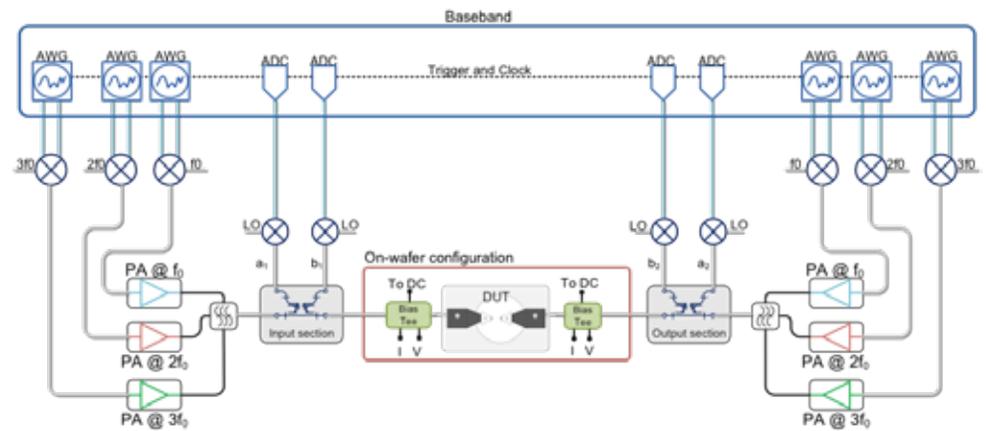


Figure 4 Typical Mixed Signal Active Load Pull System Architecture

A novel calibration and optimization technique correlates the user-desired RF signals at the DUT reference plane with the required baseband signals at the AWG reference plane. This robust technique takes into account the linear and nonlinear characteristics of the internal upconversion/downconversion paths as well as external components including driver amplifiers and bias tees.

Mixed-signal active load pull methodology

First, a wideband signal consisting of hundreds or thousands of frequency components over tens or hundreds of MHz is injected into the input of the DUT. This can be a user-defined signal or a modulated signal compliant to a reference test standard. When driven into nonlinear operating conditions, the resulting b_1 and b_2 waves may have signal distortion as well as baseband and harmonic components.

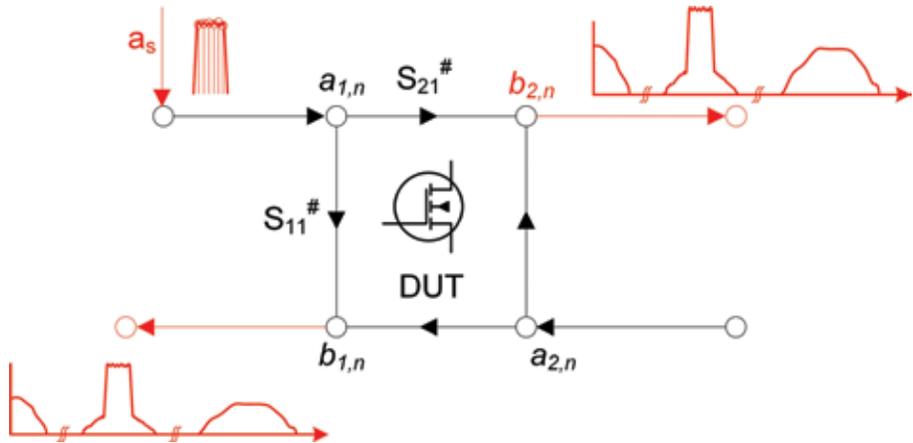


Figure 5 Injected a_s signal and resulting b_1 and b_2 waves



Second, the b_2 wave is measured at the DUT reference plane and the corresponding a_2 is calculated, generated and injected into the output of the DUT such that each frequency component of a_2 has a magnitude and phase that satisfies the user-desired $\Gamma_L = \frac{a_2}{b_2}$. Similarly, a second input signal a_1 can be superimposed on a_s to set the desired source impedances over frequency bandwidth.

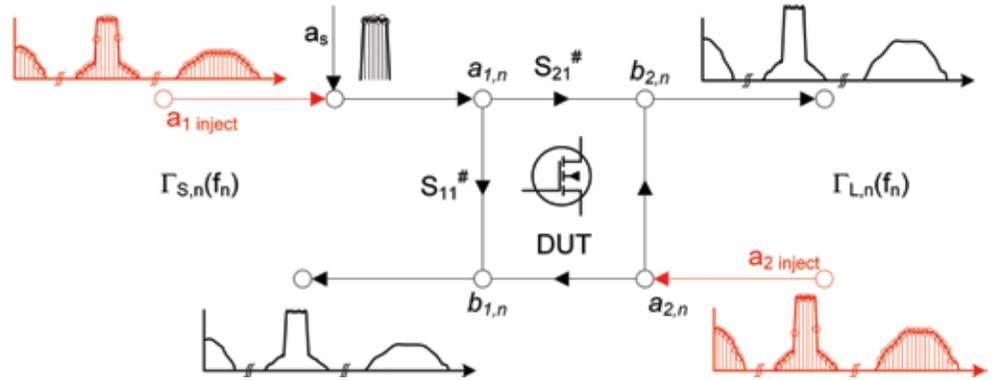


Figure 6 Active tuning a_1 and a_2 signals

Finally, the a- and b-waves are measured at the DUT reference plane, and the tuning signals a_2 and a_1 are modified to converge on the desired reflection coefficients Γ_L and Γ_S .

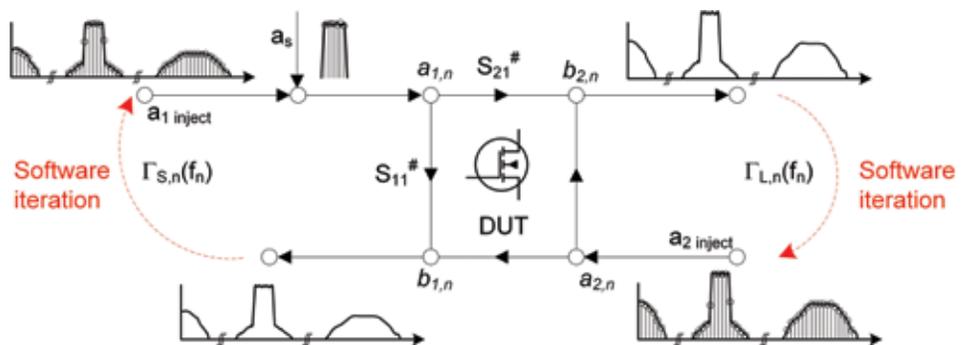


Figure 7 Software iteration of a_1 and a_2 to converge on desired impedances

Due to the use of wideband AWGs and wideband ADCs, it is possible to accurately set user-defined impedances over a bandwidth of hundreds or thousands of MHz (see page 8 for Available Models).

High Speed Single-Tone Active Load Pull Methodology

Wideband modulated signals vary in amplitude and phase over time, such that one repetition of a modulated signal may take 10 ms, as shown in Figure 8 for a LTE-A frame.

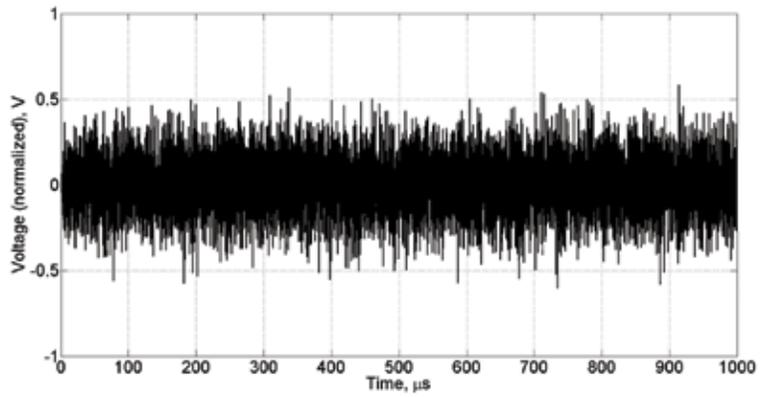


Figure 8 Time-domain representation of an LTE signal

Single-tone signals, on the other hand, can be generated in a much shorter time period, less than 100 μs (depending on whether the signal is CW or pulsed-CW, and the pulse width and duty cycle of the pulsed signal). Therefore it is possible to stitch together multiple single-tone a_2 waveforms in order to create a modulated signal, as shown in Figures 9 and 10. The convergence algorithm will treat the stitched modulated waveform in the same manner as a realistic communications modulated signal, but instead of solving $\Gamma_L = \frac{a_2}{b_2}$ for the individual frequency components of a wideband, it will be solved for many sequential single-tone reflection coefficients. In the time it takes to set the reflection coefficient of a single repetition of a wideband modulated signal, tens or hundreds of single-tone signal impedances can be tuned.

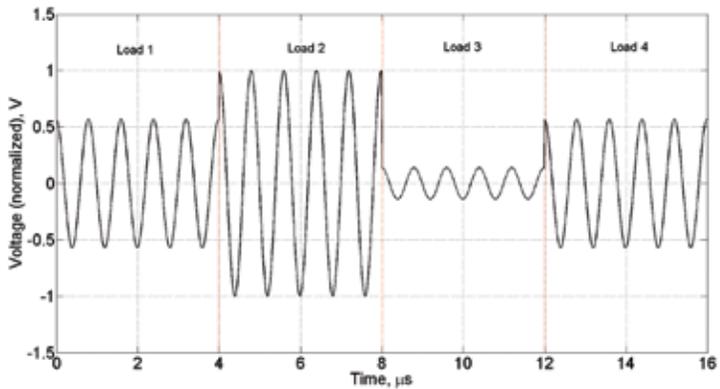


Figure 9 stitched modulated a_2 signal representing multiple single-tone CW reflection coefficients waveforms

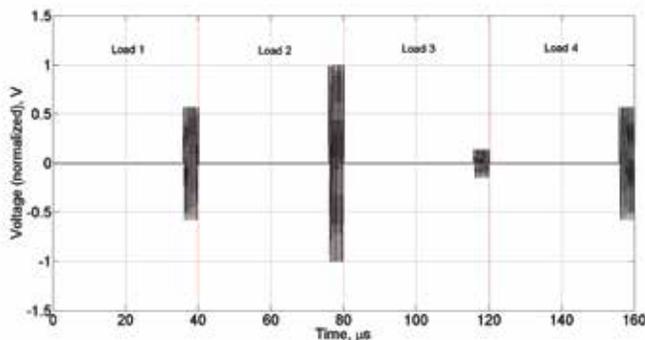


Figure 10 stitched modulated a_2 signal representing multiple single-tone pulsed-CW reflection coefficients waveforms

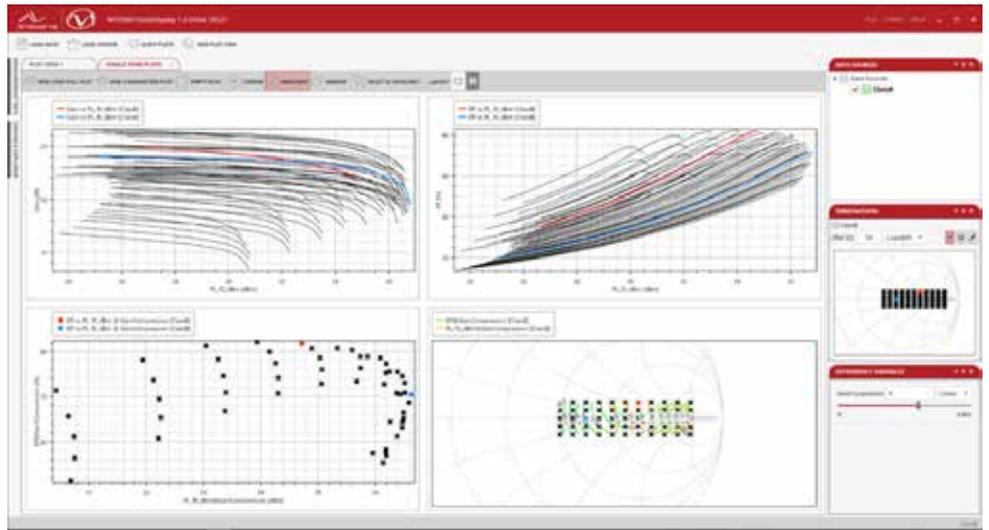
Available Models / Ordering Information

Model	System RF Bandwidth (GHz)	Number of Active Tuning Loops	Modulation Bandwidth (MHz)	Power Handling CW/Pulsed CW (W)	Typical Detection Dynamic Range (dB)	Typical Active Load Dynamic Range (dB)	Minimum Pulse Width (ns)
MT1000HF2	0.03-2.0	2	N/A	50/500	80	60	2000
MT1000HF4		4					
MT2000HF2-100	0.001-2.0	2	100				
MT2000HF2-200			200				
MT2000HF2-500			500				
MT2000HF4-100		4	100				
MT2000HF4-200			200				
MT2000HF4-500			500				
MT1000A2	0.3-6.0	2	N/A	100/1000	80	60	2000
MT2000A2-100			100				
MT2000A2-200			200				
MT2000A2-500			500				
MT1000B2	0.2-18.0	2	N/A				
MT2000B2-100			100				
MT2000B2-200			200				
MT2000B2-500		500					
MT1000B3		3	N/A				
MT2000B3-100			100				
MT2000B3-200	200						
MT2000B3-500	500						
MT1000B4	4	N/A					
MT2000B4-100		100					
MT2000B4-200		200					
MT2000B4-500		500					
MT1000B5		5	N/A				
MT2000B5-100	100						
MT2000B5-200	200						
MT2000B5-500	500						
MT1000B6	6	N/A					
MT2000B6-100		100					
MT2000B6-200		200					
MT2000B6-500		500					
MT1000E2	0.7-40.0	2	N/A	20/200	80	60	2000
MT2000E2-100			100				
MT2000E2-200			200				
MT2000E2-500		500					
MT1000E4		4	N/A				
MT2000E4-100			100				
MT2000E4-200			200				
MT2000E4-500			500				
MT1000E6		6	N/A				
MT2000E6-100			100				
MT2000E6-200			200				
MT2000E6-500			500				

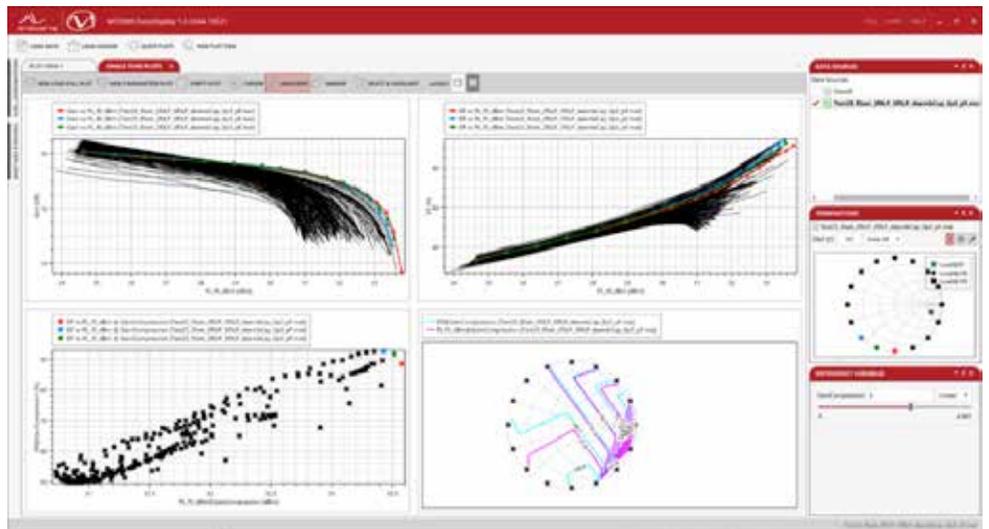
MT2001A Power Measurements

MT2001A is the core software of the MT2000 mixed-signal active load pull system and required for each system. It consists of the following capabilities:

- > Fundamental-frequency impedance control at the input and output of the DUT
- > Harmonic-frequency impedance control at the input and/or output of the DUT (requires MT2000 hardware with one active tuning loop for each harmonic frequency for each input/output desired)
- > Standard single-tone CW and pulsed-CW load pull measurements with an average speed of one impedance state at one power in 1s-3s
- > High speed “real-time” single-tone CW and pulsed-CW load pull measurements with an average speed of fifty impedance states at one power in 1s-3s
- > Pulsed-bias load pull (requires pulsed power supply or pulse modulator)
- > Power sweep / gain compression measurements with both standard and high-speed load impedance control
- > Real-time measurement of DUT input and output impedance
- > Advanced sweep plan for custom measurements of impedance, power, frequency, input voltage, output voltage
- > DC and pulsed current and voltage measurements
- > Chronogram / Pulsed configuration with trigger and measurement windows
- > Automated impedance tuner control for optional mechanical pre-match for high power load pull measurements
- > Probe station control (requires semi-automated probe station)
- > CW and pulsed-CW S-parameters measurement
- > Standard measurement parameters include Pout, Pin, Pavs, Gt, Gp, Eff, PAE, Vin, Vout, Iin, Iout, AM-AM, AM-PM; custom user-defined parameters



Fundamental-frequency high-speed load pull of 55 impedance states and power sweep at 16 power levels for a total of 880 measurement states in 3 minutes.

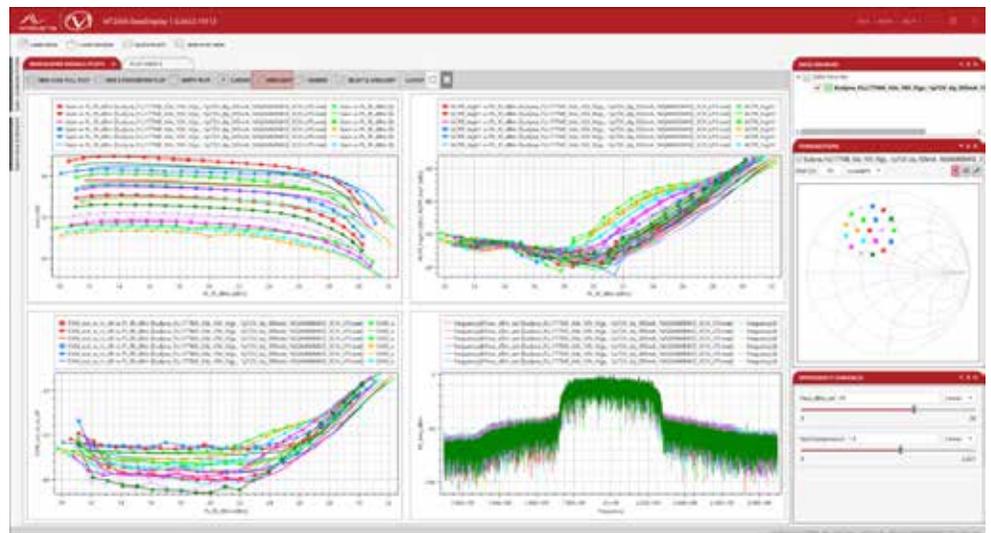


Harmonic-frequency high-speed load pull of 1 Fo impedance state, 16 2Fo impedance states, 16 3Fo impedance states and power sweep at 17 power levels for a total of 4352 measurement states in 15 minutes.

MT2001B Modulated Load Pull Measurements

MT2001B is an add-on option to MT2001A which enables wideband impedance control for modulated signals over the modulation bandwidth of the hardware (see Available Models / Ordering Information). In addition to the capabilities of MT2001A, MT2001B adds the following:

- > Library of standard commercially available modulated signals
- > Utility to define custom modulated signals
- > Automatic signal pre-distortion to create a clean modulated signal at the DUT reference plane
- > Wideband impedance control as follows
 - > Ability to set all impedance over the modulated bandwidth at a single impedance point (i.e. all frequency components of an 80 MHz 5G signal should be tuned to 5Ω)
 - > Ability to set user-defined phase delay of impedance vs frequency over the modulated bandwidth (i.e. a 0.1 degree/MHz phase delay resulting in an overall phase shift of 8 degrees on the Smith Chart for an 80 MHz 5G signal)
 - > Ability to load S1P file (user-created, from circuit simulator...) defining impedance vs frequency over the modulated bandwidth. Ideal for evaluating realistic matching network designs (i.e. stub vs transmission line) and evaluating DUT performance under realistic antenna load response
- > Vector signal analysis of modulated signals
- > Adaptive averaging enhances measurement speed without sacrificing accuracy
- > Import and export I and Q baseband waveforms for offline digital pre-distortion load pull (DPD)
- > Standard measurement parameters include ACPR, EVM, spectral mask; custom parameters

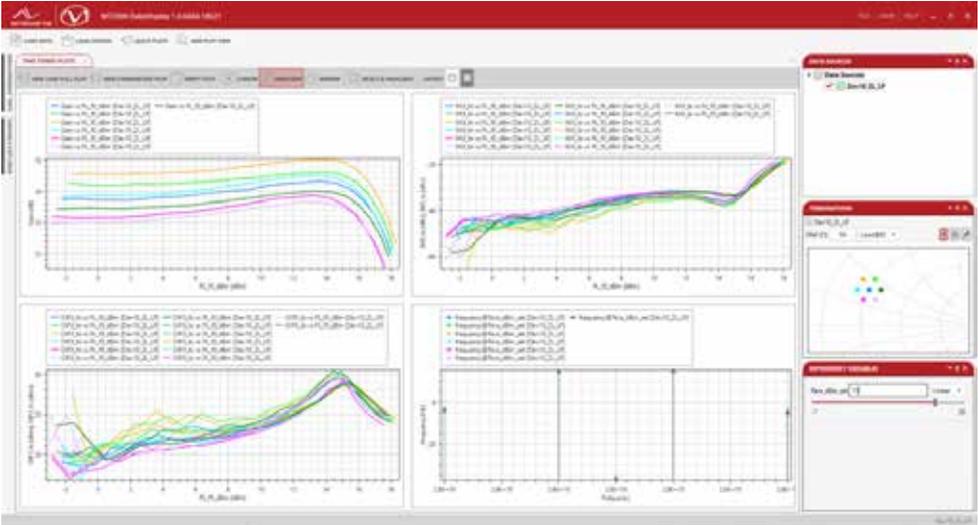


Fundamental-frequency modulated load pull of 20 impedance states and power sweep at 26 power levels, where all impedances over the modulated bandwidth of 200 MHz are set to a single impedance state.

MT2001C Two Tone Load Pull Measurements

MT2001C is an add-on option to MT2001A which enables impedance control for two-tone signals with tone spacing within the modulation bandwidth of the hardware (see Available Models / Ordering Information). In addition to the capabilities of MT2001A, MT2001C adds the following:

- > Set tone spacing to user-defined values
- > Sweep tone-spacing during load pull measurement
- > Automatic signal pre-distortion to create a balanced two-tone signal at the DUT reference plane
- > Adaptive averaging enhances measurement speed without sacrificing accuracy
- > Standard measurement parameters include IMDx, OIPx; custom parameters



Fundamental-frequency two-tone load pull of 7 impedance states and power sweep at 26 power levels, with a tone spacing of 80 MHz.

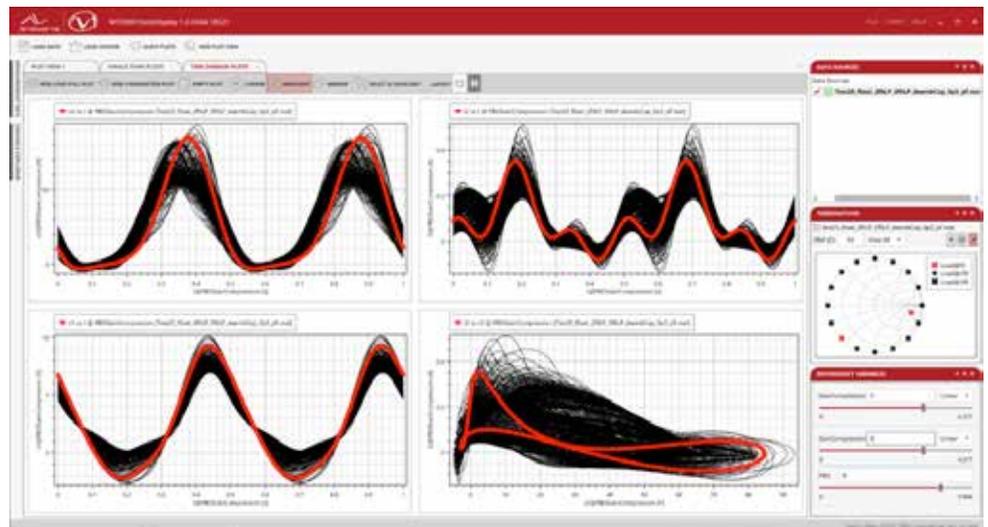
MT2001D NVNA and Time-Domain Analysis

MT2001D is an add-on option to MT2001A which enables Nonlinear VNA (NVNA) time-domain analysis of voltage and current waveforms and load lines for single-tone CW and pulsed-CW signals. In addition to the capabilities of MT2001A, MT2001D adds the following:

- > Automatically measure current and voltage waveforms and load lines
- > Standard measurement parameters include $V_1(t)$, $V_2(t)$, $I_1(t)$, $I_2(t)$; custom parameters

It is important to note that the addition of NVNA time-domain measurements does not increase the overall measurement time and is compatible with both standard and high-speed load pull methodologies.

The MT1000/MT2000 hardware includes a tone-generator which acts as a harmonic phase reference (HPR). A single external harmonic phase reference or comb generator is required for system calibration.



Harmonic-frequency high-speed load pull of 1 F_0 impedance state, 16 $2F_0$ impedance states, 16 $3F_0$ impedance states and power sweep at 17 power levels for a total of 4352 measurement states in 15 minutes, with the addition of NVNA time-domain voltage and current waveforms and load lines.

MT2001F Visualization and Analysis

MT2001F is standalone software option which enables the visualization and analysis of measurement data taken from MT2001A, MT2001B, MT2001C, MT2001D and MT2001G modules. MT2001F has the following capabilities:

S-Parameters

- > Plot S-parameters in standard and custom formats including log magnitude, linear magnitude, phase, polar, Smith Chart
- > Overlay multiple S-parameters data sets

Load Pull

- > Plot load pull contours on the Smith Chart
- > Plot load pull parameters on XY graphs
- > Plot power sweep / gain compression curves on XY graphs
- > Plot time-domain load pull contours and graphs
- > Plot contours and graphs based on dependency parameters (i.e. PAE vs Pout at a fixed gain compression)
- > Interconnected plots allow inputs on one plot to be executed on all plots (i.e. selecting an impedance on one plot will show the corresponding measurement results for that impedance on all plots)
- > Overlay multiple load pull measurement data sets

Export

- > Export measurement data in MAT, SPL, CSV, MDF and XLS formats
- > Export plots in JPG and PNG graphic formats

Templates

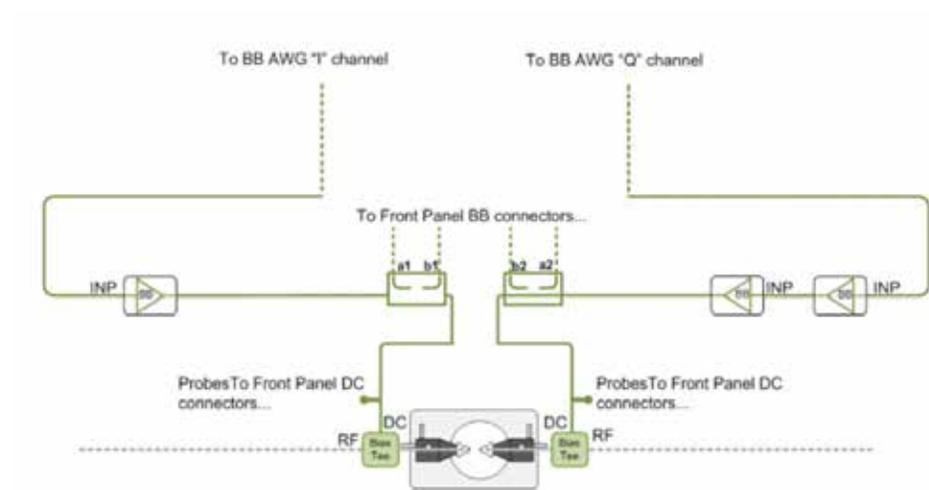
- > Save/recall customized visualization plots/graphs, associated parameters and markers
- > Save/recall layout for multiple plots/graphs on a single report

MT2001G Baseband Impedance Control

MT2001G is an add-on option to MT2001B and MT2001C which enables baseband impedance control, which may improve linearity resulting in better IMx and ACPR performance. In addition to the capabilities of MT2001B and MT2001C, MT2001G adds the following:

- > Controls impedances at baseband frequencies caused by mixing product of two-tone or modulated signals
- > Source and load baseband impedance control

In addition to the MT2000 hardware, external baseband drive amplifiers are required and are selected based on user-required voltages and currents (i.e. ADA4870 baseband amplifier to meet requirements of $V=40V$, $I=1A$, $BW=80\text{ MHz}$).



Block diagram of baseband impedance control hardware configuration

Recommended Reading

The following literature is recommended for those who wish to learn more about the MT1000 and MT2000 – Mixed-Signal Active Load Pull System (1.0 MHz to 40.0 GHz) And MT2001 System Software it supports.

5A-044 – Active Harmonic Load Pull with Realistic Wideband Communications Signals.

Abstract – A new wideband open-loop active harmonic load–pull measurement approach is presented. The proposed method is based on wideband data-acquisition and wideband signal-injection of the incident and device generated power waves at the frequencies of interest. The system provides full, user defined, in-band control of the source and load reflection coefficients presented to the device-under-test at baseband, fundamental and harmonic frequencies. The system's capability to completely eliminate electrical delay allows it to mimic realistic matching networks using their measured or simulated frequency response. This feature enables active devices to be evaluated for their actual in-circuit behavior, even on wafer. Moreover the proposed setup provides the unique feature of handling realistic wideband communication signals like multi-carrier wideband code division multiple access (W-CDMA), making the setup perfectly suited for studying device performance in terms of efficiency, linearity and memory effects.

In this work we describe the hardware and signal conditioning of the proposed setup. The high dynamic range, bandwidth and measurement speed of the system, together with its capability to engineer the large-signal operation of an active device, are demonstrated by measuring the improved RF performance of a multi-carrier W-CDMA driven laterally diffused metal–oxide–semiconductor device when the electrical delay in the setup is canceled.

5A-045 – Active Harmonic Load Pull for On-Wafer Out-of-Band Device Linearity Optimization.

Abstract – In this paper, we present an active harmonic load–pull system especially developed for the on-wafer linearity characterization/optimization of active devices with wideband modulated signals using the out-of-band linearization technique. Our setup provides independent control of the impedances at the baseband, fundamental, and second-harmonic frequencies presented to the input and output of the device under test. Furthermore, to enable realistic test conditions with wideband-modulated signals, the electrical delays in the load–pull system are kept as small as possible by implementing a novel loop architecture with in-phase quadrature modulators. We have achieved a phase variation of the reflection coefficient of only 5°/MHz for both the fundamental and second-harmonic frequencies.

We demonstrate the high potential of the system for the on-wafer evaluation of new technology generations by applying out-of-band linearization to heterojunction bipolar transistor (HBT) and laterally diffused metal–oxide–semiconductor (LDMOS) devices. For the HBT, we outline a game plan to obtain the optimum efficiency–linearity tradeoff. Finally, a record-high efficiency–linearity tradeoff was achieved (without digital predistortion) for an inverse class-AB operated Philips Gen 6 LDMOS device, yielding 44% efficiency at an adjacent channel power level of 245 dBc at 2.14 GHz for an IS-95 signal.

5A-046 – A Mixed-Signal Approach for High-Speed Fully Controlled Multidimensional Load Pull Parameters Sweep.

Abstract – A mixed-signal approach for “real-time”, fully controlled, load-pull parameters sweeps is presented. The proposed approach permits high-speed sweeping of any combination of parameters, e.g. input power and fundamental and/or harmonic source

or load termination, enabling at the same time full control of all other source and load terminations provided to the device-under-test. Using this method, a very efficient tool is created for high-speed large-signal device characterization, which can mimic realistic circuit conditions not only for single-tone signals, but also for wide-band complex modulated signals. The capabilities of the realized system are demonstrated by characterizing a NXP Gen 6 LDMOS device.

5A-047 – Base-Band Impedance Control and Calibration for On-Wafer Linearity measurements

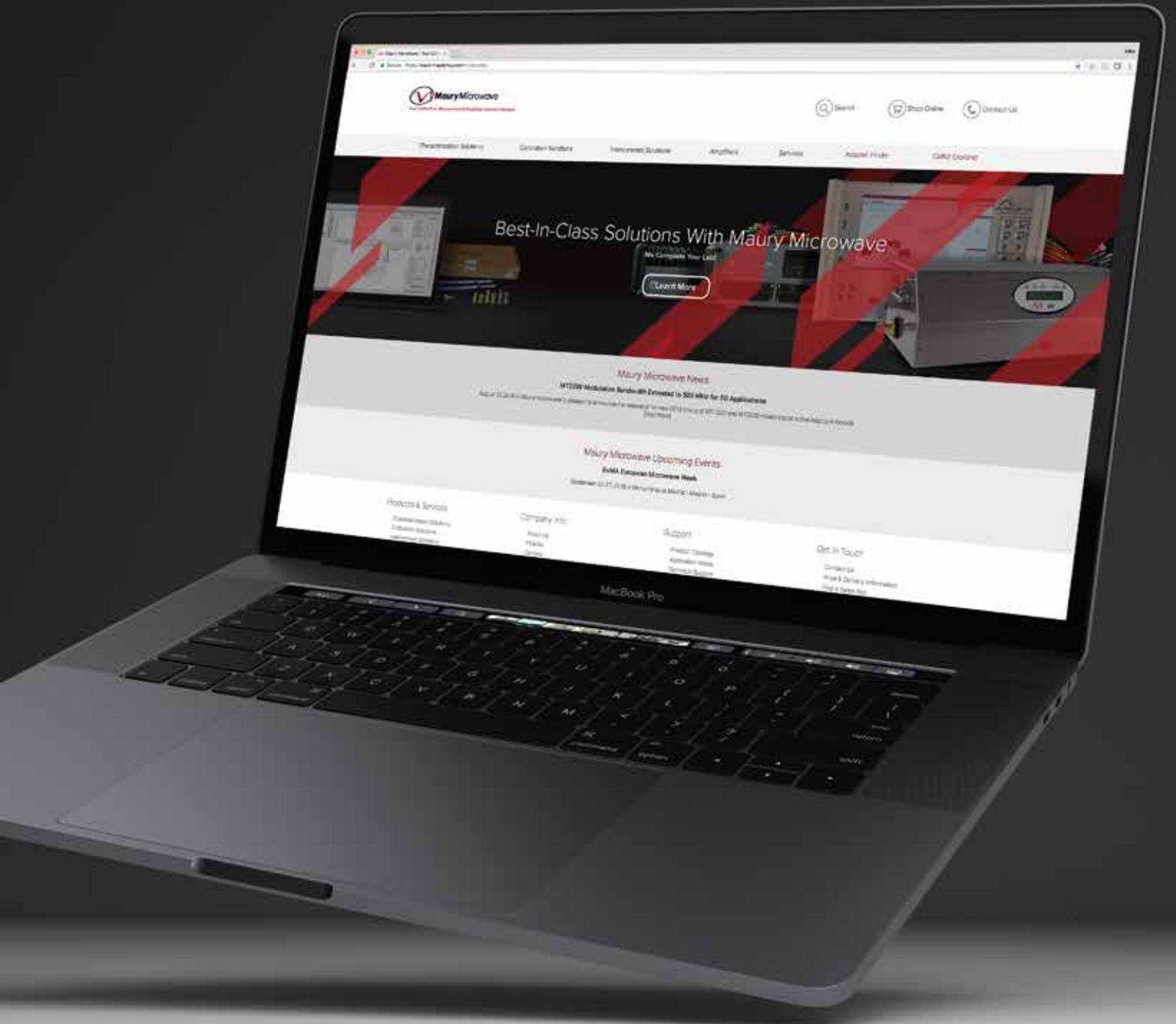
Abstract – This paper introduces a direct and accurate method for controlling and measuring the on-wafer device terminations at the base-band / envelope frequency, using an extension of a conventional network analyzer setup. The base-band impedance can be adjusted manually as well as electronically and is able to (over)_compensate the losses in the measurement setup. This facilitates on-wafer base-band terminations ranging from negative to high Ohmic values. The proposed measurement techniques are particularly useful when characterizing active devices for their linearity.

5A-048 – A Mixed-Signal Load Pull System for Base-Station Applications

Abstract – The capabilities of active load-pull are extended to be compatible with the characterization requirements of high-power basestation applications. The proposed measurement setup provides ultra-fast high-power device characterization for both CW, as well as, pulsed, duty-cycle controlled, operation. The realized system has the unique feature that it can handle realistic complex modulated signals like WCDMA with absolute control of their reflection coefficients vs. frequency.

5C-087 – Active Load Pull Surpasses 500 Watts!

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