A New Approach to Load Pull

***Abstract* — RF frontends and amplifiers are tested more and more with real application conditions. Today, this drives the usage of wideband modulation stimuli. The next level of real application conditions is to look at dispersive impedances as presented to the output of the RF frontend. This paper brings these to important item together.**

***Keywords* — Power amplifier, modulated load pull, target application conditions.**

I. Introduction

RF power amplifiers (PA) often are used in a communication, radar or satellite link system. In all of these cases, they drive power into an antenna system which should cover a maximum frequency range. Even so all elements are nominal 50 Ohm, the reality is that the components and modules are made for 50 Ohm environments but in reality can be off by a large range and show dispersive impedance values across the used frequency ranges. This effects the capabilities of the RF frontend (RFFE) including the amplifier stage. On top, there is no prediction of capabilities and performance across different impedances. Theoretically round shaped concentric performance contour plots (e.g. Gain circles, Power circles) cannot not be assumed for active RFFE. Increasing signal bandwidths exacerbate this problem, due to unintended load impedance variations.

Load pull is a common technique to understand the behavior of RF frontends with varying conditions and matchings in the target application, optimize the DUT or create accurate models. Traditional load pull is using continuous wave signals to look at the device behavior. With increasing signal bandwidths, modulated signals are being used more and more in load pull environments. In this paper we look at use-cases and a new method to run load pull testing with modulated signals.

II. MAIN USE CASES OF LOAD PULL

Load Pull techniques are used in various applications with different tasks and challenges. In principle these can be categorized in two main areas: Design optimization and modelling.

A. Design Optimization

- Validation and optimization of key performance indicators (KPI) across different impedances: KPIs are shown in contour plots across the Smith chart indicating similar behavior across varying impedances. As the optimum for different KPIs are at different points on the Smith chart, design decisions for individual use cases must be taken.
- Energy efficiency optimization by creating defined impedances at harmonic frequencies: Especially high-power amplifiers exhibit significant power at harmonic frequencies. Creating a defined and optimized load for these frequencies optimizes the overall energy efficiency.
- Design of the matching network for PA transistors: Based on the inherent device impedance the matching network needs to be designed which requires understanding of the inherent impedance of the device (this suggests Thevenin-esque real world device).
- Optimization at system level: This requires the target waveform usage and looks at modulation parameters such as ACLR or EVM in addition to distortion, intermodulation, Gain and maximum output power under modulated conditions.

B. Modelling

Modelling is used to create a reliable mathematical approximation of the device behavior under various conditions to be used in design tools such as Cadence Microwave Office. Load Pull is one critical item to include in device models. These models are typically created using CW and pulse signals.

In new wideband applications, these models are challenged using wideband modulation scenarios such as used in Wi-Fi7 or satellite links to ensure they are valid for these application cases.

III. Load Pull Approaches

Load-Pulling is created by introducing an intentional a_2 signal to create different impedances towards the test device. This can be created by a physical reflection of b_2 or by active injection of the b_2 signal.

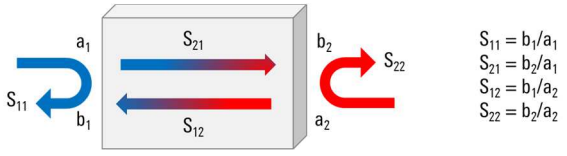

Fig. 1 Definition of a_1 and b_1 as well as a_2 and b_2

Today, the major load pull applications target CW use cases with a Vector Network Analyzer (VNA) as the core of the system. There are different categories plus specialized variants used today:

- Passive, active or hybrid systems – three variants
- Using modulated or quasi-CW signals – two variants
- Fundamental, optionally Harmonic and/or IF including simultaneous Envelope tracking support – four variants

In total there are 24 architectures possible. Below, the main variants are shown.

A. *Passive Load Pull*

Passive load pull is the traditional approach using mechanical impedance tuners. These are placed on the DUT input for source pulling and on the output for load pulling.

This approach is stable and proven. It also allows high power handling based on the capabilities of the tuners. Different formfactors of the tuners also allow an easy integration into on-wafer systems.

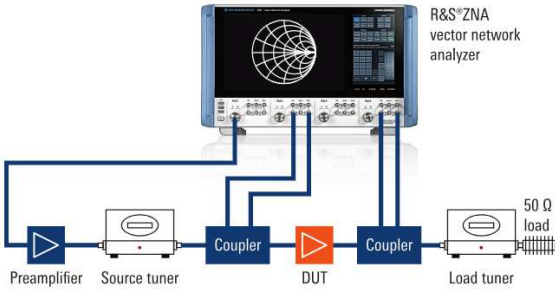

Fig. 2 Typical setup for passive load pull

B. *Active Load Pull*

In active load pull scenarios, the reflected signal is not created by a mismatch created from a mechanical tuner, but the return signal, the a2 wave, is synthesized and injected from an external source as tune signal into the output of the DUT for load pull scenarios.

Active load pull is both fast and wideband. It enables arbitrarily precise a2 signals to be synthesized. On the downside, significant power levels are needed for the tune signal, the a2 wave, to create a large range of impedances. Thus, an addition amplifier might be required.

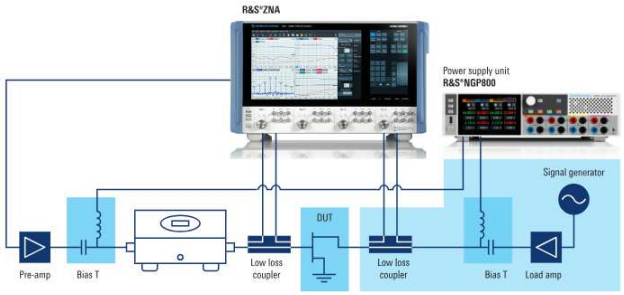

Fig. 3..Exemplary active load pull setup

C. *Hybrid Load Pull*

Hybrid load pull combines the active and passive approach by integrating tuners and active signal injection. This allows to overcome losses from the tuners to access the full range of the Smith chart and even beyond plus gives the speed enhancement capabilities of the active part.

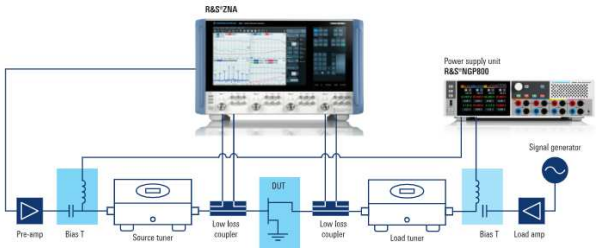

Fig. 4 Possible setup of a hybrid load pull setup

D. *Harmonic Load Pull*

Harmonic load pull adds user defined impedances for typically 2nd and 3rd harmonic frequencies. This can be achieved by use of special tuners, which have multiple internal stubs for the different harmonics or use of traditional tuners with a signal splitting and corresponding frequency filtering. An other approach is to use active load pull techniques for the higher harmonic frequencies.

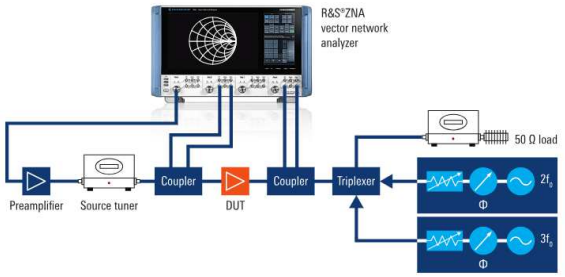

Fig. 5 Harmonic load pull using passive tuning at f_0 and active tuning at higher order harmonics $2f_0$ and $3f_0$

E. *Traditional Modulated Load Pull*

In traditional modulated load pull setups, the principle of passive tuning is used in many cases. In this approach, the input signal to the DUT is generated by a vector signal generator, while the output is sent into a vector signal analyzer after the load tuner.

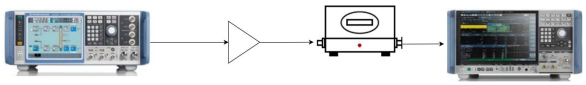

Fig. 5 Traditional modulated load pull scenario using a vector signal generator for the stimulus and a vector signal analyzer for the measurements

This approach is often used in validation and design labs today. Tuners show a frequency response and group delay over the used signal bandwidth and create distortion which can not be separated from the effect of the test device. Thus this method is prone to higher uncertainties, often unknown to the user. Wide range of characterizations over different impedances plus superimposed sweeps over frequency, temperature, power levels, different waveforms or different temperatures create long test campaigns while the mechanical tuner contributes a significant amount.

IV. The New Load Pull Approach

The new approach for load pull is targeting wideband modulated load pull. The goal is to enable a wideband system

offering fast and highly accurate impedance synthesis for a wide range of modulation waveforms.

The proposed setup is limited only by the bandwidth capability of the used vector signal generator (VSG) and the frequency range of the RF sampling oscilloscope. The system follows the principle of active load pull, transferring it to a wideband system.

The key characteristic of the VSG is the time synchronization and stable phase relationship between the two RF signals while one creates the input waveform, the second the impedance tune signal.

The RF sampling oscilloscope offers 4 coherent, perfectly time aligned measurement paths needed to measure the wave quantities to calculate the represented impedance.

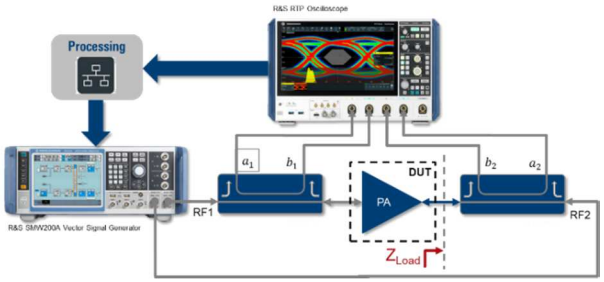

Fig. 7 The proposed new wideband modulated load pull system

The sampled data of the output signal of the device under test, the b_2 signal, can in addition be used to run all the wanted modulation measurements.

In order to get a higher power tune signal, the a_2 signal, a linear amplifier may be looped in as booster. It is also recommended to add a circulator between the RF2 drive source an the coupler at the device output to avoid unwanted impedance tuning of the a_2 signal chain by the DUT output signal.

A. Calibration and Basic Operation of the System

VNA calibration techniques are used to achieve a full vector corrected system.

The goal is to enable a calibrated synthesis and measurement of the Zload impedance, i.e. the impedance at the output plane of the DUT looking towards the "load", or "to the right".

As first step, the input port to the DUT is calibrated and verified using open, short and match. While doing so, the a_1 and b_1 are monitored.

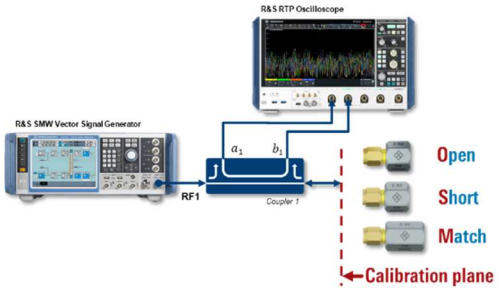

Fig. 8 Calibration setup for step 1

Then a known through is connected between the input and output coupler to transfer the calibration to the output side of the DUT. This is achieved by manipulating the b_2 signal to create the same conditions for open, short and match at the DUT position based on the recorded OSM a_1 and b_1 measurements.

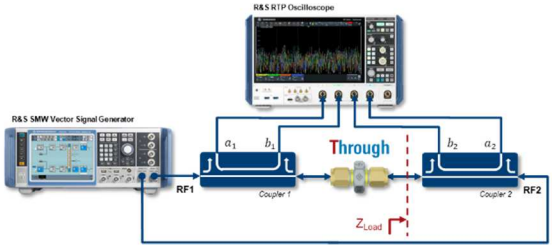

Fig. 9 Calibration setup for step 2

The system is now ready and the DUT is inserted instead of the through. To improve the Gamma accuracy, the output of the DUT, the b2 signal, is recorded and used as tune signal a2 as the DUT may modify the waveform based on its non-linearities. Then the tuning is achieved by iterating level and phase of the tune signal, monitored by the RF sampling oscilloscope.

Once the target impedance is reached, the DUT characteristics can be taken.

B. Dispersive Impedance

The load of the DUT in the target application can show variation of its impedance in the bandwidth of interest, such as an antenna system.

The proposed scenario allows to load a S parameter file to include the effect of a dispersive impedance across the used bandwidth around a target value.

In the target application, different components such as filters or matching networks are typically placed in between the DUT and the antenna. An additional de-embedding allows to take care based on the S2P file of the included network. This supports de-embedding of steep filters even in the passband, or offers a design tool for the matching circuit. This circuit is typically designed manually by iteration of individual components such as capacitors, resistors and inductors. To simplify this process, various matching networks can be simulated, their S parameter data taken and run together with the target PA in the modulated load pull setup to see their effect without having to manipulate the components manually.

In summary, various augmentations using a cascade of S parameter networks is supported:

- .s2p(OMN) - an optional series of .s2p networks, to be de-embedded, representing the contributions of device packaging, matching networks and evaluation boards, and mechanical tuner settings.
- .s2p(BPF) - an optional series of .s2p networks, representing the intentional dispersive load. In the case of mobile devices, it might be a library of candidate piezoelectric filter devices or their corner cases.
- .s1p(ANT) or Gamma value - a definition of the terminating impedance.

To replicate the classical load pull case, the .s2p(BPF) would be replaced with an "allpass" characteristic, and ANT would be represented with a Gamma value.

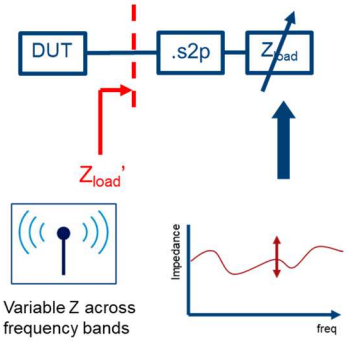

Fig. 10 Dispersive impedance and de-embedding

The de-embedding is enabling a wider use case: a hybrid load pull system. As the de-embedding works for anything which would be added, a traditional tuner can be characterized by its S parameters for a given center frequency and bandwidth and de-embedded elegantly to create a modulated hybrid load pull system.

V. Conclusion

A scalable and powerful wideband modulated load pull system has been introduced. Its use cases are manyfold but targeting the verification of RF frontends as closely as possible to the target use case and surrounding. The use of commercial standard lab instrumentation make it affordable and offers commercial aspects not available on specialized systems.

Acknowledgment

I want to thank Paul Gareth Lloyd who was designing, building and verifying the first prototype of the described wideband modulated load pull solution.

References

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