# VECTOR TRANSCEIVER BASED WIDEBAND ACTIVE LOAD-PULL

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*Abstract* - **With the continued development of modern communication systems and standards, the specifications for active components are becoming increasingly more demanding. This is driving the increasing need to characterise active components with the newest specification of New Radio and Wi-Fi modulated signals that have increased bandwidth, phase noise and linearity requirements as well as modulation orders of up to 1024QAM.**

**To this end, this work presents a vector transceiver based active load-pull system capable of characterising devices with up to 1GHz modulated bandwidth allowing for a comprehensive look into a device's Adjacent Channel Power Ratio (ACPR) behaviour and Error Vector Magnitude (EVM) performance in a non-50 Ohm environment.**

## INTRODUCTION

For several decades, RF amplifier designers have been utilising measurement data collected in both 50 Ohm and non-50 Ohm environment to characterise transistors and model their behaviour. Load-pull is the means by which a non-50 Ohm environment is presented to a Device Under Test (DUT) [1]. A common starting point is to perform these measurements using Continuous Wave (CW) and pulsed signals with either passive or active load-pull tuners. The information obtained from these measurements was often sufficient for a designer to meet the design specifications and has resulted in many successful designs [2]. From years of refinement, these passive load-pull tuners have become simple to use, relatively low cost with an increasingly broad frequency range of operation while also remaining capable of handling high powers.

However, in the past 2 decades, there has been an explosive development in modern communication systems using complex modulated signals. As the world becomes increasingly connected, the data transfer rates requirements have become increasingly demanding and as a direct result, signal modulation order and signal carrier bandwidths have increased. The latest communication standards, such as 5G New Radio and Wi-Fi 802.11ax, are driving the need for active devices that can more strictly maintain signal fidelity while also limiting interference with signals outside of the carrier bandwidth [3].

Ultimately these new design challenges require a more comprehensive understanding at the device characterisation and design level to emulate performance over bandwidth in a realistic final application. Such an understanding can be obtained from load-pulling the DUT using wideband modulated signals. Unfortunately, passive load-pull tuners are limited in that they present the set impedance at only the specified frequency [4]. As a modulated signal spans a range of frequencies, passive tuners are only suitable for use with narrow bandwidth modulated signals where the impedance skew would show little variation in the presented impedance across bandwidth. However, passive tuners are very sensitive in this regard due to additional transmission media between the tuner and the DUT. Consequentially, there has been increased development of active load-pull systems which do not suffer from the same issue.

In this paper, a brief explanation of active load-pull will be given followed by the presentation of a fully realised vector transceiver based active load-pull system capable of wideband modulated signal measurements.

## LOAD-PULL – A QUICK RECAP

As stated previously, load-pull is the means by which a non-50 Ohm impedance is presented to a DUT. The process of load-pull is controlled by changing the load reflection coefficient ($\Gamma_L$) shown in Figure 1 where $\Gamma_L$ is defined as $a_2/b_2$ [5]. On an additional note, a similar process can be performed by changing the source reflection coefficient ($\Gamma_S$) which is appropriately named source-pull.

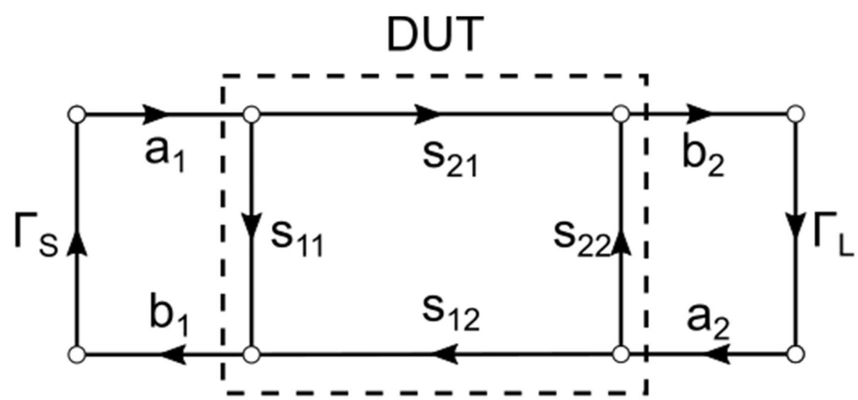



*Figure 1: Two port signal flow diagram of a DUT*

Changing the load reflection coefficient can be done in one of two ways: using a passive mechanical tuner to move a probe with respect to a transmission line, varying the reflection of $b_2$ which changes the value of $a_2$ (passive load-pull) [6] [7]; or by injecting an active signal $a_2$ of an appropriate magnitude and phase which is coherent with $b_2$ (active load-pull) [8]. It is also possible to use a combination of these two methods, which is aptly named hybrid load-pull. Active load-pull is broadly split into two forms, open-loop and closed-loop [9]. The system presented in this paper is an open-loop system.

An open-loop active load-pull system uses a signal source that generates an input $a_2$ signal independent of $b_2$ while $b_2$ is terminated [10]. This signal source is independently controlled but synchronised and frequency locked with the input source. The second source is able to vary the magnitude and phase of the injected signal to alter the load reflection coefficient electronically. A simplified system block diagram can be seen in Figure 2.

Since the injected $a_2$ signal being generated independently of $b_2$ and that, when a signal is injected, the relationship between $a_2$ and $b_2$ changes, achieving the desired impedance is an iterative process requiring computer-controlled algorithms.

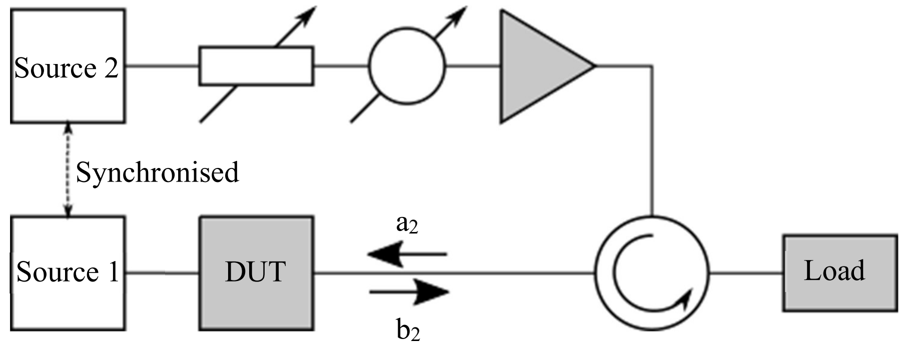



*Figure 2: Simplified open-loop active load-pull system block diagram.*

To perform modulated load-pull with such a system, not only does the sources need to be able to transmit a signal of a specified bandwidth, but the receivers used to measure the $a_-$ and $b_-$ waves needs to have sufficient measurement bandwidth. Another consideration is the requirement for a large dynamic range in power for both the transmitter and receiver.

## A Fully Realised Vector Transceiver Based Load-Pull System

By using National Instruments (NI) vector signal transceiver modules (VST), a wide bandwidth active load-pull solution has been realised and named as the "Rapid-VT" as shown in Figure 3. NIs' PXIe-5841 VSTs are able to both analyse and generate signals up to 6GHz with an instantaneous bandwidth of up to 1GHz, performing signal processing and control in real-time [11]. These VSTs are mounted within NIs' PXIe-1092 chassis and are synchronised with each other using NIs' proprietary "TClock" technology.


*Figure 3: 6GHz Rapid-VT measurement system comprising of two NI PXIe-5841 VSTs and a Mesuro 6GHz test set [12].*

These VSTs are connected to a test set which isolates the individual travelling waves for load-pull measurements and analysis. There are multiple test set configurations for 6GHz and 18GHz. A simplified block diagram of a 6GHz setup can be seen in Figure 4.

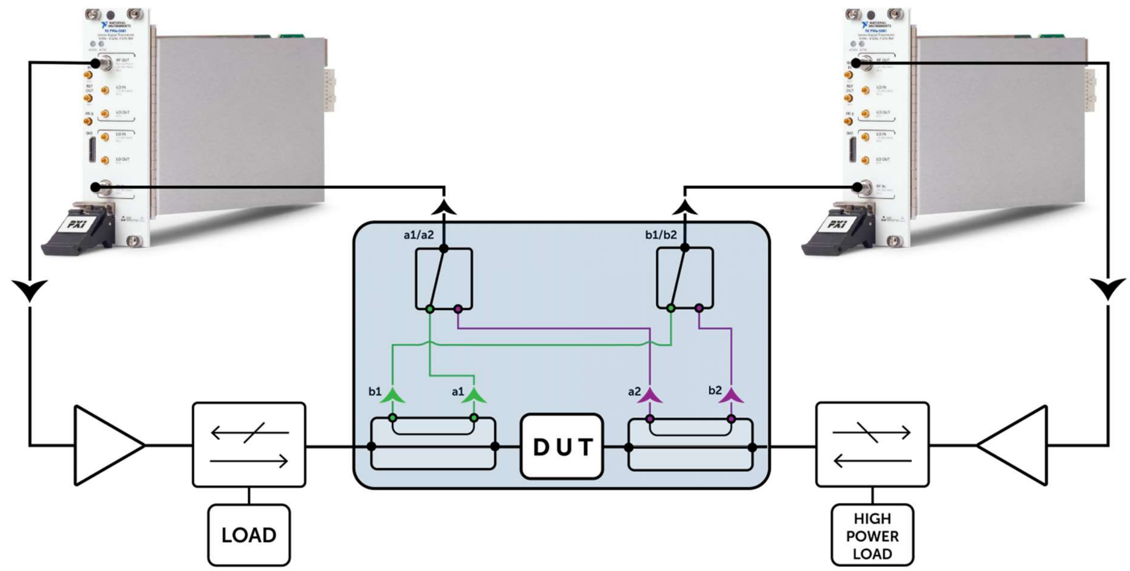



*Figure 4: Simplified 6GHz Rapid-VT setup block diagram [12]. The master VST and the slave VST can be seen in the top left and right respectively.*

As this is a 6GHz setup and the VST is capable of generating and analysing signals up to 6GHz, no additional up-conversion and/or down-conversion is required. Optional external source and load amplifiers can be added to increase the power presented to the DUT as needed. External isolators are used to terminated the $b_1$ and $b_2$ waves to prevent signals being injected back into the source/load amplifiers and VSTs' RF output ports. Inside the test set, couplers are used to extract the individual $a_-$ and $b_-$ travelling waves. These travelling waves are connected to a set of switches that can switch between measuring the port 1 or port 2 travelling waves. These waves are then sent to the VST input port for analysis.

For an 18GHz setup, it is necessary to perform frequency up-conversion for signal generation and frequency down-conversion for signal analysis. This is all done inside the 18GHz test set and a simplified block diagram of an 18GHz setup can be seen in Figure 5. To span the full frequency range, extra internal switching is used to switch between the above 6GHz path with the necessary up-conversion/down-conversion and the 6GHz and below path without any frequency conversion.

Through the combination of the instantaneous frequency bandwidth of the PXIe-5841 VSTs and the frequency range of the test set, it is possible to load-pull and measure a device across a 1GHz bandwidth up to 18GHz using the latest load-pull algorithm.

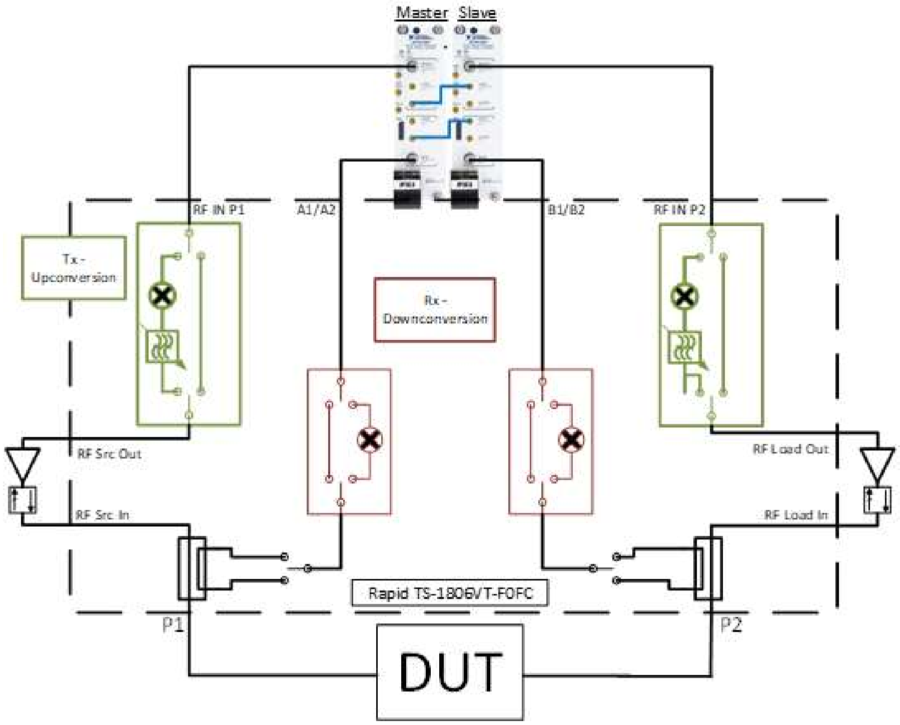
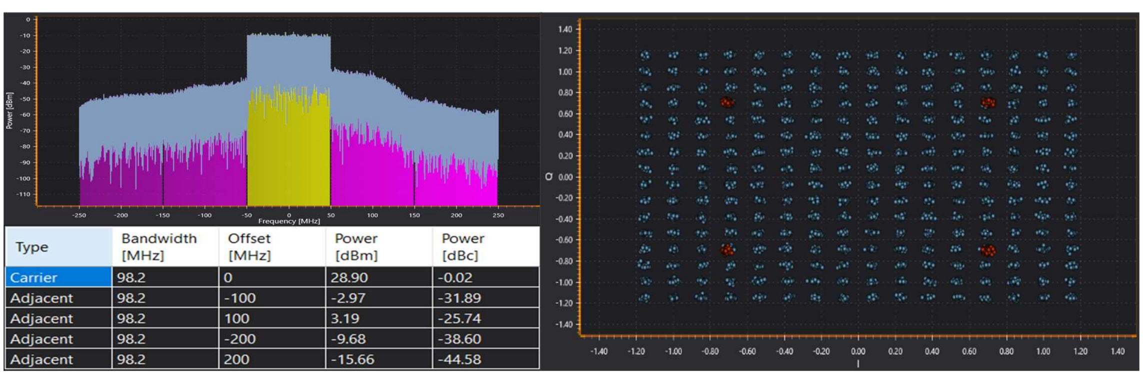



*Figure 5: Simplified 18GHz Rapid-VT setup block diagram.*

## System Measurements

To demonstrate the system capability of performing wideband active load-pull measurements, a 4W Skyworks SKY66292-11 device biased at 5V was load-pulled with a centre frequency of 2.35GHz using both a 10MHz 256QAM NR uplink waveform across a 50MHz measurement bandwidth and a 100MHz 256QAM NR uplink waveform across a 500MHz measurement bandwidth. The 100MHz waveform output spectrum, Adjacent Channel Power Ratio (ACPR) results and Error Vector Magnitude (EVM) constellation plots can all be seen in Figure 6.



| Type | Bandwidth [MHz] | Offset [MHz] | Power [dBm] | Power [dBc] |
|---|---|---|---|---|
| Carrier | 98.2 | 0 | 28.90 | -0.02 |
| Adjacent | 98.2 | -100 | -2.97 | -31.89 |
| Adjacent | 98.2 | 100 | 3.19 | -25.74 |
| Adjacent | 98.2 | -200 | -9.68 | -38.60 |
| Adjacent | 98.2 | 200 | -15.66 | -44.58 |

*Figure 6: 4W Skyworks SKY66292-11 load-pulled using 100MHz 256QAM NR uplink waveform across a 500MHz measurement bandwidth.*
*Left – Output spectrum and ACPR results. Right – EVM constellation plot.*

The measurement sweep output power contours and upper and lower ACPR results for the 10MHz NR waveform can be seen in Figure 7 and the same data for the 100MHz NR waveform can be seen in Figure 8.

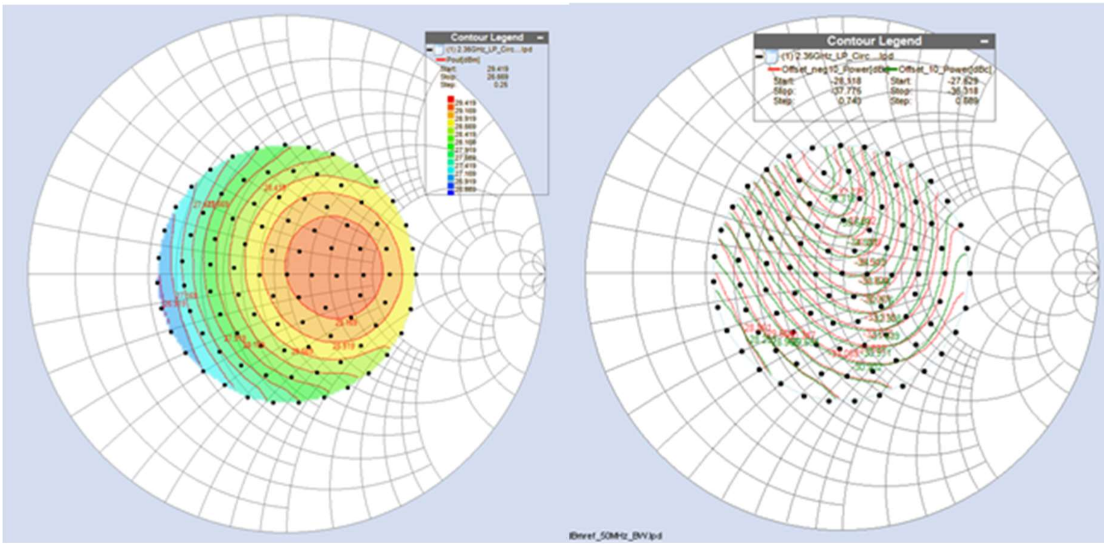



*Figure 7: Load-Pull sweep contour plots using the 10MHz carrier waveform.*
*Left – Output Power Contours. Right – Upper and Lower ACPRs Contours.*

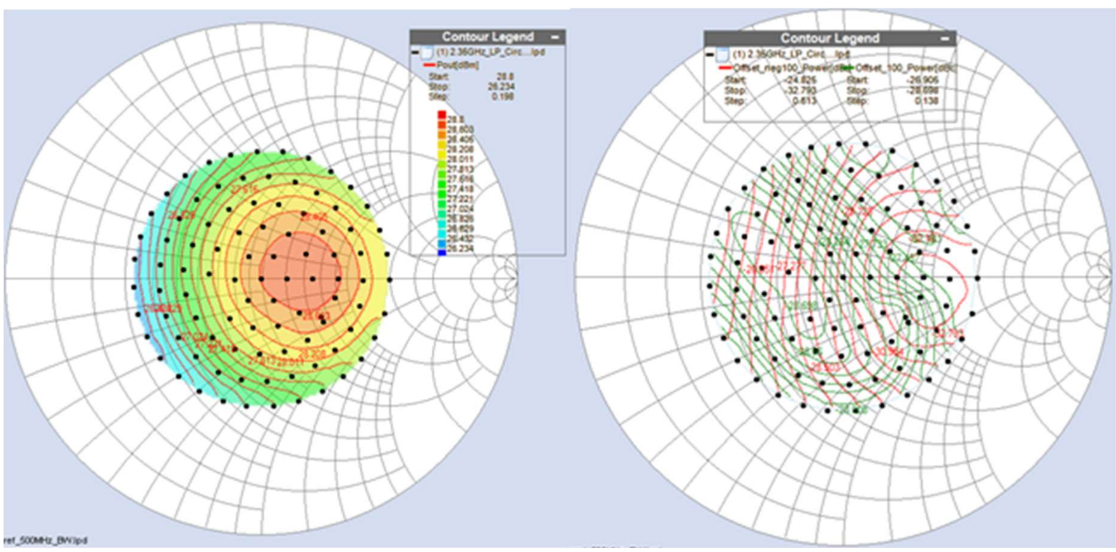



*Figure 8: Load-Pull sweep contour plots using the 100MHz carrier waveform.*
*Left – Output Power Contours. Right – Upper and Lower ACPRs Contours.*

From this data, it can be seen that the optimum impedance for maximum output power is the same for both waveforms. However, from Figure 7 it can be seen that, for the 10MHz signal, the upper and lower ACPRs have almost overlapping with a common optimum impedance. Meanwhile from Figure 8, it can be observed that, for the 100MHz signal, the upper and lower ACPRs have clearly changed with optimum impedances being significantly different for one another. From this data, it can be seen that having the ability to both generate and measure signals across a wider bandwidth allows for a more in-depth understanding of device behaviour in a variety of end-user applications. To a designer, having this extra information can be the difference between passing or failing to meet a specification and may highlight issues that would usually be identified further down the development cycle.

## CONCLUSION

In this paper, one of the key driving factors for the development of active load-pull systems has been highlighted alongside a basic overview of the concept of open-loop active load-pull and load-pull in general.

Additionally, Rapid-VT, a fully realised wideband open-loop active load-pull system, has been presented. This was used to perform wideband modulated load-pull on a DUT with waveforms of different carrier bandwidths, demonstrating the additional information that can be obtain from wideband measurements.

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