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A Mixed-Signal Load-Pull system for Base-Station Applications

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Abstract *— The capabilities of active load-pull are extended to be compatible with the characterization requirements of high-power base-station 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 W-CDMA with absolute control of their reflection coefficients vs. frequency.*

Index Terms — load-pull, base-station, high power, linearity, modulated signals, W-CDMA.

I. Introduction

Up to date, passive load-pull systems employing mechanical tuners [1][2] have been industry's preferred choice for large-signal characterization due to their simplicity and high power handling capabilities. However, passive tuner systems suffer from loss limitations and electrical delay. Losses in the tuner, interconnects and device test-fixture, limit the maximum magnitude of the reflection coefficient that can be offered to the device under test (DUT), while electrical delay in the tuner and interconnects to the DUT causes large phase variations in the reflection coefficient offered to the DUT vs. frequency, making testing with wideband communication signals (e.g. multi-channel W-CDMA) meaningless [3]. These constrains are even more severe when characterizing high power devices (> 100 W) for base-station applications. Here the low impedance levels of the active device require the use of reflection coefficients with a high magnitude, while the high-Q conditions in the mechanical tuners used to reach these coefficients tend to worsen the phase vs. frequency behavior of these reflection coefficients. In addition, self heating is more pronounced in power devices, demanding duty-cycle controlled pulsed operation, or appropriate testing with signals that have a comparable peak-to-average power ratio as used in the final application.

Active load-pull systems (**Figure 1a**) [3]-[7] can, due to the use of injection amplifiers, solve for the losses. However, when aiming for linear DUT operation their practical use in high power applications has always been restricted due to extreme high power and high-linearity requirements of the injection/loop amplifiers. To overcome these limitations, in this work, a novel active load-pull system is presented that is capable of performing high speed load-pull measurements with both CW, as well as, pulsed test signals. The same setup is also capable of handling high power wide-band communications signals, with peak output powers exceeding 150 W, while offering circuit like loading conditions by totally eliminating the impact of electrical delay. These capabilities make the proposed system a perfect candidate for the large-signal characterization of high power devices for base-station applications.

a)

b)

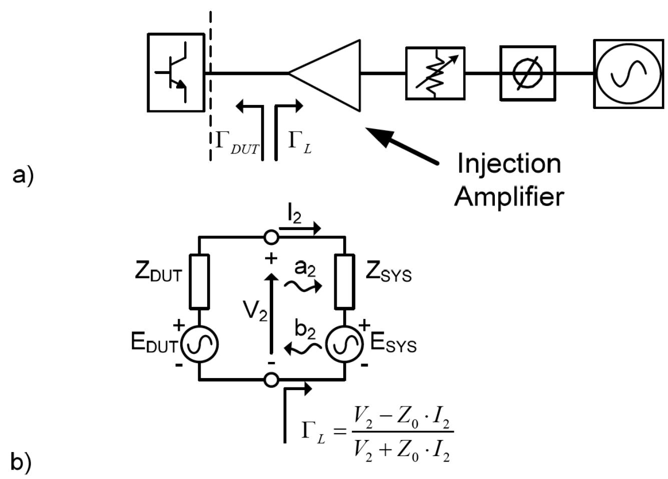

Figure 1. a) Open-loop active load-pull configuration. b) Thevenin equivalent schematic of an active load-pull configuration. The load impedance offered to the DUT at the reference plane is varied by adjusting the equivalent voltage source E_{SYS} in amplitude and phase. The related power needed to synthesize specific impedances depends strongly on the equivalent system impedance (Z_{SYS}).

II. Injection Power and Load Amplifier Linearity

To provide the DUT with a specific Γ_L an injection power is needed, which not only depends on the output power of the DUT and the desired Γ_L, but also on the output impedance of the device [8]. When considering high-power devices, with output impedances in the order of few Ohms, the required injection power to cover the desired Smith chart area can be extremely high (e.g. 2 to 10 times higher than the maximum output power of the DUT). To overcome this issue, typically pre-matching is used, which converts the 50 Ω impedance of the system to a value that is much closer to the output impedance of the DUT. This widely used technique (also applied in passive load-pull) does not only reduce the losses but also lowers the power requirement of the load injection amplifier [8]. E.g. a DUT with an output impedance of 2 Ω and an available output power of 200 W requires, when the system impedance is pre-matched to 10 Ω, an injection power of 360 W to synthesize a load impedance of 1 Ω. Reducing the system pre-matched impedance to 5 Ω, lowers the required injection power for the same load condition to 142.2 W. When considering multi-tone or modulated signals, the situation becomes more complicated as the linearity of the injection amplifier needs to be taken into account [9]. To study the linearity constrains on the injection amplifier, we consider a two-tone test signal, for which the power injected by the load amplifier at the IM3 frequencies of the two-tone test signal is given by,

$$P_{a_2,IM_3} = 3\cdot P_{a_2,fund} - 2\cdot IP_{3,a_2} = \\ = 3\cdot P_{b_2,fund}\cdot\frac{\left(1-\left|\Gamma_{DUT}\right|^2\right)}{\left(1-\left|\Gamma_{SYS}\right|^2\right)}\cdot\frac{\left|Z_{DUT}+Z_0\right|^2}{\left|Z_{SYS}+Z_0\right|^2}\cdot\frac{\left|Z_L-Z_{SYS}\right|^2}{\left|Z_{DUT}+Z_L\right|^2} - 2\cdot IP_{3,a_2} \quad (1)$$

where Z_{DUT} and $P_{b2,fund}$ are the output impedance and the available power coming out of the DUT (**Figure 1b**), Z_{SYS} is the passive load impedance at the DUT reference plane, $P_{a2,fund}$ and $IP_{3,a2}$ are respectively the power injected by the load amplifier and its output third-order intercept point. Fig. 2 shows the results of a harmonic balance simulation, where the apparent IM3 of the DUT vs. decreasing output IP_3 of the injection amplifier is shown for different pre-matching conditions of the system impedance. In this experiment the same DUT is used as for the single-tone considerations, (P_{avs}=200 W, output impedance=2 Ω), which is set in the simulation to have an output IP_3 of 63 dBm. For this device the output power is set equal to 50 W per tone, to have the same peak voltage as in the single-tone case. These conditions yield an actual IM3 of the DUT of -30.35 dBc. From **Figure 2** we can observe that this level is only achieved for sufficiently high IP3 of the injection amplifier. When the injection amplifier is less linear, it will introduce significant IM3 products, which can be approximated by eq. (1), and are also plotted in **Figure 2**. Note that IM3 cancelation effects can also occur.

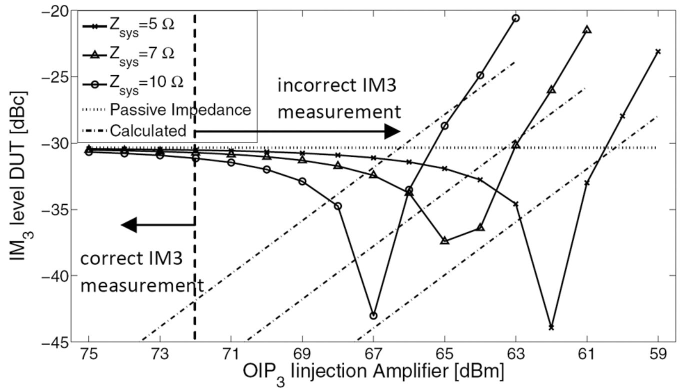

Figure 2. Harmonic balance simulated IM3 level of the DUT vs. decreasing output IP_3 of the injection amplifier for different impedance pre-match values. The dotted line is the actual IM3 level as would be achieved with passive matching techniques. The dot-dash line represents the IM3 level due to the $P_{a2,IM3}$ as approximated by Eq. (1). A polynomial model was used for the amplifier linearity.

Consequently, to have reliable linearity measurements in a conventional active load-pull setup, even when pre-matching is used, the injection amplifier linearity (and thus its peak power) needs to be at least 10 times higher than that the of the DUT.

It is obvious that at high power, these amplifiers, if available, will be extremely expensive. For this reason, active load-pull systems that can offer communication standard compliant device testing for e.g. W-CDMA at base-station power levels (100 W and above) have not been demonstrated up to date.

III. System Description

A simplified diagram of the realized open-loop active harmonic load-pull setup is shown in **Figure 3**. The system makes use of mixer-based down-conversion after which the data is captured by synchronized (100 MS/s) analogue-to-digital converters. With this hardware configuration it is possible to measure the reflection coefficients of the DUT over a wide frequency band and/or time span.

The reflection coefficients at the device reference plane are synthesized by injecting fully coherent RF signals that are generated by IQ up-converted baseband signals, which are provided by (200 MS/s) arbitrary-waveform-generators (AWGs). Since all data generation and data acquisition of both RF signals and DC parameters are handled through the PXI based DA

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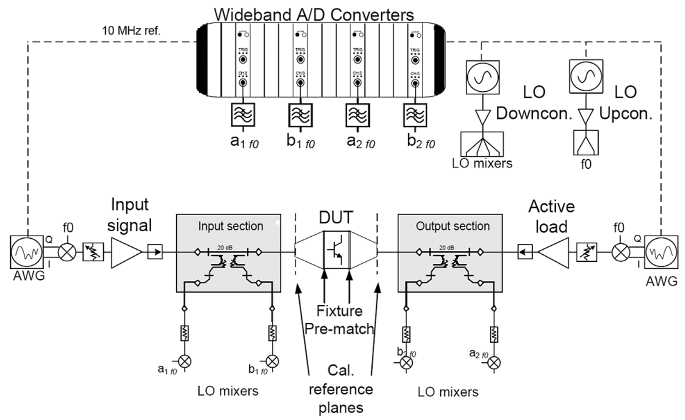

Figure 3. Simplified schematic of the phase coherent mixed-signal active load-pull setup.

and AD instrumentation, no mechanical tuners, NWA or DC-parameter analyzer is needed, yielding a cost effective high-end characterization solution.

IV. Real Time Pulsed RF Measurements

For single-tone CW signal conditions, the described system configuration is able to generate and measure in a single acquisition thousands of source and load conditions at different power levels. This feature provides ultra-fast load-pull device characterization [10]. For high-power devices, however, the use of CW conditions needs to be omitted to avoid self-heating, which in extreme conditions can even yield device failure. This is especially true for base-station devices which are optimized for operation with complex modulated signals. These signals reach only occasionally their peak values; as result the active device operates most of its time in power back-off. Consequently, in order to create realistic load pull testing conditions, pulsed RF operation is required. For this reason we extend the original concepts of [10] to pulsed operation at much higher peak power levels (above 100 W). These additional features allow the user to perform accurate high power ultra-fast device characterization, while providing full control on the maximum operating conditions of the active device, and thus avoiding voltage and thermal breakdown conditions.

All the waveforms to be injected into the input and output ports of the DUT are defined such that they contain multiple sinusoidal time-segments with different amplitude and phase information (**Figure 4**). As a result the device will experience a sequence of time segments with different input powers and loading conditions. Note that for correct operation the system needs to be fully coherent and time aligned. It is also important to remember that both RF and DC bias conditions need to be measured in the proper time segment. Although the tendency is to emphasize the measurement of the RF conditions, the measurement of the DC bias conditions is equally important and quite often difficult for pulsed operation. This can be understood by considering the fact that power devices need sufficient bias decoupling for their correct operation, which increases the time constant on the DC measurement port, troubling the correct measurement of the **Figure 4**. "DC bias" conditions. To overcome this problem a two step measurement procedure has been followed, which is described below.

A. Phase 1: Calculation of the Injection Signals

In this phase we only measure the RF properties and perform the necessary iterative calculations in order to find the proper injection signals. To keep the measurement speed at its maximum, the duration of each "time-segment" can be as short as 100 ns. In this phase, the desired duty cycle is achieved by adding a sufficient "idle time" after the stimulus representing the different power and load states. An example is shown in **Figure 4** where the input waveform to the DUT and the load injected waveforms are depicted. In this simplified case the DUT will "experience" two input power levels, one for each pulse, and three different load impedances. The desired injection signals are then optimized to synthesize the desired impedances seen by the DUT. Note that the use of iterations to optimize the injection signals opens the possibility to introduce

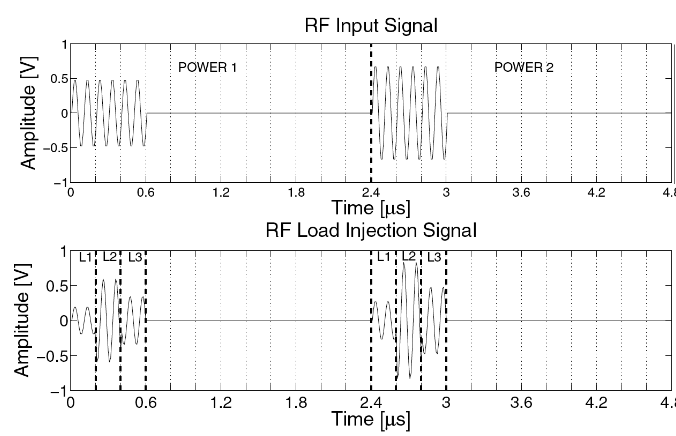

Figure 4. Time-segmented RF waves for multiple input power (upper plot) and load termination control (lower plot) with pulsed RF. In this simplified example 3 different loads for 2 input power levels are presented to the DUT.

several features that ensure safe device operation during the measurement, something that is extremely useful especially at high power levels. For example it is possible to exclude from the measurement an area of impedances that might cause device instability [10]. Furthermore, during each iteration, it is possible to check the gain compression of the device for every impedance, thus limiting the input power for those impedances where the DUT gain reduces by more than a user-specified amount. Also the shape of the pulse defined by its rise and fall time can be arbitrarily adjusted which proves to be very important in ensuring safe device operation.

B. Phase 2: Final Real-Time Pulsed Measurement

In this last part of the measurement routine, the actual measurement is taken. Now each individual load and power condition is represented by a separate pulse which has the user specified width and duty-cycle. The proper injection signals conditions were found in Phase 1, so no additional iterations are needed to reach the user specified loading and power conditions. In this final phase also the DC parameters are measured. This one data point at the time scheme is slower than the time segmented approach of Phase 1 (**Figure 4**), but it guarantees the highest accuracy for measurement of the pulsed DC parameters.

As application example of the proposed active load-pull concept introduced above, a complete load-pull and power sweep for a NXP BLF7G22LS-130 device was carried out at a frequency of 2.14 GHz, with a pulse width of 10 µs, rise and fall times of 100 ns and 10 % duty cycle. During this measurement the power gain compression was limited to a value of 4 dB to avoid device degradation due to undesirable extreme gain compressions, e.g. in higher load line regions. The results are shown in **Figure 5**, where the PAE vs. output power at a gain compression level of 3 dB is shown. Note that such a complete device characterization with 25 power levels at each of the 50 load impedances takes less than 3 minutes.

V. Modulated Signals Measurements

The realized system has the unique feature to perform active load-pull device testing with communication standard compliant wide-band modulated signals like W-CDMA. This feature has been described in detail for low-power levels in [3] and has been extended in this work to the power levels that are typically in use for base station applications (e.g. peak envelope power ~ 200 W). As example consider **Figure 6** which shows

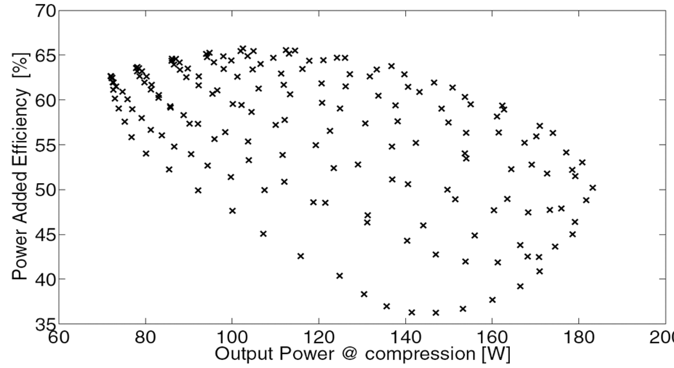

Figure 5. Measured PAE vs. output power at 3 dB power gain compression level of a NXP Gen7 LDMOS device for different load states and input powers, using pulsed single tone conditions (10 µs pulse width and 10 % duty cycle).

ACPR and average PAE for a single-channel WCDMA signal at 2.14 GHz with a peak to average ratio of 9.5 dB.

It should be stressed that in these experiments the maximum saturated power rating of the injection amplifier is only 200 W with an associated 60 dBm output IP3. The reason that the nonlinearity of the injection amplifier does not affect the measurement results showing a non correct IM3 measurement, as was

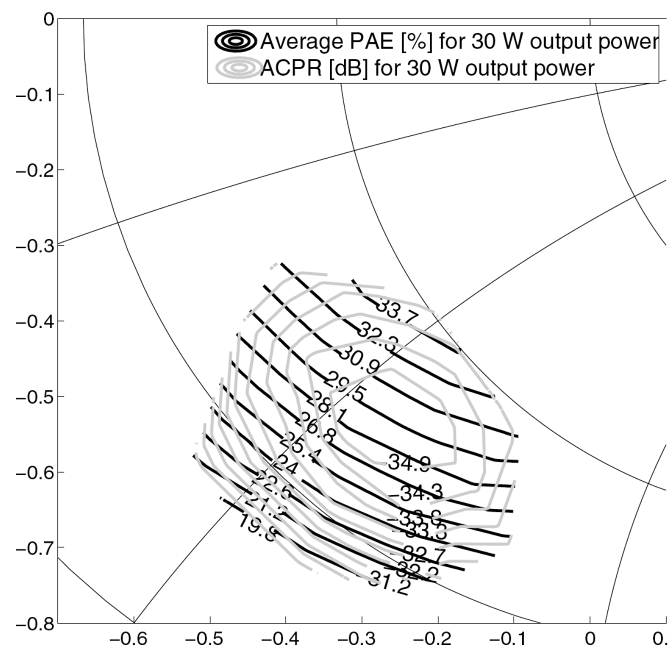

Figure 6. Load-pull contours of average power added efficiency and ACPR for an average output power of 30 W. The related peak to average power (PEP) is as high as 150 W.

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shown in **Figure 2**, derives from the iteration process performed to optimize the reflection coefficient of each individual frequency component of the WCDMA signal (in this experiment 11681 tones with 3 kHz spacing). Due to these iterations the injection amplifier is basically pre-distorted for its own nonlinearities, which allows the use of injection amplifiers with a much lower linearity as what is typically required in conventional active load pull systems.

VI. Conclusions

A cost effective active load-pull system compatible with the requirements of high power, high linearity base-station applications has been presented. It provides ultra-fast large-signal device characterization for both CW and pulsed conditions. For the latter, both the duty-cycle as well as the pulse shape can be independently controlled, limiting at the same time the gain compression of the DUT during the measurement. All these features are crucial in guaranteeing the safe operating conditions of high power DUTs (> 100 W). In addition, for the first time high power device characterization with realistic W-CDMA signals has been performed. It was shown that the realized system can compensate for the nonlinearities of the injection amplifiers, which normally would obscure the linearity / ACPR measurements. This property allows the use of cheaper injection amplifiers providing a lower Psat than required in conventional active load-pull systems. The ability to eliminate losses and electrical delay, while being completely free in defining the source and load reflection coefficients vs. frequency allows perfect mimicking of in circuit situations, making the system an interesting tool for the RF power amplifier developer.

VII. Acknowledgment

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