THE DUAL INPUT DOHERTY AMPLIFIER

Gareth LLOYD[1]

[1] Rohde & Schwarz GmbH & Co. KG, Mühldorfstrasse 15, 81671, München, Germany

The Doherty Amplifier (hereinafter "Doherty"), invented early in the 20th century has enjoyed a commercial renaissance over the last 15-20 years, beginning with cellular infrastructure products.

As a quasi-linear combining technique, its primary advantage is that it improves the amplifier's efficiency characteristic, without any theoretical degradation in linearity.

Whilst the technique itself relies on two unrealizable requirements (the amplitude-domain dog-leg current transfer characteristic, and the finite bandwidth impedance inverting combiner), in narrowband applications it can still outperform the closely related "balanced" architecture.

This paper proposes the introduction of a test and measurement approach into the development cycle, with focus on the input side of the Doherty. This way, more measurement data can be gleaned more quickly by the engineer, allowing a better-informed design decision.

Doherty Challenges & Limitations

For the sake of brevity a full treatment of the Doherty is not performed here, the reader is directed to, for example, [1].

There are a number of other limitations and challenges associated with building a Doherty. Some of those challenges are highlighted here.

Signal Summation

The Doherty comprises (at least) two signal paths, shown in Figure 1. Naturally, these signals need to be combined with correct amplitude/phase to minimise undesirable effects.

The incident amplitude/phases might vary according to temperature, operating frequency, natural device-device variation, and even age.

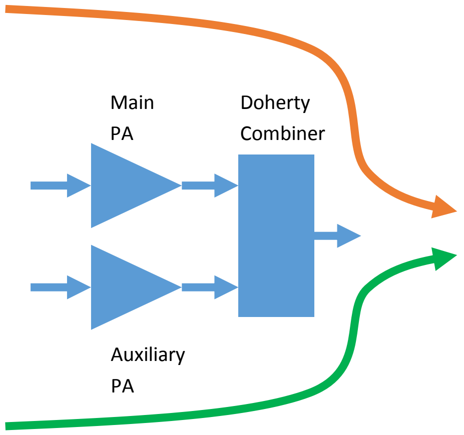


Figure 1 - Two paths of the Doherty, Main and Auxiliary

Dog Leg/Hockey Stick

Ideal performance requires that the output of the Auxiliary amplifier achieves a "dog-leg", or "hockey stick" shaped characteristic, shown in Figure 2 (bottom).

Deviation from this can cause an efficiency degradation.

In the simplest Doherty implementations, a "class C" amplifier is used to approximate the ideal, but this approach is itself the cause of other deficiencies.

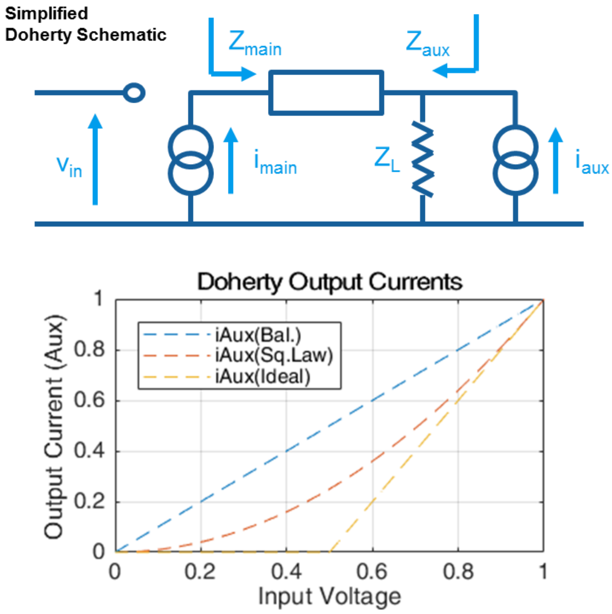


Figure 2 - Simplified Doherty schematic and associated, exemplary, Aux currents

Power/Efficiency & Load Modulation Trade-Off

Practical implementations often attempt to create the iAux/iMain difference engine by using different bias classes.

Cripps [1] showed that modification of the bias class also affects the useful power that can be generated as well as the maximum operating efficiency (see opposite).

Reduction of the Aux bias point decreases output power, whilst increasing Main increases stand-by or quiescent consumption.

Furthermore, increasing the conduction angle of Main reduces its responsiveness to Load Modulation.

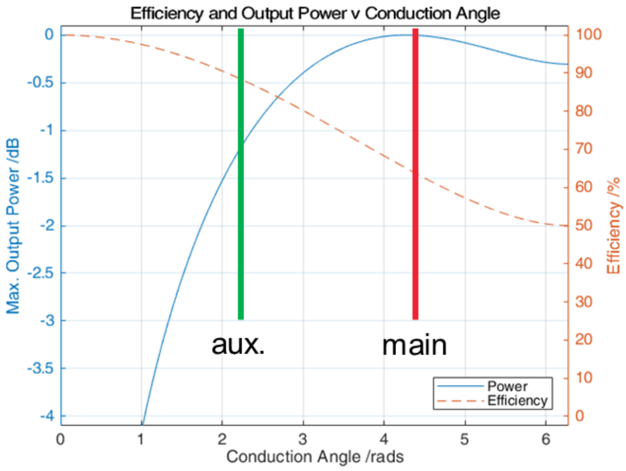


Figure 3 - Output Power and Efficiency versus Conduction Angle

Cut-and-Try Phasing

The typical Doherty development process still requires a final phasing adjustment on the input side. Often, implemented as shown in Figure 4.

This practice has a number of problems, including its labour intensive nature, sparse solution characterisation, unconfirmed global maxima, poor amplitude adjustment control, poorly defined structures, lossy elements, matching variations, to name just a few.

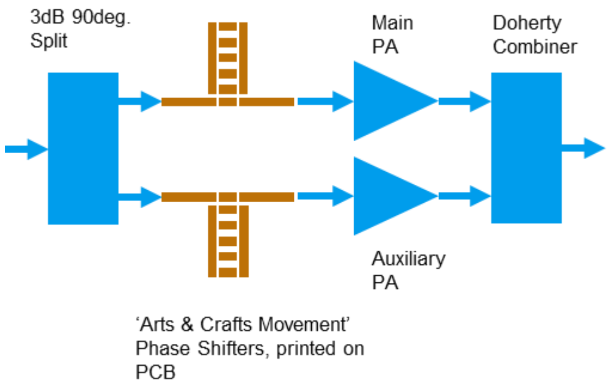


Figure 4 - Hybrid schematic/layout showing an exemplary printed phase adjustment network

The Input Side

To address these challenges and limitations, at least four input side implementations have been documented in the literature. These can offer significant improvements in performance and industriability, compared to the 3dB 90 degree split. Each offers its own set of pros, cons, and complexity.

i. The linear, intentionally dispersive, fixed structure.

- The amplitude and phase differences applied to the two paths differ intentionally over the bandwidth of operation. However, the signals in the two paths are linear with respect to each other. The split characteristic is set at “design time”, and is fixed for the life of the product. An example embodiment would be to use a Low-Pass filter in one path, and High-Pass in the other.

ii. The linear, non-dispersive, programmable structure.

- In essence, a programmable amplitude/phase split is realized using, for example, a variable attenuator and phase shifter. This variant may be adjusted even in the field. It offers higher performance over a narrower-bandwidth. There are several commercial IC products on the market, targeted at Doherty applications.

iii. The amplitude-domain multiplier

- Provides a different signal to the Auxiliary path, derived from the instantaneous amplitude of the Main path.

iv. The Dual-DPD solution

- The magnum opus of the variants presented in this document. Ostensibly provides the most superior performance. See [3].

This paper proposes a test and measurement solution that offers the engineer significant insight into their Doherty design, enabling them to understand the performance potential of their design and to enable the correct choice of input split architecture for their application.

Measurement of the special cases of variants (i) and (iii) will be demonstrated.

Test & Measurement

Background

At the core of the proposed test set-up, is a flexible signal generator, with multiple outputs, providing signals that are stable, repeatable, high resolution, programmable, calibrated and most importantly, potentially non-linear with respect to each other.

Apparatus

Many hardware configurations are capable of performing this measurement. For the purposes of illustration, the following hardware is used:

- SMW200A Dual-ARB Signal Generator.
- FSW Signal Analyser.
- Doherty prototype amplifier, ("DUT") with access to individual inputs.

Depending on the application, laboratory amplifiers may be installed to boost the drive power of the system. Naturally, these should be chosen with sufficient linearity and gain/phase stability to meet the needs of the measurement. (In this case, 2 x Mini-Circuits® ZHL-42 were used).

The set-up is shown in Figure 5.

Figure 5 - Photo of the test set-up used in this paper.

Method

In many cases, the designer has a reference test signal(s) and linearity metrics. The signal generator and signal analyser should be configured with these. For this experiment, a band limited noise signal was created (with noise-like signal statistics).

The signals incident to the DUT need to be "calibrated". That is to say, the signals need to be aligned to have a reference amplitude, phase and delay.

With the test set-up calibrated, the two distinct phases of testing can be performed.

The following measurement processes can also be extended to the design qualification process, for example, by building a series of DUTs (e.g. using devices from different batches, etc.) and analysing the bulk data gathered.

i. Differential-Linear (Figure 6)

    - With a common signal waveform output from both generator ports, sweep the amplitude and phase difference between them. This innermost loop should be complemented with an absolute input power level sweep.

- The sweeps may be performed open loop, pre-programmed over a range of amplitude/phase difference values. Alternatively, the sweeps may be programmed to iterate towards a target value.

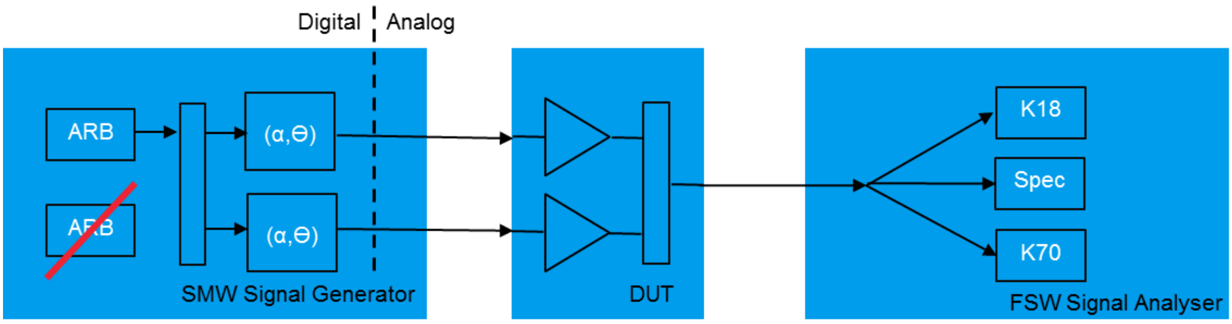


Figure 6 - Test set-up for the Differential Linear measurement

ii. Differential Non-Linear (Figure 7)

- The bias points of the devices are ideally made equal. The goal of this phase is to establish two values; (a) the amplitude/phase/power to give highest saturated power and (b) the most appropriate shaping characteristic, (preferentially including a dynamic phase variation), to maximise efficiency.

- Various test signals are proposed in the literature, including for example, the *tanh* function [2], as well as square-law and theoretical Doherty. These shaped signals may be parameterised, and those parameters themselves swept.

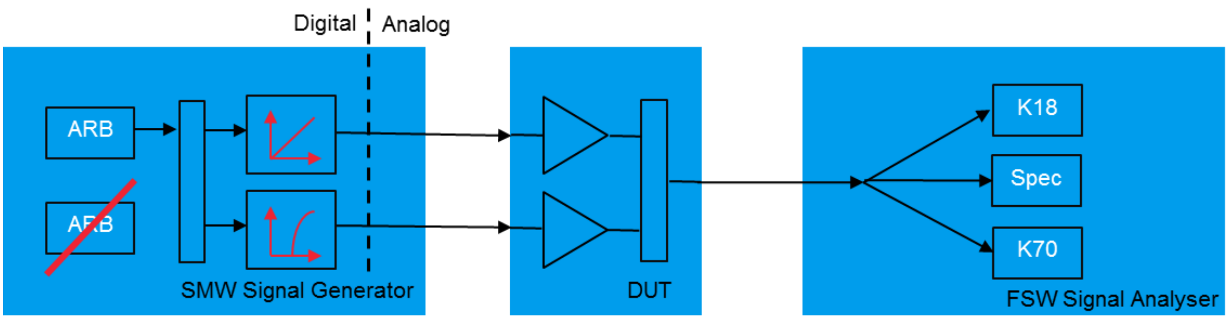


Figure 7 - Test set-up for the Differential Non-Linear measurement.

Results

Linear Signal Sweep

In this case, the independent parameters were input power, frequency, and amplitude/phase difference. The results were post-processed, using interpolation of the dependent average output power, to find target output power levels. (see Figure 8). These measured results provide visibility of some very interesting features.

i. The "Efficiency-Linearity" paradigm: For this specific amplifier prototype, there is a significant difference between the amplitude/phase balance values to achieve best efficiency and best linearity, at the specified output power.

ii. More importantly, assuming supplementary linearization is to be used, saturated power at the highest frequency absolutely does not coincide with highest efficiency. Saturated power is the sole determinant of the ultimate linear output power than can be achieved.

iii. The assumed operating point (based on the DUT provider's single input measurement) is shown with the red dotted line "--". This is a quasi-constant value, intersecting key characteristics where the rate-of-change of the dependent parameter is not only sub-optimal, but also located at points with relatively high rates of change.

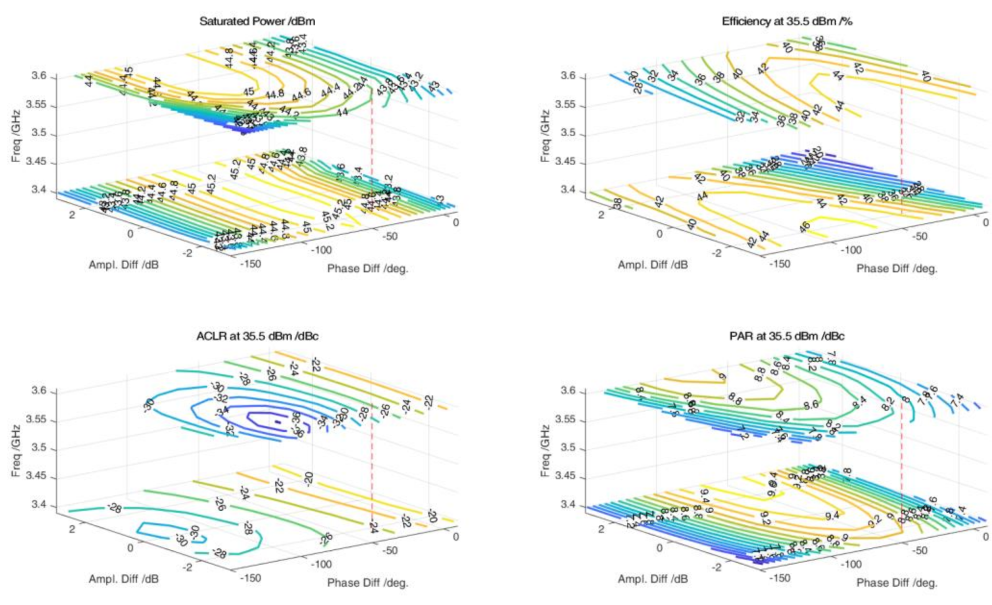


Figure 8 - Contours of saturated power, Modulated efficiency, ACLR and PAPRo, plotted against (input) Amplitude and Phase difference.

Thus, (ii) and (iii) ostensibly form a double whammy. Lower than potential performance AND higher than necessary variation. Using this data, the designer may opt for an intentionally dispersive design to equalise the performance achieved across the band.

Non-Linear Signal Sweep

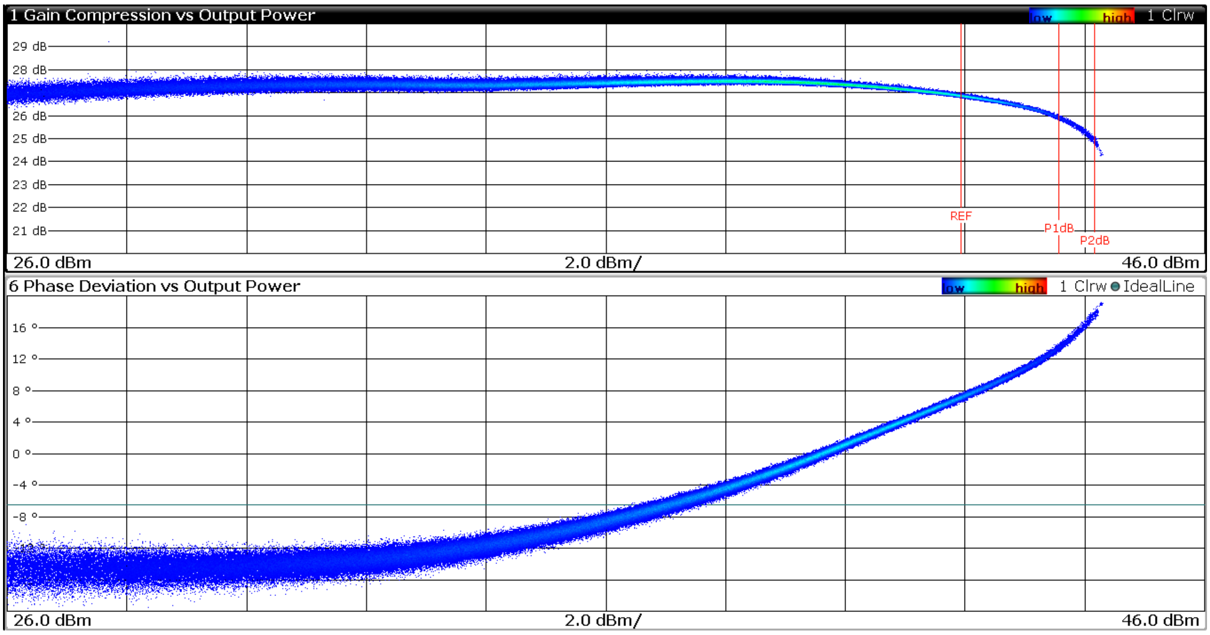
Next, the same DUT is tested in dual-input mode, using drive signals that are non-linear with respect to each other.

The signal bias points are made equal, and a search to establish maximum saturated power (PSat) is performed (by sweeping bias point, amplitude/phase difference).

Herein lies a key result. For this DUT, an increase in 1.7dB (+48%) in worst case saturated output power is observed whilst simultaneously decreasing the quiescent power consumption by 94%. This already represents a massive improvement, especially significant for deployment in TDMA applications.

With the bias point and amplitude/phase balance required for saturated output power derived, the parameterised, simple, square-law shaping was applied. In this case, to both auxiliary amplitude and phase.

Plots of the transfer characteristics are shown in Figure 9, for the reference, fixed RF input split case, and the dual-input case.



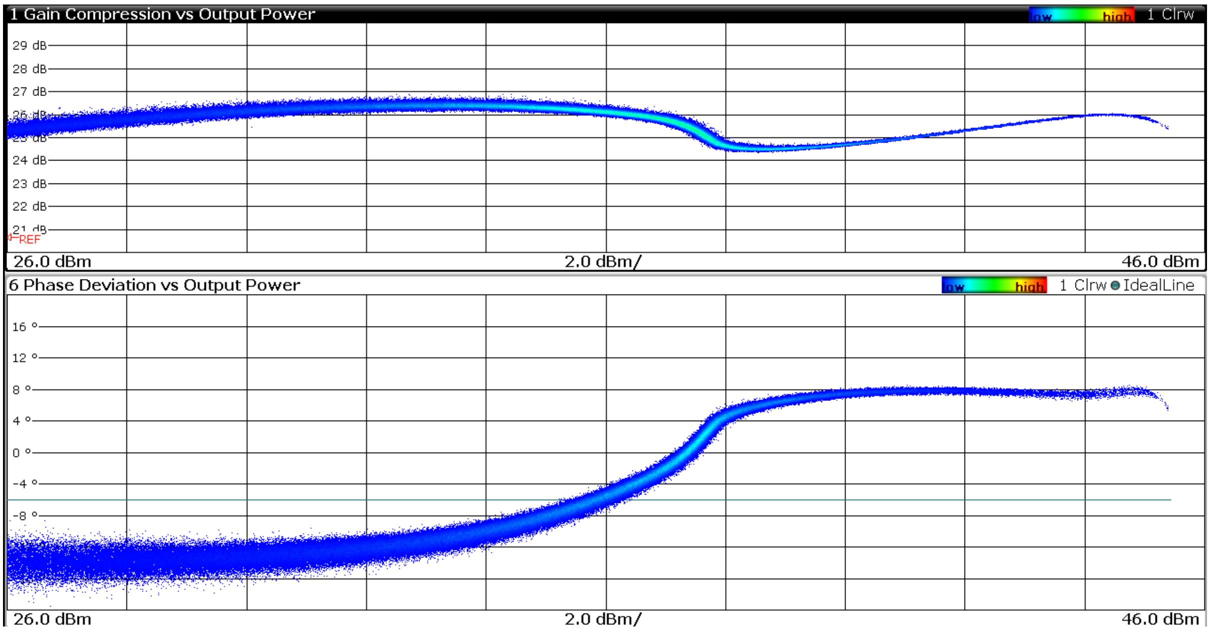


Figure 9 - Comparison of AM-AM and AM-PM Characteristics for (top) the Reference, Conventional, Fixed RF Input Split Doherty and (bottom) the Dual-Input Doherty (using Square Law)

The increase of 1.7dB in saturated output power (an improvement which itself could only increase in the production and field operation environments) allows for an increase in output average power from the device, for a given level of signal clipping – e.g. operation at 37.2dBm instead of 35.5dBm.

This increase in nominal average operating output power also drives an efficiency increase of 11% (from 44% to 49%).

The salient improvements are presented, normalised, in Figure 10.

Parameter	Fixed RF Input Split	Dual-Input Doherty	Improvement
Quiescent Power Consumption	100	6	94%
Saturated Output Power (Linear)	100	148	48%
Efficiency at PSat/PAvg = 8.3dB	100	111	11%

Figure 10 - Summary of the measurements in Fixed RF and Dual-Input modes.

These improvements are in line with those reported in [2] (over a 150% bandwidth reported improvements of 60% in power, 20% in efficiency), with no reduction in the predictability of the distortion (e.g. no negative impact on performance with digital predistortion)

The shaping characteristic used, square-law, may be replaced with better shaping characteristics (e.g. theoretical Doherty or *tanh*), which would impact efficiency further.

Conclusions

The Dual-Input test platform, with calibrated, precision, repeatable programming of input phasing and amplitude offers a hitherto difficult-to-achieve insight into Doherty designs.

Whether or not the designer intends eventually to use a dual-input configuration, significant advantages in performance and reductions in development time can still be achieved.

- Without dual-input, it still provides the designer with, (a) an insight into the performance actual versus potential of the design, (b) a sensitivity analysis. The designer may then choose their operating point(s) with increased confidence.

- With dual-input, the advantages are starker – even in this simple case, where the decomposition is performed with the auxiliary input derived from the main or reference input – and using a simple square-law shaping.

Finally, the proposed test platform, using two independent ARB sources, may be extended to measure the yet higher performance dual-DPD concept, shown in [3].

Bibliography

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