

Doherty, Balanced, Push-Pull & Spatial Amplifier Performance Enhancement

Application Note

Products:

- R&S®SMW200A
- R&S®QuickStep
- R&S®FSW
- R&S®WinIQSIM2
- R&S®HMC804x
- R&S®Forum

Development of front-ends for microwave and millimeter-wave bands continues to proliferate into the high-volume mainstream, mainly because of 5G, Automotive and SatCom applications. Modulation schemes in comm's and potentially also in upcoming mmW band radar requires linearity targets over earlier designs that often can only be met by operating traditional frontends with large back-off, resulting in size, cost and efficiency penalties.

Optimum design and development of amplifiers for these higher frequencies present additional challenges. Often, amplifying blocks are realized using 2 or more devices in parallel to achieve, for example, a given (higher) power level, or to improve the bandwidth of a parameter.

This application note describes a hybrid simulation-/measurement- based development methodology, to achieve enhanced amplifier performance with linear form of pre-distortion. The approach shown may be combined with DPD to achieve an even better result. It may also be used to lower DPD requirements.

The illustrated architecture is the "Doherty". The same methodology however, applies to balanced, spatially combined and anti-phase (so-called "push-pull" or "differential") amplifiers, the latter often itself nested within Doherty configurations.

Note:

Please find the most up-to-date document on our homepage

<http://www.rohde-schwarz.com/appnote/1MA279>.

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This application note uses the following abbreviations for Rohde & Schwarz products:

- | The R&S®SMW200A Vector Signal Generator is referred to as SMW
- | The R&S®FSW Signal and Spectrum Analyzer is referred to as FSW
- | The R&S®HMC804x Power Supply is referred to as HMC
- | The R&S®QuickStep Test Executive software is referred to as Quickstep
- | The R&S®WinIQSIM2 software is referred to as WinIQSIM2
- | The R&S®Forum software is referred to as Forum

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Studio Suite® is a trademark of Computer Simulation Technology AG

MATLAB™ is a registered trademark of The Mathworks Inc.

Airfast™ is a registered trademark of NXP.

1 Introduction

1.1 Reader's Guide

In Chapter 1, motivations for the measurement-based methodology are introduced. References for a more thorough grounding in the Doherty Amplifier subject matter are also provided.

Chapter 2 introduces the basic instrument and test bench set-up. Reference signals to drive the experiment (example signals provided) are described. Use of a higher power attenuator is recommended and guidelines are provided for its selection and measurement.

The automated process for phase coherent calibration of the test cables is described in Chapter 3, and an example script given in the Appendices.

Testing of the DUT is described in Chapter 4. In this case, the nested loop testing is driven using the professional test executive software, Quickstep.

An example post-processing of the results taken from the DUT is shown in Chapter 5. Variations in the Doherty optimization will be shown, demonstrating "flexible for the expert" capabilities of the NXP Airfast Doherty reference design.

Chapter 6 presents two exemplary approaches to synthesize the splitter networks, using Studio Suite tools. One approach using a pure distributed rat-race and Schiffman (Schiffman 1958), (Ramos Quirarte and Starski 1991) cascade; the alternative using a classic filter synthesis approach.

Chapter 7 includes measurements taken on additional devices, but for the sake of brevity, are not supported by synthesis.

The Appendices contain SCPI commands for initialization of the three instruments, in addition to two Forum scripts for (i) calibration and (ii) measurement of the DUT.

1.2 Background

The Doherty amplifier, since its invention in the 1930s (Doherty 1936), has enjoyed something of a renaissance in recent years in transmitter frontend hardware. Its persistent presence in the literature, including conference proceedings and patent databases, are testament to its elegance and flexibility.

An intensive treatment of Doherty theory is beyond the scope of this document. For further background, the reader is hereby referred to pp290-298, Chapter 10.2 of (Cripps 2006) and pp9-16, Chapter 2 of (Gustafsson 2014).

To achieve operation as Doherty intended, two broad conditions should be met by the amplifiers and combiners, shown in Fig. 1-1 (iii):

- The output current sourced by the auxiliary amplifier must have a specific characteristic, anyway discontinuous relative to the drive signal.
- The combiner ("impedance inverter") must be 90 degrees length.

Despite the effort devoted to making each of the three sub-circuits (the splitter, the amplifiers with their matching networks, and the combiner) more ideal (e.g. less dispersive), neither of the two conditions can be met in practice. As a result, the load modulation process is not purely real.

Regardless, performance in a narrow band exceeds that of the reference class AB, and amplifier products continue to be labelled "Doherty" and shipped in a range of products.

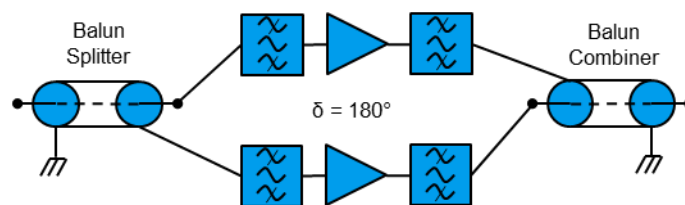
This application note shows how performance improvements can be made by optimizing the input splitter, to accommodate dispersions in the amplifier and combiner, effectively performing a frequency domain equalization.

This design technique becomes increasingly important as the Doherty concept rolls out in 5G and other millimeter wave frequency applications. At these higher frequencies, the sub-circuits have the potential to significantly increase in electrical size. In turn, causing increased frequency dispersion and degraded bandwidth.

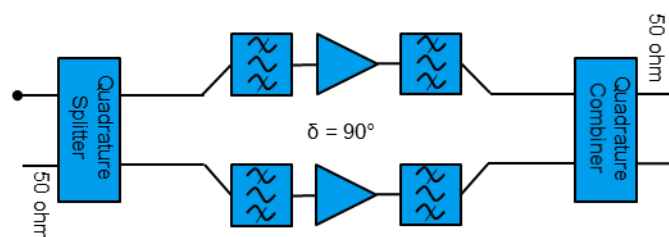
These enhanced Doherty-type amplifiers may be developed using a R&S and CST tool set. Enhancement will be demonstrated on a state-of-the-art NXP Airfast test fixture.

Although not explicitly detailed, the design technique may also be extended to improve the performance bandwidth of anti-phase (also called "push-pull" or "differential"), balanced and spatially combined amplifiers, as illustrated in Fig. 1-1.

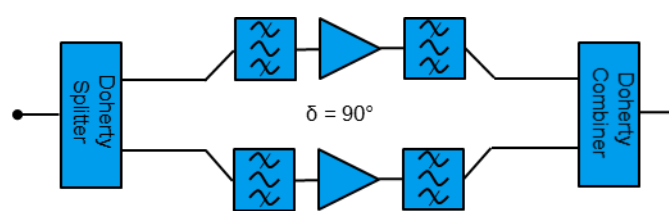
Note that the architectures are not mutually exclusive; e.g. a Doherty amplifier may be constructed using one or more anti-phase amplifiers. Multiple anti-phase amplifiers be balanced, etc.



(i) Anti-Phase (Push-Pull)



(ii) Balanced



(iii) Doherty

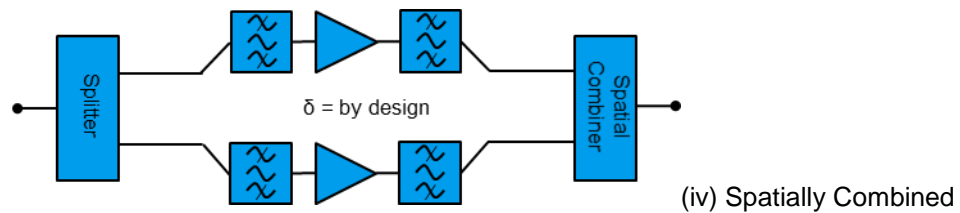


Fig. 1-1: Schematic representations of the (i) Anti-Phase ("Push-Pull"), (ii) Balanced amplifiers, adapted from (NXP 1993) and (iii) Doherty (iv) Spatially combined amplifiers.

1.3 Measurement-based Design Methodology

In general, the development of Doherty hardware comprises both non-linear and electromagnetic (EM) simulation of the components and sub-circuits, followed by prototype build and design centering. Achieved performance will be limited to model accuracy, modelling methodology and dispersion in the sub-circuits.

In this alternative approach, the amplifiers/matching networks and combiners are prototyped in hardware much earlier in the development phase. Those two imperfect circuits are then empirically characterized and subsequently compensated for, during the design of the third (the splitter).

That splitter may be synthesized to recreate the optimum values for differential amplitude and phase over frequency. In effect, a frequency-domain equalization is performed.

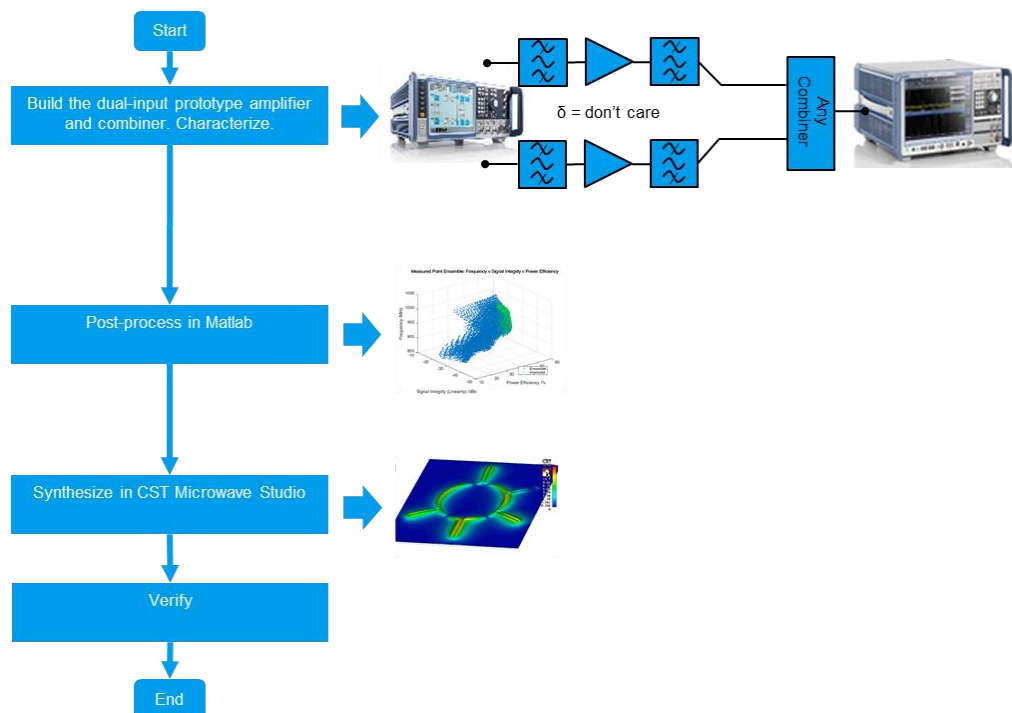


Fig. 1-2: Summary of the proposed design flow

The characterization process is made easy using the SMW and FSW, whilst rapid measurements are enabled with Quickstep (see Chapter 4). The optimized splitter may then be designed using the high performance EM simulation tool, CST Studio Suite.

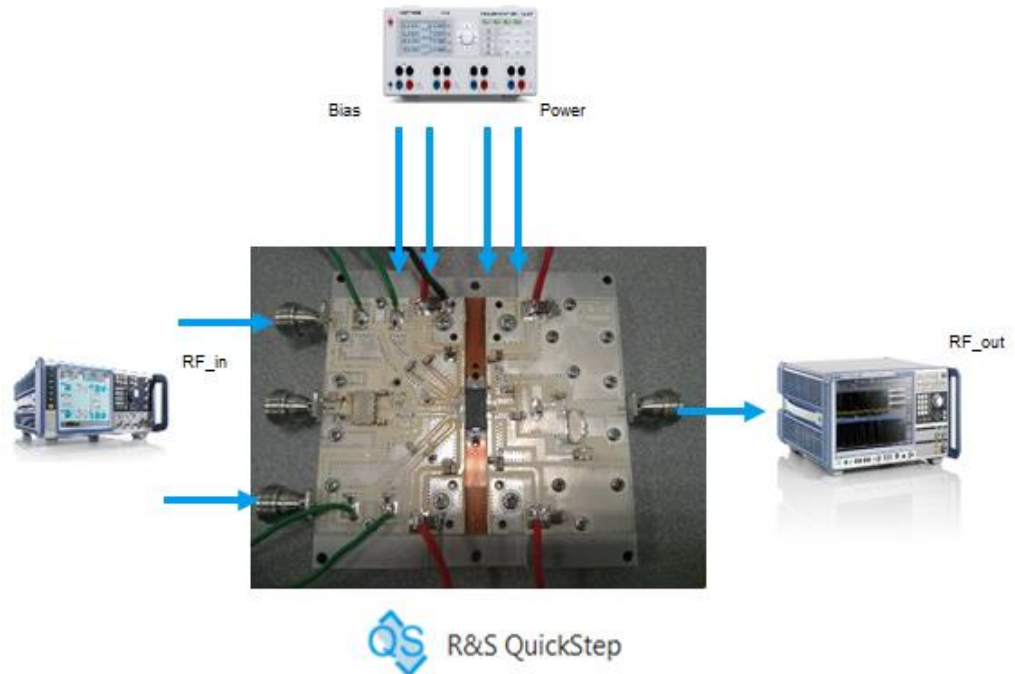


Fig. 1-3: Test bench for development of the optimized amplifiers, using the modified NXP AirFast Doherty test fixture.

2 Preparation

2.1 Signal Library Generation

2.1.1 Provided Library (License Free)

The library of signals used in this document are already included in the distributable from the Application Note's homepage at <http://www.rohde-schwarz.com/appnote/1MA279>.

The signal library comprises a total of 18 files, stored in a binary format used by the SMW:

- 'File_3C_80MHz.iq.wv'
 - a construction of 3 modulated carriers, separated by 80MHz, with 200MHz sampling frequency.
 - in the measurements performed in this document, with 940MHz centre frequency, these three carriers will appear at 840, 940 and 1020 MHz.
 - the signal may be reused at other centre frequencies.

- 'Filexxxx.iq.wv'
 - a family of 17 single carrier files, whose carrier has characteristics similar to the 3GPP Test Model 1 with 64 DPCH (which was actually used in the measurements in this document)
 - the different signal files have the single carrier placed at offset intermediate frequencies, from -80MHz to + 80MHz, in steps of 10MHz
 - the measurements were performed over the frequency range 840 MHz to 1020 MHz; the 'xxxx' of the filename refers to that intended RF frequency

Using a baseband frequency sweep with the library of test signals, with fixed frequency on the SMW, enables a single phase coherence calibration of the two SMW channels for amplitude, phase and time delay.

It is recommended that these files are stored in a suitable working directory on the SMW itself, ahead of beginning the measurement.

2.1.2 Signal Library Variations

The user is free to generate their own signal library, using WinIQSIM2 software, or other software as appropriate.

As an alternative to using the IF sweep shown in this document, the user may also perform a true RF sweep with a single signal file.

This advantageously increases the frequency sweep bandwidth arbitrarily, and reduces the number of signal files to be pre-generated.

However, in doing so, a calibration (amplitude, phase, delay) at different associated SMW RF frequencies must be performed. The user may pre-calibrate, store and recall

these calibration values (delay, baseband phase and baseband amplitude) for each frequency.

Note also that the calibration signal should be sufficiently long and uncorrelated, so as to provide a consistent and unambiguous calibration.

2.2 DUT Load/Attenuator Verification

Sometimes, the output power capability of the amplifier will exceed that of the FSW ability to handle such power.

It is common practice therefore, to protect the FSW from RF damage by introducing an attenuator between the DUT and FSW.

Verification of the performance of that attenuator is described here.

2.2.1 Reflection

The VSWR presented to the output of the DUT should be verified sufficient for the required measurement accuracy and application.

In many cases, an RF attenuator may need to be inserted between the FSW and DUT output, to protect the FSW from overload.

Generally, the attenuator is used with a coaxial cables; in many cases the characteristic impedance and lengths of the test cables varies. The cable and attenuator pair should be selected together, to give best VSWR over the band.

The VSWR is measured using a network analyzer, e.g. ZVA-67. In this example, the 100 W rated 20 dB attenuator and one selected test cable, achieved a minimum 30 dB return loss over the band of interest.

2.2.2 Insertion Loss

With sufficient VSWR verified, the loss between the DUT output and power measurement device (in this case, the FSW) needs to be measured.

There are at least two methods that may be used.

1. SMW & FSW

The attenuator from Chapter [2.2.1](#) is connected directly to one of the SMW output ports.

The FSW reference level offset is then adjusted to equalize the SMW output power with the FSW measured power. Frequency variations may be applied in the post-processing phase.

This loss calibration may be performed using a CW or modulated signal.

2. Network Analyzer

A simple insertion loss measurement is made across the band of interest using a 2-port calibration (reflection-thru') with the network analyzer. Usually, this can be

performed at the same time as Chapter [2.2.1](#), without additional connect-disconnect cycles.

2.3 Instrument Connection

The (minimum) three instruments (FSW, SMW and HMC) plus the host controller (PC) should be connected via a LAN, to allow the exchange of commands and data.

3 Initialization and Calibration

3.1 Instrument Initialization

The series of SCPI commands used to set the SMW and FSW to the correct operating states for this experiment are given in the Appendices.

These initialization command sequences are already embedded in the QuickStep project files described in Chapter 4, but are given for reference.

Quickstep will automatically ensure that the signal libraries are copied to the SMW.

In case QuickStep is not used, the user must ensure that the calibration and library files are available to the SMW (e.g. copied) and filename references are updated in any scripts (e.g. Forum).

3.2 Dual Path Calibration

A calibration must be performed to ensure the two signal outputs from the SMW are properly aligned in time, phase and amplitude at the end of test cables, i.e. that the effect of the test cables needs to be removed.

The calibration procedure is already embedded within the QuickStep project files. Within that QuickStep project, the calibration is performed using a Forum script. This script is also included in the appendices for reference.

Forum is a free tool, enabling easy instrument control within a Python scripting environment, and is available from <http://www.rohde-schwarz.com/appnote/1ma196>.

The two cables at the outputs of the SMW, labelled "A" and "B" in Fig. 3-1, must be calibrated for amplitude, phase and time delay. This calibration:

- Is best performed using a combiner, usually isolated (e.g. resistive splitter). Preferably, a dedicated calibration kit is built, replicating the input side of the DUT.



Fig. 3-1: Apparatus for calibration of the input test cables (A and B) with a resistive splitter, whose third port (C) is connected to the FSW (left). Also shown with DUT connected, post-calibration (right).

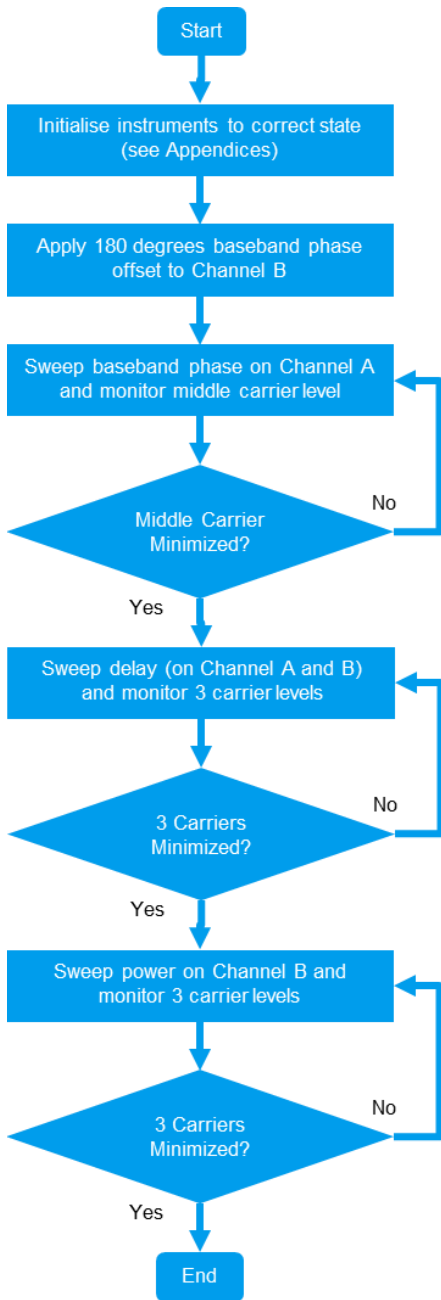


Fig. 3-2: Calibration flow chart

- In this case, will be performed at a single RF frequency on the SMW (covering a signal bandwidth of 160 MHz in this case) with the FSW sweep set wide enough to capture the entire three carrier bandwidth.

- Shall detect the cancellation or anti-phase condition, as it is more accurately detected than the in-phase condition.

The calibration procedure is summarized in Fig. 3-2.

Designing a simple "home-made" calibration kit replicating the DUT offsets is highly recommended.

If not, as in this case, effect of any calibration plane shift between DUT and the calibration object, needs to be understood before a final splitter design can be made.

Normally, this plane shift (through passive components) would be calculated and de-embedded through simulation, e.g. using CST Studio Suite. Correction may be introduced by offset of the respective channels during calibration, or in the post-processing phase.

The Forum script used to auto-calibrate this example is included in the Appendices.

The values returned by the calibration are valid for the LO frequency of the SMW and the specific test cables.

If either LO frequency or test cables are changed, different calibration values are needed.

The values are however stable and may be stored and re-used.

Thus, a true RF frequency sweep, rather than IF, is possible.

Executing the FSW and SMW set-up scripts, with the two channels of the SMW and FSW connected to (in this case) a 3-port resistive splitter, results in the screenshots shown in Fig. 3-3. Note that the three carrier signal generated in Chapter 2.1 has been loaded into the SMW.

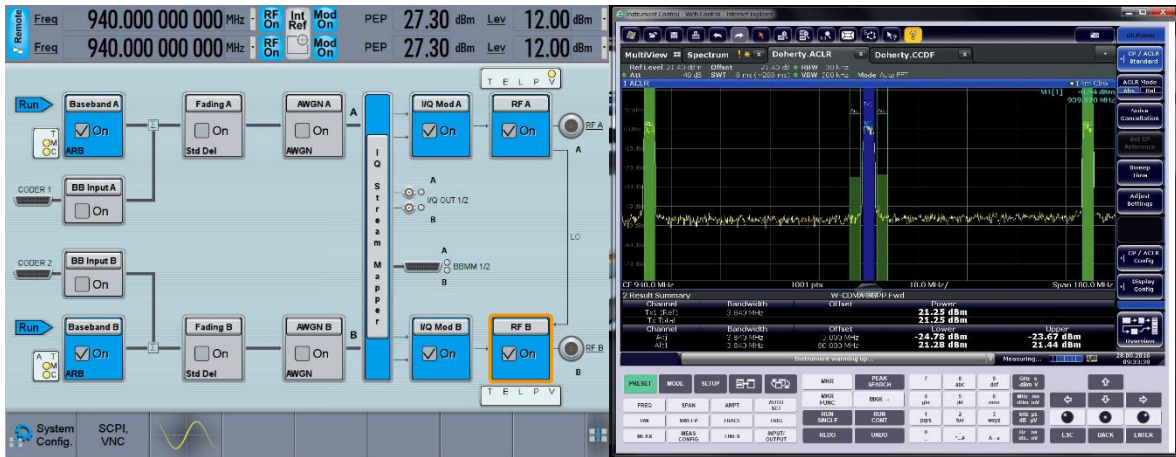


Fig. 3-3: Screenshots from the SMW and FSW after initialization, and prepared for calibration

At this point, the signals incident to the splitter's inputs, have an arbitrary amplitude, phase and delay difference.

The calibration algorithm (script included in the Appendices), and flow chart shown in Fig. 3-2 is as follows:

1. With Channel B phase set to 180 degrees, sweep the baseband phase of Channel A and minimize the level of the middle carrier.

Write the phase, corresponding to minimum amplitude level, to Channel A.



2. With phase minimized in Step 1, sweep the relative delay of Channel A and B. Negative delays cannot be used.

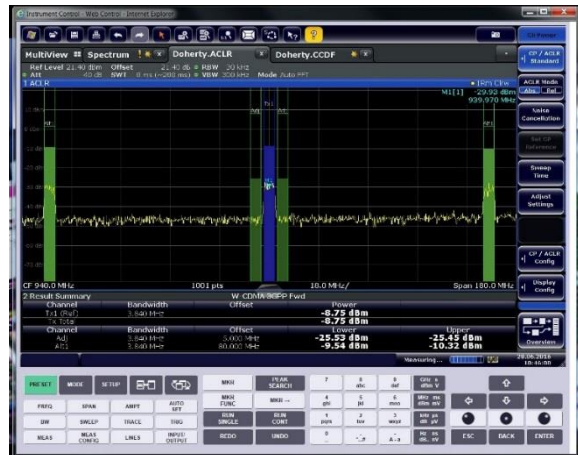
Detect and minimize the levels of all three carriers. Typically, select delay giving lowest, worst case, carrier level, e.g. $\min(\max(C1, C2, C3))$

Write the delay to the corresponding channel.



- Sweep the amplitude of Channel B and again detect the lowest, worst case, carrier level.

Record the power offset, it does not need to be written. The relative value of Channel B will be swept anyway. It is possible to apply the offset even in post-processing.



With values for differential phase, amplitude and delay that minimize the three carrier level now set in the SMW, the calibration efficacy may be verified by:

- Noting the level of each of the three carriers
- Applying a baseband phase offset of 0 degrees (i.e. in-phase) to channel B, putting the carriers into a state of in-phase combining, and re-measuring the carrier levels.
- Calculate the amplitude level difference for each of the three carriers according to the previous two steps.



In this case, the minimum difference between in-phase and anti-phase is better than 35 dB for each of the three carriers.

The calculated cancellation provides an indication of the achieved amplitude and phase balance, hence the accuracy of the subsequent measurement. A 30dB difference corresponds approximately to a 0.1dB and 1.0 degree error.

A universal calibration accuracy cannot be specified. The user should determine a suitable level of differential amplitude and phase, on an application-by-application basis.

4 Testing with QuickStep

4.1 QuickStep Introduction

The rapid test executive software, QuickStep, is used to drive the characterization. An evaluation version is available for download from the [Quickstep](#) homepage. A link to download the project required to drive this application, may also be found there.

4.2 Characterization Algorithm

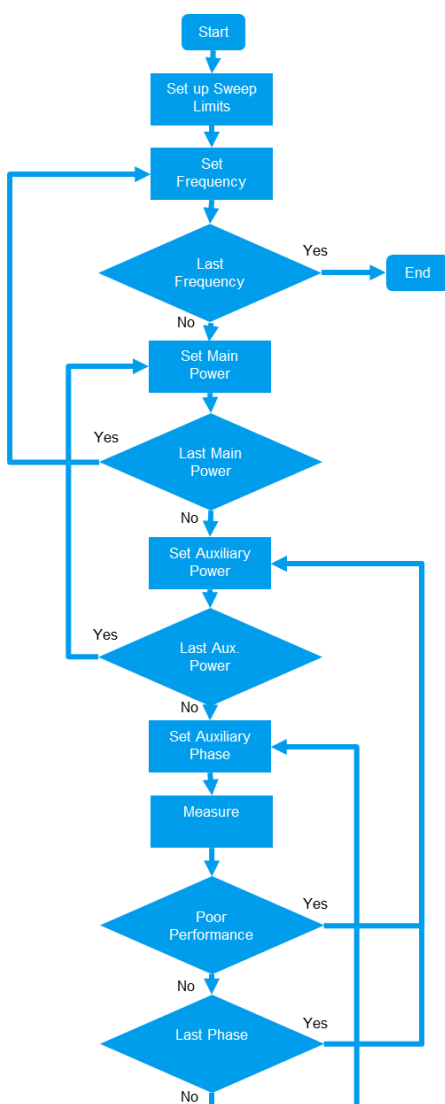


Fig. 4-1: Generalized flow chart of the test procedure, showing loop nesting.

In this example, a broad, nested loop sweep characterization of the DUT is performed.

Other characterization methodologies are possible, including for example, searches for operating points of specific interest.

Independent swept variables include frequency, differential input amplitude, differential input phase and absolute input power. Successive values are set using nested loops.

This particular exercise did not include a sweep of the bias points, but the introduction of this as an independent variable would likely be beneficial.

Measured (dependent) quantities measured include current consumption, in channel output power, adjacent channel power(s) and output crest factor.

Those values are checked against a list of conditions intended to minimize time wasted performing measurements in operating regions that are unlikely to be of interest. Doing so also reduces the risk that potentially damaging operating conditions are created.

Before any DUT characterization can be performed, however, a calibration of the test cables must be performed, to ensure a controlled Phase Coherent environment. This is described in Chapter 3, and automated routines described in the Appendices as well as Chapter 4.3.

4.3 Getting Started

This section describes how to get the example project up and running within the QuickStep environment.

The example project "Quickstep_DohertyCharacterization_and_WaveformLibrary.zip" may be downloaded from the Application Note's homepage.

1. Save the project archive to the destination directory (the default is assumed to be "C:\Users\Public\Documents\Rohde-Schwarz\QuickStep")
2. Run the de-archiving tool (this will create a directory structure based at the destination directory)
3. Enter the "\Doherty_Characterization\Projects\Doherty_Characterization" subdirectory and open the "Doherty_Characterization.tpl" project
4. The QuickStep test executive environment will be presented as per [Fig. 4-2](#):

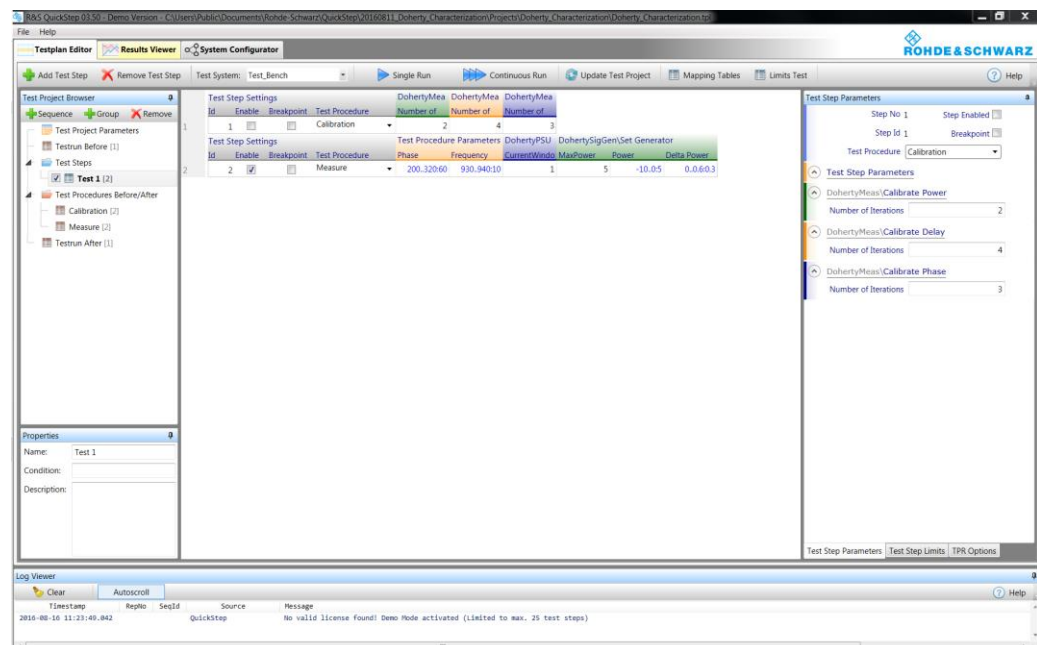


Fig. 4-2: The QuickStep "Doherty Characterization" project landing page, in "Demo Mode"

5. The network addresses of the instruments must now be set-up. The IP addresses are set in the "System Configurator->Visa Instruments" dialog.

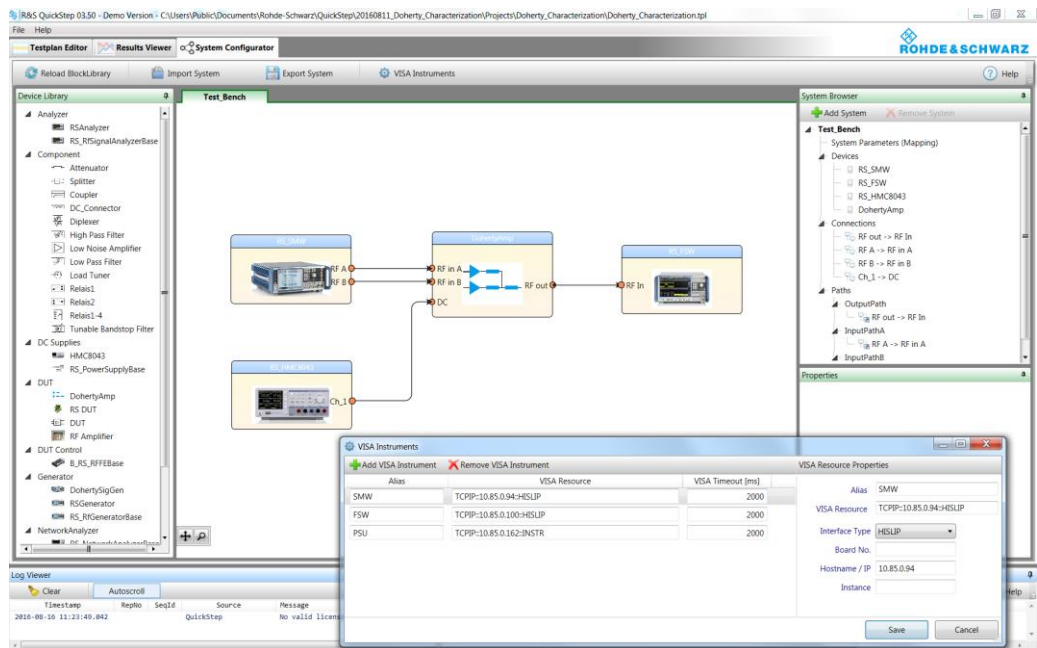


Fig. 4-3: Setting up the IP addresses of the test instruments in the "System Configurator" -> "VISA Instruments" tab

6. Returning to the "Testplan Editor" tab, ensure that "Update Test Project" is updated and "Calibration" Test Step is enabled.
7. Run the Calibration routine by pressing "Single Run".

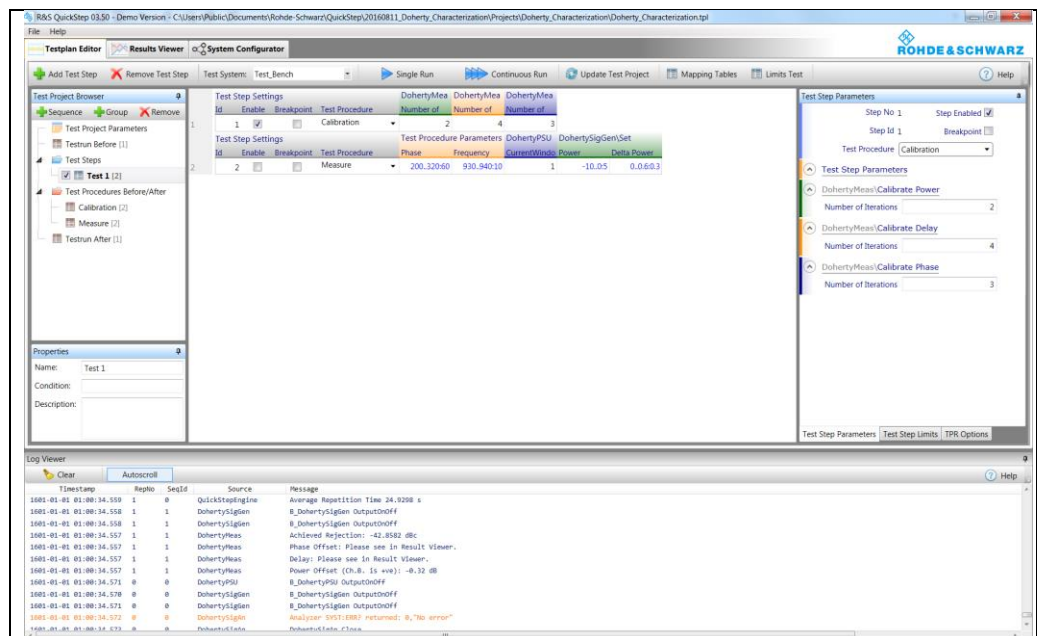


Fig. 4-4: Calibration successfully executed, with an achieved rejection ratio of better than -42 dBc.

8. The test system is now calibrated for phase coherence. The user may now replace the calibration component with the DUT.

9. Alternatively, the user may perform a coarse set-up (boundary condition test) with the calibration component still connected, for verification of their own settings.

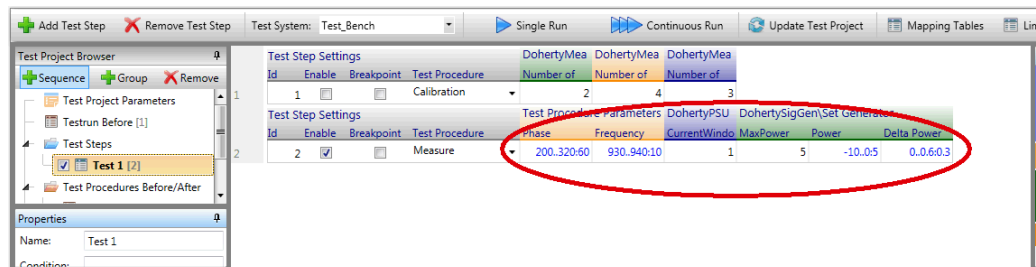


Fig. 4-5: Sweep variables used include "Differential Phase", "Frequency", "Current Measurement Tolerance", "Maximum Power", "Reference Power" and "Differential Power".

10. Having ensured that appropriate sweep values are set in the "Measure" test procedure, uncheck the "Calibration" enable box and check the "Measure" enable box.

The DUT may now be measured.

11. Measurement results may be exported to .csv format, for post-processing, using "Results Viewer" -> "Export".

4.4 Selected Quickstep Tips and Tricks

4.4.1 Loop Nesting

This characterization algorithm uses nested loops to control the independent variable sweep.

Within the QuickStep executive, the nesting is easily created and modified using the "priority" switch in the parameter sweep definition. This is set within the "Testplan Editor->Test Step" item.

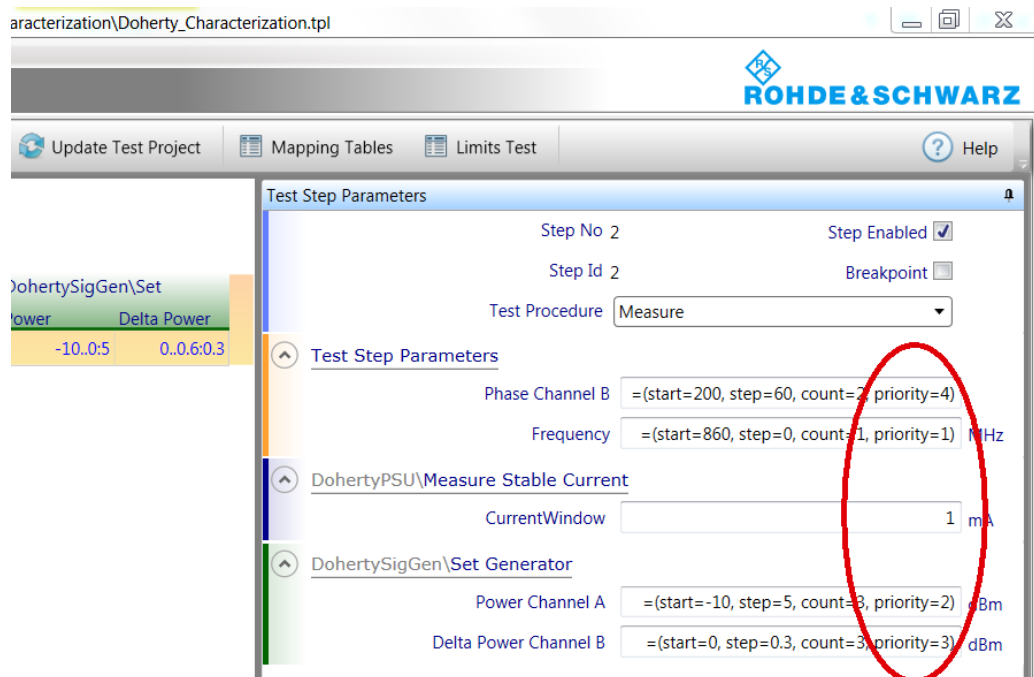


Fig. 4-6: Creation of nested loops, using the "priority" switch, of multiple independent variables in the "Testplan Editor" -> "Test Step Parameters" tab.

With a nested loop sweep, innermost parameters are swept more often than the outermost. Normally therefore, parameters which can be set most quickly are allocated in the innermost loops.

In this case, "Frequency" is placed in the outermost loop. The specific waveform for that intermediate frequency needs to be loaded into the current ARB, and the ARB generators retriggered.

The innermost loop is assigned to the phase differential, which is set merely by assigning a new value to the baseband phase on Channel B in the SMW.

4.4.2 Parallelism - Efficient Testing

QuickStep enables the developer to implement parallel (rather than sequential) testing of parameters. In this case, the measurement functions that query the ACLR and Output Power from the spectrum analyzer are performed in parallel with the Current Consumption measurement from the power supply.

This parallelism is created easily using the fork/join component in the Test Procedure Editor, as shown in Fig. 4-7.

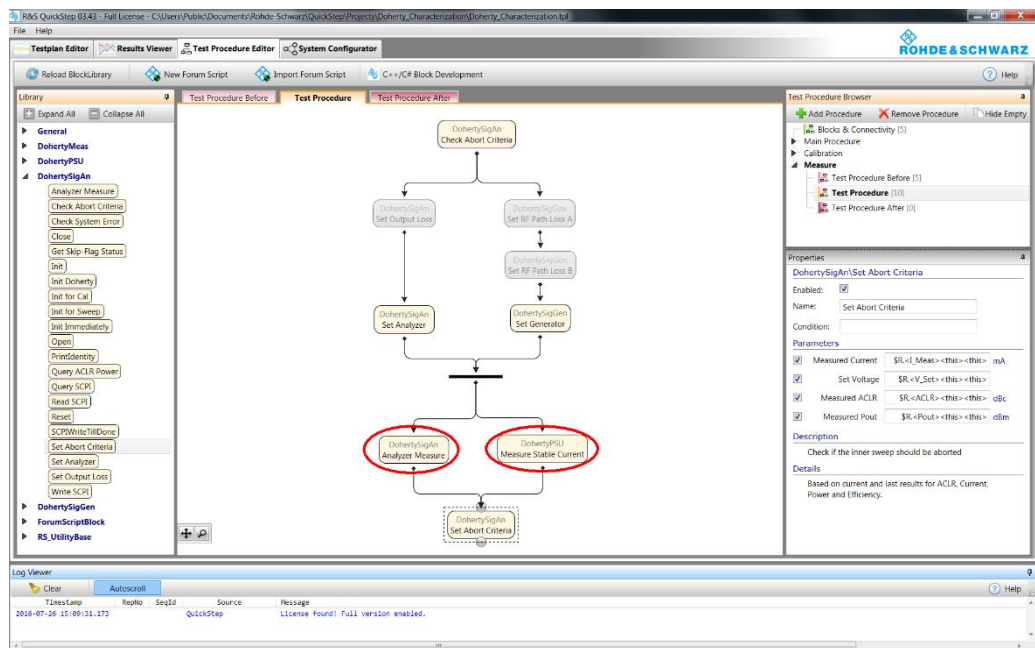


Fig. 4-7: Improved test throughput with parallelism

4.4.3 Using Forum Scripts in QuickStep

For test procedures that are not necessarily time-critical, the developer may also use the "Import Forum Script" feature.

In this case, the script used to calibrate the test cables for phase, amplitude and delay (given in the Appendices) is already included in the QuickStep project.

This is performed in the "Test Procedure Editor", by clicking "Import Forum Script" button and following the simple dialog. See Fig. 4-8.

During the importation process, the developer is given the opportunity to create parameters, to be passed to and from the script.

The underlying Python environment of Forum allows access to a mass of processing toolboxes.

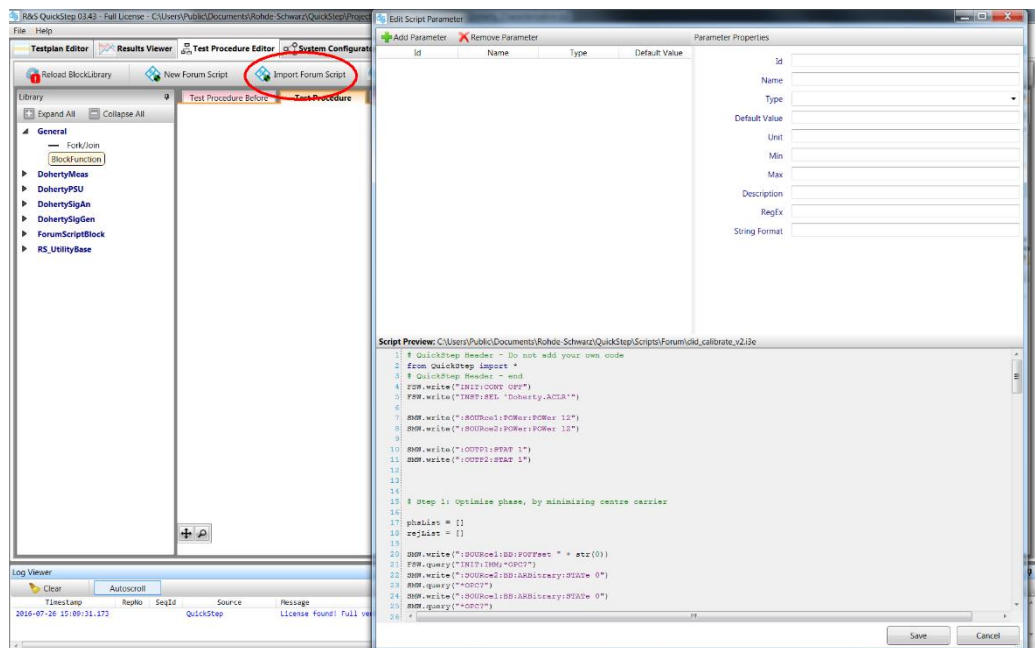


Fig. 4-8: Importing a Forum script to the QuickStep project, showing the final import dialog.

4.4.4 Salient QuickStep Highlights

Other exemplary features of QuickStep include:

- Flexible Testplan- and Parameter- handling
- Result file generation and result viewer
- Execution protocol including SCPI tracing and timing
- DUT Loop control
- Limit tests
- Handling of multiple test systems with parameters and losses
- Structured development environment enhancing refutability of code
- Comprehensive API simplifying recurring programming tasks
- High speed execution of the tens of thousands of characterization measurements presented

5 Post-Processing in MATLAB

The goal of the post-processing exercise is to identify the input conditions that offer desired, optimized, performance.

To that end, data captured in the characterization phase was ported to MATLAB for post-processing.

5.1 Single Input, Baseline, DUT Performance

A baseline measurement of course, is not required to support this methodology. The inclusion of an input network on the NXP DUT however, made it worthwhile establishing that scenario.

Baseline performance therefore was establishing sweeping input signal level and frequency. The measurement data was ported to MATLAB for post-processing.

5.1.1 Efficiency, Linearity & Output Power

With swept input power and frequency (independent variables), measurements were made of efficiency, output power, ACLR (adjacent channel power) and output PAPR (peak to average power ratio).

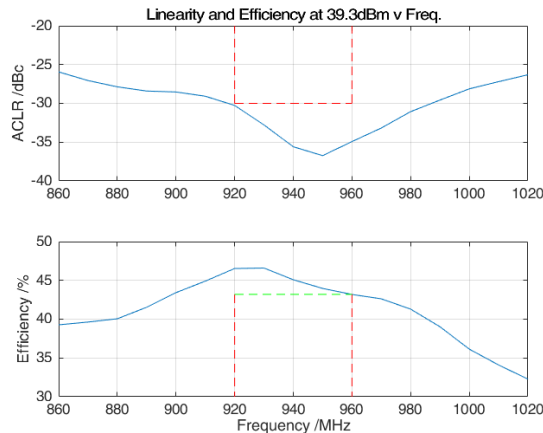


Fig. 5-1: Reference device linearity and efficiency at the rated output power

In the frequency range 920~960 MHz, with an average output power (in channel) of 39.3 dBm, the minimum achieved open-loop linearity was -30 dBc, and efficiency 43.2 %, using the 3GPP Test Model 1 with 64 DPCH signal.

Both output power (in-channel) and ACLR were taken directly from the FSW. The efficiency calculation was derived by reading the power supply's own output current sense value.

5.1.2 Saturated Output Power

Saturated output power, for the purposes of this Application Note, was defined to be the maximum peak envelope power (calculated as the sum of the average output power (in-channel) and CCDF crest factor) observed for each differential amplitude/phase and frequency combination. It does not necessarily occur with a 39.3 dBm average output power.

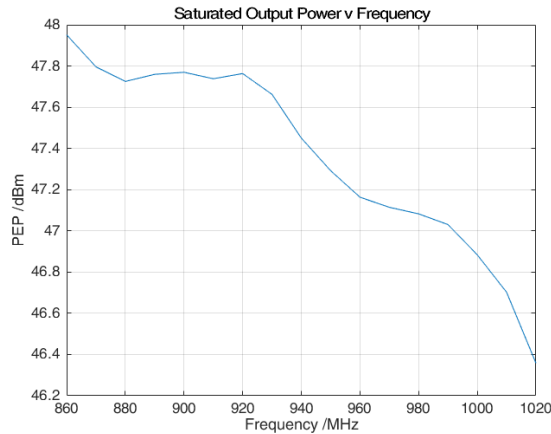


Fig. 5-2: Saturated output power versus Frequency for the single input configured DUT

5.1.3 Baseline Performance Summary

The baseline splitter uses a discrete component, XC0900A-05S. Analysis of its specified s-parameters, provided by the manufacturer, yields an amplitude and phase balance shown in Fig. 5-3. The amplitude and phase balance provided by the splitter, to the inputs of the two amplifiers is a broadly constant -90 degrees and 3.2dB.

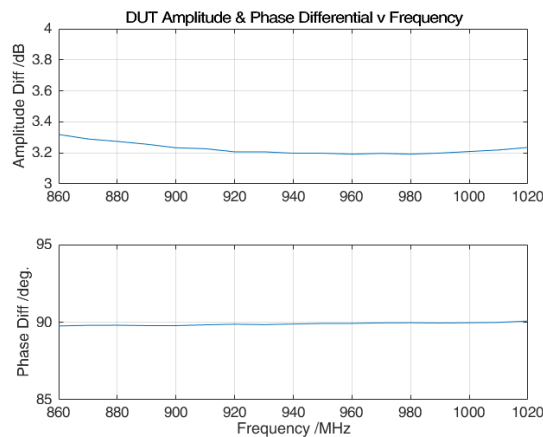


Fig. 5-3: Differential Amplitude and Phase for the DUT discrete 5dB splitter

The baseline performance of the single input configured test fixture is summarized.

Baseline Performance (920~960 MHz)					
Average Output Power	Efficiency	ACLR	Saturated Output Power	Differential Amplitude	Differential Phase
39.3 dBm	43.2 %	-30 dBc	47.15 dBm	~3.2 dB	~-90 deg.

Finally, a quick note on the phase values stated from hereon in. The SMW uses a baseband phase convention that allows values of 0 thru' 360 degrees. The calibration was performed detecting anti-phase condition of the signals. To that end, a reference phasing of 180 degrees was applied to Channel B baseband during calibration.

With the calibrated system, 0 deg. creates signals that are aligned at the end of the cables, 180 deg. refers to the anti-phase condition and most importantly, 270 deg. would correspond to conventional Doherty operation.

5.2 Dual Input DUT Performance Options

The DUT was then reconfigured for dual-input operation and a massive dataset created by the sweeping of:

1. differential input phase (dPhs)
2. differential input amplitude (dAmp)
3. absolute input amplitude of the reference channel (pChA)
4. frequency (rFrq)

Meanwhile, measurements of the following were performed:

5. Efficiency
6. ACLR
7. Output _Power

Each combination of swept and measured values are stored as individual data items.

Now, logical indexing may be used to extract ranges of interest from the dataset. This process is agnostic to whether the data source is independent or measured.

For example, the following query would return the range of differential phases at 960MHz which achieved better than 43 % efficiency and -30 dBc ACLR. The query includes both swept and measured parameters.

```
unique(dPhs(rFrq==960e6 & Efficiency>43 & ACLR<-30))
```

5.2.1 Efficiency, ACLR and Output Power

In this example, the most basic "open-loop" parameters of the amplifier will be optimized.

It should be noted that the NXP DUT input network was not optimized for these quantities. Therein lies one of the motivations for this work. The NXP reference design offers both state-of-the-art performance and significant degrees of flexibility, for the expert.

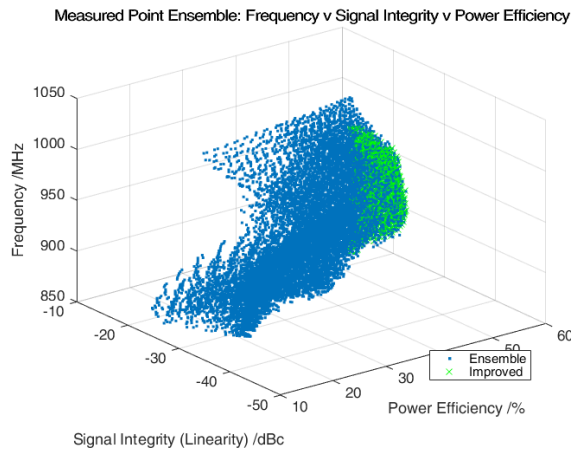


Fig. 5-4: Ensemble of all dual-input measured points (blue), simultaneously improved power, linearity and efficiency highlighted (green), over the range of measurement frequencies.

The ensemble plot of Fig. 5-4 shows the thousands of points in the measurement sweep whose specific combination of differential input amplitude and phase has offered simultaneously higher output power, efficiency and better linearity compared with the baseline.

There are a plurality of operating conditions meeting this condition. Extracting the relevant data at two discrete frequencies, 920 and 960 MHz yields Fig. 5-5.

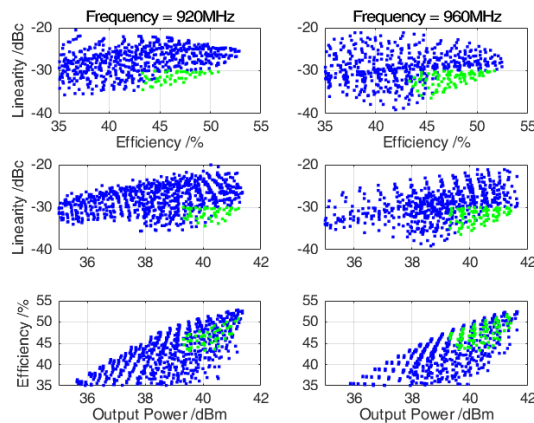


Fig. 5-5: Ensemble of measurement points at 920 MHz and 960 MHz, highlighting those with enhanced performance

Available performance improvements may be extracted thus:

Solution 1: Maximum Efficiency						
Frequency	Output Power	Linearity	Efficiency	Efficiency & Power Improvement	Differential Amplitude ¹	Differential Phase ¹
920	41.2 dBm (baseline + 1,9dB)	-30.0 dBc (baseline)	>50.8 % (baseline + 7,6 %-pts)	7.6 %-pts and 1,9dB	3	260
960					3	250

Note that the phase differential values quoted in the solution¹

Solution 2: Maximum Linearity						
Frequency	Output Power	Linearity	Efficiency	Linearity & Power Improvement	Differential Amplitude	Differential Phase
920	40.1 dBm (baseline + 0,8dB)	-34.4 dBc (baseline - 4,4 dB)	43.3 % (baseline)	4.4 dB and 0,8dB	5	290
960					3	250

A third solution might consider the widest bandwidth over which the baseline performance can be achieved. The following points were extracted from the raw dataset.

Solution 3: Maximum Bandwidth						
Frequency	Output Power	Linearity	Efficiency	Bandwidth Improvement	Differential Amplitude	Differential Phase
900	>39.3 dBm (baseline)	<-30.0 dBc (baseline)	>43.2 % (baseline)	from 40 MHz to 120MHz	4	295
1020					0.5	220

5.2.2 Saturated Power & Efficiency at Back-Off

In this example scenario, two parameters are considered:

- Saturated Output Power (which ultimately places a limit on the maximum linearized output power of an amplifier)
- Modulated Efficiency (at a fixed average power)

In the case where linearization would be applied, regardless of its nature, these two metrics would certainly be of interest.

The measurement plots of Fig. 5-1 and Fig. 5-2 show that both parameters (saturated power and efficiency at back off) are at their least best at 960 MHz.

Fig. 5-6 presents a stack plot of these metrics for the DUT, at selected frequencies (for the sake of clarity), across the range of differential input values. It is of note that the

¹ Baseband phase values in the SMW are mapped from 0 to 360 degrees. A value of -90 degrees written to the SMW, to create normal Doherty operation, will be modified to 270 degrees by the SMW automatically.

"Differential Amplitude" is a transformation of the coupler value. The two outputs of the 5dB coupler used in the reference design, have a differential amplitude of 3.35 dB, e.g. $10 \cdot \log_{10}((1 - \text{power}(10, -5/10)) / (\text{power}(10, -5/10)))$.

saturated output power demonstrates a clear maxima trend at, or around, 270 (i.e. -90) degrees¹.

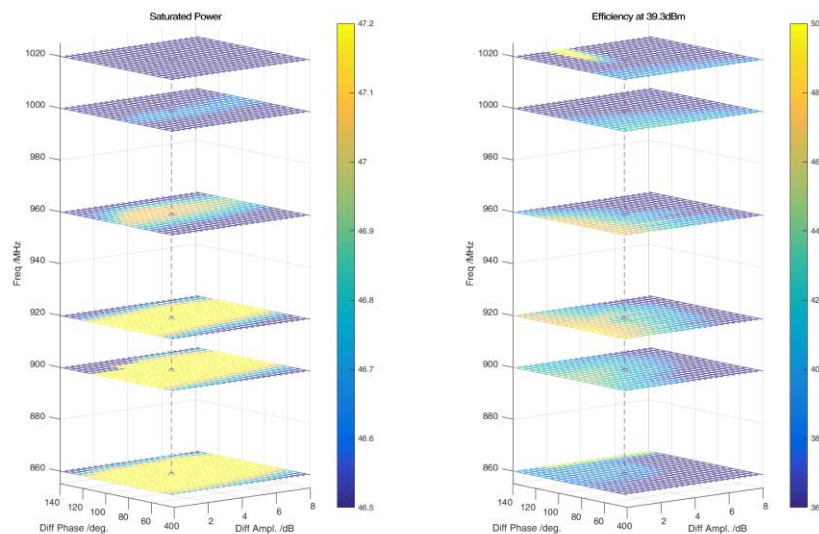


Fig. 5-6: Stacked plot of saturated power and modulated efficiency at back-off versus differential input amplitude and phase.

The dataset was processed according to the following algorithm:

1. Extract measurements at the worst case frequency, 960 MHz (simultaneously lowest efficiency and saturated output power)
2. For each differential amplitude and phase pair, extract a saturated power
3. For each saturated power, calculate the supported average power by subtracting 7.85dB (i.e. the peak-to-average ratio of the reference signal, ensuring potentially complete linearizability)
4. Extract the efficiency at that supported average power.

The scatter plot of Fig. 5-7 shows the result of this processing. Indeed, the point corresponding most closely to the single-input DUT reference design can be seen, offering the highest saturated power ($y = 47.15$ dBm)

Fig. 5-7 also highlights alternative design values that might be of interest. For example, that trading off circa. 0.3 dB of power (both average and saturated) allows an increase in efficiency of 3-4%-pts ($x > 46\%$).

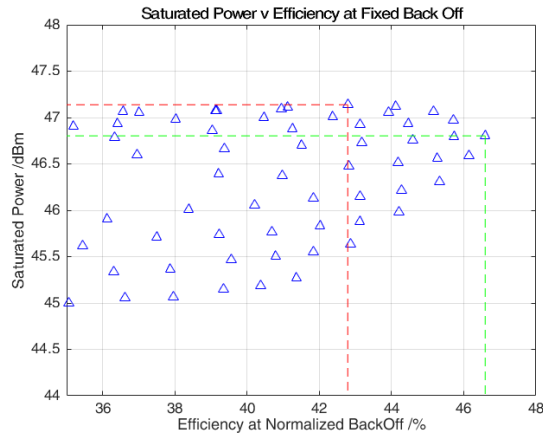


Fig. 5-7: Scatter of saturated power versus efficiency at a fixed 7.85dB back off, for varying differential amplitude and phase, at 960 MHz.

Fig. 5-8 shows a transformation and contour fit of that data in the differential domain.

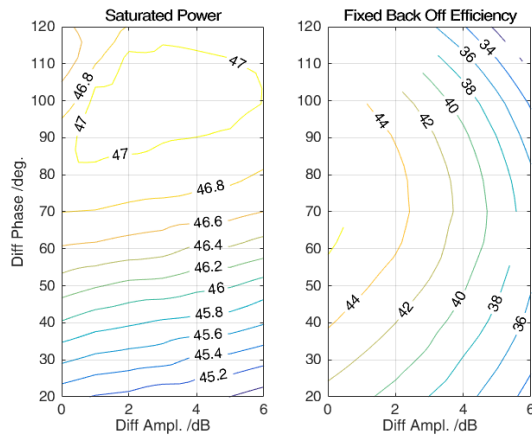


Fig. 5-8: Contours of (i) saturated power and (ii) efficiency at a fixed 7.85dB back off, against differential amplitude and phase, at the worst case frequency, 960 MHz

Solution 4: Maximum Efficiency, Saturated Power Preserved					
Frequency	Saturated Output Power	Efficiency at 7.85dB Back Off	Improvement	Differential Amplitude	Differential Phase
920	>46.8	>46.2	ca. 3 %-pts	Multi-value	Multi-value
960	(baseline - 0,3 dB)	(baseline + 3 %-pts)		0	250

Alternatively, a bandwidth improvement over which 43% efficiency can be achieved whilst supporting a 7.85dB peak to average ratio at the output, with a further 0.2dB output power reduction is shown in Fig. 5-9 and Fig. 5-10.

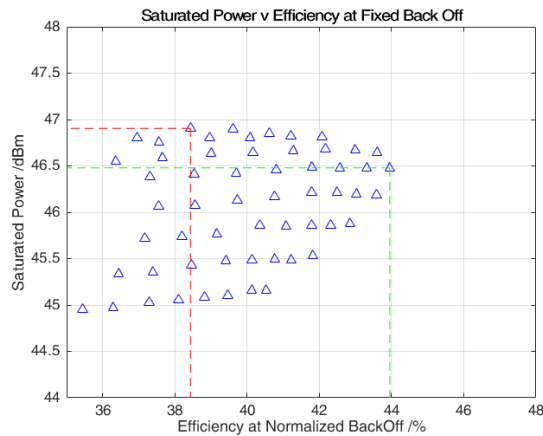


Fig. 5-9: Scatter of saturated power versus efficiency at a fixed 7.85dB back off, for varying differential amplitude and phase, at 990 MHz.

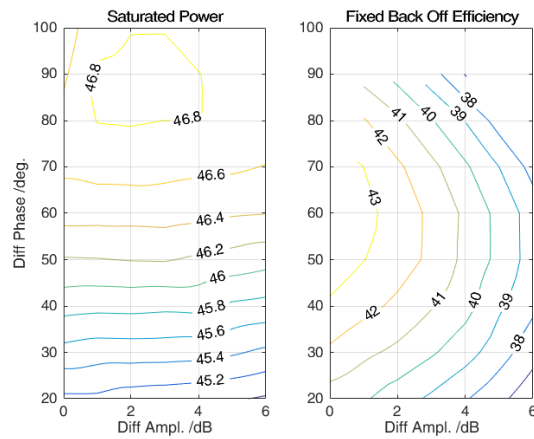


Fig. 5-10: Contours of saturated power and efficiency at a fixed 7.85dB back off, against differential amplitude and phase, at the worst case frequency, 990 MHz.

Solution 5: Maximum Bandwidth, Efficiency Preserved					
Frequency	Saturated Output Power	Efficiency at 7.85dB Back Off	Improvement	Differential Amplitude	Differential Phase
910	46.5 (baseline - 0,6 dB)	>43,2 (baseline)	from 40 MHz to 80MHz	0	220
990				0	240

5.3 Conclusions

It has been shown that performance of the Doherty amplifier is strongly affected by design of the input network; this linear network drives significant changes in efficiency, power and linearity.

Specific deviations from the industry standard quasi-constant -90 (e.g. 270) degree phase differential and quasi-constant amplitude balance can have significant performance advantages, depending on the application's demands.

6 Synthesis in CST Studio Suite

6.1 Introduction

In this example scenario, two different splitter syntheses will be presented using CST Studio Suite:

1. The first, is based on a general filter construction technique. Filter components may be calculated and synthesized as discrete, distributed or a mixture of both, elements. The filters are, in this case, connected using a Wilkinson splitter.
2. A second, distributed, method uses a cascaded Rat-Race hybrid and Schiffman phase shifter.

Which, if either of the proposed implementation prototypes are used, would depend entirely on the user's application.

Examples are presented for Solutions #1 and #5 of Chapter 5.

6.2 Solution #1: Maximum Efficiency using Rat-Race & Schiffman

6.2.1 Background

An example, distributed, implementation for Solution 1 of Chapter 5 will be presented using CST Studio Suite macros.

Solution 1: Maximum Efficiency						
Frequency	Output Power	Linearity	Efficiency	Efficiency & Power Improvement	Differential Amplitude	Differential Phase
920	41.2 dBm	-30.0 dBc	>50.8 %	7.6 %-pts and 1,9dB	3	260
960	(baseline + 1,9dB)	(baseline)	(baseline + 7,6 %-pts)		3	250

Two .zip files should be downloaded from the Application Note homepage:

- 'CST_Macros_R+S.zip'
- 'CST_solution1_models.zip'

6.2.2 Getting Started: Installation

The required prototype macros are provided for download at the Application Note homepage.

The installation process is as follows:

1. De-archive the files from the 'CST_Macros_R+S.zip' file

2. Manually move the following files to the following CST installation sub-directories (e.g. 'C:\Program Files (x86)\CST STUDIO SUITE 2016'):
 - a) .mcs files to '\Library\Macros\Construct\Miscellaneous'
 - b) .lib file to '\Library\Includes'
3. De-archive the files from 'CST_solution1_models.zip' and store the project files in the user's working directories.
4. Restart CST Studio Suite

6.2.3 Getting Started: Running the Macro(s)

Executing the following macro will create the Schiffman phase shifter prototype layout from user defined parameters.

1. Create a new project, using the Planar Coupler & Divider template

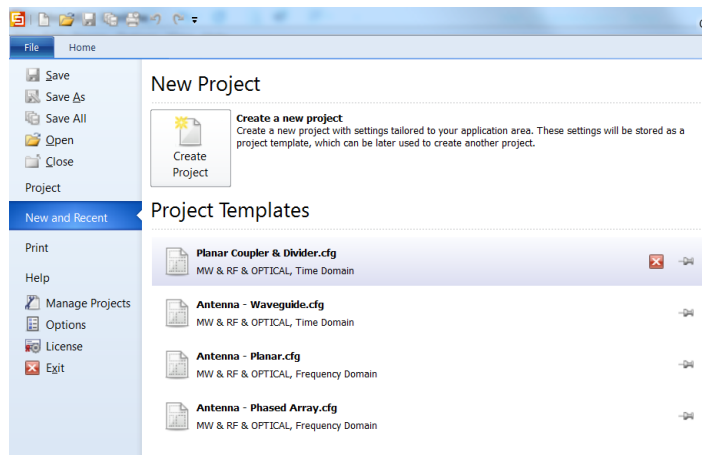


Fig. 6-1: New project dialog in Studio Suite

2. In the 'Home' tab, select 'Macro->Construct->Miscellaneous->rat-race + schiffman'.

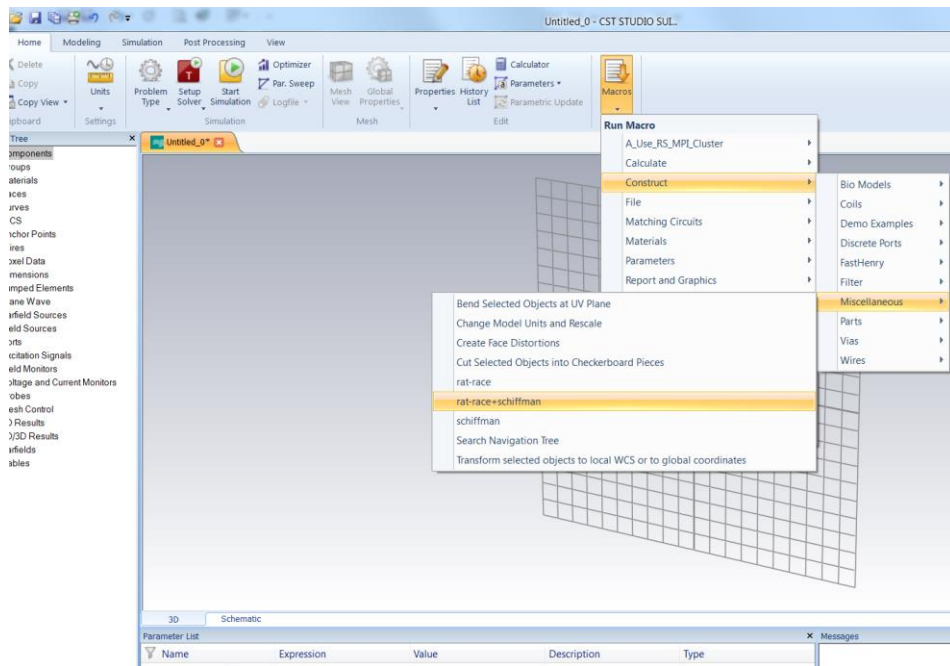


Fig. 6-2: Accessing the three provided macros (Rat-Race, Schiffman and combined Rat-Race + Schiffman) in the newly created project.

3. The following dialog will appear, in which the user can set the appropriate values for their application.

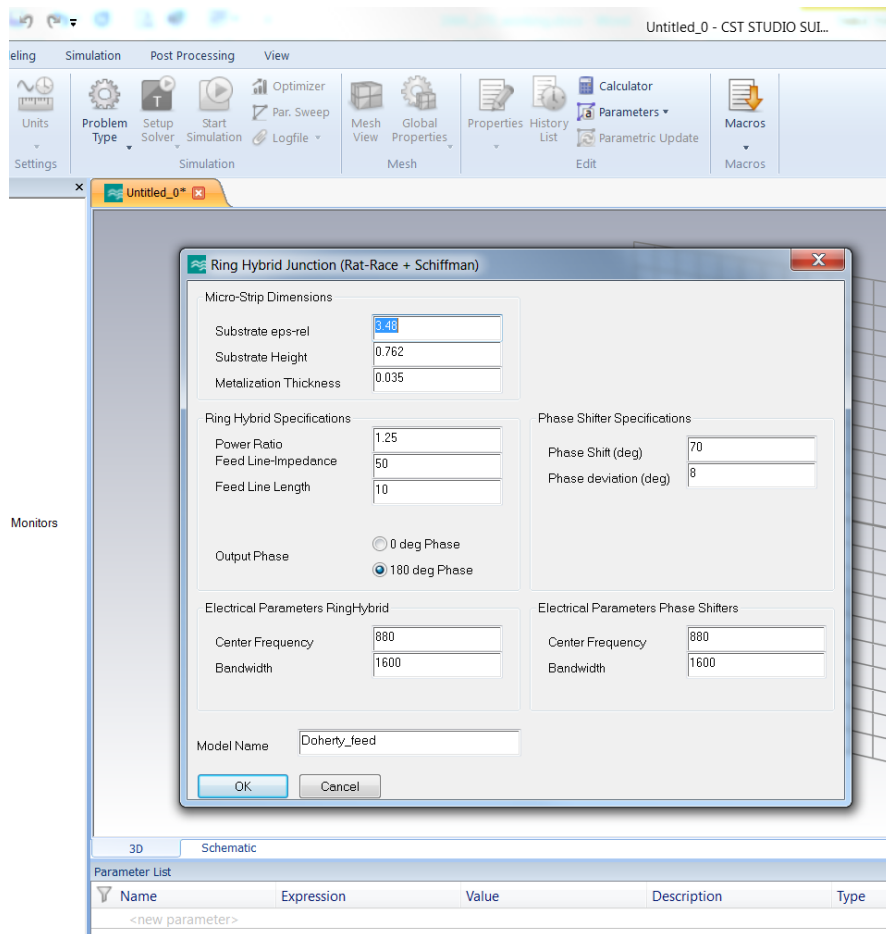


Fig. 6-3: Dialog box for user entry of parameters, created by the macro.

4. With application specific values entered in the dialog, clicking "OK" will create the prototype layout, derived from those values.

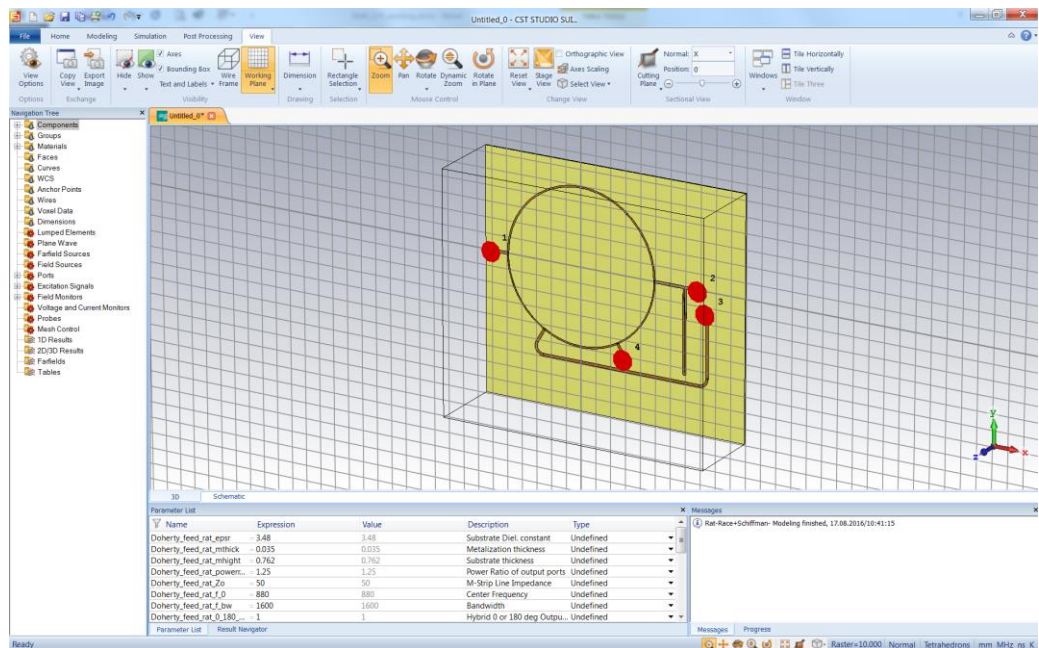


Fig. 6-4: Prototype layout generated by the macro, from the user-specified parameters.

- In the 'Simulation' tab, clicking 'Optimizer' will bring up the parameterized optimization dialog box.

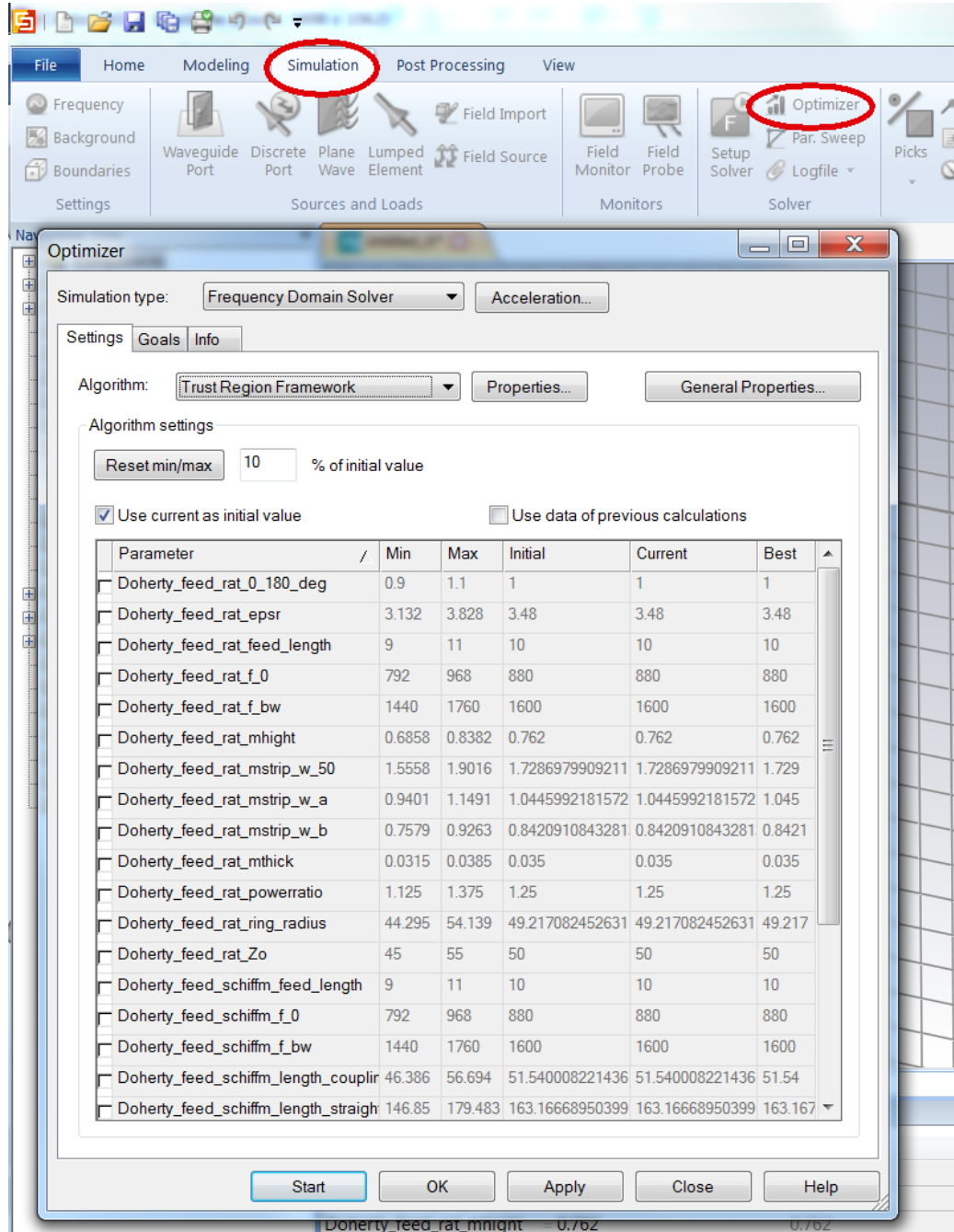


Fig. 6-5: Optimizer dialog, allowing selection of optimizable parameters and setting of goals.

6.2.4 Optimized Solution

A pre-optimized solution is provided, in Studio Suite project file format, 'solution1_schiffman+hybrid_opt_archive.cst'.

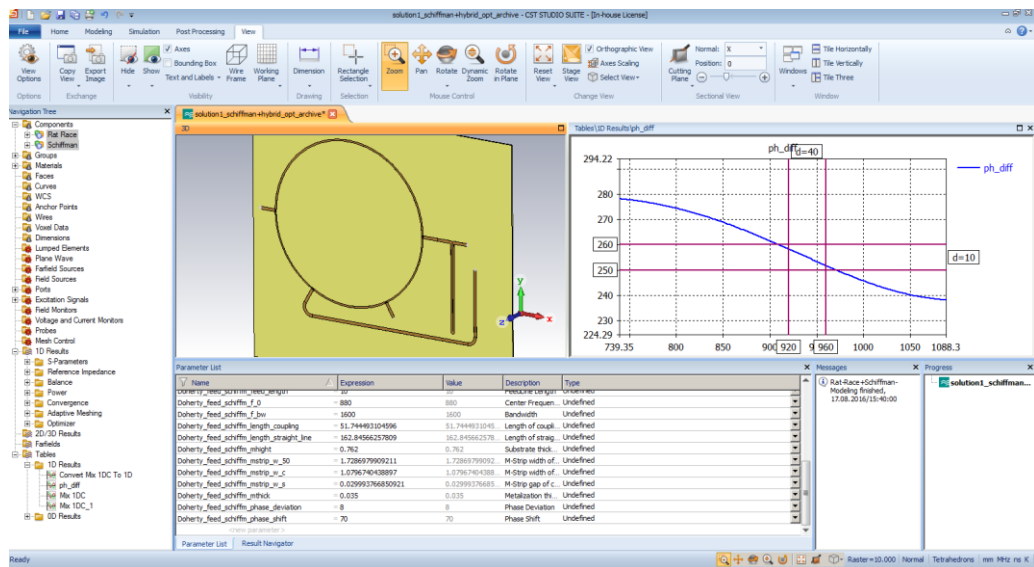


Fig. 6-6: Optimized Rat-Race Schiffman cascade

6.3 Solution #5: Maximum Bandwidth using Wilkinson + Filters

6.3.1 Background

In this section, an example network capable of providing the response extracted for Solution 5 of Chapter 5 is presented.

This Studio Suite solution is available for download from the Application Note homepage as, 'CST_solution5_wilkinson.zip'.

In this case, a sacrifice of 0,6 dB output power is made in order to achieve a doubling of bandwidth, whilst preserving operating efficiency.

Solution 5: Maximum Bandwidth, Efficiency Preserved					
Frequency	Saturated Output Power	Efficiency at 7.85dB Back Off	Improvement	Differential Amplitude	Differential Phase
910	46.5 (baseline - 0,6 dB)	>43,2 (baseline)	from 40 MHz to 80MHz	0	220
990				0	240

The desired amplitude and phase balance will be demonstrated using a cascade of a Wilkinson splitter and prototype Low Pass and High Pass filters.

In the first step, the differential phase is achieved using prototype Low Pass/High Pass filters in a diplexer configuration, supplemented by inverters.

In the second step, the inverter characteristics and the isolated split function will be absorbed by a Wilkinson splitter.

6.3.2 Wilkinson + Low-Pass High-Pass

This solution architecture comprises a three port diplexer network, containing a Low Pass and High Pass filter.

1. Synthesize prototype low pass and high pass networks, to get starting values, using the "Filter Designer 2D" tool:

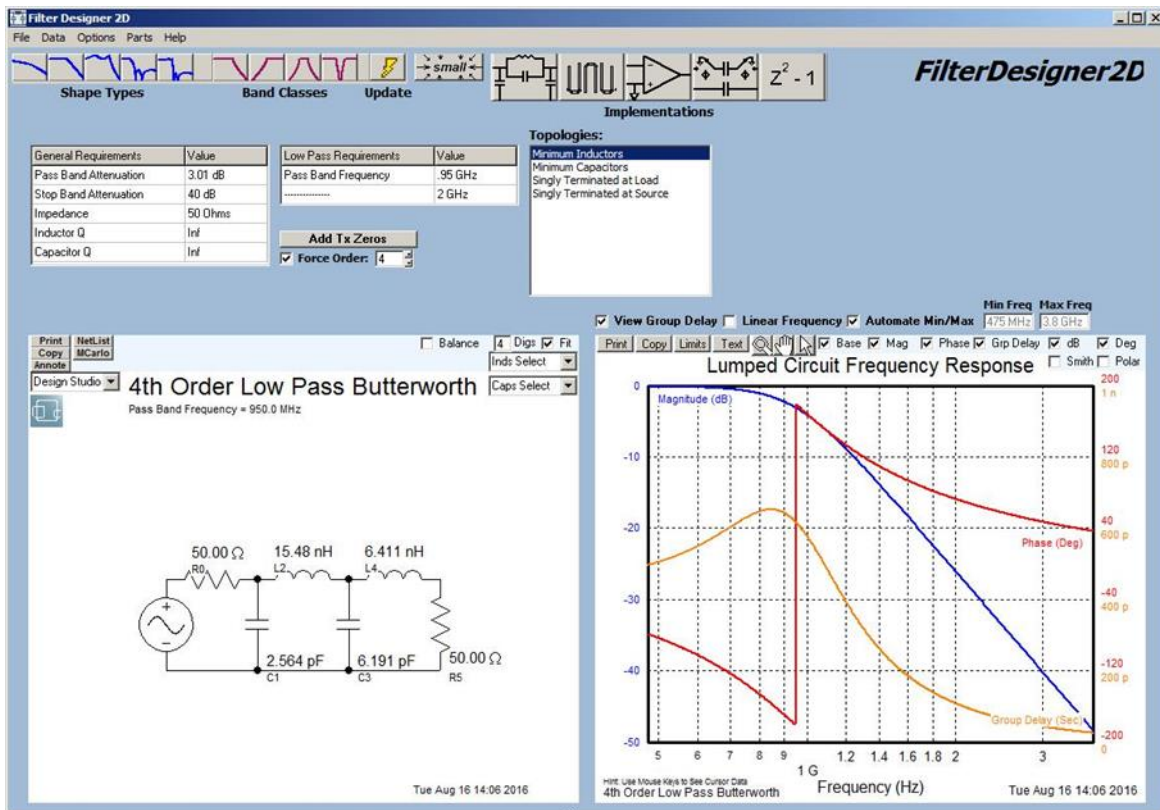


Fig. 6-7: Filter Designer 2D dialog, prototyping the Low Pass structure

In this case, the order of the filters are forced to fourth order, and the pass-band frequency is set to 0,95 GHz.

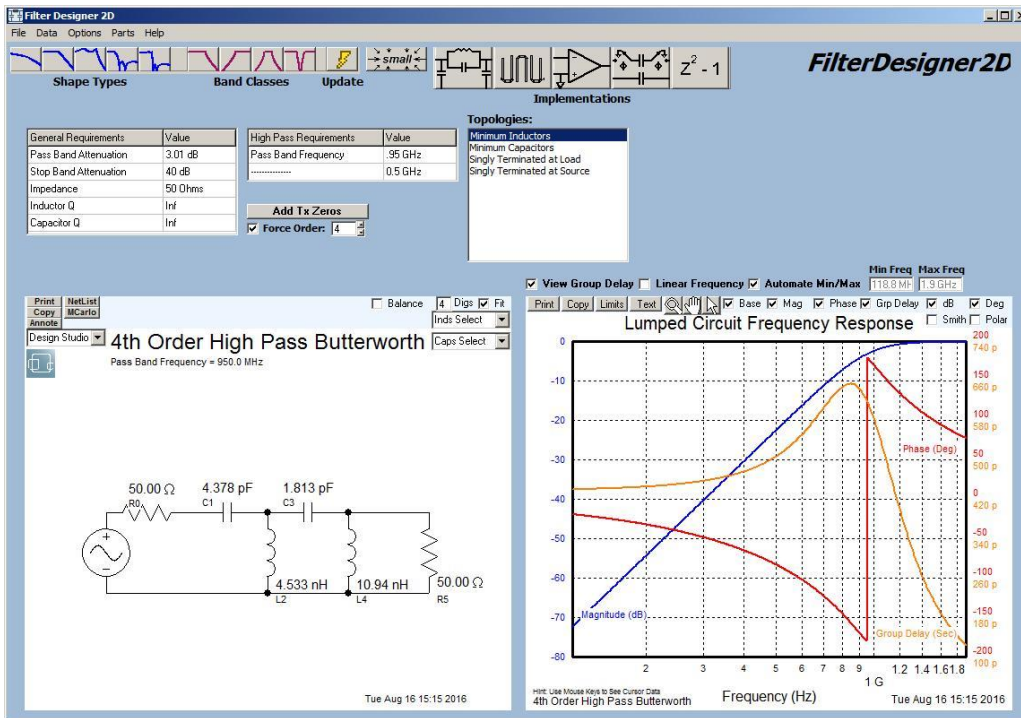


Fig. 6-8: Filter Designer 2D dialog, prototyping the High Pass structure

- Goals are set-up in the Optimizer, to set targets for differential amplitude and differential phase.

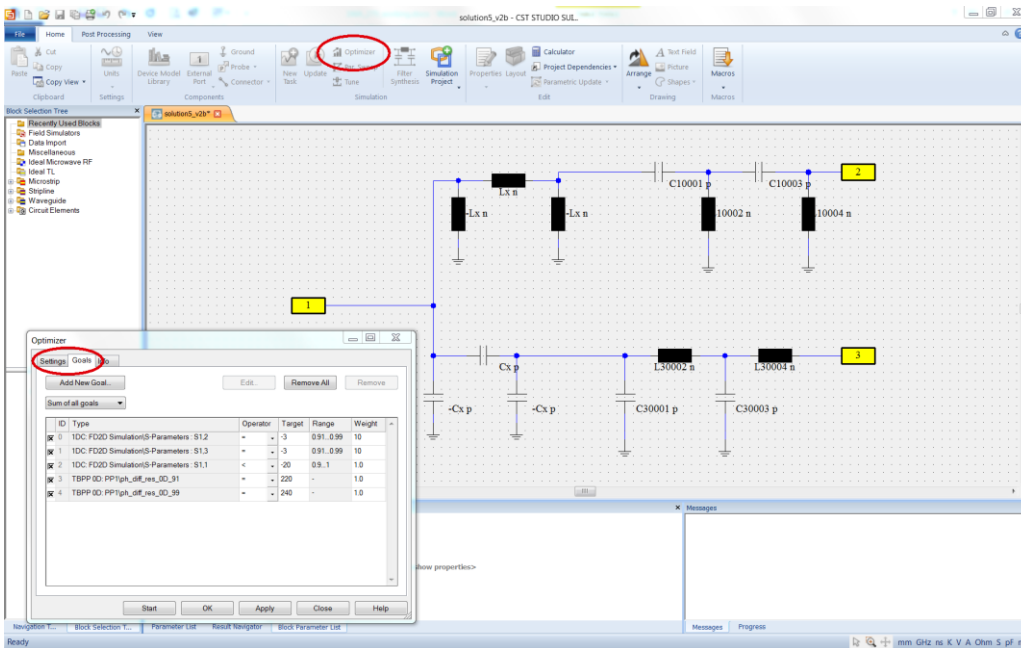


Fig. 6-9: Optimization of the prototype diplexer network

- With optimization complete and network values updated, the transfer characteristics of the 3-port may be plotted.

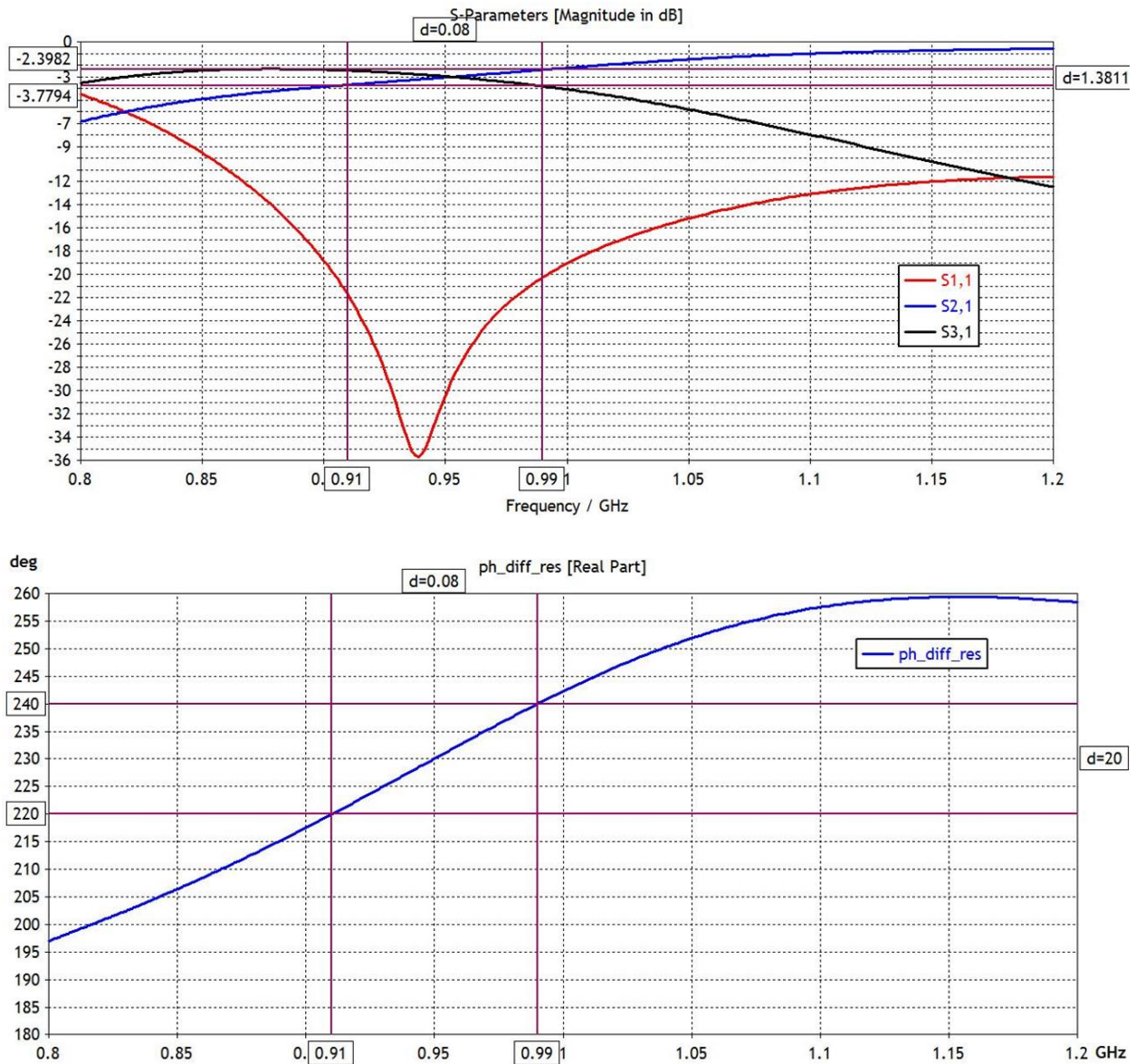


Fig. 6-10: Characteristics of the synthesized splitter

- The functionality of the inverter networks may then be absorbed into a Wilkinson splitter, and the whole ensemble further optimized.

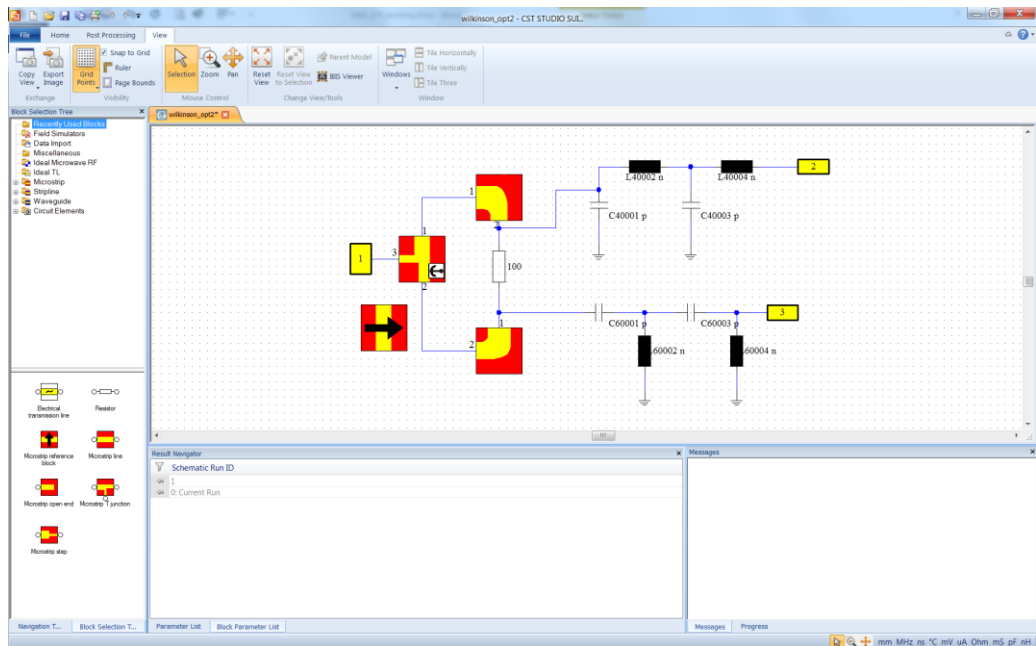


Fig. 6-11: Wilkinson splitter implementation, absorbing the inverter structures

5. Re-optimization of this network gives the result shown in Fig. 6-12.

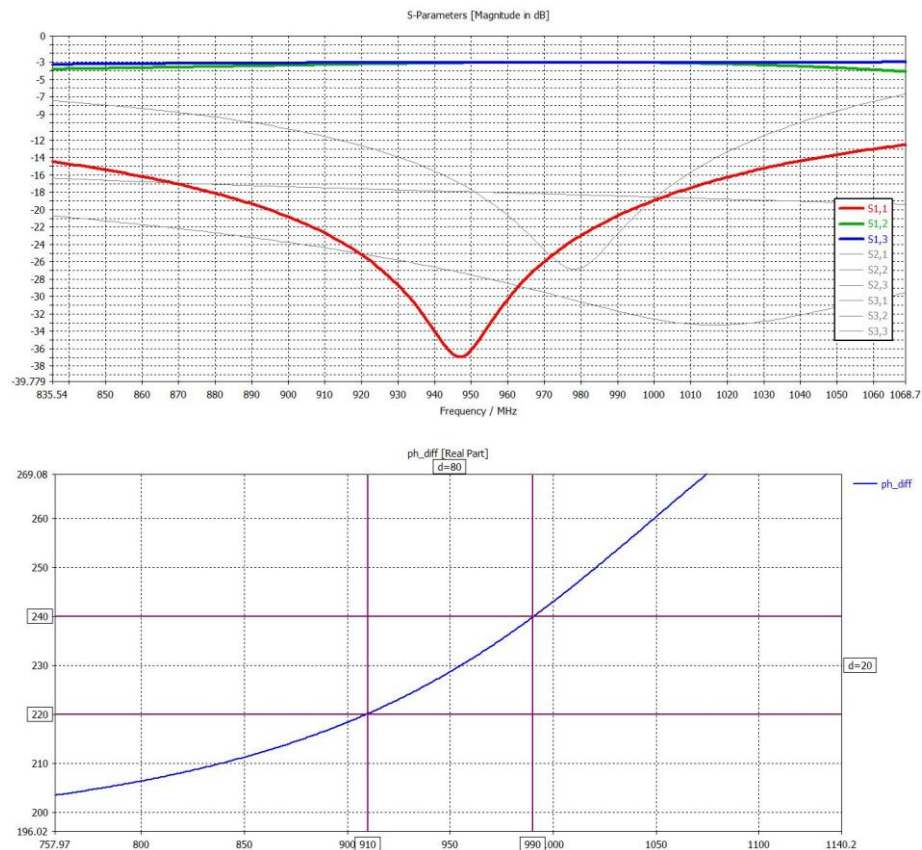


Fig. 6-12: Differential Amplitude and Phase for the Wilkinson-Filter cascade, demonstrating the requisite performance for Solution #5.

7 Other Measurement Examples

Measurements on other devices are presented in this Chapter, to illustrate the effectiveness of the technique applied to other technologies, frequency bands, etc. To avoid apples-with-pears comparisons, absolute measurement values are omitted.

7.1 GaN Doherty - Vendor "B"

7.1.1 Background

A Gallium Nitride Doherty amplifier, from a leading supplier of such technologies was measured.

The DUT was designed to illustrate performance in base-station applications for 5G New Radio front ends.

Headline specifications are tabulated in [Table 7-1](#).

Parameter	Value			Units
	Min	Typ	Max	
Frequency	3.4		3.6	GHz
Bias Point (Carrier)		100		mA
Bias Point (Peak)		-4.4		V
Saturated Output Power	43.8			dBm
Drain Efficiency (35.5 dBm, PAPR _i > 10dB)	44.3			%
ACLR (35.5dBm, 5MHz BW, PAPR _i > 10dB)	-24.0			dBc

Table 7-1: Headline specifications and measurements for the supplied GaN Doherty DUT.

7.1.2 Measurement Findings

A sweep of amplitude and phase balance, frequency and drive power was performed. Measurement captures include average output power, efficiency, linearity and PAPRo.

Summary contours of Saturated Output Power, Efficiency and Linearity, at the low- and high- frequencies are presented in [Fig. 7-1](#), albeit with 2dB higher average power than the specified case.

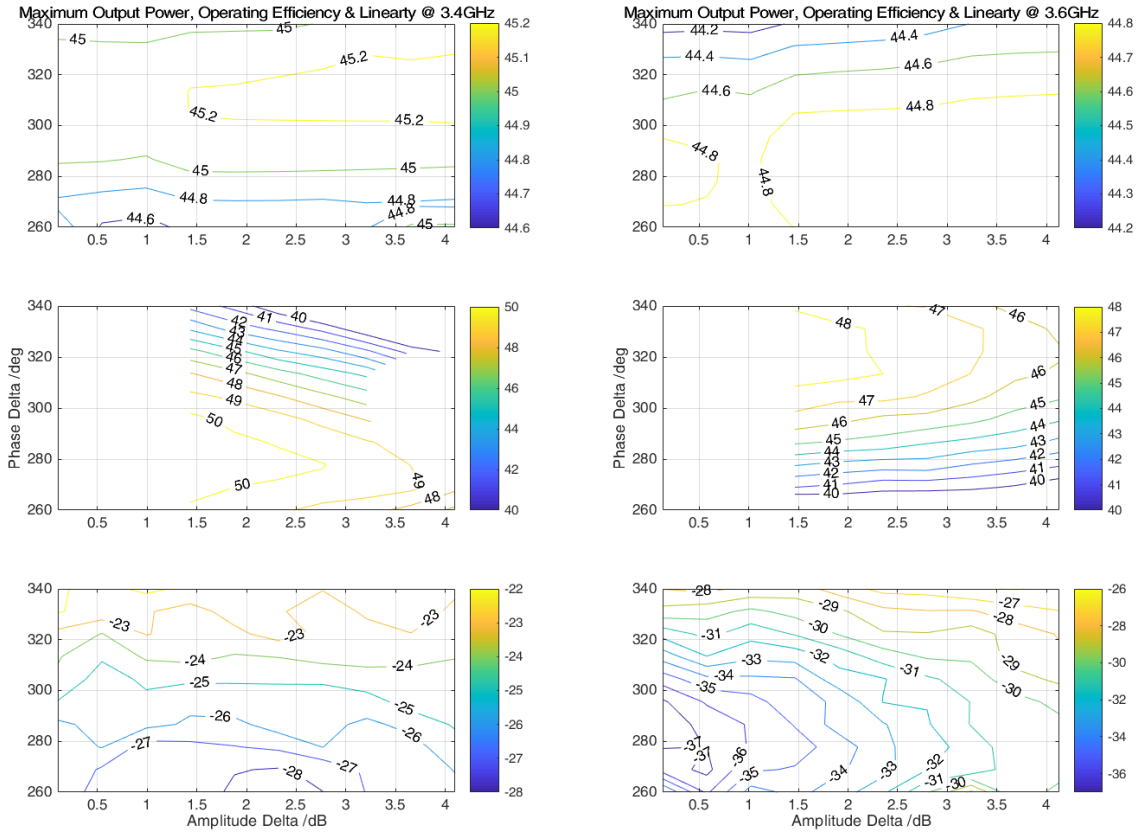


Fig. 7-1: Contour of performance showing Saturated Power, along with Drain Efficiency and ACLR (the latter with an average power of 37.5dBm)

Despite the difference in average power reporting for Efficiency and Linearity, it is clear that optimum operating points (i.e. constant x, y values for all 6 graphs) for the two measured frequencies do not coincide.

In this case, for example, in order to support highest efficiency and lowest power consumption, a phase value of 280 degrees (-80 degrees) might be chosen for the lowest frequency and 320 degrees (-40 degree) for the highest frequency.

Compare this with the constant amplitude/phase balance approach, and a potentially more important design choice manifests itself.

The efficiency exhibits strong roll-off at low frequency, as the phase delta increases beyond 300 degrees. Simultaneously, roll-off occurs at values below 300 degrees at high frequency.

In a high volume production environment, perturbation of these curves due to natural variations could significantly degrade specified performance.

8 References

- [1] Cripps, Steve C. 2006. *RF Power Amplifiers for Wireless Communications*. Norwood, MA: Artech House.
- [2] Doherty, William H. 1936. Amplifier. United States of America Patent 2,210,028. April 1.
- [3] Gustafsson, David. 2014. *Extending the Bandwidth of the Doherty Power Amplifier*. Gothenburg: Chalmers University of Technology.
- [4] NXP. 1993. "http://www.nxp.com/files/rf_if/doc/app_note/AN1034.pdf." Vers. 0. *www.nxp.com*. 7. Accessed 08 05, 2016. http://www.nxp.com/files/rf_if/doc/app_note/AN1034.pdf.
- [5] Ramos Quirarte, J. L., and J. P. Starski. 1991. "Synthesis of Schiffman phase shifters." (*IEEE Transactions on Microwave Theory and Techniques*) 39 (11): 1885-1889.
- [6] Schiffman, B. M. 1958. "A New Class of Broad-Band Microwave 90-Degree Phase Shifters." (*IRE Transactions on Microwave Theory and Techniques*) 6 (2): 232-237.

9 Ordering Information

Designation	Type	Order No.
Vector Signal Generator	R&S [®] SMW200A	1412.0000.02
	Option B106 (6GHz Path A)	1413.0104.02
	Option B206 (6GHz Path B)	1413.0904.02
	Option B10 x 2 (Baseband Generator)	1413.1200.02
	Option K522 x 2 (160MHz RF Bandwidth Extension)	1413.6960.02
	Option K242 x 2 (3GPP waveform)	1413.4839.02
Signal & Spectrum Analyzer	R&S [®] FSW26	1312.8000.26
Test Executive Software	R&S [®] QuickStep (License dongle)	1528.9003.02
Power Supply	R&S [®] HMC8043	3593.1041.02

Appendices

A Instrument Set-up Using SCPI

A.1 SMW

The SMW signal generator is prepared for operation using the following SCPI sequence.

```
*RST
*CLS
*OPC?

#Baseband configuration (Triggering, Waveform)
:SOURce2:BB:ARBitrary:TRIGger:SOURce INTA
:SOURce2:BB:ARBitrary:TRIGger:SEQuence AAUT
:SOURce2:BB:ARBitrary:WAVEform:SElect
'/var/user/File_3C_80MHz.iq'
:SOURce2:BB:ARBitrary:STATe 1
*OPC?

:SOURce1:BB:ARBitrary:WAVEform:SElect
'/var/user/File_3C_80MHz.iq'
:SOURce1:BB:ARBitrary:STATe 1
*OPC?

#Delay configuration
:SOURce1:BB:IMPairment:RF1:DELay 0
:SOURce1:BB:IMPairment:RF2:DELay 0
:SOURce1:BB:IMPairment:RF1:STATe ON
:SOURce1:BB:IMPairment:RF2:STATe ON

#RF configuration
:SOURce1:FREQuency:LOSCillator:MODE COUP
:SOURce1:FREQuency:CW 940000000
:SOURce1:POWer:LEVel:IMMediate:AMPLitude 12
:SOURce2:POWer:LEVel:IMMediate:AMPLitude 12
:SOURce1:POW:ALC:STATe OFF
:SOURce2:POW:ALC:STATe OFF
:SOURce1:POWer:ATTenuation:DIGital 0
:SOURce2:POWer:ATTenuation:DIGital 0
:OUTP1:STAT 1
:OUTP2:STAT 1
*OPC?

#Check for errors
SYSTem:ERRor?
```

A.2 FSW

The FSW signal analyzer is prepared for operation using the following SCPI sequence

```
*RST
*CLS
*OPC?

INST:CRE SAN, 'Doherty.ACLR'
INIT:CONT OFF
FREQ:CENT 940MHz
INP:ATT 40dB
CALC:MARK:FUNC:POW:SEL ACP
CALC:MARK:FUNC:POW:PRES FW3G
DISP:TRAC:Y:RLEV:OFFS 21.4DB

Power:ACHannel:SPACing:ALternate 80MHz
Power:ACHannel:TXChannel:COUNT 1
FREQ:SPAN 180MHz
POW:ACH:MODE ABS

INST:CRE SAN, 'Doherty.CCDF'
INIT:CONT OFF
FREQ:CENT 940MHz
CALC:STAT:CCDF ON
BWID:RES 15MHZ
CALC:STAT:NSAM 1e6
DISP:TRAC:Y:RLEV:OFFS 21.4DB

SYST:ERR?
```

A.3 HMC

The HMC power supply is prepared for operation using the following SCPI sequence

```
*RST
*CLS
*IDN?

INST:SEL OUTP1
VOLT 28
CURR 1.1

OUTP:STAT ON
MEAS:CURR?
SYST:ERR?
```

B Forum Script Examples

B.1 Calibration

The Forum program and further information may be downloaded from the R&S website, free of charge at <http://www.rohde-schwarz.com/appnote/1ma196>.

The following script may be used to calibrate the relative phase, relative delay and relative amplitude to the end of the test cables.

This calibration script should only be executed after the SCPI initialization sequences for the SMW and FSW given in "Instrument Set-up Using SCPI".

A description of the algorithm is given in Chapter 3.2.

The script contains references to instruments FSW and SMW. Resources (e.g. IP addresses) for these instruments need to be set-up in Forum.

The calibration/optimization values are found using a simple best value-successive approximation algorithm.

```
FSW.write("INIT:CONT OFF")
FSW.write("INST:SEL 'Doherty.ACLR'")

SMW.write(":SOURce1:POWer:POWer 12")
SMW.write(":SOURce2:POWer:POWer 12")
SMW.write(":SOURce2:BB:POFFset 180") #set the calibration
target = anti-phase

SMW.write(":OUTP1:STAT 1")
SMW.write(":OUTP2:STAT 1")

# Step 1: Optimize phase, by minimizing centre carrier

phsList = []
rejList = []

SMW.write(":SOURce1:BB:POFFset " + str(0))
FSW.query("INIT:IMM;*OPC?")
SMW.write(":SOURce2:BB:ARBitrary:STATe 0")
SMW.query("*OPC?")
SMW.write(":SOURce1:BB:ARBitrary:STATe 0")
SMW.query("*OPC?")
SMW.write(":SOURce2:BB:ARBitrary:STATe 1")
SMW.query("*OPC?")
SMW.write(":SOURce1:BB:ARBitrary:STATe 1")
SMW.query("*OPC?")

xmin = float(0)
xmax = float(360)

xminTmp = xmin
xmaxTmp = xmax
```



```
for loop1 in range (1, 4):
    swpRange = float(xmaxTmp)-float(xminTmp)
    curStep = float(swpRange)/10

    for loop2 in range (0,11):
        dphs = xminTmp + float(loop2) * float(curStep)
        SMW.write(":SOURcel:BB:POFFset " + str(dphs))
        FSW.query("INIT:IMM;*OPC?")
        cp =
FSW.query("CALCulate:MARKer:FUNCTION:POWER:RESult? ACPower")
        x = cp.split(',')
        curval = float(x[0])
        phsList.append( float(dphs) );
        rejList.append( curval );

        xminTmp = max(xmin,
float(phsList[rejList.index(min(rejList))]) - curStep)
        xmaxTmp = min(xmax,
float(phsList[rejList.index(min(rejList))]) + curStep)

SMW.write(":SOURcel:BB:POFFset " +
str(float((phsList[rejList.index(min(rejList))]))))

# Step 2: Optimize delay, by minimizing ALT channels

delList = []
rejList = []

xmin = float(-10e-9)
xmax = float(10e-9)

xminTmp = xmin
xmaxTmp = xmax

for loop1 in range (1, 5):
    swpRange = float(xmaxTmp)-float(xminTmp)
    curStep = float(swpRange)/10

    for loop2 in range (0,11):
        delay = xminTmp + float(loop2) * float(curStep)

        if delay > 0:
            chanNo = 1
            SMW.write(":SOURcel:BB:IMPairment:RF2:DElay 0e-
12")
        else:
            chanNo = 2
            SMW.write(":SOURcel:BB:IMPairment:RF1:DElay 0e-
12")

        SMW.write(":SOURcel:BB:IMPairment:RF" + str(chanNo) +
":DElay " + str(abs(delay)))
        FSW.query("INIT:IMM;*OPC?")
```

```
        cp =
FSW.query("CALCulate:MARKer:FUNCTION:POWer:RESult? ACPower")
        x = cp.split(',')
        txref = float(x[0]);
        curval = max(txref + float(x[3]), txref + float(x[4]))

        delList.append( delay );
        rejList.append( curval );

        xminTmp = max(xmin,
float(delList[rejList.index(min(rejList))]) - curStep)
        xmaxTmp = min(xmax,
float(delList[rejList.index(min(rejList))]) + curStep)

delOffset = (delList[rejList.index(min(rejList))])
if delOffset > 0:
    chanNo = 1
else:
    chanNo = 2

SMW.write(":SOURce1:BB:IMPairment:RF" + str(chanNo) + ":DELay
" + str(abs(delOffset)))

# Step 3: Optimize power/amplitude, by minimizing ALT

curPow =
float(SMW.query(":SOURce1:POWer:ATTenuation:DIGital?"))
FSW.write("POW:ACH:MODE ABS")

powList = []
rejList = []

xmin = curPow - 2.0 # attenuation is +ve, gain is -ve!
xmax = curPow + 2.0

xminTmp = xmin
xmaxTmp = xmax

for loop1 in range (1, 3):
    swpRange = float(xmaxTmp)-float(xminTmp)
    curStep = float(swpRange)/10

    for loop2 in range (0,11):
        powB = xminTmp + float(loop2) * float(curStep)

        SMW.write(":SOURce2:POWer:ATTenuation:DIGital "+
str(powB))
        FSW.query("INIT:IMM;*OPC?")
        cp =
FSW.query("CALCulate:MARKer:FUNCTION:POWer:RESult? ACPower")
        x = cp.split(',')
        curval = max(float(x[0]), float(x[3]), float(x[4]))
        powList.append( powB );
        rejList.append( curval );
```

```
xminTmp = max(xmin,
float(powList[rejList.index(min(rejList))]) - curStep)
xmaxTmp = min(xmax,
float(powList[rejList.index(min(rejList))]) + curStep)

SMW.write(":SOURce2:POWer:ATTenuation:DIGital " +
str(powList[rejList.index(min(rejList))]))

# Report rejection ratios

SMW.write(":SOURce2:BB:POFFset 180") # set anti-phase and
measure
FSW.query("INIT:IMM;*OPC?")
cpNull = FSW.query("CALCulate:MARKer:FUNCTion:POWer:RESult?
ACPower")
xNull = cpNull.split(',')

SMW.write(":SOURce2:BB:POFFset 0") # set in-phase and measure
FSW.query("INIT:IMM;*OPC?")
cpMax = FSW.query("CALCulate:MARKer:FUNCTion:POWer:RESult?
ACPower")
xMax = cpMax.split(',')

pchA = float(SMW.query(":SOURce1:POWer:ATTenuation:DIGital?"))
pchB = float(SMW.query(":SOURce2:POWer:ATTenuation:DIGital?"))
pDelta = float(pchA - pchB)

SMW.write(":SOURce1:POWer:ATTenuation:DIGital 30")
SMW.write(":SOURce2:POWer:ATTenuation:DIGital " + str(30.0-
pDelta))

valRejection = -min(float(xMax[0])-float(xNull[0]),
float(xMax[3])-float(xNull[3]), float(xMax[4])-
float(xNull[4]))

print ("Achieved Rejection: " + str(valRejection) + "dBc")
print ("Phase Offset: " +
str(SMW.query(":SOURce1:BB:POFFset?")) + "deg.")
print ("Delay on Ch." + str(chanNo) + ": " +
str(1e9*float(SMW.query(":SOURce1:BB:IMPairment:RF" +
str(chanNo) + ":DELay?")))+ "ns")
print ("Power Offset (Ch.B. higher power is +ve): " +
str(pDelta) + "dB")

SMW.write(":OUTP1:STAT 0")
SMW.write(":OUTP2:STAT 0")

# check they're happy...
FSW.query("SYST:ERR?")
SMW.query("SYST:ERR?")
```

B.2 Amplifier Characterization

An example Forum script to characterize the amplifier for Doherty operation is given in this section.

It assumes that "Calibration" has already been performed taken place and values written to the SMW. The HMC should also be initialized using the SCPI initialization given in "HMC".

Sweep ranges for variables for Channel A and Channel B power (hence Differential Amplitude), Differential Phase, Frequency are set-up in the opening lines.

Current consumption measurement is performed using the HMC indicated current. The HMC does not respond to instruction to measure. Rather, it reports the current output in an asynchronous sample-and-hold fashion. Therefore, the script polls the power supply looking for both a finite change in value but also a change of less than (e.g.) 1 mA, to minimize effects of the DUT decoupling network.

Independent sweep values and associated measurement results are then appended to a list. On completion of the complete sweep, the aggregated values are written to a .csv file. This may easily be imported into MATLAB.

After each measurement, the observations may be passed through a check. That check may be used to avoid unfavorable operating conditions. Alternatively, even just to check if "performance is not good and getting worse". In the event of a break condition being detected, the loop can break, saving time and potentially even the DUT integrity.

```
#
# set some sweep variables

maxPower = 9                # overall maximum power from
either channel
pCHAsweep = range(18, 7, -1) # attenuation values, relative
to maxPower
diffAmp = range(-3, 7)      # rel. to pCHAsweep, i.e. 3 =
3dB higher
diffPhs = range(225, 335, 10) # 270 = Doherty, 180 = anti-
phase
frqSweep = range(860, 1021, 10) # test frequencies

#
# modify the instrument set-up from calibration
# also initialize "lists"

PSU.write("OUTP:STAT ON")

SMW.write(":SOURce1:POWer:ATTenuation:DIGital 30")
SMW.write(":SOURce2:POWer:ATTenuation:DIGital 30")
SMW.write(":SOURce1:POWer:POWer " + str(maxPower))
```

```
SMW.write(":SOURce2:POWer:POWer " + str(maxPower))

SMW.write(":OUTP1:STAT 1")
SMW.write(":OUTP2:STAT 1")

FSW.write("INST:SEL 'Doherty.ACLR'")
FSW.write("POWer:ACHannel:SPACing:ALternate 10MHz")
FSW.write("POWer:ACHannel:TXChannel:COUNT 1")
FSW.write("FREQ:SPAN 25MHz")
FSW.write("POW:ACH:MODE REL")

FSW.write("INST:SEL 'Doherty.CCDF'")
FSW.write("INIT:CONT OFF")
FSW.write("CALC:STAT:CCDF ON")
FSW.write("BWID:RES AUT")
FSW.write("CALC:STAT:NSAM 1e6")

bigList = []
zzz = 0
tstart = time.time()

#
# perform the nested loop sweep

for frq in frqSweep:
    FSW.write("INST:SEL 'Doherty.ACLR'")
    FSW.write("FREQ:CENT " + str(frq) + "MHz")
    FSW.query("*OPC?")

    FSW.write("INST:SEL 'Doherty.CCDF'")
    FSW.write("FREQ:CENT " + str(frq) + "MHz")
    FSW.query("*OPC?")

# create the library filename here
filetoload = str("File" + str(frq) + ".iq")

    SMW.write(":SOURce1:BB:ARBitrary:WAVeform:SElect
'/var/user/" + str(filetoload))
    SMW.write(":SOURce2:BB:ARBitrary:WAVeform:SElect
'/var/user/" + str(filetoload))
    SMW.query("*OPC?")

    SMW.write(":SOURce2:BB:ARBitrary:TRIGger:SEQuence AAUT")
    SMW.write(":SOURce2:BB:ARBitrary:TRIGger:SOURce INTA")

# make sure everything is re-triggered
SMW.write(":SOURce2:BB:ARBitrary:STATE 0")
SMW.query("*OPC?")
SMW.write(":SOURce1:BB:ARBitrary:STATE 0")
SMW.query("*OPC?")
SMW.write(":SOURce2:BB:ARBitrary:STATE 1")
SMW.query("*OPC?")
SMW.write(":SOURce1:BB:ARBitrary:STATE 1")
SMW.query("*OPC?")
```

```
for pCH_A in pCHAsweep:
    pCHA = float(pCH_A)
    SMW.write(":SOURcel:POWer:ATTenuation:DIGital " +
str(pCHA))

    for dpCH_B in diffAmp:
        pCHB = pCHA - float(dpCH_B)
        SMW.write(":SOURce2:POWer:ATTenuation:DIGital " +
str(pCHB))

        iamplast = float(0)
        nmmts = float(0)
        pwrlast = float(0)
        efflast = float(0)
        aclrlast = float(0)

        for dphs in diffPhs:
            SMW.write(":SOURce2:BB:POFFset " + str(dphs))

            iampRef = float(PSU.query("MEAS:CURR?"))

            FSW.write("INST:SEL 'Doherty.ACLR'")
            FSW.query("INIT:IMM;*OPC?")
            mACLR =
FSW.query("CALCulate:MARKer:FUNCTION:POWer:RESult? ACPower")

            FSW.write("INST:SEL 'Doherty.CCDF'")
            FSW.query("INIT:IMM;*OPC?")
            mPAPR = FSW.query("CALC:STAT:RES1? CFAC")
            mPOUT = FSW.query("CALC:STAT:RES1? MEAN")

            iamp = PSU.query("MEAS:CURR?")
            for loop in range (1,500): # wait for the
sample/hold to update to a value less than 1mA more than
                iampRef = iamp
                iamp = PSU.query("MEAS:CURR?")
                if (iamp != iampRef) and (abs(float(iamp)
- float(iampRef)) < 1e-3):
                    break

            x = mACLR.split(',')
            pout = float(mPOUT)
            iamp = float(iamp)
            vdc = float(28);
            eff = 100*pow(10, (pout-30)/10)/(vdc*iamp)
            aclr = max(float(x[1]), float(x[2]))

            bigList.append ( pCHA )
            bigList.append ( pCHB )
            bigList.append ( dphs )
            bigList.append ( pout )
            bigList.append ( aclr )
            bigList.append ( iamp )
            bigList.append ( frq )
            bigList.append ( mPAPR )
```

```
        zzz = zzz + 1
        nmmts = nmmts + 1

#           don't waste time if things are bad and getting
worse (example conditional loop break)
#           if (aclr > -30 and aclr > acrlast and nmmts
> 1):
#           break

        iamplast = float(iamp)
        acrlast = float(aclr)
        pwrlast = float(pout)
        efflast = float(eff)

tstop = time.time()

SMW.write(":SOURce1:POWer:ATTenuation:DIGital 30")
SMW.write(":SOURce2:POWer:ATTenuation:DIGital 30")

SMW.write(":OUTP2:STAT 0")
SMW.write(":OUTP1:STAT 0")
PSU.write("OUTP:STAT OFF")

#
# write the results to csv

thefile = open('dualInput_measurementData.csv', 'w')
for item in bigList:
    thefile.write("%s\n" % item)
thefile.close()

print(str(zzz) + " measurements in " + str(tstop-tstart) + "
seconds = " + str(zzz/(tstop-tstart)) + " mmts/s")
```

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