Outphasing, Envelope & Doherty Transmitter Test & Measurement

Application Note

Products:

- R&S®SMW200A
- R&S®FSW
- R&S®FSW-K18
- R&S®FSW-K70

Energy efficiency of RF Frontends (RFFE), especially transmitters, continues to gain greater prominence. Meeting the efficiency challenge is increasingly difficult at higher operating frequencies and bandwidths, such as those proposed for 5G.

There is a group of transmitter RFFE architectures whose signal output is constructed from two, or more, efficiently generated components. This signal construction in effect, means that such architectures use predictive, post-correction linearization. Their predictive nature enables distortion to be completely eliminated.

The capabilities of multi-channel signal synthesis setups with R&S®SMW200A, in combination with the R&S®FSW analyzer enable measurement, hence development, of these types of transmitters.

The document focusses on devices for the 3.5 GHz NR (5G New Radio) candidate band, but its findings are equally applicable to developments and measurements for, for example, K-band satellite applications or mmW NR candidate bands, where efficiency is an even more crucial design target.

Note:

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Application Note

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3.2018 – 1MA289_2e

ROHDE&SCHWARZ

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

- R&S® is a registered trademark of Rohde & Schwarz GmbH und Co. KG.
- The R&S®FSW Signal and Spectrum Analyzer is referred to as FSW.
- The R&S®FSW-K18 Distortion Analysis option for FSW is referred to as K18.
- The R&S®FSW-K70 Vector Signal Analysis option for FSW is referred to as K70.
- The R&S®SMW200A Vector Signal Generator is referred to as SMW.

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1 Introduction

1.1 Background

The Outphasing, Doherty and Envelope architectures have been known for many decades. More recently, significant research and development effort has been directed at these schemes themselves and also variants that hybridize, or use two (or more) of these techniques.

This document provides a starting reference, supported by working measurement examples, enabling the user to get started with test and measurement of them.

1.2 Reader's Guide

Chapter 2 provides a brief overview of each of the three foundation techniques, recommendations for further reading (a treatise of each is beyond the scope of this document) and examples of hybridization.

In Chapter 3, the generalized procedure to be followed is described.

In Chapters 4 and 5 application of the procedure to create exemplary Outphasing and Envelope transmitters (LINC and Envelope Restoration respectively), is illustrated.

In Chapter 6, the same process is extended to Doherty transmitters, demonstrating exemplary math and measurements.

1.3 Glossary

ACLR: Adjacent Channel Level Ratio, a frequency-domain measure of non-linear (unwanted) distortion as a ratio (usually expressed as dBc) of the wanted signal level.

AM: Amplitude Modulation, a method for adding and conveying information stored on the instantaneous envelope amplitude of a carrier.

ARB: ARBitrary signal generator, a device for creating a synthesized signal waveform, either played from a memory or generated real-time.

DUT: Device Under Test, the component being tested.

ER/EER: Envelope (Elimination and) Restoration, a method for constructing a signal from amplitude and phase components.

ET: Envelope Tracking, a range of schemes where the PA power supply is operated with a reduced margin and the PA input signal is quasi-linear.

IF: Intermediate Frequency, a frequency forming part of an RFFE frequency plan, which is neither the baseband nor the radio frequency of operation of the system.

IQ: In-phase and Quadrature-phase, commonly used abbreviation for two time-domain orthogonal components, used to represent a signal.

LINC: LInear amplification with Non-linear Components, a method for creating a (amplitude) modulated signal using constant envelope components.

LO: Local Oscillator, an RFFE component, usually providing an RF carrier onto which a data signal may be modulated (or off of which, a signal may be demodulated).

PA: Power Amplifier, last active component in the transmit chain of a radio, used to boost signal level to the level required to create a communication link.

New Radio: the 3GPP term describes cellular communication in legacy environments "non-standalone 5G NR" and in a later stage "standalone 5G NR"; also see entry **5G**.

PAPR: Peak-to-Average Power Ratio, the ratio (usually expressed in dB) between the maximum instantaneous envelope level and the longer term average envelope value.

PM: Phase Modulation, a method for adding and conveying information stored in the instantaneous phase of a carrier.

RF: Radio Frequency, the frequency at which an RFFE should transmit or receive. Also commonly used to describe a range of absolute frequencies below the "Microwave" frequency range.

RFFE: Radio Frequency FrontEnd, the PHY-layer component responsible for analog conditioning of a signal, after encoding in transmission and before decoding on reception.

5G: 5th Generation of Mobile Communication, also referred to as New Radio (NR) and generally regarded to stand on the three pillars mobile broadband, internet of things connectivity, and ultrareliable communication.

64-QAM: A specific type of modulation, conveying 6-bits of data for each symbol.

2 Predictive, Post-correction Transmitters

2.1 Family of Multipath Variants

A family of higher performance (efficiency and linearity) transmitters may be realized using multiple paths and signal decomposition. Synthesis of the signal from two or more components enables that signal to be constructed in a different, usually more efficient, way.

These architectures are characterized by their "predictive post-correction" synthesis of signals from two (or more) components, that are substantially non-linear with respect to each other and/or the signal to be synthesized.

Fig. 2-1 shows three basic types to be Outphasing, Envelope and Doherty. Note that these families of multiple-path types do not complete the entire predictive, post-correction solution set. Further reading on predictive post-correction and other RFFE classes, including additional references and a more expansive treatment of linearization, is provided in (Lloyd, Linearization of RF Frontends, 2016).

Alternative architectures, along with their hybrids (some also shown in Fig. 2-1) have been the focus of much attention in recent years, especially with a migration to higher bandwidths and carrier frequencies for 5G devices.

2.2 Outphasing

A special case of Outphasing was first mentioned by (Chireix, 1935). The LINC derivative was developed by (Cox & Leck, 1975).

Broadly speaking, Outphasing is characterized by the use of two, equal amplitude vectors (with varying phase difference), summed in a combiner network. As such, in its purest form, both signal paths contribute equally to the output signal, all the time.

2.3 Envelope Schemes

There are a plurality of Envelope schemes in the literature.

Transmitters of this type would have the two (or more) signal paths operating at different frequencies; usually one of the signals conveys envelope information centered on a very low frequency (e.g. DC).

Examples of such architectures include EER (envelope elimination and restoration), ET (envelope tracking) and Load Modulation. The solution set might well include schemes like AGC (automatic gain control), too.

In this document, an example EER architecture will be demonstrated, similar in method to that first shown by (Kahn, 1952).

2.4 Doherty

Since the early 2000's, the (Doherty, 1936) architecture has enjoyed something of a renaissance in industrial implementations.

Doherty transmitters are characterized by their "linearity preserving" combining network, differential currents sourced into that combiner, and quasi-linear drive requirements.

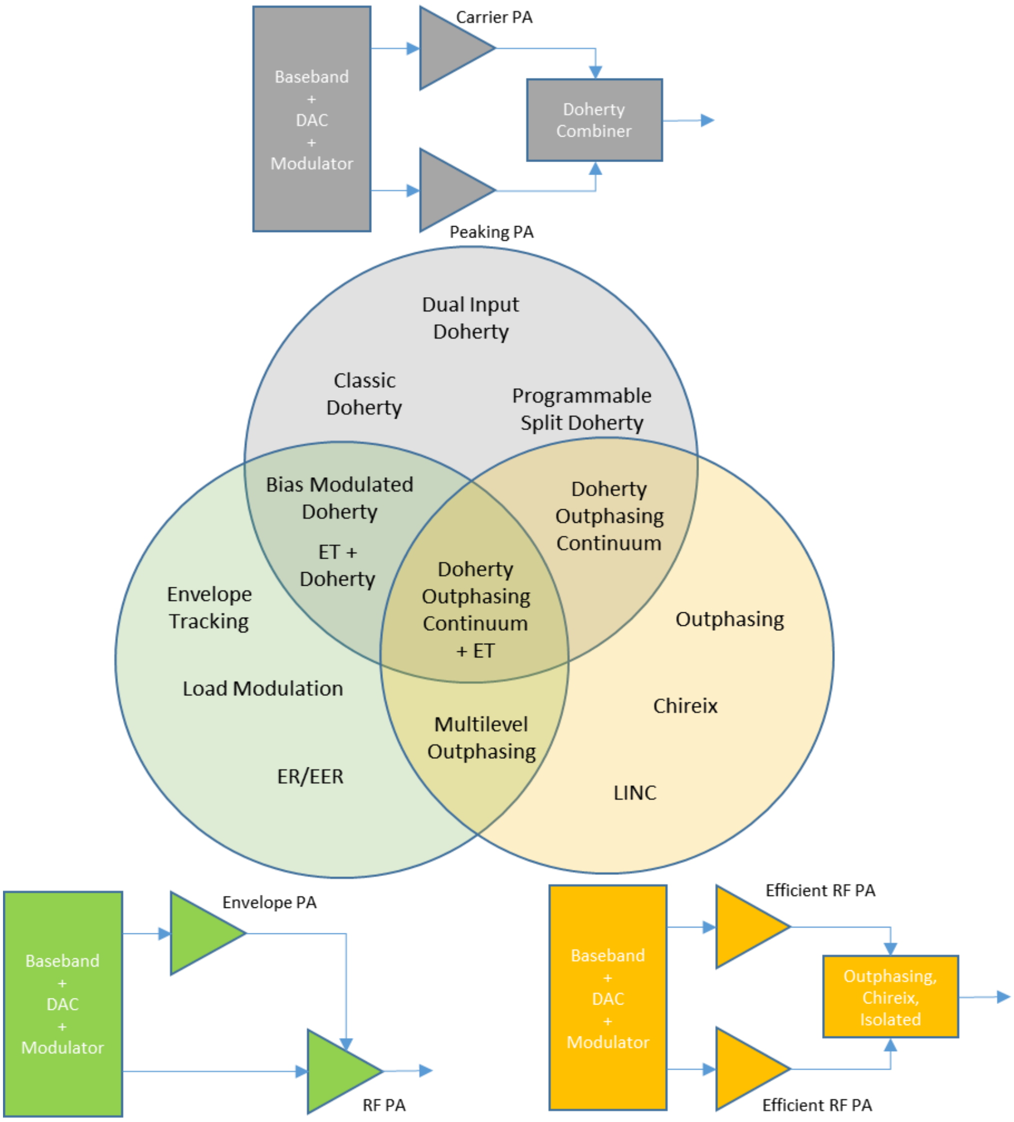

Fig. 2-1: Outphasing, Envelope & Doherty & exemplary solutions

3 Development

3.1 Design Process

The general process, regardless of which transmitter architecture is to be evaluated, is described in Fig. 3-1.

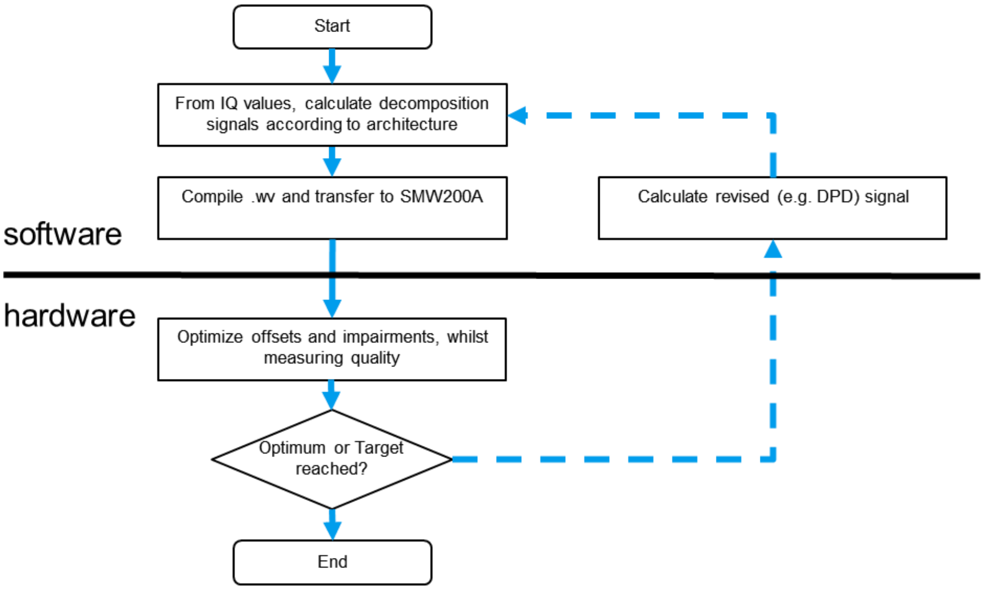

Fig. 3-1: Generalized process for test and measurement of multipath transmitters, used in this document

It should be noted that R&D on any of the transmitters described herein begins with the definition of a single, wanted, target signal.

Derivation of the decomposition signals are calculated from that single reference.

As such, that single reference may be modified, for example, predistorted digitally - as long as the digital decomposition is performed after, or downstream, of the DPD.

Enacting the feedback loop (dashed line in Fig. 3-1), e.g. with DPD, is beyond the scope of this document.

An exemplary MATLAB function, for converting matrices representing time domain IQ data into the native SMW .wv format, is given in (Lloyd, Linearity Measurements on RFFE Components, 2017), as well as an introduction to K18 measurements.

4 Envelope Scheme (Envelope Restoration)

4.1 Background

The multiplicative operation performed in an Envelope Restoration (ER) scheme is illustrated here using an off-the-shelf mixer DUT (Mini-Circuits ZX05-C60MH-S+).

The constituent signals comprise (i) a baseband envelope signal, derived from an AM (amplitude modulated) signal, and (ii) an RF signal, representing a PM (phase modulated).

These IQ time-domain decomposition signals are calculated and passed to the SMW as two independent ARB files.

Both the decomposition calculation of IQ values, and creation of SMW compatible ARB files is performed (in this example), in MATLAB.

"Theoretical" in this context means that no modifications are made, e.g. regarding shaping.

The decomposition is performed according to Equation 4-1.

```
chAI = real(signal)./abs(signal);
chAQ = imag(signal)./abs(signal);

chBI = abs(signal);
chBQ = 0 * abs(signal);

chA = chAI + 1i * chAQ;
chB = chBI + 1i * chBQ;

where:
chAI and chAQ are the remapped time domain IQ values for ARB
channel A
chBI and chBQ are the remapped time domain IQ values for ARB
channel B
```

Equation 4-1: Decomposition of the desired waveform, to multiplicative ER, in MATLAB format

An attractive practical advantage of ER is that generation of the envelope channel needs only one, rather than two, DACs.

The resultant waveforms, including the expected output (the simple product of the two channels, chA and chB) are shown in Fig. 4-1:

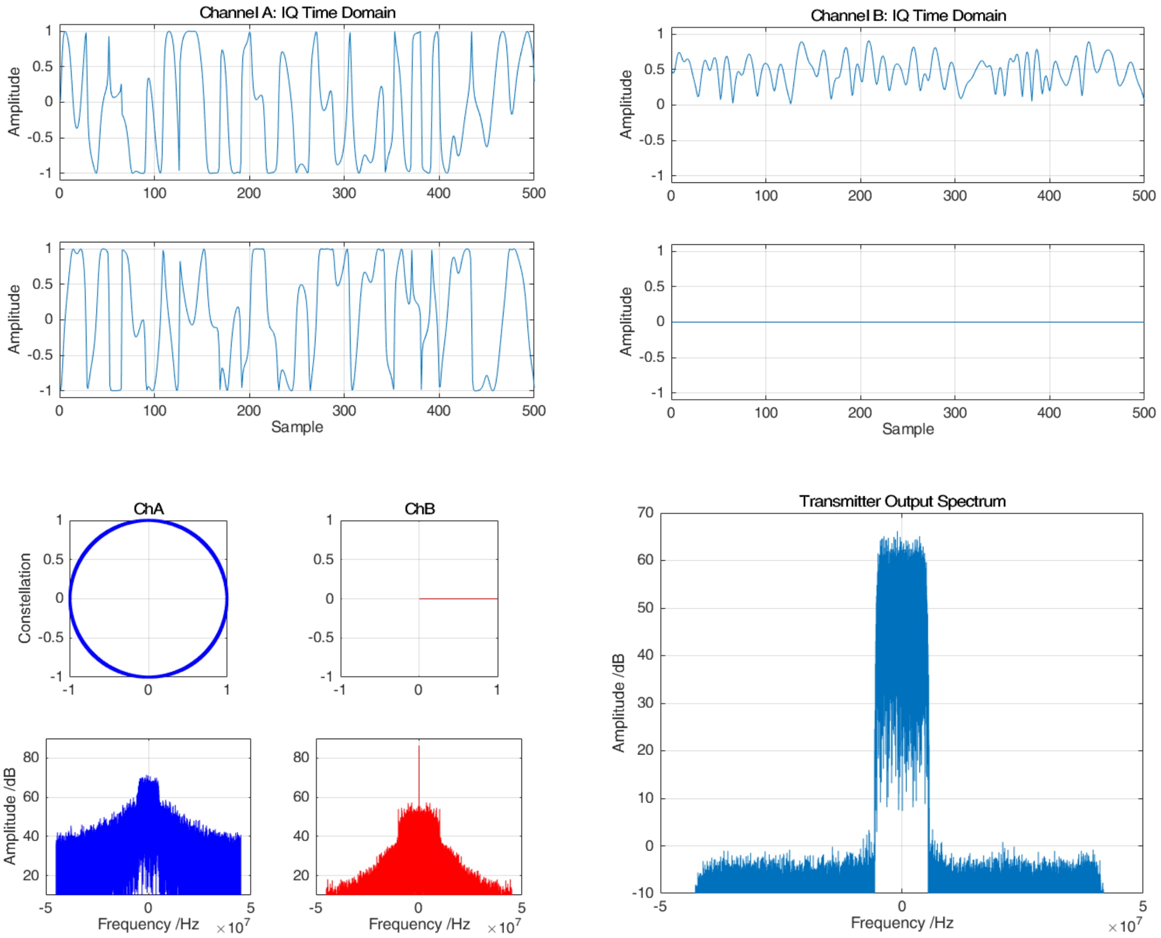

Fig. 4-1: Two decomposed waveforms, derived from the wanted signal, including; IQ time domain waveforms for the 2 ARB channels, constellation and spectrum plots and the theoretical multiplication spectrum

The signals are loaded into the ARBs of the SMW, and the SMW is configured for Envelope operation.

The AM/envelope signal is mapped to (one channel of) the IQ outputs on the rear panel of the SMW, and connected to the IF port of the mixer DUT.

The PM signal is mapped to (one of) the RF outputs on the SMW front panel and connected to the LO port of the mixer DUT.

4.2 Measurement

With the two sources of the SMW connected to the LO and IF ports of the mixer DUT, the DUT output (RF port) is connected to the FSW for signal analysis. Schematic connection and photo are shown in Fig. 4-2.

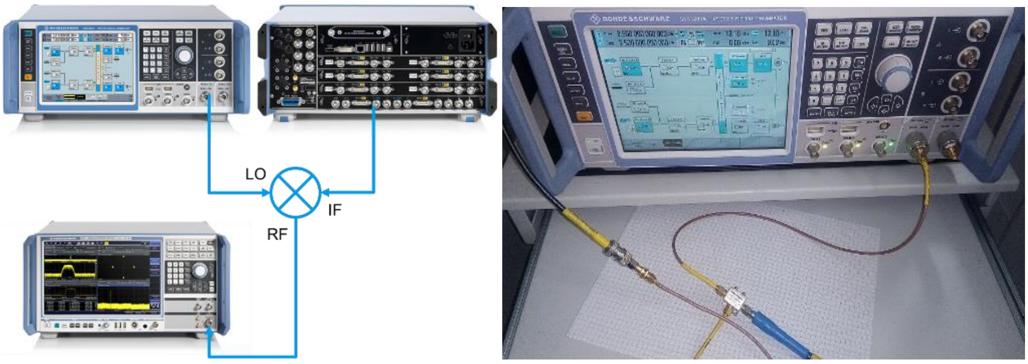

Fig. 4-2: Schematic and photo of the test set-up used to generate the signal by ER

A screenshot of the SMW, configured for ER test and measurement, is shown in Fig. 4-3.

Note that the peak envelope power reported by the SMW on Channel A is equal to its average power; i.e. the signal driving the mixer LO port (phase modulated) has quasi-zero peak-to-average power ratio.

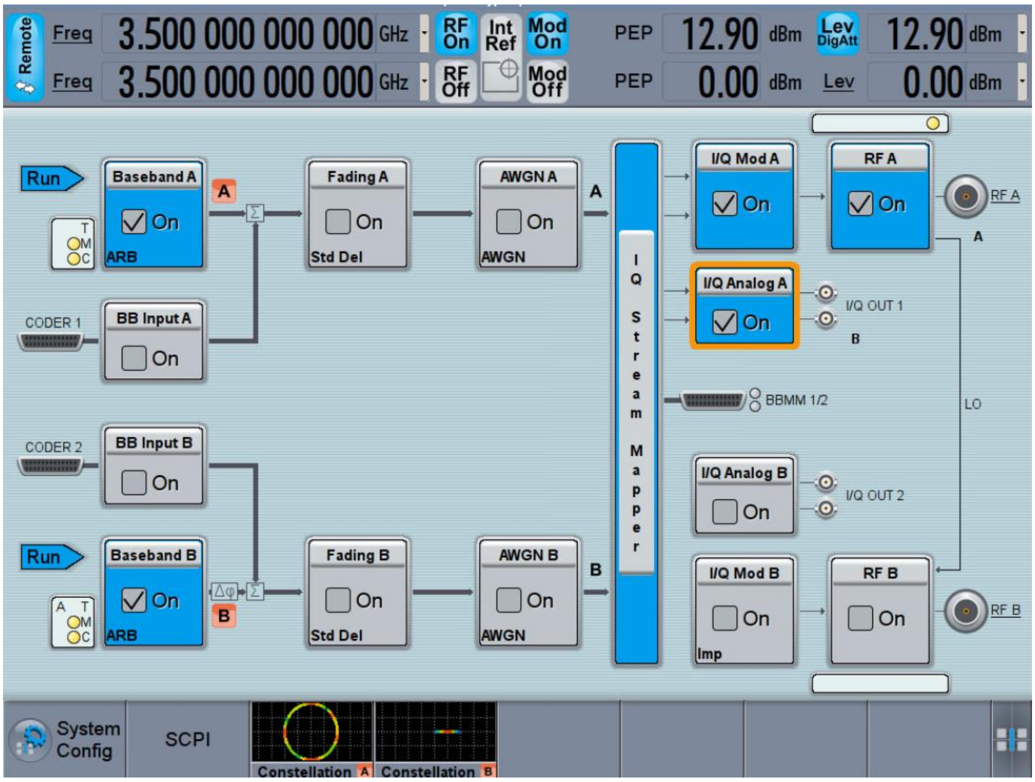

Fig. 4-3: Screenshot of the SMW, configured for ER generation

The FSW analyzer with K18 personality is pre-loaded with the original waveform.

In this case, the drive level of the PM signal to the mixer LO port and the amplitude of the envelope signal provided to the mixer IF port are modified, whilst observing ACLR (using the FSW in spectrum analysis mode), EVM (using the K70 signal analysis) and AM-xM dispersion (K18 distortion analysis).

The three FSW reports are presented.

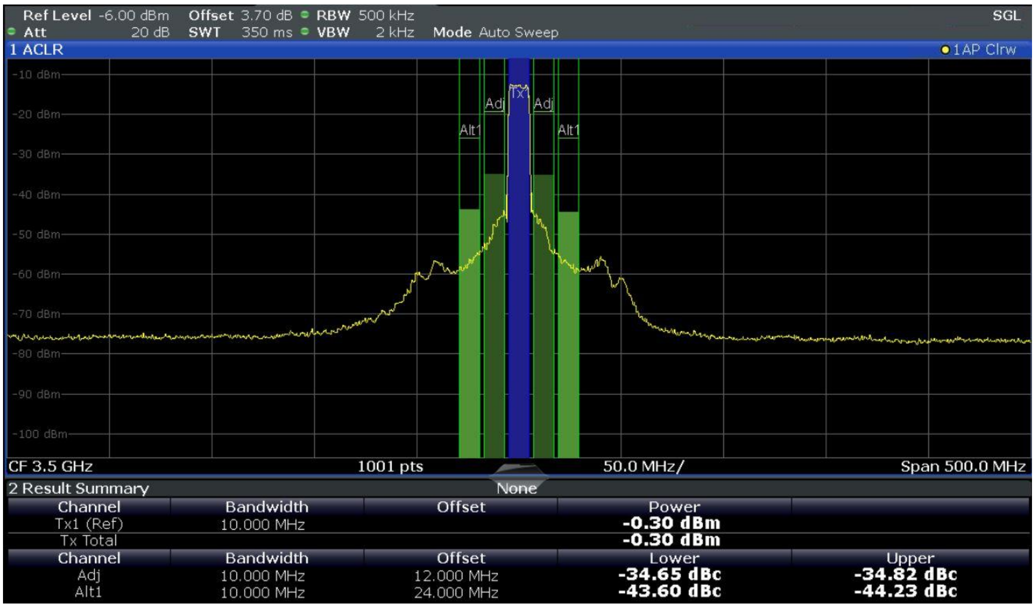

Fig. 4-4: FSW spectrum analysis of the ER output signal

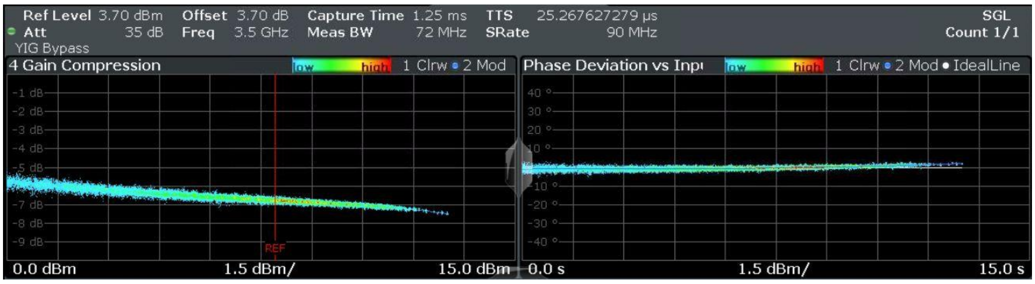

Fig. 4-5: K18 measurement of the ER transfer characteristics

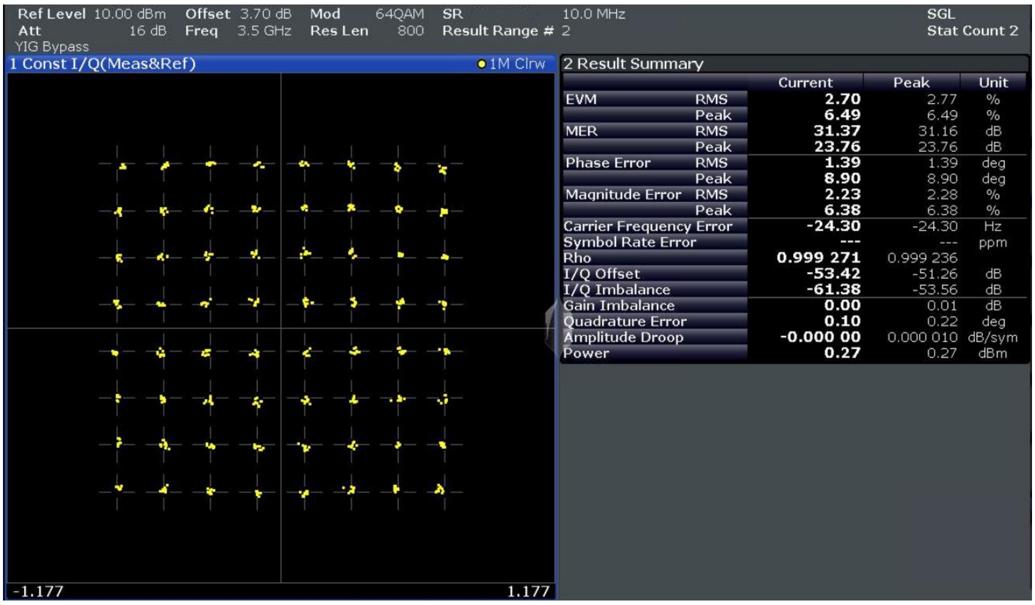

Fig. 4-6: K70 modulation quality analysis of the 64-QAM ER output signal

The input signals are calculated theoretically, and left as-is. No engineering of the mixer or circuit has been performed; it is straight off-the-shelf. Coarse time and amplitude alignment of the two channels, monitoring the output signal quality, has been performed before taking the results screenshot.

It can be observed that although a relatively high level of non-linear distortion (e.g. ACLR) is present in the signal, this is not caused by saturation effects (see Fig. 4-5, from K18). This justifies expectation that observed distortions, if required, could be almost completely cleaned up with linearization.

In Fig. 4-4, there is no discernable image frequency (or LO leakage). This in itself is interesting from an architectural perspective, modifying the traditional post-mixing filter requirement.

4.3 Comparison with Conventional Mixer Operation

For reference purposes, the mixer DUT was also operated in its conventional mode, i.e. using a CW tone to drive the LO port and an unmodified IQ time domain waveform applied to the IF port.

The SMW may easily and quickly be reconfigured to perform this operation (settings shown in Fig. 4-7), although a physical reconnection of the device is required.

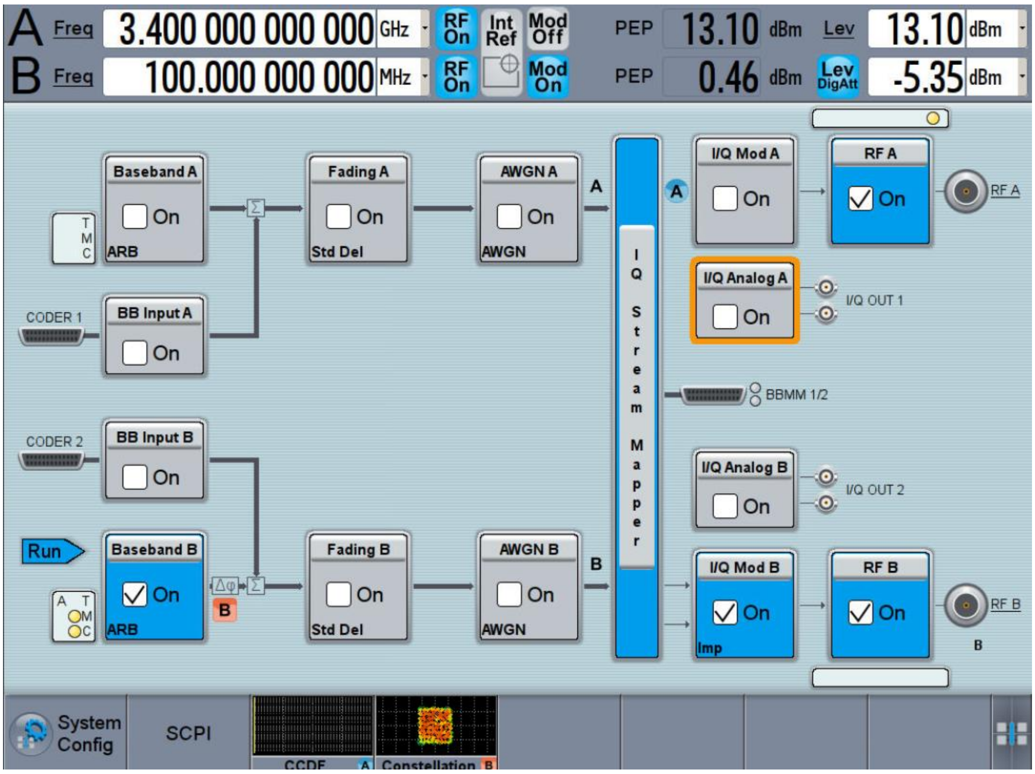

Fig. 4-7: SMW settings screenshot for conventional mixer operation

Changing connection of the mixer IF input to the second RF output on the SMW front panel, the following measurements on conventional mixer operation may be made:

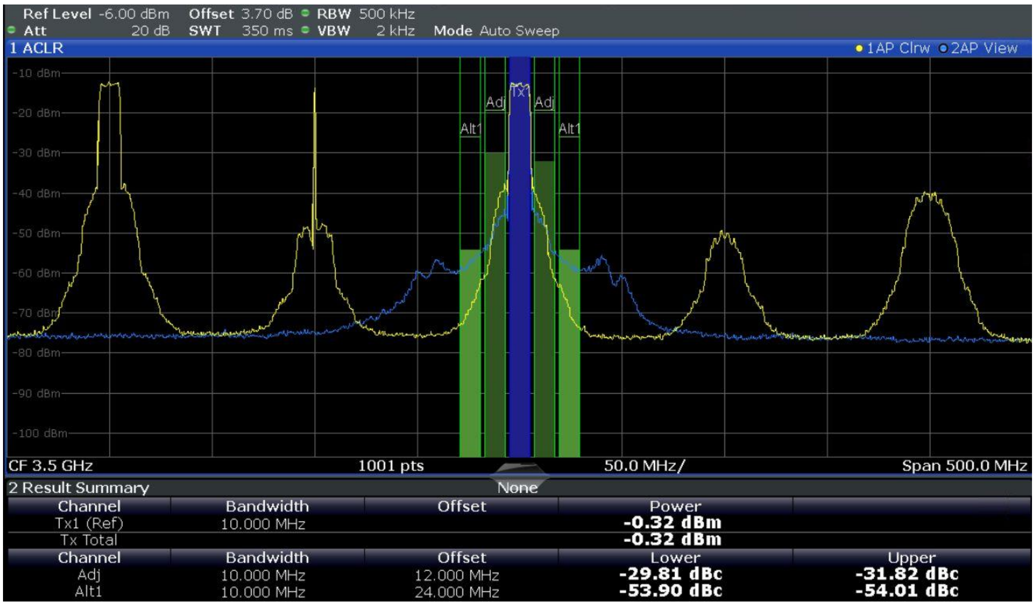

Fig. 4-8: FSW spectrum analysis of the conventionally operated mixer (with overlaid ER operation spectrum)

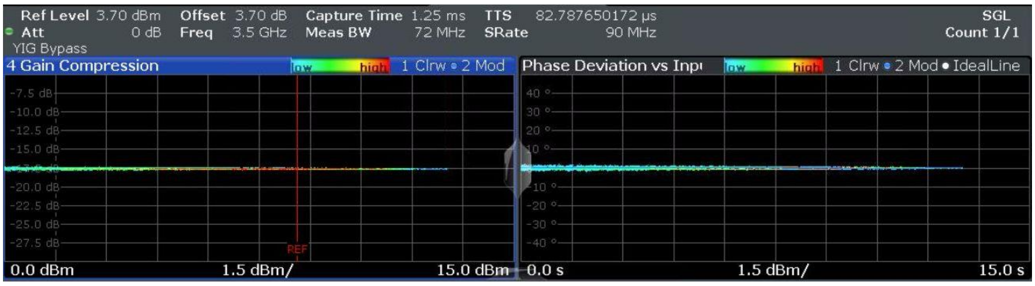

Fig. 4-9: K18 measurement of the conventionally operated mixer

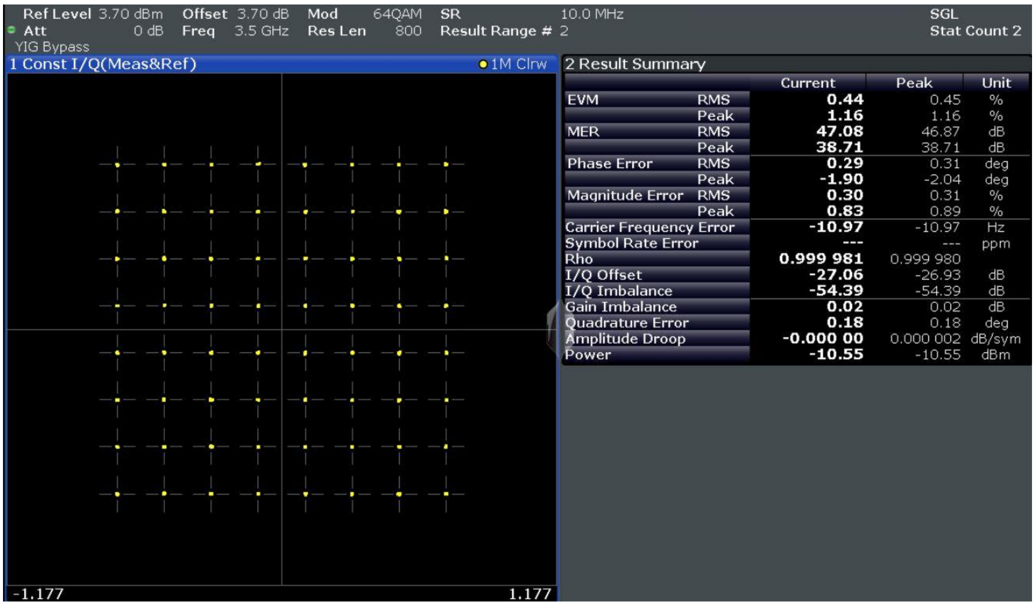

Fig. 4-10: K70 demodulated signal quality analysis of the conventionally operated mixer

Fig. 4-9, Fig. 4-8 and Fig. 4-10, show that, for this case, a better demodulated signal quality can be achieved, but that the output spectrum has been affected by image frequencies and LO leakage.

5 Outphasing Scheme (LINC)

5.1 Background

LINC (LInear amplification with Non-linear Components) will be used to illustrate the measurement of Outphasing type radio architectures. Combining in the LINC transmitter is performed with an isolated structure, in this case using an off-the-shelf combiner as the DUT (Mini-Circuits ZN2PD-9G-S+).

In essence, the common-mode parts of the two incident signals to the combiner are summed, and the difference-mode removed.

The isolated combiner may be realized in any number of different ways, including Wilkinson or hybrid structures. The difference signal is passed to the isolated port (where it may be further utilized and/or processed).

The constituent signals are, in their purest form, constant envelope; effectively PM (phase modulated) at the system RF frequency. Outputs for the two composite signals are taken from the RF ports on the front of the SMW.

Transformation of the wanted signal time-domain IQ values is trivial, implemented in Equation 5-1, as MATLAB functions:

```
angPhi = angle(signal);
angAmplitude = acos(abs(signal));

chA = exp(1i*(angPhi + angAmplitude));
chB = exp(1i*(angPhi - angAmplitude));
```

Equation 5-1: Decomposition of the desired quasi-linear waveform, to LINC, in MATLAB format

The relevant signals within the transmit chain, including the predicted output (the sum of channel A and channel B) are presented in Fig. 5-1.

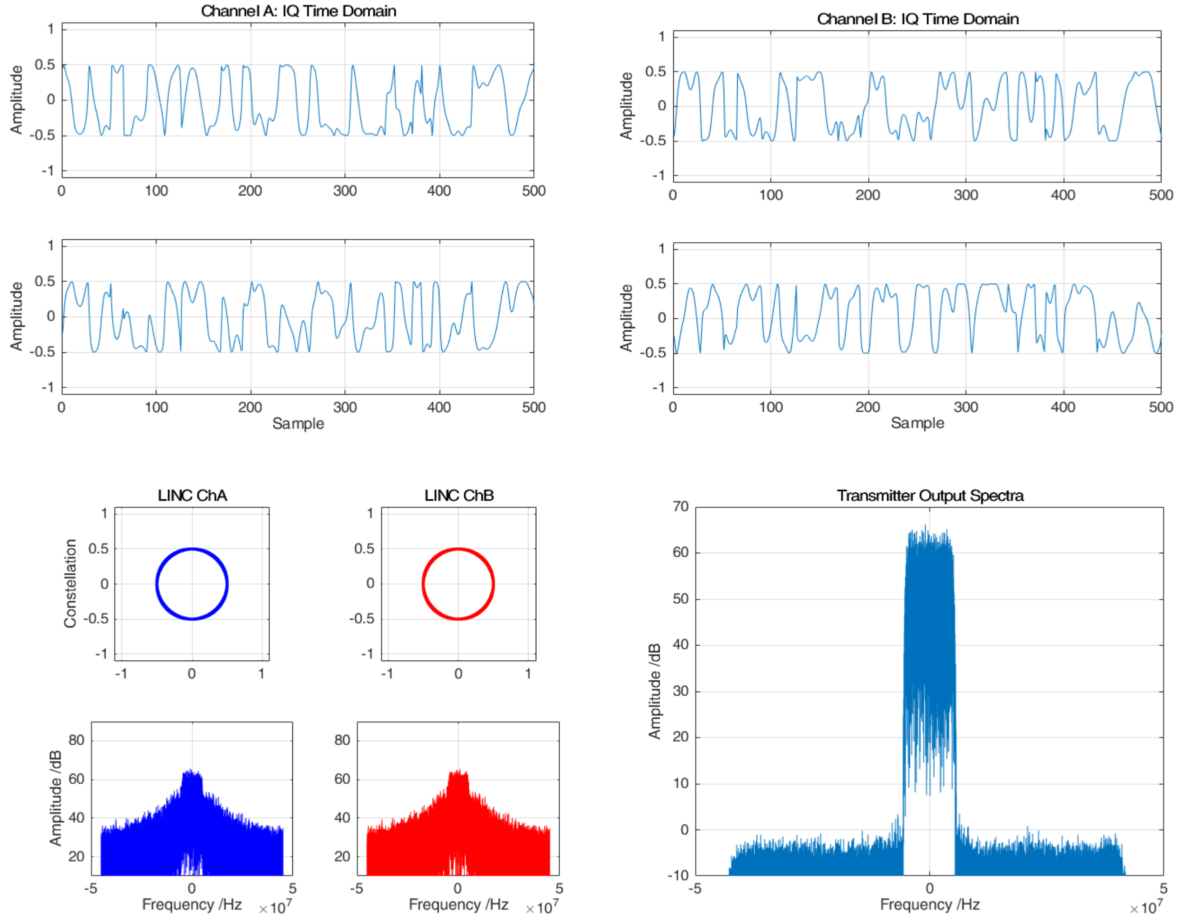

Fig. 5-1: Two decomposed waveforms, derived from the wanted signal, including; IQ time domain waveforms for the 2 ARB channels, constellation and spectrum plots and the theoretical multiplication spectrum

5.2 Measurement

With the two constituent signal files loaded into the SMW, and the isolated, in-phase combiner connected as DUT (Fig. 5-2), the measurement may be made.

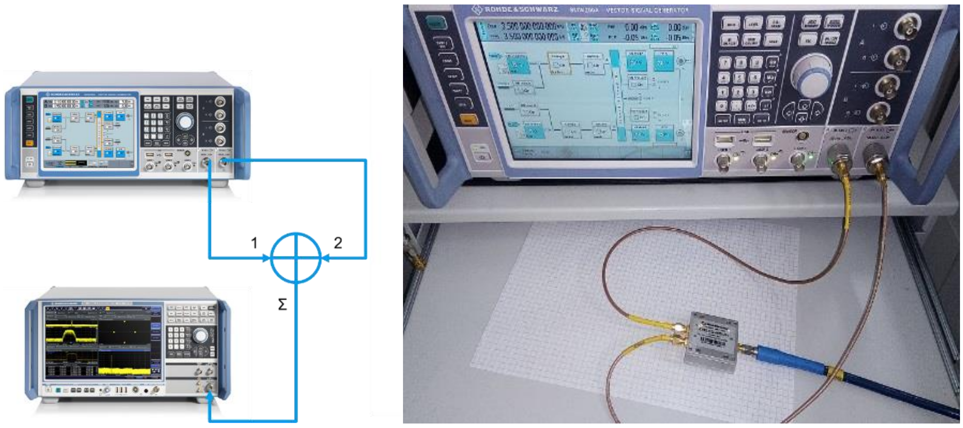

Fig. 5-2: Schematic and photo of the test set-up used to generate the signal by LINC

SMW configuration for LINC/Outphasing signal generation is shown in Fig. 5-3.

Note that, although the signal to be generated is 64-QAM, the constituent signals as shown in SMW "monitor" constellation diagrams (observe bottom of Fig. 5-3 screen) demonstrate constant envelope levels, or zero PAPR.

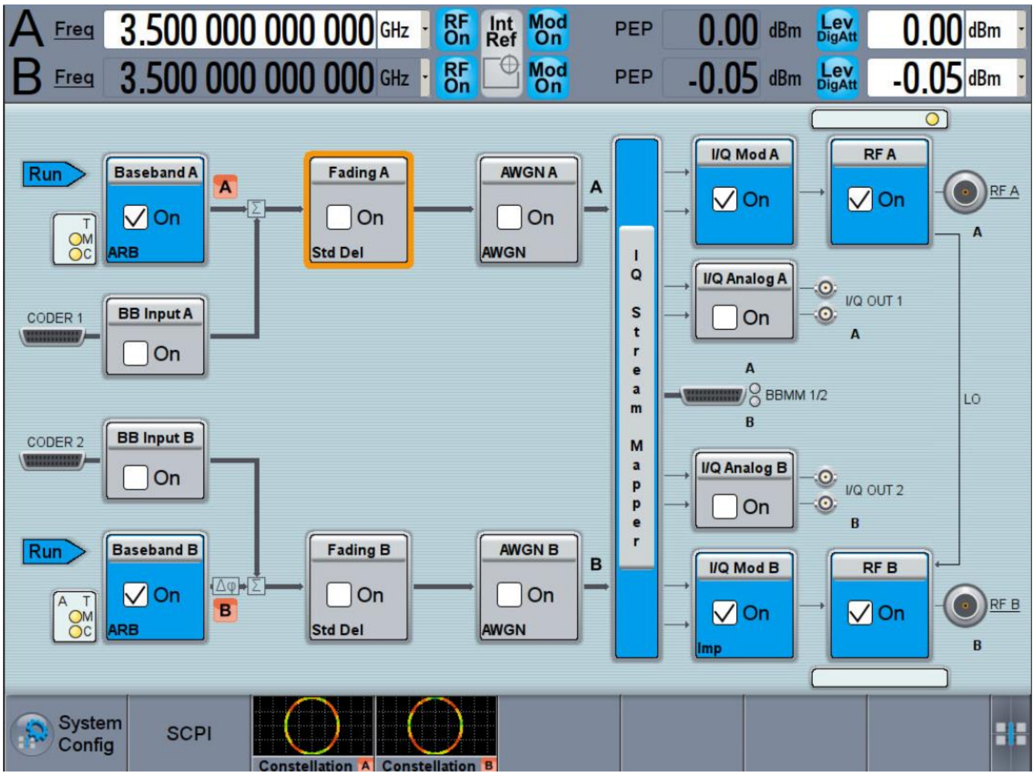

Fig. 5-3: Screenshot of the SMW, configured for LINC signal generation

Measurement captures using the same three different signal analysis methods as used before are presented in Fig. 5-4, Fig. 5-5 and Fig. 5-6 respectively:

Fig. 5-4: FSW spectrum analysis of the LINC output signal

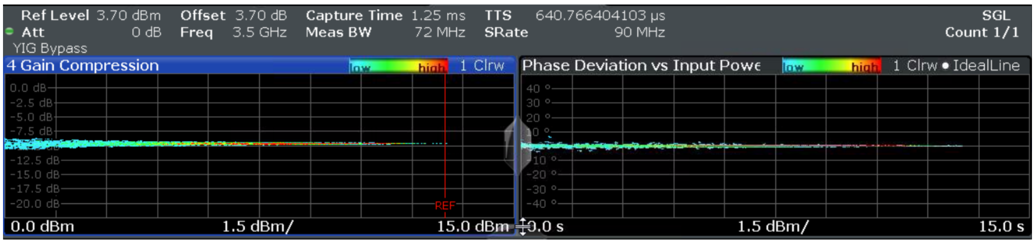

Fig. 5-5: K18 measurement of the LINC signal

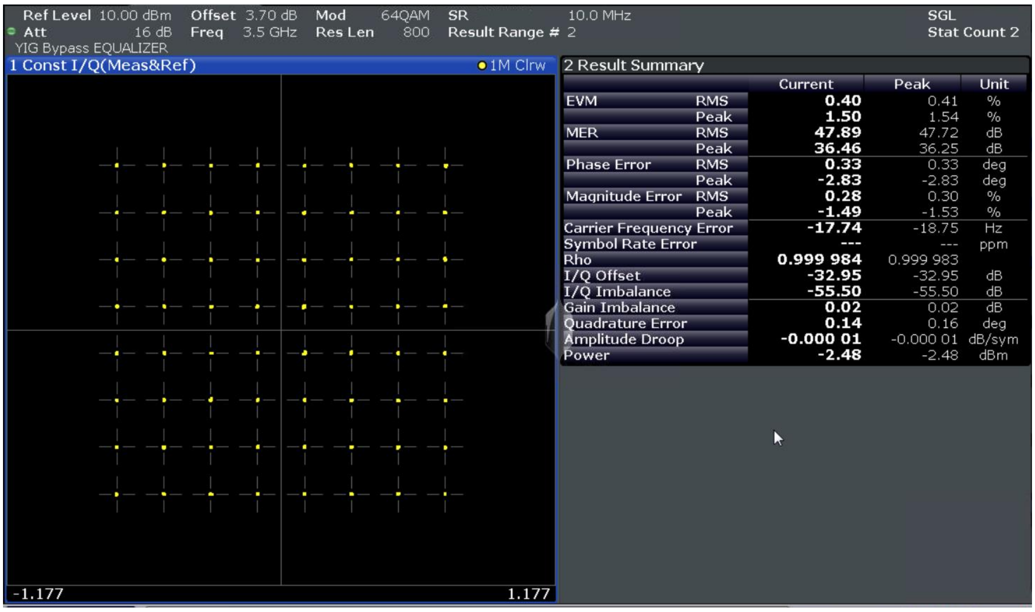

Fig. 5-6: K70 modulation quality analysis of the 64-QAM LINC output signal

The synthesized signal quality, according to the K70 measurement (Fig. 5-6), closely approaches that of the reference signal. Using LINC, a high-order, digitally modulated output signal (with around 6 dB PAPR in this case) has been created from 2 constant envelope input signals.

This changes the design requirements of the constituent RF paths, and provides the opportunity to differentiate the RFFE.

5.3 Comparison with Conventional Combiner Operation

Conventional operation in this case is defined by loading the basic 64-QAM reference signal into both ARB channels. An electronic-only reconfiguration of the SMW is required (for settings, refer to Fig. 5-7).

Note from the footer part of the Fig. 5-7 screenshot, that the generator's output signal is linearly representative of the DUT output. And therefore, that the same wanted signal has been generated using two quite different methods (Fig. 5-10, Fig. 5-8, and Fig. 5-9).

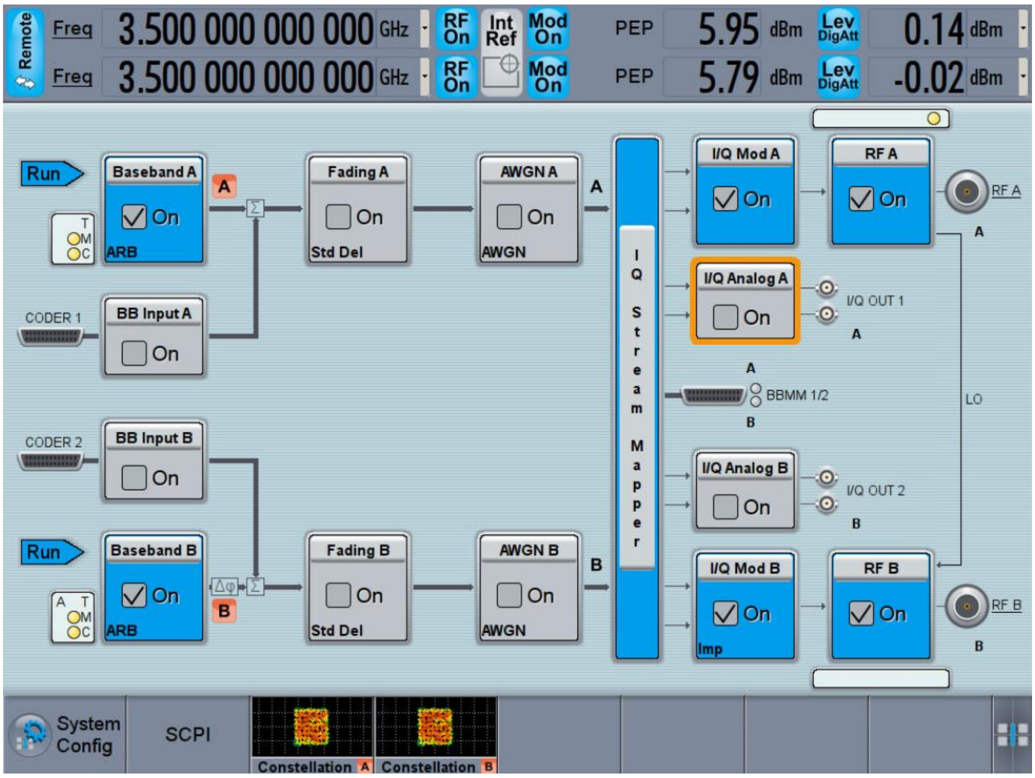

Fig. 5-7: SMW screen capture of the conventionally operated in-phase combiner.

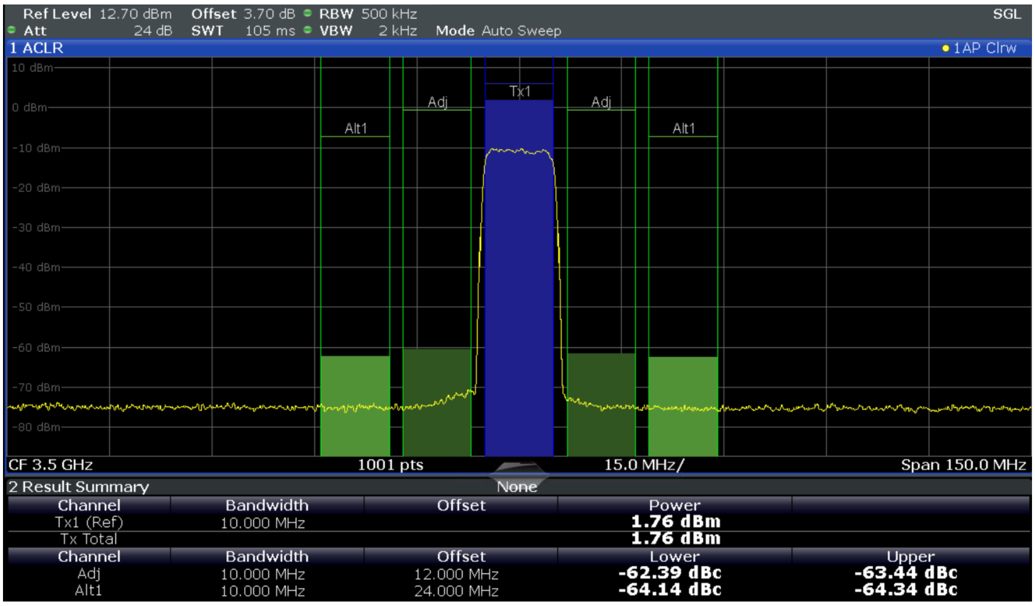

Fig. 5-8: Spectrum analysis of the conventionally operated in-phase combiner.

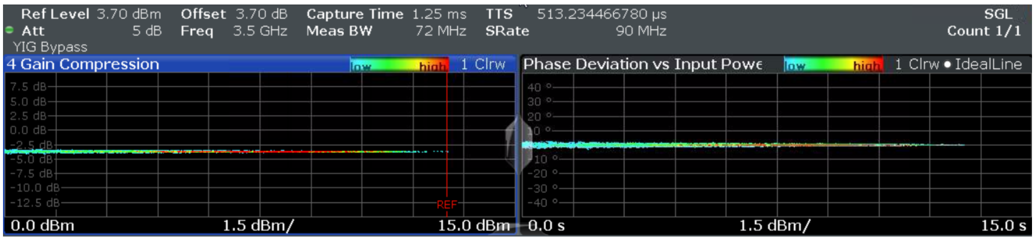

Fig. 5-9: K18 measurement of the conventionally operated in-phase combiner.

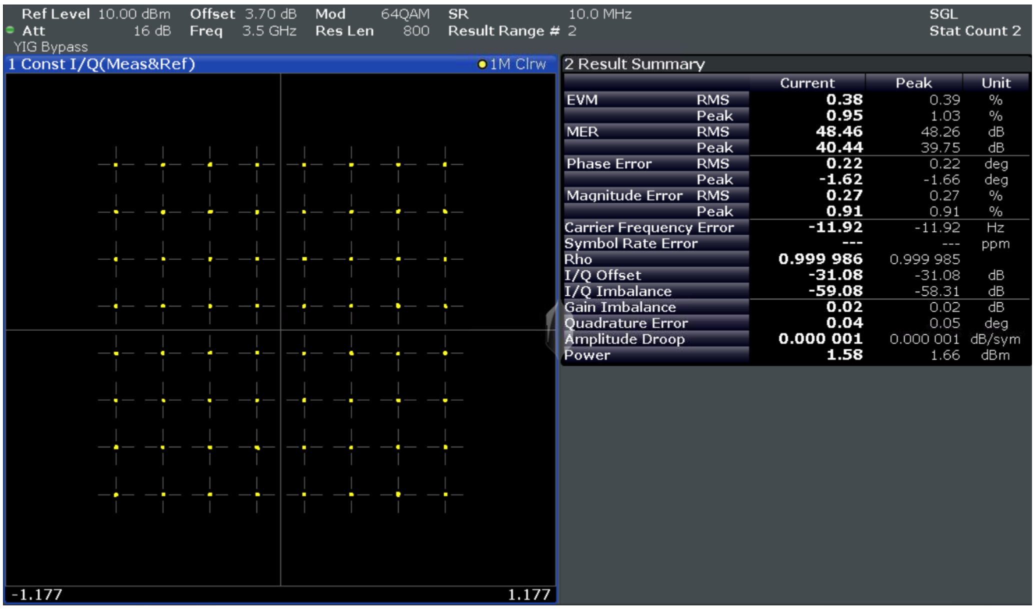

Fig. 5-10: K70 signal quality measurement of the conventionally operated in-phase combiner.

6 Doherty

6.1 Background

There is arguably no subject more comprehensively published on than Doherty and related schemes. A more comprehensive treatment is not performed here. The reader is directed to (Cripps, 2006). In (Lloyd, Doherty, Balanced, Push-Pull & Spatial Amplifier Performance Enhancement, 2016), an "analog way" to achieve Doherty performance enhancements for efficiency, bandwidth, linearity, or a user-selectable combination thereof, is shown.

As is increasingly the case in RFFE development, flexibility in the analog domain may be created by introducing modifications in the digital domain. Doherty performance is driven by the **difference** between currents sourced into the combiner's inputs. As the difference between the currents is reduced to zero, then operation tends towards that of "balanced" operation. In the vast majority of past implementations, the difference is created in the analog domain by operating the two amplifiers at different bias points (e.g. "class AB" and "class C").

Unfortunately, this differential biasing leads to sub-optimal amplifier performance and/or utilization, both in theory and practice. In this example, the difference current is driven digitally, rather than in the analog domain.

The introduction of a second, "digital", input to the Doherty yields opportunities to improve performance, at least on two fronts:

- The difference current may be created in the digital domain
- Both amplifier bias points may be set equal AND therefore optimally

6.2 Signal Synthesis

Channel A of the SMW, is connected to the "carrier" device and Channel B to the "peaking" device. An example embodiment of digital domain Doherty is therefore:

```
% no modification of the reference signal for channel A
chA = signal;

% detect and scale the amplitude of Channel B, from A
chBamp = (2 * abs(chA)) - 1;
% reset scaled Channel B negative values, to zero.
chBamp(chBamp<0) = 0;
```

```
% assume equal phasing between Channel B and A
chBphs = angle(signal);

% reconstruct Channel B from Amplitude & Phase values
chB = chBamp .* exp(1i * chBphs);
```

Equation 6-1: Decomposition of the desired waveform, to Doherty, in MATLAB format

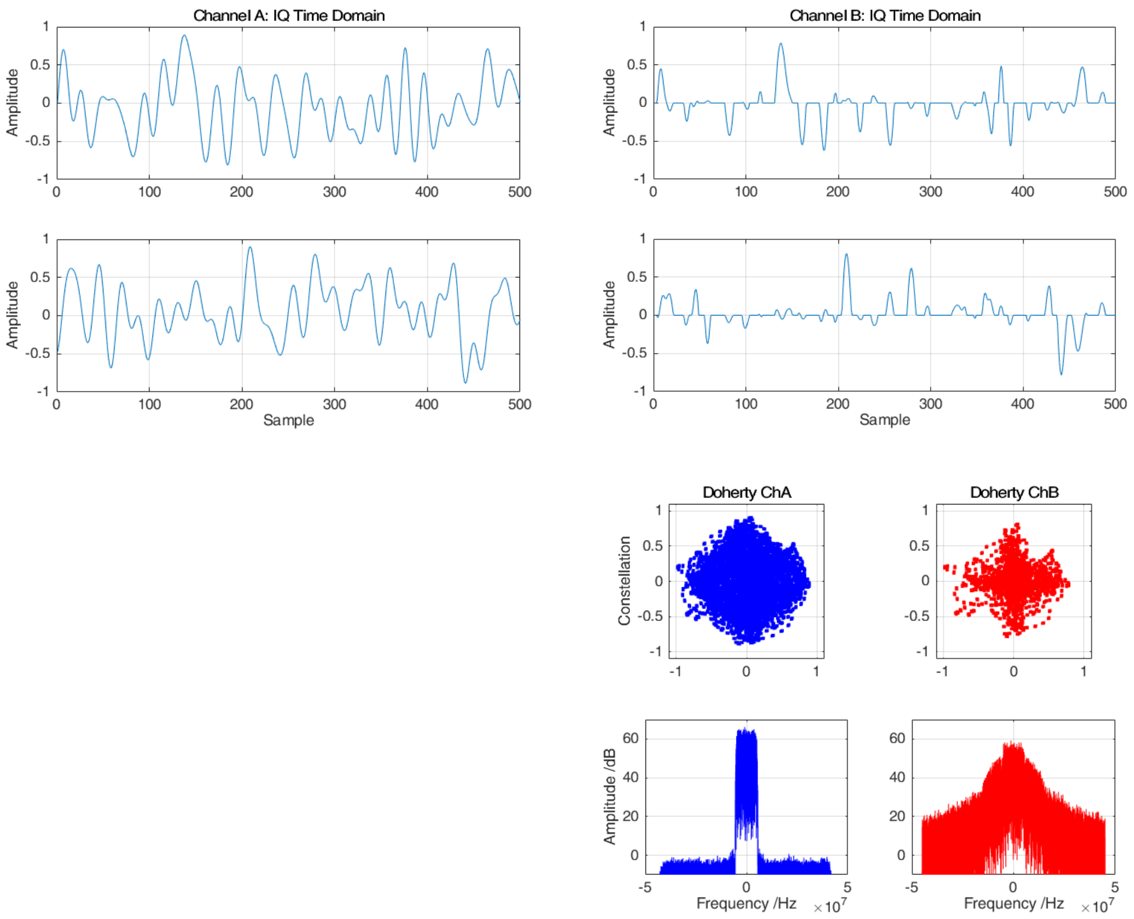

Fig. 6-1: Two decomposed waveforms, derived from the wanted signal, including: IQ time domain waveforms for the 2 ARB channels, constellation and spectrum plots and the theoretical multiplication spectrum

The two signals should be loaded into the ARB of the SMW and baseband signals routed to the RF output ports.

Simplification of the Doherty combining operation (perfect current source operation, non-dispersive components, etc.) allows the following theoretical calculation to be made:

```
% output currents of "Carrier" and "Peaking" devices equal to
the input magnitude

iA = abs(chA);

iB = abs(chB);


% ratio of those currents drives the Doherty effect

current_ratio = iB./iA;


% the impedances mutually presented to each device are given by

zA = 100 - 50*current_ratio;

zB = 50./current_ratio;


% voltages generated by those currents sourced into those
impedances

vA = iA.*zA;

vB = iB.*zB;


% power generated by each device

pC = vA.*iA;

pP = vB.*iB;
```

Equation 6-2: Theoretical calculation of the Doherty effect, in MATLAB format

Application of the theoretical calculation result in the following salient current, voltage, impedance and power characteristics.

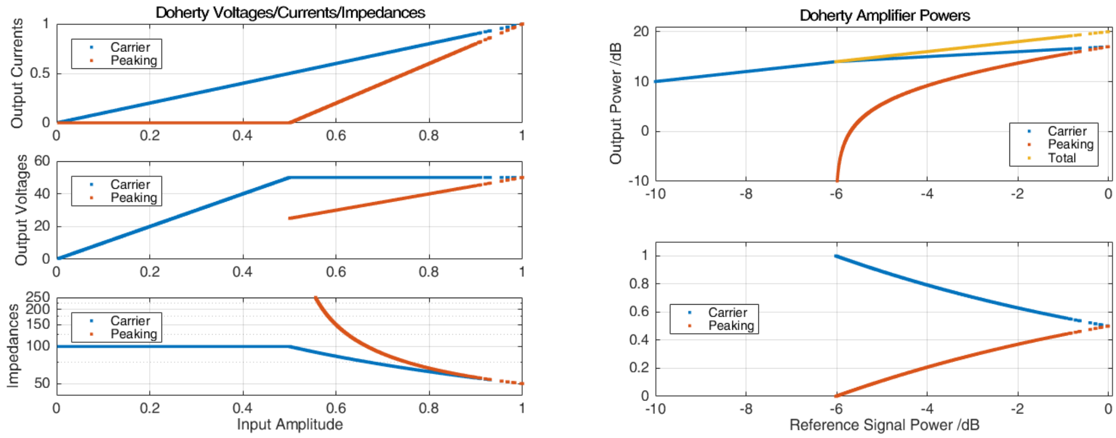

Fig. 6-2: Theoretically created Voltages, Current, Impedances & Powers in the Doherty architecture

Modification of Doherty's "hockey stick" output current characteristic, modifies the dynamic currents, impedances, voltages and constituent powers.

Remarkably, however, it does not modify the overall linearity (as long as the "Peaking" current characteristic falls inside the area bounded in Fig. 6-2).

Better tracking of Doherty's "hockey stick" characteristic, results in better efficiency. As the "Peaking" current tends towards the "Carrier" (i.e. away from the hockey stick), efficiency tends towards the special case of the "non-isolated, balanced" amplifier.

In the ensemble of Fig. 6-3 and Fig. 6-4, a "square law Peaking" characteristic is used and results replotted.

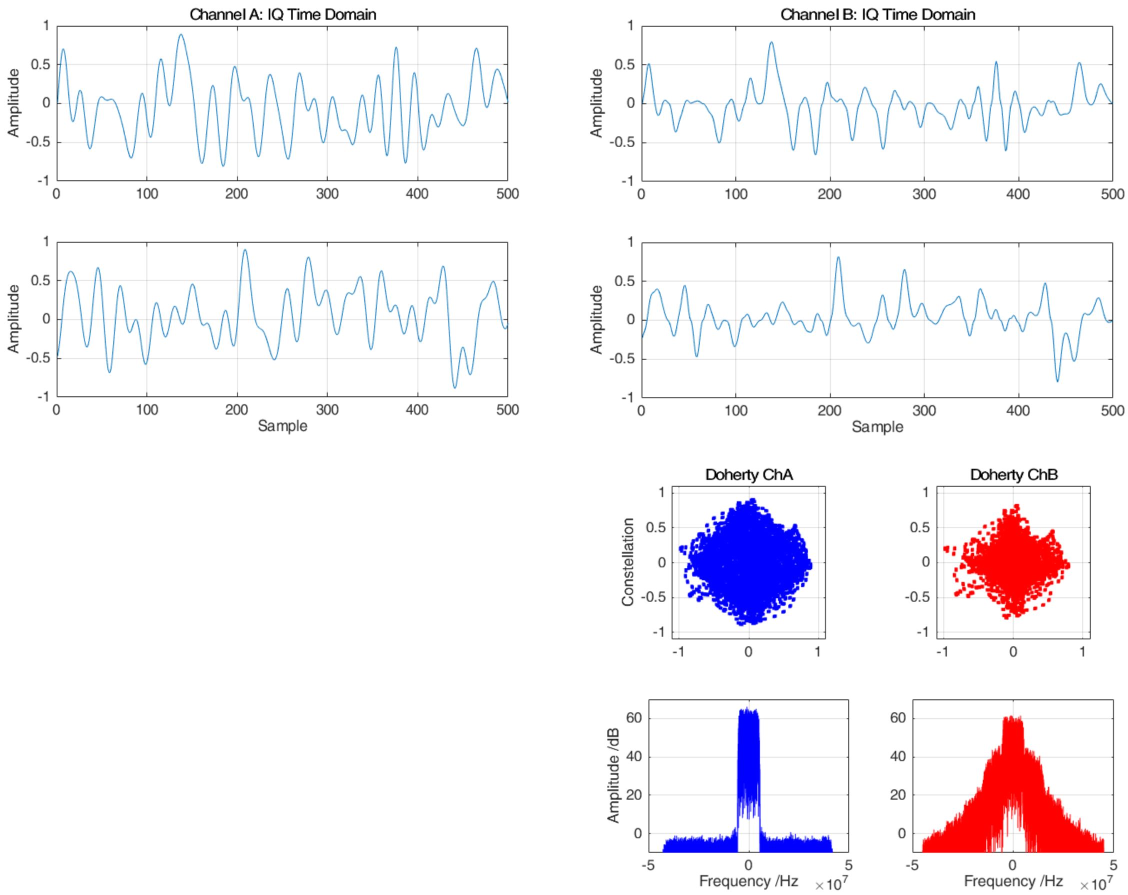

Fig. 6-3: Doherty using "square law Peaking" time domain, constellation and spectrum

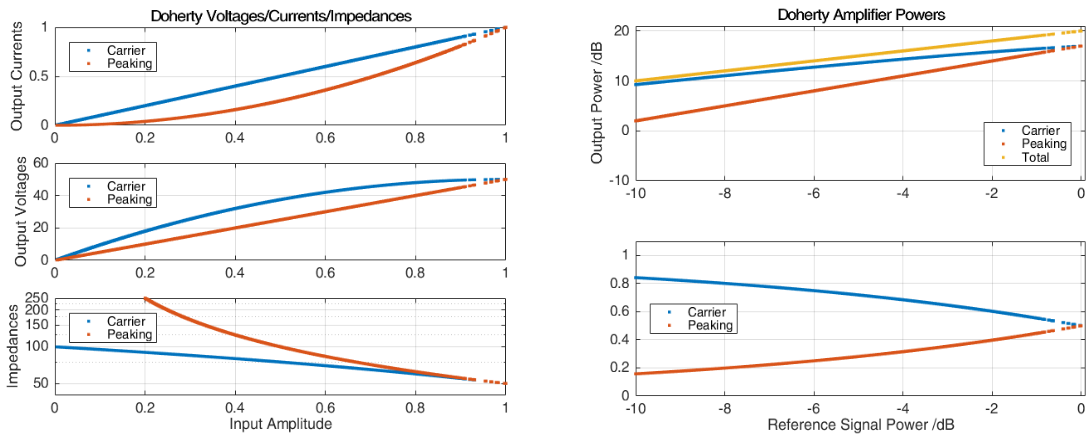

Fig. 6-4: Doherty using "square law Peaking" currents, impedances, voltages and powers

6.3 Measurement of Single- & Dual-Input

To demonstrate the measurement of the dual-input Doherty, a DUT intended for 5G NR in the band 3.4~3.6GHz is used. The devices are constructed using depletion mode GaN.

The two scenarios presented are the single-, and dual-input architectures.

For the single input case, measurement is arbitrary.

For the dual-input case, the illustrated 'square-law' signal is prepared in MATLAB™ and loaded into the second ARB of the SMW. Meanwhile, the signal intended for the 'main' signal path is not changed.

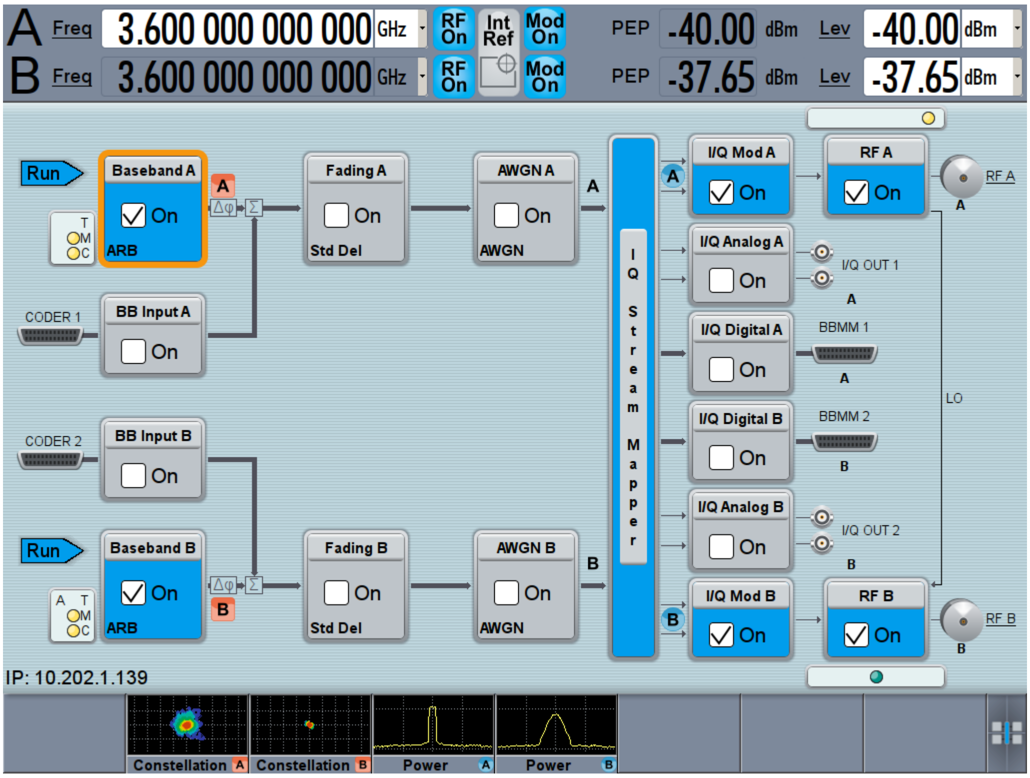

Fig. 6-5: SMW screen capture of the dual-input operated Doherty amplifier.

With the two signals created and loaded into the ARBs of the SMW, and triggered, the generator display

The FSW-K18 measurement is prepared using that unchanged 'main' path signal as the reference.

Firstly, with the classical fixed RF input split.

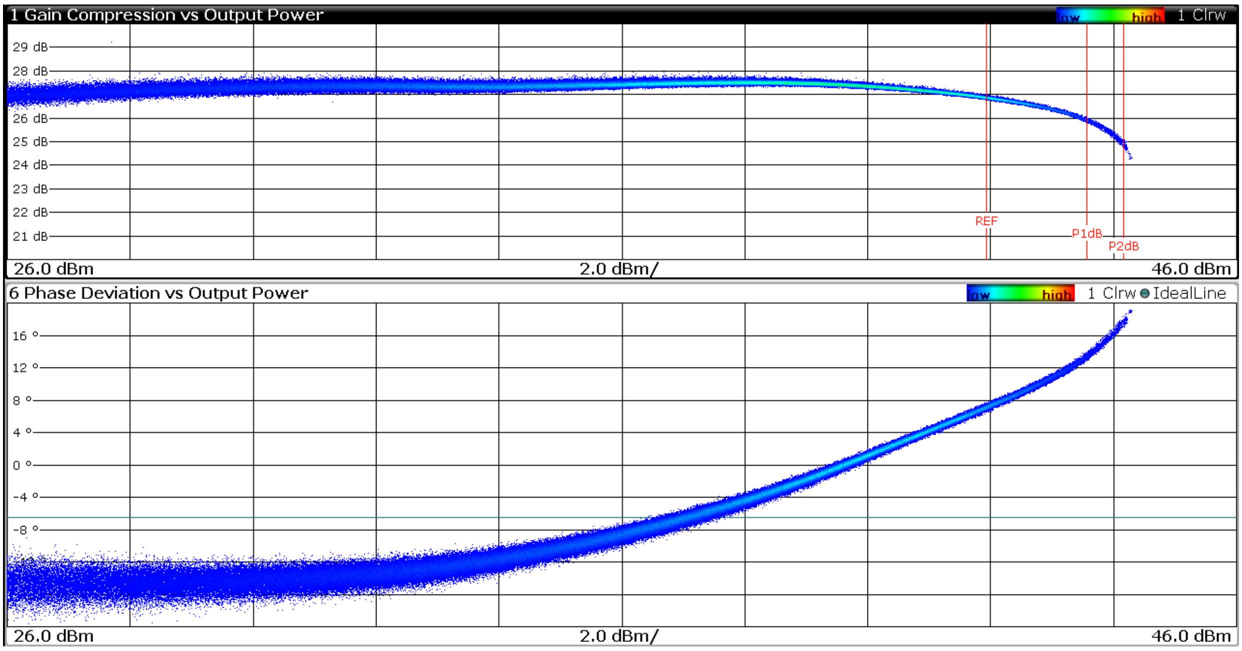

Fig. 6-6: AM-AM and AM-PM response of the Reference Doherty amplifier DUT, with fixed RF input split, at the worst case frequency of operation, using specified "Class AB" and "Class C" biasing.

Secondly, shaping the pre-DAC shaping of the auxiliary channel, with the "square-law" characteristic previously described.

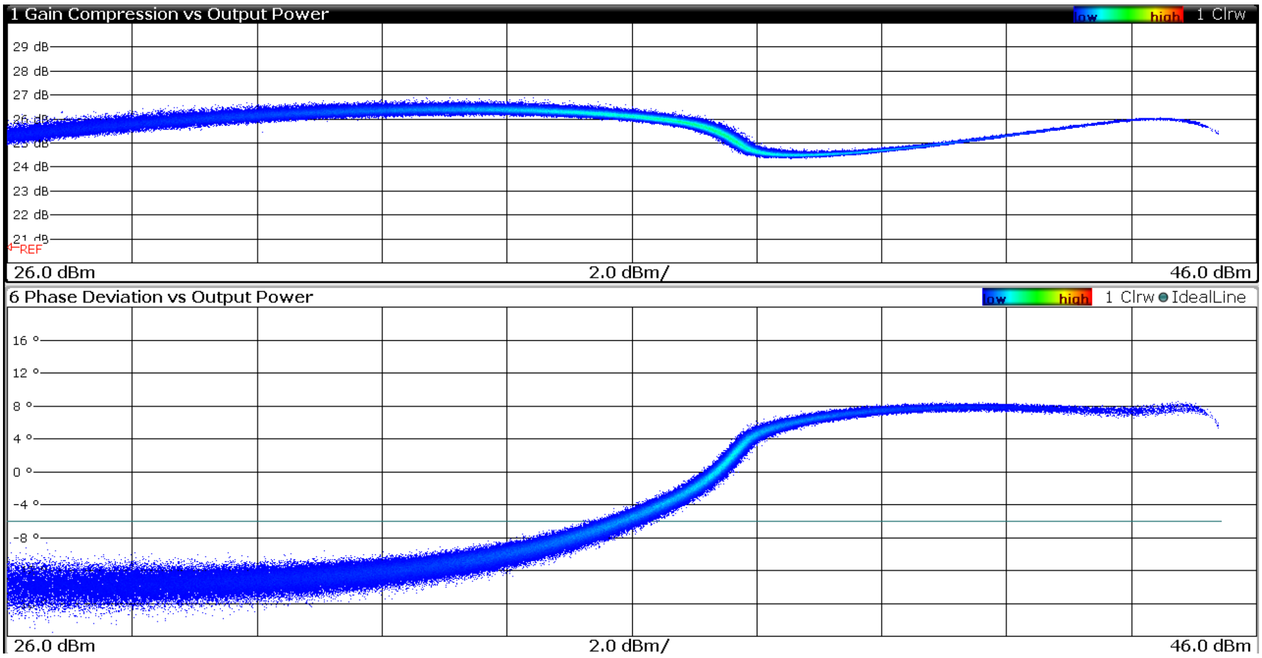

Fig. 6-7: AM-AM and AM-PM response of the Reference Doherty DUT, using pre-DAC shaping and a common bias point "Class B".

Comparing Fig. 6-6 and Fig. 6-7, it can be seen directly from the plot that a significant increase in saturated output power has been achieved (up to 1.7dB or 48%). This is due to (i) improved amplitude and phase matching of the two paths and (ii) the use of a bias class (B) that gives intrinsically higher power than the traditional (AB and C).

What is not apparent from the plots is that this increase in output power, is accompanied by an increase energy efficiency of 11%, due to (i) more ideal load-pulling and (ii) improved raw performance from the bias class.

These improvements (48%, 11% for a 100% bandwidth) are generally in-line with those (60%, 20%, 150%) reported by (Darraji, Mousavi, & Ghannouchi, 2016).

Finally, using the 'main' amplifier in class B, rather than class AB has resulted in a 94% reduction of power consumption in "stand-by" mode, i.e. when no RF input signal is applied. This is especially important for either TDMA applications, or state-of-the-art GaN devices whereby typical quiescent currents are generally "higher" than their Si-LDMOS counterparts.

All the above improvements were made despite the relatively crude square-law characteristic. The use of the SMW as the signal generator allows the use of much more sophisticated shaping functions to be applied, improving performance further.

7 Further Reading

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8 Ordering Information

Designation	Type	Order No.
Vector Signal Generator	R&S®SMW200A	1412.0000.02
	Option SMW-B106 (6GHz Path A)	1413.0104.02
	Option SMW-B206 (6GHz Path B)	1413.0904.02
	Option SMW-B10 x 2 (Baseband Generator)	1413.1200.02
	Option SMW-K522 x 2 (160MHz RF Bandwidth Extension)	1413.6960.02
	Option SMW-B13T	1413,3003.02
Signal & Spectrum Analyzer	R&S®FSWxx	1312.8000.xx
	FSW-K18 (Amplifier Measurements)	1325.2170.02
	FSW-K70 (Vector Signal Analysis)	1313.1416.02

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