Envelope Tracking and Digital Pre-Distortion Test Solution for RF Amplifiers

Application Note

Products:

| R&S®SMW200A

| R&S®FSW

The R&S®SMW200A together with the R&S®FSW is a state of the art testing solution that significantly reduces the required hardware for testing power amplifiers with envelope tracking and/or digital pre-distortion.

This application note introduces the test solution in detail and presents corresponding measurement examples.

ROHDE&SCHWARZ

Application Note

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09.2017-1GP104_2E

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1 Introductory Note

The following abbreviations are used in this application note 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®FSW-K18 amplifier measurements option (application) is referred to as FSW-K18.
- SMW instrument options, e.g. R&S®SMW-K540 are referred to as SMW-K540.

2 Overview

An increasing number of power amplifiers (PA) support the envelope tracking (ET) technology in order to reduce power consumption and improve efficiency, for example in smartphones and tactical radios. Typical setups to test PAs consist minimally of a signal generator and a spectrum analyzer. Envelope tracking requires an additional generator to provide the envelope signal for the DC supply modulator. Rohde & Schwarz offers a compact solution for characterizing power amplifiers with envelope tracking using the SMW vector signal generator and the FSW signal and spectrum analyzer, effectively replacing complex test setups.

Equipped with the SMW-K540 envelope tracking option, the SMW generates both the RF signal and the corresponding envelope signal. Since the envelope signal is generated from the baseband signal in realtime, any user-specific I/Q file or wireless communications standard, such as LTE or WCDMA, can be used. Generating the RF signal and the related envelope signal in a single instrument makes it possible to precisely adjust the delay between the two signals in realtime. The SMW offers a high bandwidth of up to 1000 MHz for the envelope signal and best spectral purity with a typical noise of only –160 dBc.

When characterizing the performance of the PA, the power added efficiency (PAE) is a key parameter. Analyzing the PAE requires time synchronous measurement of the PA's input and output power and corresponding power consumption. To address this need the FSW offers synchronous RF and baseband measurement. When equipped with the FSW-B71 option the FSW provides two additional baseband input ports for voltage and current measurement via probes. The measurements are processed by the FSW-K18 amplifier measurements option.

The envelope tracking technology is often used in conjunction with digital pre-distortion. Equipped with the SMW-K541 AM-AM, AM-PM pre-distortion option, the SMW applies digital predistortion in realtime to correct for AM-AM and AM-PM effects. Again, any user-specific I/Q file or wireless communications standard can be used. Users can load their own pre-distortion tables or alternatively use the FSW to measure the AM-AM, AM-PM distortion, automatically generate the pre-distortion tables from the measured data, and send the tables to the SMW for immediate use.

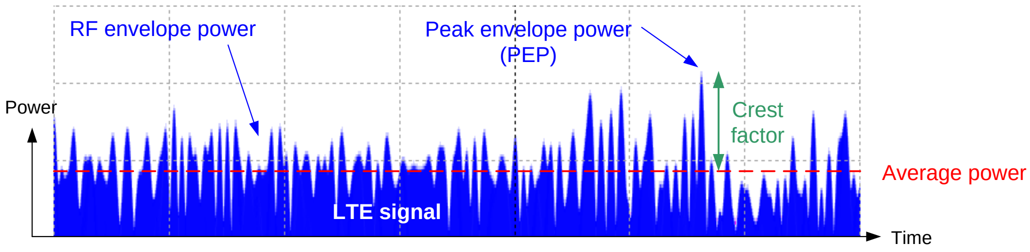
The following table gives an overview of the required instrument options for envelope tracking and optionally digital pre-distortion (minimum configuration).

Instrument options for envelope tracking and digital pre-distortion		
SMW (minimum configuration)		
Option	**Name**	**Remark**
SMW200A	Vector signal generator	
SMW-B103	Frequency option , RF path A, 100 kHz to 3 GHz	More frequency options available
SMW-B13	Baseband main module, one I/Q path to RF	SMW-B13T for two I/Q paths SMW-B13XT for two wideband I/Q paths
SMW-B10	Baseband generator with ARB (64 Msample) and digital modulation (realtime), 120 MHz RF bandwidth	SMW-B9 wideband baseband generator available for wideband applications
SMW-K16	Differential analog I/Q outputs	SMW-K17 when using SMW-B9
SMW-K540	Envelope tracking	
SMW-K541	AM-AM, AM-PM pre-distortion	Only if DPD is required
FSW (minimum configuration)		
FSW8	Signal and spectrum analyzer, 2 Hz to 8 GHz	More frequency options available
FSW-B80	80 MHz RF analysis bandwidth	More RF analysis bandwidth options available
FSW-B71	Analog baseband inputs	
FSW-B71E	80 MHz bandwidth for analog baseband inputs	
FSW-K18	Amplifier measurements	

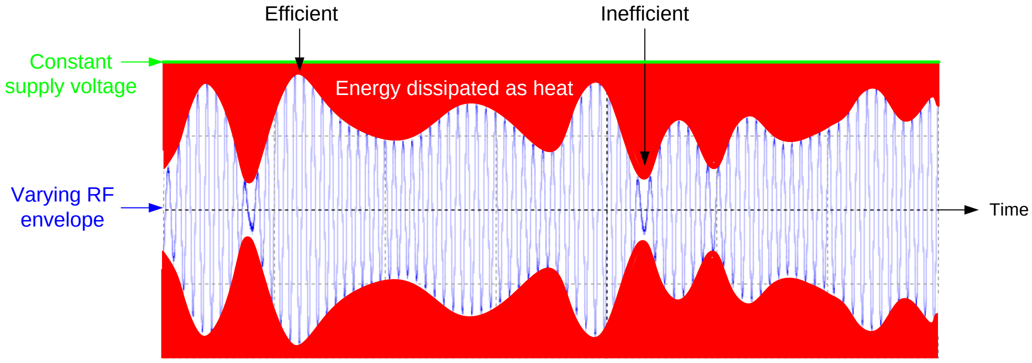
Please see reference [1] for the full list of SMW instrument options and details. Please see “R&S®FSW Signal and Spectrum Analyzer” data sheet for the full list of FSW instrument options.

3 Envelope Tracking Basics

The digital modulation schemes used for the modern communication standards such as LTE involve high crest factors. The crest factors, i.e. the peak-to average power ratios are in the range of several dBs.

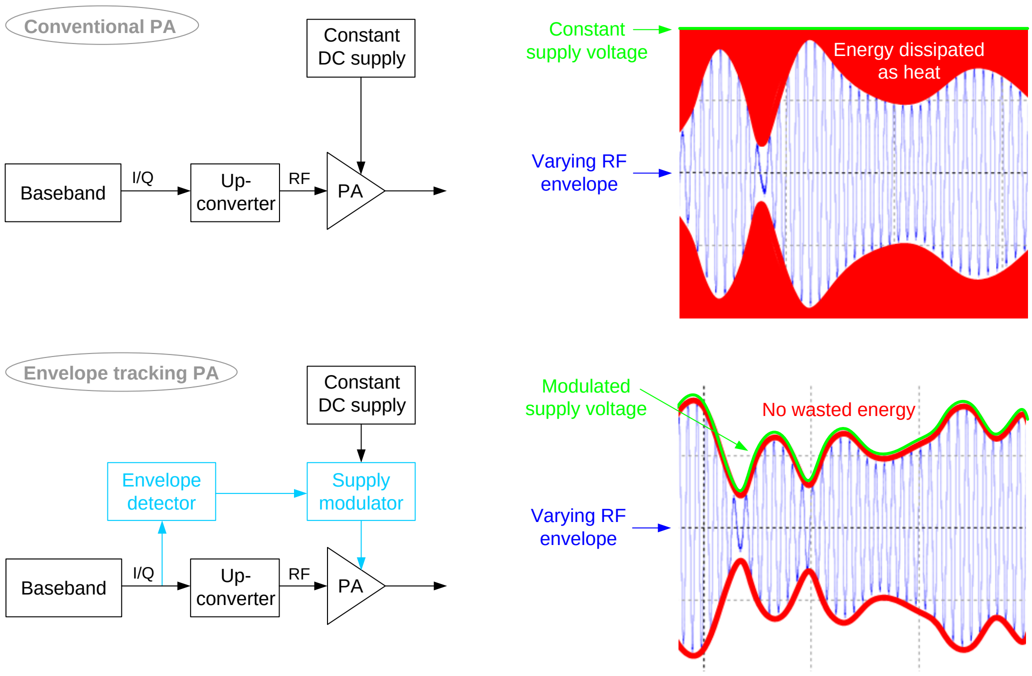


The instantaneous signal power of an LTE signal varies significantly over time which prevents operating the PA in saturated state. This means a loss of efficiency, since PAs are most efficient when operated at their peak output power. At low instantaneous powers the PA is forced to operate way below its peak output power. As a result, a significant amount of power is dissipated as heat.



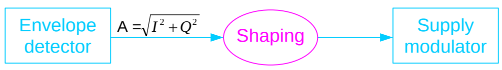
To overcome this, envelope tracking is applied. The idea of ET is to dynamically adjust the supply voltage of the PA according to the envelope of the RF input signal. By modulating the supply voltage to track the input signal's envelope, the PA's efficiency is significantly increased. This yields less overall power consumption. For example, for battery-powered PAs this means longer battery lives, which is desirable for all kinds of mobile devices.

The basic principle of ET is shown in the following figure in relation to the conventional approach.

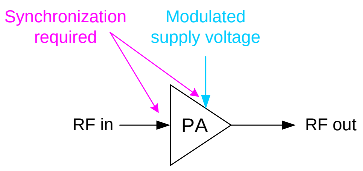


The I/Q signal generated by the baseband is upconverted to the RF and fed to the PA. In addition, the I/Q signal is used to calculate the RF envelope according to $A = \sqrt{I^2 + Q^2}$. The envelope signal is sent to the supply modulator that modulates the DC supply voltage of the PA accordingly.

Typically the direct magnitude signal *A* is not the most ideal to modulate the DC supply voltage and is usually modified by shaping, for example to optimize the PA's performance with regard to efficiency or linearity (see section 5.4 for details on shaping).



The modulated supply voltage and the RF input signal have to be aligned in time at the PA. Even small time deviations in the ns range have a substantial influence on the quality of the RF output signal. For example, the EVM can increase significantly. (See section 5.6 for details on time alignment).

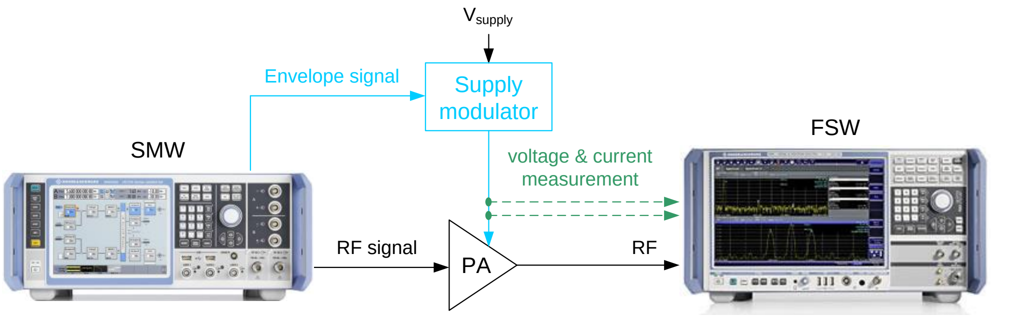


For more basics and details on envelope tracking please refer to reference [3]. This white paper gives an excellent and comprehensive introduction on ET.

4 Test Solution Overview

4.1 Complete Solution

The test solution from Rohde & Schwarz for testing envelope tracking power amplifiers is extremely powerful and yet very easy to use. It consists of the high-end vector signal generator SMW and the high-end signal analyzer FSW. All challenges involved with testing ET PAs are addressed in a user-friendly way to ease and accelerate the testing process.



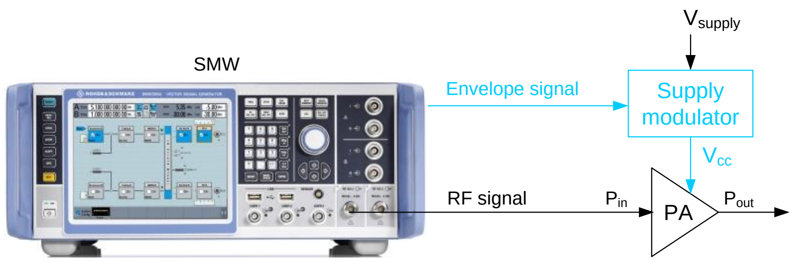
- Simultaneous RF and envelope signal generation
- Realtime pre-distortion

- RF analysis (ACLR, Rx band noise, EVM, harmonics, etc.)
- Distortion analysis (AM-AM / AM-PM conversion)
- PAE analysis

4.2 RF and Envelope Signal Generation out of One Box

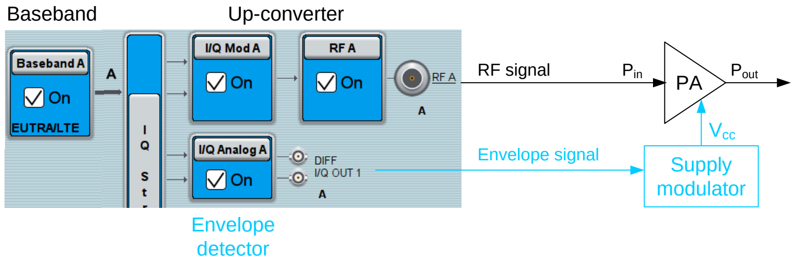
Other test solutions use separate signal generators for generating the RF signal and the envelope signal. The latter is usually generated via an ARB waveform file. A big challenge with this approach is the synchronization of the two signals/generators which is absolutely crucial for ET.

The user does not face this problem when using the SMW because the instrument generates the envelope signal automatically in realtime based on the set RF signal. Additional time alignment on the picoseconds to nanoseconds scale is easily possible.



- RF and envelope signals out of one box
- Synchronous signals with adjustable delay
- All in realtime

The SMW calculates the envelope signal directly from the baseband I/Q signal and outputs it at the analog I/Q connectors.



The SMW supports signal generation for all important mobile communications standards and for user-specific data via the ARB. The envelope signal is calculated automatically in realtime, i.e. it is immediately adjusted when the user changes the baseband/RF signal characteristics. This means, the user can reconfigure the baseband/RF signal settings as desired and the envelope signal adapts accordingly without any user-action – there's no easier and quicker way.

Please see section 5 for details on the envelope tracking feature of the SMW.

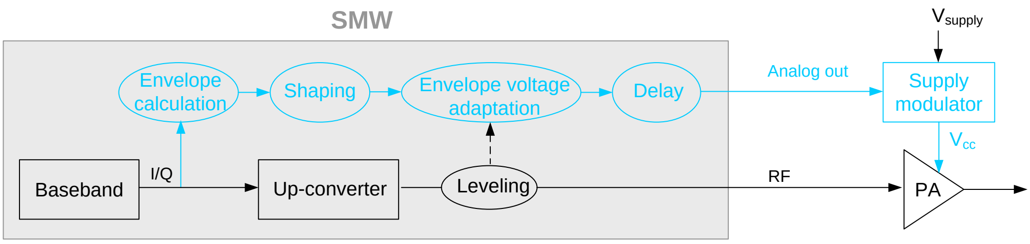
Conventional approach: Dual ARB method

When equipped with a second instrument path (path B), the SMW comprises two complete signal generators in a single box. The two internal ARB/baseband sources can be easily synchronized. The user can therefore use the SMW also in the conventional way by generating the envelope signal via the ARB generator in the second instrument path (i.e. via path B). With this method time alignment with adjustable delay on the picoseconds to nanoseconds scale is also possible and straightforward on the SMW.
This application note however focuses on the realtime approach using the SMW-K540.

5 Envelope Tracking with the SMW

5.1 Overview

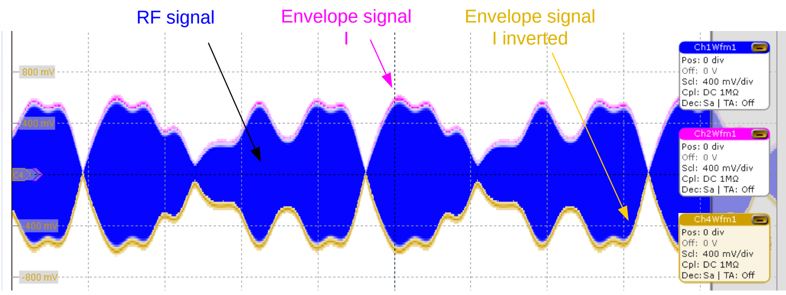
In an envelope tracking test setup, a single SMW provides the two required test signals (RF and corresponding envelope) for testing the PA in combination with the DC supply modulator. The envelope signal can be shaped in a flexible way and a time delay can be applied to achieve perfect synchronization of the two signals at the PA inputs.



The envelope signal is output at the analog I/Q output:

- at the “I” connector (single-ended)
- at the “I” and “I inverted” connectors (differential)

The envelope signal stimulates the DC supply modulator which then provides a modulated supply voltage (V_{cc}) to the PA.



The following sections give more information about the individual blocks shown in the logical block diagram above.

5.2 Baseband Signal

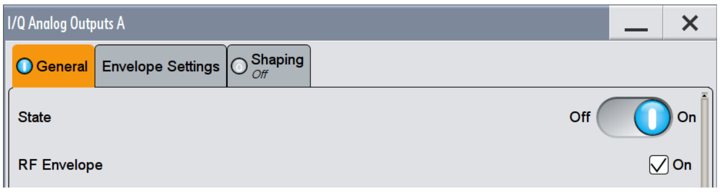
Any baseband signal can be used. The envelope tracking function works with all available digital standards (such as LTE, WLAN, etc.) and ARB waveforms. Downlink as well as uplink signals can be used for base station and user equipment test.

5.3 Envelope Calculation

The envelope signal is calculated directly from the I/Q signal according to $A = \sqrt{I^2 + Q^2}$.

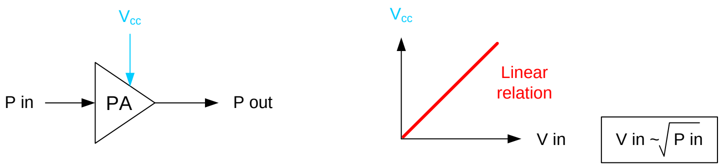
The envelope signal is calculated in realtime. It adapts immediately and automatically to setting changes of the baseband/RF signal.

Envelope calculation is enabled by checking the “RF Envelope” check box in the “I/Q Analog Outputs” menu.

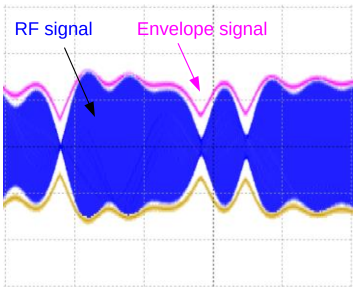


5.4 Shaping

The pure magnitude signal *A* gives a simple linear relation between the envelope-modulated supply voltage (V_{cc}) and the RF input.



This perfect linear relation is not used in practice. For example, real envelope signals usually do not track down to zero volts.



This modification of the linear relation is called envelope shaping. Shaping is an essential part of ET and makes it possible to optimize the PA’s performance. The shaping of the envelope signal determines whether the PA is optimized for highest efficiency or maximum linearity (see reference [3] for more details).

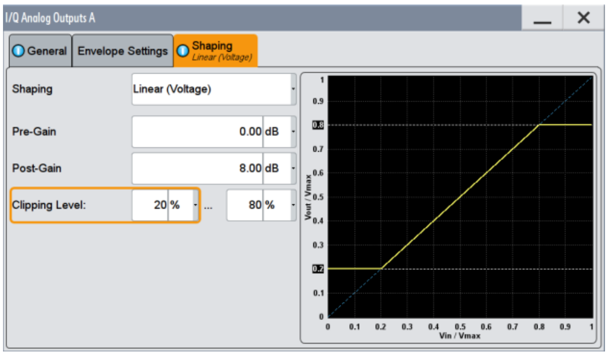
With the SMW shaping is easily possible in a very flexible way. The SMW offers the following configurable shaping functions:

- Linear (Voltage) and Linear (Power)
- Lookup table
- Polynomial
- Detroughing

The shaping is applied in realtime with immediate effect on the envelope signal.

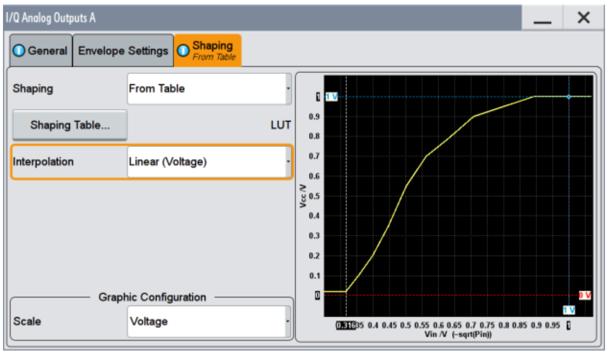
Linear

The shaping function shows the linear relation but with configurable clipping levels and pre- and post-gains (in manual mode – see section 5.5.1).



Lookup table

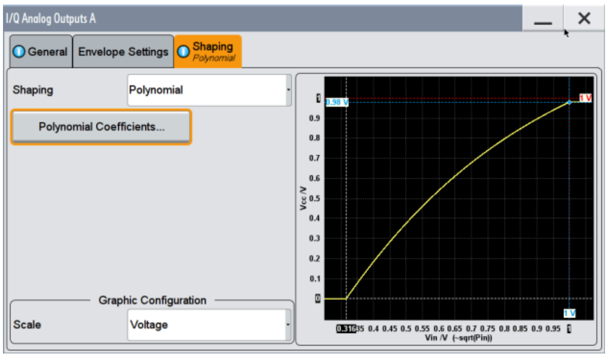
The shaping function is defined by a table of user-specific value pairs (up to 4000). A linear interpolation can be applied in between the specified points to smooth the shaping curve.



See section 11.1 for details on the file format.

Polynomial

The shaping function is defined by a polynomial. The order of the polynomial function can be selected – up to 10th order is supported with definable polynomial coefficients.

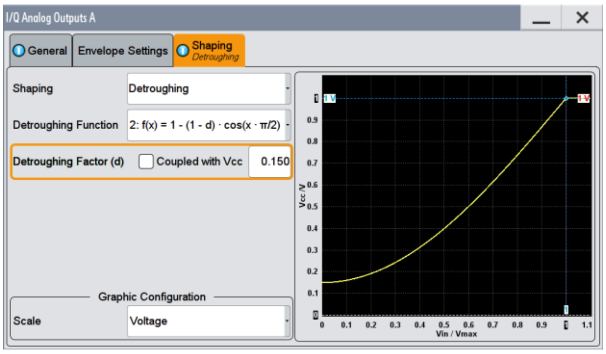


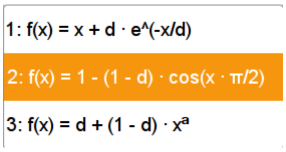
Detroughing

The shaping function is defined by a detroughing function. Three different detroughing functions can be selected with configurable detroughing factors (see screenshot below).

Detroughing prevents V_{cc} to drop down to zero volts, i.e. it ensures that a minimum supply voltage is present at the PA.

The detroughing factor *d* determines the shaping curve and the minimum clipping level via the (selectable) detroughing function.

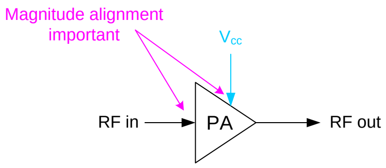




If the check box “Coupled with Vcc” is enabled, the detroughing factor is calculated from the Vcc values entered in the “General” tab (see section 5.5) according to
$d = Vcc_{min} / Vcc_{max}$.

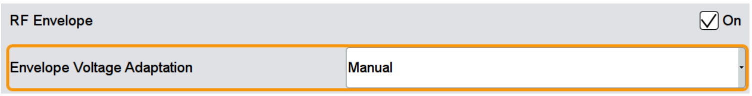
5.5 Envelope Voltage Adaptation

It is important that V_{cc} and the RF input signal are closely aligned in magnitude at the input of the PA. For this reason, gain and offset adjustment of the envelope signal must be possible.

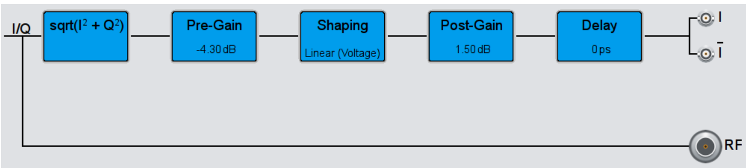


With the SMW, the user has the choice between manual and automatic adjustment of the envelope magnitude.

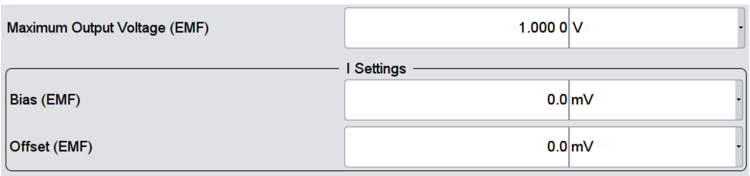
5.5.1 Manual Envelope Voltage Adjustment



In manual mode, the user can set pre- and post-gains and define upper and lower clipping levels for the envelope signal (via the “Shaping” tab).



In addition, the maximum output voltage, a bias and an offset can be defined.

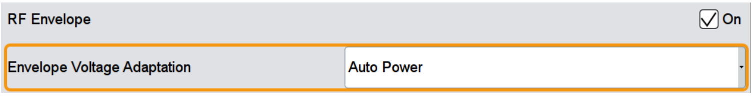


The user can therefore adjust and optimize the magnitude of the envelope signal for a single RF input signal level.

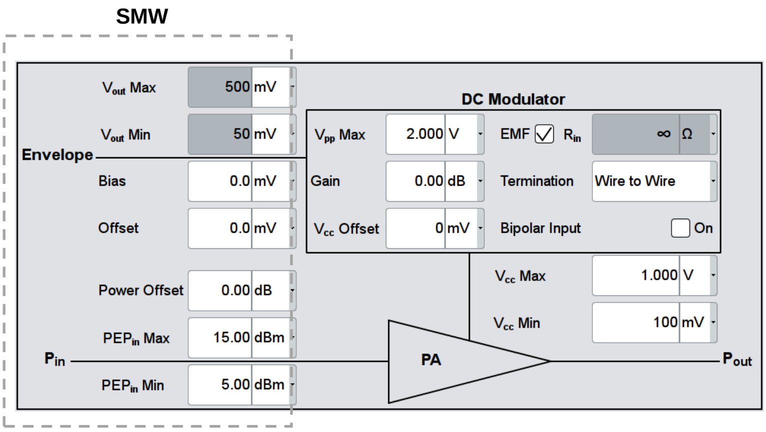
If the level of the RF signal changes, the envelope signal level needs to be adapted accordingly. The SMW is able to do this automatically as explained in the following section.

5.5.2 Automatic Envelope Voltage Adjustment

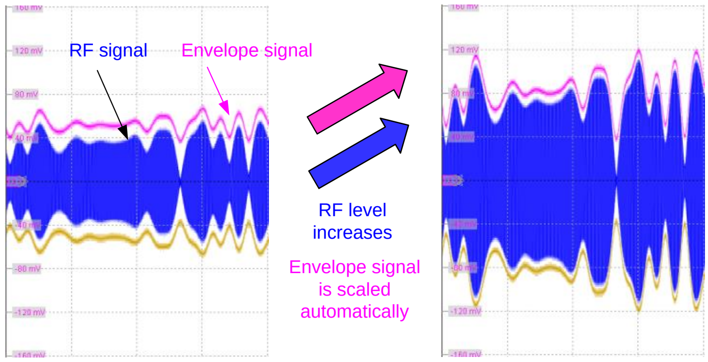
All power amplifiers are tested over a range of different RF input levels. This can be achieved by varying the mean RF level of the signal generator. When sweeping the RF input level it is important that the magnitude of the envelope signal scales with the mean RF level. In the SMW, the user can define ranges for the RF input level and Vcc which he intends to apply to the PA, and the SMW automatically adjusts the magnitude of the envelope signal according to the current RF level. This feature provides an enormous testing time reduction compared to other solutions on the market.



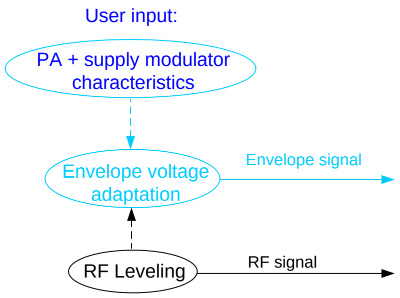
In automatic mode ("Auto Power" and "Auto Normalized"), the user can enter the physical characteristics of the used DC supply modulator and the PA under test. Design parameters such as RF input power (Pin), Vcc, DC modulator gain, etc. can be entered via an intuitive graphical user interface (see section 6 for further details). The parameters are used in the SMW to determine the required output voltage level (V_{out}) at the analog I/Q outputs.



The magnitude of the envelope signal is scaled automatically based upon the specified parameters and the set RF power level.



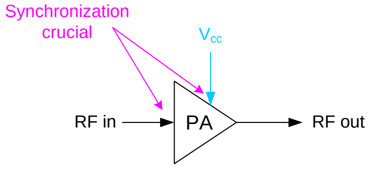
When changing the mean RF level, the envelope voltage level is automatically adapted. This is a great benefit for the user, because time-consuming adjustments of parameters for different RF levels are no longer necessary.



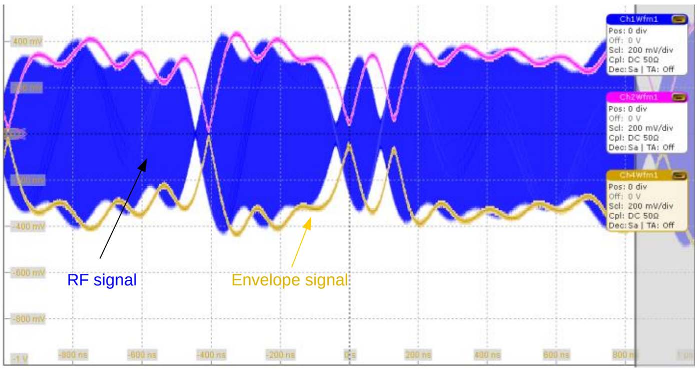
The automatic magnitude scaling of the envelope signal is especially beneficial during RF level sweeps. Here, it can provide enormous time savings compared to the manual method.

5.6 Time Delay

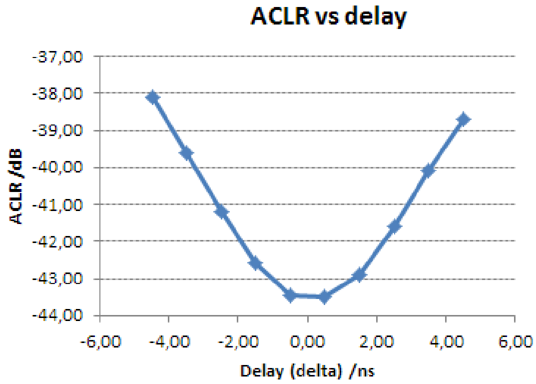
It is crucial that V_{cc} and the RF input signal are aligned in time at the input of the PA. For this reason, delay adjustment of the envelope signal must be possible.



The SMW offers the possibility to adjust the delay between the RF and envelope signal in a range of ± 500 ns with a resolution of 1 ps. The delay adjustment is done in realtime with immediate effect on the signals. This allows the user to perfectly synchronize the signals at the input of the PA, compensating e.g. cable delays – quick and easy.



The importance of synchronization becomes obvious when looking at the ACLR of the PA's output signal, i.e. at the power in the adjacent channel. The ACLR increases already significantly if the RF input signal and the envelope-modulated supply voltage (V_{CC}) deviate from the optimum by a few nanoseconds.



The same behavior is observed when looking at the EVM, i.e. at the modulation accuracy of the PA's output signal. (See also section 9.2.)

5.7 Up-Conversion & Leveling

The baseband signal is upconverted to generate the RF signal.

The user can set the mean RF level via the "Level" parameter.

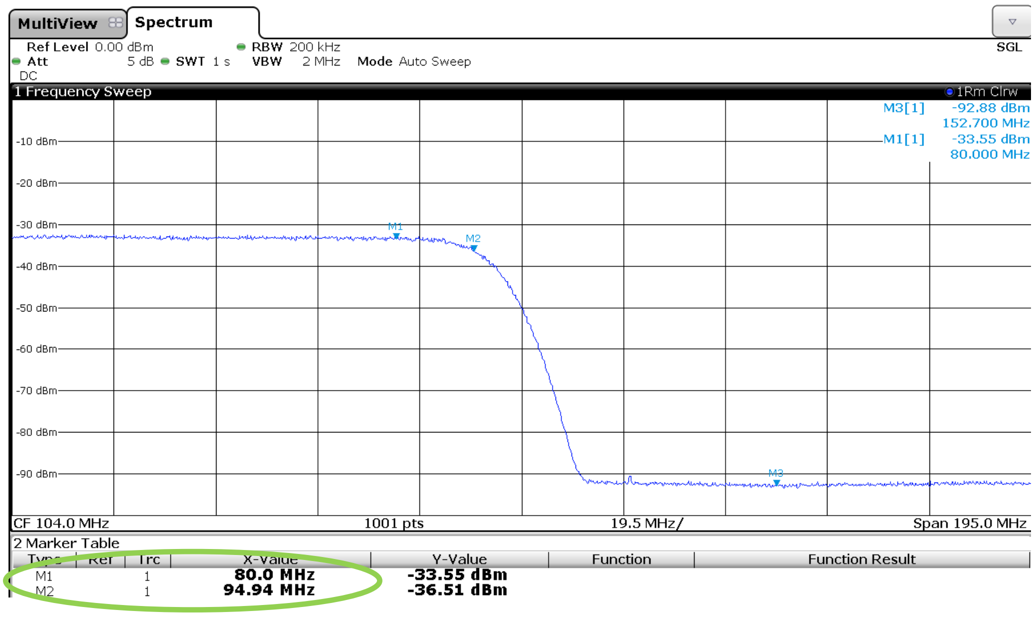
As described in section 5.5.2, this setting influences the voltage level of the envelope signal (when automatic envelope voltage adaptation is enabled).

5.8 Properties of the Envelope Signal

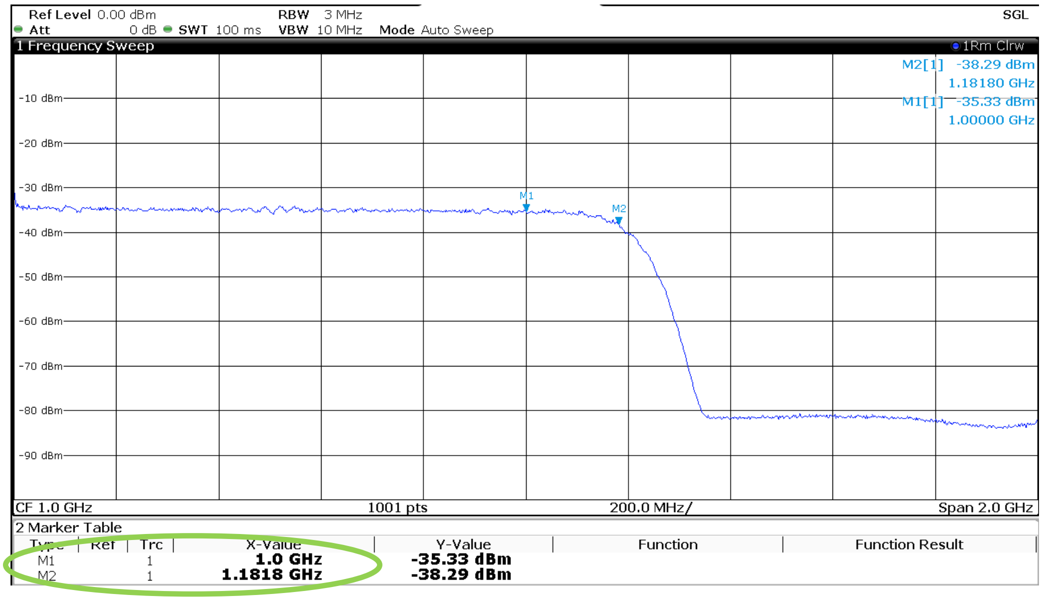
The following table gives an overview of some important properties of the envelope signal generated by the SMW.

Overview of envelope signal properties		
Baseband generator / diff. analog I/Q outputs	**SMW-B10 / SMW-K16**	**SMW-B9 / SMW-K17**
Bandwidth	80 MHz max.	1000 MHz max.
Sample rate	200 MHz	2400 MHz
Noise	< -148 dBm/Hz (measured, LTE signal, see below)	-160 dBc (typical, 10 MHz sine wave at 1 MHz offset, see [1])

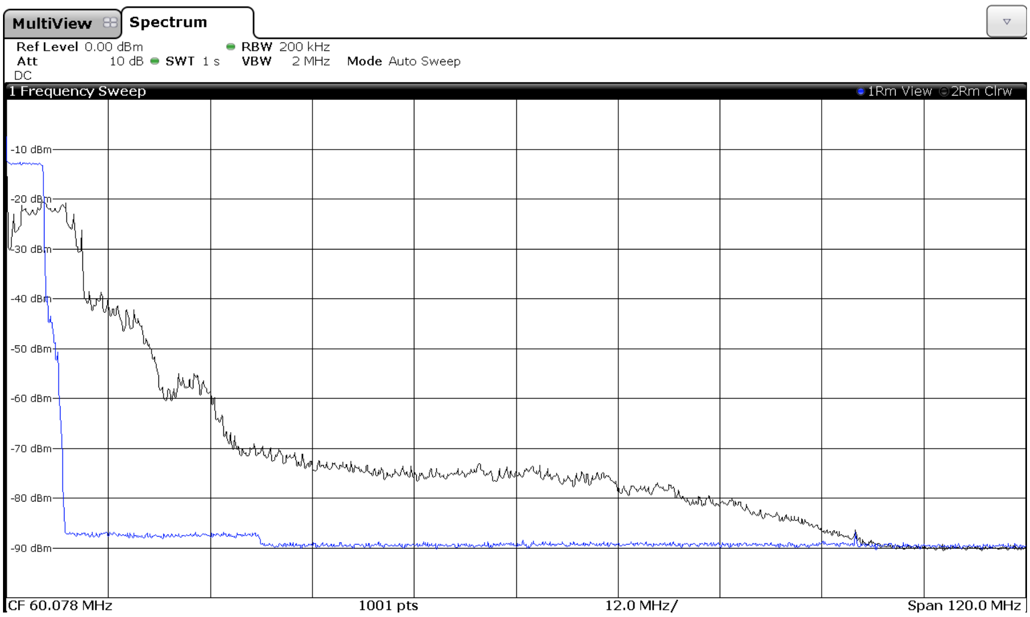
The specified bandwidth of the analog I/Q outputs (SMW-K16) is 80 MHz. The following figure shows the bandwidth of the I signal with an AWGN signal as source.



The specified bandwidth of the wideband analog I/Q outputs (SMW-K17) is 1000 MHz. The following figure shows the bandwidth of the I signal with an AWGN signal as source.

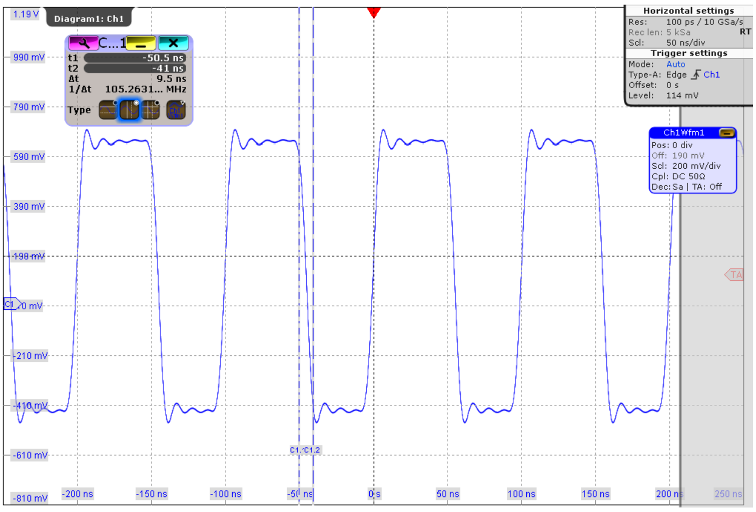


A large bandwith is important since the envelope signal can have a two to three times greater bandwith than the corresponding RF signal – and even greater. For LTE signals with a maximum bandwith of 20 MHz, the envelope signal can have e.g. 60 MHz bandwith, which is well within the 80 MHz analog I/Q bandwidth of the SMW-K16. The following figure shows the I signal of a 10 MHz LTE signal (blue) and the corresponding envelope signal (black) making the difference in bandwidth evident.

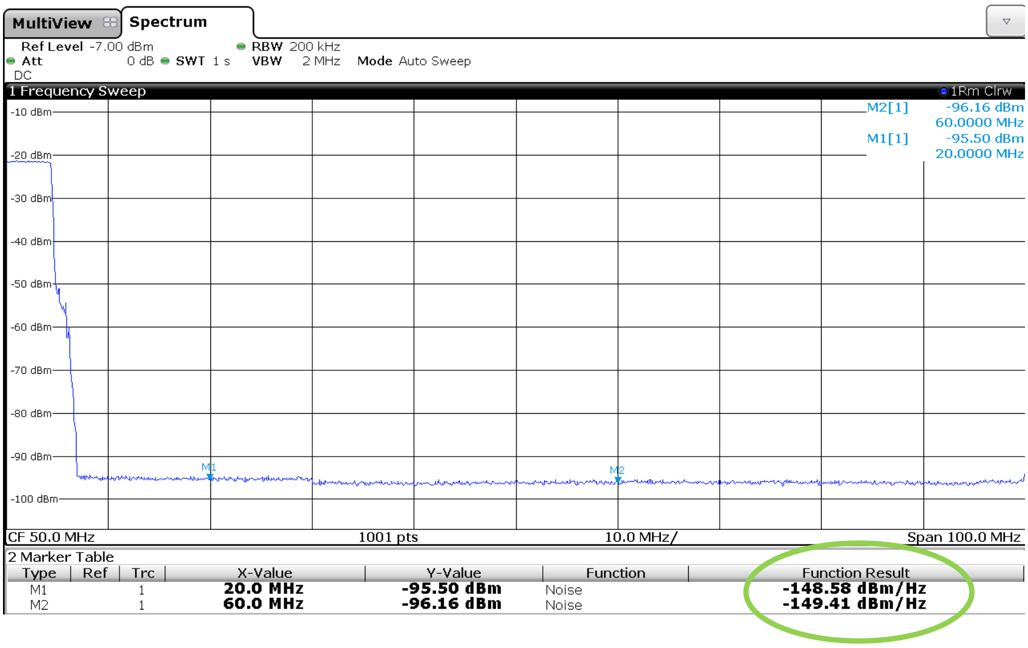


Due to the fact that the envelope signal bandwidth is larger than the RF signal bandwidth it is not sufficient to use the same sample rate for both signals. For example, using a sample rate of 30.72 MHz for a 20 MHz LTE signal is appropriate for generating the RF signal, it is however not enough for generating the wider envelope signal. For calculating the envelope signal, a higher sample rate must be used. With the SMW the user is on the safe side, since the envelope signal is generated at a sample rate of 200 MHz (SMW-B10) or 2400 MHz (SMW-B9) – enough for the supported 80 MHz (SMW-K16) or 1000 MHz (SMW-K17) analog I/Q bandwidth, which equals 160 MHz RF bandwidth or 2000 MHz, respectivly.

The slew rate of the analog I/Q outputs is greater than 100 V/µs. The following figure shows the I signal with a rectangular signal as source.



The analog I/Q outputs of the SMW offer high spectral purity as can be seen for example in the following figure (SMW-K16 signal). It shows the I signal of a 10 MHz LTE signal and two noise markers which read nearly 150 dBm/Hz.



The following table lists some fundamental properties of the analog I/Q outputs.

Properties of the analog I/Q outputs		
Baseband generator / diff. analog I/Q outputs	**SMW-B10 / SMW-K16**	**SMW-B9 / SMW-K17**
Slew rate	> 100 V/µs	> 100 V/µs
Impedance	50 Ω (single-ended) 100 Ω (differential)	50 Ω (single-ended) 100 Ω (differential)
Voltage range	0.02 V to 2 V (V_p, single-ended) 0.04 V to 4 V (V_{pp}, differential)	0.02 V to 1 V (V_p, single-ended) 0.04 V to 2 V (V_{pp}, differential)

Please see reference [1] for the full specifications of the analog I/Q outputs such as bias and offset voltage ranges, etc.

6 Operating the SMW

6.1 Quick Start Guide

This section briefly lists the steps required to configure the SMW for ET testing.

RF part

- Configure and turn on a baseband signal in the "Baseband" block.
- Set RF frequency and level.[1]
- Turn on the RF output.

Envelope part

- Click on the "I/Q Analog" block and open the "I/Q Analog Outputs" menu.

"General" tab

- In the "General" tab, enable the "RF Envelope" check box.
- Select the desired "Envelope Voltage Adaptation" mode, e.g. select "Auto Power".
- Select the desired "I/Q Output Type", e.g. select "Differential".
- Select the desired "Envelope Voltage Reference", e.g. select "Vcc" (default setting).
- Start first with defining the parameters of the "DC Modulator" (properties of the external DC supply modulator).
- Define a bias (and offset) for the analog I/Q output signal V_{out}.
- Then, define the parameters for V_{cc} (i.e. the modulated supply voltages to be applied).
- Define the parameters for P_{in} (i.e. the RF input powers to be applied).[1]

→ The defined parameters are used for determining the magnitude of the analog I/Q output signal V_{out} (envelope signal) for the currently set mean RF level.

"Shaping" tab

- Switch to the "Shaping" tab and select a shaping function, e.g. "Detroughing".
  - Choose a detroughing function.
  - Define a detroughing factor.

→ The resulting shaping function is graphically displayed.

"Envelope Settings" tab

- Switch to the "Envelope Settings" tab and adjust the "Envelope to RF Delay" (time delay) as required.

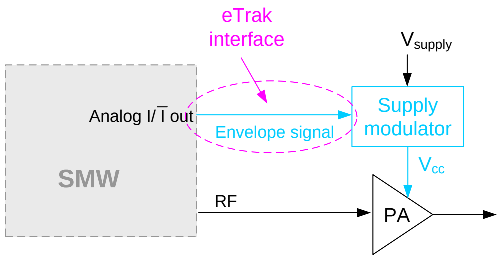
→ This parameter is used to compensate a possible time delay between the RF and the envelope signals at the PA.

[1] The set mean RF level (in "RF part") should be within the defined P_{in} range (in "Envelope part").

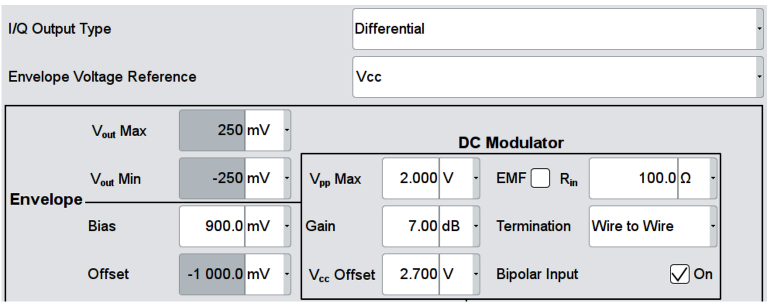
See also reference [2] for details on the individual setting parameters and the graphical display of the shaping curve.

6.2 Configuring the DC Modulator Settings

Many DC supply modulators on the market are compliant with the eTrak specification. The MIPI alliance has defined a specification for an analog reference interface for envelope tracking (abbreviated as eTrak) to support the deployment of ET. The eTrak interface is the standardized analog interface between the transmitter (SMW in this case) and the DC supply modulator (termed ET power supply (ETPS) in the specification). The eTrak interface uses differential signaling. The specification includes three interface voltage classes: 2V_{PP} interface class, 1.5V_{PP} interface class and 1.2V_{PP} interface class. In the following example, the DC modulator settings are configured for an eTrak-compliant DC supply modulator with 2V_{PP} interface.



- In the “General” tab, set the “I/Q Output Type” to “Differential”.
  → Differential signaling.



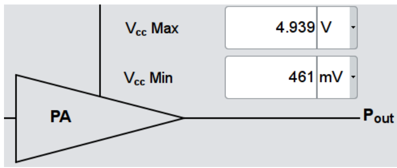
- Set the “V_{PP} Max” parameter to 2.0 V.
  → 2V_{PP} interface class. Differential voltage V_{diff} can be between ± 1 V.
- Enter the gain of the DC supply modulator.
  → The gain describes the amplification of the differential input voltage by the DC supply modulator. The gain is device-specific and not specified by the eTrak standard. It is typically different from zero.
- Specify the input impedance (R_{in}) and the termination of the DC supply modulator.
  → The impedance is device-specific and not specified by the eTrak standard.
- Enable “Bipolar Input”.
  → The “Offset” parameter is automatically set to Offset = – 0.5 · V_{PP} Max.

- Adjust the "V_{CC} Offset" parameter.
  → The V_{CC} Offset is the output voltage of the DC supply modulator when V_{diff} is 0 V. The V_{CC} offset is device-specific and not specified by the eTrak standard. The V_{CC} offset can be determined by applying 0 V differential voltage at the input of the DC modulator and measuring the output voltage.
- Set the "Bias" parameter to 900 mV.
  → The common mode voltage is 900 mV as requested by the standard.

The parameters "V_{PP} Max", "Gain", and "V_{CC} Offset" determine the possible Vcc range according to the following formulas:

$$V_{diff,\,min} = -0.5 \cdot V_{PP}\,Max$$
$$V_{diff,\,max} = +0.5 \cdot V_{PP}\,Max$$

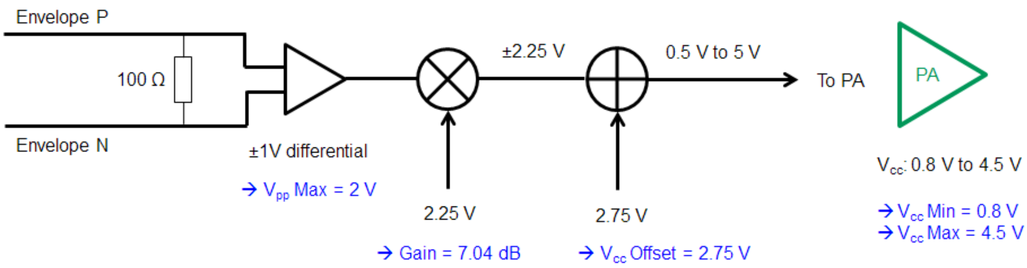
$$V_{CC,\,min} = V_{CC}\,Offset + Gain \cdot V_{diff,\,min}$$
$$V_{CC,\,max} = V_{CC}\,Offset + Gain \cdot V_{diff,\,max}$$

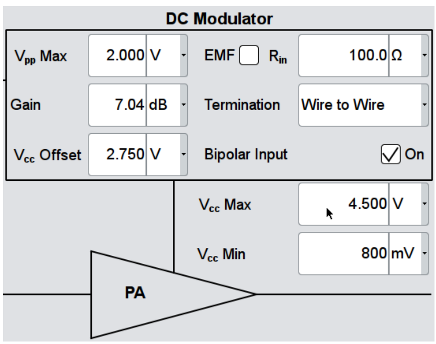


The parameters "V_{CC} Max" and "V_{CC} Min" in the "General" tab can be used to further limit the Vcc range if required by the PA under test.

6.2.1 Example

The following figure shows a simplified schematic of a DC supply modulator and the corresponding settings in the GUI.





7 Envelope Tracking with the FSW

The FSW is the ideal high-end analysis platform for characterizing the performance of an envelope tracking PA. It supports conventional RF measurements such as modulation accuracy (EVM) and spectral purity (e.g. ACLR) and in addition ET-relevant measurements such as power added efficiency (PAE).

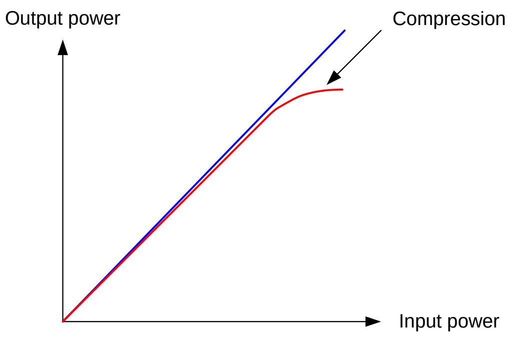
The high measurement speed of the FSW reduces testing times. For example, the instrument can analyze the EVM of a WCDMA uplink signal in 23 ms (one slot). Its very high dynamic range of 88 dBc for WDCMA makes it possible to perform receive band noise measurements without additional filters which simplifies the setup.

For envelope tracking, a FSW equipped with analog baseband inputs (FSW-B71) allows to measure the RF signal and the supply voltage/current signals in parallel using probes (see section 7.2 for details).

The on-instrument FSW-K18 application supports measurements such as AM-AM, AM-PM distortion analysis, PAE calculation, raw EVM and ACLR measurements, and more. The FSW-K18 can control the SMW via LAN, e.g. to send/receive a signal waveform. By comparing this reference waveform with the measured signal sample by sample, the FSW-K18 can determine the mentioned measurements (raw EVM, AM-AM, AM-PM distortion, etc.). In addition to the reference waveform, the FSW-K18 needs to know the output power of the SMW (user input).

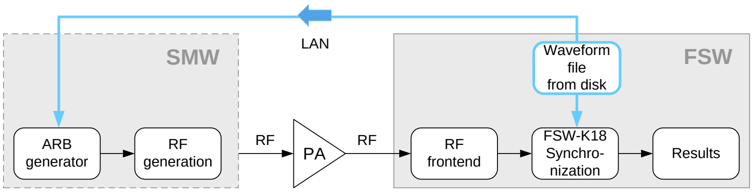
7.1 AM-AM and AM-PM Distortion Analysis

The AM-AM, AM-PM distortion analysis is an important measurement to characterize a PA. AM-AM and AM-PM conversions are a measure of the PA's nonlinearity.

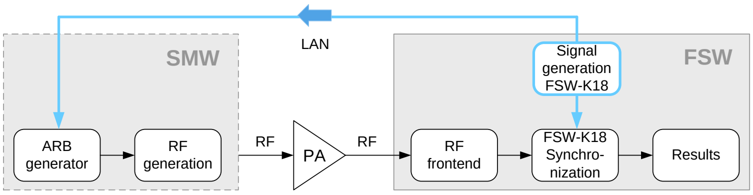


AM-AM conversion

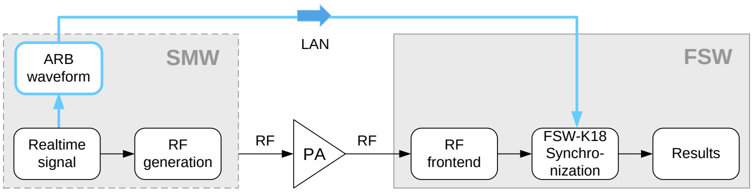
To perform this measurement the FSW must have knowledge of the ideal signal waveform. This waveform serves as a reference for calculating the distortion. There are three possibilities:
(1) The FSW can transmit a known waveform (from a file) to the SMW and the SMW plays back this signal via its internal ARB generator. The supported file formats are *.iq-tar, *.wv, *.iqw.



(2) The FSW can generate an OFDM-like multicarrier signal with user-settable parameters such as signal bandwidth, length, target crest factor, pulse duty cycle, etc. The carriers have equal levels with variable phases. The user can insert a notch with definable width and position. The generated signal waveform is transmitted to the SMW and the SMW plays it back via its internal ARB generator.



(3) The FSW gets the waveform directly from the SMW by saving the currently used signal to a waveform file and downloading it. The currently used signal on the SMW can be a realtime signal or an ARB signal – that makes no difference. The file length (e.g. in frames) can be set in the SMW.



The FSW can then measure the RF output signal of the PA and compare the measured waveform with the reference waveform to calculate the distortion. Instantaneous as well as averaged AM-AM, AM-PM distortion is calculated. See section 9.5 for an example measurement. The obtained AM-AM and AM-PM curves can be exported, e.g. to the SMW for use with the SMW's pre-distortion feature (see section 8 for details).

The FSW-K18 application can be used to

- send/read a signal waveform to/from the SMW

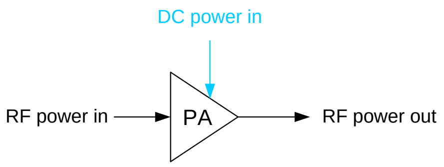
- perform the AM-AM and AM-PM measurements
- calculate pre-distortion tables from the measurements (done automatically) and transfer the tables to the SMW
- enable pre-distortion on the SMW

7.2 Instantaneous PAE Analysis

The baseband input ports of the FSW can be used together with probes, e.g. with oscilloscope probes from Rohde & Schwarz, for measuring the supply voltage (Vcc) and the supply current. The supply current can be measured by means of a shunt resistor (see section 7.2.1 for details).

The simultaneous measurement of supply voltage and current gives the power consumption of the PA. With knowledge of the RF input power to the PA (via reference waveform) and the RF output power (via RF measurement) the PAE can be calculated. See section 9.8 for an example measurement.

$$PAE = \frac{Pout_{RF} - Pin_{RF}}{Pin_{DC}} \%$$

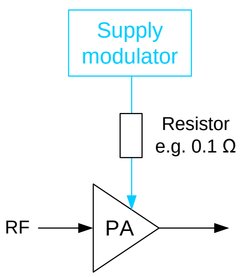


The RF input power is not measured but determined based on the signal waveform and the average power of the input signal (user input). Thus, the FSW must have knowledge of the signal waveform (reference waveform). As mentioned in section 7.1, the FSW can send a waveform file to the SMW for playback or alternatively the FSW reads the currently used signal waveform directly from the SMW.

The PAE is an important parameter when characterizing envelope tracking PAs since this value directly indicates the gain in efficiency achieved through ET.

7.2.1 Probing the Supply Current

The supply current can be measured by means of a shunt resistor. A resistor with small known resistance, e.g. 0.1 Ω, is included in the circuit between the DC supply modulator and the PA. A measurement of the voltage drop over the resistor gives the desired current signal.



There are several challenges when measuring the current [4]. The common mode rejection of the probing device must be very high over the whole measurement bandwidth. The modulated supply signal can have a two to three times greater bandwith than the corresponding RF signal. For LTE signals with a maximum bandwith of 20 MHz, the measurement bandwidth can therfore be up to 60 MHz. A high common mode rejection is necessary because the voltage excursions are significant at both sides of the resistor and they vary fast. However, the voltage drop to be measured is very small due to the small resistance value. In addtion, the probing device must not introduce significant impedance into the line, i.e. the impedance seen by the PA must not increase significantly. To achieve highest measurement accuracy, users utilize special (custom) circuitry for probing the current.

In many cases, a voltage probe is used to measure the voltage drop over the resistor. For example, a Rohde & Schwarz RT-ZD differential voltage probe can be directly connected to the FSW for this purpose. The FSW converts the measured voltage signal into a current signal.

R&S® RT-ZD oscilloscope probe

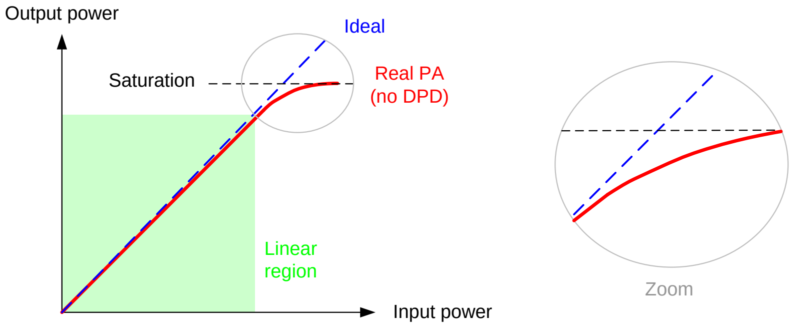
8 Digital Pre-Distortion

The shaping of the envelope signal can be adjusted to achieve maximum linearity of the PA, i.e. constant amplifier gain. Such shaping yields low AM-AM distortion [3]. If the applied shaping rather aims at achieving maximum efficiency (compared to linearizing the PA), the amplifier gain can vary with output power. Such shaping causes AM-AM and AM-PM distortion, which can be compensated however by digital pre-distortion (DPD).

8.1 Basics

DPD is applied to linearize the PA to correct for AM-AM and AM-PM effects and to increase the efficiency by pushing the compression point to higher output powers.

The following figure illustrates the performance of an unlinearized PA. At a certain input power the PA begins to compress and finally goes into saturation. The wanted signal, e.g. a LTE signal with a crest factor in the order of 10 dB, must be entirely within the linear region of the PA transfer curve. Otherwise clipping of the signal peaks takes place which results in degraded EVM and ACLR performance.

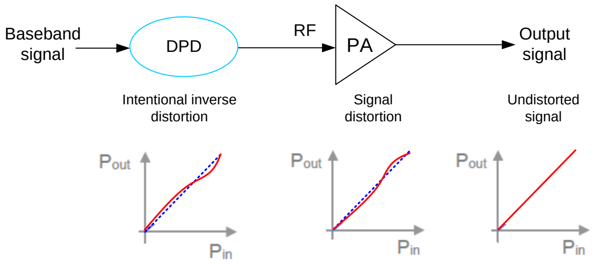


Without predistortion – unlinearized performance

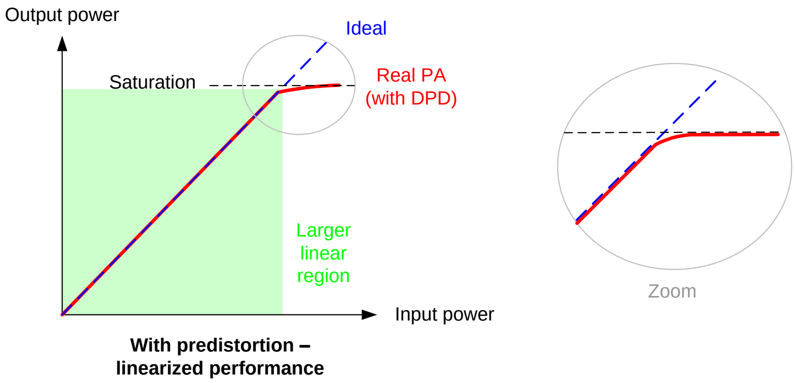
DPD can be used to

- improve the linearity in the linear region (amplitude and phase).
- increase the linear region by compensating the compression.

To reduce the overall distortion (including linear and nonlinear regions) at the output of the PA, DPD uses the following principle: The digital baseband signal is intentionally distorted such that the pre-distorted RF signal at the PA's input results in a correct (undistorted) signal at the output of the PA.



The following figure illustrates the effect of DPD on the PA's transfer curve.



DPD allows the PA to operate more close to its saturation point. The linear region extends. DPD therefore leads to additional (linearized) output power.

Please note that there is an intrinsic limit to any predistortion solution: the PA's saturation level. DPD cannot correct signals whose peaks extend much past the saturation point because the amount of signal clipping gets too significant. The consequence of clipping would be poor signal ACLR and EVM.

DPD can be implemented as "open loop" DPD or "closed loop" DPD. Open loop systems typically apply a lookup table that contains correction values for amplitude and phase derived from AM-AM and AM-PM measurements. In contrast to this static approach, closed loop systems apply a receiver for measuring the PA's output signal that is compared with the ideal signal to find the correction values. Closed loop DPD is adaptive, i.e. the correction values are constantly updated based on the measurement.

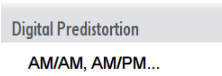
There are two types of DPD: "memoryless" DPD and DPD "with memory". Memoryless DPD corrects amplitude and phase of an I/Q sample on the basis of the current sample only. In contrast, DPD with memory corrects amplitude and phase of an I/Q sample on the basis of several previous samples and their interdependencies. The response of the PA generally does not only depend on the current signal amplitude but also on the amplitudes of the previous samples. This memory effect in not taken into account by memoryless DPD. The advantage of memoryless DPD is however that it can be implemented relatively straightforward as a lookup table, whereas DPD with memory involves much higher computational complexity.

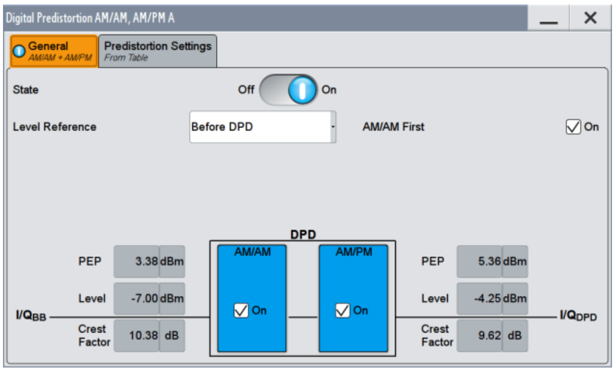
8.2 DPD in the SMW

The SMW is capable of applying AM-AM and/or AM-PM predistortion in realtime. The pre-distortion feature works with any baseband signal, i.e. with all digital standard signals (such as LTE, WLAN, etc.) and ARB waveforms. DPD works for all signal bandwidths, i.e. 160 MHz RF bandwidth at maximum with the SMW-B10 and 2000 MHz RF bandwidth with the SMW-B9. DPD is applied on each I/Q sample, i.e. from sample to sample.

The SMW applies memoryless DPD in an open loop system.

DPD can be activated via the “I/Q Mod” block. AM-AM and AM-PM pre-distortions can be enabled separately or simultaneously. Either AM-AM or AM-PM predistortion can be applied first.





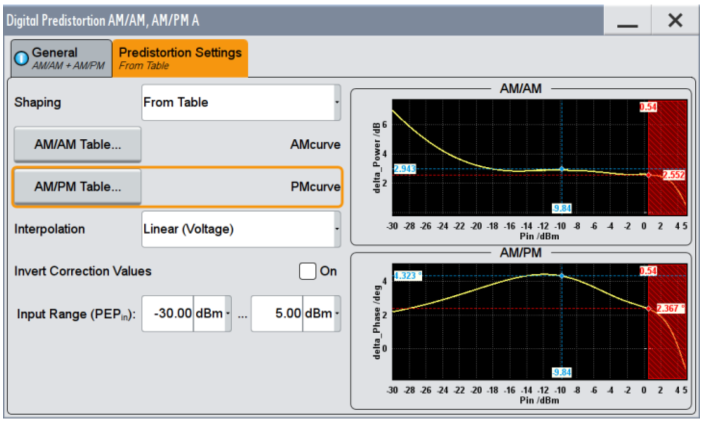
DPD alters the signal statistics and the signal level. The user can therefore define if the set mean RF level shall be the signal level before or after applying DPD. See section 8.2.1 for details.

The user can define the pre-distortion curve in the following ways:

- via table
- via polynomial

Table

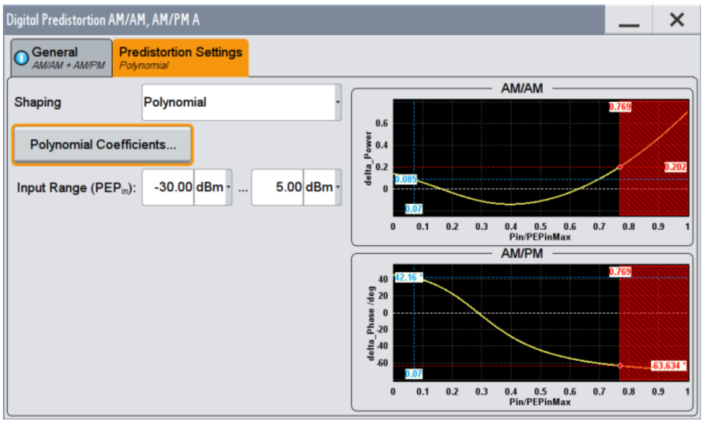
The pre-distortion function is defined by a table of user-specific value pairs (up to 4000). There are two separate tables, one for AM-AM and one for AM-PM distortion. A linear interpolation can be applied in between the specified points to smoothen the curve. The specified delta power and delta phase values can be inverted. (Note that not every curve is mathematically invertible. The inverse function of the curve must be uniquely determinable. Therefore, only strictly monotonic increasing/decreasing data can be inverted.)



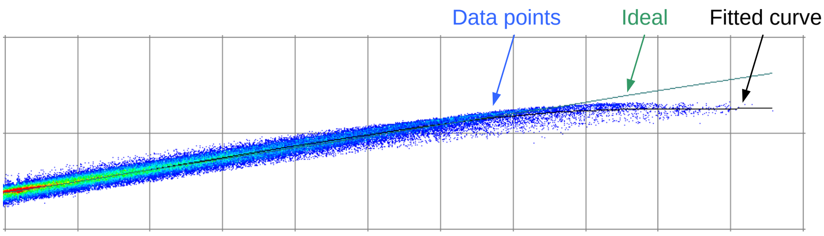
See section 11.2 for details on the file format.

Polynomial

The pre-distortion function is defined by a polynomial. The order of the polynomial function can be selected – up to 10th order is supported with definable polynomial coefficients.



In table mode, the user can load his own AM-AM and AM-PM tables or he can use the FSW-K18 to directly generate and load the pre-distortion tables (see also section 7). In the latter case, the AM-AM, AM-PM data measured with the FSW is approximated with a polynomial curve fit. (The parameters of the polynomial fit such as the order can be adjusted by the user.) These AM-AM and AM-PM curves are then inverted and saved as pre-distortion tables for direct use in the SMW.



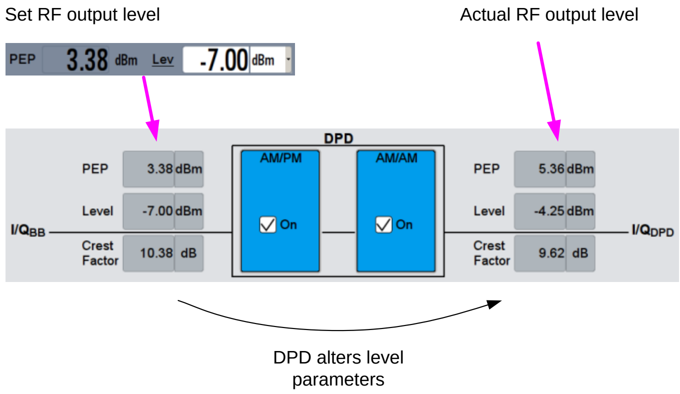
See also reference [2] for details on the individual DPD setting parameters and the graphical displays.

8.2.1 Leveling with DPD

The user can define if the set mean RF level shall be the signal level before or after applying DPD.

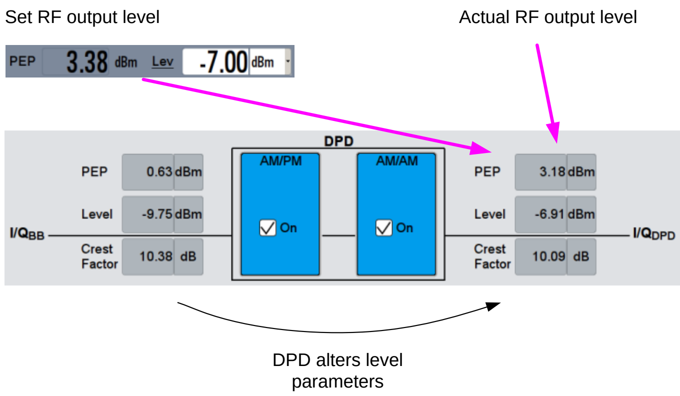
Before DPD

The set mean RF level is taken as the level reference before DPD. The actual RF output level will differ from the set level. The resulting RF level parameters after DPD are displayed.

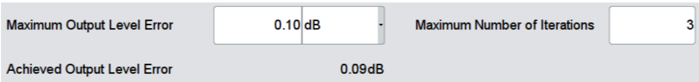


After DPD

The set mean RF level is taken as the level reference after DPD. The actual RF output level will be very close to the set level. The remaining level error is displayed (parameter “Achieved Output Level Error”).



The SMW has to perform several iterations (level measurement and adjustment) to approach the RF output level set by the user. This process is a trade-off between speed, i.e. number of iterations and level accuracy, i.e. remaining level error. The user can therefore define the maximum number of iterations to perform. In addition, he can define the maximum allowable level error. The iteration process stops when the defined number of iterations is reached. It will stop earlier if the defined maximum level error is already reached. (If the defined number of iterations is not enough to reach the desired level error, the user needs to increase the number of iterations.)



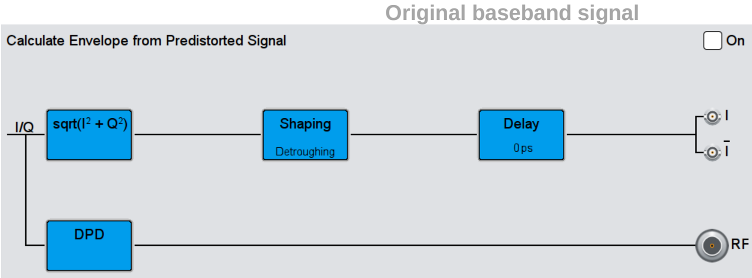
The actual RF level parameters after DPD are displayed.

8.2.2 DPD Interaction with ET

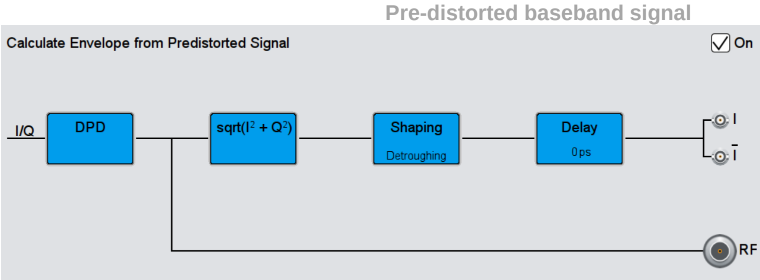
When digital pre-distortion is used in combination with envelope tracking, the user can set if the envelope signal is calculated from the original baseband signal or from the pre-distorted baseband signal.

This selection can be made in the “I/Q Analog Outputs” menu:

Original baseband signal

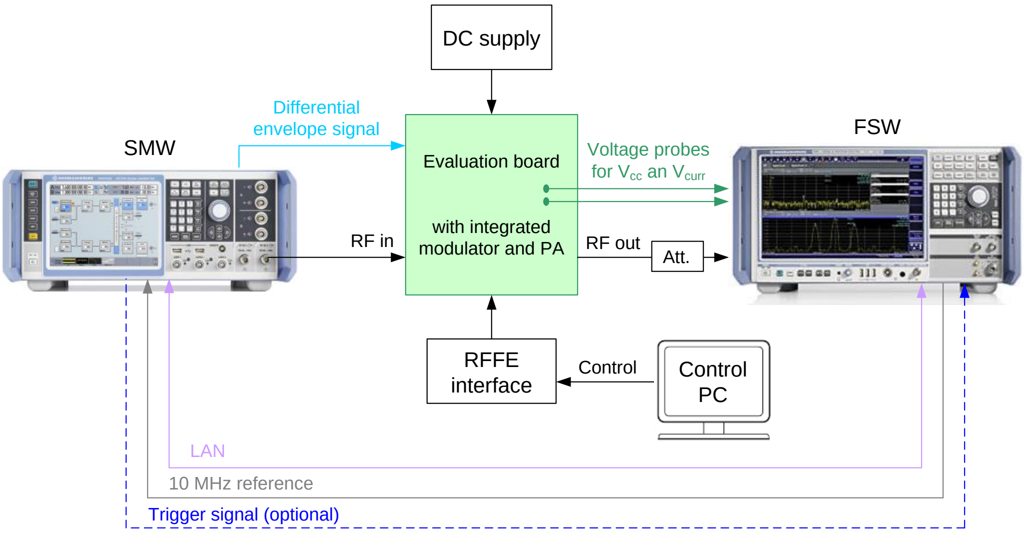


Pre-distorted baseband signal



9 Measurements & Results

The following measurements were performed with an ET evaluation board that is controlled via an RFFE interface module from a PC. The board includes a DC supply modulator and a PA. The following figure shows the used demonstration test setup. The FSW provides a 10 MHz frequency reference signal to the SMW for instrument synchronization. If external triggering is desired, the SMW can provide a “restart” marker signal to the FSW.

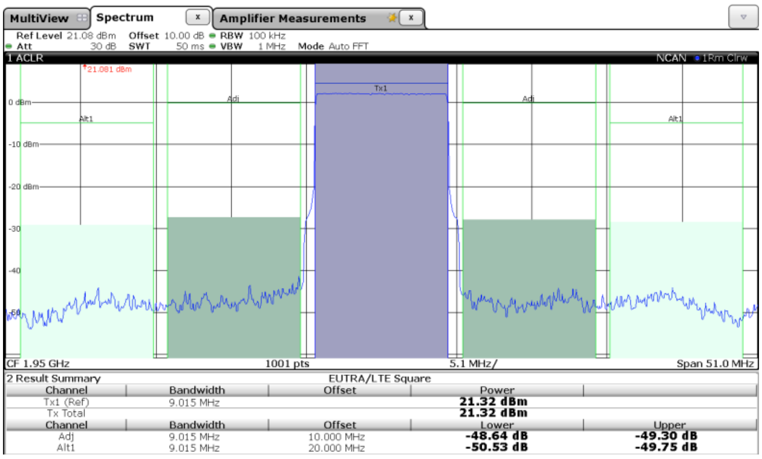


Some of the measurements presented in the following sections were performed using the FSW-K18 application. The FSW-K18 needs to know the

- Reference waveform (generated from the SMW realtime signal using the FSW-K18).
- Output power of the SMW (set via FSW-K18 and transferred to SMW).

9.1 ACLR

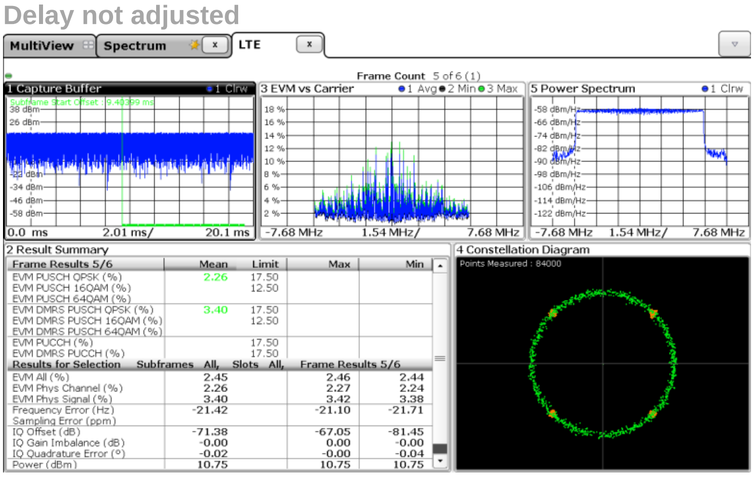
The ACLR measurement is one of the basic measurements for PA characterization. This measurement of the PA’s RF output signal requires only the RF port of the FSW. The following figure shows a 10 MHz LTE uplink signal at 1.95 GHz. The time delay between the envelope signal and the RF signal is adjusted to the optimum.



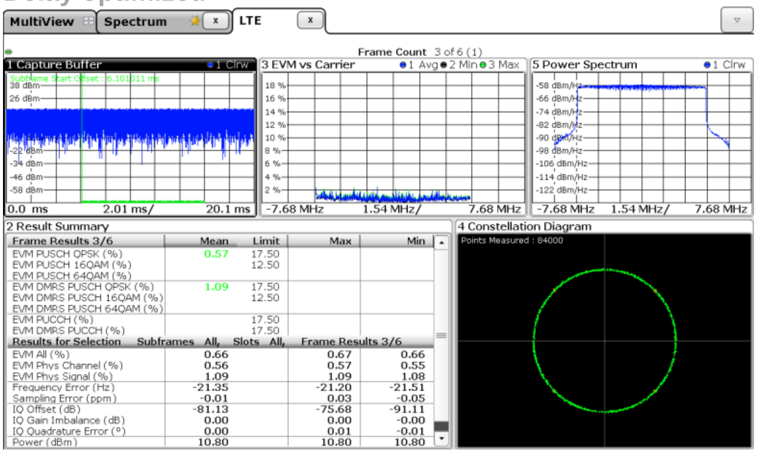
9.2 EVM

The EVM is a measure for the modulation accuracy. This measurement of the PA's RF output signal requires only the RF port of the FSW. The following two figures show the EVM of a 10 MHz LTE uplink signal at 1.95 GHz. In the first case, the envelope signal and the RF signal are not perfectly aligned resulting in a significant increase of the EVM. In the second case, the delay between the envelope and RF signals is adjusted to the optimum.

Delay not adjusted



Delay optimized

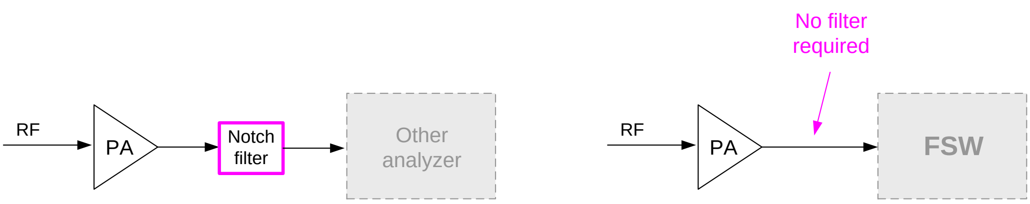


This measurement is based on data demodulation of unknown data, i.e. no reference waveform is required for this measurement. The EVM is calculated as stipulated by the LTE standard specification.
In contrast, the FSW-K18 application provides a measurement of the raw EVM. That measurement is based on data demodulation of known data, i.e. a reference waveform is required. The measured signal is compared to the known reference signal to determine the raw EVM (independent from any standard specification). This method makes it possible to determine a raw EVM measurement for virtually any signal, i.e. also for non-standardized signals.

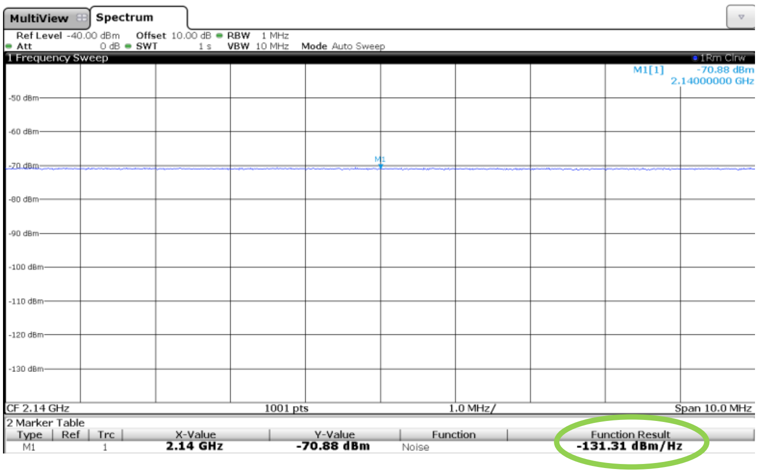
9.3 Receive Band Noise

The noise generated by the PA in the receive frequency band is an important measure when characterizing the performance of the PA. This measurement of the PA's RF output signal requires only the RF port of the FSW.

FSW:
Due to its very high dynamic range the FSW can measure receive band noise without an external notch filter. Other analyzers usually require a filter to absorb the transmit signal. The FSW can do low-noise measurements even in the presence of the strong transmit signal. As a consequence, a higher measurement speed can be achieved.

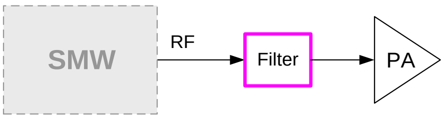


The following figure shows a noise measurement in the receive band (at 2.14 GHz for a transmit frequency of 1.95 GHz). The average output power of the PA is 16 dBm.



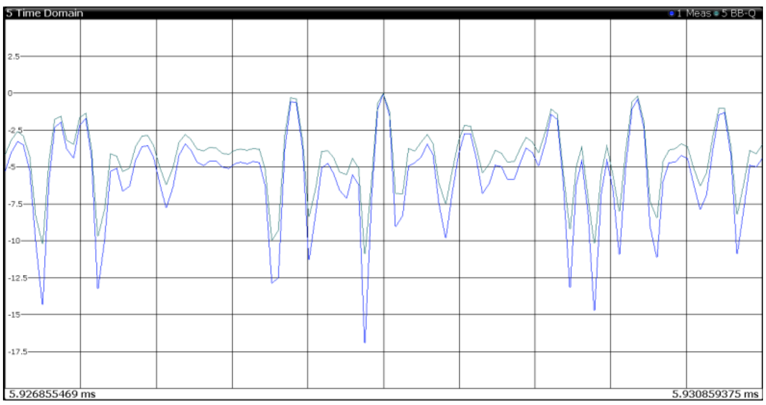
SMW:

The noise at the RF input of the PA must be extremely low to truly measure the noise generated by the PA. To improve the noise of the RF source an external RF filter can be used between the SMW and the PA.



9.4 Time Domain

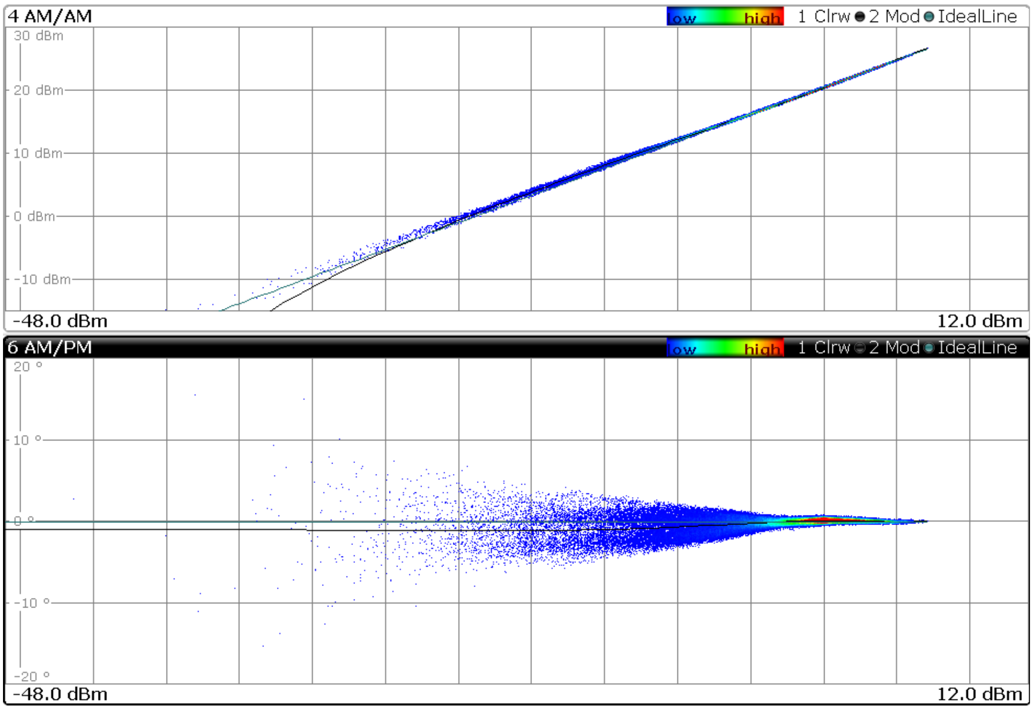
The following figure shows the Vcc signal (dark green) and the RF output signal of the PA (blue) in the time domain. This measurement requires the RF port of the FSW (for measuring the PA's RF output signal) and the baseband input ports of the FSW (for measuring the Vcc signal). The Vcc signal is measured using a probe connected directly to the FSW.



By connecting a second probe to the FSW the current signal can be measured also in parallel. The simultaneous capture enables the calculation of the instantaneous PAE. Furthermore, the data capture in a single instrument avoids jitter between the RF and the baseband captures.

9.5 AM-AM and AM-PM

The AM-AM and AM-PM measurements belong to the essential measurements for PA characterization. These measurements require only the RF port of the FSW. In addition, the signal waveform must be known (→ reference waveform) for determining the distortion. The user can simply use the FSW to query the current signal waveform from the SMW. In this example, the SMW generates a 10 MHz LTE uplink signal in realtime. The FSW controls the SMW to generate a waveform file from the realtime signal and directly downloads this waveform file.

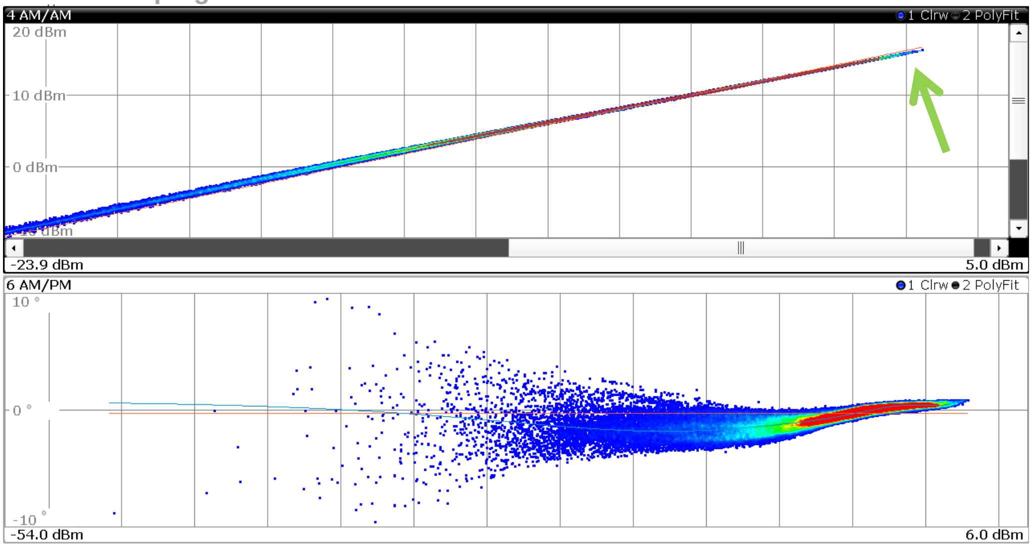


The measurement shows relatively low AM-AM distortion and some AM-PM distortion which is characteristically for ET power amplifiers.
A fitted polynomial curve is shown in black. The dark green curve is the ideal line.

9.6 Effect of Shaping

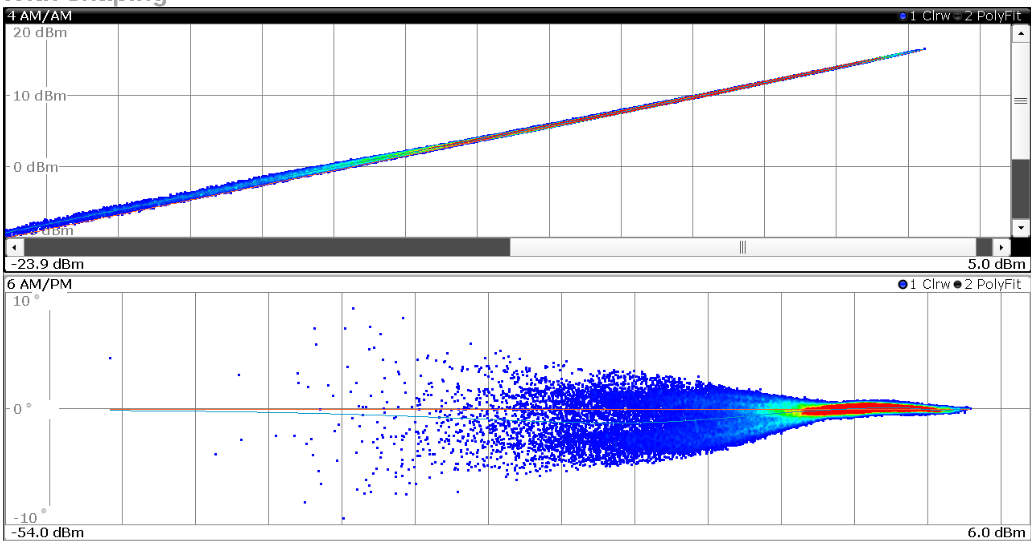
The following AM-AM and AM-PM measurements are obtained with the “Linear (Voltage)” shaping function, i.e. no real shaping is applied. The AM-AM distortion is already very low. The AM-PM measurement shows some distortion.

Without shaping



By using a special shaping function this AM-PM distortion can be further improved. The following AM-AM and AM-PM measurements are obtained with a lookup table containing a shaping curve that linearizes the PA.

With shaping



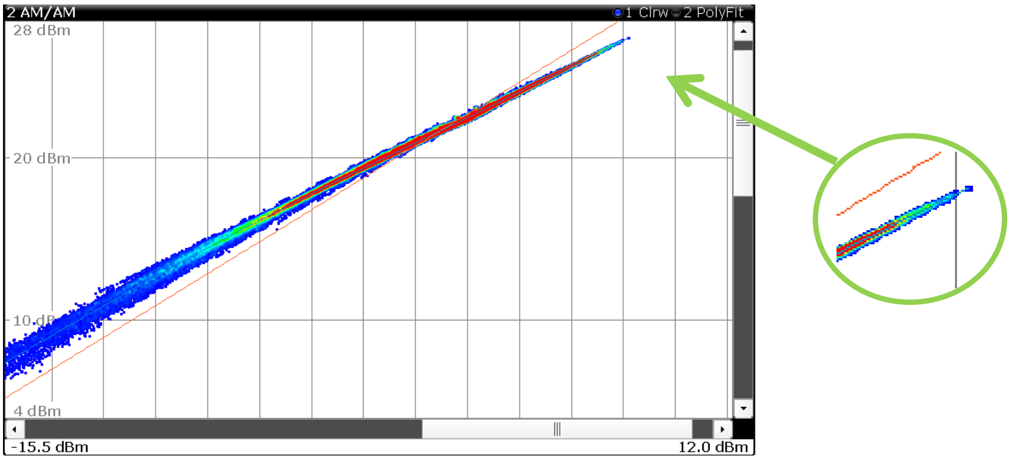
In contrast to DPD, shaping does not alter the RF input signal. Shaping modifies only the envelope signal – mostly with the aim to optimize the PA's efficiency.

9.7 Effect of DPD

DPD is applied with the aim to linearize the PA. In contrast to shaping, DPD influences the RF input signal. Optionally, it can be applied to the envelope signal, too. (See also section 8.2.2.) While envelope shaping is a must for ET, DPD may not be applied in every ET-capable device.

The following AM-AM measurement is obtained without pre-distortion. The PA exhibits compression at high input powers.

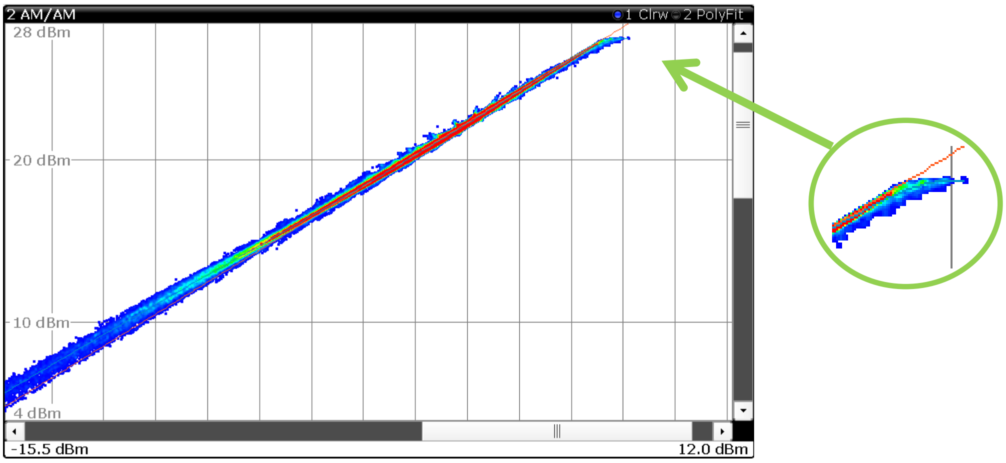
Without DPD



The distortion caused by the PA can be minimized by applying DPD. The user can use the FSW-K18 to first measure the AM-AM and AM-PM distortion, secondly generate pre-distortion tables from this measurement, and finally transmit these tables to the SMW and activate DPD. The generation of the predistortion tables requires just one button click. The file transmission to the SMW and the activation of DPD happen all automatically at a further button click on the FSW.

The following measurement is obtained with activated pre-distortion (memoryless). The linear range is extended by about 4 dB towards higher powers and the overall linearity of the PA is improved. At the highest input powers the DPD reaches a limit because the PA's compression is too significant to correct for.

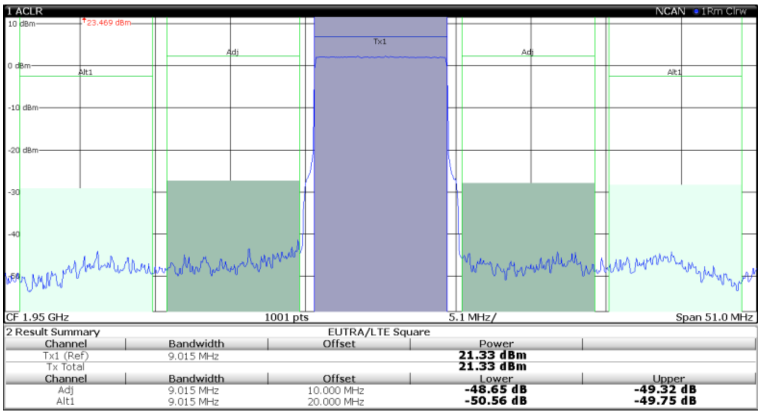
With DPD



DPD is also beneficial when the PA is not operated in compression but in its linear region. Also here DPD can improve the performance as shown in the following example.

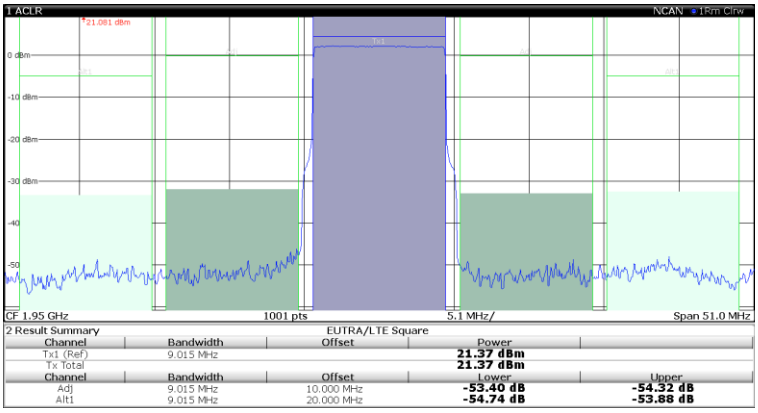
The following measurement is obtained without pre-distortion. The measured ACLR is around -48.99 dB for the adjacent channel. The PA is not in compression.

Without DPD

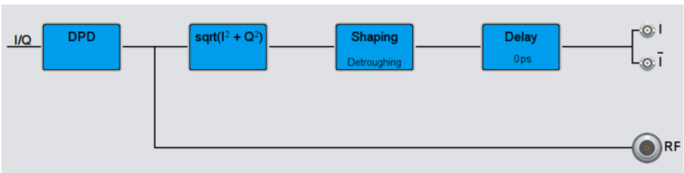


Activated pre-distortion (memoryless) yields the following measurement. The measured ACLR is around -53.86 dB for the adjacent channel – an improvement of almost 5 dB.

With DPD

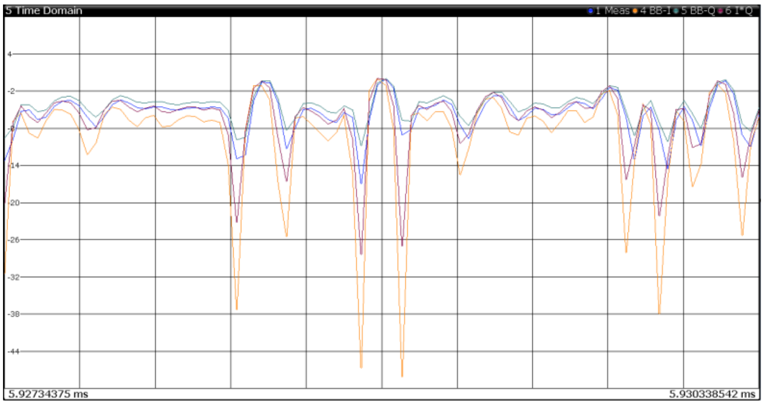


In the measurements above, DPD was applied to both, the RF signal and the envelope signal.

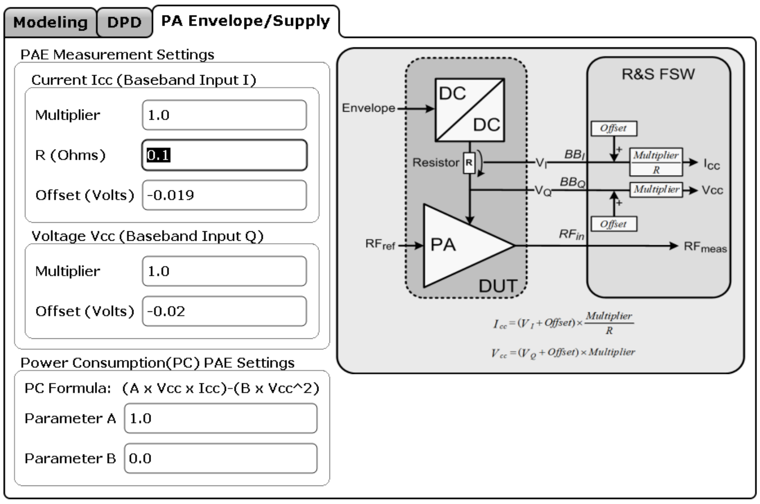


9.8 PAE

The following figure shows the RF output signal of the PA (blue), the Vcc signal (dark green), the current signal Icc (orange), and the resulting DC power P_{DC} = Vcc · Icc (violet) in the time domain. All traces are normalized to zero. This measurement requires the RF port of the FSW (for measuring the PA's RF output signal) and the baseband input ports of the FSW (for measuring the Vcc and Icc signals).



The Vcc signal is measured using a Rohde & Schwarz RT-ZD differential voltage probe connected directly to the FSW. The Icc signal is measured using a second RT-ZD probe. The second probe measures the voltage drop over a 0.1 Ω shunt resistor. The measured voltage signal is multiplied by factor 1/0.1 to obtain the corresponding current signal according to Ohms law I = U/R. The user can input the resistance value directly on the FSW.

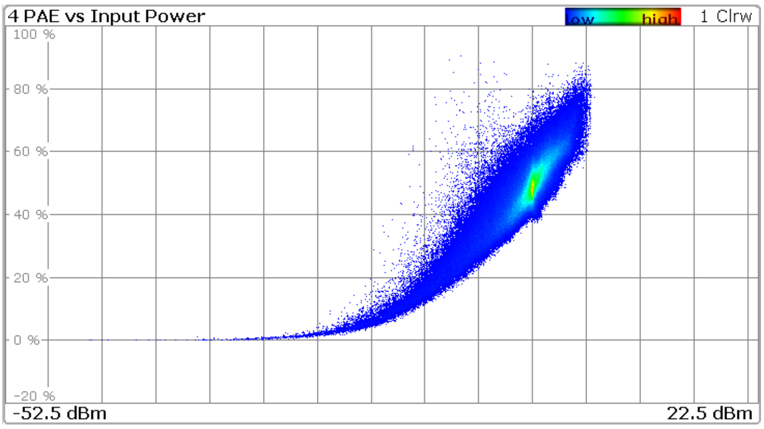


In addition, the user can correct for an offset caused by the probe, 0.019 and 0.020 in this example. The offset can be determined by shorting the differential probe and reading the measured offset from the result summary (parameter "Baseband Input Voltage"; see section 9.9).

The external attenuator and cable loss (i.e. output losses) can be compensated by setting a reference level offset in the FSW. The input losses can be compensated by setting a power offset in the SMW.

The measured time-averaged PAE of the PA is 52 % in this example. This value is calculated from the time-averaged input RF power (user input), output RF power (measured), and input DC power (measured).

The following figure shows the measured PAE over input RF power. The red color indicates high density of data points.



9.9 Result Summary

The following figure shows the result summary with the results for e.g. raw EVM, input and output power and resulting amplifier gain, measured voltage and current, average PAE, and many more.

1 Result Summary

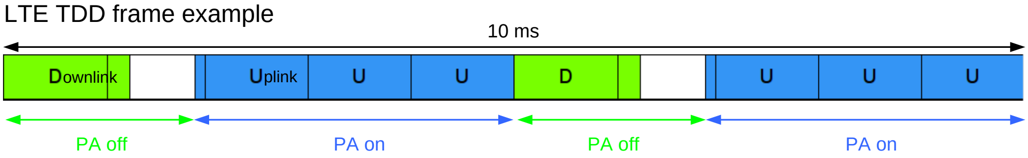
Mod. Acc.	Min	Current	Max	Unit
Raw EVM	2.224	2.224	2.224	%
Raw Model EVM	0.033	19.363	417.928	%
Frequency Error	---	-0.007	---	Hz
Power	**Min**	**Current**	**Max**	**Unit**
Power In	-44.16	-0.00	6.14	dBm
Power Out	-28.93	26.28	30.51	dBm
Gain	26.28	26.28	26.28	dB
Crest Factor Out	---	4.23	---	dB
AM/AM Curve Width	---	0.082	---	dB
AM/PM Curve Width	---	0.279	---	°
Voltage/Current	**Min**	**Current**	**Max**	**Unit**
Baseband I Input Voltage	0.021	0.038	0.054	Volt
Baseband Q Input Voltage	0.778	2.155	3.378	Volt
Voltage (V_cc)	0.030	2.134	0.702	Volt
Current (I_cc)	0.757	0.378	3.357	Amp
Power (V_cc * I_cc)	0.050	0.808	1.792	Watt
Average PAE	---	52.457	---	%

The average PAE value is calculated from the time-averaged input RF, output RF, and input DC powers.

10 LTE TDD Applications

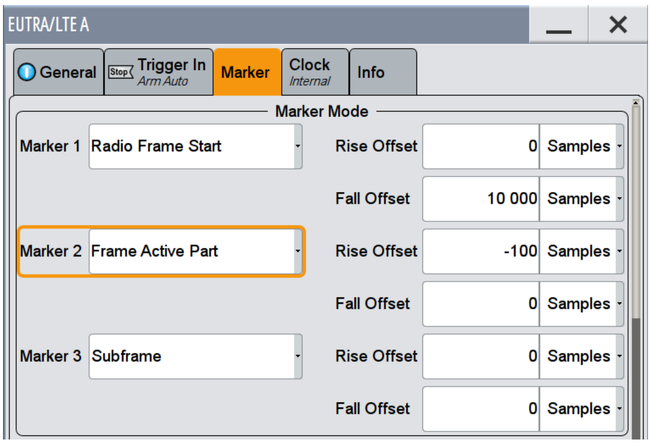
For LTE TDD applications, the overall power consumption can be further reduced by disabling the DC supply modulator and the PA during the non-active downlink subframes. To test this, the DC supply modulator and the PA need to be controlled with proper timing.

LTE TDD frame example

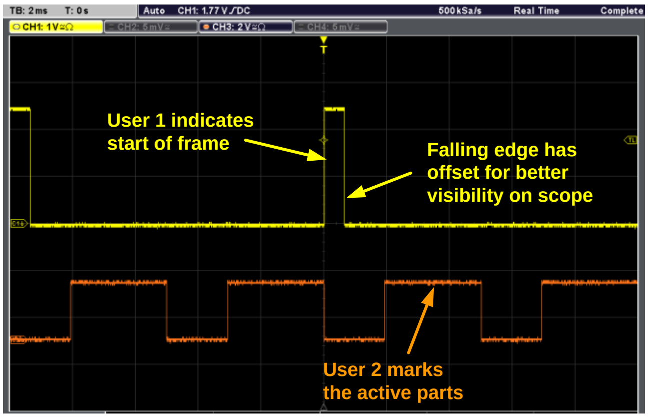


The SMW provides various marker outputs. For example, the SMW can be programmed to send a trigger pulse at the start of each frame of a LTE signal. Such marker signals can be used for control of other equipment and instruments (e.g. oscilloscope). The marker signals are output at BNC "USER" connectors on the front panel. For example, the SMW can be configured to provide the following marker signals:

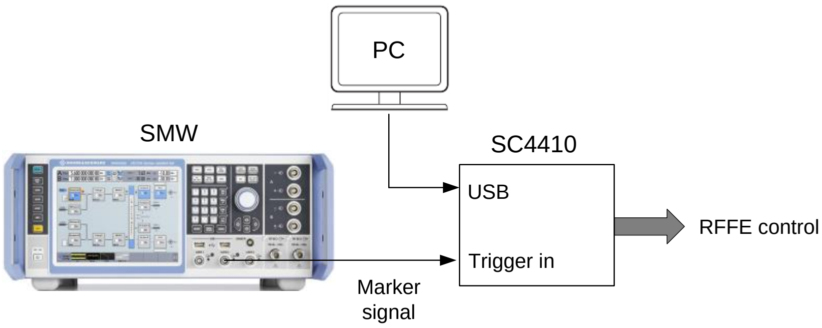
- USER 1 connector outputs marker 1 signal. Marker 1 will pulse at the start of each frame LTE frame, e.g. to trigger oscilloscope
- USER 2 connector outputs marker 2 signal. Marker 2 will be high during the active uplink sub-frame of a LTE TDD signal, e.g. to trigger external equipment for TD-LTE applications



The settings for marker 1 and 2 in the "Marker" tab of the LTE menu as shown above will create the following signals:



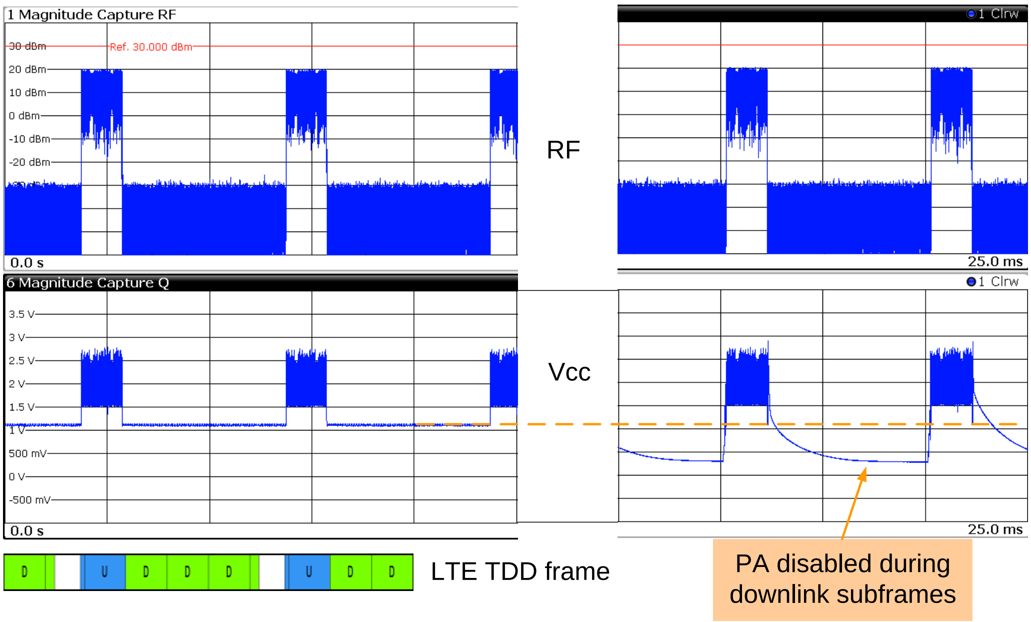
For TD-LTE applications, the user can use the SMW's USER output (marker 2 in this example) to trigger external equipment such as the SCOUT SC4410 (USB-to-GPIO/serial adaptor) from Signal Craft Technologies. This device supports RFEE-like interface for communication with MIPI RFFE devices. It can be used to trigger RFFE commands to the DC supply modulator and the PA for TDD operation.



The user can load appropriate MIPI RFFE commands into the SC4410. For example, one command to enable the DC supply modulator and the PA and one command to disable them. The enable command is triggered on the rising edge of the marker 2 signal, the disable command is triggered on the falling edge of the marker 2 signal. When triggered, the SC4410 sends the corresponding RFFE command to the connected DC supply modulator and the PA.
To provide enough time for the enable procedure, the rising edge of marker 2 can be advanced by selecting a negative rise offset. In the example above, the marker signal will go high 100 samples before the uplink subframe actually begins. This leaves enough time for sending the enable command such that the DC supply modulator and the PA are operational when the uplink subframe starts.

By disabling the DC supply modulator and the PA during the non-active downlink subframes the overall power consumption can be further reduced. This is illustrated in the following figure.

Parallel RF and Vcc time domain traces



Side note:
Users can use the R&S®RTO digital oscilloscopes to look at the RFFE protocol contents. This analysis requires the R&S®RTO-K40 “MIPI-RFFE trigger and decode” option on the instrument. Please see the R&S®RTO product website at www.rohde-schwarz.com for details.

11 Appendix

11.1 Shaping Table Format for ET

There are two ways to create a shaping table:

- Internally using the built-in table editor.
- Externally using custom tools.

The file format is very simple. It is basically a comma separated value (CSV) file with a short, optional header and special file extension. The simple file format assures that the conversion of user-specific table formats to SMW format is straightforward. For example, many third-party tools such as MATLAB and others support data export in CSV format.

The file extension "*.iq_lutpv" is used for tables in "Auto Power" and "Auto Normalized" modes. The file extension "*.iq_lut" is used for tables in "Manual" mode.

***.iq_lutpv** file format example:

```
# Rohde & Schwarz - IQ Output Envelope Shaping Table
# Power[dBm], Vcc[V]
0, 0.02
1, 0.1
2, 0.2
3, 0.35
4, 0.55
…
```

"Power" is the instantaneous RF power (P_{in}).

***.iq_lut** file format example:

```
# Rohde & Schwarz - IQ Output Envelope Shaping Table
# Vin/Vmax, Vcc/Vmax
0.3, 0.4
0.35, 0.45
0.56, 0.55
0.4, 0.5
0.6, 0.65
…
```

The header is optional and can be omitted. The file content is a list of comma separated value pairs. The pairs are separated by a newline. The file may contain up to 4000 lines.

The file formats are also described in reference [2].

11.2 AM-AM and AM-PM Table Format for DPD

There are two ways to create an AM-AM or AM-PM table:

- Internally using the built-in table editor.
- Externally using custom tools.

The file format is very simple. It is basically a comma separated value (CSV) file with a short, optional header and special file extension.

The file extension “*.dpd_magn” is used for AM-AM tables. The file extension “*.dpd_phase” is used for AM-PM tables.

***.dpd_magn** file format example:

```
# Rohde & Schwarz – Digital AM/AM Predistortion Table
# Pin[dBm], deltaPower[dB]
0.0, 0.02
0.1, 0.1
0.2, 0.2
0.3, 0.35
…
1, 0.7
```

"Pin" is the instantaneous RF power. “deltaPower” is the power difference to the instantaneous P_{in}.

***.dpd_phase** file format example:

```
# Rohde & Schwarz – Digital AM/PM Predistortion Table
# Pin[dBm], deltaPhase[deg]
0.0, 0.05
0.1, 0.07
0.2, 0.12
0.3, 1.2
…
1, 14.7
```

The header is optional and can be omitted. The file content is a list of comma separated value pairs. The pairs are separated by a newline. The file may contain up to 4000 lines.

The file formats are also described in reference [2].

12 Abbreviations

ACLR	Adjacent channel leakage ratio
AM-AM	Amplitude-to-amplitude modulation
AM-PM	Amplitude-to-phase modulation
ARB	Arbitrary waveform generator
AWGN	Additive white Gaussian noise
DC	Direct current
DPD	Digital pre-distortion
DUT	Device under test
ET	Envelope tracking
EVM	Error vector magnitude
I/Q	In-phase/quadrature
LTE	Long term evolution
PA	Power amplifier
PAE	Power added efficiency
PEP	Peak envelope power
RF	Radio frequency
RFFE	Radio frequency front end
TD	Time-division
TDD	Time-division duplex
V_{cc}	Voltage at the Common Collector

13 References

[1] Rohde & Schwarz, R&S®SMW200A Specifications (data sheet)

[2] Rohde & Schwarz, R&S®SMW-K540, R&S®SMW-K541 Envelope Tracking and AM/AM, AM/PM Predistortion User Manual

[3] Steven Baker. ET101 An Introduction to Envelope Tracking for RF Amplifiers (1.0). 2011 OpenET Alliance Limited

[4] Chris Potter. Envelope Tracking for Enhanced Power Amplifier Efficiency. 2014 Seminar Cambridge UK

14 Ordering Information

Please visit the Rohde & Schwarz product websites at www.rohde-schwarz.com for comprehensive ordering information on the following Rohde & Schwarz instruments:

- R&S®SMW200A vector signal generator
- R&S®FSW signal and spectrum analyzer

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Rohde & Schwarz is an independent group of companies specializing in electronics. It is a leading supplier of solutions in the fields of test and measurement, broadcasting, radiomonitoring and radiolocation, as well as secure communications. Established more than 75 years ago, Rohde & Schwarz has a global presence and a dedicated service network in over 70 countries. Company headquarters are in Munich, Germany.

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- ISO 14001-certified environmental management system

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ISO 9001

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