

Application Note

DIGITAL PRE-DISTORTION FOR IMPROVED EVM PERFORMANCE

Products:

- R&S®SMW200A
- R&S®FSW

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1 Overview

1.1 Digital pre-distortion

Digital pre-distortion (DPD) constitutes an invaluable tool to operate high-power amplifiers (PAs) close to their maximum output power which is vital to ensure a high efficiency. Inherent non-linearities in a PA lead to impairments of the signal quality when operated at elevated power levels. Using DPD allows to counteract these limitations by pre-distorting the signal with the inverse PA characteristic before feeding it to the PA. The cascade of the PA and the DPD leads to a linear characteristic. This method is used in most state-of-the-art cellular, non-cellular or satellite communication devices. As the architecture of the RF chain of a signal generator is similar, it may also be used to improve the performance of a signal generator's output stage. DPD is an invaluable, industry standard tool to combat effects of non-linearities in RF components.

1.2 Scope of this application note

The scope of this application note is to give a comprehensive guide on how the R&S®FSW signal and spectrum analyzer with the option R&S®FSW-K18 may be used to create a Hammerstein model for the R&S®SMW200A vector signal generator's output stage. This model can then be applied to counteract inherent non-linearities and memory effects and improve the Error Vector Magnitude (EVM) at high output powers of the R&S®SMW200A vector signal generator.

Further on the vector signal generator R&S®SMW200A will be referred to as SMW and FSW will be used synonymously with R&S®FSW.

2 Introduction

2.1 Digital pre-distortion of power amplifiers

Intermodulation products caused by non-linear power amplifiers (PAs) have a major impact on the signal quality, e.g. of a communication signal, in terms of Error Vector Magnitude (EVM) or Adjacent Channel Leakage Ratio (ACLR).

Digital pre-distortion is used to operate power amplifiers in devices such as mobile phones at best efficiency and at best signal performance. To achieve this, the signal entering the power amplifier is pre-distorted in a way so that non-linear effects of the power amplifier are cancelled out.

It is often a use case to identify the performance of the selected pre-distortion method together with the PA. The combination of a vector signal generator, like the SMW, and a vector signal analyzer, such as the FSW, provides the perfect test bench to characterize all kinds of DUTs using modulated signals.

2.2 Linearization of vector signal generators

If the EVM performance of a DUT, e.g., a PA, is to be measured, it is imperative for the SMW - FSW combination to have negligible contributions to EVM. This requirement is usually very well met when the generator is operated at low and intermediate power levels. PAs often require very high input power levels with high signal quality e.g., very low distortion levels.

In order to provide that, the SMW's output chain contains cascaded power amplifiers which are essential for the generation of top-quality wideband signals. To allow very high output power levels with negligible EVM degradation from non-linearities of the instruments internal output power section, digital pre-distortion can also be used to linearize the signal chain of a vector signal generator and optimize the signal performance.

2.3 DPD approaches

There are two methods to perform digital pre-distortion of an input signal to improve the linearity of power amplifiers.

- The direct DPD (DDPD) is an iterative process in which the correction values are determined for each sample of the input signal. The direct DPD is not based on a model. It rather calculates the correction values for each sample directly by comparing measured and reference signal sample by sample.

The direct DPD is especially useful for the following test cases:

- Determining the best performance of a DUT, as the pre-distortion is not limited by polynomial or memory order.
- Removing external effects from the measurement results, for example a preamplifier that should not be considered in the final measurement results.

Note: The result of the DDPD is an I/Q file that contains a pre-distorted waveform. This waveform only applies to the specific generator level that was set during creation, requiring measurement and re-calculation if the level setting is changed.

- With a model based DPD algorithm, the nonlinear behavior of a device is fully characterized and applied to a certain model. Well known models are, among others, the memoryless polynomial model to account for AM/AM and AM/PM effects on one hand, and the Hammerstein model, the memory polynomial, or the generalized memory polynomial, which also account for power amplifier memory effects on the other hand.

In contrast to the direct DPD, model based DPD approaches characterize a PA throughout a large level range. There is no need for repetitive measurements when the RF power level is changed. The SMW even supports real-time application of the polynomial model and Hammerstein model. This is much more practical and saves a lot of computational time.

2.4 Content of this Application Note

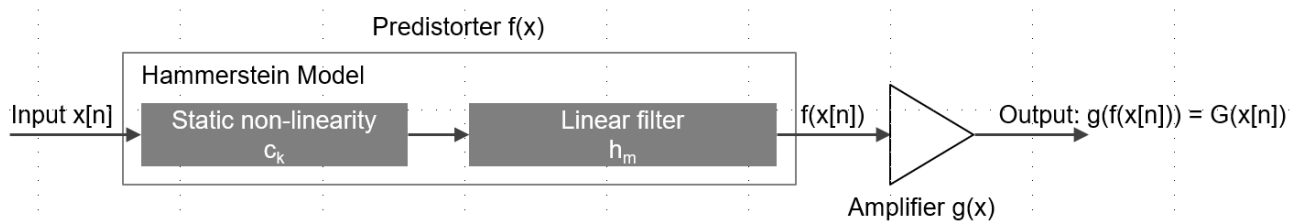
This application note aims to give a comprehensive, step-by-step guide on how a pre-distortion model for the SMW in the form of a relatively computationally inexpensive Hammerstein model can be generated to provide a perfectly linearized signal. With this approach, the true performance of the DUT can be measured and is not masked by avoidable side-effects of the instrument. This model can then be applied in real-time to various different waveforms without taking additional measures. The Hammerstein model can be used in a variety of measurements, such as EVM or ACLR. In this document, we focus on EVM as performance indicator for the quality of the digital pre-distortion model.

This application note is structured the following way.

- Chapter 3 will provide an overview of the linearization technique – the Hammerstein model – used by the FSW to pre-distort the SMW’s signal in the digital baseband. An in-depth knowledge about the theory of digital pre-distortion is not required to use the linearization proposed in this application note.
- Chapter 4 describes the setup, consisting of an FSW – vector signal analyzer (VSA) and an SMW – vector signal generator (VSG). Furthermore, the required options are outlined.
- In chapter 5, detailed step-by-step instructions on how a Hammerstein model to pre-distort the SMW is generated. A description of one of the most prominent use cases of DPD, the EVM measurement of a DUT is given in chapter 6.
- Chapter 7 provides some examples on how pre-distortion was used to improve the EVM of exemplary signals.
- Chapter 8 summarizes the application note and offers an outlook.

3 Direct DPD and Hammerstein Model

Pre-distortion is a linearization technique that is applied in order to be able to use an inherently non-linear power amplifier with both high efficiency and enough linearity to fulfill linearity requirements of the transmitter system. The goal is to pre-compensate the input signal, resulting in a linear overall transfer function. In this application the linearization is not limited to a single amplifier, but the entire SMW output stage.



There are two causes of distortion which are to be considered. First the non-linearities of the amplifier’s transfer function, and second the memory effects of said amplifier contribute to the total distortion. The Hammerstein model reflects both contributions in its structure. It consists of a static non-linearity, compensating the non-linear contribution to the total distortion as well as a linear filter which is responsible for memory effects. Mathematically it can be expressed as follows:

$$y_{HM}[n] = \sum_{m=0}^{M-1} \sum_{k=1}^K h_m c_k x[n-m] |x[n-m]|^{k-1},$$

where M and K are the memory and the polynomial degree, c_k are the complex coefficients of the non-linearity and h_m are the filter coefficients.

The Hammerstein model approximates the memory polynomial model which itself is a simplified form of the Volterra Series Model.

The Volterra series is the most generic way to describe a nonlinear, time invariant system. However, due to its complexity, the number of parameters increases exponentially with the polynomial degree and memory depth. It is therefore not suited to perform pre-distortion in this application.

The direct digital pre-distortion (DDPD), on the other hand, provides a theoretically perfect compensation of distortions by measuring the deviation of every sample after passing through the channel and the undistorted

sample. These deviations can then be applied in baseband to pre-distort the signal. Pre-distorting like this will yield an optimal result (only limited by the max. sample rate of the signal generator/spectrum analyzer setup) but is only valid for a limited level range while the Hammerstein model can be used more flexible for instance in a wider power range and for multiple different signals. The Hammerstein model is calculated from the DDPD values.

Figure 1 describes the idealized working principle of the digital pre-distortion. Here the blue curve displays the transfer-function of a power amplifier, showing linear behavior for low powers and compression for higher powers. The green curve shows the digitally pre-distorted signal. Here, the signal deviates from the linear characteristic at higher powers to compensate the compression of the PA. Finally, as combination of both previously described transfer-functions, the ideal linear behavior is displayed in orange. Note, that this idealized output cannot be reached, as the PA's maximum output power can't be exceeded. Therefore, the best resulting transfer-function that could be reached would be linear until the PA's maximum output power is reached. Afterwards, the output power would experience hard clipping and stay constant. This behavior is shown by the red curve in Figure 1.

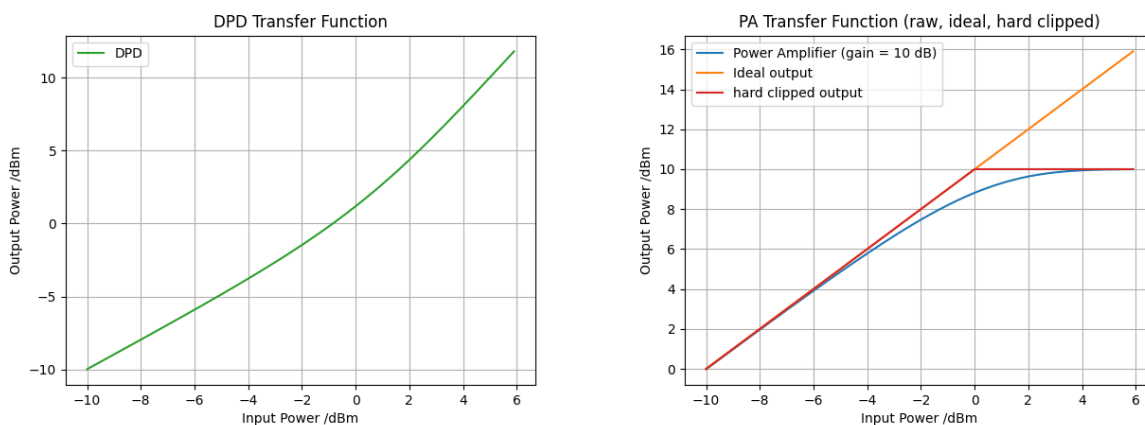


Figure 1: The transfer characteristic of a non-linear Power Amplifier and of the Digital Pre-distortion (DPD) are shown in blue and green. The orange curve displays the idealized behavior of the combination of both functions. The red curve shows the hard clipped output of a real PA, which is limited by the max. available output power.

Next to this amplitude correction, the Hammerstein model also applies the inverse of the DUT's AM/PM conversion. Furthermore, it contains a linear filter and therefore provides means to correct memory effects of a PA.

4 Setup for Hammerstein Model Calculation

4.1 Required Options for Digital Pre-Distortion

Instrument options for Digital Pre-Distortion	
Option	Name
SMW200A	
SMW-B10xx	Frequency range 100 kHz to xx GHz for RF path A
SMW-B13 or SMW-B13T or SMW-B13XT	Standard baseband main module, 1 I/Q path to RF Standard baseband main module, 2 I/Q paths to RF Wideband baseband main module, 2 I/Q paths to RF
SMW-B9 or SMW-B10	Wideband baseband generator, 500 MHz, 256 MS Baseband generator, 120 MHz, 64 MS
SMW-K541	AM/AM, AM/PM pre-distortion
SMW-K544	User-defined frequency response correction
FSW (any frequency option)	
FSW-K18	Amplifier measurements
FSW-K18D	Direct DPD measurements
FSW-K18M	Memory polynomial DPD
FSW-K18F	Frequency response and group delay measurements

4.2 Block Diagram and Description

This application requires an R&S®SMW200A as well as an R&S®FSW equipped with the options listed in section 4.1. These two devices are to be connected via their respective RF in- and output ports. Furthermore, they must also be connected to the same local network, for instance via ethernet.

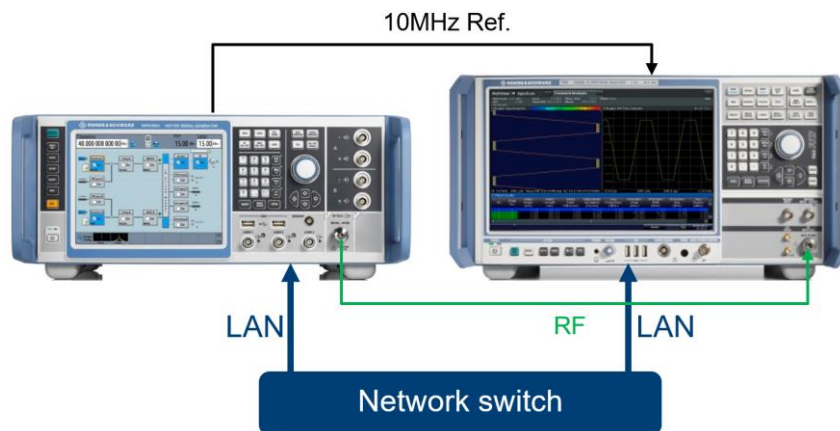


Figure 2: The setup necessary to generate a Hammerstein model of an SMW is shown. The SMW is connected to the FSW via coaxial cable. Furthermore, both devices are to be connected to the same local network and share a 10MHz reference signal. The ethernet ports are located at the rear of the devices.

5 Hammerstein Model Generation

This chapter provides a comprehensive, step by step guide on how the FSW-K18 (incl. FSW-K18D and -K18M) option can be used in combination with the SMW to

- generate a reference signal,
- perform iterative direct DPD on it and
- finally arrive at a full Hammerstein model

which can be applied to pre-distort the test signal to improve, e.g. EVM performance of the measurement setup. The full process is illustrated in Figure 3. Pictures and explanations are provided to ease the manual handling of this process. Furthermore, the required SCPI commands are given to facilitate the automation of this process, e.g., using the **Rsinstrument python package**¹. Exemplary Python code, that generates a Hammerstein model and activates it on the SMW is provided in Appendix A.1.

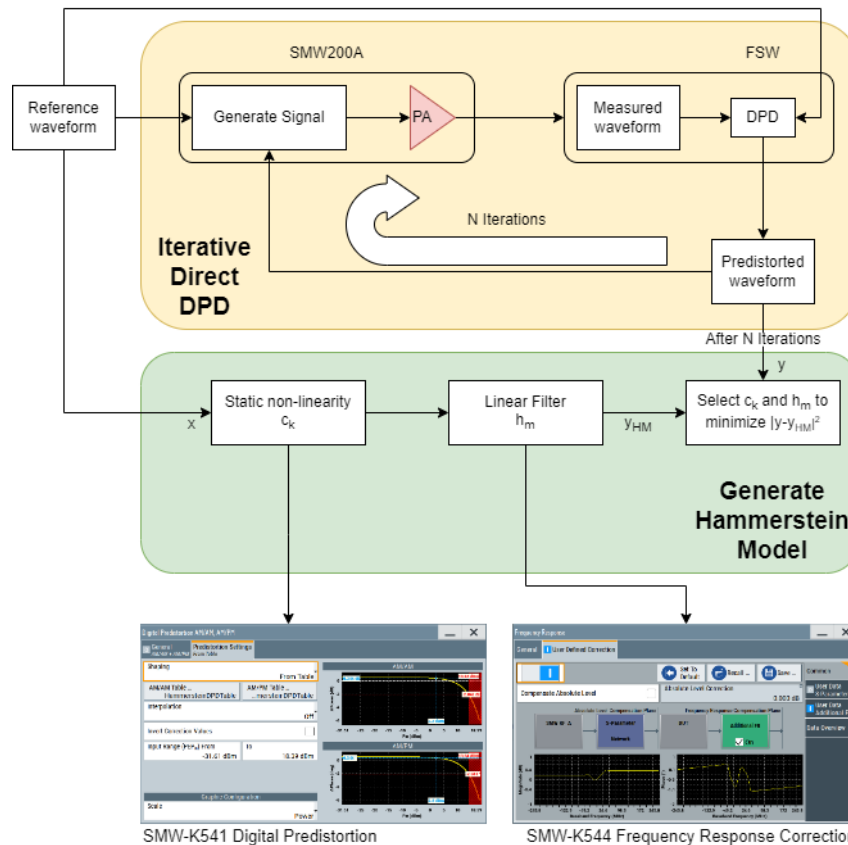


Figure 3: Illustration of the steps required to generate a Hammerstein model that can be applied to pre-distort the test signal.

5.1 Set up Generator Control on the R&S®FSW

In order to transfer the reference signal to the signal generator, automatically execute DDPD and later on load the Hammerstein from FSW to SMW, a connection between the SMW vector signal generator and the

¹ <https://rsinstrument.readthedocs.io/en/latest/StepByStepGuide.html>

FSW spectrum and signal analyzer must be established. This functionality of the FSW is provided by the FSW's **Amplifier** measurements option which is further on referred to as FSW-K18. A new instance with this option is created via *Mode >> Amplifier*. The generator control may then be accessed via *Reference Signal >> Open Generator Control*. To establish a connection between the devices, the generator's IP-Address needs to be provided under **Generator IP Address**. The connection is established after pressing the **Connect** button. Both devices must be connected to the same Ethernet network. In the preceding *Generator Setup* menu, the **Level (RMS)** and the **Center Frequency** can be selected. A screenshot of the *Generator Setup* is displayed in Figure 4.

Step-by-step (incl. SCPI commands):

1. Open K-18 “Amplifier” Option	:INST:CRE:NEW AMPL, “<your channel name>”
2. Select SMW IP-Address	:CONF:GEN:IPC:ADDR <SMW IP>
3. Connect Devices	:CONF:GEN:CONN:STAT <ON>
4. Set SMW RMS Power Level	:CONF:GEN:POW:LEV <Your RMS Power>; *WAI
5. Set SMW Center Frequency	:CONF:GEN:FREQ:CENT <Your center frequency>;*WAI

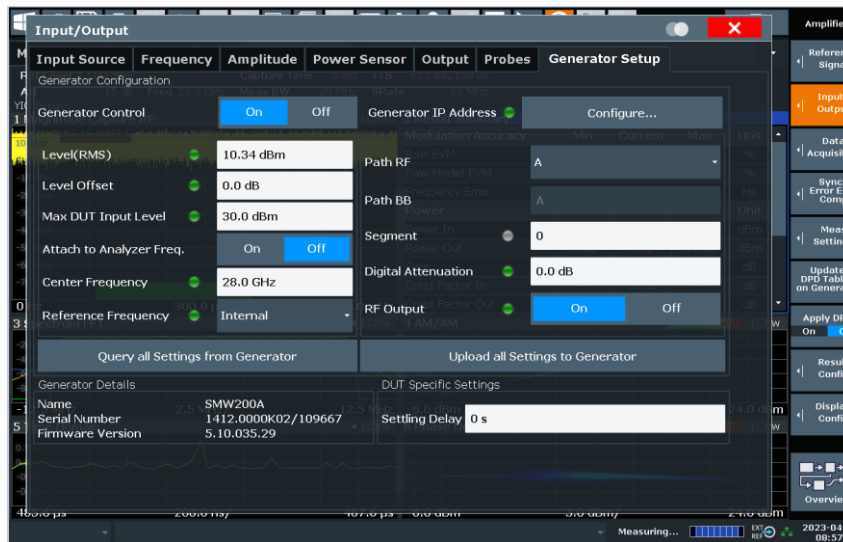


Figure 4: Generator Setup Dialog

After device-connection has been established, the FSW grants limited control over the SMW to generate an Arbitrary Waveform (ARB) file for the reference signal and to upload it to and play it in the generator.

5.2 Reference Signal Generation

The FSW-K18 provides means to automatically generate signals which are well suited to develop Hammerstein models with. The magnitude of these signals – further on called “reference signals” – approximately follow a Rayleigh distribution and are therefore well suited to model standard signals in communication engineering applications. Furthermore, Rayleigh distributed signals have few high-power components, driving the SMW's output stage well into the non-linear region, while keeping the bulk of the samples within the linear region. This ensures that non-linear behavior can be depicted properly while also making sure that the linear region is maintained in the resulting model.

The probability density function of an exemplary reference signal with a bandwidth of 400 MHz and a crest factor of 8 dB is shown in Figure 5. The red line marks the mean value of all samples. It can nicely be seen that most samples assemble at low and intermediate powers, while a few still reach higher values.

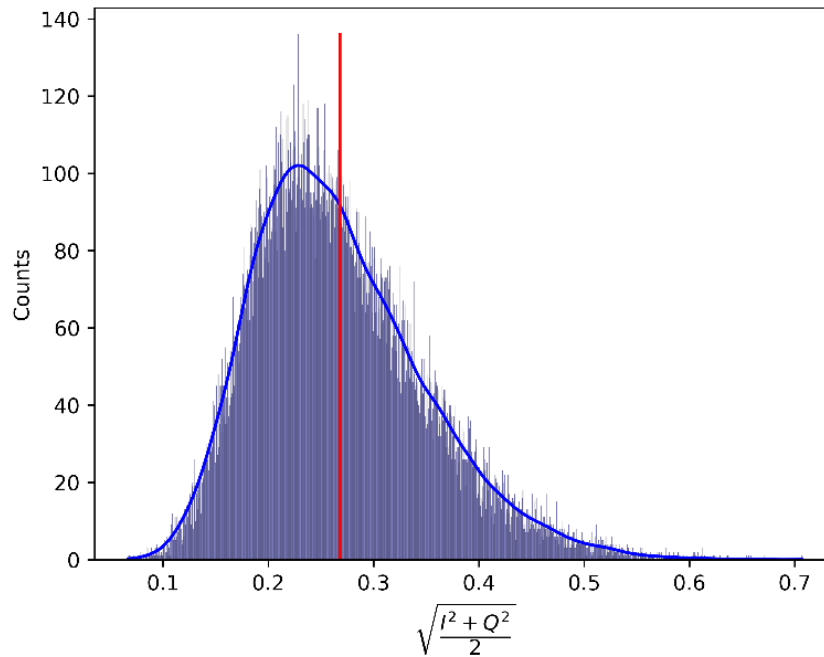


Figure 5: The probability density function of a reference signal generated with the FSW-K18 with a bandwidth of 400MHz and a crest factor of 8 dB. The red line indicates the mean value of the distribution.

5.2.1 Choosing Parameters for Digital Pre-Distortion

Assuming a 100% duty cycle reference signal without notches and the above-mentioned Rayleigh distribution, a reference signal is fully defined by the parameters **bandwidth, signal length, center frequency** and **crest factor**. Furthermore, it is necessary to choose the **RMS power** at the SMW's RF output at which the Hammerstein model is generated. The parameters should be chosen according to the following recommendations.

It is recommended to choose the bandwidth to be the same as the bandwidth of the signal used in further measurements, also referred to as **test signal** in the following. It would also be possible to use a higher bandwidth, for example when the same Hammerstein model is used in combination with multiple signals with different bandwidths. Note, that a larger bandwidth might worsen the result. It is also necessary to adapt the center frequency according to the application. It is advised to record a Hammerstein model for every center frequency the SMW will be operated at. The crest factor should be chosen such that both the linear and the non-linear region of the RF chain is sufficiently covered. Values of 8-10 dB have been found to work well for 5G NR down- and uplink signals. The signal length can be kept at its default value of 30000 samples.

Last, the RMS power level should be selected considering the indicated output power upper limit of the SMW. This upper limit of the output power range can be read out according to Figure 7 under *RF >> RF Level >> Level ...: Level Range*. It is necessary to set the internal step attenuator to 0 dB. Otherwise, the upper limit of the level range will display the next RF path switching point. This can be achieved, by setting the RMS level such, that the indicated PEP level is larger than 0 dBm.

The level range upper limit provides an approximation of the maximum output power of the SMW. With a peak envelope power equal to this upper limit, linearization isn't possible anymore. Therefore, it is

recommended to subtract some margin x from the output power upper limit to find a suitable maximum power at which the Hammerstein model is generated. This margin must not be too large, as the generator should still be driven well into its non-linear region. Values of 1 or 2 dB have been proven to source good results. Figure 6 provides a graphical explanation on the significance of subtracting a margin x from the saturation power. The RMS power level is then calculated according to:

$$P_{RMS} = \text{Maximum Output (SMW)}[dBm] - \text{Crest Factor}[dB] - \text{margin}[dB].$$

Figure 7 shows how an upper limit of the SMW output power of 19.34 dBm and a crest factor of 8dB results in an RMS power of 10.34 dBm if the margin x is chosen to be 1 dB.

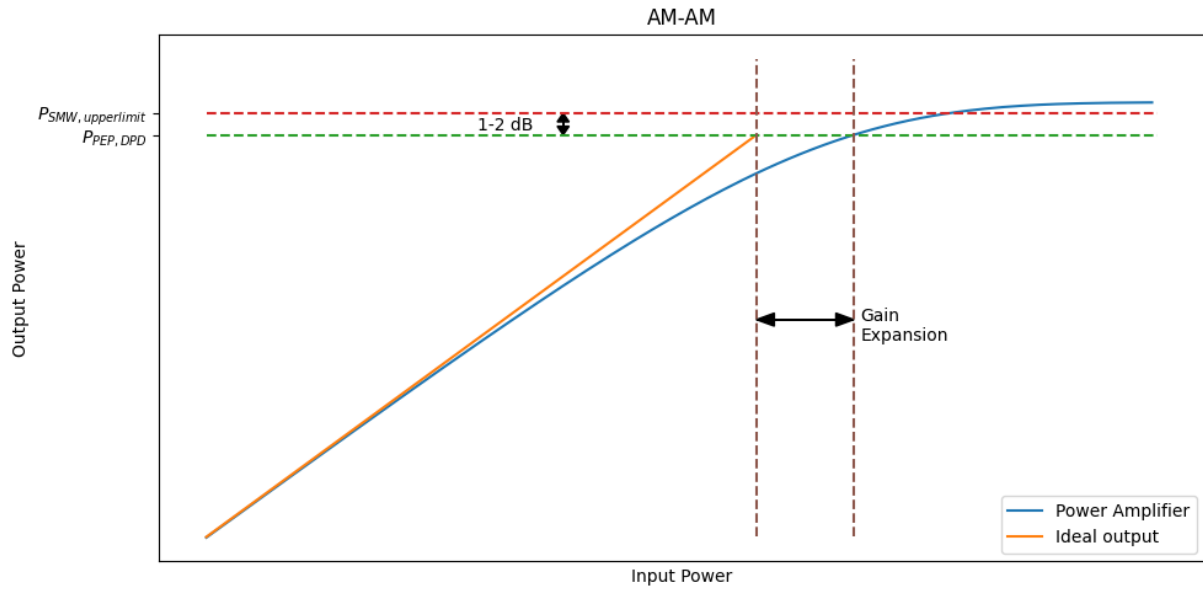


Figure 6: The significance of subtracting some small value x from the saturation output power of the SMW is shown. The pre-distortion required to compensate for clipping behavior of the SMW's output stage would need to be infinite. As this cannot be done, some small value is to be subtracted from the saturation power to build the power for the reference signal.

Step-by-step (incl. SCPI commands):

6. Select Reference signal parameters	<p>Bandwidth: Same as that of signal used in further measurements.</p> <p>Center Frequency: Same as that of signal used in further measurements.</p> <p>Crest Factor: 8 dB</p> <p>RMS Power: $\text{Maximum Output (SMW)}[dBm] - \text{Crest Factor}[dB] - x[dB].$</p>
7. Get SMW Maximum Output Power:	<code>:OUTP1:AFIX:RANG:UPP?</code>

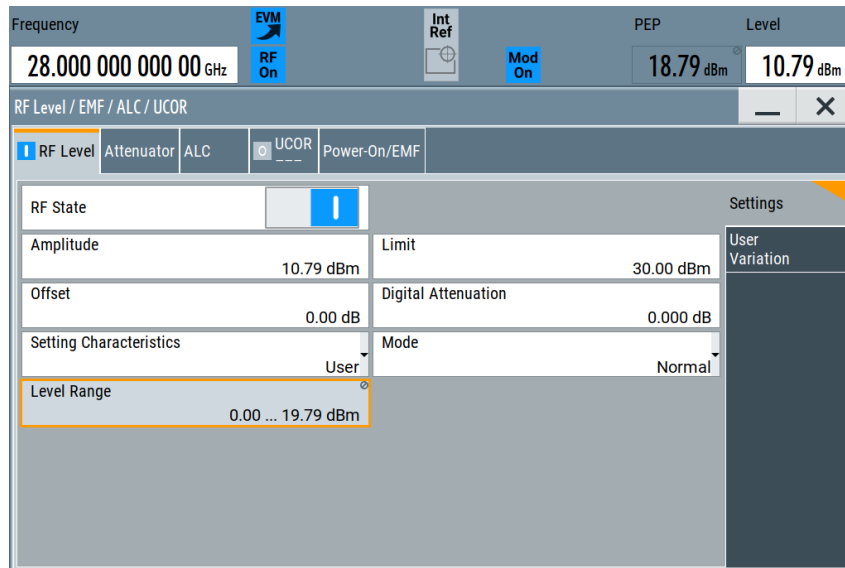


Figure 7: RF Level dialog in the SMW shows level range and RMS power (Amplitude).

5.2.2 Generating the Reference Signal and Uploading it to the Generator

In the *Reference Signal* menu in the tab *Generate Own Signal* (Figure 8) the parameters **Signal BW** (Bandwidth) and the **Crest Factor** can be selected. The reference signal is uploaded to the generator after clicking on **Generate, Play on Generator**. Afterwards, the FSW's center frequency needs to be configured. The center frequency can be chosen via *Input/Output >> Frequency >> Center*.

Step-by-step (incl. SCPI commands):

8. Set Reference Signal Bandwidth :CONF:REFS:GOS:BWID <Your Signal Bandwidth>

9. Set Reference Signal Crest Factor :CONF:REFS:GOS:CRES <Your Crest Factor>

10. Generate Reference Signal and Play on Generator :CONF:REFS:GOS:WRIT; *WAI

11. Choose FSW center frequency :SENS:FREQ:CENT <Your FSW Center Frequency>

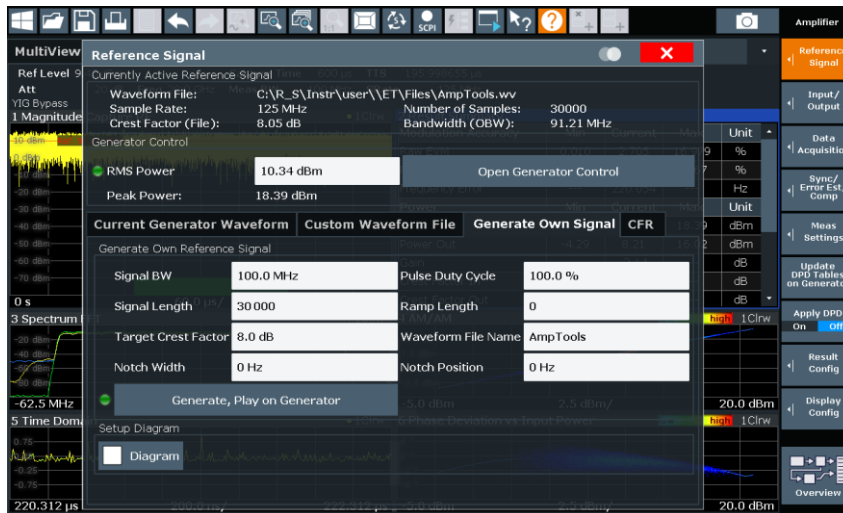


Figure 8: Reference Signal Dialog

At this point, the SMW should play the reference signal at the desired RF frequency and RF RMS level and the FSW should synchronize on the received signal and provide measured data, like raw EVM or input power.

5.3 Performing DPD and Generating the Hammerstein Model

5.3.1 Additional Settings on the R&S®FSW

On the FSW, it is recommended to activate I/Q averaging to reduce the effect of noise on the measured reference signal provided by the SMW and therefore on the generated model. The respective window is shown in Figure 9. Noise is a random process, and its influence needs to be mitigated as the DPD aims to negate a systematic error of the SMW's output stage. It is recommended to set the number of I/Q averaging steps to 10.

Furthermore, the sample rate should be increased to not only consider in-band distortions but also out-of-band intermodulation products ("shoulders"). A factor of two in respect to the reference signal bandwidth proved to be a good choice. If the used FSW doesn't provide this sample rate, it is also possible to just choose the highest sample rate the instrument allows. Note that the maximum sample rate supported by the SMW might also be limiting.

Before starting the direct DPD, it has to be assured that the FSW is operated well in its linear range and doesn't add distortions. Therefore, it is recommended to either auto level the FSW or manually increase the reference level setting to avoid that the FSW is overdriven. Auto levelling can be initiated under *AUTO SET >> Auto Level*.

Step-by-step (incl. SCPI commands):

- | | |
|---|---|
| 12. Activate MultiFrame Statistics | :SENS:SWE:STAT:STAT <ON> |
| 13. Selects Statistics Mode: I/Q Averaging | :SENS:SWE:STAT:MODE: <IQAV> |
| 14. Sets Number of I/Q Averaging steps | :SENS:SWE:STAT:COUN <Your number of I/Q averages> |

15. Deactivate automatic selection of sample rate :TRAC:IQ:SRAT:AUTO OFF

16. Set FSW sample rate :TRAC:IQ:BWID <Your sample rate>

17. Perform AUTO SET :SENS:ADJ:LEV; *WAI

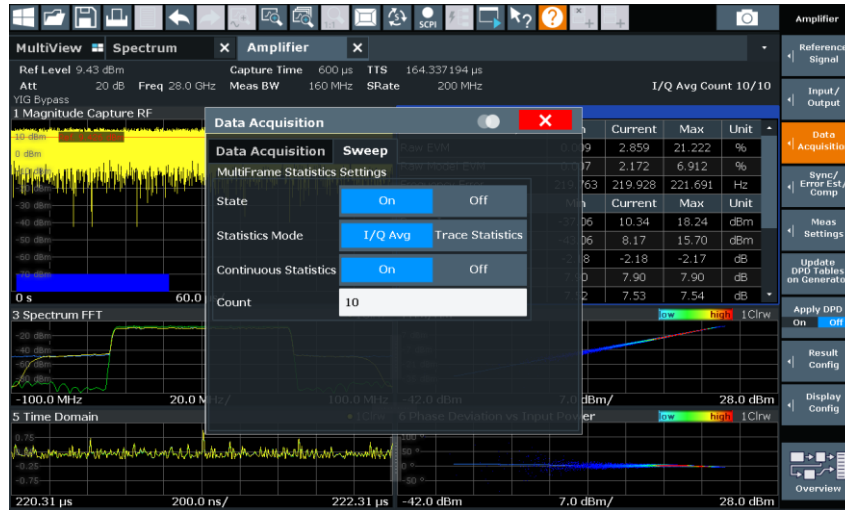


Figure 9: I/Q Averaging

5.3.2 Performing Direct Digital Pre-distortion

To generate a Hammerstein model, a Direct Digital Pre-distortion (DDPD) needs to be performed first. Under *Meas Settings* >> *DPD* >> *Direct DPD* options for the DDPD can be chosen (Figure 10). Here, the settings for the DDPD need to be provided. These consist of **Number of DDPD Iterations**, **DPD Power/Linearity Tradeoff**, and the **Gain Expansion**.

As DDPD is an iterative process, better results are expected for a larger number of iterations. Nevertheless, the EVM as a function of DDPD iteration steps converges rather quickly. It could therefore be beneficial to use less iterations if the generation of the Hammerstein model is time sensitive. The FSW-K18 provides a measurement window to display the EVM as a function of DDPD iterations directly which is accessed via *Meas* >> (*Drag and Drop*) *DDPD Results*. Using this plot, a well-educated decision on the number of DDPD iterations can be made. A value of 5 DDPD iterations is sufficient in most cases.

The **DPD Power/Linearity Tradeoff** parameter provides means to choose whether the DDPD aims for a highly linear transfer-function of the SMW's output stage accepting reduced output power (at 0%), or if the SMW's output power should be as large as possible with less weight given to linearity. Please refer to **the R&S Amplifier Masterclass Video 6 – Memory Polynomial Digital Pre-Distortion²** for a very detailed description of the **DPD Power/Linearity Tradeoff**. It is recommended to stick to the default value of 50% which aims to keep the RMS power of the pre-distorted waveform equal to the RMS power of the undistorted waveform.

The option **Gain Expansion** indicates how much the crest factor of the ARB waveform may increase during the DDPD process compared to the undistorted waveform. A value of 3 dB has been proven to be sufficient. Pressing **Start Direct DPD Sequence** starts the iterative DDPD. During each step, a new pre-distorted ARB

² https://www.youtube.com/watch?v=vglAYsUvN5E&list=PLKxVoO5jUTlvZVUh2Gn_6BYZtAsQtUHAC&index=6

file is loaded on the generator to create a more and more linear output characteristic of the generator. This may take a couple of seconds to minutes depending on how the reference signal length was chosen.

Step-by-step (incl. SCPI commands):

18. Activate Direct DPD Option	:CONF:DDPD:STAT <ON>
19. Select Power/Linearity Tradeoff	:CONF:DDPD:TRAD <Your Power/Linearity Tradeoff>
20. Select Number of DDP Iterations	:CONF:DDPD:COUN <Your Number of DDP Iterations>
21. Select Gain Expansion	:CONF:DDPD:GEXP <Your gain expansion>
22. Start DDP Sequence	:CONF:DDPD:STAR; *WAI

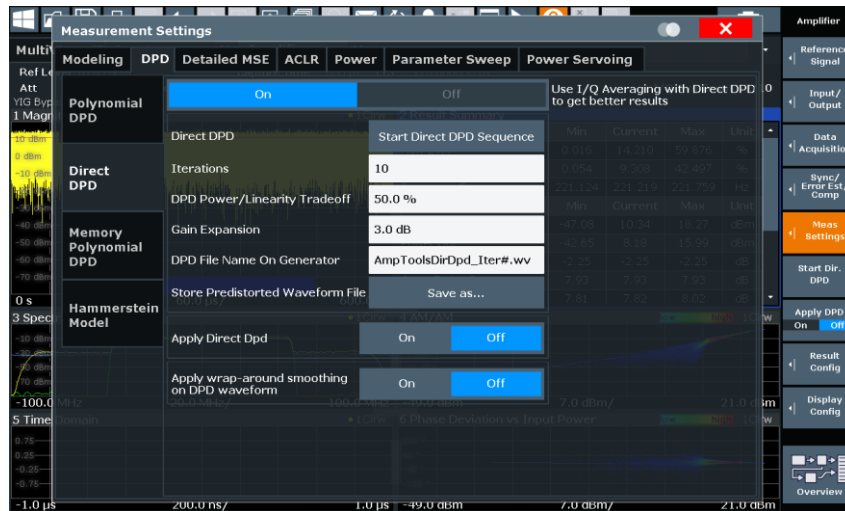


Figure 10: DDPD Settings Dialog

5.3.3 Generating the Hammerstein Model

Finally, the Hammerstein model can be generated from the results of the DDPD. Under *Meas Settings* >> *DPD* >> *Hammerstein Model* the **DDPD iteration step to use for the Model generation**, the **order of the generated polynomial** and the **Memory order** can be selected. The last DDPD step typically yields the best result but can be checked using the aforementioned *DDPD Result* plot. The polynomial order should be selected to be “1-5” to prevent overfitting. It is advisable to choose the memory order to “0-20”. Picking lower orders may ensue in suboptimal results. Pressing **Model and Update Generator** starts the calculation of the Hammerstein model. Once finished, FSW uploads the files – modeling the inverse of the memory effects, the AM/AM and the AM/PM – automatically to the signal generator and activates them. Note that all three files are required to apply the full Hammerstein model.

Step-by-step (incl. SCPI commands):

23. Activate Hammerstein model Option	:CONF:HAMM:STAT <ON>
24. Set Polynomial Order Range	:CONF:HAMM:ORD:POLY <Your Polynomial Order Range>
25. Set Memory Order Range	:CONF:HAMM:ORD:MEM <Your Memory Order Range>

23. Activate Hammerstein model Option : CONF : HAMM : STAT <ON>

26. Start Hammerstein model Generation and Upload it to the SMW : CONF : HAMM : MUPG ; *WAI

The pre-distortion could at this point already be used to reduce the influence of non-linearities and frequency response of the SMW and the FSW on an EVM measurement. It is still worth to demonstrate how the Hammerstein model files can be manually applied to the SMW.

5.4 Handling Hammerstein Model Files

By default, the Hammerstein model files are saved on the SMW in *"/var/user/"* and are named *"HammersteinDPD.fres"*, *"HammersteinDPDTable.dpd_magn"*, and *"HammersteinDPDTable.dpd_phase"*. The frequency response file can manually be chosen at *"I/Q Mod >> Frequency Response ... >> User Defined Correction"*. Here, the frequency response file can be selected after checking the box below **Additional FR** and opening the **User Data Additional FR** window on the right-hand-side (Figure 11).

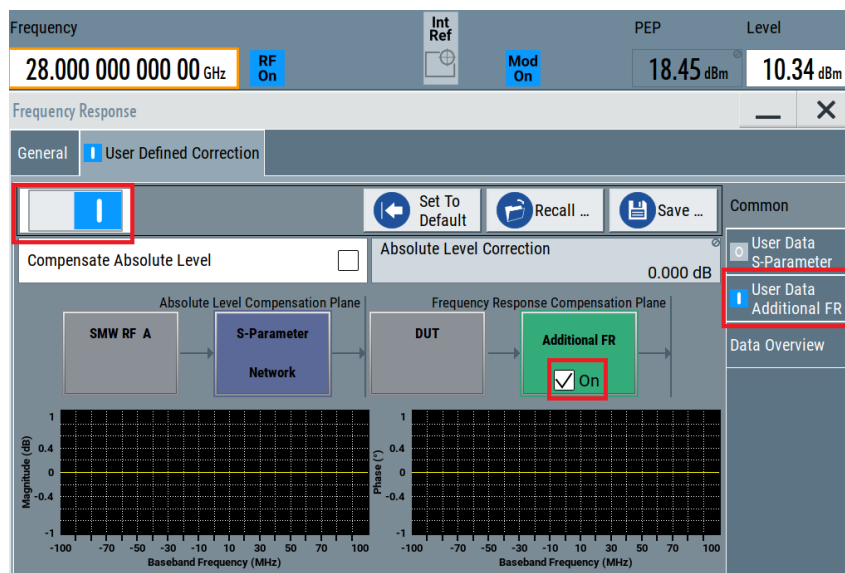


Figure 11: SMW Frequency Response Selection

The frequency response file can be selected by pressing on the button which is for now labeled with **none** (Figure 12). Then, the desired file can be found after selecting **Additional Freq Response File** in the **File Type** Menu. Afterwards, the *"*.fres"* file can be selected. The frequency response phase and magnitude correction are activated by pressing the buttons below **Magnitude** and **Phase**. The activation is indicated by the buttons turning blue and their labels saying **On**. Then the Correction is applied using the **Apply** button. Lastly, the filter must be activated in the *"User Defined Correction >> Common"* window (Figure 11).

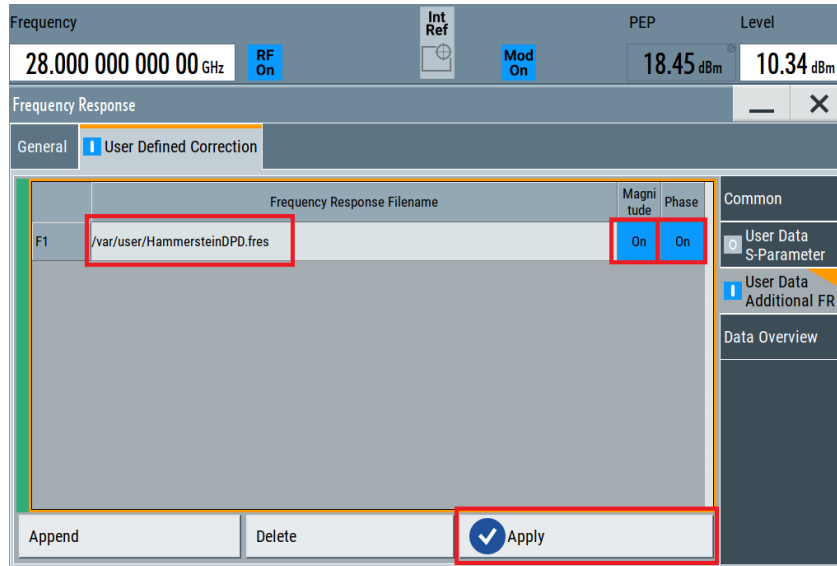


Figure 12: Select Frequency Response file.

Step-by-step (incl. SCPI commands):

27. Activate Additional User Defined Frequency Response Correction	: SOUR1:CORR:FRES:RF:USER:FLIS1:STAT <1>
28. Activate Frequency Response Correction	: SOUR1:CORR:FRES:RF:USER:STAT <1>
29. Select Hammerstein model Frequency Response File	SOUR1:CORR:FRES:RF:USER:FLIS1:SEL "</path/to/you/file/your_file.fres>"
30. Activate Frequency Response Magnitude Correction	SOUR1:CORR:FRES:RF:USER:FLIS1:MAGN:STAT <1>
31. Activate Frequency Response Phase Correction	SOUR1:CORR:FRES:RF:USER:FLIS1:PHAS:STAT <1>
32. Apply Frequency Response Correction	SOUR1:CORR:FRES:RF:USER:APPL

The Digital Pre-distortion AM/AM and AM/PM (*.dpd_magn and *.dpd_phase) can be activated at "I/Q Mod >> AM/AM, AM/PM ... >> Predistortion Settings". The files can be selected in the file selection dialog which opens after clicking on **AM/AM Table...** or on **AM/PM Table...** respectively (Figure 13). Additionally, the level range (the range the Hammerstein model is valid for) needs to be selected. Here, a value of $P_{PEP,DPD}$ (as described in 5.2.1) – 50 dB has to be entered under **Input Range (PEP_{in}) From** and a value of $P_{PEP,DPD}$ under **To**. The range of 50 dB is a default setting and can be adapted in the FSW under *Meas Settings >> Modeling >> Modeling Level Range*.

After that, the AM/AM and the AM/PM components must be activated by checking the boxes below **AM/AM** and **AM/PM** in the **DPD** frame on the *General* tab. Finally the **Level Reference** should be set to *After DPD*, the **Maximum Output Level Error** to *0.01 dB* and the **Maximum Number of Iterations** to *10*.

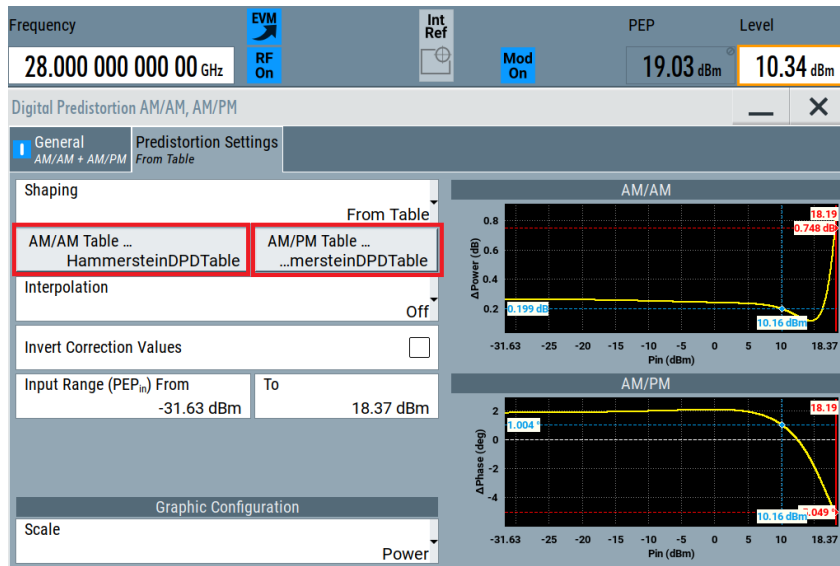


Figure 13: Selection of AM/AM and AM/PM Tables

Step-by-step (incl. SCPI commands):

33. Load AM/AM Table	:SOUR1:IQ:DPD:SHAP:TABL:AMAM:FILE:SEL "</path/to/your/file/your_file.dpd_magn>"
34. Load AM/PM Table	:SOUR1:IQ:DPD:SHAP:TABL:AMPM:FILE:SEL "</path/to/your/file/your_file.dpd_phase>"
35. Read out Input Range Minimum	:SOUR1:IQ:IQ:DPD:PIN:MIN?
36. Read out Input Range Maximum	:SOUR1:IQ:DPD:PIN:MAX?
37. Select Input Range Minimum	:SOUR1:IQ:DPD:PIN:MIN <Your Pmin>
38. Select Input Range Maximum	:SOUR1:IQ:DPD:PIN:MAX <Your Pmax>
39. Activate Digital Pre-distortion	:SOUR1:IQ:DPD:STAT <1>
40. Activate AM/AM DPD Component	:SOUR1:IQ:DPD:AMAM:STAT <1>
41. Activate AM/PM DPD Component	:SOUR1:IQ:DPD:AMPM:STAT <1>

For additional information on how files on the SMW can be handled, e.g., renamed, moved, or transferred to an external computer, please refer to the user manual³.

6 Application Software: R&S Optimize SMW

Attached to this application note, there is an application software called R&S Optimize SMW, which helps to generate a Hammerstein model according to the description provided in chapter 5.

The software is available in two versions: One version can be run directly on the FSW and is started from the application starter. This means that no additional PC is required. The other version can be executed on a PC

³ <https://www.rohde-schwarz.com/us/manual/smw200a/>

and communicates from there with SMW and FSW. How to add the software to the application starter is described in section 6.1. The operation of both versions of the software is explained in section 6.2.

6.1 Add R&S Optimize SMW to the Application Starter in the FSW

First, download the file 'RS_optimize_SMW_FSW.exe' from www.rohde-schwarz.com/appnote/1GP139. Transfer the downloaded application to the FSW (e.g., using a USB-Stick or via network). Open the application starter by clicking on the related symbol in the toolbar.



Figure 14: Toolbar of the FSW

Go to *User Applications* >> *Add Application*. Then select the file 'OptimizeSmw.exe'. Enter the parameter 'fsw'. The displayed name can be changed in the upcoming Edit Properties dialog.

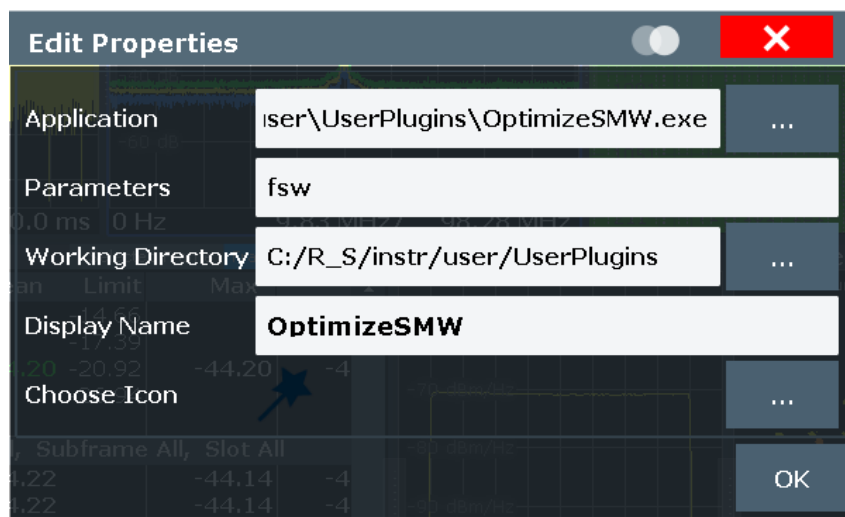


Figure 15: Edit properties dialog in the FSW

Confirm the settings by clicking on *OK*. The application software will now be displayed in *User Applications* and can be started by clicking on it.

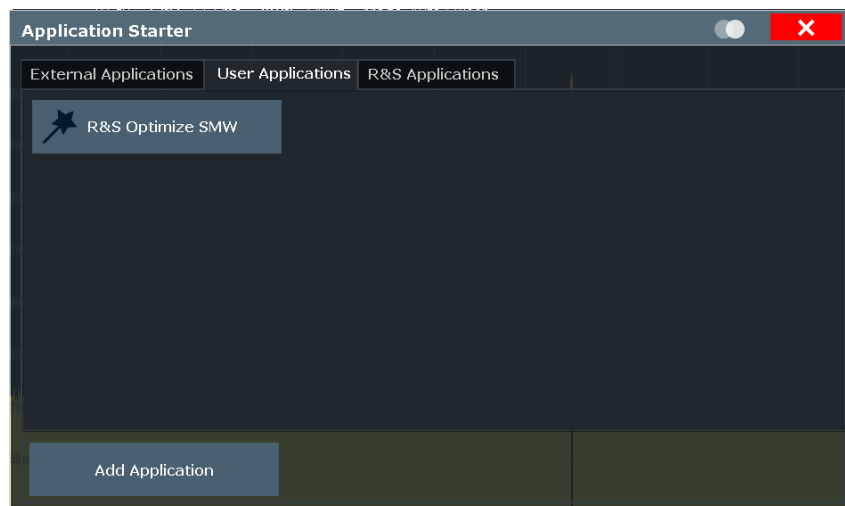


Figure 16: R&S Optimize SMW has been added to the Application Starter in the FSW

6.2 Use R&S Optimize SMW to generate a Hammerstein model

R&S Optimize SMW generates a Hammerstein model, loads, and activates it on the SMW. An initial set of parameters used to generate the model is provided automatically based on the signal loaded on the SMW.

To generate a Hammerstein model with R&S Optimize SMW, the program needs to establish connection the SMW and FSW via the local network. To do this the respective IP addresses need to be entered and the *Connect* buttons need to be clicked. If R&S Optimize SMW is run on the FSW with its application starter the FSW IP address is not required.

R&S Optimize SMW comes with two operation modes. The basic mode chooses a set of recommended parameters for Hammerstein model generation and uses them to create the model. Afterwards both the SMW and FSW are returned to their initial states with the exception that the Hammerstein model is now activated on the SMW. The process is started by clicking on *Optimize SMW*.

The advanced operation mode also provides means to draw recommended parameters by using the *Get recommended settings* button. Additionally, this mode allows for tweaking of the parameters according to the specific application. The recommended settings are chosen as described in chapter 5. Afterwards, the Hammerstein model is generated by using the *Start pre-distortion* button. Finally, the FSW and the SMW are returned to their initial states and the model is loaded and activated in the SMW.

In order to start the optimization process, the SMW needs to be configured such, that the desired test signal is generated at the RF output **A**. That means, that

- a baseband module, e.g., ARB or 5G NR, in the SMW has to be switched on in baseband **A**.
- the RF output **A** of the SMW has to be enabled.
- any previously activated predistortion files need to be deactivated in the SMW.
- the SMW's output power needs to be set sufficiently high for the internal step attenuator to be at least in the 0 dB stage (this can be checked via *RF >> Level >> Attenuator >> Attenuation Active*).

The R&S Optimize SMW PC version also allows to save the Hammerstein model correction files to a PC and plot them.

Figure 17 shows the GUI elements of the basic and advanced operation mode of R&S Optimize SMW run on an FSW.

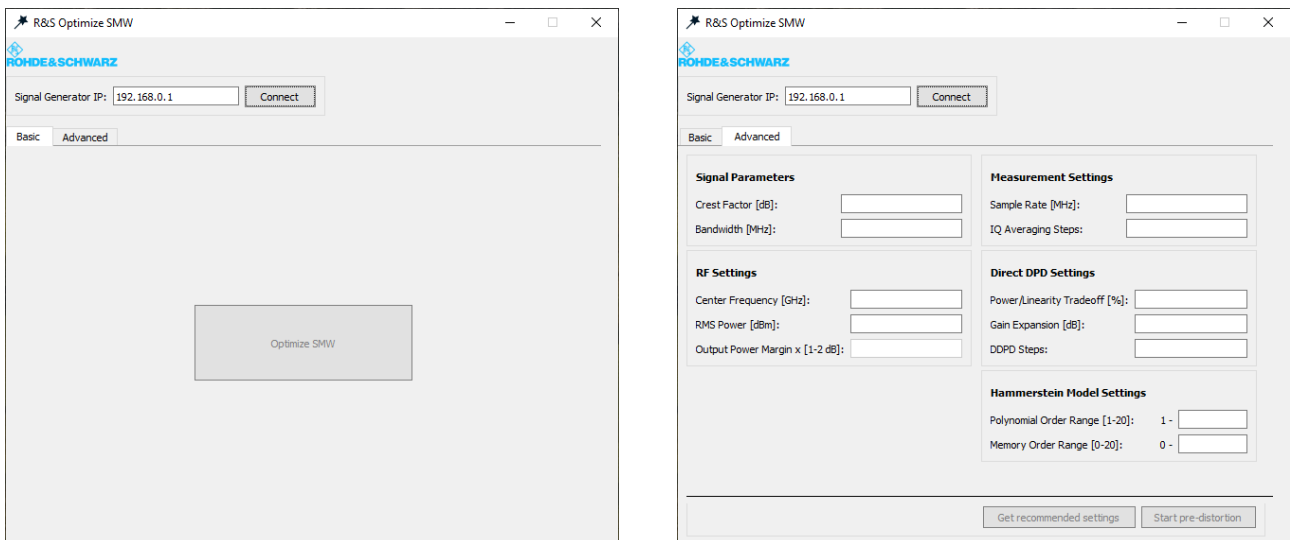


Figure 17: GUI of R&S Optimize SMW in basic and advanced operation mode.

7 Error Vector Magnitude

The Error Vector Magnitude (EVM) is a central metric for evaluating the quality of a transmission channel. The EVM denotes the length of a vector from the ideal location of a symbol in the I/Q plane to the location where the symbol is actually measured and is typically expressed in *dB* or % relative to a reference power.

$$EVM(dB) = 10 \cdot \log_{10} \left(\frac{P_{\text{Error}}}{P_{\text{reference}}} \right)$$

The EVM is clearly a well-suited indicator to assess the quality of a transmission channel as it shows how much a symbol may spread around its ideal location and therefore indicates the probability to detect the received symbol as intended. Figure 18 shows how a non-zero EVM influences a received symbol. The EVM is defined as the magnitude of the vector between the received vector and the transmitted, ideal symbol.

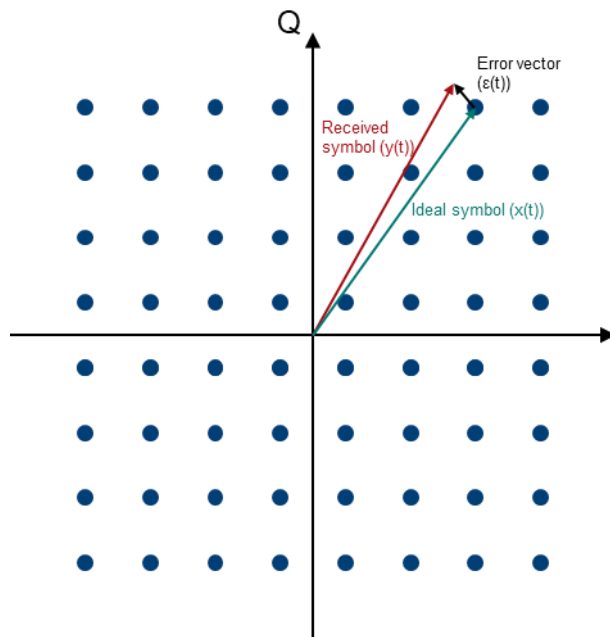


Figure 18: The definition of the Error Vector Magnitude is illustrated. It is defined as the magnitude of the vector between the received and the transmitted symbol. Therefore, it provides a well-suited metric for the quality of a transmission channel.

It is therefore crucial to evaluate the influence of every single component on the EVM of the entire transmission channel. The component with the largest influence on the EVM limits the performance of the setup. The weight of a single device on the EVM can be evaluated by using the combination of vector signal generator – device under test (DUT) – vector signal analyzer. In this context, the EVM, introduced by the generator – analyzer Setup must be sufficiently below the EVM contribution of the DUT. This may not necessarily be fulfilled, especially for higher input powers, as non-linearities of the generator's output-stage may dominate the EVM. At these high-power levels, DPD can be used to linearize the output characteristic of a generator to increase the dynamic range in which a DUT may be evaluated by the simple Vector Signal Generator – DUT – Vector Signal Analyzer setup.

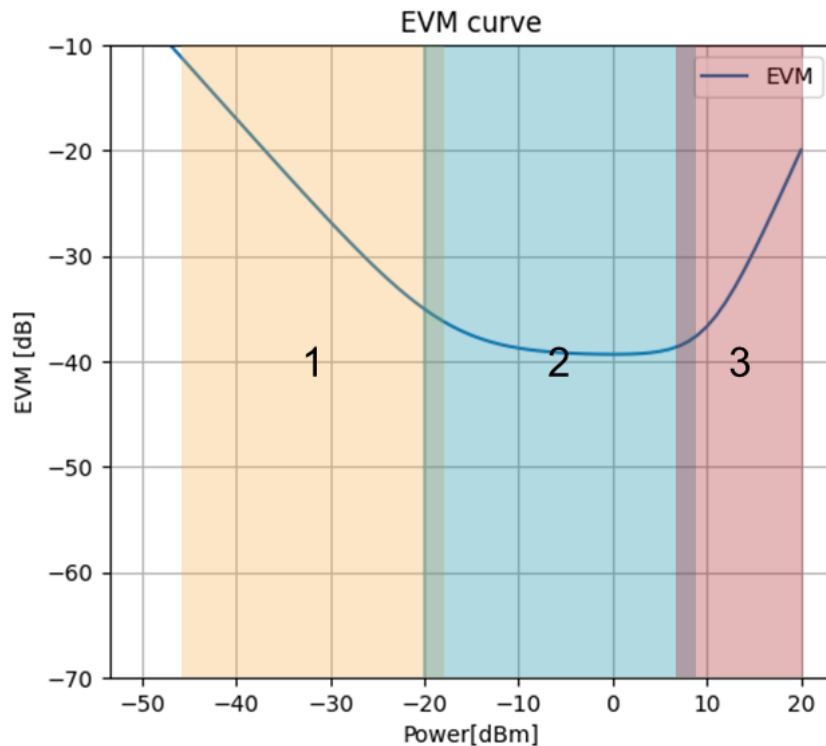


Figure 19: EVM “bathtub” curve. At low powers (1) the EVM is dominated by thermal noise. At intermediate powers (2) mainly the phase-noise limits the EVM. At high powers (3) the non-linearities outlined in this application note take over. The goal of Digital Pre-distortion (DPD) is to enlarge the phase-noise limited range towards higher powers and push the rising slope at (3) further to the right. There are also other effects, which are not mentioned here, as they tend to be negligible compared to the impairments described above.

Figure 19 displays the EVM as a function of the power. The EVM is dominated by thermal noise for low powers (1), by phase noise for intermediate powers (2) and the aforementioned non-linearities at high powers (3). The proceedings described in this application note aim to push the increasing slope at (3) to even higher power levels.

8 Use Cases with Examples

The capability of the Hammerstein model to compensate distortions caused by the SMW’s output stage have been tested for 5G NR down- and uplink signals as well as single carrier signals. In the following the results of some example measurements are shown. The EVM is shown versus the RMS power levels. The curves of the EVM with a Hammerstein model applied as well as the curves without pre-distortion are shown.

8.1 5G NR Uplink / OFDM

The EVM as a function of FSW input power of a 100 MHz wide 5G NR uplink signal transmitted at 28 GHz is shown. The parameters for the DDPD and the Hammerstein model were chosen as follows:

Hammerstein Model Memory Order	0-20
Hammerstein Model Polynomial Order	1-5
Gain Expansion	3 dB
Reference Signal Crest Factor	8 dB
DDPD Iterations	10
IQ Averaging Steps	10
Reference Signal Bandwidth	100 MHz

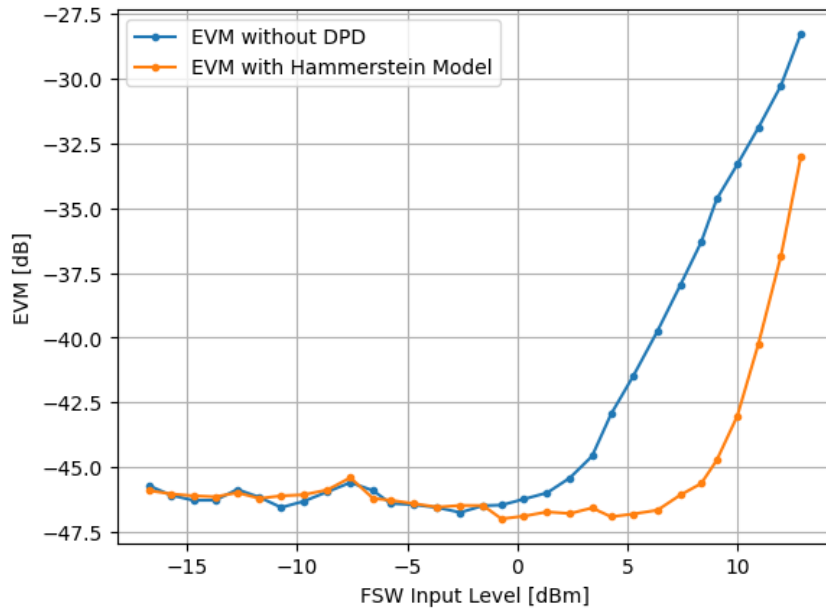


Figure 20: EVM vs. level for 5G NR Uplink signal

8.2 5G NR Downlink / OFDM

The EVM as a function of FSW input power of a 100 MHz wide 5G NR downlink signal transmitted at 28 GHz is shown. The parameters for the DDPD and the Hammerstein model were chosen as follows:

Hammerstein Model Memory Order	0-20
Hammerstein Model Polynomial Order	1-5
Gain Expansion	3 dB
Reference Signal Crest Factor	8 dB
DDPD Iterations	10
IQ Averaging Steps	10
Reference Signal Bandwidth	100 MHz

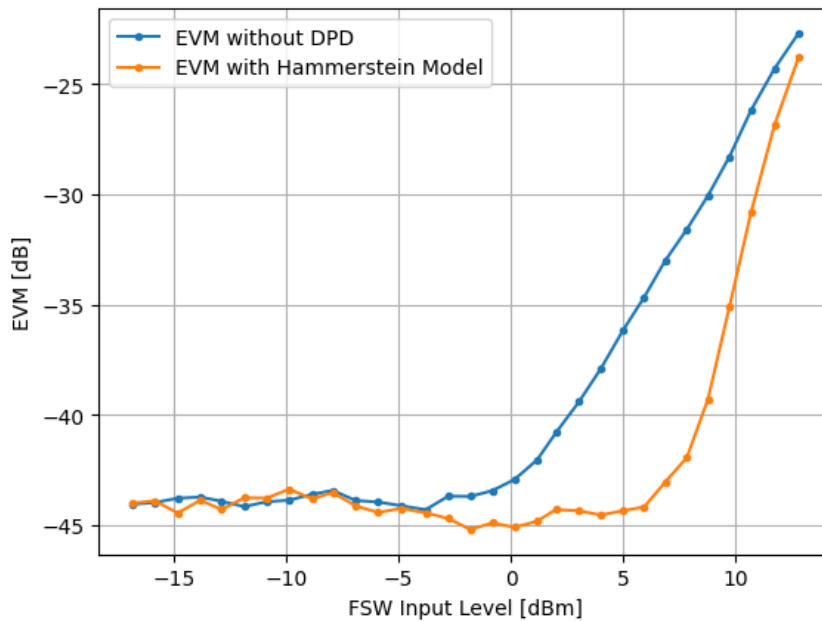


Figure 21: EVM vs. level for 5G NR Downlink signal

8.3 Single Carrier Signal with Digital Modulation

The EVM as a function of FSW input power of a 500 MHz wide single carrier signal modulated used 256 QAM transmitted at 3.5 GHz is shown. The parameters for the DDPD and the Hammerstein model were chosen as follows:

Hammerstein Model Memory Order	0-20
Hammerstein Model Polynomial Order	1-5
Gain Expansion	3 dB
Reference Signal Crest Factor	6.65 dB
DDPD Iterations	5
IQ Averaging Steps	10
Reference Signal Bandwidth	500 MHz

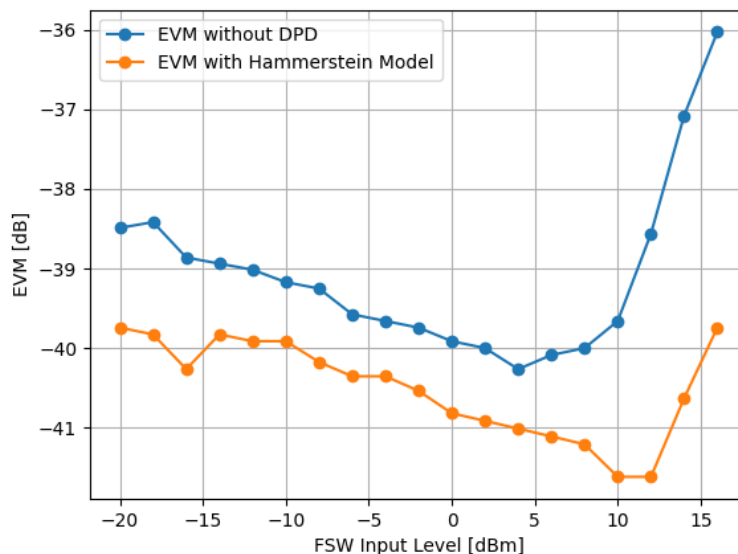


Figure 22: EVM vs. level for single-carrier signal

9 Conclusion

This application note showed how an FSW equipped with the K18 option can be used to generate a pre-distortion model for an SMW in the form of a Hammerstein model. By generating a reference signal, performing the DDPD and then calculating the Hammerstein model from the result, a pre-distortion model is produced that can be used for a variety of signals in a large power range. This pre-distortion model can then be used to linearize an SMW signal generator to use it, as shown in this application note, in EVM measurements, but also for other measurements, such as ACLR.

10 Further Reading

1. Rohde & Schwarz: Application Note; Tröster-Schmid: “Envelope Tracking and Digital Pre-Distortion Test Solution for RF Amplifiers”; URL: https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_application/application_notes/1qp104/1GP104_2E_ET_DPD_testing_for_amplifiers.pdf
2. Rohde & Schwarz: Application Note; Dr. F. Ramian: “Iterative Direct DPD”; URL: https://www.rohde-schwarz.com/us/applications/iterative-direct-dpd-white-paper_230854-478144.html
3. Rohde & Schwarz: Application Note; G. Lloyd: “Linearization of RF Frontends”; URL: https://www.rohde-schwarz.com/us/applications/linearization-of-rf-frontends-white-paper_230854-194049.html
4. Rohde & Schwarz: Application Note; M. Lörner, et al.: “Investigate RF Power Amplifier Linearization Benefits in EDA”; URL: https://www.rohde-schwarz.com/us/applications/investigate-rf-power-amplifier-linearization-benefits-in-eda-application-note_56280-1208256.html
5. Rohde & Schwarz: Application Note; M. Lörner, et al.: „Linearization of RF Amplifiers”; URL: https://www.rohde-schwarz.com/us/applications/linearization-of-rf-amplifiers-application-note_56280-1110210.html

11 Appendix

A.1 Python Code to Generate Hammerstein Model

```
from RsInstrument import RsInstrument

frequency_hz = 2e9 # Replace with your frequency
crest_factor_db = 8 # Replace with your crest factor
smw_upper_limit_dbm = 19.34 # Replace with the Level Range Maximum read out from your SMW
rms_level_dbm = smw_upper_limit_dbm - crest_factor_db - 1 # The RMS level, the Hammerstein model is calculated for.
# The "1" could also be replaced with a "2"

gain_expansion_db = 3 # Replace with your gain expansion
polynomial_order = "1-5" # Replace with your polynomial order
memory_order = "0-20" # Replace with your memory Order

iq_averages = 10 # Replace with the number of desired IQ averages during DDPD
ddpd_steps = 10 # Replace with number of desired DDPD iterations
bandwidth_hz = 20e6 # Replace with the bandwidth the Hammerstein model should be calculated for
sample_rate_hz = bandwidth_hz * 2 # If FSW doesn't provide sufficient sample rate -> Replace with FSW's maximum sample rate
time_out_ms = 60_000 # Set timeout to a high value to ensure that DDPD and Hammerstein model calculation can be finished
smw_ip = "smw200a-110902"
fsw_ip = "fsw8 265716"
smw = RsInstrument(f'TCPIP::{smw_ip}::hislip0', reset=False)
smw.instrument_status_checking = False
fsw = RsInstrument(f'TCPIP::{fsw_ip}::hislip0', reset=False)
fsw.visa_timeout = time_out_ms
fsw.opc_timeout = time_out_ms

# SMW Setup:
smw.reset() # Reset SMW
smw.write_with_opc('SOURcel:CORRection:OPTimize:EVM ON')
smw.write_with_opc(f'SOURcel:frequency_hz:CW {frequency_hz}') # Set SMW output to your frequency
smw.write_with_opc('OUTPut1:STATe 1') # Turn SMW output on
smw.write_with_opc(f'SOURcel:POWer:POWer {rms_level_dbm}')

# FSW Setup:
fsw.reset()
fsw.write_with_opc('SYStem:DISPlay:UPDate ON') # Enable built-in display to be updated while remote controlled
fsw.write_with_opc('INStRument:CREate:NEW AMPL, "Amplifier"') # Open K18 "Amplifier" option
fsw.write_with_opc('INITiate:CONTinuous OFF') # Turn off continuous sampling
fsw.write_with_opc(f'CONFIgure:GENerator:IPConnection:ADDRESS "{smw_ip}"') # Set Generator IP Adress for Remote Control
fsw.write_with_opc('CONFIgure:GENerator:CONN:STAT ON') # Establish connection to Generator
fsw.write_with_opc(f'CONFIgure:REFSignal:GOS:EWIDth {bandwidth_hz}') # Select Reference Signal bandwidth
fsw.write_with_opc(f'CONFIgure:REFSignal:GOS:CRESt {crest_factor_db}') # Select Reference Signal Crest Factor
fsw.write_with_opc('CONFIgure:REFSignal:GOS:WRITe;*WAI') # Generate Reference Signal and play it on the Generator
fsw.write_with_opc('CONFIgure:DDPD:STAT ON') # Activate DDPD option
fsw.write_with_opc(f'CONFIgure:DDPD:COUN {ddpd_steps}') # Set number of DDPD steps
fsw.write_with_opc('SENS:SWE:STAT:STAT ON') # Activate Sample Averaging
fsw.write_with_opc(f'SENS:SWE:STAT:COUN {iq_averages}') # Set number of averages
fsw.write_with_opc('TRAC:IQ:SRAT:AUTO OFF') # Deactivate automatic selection of the sample rate
fsw.write_with_opc(f'TRAC:IQ:BWID {sample_rate_hz}') # Set Sample Rate
fsw.write_with_opc('INP:ATT:AUTO OFF') # Deactivate automatic selection of the input attenuation

# Deactivate potentially loaded Hammerstein model files
smw.write_with_opc('SOURcel:CORRection:FRESponse:RF:USER:STATe 0')
smw.write_with_opc('SOURcel:IQ:DPD:STATe 0')
smw.write_with_opc(f'SOURcel:POWer:POWer {rms_level_dbm}') # Set SMW level
fsw.write_with_opc('SENS:ADJ:LEV; *WAI') # Perform Auto Set
fsw.write_with_opc(f'CONFIgure:DDPD:GEXP {gain_expansion_db}') # Set Gain Expansion
fsw.write_with_opc('CONFIgure:DDPD:STAR') # Start DDPD Sequence
fsw.write_with_opc('CONFIgure:HAMM:STAT ON') # Activate Hammerstein model Option
fsw.write_with_opc(f'CONFIgure:HAMM:ORD:MEM "{memory_order}"') # Set memory polynomial order
fsw.write_with_opc(f'CONFIgure:HAMM:ORD:POLY "{polynomial_order}"') # Set DPD polynomial

fsw.write_with_opc('CONFIgure:HAMM:MUPG; *WAI') # Start Hammerstein model calculation
```

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1GP139 | Version 0e | 08.2023

Application Note | Digital pre-distortion for Improved EVM Performance
Data without tolerance limits is not binding | Subject to change

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