

LINEARIZATION OF RF AMPLIFIERS

Connecting simulation and measurements on physical devices

Products:

- ▶ R&S®FSW
- ▶ R&S®SMW200A
- ▶ MathWorks® MATLAB® and Simulink®

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1 Overview

This application note is based on collaborative work between MathWorks® and Rohde & Schwarz. The focus is on linearization of a non-linear device, in our case the RF power amplifier. It is shown how simulation and the integrated functions of the Rohde & Schwarz instruments R&S®SMW200A and R&S®FSW work hand-in-hand with the simulation capabilities from MathWorks in MATLAB / Simulink. The goal is to provide a toolset to enable proper modeling and linearization approaches to optimize and verify the behavior of the power amplifier when used with complex wideband signals as used in 5G NR or latest satellite links.

The application note brings code examples and an exemplary block set for MATLAB / Simulink to provide an easy start to replicate and use the described procedure.

2 Introduction

2.1 Why linearization?

New applications put new requirements on RF systems and RF frontends. When looking at 5G, not only mmW applications but also modified topologies are added: massive MIMO ask for 64 or more coherent channels. In FR1, every path is typically connected to a digital back end allowing individual linearization. In FR2, we are using often hybrid beamforming where a sub-tile is connected to one digital path. This is required for economic reasons as we are looking at 256, 512 or even 1024 antenna elements.

In order to increase the data throughput in a communication system, 2 methods are used: increasing bandwidths, for example up to 400 MHz in one 5G FR2 carrier as well as higher order modulation schemes allowing improved usage of the occupied bandwidth.

Similar developments can be seen in satellite space with digital regenerative payloads, basically a 'base station in the sky' which are also using beamforming with phased array antenna systems. Similar enhancements are applied in electronic warfare for radar or other signals.

All of the above ask for highly linear characteristics of the RF modules to ensure proper functioning and high data throughput. The increasing bandwidths ask for new technologies such as Gallium Nitrate (GaN) which might create challenges due to their inherent nonlinear behavior. Higher order modulations on the other side push for less distortions as the distance between the constellation points become smaller thus lower error vector magnitude (EVM) is required for stable demodulation of the sent data.

Significant power consumption in any wireless transmission system happens in the RF front end. Amplifiers are used where they offer best energy efficiency to reduce operating costs in cooling, dimension and power consumption. This is the case close to saturation, but non-linearity is also high in this operation mode. Newer PA technologies such as GaN offer best efficiency and energy density but require linearization in almost any use case.

Linearization can be done in various ways. The most prominent approach today is to use a digital predistortion (DPD) of the signal where the incoming waveform is modified on the fly in order to pre-compensate the nonlinear behavior of the power amplifier. In the target application, it helps to improve signal quality as seen in the error vector magnitude as one figure of merit. The other effect where DPD helps is to minimize out of channel leakage ratio to minimize noise creation in the neighboring bands.

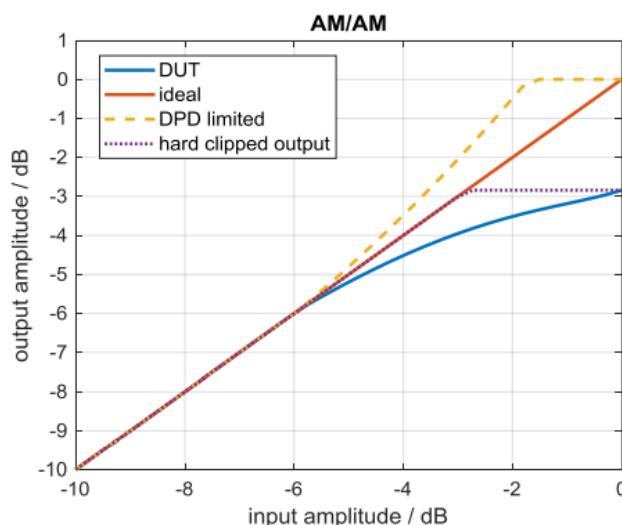


Figure 1: Overview plot of PA behavior: measured AM/AM, ideal output, pre-distorted signal (hard clipped)

Many activities focus on the design of different amplifier topologies such as Doherty or load modulated balanced amplifiers to improve energy efficiency. But in any case, the need for linearization remains. Actually, having access to proper and sophisticated linearization capabilities allows to look into a wider range of amplifier structures with the final goal of increasing efficiency.

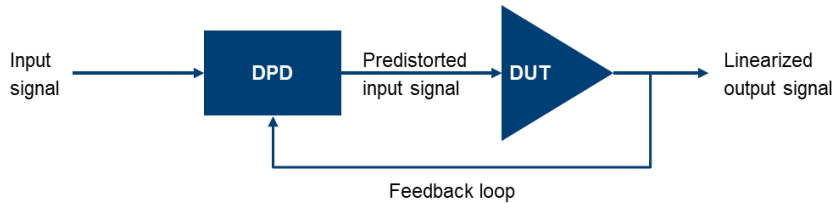


Figure 2: Simplified block diagram for linearization

2.2 Different approaches complementing each other

Digital predistortion is - as the name says - a digital process using mathematical algorithms. To develop and optimize these, a mathematical environment with simulation capabilities seems a natural choice to develop, tune and optimize the linearization methods. A simulation environment allows to easily adopt the complexity of the predistortion. This helps to investigate various predistortion models and cross-check the gained benefit coming with additional algorithmic complexity. In the described work in this application note, the MathWorks tools MATLAB and Simulink are used.

On the other side, a test-instrument assisted approach can deliver fast results at an easy process flow using fully integrated features. The R&S®FSW signal and spectrum analyzer offers integrated methods for linearization including the creation of a memory polynomial approach for the DPD. The complexity with regards to the polynomial order and memory depth are user-definable. A direct verification of the derived DPD algorithm against the physical power amplifier completes the instrument-based approach.

While the first approach offers more flexibility to the user, the second simplifies the process flow for the development engineer. Bringing both together allows maximum flexibility and more confidence in the derived digital predistortion method for the target environment including the used power amplifier as well as the complex signal used in the final application.

3 Process flow and model creation

In order to define a linearization method, a model of the power amplifier is required. This could be provided by the vendor or derived from an RF measurement on the device.

Different methods are used to create and validate models. In our case, we want to use a modulated wideband signal traveling through the nonlinear device. Knowing the transmitted ideal signal $A(nT)$ and measuring the output $M(nT)$ of the device allows to create a model using a memory polynomial approach describing the behavior of the power amplifier.

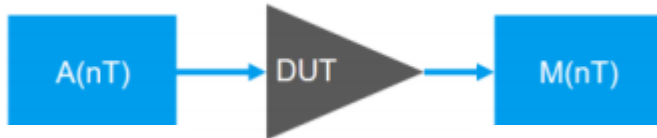


Figure 3: Input and output of the nonlinear power amplifier

$$\tilde{P}(nT) = \sum_{p=1}^P \sum_{m=1}^M k_{p,m} A(nT - \tau_m) |A(nT - \tau_m)|^{p-1}$$

Equation 1: Power transfer function to model the power amplifier behavior

3.1 Measurement setup to collect the needed data

The required measurements to create a model of the power amplifier can be done easily using the vector signal generator R&S®SMW200A in conjunction with the vector signal analyzer R&S®FSW. The internal capabilities of the SMW to create various test signals such as 5G compliant scenarios support the task. In addition, any custom waveform can be used in the internal arbitrary waveform generator. In the analyzer, the amplifier characterization application FSW-K18 performs all characterization measurements for any test signal from a single data acquisition.

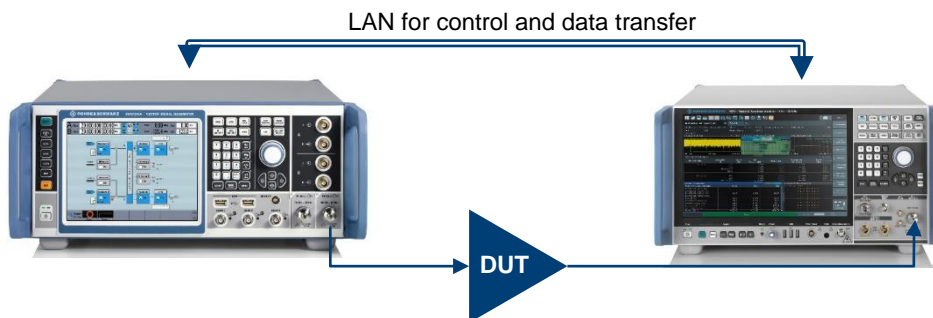


Figure 4: Measurement setup to gather the data used for modelling

All characterization results (e.g. EVM, AM/AM, AM/PM, gain compression, frequency response, group delay and many more) can easily be extracted from the analyzer and be used for further evaluation.

The K18 amplifier test solution supports Iterative Direct DPD creating an ideally pre-distorted signal based on the original input waveform with the hardware setup as shown in figure 4. By its concept, it compensates any nonlinearity including memory effects simply by adjusting sample by sample individually until the output matches a linear copy of the original reference file. See white paper [Iterative Direct DPD | Rohde & Schwarz \(rohde-schwarz.com\)](https://rohde-schwarz.com) for more information.

The pre-distorted waveform and the corresponding measured output signal of the device under test (DUT) may be used to either generate or validate the DUT model. Obviously, the more accurate the model of the power amplifier is, the better the subsequent linearization work can be while making use of it.

The baseline data to create the model needs to be long enough to capture the complex behavior of the power amplifier and include large power variations. Using a wideband signal such as a 100 MHz wide 5G signal brings the required signal fidelity and variance. Tests have shown, that using a signal duration of 1 frame which is 10 ms long is sufficient for the 100 MHz wide signal.

3.1.1 Examples to collect data

This chapter holds an easy MATLAB script that configures the R&S SMW200A and the R&S FSW to run measurements on a PA and to retrieve all relevant data into the MATLAB workspace.

In order to make sure all signals have the same reference, we will scale all signal vectors to Volts, i.e., all real and imaginary samples are then given in Volts.

Note:

Signal generator files (wv file extension) are normalized to a magnitude of "1", so they need rescaling depending on the current level setting of the signal generator.

I/Q data captures from the signal analyzer are typically in unit Volts.

The attached script `<GetDataForModelling.m>` is divided into three sections:

1. K18 measurement, i.e., amplifier characterization including retrieval of input and output data
2. Iterative Direct DPD measurement (K18D), including retrieval of pre-distorted input data and corresponding output data
3. Memory polynomial DPD, including retrieval of pre-distorted input data and corresponding output data

With all data scaled properly in the MATLAB workspace, we're ready for the next step - feeding the simulation.

Variable name overview (all in Volts):

<code>iq_in</code>	original input file (reference)
<code>iq_out</code>	original output file (no DPD active)
<code>iq_in_dpd_g0</code>	pre-distorted input signal (Iterative Direct DPD)
<code>iq_out_dpd_g0</code>	output signal with DUT while using <code>iq_in_dpd_g0</code> as input signal
<code>iq_in_mdpg0</code>	pre-distorted input signal (memory polynomial DPD)
<code>iq_out_mdpg0</code>	output signal with DUT while using <code>iq_in_mdpg0</code> as input signal

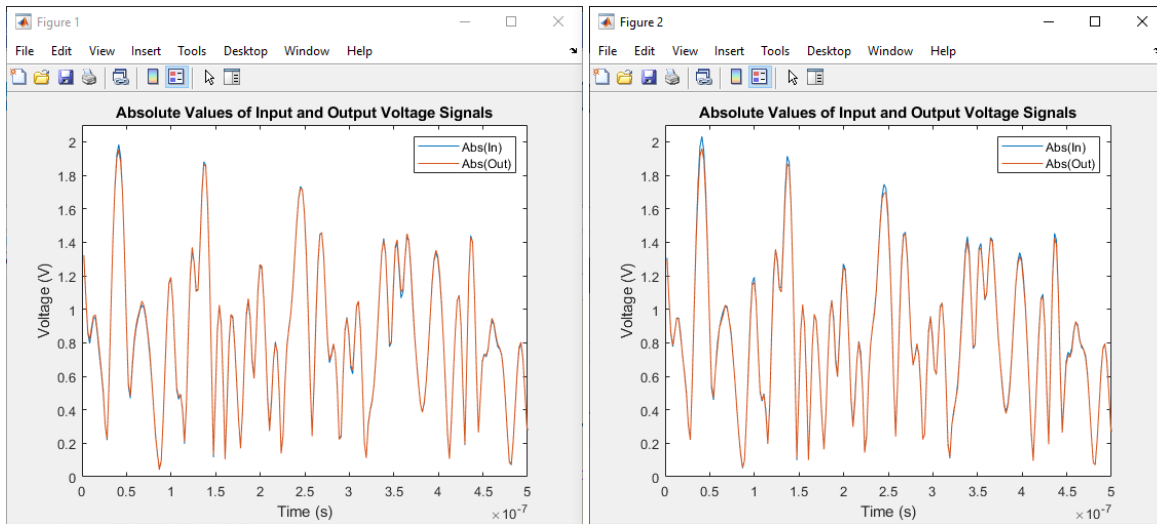


Figure 6: Measured input/output time domain waveforms of the power amplifier. In blue, absolute value of the input waveform multiplied times the PA linear gain. In red, the absolute value of the output waveform, On the left, the PA is driven by the 5G test model NR-FR1-TM3.1. On the right, the PA driven by the same 5G waveform including Iterative Direct DPD. The data on the right has been used for the model identification as the dynamic range of the input signal is larger as it can be seen from the peaks of the blue waveform.

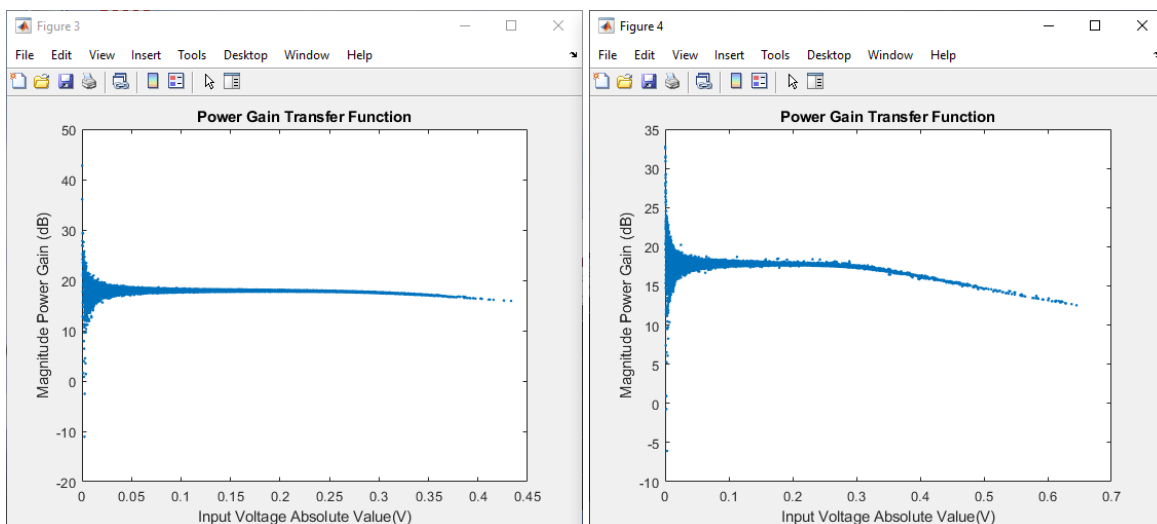


Figure 7: Measured PA power gain transfer function. On the left, the PA is driven by the 5G test model NR-FR1-TM3.1. On the right, the PA driven by the same 5G waveform including Iterative Direct DPD. The data on the right has a larger dynamic range and it has been used for the model identification.

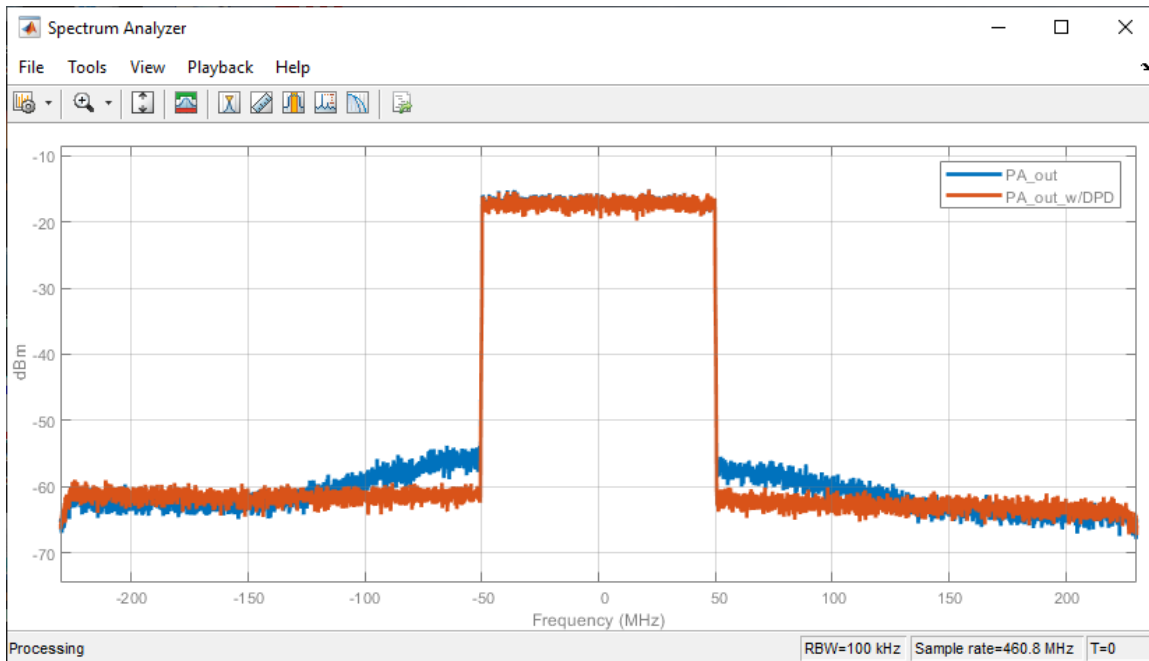


Figure 8: Spectrum analysis of the PA measured waveforms. In blue, the PA is driven by the 5G test model NR-FR1-TM3.1 with 100MHz bandwidth and 30kHz subcarrier spacing. In red, the PA driven by the same 5G waveform including Iterative Direct DPD. The data in red has been used for the model identification.

We can now identify the memory polynomial model of the PA using the helper function `<fitModelPA.m>` [5]. This function allows to experiment with different parameters such as the order of the polynomial, the depth of the memory in number of samples, and the type of polynomial model with or without memory cross terms. A higher polynomial is required to model devices driven in the non-linear region. A higher memory depth and a model with memory cross terms can be beneficial to better capture short term memory effects.

The function returns a square matrix with the complex coefficients of the model computed by solving the overdetermined problem with a least mean square approach. The matrix columns represent the non-linear coefficients, and the rows represent the memory coefficients. You can edit the MATLAB function and verify how the model is identified.

Variables - fitCoefMat					
PLOTS VARIABLE VIEW					
fitCoefMat					
5x3 complex double					
	1	2	3	4	5
1	7.4945 - 0.0641i	3.8193 + 1.4466i	-15.2952 - 4.0217i		
2	0.1125 - 0.0418i	0.5621 + 0.6208i	-1.0374 - 1.0670i		
3	-0.0053 - 0.0294i	-0.3467 - 0.2849i	1.1647 + 0.7305i		
4	-0.1952 - 0.1247i	0.0381 + 0.0797i	-0.1560 + 0.2098i		
5	0.1436 + 0.0853i	0.0230 - 0.0331i	-0.0577 - 0.1917i		
6					
7					

Figure 9: Example of matrix of complex coefficients representing a memory polynomial model of order 3 and memory depth 5.

The PA behavioral model is identified, and its results are verified in the next section. As a best practice, it is recommended to keep the order and the memory depth as low as possible depending on the semiconductor technology and device non-linearity. Often increasing the model complexity leads to marginal improvements, and potentially makes the model less robust to numerical artefacts.

In this example, we identify the model using the pre-distorted measured data using the Iterative Direct DPD approach as it has a larger dynamic range. The measured data is stored in the matrix `in` for the input waveforms, `out` for the output waveforms. Each row represents a complex (i,q) sample in the time domain. Each column of the matrixes represents a dataset. The first column stores the datasets `iq_in` and `iq_out`. The second column stores the datasets `iq_in_dpd_g0` and `iq_out_dpd_g0`. Using a single matrix for all measured input and output waveforms allows to easily change the set of data used for the model identification and helps to verify the model using an extended data set of measurements. In this example we use the measured data that includes Iterative Direct DPD, by selecting the data in the matrix with the column index `i=2`.

To identify the model, we use a polynomial order and memory depth equal to 3. Given that the measurement bandwidth is less than 5 times the signal bandwidth, it is recommended using a polynomial order smaller than 5. The robust identification of a higher order polynomial requires a larger measurement bandwidth to isolate the contribution of the different non-linear terms.

The identified PA model can be used for simulation of arbitrary waveforms with dynamic range and bandwidth smaller than the dataset that has been used for its identification.

3.2.2 Verify model fitting

The identified model is verified against the measured output data using as input signal a 5G test model with and without predistortion. The function `<verificationModelPA.m>` computes the model RMS error, and shows the comparison of the predicted and measured time domain waveforms, power transfer functions (Figure 10), spectrum analysis, and ACPR (Figure 11 and Figure 12).

With this MATLAB approach, you can easily iterate and explore different parameters for the model identification and verify the quality of the prediction.

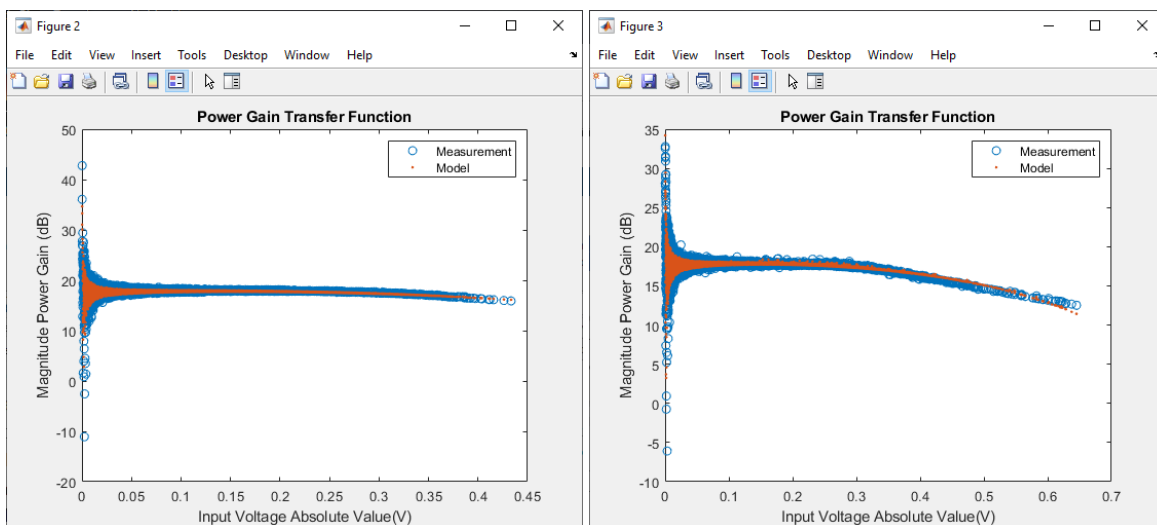
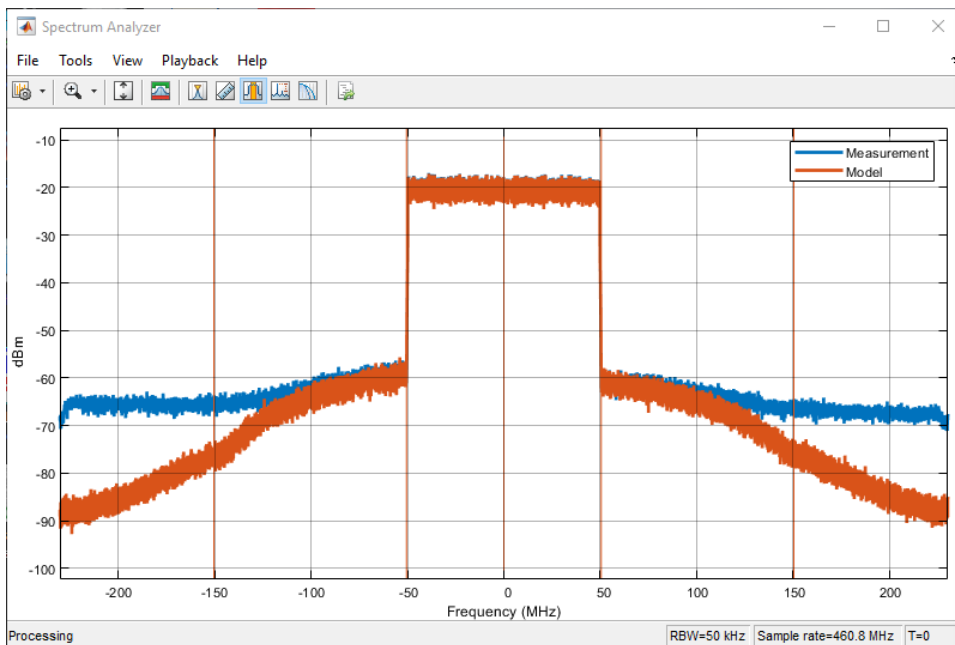


Figure 10: Measured and predicted PA power gain transfer function. On the left, the PA is driven by the 5G test model NR-FR1-TM3.1. On the right, the PA driven by the same 5G waveform including Iterative Direct DPD. In blue the measured data, in red the model prediction. The data on the right has a larger dynamic range and it has been used for the model identification.

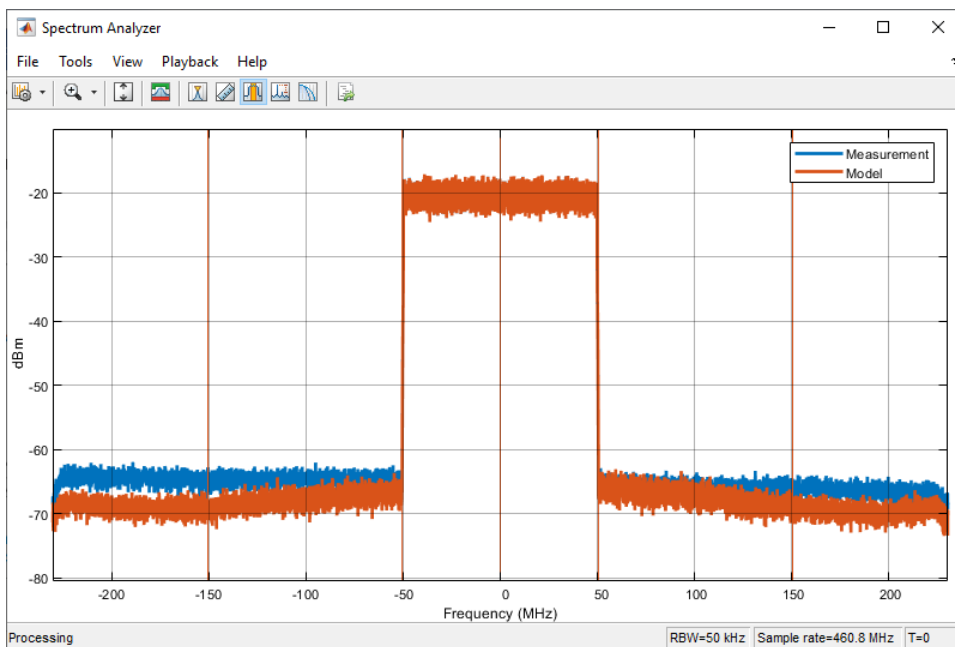


Signal standard deviation = 4.3301%

ACPR data = -41.8094 -43.0403

ACPR fit = -43.4163 -44.6235

Figure 11: Spectrum analysis of the PA measured and predicted output waveforms. In blue, the measured output waveform. In red, the predicted waveform. Below, the model standard deviation and the comparison between measured and predicted ACPR in the 100MHz adjacent bandwidths. The model predicts with acceptable accuracy the spectral regrowth due to third order non-linearity in the adjacent bandwidths.



Signal standard deviation = 4.9761%

ACPR data = -44.4055 -45.5616

ACPR fit = -47.4488 -47.0815

Figure 12: Spectrum analysis of the PA measured and predicted output waveforms. In blue, the measured output waveform including Iterative Direct DPD and used for the model identification. In red, the predicted waveform. Below, the model standard deviation and the comparison between measured and predicted ACPR in the 100MHz adjacent bandwidth. The model predicts with acceptable accuracy the spectral regrowth due to third order non-linearity in the adjacent bandwidths.

The last verification step consists in using the PA polynomial model for circuit envelope simulation using RF Blockset. In the testbench <verificationPA.slx> (Figure 13), the same PA model is excited with the two measured input waveforms, and the output of the PA model is compared, sample by sample, with the respective measured waveform. In the testbench, it is also possible to include, for example, a limiter block to guarantee that the input signal does not exceed the characterization range.

The PA block included in the RF Blockset directly uses the matrix of coefficients identified at the previous step, and it can be used also with cross-terms or Hammerstein memory polynomials [6].

The same testbench can be used to stream any arbitrary time domain waveform through the PA model and include additional RF and baseband components in the system such digital filters, modulators, and antennas.

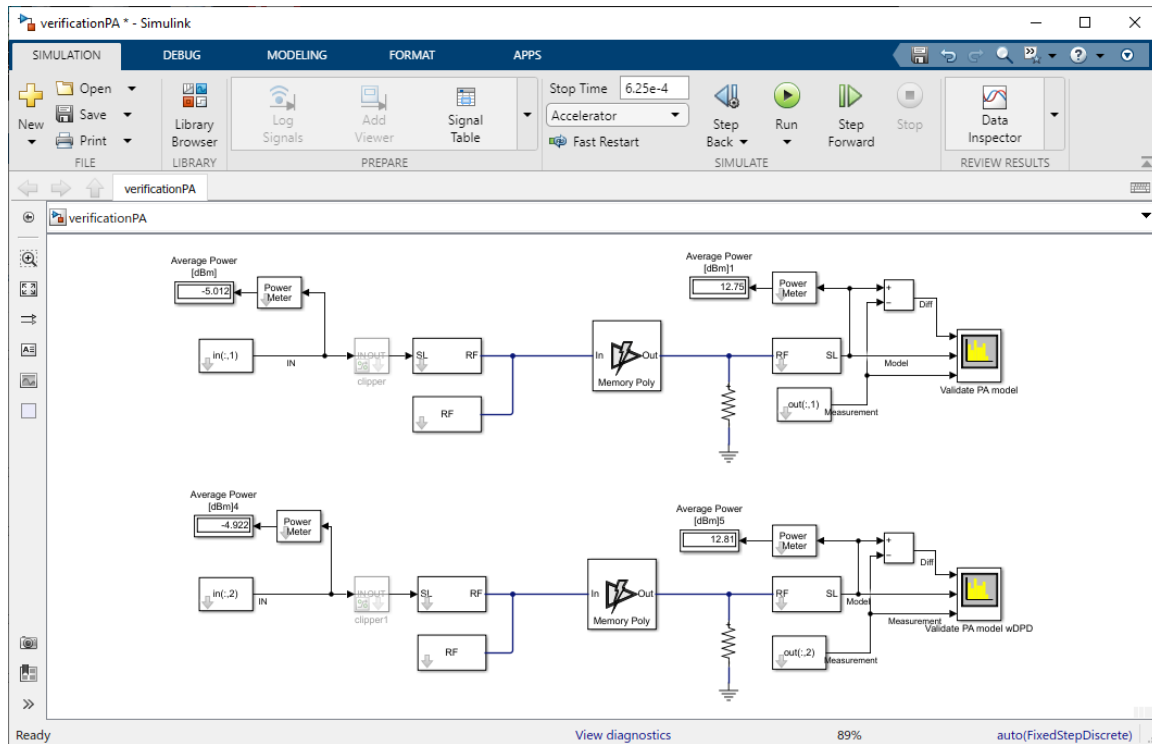


Figure 13: RF Blockset verification testbench for the circuit envelope simulation of the PA model. On the top branch the PA model is tested with the 5G test model NR-FR1-TM3.1. On the bottom branch, the same model is tested with the pre-distorted waveform using the Iterative Direct DPD approach. The output of the model is compared with the measured results.

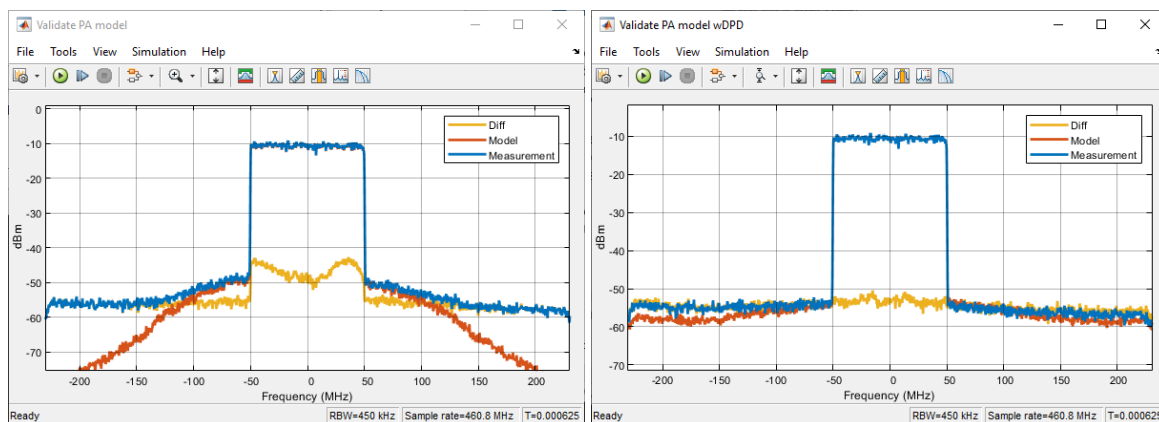


Figure 14: Results of the PA testbench described in the previous figure. On the left, comparison of the model prediction and measured data for the 5G test model NR-FR1-TM3.1. On the right, the same comparison is reported for the Iterative Direct DPD waveform. In the blue the measured data, in red the model prediction, and in yellow the spectrum analysis of the instantaneous difference between the two data sets. The error is in the similar range as the signal noise floor.

4 Linearization methods

As mentioned above in the introduction, simulation and instrument-assisted methods bring different capabilities for digital predistortion. In this section, a more extensive explanation is provided including a comparison of the results.

4.1 MATLAB based approach

We will simulate the PA in closed-loop configuration including digital predistortion algorithms and verify the performance of the linearized system.

In the top branch of the Simulink testbench `<DPD.slx>` (Figure 15), the PA model is simulated in closed loop with an adaptive digital predistortion algorithm. On the bottom branch, the PA is linearized using a fixed-set of DPD coefficients. The PA model coefficients and some of the DPD parameters and coefficients are calculated in the MATLAB script `<verificationModelPA.m>` that needs to be executed before running the Simulink testbench.

On the bottom branch, the DPD coefficients are time invariant, and have been calculated by the instrument as described in the next paragraph (4.2 Instrument-assisted approach). The scaling factors are required as the instrument-assisted approach normalizes the input signal to its maximum absolute value.

On the top branch, the DPD coefficients are adaptive and computed using a recursive least mean square algorithm that compares the output and the input waveform of the PA [3].

Although the testbench does not model the low-power electronics, such as the RF modulator and the observer receiver, it is possible to model these additional components of the system as shown by different RF Blockset examples.

In the testbench, the PA output signal linearized using different strategies for the computation of the DPD coefficients are compared against measurements results with and without linearization (Figure 16). This approach can be used to study and compare different linearization strategies.

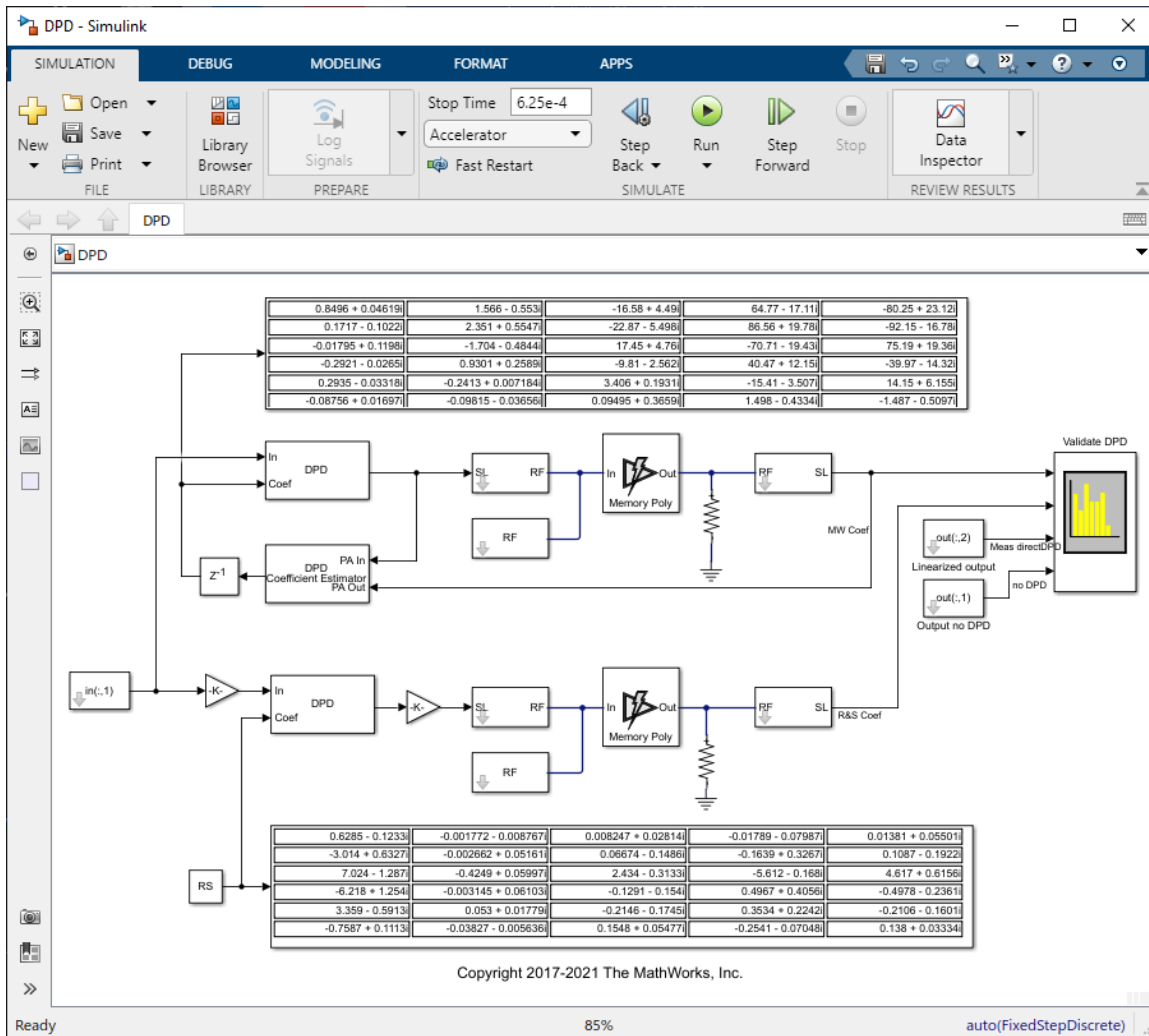


Figure 15: Simulation testbench used to compare linearized waveforms obtained with different DPD coefficients and measurement conditions.

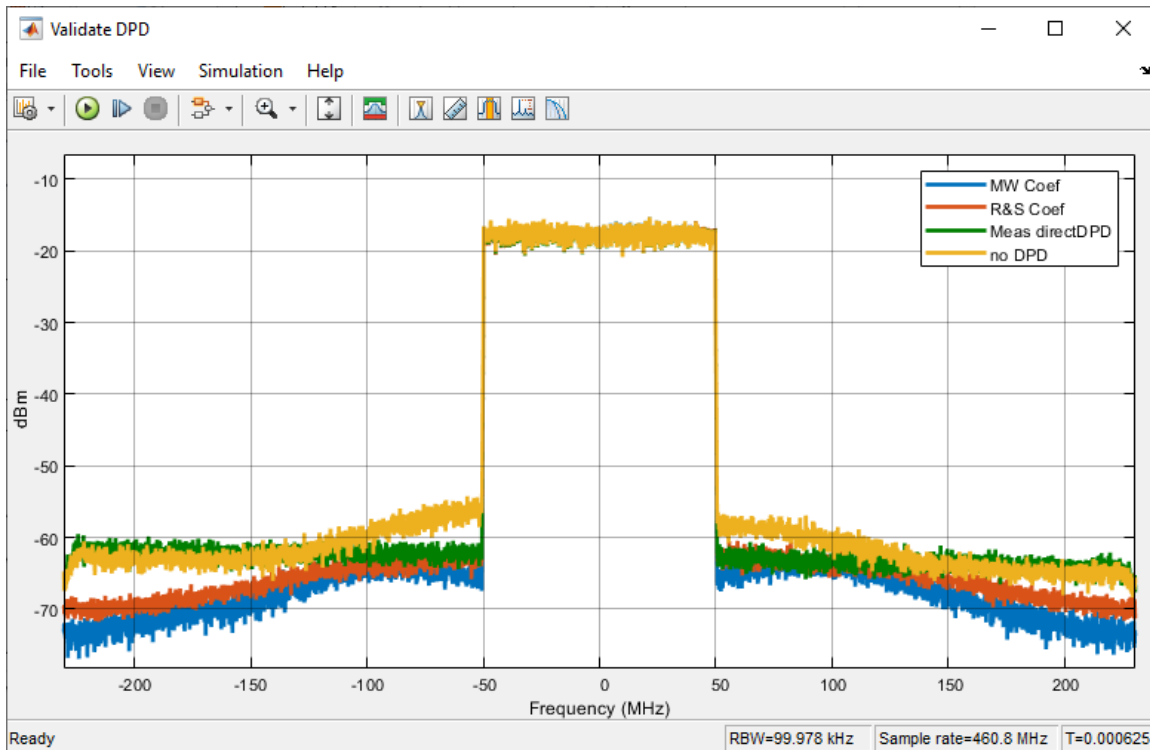


Figure 16: Spectral analysis results of the linearization testbench described in the previous figure. In blue, the linearized waveform computed using the adaptive DPD. In red, the linearized waveform using the fixed DPD coefficients determined with the instrument assisted approach. In green, the measured output waveform obtained with the Iterative Direct DPD approach. In yellow, the measured PA output waveform obtained without any linearization. Note that Direct DPD is limited in this example by wideband noise, as I/Q averaging was not used for speed reasons.

4.1.1 Linearization of 5G 3GPP waveforms

In the example `<EVMMMeasurementOf5G_DPD.m>`, we test the PA simulation model with a standard compliant 3GPP waveform generated with 5G Toolbox™ and measure the EVM of the signal at the output of the PA. We subsequently linearize the PA with a DPD algorithm and compare the results.

The first sections of the MATLAB script generate the waveform, scale its amplitude to excite the PA nonlinearity, apply a digital interpolation filter to increase the simulation bandwidth and capture spectral regrowth due to the PA nonlinearity.

The parameters of the PA model are loaded from the file `<PA_model.mat>` that has been generated with the previous script `<PA_Identification_DPD.m>`. The PA model is simulated using the RF system object `<rf_dpd>` loaded from the file `<RF_system.mat>`. The object wraps the Simulink model `<rf_dpd_model.slx>` for simulation in MATLAB.

The model is first simulated with the input switch bypassing the DPD algorithm. Then the state of the switch is changed, and the same model is used to simulate the effects of linearization (Figure 17, Figure 18).

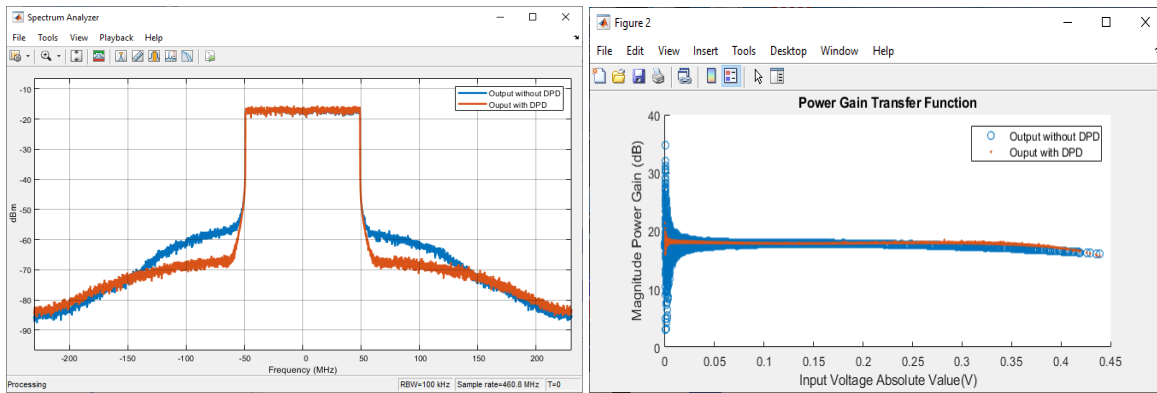
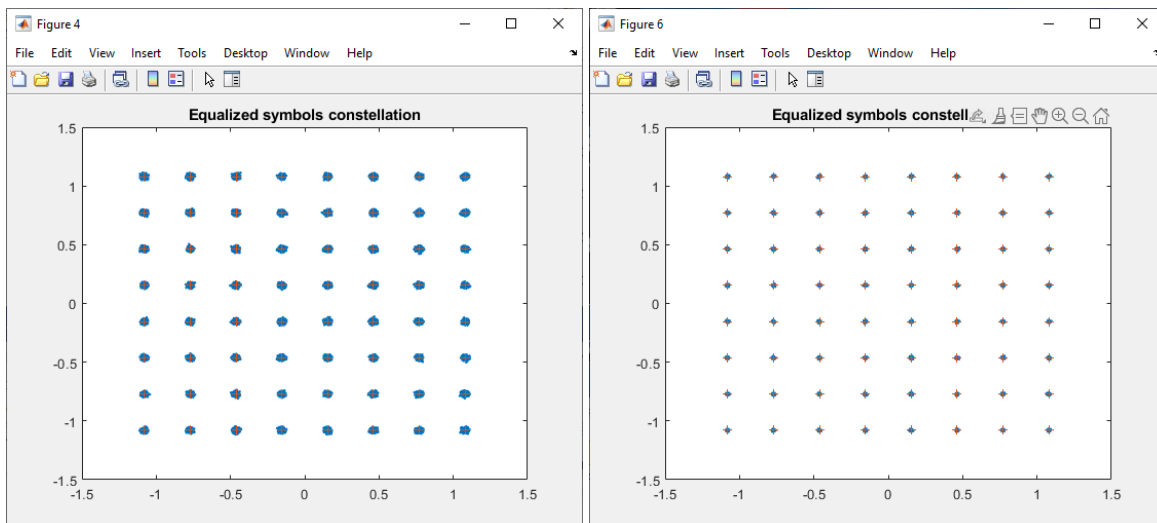


Figure 17: Results of the linearization testbench applied to a 3GPP standard compliant waveform. On the left, spectral analysis of the PA output signal: in blue the PA without linearization; in red, the linearized waveform computed using the adaptive DPD. On the right, the power gain transfer function: in blue the PA without DPD, in red the PA with adaptive DPD.



Averaged overall RMS EVM: 1.209%
Peak EVM = 4.4297%

Averaged overall RMS EVM: 0.367%
Peak EVM = 1.8606%

Figure 18: Constellation and EVM measurement of a 3GPP standard compliant waveform. On the left the PA without linearization. On the right, the PA has been linearized using the adaptive DPD.

4.2 Instrument-assisted approach

The FSW-K18M extension for amplifier measurements offers the ability to derive a memory polynomial based on the Iterative Direct DPD result. The user can define which iteration step of the Direct DPD is used as baseline for the modeling. A graphical comparison of the results helps to decide on the used iteration step. After selection of the complexity with regards to memory depth versus number of samples and polynomial order, an automatic fitting will be performed.

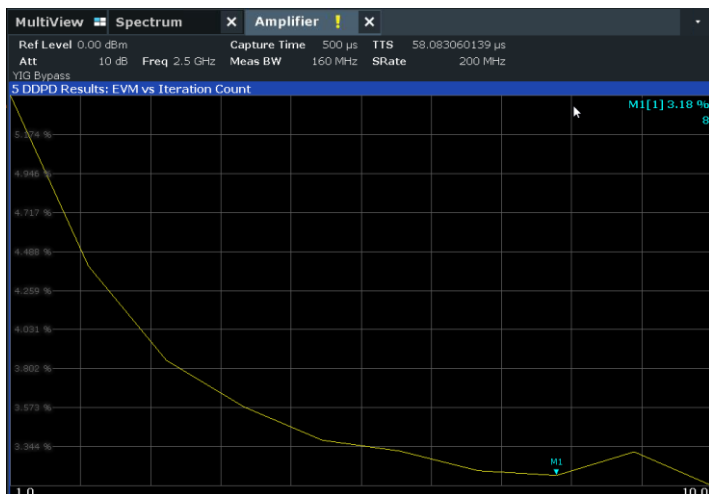


Figure 19: Comparing the iteration steps of the Iterative Direct DPD

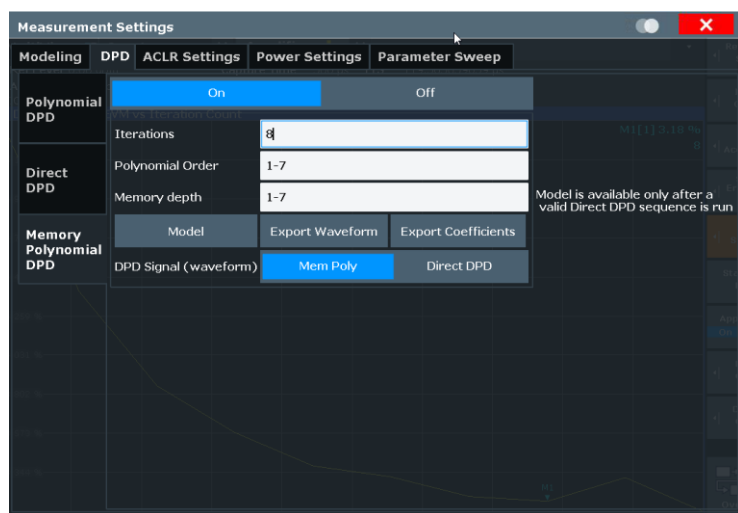


Figure 20: Define complexity of memory polynomial

The resulting coefficients can be displayed in the instrument but more important can be extracted from the instrument for in hardware implementations. In addition, a verification of the derived model can be performed by using the coefficients to create a new test waveform applying the memory polynomial based DPD.

Polynomial Order	t-0	t-1	t-2	t-3	t-4	t-5	t-6
1 (Real)	0.081	0.027	0.035	0.027	0.027	0.027	0.027
1 (Imag)	2.244	0.088	0.099	0.088	0.088	0.088	0.088
2 (Real)	0.492	0.075	0.084	0.075	0.075	0.075	0.075
2 (Imag)	1.369	0.024	0.032	0.024	0.024	0.024	0.024
3 (Real)	0.073	0.057	0.062	0.057	0.057	0.057	0.057
3 (Imag)	0.362	0.004	0.016	0.004	0.004	0.004	0.004
	0.080	0.015	0.020	0.015	0.015	0.015	0.015
	0.096	0.013	0.019	0.013	0.013	0.013	0.013
	0.023	0.020	0.027	0.020	0.020	0.020	0.020
	0.027	0.008	0.016	0.008	0.008	0.008	0.008

	0.111	0.107	0.121	0.107	0.107	0.107	0.107
	0.226	0.054	0.061	0.054	0.054	0.054	0.054
	0.220	0.030	0.036	0.030	0.030	0.030	0.030
	0.002	0.045	0.061	0.045	0.045	0.045	0.045
	0.083	0.007	0.013	0.007	0.007	0.007	0.007
	0.988	0.005	0.010	0.005	0.005	0.005	0.005
	1.909	0.026	0.027	0.026	0.026	0.026	0.026

	0.317	0.025	0.032	0.025	0.025	0.025	0.025
	0.157	0.085	0.098	0.085	0.085	0.085	0.085
	0.209	0.019	0.025	0.019	0.019	0.019	0.019
	0.339	0.025	0.039	0.025	0.025	0.025	0.025
	0.154	0.027	0.032	0.027	0.027	0.027	0.027
	0.234	0.050	0.057	0.050	0.050	0.050	0.050
	0.296	0.015	0.021	0.015	0.015	0.015	0.015
	0.015	0.082	0.090	0.082	0.082	0.082	0.082
	0.038	0.037	0.064	0.037	0.037	0.037	0.037

Figure 21: Display of resultant model coefficients

Note:

In order to minimize noise effects summing up in Iterative Direct DPD, it can be beneficial to activate IQ averaging to reduce the noise floor in the measurement added by the amplifier. For the derived model with K18M, this has no effect as the equally distributed noise has no effect on the model creation. But the higher noise floor in a spectral measurement from the Iterative Direct DPD approach when compared with the applied K18M model may be misleading if no IQ averaging is used.

5 Summary

Modern RF amplifiers use various topologies and linearization methods to improve energy efficiency. Sophisticated digital predistortion methods not only enhance the performance of the amplifier but even allow to go further in topologies and technologies which might bring higher nonlinearities at the first hand. A sophisticated model of the amplifier behavior allows proper design of the linearization to be used.

Two methods have been introduced, simulation based and instrument-assisted. But most beneficial is the collaboration of both worlds linking the extensive capabilities in simulation with the link to real measurements on the nonlinear device.

The goal of a faster, more sophisticated design process has been reached and described thanks to the successful collaboration between MathWorks and Rohde & Schwarz.

6 Literature

- [1] Dr. Florian Ramian, Iterative Direct DPD, White Paper 1EF99_1E, 2017, [Iterative Direct DPD | Rohde & Schwarz \(rohde-schwarz.com\)](https://www.rohde-schwarz.com).
- [2] Dennis R. Morgan, Zhengxiang Ma, Jaehyeong Kim, Michael G. Zierdt, and John Pastalan. "A Generalized Memory Polynomial Model for Digital Predistortion of Power Amplifiers." IEEE(R) Transactions on Signal Processing_. Vol. 54, No. 10, October 2006, pp. 3852-3860.
- [3] Gan, Li, and Emad Abd-Elrady. "Digital Predistortion of Memory Polynomial Systems Using Direct and Indirect Learning Architectures." In Proceedings of the Eleventh IASTED International Conference on Signal and Image Processing (F. Cruz-Roldan and N. B. Smith, eds.), No. 654-802. Calgary, AB: ACTA Press, 2009
- [4] J. Hantgan, A. Ludwig, "Internal private communication", May, 2017.
- [5] Coefficient script ("`fitModelIPA.m`") originally implementation by Jeffrey Hantgan.
- [6] Power Amplifier Block: <https://www.mathworks.com/help/simrf/ref/poweramplifier.html>

7 Ordering Information

Designation	Type	Order No.
Vector Signal Generator	R&S®SMW200A	1412.0000.02
Signal and Spectrum Analyzer	R&S®FSW	1331.5003.08
Amplifier Measurements	R&S®FSW-K18	1325.2170.02
Direct DPD Measurements	R&S®FSW-K18D	1331.6845.02
Memory Polynomial DPD Measurements	R&S®FSW-K18M	1345.1470.02

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