Application Note

INVESTIGATE RF POWER AMPLIFIER LINEARIZATION BENEFITS IN EDA

Products:

- R&S®VSESIM-VSS
- R&S®FSW
- R&S®SMW200A
- Cadence® AWR® Visual System Simulator™

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https://www.rohde-schwarz.com/appnote/1SL383

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Contents

1 Overview

This application note is based on collaborative work between Cadence and Rohde & Schwarz.

The focus is on understanding as early as possible in the design process performance enhancements through linearization of non-linear devices, in our case the RF power amplifier (PA). In other words, what performance benefits can be reached with linearization techniques such as digital predistortion (DPD). Typically, this is investigated when the device is available and physical RF measurements are conducted. In this application note, it is looked at earlier in the design process while using electronic design automation (EDA) such as Cadence® AWR® Visual System Simulator™ (VSS) software. The goal is to allow an RF designer to evaluate the linearizability of his design without in-depth knowledge of DPD algorithms. In the end, the designer can get closer to the optimal efficiency with earlier access to DPD, while at the same time improving time-to-market.

The described process is applicable to any end application. Complex modern wideband systems such as 5G new radio (NR), Wi-Fi 7 or latest satellite links (e.g. DVB-S2X) have dense constellation diagrams asking for best linearity while the RF frontend must be optimized also for power efficiency and minimal heat dissipation. The solution addresses these needs as designers can use standard-compliant signals and demodulation techniques in the EDA environment through the process.

The application note brings code examples and an exemplary setup for VSS software to provide an easy start to replicate and use the described procedure.

2 Introduction

2.1 Why linearization?

Emerging applications put new requirements on RF systems and RF frontends. When looking at 5G, not only mmW applications but also modified topologies are added: a massive multiple-in-multiple-out (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 often using hybrid beamforming where a subtile 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, two 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. Comparable enhancements are applied in electronic warfare for radar or other signals.

Such applications call for highly linear characteristics and / or large numbers of devices with identical behavior to ensure proper functioning and high data throughput. The increasing bandwidths ask for new technologies such as gallium nitride (GaN), which might create challenges due to their inherent nonlinear behavior. On the other hand, higher order modulations require smaller distortion levels as the distance between the constellation points becomes smaller, thus lower error vector magnitude (EVM) is needed for stable demodulation of the sent data.

RF frontend electronics experience significant power consumption in any wireless transmission system. Amplifiers typically operate close to their saturation point where they offer the best power efficiency in order to reduce operating costs due to cooling, power consumption and size. However, nonlinearity is also high in this operation mode, resulting in signal degradation and spurious signal generation (or adjacent channel power for digitally modulated signals) . Newer PA technologies such as GaN offer best efficiency and energy density but require linearization in almost any use case.

In addition to the use of different semiconductor technologies, different PA topologies are investigated and applied. The Doherty amplifier can be called the workhorse for many applications such as in 4G and 5G infrastructure. Using two amplifiers enhances the linear range in a Doherty concept in an efficient way, but for DPD it is typically treated as a single PA. Work has been started lately to create different DPD scenarios in a digital Doherty design where each path has a direct individual link to the digital signal processing allowing optimal DPD for the root mean square (RMS) / main path as well as the peak / auxiliary path. In addition, new structures such as load modulated balanced amplifiers (LMBAs) and other variants are being studied. Having access to proper DPD insights allows more freedom in designing new PA concepts supporting enhanced efficiency and wider frequency coverage to minimize the number of RF channels for a wide frequency range RF frontend system.

Linearization can be done in various ways. The most prominent approach today is to use digital predistortion (DPD) of the signal where the incoming digital waveform is modified on the fly in order to pre-compensate for the nonlinear behavior of the PA (Figure 1). In the target application, it helps to improve both, adjacent channel leakage ratio (ACLR) as well as EVM. These two numbers are the key figures of merit for signal quality.

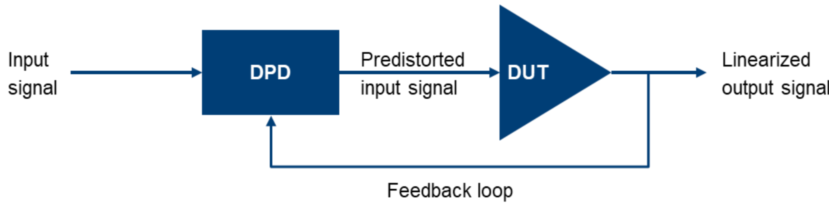

Figure 1: Simplified block diagram for linearization

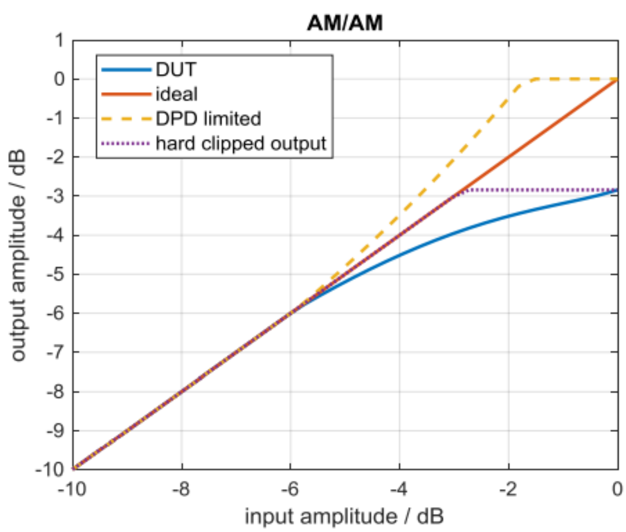

Figure 2: Overview plot of PA behavior: measured AM/AM, ideal output, predistorted output signal (hard clipped)

2.2 Joint solution: Rohde & Schwarz and Cadence

Rohde & Schwarz and Cadence have collaborated on a solution that allows RF designers to accurately predict the behavior of linearized PAs using realistic modulated RF signals. The solution combines capabilities within the Cadence VSS system simulation platform, along with Rohde & Schwarz signal creation and analysis knowhow for standard-compliant signal creation and analysis. The standalone software packages R&S WinIQSIM2 and R&S VSE have been bundled into R&S VSESIM-VSS together with necessary plug-ins that allow seamless connectivity to VSS software. The R&S software additions provide signal creation and analysis for a wide range of digital signals, including standards such as 5G NR and Wi-Fi. The digital signal processing for creation and analysis is identical to those algorithms used in the test and measurement RF instruments from Rohde & Schwarz.

More information on the joint solution can be found in the online application card: [From electronic design automation (EDA) to hardware implementation | Rohde & Schwarz (rohde-schwarz.com)](rohde-schwarz.com).

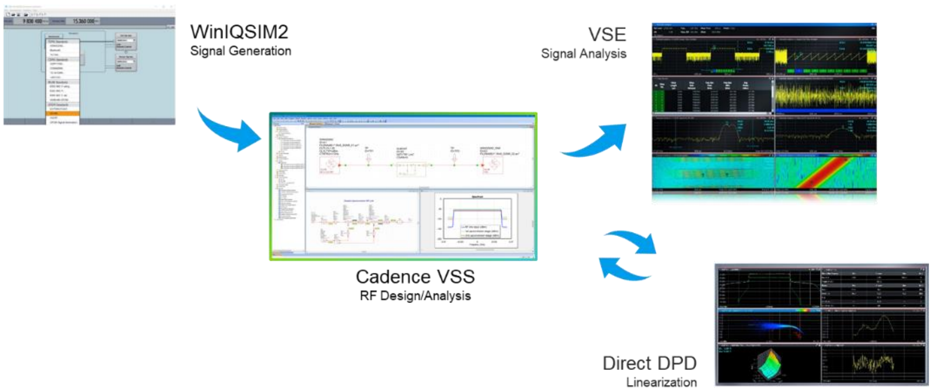

Figure 3: Interaction between Cadence VSS and R&S VSESIM-VSS

The RF PA test application known from R&S spectrum and signal analyzers is also part of VSE and thus available in the joint solution. It includes a rich set of amplifier characterization measurements such as compression, distortion, EVM and many more. In addition, it offers a digital predistortion technique allowing to check the best possible performance of a non-linear device when using DPD, without going into the details of DPD algorithms. It is using Direct DPD, an iterative approach manipulating the input signal to receive the most linear output signal from the device under test (DUT). More details on the Direct DPD process can be found in the white paper [Iterative Direct DPD | Rohde & Schwarz (rohde-schwarz.com)] [1]. Using the Direct DPD feature with Cadence VSS allows verification of linearization benefits in simulation.

Furthermore, the amplifier application in VSE can create a memory polynomial model using the linearized data set created with Direct 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 power amplifier model completes the package.

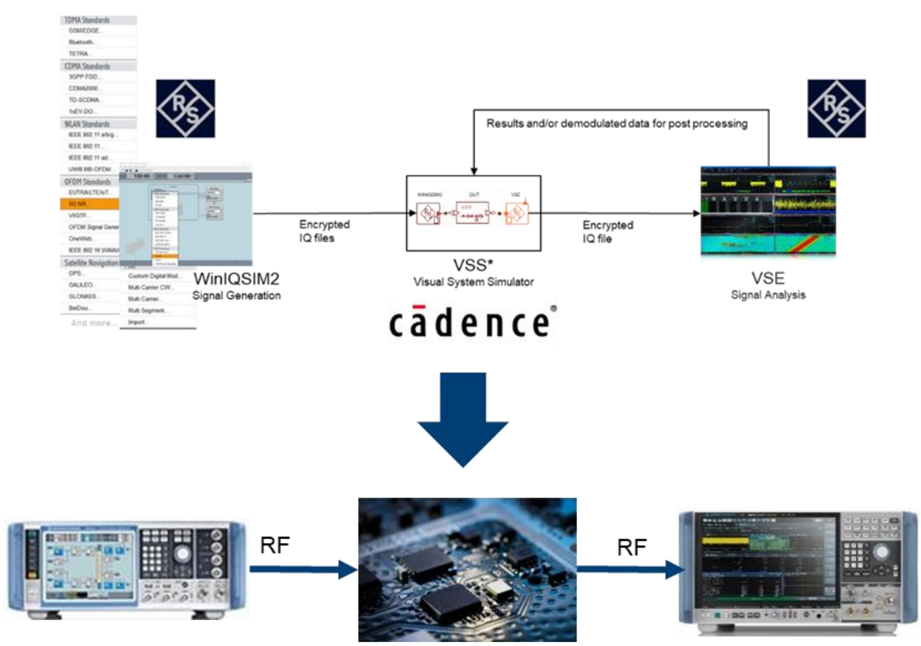

Figure 4: Transition from simulation to real-world

As WinIQSIM2 and VSE included in VSESIM-VSS use the same calculation methods for signal creation and analysis as the vector signal generator SMW200A and signal and spectrum analyzer FSW, the switch to test hardware is easy. All test signals and demodulation setups can be reused ensuring maximum correlation between simulation and real-world RF testing. In addition, Direct DPD to linearize the PA as DUT is offered to verify the best possible performance on the hardware using the same concept as in simulation.

While the first approach offers an early insight to linearization benefits already in EDA, the second ensures that this translates into real hardware and real-world conditions, which requires a real-time DPD implementation. Bringing both together helps streamlining the development process while providing the engineers with a better understanding of the DUT earlier in the design phase.

2.3 Preparing the PC

Ideally you follow the following order to install the software:

1. Start with the latest version of Cadence VSS
2. Load and install the latest VSE version from [VSE | Software | Rohde & Schwarz (rohde-schwarz.com)]
3. Load and install the latest WinIQSIM2 version from [WINIQSIM2 | Software | Rohde & Schwarz (rohde-schwarz.com)]

Ensure to check the following options when installing VSE as it will install the plug-ins for VSS directly into the VSS folder and provides level information:

► VSE Cadence VSS Integration: Ensures installation of Plug-ins

► R&S Power Meter device drivers: Recommended for Direct DPD Linearization usage as it includes proper power level information sharing between Cadence VSS and R&S VSE

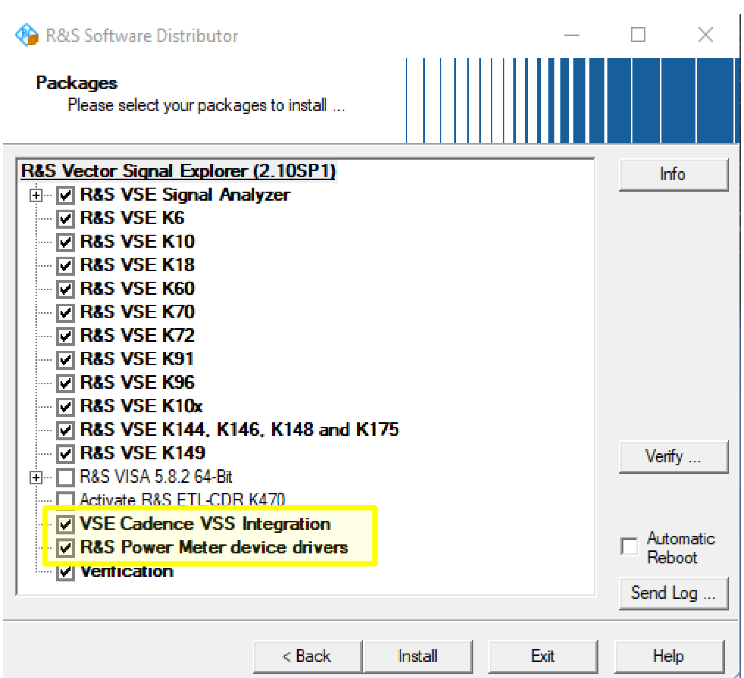

Figure 5: R&S VSE Installer options

3 Process flow and model creation

In order to simulate the PA behavior and apply linearization in EDA, a model of the PA is required. Models are often provided by the PA vendors. As an alternative, the model can be derived from measurements on the real PA.

In our example project, we are using a model derived by VSS software from measurements on the real device, using the so-called time-delay neural network (TDNN) model.

Obviously, every model approximates the real-world behavior, but striving for the best fit is an important step for meaningful simulations.

3.1 TDNN modeling in Cadence VSS

VSS software offers several methods for modeling nonlinear devices, which can be behavioral, based on measured data or based on a specific circuit design. These models are intended for devices that exhibit different behaviors during operation, e.g., some are better suited for small-signal operation, while others are designed to meet the needs of nonlinear devices with memory. The model used in this case is the TDNN, which supports short- and long-term memory effects of nonlinear devices. The TDNN model is generated using the amplifier generation wizard in VSS software and is trained based on IQ data collected at the input and the output of the device, as well as with its AM/AM and AM/PM characteristics.

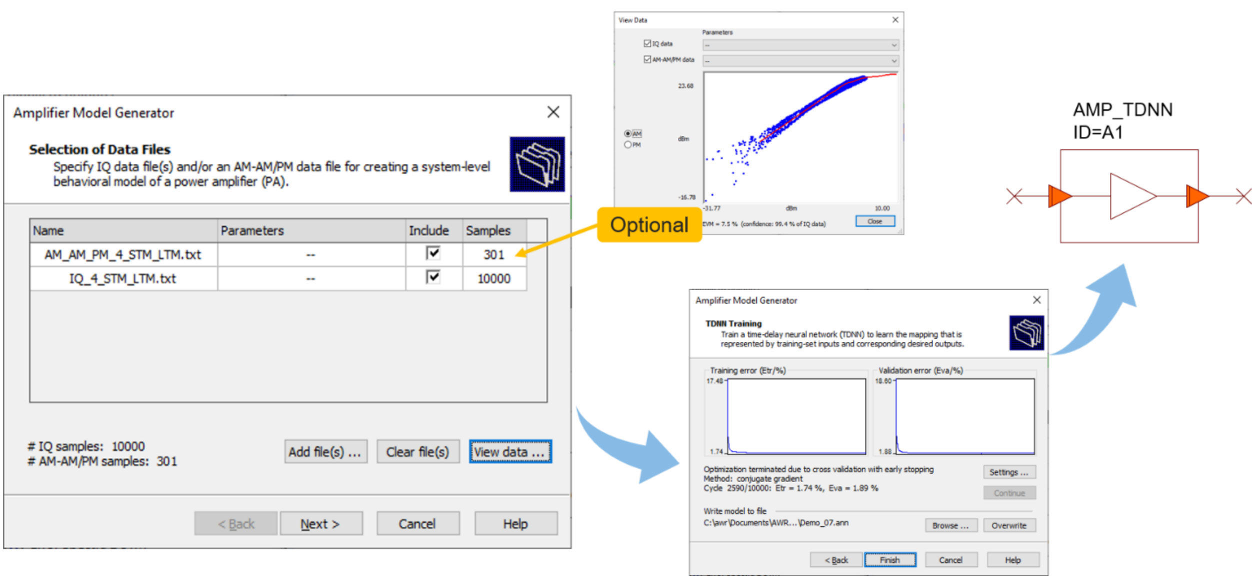

Figure 6: TDNN model generation

The data used for training the model can be measured in the lab or collected from circuit simulations. The benefit of using a TDNN model is that, after the initial training, the simulations are much, much faster compared to using the circuit model itself. Once the training is complete, the TDNN model may be used in VSS simulations and become part of the desired test bench.

3.2 Measurement setup to collect data for TDNN modeling

The required measurements to create the power amplifier model can be easily performed using the vector signal generator R&S®SMW200A in conjunction with the vector signal analyzer R&S®FSW and the FSW-K18 amplifier measurement personality. The internal capabilities of the SMW to create various test signals such as 5G or DVB-S2X compliant scenarios support the task. In addition, any custom waveform can be used in the internal arbitrary waveform generator.

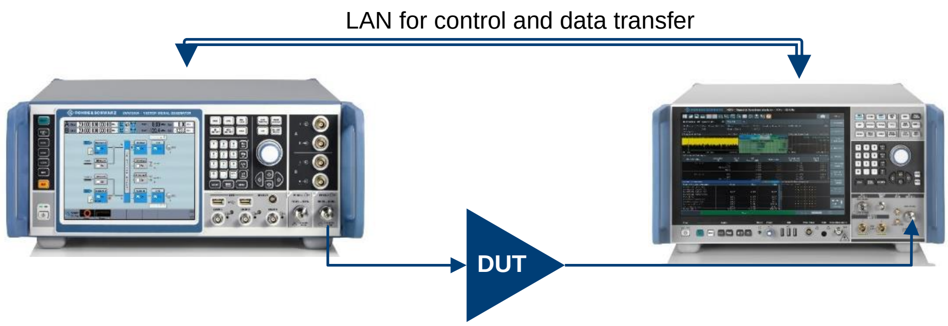

Figure 7: Measurement setup to gather the data used for modelling

All required characterization results (EVM, AM/AM, AM/PM, and input vs. output I/Q data) can easily be extracted from the analyzer and be used for the TDNN modelling.

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 allowing very short signal durations to create a proper model.

4 Linearization process in simulation

4.1 Linearization process

The linearization process using VSS software and Direct DPD implemented in R&S VSE is an iterative, non-algorithmic approach. Non-algorithmic essentially means predistorting each sample of the output signal, so that it approaches a linear copy of the original test signal after the next simulation run. Due to the nonlinear characteristic of the DUTs, this process requires several iterations, typically 5-10. This process corresponds to the feedback loop for DPD shown in Fig. 8.

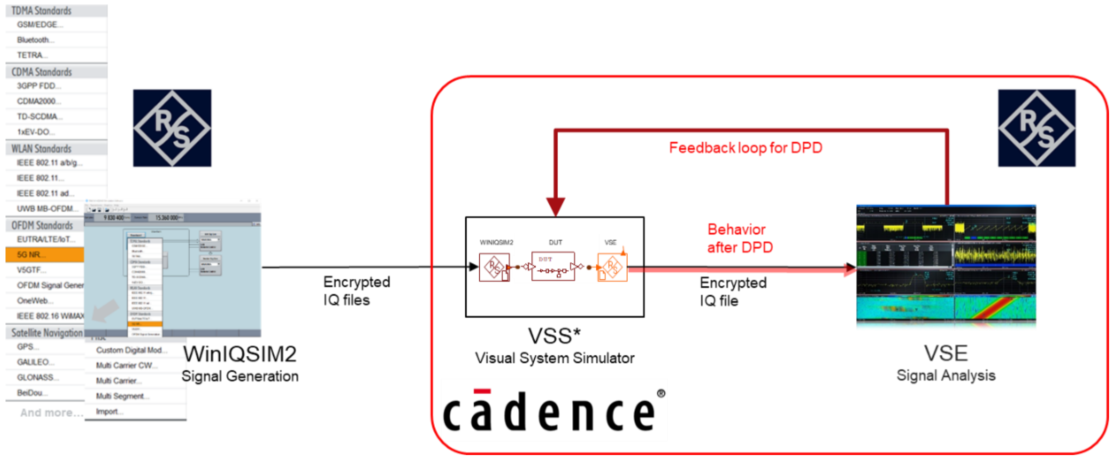

Figure 8: Concept of Direct DPD in conjunction with VSS

A flow diagram showing more detail of the required steps is shown in Fig. 9.

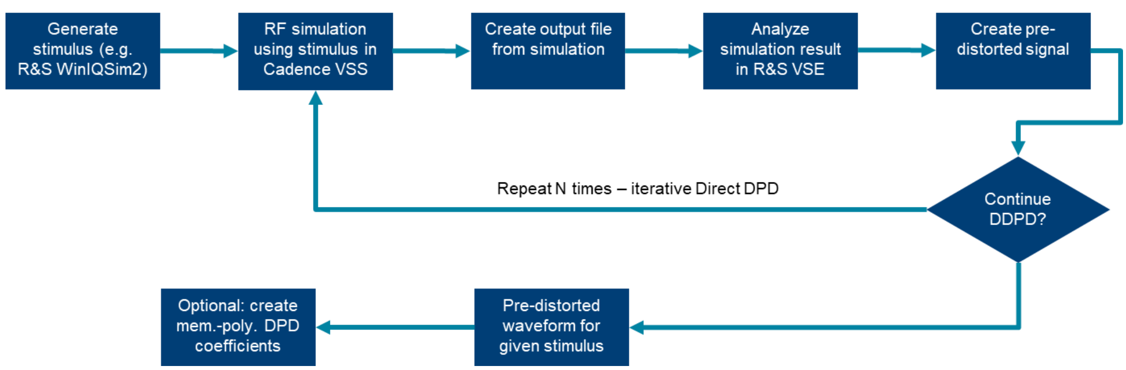

Figure 9: Process flow for predistortion

1) Generate a stimulus or test signal; R&S WinIQSim2 offers standard compliant signals, such as 5G, Wi-Fi, DVB-S2X, as well as easy to configure generic signals.

Iterative:

2) Run VSS simulation using the signal from 1) and your PA model

3) Have VSS create the output signal file (wv file format)

4) Feed output signal file into VSE and analyze file (compare against test signal from step 1))

5) Create a predistorted signal and provide this as input signal for the next iteration

6) Obtain final DPD file and determine PA characteristics under DPD conditions

7) (optional) Determine memory polynomial coefficients for current PA model

4.2 Automation

In order to run an iterative DPD on a simulated device, automation of the simulation as well as the DPD software is highly recommended.

In the attached example, a Python script controls VSS software using COM objects and VSE using SCPI commands. It uses the win32com.client and rskfd packages (both available from pypi.org).

The script controls the loop as shown in Fig. 8. One loop includes:

In VSS software:

1) Reading in the stimulus or test signal

2) Running the test signal through the PA model

3) Exporting the (time domain) result into a waveform file

In R&S VSE:

4) Reading in the file from Step 3 above

5) Analyzing the file against the known reference

6) Calculating a predistorted signal

In the next iteration, the predistorted signal from step 6 is then used as the input signal (step 1) of the next iteration.

For a detailed description of the remote-control mechanisms of VSS software or R&S VSE, please visit the respective web pages.

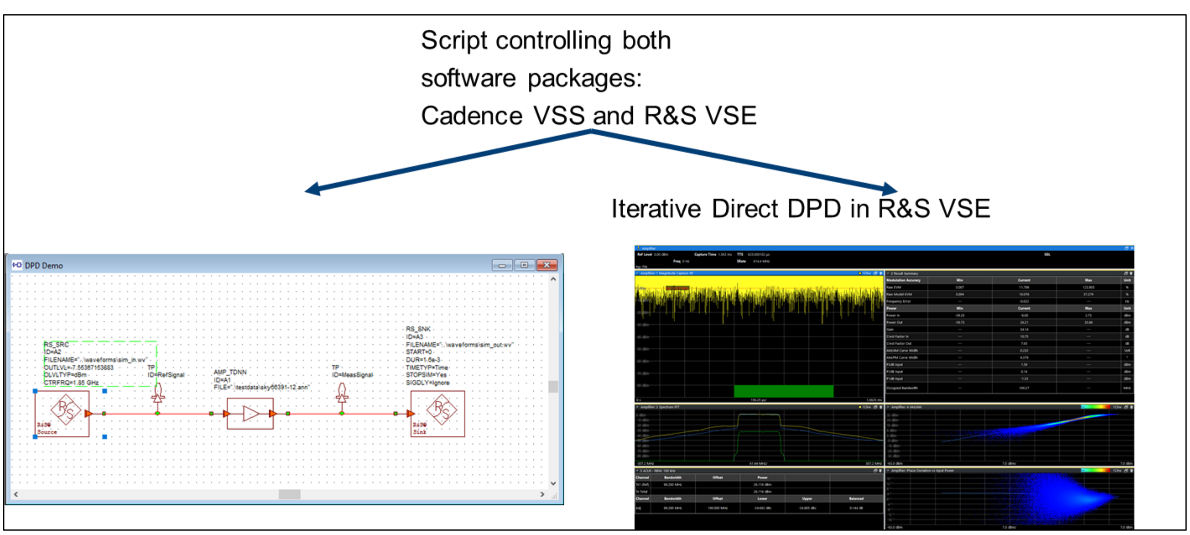

Figure 10: Schematic of script control

5 Comparison simulation and measurement

In order to validate the concept of applying Direct DPD in simulation using a TDNN based model, we compared the VSS simulation results to the measurements on the hardware DUT. The VSS simulation used VSE to implement the DUT, while the hardware setup used the vector signal generator R&S SMW200A, the signal and spectrum analyzer R&S FSW, and the amplifier characterization application package FSW-K18/K18D as shown in figure 7.

The measured results are summarized below:

5G NR FR1 signal TM3.1 100 MHz, 256QAM	EVM	ACLR
Simulation	0.921	47.519 dBc (lower) / 46.698 dBc (upper)
Hardware measurements	0.937	46.61 dBc (lower) / 47.68 dBc (upper)

Figure 11: Results from simulation approach

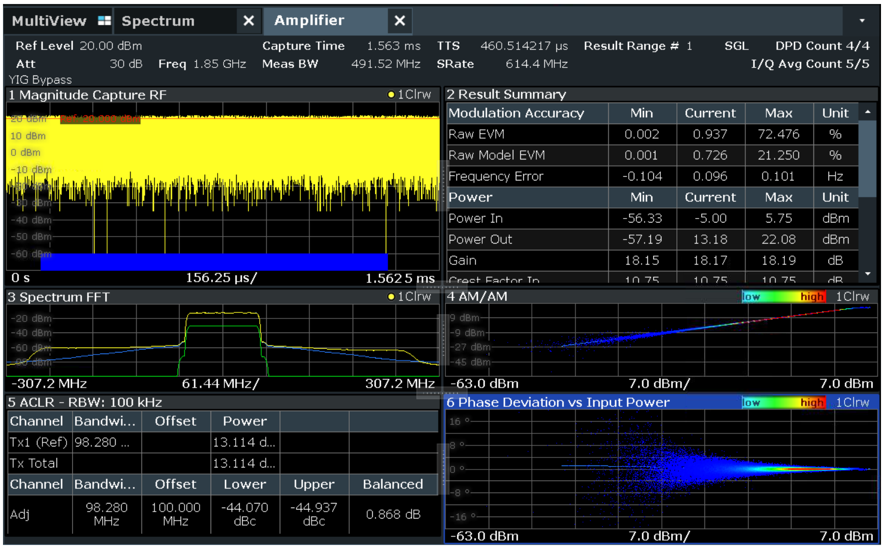

Figure 12: Results from RF measurements on the physical device

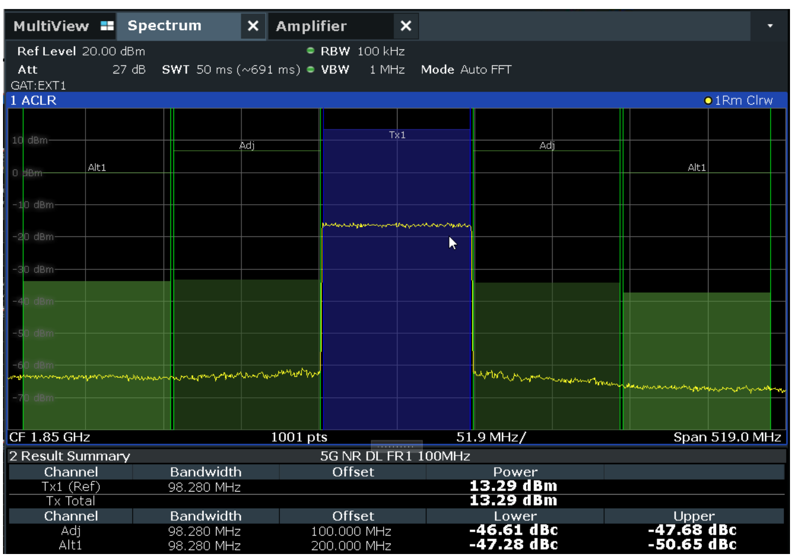

Figure 13: Results from RF measurements on the physical device using spectrum mode for enhanced dynamic range leading to most accurate ACLR measurements

6 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 also allow further exploration of topologies and technologies to compensate for higher nonlinearities during operation.

The earlier one understands linearization benefits, the better the PA design can be optimized for the desired performance with focus on efficiency, maximum output power or best modulation support, and with minimal distortions. Having access to DPD in the EDA stage enables a faster design process and allows taking pre-caution and action in the physical design and layout. A sophisticated model of the amplifier behavior is required in order to get realistic DPD results.

Verification of the resulting hardware is easily done using the same processes and algorithms in DPD and signal creation and analysis using R&S test and measurement instruments.

The combination of VSS system simulation software and Rohde & Schwarz VSESIM-VSS with its Direct DPD capabilities gives access to a proven process and enables faster and better RF PA designs.

7 Literature

[1] Dr. Florian Ramian, Iterative Direct DPD, White Paper 1EF99_1E, 2017, Iterative Direct DPD | Rohde & Schwarz (rohde-schwarz.com).

[2] Rohde & Schwarz VSE Base Software User Manual, https://www.rohde-schwarz.com/us/manual/r-s-vse-base-software-user-manual-manuals-gb1_78701-122176.html?change_c=true

[3] AWR Design Environment API Scripting Guide, https://awrcorp.com/download/kb.aspx?file=docs/ApiReference.pdf

8 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
Cadence® AWR® VSS integration for digital signal creation and analysis with R&S®WinIQSIM2 and R&S®VSE	R&S®VSESIM-VSS	1345.1511.52

Please check with Cadence for VSS ordering information.

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