

# Iterative Learning Control (ILC)

DPD N9055MOE Power Amplifier measurement application GUI overview



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# Power Amplifier Measurement Application

Modern mobile communications, such as 5G NR and WLAN place new demands on linearity, bandwidth, and power consumption in wireless components, mobile terminals, or base stations. One of the most non-linear components within wireless devices is the Power Amplifier (PA). Power Amplifier are essential to device designs providing increased spectral efficiency and reduced distortion and non-linearity.

Keysight's N9055EM0E Power Amplifier measurement application is an integrated PA testing system targeting 5G NR, WLAN, or other wideband PA test scenarios. N9055EM0E operates within Keysight's X-Series signal analyzers and when combined with a Keysight signal generator, enables both Pre-DPD and Post-DPD PA measurements.

## Digital Pre-Distortion Technology

Power amplifiers with high PAPR (Peak to Average Power Ratio) signals can create non-linearity problems. When applying a high-power signal to the PA input, the PA can't linearly amplify the signal causing gain saturation and distortion and leads to signal quality degradation, such as worse Adjacent Channel Power (ACP) and Error Vector Magnitude (EVM). To compensate for the non-linear behavior of the PA, we can apply a DPD method. In general, DPD technology applies "inverse" distortion to the PA input signal to cancel distortion generated by the PA as shown in Figure 1. Several types of DPD methods include memoryless and memory, which convey the memory effect on a PA. N9055EM0E supports the following methods:

- Look-up table
- Volterra Series
- Memory polynomial
- Iterative Learning Control (ILC)
- User-defined DPD model with MATLAB scripts

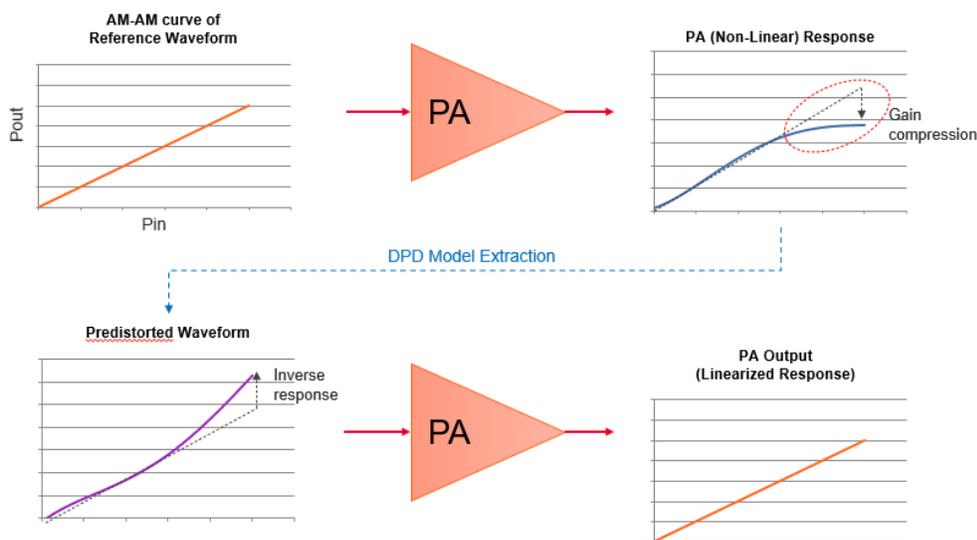


Figure 1. Digital Pre-Distortion (DPD)

A DPD algorithm pre-distorts the PA's input signal in the exact opposite way the PA distorts the signal as shown in Figure 1.

An alternate approach to creating an inverse model is to pre-distort the signal iteratively to remove the error at the PA output. The advantage of this iterative DPD approach is the ability to obtain the best possible output ACPR and EVM without being bound by the computational complexity of the model. The new approach is Iterative Learning Control (ILC), described in detail in the Iterative Learning Control for RF Power Amplifier linearization paper.<sup>1</sup>

Let's compare a model-based DPD algorithm to an ILC DPD computation.

## Digital Pre-Distortion (DPD) Algorithm

The rise of increasing bandwidths and PAPR in wireless communications systems requires more complex Power Amplifier (PA) technologies. These power amplifiers exhibit phenomena known as memory effects where the current output signal is influenced not only by the current input signal but also by past input signals. These effects are due to the time-varying behavior of the amplifier's components and materials, which causes a deviation from the ideal, instantaneous response.

Figure 2 shows the well-known Volterra and memory polynomial DPD models used to compensate for these memory effects. The disadvantage of model-based DPD that can compensate for memory effects is that it requires complex signal processing to implement a reliable inverse model of the PA.

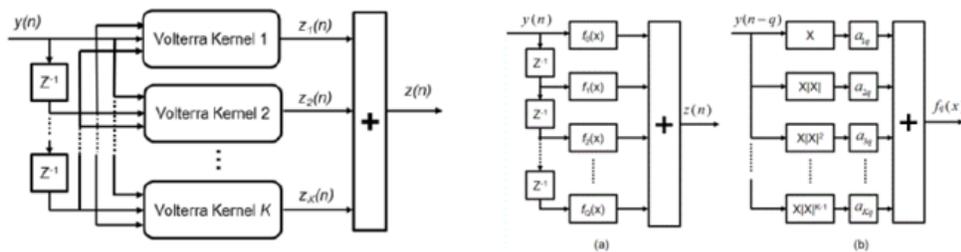


Figure 2. Standard DPD models

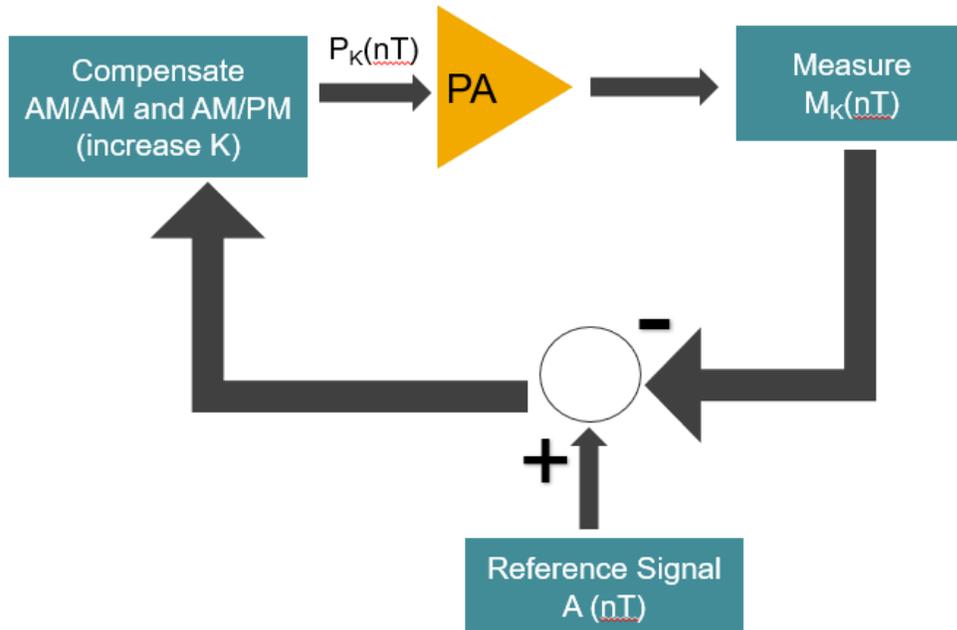
## Iterative Learning Control (ILC) DPD

Iterative Learning Control (ILC) is an iterative technique that inverts an amplifier's linear and non-linear signals. Rather than identifying the pre-distorter parameters, ILC uses an interactive, sample-based learning algorithm to find an optimal PA input signal that produces the desired linear output response. ILC works to ensure a PA's output signal closely resembles the input reference waveform without applying complex, computation-limited memory model methods. Additionally, the ILC DPD approach enables

<sup>1</sup> Jessica Chani-Cahuana, Per Niklas Landin, Christian Fager, Senior Member, IEEE, and Thomas Eriksson, Member, IEEE, "Iterative Learning Control for RF Power Amplifier Linearization" (IEEE Transactions on Microwave Theory and Techniques, Vol. 64, NO.9, September 2016)

comparable measurements across devices and prevents the need for amplifier designers to identify the influences of different DPD algorithms.

Unlike other iterative techniques, the ILC algorithm does not require details for a specific power amplifier and is computationally less expensive.



**Figure 3.** Iterative Learning Control Digital Pre-Distortion (ILC DPD) approach

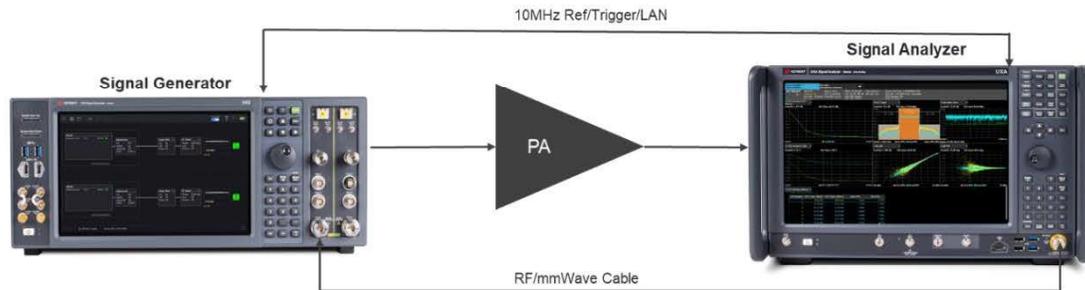
The pre-distorted input sample,  $\mathbf{P}(nT)$ , depends on the measured output sample  $\mathbf{M}(nT)$ . Comparing the output waveform  $M$  to the desired reference output waveform  $A$ , for each sample iteratively until  $M$  converges to  $A$  in terms of EVM or ACPR as shown in Figure 3.

The N9055EM0E Power Amplifier measurement application enables easy export of an approximated DPD model or pre-distorted waveform following the ILC DPD measurement to help DPD algorithm developers in their performance evaluation and comparison between the algorithm output and the ILC DPD pre-distorted waveform.

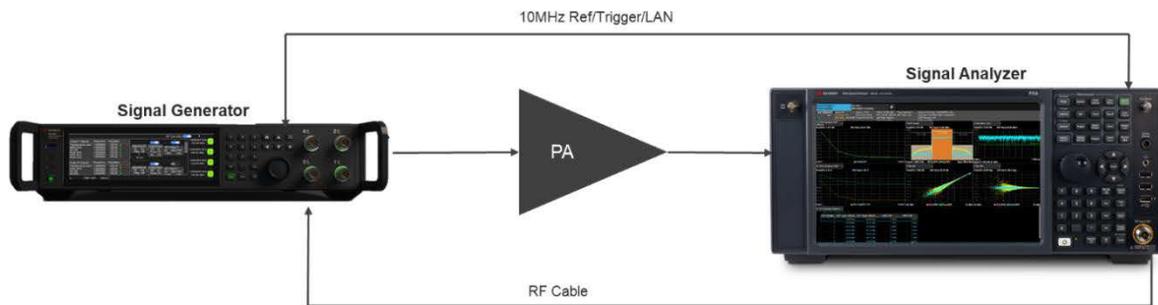
# Hardware Connections

Refer to the details and diagram below to set up and use the N9055EM0E Power Amplifier measurement application.

- Connect the signal analyzer and signal generator using a LAN connection.
- Connect the signal generator “10 MHz Out” to the SA “EXT REF In”
- Connect the signal generator “CH2 SYNC Out” to the SA “EXT Trigger In1”
- Connect PA (DUT) between SA and signal generator RF or mmWave port.



**Figure 1.** N9055EM0E Power Amplifier test connections using M9484C VXG (signal generator) and N9042B UXA (signal analyzer)



**Figure 4.** N9055EM0E Power Amplifier test connections using N5186A MXG (signal generator) and N9032B PXA (signal analyzer)

Once your connections are made and the instruments powered on, the signal analyzer, with the installed N9055EM0E Power Amplifier measurement application and a valid license, will display the power amplifier measurement application's Mode/Measurement/View Selector view. Users can enter a power amplifier measurement by selecting "Power Amplifier" for the mode, "Power Amplifier" for the measurement, and "Normal" for the view as shown below. Press 'OK'.

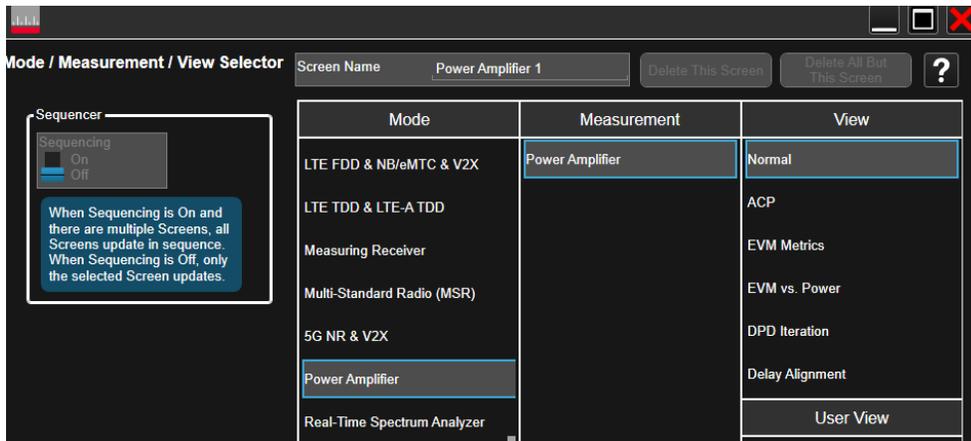


Figure 5. N9055EM0E Power Amplifier measurement application in Mode/Measurement/View

Establishing a connection between the signal analyzer and signal generator is accomplished in the LAN connections in the power amplifier measurement mode. The first time you connect to a specific signal generator, you must input the IP address or instrument Hostname. Use the application to input the signal analyzer's configuration in the "Signal Generator List" where details are stored even after the signal analyzer is rebooted. Once you establish a connection between the signal analyzer and the signal generator, the signal generator's details are displayed in the information box. A Connected/Disconnect indicator will display "Disconnect" as a choice for the connected signal generator. Multiple signal generators can be entered but only the "Connected" signal generator is highlighted in green.

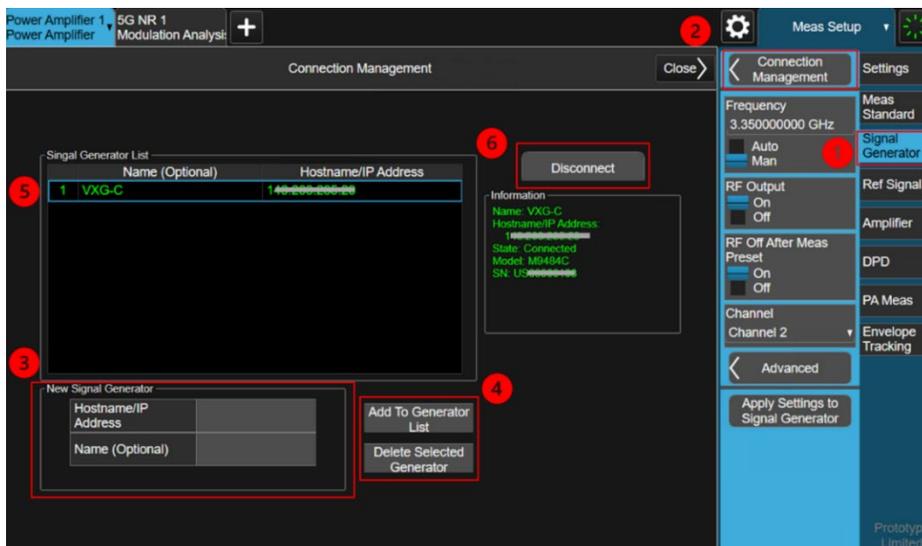


Figure 6. N9055EM0E signal generator connection management

## Steps to establish LAN connection to signal generator:

1. Select "Signal Generator" in the 'Meas Setup' menu
2. Select "Connection Management" to open the connection management view
  - a. Enter the signal generator IP address or Hostname
3. You can select "Add to Generator List" to add the new analyzer to the signal generator list or select "Delete Selected Generator" to remove a generator from the list
4. Select a signal generator you want to connect to, and you will see the border highlighted in blue
5. Select "Connect" to establish a connection to the selected generator. Once connected, the signal generator border will be highlighted in green, the signal generator Information will display in the information box, and the button will change to "Disconnect".

## Download a Reference Waveform to the Signal Generator

Keysight's PathWave signal generation desktop or the generator's embedded software, accompanied by a valid N7631APPC license, can configure and generate a 5G NR reference waveform. Figure 7 shows a reference waveform downloaded to the signal generator.

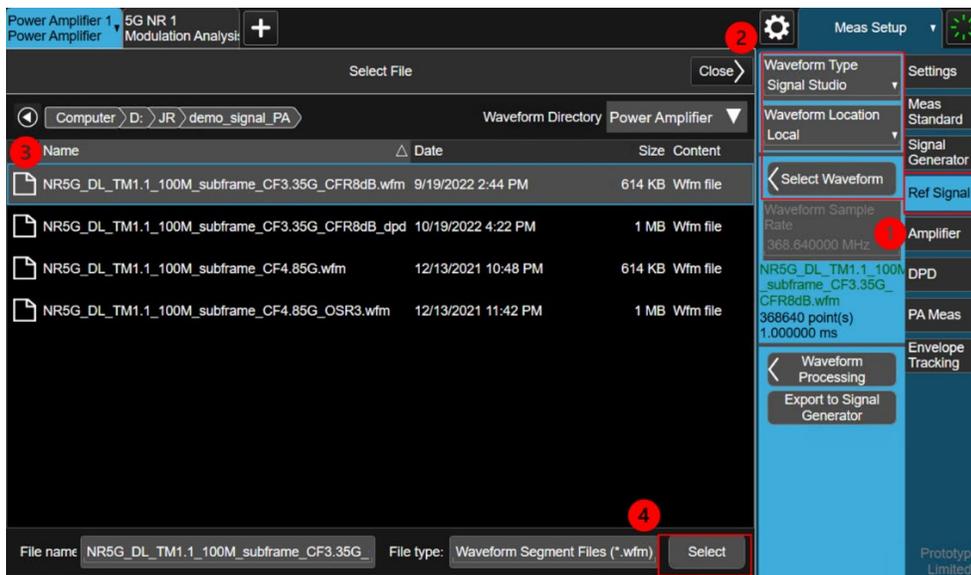
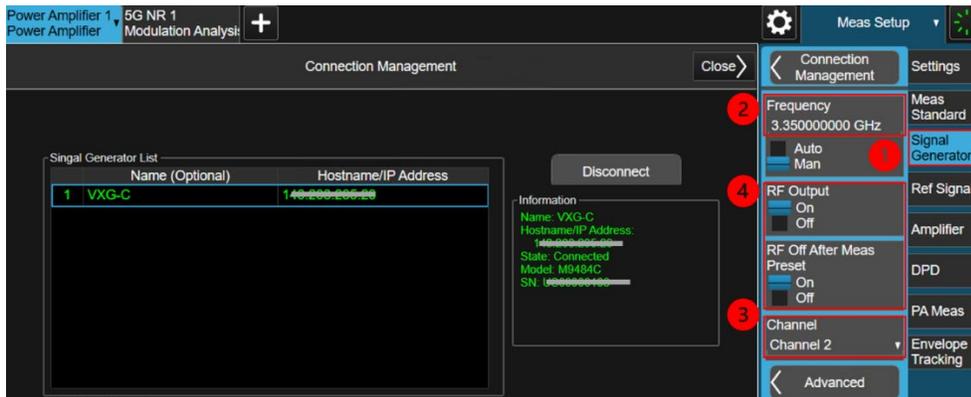


Figure 7. N9055EM0E reference signal waveform configuration

## Steps to download reference waveform to the signal generator:

1. Select “Ref Signal” under the “Meas Setup” menu
2. Select “Signal Studio” for the “Waveform Type”
3. Select “Local” for the “Waveform Location”
4. Press the “Select Waveform” button to open the “Select File” view
5. Select the reference waveform you want to use. Once selected, the waveform will be highlighted in blue
6. Press the “Select” button, to send the reference waveform to the signal generator

Once you have completed the reference waveform setup, you will configure the source settings in the “Signal Generator” tab as shown in Figure 8.



**Figure 8.** Signal Generator Settings include center frequency, channel source, and more.

## Steps to configure signal generator settings:

1. Select “Signal Generator” under the “Meas Setup” menu
2. Enter the center frequency in the “Frequency” text box
3. Select the correct channel from the drop-down menu in the “Channel” text box. For this document’s demo, the VXG’s channel 2 is selected.
4. Select “RF Output” “On”. For this example, the reference waveform is located on the VXG’s channel 2.
5. The “RF Off After Meas Preset” is set to “On”, by default, and will switch to “Off” after the measurement preset. You can also choose to control RF On/Off manually

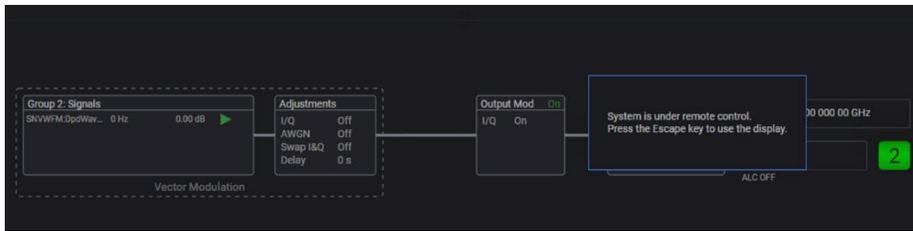


Figure 9. M9484C VXG displays it is under remote control and channel 2 is generating the waveform

The screenshot in Figure 9 shows the M9484C VXG signal generator's display after the reference waveform is downloaded from the signal analyzer. The reference waveform's file is displayed while it is generating the signal.

## Pre-DPD Measurements

Following the signal generator configuration, you will configure the analyzer demodulation and power measurement settings. The N9055EM0E Power Amplifier measurement application provides a radio standard preset to help you quickly configure parameters based on a specification.

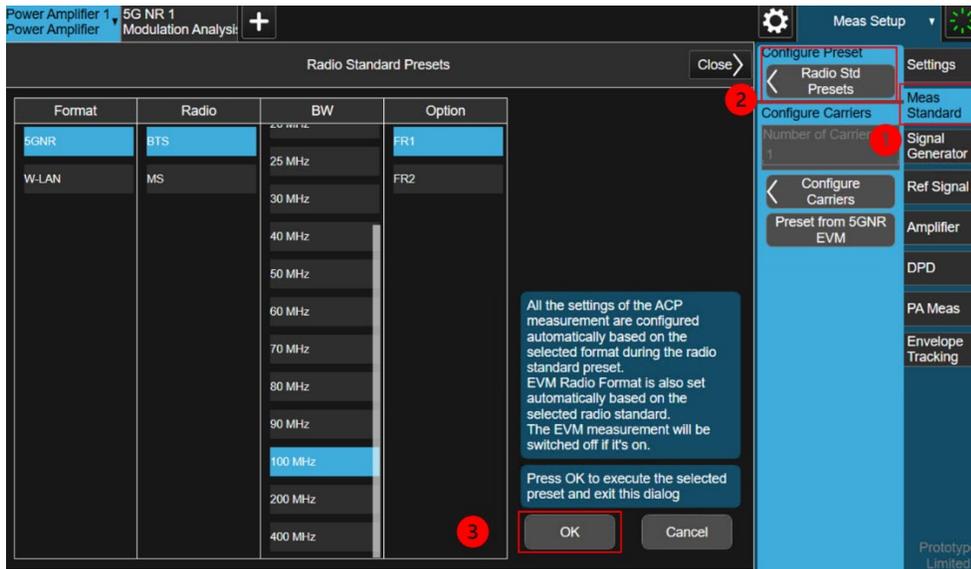
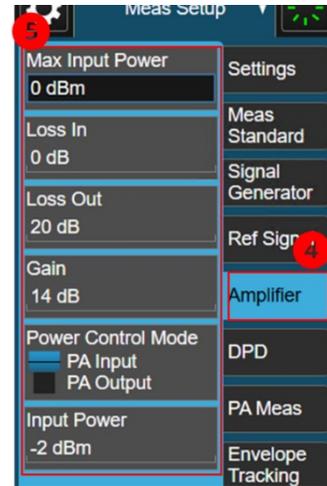


Figure 10. N9055EM0E radio standard preset for ACP and EVM measurement

## Steps to configure signal analyzer settings:

1. Select "Meas Standard" in the "Meas Setup" menu
2. Select "Radio Std Presets" to open the radio format view
3. Set the "Format" to "5G NR", "Radio" to "BTS", "BW" to "100 MHz", and Option to "FR1" representing frequency range 1. Press the "OK" button.
4. Next, select "Amplifier" in the "Meas Setup" menu
5. Enter the power amplifier parameters, including "Max Input Power", "Loss In", "Loss Out", "Gain", and "Power Control Mode".
6. Select "Frequency" and enter the analyzer's center frequency



**Figure 11.** N9055EM0E Power Amplifier configuration menu

Pre-DPD measurements are performed by measuring the signal generator's reference signal. The screen capture below shows the pre-DPD measurement results in yellow for all the PA test trace windows.

You can restart the measurement to see new results, or use "Continuous" mode to check pre-DPD results continuously by pressing the  button as shown in Figure 12.



Figure 12. N9055EM0E Pre-DPD measurements

Window 6 of Figure 12 (highlighted in red) shows the optional demodulation EVM results and supports 5G NR and WLAN demodulation. To view demodulation EVM measurements, a N9085EM0E license for 5G NR, N9077EM1E for 802.11ac/ax, and N9077EM2 for 802.11be is required. The next section describes how to enable 5G NR demodulation EVM results in power amplifier measurement. You can refer to the same steps to enable WLAN demodulation in PA measurements.

# Enable 5G NR Demod EVM

Figures 13 and 14 demonstrate how to enable 5G NR demodulation EVM results in power amplifier measurements. Start by configuring demodulation parameters in the 5G NR modulation analysis measurement. The 5G NR license, N9085EM0E, provides several test models under “Meas Standard”. Demodulation parameters can be configured quickly by selecting the preset button. If fast power amplifier measurements are important for your application, it is good to know that the length of the reference waveform is typically one subframe. Within “Meas Time” you can configure the result length and search time to optimize measurement time.



Figure 13. N9085EM0E 5G NR modulation analysis measurement

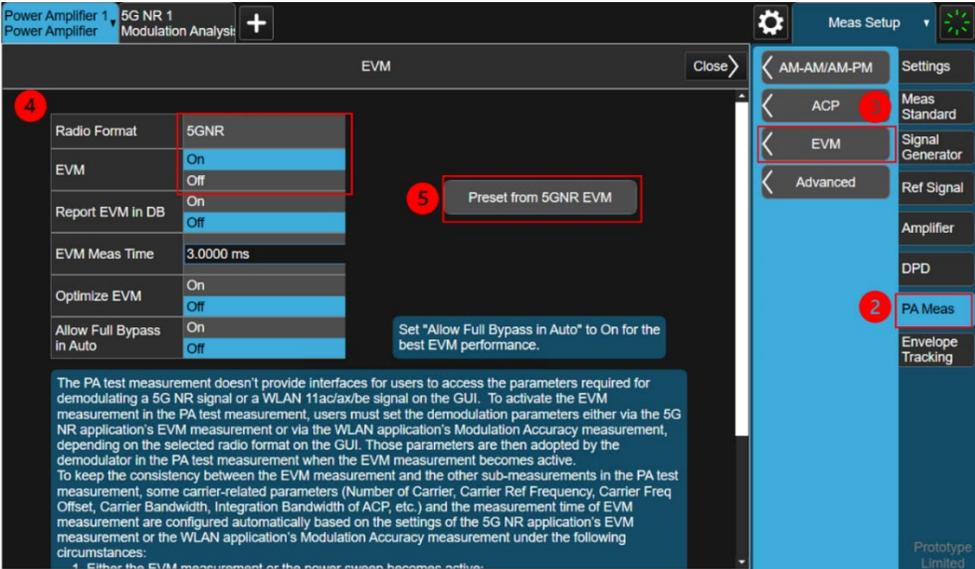


Figure 14. Enable 5G NR demodulation EVM results in power amplifier measurement

## Steps to enable 5G NR demod EVM:

1. For a 5G NR modulation analysis measurement, you must configure the demodulation parameters and the measurement time
2. Switch to the N9055EM0E Power Amplifier measurement, then, select “PA Meas” in the “Meas Setup” menu
3. Select the “EVM” button to open the EVM configuration page
4. In the EVM configuration page set the Radio Format to “5G NR” and select “On” for EVM
5. Click on the “Preset from 5G NR EVM” button to couple the demodulation parameters for PA measurement.

The demodulated EVM results will be displayed in the “EVM Error Summary” table.

## ILC DPD Measurements

Figure 15 demonstrates how to enable an iterative learning control (ILC) DPD measurement. The DPD iteration measurement makes it easy to acquire AM/AM, AM/PM, ACP, delta EVM, and demodulation EVM for each iteration. Post-DPD measurement results are displayed in blue for all the PA Test trace windows.



Figure 15. Enable ILC DPD measurement

## Steps to enable Iterative Learning Control (ILC) DPD:

1. Switch the measurement to single mode
2. Select “DPD” in the “Meas Setup” menu
3. Select “ILC DPD” in the “DPD Algorithm” drop-down menu
4. Select DPD “On” to display post-DPD measurement results
5. Select Meas DPD Iteration “On” to start measurements based on the iterative number you set
6. Click on the “Restart DPD Iteration” button to start the iterative DPD measurement.

The ACP, EVM results will be displayed for each iteration. For this example, the default number of 6 iterations is used. You can modify the number of iterations to align with your DUT PA performance.

## Over-Sampling a Reference Waveform

Figure 16 demonstrates how to resample the signal analyzer’s reference waveform in the N9055EM0E Power Amplifier measurement. The new, resampled waveform is input to the signal generator for generation by setting the “RF Port” in the “Signal Generator” menu to “On”.

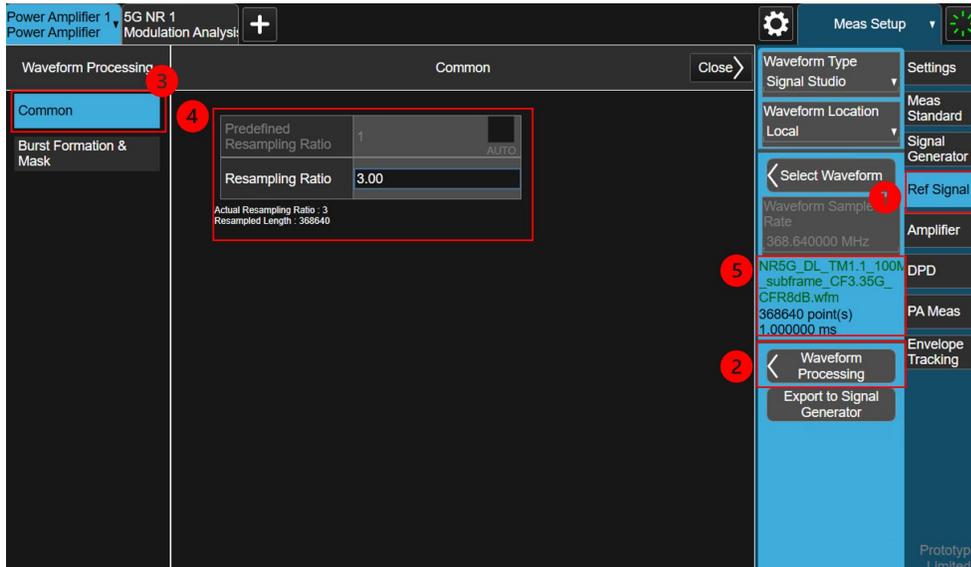


Figure 16. Enable reference waveform over-sampling ratio

## Steps to enable over sampling:

1. Select "Ref Signal" in the "Meas Setup" menu
2. Select the "Waveform Processing" button to open the waveform configuration page
3. Select "Common" under Waveform Processing
4. Disable "Auto" for the Predefined Resampling Ratio and the Resampling Ratio value
5. The resampling points are updated based on the resampling ratio. For this example, the 100MHz bandwidth 5G NR signal has 3 X 122880 sample points.

Figure 17 demonstrates how a 3rd-order distortion appears in adjacent channels. To improve ACPR, the pre-distorted waveform bandwidth needs to also be used for adjacent channels. To achieve this, we need a wider bandwidth waveform. In this example, a 100MHz bandwidth 5G NR waveform is used with a base sample rate of 122.88MHz. Since there is no 3rd order bandwidth coverage, the DPD doesn't improve the ACPR performance. However, by applying a 3 X higher sample rate, we can achieve ACPR improvement with DPD. Therefore, the signal generator and signal analyzer used in the system must be capable of 3 X the carrier bandwidth. To measure PA with DPD for a 100MHz bandwidth, the system requires a signal generator and signal analyzer capable of a 300MHz bandwidth.

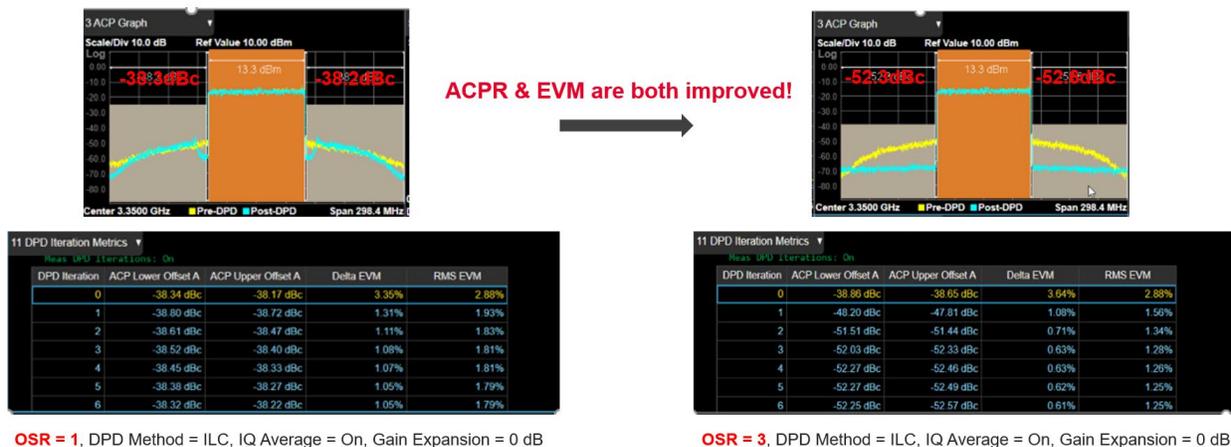


Figure 17. Effect of over-sampling ratio

# IQ Coherent Averaging

The ILC DPD method compares a measured signal to an ideal signal where noise is a significant portion of the difference. Every active part in a measurement setup adds noise, including the DUT and the measurement instruments. The combined test system noise reduces the measured signal's signal-to-noise ratio. To effectively apply ILC DPD, there must also be a method to minimize the influence of noise and non-linearity. The N9055EM0E Power Amplifier measurement application's "IQ Coherent Averaging" minimizes the influence of noise when the ILC DPD method is used. Figures 18 and 19 show two methods of enabling IQ averaging for a power amplifier measurement.



Figure 18. Enable IQ averaging in the Settings menu

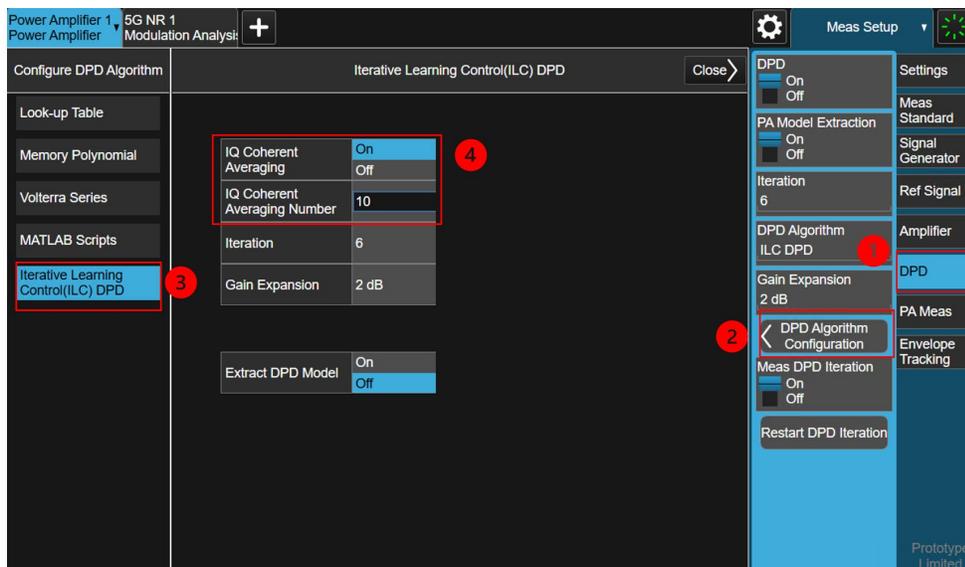


Figure 19. Enable IQ averaging in the Iterative Learning Control DPD configuration window

## Steps to enable IQ coherent average:

1. Select "DPD" in the "Meas Setup" menu
2. Click on the "DPD Algorithm Configuration" button to open the configuration window
3. Select "Iterative Learning Control" under Configuration DPD Algorithm
4. Set "IQ Coherent Averaging" to "On", and enter an IQ Coherent Average Number

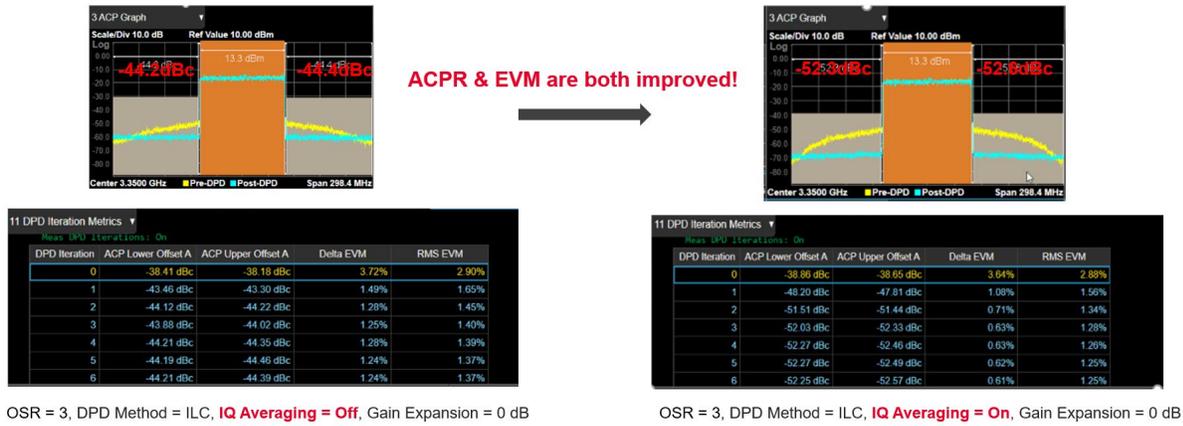


Figure 20. IQ averaging improves ACPR and EVM

# Gain Expansion

Gain expansion is the ratio of a pre-distorted waveform's peak power and the reference waveform. An increased gain can linearize the PA but it will clip when there is too high of gain. The N9055EM0E Power Amplifier measurement application provides a gain expansion configuration parameter that helps to achieve measurements in this extreme case. Figures 21 and 22 show two methods you can use to configure the gain expansion parameter.



Figure 21. Configure the Gain Expansion value in the DPD menu

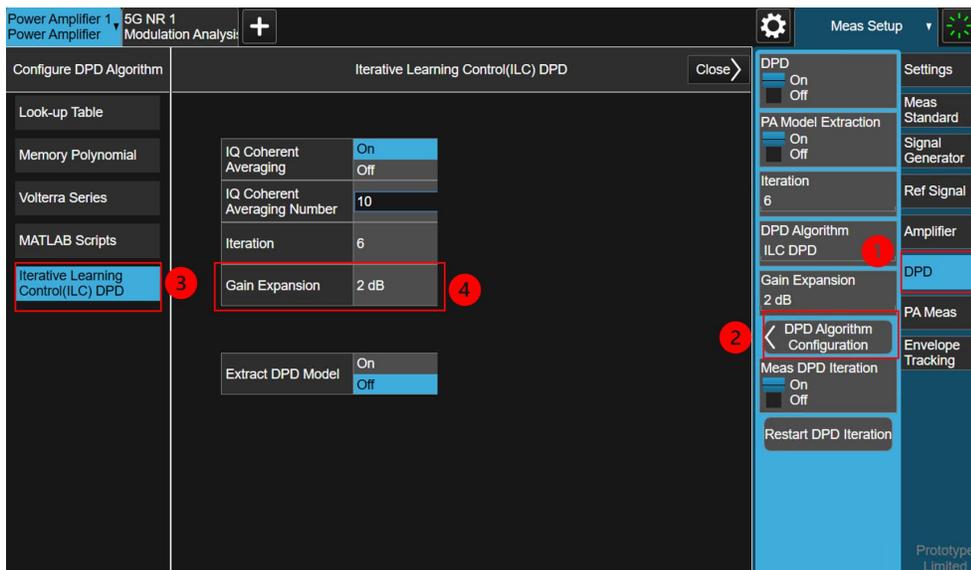
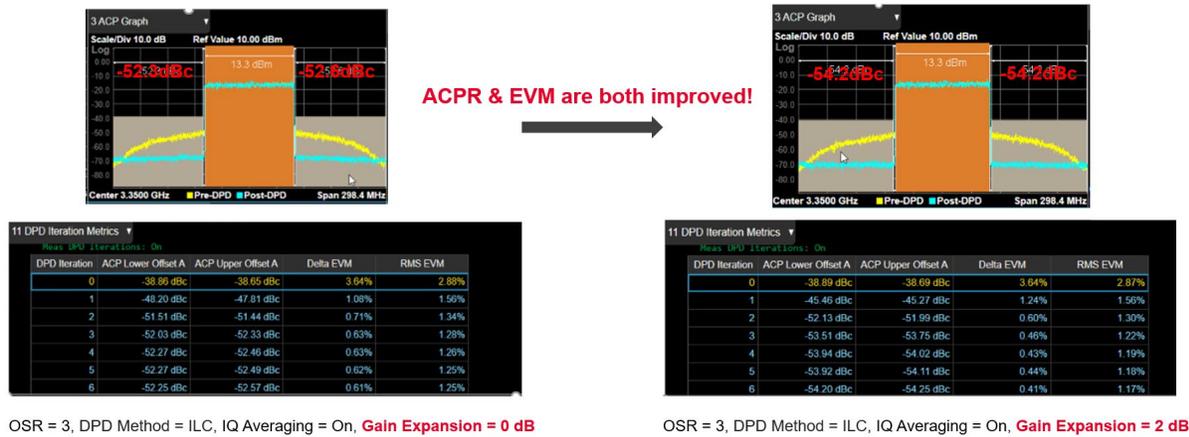


Figure 22. Configure Gain Expansion value in ILC DPD window

## Steps to enable gain expansion:

1. Select "DPD" in the "Meas Setup" menu
2. Click on the "DPD Algorithm Configuration" button to open the configuration page
3. Select 'Iterative Learning Control' under Configure DPD Algorithm
4. Enter a gain expansion value in the "Gain Expansion" cell



**Figure 23.** Improved ACPR and EVM by increasing the gain expansion

# Export ILC DPD Results

The N9055EM0E Power Amplifier measurement application enables the export of DPD results, including PA model, DPD model, and the pre-distorted waveform, as shown in Figure 24.

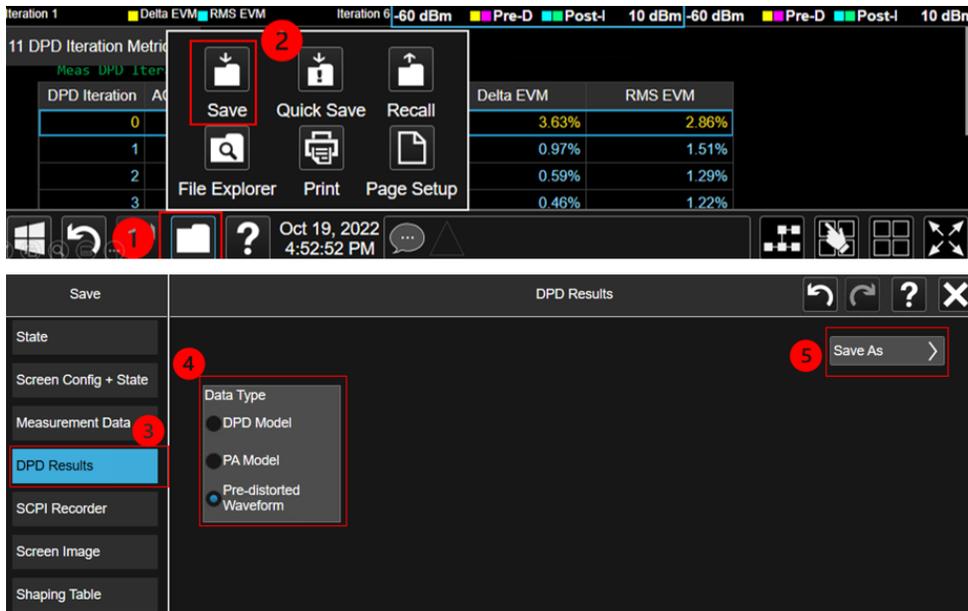
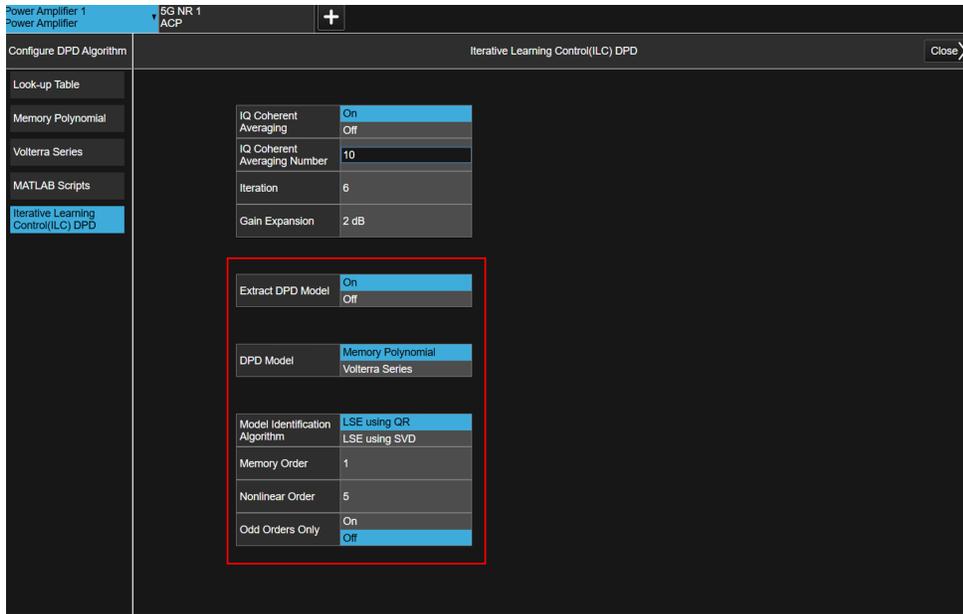


Figure 24. Export DPD results

## Steps to export PA DPD measurement results:

1. Select the file button on the bottom left
2. Click on the "Save" button to save the configuration information
3. Select "DPD Results" under the Save/State
4. Select the Data Type by clicking on the circle next to DPD Model, PA Model, or Pre-distorted Waveform
5. Click on the "Save As" button to export the selected DPD results file to the specified location



**Figure 25.** Extract an approximate DPD model based on ILC DPD measurement

You can export an approximate DPD model, as a reference, to verify your DPD modeling design after an ILC DPD measurement. Start by configuring the DPD model type and other related parameters in the ILC DPD configuration window as shown in Figure 25.

For more information, see the [N9055MOE Power Amplifier measurement application technical overview](#)

## Additional Information

- X-Series measurement applications: [www.keysight.com/find/X-Series\\_apps](http://www.keysight.com/find/X-Series_apps)
- Download X-Series measurement application: [www.keysight.com/find/X-Series\\_apps\\_software](http://www.keysight.com/find/X-Series_apps_software)
- Learn about compatible instruments: [www.keysight.com/find/X-Series\\_apps\\_platform](http://www.keysight.com/find/X-Series_apps_platform)
- 30-day trial license for X-Series measurement application: [www.keysight.com/find/X-Series\\_apps\\_trial](http://www.keysight.com/find/X-Series_apps_trial)
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