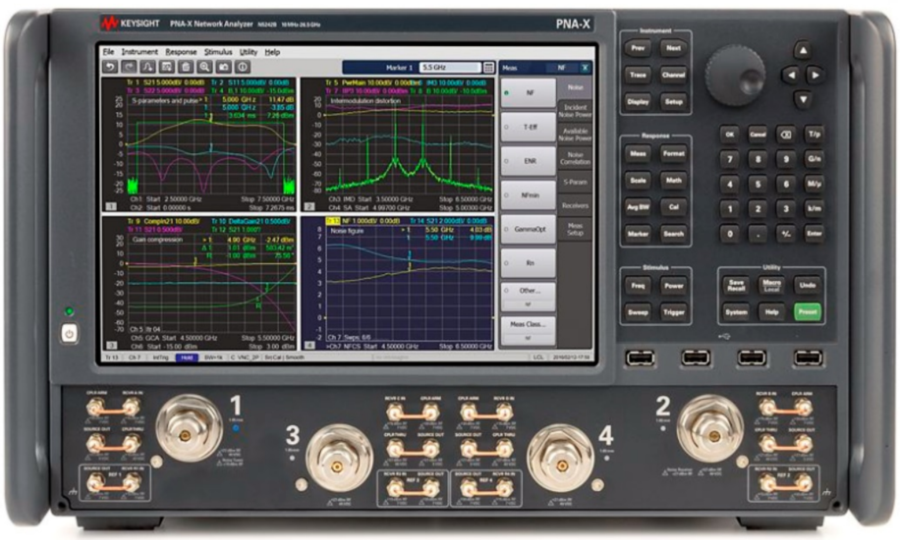
APPLICATION NOTE

Create Accurate EVM Measurements with the PNA-X Series Network Analyzer



KEYSIGHT TECHNOLOGIES

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Nonlinearity Evaluation of a Power Amplifier

Power amplifiers in the wireless communication system

Power amplifiers make a significant contribution to the quality of the RF chain in wireless communication systems. They determine the quality of the communication service in terms of signal quality and battery life. Power amplifiers reside in the last stage of the transmission chain and generate the necessary RF power; the power transmits over the antennas.

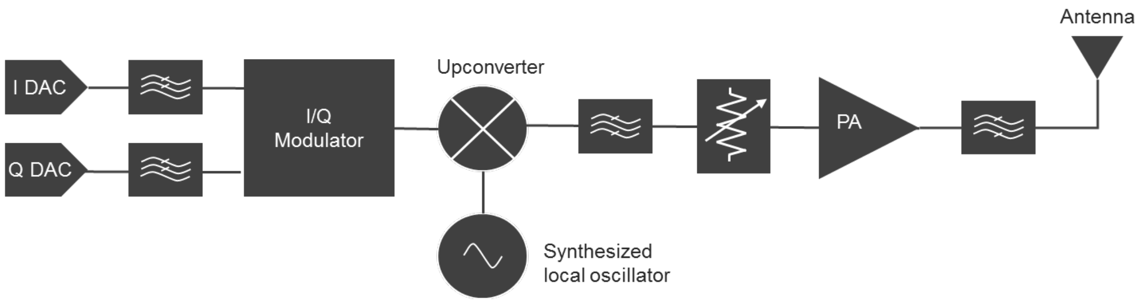


Figure 1: Tx path in a wireless communication system

Modern wireless standards use orthogonal frequency-division multiplexing (OFDM) for digital signal modulation. It is important to achieve high linearity to avoid errors in the demodulation process. Spectral regrowth can occur because of nonlinearity, which causes interference in adjacent frequency bands. It is critical to maintain linearity in the RF chain to achieve high-quality wireless communication links.

A power amplifier's power consumption directly impacts the quality of service in a wireless communication system. Power amplifiers with poor power efficiency have a shorter battery life. Power amplifier designers aim to maximize linearity while maintaining a high level of efficiency. This process is especially challenging to accomplish in mmWave frequency spectrum and across extremely wide signal bandwidths.

The industry uses error vector magnitude (EVM) as a figure of merit (FOM) for in-band characteristics and adjacent channel power ratio (ACPR) for out-of-band characteristics. This process measures the nonlinearity of the power amplifier under a modulated stimulus condition.

In this application note, you will learn an innovative method for characterizing nonlinearity of the power amplifier under modulated stimulus condition.

Modulation distortion: Nonlinearity of the power amplifier under modulated signal

Intermodulation (IM) is a commonly known parameter for quantifying the nonlinearity of a power amplifier. The power amplifier is first excited by a two-tone stimulus to establish an IM measurement. You can then measure the intermodulation tones on the high-side and low-side of these tones. These measurements establish the nonlinear distortion of the power amplifier under a two-tone stimulus condition.

Modulation distortion offers an alternative measurement method that accurately reveals the performance of the device under test (DUT) under actual operational bias conditions. You can achieve this result by using a modulated waveform with a specific signal bandwidth to create a high number of tones that stimulate the DUT. The use of a significantly higher number of tones compared to the IM method leads to more accurate performance measurements.

Example: Assume the power amplifier creates a nonlinear response, and there is spectral regrowth at the output of the power amplifier; see Figure 2.

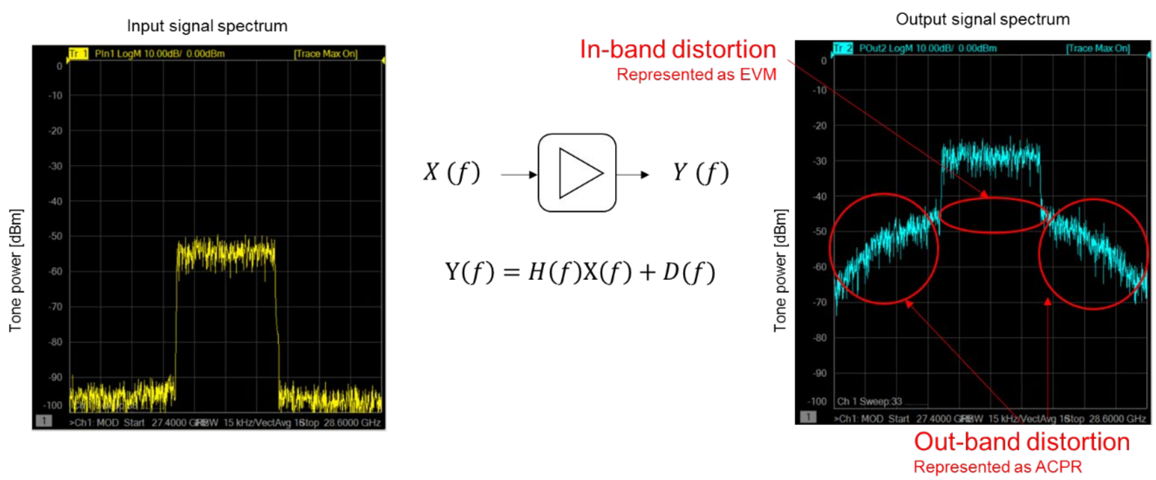


Figure 2: Nonlinear distortion model using a multitone stimulus.

- $H(f)$ is a complex number that represents a linear transfer function.
- $D(f)$ represents the distortion parameter generated by aggregating all the nonlinear interactions between tones present in the power amplifier.
- ACPR represents out-of-band distortion — compares the measured channel power of the signal with the adjacent channel.

The in-band distortion — typically represented as EVM — is challenging to assess since the distortion tones form part of the measured in-band signal.

Measuring Error Vector Magnitude Using a Vector Signal Analyzer

Wireless communication industry uses error vector magnitude (EVM) as a figure of merit (FOM) to quantify the power amplifier distortion that affects the signal quality. A vector signal generator (VSG), in combination with a vector signal analyzer (VSA), traditionally measures EVM.

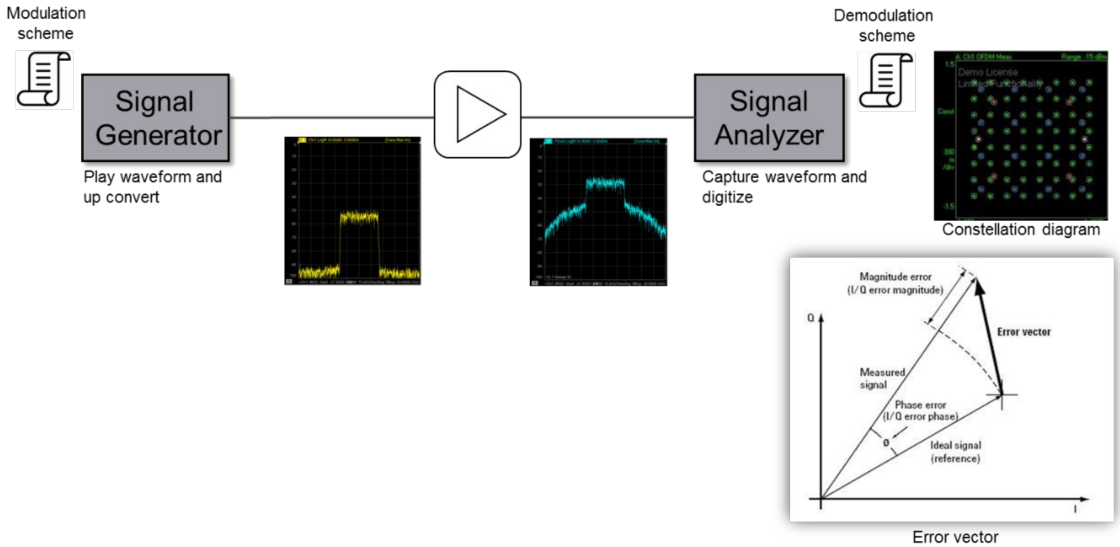


Figure 3: The VSA (demodulation) method uses a VSG and VSA to measure EVM

Measurement process:

1. Modulate signal— a specific scheme (such as 64 QAM) is used to create an IQ waveform.
2. Play the IQ waveform using an arbitrary waveform generator (AWG), then upconvert to a carrier RF frequency using the VSG.
3. Stimulate the power amplifier, which results in an output that contains distortion.
4. Capture the output by the signal analyzer, then quantify the captured signal by a wideband digitizer.
5. Demodulate the digitized quantity then plot the constellation diagram.
6. Evaluate the error vector using the measured constellation for each data point.
7. Compute EVM by root mean square (RMS) of the error vector over a certain waveform period.

In the VSA demodulation method, the assumption is that the input signal is perfect and does not contribute to a degradation of the EVM measurement. However, an input signal includes non-ideal factors such as noise and IQ imbalance, which can contribute to degrading the measurement.

The VSA method uses a wideband digitizer which captures wide-band noise, which further deteriorates the signal to noise level compared to using a narrow-band digitizer.

Challenges in device characterization with a wideband modulated signal

The introduction of 5G New Radio (NR) means designers must perform EVM measurements using extremely wide signal bandwidths in the mmWave spectrum. It is challenging to measure EVM under these conditions for the following reasons:

Errors contributed by the stimulus

The error vector is the value obtained when comparing the ideal signal with the measured signal for each constellation using the VSA method. The integrity of the signal source has a direct impact on the measurement result. The distortion of the generated signal needs to be lower than the power generated by the DUT.

The VSA method is sensitive to the IQ imbalance and phase noise not usually created by the DUT.

The random noise at low power levels result in less accurate EVM measurements since the signal-to-noise ratio (SNR) decreases as the bandwidth of the signal gets wider.

Errors contributed by the receiver

The input signal requires digitizing using a signal analyzer that does not produce any nonlinear distortion to minimize any errors in the EVM measurement result. Also, the noise floor of the receiver needs to be lower than the target signal. This process is especially challenging to accomplish across wider signal bandwidths since the SNR of the receiver is also lower.

The attenuation and gain settings of the receiver chain require careful monitoring to manage the input level. Iterating across different input levels and settings to optimize receiver optimization slows down the measurement process.

Signal fidelity

There are multiple approaches to calibrate the test system using the VSA method. It compensates the IQ waveform so that the input signal is a flat response at the reference plane. This method can include an error, especially if the test signal uses a wide bandwidth. This scalar compensation process results in a DUT with an impedance mismatch, which leads to the occurrence of a standing wave.

Modulation Distortion Measurements on a PNA-X Vector Network Analyzer

Modulation distortion offers an innovative approach to overcome measurement challenges. The Keysight PNA-X modulation distortion application with the Keysight vector signal generator characterizes the nonlinear distortion of a device under a modulated signal.

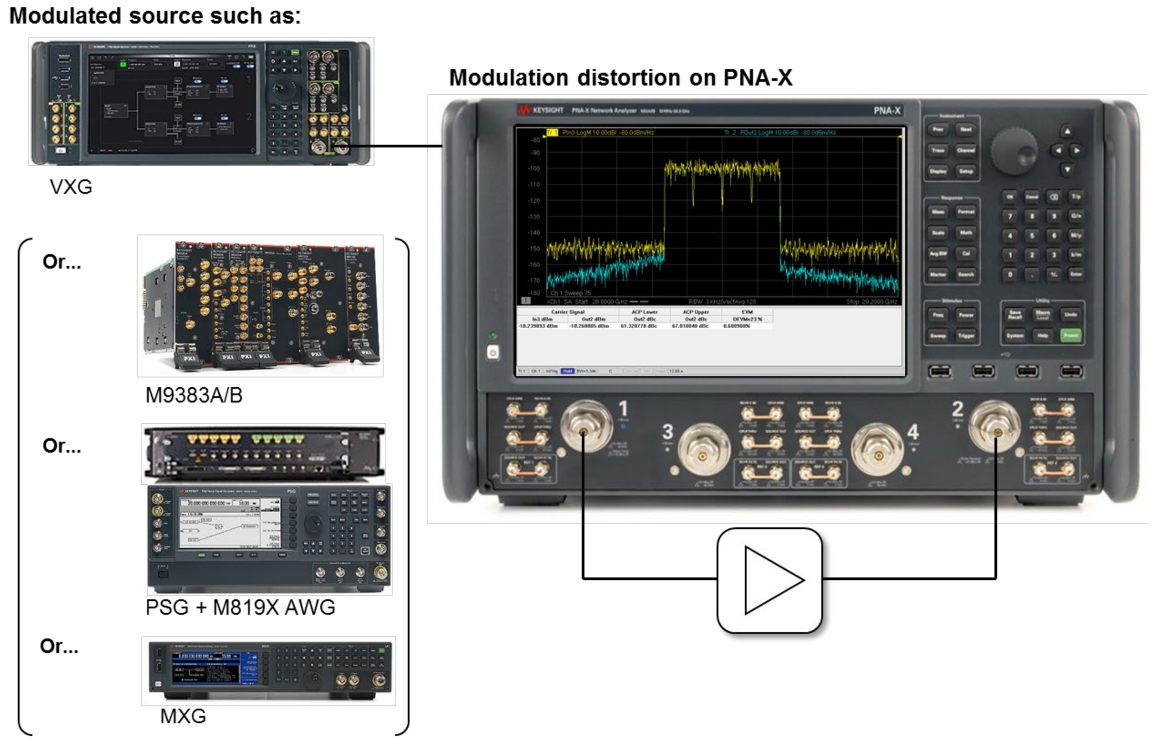


Figure 4: Modulation distortion is a software application that runs on the PNA-X, offering an innovative approach that enables you to perform device characterization under wideband modulated signals

The modulation distortion application enables you to access additional measurements; beyond the typical PNA-X measurements such as S-parameters, gain compression, intermodulation distortion, and noise figure. The modulation distortion application on the PNA-X also supports nonlinear distortion measurements under a modulated stimulus condition without the need to change the connection.

You can easily configure the measurements since the entire setup integrates into the PNA-X firmware. Also, the measurement leverages state-of-the-art calibration techniques for the best accuracy.

Compacting modulated waveform

The modulation distortion application does not require a long waveform, such as a full-frame or even a subframe. The modulation distortion application uses a short waveform period to perform an accurate measurement within a relatively short time frame. This process is known as compacting the waveform.

For example, you want to know the response of the DUT using a waveform under a specific modulation scheme (parent waveform). The PNA-X firmware helps to create a slice of the parent waveform. The waveform inherits the frequency signature and statistical characteristics. The sliced waveform is the compact test signal.

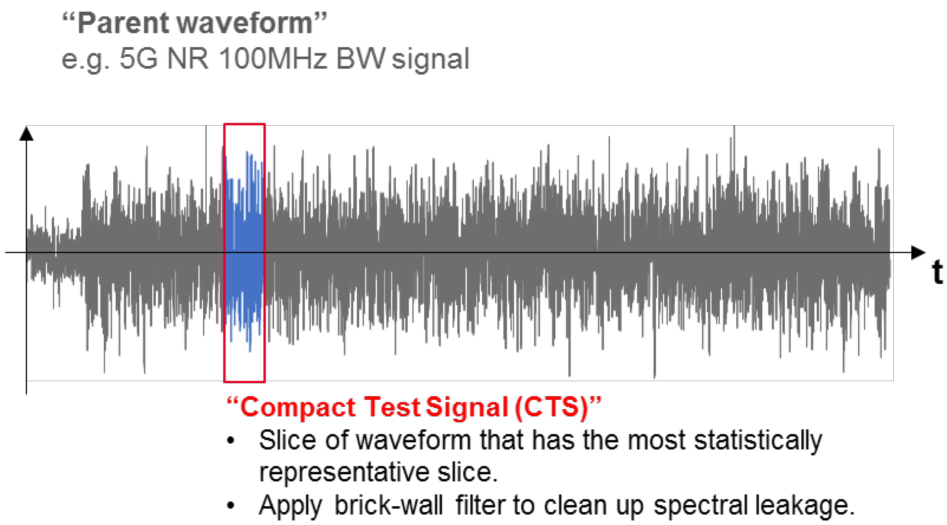


Figure 5: Illustrates a compact test signal

The PNA-X firmware uses a unique algorithm to determine the most statistically representative slice from the parent signal. The results are from the parameters selected by you. The firmware then applies a brick wall filter to remove spectral leakage when the compact test signal plays.

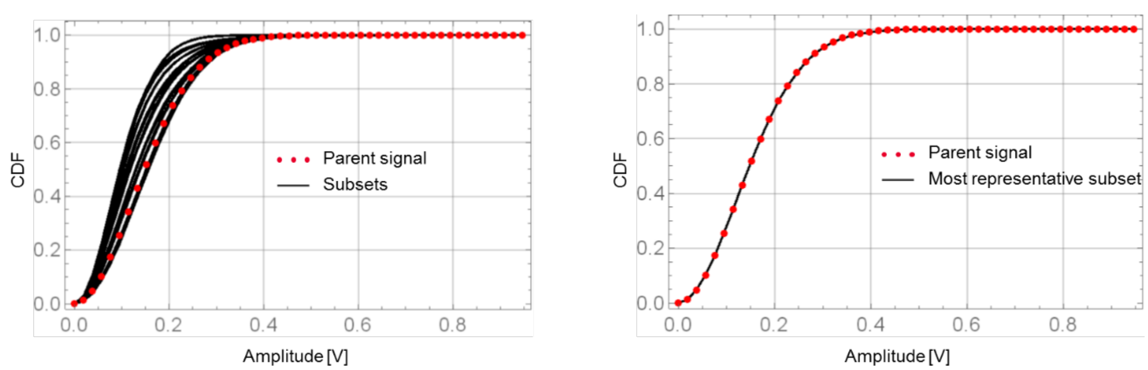


Figure 6: CDF of parent signal and subset slice

Depending on your parameters, the compact test signal displays different characteristics, which can affect the measurement result.

For example, you are using a 5G NR 100 MHz bandwidth waveform as a parent waveform to create a compact test signal. Figure 7 illustrates two different compact test signal characteristics when using different parameters for the same parent waveform.

- The yellow trace indicates the parent waveform, and the blue trace shows the compact test signal.
- Top plots represent the spectrum of the waveform. The results show what the waveform looks like in the frequency domain by applying the Fast Fourier Transform (FFT) to each waveform.
- The center plots represent the position of a compact test signal in the parent signal.
- Bottom plots represent the complementary cumulative distribution function (CCDF) curve of the parent signal, compact test signal, as well as Gaussian distribution (pink trace).

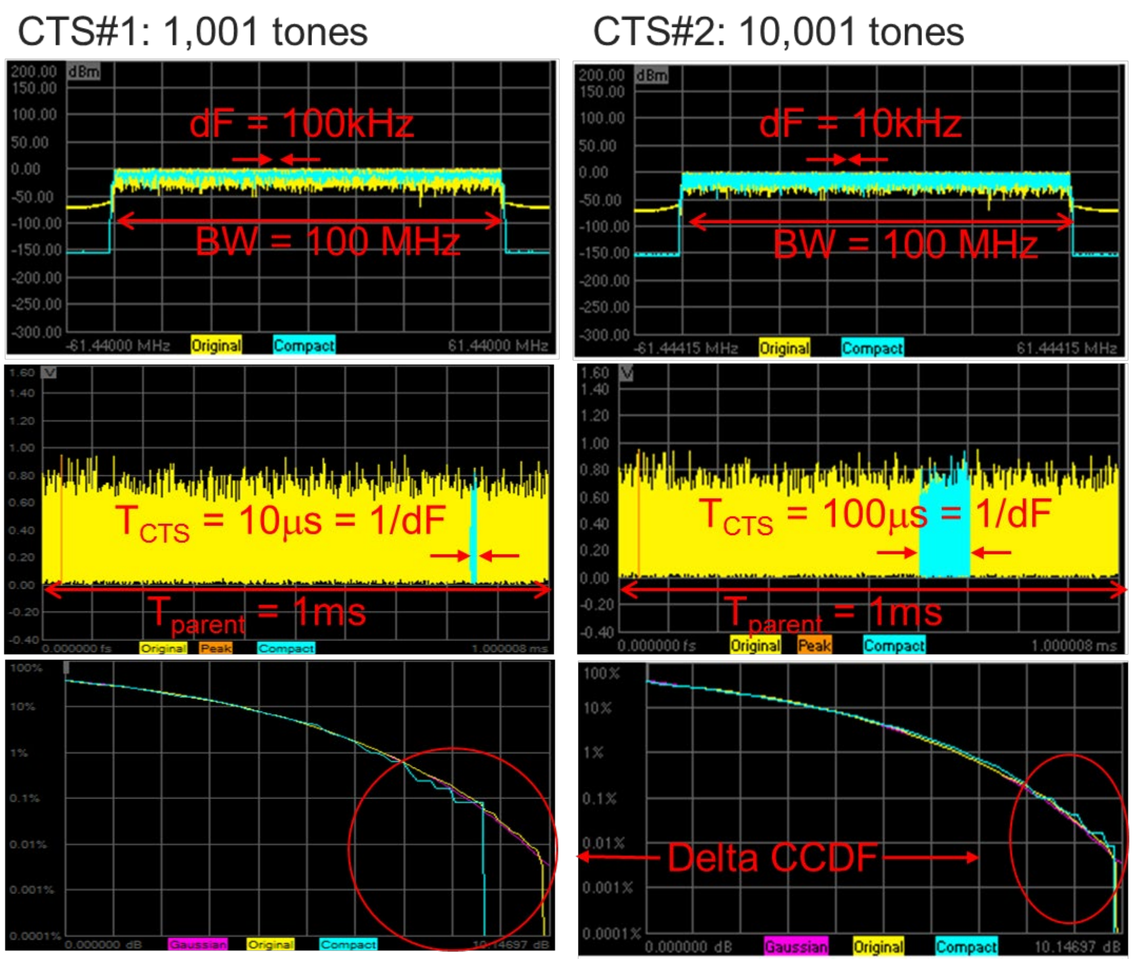


Figure 7: Frequency domain view, time domain view, and CCDF view of a waveform

Compact test signal parameters

There are a couple of approaches to compact test signal parameters — let us consider the number of tones that are present in-band of the modulated signal:

- The left plot displays a compact test signal that consists of 1,001 tones.
- The right plot is a compact test signal that includes 10,001 tones.
- The left compact test signal has a 100 kHz tone spacing, while the right compact test signal has a 10 kHz tone spacing.

The frequency signature of both signals has the same bandwidth as the original signal. The original signal has a higher out-of-band spectrum. The compact test signal has a low out-of-band spectrum that uses the brick wall filter for cleaning the signal.

The numbers in the center represent the time domain view; the waveform length is reciprocal to the tone spacing. The left compact test signal has a waveform length of 10 us; the waveform length of the right compact test signal is 100 us. A finer tone spacing waveform results in an extended period of the compact test signal waveform.

Statistical characteristics

The CCDF of this specific parent waveform is in alignment with the Gaussian distribution. The CCDF of a compact test signal that consists of 10,001 tones aligns with the parent waveform across the entire probability. The CCDF of a compact test signal that includes 1,001 tones aligns with the parent waveform, but only until it is approximately a 0.1% probability.

Measuring spectrum using PNA-X receivers

Figure 8 shows a simplified block diagram of the measurement system using a PNA-X and VSG.

The VSG replays the compact test signal without any interruptions. Three PNA-X receivers capture the spectrum at the reference plane at the input and output of the DUT. The instantaneous bandwidth of the PNA-X ADC(Analog-to-Digital Converter) is at 30 MHz. When the modulation distortion application measures the spectrum of the signal with a bandwidth wider than 30 MHz, it moves the local frequency of the PNA-X to measure the spectrum for each instantaneous bandwidth. It then combines the captured partial spectrum to obtain a complete spectrum response.

When the modulation distortion application measures the spectrum for each section, it uses multiple receivers coherently and applies linear calibration terms. The modulation distortion application offers a measuring technique where the PNA-X completes accurate vector corrected measurements at the reference plane.

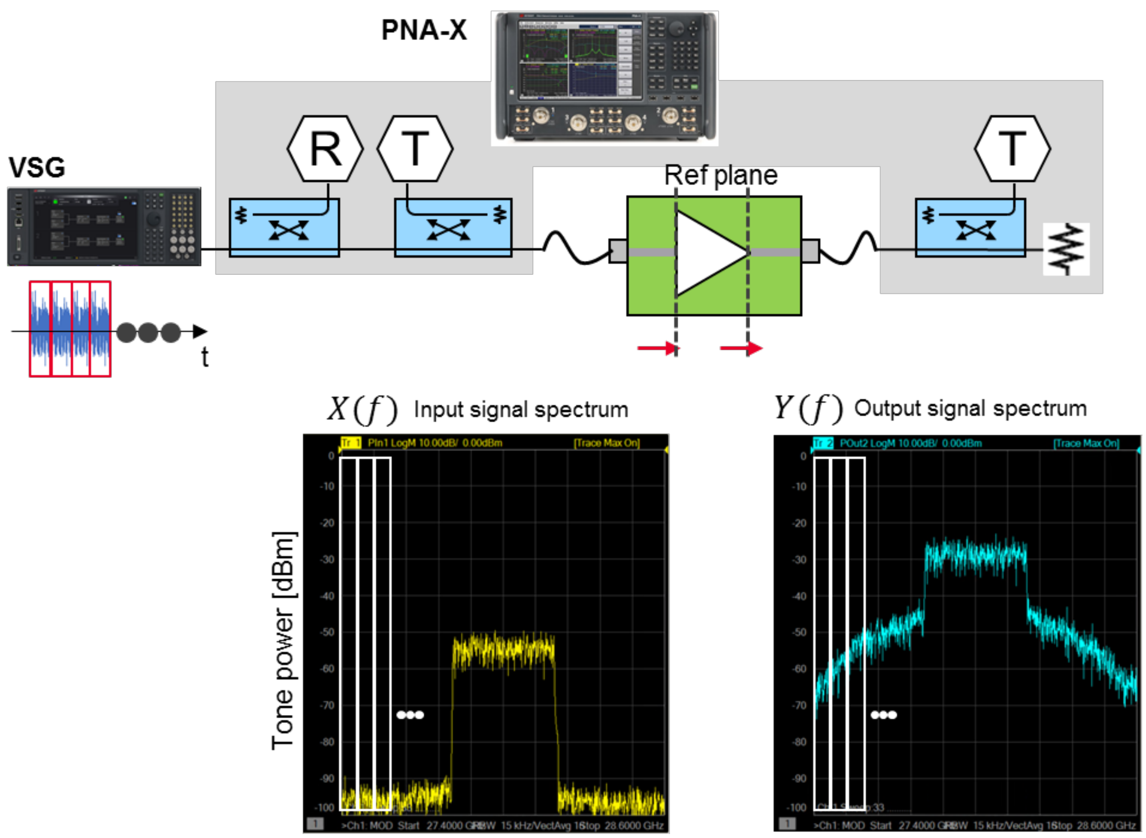


Figure 8. The PNA-X receiver captures the signal spectrum at the input and output of the power amplifier

Figure 8 illustrates how the PNA-X measures the input signal and the output signal spectrum. A signal generator reiterates the compact test signal. The PNA-X receiver measures the input signal spectrum and output signal spectrum in the frequency domain. The output signal spectrum has spectral regrowth created by the nonlinear response of the DUT.

Spectrum decomposition

The modulation distortion application then processes the data and compares the input spectrum and the output spectrum known as spectral correlation. As a result, the modulation distortion decomposes the output signal spectrum into a spectrum of *H(f),* which linearly correlates to the input. The spectrum of *D(f)* does not linearly correlate to the input.

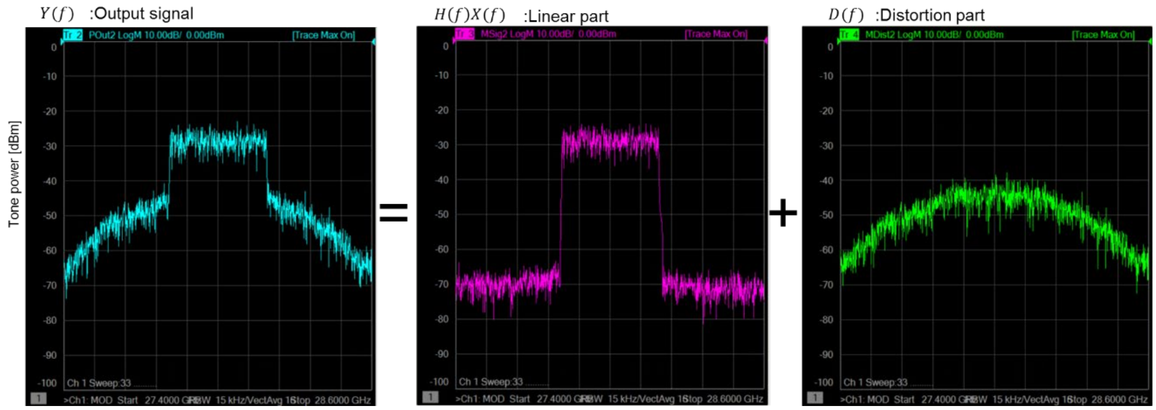


Figure 9: Output spectrum decomposition

For this example, $H(f)$ represents the linear transfer function, and $D(f)$ represents distortion:

(1) $Y(f) = H(f)X(f) + D(f)$

Multiply the complex conjugate of X on both sides of the equation, and then calculate the averaged expectation:

(2) $E[Y(f)X^*(f)] = H(f)E[X(f)X^*(f)] + E[D(f)X^*(f)]$

In this equation, $E[.]$ denotes the expectation operator. The expectation operator evaluates the mean of a significant enough number of adjacent tones, a minimum of 100 tones. Because there is no linear correlation between the input spectrum and distortion spectrum, (2) is expressed as:

(3) $E[Y(f)X^*(f)] = H(f)E[X(f)X^*(f)]$

Compute the linear transfer function of the response:

(4) $H(f) = E[Y(f)X^*(f)]/E[X(f)X^*(f)]$

By knowing $H(f)$, you can calculate the remaining part of the equation (1), which consists of the distortion response of the DUT:

(5) $D(f) = Y(f) - H(f)\,X(f)$

Computing Figure of Merit

You are now ready to compute the FOM of a nonlinear response, such as ACPR and EVM.

Computing ACPR is straightforward. It is similar to the traditional signal generator and signal analyzer approach. The channel power of the in-band channel of interest and the channel power of the adjacent channel band undergoes evaluation. The ratio between the BAND and AC then computeed.

The modulated distortion application defines EVM; see the following equation:

$$DEVMe\ (\%) = 100\sqrt{\frac{\int_{BAND}|H^{-1}(f)D(f)|^2 df}{\int_{BAND}|X(f)|^2 df}} = 100\sqrt{\frac{\int_{BAND}|X(f) - H^{-1}(f)Y(f)|^2 df}{\int_{BAND}|X(f)|^2 df}}$$

The suffix *e* on in the above equation denotes equalized EVM. In practice, modern communication systems use equalization to compensate for in-band amplitude and group delay distortions to create more linear characteristics in the power amplifier (such as frequency dispersion). The prefix D is added to the EVM to describe that the EVM in the modulation distortion application.

The modulation distortion application computes the EVM using:

$$DEVM_e\ (\%) = 100\sqrt{\frac{\sum_{i=1}^{N}|X(f_i) - H^{-1}(f_i)Y(f_i)|^2}{\sum_{i=1}^{N}|X(f_i)|^2}} = 100\sqrt{\frac{\sum_{i=1}^{N}|X(f_i) - c_G^{-1}(f_i)g_{SM}^{-1}(f_i)Y(f_i)|^2}{\sum_{i=1}^{N}|X(f_i)|^2}}$$

The PNA measures the response in Discrete Fourier Transfer (DFT), and PNA-X tunes its ADC sample so that each of the tones of the compact test signal falls to the grid of the DFT. Accumulating power spectral density (PSD) of each tone in the desired band could compute EVM of the specified band.

As a default function, modulation distortion uses spline fitting to estimate H^{-1} to compute EVM. The c_G is gain compression of the DUT and the g_{SM} is a small signal gain of the DUT. You can optionally use this equation by measuring g_{SM} in a separate process.

Correlation to EVM measured in time domain measurement

As mentioned above, there are two different methods to compute EVM:

- time domain demodulation method using VSG and VSA
- frequency domain spectral correlation method using VSG and PNA-X

Both quantities are equivalent, which is explained by Parseval's theorem:

$$\sqrt{\frac{\int_{TIME}|(h^{-1}*d)(t)|^2dt}{\int_{TIME}|x(t)|^2dt}} = \sqrt{\frac{\int_{BAND}|H^{-1}(f)D(f)|^2df}{\int_{BAND}|X(f)|^2df}}$$

Traditional instrument setup versus using modulation distortion

In the traditional instrument setup, you measure the EVM of the DUT using signal analyzers and signal generators. After creating a waveform with a specific modulation scheme, you can replay it using the VSG. The DUT then amplifies the signal captured by the wideband digitizer of the signal analyzer. You can process using the Keysight 89600 vector signal analyzer software, which leads to the computation of the EVM in the time domain.

In the modulation distortion setup, the compact test signal is created based on the same parent waveform. The compact test signal plays continuously in the signal generator following the measurement of the input and output response of the DUT in the frequency domain. You can then perform the spectrum correlation to compute the EVM.

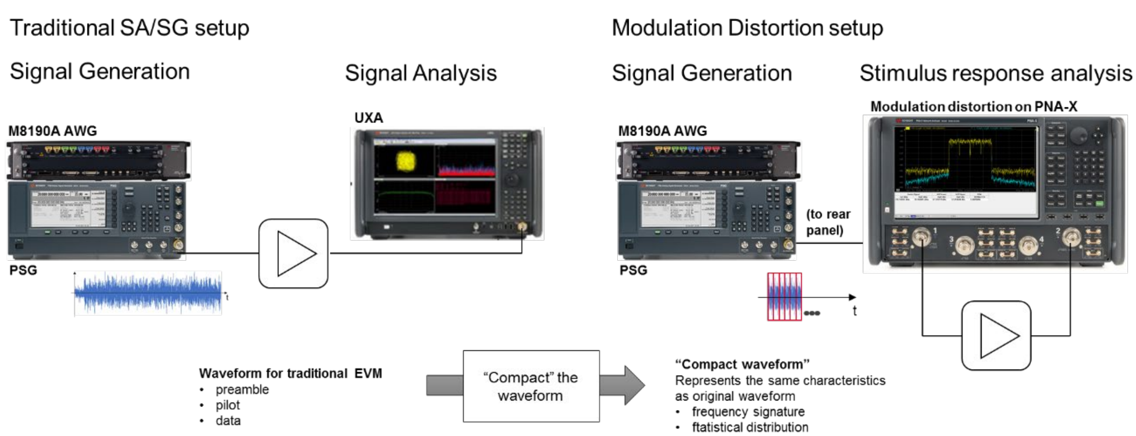


Figure 10: Comparing the measurement setups using two different EVM measurement methods

Results

This comparative study uses several waveforms:

- Verizon 5G 1-channel 100MHz bandwidth
- 5G New Radio 400 MHz 64 QAM
- 5G New Radio 800 MHz 64 QAM
- 5G New Radio 800 MHz 256 QAM

You can measure the DUT at the carrier frequency of 27, 28, and 29 GHz. Plot the EVM as a function of output power level, which results in a “bathtub curve.”

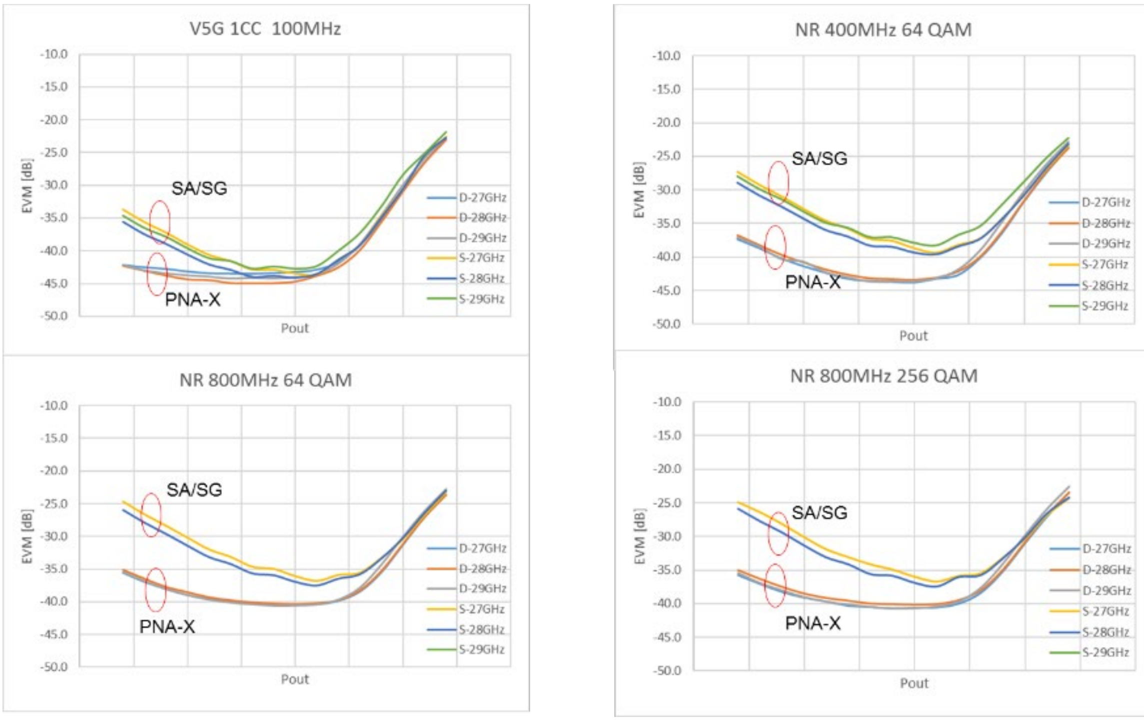


Figure 11: EVM comparison results

The nonlinear response of the DUT affects the EVM at the high-power region (right-hand side of each plot). In this region, you can see good alignment between both methods.

SNR of the test system affects the EVM at the low power region (left-hand side of each plot). The low system noise generated by the modulation distortion setup results a lower EVM measurement as compared to the traditional instrument setup. The lower EVM enables you to better assess the achieved EVM at specific output power from the DUT — even when the power is low.

It is important to know at which point the power amplifier starts to show nonlinear behavior. You can accurately characterize the performance of a power amplifier with the modulation application using the PNA-X with low residual EVM.

PNA-X Implementation

In this section, you will learn the PNA-X's implementation of the EVM measurement and the different types of measurements that are relevant for assessing a power amplifier.

Hardware configuration

Figure 12 represents the measurement system for the PNA-X and a VSG. The following steps are to configure the hardware:

1. Synchronize the PNA-X and the VSG using 10 MHz reference.
2. Connect the output of the VSG to the rear panel of the PNA-X (J10) to allow the signal to go through the internal path of the PNA-X.
3. The modulated signal is available from the test port 1 of the PNA-X, then to the input of the DUT.
4. Connect test port 2 of the PNA-X to the output of the DUT.
5. Use PNA-X receivers R1, A, and B to measure the input and output spectrum of the modulated signal.

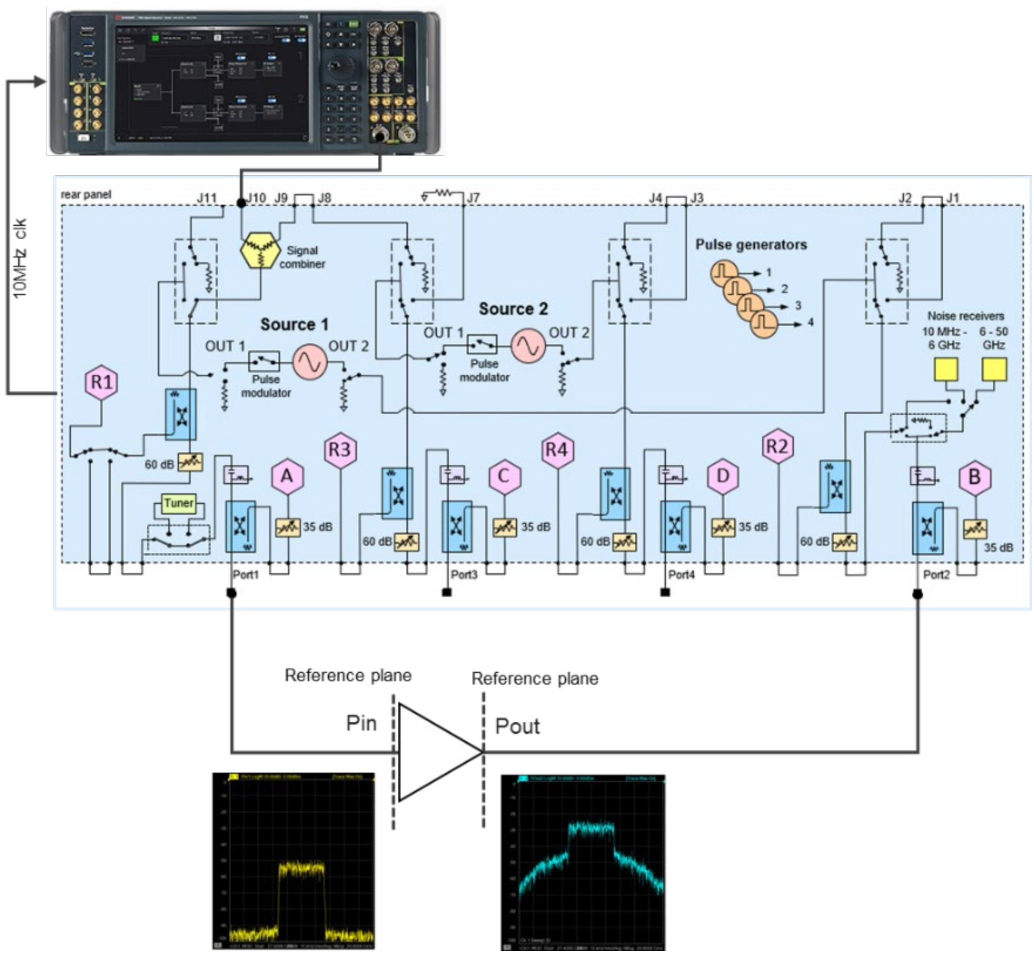


Figure 12: PNA-X modulation distortion measurement process

The PNA-X hardware allows flexible configurations using an external coupler and direct receiver access port.

Modulation distortion application

You can easily configure the modulation distortion software application with integrated PNA-X firmware.

Similar to other application software that runs on a PNA-X, measurements begin by creating a channel. The channel contains all the stimulus-response information, as well as calibration information necessary for the measurement. The PNA-X firmware can create multiple channels for the modulation distortion class as needed.

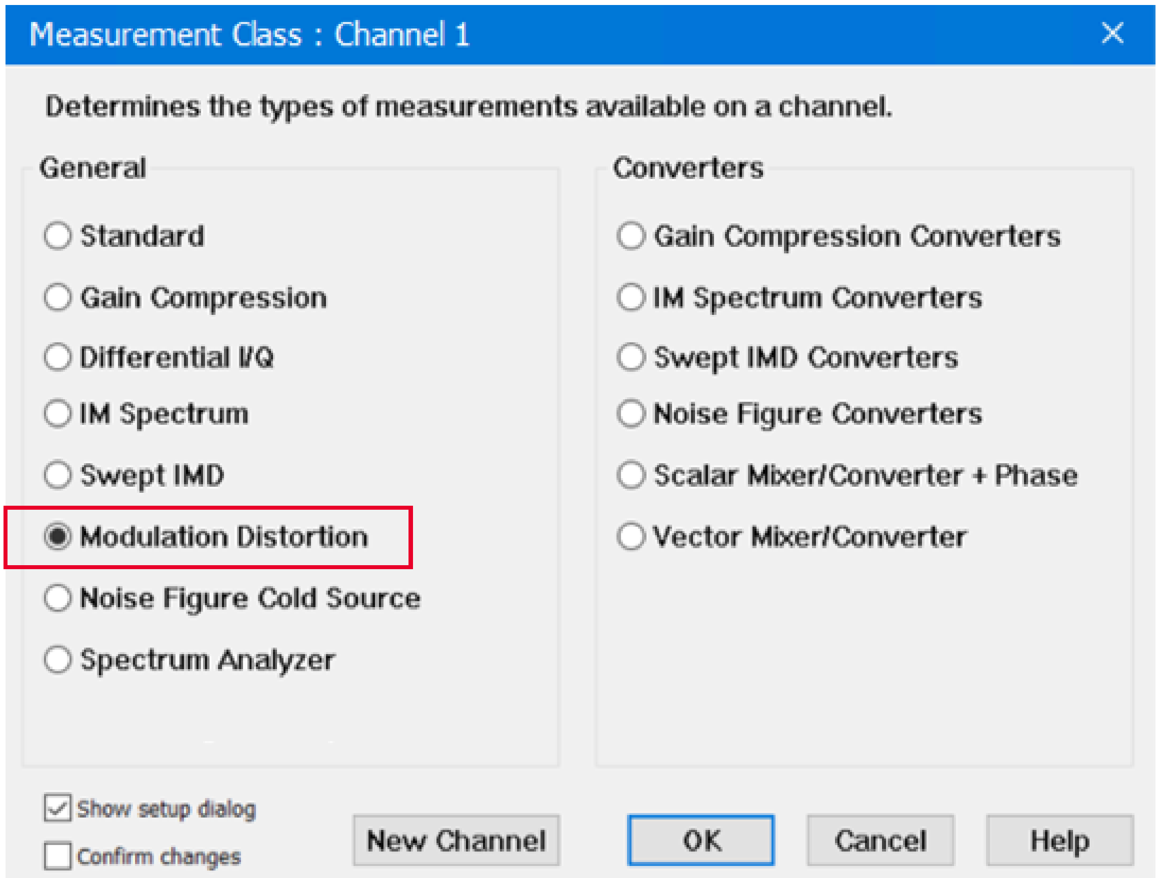


Figure 13: Measurement class selection window

Modulation distortion setup window

A setup window enables you to establish different configurations quickly. For example, let us look at creating a measurement using the following conditions:

- carrier frequency: 28 GHz
- span for spectrum analysis: 500 MHz
- compact test signal: 1,001 tones from 5G NR with 100 MHz bandwidth waveform
- measurement: EVM and ACPR for the high side and low side

In this example, the VSG connects via the LAN, and the PNA-X is communicating with the VSG via HiSLIP.

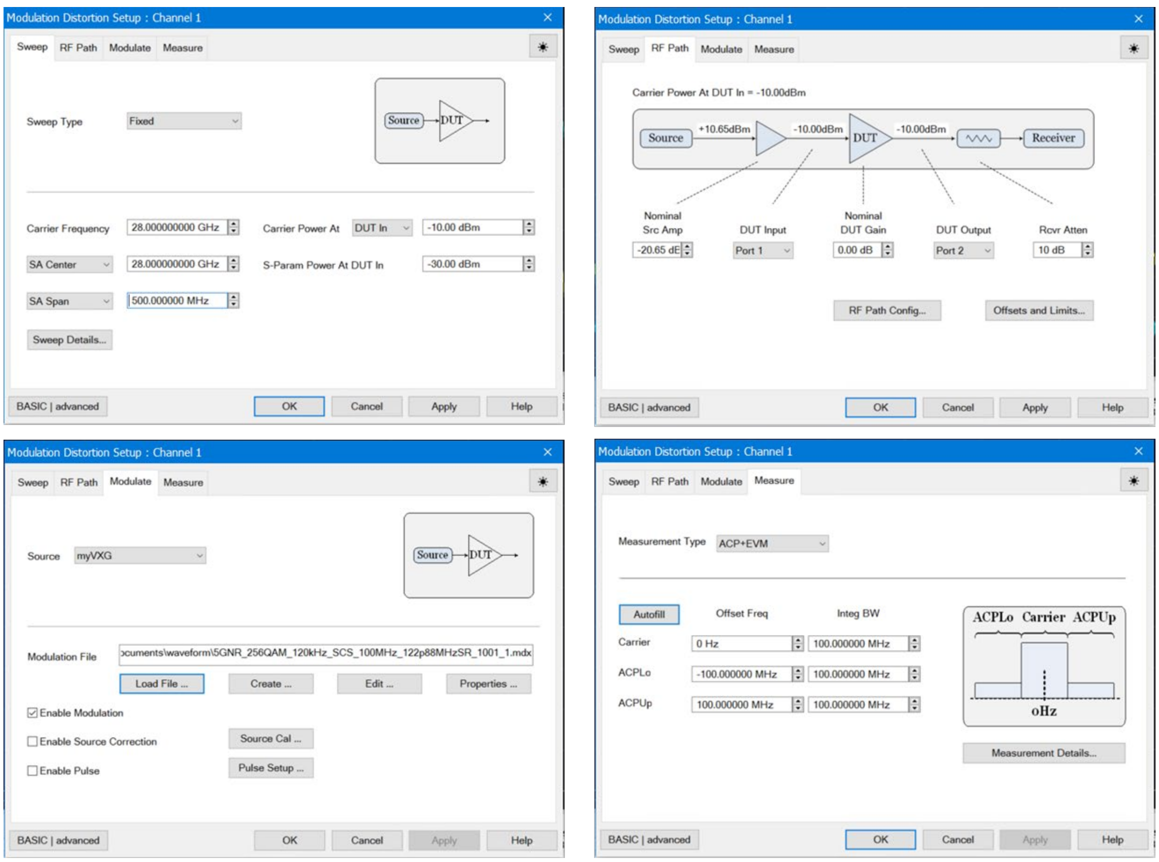


Figure 14: Setup window to set your parameters

Compact test signal creation

You can easily generate the compact test signal in the “modulate” tab of the modulation distortion setup window. In the following example, use a parent signal (*.wfm file format) from Keysight’s Signal Studio software. In addition to the *.wfm file, a *.csv file format created by any of application is usable.

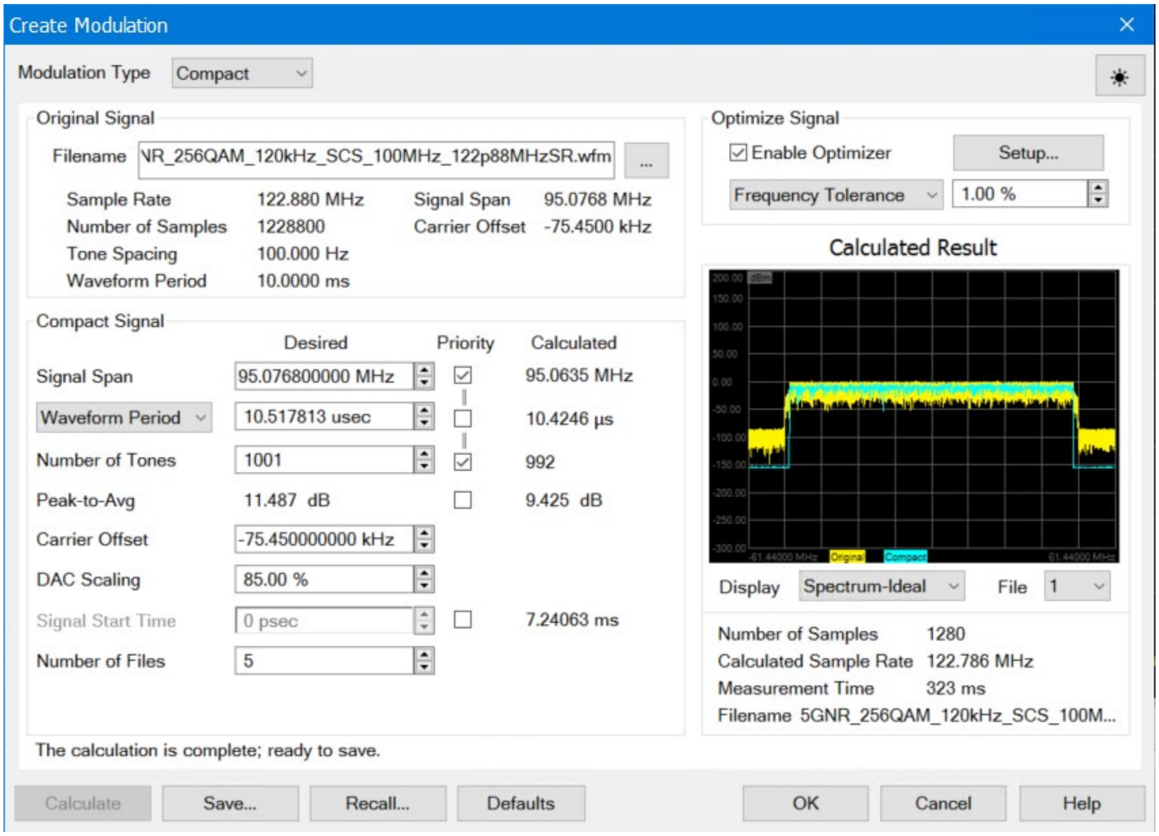


Figure 15: Create your modulate window parameters

In this example, the parent signal has a 10 ms waveform period, with 122.88 MHz of the sample rate. Specify the parameters in the “compact signal” area; the firmware generates a compact test signal based on the provided parameters.

For example, you can create a compact test signal with a target of 1,001 tones. The PNA-X uses its algorithm to identify the most statistically representative slice in the parent waveform. It then applies resampling and a brick wall filter to optimize the compact test signal.

As a result, the firmware creates the compact test signal that has 992 tones within the spectrum (in-band) and a 10.4246 us waveform period.

Calibrating the System

The calibration of the measurement system plays a critical role when making an accurate measurement. There are two types of calibrations you can use:

- A linear calibration to remove the linear error from the raw measurement result.
- A modulated source correction to generate the desired modulated waveform at the reference plane.

Linear error calibration of the PNA-X receiver

The calibration procedure is the same as the other S-parameter calibrations in the PNA-X. It uses the "CalAll" function of the PNA-X. Conventional accessories (mechanical calibration kit, Ecal, and power sensor) are available in the "CallAll." During this procedure, the PNA-X uses its internal source. The conventional fixturing feature of the PNA-X is available to move the calibration plane as necessary.

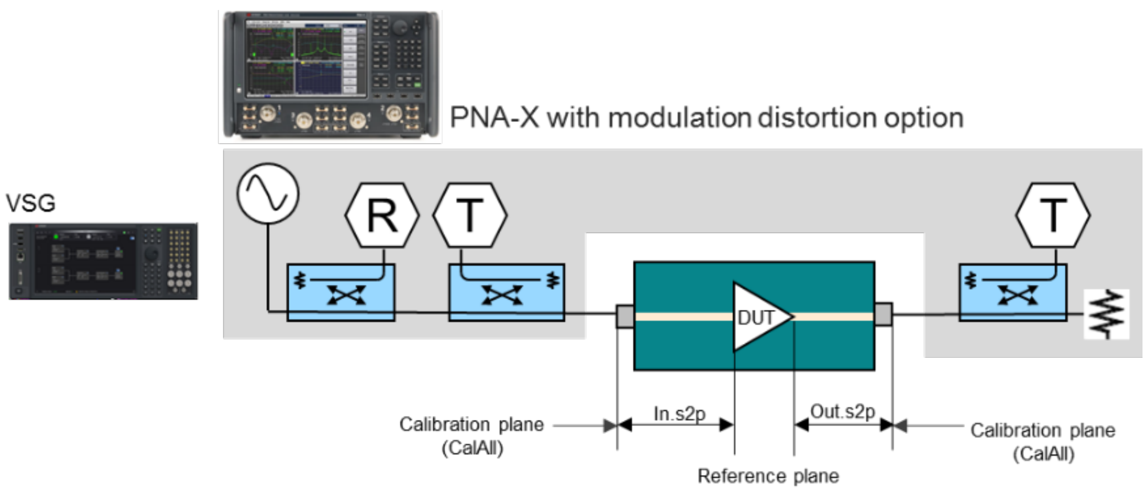


Figure 16: linear error correction of the PNA-X receiver

The PNA-X establishes a correction plane that removes the linear error of the measurement system to measure the input and output signal spectrum at the reference plane. The corrected measurement removes the mismatch error created by the DUT and test system.

Modulated source correction

You now have a measurement system that can accurately capture the input and the output signal spectrum at the desired reference plane. This system makes it possible to perform a modulated source correction by stimulating the DUT by the desired modulated signal.

In this process, the VSG stimulates the DUT. There are different options to perform this correction. Select the calibration plane from either the input (DUT IN) or the output (DUT OUT) of the DUT.

1. Calibrate the channel power at the specified reference plane. In this procedure, the RF gain of the VSG adjusts, so the power level at the reference plane is the target level.
2. Calibrate the flatness response of the modulated signal from the specified frequency range and power level.
   a. Measure the spectrum of the reference plane; apply the correction term to the compact test signal waveform. The desired signal spectrum is now available on the reference plane.
3. Calibrate the out-of-band characteristics of the modulated signal given the specified frequency range and power level.
   a. Measure the out-of-band spectrum at the reference plane.
   b. Apply the compensation to the compact test signal suppressing the out-of-band power under the target value. This calibration is useful when the input spectrum has larger ACPR than the DUT performance.

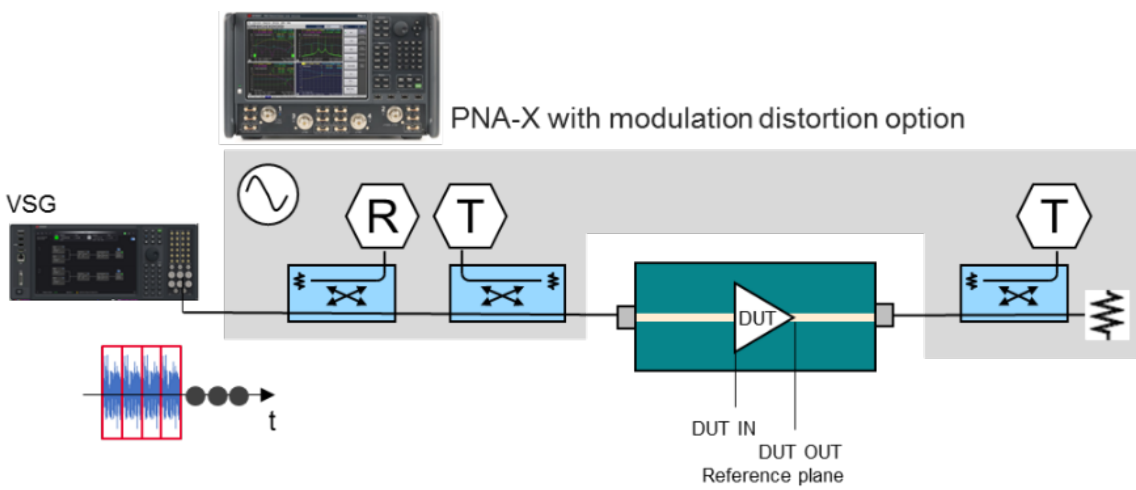


Figure 17: Modulated source correction

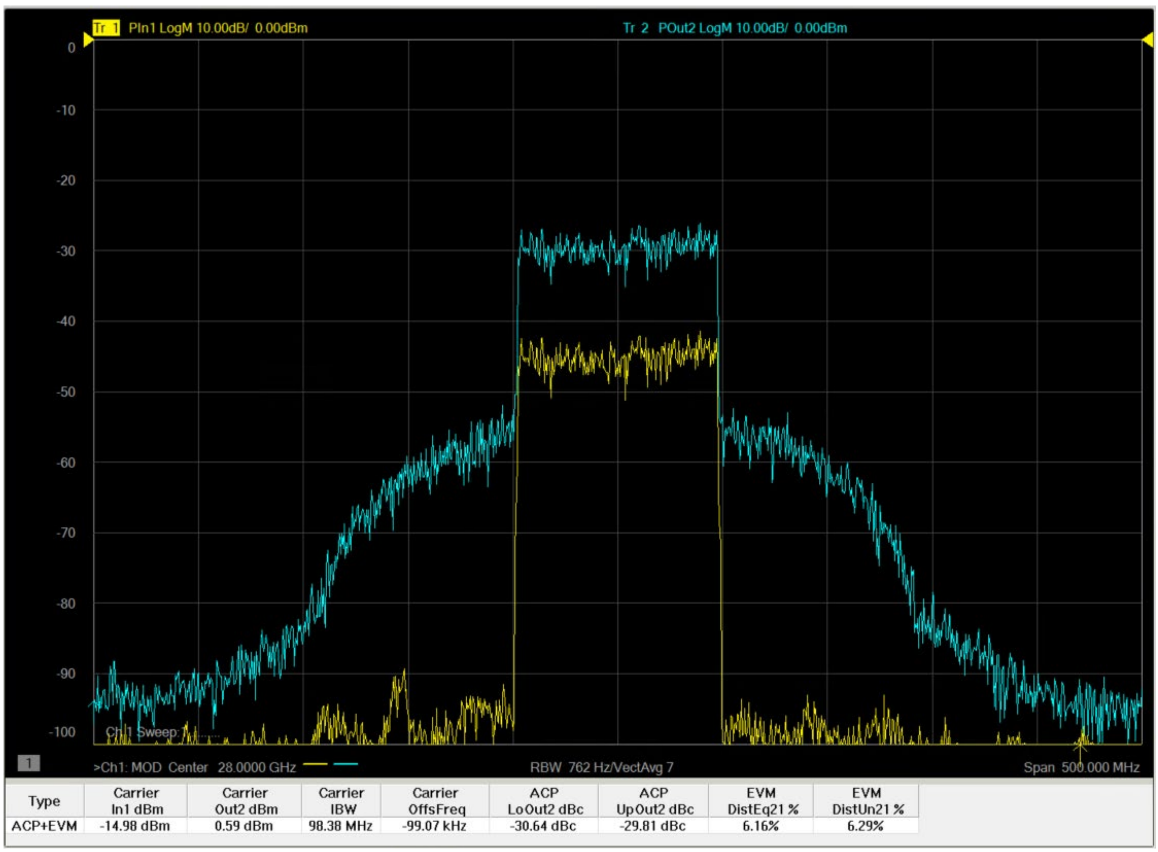
Performing Modulation Distortion Measurement

Distortion measurement

The modulation distortion measures the nonlinear response of the DUT using the compact test signal. Figure 18 displays the input signal spectrum (yellow trace) and the output signal spectrum (blue trace). Spectrum regrowth is in the output signal spectrum.

In the modulation distortion application, the firmware makes spectral correlation and processes signal decomposition automatically in the background. This measurement occurs when you select EVM as the measurement type.

In this example, the compact test signal is 5G New Radio 100 MHz bandwidth signal at 28 GHz carrier frequency. Measured gain is approximately 16 dB, with EVM of 6.16 % at 0.59 dBm output power.



Type	Carrier In1 dBm	Carrier Out2 dBm	Carrier IBW	Carrier OffsFreq	ACP LoOut2 dBc	ACP UpOut2 dBc	EVM DistEq21 %	EVM DistUn21 %
ACP+EVM	-14.98 dBm	0.59 dBm	98.38 MHz	-99.07 kHz	-30.64 dBc	-29.81 dBc	6.16%	6.29%

Figure 18: Modulation distortion measurement result

Making power sweep measurements

In the typical power amplifier evaluation under a modulated signal, measurements occur at multiple power levels. The results are available in a plot format. In the modulation distortion application, data is readily available by automating the measurement.

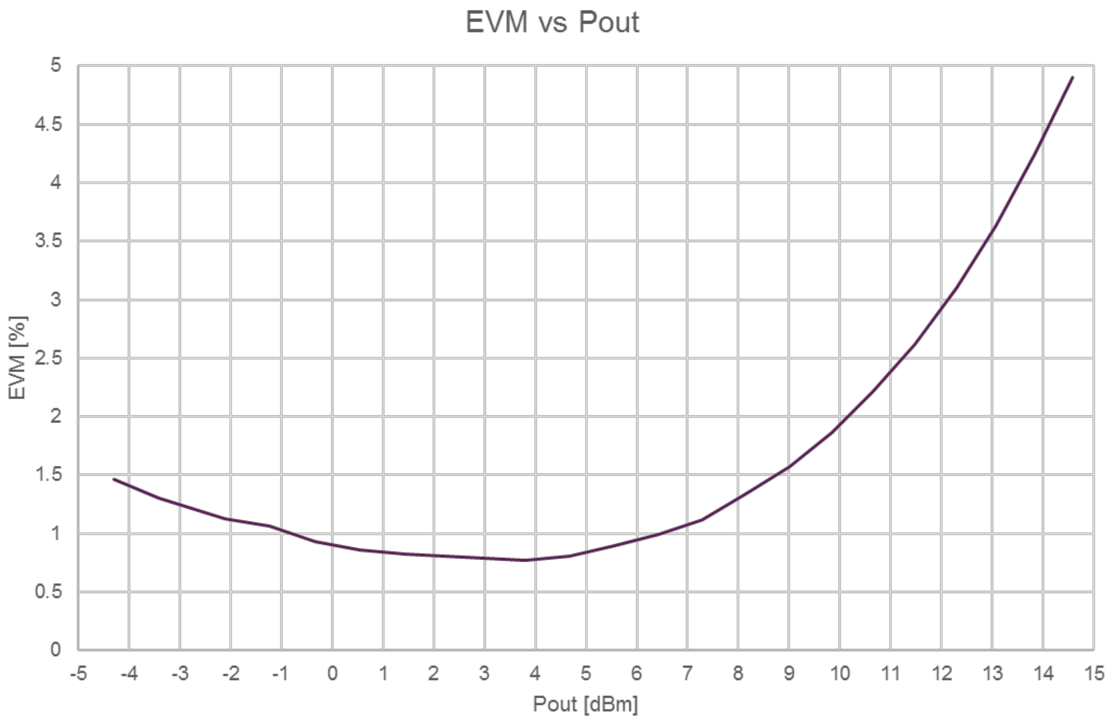


Figure 19: Power sweep measurement result

When the power amplifier is in the non-linear operating mode (right side of the plot), distortion of the power amplifier typically dominates its EVM performance. In this region, the EVM increases as the power level increases.

When the power amplifier is in linear operating condition (left side of the plot), the key contributor of EVM is now SNR. EVM increases as the power level decreases as the SNR of the measurement degrades. Narrowing noise bandwidth of the test improves the reported EVM. This outcome is a result of the improved SNR of the test system.

The measured noise is a combination of noise from the measurement system and noise from the DUT. It is not possible to separate the noise from the system or noise from the DUT. The modulation distortion application has a feature to compute the EVM from the noise figure of the DUT. This feature accurately estimates the DUT's contribution to the EVM at the linear operating condition. You can enter the noise figure of the DUT in the measurement setup wizard.

Optimizing Modulation Distortion Measurement

It is critical to optimize the setup to make an accurate measurement. In this section, you will learn about the optimization of the modulation distortion measurement.

Signal-to-noise ratio of the spectrum measurement

Poor EVM occurs when the random noise is the dominant factor of the EVM, where it likely happens at the left side of the bathtub curve. Improving the SNR of the measurement can improve the accuracy of the measurement.

Noise bandwidth

The resolution bandwidth and the number of coherent averaging of the measurement determine the noise bandwidth. Default value of the noise bandwidth is 1 kHz. Noise bandwidth determines the signal-to-noise ratio (SNR) of the measurement system and measurement time.

As noise bandwidth decreases, modulation distortion increases the underlying coherent average. The result is a wider signal noise ratio and longer measurement time. The resolution bandwidth is set automatically with firmware from the compact test signal waveform length; it is a discrete number. It is the closest value to the one you entered.

Signal noise ratio of the vector signal generator

The SNR of the VSG differs depending on multiple factors. A key factor is the number of tones of the compact test signal. As you increase the number of tones, the SNR of the VSG degrades. For example, let us compare the compact test signal with 1,000 tones and the compact test signal with 10,000 tones given the same channel power: -10dBm.

The tone power level of the compact test signal with 1,000 tones is -40 dBm, while the tone power of the compact test signal with 10,000 tones is -50 dBm. If the measurement has the same noise floor for each compact test signal, the compact test signal with 1,000 tones is 10 dB better than the compact test signal with 10,000 tones.

Nonlinearity of the test receiver

If there is a nonlinear response in the test receiver, it is unable to distinguish nonlinearity that comes either from DUT or receiver of the test system. The PNA-X test receiver needs to be in linear when measuring the signal. When it measures the subtle nonlinearity of DUT, such as the EVM level of 1%, the recommendation is to keep the power level to be less than -5 dBm at the test port of the PNA-X. Use the receiver attenuator to adjust the power level if the test port power is higher than -5 dBm.

Nonideal compact test signal

The linear error due to the test system can be corrected to have the desired compact test signal at the reference plane. You can do this by adjusting the channel power and linear flatness response using the modulated correction feature. Also, out-of-band spectral regrowth is suppressible by adjusting the ACPR.

Compact test signal statistical characteristics

It is critical to understand that nonlinear characteristics of the DUT under modulated signal condition is highly dependent on the stimulus signal. It is also important to create the compact test signal that can stimulate the DUT with the most representative statistical characteristics to the practical usage of the DUT.

It is best practice to align the complementary cumulative distribution function (CCDF) of the compact test signal with the parent signal. However, the CCDF is not the same since the compact test signal is a slice of the parent waveform. The recommendation is to match the CCDF until it is 0.1% of probability. By choosing more than 3,000 tones gives you a good match of the CCDF — up to 0.1%.

Measurement throughput

Faster measurement time gives faster throughput to complete the evaluation. You can determine measurement time using these parameters:

- signal analyzer span
- noise bandwidth
- compact test signal number of tones

Measurement time and measurement accuracy is generally a trade-off. It is essential to have the right balance of speed and accuracy to modify the parameter depending on the target measurement value.

Summary

The PNA-X network analyzer uses the modulation distortion method to characterize EVM of power amplifier in frequency domain. The modulation distortion feature on PNA-X enables you to access additional measurements; beyond the typical PNA-X measurements such as S-parameters, gain compression, intermodulation distortion, and noise figure.

We have discussed modulation distortion’s innovative approach to overcome measurement challenges associated with the wide-band modulated signal at mmW frequency. The modulation distortion provides accurate EVM measurement with vector correction, which is fully integrated in the firmware. Also, we discussed optimization of the measurement to achieve accurate measurement result within the shortest measurement time.

Using the modulation distortion method, you can characterize nonlinear behavior of the power amplifier in the most accurate way.

Appendix A: Measurement Techniques Comparison

Measuring the EVM of components has historically used the same method as measuring the EVM at the system level and characterizing the performance of a transmitter. For example, the output of a transmitter is measured using a signal analyzer with the Keysight 89600 vector signal analyzer (VSA) software. The output of the transmitter is measurable in the time domain. The captured waveform demodulates using the known parameters of the input signal modulation format. Then, compare the results to a calculated ideal reference waveform. The EVM is the delta between the reference and demodulated waveform at the decision point or ideal constellation.

For system level and transmitter testing, EVM measurements are an important FOM since the aggregate EVM is from many contributors. For example, the EVM contributors in a transmitter are due to non-linear distortion, added noise, phase noise of the LO, and carrier with potential assimilation onto subcarriers. For IQ based systems, the IQ imbalances such as quadrature, gain differences, and DC offsets contribute to the EVM. These errors all add to the delta between the measured signal of the transmitter and the calculated reference.

Now consider the EVM contribution of a component, such as a power amplifier, used in a system or transmitter. Contributions from distortion or noise dominate the EVM of a component from the amplifiers operating point. The IQ balance errors do not originate in the amplifier. Another system error is phase noise with the main contribution from the system oscillators and not the amplifier. The amplifier generates residual phase noise — you would disregard the contribution from residual phase noise.

The error contribution of the EVM for a component uses the typical bathtub curve; see Figure 19. The bathtub curve represents the measured EVM versus power with the error contributor dependent on the power range. For low power levels, the SNR or noise figure contributes to the EVM error. At high power, non-linear distortion dominates the EVM. Most system designs will operate somewhere on the distortion side to optimize power added efficiency (PAE) while maintaining overall system-level performance targets. When measuring components using the traditional VSA method, there is an assumption that the input signal is perfect. This error will set the minimum EVM measurable by the receiver.

For modulation distortion on the PNA-X, the measurement focuses on the key contributions of the device. The measured output signal separates into a linear portion and the non-linear distortion contribution of the EVM. The residual EVM noise floor shows improvement versus the traditional VSA approach. This improvement is due to eliminating the contribution of the input signal and the sensitivity of the PNA-X receiver.

	Keysight 89600 VSA and X-Apps	**Keysight S93070xB Modulation Distortion**
Supported instruments	Keysight signal analyzers, oscilloscopes, PXI VSAs	Keysight PNA-X
Benefits	• standard-compliant algorithms • flexible views of EVM (time, frequency, subcarrier) • constellations diagrams • measures all system and transmitter EVM contributors	• wide measurements to align with the signal generator bandwidth • lower residual EVM enabled by accurate sensitivity • eliminates contributions of the input signal • measures contribution of the device only

Appendix B: Spectral Correlation Theory

The modulation distortion is a frequency domain analysis method. The real and imaginary parts of the spectrum $M(f)$ corresponds to a theoretical, infinitely long modulated input waveform. If the modulation corresponds to a stationary stochastic process, the real and imaginary parts of $M(f)$ are uncorrelated. Distributed stochastic variables are with zero mean. The variance of the real and imaginary parts are a function of the frequency and is known as the "power spectral density" (PSD). The modulation distortion method is from the statistical correlations of such stochastic spectra. The spectral correlation of a signal $U(f)$ and a signal $V(f)$ is denoted by $S_{UV}(f)$ and is defined as

(1) $$S_{UV}(f) = E[U^*(f)V(f)],$$

whereby $E[.]$ represents the statistical "expectation" or "mean" operator, and the superscript "*" denotes the complex conjugate operator. $S_{UV}(f)$is the cross-spectral density of $U(f)$ and $V(f)$. The PSD of any signal $M(f)$ is equal to $S_{MM}(f)$, the cross-correlation of the stochastic spectrum with itself (auto-correlation). Under linear small signal operating conditions, the relationship between the spectrum of the input signal $X(f)$ and the spectrum of the output signal $Y(f)$ is

(2) $$Y(f) = g_{SM}(f)X(f),$$

whereby $g_{SM}(f)$ represents the complex transfer function corresponding to the small signal gain of the amplifier. When the input power increases, the amplifier will start to behave in a nonlinear way. This nonlinear behavior manifests itself in two ways:

1. The ratio between the input spectrum and output spectrum changes (gain compression).
2. Noise distortion signals occur both in-band (EVM) and out-of-band (ACPR).

The mathematical expression for this process is:

(3) $$Y(f) = c_G(f)g_{SM}(f)X(f) + D(f),$$

with $c_G(f)$ representing the gain compression function and with $D(f)$ representing the nonlinear distortion that does not linearly correlate with $X(f)$.

The linear uncorrelatedness mathematical expression is

(4) $$S_{XD}(f) = 0.$$

Note that $c_G(f)$ is a complex-valued continuous frequency response function. It is equal to one under small signal linear operating conditions. The stochastic variable is $D(f)$ similar to $X(f)$ and $Y(f)$. $D(f)$ interpretation is the superposition of all cross-frequency intermodulation products that end near the carrier frequency.

Equations (3) and (4) are the constitutive set of equations defining the quantities $c_G(f)$ and $D(f)$. The assumption is for a given amplifier, $c_G(f)$ and $S_{DD}(f)$ are determined by the:

- power spectral density of the input signal $S_{XX}(f)$
- statistical distribution of the amplitude of the corresponding time domain complex envelope $x(t)$

This statistical amplitude distribution is the complementary cumulative distribution function (CCDF) of the instantaneous power levels. The CCDF is a function of power and expresses the percentage of time the instantaneous output power is higher than any given power level.

The modulation distortion measurement problem is:

Given $X(f)$ corresponding to a given CCDF and PSD, decompose $Y(f)$ into the component $c_G(f)g_{SM}(f)X(f)$, which linearly correlates with $X(f)$. The remaining part of $D(f)$ contains the nonlinear distortion.

Begin by measuring $g_{SM}(f)$ using a VNA. Next trigger the DUT with a signal $X(f)$ that has a CCDF and PSD corresponding to the modulation format and power level for which you wish to know $c_G(f)$ and $D(f)$. Use the VNA to measure the complex vector ratio $Y(f)/X(f)$, denoted by $R(f)$, as well as $|X(f)|$ and $|Y(f)|$. Note that these measurements require both a power calibration and a vector calibration. The spectral correlation quantities $S_{XY}(f)$, $S_{XX}(f)$ and $S_{YY}(f)$ are the intermediate variables.

The calculation is:

(5) $S_{XY}(f) = E\left[|X(f)||Y(f)|e^{j\varphi(R(f))}\right] = E[X^*(f)Y(f)]$,

(6) $S_{XX}(f) = E[|X(f)|^2] = E[X^*(f)X(f)]$, and

(7) $S_{YY}(f) = E[|Y(f)|^2] = E[Y^*(f)Y(f)]$.

With a dense enough tone spacing, the expectation operator $E[.]$ is practically performed by calculating the mean for a significant number, for example, 100, of the adjacent tones. Perform the calculation $c_G(f)$ using

(8) $c_G(f) = \frac{S_{XY}(f)}{g_{SM}(f)S_{XX}(f)}$,

and substitution of (8) in to (3) and solving for the nonlinear distortion component $D(f)$ results in

(9) $D(f) = Y(f) - \frac{S_{XY}(f)}{S_{XX}(f)}X(f)$.

The PSD of the nonlinear distortion, $S_{DD}(f)$, is

(10) $S_{DD}(f) = \left(1 - \gamma_{XY}^2(f)\right)S_{YY}(f)$, with

(11) $\gamma_{XY}^2(f) = \frac{|S_{XY}(f)|^2}{S_{XX}(f)S_{YY}(f)}$.t

For conciseness, the frequency dependency is not in the following equations.

The quantity $\gamma_{XY}^2(f)$ is the linear coherence function. Equations (8), (10), and (11) calculations are from multiplying both sides of (3) by X^* and calculating the expectation results in

(12) $E[X^*Y] = E[X^*(c_G g_{SM}X + D)]$, is

(13) $S_{XY} = c_G g_{SM} S_{XX} + S_{XD}$.

Substitution of (4) into (13) and solving for c_G results in (8).

Multiplying both sides of (3) by Y^* and calculating the expectation results in

(14) $E[Y^*Y] = E[(c_G g_{SM} X + D)^* (c_G g_{SM} X + D)]$,

which, after substitution of (4), is

(15) $S_{YY} = |c_G|^2 |g_{SM}|^2 S_{XX} + S_{DD}$.

Substitution of (8) into (15) results in

(16) $S_{YY} = \frac{|S_{XY}|^2 |g_{SM}|^2 S_{XX}}{|g_{SM}|^2 |S_{XX}|^2} + S_{DD}$,

which when solved for S_{DD} results in

(17) $S_{DD} = \left(1 - \frac{|S_{XY}|^2}{S_{XX} S_{YY}}\right) S_{YY}$, thereby proving (10) and (11)

Appendix C: Relationship to EVM Measured by Demodulation

With EVM, you can measure the output signal $y(t)$ using a VSA. Modulation formats based on orthogonal frequency domain multiplexing (OFDM) are common for 4G, 5G, and Wi-Fi. EVM is the normalized-root-mean-square-error (NMSE) between the bandpass filtered $y(t)$, compensated for complex gain, group delay and frequency dispersion, and the ideal input signal $x(t)$, whereby $x(t)$ is from the through demodulation of $y(t)$. EVM is expressed in a percentage or dB. EVM is:

(18) $EVM = \sqrt{\frac{\sum_{i=1}^{N} |x(t_i) - (y * e)(t_i)|^2}{\sum_{i=1}^{N} |x(t_i)|^2}}$,

whereby N represents the total number of time samples acquired by the VSA, "*" represents convolution and $e(t)$ represents the equalization filter. The equation typically includes compensation for group delay, phase rotation, and frequency dispersion. The time instances t_i are determined by the demodulation process. Both the numerator and denominator present in (18) are sums of amplitudes squared. They are equal to their frequency domain equivalents following Parseval`s theorem.

(19) $EVM = \sqrt{\frac{\sum_{i=1}^{N} |X(f_i) - E(f_i) Y(f_i)|^2}{\sum_{i=1}^{N} |X(f_i)|^2}}$,

whereby $X(f_i)$,$Y(f_i)$ and $E(f_i)$ represent the discrete Fourier transforms of $x(t_i)$,$y(t_i)$ and $e(t_i)$.

The definition of a new quantity called equalized distortion error vector magnitude ($DEVM_e$) from the measurement of $c_G(f)$, $g_{SM}(f)$, $X(f)$ and $Y(f)$:

(20) $DEVM_e = \sqrt{\frac{\sum_{i=1}^{N} \left|X(f_i) - c_G^{-1}(f_i) g_{SM}^{-1}(f_i) Y(f_i)\right|^2}{\sum_{i=1}^{N} |X(f_i)|^2}}$,

whereby the frequencies f_i correspond to the in-band frequencies of the compact test signal. Considering (19) and (20) concludes that the classic measure of EVM is identical to $DEVM_e$ under the condition that the equalization filter that is used for the classic EVM is the inverse of the gain compression times the small signal gain.

The modulation format associated with the EVM may not perform an equalization, in which case $E(f_i)$ represents a group delay τ and a complex gain G. In that case (19) and (20) become

$$(21) \quad EVM = DEVM_u = \sqrt{\frac{\sum_{i=1}^{N}\left|X(f_i) - Ge^{-j2\pi f_i \tau}\, Y(f_i)\right|^2}{\sum_{i=1}^{N}|X(f_i)|^2}},$$

whereby the subscript "u" in $DEVM_u$ represents "unequalized." $DEVM_u$ is always higher than $DEVM_e$ as it contains the linear distortion contributions. These contributions are due to frequency dispersion as well as the nonlinear contributions. The $DEVM_e$ only includes nonlinear contributions.

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Spectrum and Signal Analyzer Measurements and Noise Application – Application Note (link)

Characterizing Digitally Modulated Signals with CCDF Curves – Application Note (link)

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