Breakthroughs in Wideband Millimeter-Wave Power Amplifier Test

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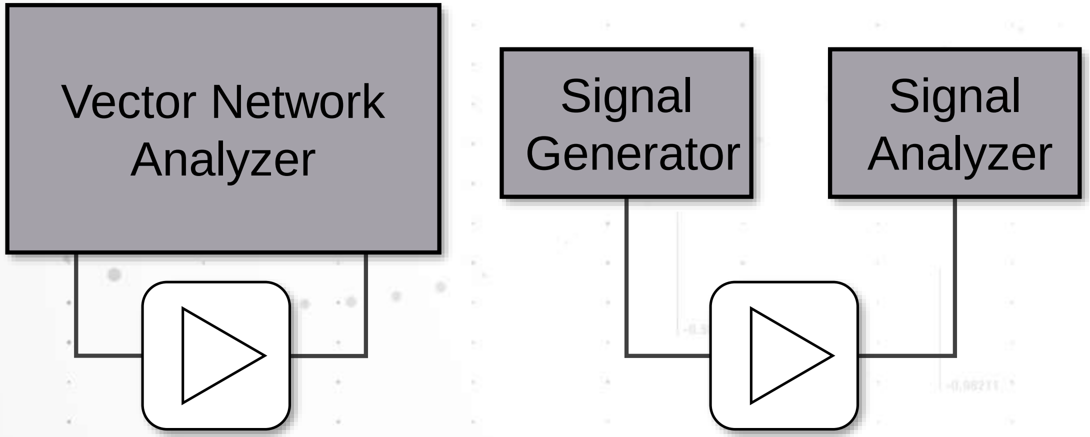
Industry Common Practice

"I need two sets of instrumentation to characterize my power amplifier…"



S-parameter
Gain compression
IP3
Noise Figure

ACPR
NPR
EVM

Overcoming New Challenges

- Challenging EVM Requirements
- mmW Frequency
- Extremely Wide Modulation BW
- New Challenges
- Instrument Cost
- Evolving Standards
- Calibration and Accurate Power

S-parameter
Gain compression
IP3
Noise Figure

ACPR
NPR
EVM

Intro: Target Device / Measurement Challenge

Keysight Solution

Underlying Technology

Measurement Example

Summary

Target Device: PA with a Wideband Signal

Any amplifier which operates under modulated signal conditions is a target device for this solution. Power amplifiers in 5G FR2 front end are a “sweet spot” application.

- **Requirements**
  - Operate at extremely wide bandwidths at mmW frequencies
  - Good power efficiency for higher power density with power/heat management
  - OFDM operation scheme requires linear output signal for better signal quality

- **Key challenges for designers**
  - Linear amplification at high power, with high efficiency in any operating conditions
  - Integration into beamformer component

- **Key measurement for design verification**
  - Linearity evaluation with wide bandwidth at mmW frequencies
  - Figures of merit: EVM, ACPR

Device Example: PA in 5G FR2 System

https://www.qorvo.com/products/p/QPF4001

qorvo

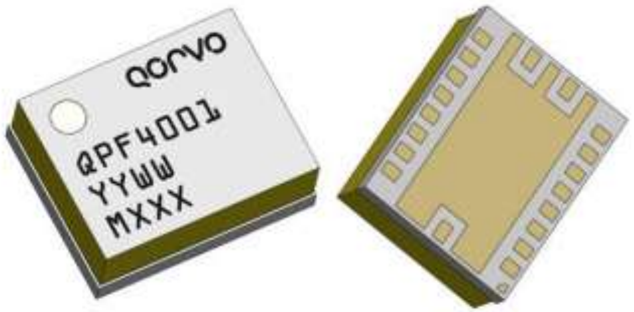
Product Description

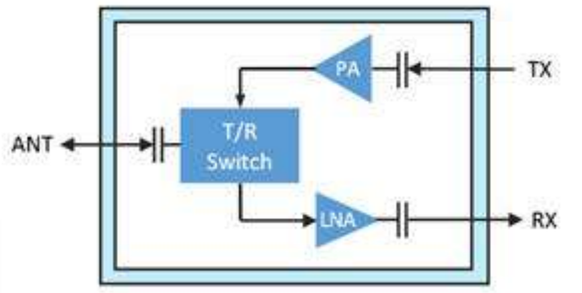
The QPF4001 is a multi-function Gallium Nitride MMIC front - end module targeted for 28 GHz phased array 5G base stations and terminals. Fabricated on Qorvo's 0.15um GaN on SiC process, the device combines a low noise high linearity LNA, a low insertion-loss high - isolation TR switch, and a high - gain high - efficiency multi-stage PA.

The QPF4001 operates from 26 GHz to 30 GHz. The receive path (LNA + TR SW) is designed to provide 17 dB of gain and a typical noise figure of 3.5dB. The transmit path (PA + SW) provides 27 dB of small signal gain with high linearity of 35 dBc ACPR and low EVM of 3% at 23 dBm average output power, while supporting peak power of 1 - Watt.

QPF4001

26 – 30 GHz 1W GaN Front End Module





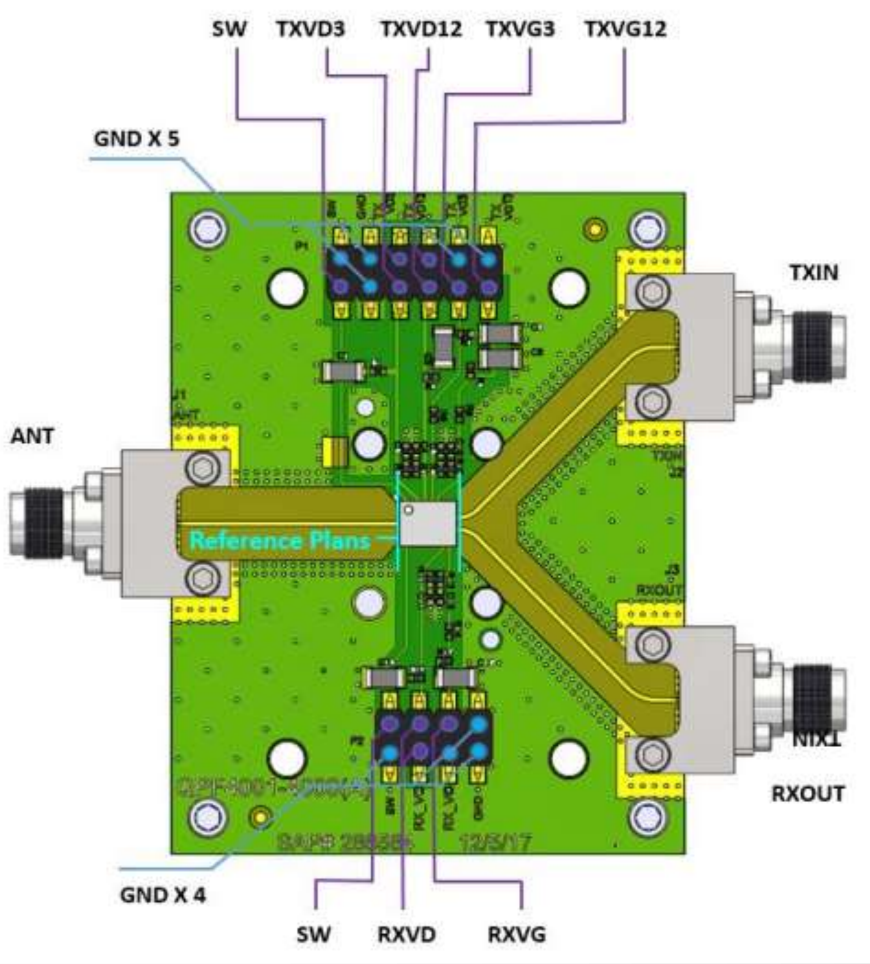
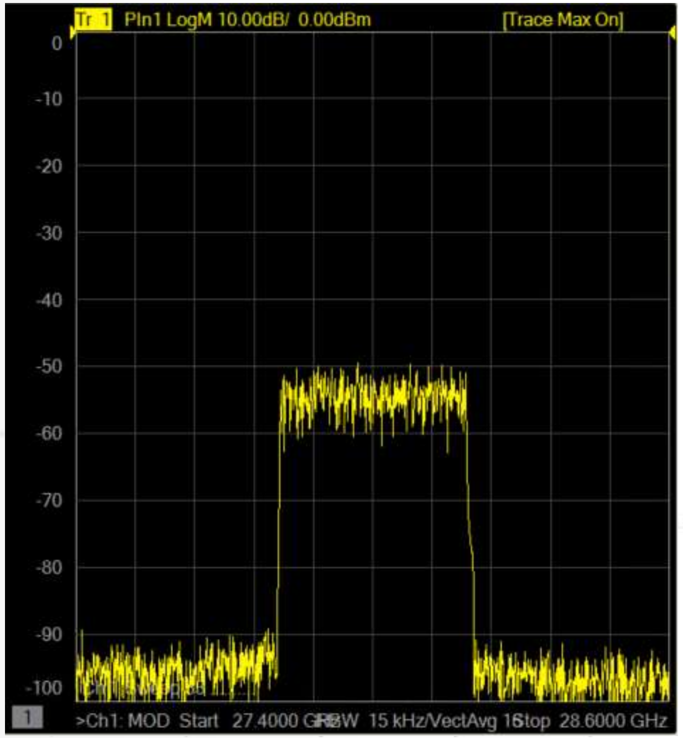


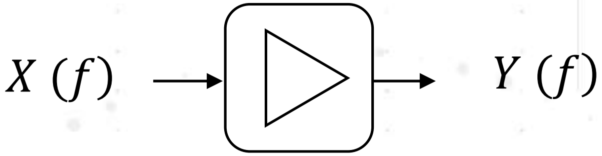
Image courtesy of Qorvo

Linearity Evaluation Under Modulated Conditions

Nonlinear Distortion Model

Input Signal Spectrum

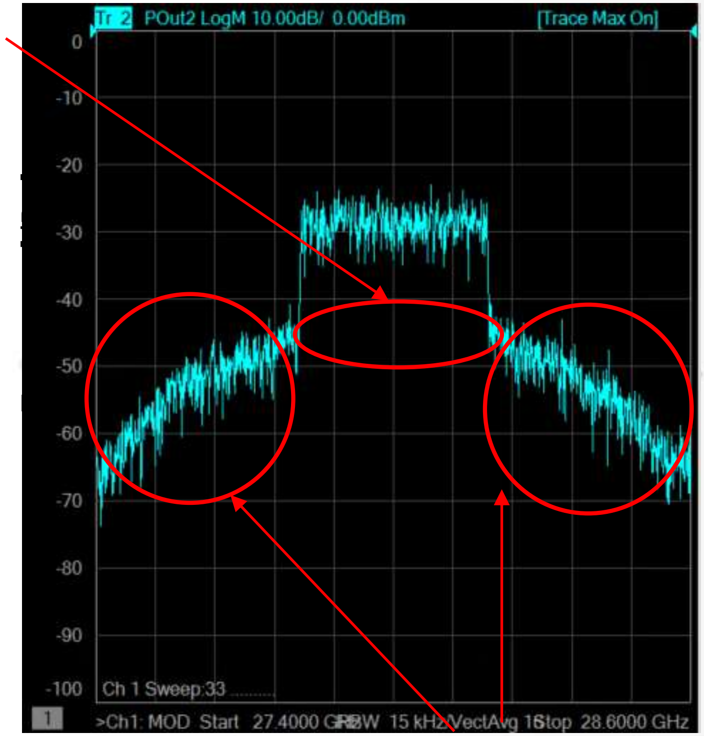




Output Signal Spectrum

In-band distortion

Typically represented as NPR or EVM



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

$$= c_G(f)\ g_{SM}(f)X(f) + D(f)$$

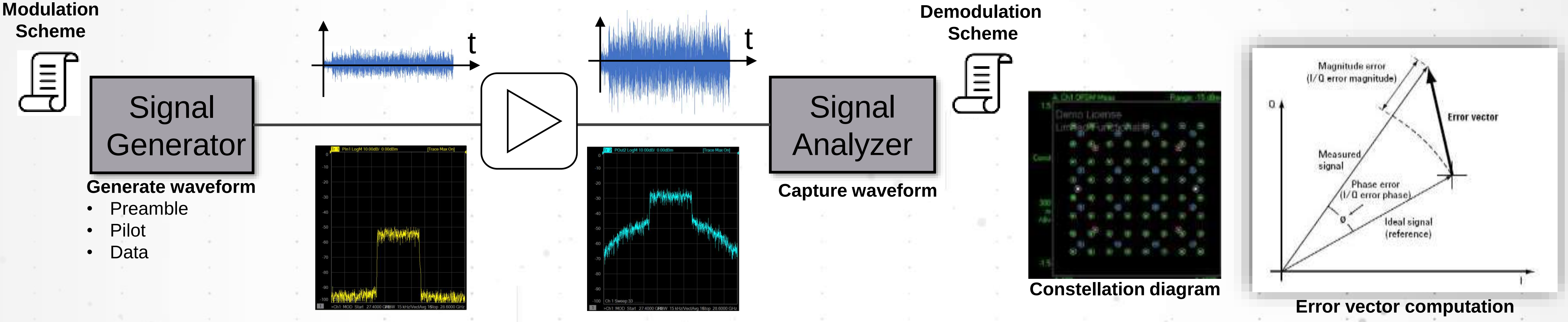
Out-band distortion

Typically represented as ACPR

- Nonlinear distortion performance is traditionally measured with signal generator and signal analyzer
- EVM is commonly used as the figure of merit to show performance of in-band distortion

Traditional EVM Measurements

Challenges of component testing with wideband modulated signals



$$\text{RMS EVM [\%]} = \sqrt{\frac{\frac{1}{N}\sum_{t=1}^{N} e[t]\cdot e^{*}[t]}{\frac{1}{N}\sum_{t=1}^{N} r[t]\cdot r^{*}[t]}} \times 100\ [\%]$$

- **Residual EVM (EVM of test system) is close to EVM of DUT**
  - Source: Imperfections in generated signal directly affect measured EVM
  - Receiver: Capturing wideband signal also captures wideband noise. S/N ratio degrades as bandwidth increases.
- **Signal fidelity**
  - Lossy cable and mismatch in high frequency. Actual signal applied to DUT is different from ideal.
- **Test system optimization** for specific power level to minimize nonlinearity of receiver while optimizing S/N ratio

KEYSIGHT TECHNOLOGIES

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Keysight Solution

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Measurement Example

Summary

Modulation Distortion App on PNA-X with SG

Modulated source such as:

VXG

Or…

M9383A/B

Or…

PSG + M819X AWG

Or…

MXG

Modulation Distortion app on PNA-X

- Software option of PNA-X that characterizes distortion of the device under modulated stimulus conditions
- **Simple & easy setup**. Measurement setup fully integrated in PNA-X
- Leverages state of the art calibration for **the best accuracy**
- **Single connection** for existing VNA measurements and new feature which delivers ACPR, EVM and NPR.
- **Lowest residual EVM system in the market**

Key Contributions to PA Industry

- Overcome wideband measurement challenges
  - Low residual EVM due to wider system dynamic range (lower noise floor)
  - Signal fidelity at the DUT input easily achieved by PNA calibration techniques
  - Easy calibration for “vector corrected” EVM measurements
- Measurement reproducibility
  - Obtain consistent measurement results, supported by PNA calibration techniques
- Faster measurement speed
  - *“Test time is reduced by a factor of 10 in my DVT test scenario”*
- Design flow improvement with simulation
  - Same computation engine as PNA-X to simulate nonlinear behavior in ADS will be available
- Leverages PNA-X hardware to make analysis under modulated conditions
  - PNA-X: De facto standard
  - Single connection, multiple measurement

Underlying Technology

Compact Test Signal

Modulation Distortion “compacts” the stimulus waveform to make measurements faster.

“Parent waveform”
e.g. 5G NR 100MHz BW signal

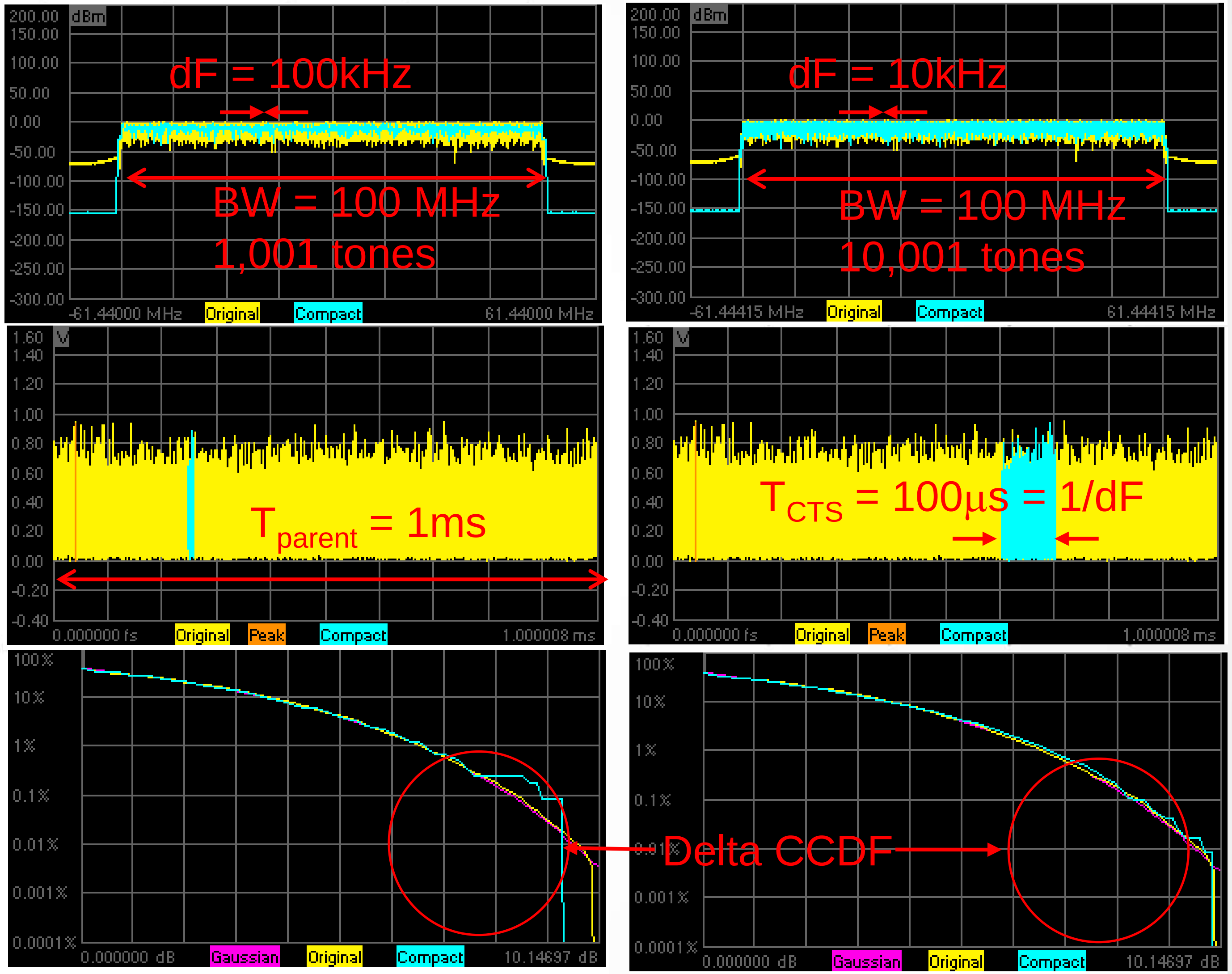
“Compact Test Signal”
Slice of waveform that represents same

- Frequency signature
- Statistical distribution (CCDF)

BW: parent signal bandwidth
dF: tone spacing
N: number of tones
T_{CTS}: Compact test signal period
BW: N x dF
T_{CTS}: 1/dF = N/BW

Tone spacing: 100 kHz
Number of tones: 1001

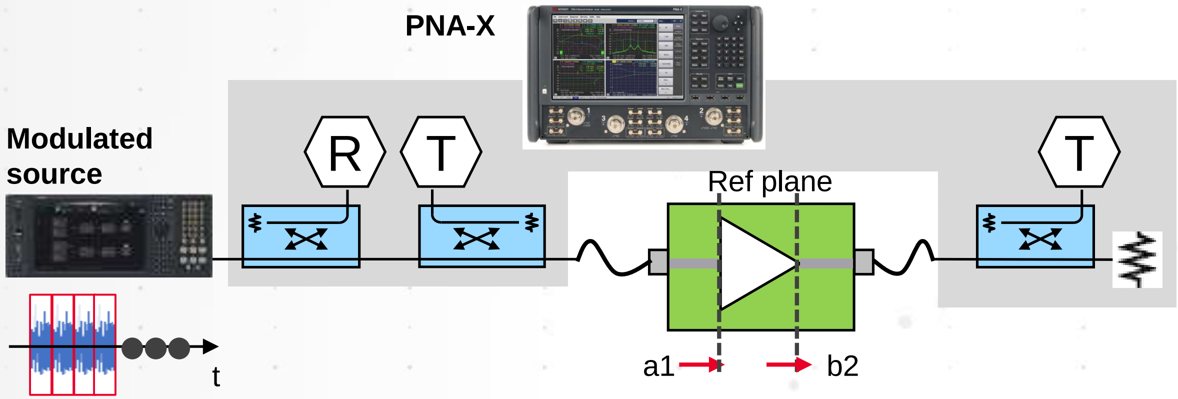
Tone spacing: 10 kHz
Number of tones: 10,001



- A finer tone spacing results in a longer period for the compact test signal
- A longer period results in more accurate CCDF

Underlying Technology

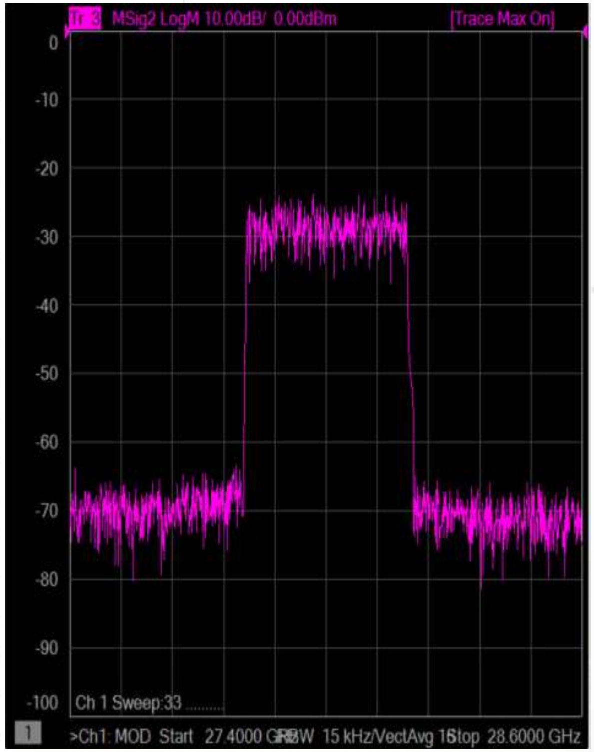
Multitone measurement and signal decomposition



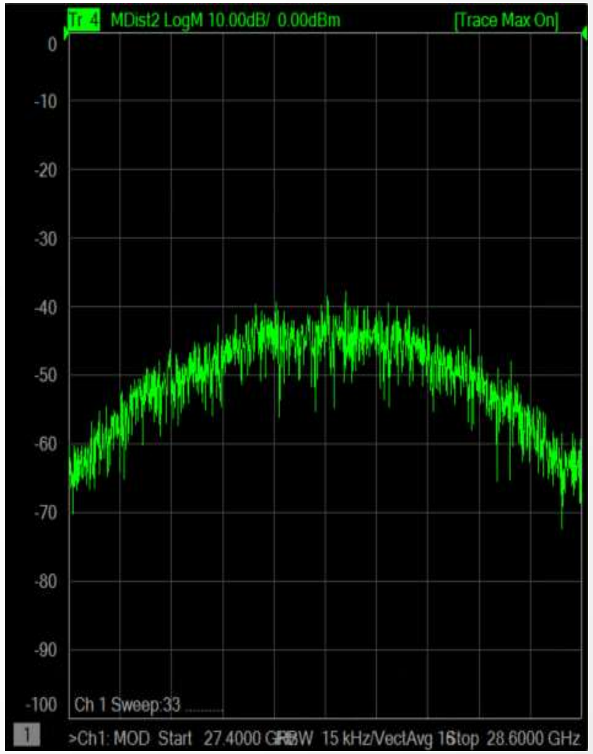
$$Y(f) = H(f)X(f) + D(f)$$

- Decompose output spectrum into linear and distortion part
- Use "spectral correlation" technique. Statistical approach.

$H(f)X(f)$:Linear part

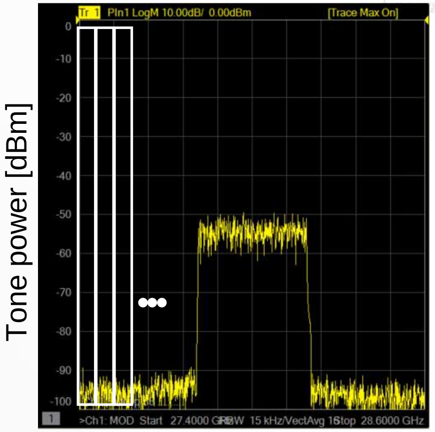


$D(f)$:Distortion part

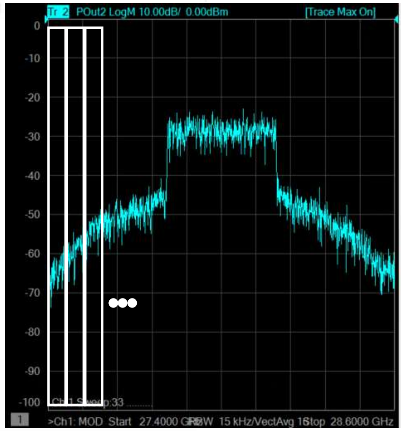


- Stimulate DUT by repeating CTS
- Measure input and output signals tone-by-tone **in frequency domain**
- Coherent measurement at input and output
- Vector corrected measurement using VNA calibration
- Wideband measurement by stitching frequency

$X(f)$ Input Signal Spectrum



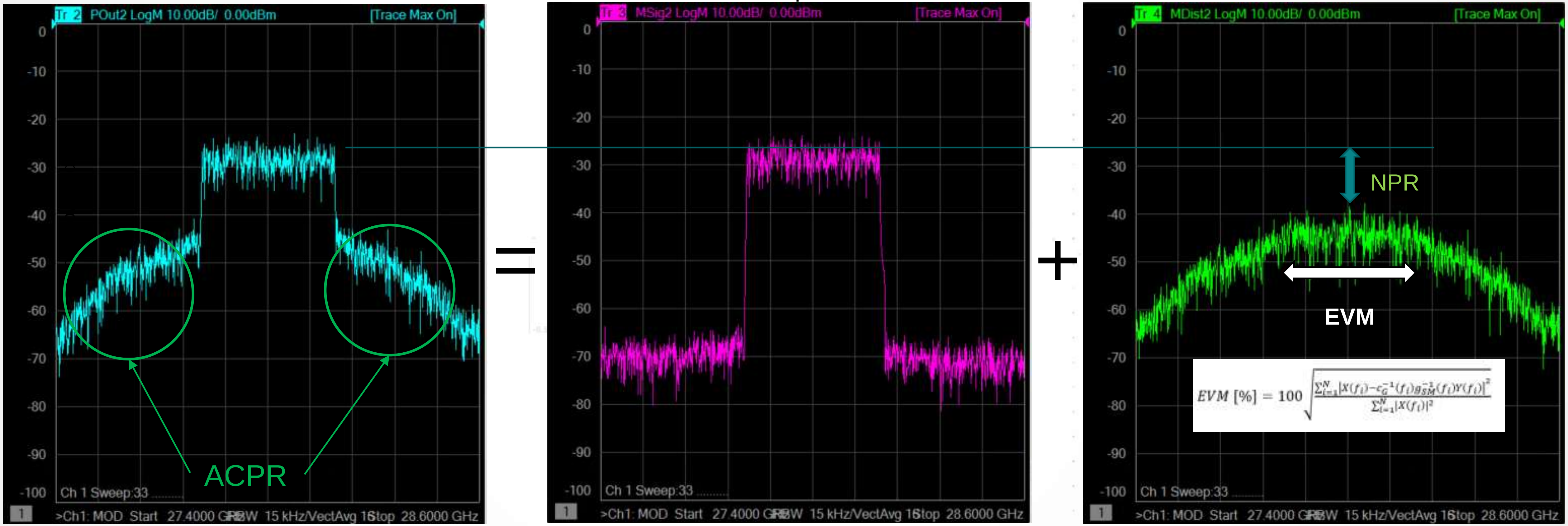
$Y(f)$ Output Signal Spectrum



Underlying Technology

Computing figures of merit

$Y(f)$:Output signal $\quad H(f)X(f)$:Linear part $\quad D(f)$:Distortion part

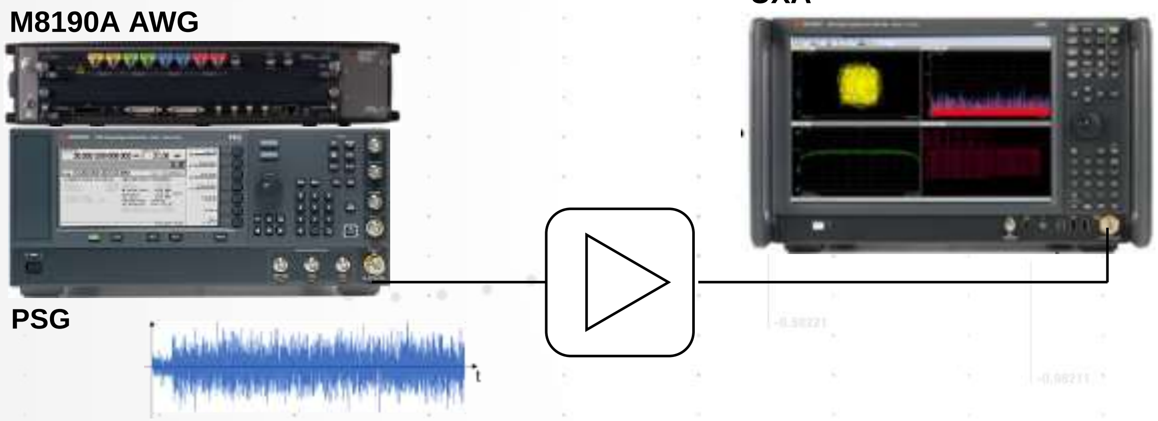


- EVM computed in time domain or frequency domain are mathematically equivalent (Parseval's theorem)

Correlation Study - Setup

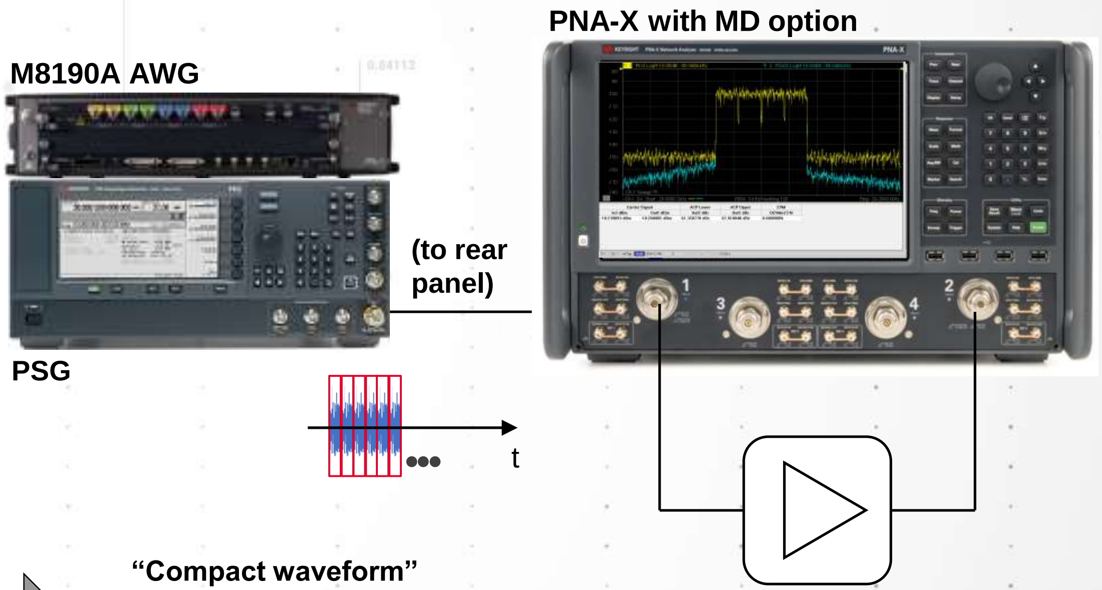
Traditional SA/SG setup

Signal Generation | **Signal Analysis**



Modulation Distortion setup

Signal Generation | **Stimulus response analysis**



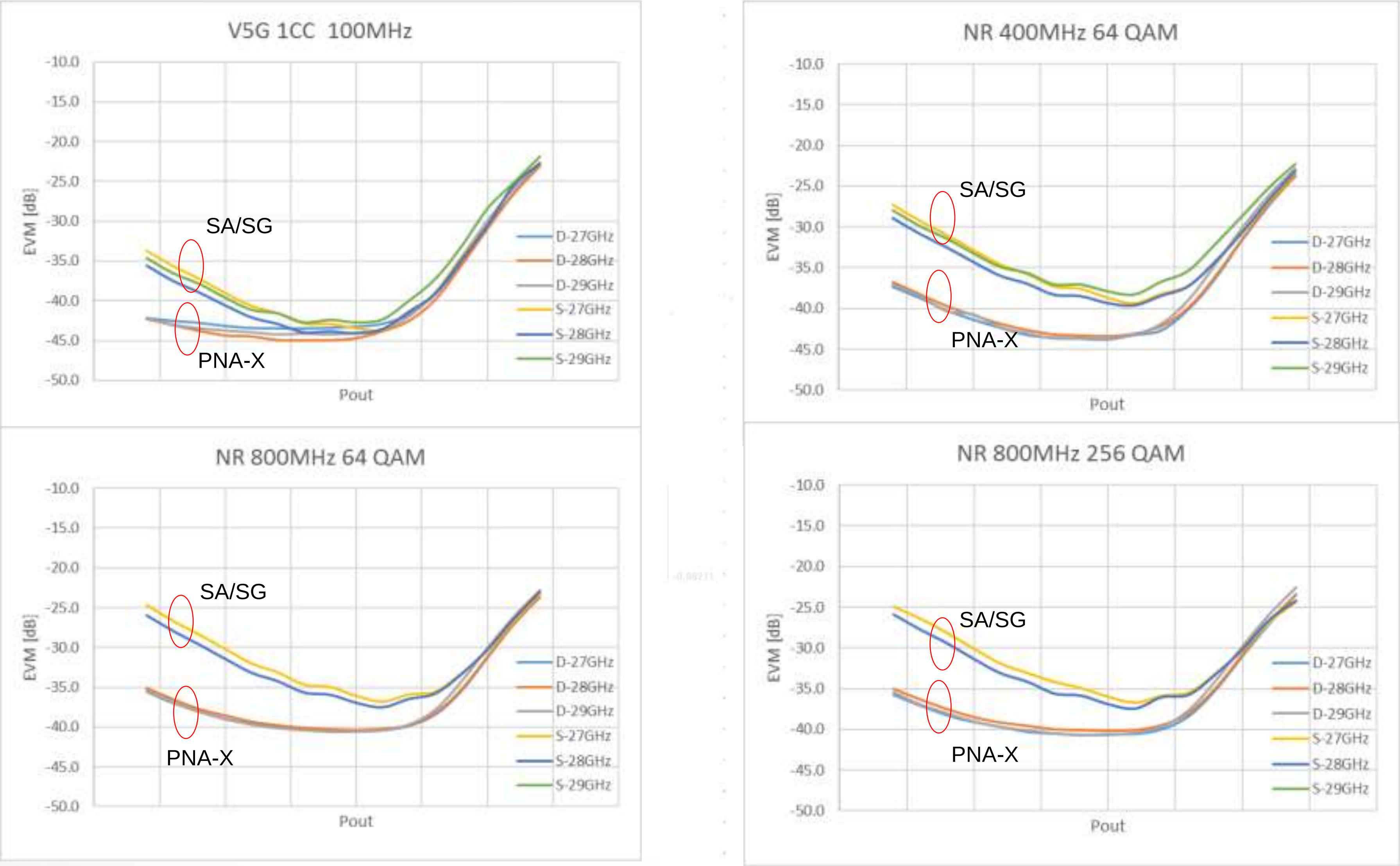
Waveform for traditional EVM
- Preamble
- Pilot
- Data

“Compact” the waveform

“Compact waveform”
Represents the same characteristics as original waveform
- Frequency signature
- Statistical distribution

Correlation Study - Results

DUT: Keysight 50GHz amplifier, 12 dB Gain



- SA/SG and PNA-X results correlate when the device is operating under nonlinear conditions
- PNA-X shows lower residual EVM which shows the Pout where the DUT starts nonlinear behavior

KEYSIGHT TECHNOLOGIES

Technique Comparison for Measuring EVM for Amplifiers

89600 VSA and X-Apps

Measures all contributors to EVM

Keysight signal analyzers, oscilloscopes, PXI VSAs

Benefits

- Standards compliant algorithms (ex: 3GPP, IEEE, etc.)
- Flexible views to view EVM vs. time, frequency, subcarrier, power…and many more
- Constellation diagram view

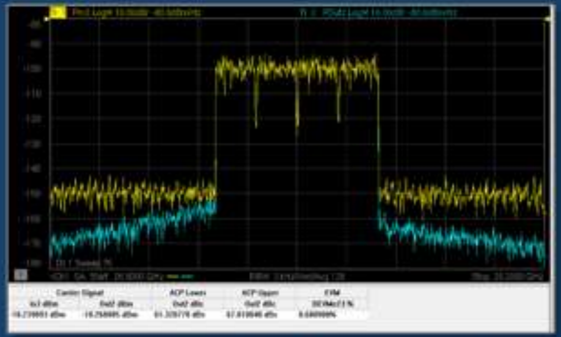
Considerations

- Includes contribution of DUT and input signal
- Limited by the intrinsic BW of the analyzer

Modulation Distortion App

Isolates the distortion and additive noise contributions

PNA-X



Benefits

- Removes contribution of phase noise, imbalance and signal inputs
- Very wide measurements bandwidth limited only by the signal generator
  - High dynamic range and low EVM noise floor

Considerations

- Requires repetitive waveform
- No constellation diagram

EVM
= distortion +
noise +
phase noise +
IQ imbalance +
input signal

Intro: Target Device / Measurement Challenge

Keysight Solution

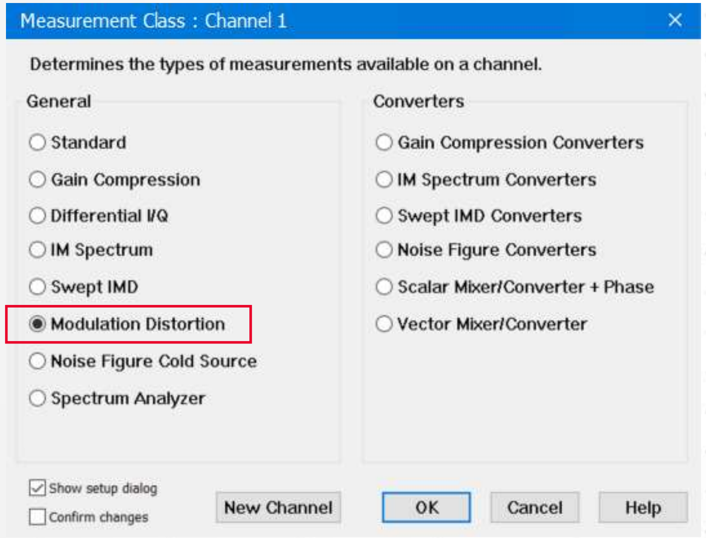
Underlying Technology

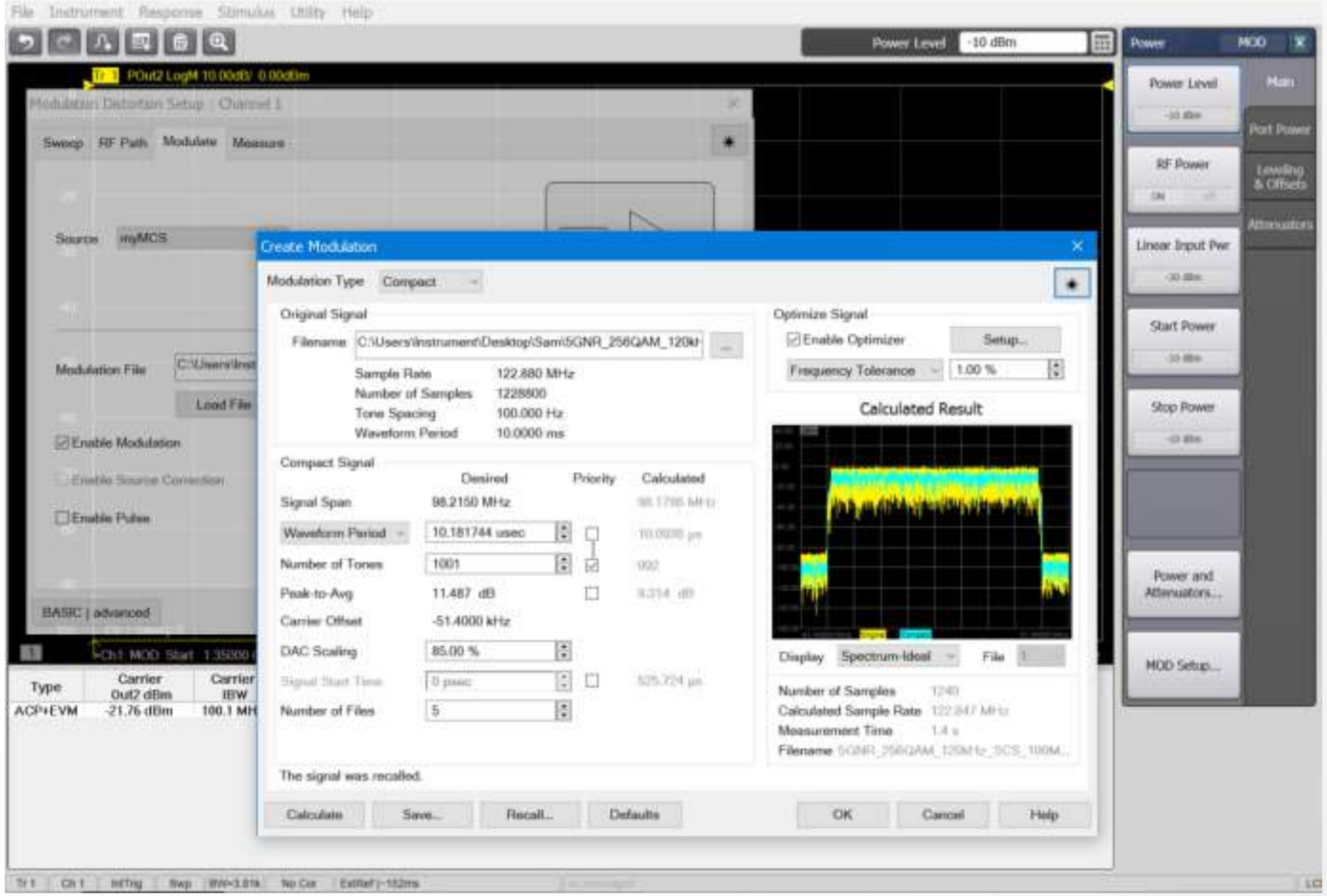
Measurement Example

Summary

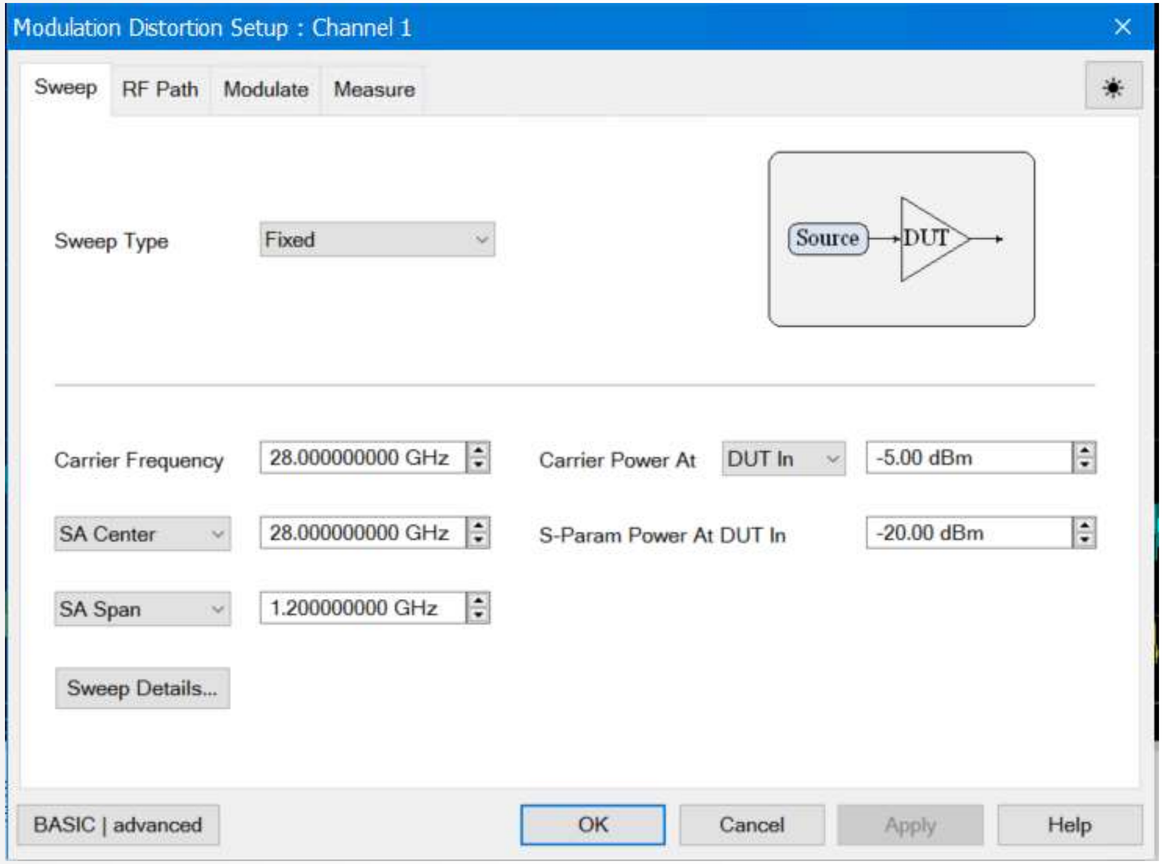
PNA-X Measurement Class “Modulation Distortion”

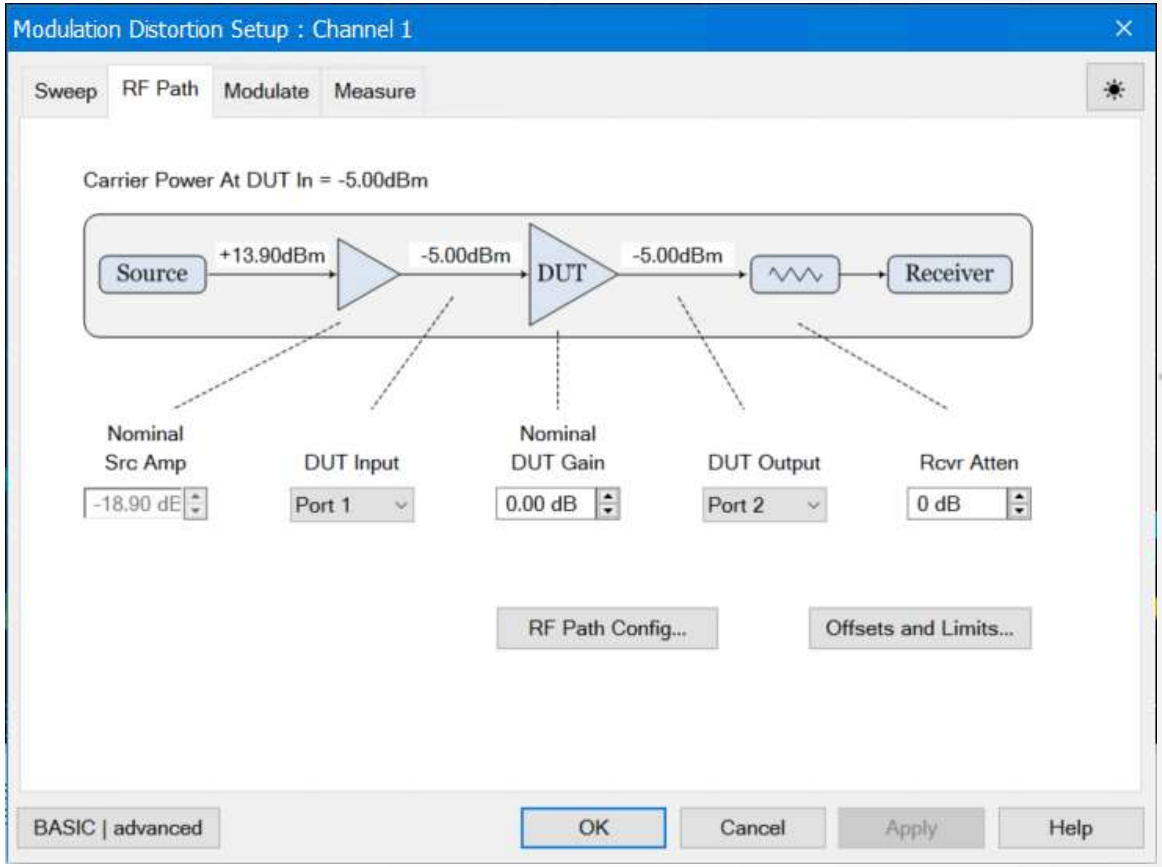
- PNA-X firmware has the Modulation Distortion app which has everything required for the measurement
  - Creates stimulus
  - Controls external generator
    Calibrates the measurement system
  - Makes measurement



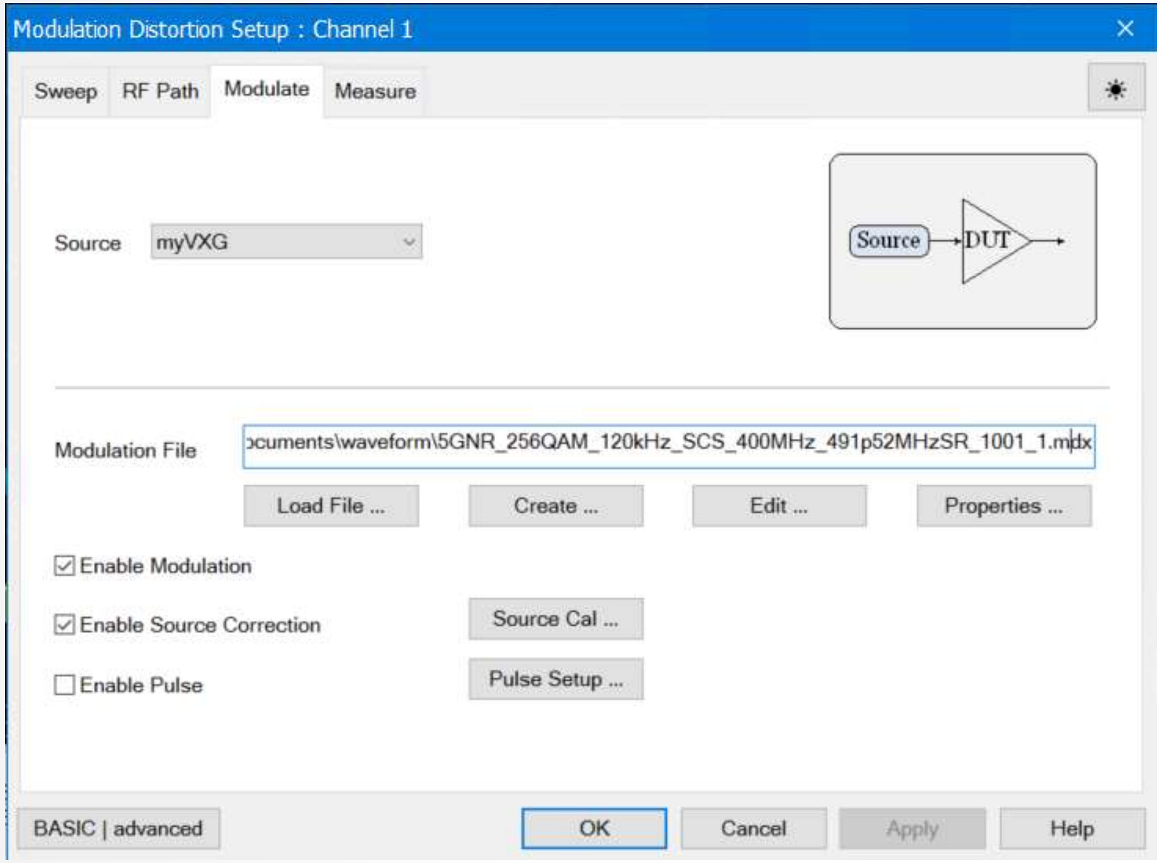


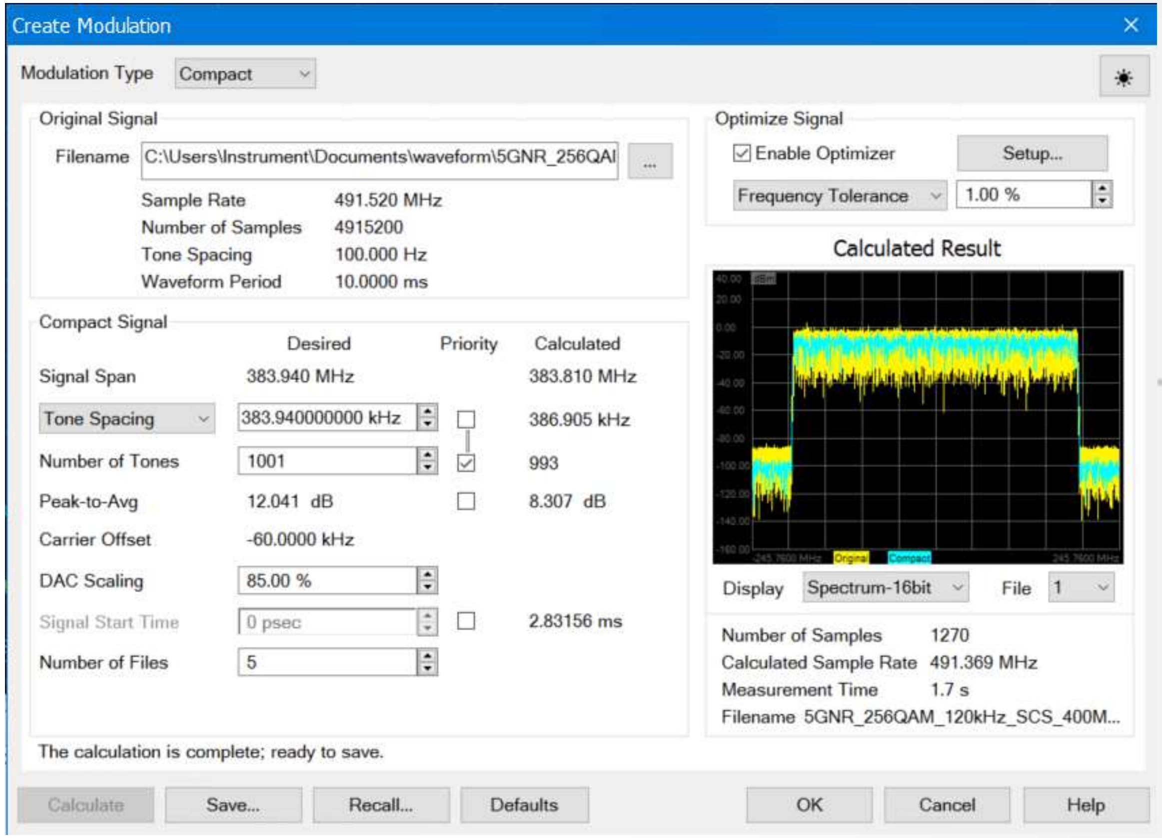
Setup Channel (Sweep and RF Path Setup)





Setup Channel (Modulate Setup)

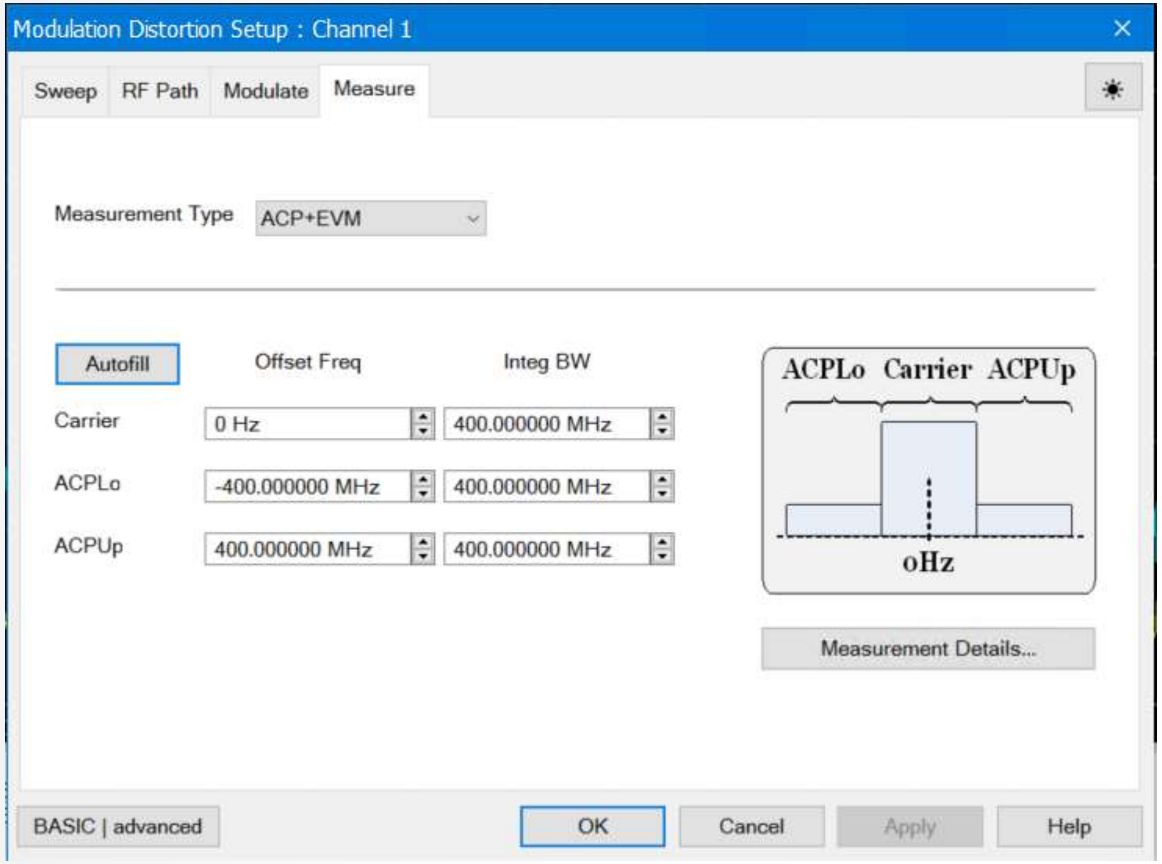


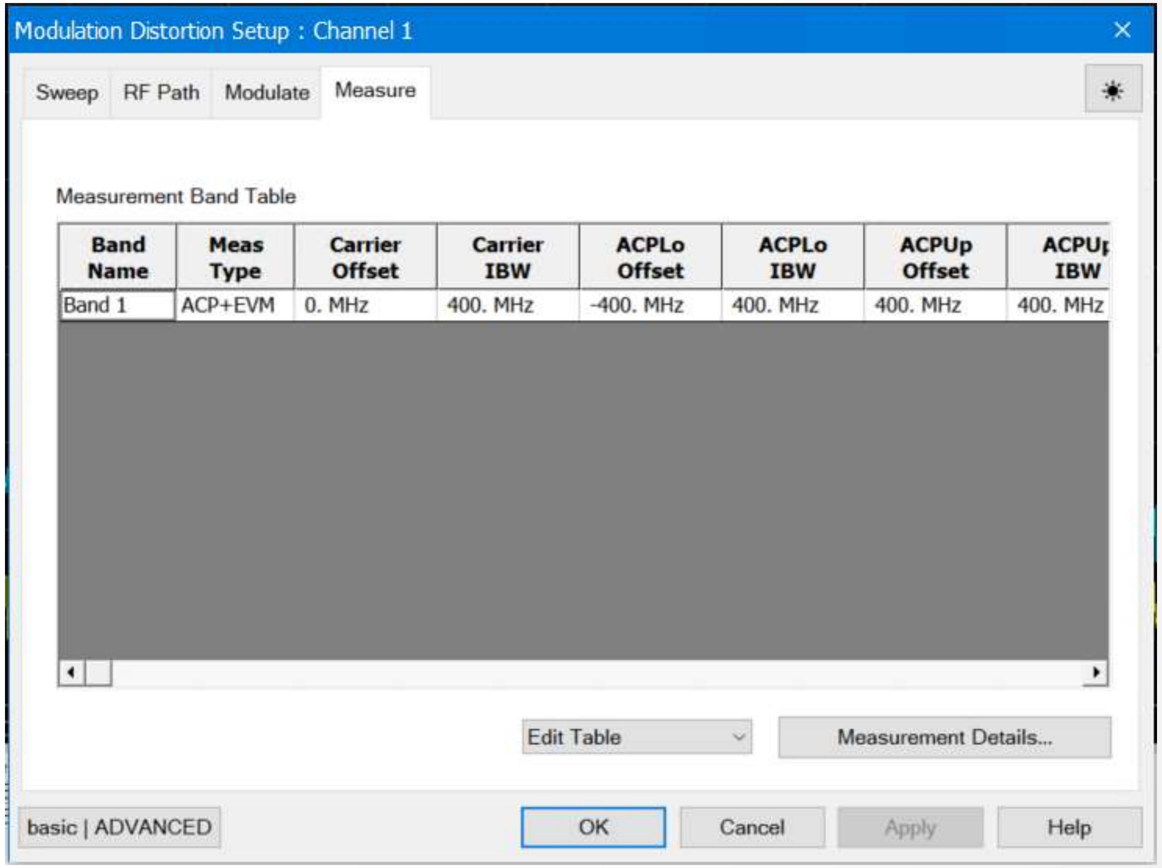


Original signal file can be:

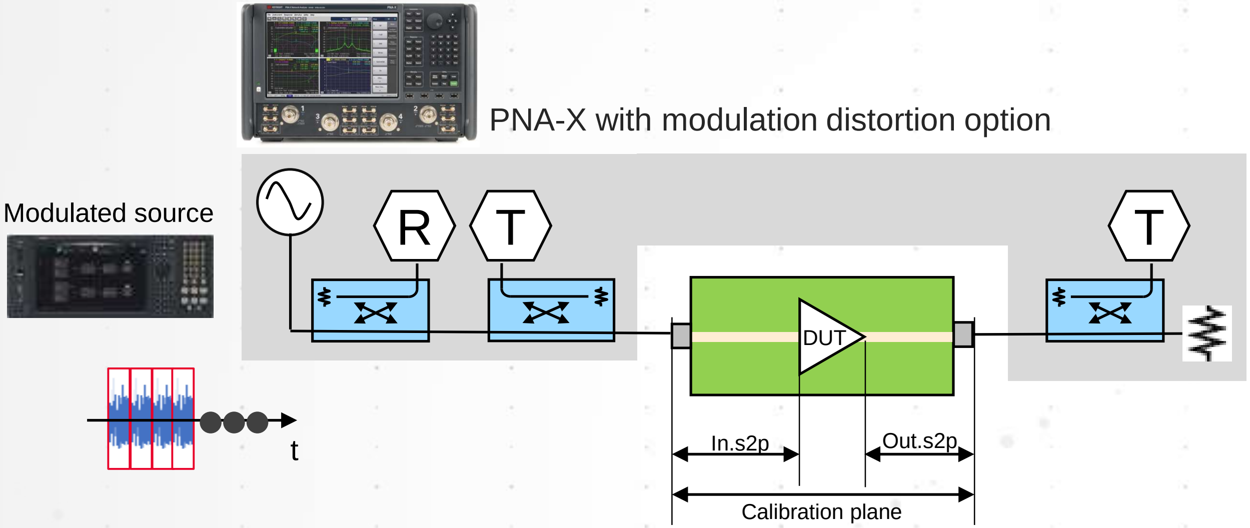
- .wfm file (created by Keysight Signal Studio software)
- .csv file created by any tool

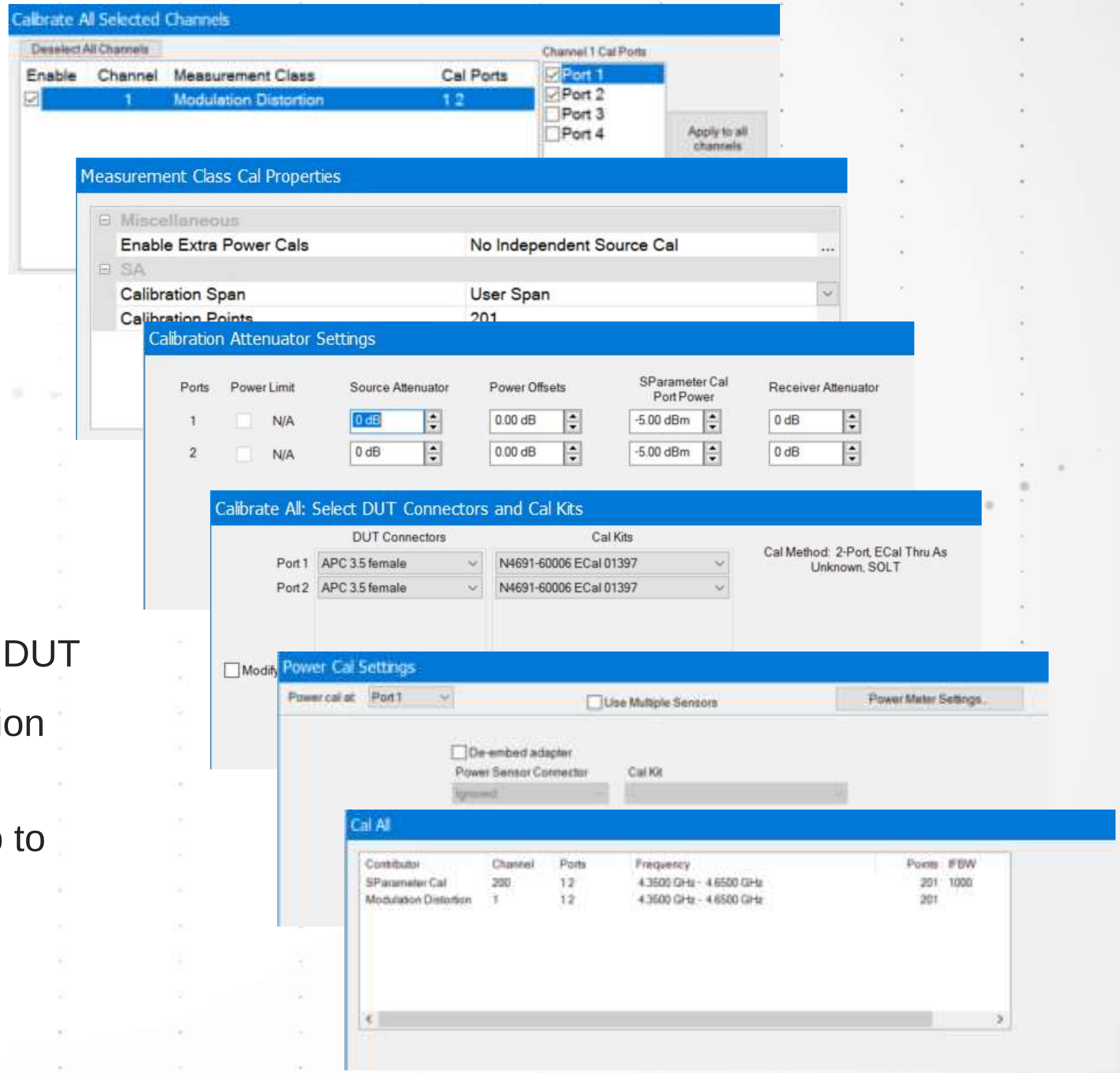
Setup Channel (Measure Setup)





System Calibration (1)

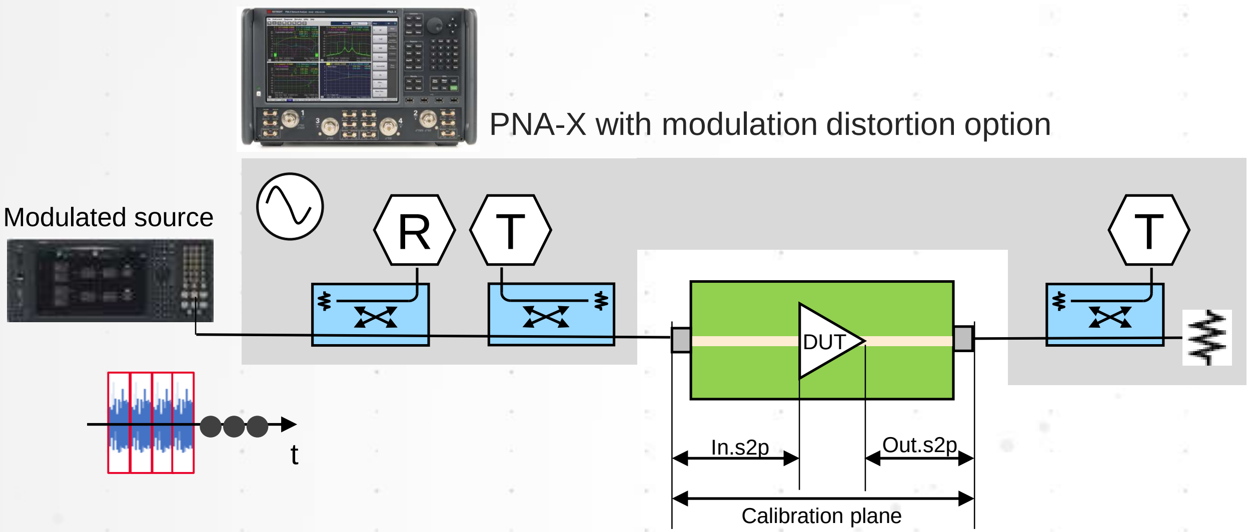




Use PNA-X “CalAll” to establish S-parameter calibration plane at DUT

- Conventional calibration method directly leveraged for modulation distortion measurement
- Fixture simulation feature available to move reference plane up to DUT
- Mismatch of the input port can be removed

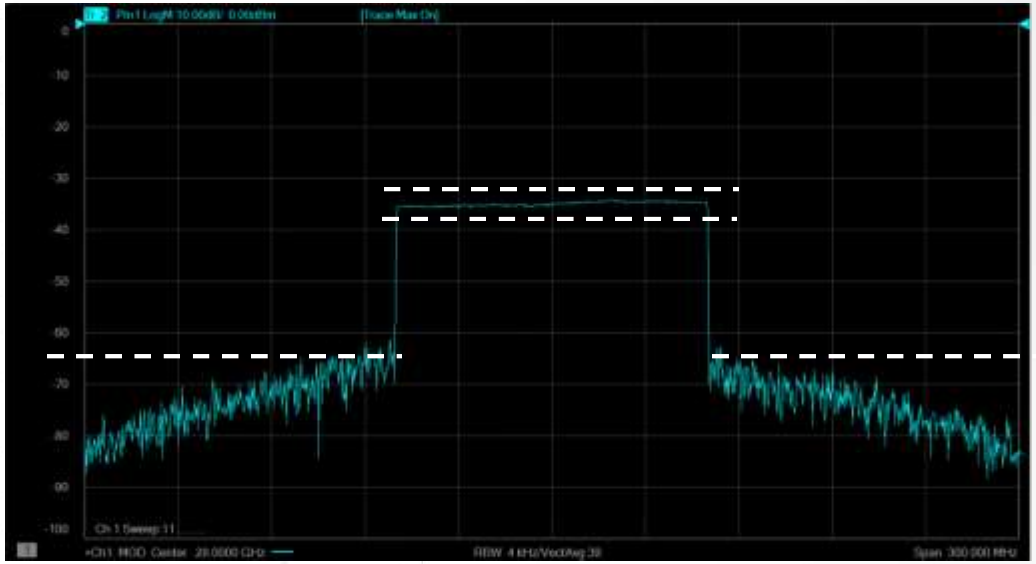
System Calibration (2)



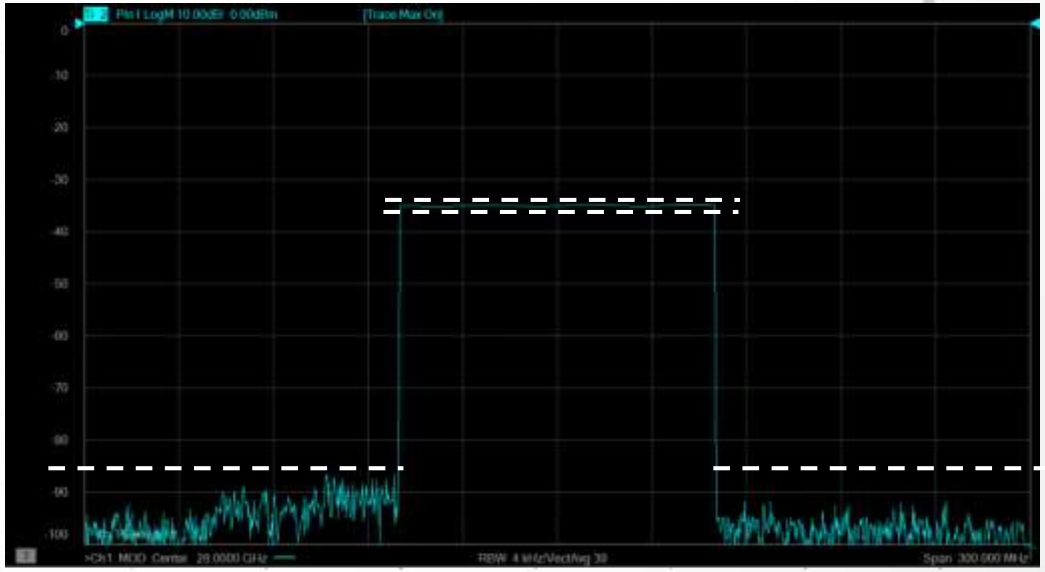
Use vector calibrated receivers to correct stimulus at DUT plane

- Correct channel power
- Correct IQ data to have flat input signal at reference plane
- Suppress ACPR of the signal at reference plane

Before correction



After correction



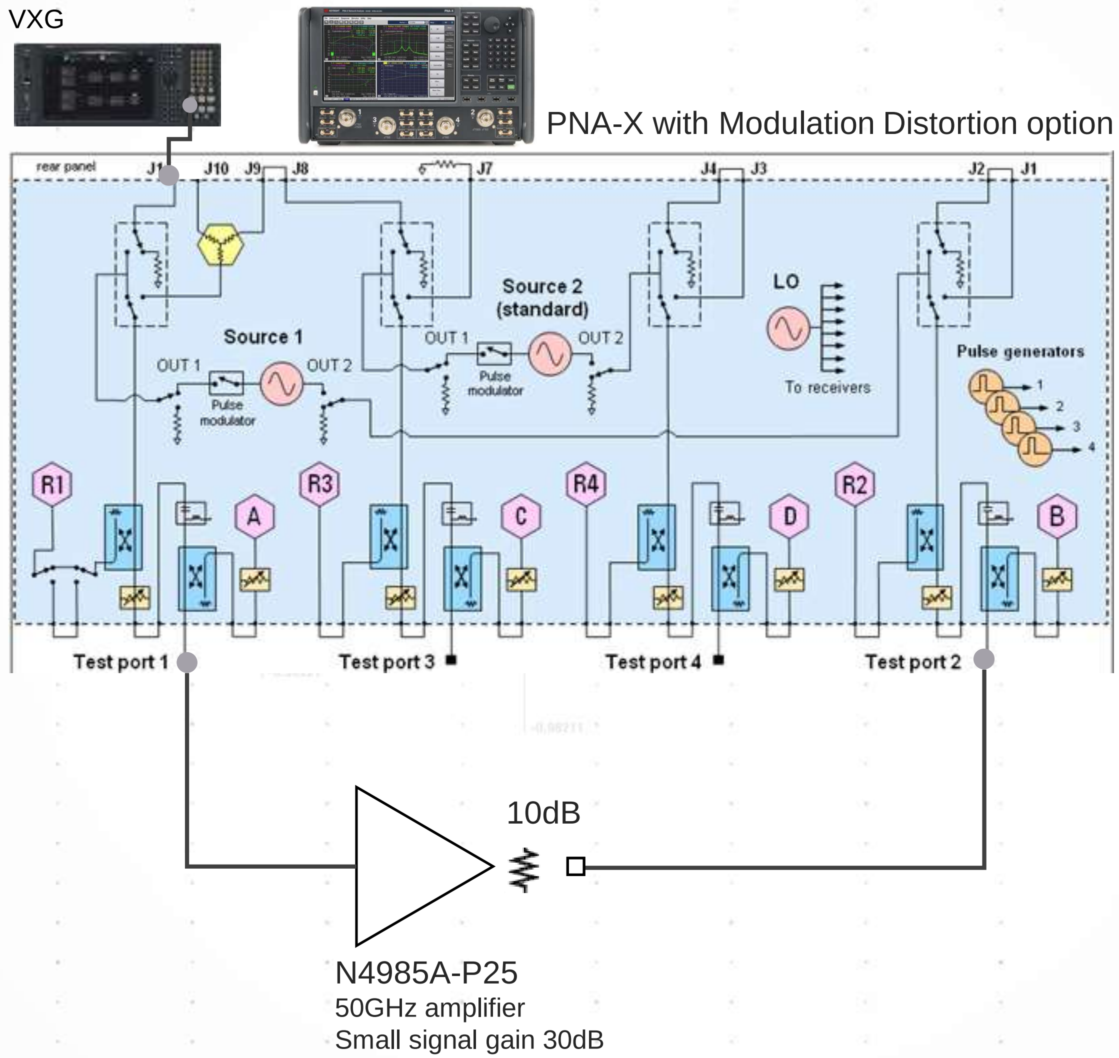
Measurement condition: 100MHz Flat tone, 400MSa.

KEYSIGHT TECHNOLOGIES

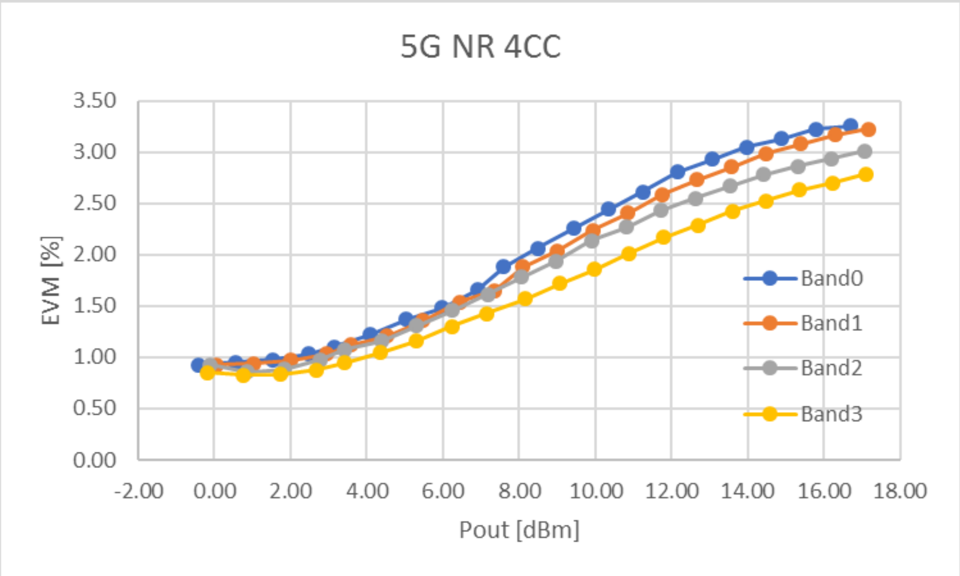
Measurement Examples

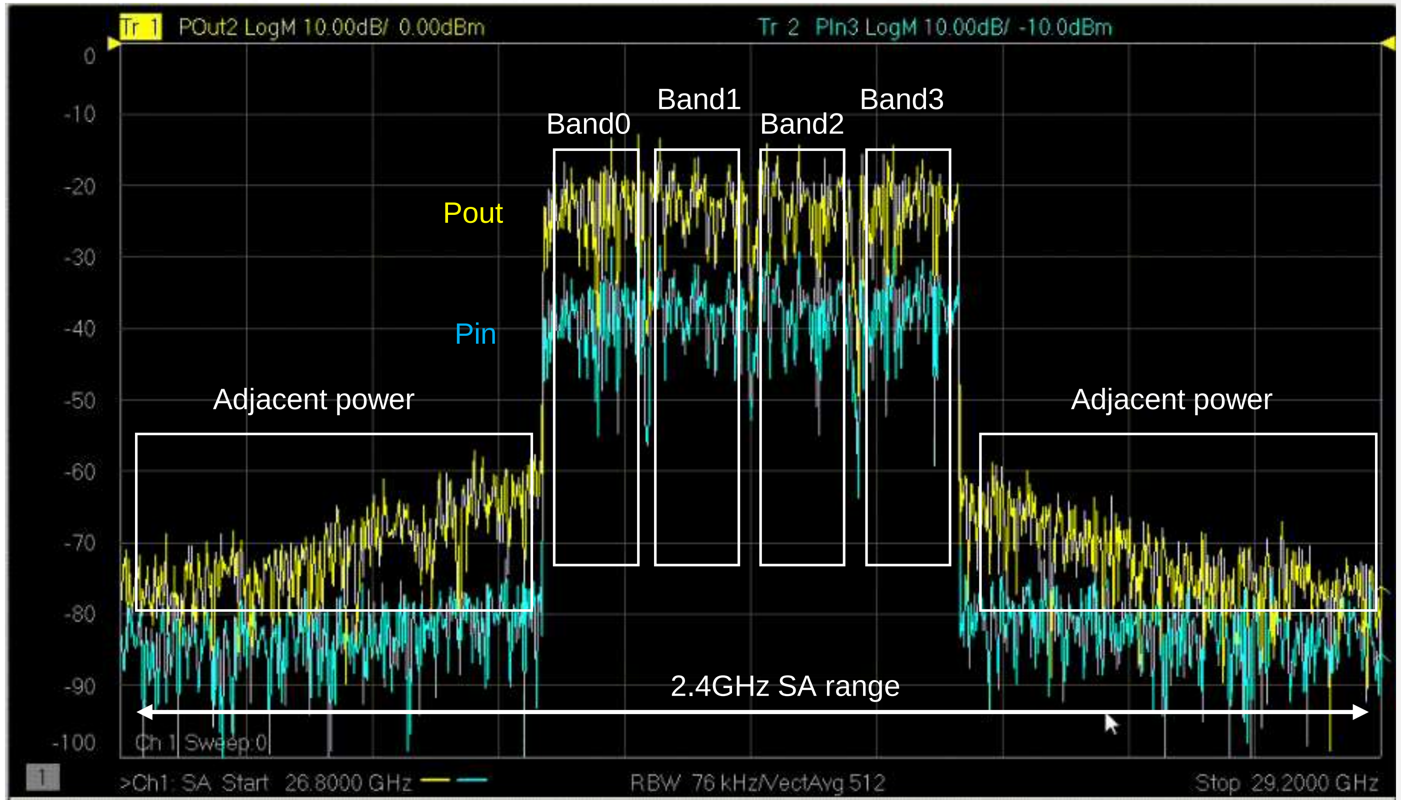
1. 5G NR 4 x 200MHz (4CC)
2. 2GHz BW flat tone Gaussian signal

Measurement Example 1: 200MHz 4CC Measurement



Measurement Example 1: 200MHz 4CC Measurement



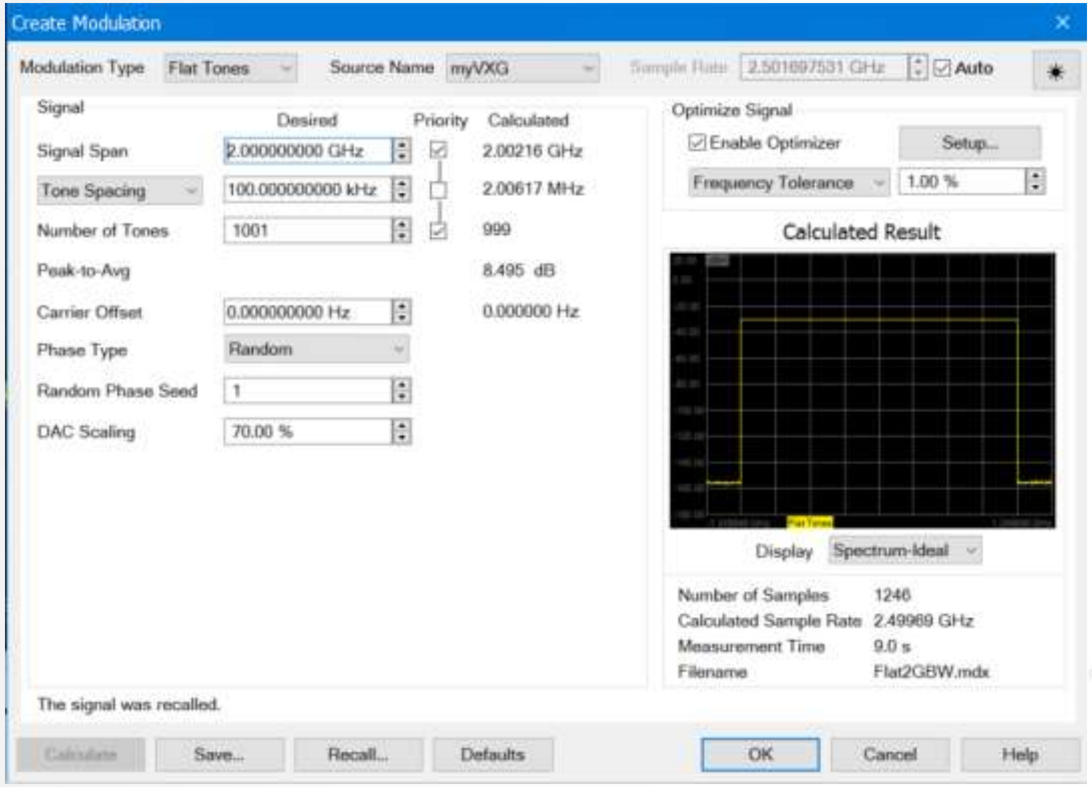


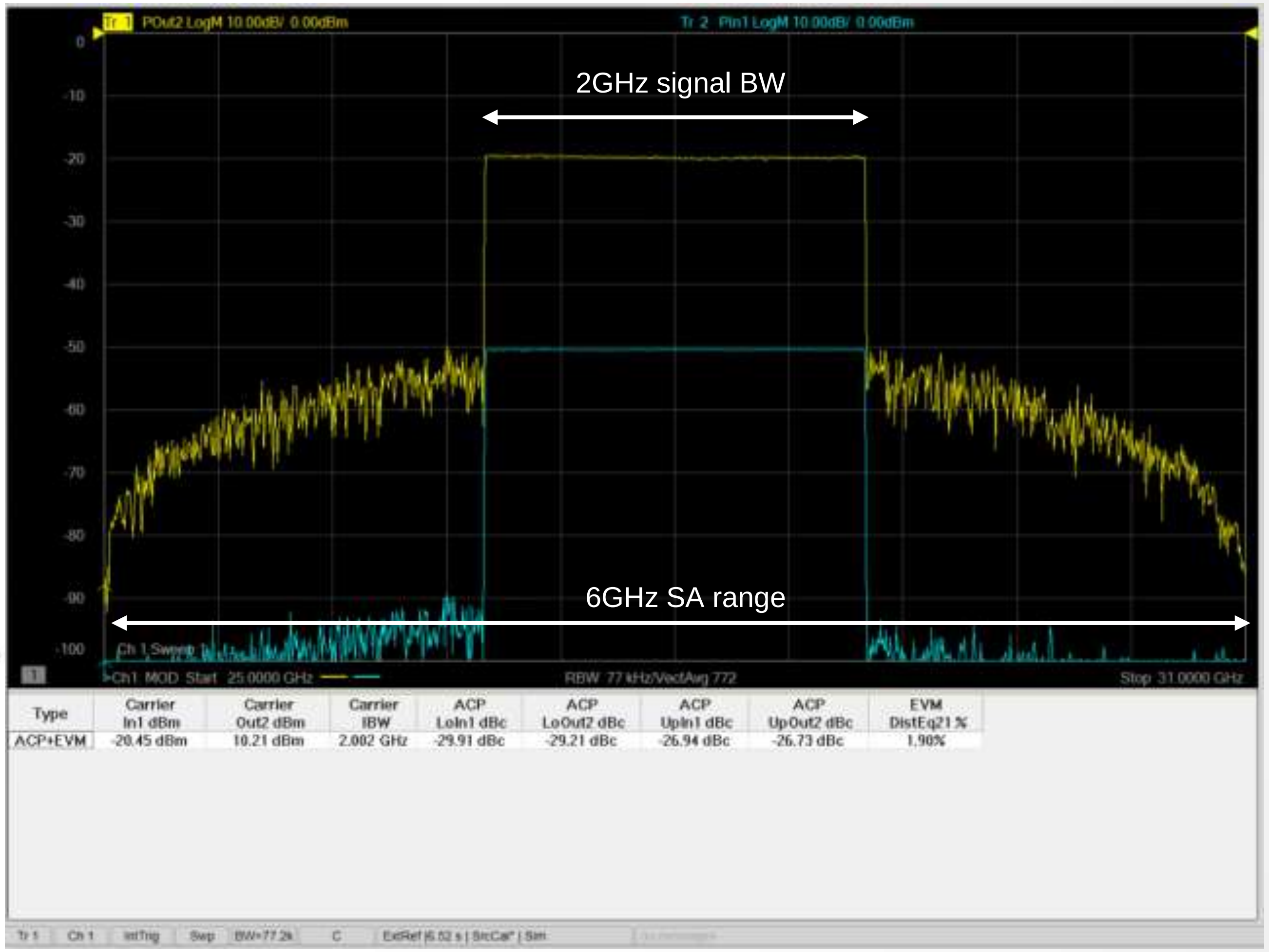
Band	Type Type	Band Power BPwrIn3 dBm	Band Power BPwrOut2 dBm	Band Power BPwrIBW	EVM EVMDistEq23 dBc	EVM EVMDistEq
Band0	ACP+EVM	-25.918865 dBm	-0.603815 dBm	200.000 MHz	-40.588318 dBc	0.934510%
Band1	ACP+EVM	-25.142900 dBm	-0.156669 dBm	200.000 MHz	-40.590702 dBc	0.934254%
Band2	ACP+EVM	-25.252869 dBm	-0.336231 dBm	200.000 MHz	-41.015526 dBc	0.889659%
Band3	ACP+EVM	-24.743153 dBm	-0.388541 dBm	200.000 MHz	-41.614681 dBc	0.830359%

1.8 sec for each power point

- EVM measurement for all bands
- Adjacent power measurement

Measurement Example 2: 2GHz Flat Tone Gaussian Signal





DUT: N4985A-P25, Gain = 30dB

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Measurement Example

Summary

Software Product Information

- Software models for PNA-X
  - Supported only for PNA-X B model
  - No other software options required to make Modulation Distortion measurements
  - Options for each frequency range

Model number and description
S930700B Modulation Distortion up to 8.5 GHz
S930701B Modulation Distortion up to 13.5 GHz
S930702B Modulation Distortion up to 26.5 GHz
S930704B Modulation Distortion up to 43.5 GHz
S930705B Modulation Distortion up to 50 GHz
S930707B Modulation Distortion up to 67 GHz

- Supported SG:
  - VXG (M9383B/84B)
  - M9383A
  - PSG + M8190A
  - PSG
  - MXG

Modulation Distortion App on PNA-X with SG

Modulated source such as:

VXG

Or…

M9383A/B

Or…

PSG + M819X AWG

Or…

MXG

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