WHITE PAPER

Power Amplifier Characterization Fundamentals

Modulation distortion analysis using a network analyzer

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Challenges of Power Amplifier Characterization

5G frequency range 2 (FR2) implementation demands revolutionary transformation in communication technology. As a result, the wireless communications industry's emphasis on system integration, power efficiency, and device reliability continues to grow. Mission-critical requirements for a complete 5G infrastructure, notably network densification and rapidly growing consumer demand for electronic and electrified products, stress the need for faster development of highly integrated, reliable radio frequency (RF) devices.

An essential component in modern RF communication chains is the power amplifier (PA). A critical determining factor of transmission quality and battery life, PAs provide needed power to antennas. To satisfy 5G demands, designers need to optimize PA performance. However, the millimeter-wave (mmWave) carrier frequencies, wide bandwidth signals, and complex modulation schemes required to implement 5G impose stringent component error vector magnitude (EVM) qualifications. Designers face increasing challenges in generating accurate device models, minimizing design cycles, and certifying a device's 5G conformance with a traditional EVM measurement vector signal analyzer (VSA) setup.

Typically, designers conduct nonlinear PA measurements in the time domain using a VSA and vector signal generator (VSG) in what is known as the VSA method. However, Keysight's evolved frequency domain characterization method, called vector component analysis (VCA), uses a vector network analyzer (VNA) and modulation distortion software application. This method improves access to and accuracy of figures of merit (FOM).

This white paper examines the importance of power amplifier nonlinear characterization, time domain versus frequency domain characterization measurements, and three key measurements using VCA.

Highlights in this paper include the following:

- importance of nonlinear power amplifier characterization
- time domain versus frequency domain characterization measurements
- three key measurements using modulation distortion analysis on a VNA

Importance of Nonlinear Power Amplifier Characterization

The significance of PA characterization lies in the following three key reasons:

- verification by designers that the amplifier meets performance specifications
- determination by customers that the PA meets their system demands
- assignment of market value to the device based on its performance

Why characterize the nonlinearity of power amplifiers?

While test parameters for robust amplifier characterization abound, the most critical for PA modeling are EVM and adjacent channel power ratio (ACPR). EVM and ACPR quantify PA nonlinearity, data that designers need for the following reasons:

- Nonlinear response directly affects signal demodulation and bit error rate.
- Nonlinearities cause spectral regrowth, creating interference in frequency bands outside the channel of interest.

For PAs stimulated with wideband input signals, nonlinearity causes in-band and out-of-band distortion products. Correction of linear distortion is straightforward, but nonlinear effects are harder to address. Designers must quantify the PA's nonlinearity to ensure that the device meets performance specifications and follows strict 5G EVM and ACPR standards.

Essentially, "good" linearity indicates that the PA will amplify the input signal without adding distortion. EVM represents in-band amplifier distortion, and ACPR represents out-of-band distortion.

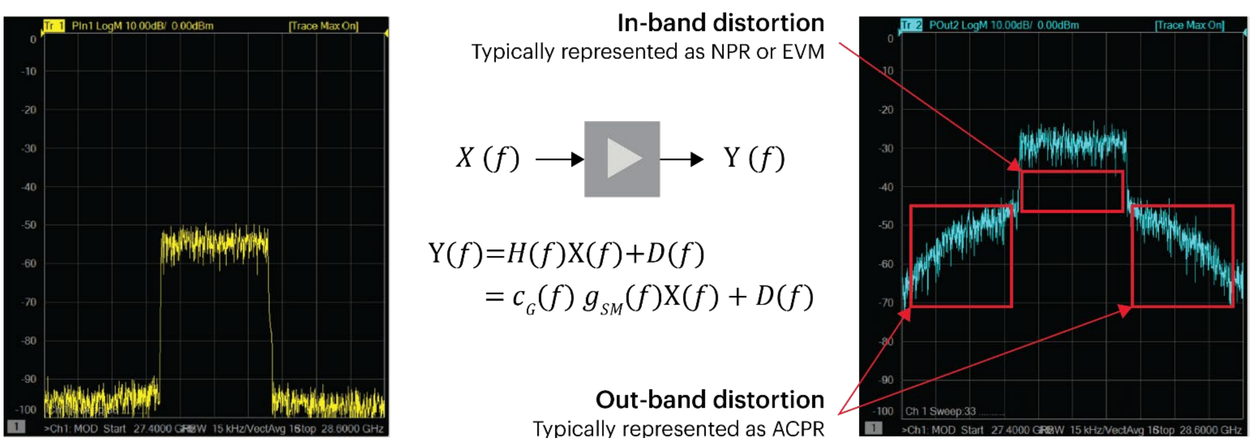

Figure 1. In-band distortion gets buried under the signal

What is EVM, and why is it important?

EVM is the industry-standard FOM for evaluating the in-band distortion of a communication system. The error vector is the vector difference between the ideal reference signal and the measured signal at a given time. Nonidealities will distort the received and transmitted signals, so quantifying modulated signal quality requires EVM measurements. Modulation standards, such as 802.11ac and 5G New Radio (NR), set the minimum acceptable EVM level. As standard stringency increases, PA designers want to provide standard-specific EVM to their customers.

What is ACPR, and why is it important?

ACPR, adjacent channel power level, and adjacent channel leakage ratio all describe the ratio of transmitted power on the assigned channel to the power received in an adjacent radio channel after a receive filter. These FOMs measure how much one channel may interfere with another. ACPR is the industry-standard FOM for quantifying out-of-band distortion characteristics. ACPR measurements hold particular importance for the UMTS and LTE standards.

PA characterization is critical for designers, customers, and the market at large to understand a device's performance quality and value. While linear performance characterization gives basic amplifier behavior information, designers need accurate nonlinear characterization to fully understand a PA's efficiency and standard compliance.

Two key nonlinear characterization measurements are EVM and ACPR. While these measurements have been important for previous communication system generations, because of steep increases in system complexity, they function as the benchmarks for 5G NR standard compliance.

Time Domain vs. Frequency Domain Characterization Measurements

The time domain and frequency domain are two characterization schemes. Traditional time domain characterization was satisfactory for previous needs, but 5G NR requires a more streamlined characterization scheme.

Time domain characterization

Time domain measurement refers to measurements taken with respect to time. An oscilloscope is a prime example of a time domain device, measuring voltage and current across a component (y-axis) as a function of time (x-axis). Traditionally, characterization of PA nonlinearity required measurements taken in the time domain using a VSA and VSG. The VSG provided the input signal to the device under test (DUT), while the VSA captured the output signal and calculated metrics such as EVM and ACPR.

While this method of time domain characterization satisfied past communication requirements, implementing 5G NR demands designers measure performance metrics using extremely wide signal bandwidths in the mmWave spectrum. This new-generation technology makes VSA PA characterization — especially EVM — increasingly challenging for several reasons, as discussed in the following sections.

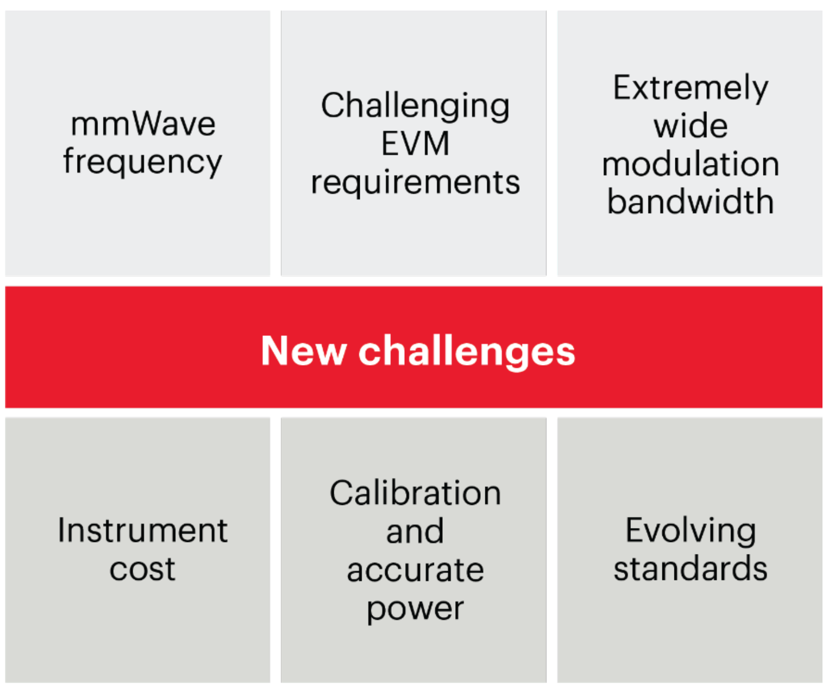

Figure 2. New technological challenges introduced by 5G NR

System and DUT EVM differentiation

Signal source integrity directly impacts EVM results. In the VSA method, the EVM of the test system — known as the "residual EVM" — is indistinguishable from the DUT EVM. The VSA assumes whatever error measured is attributable to the PA. Not only is this inaccurate, but as EVM requirements get more stringent, it presents a significant barrier to qualifying a PA as 5G compliant.

Furthermore, as signal bandwidth gets increasingly wider, the system's signal-to-noise ratio degrades. This noise limits the minimum EVM resolvable by the measurement. Random noise at low power levels also results in less accurate and reliable EVM measurements. Nonidealities of the generated input signal and wideband noise at the receiver limit the minimum EVM attainable by the VSA.

Calibration capability

Issues calibrating the VSA method include complexity, robustness, signal fidelity, and repeatability. While multiple ways to calibrate the test system exist, even the most advanced techniques may include errors — especially when the test signal has a wide bandwidth and the DUT has a poor mismatch.

Digitizing the input signal using a signal analyzer that does not produce any nonlinear distortion mitigates these EVM measurement errors. However, this solution presents significant implementation challenges across wide bandwidths. It also requires intimate knowledge of the VSA and drastically slows the entire measurement process. These calibration methods both complicate implementation and suffer from non-robust error mitigation. In many cases, you trade one error vulnerability for another. Signal fidelity presents another issue for the VSA method because of lossy cables and mismatch at higher frequencies, causing the actual signal applied to DUT to deviate from the ideal.

Equipment required

As mentioned before, the traditional time domain characterization measurement setup requires three primary pieces of equipment: a VSG, VSA, and VNA. Beyond this, time domain characterization needs unique cabling and calibration equipment for each device. Alternating between the VSA and VNA for DUT parameterization costs more in terms of test hardware, software, and peripherals. It increases device testing time because of recalibration and serially switching setups.

Fortunately, there is a better, more streamlined characterization scheme: frequency domain characterization using the VCA solution.

Frequency domain characterization

Frequency domain measurement refers to measurements taken with respect to frequency. A VNA is an example of a frequency domain device, measuring signals (y-axis) as a function of a given frequency range (x-axis). VNAs are the go-to component test and electrical network measurement instruments. Quintessential VNA component tests include S-parameters, gain compression, and IP3 measurements. However, with modulation (MOD) software, the VNA does even more. As in the time domain, the VSG supplies the input to the DUT. The VNA connects directly to the DUT and takes linear and nonlinear characterization measurements with the MOD software.

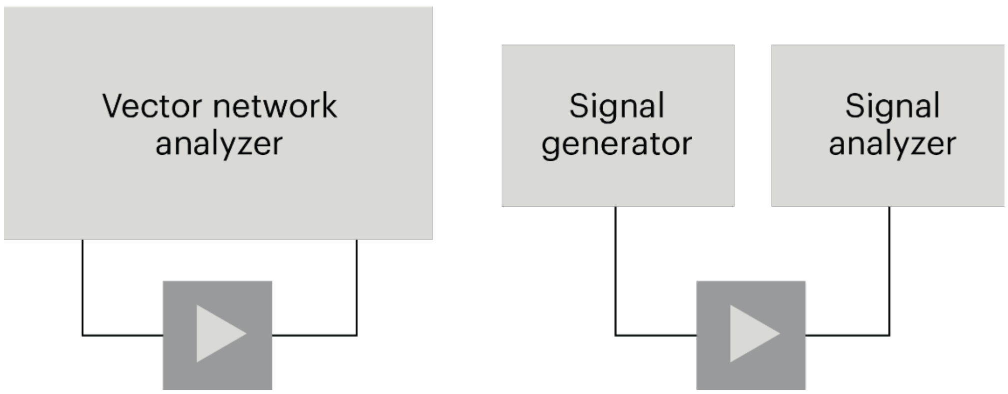

Figure 3. Traditional characterization needs a VNA for S-parameter, gain, IP3, and noise figure in addition to an SA for APR, noise power ratio, and EVM

Frequency domain characterization reduces measurement complexity by offering a fully integrated, “single-connection, multiple-measurement” characterization setup — including EVM and ACPR — on a VNA. Furthermore, frequency domain characterization leveraging MOD software achieves the lowest residual EVM on the market and enables robust calibration for enhanced accuracy.

What is modulation distortion analysis, and what does it improve?

Many PAs amplify modulated signal stimulus, increasingly so as 5G development progresses. Just as with simpler signal stimulus using modulated schemes, the PA achieves the greatest efficiency at power levels close to the amplifier's saturation point. However, wireless standards such as 802.11ac restrict the maximum spurious emissions allowed for a given RF component over a range of frequencies. To comply with these restrictions, designers must characterize their amplifiers under these complex modulation schemes.

The modulation distortion software application reimagines amplifier distortion measurements using a vector-calibrated VNA to achieve the most accurate and repeatable EVM results. In this method, the VSG's wideband input signal stimulates the DUT as the MOD application measures the input and output signal tone by tone in the frequency domain. Then, the VNA stitches the frequency together to achieve a wideband coherent measurement. The measured output signal decomposes into linearly and nonlinearly correlated components. From this, the MOD distortion application calculates EVM and ACPR in the frequency domain. Measurement capabilities expand even further with the additions of arbitrary load control (ALC), VSA link, and DPD analysis software applications.

The VNA leverages state-of-the-art calibration techniques to remove any contributions of the test setup from the measurement. Additionally, the wider dynamic range and source power calibration create more accurate and repeatable EVM measurements.

Simple setup and single connection

The same setup used for measuring S-parameters, gain compression, noise figure, and IP3 also captures EVM and ACPR with the addition of a VSG or the internal modulated source (Keysight S93072B internal 6 GHz arbitrary waveform generation application). You can take both linear and nonlinear performance parameters with one setup, one connection, and one “cal all” calibration.

Figure 4. The VCA solution allows the VNA to conduct multiple measurements with a single connection

Best accuracy and measurement repeatability

When using the VNA to measure nonlinear DUT behavior, calibration methods like fixture de-embedding move the calibration plane to the DUT plane. Input port mismatch and channel power are also correctable — as is the IQ data — yielding a flat input signal at the reference plane with suppressed signal ACPR. Given this measurement's coherent nature, every trace comes out the same. Thus, these VNA calibration techniques quickly deliver measurement reproducibility and input signal fidelity.

Lowest residual EVM

The MOD application isolates the distortion contributions of the DUT because of a wider system dynamic range (lower noise floor). This means the frequency domain PA characterization differentiates system distortion and noise from the DUT EVM, purifying the PA characterization and revealing the true performance of the PA.

Three Key Measurements Using Modulation Distortion Analysis on a VNA

ALC, VSA link, and DPD analysis applications expand and enhance your measurement capabilities.

What is ALC?

While normalized loads and linear behavior are every amplifier designer's dream, massive multiple- input / multiple-output and beamforming architectures experience highly variable load conditions in practical applications. DUT behavior varies dramatically with changing load and stimulus conditions. Difficult to address, this circumstance also presents a challenge to in-lab simulation for the time domain characterization setup.

However, using the VCA method with ALC effectively quantifies PA variable load behavior while maintaining the lowest residual EVM possible. As the power amplifier load continuously shifts to simulate real-world conditions, the VNA characterizes worst-case DUT EVM and ACPR. This gives designers highly accurate sensitivity and performance metrics. The components for this solution are a Keysight PNA-X VNA, external source, tuner, and the MOD application with ALC companion software.

What is VSA link?

Modern demand for high data throughput and low latency pushes device specifications and operational standards toward wideband modulation. Wideband performance benefits come with a heavy cost: significantly increased noise. This noise introduces additional test complexity and measurement uncertainty, exacerbated by the desire to pack as many modulated signals into the available bandwidth as possible. This constrains EVM requirements and degrades system signal- to-noise ratio. So how do you simplify the performance verification process while ensuring a component's standard compliance?

The Keysight PathWave Vector Signal Analysis (89600 VSA) application is advanced signal analysis software that uses many measurement devices, including the PNA-X VNA. After the PNA-X acquires the data and performs inverse fast Fourier transforms, VSA link sends the IQ data collected by the PNA-X to the VSA for demodulation and calculation of EVM in the time domain.

The application uses special spectrum stitching, multi-receiver, AM / AM, and AM / PM measurements to support ultra-wideband analysis plus full EVM demodulation. PA designers who need EVM under a specific modulation scheme (such as 5G NR, Wi-Fi, or DBSX2) may find VSA link particularly useful.

What is DPD analysis?

To meet the linearity and efficiency demands of modern communication standards with high peak- to-average power ratios, designers frequently use digital pre-distortion (DPD) to compensate for the nonlinear behavior of the PA. DPD methods distort the modulated input signal before feeding it into the amplifier. The pre-distortion applied to the input signal is the inverse of the distortion contributed by the amplifier, resulting in a linearized signal at the output of the PA.

The new DPD analysis application uses a direct learning architecture to create direct DPD (also known as memoryless) and model DPD (DPD with memory). Using DPD analysis software on the VNA, PA designers gain insight into the minimum achievable EVM and DPD cost by comparing the characteristics of the different DPD models.

Conclusion

Designing power amplifiers compatible with the 5G infrastructure poses significant challenges because of mmWave carrier frequencies, wide bandwidth signals, complex modulation schemes, and increasingly strict EVM and ACPR requirements. The traditional VSA characterization method no longer satisfies design engineers' needs. The PNA-X MOD application provides numerous PA characterization benefits that overcome wideband measurement challenges:

- Wide dynamic range enables low residual EVM because of the lower noise floor.
- Easy calibration for "vector-corrected" measurements enhances signal fidelity at the DUT input, resulting in significantly improved measurement reproducibility.
- Compatibility with Keysight PathWave Advanced Design System (ADS) simulation environment for nonlinear device behavior allows design cycle acceleration.
- Sophisticated software permits distortion analysis under modulated conditions.

For any PA characterization, a VNA is essential to characterize linear and nonlinear performance. With the MOD application, the test system makes traditional VNA measurements as well as EVM and ACPR. The unique architecture of the PNA-X allows users to perform multiple measurements with a single connection, simplifying test setup, improving measurement accuracy and reproducibility, and generating the lowest residual EVM results on the market.

Related links

- Technical Overview: S93070xB Modulation Distortion Application for the PNA-X
- Application Note: Create Accurate EVM Measurements with the PNA-X Series Network Analyzer
- Article: An Innovative Method for High-Accuracy EVM Measurements
- Video: ADS2021 — Compact Test Signal and Distortion EVM
- Solution Partner Focus Microwaves Group: Nonlinear Measurements Using PNA-X

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