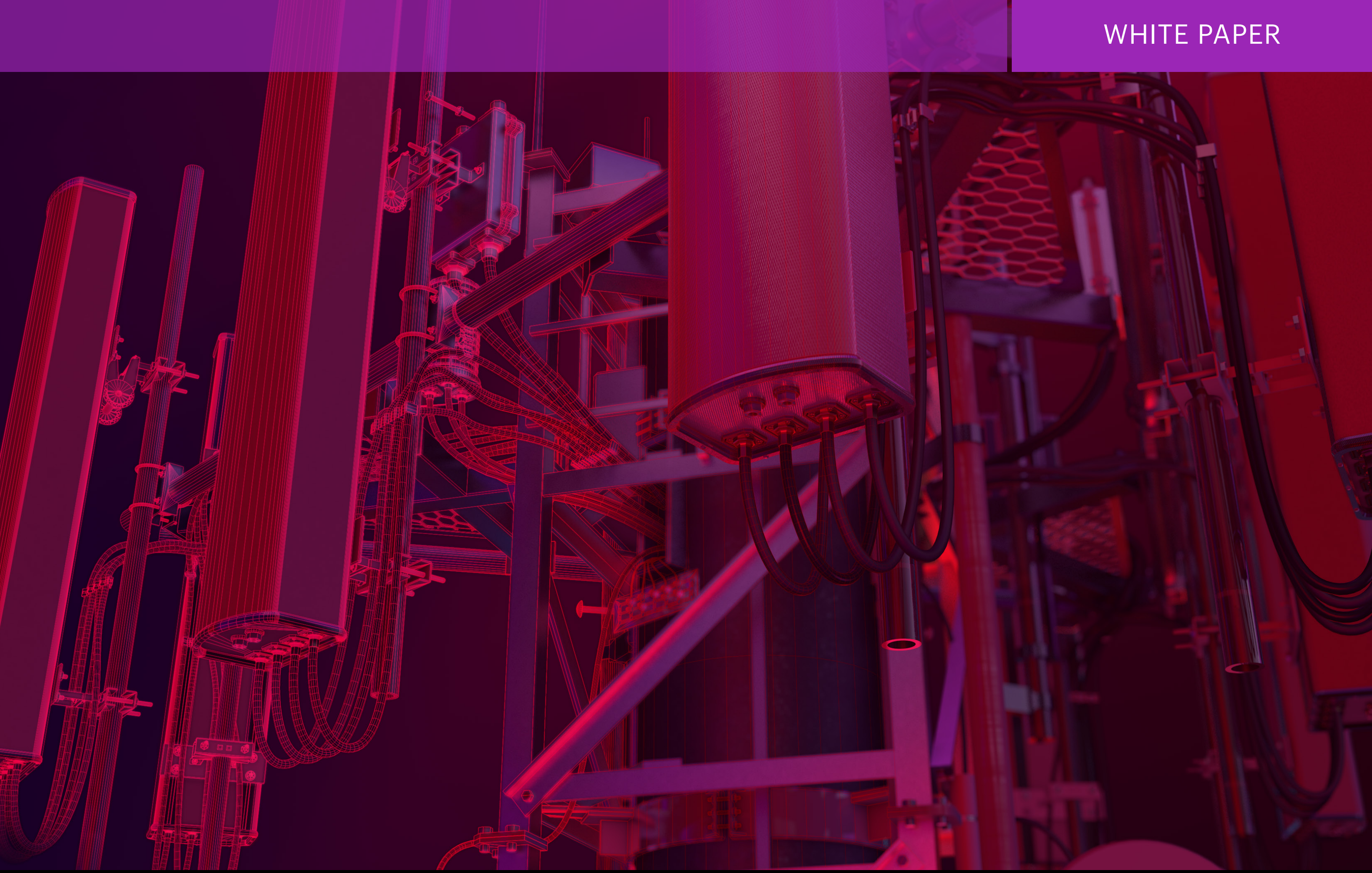
WHITE PAPER



How to Characterize Low-Noise Amplifiers

KEYSIGHT

Introduction

System developers depend on low-noise amplifiers (LNAs) across various applications, including wireless communications, sensor networks, navigation satellites, and radio telescopes. These LNAs amplify low-power signals while maintaining a high system signal-to-noise ratio (SNR). Along with common amplifier considerations like gain and linearity, LNAs must offer low noise figure functionality to preserve signal quality and system sensitivity.

A low-noise amplifier's performance impacts receiver quality and reliability more than any other component, making it critical for cellular-end equipment, base stations, wireless local area networks (Wi-Fi), and aviation and satellite communication systems. Testing receivers operating in the FR1 and FR2 frequency bands requires accuracy and repeatability to ensure conformance with the latest standards. However, convoluted conventional active device measurement setups require multiple instruments.

In this white paper, learn how the flexible hardware and advanced software capabilities of the ENA-X network analyzer simplify a low-noise amplifier's performance characterization while improving measurement accuracy and repeatability.

Key LNA Performance Parameters

Engineers optimize receiver sensitivity using data from the LNA's noise figure, gain, and linearity measurements. By improving the sensitivity of a system, a low-noise amplifier reduces the need for larger, more expensive antennas or complex systems to achieve the desired signal quality and range.

Noise Figure Measurements

The LNA typically occupies the first stage of the receiver chain. As a result, the LNA determines the system link budget, noise figure, and the minimum detectable signal for the receiver. Even with no input signal noise, the low-noise amplifier would still produce some noise due to noise generation processes within the amplifier's active circuitry. The noise figure characterizes this amplifier-generated noise. According to the Friis formula for noise factor, shown in Figure 1, the noise figure of the F1 first amplifying stage sets the minimum noise figure for the overall receiver.

$$F_{Total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \cdot G_2} + \cdots + \frac{F_N - 1}{G_1 \cdot G_2 \cdots G_{N-1}}$$

Figure 1. Friis's formula shows that the total receiver noise factor, FTotal, accounts for the noise factor, FN, and gain, GN, per stage. The first stage noise factor, F1, affects the overall receiver noise figure.

The noise figure describes the amount of excess noise present in a system. Minimizing the noise figure reduces system impairments that result from noise. Excess noise degrades the signal quality, like static on a television broadcast or cell phone call. In military applications like radar or secure communications, receiver noise limits the system's effective range.

System designers try to optimize the overall system SNR by either increasing the signal power or by reducing noise. Developers might increase transmit signal power using more powerful components or minimize path loss between the transmitter and receiver. However, improving the receiver's noise figure is the easiest and most cost-effective way to optimize SNR.

Traditionally, engineers use the Y-factor method to measure the noise figure, as shown in Figure 2. The Y-factor method setup includes a calibrated noise source with a specially designed noise switch, an attenuator to provide a good output match, and either a spectrum analyzer or noise figure analyzer. When the diode is off, the noise source presents a room temperature — cold — termination to the DUT.

During reverse bias, the diode undergoes avalanche breakdown, creating considerable noise. Engineers characterize this extra noise as the excess noise ratio (ENR). Engineers use the noise source to conduct two noise power measurements at the output of the DUT and then use the ratio of the two measurements, called the Y-factor, to calculate the noise figure.

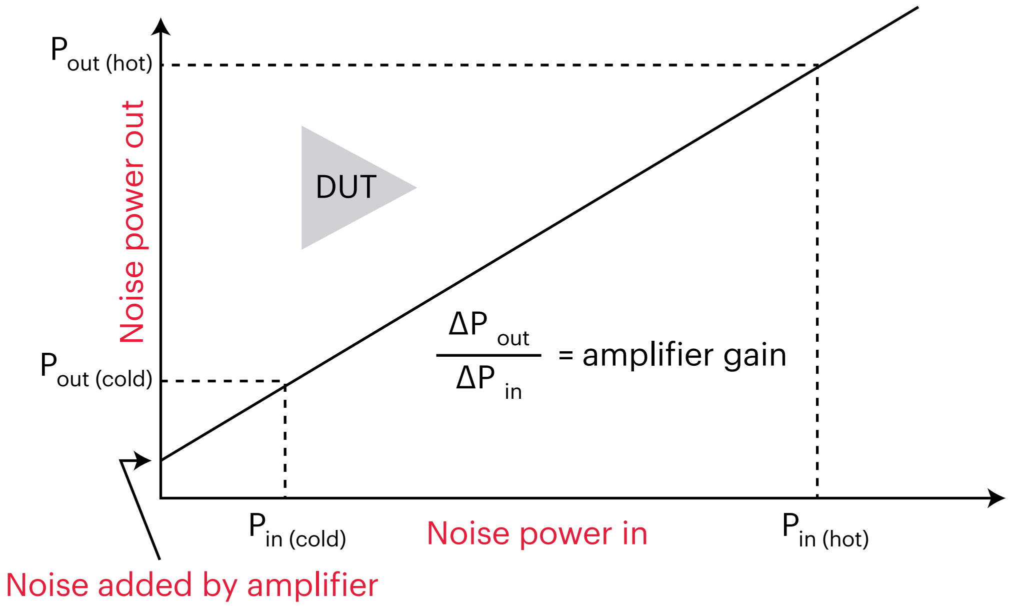


Figure 2. Graphical representation of the Y-factor method

Based on the limitations of the test instruments, when performing noise figure measurements using the Y-factor method, engineers must assume a 50-ohm match for the noise source during both the hot and cold measurements. Additionally, since the conventional test setup is unable to correct for any mismatch at the input of the DUT, accuracy degrades as the DUT's match gets worse. These test set limitations and introduce significant uncertainty into the noise figure data captured with the Y-factor method, especially for non-connectorized devices.

Gain and Linearity Measurements

Scattering parameters (S-parameters) are the fundamental measurement for RF networks. Altogether, S-parameters capture the linear behavior of the LNA, namely the forward gain, reverse isolation, and input or output match. If the amplifier behaves linearly, then the S-parameters remain constant regardless of input power. However, robust amplifier evaluation must contend with nonlinear behavior as well.

Distortion effects critically impact signal quality — particularly nonlinear distortion contributed by the amplifier. In-band distortion contributions cause particular concern since filtering proves ineffective. The communication systems industry considers error vector magnitude (EVM), defined in Figure 3, as the benchmark figure of merit for in-band distortion.

Modulation standards, such as 802.11ac and 5G New Radio (NR), set the minimum acceptable EVM level. As standard stringency increases, so does the need to capture and optimize LNA linearity and EVM accurately.

$$\text{EVM}[n] = \sqrt{I\,err[n]^2 + Q\,err[n]^2}$$

when [n] = measurement at the symbol time

$$I\,err = I\,ref - I\,meas$$

$$Q\,err = Q\,ref - Q\,meas$$

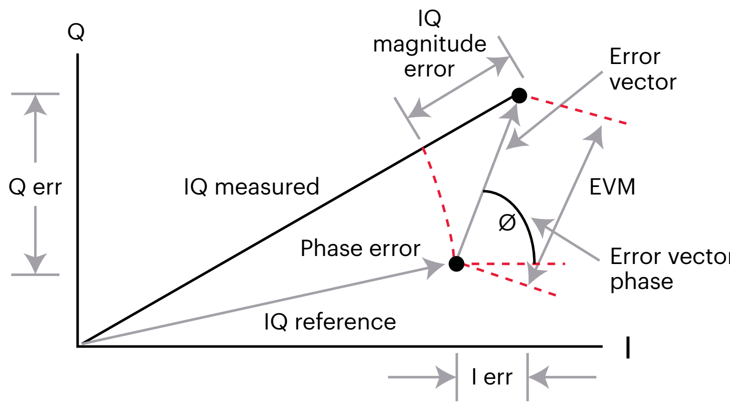


Figure 3. The definition of EVM is the root mean square (RMS) of the error vector over time at the instants of the symbol clock transitions, where the error vector is the vector difference at a given time between the ideal reference signal and the measured signal

The instrument of choice for all typical continuous wave (CW) and two-tone testing is a vector network analyzer (VNA). However, modern communication standards require complex modulation of wideband signals.

Testing the modulated wideband signal distortion measurements like EVM and adjacent channel power ratio (ACPR) using the conventional method requires a signal analyzer and signal generator setup. Switching between two separate test setups to complete gain and linearity measurements not only wastes valuable test time but also introduces complexity in correlating results between the two stations. Furthermore, the external test fixtures needed to perform EVM measurements on a signal analyzer, such as attenuators or booster amplifiers, present even more measurement uncertainty.

Multiple Measurements on One Setup

The ENA-X network analyzer platform helps engineers develop and deploy low-noise amplifiers faster. The ENA-X includes integrated low-noise receivers, modulation distortion analysis capabilities, and full vector correction to address input port mismatch, channel power, and source error contributions in a single test setup. The ENA-X, built with custom monolithic microwave integrated circuits (MMICs), offers developers the highest measurement accuracy and repeatable results. RF developers only need to connect and calibrate the test setup once to perform measurements.

Advancements in network analyzer technology enable engineers to conduct fully calibrated noise figure measurements using the cold-source method, illustrated in Figure 4. The ENA-X additionally performs EVM and ACPR measurements. Beyond simplifying the test setup, the measurement methods and techniques enabled by the network analyzer enable more accurate results.

Alternative to the Y-factor method, the cold-source method offers more advanced error correction that yields higher accuracy measurements. The engineer measures a single noise power measurement with a cold termination on the input of the device under test (DUT). The noise measured includes both the amplified input noise and the noise contributed by the LNA. As part of the overall noise figure measurement, the VNA captures the DUT's S-parameters and gain. The VNA automatically subtracts the amplified input noise from the measurement, leaving only the noise contributed by the DUT. From this, the network analyzer calculates noise figure.

Like the Y-factor method, the cold-source method requires a calibration step to characterize the noise figure and gain of the test instrument's noise receiver. However, the cold-source method requires a noise source (or power meter) only during calibration, not during the measurement of the DUT.

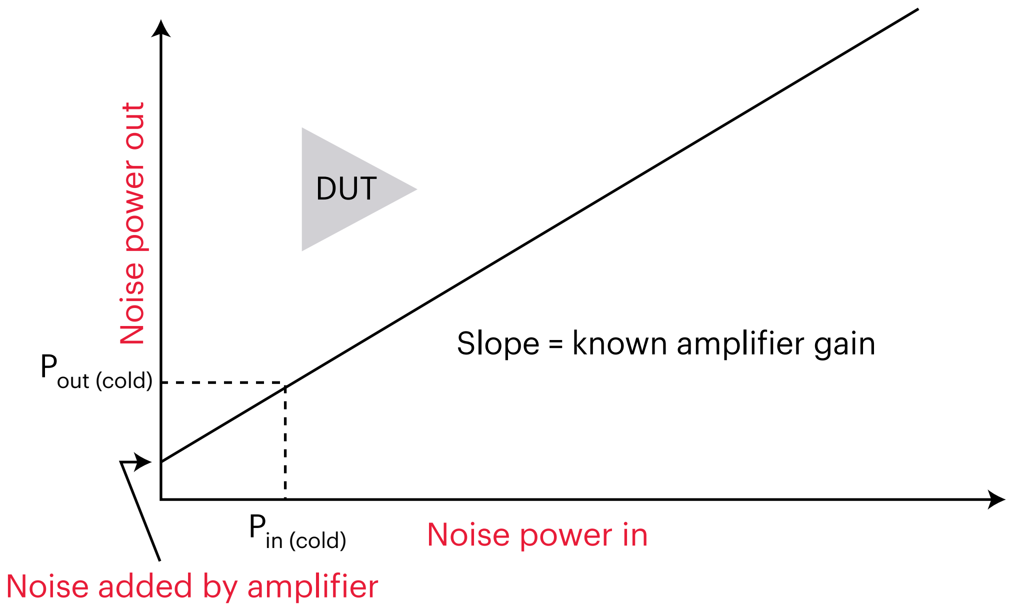


Figure 4. Graphical representation of the cold source method

By using a VNA to capture the noise figure using the cold-source method, engineers get the fully vector-corrected noise parameters of the LNA. This data allows for the accurate analysis of the DUT's noise figure at 50-ohms. Additionally, the network analyzer offers the highest accuracy gain measurements through full vector correction.

Simplified Setup and Calibration with Integrated Hardware

The ENA-X network analyzer offers enhanced hardware integrations, such as a built-in upconverter on port 1 and a low-noise receiver on ports 1 and 2. These integrations provide greater measurement flexibility. The upconverter enables the ENA-X to pair with lower frequency signal generators, like the Keysight MXG signal generator, and still conduct measurements up to 44 GHz. The two integrated low-noise receivers simplify noise figure calibration by reducing fixturing and enabling the ENA-X to measure the DUT in any direction. By connecting and calibrating the test set just once, engineers can collect standard network analysis measurements in conjunction with the cold-source noise figure.

The low noise figure of the ENA-X network analyzer's internal receivers enables increased noise figure measurement sensitivity. This enables the ENA-X to out-perform or equal the noise figure measurement quality of the high-performance PNA-X network analyzers up to 30 GHz, as shown in Figure 5.

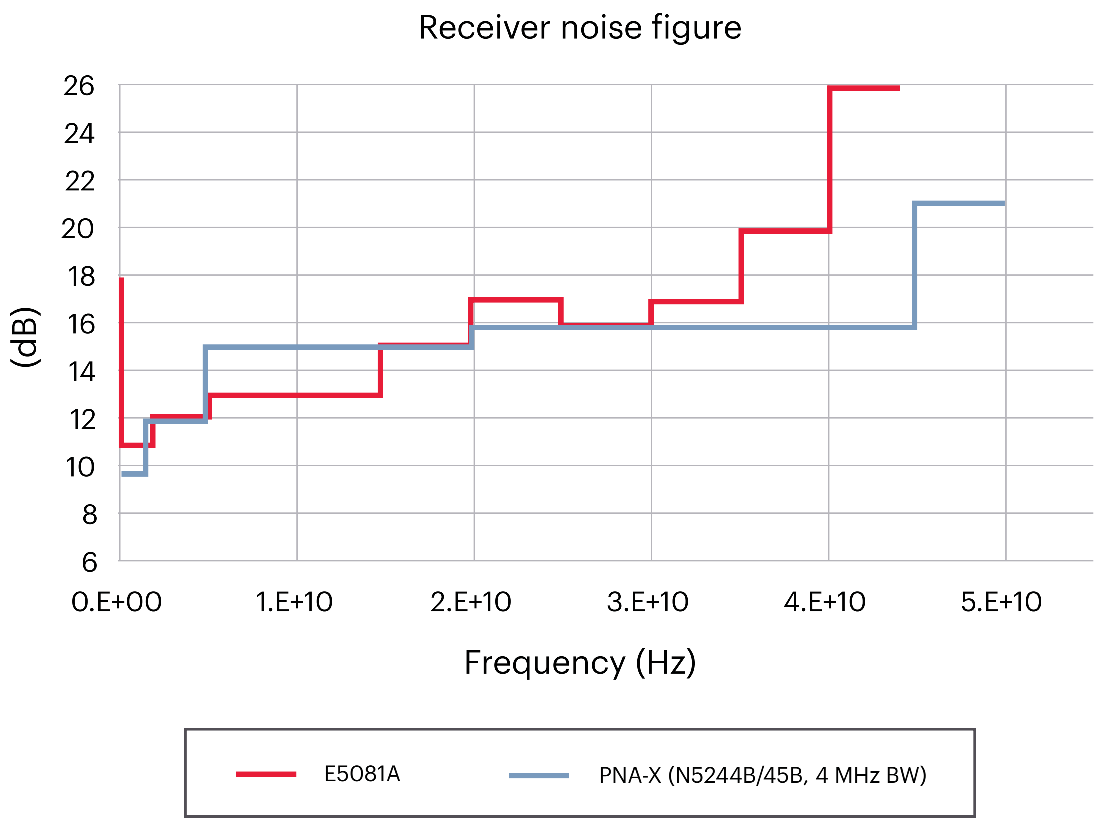


Figure 5. ENA-X exceeds PNA-X noise figure measurement performance up to 20 GHz and performs comparably up to 30 GHz

Linearity Testing Using Modulation Distortion Analysis Software

Multiple test setups inflate verification cycle time and introduce additional error potential. The signal quality of the test instruments limits the error vector magnitude (EVM) of the test system — known as the residual EVM. While this degree of inherent error was acceptable in previous communication systems, today's millimeter-wave transmission systems need precise measurement to certify performance compliance to stringent EVM requirements (3.5% in 256 QAM to 1% for 1000 QAM).

The ENA-X offers expanded software application features, which enable spectrum and signal analysis. This functionality makes fully vector-corrected modulated signal EVM and ACPR measurements available on the same setup used for CW and two-tone testing. The ENA-X employs the Keysight spectral correlation technique to directly analyze the modulated input and output signals in the frequency domain.

Figure 6 shows that by applying vector and source calibration to the EVM measurement, the VNA delivers the residual EVM by moving the reference plane to that of the DUT. This process means that the network analyzer removes all test system error contributions from the LNA EVM results.

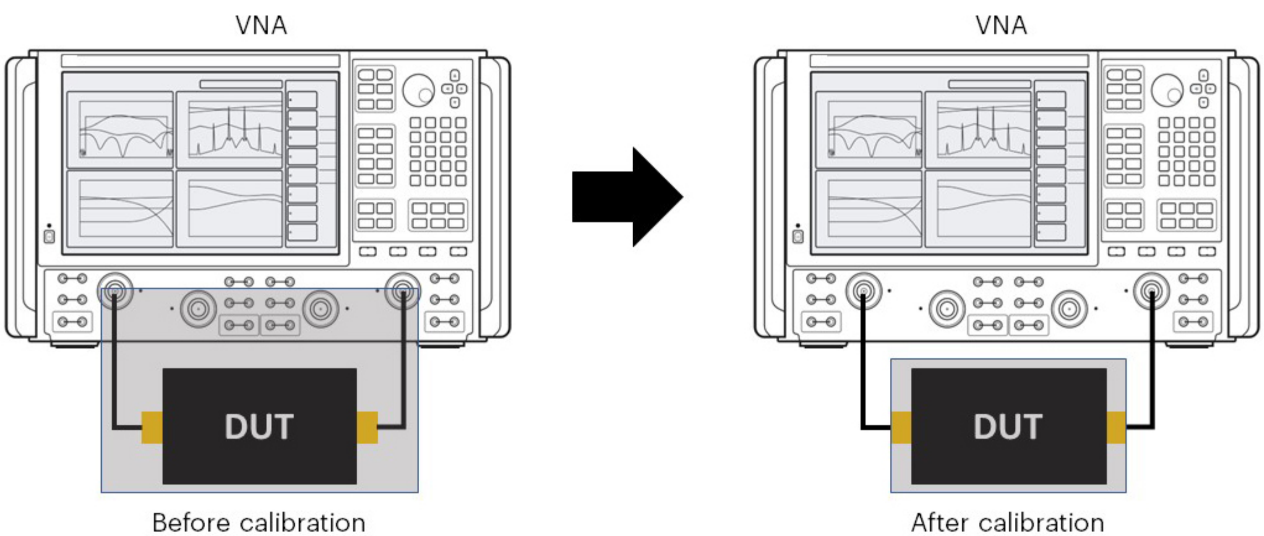


Figure 6. Before vector calibration, the VNA measures everything beyond its ports, including cables and connectors. After calibration, the VNA moves the test reference plane to that of the DUT, correcting for all fixtures.

The direct receiver access on the ENA-X network analyzer enables even more test set flexibility by enabling engineers to loop booster amplifiers or directional couplers into the measurement while maintaining the quality of the incident modulated signal and the VNA calibration of the internal receivers.

Conclusion

The performance of the LNA crucially impacts signal quality and receiver sensitivity across various industries and communication systems. To optimize receiver performance, engineers need dependable data from LNA noise figure, gain, and linearity measurements. However, conventional noise figure and EVM measurements require multiple setups, increasing test cycle time and complexity, as well as introducing potential error.

With the ENA-X network analyzer, avoid wasting valuable time manually reconfiguring setups or automating complex switch-based systems. The ENA-X network analyzer provides flexible hardware and advanced software capabilities that developers need to consolidate their test setup for robust characterization of LNAs. The VNA cold-source method and integrated low-noise receivers simplify the noise figure measurement setup while improving accuracy.

By combining vector and source correction, integrated hardware, and direct receiver access, an engineer can create a single test set. This test set is capable of executing accurate and repeatable CW, two-tone, and modulated signal measurements at the DUT’s reference plane. A single setup offers engineers realistic and repeatable LNA performance characterization under modulated stimulus in high-power systems operating at up to 44 GHz.

Related Literature

- High Accuracy Noise Figure Measurement Using a Network Analyzer - Application Note
- E5081A ENA-X Vector Network Analyzer – Data Sheet
- ENA and ENA-X Vector Network Analyzer – Configuration Guide
- Use the Right Vector Network Analyzer for the Job – Product Fact Sheet

Web Resources

- Keysight ENA Vector Network Analyzer
- Keysight Vector Network Analyzer Software
- Keysight Electronic Calibration (ECal) Module