WHITE PAPER

Tackling Millimeter-Wave Signal Analysis Challenges

Introduction

Millimeter-wave technology transforms wireless communications. Next-generation 5G, satellite, and automotive radar communications achieve higher data throughput and super-fine range resolution using ultra-wide bandwidth. Millimeter-wave technology is a key enabler and provides ample margin for performance improvement, but it creates challenges such as path loss, tight design margins, complex modulation, and stringent standards.

At millimeter-wave frequencies, excessive path loss makes radio-frequency (RF) power limited and costly. Also, measuring performance metrics using over-the-air (OTA) test methods makes achieving accurate and repeatable results more difficult. Wide bandwidths enable high-throughput data, range resolution and accuracy, and low latency but also introduce more noise. The excessive path loss and noise increase test complexity and measurement uncertainties.

This paper discusses key considerations when tackling the test challenges for today's and tomorrow's millimeter-wave applications.

Millimeter-Wave Test Challenges

Wireless technologies increase signal bandwidth and use higher-order modulation schemes to achieve faster data rates. Wider bandwidth is an alluring millimeter-wave feature. However, wider bandwidth and higher-order modulation schemes introduce challenges related to link quality requirements at millimeter-wave frequencies. Any skew in a flange connection can cause unwanted reflections that degrade signal quality and power. Engineers need to take extra care to evaluate millimeter-wave components and devices accurately.

Excessive path loss

At millimeter-wave frequencies, the excessive path loss between instruments and devices under test (DUTs) results in a lower signal-to-noise ratio (SNR). Lower SNR makes signal analysis measurement, such as error vector magnitude (EVM), adjacent channel power, and spurious emissions, challenging.

The components are also compact and highly integrated with no place to probe, resulting in the need for radiated tests, also known as OTA tests, as shown in Figure 1. The signal level decreases dramatically and requires you to control and calibrate the radiated environment around the test setup.

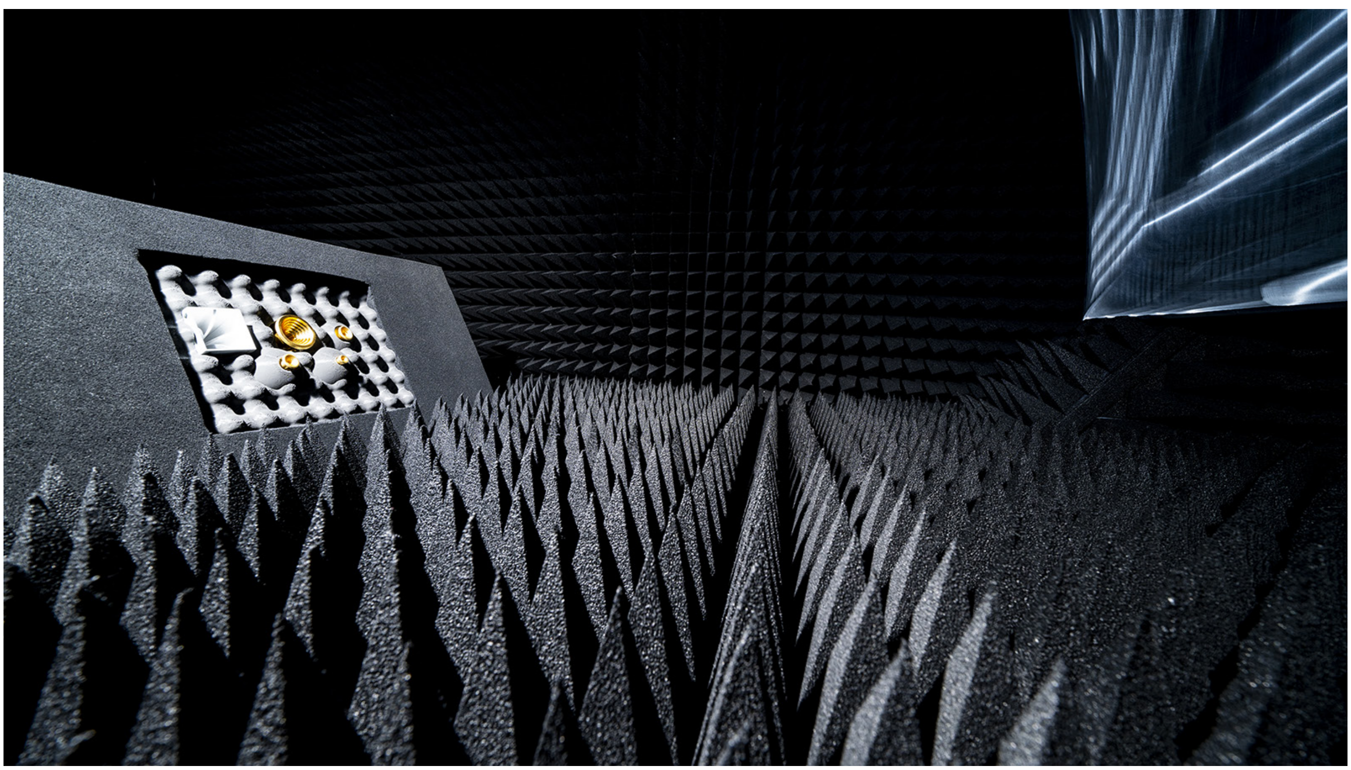

Figure 1. An OTA test chamber

Wideband noise

Millimeter-wave frequency bands provide wider available bandwidths. However, a transmit signal needs to compete with the channel's noise floor to get better sensitivity at a receiver. Similarly, increasing analysis bandwidth introduces more noise to a signal analyzer. The noise reduces the SNR in measurements and makes accurate millimeter-wave measurements more difficult.

Frequency responses

A test system's key objective is to characterize a DUT. The system must isolate the DUT's measured results from all other test segment effects. When you build a test system, components between a signal analyzer and a DUT — such as mixers, filters, and amplifiers — contribute to frequency responses. These responses occur at different frequencies and include amplitude and phase errors. The errors in the amplitude and phase of the modulated signal degrade modulation quality. The frequency responses get worse when you test signals with wider bandwidths and higher frequencies. Figure 2 illustrates an orthogonal frequency-division multiplexing signal with poor frequency responses (on the left) and flat frequency responses (on the right).

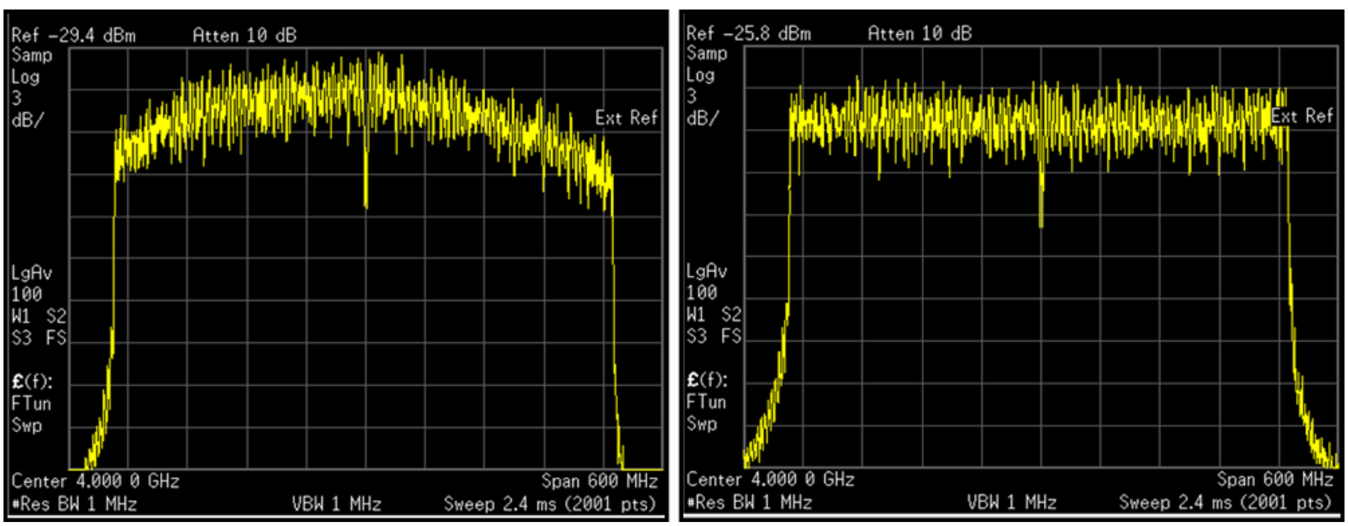

Figure 2. Frequency responses' impact on frequency domain

Reduce Signal Path Loss

Whether you're assessing transmitters, troubleshooting receivers, or analyzing OTA signals, the flexibility of signal analyzer hardware and software lets you create the optimum solution. Input signals could be high power to noise-like, low-frequency to terahertz, and a continuous wave to complex wideband modulation. To measure the variety of input signals, signal analyzers can apply attenuation at higher power levels or a preamplifier at lower power levels. Signal analyzers provide several RF signal paths — such as default path, microwave preselector bypass, low-noise path, and full-bypass path — to lower noise, improve sensitivity, and reduce signal path loss for a better SNR.

Default path — measuring low-level signals

Figure 3 shows the normal signal path of a signal analyzer. The input travels through the RF attenuator, preamplifier, and preselector before reaching the mixer. This is the default path. It is most useful for measuring low-level signals with a bandwidth under 45 MHz, limited by the bandwidth of the preselector.

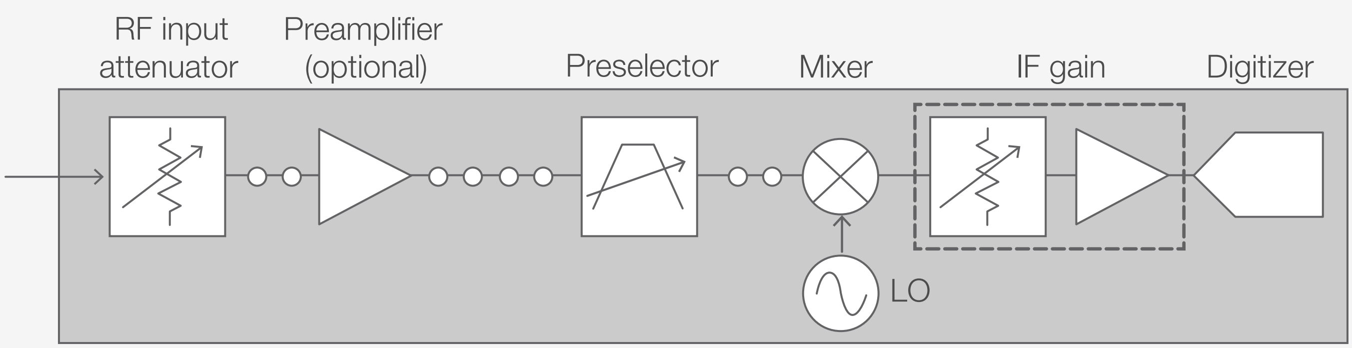

Figure 3. The RF default path of a signal analyzer

Microwave preselector bypass — analyzing wideband vector signals

The RF preselector has a limited bandwidth of 45 to 70 MHz, depending on the tuned frequency for image-free analysis. However, the bandwidth limits the RF analysis bandwidth. Bypassing the preselector enables a wideband analysis and a flat spectrum response over the bandwidth of the digitizer, as shown in Figure 4. Also, it improves amplitude accuracy without the amplitude drift and passband ripple of the preselector. Bypassing the microwave preselector allows you to measure wideband signals, such as 5G, satellite communications, 802.11ax / be, and radar signals.

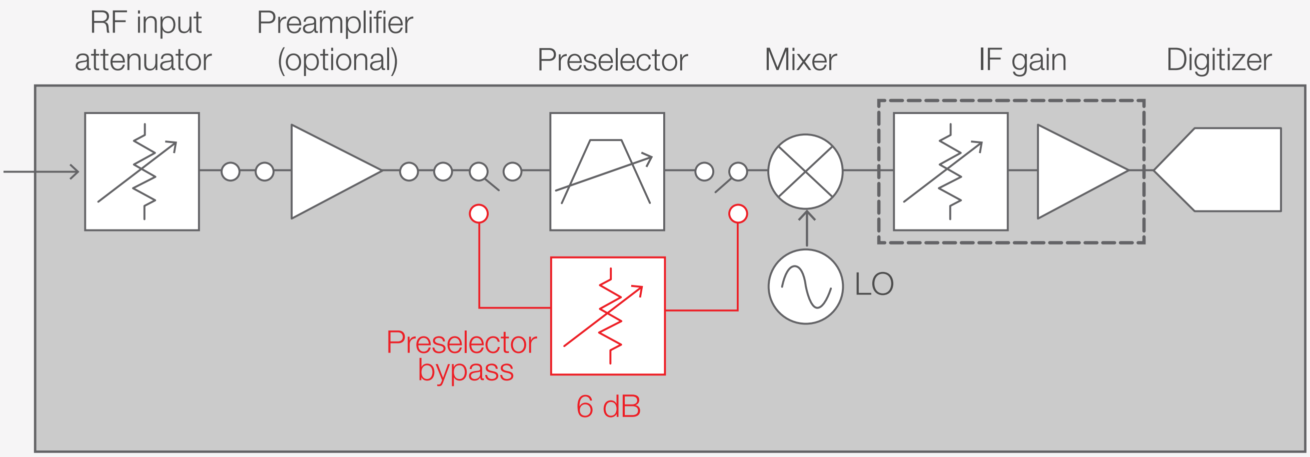

Figure 4. The microwave preselector bypass path

When the input signal includes strong out-of-band signals, such as testing a mixer with local oscillator (LO) leakage or spurs, these signals can lead to imaging and in-band interference in the analysis bandwidth. The images may cause the measurement to fail. Using a bandpass filter at the input of the signal analyzer can avoid these unwanted signals.

Low-noise path — improving modulation analysis

When testing transmitter modulation quality at higher power levels, such as EVM measurements, you can choose a low-noise path, bypassing the lossy switches in the preamplifier path and the preamplifiers, as shown in Figure 5. At higher frequencies, the gain of the amplifier, frequency responses, and insertion loss get worse. This optimal path reduces path loss and eliminates frequency responses and noise caused by the preamplifiers and switches. That process improves signal fidelity and measurement sensitivity for optimizing wideband EVM measurement results at higher frequencies.

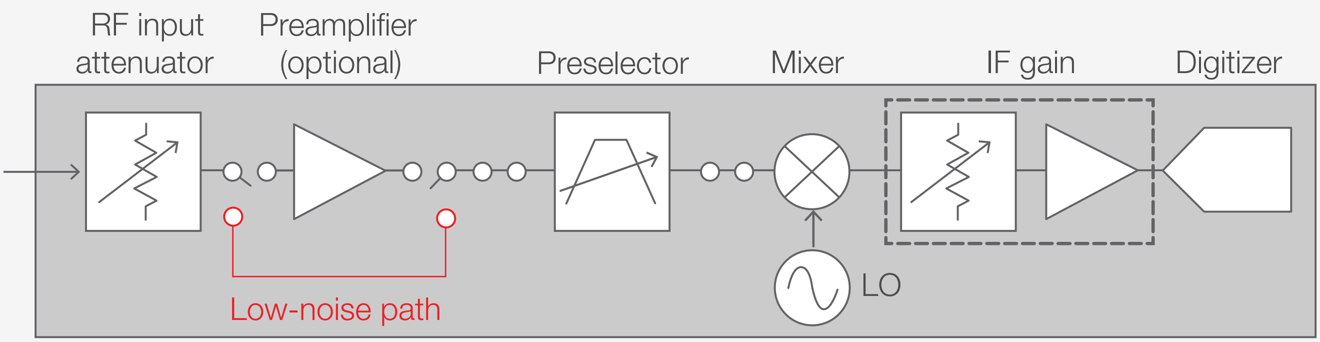

Figure 5. The low-noise path bypasses lossy switches in the preamplifier path

For lower-power-level testing, such as OTA tests, you still need an internal or external preamplifier to achieve enough SNR for modulation analysis.

Full-bypass path — testing wideband modulation analysis

Figure 6 illustrates the full-bypass path, which combines the low-noise path with the microwave preselector bypass path. This RF path avoids multiple switches in the low-band switch circuitry and bypasses the microwave preselector. At millimeter-wave frequencies, the full-bypass path has up to 10 dB less loss than the default path.

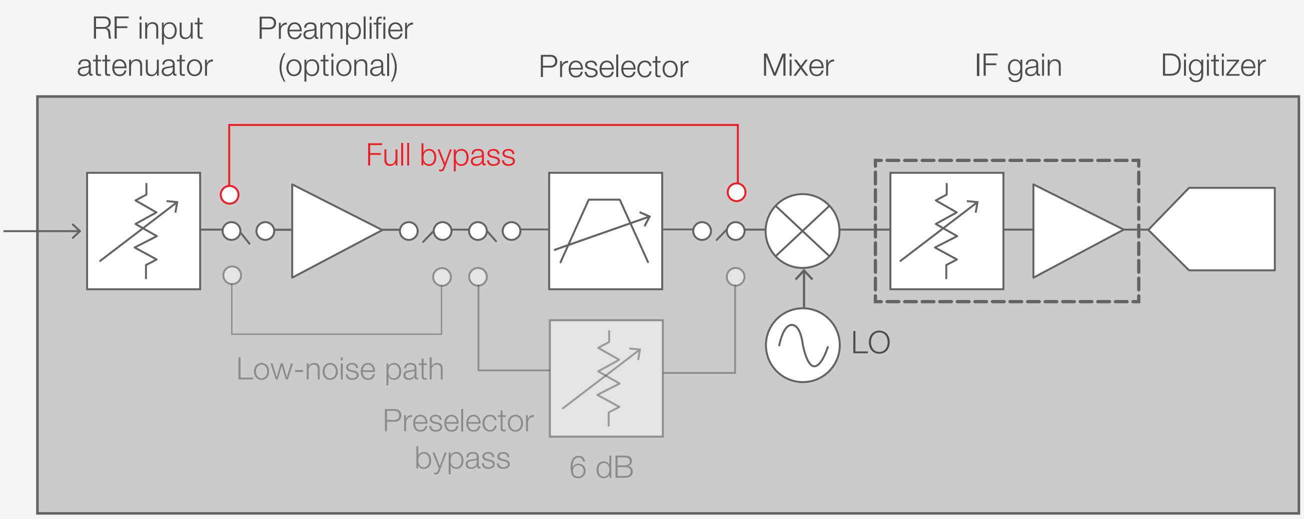

Figure 6. The full-bypass path goes around the preamplifier and the preselector

The full bypass has the advantage of less path loss, signal fidelity, and measurement sensitivity. However, it also brings a few downsides, including in-band imaging and low SNR for testing lower power levels. Adding a bandpass filter can improve 1 to 2 dB EVM results by eliminating images in the band of interest. Also, adding an external preamplifier can improve SNR when testing a lower-power-level signal.

> **Learn more about reducing signal path loss for a better SNR, download the application note Full Bypass Path for X-Series Signal Analyzers.**

External mixing — extending frequency range and measurement plane

When you build a millimeter-wave test system, cables and accessories in the paths between the signal analyzer and the DUT increase insertion loss. The cable loss can be up to 5 dB and can reduce the SNR of the test system. Adding an external mixer is a cost-effective way to extend the frequency range of a signal analyzer. This allows you to move the mixer close to the DUT to shorten the millimeter-wave signal routing — reducing the path loss and improving SNR.

The analyzer supplies a microwave LO signal to the external mixer and receives an intermediate frequency (IF) signal from the mixer. The analyzer further processes the IF signal with filtering, digitizing, analysis, and display operations similar to those for internal mixed signals. Keysight’s USB smart mixers simplify connection and measurement setups. The analyzer can detect the mixer, automatically download the conversion coefficient, and monitor drive levels. Figure 7 shows a signal analyzer frequency extension solution with an external mixer.

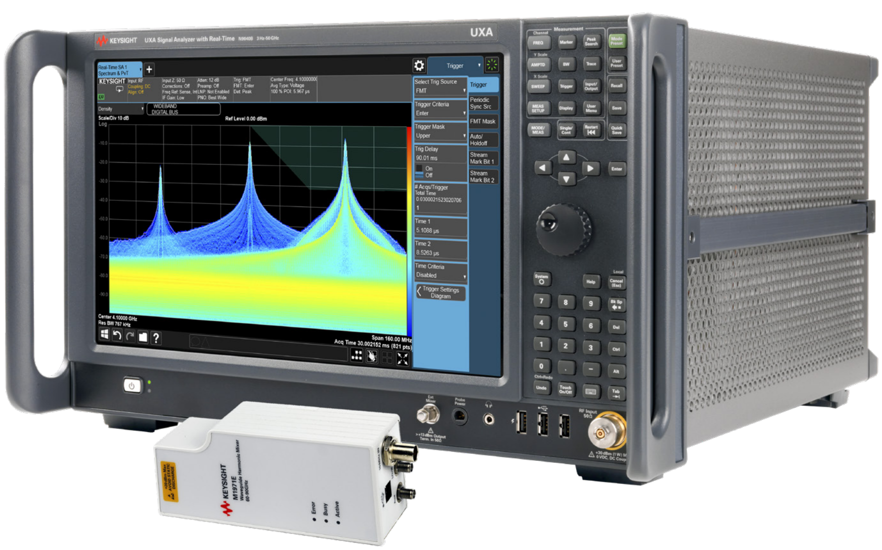

Figure 7. Move the first mixing stage outside the analyzer with a smart mixer

For production test, millimeter-wave test system integrations and test costs create higher barriers from research and development to volume production. A banded solution is a common approach to high-volume production tests. For example, an RF vector signal analyzer (VSA) and an RF vector signal generator (VSG) are essential for 5G frequency range 1 (FR1) in-band RF test cases. The VSA and VSG can be an IF signal analyzer and signal generator, coupled with an external millimeter-wave transceiver for FR2 in-band tests, as shown in Figure 8. This approach is less costly than using a high-performance microwave signal analyzer and signal generator.

Figure 8. Keysight's S9130A 5G performance multiband vector transceiver covers 5G FR1 and FR2

External mixing provides a cost-effective solution for millimeter-wave signal analysis and moves the test port close to the DUT. However, there is no preselector at the front end of the mixer. Strong out-of-band signals may lead to unwanted images in the band of interest and degrade measurement accuracy. When measuring frequency outside of the mixer's frequency band (for example, the frequency range of the Keysight M1970W is 75 to 110 GHz), you need to reconnect the test signal to the signal analyzer's RF input port or another mixer with a different band. Then you need to change the input source from the operation interface correspondingly. These steps increase test complexity and measurement uncertainty.

Keysight's V3050A advanced external frequency extender integrates a preselector and an RF switch into a high-dynamic-range mixer with the seamless operation interface of the signal analyzer, as shown at the center of Figure 9. This solution enables unbanded and preselected swept power spectrum from 2 Hz to 110 GHz without managing band breaks and images. For the vector mode, the IF bandwidth can be up to 11 GHz. You can also get the most out of your measurement and see the real performance of your device by removing magnitude and phase errors in the measurement setups up to 110 GHz with the Keysight U9361 RCal receiver calibrator, as shown at the right of Figure 9. We will discuss system calibration later.

Figure 9. Keysight's V3050A frequency extender (center) and U9361 RCal receiver calibrator (right) innovate millimeter-wave test and measurement

Improve Signal Condition

Exponential growth in demand for faster-data-rate applications triggers the need for technologies capable of wide signal bandwidth at higher frequencies. Unfortunately, wider bandwidths also gather more noise. Wideband noise and excess path loss at millimeter frequencies between signal analyzers and DUTs result in a lower SNR for the digitizer. The low SNR causes the transmitter measurements to have a poor EVM and adjacent channel power ratio performance, which does not represent the DUT's performance.

Figure 10 is a simplified block diagram of a VSA. When making EVM measurements, you need to set optimum levels for the signal analyzer's input mixer, the phase noise configuration of the LO, and the digitizer to achieve the best results. Each of these components has its constraints and use cases.

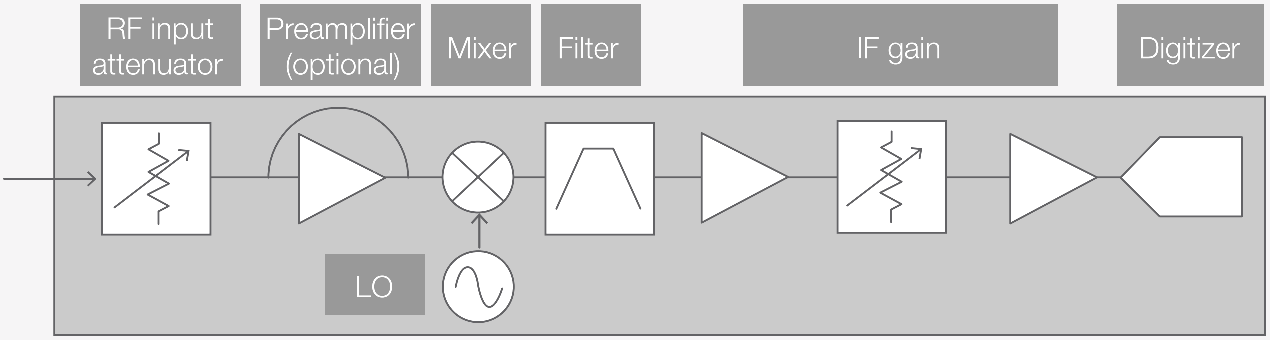

Figure 10. A signal analyzer block diagram

Optimize input mixer level

All wireless standards specify transmitter measurements at the maximum output power. You can attenuate the power level at the first mixer of a signal analyzer to ensure that the high-power input signal does not distort the signal analyzer. In scenarios such as OTA tests and test systems with huge insertion loss, the input signal level can be lower than the optimum mixer level. A built-in preamplifier provides a better noise figure but a poorer intermodulation-distortion-to-noise-floor dynamic range. You can enable this setting for low-input-level test scenarios.

The input mixer-level setting is a trade-off between distortion performance and noise sensitivity. You can achieve a better SNR with a higher input mixer level or better distortion performance with a lower input mixer level. The best mixer-level setting depends on the measurement hardware, characteristics of the input signal, and specification test requirements.

You can also apply an external low-noise amplifier (LNA) at the front end, with or without the internal preamplifier, to optimize the input level of the mixer. Keysight's new signal analyzer provides a built-in LNA and preamplifier for various test scenarios, as shown in Figure 11. The two-stage gain delivers greater flexibility to balance noise and distortion for optimizing the best low-input-level measurement performance.

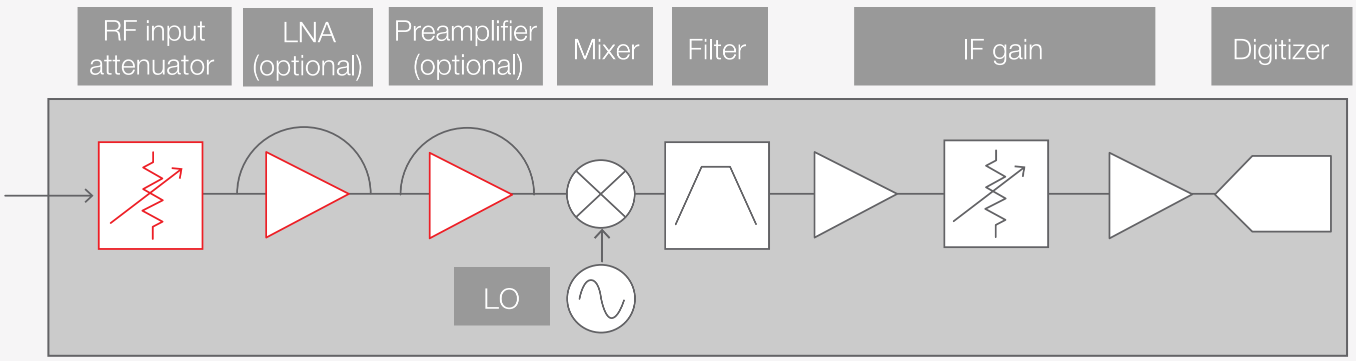

Figure 11. The built-in LNA drives down the noise, and the two-stage gain delivers greater flexibility to balance noise and distortion

Optimize SNR for an IF digitizer

The system IF noise of a signal analyzer must be low enough to get the best EVM measurement results. At the same time, the input signal to the digitizer must be high enough without overloading the digitizer. This balance requires a combination of RF attenuator, preamplifier, and IF gain value based on the measured signal peak level.

New signal analyzers let you press a single key to optimize these hardware settings, improving SNR and avoiding digitizer overload, as shown in Figure 12. The optimization processing requires measuring the signal peak level and setting up the analyzer. However, the measured period may not represent the complete power characteristics of the input signal. A user can manually tweak the settings, such as IF gain and RF attenuators, to achieve the best measurement results.

Learn the best practices for accurately making and optimizing EVM measurements, download the white paper Three Best Practices for Optimizing EVM Measurements for Wideband Signal.

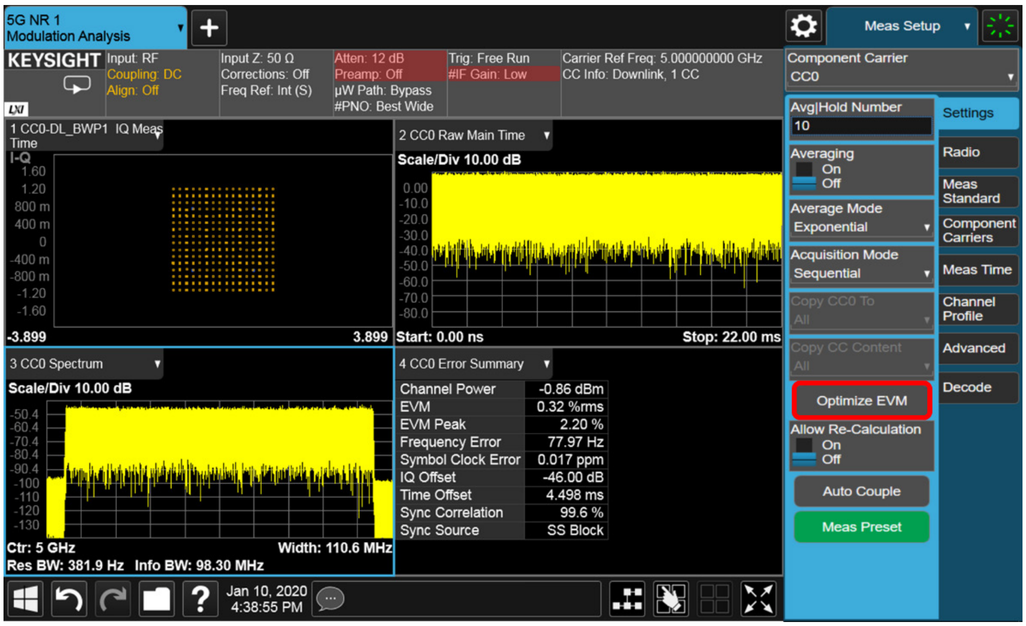

Figure 12. Optimizing EVM measurements for 5G NR modulation analysis

Move Reference Plane to Your DUT

The instrument's specifications determine the accuracy of the test equipment or signal analyzer. The signal analyzer's specifications are valid up to the instrument's input or output connectors, where the instrument sets the reference plane. Outside the test instrument, you need to consider the impact of the components in the path between the test instrument and the DUT. The impact may degrade the system's overall measurement accuracy.

As bandwidths grow wider and frequencies soar to millimeter wave and beyond, small margins for error on wideband measurements force RF engineers to look for new ways to reduce frequency response errors. The responses occur at different frequencies, affecting phase and amplitude responses. A signal analyzer provides an internal calibration routine to correct its frequency responses.

When you connect cables, connectors, switches, and fixtures in the paths between the signal analyzer and the DUT, these components can degrade measurement accuracy because of frequency response errors. You need to extend the measurement accuracy from the signal analyzer's input port (reference plane) to the DUT's test port (measurement plane), as shown in Figure 13. Signal analyzers allow you to configure amplitude corrections and complex corrections (amplitude and phase) to remove frequency responses. Correcting for magnitude and phase errors in the test network allows you to get the most out of your measurement and see the real performance of your device.

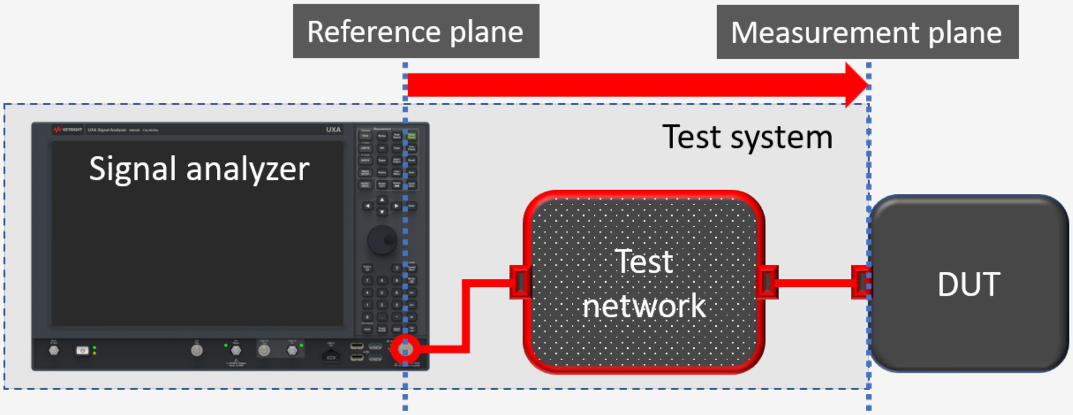

Figure 13. Consider the test network elements for channel correction

Using a signal generator and power sensor for amplitude corrections

Signal analyzers allow you to configure amplitude corrections and complex corrections, including amplitude and phase corrections, to correct frequency responses. For amplitude corrections, you can measure the amplitude frequency responses of the test network using a signal generator plus a power meter and sensor, then input the correction values to the signal analyzer.

Use a vector network analyzer for complex corrections

For complex corrections, you can make frequency response measurements of the test network using a vector network analyzer and save the measurement results in the .s2p format. Keysight X-Series signal analyzers allow you to load the .s2p file and correct amplitude and phase frequency responses.

Use a comb generator for complex corrections

Another calibration tactic is using a comb generator. The comb generator is a universal receiver system calibrator easily injected at the desired calibration plane (the input of the test network). It generates continue wave (CW) tones of known amplitude and phase, as shown in Figure 14. A signal analyzer measures each tone's amplitude and phase at the output of the test network and compares them to the known amplitude and phase. Figure 15 shows a channel response of magnitudes and phases of a test network.

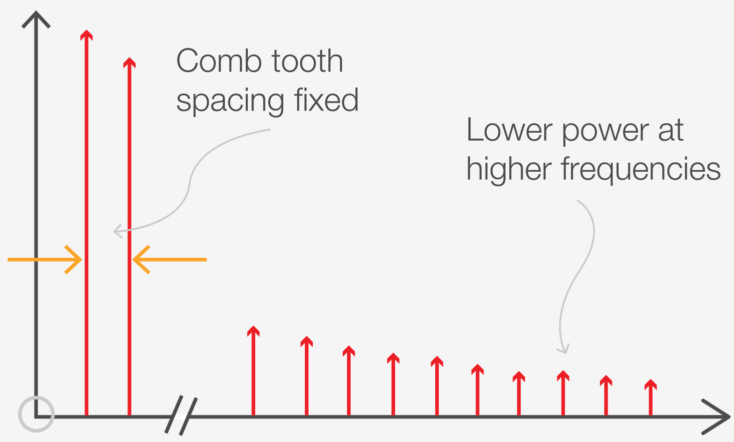

Figure 14. The comb generator produces CW tones of known amplitude and phase

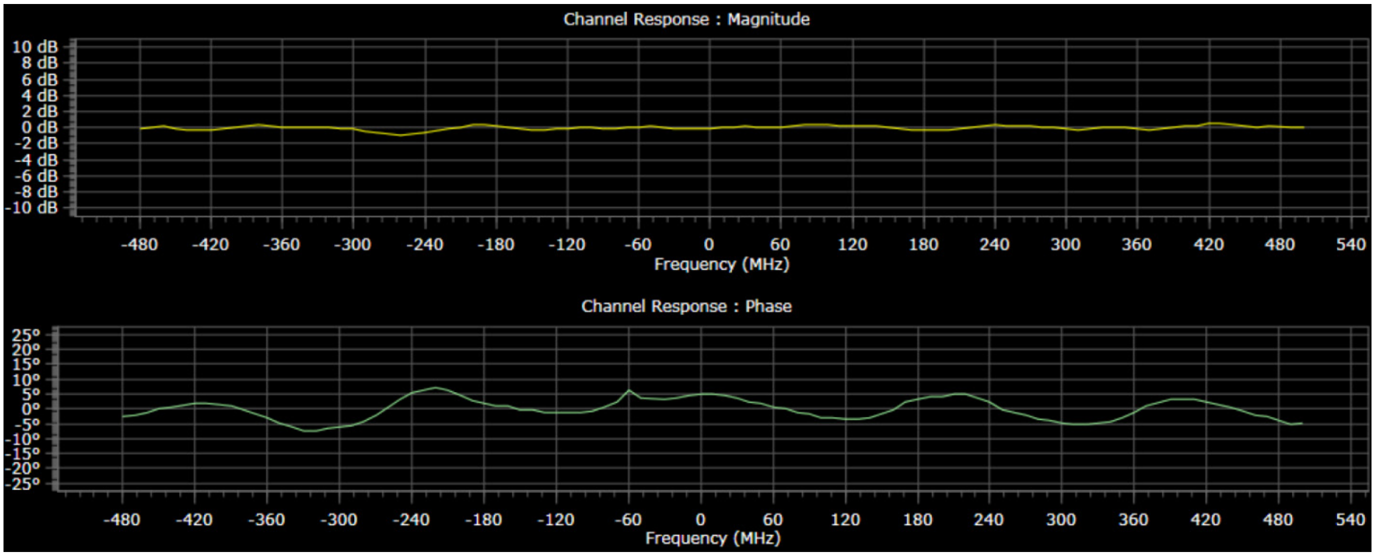

Figure 15. Measured frequency responses of a test network

Use an RCal receiver calibrator

The U9361 RCal receiver calibrator brings accuracy, efficiency, and value to the calibration of your test receiver system by allowing you to move the reference plane to the DUT. Unlike the comb generator with a fixed tone spacing and lower power at higher frequencies, RCal can change the center frequency, and the spacing of the comb tooth is tunable, as shown in Figure 16. It is beneficial when testing wider bandwidths at higher frequencies.

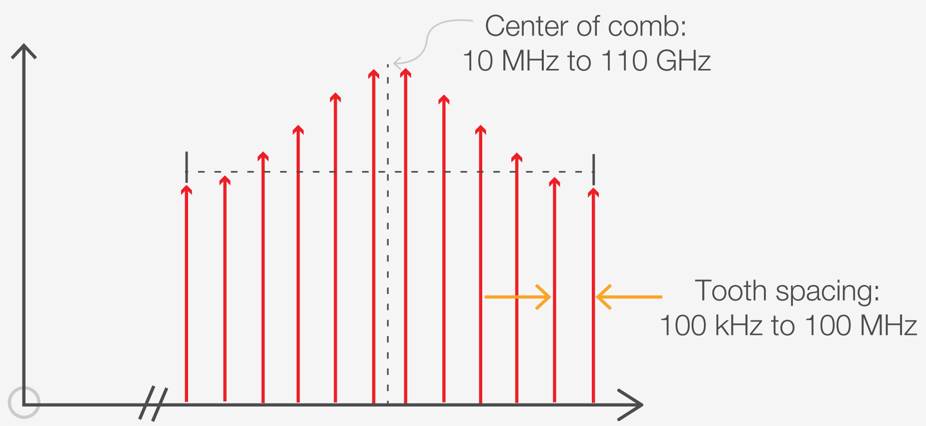

Figure 16. The RCal receiver calibrator generates tones with tunable center frequency and tone spacing

To keep your test setup efficient with the palm-sized, USB-powered and -controlled RCal, the calibrator automatically transfers data from the memory to the signal analyzer through the USB plug-and-play feature, as shown in Figure 17. The analyzer also auto-detects the model, serial number, and options present on the calibrator. This setup can reduce the effort and complexity required to calibrate your test receiver system.

Learn about how to improve signal analyzer test accuracy, download the application note **The Essential Guide to Receiver Calibration.**

Figure 17. A signal analyzer with a palm-sized, USB-powered and -controlled RCal

The RCal allows you to correct absolute power accuracy, magnitude flatness, and phase flatness with a single device. RCal eliminates the need for multiple pieces of equipment to calibrate your signal analyzer measurement system.

Advance Your Millimeter-Wave Measurements

Next-generation wireless communication systems such as 5G, satellite, and automotive radar require higher frequency, wider bandwidth, and more complex modulation. You face new challenges, including increased test complexity, measurement uncertainty, excessive path loss, and noise, that impact your device's performance.

Keysight can help you be certain of your device's performance with test solutions that provide greater visibility, accuracy, and repeatability, so you can focus on your next breakthrough.

Learn more at: www.keysight.com

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