WHITE PAPER

The Essential Signal Generator Guide

Building a solid foundation in RF — Part 1

KEYSIGHT

Eliminate Uncertainties from Your Test Results with a Reliable Signal Source

Engineers designing consumer wireless, military communications, or radar devices face an ongoing bandwidth crunch in spectrum filled with interference. An accurate signal generator offers precise and stable test signals for characterizing your device under test (DUT). It also lets you apply impairments to help you test your design within and beyond its limits.

Getting to market faster with test results you can trust starts with selecting the right test instrument for the job. Our two-part series will help you better understand how signal generators work and which key specifications are critical for your projects.

Part 1 introduces you to the inner workings of the signal generator. It provides a deeper look at basic specifications such as power, accuracy, and speed. Part 2 covers more advanced features such as modulation, spectral purity, and distortion.

Contents

Section 1. What Is a Signal Generator?

A signal generator is a source that outputs a signal. This signal can be a basic sinusoidal wave, a pulse, or a modulated signal. Also called a signal source, this instrument enables you to output signals at various frequencies, amplitudes, and times.

What does a signal generator do, and why is it important?

Engineers use signal generators to test components, receivers, and systems for various applications throughout the product development cycle. The output signal can be as simple as a continuous wave (CW) or as complex as a digitally modulated signal. The signal generator simulates signals at various stages of communication systems. Figures 1-1 and 1-2 show common signal generator use cases for component and receiver tests.

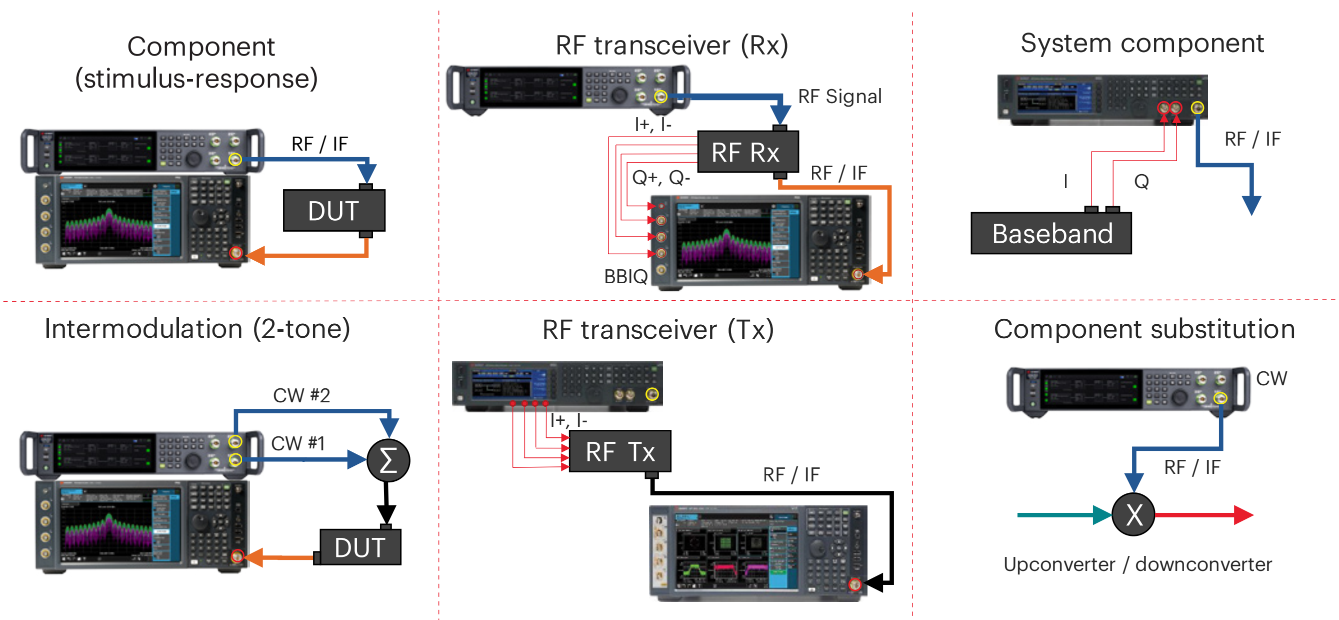


Figure 1-1. Signal generator use cases for component characteristic tests or a system component

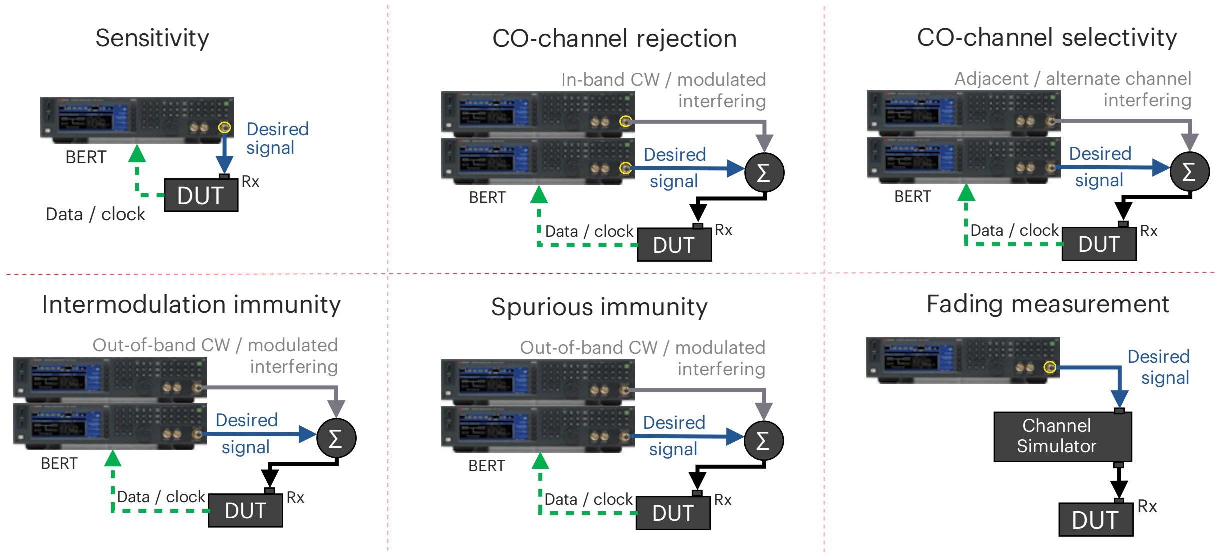


Figure 1-2. Signal generator use cases for receiver sensitivity tests

Why is a signal generator important? Signal generators produce precise and stable test signals for characterizing your DUT. They can simulate different kinds of signals, from digital IQ to high-frequency signals. A signal generator can also apply impairments to characterize your device's behavior and test your design within and beyond its limits.

Types of signal generators

Signal generators can be classified based on their form factor and capabilities.

Form factor: Benchtop or modular?

The most common signal generator form factor is benchtop. These instruments typically sit on benches and in racks. Benchtop signal generators are well-suited for research and development (R&D), where engineers use the front-panel controls to analyze and troubleshoot devices.

Portable signal generators are a popular subgroup in the benchtop category. R&D labs typically invest in portable benchtop signal generators to maximize asset utilization while improving cost-effectiveness. Because of their compact size, portable signal generators are easier to share among several benches. R&D labs often use advanced benchtop units and portable units in tandem to minimize cost per port.

The PXIe modular form factor signal generators are compact instruments housed in a PXIe chassis and controlled using a PC. Engineers can put several PXIe signal generators in a single chassis, making them suitable for applications that require multichannel measurement capabilities, fast measurement speed, and a small footprint. A PXIe signal generator often uses the same software applications as a benchtop signal generator, providing measurement consistency and compatibility from product development to manufacturing and support.

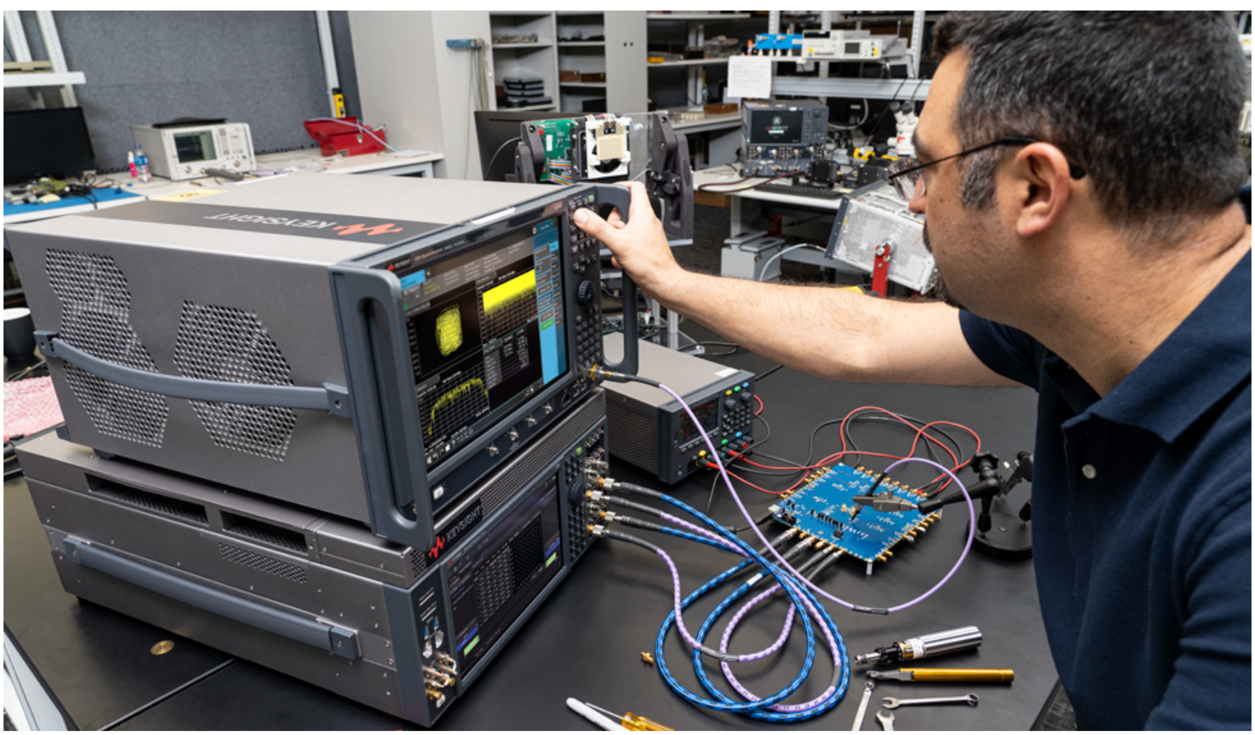
Figure 1-3. Benchtop and PXI modular signal generator

Capabilities: Analog, vector, and agile signal generators

Analog signal generators supply sinusoidal CW signals and several types of analog modulation, such as amplitude, frequency, and pulse modulation. Analog signal generators cover a frequency range from RF to microwave. Most generators feature step / list sweep modes for passive device characterization or calibration.

Vector signal generators add the ability to create digital modulation schemes. Traditional vector signal generators have a built-in baseband IQ modulator to generate complex modulation formats, such as quadrature phase-shift keying, quadrature amplitude modulation, or more complex orthogonal frequency-division multiplexing signals. Some next-generation vector signal generators replace the IQ modulator with direct digital synthesis technology to produce the same complex formats with higher signal fidelity and better overall modulation quality. Combining the system with an IQ baseband generator enables the emulation and transmission of virtually any signal within the supported modulation bandwidth.

Optimized for speed, agile signal generators can quickly change the frequency, amplitude, and phase of the signal. They also have the unique capability to be phase-coherent at all frequencies at all times. This attribute, along with extensive pulse modulation and wideband chirp capabilities, makes them ideal for electronic warfare (EW) and radar applications.



Overview of key specifications

To select the right signal generator for your project, you need to understand its performance specifications. Specifications tell you about the capability of your signal generator. Let's explore the major specifications: frequency, amplitude, and spectral purity performance.

Frequency specifications

The frequency specification defines the range, resolution, accuracy, and switching speed of your signal generator.

- Range refers to the maximum and minimum frequencies your signal generator can output.
- Resolution is the smallest frequency change.
- Accuracy describes how close the source's output frequency is to the set frequency.
- Switching explains how fast the output settles to the desired frequency.

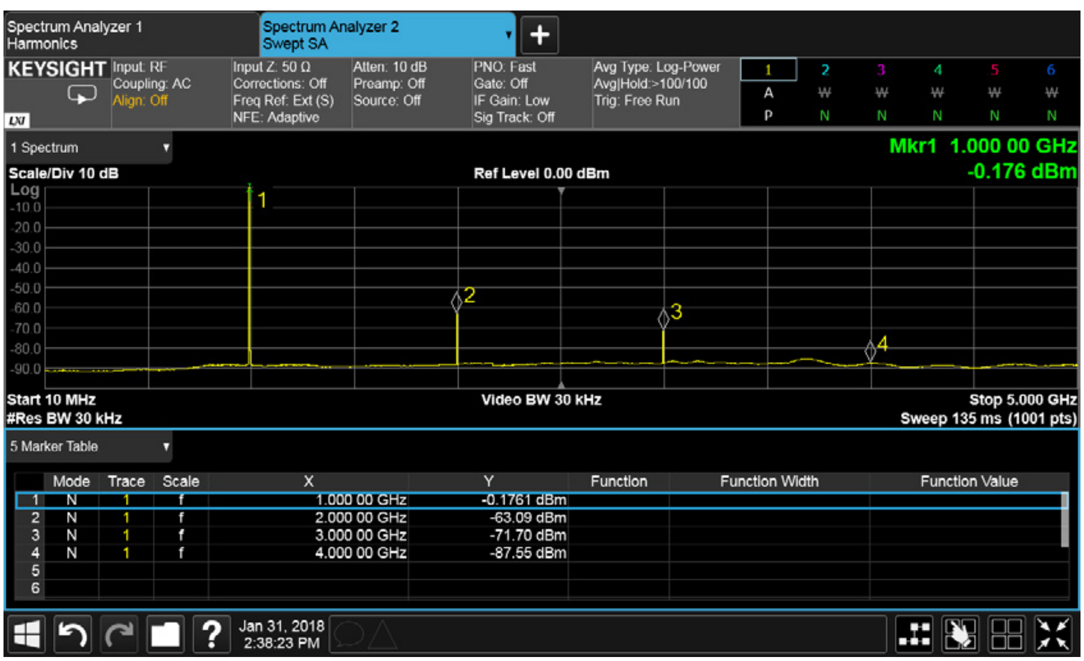


Figure 1-4. Spectrum analysis with frequency and amplitude readouts

Amplitude specifications

Amplitude specifications include range, resolution, and switching speed.

- Range is the difference between the maximum and minimum output power capability of the signal generator. The signal generator's output attenuator design determines its range. The output attenuator enables the signal generator to produce extremely small signals used to test a receiver's sensitivity.
- Resolution is the smallest possible power increment.
- Switching speed describes how fast the source can change from one power level to another.

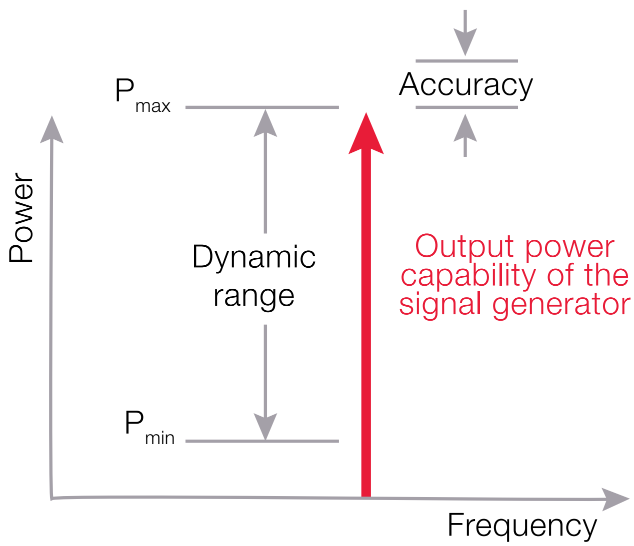


Figure 1-5. Power output range and accuracy

Spectral purity

Spectral purity is a signal's inherent stability. A perfect signal generator creates a sinusoidal wave at a single frequency without the presence of noise. However, signal generators consist of nonideal components that introduce noise and distortion. The specifications associated with spectral purity are often the most difficult to understand. These specifications include phase noise, harmonics, and spurs, as shown in Figure 1-6.

- Phase noise is a frequency-domain view of the noise spectrum around the oscillator signal. It describes the frequency stability of an oscillator.
- Harmonics refers to integer multiples of the sinusoidal fundamental frequency output. Nonlinear characteristics of components used in the signal generator cause these harmonics.
- Spurs are nonrandom or deterministic signals created from mixing and dividing signals to get the carrier frequency. These signals may be harmonically or nonharmonically related to the carrier.

Download our signal generator selection guide to learn more about Keysight's comprehensive portfolio of signal generators.

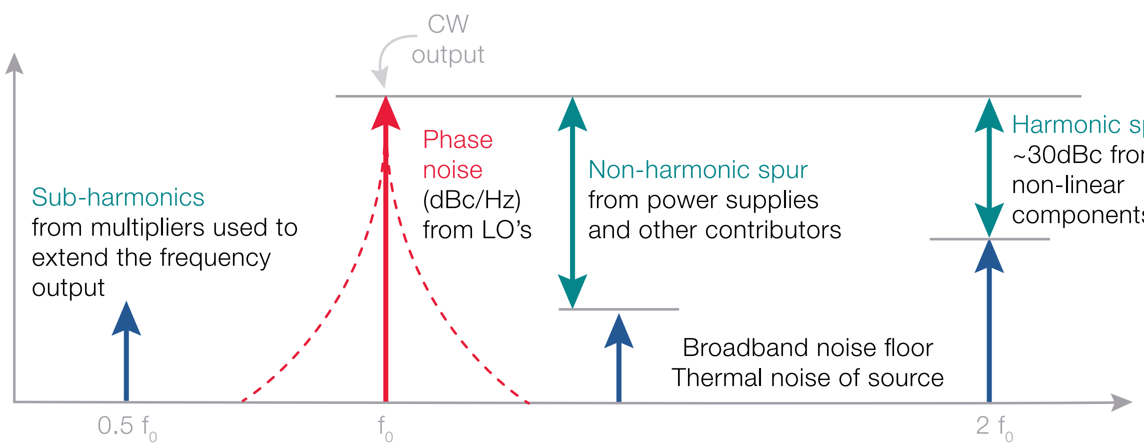


Figure 1-6. Various nonideal spectral components

Section 2. Power

Signal generators provide precise and stable test signals for various component and system test applications. An important specification of any signal generator is the output power range. Often, signal generators need output signals as low as -120 dBm in receiver sensitivity testing and as high as +20 dBm in RF power amplifier testing. They must also achieve this wide dynamic range while meeting key specifications such as accuracy, spectral purity, and noise.

There are several types of power to consider, including average power, envelope power, and peak envelop power (PEP). But before we look at each of these in detail, let's first understand the basics of power.

What is power?

The International System of Units defines the watt (W) as a unit of power — 1 W is one joule per second, used to quantify the rate of energy transfer. At direct current (DC) and low frequencies, voltage and current measurements are simple and straightforward. Power (P) is the product of voltage (V) and current (I).

For low-frequency signals, both voltage and current, vary with time. The energy transfer rate (instantaneous power) also varies with time. In Figure 2-1, the blue curve represents instantaneous power shifts around cycles. Calculate average power by integrating the area under the P curve.

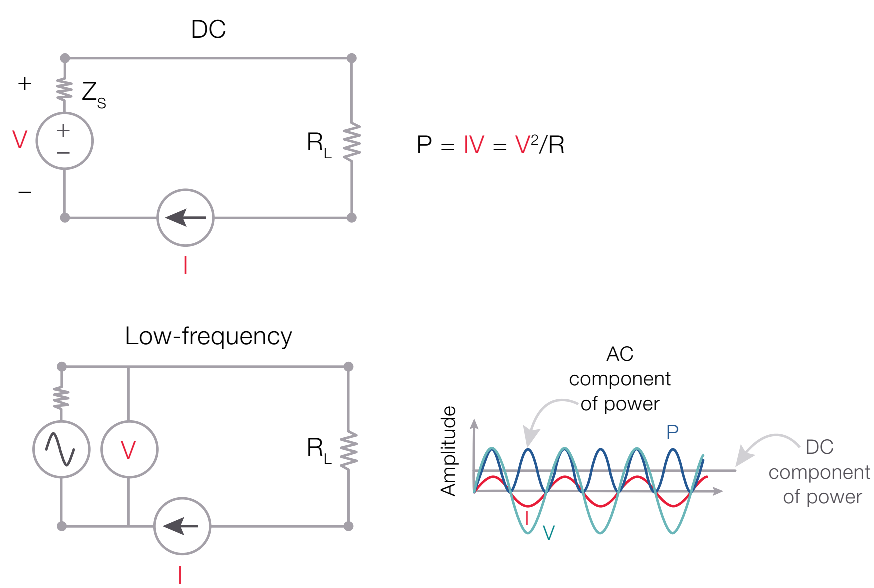


Figure 2-1. DC and low-frequency power measurements

However, as frequency increases, voltage and current measurements become difficult and impractical, so engineers measure power directly. Figure 2-2 represents three CWs with the same voltage level but different frequencies. Pi (green curve) is instantaneous power that varies with time, while Pavg (red line) is average power. Notice that average power remains constant and independent of frequency, making it suitable for high-frequency signals. Let's take a closer look at definitions of power for RF measurements.

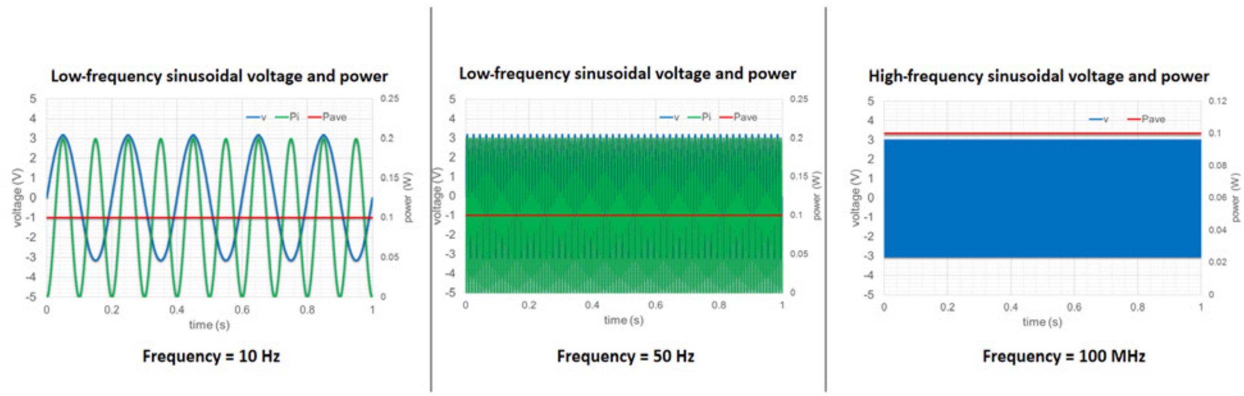


Figure 2-2. Low- and high-frequency power measurements

Average power

As frequency increases, impedance varies. RF engineers commonly use the term average power to specify all RF and microwave systems because instantaneous power variations are too fast to be meaningful. Average power is the average energy transfer rate across many periods of the lowest frequency.

Envelope power and peak envelope power

For some applications, engineers examine the effects of modulation or transient conditions without examining the details of the RF carrier waveform. Figure 2-3 illustrates high-frequency modulated signal power measurements. The upper graph represents the voltage envelope of the modulated signal. The lower left graph shows the instantaneous power of the signal in green and the average power in red. You can measure the envelope power by averaging the power over a period that is long compared to the highest modulation frequency but short compared to the carrier period. The lower right graph shows the envelope power in red. The maximum envelope power, called PEP, is an important parameter used to characterize the output power of a modulated signal.

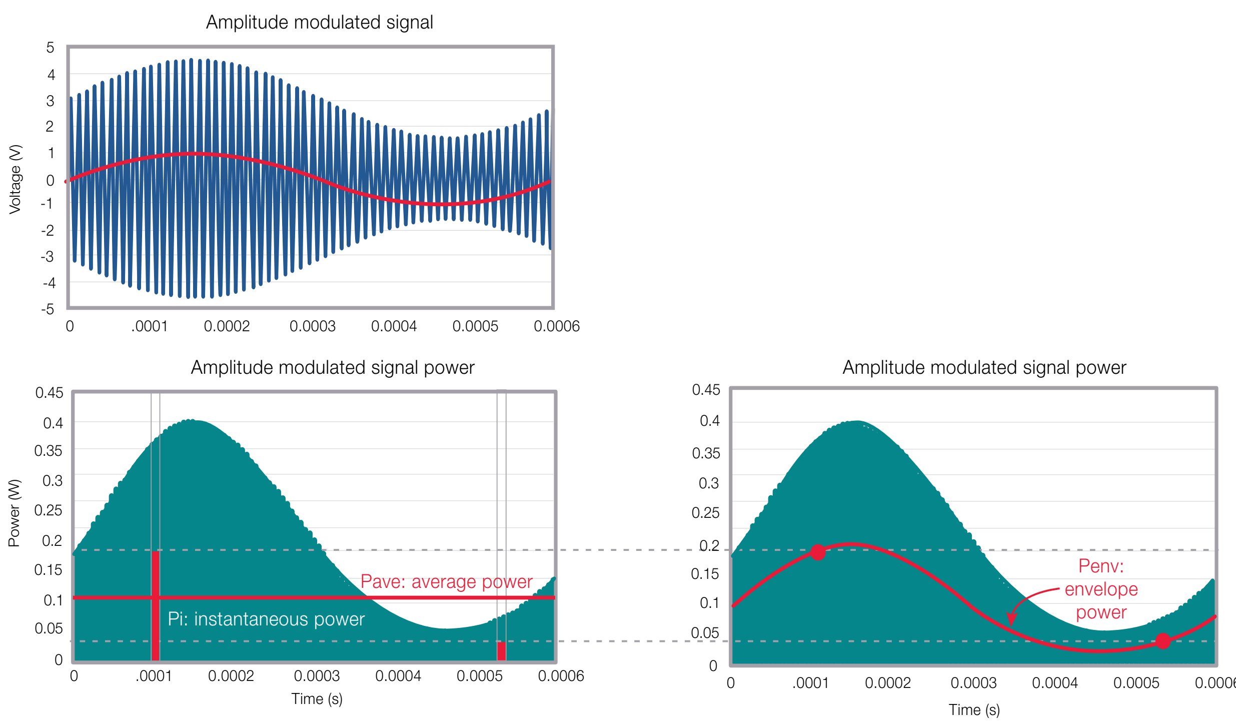


Figure 2-3. Voltage envelope and power envelope of a high-frequency modulated signal

Understanding the power specifications

Regarding power specifications, many signal generators' datasheets list the power output range, resolution, and applicable frequency ranges. There are several points to be aware of:

- Frequency ranges and operating temperatures affect output amplitude.
- Options for higher output power needs are available.
- The step attenuator provides coarse power attenuation (in 5 dB steps) to achieve low power levels. The automatic level control (ALC) in the attenuator hold range provides fine power-level adjustment.
- Maximum output power generally applies to CW mode. Some datasheets list the maximum output power for IQ modulation. The power specification for the Keysight CXG / EXG / MXG signal generators refers to PEP.

Tip: Impedance match is important because a mismatch between the source and the load impedance changes the effective signal input level to the DUT. If the mismatch is not distinguished from the measurement result, it appears as degraded DUT performance.

The Keysight N5186A MXG signal generator features an embedded reflectometer built for convenient match-corrected signal generation. It enables in situ generation of a match-corrected signal incident to the current load with a single press of a button. Learn more about the benefits of match-corrected measurements in this application note.

Table 2.1. Amplitude specifications of Keysight CXG signal generator

Output parameters	
Settable range	+30 to –144 dBm
Resolution	0.01 dB
Step attenuator	0 to 130 dB in 5 dB steps electronic type
Connector	Type N 50 Ω, nominal
Max output power [1] ( ) = typical	
Frequency	Standard
9 kHz to 10 MHz	+13 dBm
> 10 MHz to 3 GHz	+18 dBm
> 3 to 5 GHz	+16 dBm
> 5 to 6.0 GHz	+16 dBm

1. Quoted specifications between 20 °C and 30 °C. Maximum output power typically decreases by 0.01 dB / °C for temperatures outside this range.

Why use decibels (dB) and decibel milliwatts (dBm)? They make expressing very large or very small values more convenient. Using decibels also enables you to easily calculate total system gain or loss. You just need to add for gain and subtract for loss.

Characterize modulation signals

Many of the digitally modulated signals appear noise-like in the time and frequency domains, with seemingly random peaks. How do you ensure that you are not driving your signal generator to saturation during these peaks? The power complementary cumulative distribution function (CCDF) curves tell us how high these peaks will go.

Figure 2-4 shows a CCDF curve with the highest peak-to-average ratio at 5.67 dB. In this example, the maximum output power of the signal generator is 18 dBm, so the maximum power output you can set your signal generator to is 12.33 dBm (18 dBm – 5.67 dB). Remember that the signal generator's power output is the average power output. Setting your signal generator's output higher than 12.33 dBm leads to clipped peaks.

Looking for some tips on high-power applications? Get them here.

Figure 2-4. CCDF plot from Keysight E7608APPC PathWave Signal Generation for custom modulation

Measurement applications

If you need to go beyond the specified output power range, you can use an amplifier to increase the output power or an attenuator to decrease it. However, you need to take the amplifier's gain uncertainty and the attenuator's flatness and accuracy into consideration. Here are some test applications for high and low output power.

High-output-power test applications

- Overcome switching losses in automated test equipment (ATE) systems.
- Address the attenuation of signals in long cable runs.
- Conduct over-the-air tests.
- Test high-power amplifiers.
- Perform receiver blocking tests.

Low-output-power test applications

- Perform receiver sensitivity measurements.
- Measure interference signals.

Section 3. Accuracy

People often confuse accuracy with precision. The accuracy of a signal generator measures how close its output value is to the set value. Precision measures the degree to which the signal generator's output fluctuates. A high-precision generator has a stable output with little variation. However, a high-precision generator may not necessarily have an accurate output. Figure 3-1 shows the distinction between accuracy and precision.

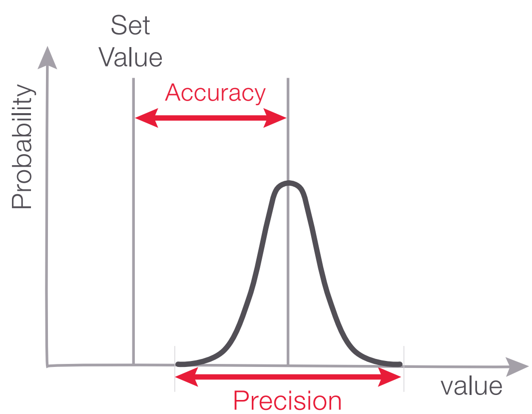


Figure 3-1. Accuracy versus precision

Why accuracy matters

In research and development, you characterize your designs with high-accuracy measurement instruments to ensure errors are from your DUT, not the instruments. In manufacturing, you test the RF receiver to ensure that it meets specifications. However, you also want to be sure that you are not rejecting perfectly good units. You can improve yield and product quality by improving the test accuracy.

Key accuracy specifications

There are two key accuracy specifications: amplitude accuracy and frequency accuracy. How much accuracy you need depends on your application. If you are testing a wireless receiver's sensitivity with ± 4 dB accuracy, you need to use a source with ± 1 dB amplitude accuracy to achieve a test accuracy ratio of 4.

Amplitude accuracy

Amplitude accuracy tells you how close your signal generator’s output amplitude is to the set amplitude. It is important to check the amplitude accuracy for the frequency and temperature range of interest because a signal generator’s output accuracy degrades with temperature and at higher frequencies. For example, the Keysight N5182B MXG signal generator’s absolute level accuracy degrades by 0.01 dB / °C when the ambient temperature is outside the 20 °C to 30 °C range. Table 3-1 shows the amplitude accuracy specification of the Keysight N5166B CXG signal generator.

Download the white paper and learn how to improve amplitude accuracy with next-generation signal generators.

Table 3.1. Accuracy specification of the Keysight N5166B CXG signal generator

Absolute level accuracy in CW mode (ALC on) ( ) = typical		
Range	Max power to -60 dBm	< -60 to -110 dBm
9 to 100 kHz	(± 0.6 dB)	(± 0.9 dB)
100 kHz to 5 MHz	± 0.8 dB (± 0.3)	± 0.9 dB (± 0.3)
> 5 MHz to 3 GHz	± 0.6 dB (± 0.3)	± 0.8 dB (± 0.3)
> 3 to 6 GHz	± 0.6 dB (± 0.3)	± 1.1 dB (± 0.3)
Absolute level accuracy in CW mode (ALC off, power search run, relative to ALC on)		
9 kHz to 6 GHz	(± 0.15 dB)	
(ALC on, relative to CW, W-CDMA 1 DPCH configuration < +10 dBm)		
5 MHz to 6 GHz	± 0.25 dB (± 0.05)	

Amplitude flatness

Frequency sweeps can test the performance of filters and power amplifiers. Amplitude accuracy affects the frequency-sweeping capability of a signal generator. The less the amplitude changes from one frequency to another, the flatter the output. The change in amplitude when moving from one frequency to another is known as flatness. While closely related to amplitude accuracy, the flatness specification is tighter than the amplitude accuracy and usually referenced to the amplitude of the starting frequency. Figure 3-2 illustrates this difference.

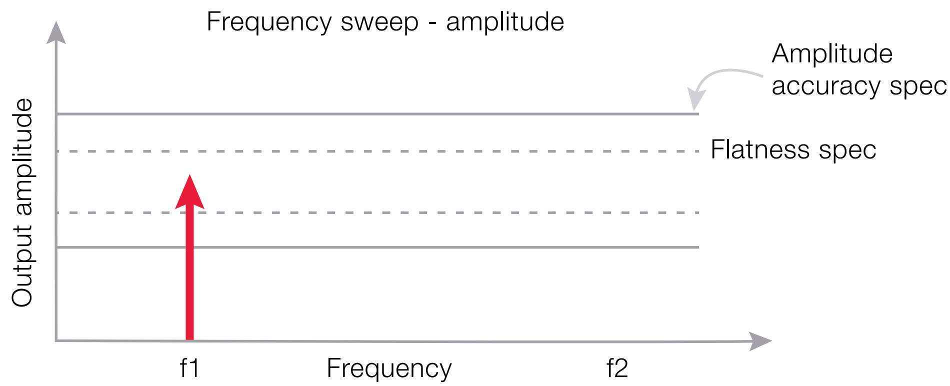


Figure 3-2. Comparison of amplitude accuracy and flatness

Improve accuracy to improve yield

Receiver sensitivity testing requires sources with accurate output power. This testing determines whether a receiver can detect weak signals above a specified power level. For example, a 4G mobile phone receiver has a specified sensitivity level of -110 dBm. If the receiver sensitivity test fails to detect signals with a power level of 110 dBm or more, it will reject the DUT.

To illustrate the effects of poor accuracy on test yield, let’s use the 4G receiver example. Consider a signal generator with an amplitude accuracy of ± 5 dB. To avoid overacceptances (or false positives), the signal generator is set up to output -115 dBm. At -115 dBm, the signal generator’s output power varies from -110 dBm to -120 dBm. As you can see in Figure 3-3, using this signal generator would cause you to inadvertently reject four perfectly good receivers with borderline performance.

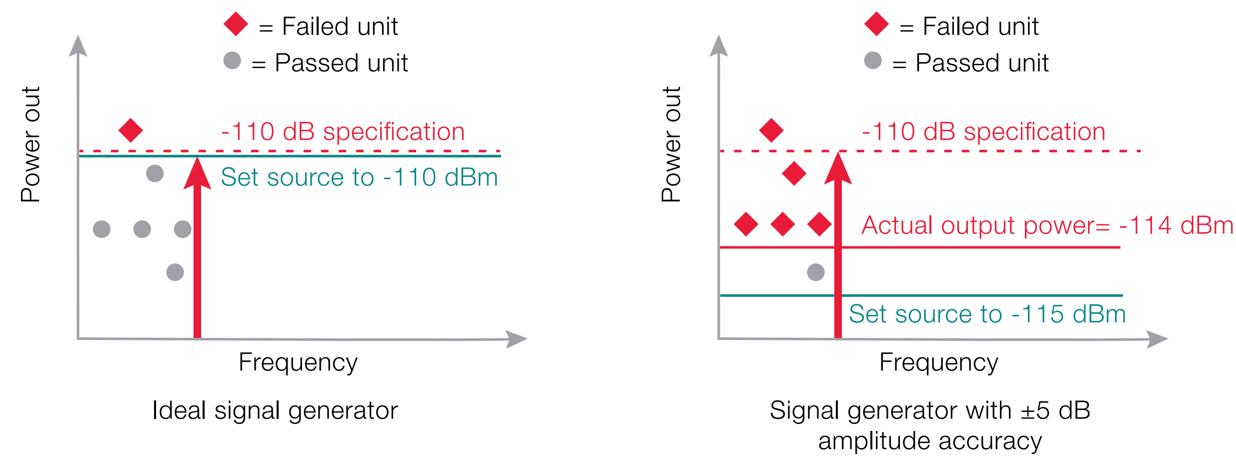


Figure 3-3. Effects of poor amplitude accuracy on test yield

You can improve test yield by using a more accurate signal generator. Figure 3-4 shows the same test using a signal generator with an amplitude accuracy specification of ± 1 dBm. Four of the same six receivers tested earlier now pass the sensitivity test. We reduced false rejects by 75% just by using a more accurate signal generator.

A more accurate signal generator may cost more. However, in the long run, the improved yield will return the investment's cost many times over.

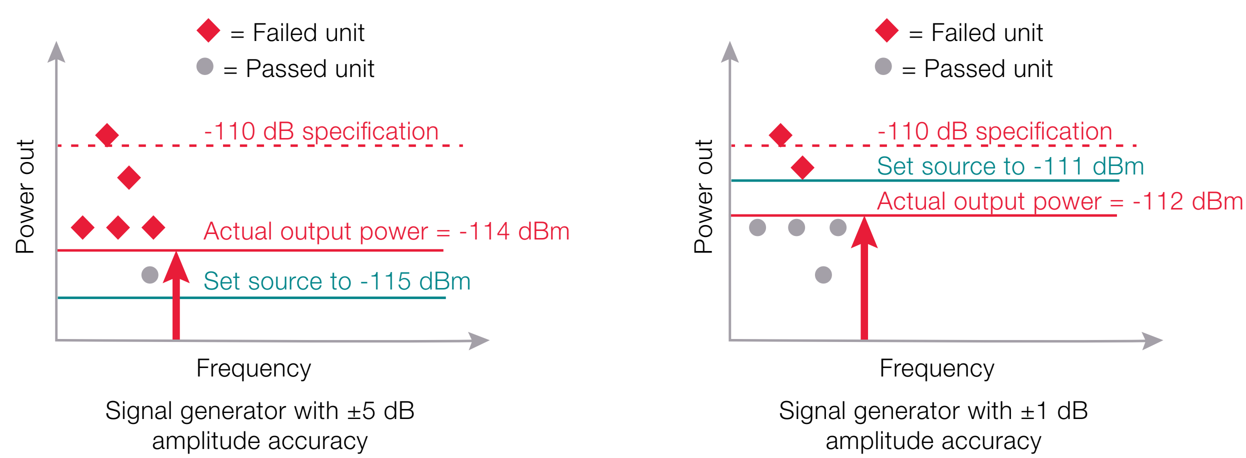


Figure 3-4. Effects of improved amplitude accuracy on test yield

Frequency accuracy

Two main factors affect the frequency accuracy of a signal generator: the stability of the reference oscillator and the amount of time that has passed since the signal generator underwent calibration. Although temperature and line voltage also affect frequency stability, its effects are several orders of magnitude less than the aging effect. Therefore, the key specification to look out for is the reference oscillator aging rate.

A typical reference oscillator used in a signal generator has an aging rate of 0.152 ppm per year. A 10 GHz signal generator with this reference oscillator that has not undergone calibration for one year will have a frequency accuracy of ± 1.52 kHz. Here is the calculation:

Frequency accuracy (Hz) = output frequency (Hz) x aging rate (ppm / year) x time since last calibration = 10 GHz x 0.152 ppm / year x 1 (year) = 1.52 kHz

Table 3.2. Frequency reference of the Keysight N5172B EXG signal generator

Frequency reference	
Accuracy	± (time since last adjustment x aging rate)
	± temperature effects
	± line voltage effects
	± calibration accuracy
Internal time base reference oscillator aging rate [1]	≤ ± 5 ppm / 10 yrs, < ± 1 ppm / yr
Initial achievable calibration accuracy	± 4 x 10^{-8} or ± 40 ppb
Adjustment resolution	< 1 x 10^{-10}
Temperature effects	± 1 ppm (0 to 55 °C), nominal
Line voltage effects	± 0.1 ppm, nominal; 5% to 10%, nominal

1. Not verified by the Keysight N7800A TME calibration and adjustment software. Daily aging rate is available as a supplementary service.

Section 4. Speed

Reducing test time can reduce costs. So, the speed of your signal generator influences the cost of test. A fast signal generator enables you to quickly switch from one frequency, amplitude, or waveform to another. Speed specifications are in milliseconds. Table 4-1 shows the frequency switching speed specification for the N5182B MXG signal generator.

Tip: Improve waveform switching speed by using the list / step sweep mode to preload the waveforms into the nonvolatile memory.

Table 4.1. Switching speed specification of the Keysight N5182B MXG signal generator

Frequency switching speed [1,2]			
	Standard	**Option UNZ [3]**	**Option UNZ, typical**
CW mode	≤ 5 ms, typical	≤ 1.15 ms	≤ 950 µs
SCPI mode	≤ 5 ms, typical	≤ 900 µs	≤ 800 µs
Digital modulation on (N5182B only)			
	Standard	**Option UNZ [3]**	**Option UNZ, typical**
CW mode	≤ 5 ms, typical	≤ 1.15 ms	≤ 950 µs
List / step sweep mode	≤ 5 ms, typical	≤ 900 µs	≤ 800 µs

1. Time from receipt of SCPI command or trigger signal to within 0.1 ppm of final frequency or within 100 Hz, whichever is greater.
2. With internal channel corrections on, the frequency switching speed is < 1.3 ms, measured for list mode and SCPI mode cached frequency points. For the initial frequency point in SCPI mode, the time is < 3.3 ms, measured. The instrument automatically caches the most recently used 1,024 frequencies. There is no speed degradation for amplitude-only changes.
3. Specifications apply when status register updates are off. For export-control purposes, CW switching speed calculations are within 0.05% of the final frequency is 190 µs (measured).

Factors affecting speed

The type of change and the source of commands affect switching speed. The time documented in the specification indicates how long it takes for the signal generator's output to stabilize once a command is sent. Typical switching times can be up to 40% faster than speed specifications, which are worst-case scenarios.

When you set the signal generator to a new frequency, the frequency synthesizer changes its output to the desired frequency. The output amplifier then adjusts the power level so that the output power stays the same at the new frequency. Essentially, frequency switching requires changes to both the frequency synthesizer and the output amplifier, which is why frequency switching is often slower than amplitude switching. During switching, command processing takes up the most time. Figure 4-1 shows each step to process a SCPI command request.

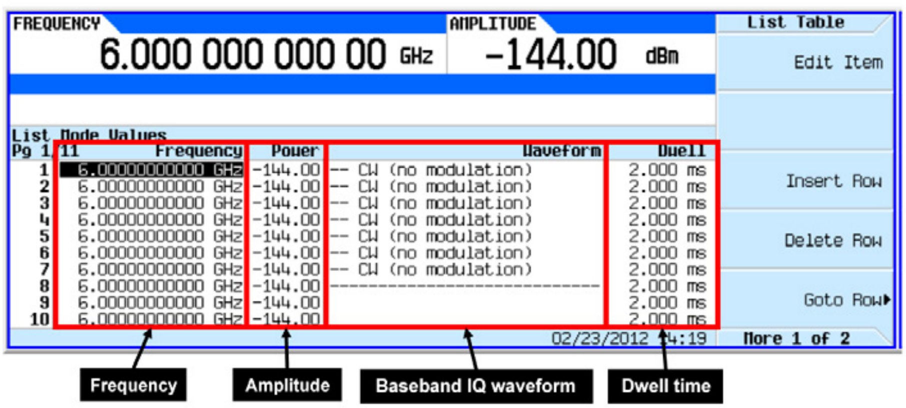


Figure 4-1. SCPI command processing time in a signal generator

Faster switching speed

Using Step or List commands can improve a signal generator's output in automatic test systems. Typically, an operator sends commands to a signal generator to set frequency, amplitude, and waveform when these states are not initially known. Using Standard Commands for Programmable Instruments (SCPI) involves overhead time for sending, parsing, and processing commands before switching can begin.

If the frequency, amplitude, and waveform combination is known in advance, using a step or list sweep significantly improves speed. The signal generator can then sequence through the states in rapid succession. Typical switching time in sweep mode is 600 µs to 800 µs compared to 2 ms in SCPI mode.

Some signal generators offer high-speed switching options. The N5182B MXG signal generator, for example, has a UNZ option that offers submillisecond switching speeds, perfect for high-volume production. Keysight's baseband tuning technology enables fast frequency and amplitude switching speeds in list mode.

Where switching speed matters

Wireless manufacturing

Test throughput is everything in manufacturing. Reducing test time leads to lower test costs. Using a fast signal generator can help with higher bandwidth and advanced features in the latest chipsets.

Device characterization

Adding integrated functions in wireless systems impacts test demands and test costs. Introducing communications standards, frequency bands, and multi-antenna techniques increases the device's complexity. This method requires switching frequencies for multiple bands, waveforms for multiple formats, and amplitude levels to characterize the device's performance.

Electronic warfare simulation

To simulate complex EW scenarios, you need a signal generator with capabilities such as fast switching, phase repeatability, and pulse modulation. This process requires direct digital synthesis technology to control frequency and phase and an agile attenuator to adjust amplitude levels.

Summary

Wireless devices are incorporating more and more functionalities, requiring more tests with more setups under more conditions. They include multiple standards, frequency bands, and antennas, significantly increasing the challenges in verification and production testing. Test engineers are constantly looking for ways to improve test throughput and cost. When equipped with the fast switching capability, these signal generators can switch frequency, amplitude, or waveform in less than 1 ms in most cases.

End of Part 1

We have reached the end of Part 1 of our two-part white paper. We hope you have a better understanding of the fundamental specifications of signal generators. In Part 2, we discuss more advanced topics, such as modulation, spectral purity, distortions, and software.

Learn about the various types of modulation schemes and gain a more in-depth understanding of harmonics and spurs. We share why distortions are not always bad and how you can improve your productivity with the latest software. To stay updated with the most recent tutorials, techniques, and best practices, check out Keysight Signal Generators and Sources online and follow the Keysight RF Test and Measurement Facebook page and the Keysight RF & Microwave Instruments & Measurements LinkedIn page.