WHITE PAPER

The Essential Signal Generator Guide

Building a solid foundation in RF — Part 2

KEYSIGHT

Introduction

Having a robust and reliable high-speed wireless connection helps companies win and retain customers. It has quickly become a requirement for doing business. In order to meet this requirement, you need the right signal generator.

The frequency spectrum is a finite resource. Complex modulation schemes increase spectral efficiency, enabling far higher data rates. Unfortunately, complex modulation schemes depend on accurate and stable signal generators to work effectively. With all the specifications and features available, getting the right signal generator for the job can be a daunting task.

In this second part of our two-part white paper, we help you gain a sound understanding of various modulation schemes, the importance of spectral purity, and the impact of distortion. We also explore how you can use smart software to significantly improve your productivity.

Contents

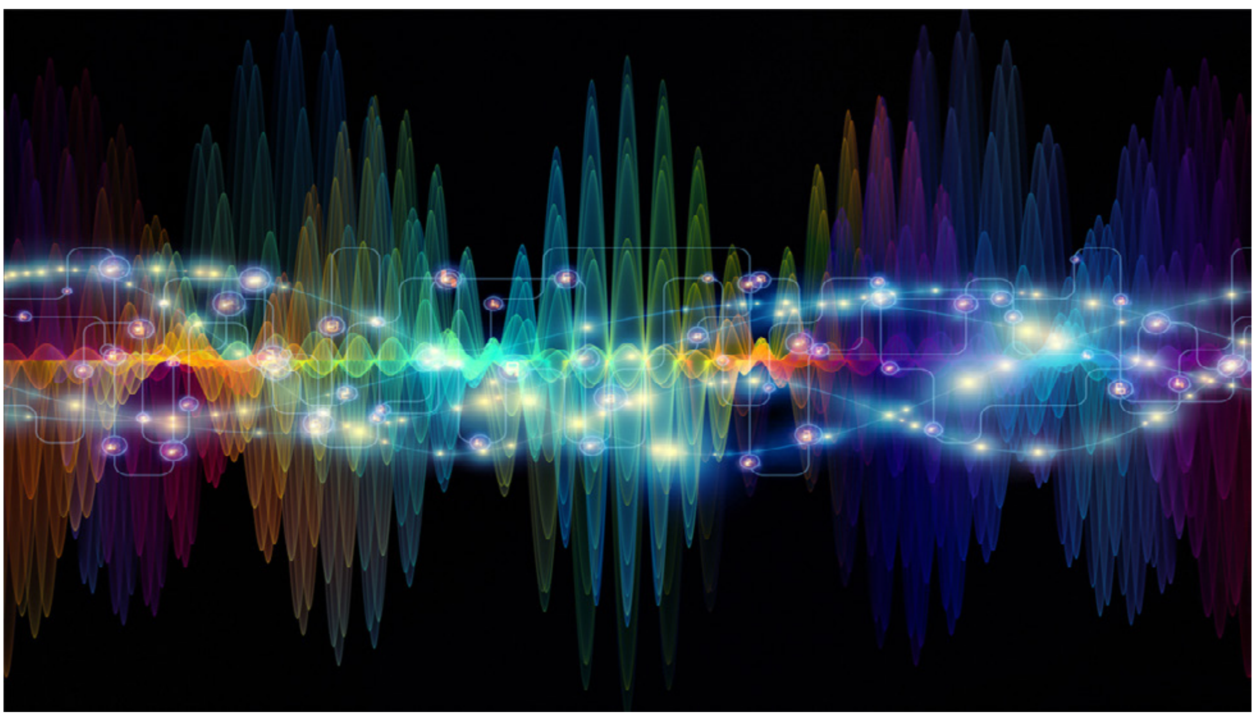
Part 2 of our two-part white paper highlights more advanced features such as modulation, spectral purity, and distortion. Part 1 introduced the signal generator and looked at basic specifications such as power, accuracy, and speed.

Section 5. IQ Modulation

Let's illustrate the concept of IQ modulation with an example. It is Friday, and you and your colleagues head to a popular Mexican restaurant for lunch. You arrive early and find a long table to seat all 10 people at your party. As you place your orders, more people enter the restaurant. While waiting for your food, everyone starts talking about their weekend plans. You try to ask Bill — seated at the far end of the table from you — if he has found a new spot for fly fishing. But you cannot hear him because of the noise in the restaurant and the fact he is sitting far away. You begin using your arms and facial expressions to try to communicate. Bill does the same.

You and Bill are essentially modulating your bodies to communicate. The efficacy of your communication depends on how well you use your hands, arms, and facial expressions. This is known as modulation quality.

Before performing your measurements, ensure your signal generator has good modulation quality. Good modulation quality ensures that you capture the performance of your device under test (DUT), not the signal generator.



What is modulation?

Modulation is like waving your arms to convey messages to Bill. In the world of electrical signals, modulation is modifying a high-frequency signal to convey information. Just like your arms carry messages, the high-frequency signal carries information.

Why do we modulate signals? Well, modulation enables you to "talk" to Bill, who is sitting at the far end of the table in a noisy restaurant. For digital communications, modulation also enables you to transmit significantly more data using narrow frequency bandwidths.

IQ modulation

The basic modulation schemes are amplitude, frequency, and phase modulation. Modulating signals can be expressed in the polar form (vector) with magnitude and phase. Digital communication often uses IQ modulation because of its spectrum efficiency. IQ modulation uses two carriers. One is known as the in-phase (I) component, and the other is the quadrature (Q) component, which phase-shifts by 90 degrees from the in-phase component, as shown in Figure 5.1.

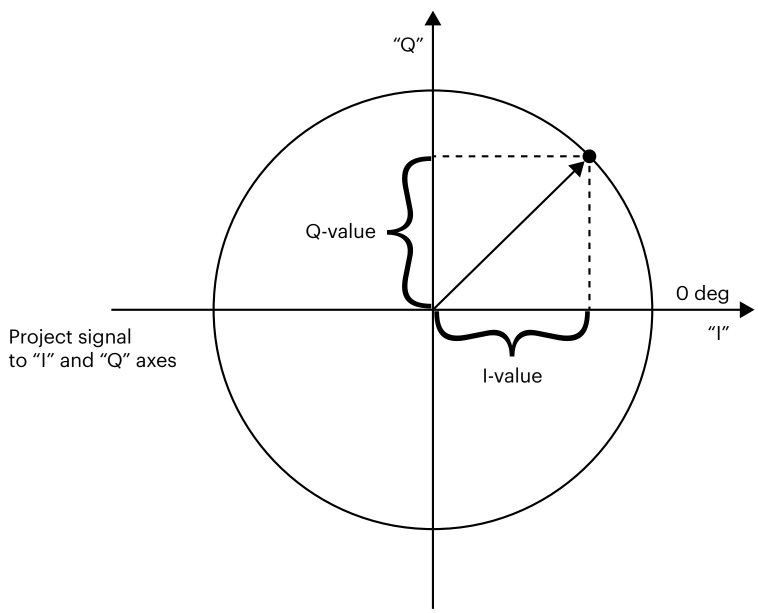


Figure 5.1. IQ phasor diagram

IQ modulation's main advantage is the symmetric ease of combining independent signal components into a single composite signal and later splitting the composite signal into its independent components.

In a digital transmitter, I and Q signals mix with the same local oscillator (LO) but with a 90-degree phase shifter placed in one of the LO paths, as shown in Figure 5.2. This 90-degree phase shift makes the I and Q signals orthogonal to each other so that they do not interfere with each other.

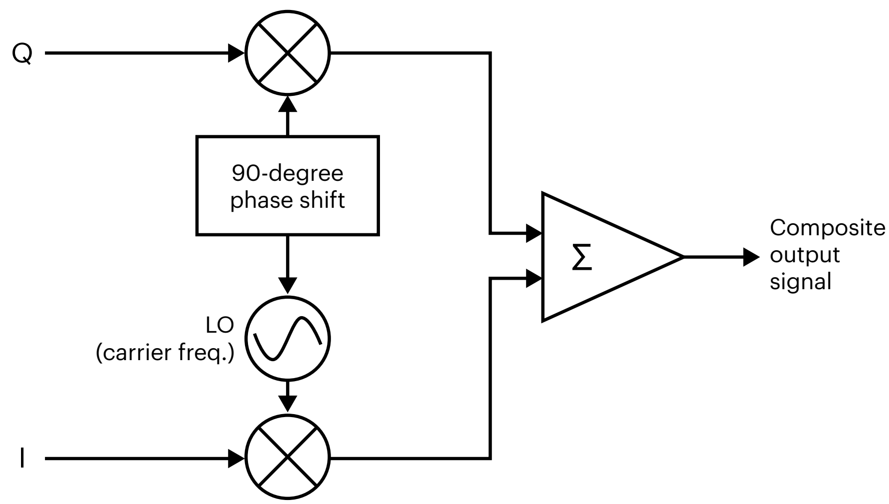


Figure 5.2. Baseband IQ modulation

To learn more about the basics of digital modulation, refer to Digital Modulation in Communications Systems.

Key IQ modulation parameters

Digital modulation schemes, such as PSK, FSK, ASK, and QAM, represent data through changes in magnitude, phase, and frequency on an IQ diagram. These schemes, along with variations like OFDM, enhance spectral efficiency and robustness, supporting higher bit rates and improved communication system performance.

Modulation schemes

Changes to vector signals on an IQ diagram can be in magnitude, phase, frequency, or some combination of those. These magnitude and phase changes result in different modulation formats. As the data conveyed is in binary, the number of constellation points must be a power of 2. The most fundamental digital modulation formats are these:

- PSK (phase-shift keying)
- FSK (frequency-shift keying)
- ASK (amplitude-shift keying)
- QAM (quadrature amplitude modulation)

Constellation and symbols

A constellation diagram shows the available symbols of a QAM format. In the case of a 16 QAM format, each symbol represents one possible combination of four binary bits. Thus, each symbol represents four bits.

To increase data bandwidth, we can increase the number of bits each symbol represents, which will increase spectral efficiency. However, as the number of symbols increases in the constellation diagram, the space between the symbols decreases. The symbols are closer together and are thus more prone to errors caused by noise and distortion. Figure 5.3 shows increases in symbol density when changing from a 16 QAM format to a 64 QAM format.

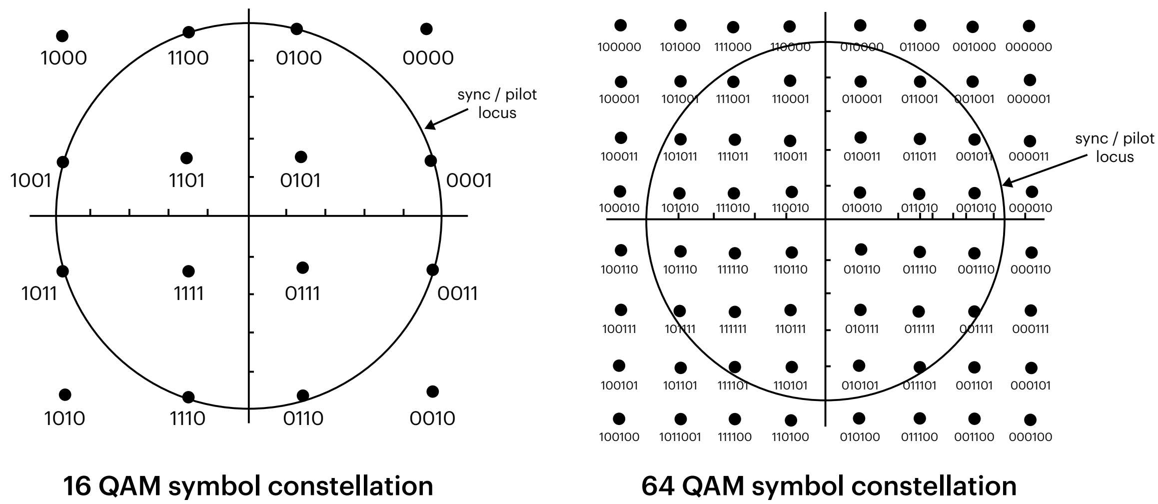


Figure 5.3. Constellation of 16 QAM and 64 QAM formats

Digital modulation types and variations

Communications systems use three main variations on the basic modulation schemes:

- IQ offset modulation: offset quadrature PSK used in ZigBee® 2,450-MHz band.
- Differential modulation: π /4 differential quadrature PSK used in *Bluetooth*® 2.0+ EDR.
- Constant envelope modulation: Gaussian minimum-shift keying used in GSM; 2-FSK used in Wi-SUN.

These variations prevent the IQ signal trajectories from going through zero (the center of the constellation). This results in power efficiency advantages.

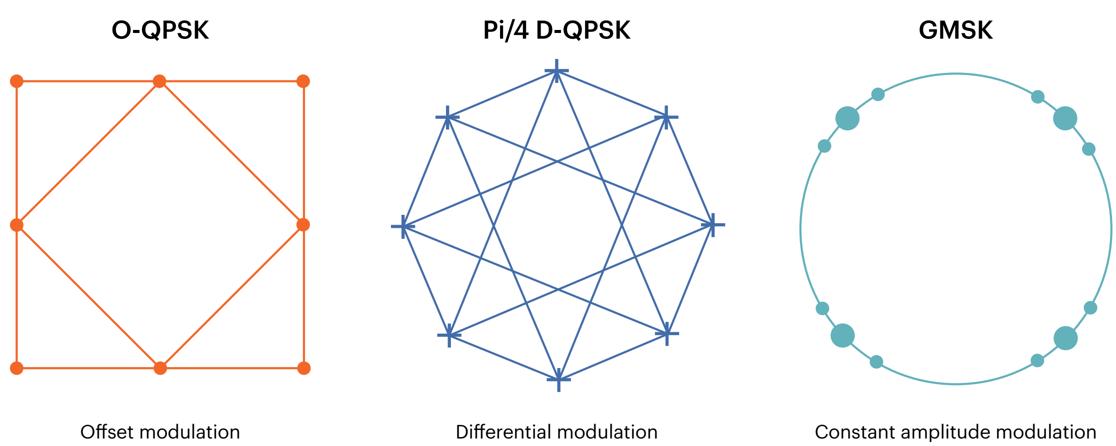


Figure 5.4. IQ modulation variations

Orthogonal frequency division multiplexing (OFDM) is another popular modulation scheme. Many of the latest wireless and telecommunication standards, such as digital broadcasting, xDSL, wireless networks, and 4G and 5G New Radio cellular technologies, have adopted this tactic.

OFDM employs multiple overlapping radio frequency carriers. Each carrier operates at a carefully chosen frequency that is orthogonal to the others to produce a transmission scheme that supports higher bit rates because of parallel subcarrier operation. In addition, OFDM provides a combination of spectral efficiency, flexibility, and robustness.

For details on OFDM signal operation, refer to our application notes: Custom OFDM Signal Generation and Making Custom OFDM Measurements.

Bit rate versus symbol rate (baud rate)

Bit rate is the frequency of a system bit stream. Symbol rate is the bit rate divided by the number of bits that can transmit with each symbol. For example, quadrature phase-shift keying (QPSK) has 2 bits per symbol. Its symbol rate is half of its bit rate. The signal bandwidth and symbol rate are in direct proportion.

Symbol rate = bit rate / the number of bits transmitted with each symbol

Error vector magnitude

An error vector is the vector difference between the ideal IQ reference signal and the measured signal. Error vector magnitude (EVM) is the magnitude of this error vector. The error vector is the result of such things as phase noise from local oscillators, noise from power amplifiers, and IQ modulator impairments.

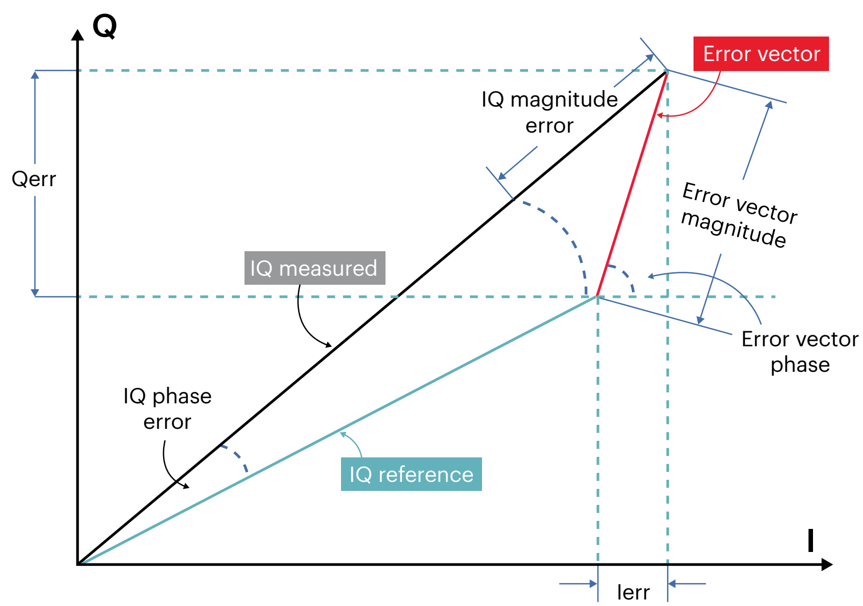


Figure 5.5. Graphical representation of the error vector

To learn more about vector modulation analysis, refer to the application note Testing and Troubleshooting Digital RF Communications Receiver Designs.

> To ensure that you are evaluating the EVM performance of your DUT, your signal generator's EVM performance must be 5 to 10 dB better than your DUT's EVM expected performance.

For example, the 802.11ax transmitter EVM standard requirement for 1024 QAM is -35 dB. The residual EVM floor of signal generators used in design validation should be lower than -45 dB. However, for production tests, EVM performance of less than -40 dB is good enough.

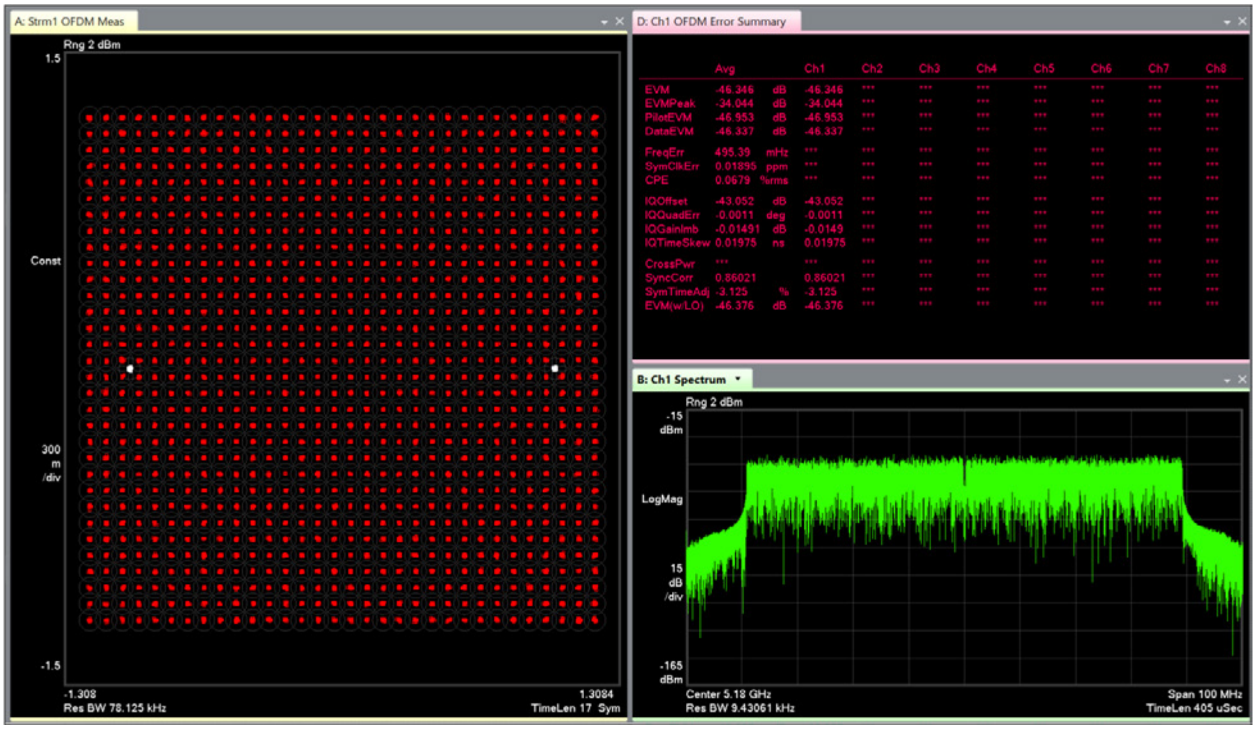


Figure 5.6. 802.11ax constellation diagram and error summary

IQ impairments

IQ impairments may crop up in your designs. When they do, you need to simulate these impairments to stress-test your designs or compensate for time and amplitude variations in the signal path. Your signal generator can generate IQ impairments. Use the following IQ adjustments to simulate the impairments you need. A summary of IQ adjustment uses and effects appears in Table 5.1.

- IQ offset: This refers to the DC offsets of the I and Q signals.
- Quadrature angle: This is the phase difference between the I and Q signals.
- IQ skew: This refers to the relative time delay between the I and Q signals.
- IQ gain balance: This is the relative amplitude of the I signal compared to the Q signal.
- IQ phase: This is the absolute phase of the IQ channel, which can be adjusted by rotating both I and Q signals together.

Table 5.1. IQ adjustment uses

IQ adjustment	Effect	Impairment
Offset	Carrier feedthrough	DC offset
Quadrature angle	EVM performance	Phase skew
	IQ images	IQ path delay
IQ skew	EVM error	High sample rate phase skew or IQ path delay
IQ gain balance	IQ amplitude difference	IQ gain ratio
IQ phase	I/A phase rotation	RF phase adjustment

In addition to IQ adjustments, you can add phase noise impairments or AM / FM to a carrier to simulate an imperfect signal or additive white Gaussian noise to a modulated signal as a source of interference for your design verification.

Download these white papers to learn more:

- Making Noise in RF Receivers
- Understanding Phase Noise Needs and Choices in Signal Generation

Section 6. Spectral Purity

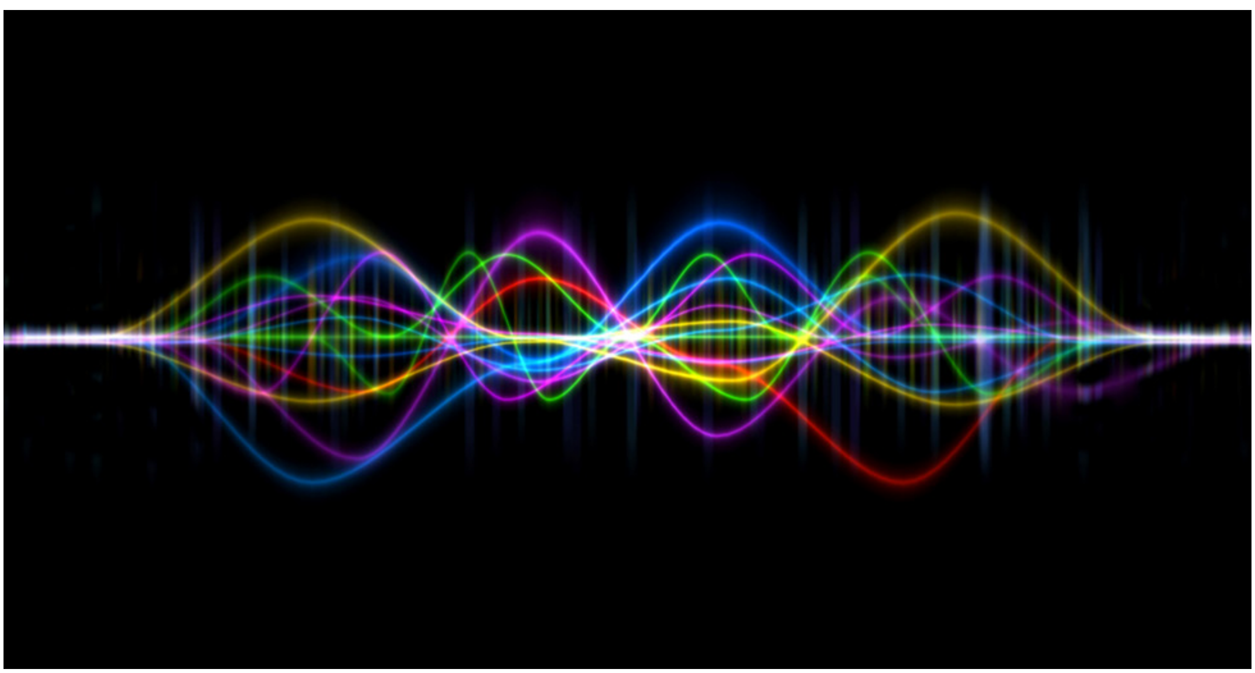
To illustrate the concept of spectral purity, let's say Davina arrives at your house and presses the doorbell. She waits a couple of minutes at the door. A mild-mannered young man opens the door, looks at Davina, and points to the living room. She enters the living room, puts her piano-tuning forks aside, and starts playing the piano. Davina came to the house to tune the grand piano.

As Davina plays each tone, she strikes the tuning fork. The fork emits a serene, almost perfect tone that fills the air each time Davina hits it. Using this perfect tone as a reference, Davina tunes the piano.

A signal generator works like a tuning fork, emitting an almost perfect signal used in RF applications such as clock references, RF power amplifier testing, and adjacent channel sensitivity testing. The integrity of the signal generator output is what we call spectral purity.

Robust signal generators output signals with as little imperfection as possible. However, random amplitude and phase fluctuations occur in real-life waveforms. A waveform has a phase shift and amplitude shift in the time domain. In the frequency domain, the signal has both amplitude and frequency modulation. The major measurements of spectral purity are phase noise, harmonics, and spurs.

In this section, you will learn what spectral purity is and why it matters.



Harmonics and spurious

Both harmonics and spurious are deterministic (nonrandom) signals generated from mixing or dividing signals to get the output signal. These are unwanted frequencies generated in RF systems. The harmonics appear as integer multiples of the carrier frequency, while the spurious frequencies appear as noninteger multiples of the carrier frequency.

Figure 6.1 shows a carrier frequency at 1 GHz and its harmonics and spurious. The second harmonic (marker 2) is -64.36 dBc relative to the fundamental carrier (marker 1), and the third harmonic (marker 3) is -72.83 dBc. Markers 4 and 5 indicate spurs.

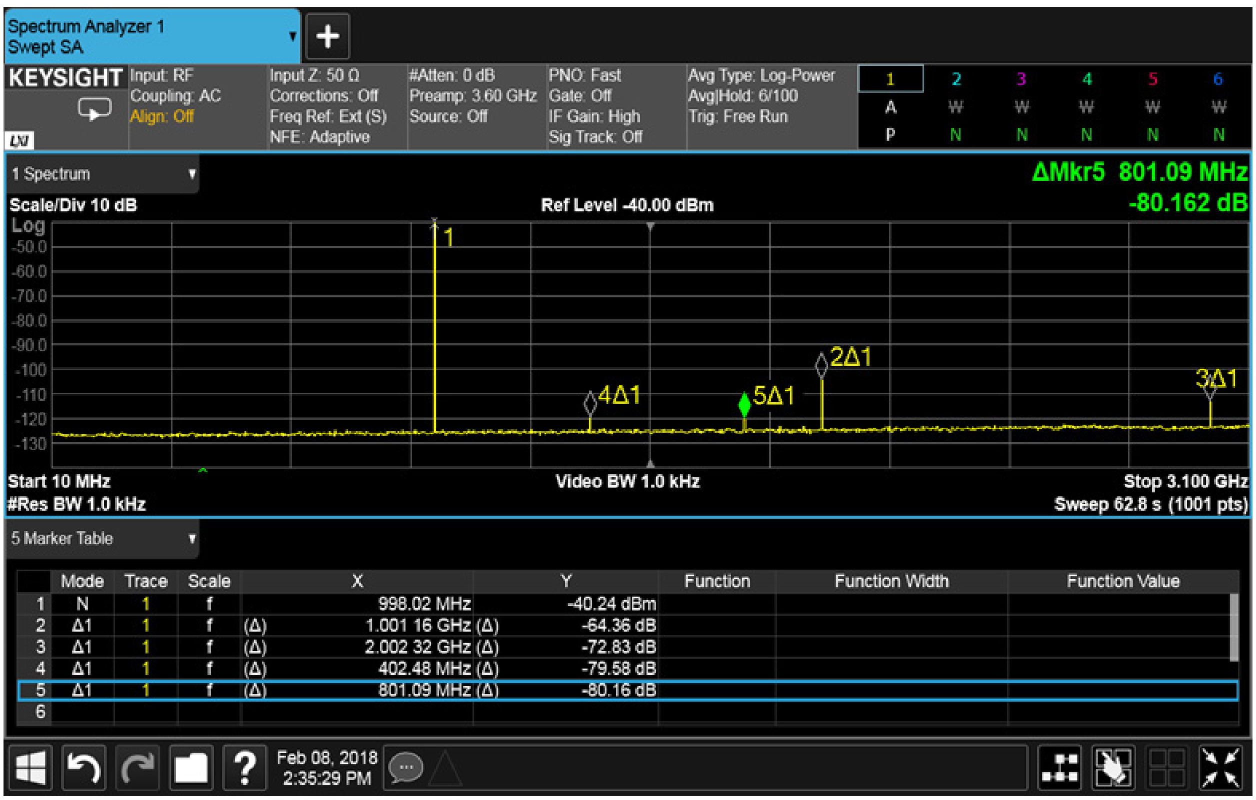


Figure 6.1. A continuous wave signal at 1 GHz generated by a signal generator

Choose a high-dynamic-range signal analyzer to measure harmonics and spurs. Otherwise, the harmonics and spurs you detect may be from the signal analyzer rather than the DUT.

Phase noise

Phase noise is a frequency-domain view of the noise spectrum around an oscillator signal. It describes the frequency stability of an oscillator. Frequency stability can be long term or short term, as shown in Figure 6.2.

Table 6.1 compares long-term and short-term frequency stability. Short-term variations contribute to phase noise, while long-term drifts impact accuracy.

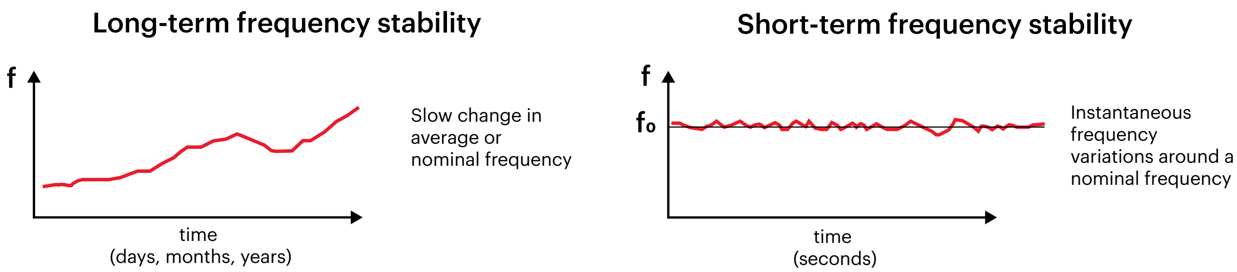


Figure 6.2. Long-term and short-term frequency stability

Table 6.1. Comparison of long-term and short-term frequency stability

	Short-term frequency stability	Long-term frequency stability
Period	Seconds	Minutes to years
Terminology	Random noise: phase noise, jitter Deterministic: spurious	Accuracy, drift, aging
Measurement	£(f) curves, integrated totals, spot measurements, jitter (p-p)	Often determined by a frequency reference

The most common way to define the amount of phase noise is to define the amount of single sideband (SSB) power contained within a 1 Hz bandwidth at a specific frequency away from the main frequency. This equation explains it:

£(f) = Noise power in a 1-Hz bandwidth / main frequency power
where £(f) has units of dBc/Hz

Figure 6.3 shows the SSB phase noise measurement of a signal generator. The yellow trace shows instantaneous power measurements, while the blue trace is the average result.

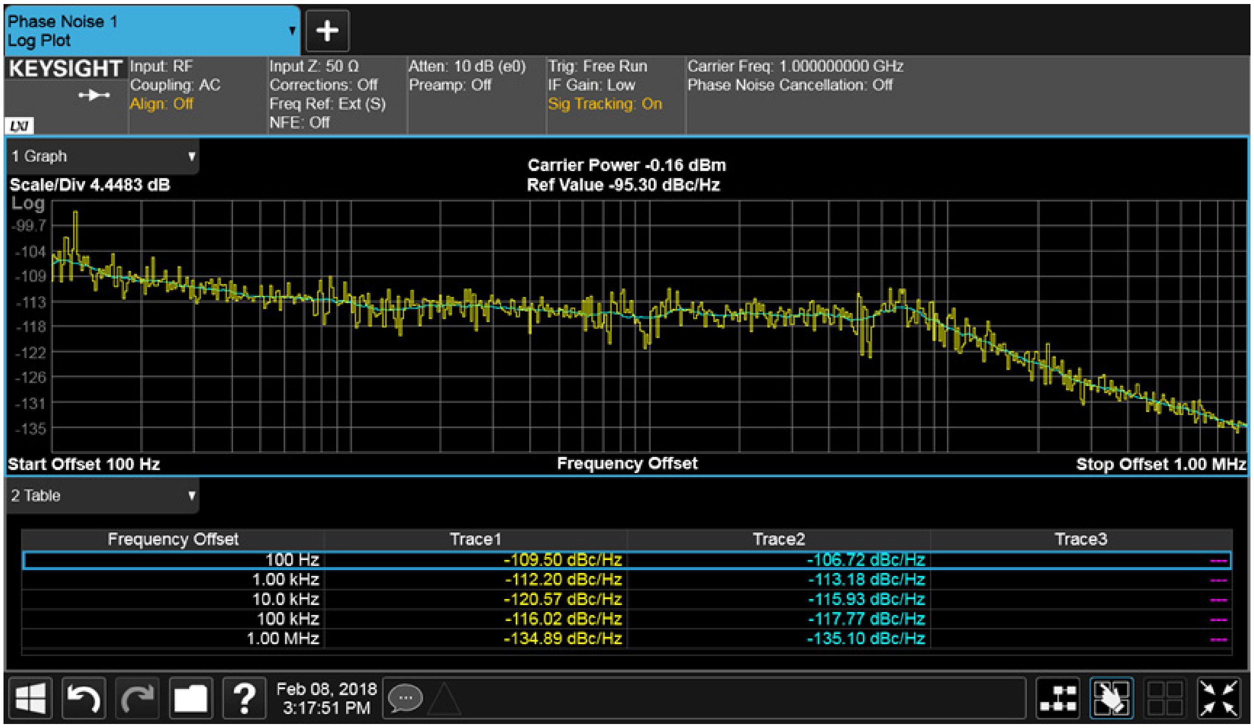


Figure 6.3. SSB phase noise measurement with a log plot and decade table

> To measure phase noise effectively, use a signal analyzer with phase noise performance that is at least -10 dB better than the expected phase noise of your signal. Otherwise, the spectrum analyzer's LO phase noise will contribute to the measured phase noise.

When phase noise matters

Understand the impact of phase noise on your measurements to get just the right amount of performance for your test. High phase noise obscures weak signals that are close to the main frequency.

Radar applications

Radar systems require excellent phase noise performance. A radar transmits pulses at a specific frequency and measures changes in the returning pulse's frequency. Changes in frequency tell us about the velocity of the object based on the Doppler effect. If the object moves very slowly, the frequency shift of the returning pulse is small.

In Figure 6.4, the returning pulse of a moving object is the signal of interest, and the returning pulse of a fixed object (ground) is the interfering signal. The radar receiver will be unable to identify the moving object if phase noise masks the downconverted signal of interest.

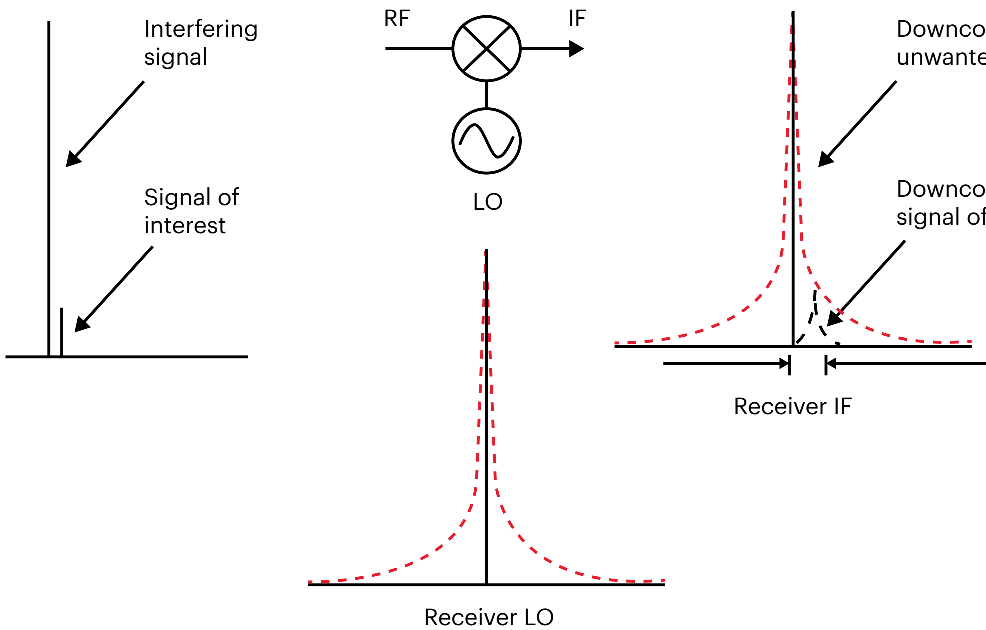


Figure 6.4. Poor LO phase noise affects receiver sensitivity

Digital modulation

Figure 6.5 shows a simplified QPSK digital receiver block diagram. The phase noise of the LO signal translates into the output of the mixers. Phase noise causes radial smearing of the symbols (shown in green) on the constellation diagram. For closely spaced symbols in a higher-order modulation scheme (for example, 256 QAM), radial smears can overlap and result in bad receiver sensitivity.

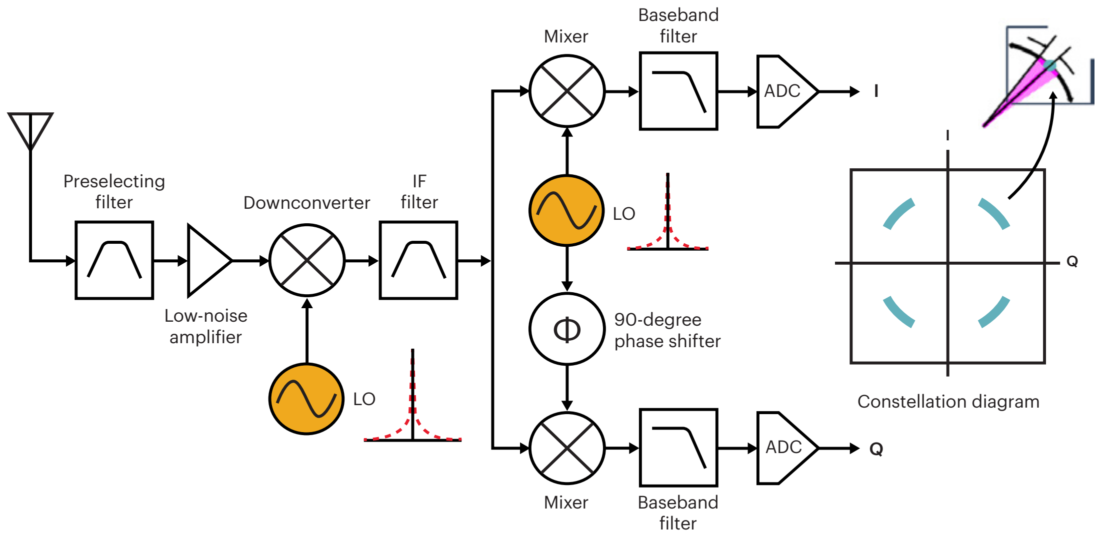


Figure 6.5. A simplified digital receiver block diagram

Orthogonal frequency-division multiplexing

Orthogonal frequency-division multiplexing (OFDM) is a popular modulation scheme for wideband digital communication. It uses many closely spaced orthogonal subcarrier signals to transmit data in parallel (shown in Figure 6.6). LO phase noise causes the subcarriers' phase noise to spread into other subcarriers as interference. The phase noise degrades the modulation quality of the OFDM signal.

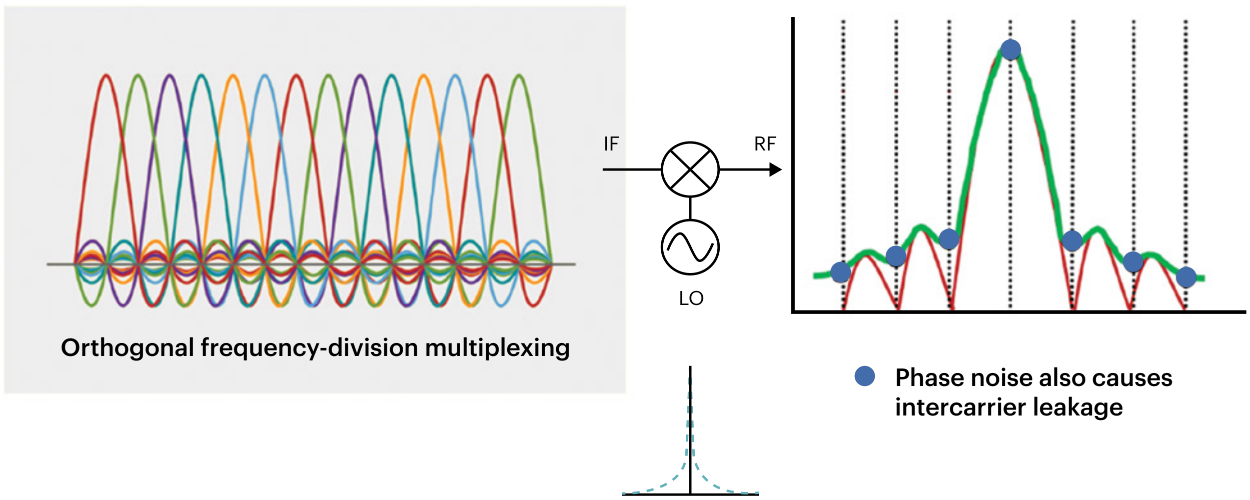


Figure 6.6. OFDM signal upconvert with a poor phase noise LO

> Sophisticated signal generators enable you to adjust phase noise at the synthesizer section. This method lets you degrade the phase noise performance of your signal generator and is helpful in evaluating the sensitivity of your receiver design.

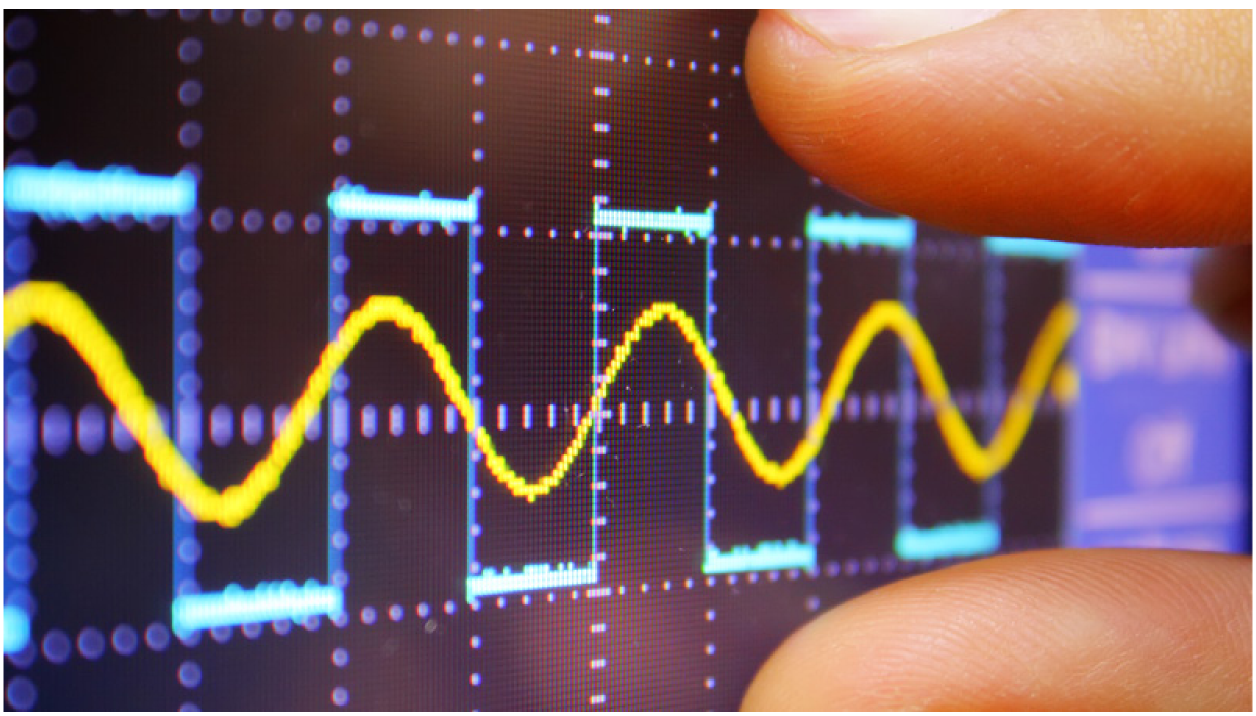
Section 7. Distortion Performance

In modern wireless communications and digital radio systems, frequency channel spacing is close in order to achieve spectral efficiency. OFDM using a digital multicarrier modulation scheme is common with wideband digital communication.

Testing for unwanted and nonlinear spectral distortion is critical for narrow-frequency channel spacing and wide-bandwidth communication systems. Components, modules, subsystems, and entire devices often generate these distortion products.

The distortion products could be in-channel, in-band, or out-of-band unwanted spectral signals. They degrade both transmitter performance and receiver sensitivity.

Distortion can creep up in signal generators. Distortion performance is one of several major specifications of signal generators. Distortion performance can affect device characterization. This section describes types of distortion and why they matter to your measurements.



What is distortion?

We all know what distortion sounds like and how unpleasant it feels to our ears. Distortions occur when you turn up the volume on digital devices. When your audio system can no longer output the full amplitude, it clips the peaks, resulting in harmonic distortions.

Distortion is an alteration of the original waveform. There are two major types of nonlinear distortion in signal generators: harmonic distortion and intermodulation distortion.

- Harmonic distortion occurs when an abrupt voltage change interrupts the smooth voltage change of a pure sinusoidal wave. Nonlinear semiconductors usually cause this abrupt change. The frequencies of the harmonics are in integer multiples of the sinusoidal wave.
- Intermodulation distortion is the spurious output you get when mixing two or more signals with different frequencies. Spurious outputs occur at the sum and difference of integer multiples of the input frequencies.

Measuring distortion

Harmonic and intermodulation distortions are critical factors in evaluating the performance of amplifiers and mixers. To ensure signal integrity, you can measure these distortions using continuous wave tones and two-tone signals. Techniques like IP3 and adjacent channel power ratio (ACPR) provide insights into spectral efficiency and interference management.

Harmonic distortion

We can explain how to measure harmonic distortion using a continuous wave (CW) tone. Figure 7.1 shows the harmonic distortion measurement setup. The DUT could be an amplifier or a mixer. The signal generator outputs a CW with a frequency of F_i. This CW goes through a low-pass filter to remove harmonic distortions from the signal generator. Notice that the cutoff frequency of the low-pass filter, F_c, is less than $2F_i$.

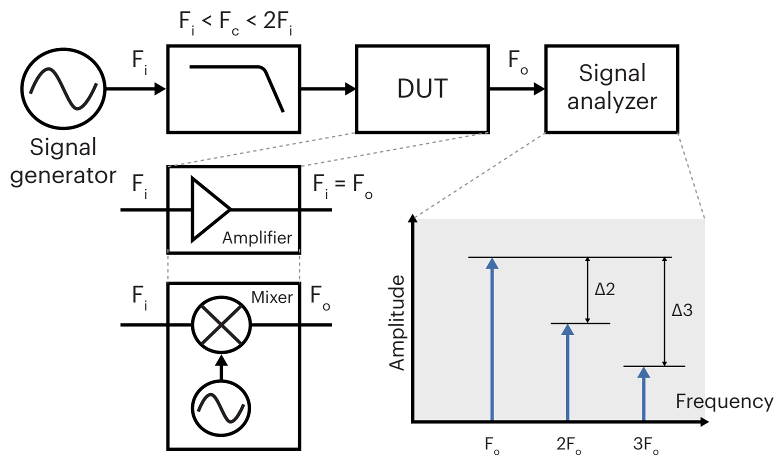


Figure 7.1. Harmonic distortion measurement setup

Harmonics are expressed as a ratio between the power in the fundamental frequency and the power in the harmonic frequency. For example, the first harmonics might look like this:

$$P_{1st\ harmonic} = P_{Fo} - P2_{Fo}\ (dBc) = \Delta 2\ dBc$$

> It's important to use a signal generator with low harmonic distortion that includes a low-pass filter between the signal generator and the DUT. This process ensures that the measured harmonics come from the DUT rather than the signal generator.

Intermodulation distortion: Two-tone intermodulation

Several techniques exist for evaluating intermodulation distortion. The simplest measurement method is the two-tone, third-order intermodulation technique, or IP3 (third-order intercept point). The IP3 technique measures the third-order distortion products generated from the nonlinear elements of the DUT with a two-tone input signal.

Figure 7.2 shows the two-tone, third-order intermodulation measurement setup. The DUT could be an amplifier or a mixer. F_1 and F_2 are frequencies within the two-tone input. Mixing two frequencies from two signal generators creates the two-tone signal. The two-tone signal must be free from any third-order products. The third-order distortion products occur at frequencies $2F_1$ to F_2 and $2F_2$ to F_1 (in red), which are the closest distortions to the original two-tone frequencies. Removing them with filtering proves difficult. In a communications system, they are interference signals to adjacent channels.

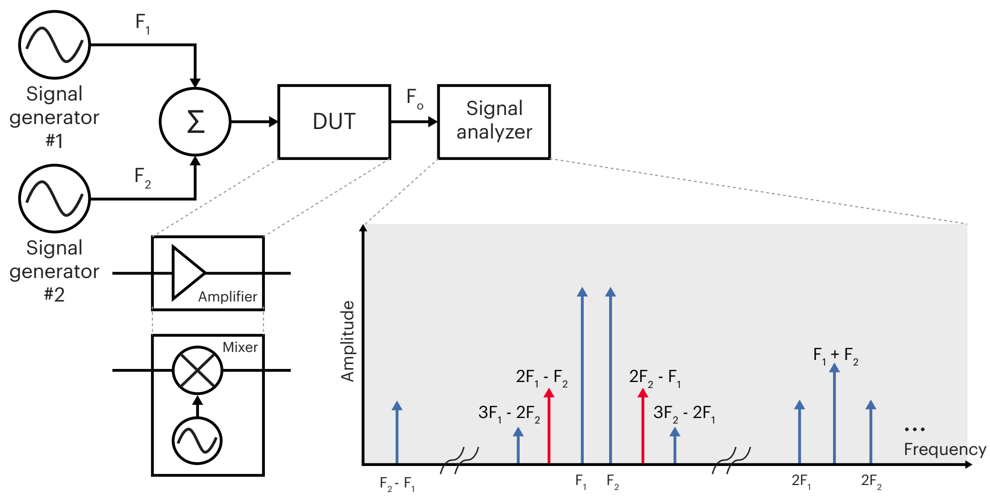


Figure 7.2. Two-tone intermodulation distortion measurement setup

Assuming the amplitudes of two test tones are equal, IP3 is the difference between the input tones and third-order products:

IP3 (dB) = Po - Po3

where Po is the amplitude of one of the output tones and Po3 (in red) is the amplitude of the third-order product on either side of the two tones.

Intermodulation distortion: Spectral regrowth

Wider bandwidths and multicarrier techniques (such as carrier aggregation) increase data throughput for the latest wireless standards. The two-tone, third-order intermodulation technique cannot completely characterize the behavior of wide-bandwidth components.

Digital modulation that employs both amplitude and phase shifts generates distortion, also known as spectral regrowth. Figure 7.3 shows the spectral regrowth (red area) of a digital modulation signal.

The spectral regrowth spreads outside of the main channel. An ACPR measurement helps analyze this type of distortion. It measures the ratio of the main channel power to the power that falls into adjacent channels

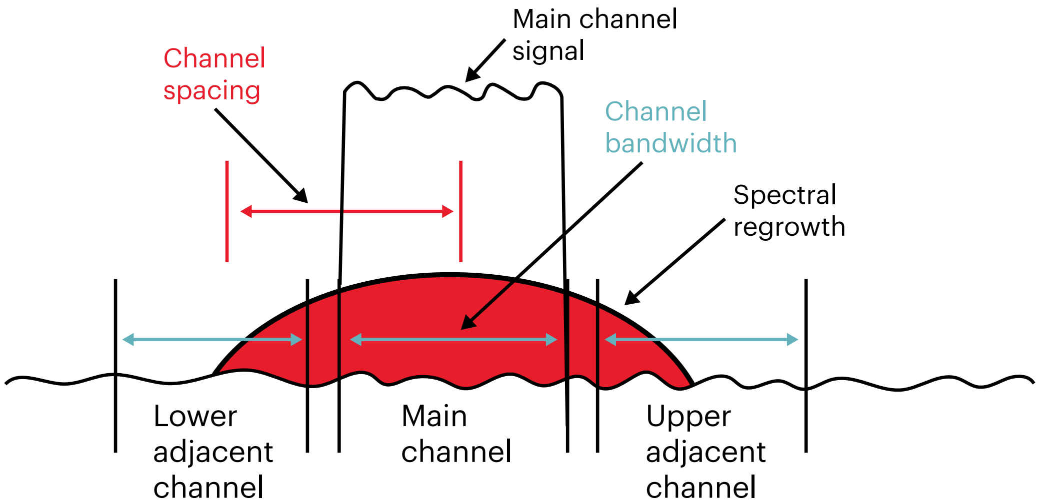


Figure 7.3. Spectral regrowth of a digital modulation signal

Looking to simulate distortions with your signal generator? Try our power amplifier test signal-creation tool.

> The ACPR measurement is a key transmitter characteristic in most cellular conformance specifications. To perform an ACPR measurement, you need a signal generator with ultra-low distortion performance to generate a specific standard-compliant test waveform.

Take your devices to the limit

For the Long-Term Evolution (LTE) Evolved Node B power amplifier test, the ACPR test requirement for research and development verification is about -60 dBc at a 10 MHz channel offset. The typical distortion performance of the N5182B is -69 dBc. With minimal distortion from your generator, you will gain confidence in your ACPR measurements. Table 7.1 shows the 3GPP LTE-FDD (frequency division duplexing) distortion performance of the Keysight N5182B signal generator.

Table 7.1. 3GPP LTE-FDD distortion performance of the N5182B vector signal generator

3GPP LTE-FTD distortion performance								
			Standard		Option UNV		Option UNV with 1EA	
Power level			≤ 2 dBm		≤ 2 dBm		≤ 5 dBm	
Offset	Configuration	Frequency	Spec	Typical	Spec	Typical	Spec	Typical
Adjacent 10 MHz	10 MHz E-TM1.1 QPSK	1,800-2,200 MHz	-64 dBc	-66 dBc	-67 dBc	-69 dBc	-64 dBc	-67 dBc
Adjacent 20 MHz			-66 dBc	-68 dBc	-69 dBc	-71 dBc	-69 dBc	-71 dBc

Section 8. Software

Picture this: Usain Bolt, the Olympic sprinter and one of the fastest human beings on earth, steps up to the starting line. As he carefully places his feet on the starting block, he rehearses in his mind the sequence of events that will take place once the gun goes off, from the first swing of his arms to crossing the finish line. However, this time is different. Usain looks nervous because he is trying to win the 100 m race in high heels.

Having a high-performance signal generator without the right piece of software is like Usain Bolt racing in high heels. In this case, you would be hard-pressed to harness the full potential of the hardware. Using the right software is like wearing the right shoes to the race. You gain traction and control and can use the hardware's raw power to move forward and win the race.

Signal Studio

Keysight Signal Studio is signal-creation software that integrates with Keysight signal generators. You can use it to create application-specific test signals at baseband, RF, and microwave frequencies. You can also use it to quickly generate custom reference signals for testing your device.

Signal Studio uses tree-style navigation and graphical layout, and it supports the latest Windows operating system.

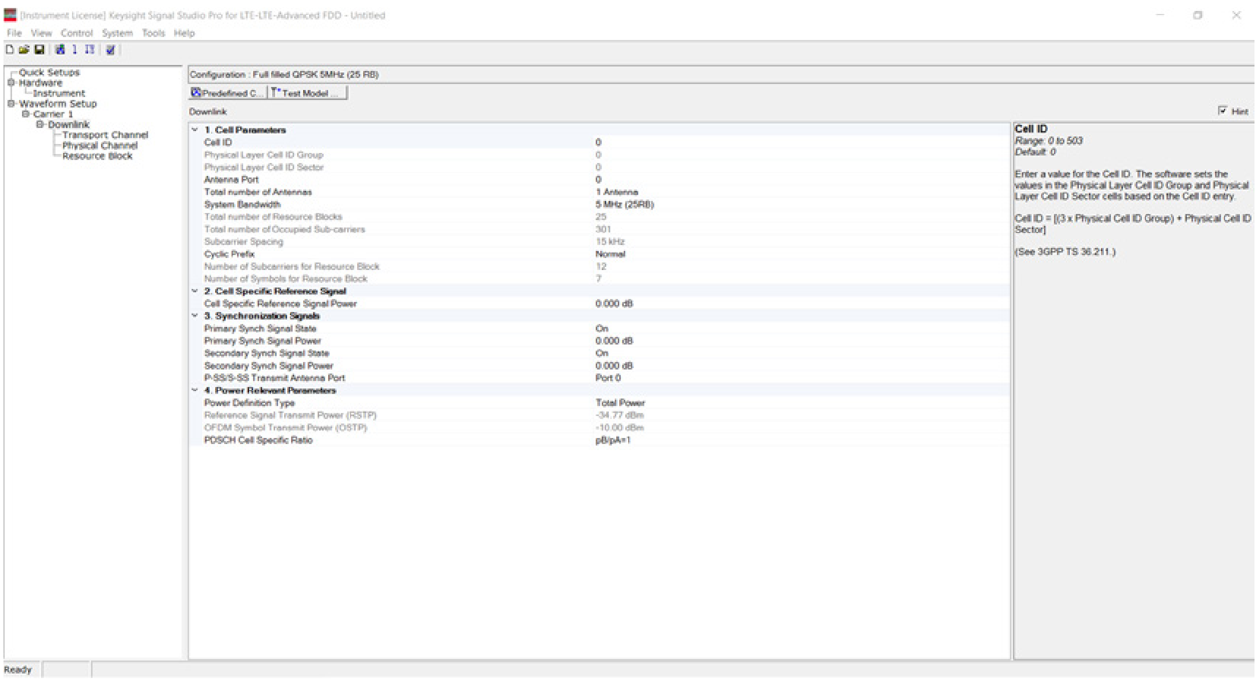


Figure 8.1. Signal Studio's tree-style navigation interface

Create signals for your bench and production line

Signal Studio enables you to connect to your signal generator and your computer through a local area network or General Purpose Interface Bus. A built-in configuration tool makes the process fast and simple. The Signal Studio user interface includes a window that enables direct control of a connected instrument. For advanced automation and control, the available application programming interface (API) exposes the signal creation and generation parameters of the software. This capability also enables the generation of custom user interfaces for signal creation.

When it comes to mass production deployment, you can download waveforms created in Signal Studio to your signal generator's nonvolatile memory. The software enables you to recall and play back these waveforms using Standard Commands for Programmable Instruments (SCPI) commands or through the front panel. You can also quickly download your custom test waveforms to multiple signal generators. However, you need to be aware of licensing requirements for waveforms created using Signal Studio.

Figure 8.2. Typical component test configuration using Signal Studio with a Keysight X-Series signal generator and analyzer

Enhance device testing with waveform playback

Signal Studio's basic waveform playback capabilities enable you to create and customize the waveform files needed to test components and transmitters. You can manipulate a variety of signal parameters, calculate the resulting waveforms, and download files for playback with a signal generator. The following are some of the things you can do with Signal Studio:

- Create spectrally correct signals for channel power, spectral mask, and spurious testing.
- View complementary cumulative distribution function (CCDF), spectrum, time domain, and power envelope graphs to investigate the effects of power ramps, modulation formats, power changes, clipping, and other effects on device performance.
- Adjust the peak-to-average ratio with the crest factor reduction technology.
- Select Signal Studio software products that enable you to save Keysight PathWave Vector Signal Analysis (89600 VSA) or X-Series measurement application setup files for further analysis. See this technical overview for product-specific information.

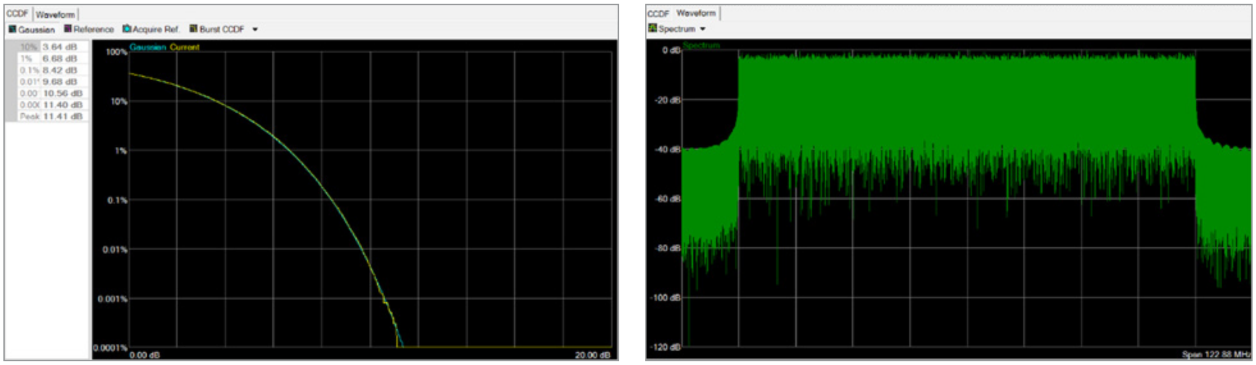


Figure 8.3. Signal Studio's CCDF and integrated spectrum view

Receiver test with real-time capabilities

Signal Studio generates standards-compliant or custom signals for early testing of the receiver system and component hardware with channel coding and multi-antenna ports. Using signal analyzers or oscilloscopes, you can evaluate receiver performance at various stages of the receiver chain (RF, IF, and IQ) together with 89600 VSA software or X-Series measurement applications.

Real-time capabilities available with selected Signal Studio software provide additional features to help you create signals for tests of receiver designs in all stages of development. Advanced options enable you to create fully channel-coded signals for analysis of receiver BER, FER, BLER, and PER so that you can verify baseband subsystem coding in application-specific integrated circuits, digital signal processing, and more. You can also check receiver performance and functionality during RF / baseband integration, system-level tests, and beyond.

Waveform download tools

Keysight provides download utilities to simplify the downloading of waveforms into the signal generator by automatically converting waveforms into the file format the baseband generator requires.

Waveform download assistant

The download assistant software is a free software utility that enables you to download your custom IQ data into the baseband generator of any vector signal generator and use a single MATLAB command to play it back. In addition, you can send SCPI commands to control your signal generators from the MATLAB command line.

Features include the following:

1. Easy to use in MATLAB. Use the download assistant's MATLAB functions to connect to the instrument, download waveform data, set parameters, and play back waveforms from the MATLAB command line. There is no need to scale or format data; the waveform download assistant handles it for you.
2. Flexible instrument control. Send SCPI commands to control your signal generator's settings from the MATLAB command line with the waveform download assistant.
3. Waveform sequencing programmable. Create, download, and play waveform sequences using a series of SCPI commands from the MATLAB command line. A provided example M-file helps you start.

BenchVue software

Keysight PathWave BenchVue is PC-based software. You can quickly configure the most commonly used measurements and setups for multiple instruments, including signal generators, as shown in Figure 8.4. You can also select the folder of waveform files and download them to the signal generator. In addition, BenchVue includes an easy-to-use test flow to control instruments automatically.

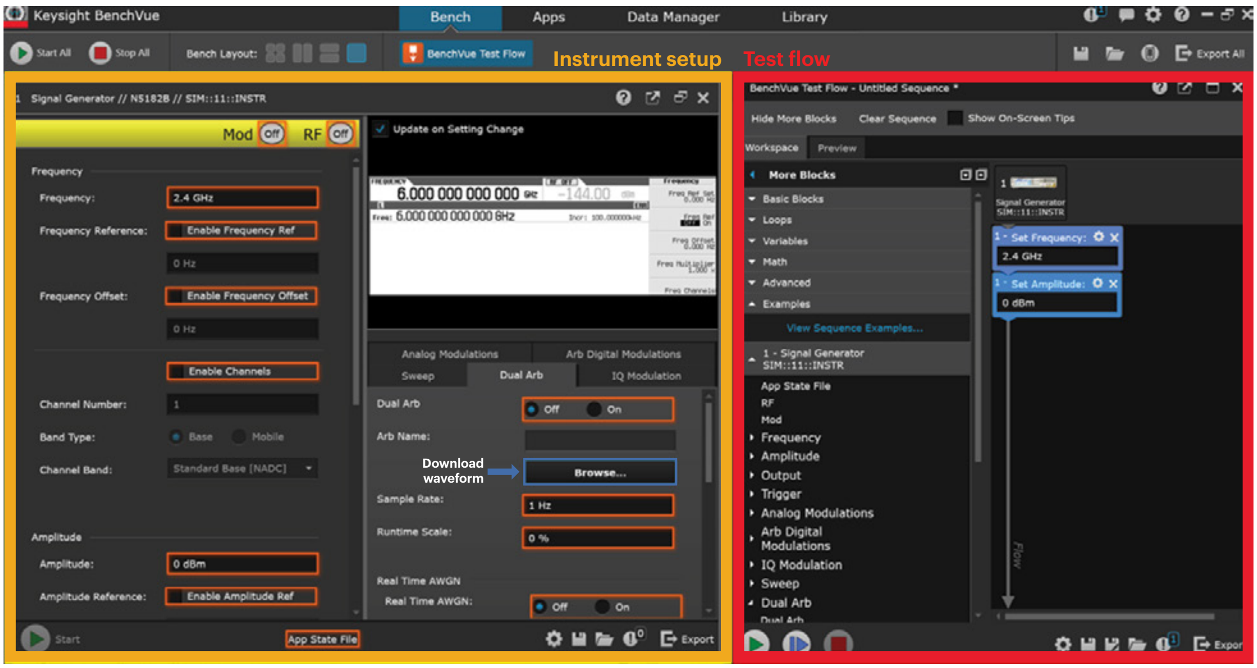


Figure 8.4. Keysight PathWave BenchVue user interface for signal generators

Programming environment

You can use various programming environments to create and download the waveform data to the baseband generator. The programming environments include the following:

- Simulation software: MATLAB and Keysight PathWave System Design (SystemVue).
- Advanced programming languages: C++, VB, VEE, MS Visual Studio.Net, and LabVIEW.

You can use either the instrument's SCPI, APIs, or an FTP command to download waveform files to the baseband generators.

Conclusion: Building a Solid Foundation

The humble signal generator is the building block of advanced RF technologies. In 1940, the HP 200B audio oscillators helped the Walt Disney Company achieve sound system breakthroughs, enabling audiences worldwide to enjoy the thrilling stereo sound in Fantasia. And now, the humble signal generator is once again helping engineers and scientists achieve breakthroughs in 5G, multiple-input / multiple-output, and radar technologies to make our world a better place.

A better tomorrow depends upon building a solid foundation for future trailblazers. We hope these sections have inspired you to build a solid foundation in your signal generator knowledge. Through a sound understanding of RF principles, we can harness the magic of RF. Now is the time for us to build on the foundation laid by those who have come before us and to lay the path for future trailblazers.

To stay current 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 Keysight RF & Microwave Instruments & Measurements LinkedIn page.