WHITE PAPER

Basics of Vector Signal Generators

Part 2: Waveform playback mode

KEYSIGHT

Introduction

In Part 1, we explored real-time waveform generation, which enables verification of receiver designs in all stages, from baseband subsystem coding to sensitivity tests. We also looked at each component in a baseband generator. In addition, we discussed additive white Gaussian noise (AWGN) and channel emulation for simulating realistic channel conditions between a transmitter and a receiver. These enable receiver performance and functionality testing during radio-frequency (RF) and baseband integration or system-level tests.

The real-time waveform generation mode characterizes the receiver performance of specific wireless standards. But not all wireless standards require such a long-period signal for receiver testing. For example, Wi-Fi IEEE 802.11ax specifies the minimum input sensitivity with a certain package error rate. The signal is in a packet and frame format. You can generate a waveform segment that includes one or several packets, then repeat the segment. The receiver gets the signal and uses cyclic error-correcting coding to determine whether each packet is corrupted.

Transmitter and component tests verify physical-layer performance. Relevant test signals are payload independent, so they don't require a long-period signal. Waveform playback mode lets you quickly generate a complex signal to characterize the transmitters and components.

Waveform Playback Mode

Waveform playback mode uses a dual arbitrary waveform generator to generate baseband I (in-phase) and Q (quadrature) waveform signals, as shown in area two of Figure 1. This mode controls the playback sequence of waveform segments written into the memory, located in the internal baseband generator. Like an MP3 player that converts an audio file to an analog signal, the arbitrary waveform generator enables you to play, rename, delete, store, and load waveform files in addition to building waveform sequences.

The waveform data will first move to the IQ digital data multiplexer. Then the digital signal processor (DSP) performs additional operations on the waveform data. To learn about baseband waveform data and structure and how to download IQ waveforms into waveform memory, refer to the application note *How to Create Baseband Waveforms and Download Them to RF Vector Signal Generators*.

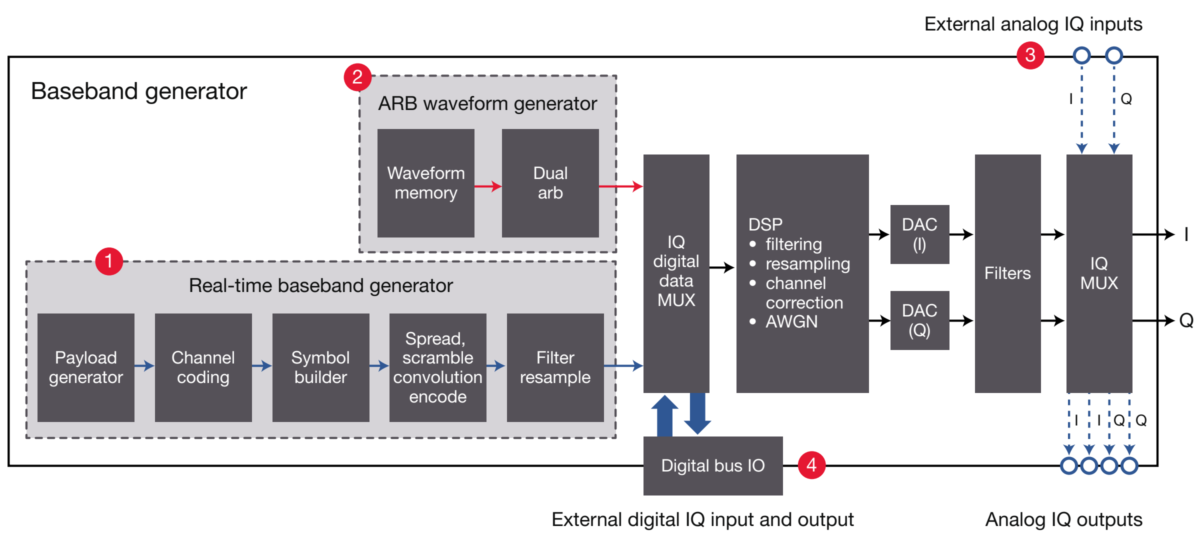


Figure 1. A vector signal generator's baseband generator block diagram

Waveform playback mode is commonly associated with a component test because baseband generators' limited memory size does not allow for an extended period of play in the waveform. The component test uses a stimulus-response methodology to examine the difference between the input and the output waveform signals. In most test cases, payload data does not impact the measurement results.

Creating baseband waveforms

Waveform playback mode is flexible and lets you generate custom digital modulation signals. However, creating baseband waveform files for a vector signal generator requires understanding the waveform data requirements of a baseband generator and the communication system you are working on.

Baseband designers need proper tools and know-how to create desired waveforms for evaluating their designs. Signal generators accept most common development environments, such as MATLAB and C++, and translate IQ waveforms that you create into a proper file format to play with generators. Keysight PathWave Signal Generation is signal-creation software that runs on PCs or signal generators and enables you to generate application-specific test signals at baseband, RF, and microwave frequencies. A fast and streamlined user interface features tree-style navigation and graphical, parameterized signal configuration.

Ensure designs meet the latest standards

Figure 2 illustrates the PC-based PathWave Signal Generation software for 5G New Radio (NR). Users can configure the instrument, waveform, resource allocation, and logical channel setups. The software can display the simulated waveform results, including the complementary cumulative distribution function (CCDF) power curve, spectrum, and IQ traces. It supports predefined, standards-based conformance test setups that save time and give you confidence that your measurements are compliant. Keysight's involvement with and leadership role in standards committees ensures that our software is at the forefront of evolving standards.

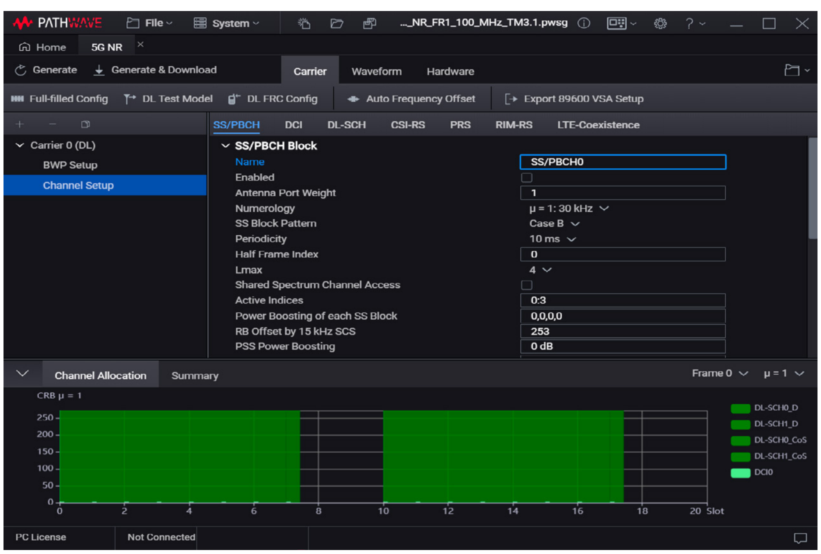


Figure 2. Simplify signal creation for 5G NR with the PC-based Keysight PathWave Signal Generation software

Generate custom waveform signals

In addition to standards-based signal creation, PathWave Signal Generation software enables you to configure custom modulation schemes. You can choose different payload data, symbol rates, modulation schemes, and baseband filters, as we did for real-time waveform signal generation. Also, you can define frame segments, such as headers and payloads with different waveform lengths (number of symbols), constellations, and a baseband filter, as shown in Figure 3.

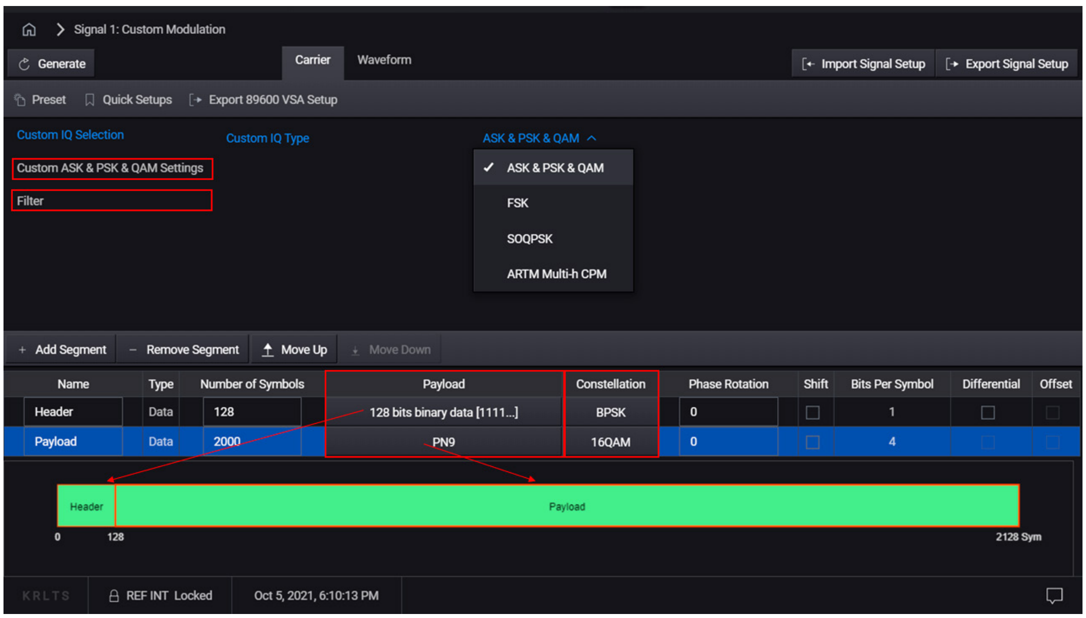


Figure 3. Custom modulation setups with PathWave Signal Generation software

You can also edit the IQ constellation and individual symbol to define custom constellations for propriety communications, such as satellite and military communications. Figure 4 shows an interface of the constellation edit. You can save the constellation setting to a file and recall the file next time. In addition, signal analysis software, such as Keysight PathWave Vector Signal Analysis (89600 VSA) and X-Series Measurement Applications, can load the file for demodulating the custom modulated signal. This process accelerates the test workflow for stimulus-response measurements.

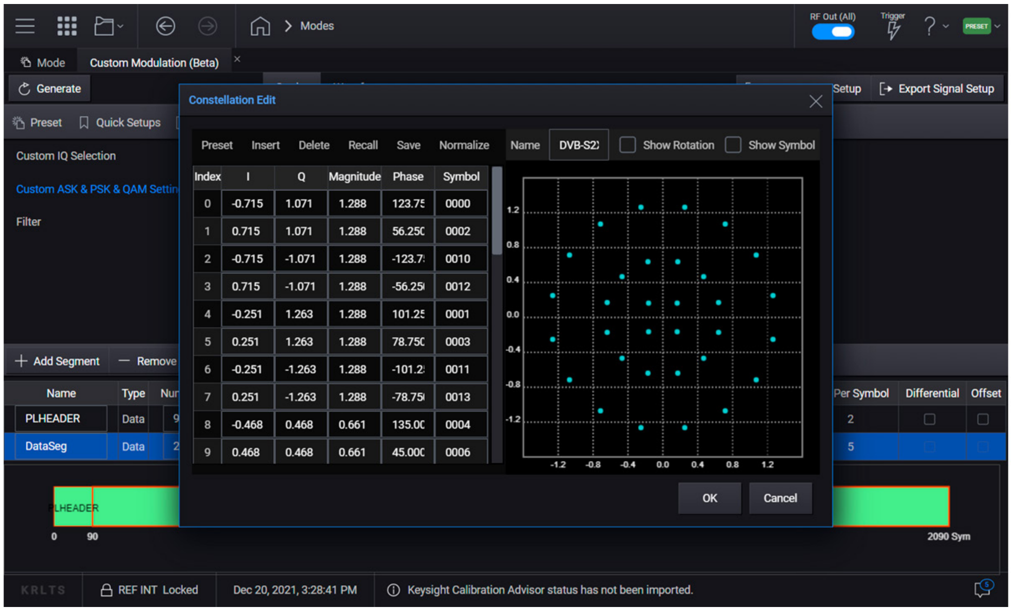


Figure 4. Custom constellation setting with PathWave Signal Generation software

Once you complete the waveform setup, you can generate the waveform and check the simulated waveform in time and frequency domains, as shown in Figure 5. The PathWave Signal Generation software is a flexible suite of tools that reduces the amount of time spent on signal simulation. The software also provides performance-optimized reference signals and enhances the characterization and verification of your devices.

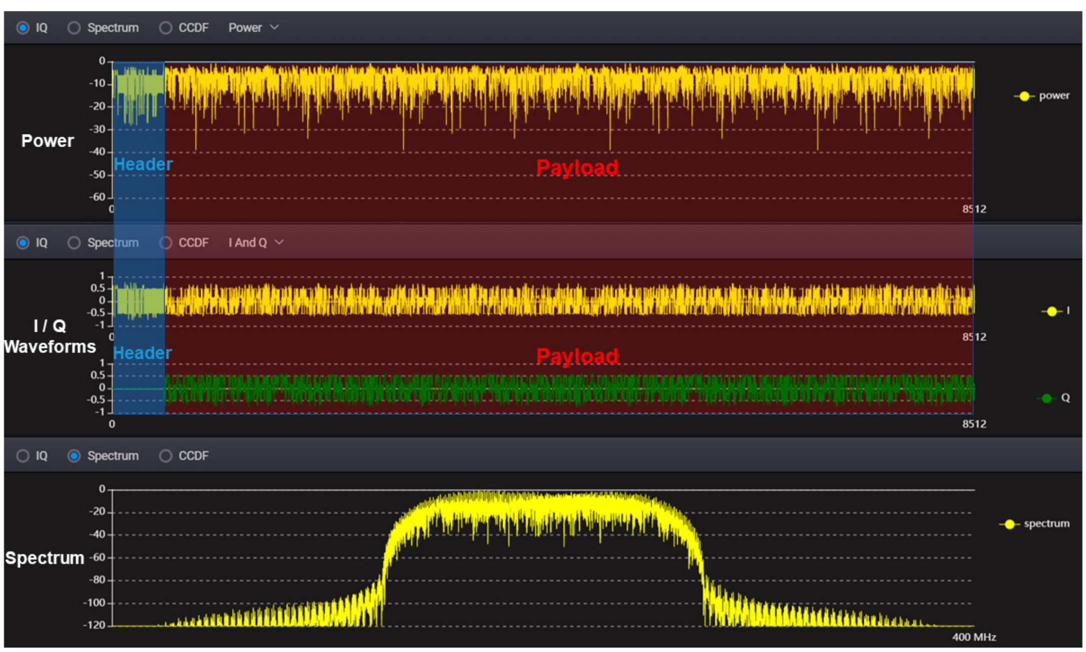


Figure 5. A preview of the waveform simulation results

Evaluate waveform designs with power CCDF statics

Many digitally modulated signals appear noise-like in the time and frequency domains. These signals are typically difficult to quantify because of their inherent randomness and inconsistency. To evaluate the signals, you must completely characterize and understand the power of digital modulation in your signals. You can do so using the power CCDF, a statistic of digitally modulated signals.

When you simulate a digital modulation signal with a signal generator, you need to ensure that the signal will not saturate the signal generator. You can use the CCDF plot capability of a signal generator to identify the power distribution curve of a signal waveform, as shown in Figure 6. The light-blue trace is Gaussian distribution. The yellow trace is the power distribution of a 64 QAM with symbol rates at 100 M symbols/s and a root-raised-cosine baseband filter. The peak-to-average ratio (PAR) is 5.66 dB, as shown in the lower left. If the output amplitude (Pout) is set to 0 dBm, the peak envelope power (PEP) equals output amplitude plus PAR — that is, +5.66 dBm.

PEP = Pout + PAR, where Pout is the amplitude setting on a signal generator (average output power of the signal).

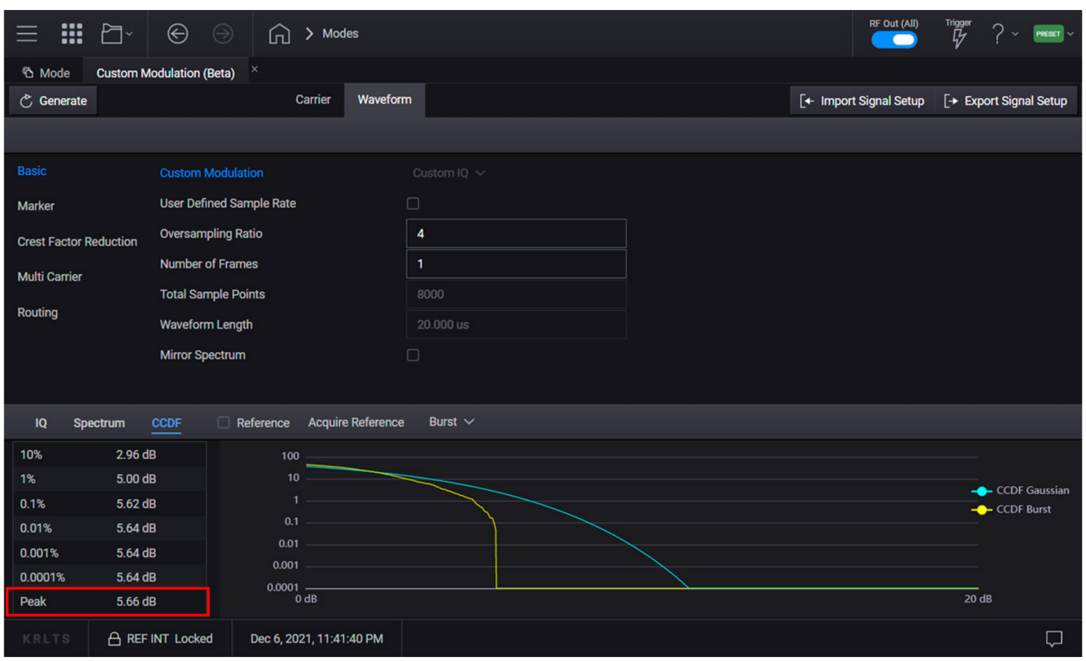


Figure 6. Power CCDF plot of a 64 QAM signal

If the output power of the signal generator is saturated, it impacts the output power level accuracy and the modulation quality because of AM-to-AM compression. You need to know the power characteristic of the simulated waveform so you can apply the right amplitude level to your signal generator.

Create multi-carrier signals

Multi-carrier or carrier aggregation (CA) is a way to increase transmission bandwidth based on an existing standard. For example, 3GPP Release 10 of the LTE specifications introduced carrier aggregation based on a component carrier (CC) defined in Release 8. The standard allows aggregation of two to five CCs to create an instantaneous bandwidth of up to 100 MHz. The channel bandwidths of the aggregated carriers need not be the same, and the aggregation can be contiguous or noncontiguous and interband CA or intraband CA. Release 15 of 5G NR specifies aggregation of multiple carriers for up to 800 MHz channel bandwidth for intraband CA and up to 1.6 GHz bandwidth for interband CA.

To validate multi-carrier components such as RF power amplifiers and transceivers, you need to simulate multi-carrier signals to fully characterize the components. You do not have to use multiple signal generators to simulate the test signals. Instead, you can create a multi-carrier waveform and generate the signals using a single vector signal generator. Figure 7 simulates a 5G NR waveform with eight contiguous CCs. Each CC has a bandwidth of 100 MHz.

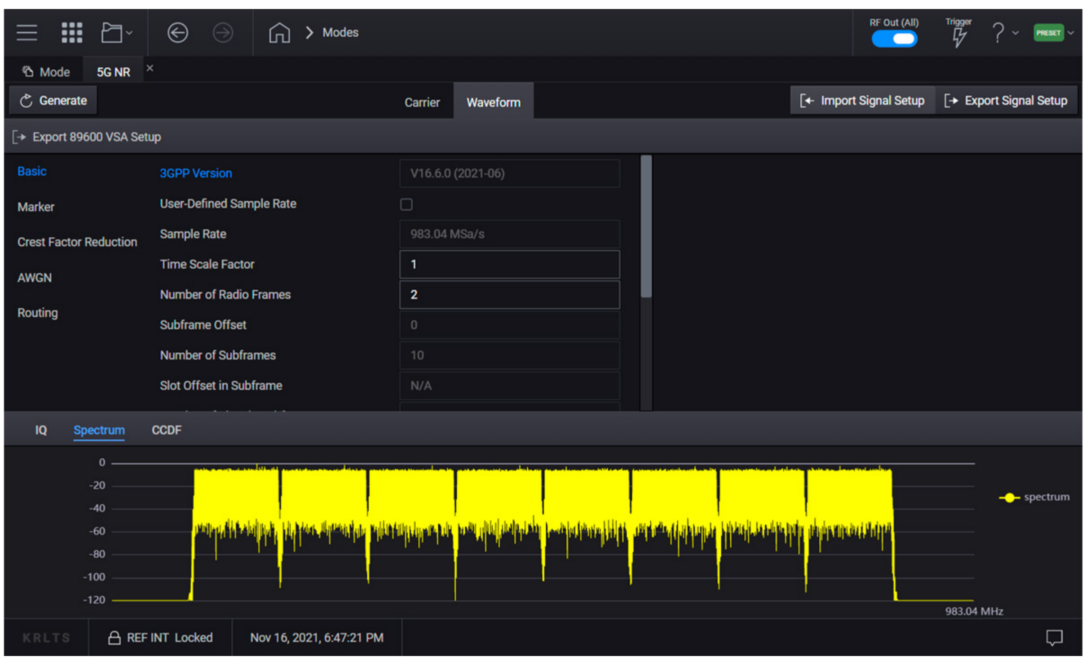


Figure 7. Create a carrier aggregation waveform with PathWave Signal Generation software

Waveform playback mode is flexible to enable you to generate complex modulation and multi-carrier signals with a single vector signal generator. However, the channel bandwidths cannot exceed the bandwidth of the signal generator. Also, consider signal impairments, such as carrier feedthrough, wideband signal distortion, and dynamic range, that may cause measurement errors. When signal bandwidth increases, the impairments get worse.

With advanced high-speed digital-to-analog converters (DACs) and digital signal processors, modern vector signal generators using direct digital synthesizer (DDS) technology can generate an intermediate frequency (IF) / RF signal directly from a high-resolution, high-sampling-rate DAC.

Figure 8 shows a traditional baseband block diagram with an analog IQ modulator and a direct IF / RF with DDS technology for multitone signal generation. The traditional method creates intermodulation image signals between tones. The direct IF / RF architecture eliminates signal impairments caused by the analog IQ modulator, such as gain imbalance, timing skew, quadrature skew, DC offset, and phase noise. This new architecture improves a signal's dynamic range, especially for wideband signal generation.

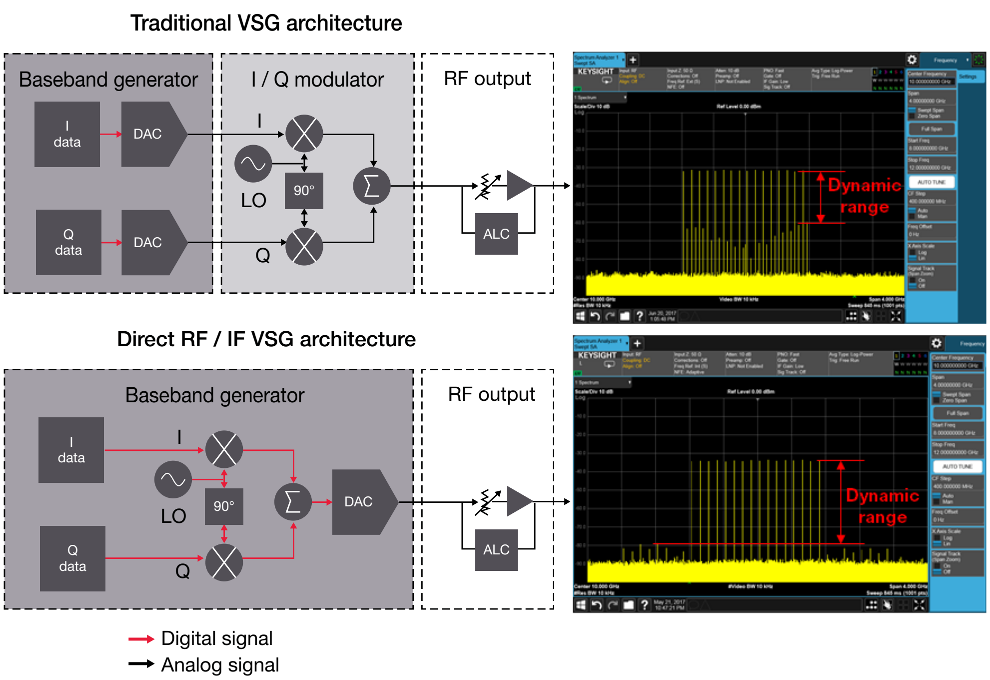


Figure 8. Comparison of analog and digital upconversion methods

Keysight UXG, M9484C VXG, and N5186A MXG signal generators apply the advanced DDS technology that offers the best signal fidelity for wideband test applications such as radar, satellite communications, and 5G.

Emulate Complex Test Scenarios

Designing receivers is challenging because wireless devices must handle various input signal conditions, which are typically difficult to predict. To characterize the receiver's performance, you need to create wanted signals and inject noise and interfering signals.

Figure 9 shows common receiver test cases. The test signal can be a simple continuous wave signal or a complex digitally modulated signal and require multiple signal generators to simulate wanted signals and interferers. In addition, you need to combine the wanted signals and interferers with RF combiners and calibrate the test system to ensure that each signal at the input of the device under test (DUT) is at the desired power level.

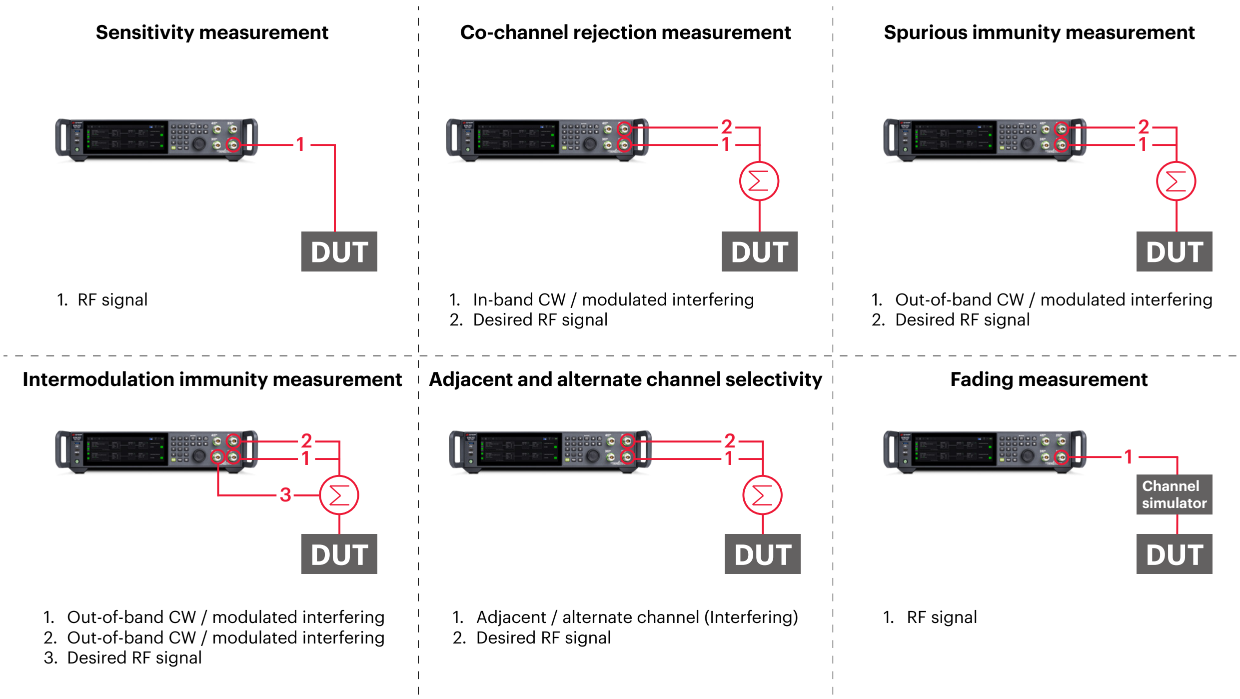


Figure 9. Signal generator's use cases for receiver sensitivity tests

Modern signal generators, such as the M9484C VXG vector signal generator, provide faster signal processing to resample multiple test waveform files and combine them into one waveform. With the high dynamic range from the advanced DDS technology, the M9484C can emulate up to 8 transmitters simultaneously per RF channel without generating intermodulation signals (image) and local oscillator (LO) carrier feedthrough, which a traditional signal generator does. This is useful for cellular receiver testing because you need multiple signal generators to emulate wanted signals and interferers. The wanted signal could be a single-carrier, interband CC or an intraband contiguous / noncontiguous CC for CA. The interfering signal could be a CW-blocking or modulated signal such as W-CDMA, LTE, or 5G NR. You must use hybrid combiners to unite all the signals and calibrate the whole test system.

With the DDS architecture, the VXG can generate all wanted and interfering signals with one signal generator as long as all the signals are within the VXG's maximum RF bandwidth of 2.5 GHz. You can set up the frequency and output level for each signal in real time without the need to calibrate the test system. The VXG simplifies the 5G receiver test setups with better signal fidelity. Figure 10 illustrates waveform emulation for one 5G intraband CA wanted signal with AWGN and seven interfering signals, including 5G, LTE, HSPA, and a CW blocking signal at different operating frequencies and levels with a single RF signal generator.

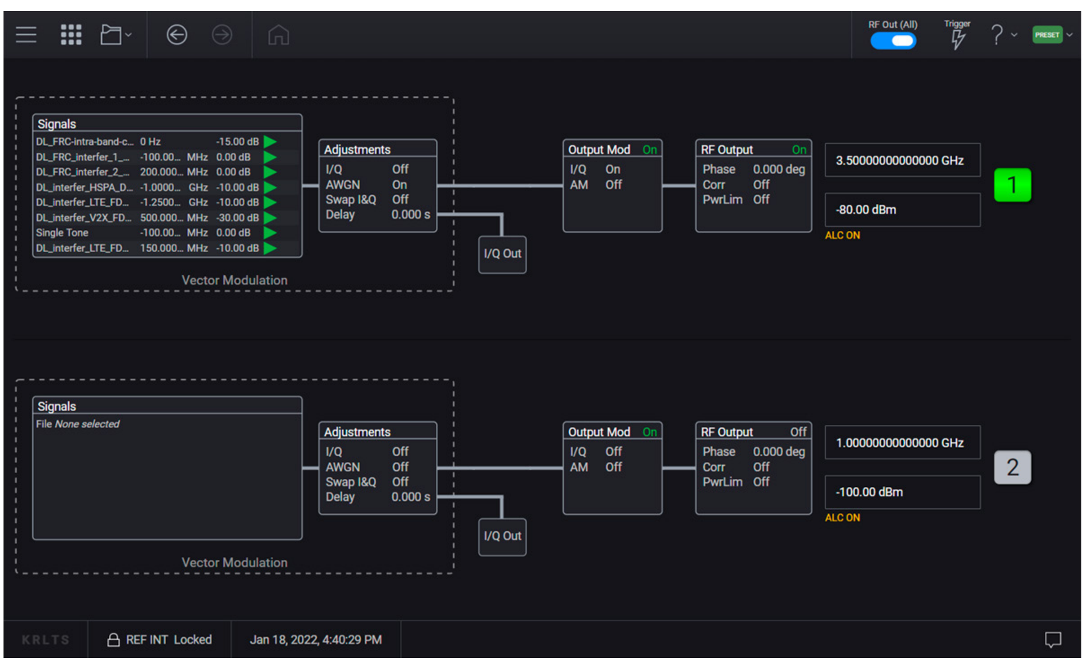


Figure 10. Emmulate multiple transmitters for complex receiver test scenarios with a Keysight M9484C VXG signal generator

Generate Synchronized Multichannel Signals

Testing multi-antenna systems such as spatial diversity, spatial multiplexing, and antenna array requires a test system capable of providing multiple signals with stable phase relationships. However, a commercial signal generator has an independent synthesizer to upconvert an IF signal to an RF signal. To simulate the multichannel test signals, a test system must provide precise timing synchronization between channels, and the phase between test signals must be coherent and controllable.

Timing synchronization

Synchronizing multiple instruments requires a primary / secondary operation in which one of the instruments is the primary and generates a trigger signal to enable secondary instruments. The secondary instruments begin generating or acquiring signals following a trigger event. Figure 11 is an example of synchronizing multiple baseband generators using the Keysight N5186A MXG signal generator. This feature can synchronize waveform generation for up to 16 signal generators within a characteristic value of ± 8 ns between the primary and last secondary instruments.

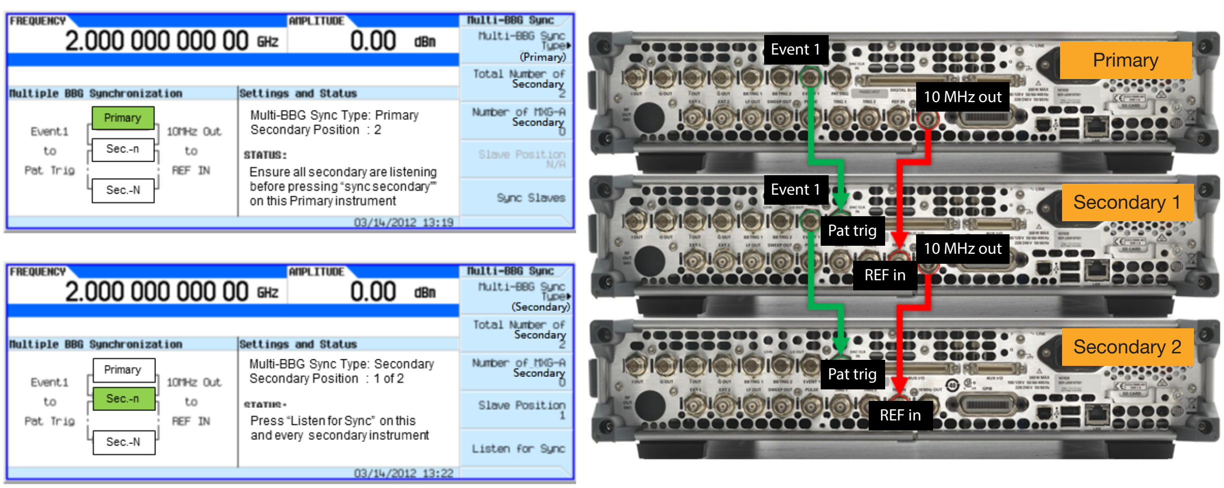


Figure 11. Multiple baseband synchronization setups

While the number of synchronized channels increases, the cabling between the instruments becomes more complicated. Achieving proper time synchronization can take a significant amount of time. Modular or fully integrated multichannel signal generators use standard instrumentation buses such as PXI and AXIe. These instruments can share clocks and trigger signals through a backplane bus. This setup makes it easy to implement and control synchronization and enables repeatable trigger events because the test environment has minimal cabling.

Phase coherence

For some applications, such as beamforming systems, test signals must be coherent and have a specific phase relationship. Therefore, signal generators need a phase-controllable capability. A simple way to minimize the sources of coherency error is to use a common LO among multiple signal generators. Figure 12 represents two Keysight N5182B MXG vector signal generators set up for a phase-coherent test system. The LO of the top signal generator outputs, splits, and inputs as the LO (red lines) for both signal generators. The RF paths of the two signal generators are fully coherent now. In the right area of Figure 12, you can see that the phase difference between the two signal generators is less than 1 degree.

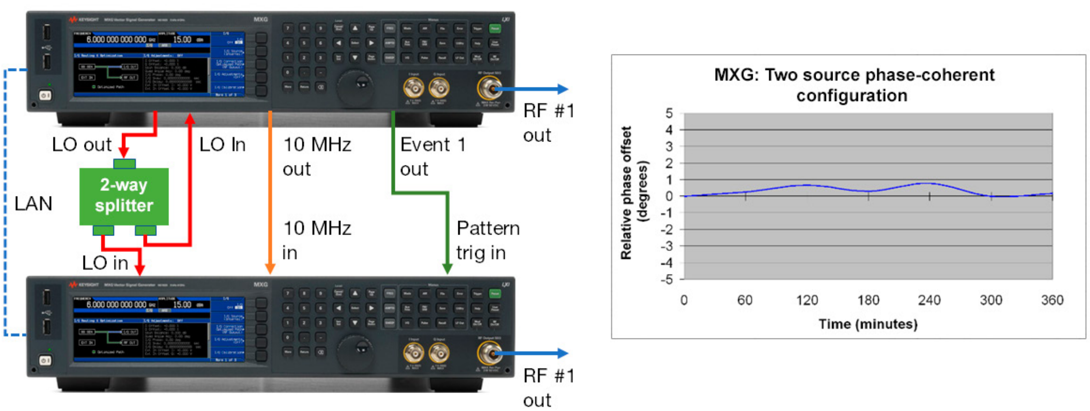


Figure 12. Setup for two phase-coherent RF channels with a common LO

Even using a shared LO, you will encounter some static time and phase skew between instrument channels. Cable lengths and connectors cause static time and phase variations. The delays and phase shifts skew the phase relationship between the channels. You need to correct these offsets and ensure that the measured differences come from the DUT, not the test system.

Direct digital synthesis

DDS produces an analog waveform by generating a time-varying signal in digital form and then performing a digital-to-analog conversion. DDS architecture provides an optimal path to low phase noise and fast frequency switching speed with extremely fine frequency tuning resolution.

DDS maintains a fixed phase relationship between its output for each frequency. The synchronization requires initial clock alignment (using a common reference clock), as shown in Figure 13. Synchronous reset (green line) to the phase accumulator can achieve phase alignment. Apply this reset on every frequency update. The synchronous reset of the phase produces a fixed and repeatable phase relationship for each channel.

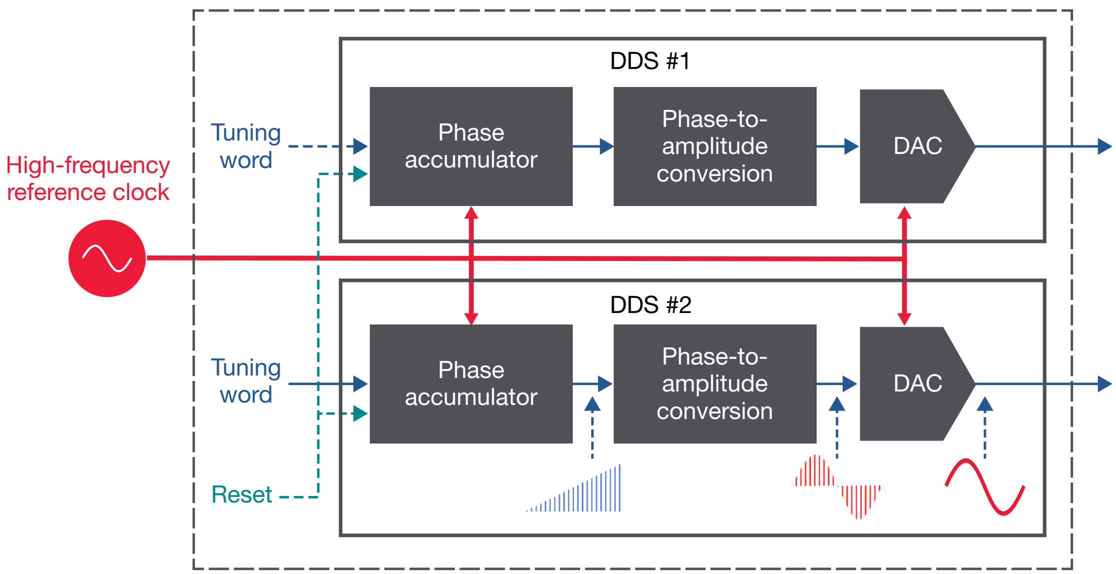


Figure 13. Shared reference clock for two DDS

Next-generation signal generators such as the M9484C VXG and N5186A vector signal generators use DDS technology. The VXG provides up to four coherent channels in one instrument with a time alignment of < 10 ps without touching any hardware. You can easily configure the coherent multichannel VXG for nonsynchronized (Independent) or synchronized (2 Tx Coherent) baseband generators, as shown in Figure 14. The VXG enables you to increase the number of channels using multiple VXGs with Keysight's advanced synchronization.

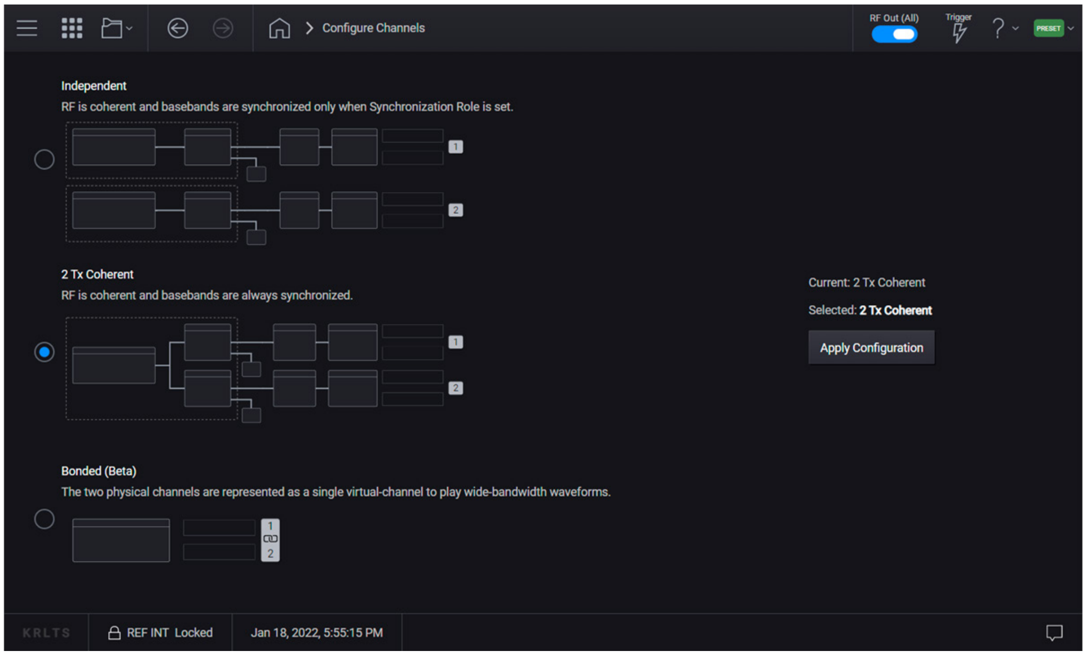


Figure 14. Easy setup for various multichannel signal generation use cases

Which Mode Is Right for Your Test?

Real-time mode lets users define the parameters of nonrepeating signals needed for receiver testing. Its graphical interface provides a direct instrument connection for parameter transfer and closed-loop or interactive control during signal generation. Waveform playback mode lets users create and customize waveform files needed to test components and receivers. PathWave Signal Generation software provides a user-friendly interface and enables you to configure signal parameters, calculate the resulting waveforms, and download files for playback.

Although waveform playback mode is more flexible for creating modulation signals for component and receiver testing, it has limitations. Table 1 offers a quick overview of the differences between real-time signal generation and waveform playback mode.

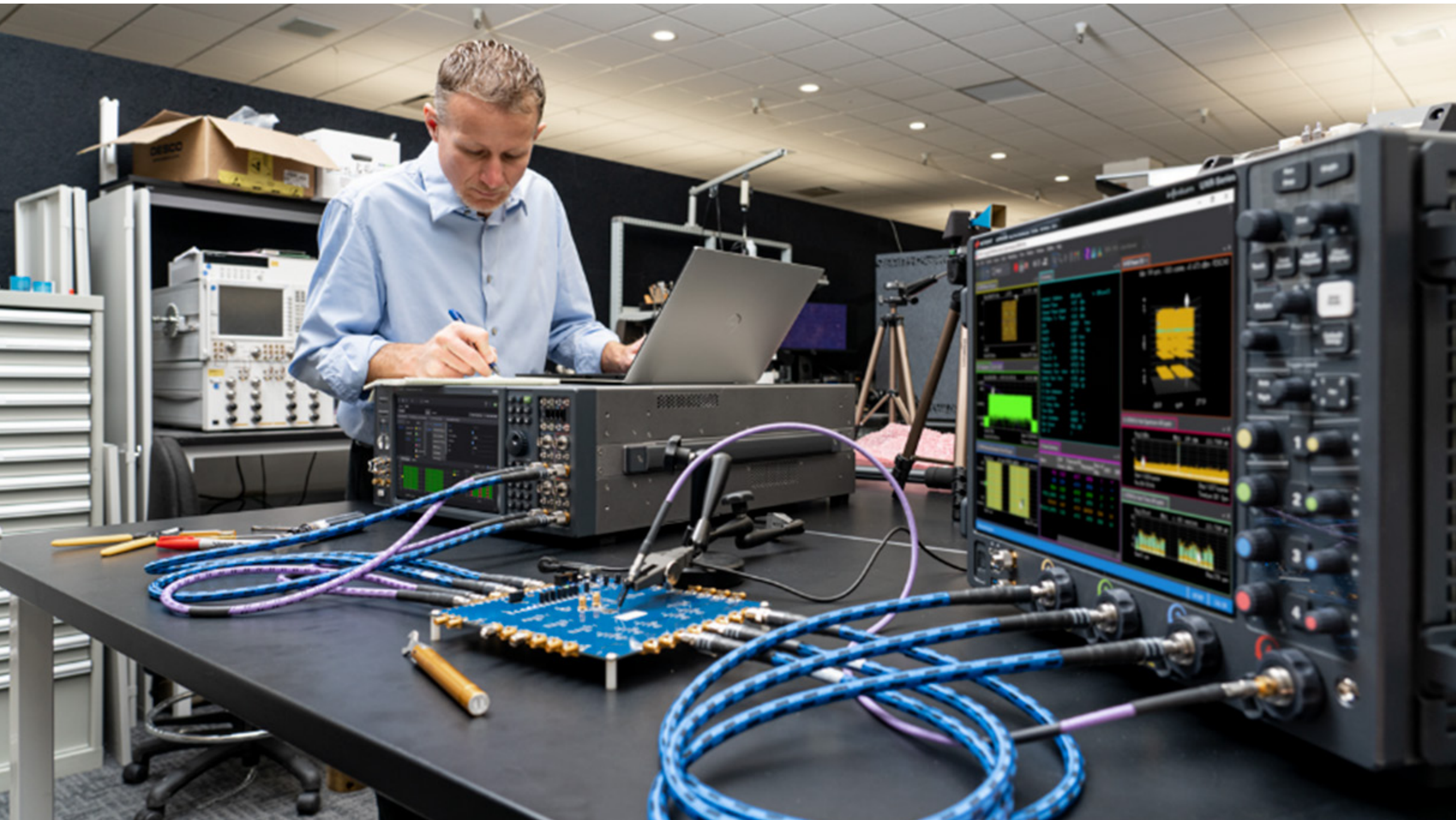
Table 1. The differences between real-time signal generation and waveform playback mode

	Real-time signal generation mode	**Waveform playback mode**
Applications	**Primarily used for receiver testing**	**Used for both component and receiver testing**
Feature	• DSP-programmed for communication standards and common modulation schemes • Fully coded and framed signal for an extended amount of time (minutes or hours) • Ideal for BER testing	• Flexibility in complex signal creation • Waveform file-based • Fully coded and framed signals for a short amount of time (milliseconds to seconds) • Ideal for packet error rate or frame error rate testing
Carrier(s)	**Supports single carrier**	**Supports multiple carriers**
Limitation	• Limited flexibility in signal creation	• Memory sizes • Waveform phase discontinuity • Inconsistent automatic leveling control
Signal-creation tools	**Offers embedded and external software**	**Software tools generate waveform files**

The Synergy of Two Baseband Generation Architectures

Engineers designing consumer wireless, military, satellite communications, or radar devices face an ongoing bandwidth crunch in a spectrum filled with interference. Vector signal generators offer precise and stable test signals for receiver tests and RF component characterization.

To effectively test your devices, you need to use the correct baseband mode to generate signals for your test applications. RF vector signal generators offer two flexible baseband architectures with complementary features for generating complex digital modulation signals. Selecting the appropriate waveform generation modes and understanding signal-creation processes are the keys to solid designs and excellent products.



Resources

- How to Create Baseband Waveforms and Download Them to RF Vector Signal Generators
- How to Minimize Measurement Uncertainty Using RF Vector Signal Generators
- 9 Best Practices for Optimizing Your Signal Generator — Part 1
- 9 Best Practices for Optimizing Your Signal Generator — Part 2
- Digital Modulation in Communications Systems

For more information, please visit our signal generator web page.