WHITE PAPER

Basics of Vector Signal Generators

Part 1: Real-time waveform generation mode

KEYSIGHT

Engineers use signal generators to test RF components, receivers, and test systems in various applications, such as design, verification, troubleshooting, manufacturing, and repair. The output can range from a simple continuous wave (CW) to a complex digitally modulated signal. Analog signal generators supply sinusoidal CW signals and several types of analog modulation, like analog, frequency, and pulse modulation. 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 (QPSK), quadrature amplitude modulation (QAM), and more complex orthogonal frequency-division multiplexing (OFDM) 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.

Many system tests require vector signal generators, driven by the popularity of digital modulation schemes in today's wireless communications systems. Testing your wireless devices via vector signal simulation is critical to making accurate and consistent tests. Knowing the basics of vector signal generators is the first step.

Baseband Generation Modes

RF vector signal generators typically offer two flexible baseband architectures with complementary features for generating complex digital modulation signals: real-time waveform generation and waveform playback modes. Vector signal generators allow external IQ signal inputs for customized modulation signals. This functionality enables you to input baseband signals from a device and provides accurate and stable output levels with analog or digital input signals. Figure 1 shows the process of generating baseband signals with a real-time baseband generator (1), an arbitrary waveform generator (2), an external analog IQ input (3), and an external digital IQ input (4).

Real-Time Waveform Generation Mode

The real-time IQ baseband generator interprets data bits and produces analog voltages representing the desired modulation. Zone 1 of Figure 1 shows the flow of a baseband processor with a real-time baseband generator and the essential components of a transmitter — from a payload generator, channel coding, IQ symbol builder, and spreading / scrambling encoding to filter resample.

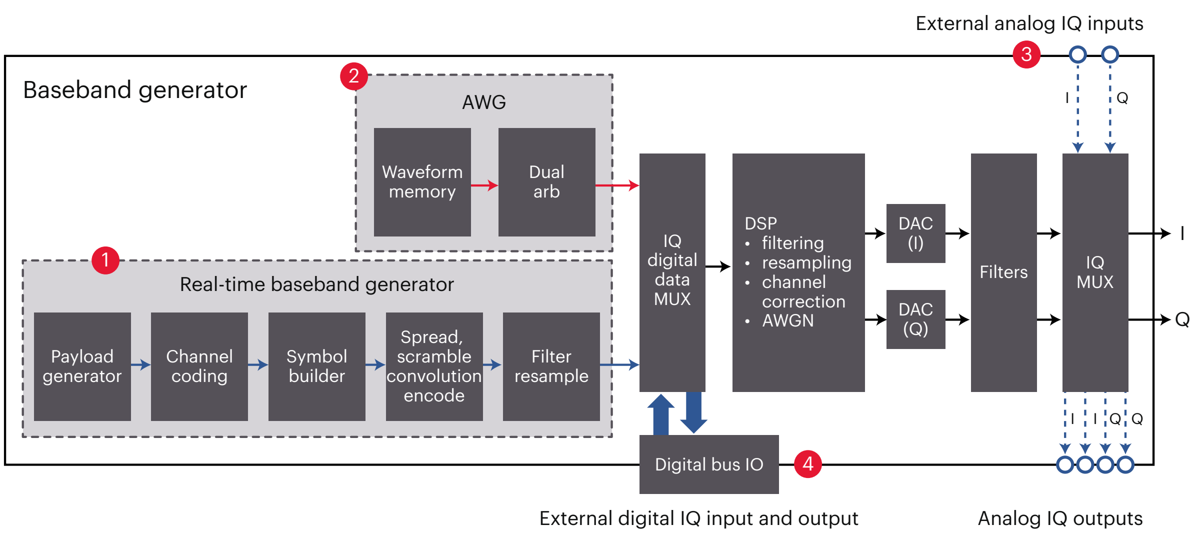


Figure 1. An example of a VSG's baseband generator's process flow depicted in a block diagram

The real-time baseband processor enables the generation of multiple fully coded logical channels, such as data, control, and broadcast. It simulates fully coded signals so the receiver can decode them and recover the original payload data. You can configure the real-time baseband processor for supported modulation schemes or standards by setting parameters for each sub-block. The baseband processor generates digital IQ waveform data streams. A digital signal processor (DSP) performs advanced real-time signal processing, such as internal channel correction and waveform resampling, and adds real-time additive white Gaussian noise (AWGN) to the waveform. Digital-to-analog converters (DAC) transfer the digital IQ waveform streams into analog IQ signals.

Payload data

Using the real-time mode, you can create payload data using a built-in payload generator or user-defined payload. A continuous data stream generated in this mode is suitable for long-period receiver bit error ratio (BER) analysis. A BER test typically uses a pseudorandom binary sequence (PRBS) as payload data and makes a long measurement.

Figure 2 illustrates an example of a 9-bit PRBS (PRBS9) generator. The PRBS9 produces a sequence length of 2^9-1 bits. The baseband waveform length for a cycle of PRBS9 could stretch several minutes, depending on the type of modulation scheme and symbol rate you use. Next, configure the user-defined modulation types along with custom finite impulse response (FIR) filters and symbol rates.

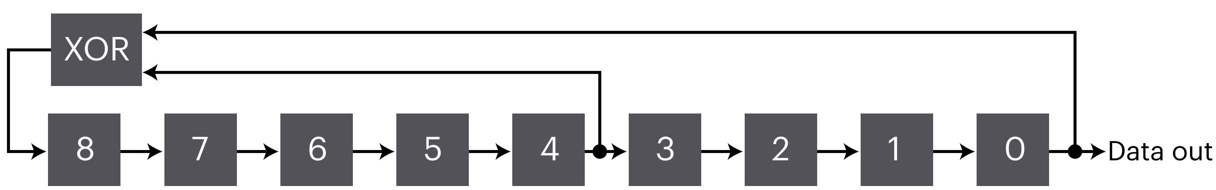


Figure 2. A 9-bit PRBS generator

Basics of IQ modulation

The basic modulation schemes are amplitude, frequency, and phase modulation. Polar form (vector) expresses modulating signal changes in magnitude and phase, as shown in Figure 3.

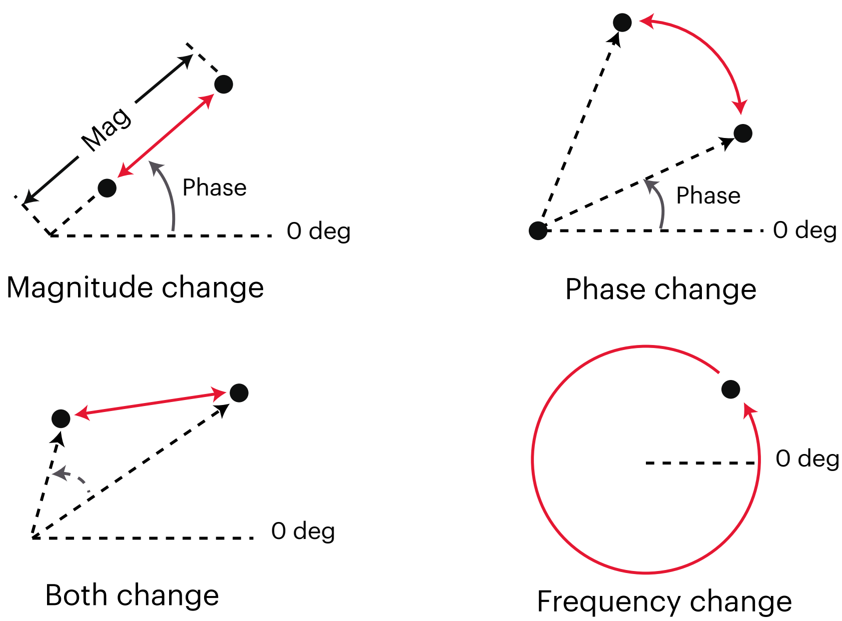


Figure 3. Vector signal changes or modifications in polar form

Digital communications widely use IQ modulation because of its spectrum efficiency. IQ modulation uses two carriers: the in-phase (I) component and the quadrature (Q) component. Figure 4 shows that the quadrature component will phase-shift by 90 degrees from the in-phase component. IQ modulation's main advantage is the symmetric ease of combining independent signal components into a single composite signal for transmitting and later splitting into independent components for receiving.

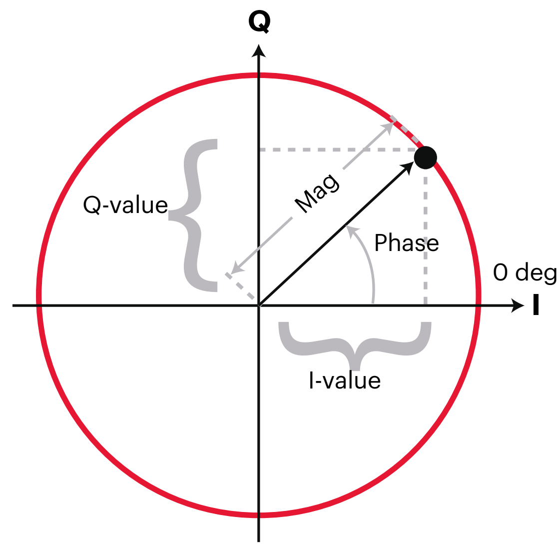


Figure 4. VI/Q phasor diagram

For implementation, the payload data maps to symbols and builds I and Q data streams. For example, QPSK is 2 bits per symbol, as shown on the right of Figure 5. The symbol rate of QPSK is half of its bit rate. The signal bandwidth and symbol rate are in direct proportion. A higher-order modulation scheme with more bits per symbol enables a higher data rate but the same bandwidth.

The I and Q streams 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. This 90-degree phase shift makes the I and Q signals orthogonal to each other so the modulator can combine the two signals without causing interference.

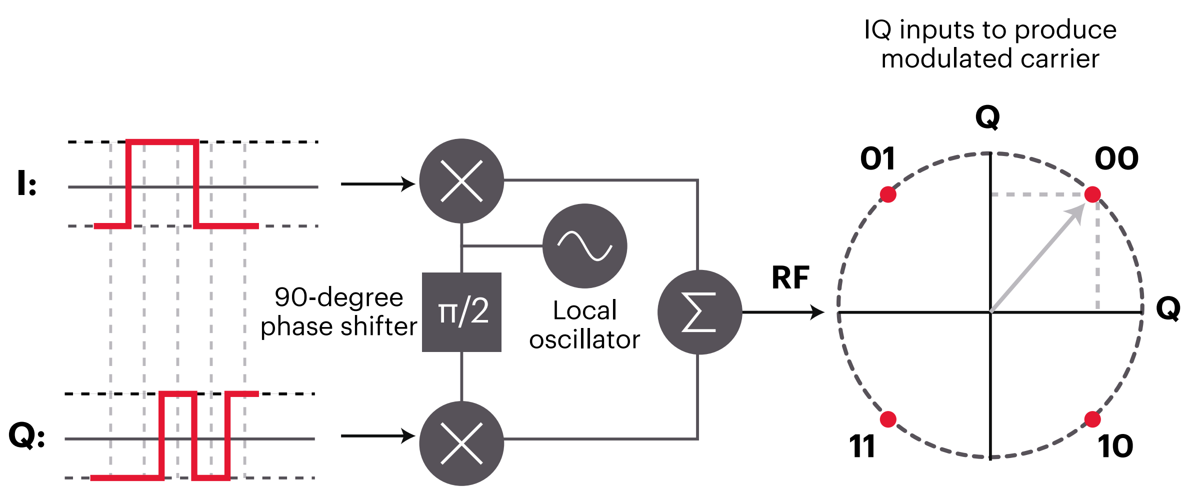


Figure 5. Example of how the IQ modulator mixes with the I and Q with a 90-degree phase shifter

Modulation schemes

A vector signal can change a carrier signal's magnitude, phase, or both. These magnitude and phase changes can result in different modulation schemes. As the data conveyed is in binary, the number of constellation points must be a power of two. The most fundamental digital modulation schemes are amplitude-shift keying (ASK), phase-shift keying (PSK), frequency-shift keying (FSK), and QAM. Figure 6 shows a data stream and the different modulation schemes.

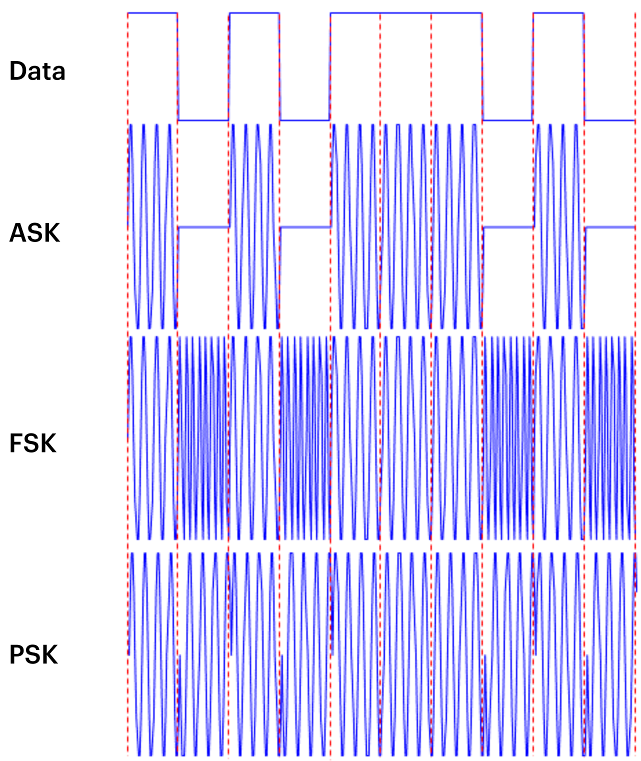


Figure 6. Data stream versus ASK, FSK, and PSK

OFDM is a common modulation scheme for high-data-throughput applications. Many of the latest wireless and telecommunication standards, such as digital broadcasting, xDSL, wireless networks, 4G, and 5G New Radio (NR) cellular technologies, have adopted this modulation scheme.

OFDM employs multiple overlapping radio frequency carriers. Each carrier operates at a carefully chosen frequency that is orthogonal to the others, producing 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. Figure 7 illustrates the constellation, time, and spectrum diagram of a Wi-Fi IEEE 802.11be signal using OFDM modulation.

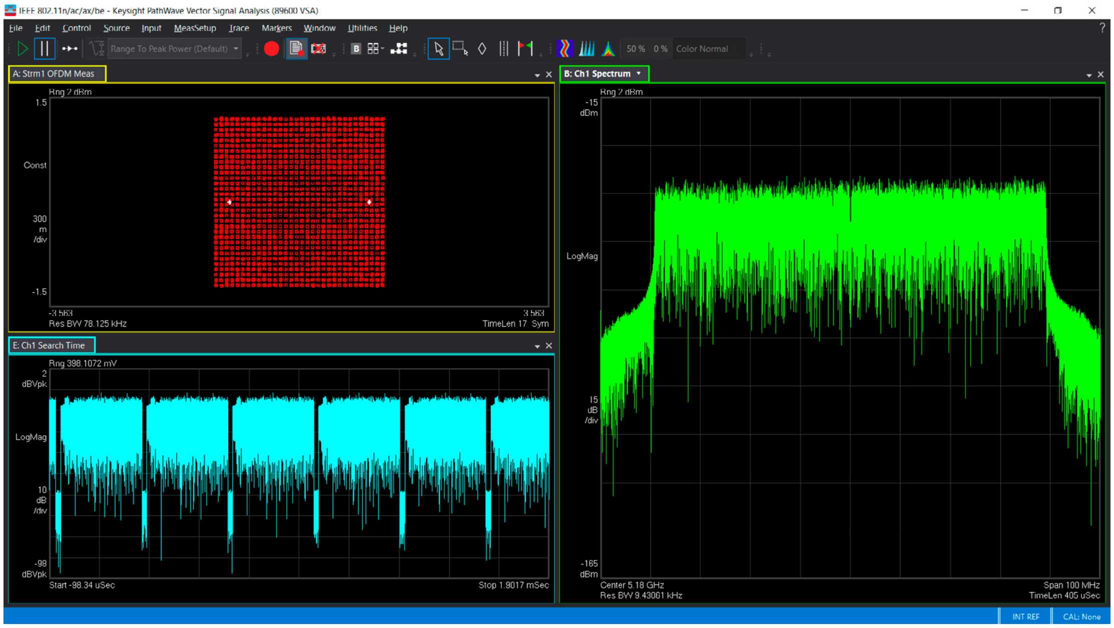


Figure 7. An OFDM signal analysis using Keysight PathWave Vector Signal Analysis (89600 VSA) software

Baseband filter

An ideal baseband I and Q waveform are square waves that result in infinite bandwidth; however, infinite bandwidth for transmission in real life does not exist. Using FIR filters limits the input bandwidth to the I and Q modulators. Filtering can reduce the transmitted bandwidth, but the symbol's energy spreads into other symbols, as shown in Figure 8. The symbols blur together, and each symbol affects those around it. Filtering creates intersymbol interference (ISI). The common baseband filters are Nyquist, square-root Nyquist, and Gaussian filters.

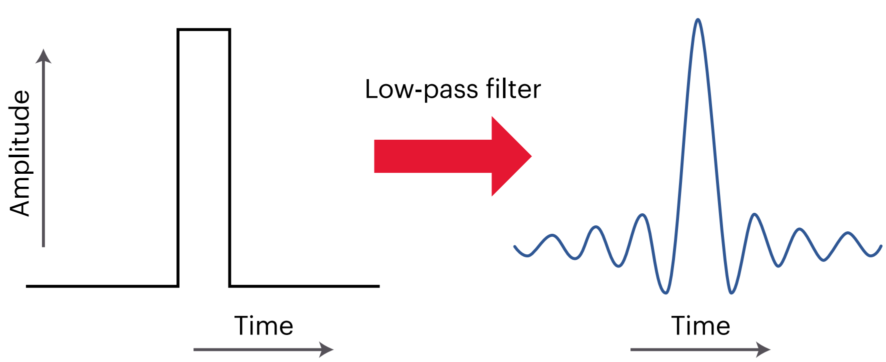


Figure 8. Low-pass filtering of a pulse

Minimize ISI

A well-designed filter can reduce bandwidth and has zero ISI at symbol times. Figure 9 illustrates the mitigation of ISI using a Nyquist filter. The tails (ringing) for the filtered pulses are zero at integer multiples of the bit period. The time response of the filter goes through zero with a period that exactly corresponds to the symbol spacing. Adjacent symbols do not interfere with each other at the symbol times because the response equals zero at all symbol times.

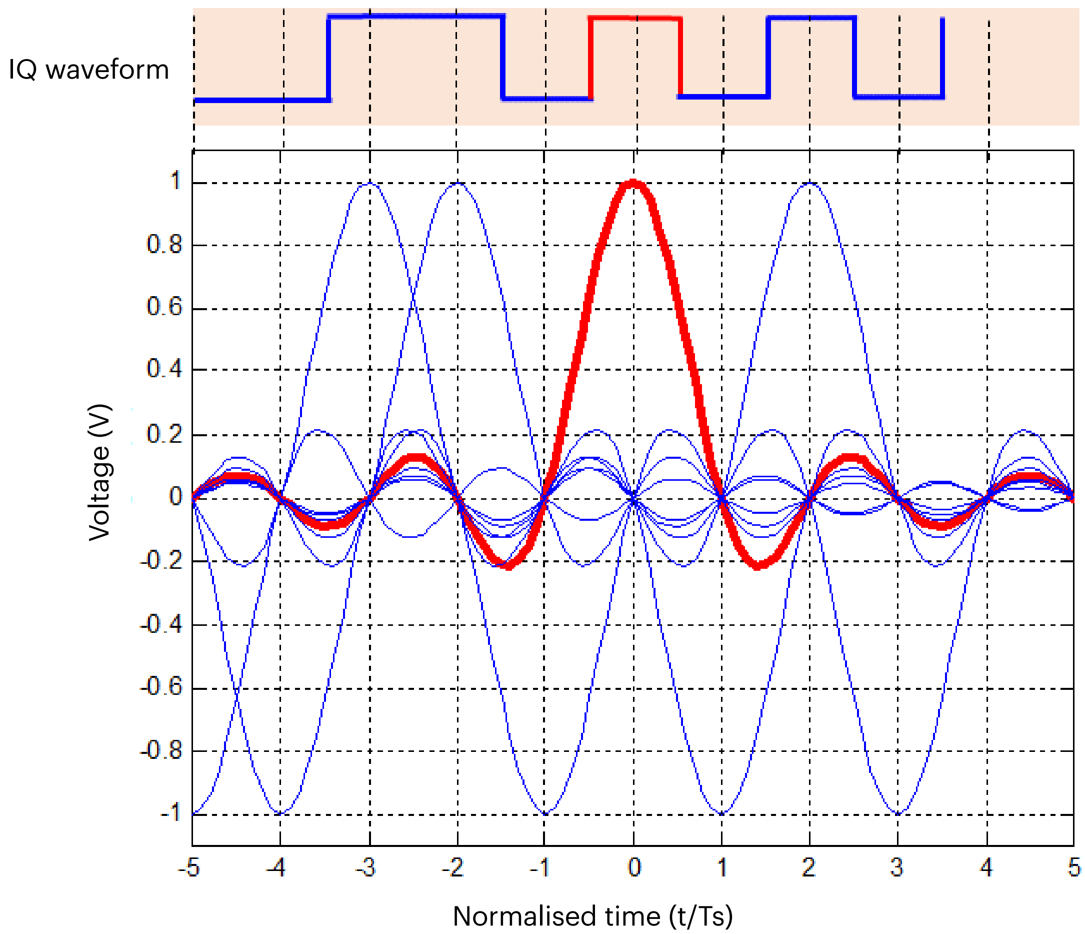


Figure 9. Using a Nyquist filter to reduce signal bandwidth and mitigate ISI

A well-designed filter can reduce the transmitted bandwidth without losing the content of the digital data. The filter improves the spectral efficiency of the signal.

Filter shape

The Nyquist filter defines the filter shape coefficient as the alpha (α). Alpha gives a direct measure of the occupied bandwidth of the system, expressed in the formula below. The higher the alpha value, the wider the signal bandwidth. Figure 10 illustrates the rectangular filter and Nyquist filters with different filter shapes. The filter α = 0.22 has a smoother transition between each symbol than α = 0.5, leading to a narrower signal bandwidth.

$$\text{Occupied bandwidth} = (1 + \alpha) * \text{symbol rate}$$

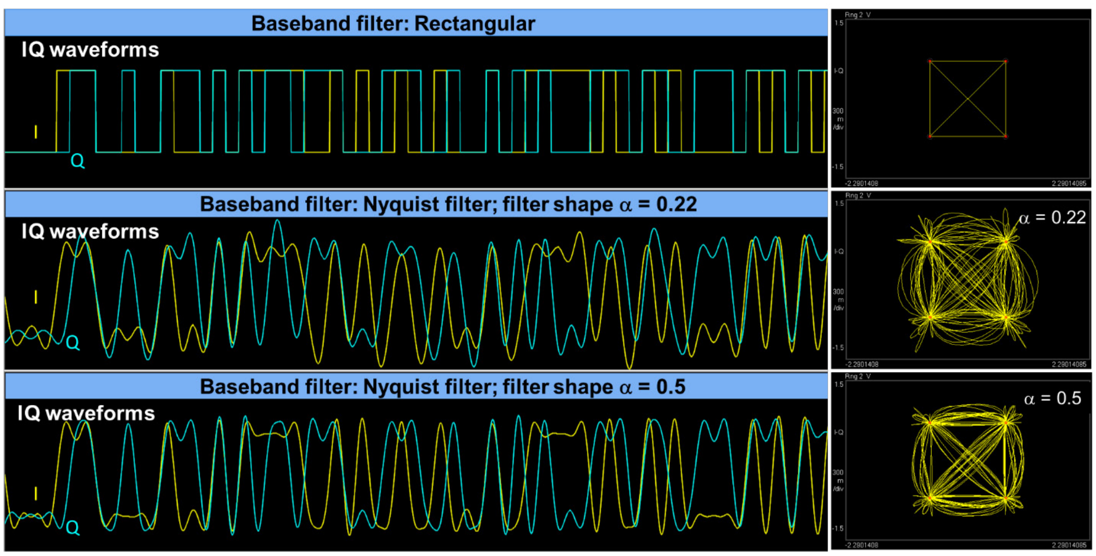


Figure 10. A QPSK signal with a different filter shape coefficient

Real-time additive white Gaussian noise

Noise is a part of all communication channels. To simulate realistic channel conditions in a repeatable manner, you need to add random noise to the wanted signal. AWGN is a mathematical model that simulates the channel between the transmitter and receiver. The model is a linear addition of wideband noise with a constant spectral density and a Gaussian amplitude distribution.

Signal generators need AWGN generation capabilities for receiver tests. Figure 11 depicts the bandwidth and power between the carrier (wanted signal) and AWGN. Carrier bandwidth is the occupied bandwidth of the carrier, and the noise bandwidth is the flat noise bandwidth. The actual flat noise bandwidth should typically be slightly wider than the carrier bandwidth. When combining the carrier and AWGN signal for receiver tests, the carrier appears larger because of the added noise power.

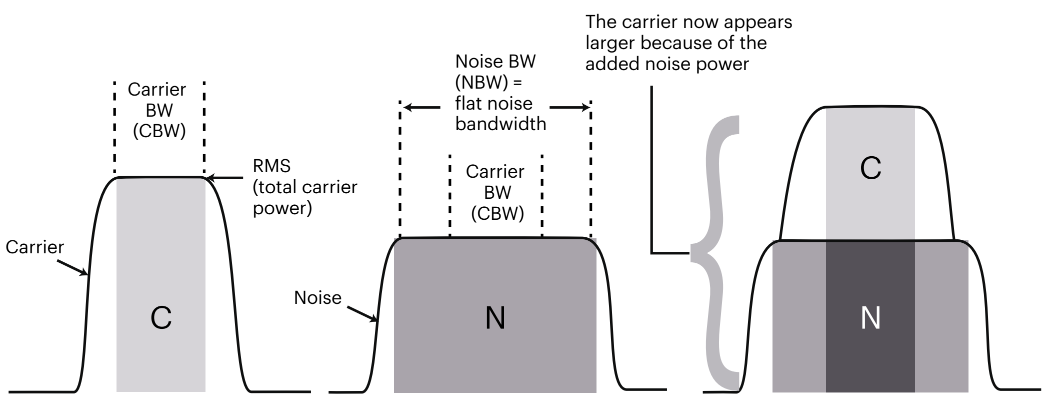


Figure 11. Add AWGN to the wanted signal for receiver tests

When performing receiver tests, measure the noise power you observe within carrier bandwidth, as shown in Figure 11. You can calculate the carrier-to-noise ratio ($\frac{C}{N}$) by knowing the noise power value. Additionally, most standards use energy per bit over noise power density at the receiver ($\frac{E_b}{N_0}$) to characterize the receiver instead of $\frac{C}{N}$. ou need to know the carrier's bit rate to perform this calculation. Below is the conversion equation for $\frac{C}{N}$ and $\frac{E_b}{N_0}$.

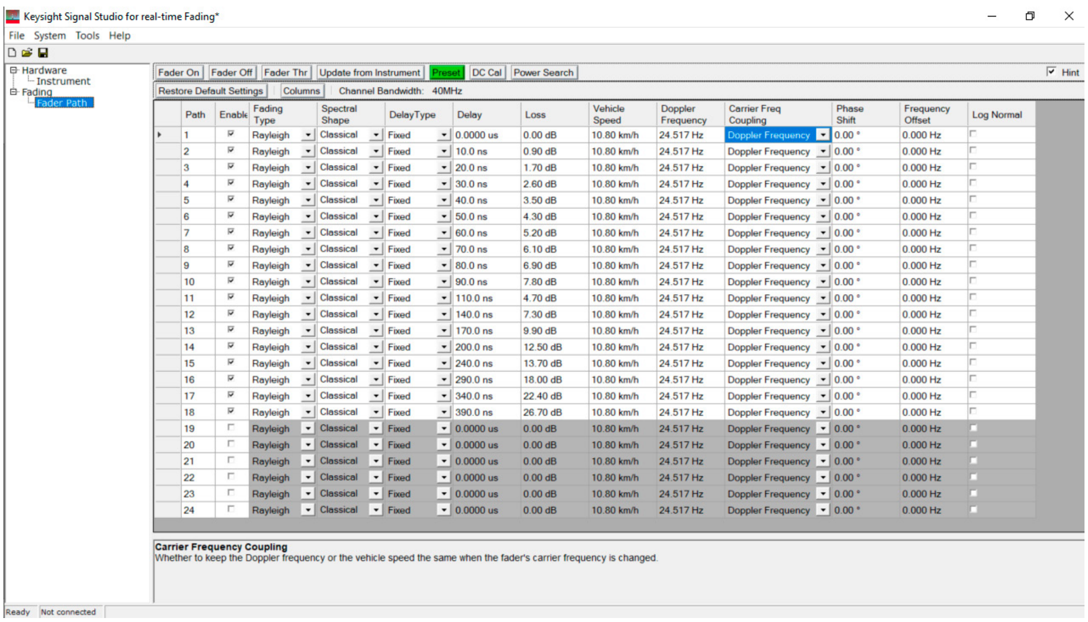
$$\frac{E_b}{N_0}(dB) = \frac{C}{N}(dB) - 10\log_{10}\frac{bit\ rate}{carrier\ bandwidth}$$

A vector signal generator enables you to add AWGN to a carrier in real time. You can easily apply real-time AWGN to the wanted signal using the signal generator's internal DSP by using a single vector signal generator.

Real-time channel emulation

To comprehensively evaluate the performance of wireless communication systems in response to real-world conditions, you need to simulate the signal propagating through a wireless channel that arrives at the destination (receiver) with multiple signal paths. These paths arise from scattering, reflection, and diffraction of the radiated energy by objects in the environment or refraction in the medium. The various propagation mechanisms influence path loss and fading models differently.

For each signal path, you must configure fading type, spectral shape, delay time, loss, Doppler frequency, phase, and frequency offset. A software tool helps you preconfigure a standards-based fading model meeting the performance requirements as defined by the respective standard. The software automatically populates the path configurations for the selected standard model, as shown in Figure 12.



Path	Enable	Fading Type	Spectral Shape	DelayType	Delay	Loss	Vehicle Speed	Doppler Frequency	Carrier Freq Coupling	Phase Shift	Frequency Offset	Log Normal
1	✓	Rayleigh	Classical	Fixed	0.0000 us	0.00 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
2	✓	Rayleigh	Classical	Fixed	10.0 ns	0.90 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
3	✓	Rayleigh	Classical	Fixed	20.0 ns	1.70 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
4	✓	Rayleigh	Classical	Fixed	30.0 ns	2.60 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
5	✓	Rayleigh	Classical	Fixed	40.0 ns	3.50 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
6	✓	Rayleigh	Classical	Fixed	50.0 ns	4.30 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
7	✓	Rayleigh	Classical	Fixed	60.0 ns	5.20 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
8	✓	Rayleigh	Classical	Fixed	70.0 ns	6.10 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
9	✓	Rayleigh	Classical	Fixed	80.0 ns	6.90 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
10	✓	Rayleigh	Classical	Fixed	90.0 ns	7.80 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
11	✓	Rayleigh	Classical	Fixed	110.0 ns	4.70 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
12	✓	Rayleigh	Classical	Fixed	140.0 ns	7.30 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
13	✓	Rayleigh	Classical	Fixed	170.0 ns	9.90 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
14	✓	Rayleigh	Classical	Fixed	200.0 ns	12.50 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
15	✓	Rayleigh	Classical	Fixed	240.0 ns	13.70 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
16	✓	Rayleigh	Classical	Fixed	290.0 ns	18.00 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
17	✓	Rayleigh	Classical	Fixed	340.0 ns	22.40 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
18	✓	Rayleigh	Classical	Fixed	390.0 ns	26.70 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
19		Rayleigh	Classical	Fixed	0.0000 us	0.00 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
20		Rayleigh	Classical	Fixed	0.0000 us	0.00 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
21		Rayleigh	Classical	Fixed	0.0000 us	0.00 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
22		Rayleigh	Classical	Fixed	0.0000 us	0.00 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
23		Rayleigh	Classical	Fixed	0.0000 us	0.00 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	
24		Rayleigh	Classical	Fixed	0.0000 us	0.00 dB	10.80 km/h	24.517 Hz	Doppler Frequency	0.00 °	0.000 Hz	

Figure 12. Preconfigured fading profile for standard WLAN model A

Multiple-input / multiple-output (MIMO) technology promises higher data rates with increased spectral efficiency. Many modern wireless systems, such as IEEE 802.11ax wireless LAN, Long-Term Evolution (LTE), and 5G NR, have adopted MIMO technology. These commercial wireless systems operate in high-multipath environments and take advantage of multipath, which provides performance improvement when using multiple antenna configurations. Figure 13 shows a multi-antenna system with a wireless channel between the transmitter and receiver. The wireless channel is the key factor that determines system performance.

Figure 13. Basic elements of a multi-antenna wireless communication system

Engineers developing and testing MIMO systems require advanced channel emulation tools that are easily configurable and accurately represent realistic wireless channels and conditions. The spatial positions of the multiple antennas, relative to each other and their placement in the surrounding environment, are important. Engineers should consider the spatial correlation between the different MIMO channels, including antenna spacing, pattern, and polarization. Figure 14 shows a 5G receiver performance evaluation with a four-channel phase-coherent signal generator. The platform enables you to increase channel counts with high-precision synchronization across multiple chassis.

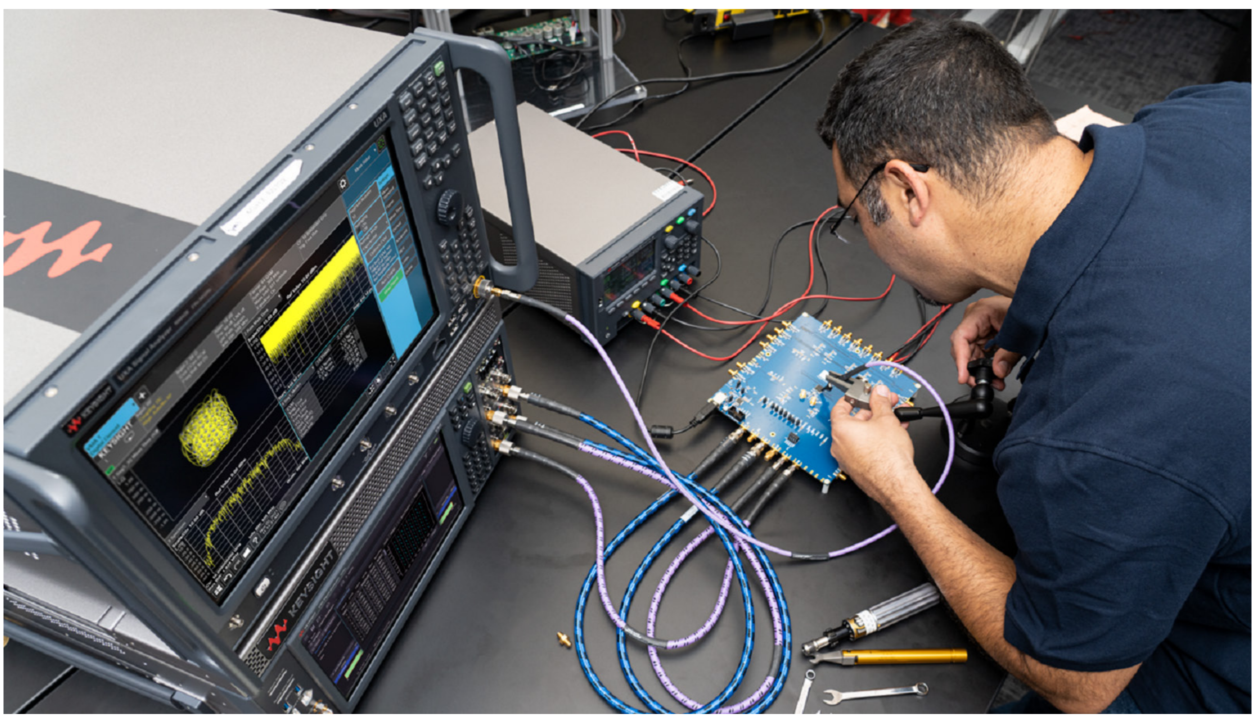


Figure 14. Keysight M9484C VXG vector signal generator supports MIMO fading profile for 5G NR performance tests

End of Part 1

As you evaluate your device's behavior, you can take many paths. Whether you are evaluating an RF receiver's performance or characterizing RF components, Keysight signal generators produce the variety of signals you need — from simple to complex, clean to dirty — to test your design within and beyond its limits.

In this first part of the two-part white paper, we discussed the real-time waveform generation mode that supports the creation of complex signal scenarios of extremely long durations for receiver designs in all stages of development. You can define the parameters of non-repeating signals needed for receiver testing, such as BER, frame error ratio, block error ratio, and packet error ratio. This mode also enables verification of baseband subsystem coding in application-specific integrated circuits, DSPs, and more. The addition of real-time AWGN and channel emulation enables receiver performance and functionality testing during RF and baseband integration or system-level test.

Part 2 explores the waveform playback mode and advanced features of vector signal generators to enable flexible waveform generation, such as custom modulation schemes, multicarrier signal generation, and complex test scenarios.

Find out more details about signal generators.

Find the industry's most advanced vector signal generator.

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