WHITE PAPER

4 Tips for 5G New Radio Signal Creation

Accelerate design validation for 5G New Radio

The promise of 5G brings faster and more reliable communications. To enable mobile broadband communications, 5G uses existing and new technologies to achieve higher data throughput. Given the limited spectrum allocation, industry-standard development organizations look for wide bandwidths at high-frequency bands and improving spectral efficiency using higher-order modulation schemes. Multi-antenna techniques, such as spatial diversity, spatial multiplexing, and beamforming can achieve high-throughput and robust communications links. These demands in the RF layer bring new design and test challenges to next-generation wireless devices.

Testing 5G New Radio (NR) RF receivers and components begins with simulating standard-compliant signals. RF engineers need to emulate a wireless channel and inject noise and interferers to characterize the receiver's performance. A robust test solution supports generating 5G test signals for various test scenarios, from component characterization, system design verification, and pre-conformance to conformance tests.

Both wider signal bandwidths and higher-order modulation schemes increase throughput. However, wider bandwidths introduce more noise into the system, and higher-order modulation schemes are more susceptible to noise. Devices require better modulation quality as the modulation density increases, requiring tighter design and test margins. As a result, accurately characterizing components and subsystems is the key to making solid design choices for creating an exceptional product.

New technologies that include 5G NR require you to think differently about how you design and test devices. Here are four tips to help you successfully generate 5G NR test signals to get your designs to market faster.

KEYSIGHT TECHNOLOGIES

Tip 1: Simplify 5G Test Waveform Creation

The 3rd Generation Partnership Project (3GPP) specifies 5G NR test requirements for both user equipment (UE) and base stations (gNB). Table 1 illustrates the Technical Specification (TS) for UE and gNB minimum test requirements and conformance tests. The conformance testing documents specify the measurement procedures. The testing method consists of conducted tests, radiated tests, or a hybrid for the various frequency ranges.

Device	Minimum requirements	Conformance tests		Frequency ranges (FR)
UE	TS 38.101	Conducted	TS 38.521-1	FR1
		Radiated	TS 38.521-2	FR2
		Conducted/ radiated	TS 38.521-3	Interworking operation
gNB	TS 38.104	Conducted	TS 38.141-1	FR1
		Radiated	TS 38.141-2	FR1 and FR2

Table 1. 3GPP technical specification for 5G NR test

Each TS specifies the transmitter and receiver characteristics and performance test requirements.

Accelerate test with pre-configured setups

To perform conformance tests, 3GPP identifies test signals for specific test cases. For example, 3GPP defines the downlink test models (TMs) for 5G NR gNB transmitter tests and the uplink fixed reference channel (FRC) for 5G NR gNB receiver tests in TS 38.141. The basis for physical channel setups for test requirements relates to the specification. These include logical channels, resource allocation, payload data, bandwidth parts, control resource sets, cell-specific settings, and RF parameters.

Each test signal has more than 50 adjustable parameters with relevant bandwidths and numerologies for sub-carrier spacing. Test equipment supporting pre-defined, standard-based conformance test setups can save you set up time and provide confidence that your measurements are standard-compliant.

Figure 1 shows the 5G NR TM1.1 for FR1 unwanted emission, transmitter intermodulation, and receiver spurious emission tests. A graphical display for the entire radio frame is visible in the lower half of the display screen. The x-axis represents the slot based on current numerology, and the y-axis represents the resource block (RB) value. The colors represent the different channel types used in the frame — green represents a downlink shared channel (DL-SCH), and the light green represents downlink control information (DCI). The pre-configured setups help you generate 3GPP 5G NR standard-compliant signals for testing receivers and RF components such as power amplifiers quickly and easily.

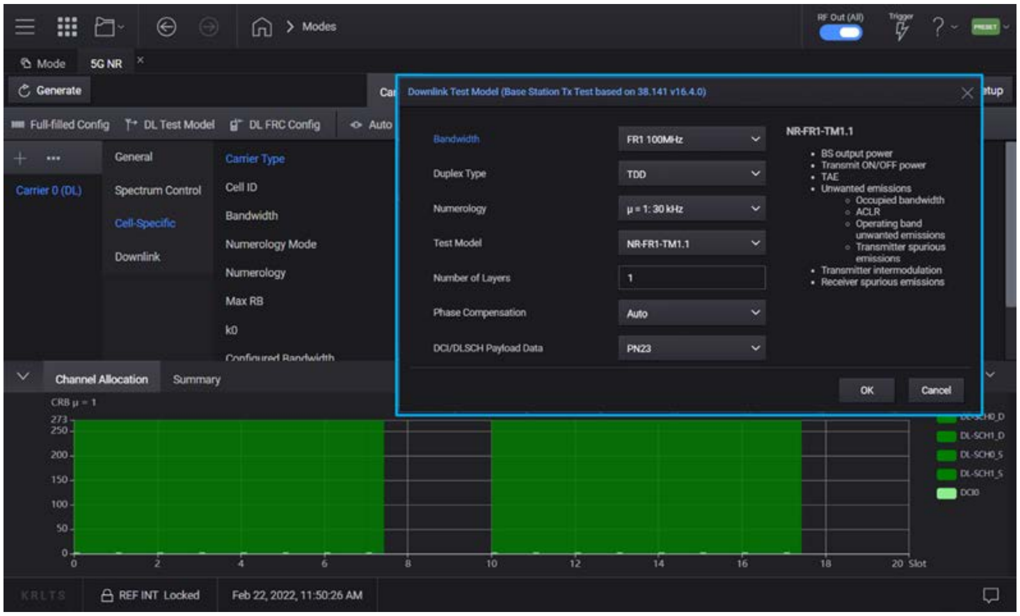

Figure 1. 5G NR downlink TMs configuration using PathWave signal generation software for 5G NR

Figure 2 illustrates the uplink FRC waveform creation software for gNB receiver testing. The optimized software integrates directly into Keysight's VXG Series signal generators' graphic user interface to run on a touch screen. A test engineer can select an FRC test type such as receiver sensitivity, in-channel sensitivity, dynamic range, or performance requirements with a pre-configured tool. To complete the test parameters, choose a reference channel with the specified sub-carrier spacing, number of resource blocks, modulation coding scheme, and coding rate.

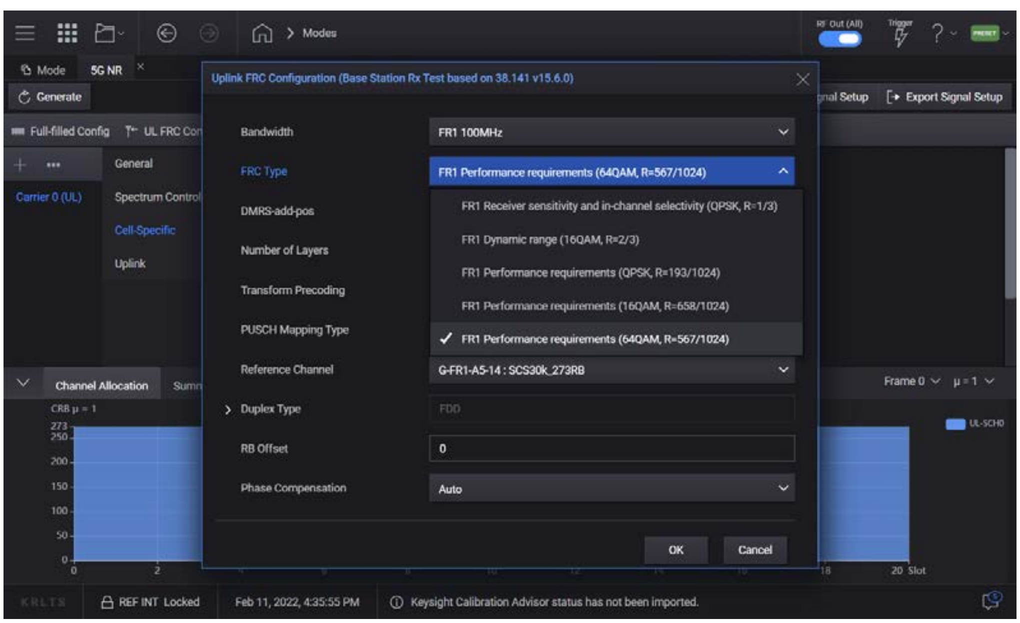

Figure 2. Configure 5G NR uplink FRC using PathWave signal generation software for 5G NR

Configure test instruments for various test cases

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

Figure 3 shows the 5G NR base station receiver intermodulation test setup. The test signals include a wanted signal (required FRC) and interferers including a simple continuous wave (CW) signal and a modulated signal. The test requires multiple signal generators to simulate the wanted signal 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 correct power level. Table 2 provides an overview of required test instruments for 5G base station receiver tests.

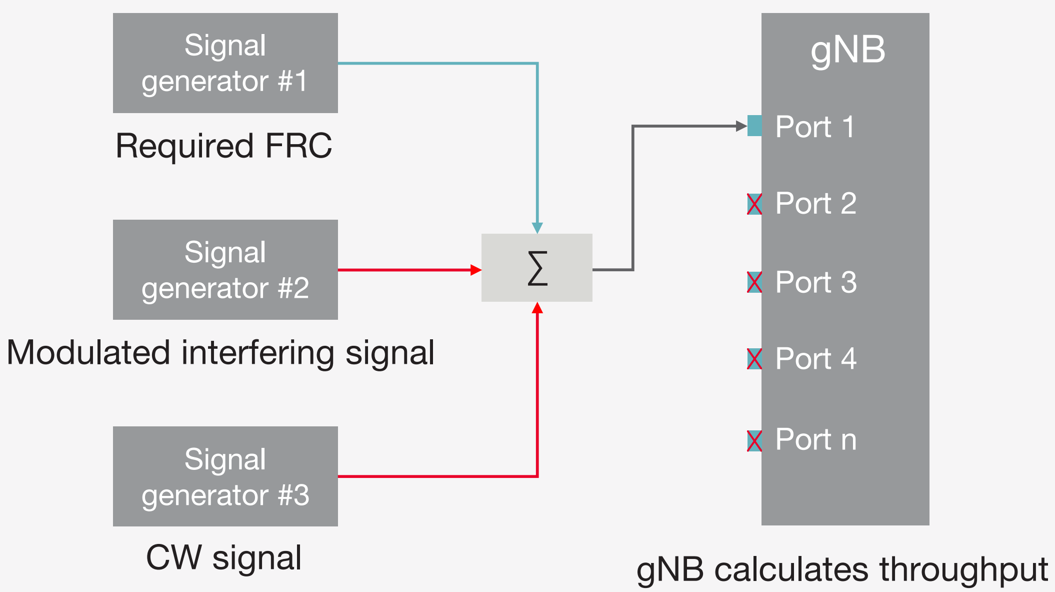

Figure 3. 5G NR gNB receiver characteristic test setup

Chapter: TS 38.141-1	Test	Wanted signal	Additive white Gaussian noise (AWGN)	Modulated interfering signal	CW signal	Signal analyzer
7.2	Receiver sensitivity level	X				
7.3	Dynamic range	X	X			
7.4	In-channel selectivity and blocking	X				
7.4.1	Adjacent channel selectivity	X		X		
7.4.2a	In-band blocking: General	X		X		
7.4.2b	In-band blocking: Narrow-band blocking	X		X		
7.5	Out-of-band blocking	X			X	
7.6	Receiver spurious emissions	X				
7.7	Receiver intermodulation	X		X	X	X
7.8	In-channel selectivity	X		X		

Table 2. Instrument requirements for 5G base station receiver conformance test

Simplify 5G complex test setups

Modern signal generators, such as the Keysight M9484C VXG vector signal generator provide faster signal processing to resample multiple test waveform files by combining them into one waveform. The digital signal processing (DSP) application-specific integrated circuit (ASIC) of the VXG can emulate up to eight baseband signals and aggregates the signals into one RF output. It provides flexible, real-time manipulation of baseband signals — each controlled baseband signal is independently filtered, faded, and placed anywhere within a 2.5 GHz bandwidth in real time. This feature simplifies the receiver test setups requiring several signal generators to simulate wanted and interfering signals with better signal fidelity, simpler test set up, and better cost-effectiveness.

To simulate a realistic environment, designers need to consider wireless channels with different test scenarios for performance testing. Additional test scenarios present challenges to designers as design and verification testing becomes more complex, time-consuming, and expensive. The 3GPP standard defines MIMO configurations, fading profiles, and signal-to-noise ratio for 5G NR base station performance testing. Figure 4 shows an M9484C VXG four-channel signal generator with a built-in DSP ASIC that enables you to emulate 2x4 MIMO fading with AWGN for performance testing.

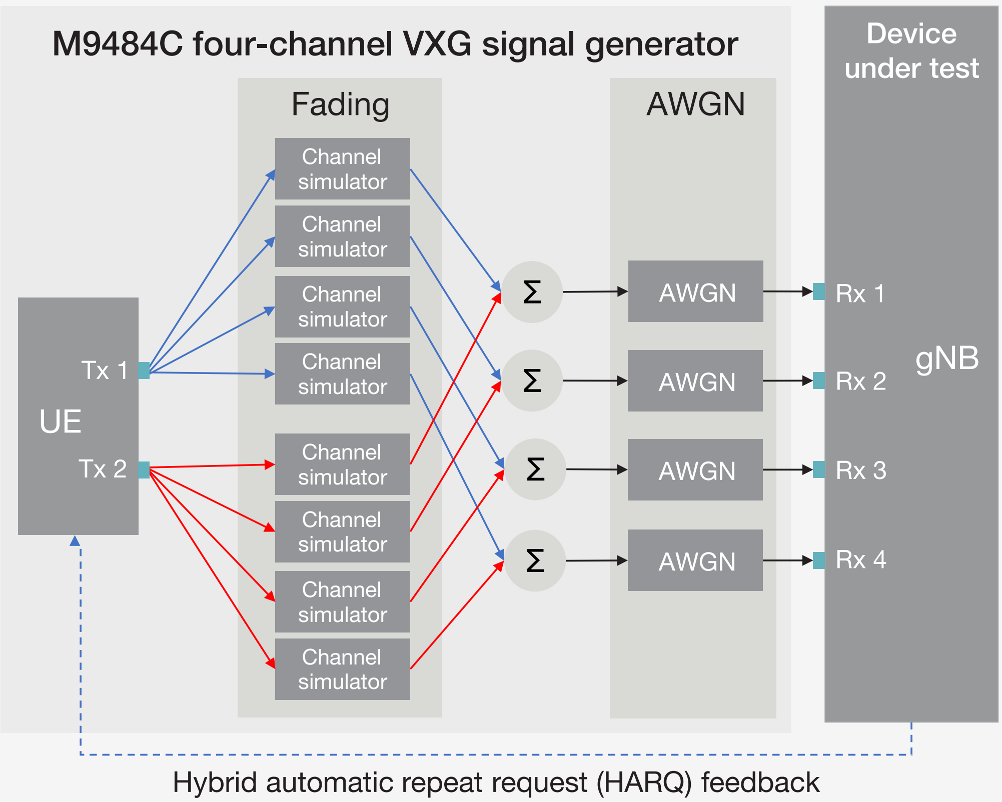

Figure 4. Test setup for 5G NR gNB performance tests using a four-channel signal generator

Tip 2: Evaluate 5G NR Waveforms

In modern wireless communications, modulation schemes are becoming more complicated. Complex modulated signals result in a higher peak-to-average power ratio (PAPR), leading to higher nonlinear distortion for DUTs such as amplifiers and mixers. A statistical analysis of the power levels to extract useful power-related information from complex waveforms is necessary for you to evaluate the test signals.

Understand RF power characteristics of a baseband waveform

Power complementary cumulative distribution function (CCDF) curves characterize the probability of a signal peak being above the average power level and provide critical information such as PAPR. The CCDF helps engineers understand the probability of a given signal creating nonlinearities in a component. This information tells the engineer how much back-off is necessary to avoid clipping the signal peaks. When you simulate a digital modulation signal using a signal generator, you need to ensure that the signal generator's output signal is not saturated, too.

Avoid gain compression of a signal generator

If the output signal of the signal generator is saturated, it impacts the output power level accuracy and the modulation quality due to unintentional amplitude and phase distortions. For a high PAPR signal, the amplitude level setting on a signal generator cannot be greater than the maximum output power of the signal generator minus the PAPR.

Figure 5 shows the 5G NR FR1 downlink signal waveform simulation with 100 MHz bandwidth using the TM 1.1. The PAPR of the waveform is up to 11.42 dB. When the maximum output power of a signal generator is +20 dBm, the maximum amplitude (average power) setting for the waveform is +8.58 dBm (20 minus 11.42 equals 8.58). The setting prevents the signal generator's power amplifier from being saturated. Signal generators require a very linear output section with less distortion for 5G signal generation.

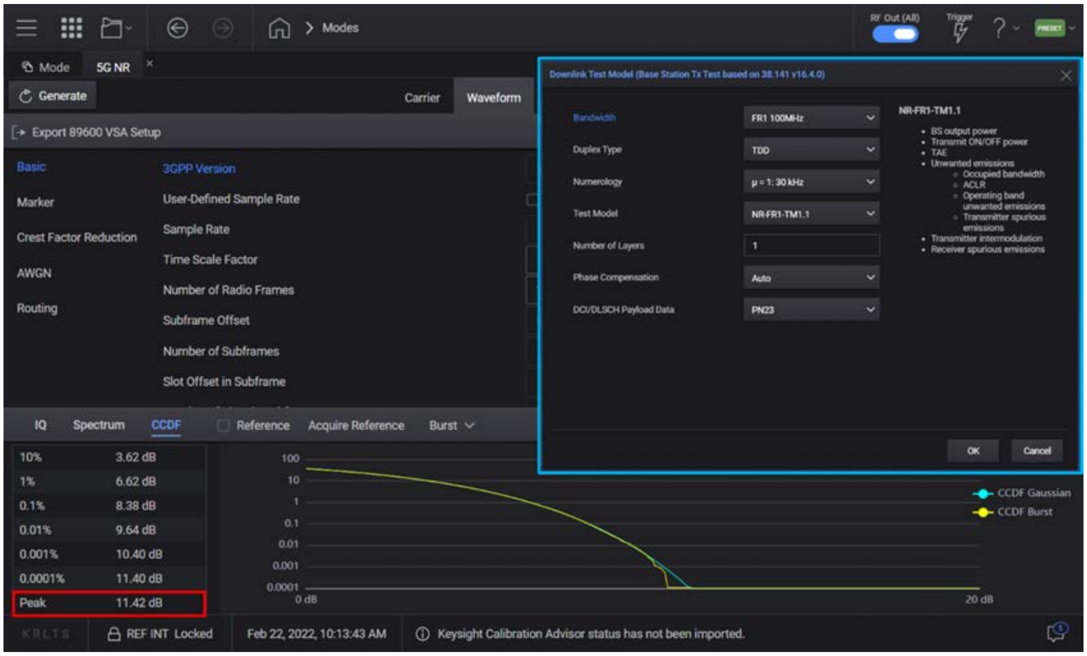

Figure 5. CCDF plot for 5G NR FR1 downlink TM1.1 with a 100 MHz signal bandwidth

Extend the usable power range of your signal generator

At millimeter-wave frequencies, excessive path loss makes RF power limited and costly. The Keysight VXG Series signal generators deliver high output power without sacrificing performance to overcome the path loss between the instrument and DUT at millimeter-wave frequencies. If you require higher output levels, the VXG signal generator supports instrument nonlinear correction (INC) using digital predistortion (DPD). The correction process uses an external receiver such as Keysight's X-Series signal analyzer for iteratively measuring and distorting an output signal to determine a correction model.

This model uses the original waveform to achieve a pre-distorted corrected waveform that exhibits improved signal characteristics when played. Figure 6 shows an instrument with nonlinear corrections — the VXG can extend the usable power range 10 dB more to minimize the instrument's nonlinear distortion at high output levels.

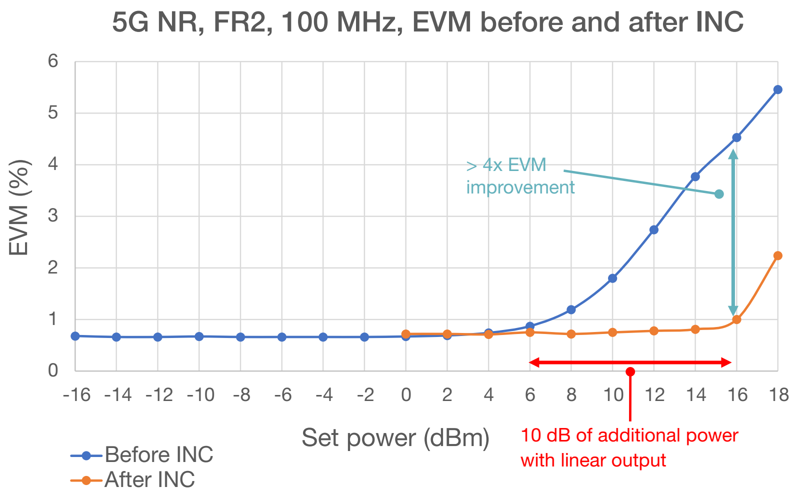

Figure 6. Overcome distortion at high power levels with INC

Tip 3: Minimize Measurement Integrity for Wide Bandwidth Signals

Enhanced mobile broadband (eMBB) is one of the use cases defined for 5G. It uses existing and new technologies to achieve the expected extreme data throughputs, including wider channel bandwidths, carrier aggregation (CA), a high modulation density, and multiple antennas. The 5G NR maximum channel bandwidth is 400 MHz for FR2, and the maximum contiguous aggregated channel bandwidth is up to 1.2 GHz. The channel flatness decreases as the channel bandwidth increases. Table 3 represents the maximum channel and aggregated bandwidths for the new wireless standards.to minimize the instrument's nonlinear distortion at high output levels.

Standard 3GPP	Revision	Technology	Maximum channel bandwidth	Maximum aggregated channel bandwidth (contiguous)
4G	R8	LTE	20 MHz	NA
	R10	LTE-A	20 MHz	100 MHz
	R13-14	LTE-A Pro	20 MHz	640 MHz
5G*	R15	NR FR1	100 MHz	400 MHz
		NR FR2	400 MHz	1200 MHz

* 3GPP TS 38.521-1/2 V15.0.0 UE conformance specification, radio transmission, and reception

Table 3. 3GPP standards maximum bandwidth

The 3GPP standards also define downlink non-contiguous intra-band CA and inter-band CA. A signal generator requires enough RF bandwidth to cover all component carriers to simulate the test signals for gNB component characterization or UE receiver testing. Also, you need to watch out for the intermodulation products created by the signal generator.

Apply internal channel correction

Most new VSGs have an internal calibration routine, also referred to as factory calibration. This process collects correction data for both the baseband and RF magnitude. It also includes phase errors over the entire RF frequency and power level range.

Enabling the correction decreases the signal's dynamic range. This correction can improve the output signal's modulation quality for common digital modulation schemes, such as quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM). However, as 5G NR receivers include an equalizer that can perform a similar correction, the internal channel correction may degrade the measurement results, such as receiver characteristics and component characterization of transmit signal quality.

Figure 7 shows measurement results of a 5G NR signal with 100 MHz bandwidth with and without internal channel correction enabled. The frequency response for amplitude is less than ±0.1 dB and 0.2 degrees for phase when you enable RF flatness correction. This correction represents flatter frequency responses.

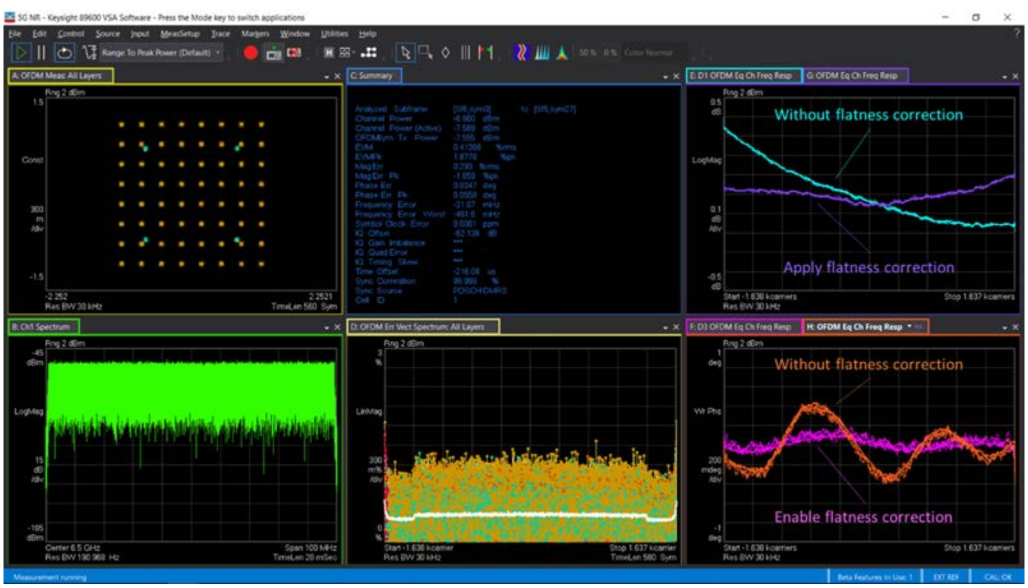

Figure 7. The frequency response of a 5G NR signal with and without flatness corrections

Extend the reference plane to the DUT plane

Calibration is critical to ensuring the measurement system produces accurate results. Cables, components, and switches in the paths between the instruments and the DUT can degrade measurement accuracy because of flatness errors.

Figure 8 is an example of how you can extend the measurement accuracy from the signal generator's output (reference plane) to the DUT's test port. Any network elements such as cables, connectors, or fixtures between the signal generator and the device will impact the signal's fidelity.

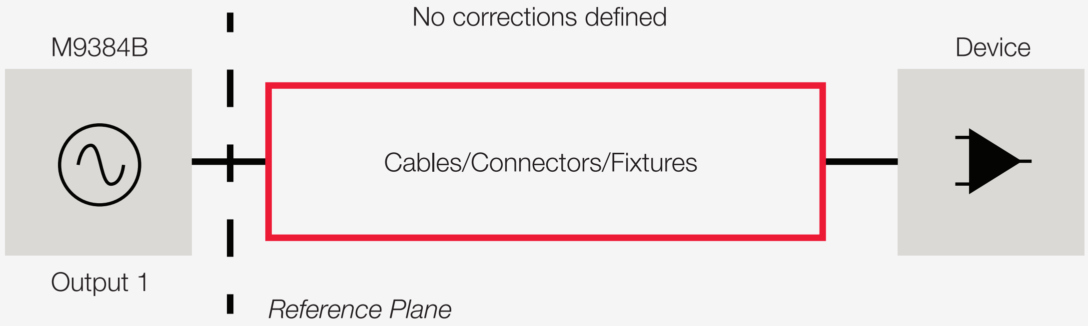

Figure 8. Network elements will impact the measurement plane

You can achieve a corrected filter by measuring the response of the network elements. Keysight provides a measure corrections block wizard to guide you through the process of measuring and calculating corrections. You can use this wizard for an external network of cables, connectors, and other passive components connected between the signal generator and the DUT. Once you have characterized the desired topology, you can remove its effects from the output signal by moving the reference plane to the connection point of the measuring device. The user channel correction also decreases the output signal dynamic range like the internal channel correction.

Improve signal dynamic range with DDS

The I (in-phase) and Q (quadrature) signals from the baseband generator's output travel to the I/Q modulator and upconverts to an intermediate frequency (IF) and RF signal. Figure 9 shows that before combining the I and Q signals, the I and Q signals mix with the same local oscillator (LO). The oscillator then inserts a 90-degree phase shifter in one of the LO paths. Each component in the I/Q modulator contributes a certain kind of error, such as DC offset, timing skew, quadrature skew, gain imbalance, and phase noise.

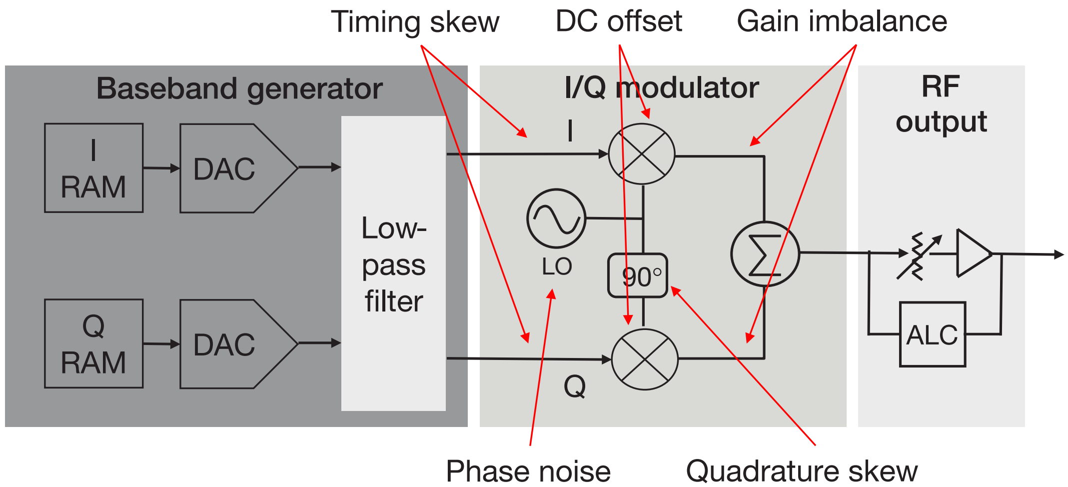

Figure 9. A block diagram of an I/Q modulator and possible errors

Modern VSGs, such as the M9484C signal generators, with a direct digital synthesizer (DDS) architecture, can directly generate an IF/RF signal from a high-resolution, high-sampling rate digital-to-analog converter (DAC). Figure 10 shows a traditional baseband block diagram with an analog I/Q modulator and a direct IF/RF with DDS technology for a multitone signal generation. In the upper right-hand corner of Figure 10, the traditional method creates intermodulation distortion between the desired tones.

The lower left-hand corner of Figure 10 shows a direct RF/IF VSG block diagram. It implements an I/Q modulator digitally and uses a high-speed DAC to output an RF/IF signal directly. The direct RF/IF with DDS technology eliminates signal impairments caused by the analog I/Q modulator. This new architecture improves the signal's dynamic range, especially for wideband signal generation. The signal generators can improve both in-channel distortion error vector magnitude (EVM) and out-of-channel distortion adjacent channel power (ACP) performance with a higher dynamic range.

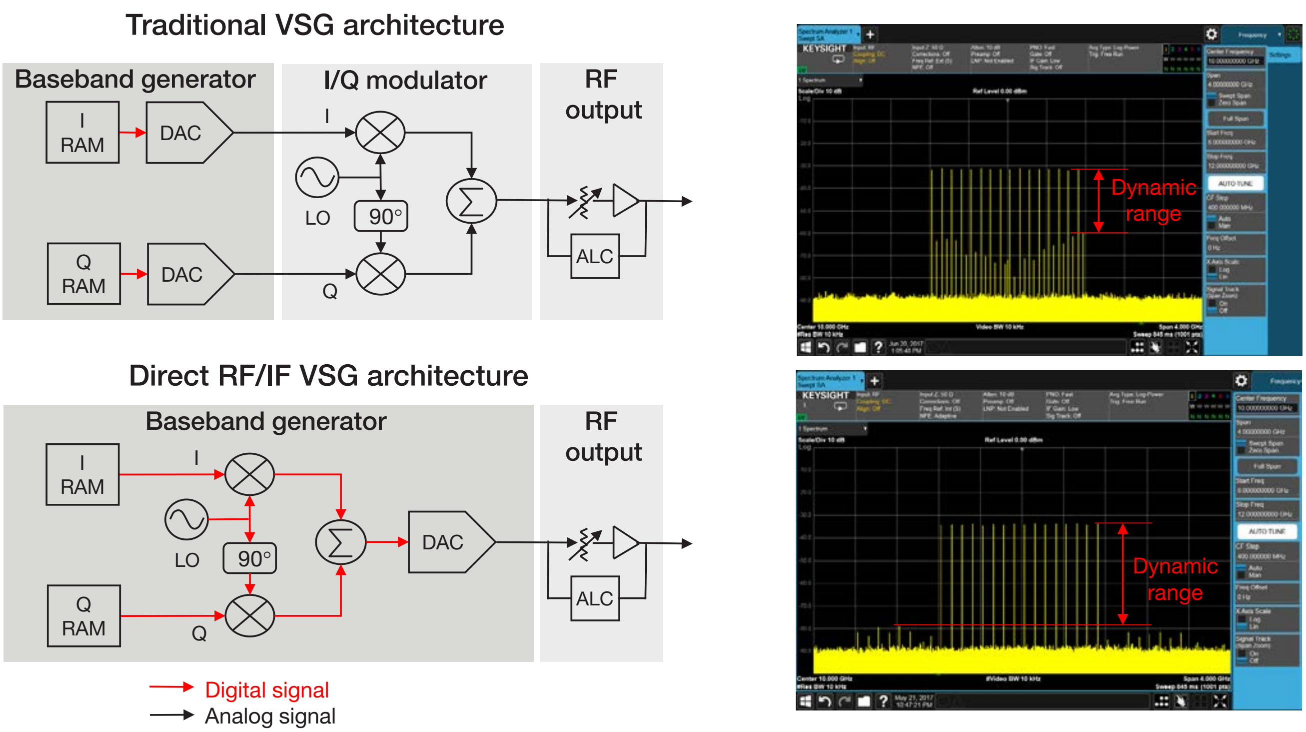

Figure 10. Comparison of an analog and a digital I/Q modulator

Tip 4: Improve the Out-of-Channel Performance

Digital modulation that uses amplitude and phase shifts will generate nonlinear distortion from RF active components, such as RF power amplifiers and mixers. The distortion generates spectral regrowth, leading to unwanted radiation and adjacent channel interference. The spectral regrowth within the main channel causes the degradation of the transmitting modulation quality. You need to perform stimulus-response tests to characterize these critical RF components accurately.

Figure 11 shows the use of the ACP measurement to examine out-of-channel distortion for RF transmitters or components. It measures the ratio of the main channel power to the power that falls into adjacent channels, and it is a key transmitter characteristic in most cellular conformance specifications.

To perform an ACP measurement for RF component characterization, you need to ensure that the measured distortion is from the DUT, not the test instruments. However, a VSG can provide a high-dynamic-range stimulus signal; two methods can improve out-of-channel performance for accurate component characterization, baseband filtering and crest factor reduction.

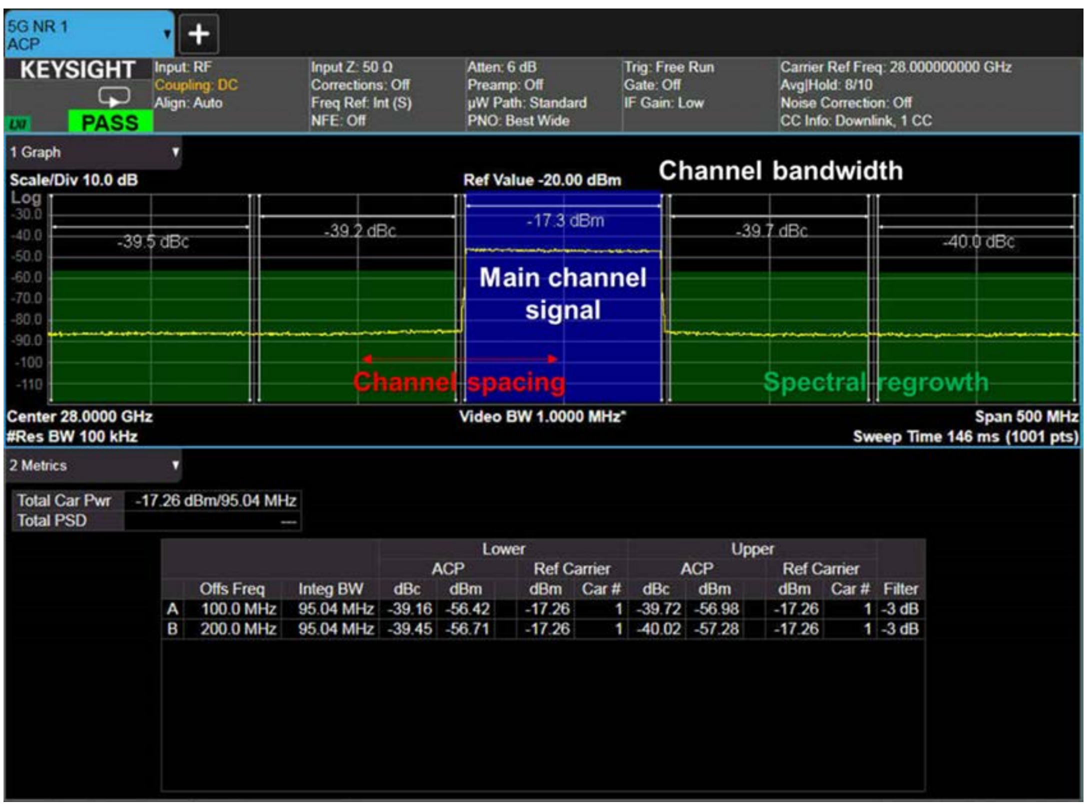

Figure 11. 5G Adjacent channel power (ACP) measurements

Apply baseband filtering

The 3GPP 5G NR standard does not define a particular baseband filter for orthogonal frequency-division multiplexing (OFDM) signals. In practice, designers will implement OFDM windowing and baseband filtering to minimize in-band and out-of-band emissions effectively.

Keysight PathWave signal generation software for 5G NR offers options for baseband windowing and filtering for 5G RF component testing. Figure 12 shows how this solution uses a power amplifier so you can modify the EVM and ACPR characteristics of the signal.

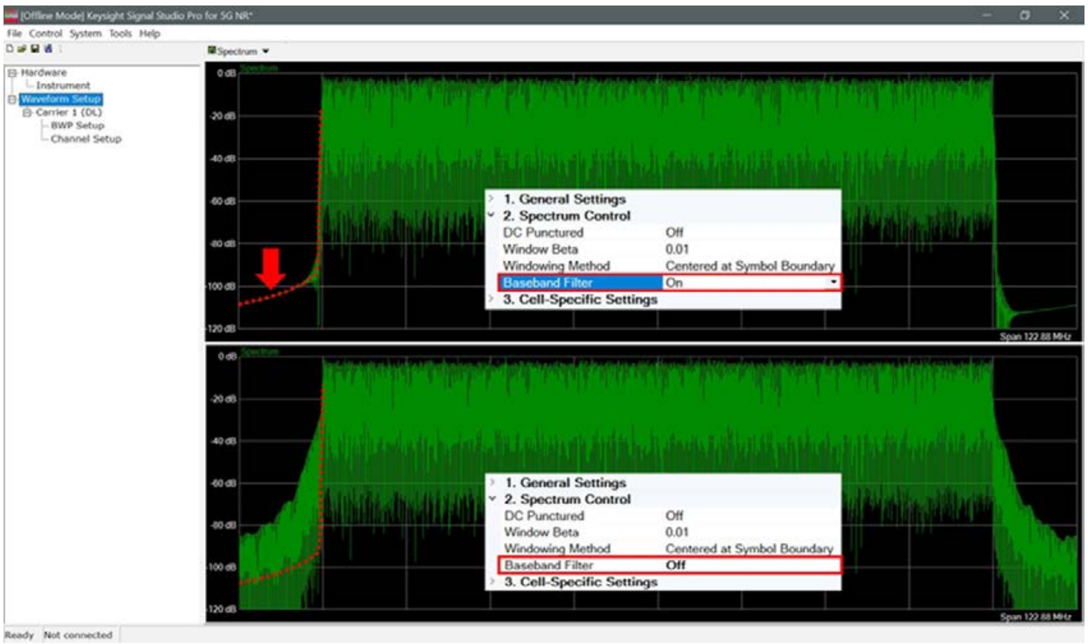

Figure 12. 5G NR signal spectrum simulation with and without a baseband filter

A signal generator needs higher output power levels to compensate for excessive path loss at millimeter-wave frequencies. However, a high-power signal may result in a distorted signal, poor modulation quality (EVM), and spectrum regrowth (ACP). It requires optimizing the signal generator's output linearity and minimizing phase noise at high output levels, which provide the best EVM and ACP performance for 5G NR tests.

Adjust peak-to-average ratio with CRF

Most 5G gNB vendors employ a crest factor reduction (CFR) for their component characterization. This technique reduces the peak-to-average power ratio (PAPR) of the transmitted signals so that the power amplifier can operate more efficiently.

For 5G waveform creation, PathWave signal generation software enables you to enable CFR to strike a balance between out-of-band emission and in-band waveform quality when reducing the PAPR of the signal. The software uses a peak cancellation algorithm to identify the waveform peaks above the target PAPR. It then subtracts a weighted version of the cancellation pulses from the original waveform. If one iteration cannot achieve the target PAPR, you can perform multiple iterations.

Figure 13 shows 5G NR FR1 downlink TM1.1 with a 100 MHz signal bandwidth with CFR enabled. The set target PAPR is 10 dB, and the maximum iteration is 10 to reduce the PAPR of the waveform from 11.42 dB to 10.04 dB.

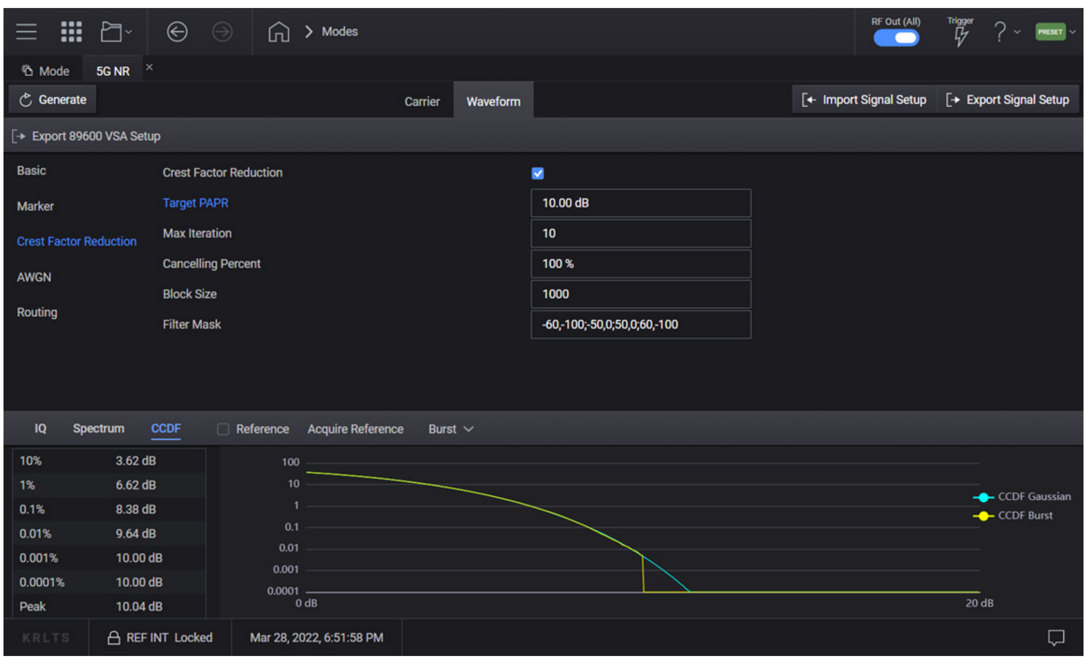

Figure 13. Crest factor reduction setups

Conclusion

Generating various standard-compliant 5G NR test signals requires a flexible waveform creation software platform and high-performance hardware. The waveform creation software enables you to quickly and easily create custom 5G waveforms from pre-configured, standard-based test signals. You should select a signal generator that meets your performance and bandwidth requirements and is flexible enough to scale as 5G standards evolve.

Keysight's 5G waveform generation solution is 5G NR-ready — it enables the characterization of 5G NR devices and equipment from RF to mmWave frequencies with precision and modulation bandwidths up to 2.5 GHz. It reduces test system setup complexity and achieves accurate and repeatable multichannel measurements with a compact and scalable design.

Our new M9484C VXG vector signal generator provides a four-channel vector signal generator with up to 54 GHz frequency range and 2.5 GHz of modulation bandwidth in one instrument. The scalable architecture of the VXG extends its frequency range up to 110 GHz with a clean-filtered Keysight V3080A vector signal generator frequency extender and a bandwidth up to 5 GHz with a bonded configuration to address the latest and evolving standards

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