First Steps in 5G

Overcoming New Radio Device Design Challenges Series

Part 2: Millimeter-Wave Spectrum

The goals for 5G are aggressive. The enhanced mobile broadband (eMBB) use case targets peak data rates as high as 20 Gbps in the downlink (DL) and 10 Gbps in the uplink (UL) to support new applications such as high-speed streaming of 4K or 8K UHD movies. While there are different ways to improve data rates, spectrum is at the core of enabling higher mobile broadband data rates. 5G New Radio (NR) specifies new frequency bands below 6 GHz and extends into millimeter-wave (mmWave) frequencies where more contiguous bandwidth is available for sending lots of data.

While consumers will appreciate the increased bandwidth, it introduces challenges pertaining to link quality requirements at mmWave frequencies. Impairments are not an issue at sub-6 GHz but become more problematic at mmWave frequencies. Extra consideration is needed to determine test approaches that provide the precision required to accurately evaluate 5G components and devices.

A Look at 5G Spectrum

Spectrum harmonization across regions is limited. It is challenging for designers to deliver a full range of capabilities and coverage for consumers around the world. 5G NR specifies frequency up to 52.6 GHz, and even the initial operating bands open up almost 10 GHz of new spectrum.

- Frequency range 1 (FR1): 410 MHz to 7.125 GHz adds 1.5 GHz of new spectrum in frequency bands 3.3 — 4.2 GHz, 3.3 — 3.8 GHz, 4.4 — 5 GHz, and 5.925 — 7.125 GHz.
- Frequency range 2 (FR2): 24.25 — 52.6 GHz initially added 8.25 GHz of new spectrum in frequency bands 26.5 — 29.5 GHz, 24.25 — 27.5 GHz, and 37 — 40 GHz.

Studies and trials in key regions and operating bands in new FR1 territory (> 2.5 GHz) and FR2 have surfaced in initial launches, as shown in Table 1.

Spectrum	0.6 GHz	2.5 GHz	3.4 to 3.7 GHz			4.4 to 4.9 GHz	28 GHz		39 GHz	47 GHz
Geography	US	US	Europe	China	Japan, South Korea	Japan	US	Japan	US	US
Commercial services	2019	Late 2019	2019	2020	2020	Mid-2020	2018	2020	2018	2021

Table 1. 5G spectrum trials from sub-6 GHz to mmWave frequencies

- Below 1 GHz, there are multiple bands of interest in 600, 700, and 800 MHz to support the Internet of Things and other mobile services.
- 1 — 6 GHz aims to increase coverage and capacity. A primary target in China, Europe, South Korea, and Japan is the 3.3 — 3.8 GHz range. China and Japan are also considering the 4.4 — 4.9 GHz range.
- Above 6 GHz will primarily support the need for ultra-high broadband use cases. Initial mmWave targets are 28 GHz and 39 GHz in Japan and the US. While 5G NR release 15 specifies frequency range up to 52.6 GHz, studies are under way for future releases to include 52.6 up to 110 GHz.

Similar to Long Term Evolution (LTE), multiple component carrier aggregation provides larger bandwidths, up to a maximum bandwidth of 800 MHz at FR2. For the initial 5G NR release, individual countries will decide on the amount of spectrum deployed. Frequency, bandwidth, and waveforms will continue to evolve with future 5G NR releases to support new use cases.

Band numbers	Range (MHz)	Duplex mode
N257	26,500 — 29,500	TDD
N258	24,250 — 27,500	TDD
N260	37,000 — 40,000	TDD
N261	27,500 — 28,350	TDD

Source: 3GPP TS 38.101-2 v15.2

Maximum Tx bandwidth

Sub-carrier spacing	50 MHz N_{RB} / SC / GB	100 MHz N_{RB} / SC / GB	200 MHz N_{RB} / SC / GB	400 MHz N_{RB} / SC / GB
60 kHz	66 / 792 / 1210 kHz	132 / 1584 / 2450 kHz	264 / 3168 / 4930 kHz	N/A
120 kHz	32 / 384 / 1900 kHz	66 / 792 / 2420 kHz	132 /1584 / 4900 kHz	264 / 3168 / 9860 kHz

Source: 3GPP TS 38.101-2 v15.2

Modulation	$\frac{\pi}{2}$ BPSK	BPSK	QPSK	2^n QAM n = 4,6,8
	UL only	UL only		

Source: 3GPP TS 38.211-2 v15 1.0

Table 2. 5G NR initial release 15 frequency and waveform specifications

FR1 introduces challenges for designs in the new bands above 3 GHz because of the complexity of the test cases, coexistence issues, and validating massive multiple-input / multiple-output (MIMO) designs over the air. FR1 is an evolution of existing LTE-Advanced capabilities, and the implementation of mmWave designs will introduce more significant challenges.

Fixed wireless access was the first mmWave introduction at the end of 2018. Initial 5G fixed wireless access implementations operate in nonstandalone mode, utilizing the 4G evolved packet core and eNodeB as an anchor and control plane. A significant change will happen when mmWave implementations go mobile. There will be new challenges establishing and maintaining the communication link when the device is moving across a parking lot, down a highway, or even on a high-speed train. Trials have been under way for some time to ensure the viability of different mmWave mobile use cases. Refining the channel models for the different use cases will require that components and devices have the necessary performance to operate in mmWave frequency bands.

mmWave Signal Quality Challenges

Many factors impact signal quality, including baseband signal processing, modulation, filtering, and up conversion. With wider channel bandwidths expected at mmWave frequencies, common signal impairments impact baseband and RF designs. These impairments become more problematic at higher frequencies or with wider bandwidths. Inherent in orthogonal frequency-division multiplexing (OFDM) systems, orthogonal properties prevent interferences between overlapping carriers. However, issues such as IQ impairments, phase noise, linear (AM to AM) and nonlinear (AM to PM) compression, and frequency error cause distortion in the modulated signal. Phase noise is one of the most challenging factors in mmWave OFDM systems. Too much phase noise in designs results in each subcarrier interfering with other subcarriers, leading to impaired demodulation performance.

Such issues impact the performance of your designs and are difficult to resolve. Device designs need to overcome the physical challenges in wide bandwidth and mmWave signals. Test solutions require better performance than the device under test (DUT) to properly measure and characterize signal quality without introducing new issues.

Characterizing signal quality

Evaluating a signal's modulation properties provides one of the most useful indicators of signal quality. Viewing the IQ constellation helps in determining and troubleshooting distortion errors. Another key indicator of a signal's modulation quality is a numeric error vector magnitude (EVM) measurement that provides an overall indication of waveform distortion.

5G NR specifies a cyclic prefix OFDM (CP-OFDM), which is a multicarrier modulation scheme. An EVM measurement reflects any variation in a circuit's phase, amplitude, or noise seen in wideband signals. EVM is the normalized ratio of the difference between two vectors: IQ measured signal and IQ reference (IQ reference is a calculated value), as shown in Figure 1. EVM is a measure of the average amplitude of the error vector from the ideal reference point. EVM is typically measured in decibels (dB) or as a percentage.

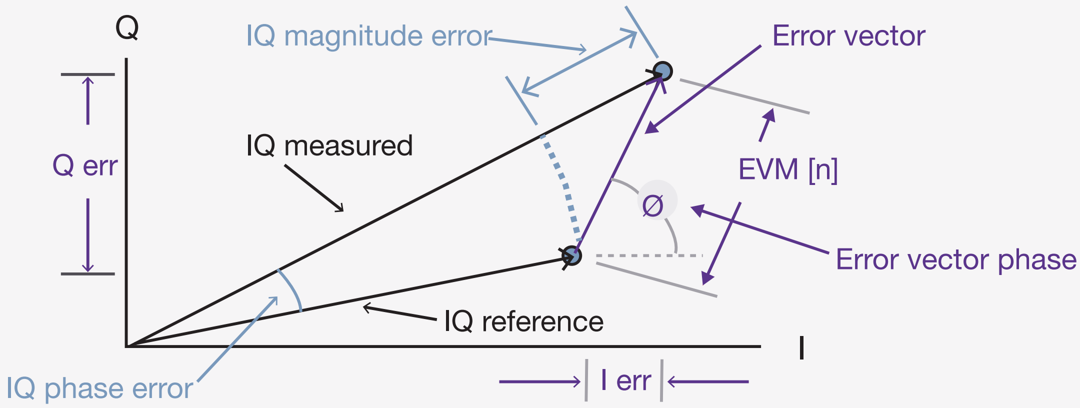


Figure 1. Understanding the EVM calculation

With the expected use of higher-order modulation schemes in 5G (up to 256 QAM initially, and up to 1024 QAM in the future), components and devices require a better EVM result as modulation density increases. For example, Table 3 shows how 3GPP EVM requirements for user equipment (UE) get tighter as modulation density increases.

Modulation scheme for PDSCH	Required EVM
QPSK	17.5%
16 QAM	12.5%
64 QAM	8%
256 QAM	3.5%

Table 3. 3GPP TS 38.101-1 EVM requirements for different 5G modulation schemes

Spectrum measurements are also necessary to validate a signal's RF performance. 5G UE spectrum measurements for transmitting products include transmitted power, occupied bandwidth (OBW), adjacent channel power ratio (ACPR), spectrum emissions mask (SEM), and spurious emissions.

A test solution needs enough performance to evaluate the constellation diagram and measure the EVM required by 5G components and devices. Flexibility to make spectrum measurements and scale to higher frequencies and bandwidths is necessary as 5G standards evolve.

Defining a measurement solution

Achieving high-quality measurements of high-bandwidth devices at mmWave frequencies requires a test solution with EVM performance that is better than the product or system under test. Typical guidelines to follow include these:

- for component test, 10 dB better than the system as a whole
- for system test, 3 dB better than the source from the radio standard

When measuring a transmitter, receiver, transceiver, or other component in a wireless device, a test solution typically consists of a stimulus and DUT; DUT and analyzer; or stimulus, DUT, and analyzer, depending on the DUT. You can typically conduct measurements in baseband and sub-6 GHz using cables. Centimeter-wave or mmWave frequencies, however, will likely require an over-the-air measurement. That is because of the high level of integration expected in the antennas and RF integrated circuits, resulting in no connector test points for the conducted test.

Figure 2 shows Keysight's 5G R&D Test Bed setup. It has the performance needed to evaluate 5G components and devices for impairments at mmWave frequencies. A vector signal generator provides a digitally modulated 5G NR signal to the DUT. A vector signal analyzer captures the RF signal properties out of the DUT and digitizes the modulated signal for analysis. This test solution offers flexible configurations to address the many combinations of frequency, bandwidth, and fidelity required for testing 5G components and devices.

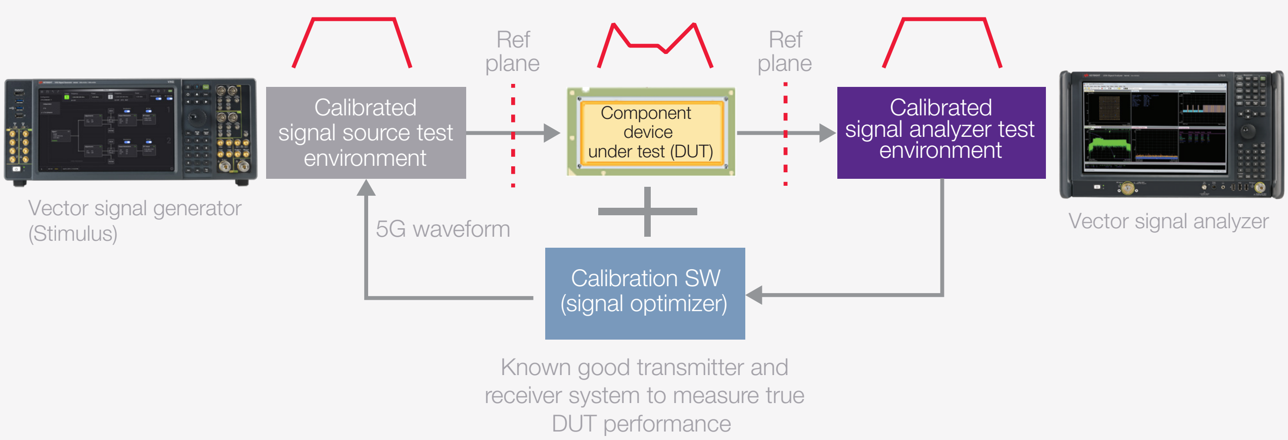
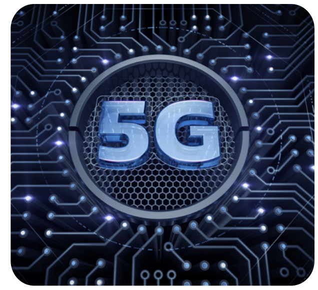


Figure 2. 5G R&D Test Bed with 5G NR-ready hardware and software, including signal optimizer calibration software

The test setup itself can introduce other sources of error in a measurement system. When considering a test setup at higher frequencies with wider bandwidths, remember that test fixtures, cables, adaptors, couplers, filters, preamplifiers, splitters, and switching between the DUT and measurement equipment have greater impact than in sub-6 GHz measurement systems. Calibrating the measurement system to the reference plane at the location of the DUT is essential to achieve the highest measurement accuracy. The goal is to see the true characteristics of the DUT without seeing the impacts of the test setup. The measurement system needs to perform better than the DUT design goals. Measurements at the DUT plane are more accurate and repeatable. A proper system-level calibration eliminates uncertainties caused by test fixtures in frequency and phase and is valuable for very wide bandwidth signals. The 5G R&D Test Bed solution includes the signal optimizer software that moves the calibration plane from the test equipment to the DUT reference plane, as shown in Figure 2.



Connectors, cables, and adapters

In addition to calibration, proper use of cables, connectors, and adapters improves the accuracy of your test setup. The materials, structures, and geometries of these components are designed for a specific operating frequency range. Avoid compromising the performance of an expensive test system with poor-quality or inappropriate cabling and accessories. Since most mmWave spectrum analyzers are used in an environment that also includes work at lower frequencies, it can be tempting to use connectors designed for these lower frequencies. However, smaller wavelengths demand smaller dimensions in the cables and connectors. For mmWave measurements, do not use common subminiature version A (SMA) and precision 3.5 mm accessories.

For mixed-frequency environments, consider standardizing on 2.4 mm or 2.92 mm accessories. Although they have slightly more insertion loss than SMA and 3.5 mm (primarily above 30 GHz), 2.4 mm and 2.92 mm accessories can cover all lower frequencies and offer superior repeatability.

A 5G NR mmWave measurement

Proper selection of test equipment, connectors, adapters, and system-level calibration enables high-performance measurements to evaluate the true performance of 5G components or devices. Figure 3 shows a calibrated measurement of a 5G antenna using Keysight's 5G R&D Test Bed solution. It enables characterization of 5G NR devices from RF to mmWave frequencies with precision and modulation bandwidths up to 2 GHz. 5G NR-compliant software lets you easily create and analyze waveforms with 5G numerology, uplink, and downlink to test 5G NR and LTE integration and coexistence.

Figure 3. Analysis of a 5G NR 256 QAM signal with antenna pattern

Addressing the Challenges of mmWave

5G operation in mmWave frequency bands is now a reality. 5G NR release 15 specifies mmWave operation up to 52.6 GHz with up to 800 MHz aggregated channel bandwidth. At mmWave frequencies, signals are more susceptible to impairments, requiring extra consideration in the selection of test solutions, cables, and connectors. System-level calibration is also essential to achieve accurate measurements. Keysight's 5G R&D Test Bed enables precision characterization of 5G NR device signal quality from RF to mmWave frequencies. It provides the performance and bandwidth needed, as well as the flexibility to scale as the 5G standard evolves.

Additional Information

See Keysight's 5G Solutions webpage to find out more about 5G NR solutions and to view the next installment of the First Steps in 5G white paper series. The next installment reviews the challenges associated with characterizing and validating multi-antenna MIMO and beam steering designs for 5G NR device designs.

You can access the different parts of the First Steps in 5G white paper series by clicking on the respective links:

- First Steps in 5G – Part 1: 5G New Radio Standard
- First steps in 5G – Part 2: Millimeter-Wave Spectrum
- First Steps in 5G – Part 3: MIMO and Beamforming
- First Steps in 5G – Part 4: Over-the-Air Test