First Steps in 5G
Overcoming New Radio Device Design Challenges Series

Part 2: Millimeter-Wave Spectrum

The goals for 5G are very 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 data rates can be improved in different ways, spectrum is at the core of enabling the 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 the increased bandwidth will be a great service for consumers, it introduces new challenges in meeting signal quality requirements at mmWave frequencies. Impairments that were not an issue at sub-6 GHz, now become more problematic and extra consideration is needed to determine test approaches that will produce the precision needed to accurately evaluate 5G components and devices.
A Look at 5G Spectrum

Spectrum harmonization across regions is needed to deliver the full range of capabilities and coverage for consumers around the world. 5G NR specifies frequency up to 52.6 GHz and new operating bands that open up almost 10 GHz of new spectrum.

- **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.

Studies and trials have taken place in key regions and some operating bands in sub-6 GHz and in higher cm and mmWave frequencies are starting to surface as initial launches as shown in table 1.

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

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>sub-6 GHz</th>
<th>mmWave</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geography</td>
<td>0.6 GHz</td>
<td>2.5 GHz</td>
<td>3.4–3.7 GHz</td>
</tr>
<tr>
<td>USA</td>
<td>USA</td>
<td>Europe</td>
<td>China</td>
</tr>
</tbody>
</table>

- Below 1 GHz there are multiple bands of interest in 600, 700, and 800 MHz that are targeted to support IoT services.
- 1–6 GHz will be used for increasing coverage and capacity. A primary target in China, Europe, Korea, and Japan is the 3.3–3.8 GHz range which can be used for many different 5G services. 4.4–4.9 GHz is also being considered in China and Japan.
- Above 6 GHz will primarily be used to 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 taking place for future releases to operate in 64–71 GHz and 71–76 GHz frequency ranges.

Similar to LTE, multiple component carriers can be aggregated to produce larger bandwidths, up to a maximum bandwidth of 800 MHz at frequency range 2 (FR2) as shown in table 2. The amount of spectrum deployed will be decided by individual countries. This is for 5G NR initial release, and it’s expected that frequency, bandwidth, and waveforms will all evolve with future 5G NR releases to support new use cases.
Table 2. 5G New Radio initial release 15 frequency and waveform specifications

| Frequency     | FR1: 410 MHz – 7.125 GHz  
|               |                          
|               | FR2: 24.25-52.6 GHz       |
| Maximum Carrier Bandwidth | FR1: Up to 100 GHz  
|                        | FR 2: Up to 400 MHz       |
| Sub Carrier Spacing   | Sub-6 GHz: 15 kHz, 30 kHz, 60 kHz  
|                        | >6 GHz: 60 kHz, 120 kHz, 240 kHz  |
| Maximum number of Subcarriers | 3300 (up to 4096 FFTs)  
| Carrier Aggregation   | Up to 16 carriers, maximum of 800 MHz BW  
| Waveform & Modulation | CP-OFDM (UL/DL): QPSK, 16QAM, 64QAM and 256QAM  
|                        | DFT-s-OFDM (UL): π/2-BPSK, 16QAM, 64QAM and 256QAM  
| MIMO              | 8x8 MIMO  
|                   | Up to 8 layers in downlink, up to 4 layers in the uplink  

Sub-6 GHz will have some new challenges implementing designs in the new 3.4-3.7 GHz and 4.4-4.9 GHz frequency bands due to the complexity of the numerous test cases, coexistence issues, and validating massive MIMO designs over-the-air (OTA). Sub-6 GHz, however, will be more of an evolution of existing LTE-A capabilities, and the bigger challenges will be with implementing mmWave designs.

Based on operator projections, fixed wireless access will be the first mmWave introductions at the end of 2018\(^1\). Today, fixed point-to-point or point-to-multipoint wireless communications are already present in IEEE 802.11ad/ay 60 GHz Wi-Fi applications. Initial 5G fixed wireless access implementations will use similar MIMO and waveform configuration and will likely operate in non-standalone mode (NSA), utilizing the 4G eNB as an anchor and control plane. The major difference will be 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 are underway to determine the viability of different mmWave mobile use cases. As channel models are developed for the different use cases, components and devices will need to have the performance necessary to operate in mmWave frequency bands.

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\(^1\) IHS Markit Report 5G Strategies & Opportunities, 2017
mmWave Signal Quality Challenges

Many factors can impact signal quality including baseband signal processing, modulation, filtering, and up conversion. With wider channel bandwidths expected at mmWave frequencies, baseband and RF designs can be impacted by common signal impairments that become more problematic at higher frequencies or with wider bandwidths. Inherent in OFDM systems, orthogonal properties prevent interferences between overlapping carriers. However, impairments such as IQ impairments, phase noise, linear compression (AM to AM) and nonlinear compression (AM to PM), and frequency error can 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 can result in each subcarrier interfering with other subcarriers leading to impaired demodulation performance.

Such issues are difficult to resolve and can impact the performance of your designs. Devices must be designed to overcome the physical challenges in wide bandwidth, mmWave signals, and test solutions must have better performance than the device being measured to properly measure and characterize the 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 CP-OFDM (cyclic prefix OFDM), which is a multi-carrier modulation scheme. Any variation in a circuit’s phase, amplitude, or noise seen in wideband signals is reflected in an EVM measurement. 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. It basically tells you how far the signal is from the reference point. EVM is typically measured in dB or as a percentage.
With the expected use of denser modulation schemes in 5G (up to 256 QAM initially, and up to 1024 QAM in the future), a better EVM result is required for components and devices as the modulation density increases. For example, table 3 shows how 3GPP EVM requirements for user equipment (UE) get tighter as the modulation density increases.

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

<table>
<thead>
<tr>
<th>Modulation scheme for PDSCH</th>
<th>Required EVM</th>
</tr>
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<tbody>
<tr>
<td>QPSK</td>
<td>17.5 %</td>
</tr>
<tr>
<td>16QAM</td>
<td>12.5 %</td>
</tr>
<tr>
<td>64QAM</td>
<td>8 %</td>
</tr>
<tr>
<td>256QAM</td>
<td>3.5 %</td>
</tr>
</tbody>
</table>

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

A test solution needs to have performance sufficient 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 will also be important as the 5G standards evolve.
Defining a Measurement Solution

To achieve 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 being measured. Here are typical guidelines:

- 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, a DUT and analyzer, or a stimulus, DUT and analyzer, depending on the DUT being measured. Measurements in baseband and sub-6 GHz can typically be conducted using cables. Measurements at centimeter-wave or mmWave frequencies, however, will likely require an OTA measurement due to the high level of integration expected in the antennas and RFICs resulting in no connector test points for conducted test. Figure 2 shows the 5G Waveform Generation and Analysis Testbed, Reference Solution test set up. It has the performance needed to evaluate 5G components and devices for impairments that can be an issue at mmWave frequencies. A vector signal generator is used to produce a digitally modulated 5G NR signal into the DUT. A vector signal analyzer is used to capture the RF signal properties out of the DUT and digitize 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.

![Diagram of 5G Testbed](image)

Figure 2. 5G Testbed with 5G NR ready hardware and software, including signal optimizer calibration software
Other sources of error in a measurement system can be from the test setup itself. When considering a test set up at higher frequencies with wider bandwidths, items such as test fixtures, cables, adaptors, couplers, filters, preamplifiers, splitters, and switching between the device under test (DUT) and measurement equipment have greater impact than what may be experienced in sub-6 GHz measurement systems. For the highest measurement accuracy, the measurement system must be calibrated to the reference plane at the same place where the DUT is connected. 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. Being able to achieve measurements at the DUT plane provides better measurement accuracy and repeatability. A proper system level calibration eliminates uncertainties due to test fixtures in frequency and phase and is valuable for very wide bandwidth signals. Included in the 5G Testbed solution is the signal optimizer software that moves the calibration plan 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 improve the accuracy of your test setup. The materials, structures, and geometries used in these are specially 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, this means that common SMA and precision 3.5 mm accessories should not be used.

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 be used to cover all lower frequencies and offer superior repeatability.
A 5G NR mmWave Measurement

With proper selection of test equipment, connectors, adapters, and system level calibration, a high-performance measurement can be made to evaluate the true performance of a 5G component or devices. Figure 3 is calibrated measurement of a 5G antenna using Keysight’s 5G Waveform Generation and Analysis Testbed solution that enables characterization of 5G NR devices from RF to mmWave frequencies with precision and modulation bandwidths up to 2 GHz. With 5G NR compliant software, waveforms are easily created and analyzed with 5G numerology, uplink, downlink, and can be used to test 5G NR and LTE integration and coexistence.

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

5G operation in mmWave frequency bands is a given. 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 solution, cables, connectors, and with a system level calibration to achieve accurate measurements. Keysight’s 5G Waveform Generation and Analysis Testbed is 5G NR-ready and 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.

See [www.keysight.com/find/5GNR](http://www.keysight.com/find/5GNR) to find out more about 5G NR solutions and to view the next installment of the First Steps in 5G white paper series that will review the challenges associated with characterizing and validating multi-antenna MIMO and beam steering designs for 5G NR device designs.

Learn more at: [www.keysight.com](http://www.keysight.com)

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