As 5G New Radio (NR) moves from the definition and specification phase into development, enabling technologies such as multiple input, multiple output (MIMO), and beamforming are critical. Engineers will use active phased array antennas to implement MIMO and beamforming in base stations and devices. In fact, these active antennas are critical to overcome signal propagation issues, such as higher path loss at millimeter wave frequencies. They also provide the ability to dynamically shape and steer beams to specific users. Active antennas offer more flexibility and improve the performance of 5G communications, especially at millimeter-wave (mmWave) frequencies.

Deploying active phased array antennas in commercial wireless communications represents a major change from the passive antennas used in previous generations. MIMO and beamforming technologies increase capacity and coverage in a cell. For 5G devices and base stations, multi-antenna techniques require support across multiple frequency bands – from sub-6 GHz to mmWave frequencies – and across many scenarios, including massive IoT connections and extreme data throughput.

Designers must overcome many new challenges while implementing MIMO and beamforming on 5G base stations. Some of the biggest hurdles include accounting for greater mmWave path loss, verifying the RF performance of 3D antenna beam patterns over-the-air (OTA), and optimizing base station performance under...
real-world conditions. Designers need to carefully select hardware and software tools needed to simulate, design, and test highly complex systems containing tens or even hundreds of antenna elements.

**MIMO and Beamforming in 5G**

It is possible to use multiple antennas on the transmitter (to implement transmit diversity), on the receiver (to implement receive diversity), or on both transmitter and receiver to implement MIMO. Single-user MIMO (SU-MIMO) multiplexes the data for one user across two or more antennas to improve the data rate for a specific user. In contrast, multi-user MIMO (MU-MIMO), a key technology deployed with massive MIMO, uses multiple antennas to transmit data to multiple users to increase the cell capacity. Massive MIMO implements MU-MIMO with significantly more antennas elements (usually in the hundreds) on the base station than there are users in the cell.

5G will transition from cell-based communications to beam-based communications by using MU-MIMO. Beamforming is a special implementation of MIMO that uses multi-element antenna arrays to dynamically control the beam pattern by applying specific spacing and phase/amplitude shifts between antenna elements. As the number of antenna elements increase and add together constructively, the radiated energy becomes more focused, effectively increasing power delivery and the signal-to-noise ratio (SNR) to the user. By applying a phase shift to the signal at each element, it is possible to change the direction of the beam away from an orthogonal orientation to the arrays. Through control of the phase shifts, electronic phase shifting enables rapid beam control without mechanical operation. Use of focused beams in beamforming maximize the user equipment’s (UEs) SNR, thereby improving the communication link for higher modulation coding schemes. (see figure 1).

![Figure 1. Creating beam patterns by applying more antenna elements and phase shifts](image-url)
Beamforming uses channel-state-information (CSI) to calculate specific weightings for each antenna element and applies real-time changes to optimize the signal for the target UE. In other words, the UE identifies the channel characteristics and shares this information with the base station so that the base station can change the phase and amplitude of the antenna elements to counter the effects of the channel conditions. This process offers better control of the transmitted signal so that the signal is strongest for the intended UE, thus improving cell coverage.

3 Key Challenges Implementing and Testing MIMO

Aerospace and defense radar and satellite communications use active phased array antennas. These antenna arrays are typically very large and expensive, and applying this technology to commercial wireless introduces new challenges.
For example, there is a long list of 3GPP required tests for base stations including radiated transmitter tests and radiated receiver tests. Depending on the base station configuration, some frequency range 1 (FR1 410 MHz to 7.125 GHz) tests require radiated tests, and all frequency range 2 (FR2 24.25 to 52.6 GHz) tests require radiated tests.

There are many different transmitter and receiver tests which fall into the following groupings:

- **Transmitters**: radiated transmit power, base station output power, output power dynamics, transmit ON/OFF power, transmitted signal quality, unwanted emissions, and transmitter intermodulation.
- **Receivers**: reference sensitivity level, dynamic range, in-band selectivity and blocking, out-of-band blocking, receiver spurious emissions, receiver intermodulation, and in-channel selectivity.
- **Performance tests** for PUCCH (physical uplink control channel) and PRACH (physical random-access channel) verify the base station receiver’s ability to achieve throughput under different multipath fading propagation conditions for a given SNR.

Access the 3GPP Technical Specification (TS) 38.141-1 and -2 documents to understand measurement uncertainties, test methods, test procedures, and test requirements.

With the use of higher frequencies, wider bandwidths, and multi-element active antennas, base station conformance tests are significantly different, and more challenging than previous LTE tests. Today’s LTE test solutions are limited in frequency and bandwidth for 5G. The use of active antenna arrays in 5G NR requires innovation in antenna designs, and new ways to test in design characterization, pre-conformance, and conformance testing.
Some of the biggest test challenges include the following:

1. Accommodate for greater mmWave frequency path loss

   Increased path loss and signal impairments are more problematic at mmWave frequencies. Issues with mmWave signal propagation greatly reduce the distances of the signal’s effectiveness. Therefore, base stations will use hundreds of antenna elements to create high-gain directional antennas.

   Test solutions for mmWave products need to accommodate higher frequencies with wider channel bandwidths, as well as address the increased path loss at mmWave frequencies. A test solution must have adequate SNR to detect and demodulate 5G signals accurately. When testing transmitters, SNR is critical in the test analyzer to make accurate error vector magnitude (EVM) and adjacent channel leakage ratio (ACLR) measurements. Choosing a signal analyzer with greater dynamic range will help overcome SNR issues. To improve SNR in a test solution that is designed for testing receivers, it is important to use vector signal generators (VSG) with high output power and low EVM to ensure the receiver can detect and demodulate the signal. In addition, system-level calibration is important to correct for system phase and magnitude shifts over the bandwidth of the measurement. Figure 4 illustrates how a corrected waveform will account for channel response at the device under test (DUT) plane. This requires a power meter/sensor, signal analyzer, or network analyzer that measures the frequency response. The measured data is then used in the signal generator to pre-correct the waveform over the entire bandwidth.

![Figure 4. Applying system-level calibration to correct for channel response in receiver test](image)
2. Verify the RF performance of 3D antenna beam patterns OTA
Most, if not all, 5G MIMO testing happens over-the-air. Early in development, OTA test solutions need to characterize the 3D beam performance across the range of the antenna, including aspects such as antenna gain, side lobe, and null depth for the full range of 5G frequencies and bandwidths.

Radiated pre-conformance and conformance tests require a calibrated OTA test solution that covers all the requirements in the 3GPP TS 38.141 documents. For example, the following key tests are required:

- Radiated transmitter characteristic tests require effective isotropic radiated power (EIRP) OTA measurements to verify accurate generation and radiated power per beam across the frequency range.
- Modulation quality tests measure the difference between the measured carrier signal and a reference signal OTA, expressed as error vector magnitude (EVM).
- Out-of-band measurements mean the test solution needs to cover up to the second harmonic, or 60 GHz per the specification OTA today and even higher to over 100 GHz in the future, as new higher frequency operating bands are added to the specification.

Radiated receiver tests include measurements such as dynamic range, or selectivity and blocking, to test the receiver’s ability to receive a desired signal at its assigned channel frequency in the presence of an adjacent interfering signal. This test setup requires multiple mmWave signal generators with high output power to overcome mmWave path losses.

OTA test systems at mmWave frequencies require test equipment to not only meet the frequency and bandwidth requirements but also have improved performance (better than the DUT) to evaluate the DUT RF performance properly.

3. Optimize base station performance under real-world conditions
5G needs to operate in higher frequencies, with wider channel bandwidths, and using multi-element phased array MIMO access techniques. In these environments, there are signal propagation issues such as excessive path loss, multi-path fading, and delay spread that can impact system performance. Engineers must take these impairments into account when they evaluate 5G designs to ensure efficient performance under real-world fading and interference channel conditions.

Performing these types of tests in the field takes several weeks, or even months, to evaluate different physical locations that require testing. Adding a channel emulator to the test setup in the lab accelerates the evaluation and enables characterization of the complete end-to-end performance with coherent real-world complex 3D propagation channels used in MIMO. Figure 5 shows a signal generator combined with a channel emulator to emulate real-world radio conditions in a lab environment. It also includes mmWave heads to minimize RF losses from the DUT to the RF test equipment. Such a test setup is useful to evaluate and optimize MIMO antenna performance for different channel conditions.
Conclusion

MIMO and beamforming are key enabling technologies for 5G. While it is necessary to use active phased array antennas to overcome signal propagation issues, this technology also comes with a host of new test challenges.

To implement base stations with multi-element phased array antenna techniques, designers need to manage greater mmWave path loss, verify the RF performance of 3D antenna beam patterns over OTA, and optimize base station performance under real-world conditions. They need to consider test solutions that cover the wide-range of frequency and bandwidth requirements, as well as multi-channel configurations with higher output power for greater SNR, so that the base station can detect and demodulate 5G signals. An ideal test solution provides the flexibility and scalability to address multiple 5G test requirements, from characterization to OTA validation, and optimizes the design’s performance with real-world channel conditions.

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