Keysight Technologies
Examining the Challenges in Implementing and Testing Massive MIMO for 5G

Application Note

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Introduction

Consumers, businesses and developers have lofty expectations for fifth-generation (5G) wireless technology. One frequently used word is “massive,” as in massive growth in demand for mobile data, massive growth in the number of connected devices, and a massive explosion in the diversity of mobile applications.

Delivering on these expectations depends on the evolution of existing technologies and revolution in new technologies. One revolutionary change is in the use of massive multiple-input/multiple-output (MIMO) antenna schemes. All of this has implications for the development and implementation of massive MIMO technology within the 5G ecosystem. It also has implications for the hardware and software tools needed to simulate, design, and test highly complex systems containing tens or hundreds of antennas and the associated communication pathways.

To provide a starting point, this application note gathers multiple perspectives in one place. It begins with a quick review of the MIMO process. We then sketch a few noteworthy challenges in the implementation of MIMO. The note concludes with a summary of challenges—and current solutions—in the simulation, design, and testing of massive MIMO systems.

Understanding the Basic Processes

In wireless communications, there are four types of antenna systems: single-input/single-output (SISO), single-input/multiple-output (SIMO), multiple-input/single-output (MISO), and multiple-input/multiple-output (MIMO). These are shown in Figure 1.

With one antenna on either side, SISO provides no diversity protection against fading. Compared to that configuration, the use of multiple antennas on the transmitter side, the receiver side, or both, can improve reliability, capacity, or both:

- **SIMO:** Creates receiver diversity, uses smart antennas to implement beamforming, and provides an improved signal-to-interference-plus-noise ratio (SINR).
- **MISO:** Creates transmitter diversity, uses smart antennas to implement beamforming, and improves SINR.
- **MIMO:** Creates transmitter and receiver diversity, uses smart antennas to implement beamforming on both sides, improves SINR, and provides greater spectral efficiency (i.e., faster data rates and increased cell capacity).

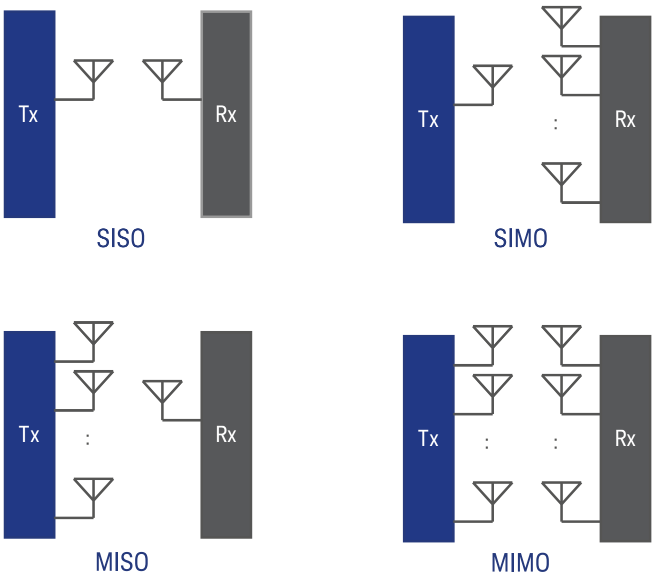

Figure 1. Multi-antenna systems add complexity, but the benefit is a gain in system performance.

As a stepping stone to massive MIMO, let's start with a single-user MIMO scenario. This technique is used to increase the data rate to a specific user, and it is currently being used in LTE as well as 802.11n and 802.11ac.

In single-user MIMO, the transmitter multiplexes the data for one user across two or more independent radios and antennas. Each receive antenna will see a combination of the signals from all of the transmit antennas (Figure 2). Part of the transmitted data will be a known sequence of pilot signals or a preamble. The receiver will use the known data to calculate the channel matrix, H, and once that matrix is known, the receiver can then use it to decode the unknown data transmission. The transmitter does not need to have any knowledge about the channel. All of the required extra computation is done in the receiver—and putting this heavy computational burden on battery-powered user equipment (UE) is not ideal.

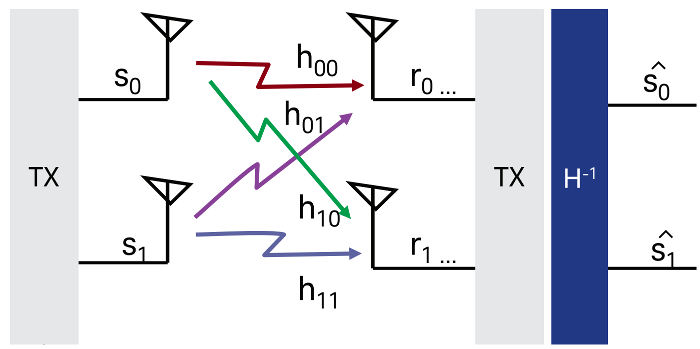

Figure 2. In this example case, the receiver de-multiplexes the two data streams based on knowledge of the channel [H].

We can use matrix math to express the direct and cross interactions within this system:

$$\begin{bmatrix} r_0 \\ r_1 \end{bmatrix} = \begin{bmatrix} h_{00} & h_{01} \\ h_{10} & h_{11} \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix}$$

From this, $R = HS$ or $\hat{S} = H^{-1} R$. Single-user MIMO requires a multi-path environment to allow the receiver to correctly generate the H matrix, which is needed to decode the received signals.

Next, let's examine multi-user MIMO, which has several differences from single-user MIMO. For example, multi-user MIMO uses multiple antennas on a single transmitter and there can be several independent receivers, each with one antenna (Figure 3).

Another difference: the transmitter pre-codes the data, shown as the W matrix in Figure 3. Again, we can use matrix math to express the direct and cross interactions within this system on the transmitter and receiver sides:

$$\begin{bmatrix} x_0 \\ x_1 \end{bmatrix} = \begin{bmatrix} w_{00} & w_{01} \\ w_{10} & w_{11} \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix}$$

$$\begin{bmatrix} \hat{s}_0 \\ \hat{s}_1 \end{bmatrix} = \begin{bmatrix} h_{00} & h_{01} \\ h_{10} & h_{11} \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \end{bmatrix}$$

From this, $W = H^T (HH^T)^{-1}$.

As shown in the matrix, the signal transmitted on each antenna, x_0 and x_1, is a combination of the symbols for each user, s_0 and s_1. On the receiver side of Figure 3, the basic process proceeds as follows:

- For user 0, the components of s_0 from all antennas arrive in phase, and thus add. The components of s_1 arrive out of phase and thus cancel, leaving only s_0 at the first receiver.
- For user 1, the s_0 signals cancel and the s_1 signals add, leaving only s_1 at the second user's input.

The difficult part of the process lies in how the transmitter learns the channel state that is needed to generate the W matrix. Several approaches are possible; however, a detailed exploration of these is beyond the scope of this note.

In single-user MIMO, the knowledge of the channel is in the receiver; in multi-user MIMO the knowledge of the channel is in the transmitter. Because all of the power-consuming calculations are performed in the transmitter, this approach is more attractive for any system in which the receivers are battery-powered.

Massive MIMO is just multi-user MIMO with a number of base station antennas that far exceeds the number of user terminals.

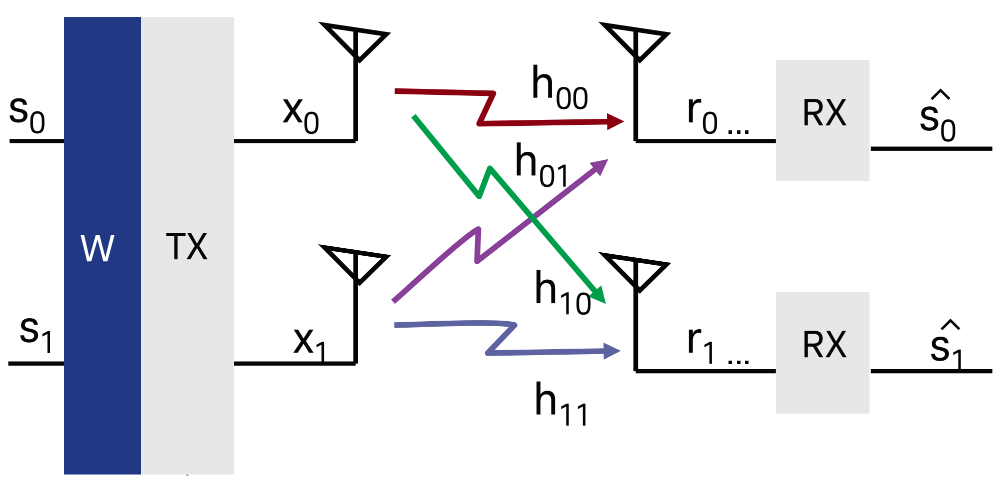

Figure 3. In this simple example, the transmitter is responsible for pre-coding (W) the data with knowledge of the channel [H].

Coordinating multiple antennas

Figure 4 illustrates the impact of using multiple antenna elements at specific spacings. In examples (a) through (d), all are sending the same signal to each antenna at the same phase. As the number of antenna elements increases, the energy becomes more focused due to the energy from the antennas adding or cancelling, depending on the phase relationships.

In the top row of Figure 4, examples (a) and (b) are the simplest cases. For examples (c) and (d) in the bottom row, using more than two antenna elements causes an increasing number of side lobes and nulls. In case (e), which uses four elements, applying a 90-degree phase shift to all four elements causes the main lobe to shift by –30 degrees. Generalizing, applying a phase shift to the signal at each element can be used to change the direction of the beam away from an orthogonal orientation to the arrays. Through control of the phase shift, beam steering becomes possible.

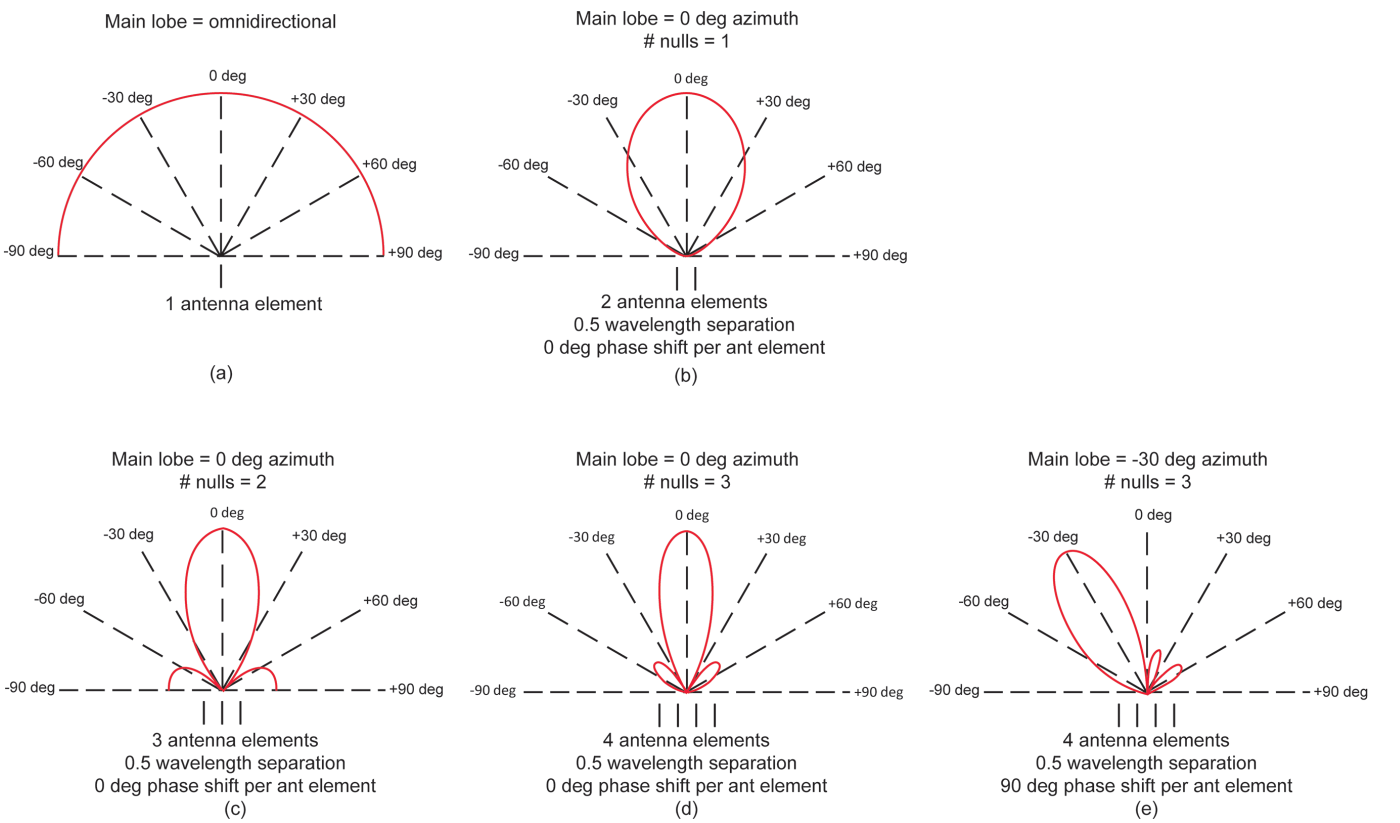

Figure 4. Using more antenna elements and controlling the phase relationships provides greater control over the transmitted signal.

From the discussion above, controlling the phase of the signals on each antenna element makes it possible to direct the beam. There are two basic approaches to controlling the antenna pattern: beam steering and beamforming. In Figure 5, a matrix-based technique can provide eight phase relationships and therefore eight discrete choices for beam position. This is an example of beam steering.

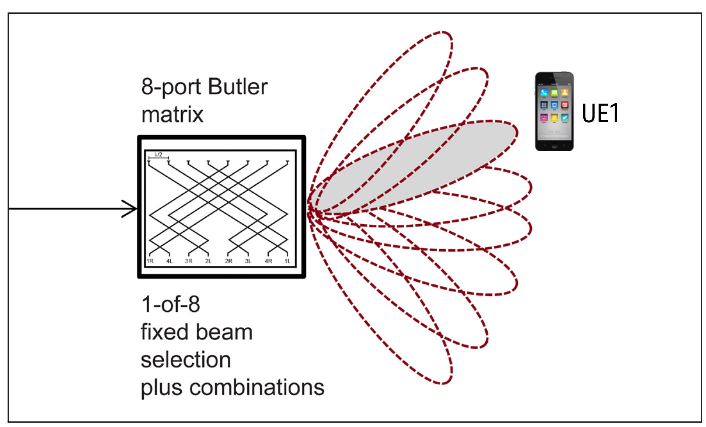

Figure 5. Beam steering provides discrete control of the direction of the transmitted signal.

There are a few methods that can be used to determine the best beam to use. Example 1: the transmitter can transmit an orthogonal code on each of the beam patterns and the UE can report back which received signal is strongest. Example 2: the transmitter can measure the angle of arrival (AoA) of the UE's uplink signal and then select the beam that is closest to that angle.

In contrast, beamforming uses on-the-fly estimations of the channel-state information to calculate specific weightings for each antenna element (Figure 6). This makes it possible to point the beam at specific—not discrete—angles and also control the direction of the side lobes and nulls. Another important consideration: the beamforming method has a direct link to the calculation of the W matrix shown earlier in our discussion of multi-user MIMO.

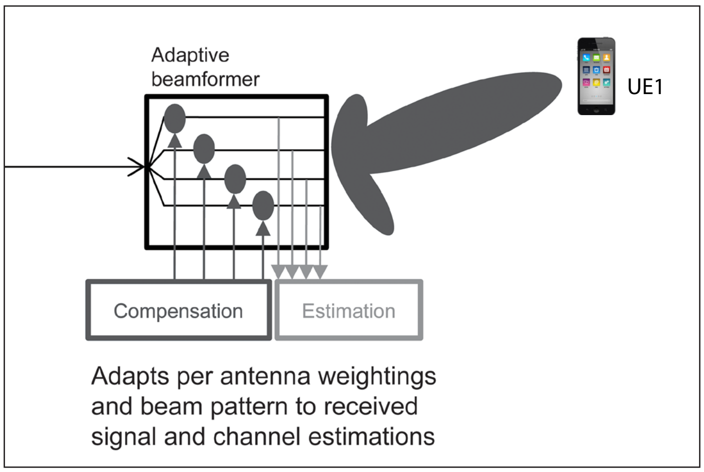

Figure 6. Adaptive beamforming provides specific, continuous control over the direction of the transmitted signal.

Our last foundational element is a comparison of co-location and massive MIMO. Let's start by considering a cluster of cells with traditional omnidirectional antennas. On the left side of Figure 7, SINR tends to be good close to the antennas (green area) and bad closer to the cell edges (orange area). As shown on the right side of Figure 7, beam steering can be used to overcome the poor SINR at the cell edge by focusing more energy in the direction of specific users. This approach has been implemented in LTE, overcoming issues with cell-edge performance.

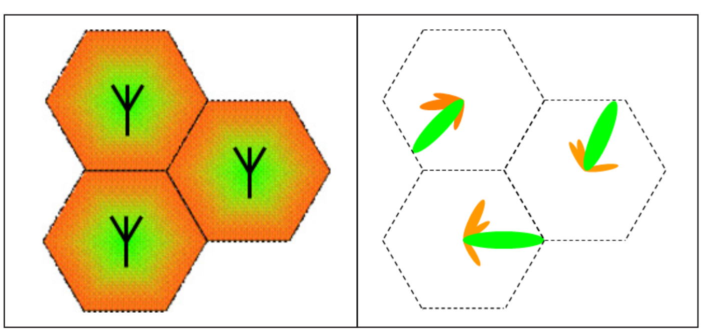

Figure 7. When cell-edge performance is poor (left), the use of beam steering can improve SINR (right).

Once the signals from each cell can be controlled in a directional manner, several cells can be placed together, or co-located, as illustrated in the left side of Figure 8. As an example, IEEE 802.11ad uses multiple independent links working in essentially the same area without interfering with each other.

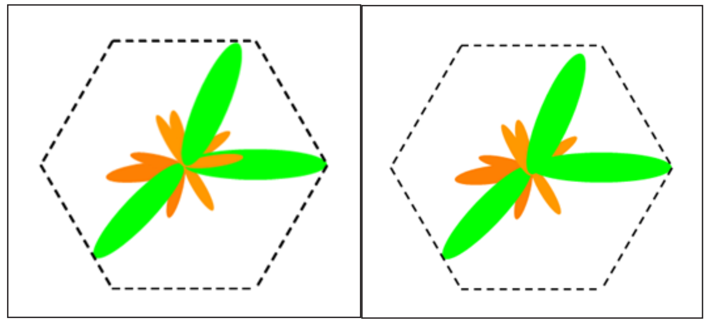

Figure 8. Directional control enables co-location (left), and the addition of massive MIMO provides additional control over sidelobes and nulls (right).

The right side of Figure 8 illustrates the massive MIMO case, showing the same three cells operating in a coordinated manner. Through coordinated control of all signals, performance is improved for each user. Comparing the left and right figures, note the difference in the right-pointing signal: with coordinated signals and the use of massive MIMO, the sidelobe from the upward-pointing signal is no longer positioned atop the other signal. In addition, each signal occurs at a null in the pattern from the other antennas, and this provides further improvement in performance for each user.

Using the array of antennas in a coordinated manner is crucial to multi-user MIMO. The key idea is to electronically control the array in such a way that the transmitted signal is strongest for the intended user and has nulls centered on the non-intended users.

Sketching the challenges in implementing massive MIMO

To establish context, this section starts with a quick overview of the massive MIMO process in a TDD system. That knowledge is the basis of two 2D simulations of massive MIMO using different numbers of antennas at different spacings. From that, we can consider possible answers to the question, “How many antennas are enough?” These three elements, taken together, provide a foundation for our sketch of the challenges that must be overcome to enable the successful implementation of massive MIMO.

Using massive MIMO in TDD

Understanding the application of massive MIMO requires a brief dive into a few details regarding the operation of TDD. Referring to the diagram in Figure 9, three things occur during the channel coherence time. First, all UEs transmit a number of orthogonal uplink pilot symbols at the same time; the number of symbols scales with the number of UE.

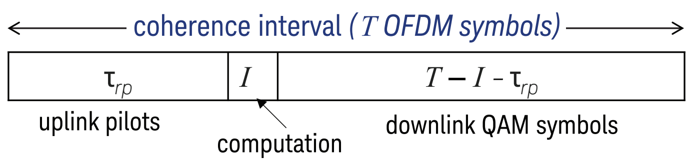

Figure 9. In TDD, coherence time is dominated by the transmission of uplink pilot symbols and downlink data symbols.

Next, the base station quickly calculates the pre-coding matrix from the received signals. Each terminal has a unique pilot sequence, allowing the base station to differentiate the pilot signals from each user. The received pilot signals provide the channel-state information from each UE to each antenna. The base station uses this to calculate the pre-coding matrix, W, shown in the multi-user MIMO discussion.

Third, the base station transmits a number of downlink symbols to each UE. The downlink symbols for all of the terminals are sent out at the same time, weighted with the pre-coding matrix. In this context, the channel coherence time is defined as the length of time that the measured channel state information will be valid. Several factors will influence the length of the coherence interval, including the carrier frequency of the system and the amount of mobility that is supported. In general, higher carrier frequencies and higher rates of mobility will decrease the channel coherence time (this is discussed later in “Outlining a few additional challenges”).

This highlights, again, an advantage of multi-user MIMO: all of the heavy computation is performed in the base station rather than the UE. The UE simply send uplink pilot symbols to the base station.

Most of the time is spent on two functions: each UE sending those uplink pilot signals and the base station sending downlink data symbols. If uplink data must be sent, the time would be split evenly between the sending of uplink data, uplink pilots, and downlink data.

TDD vs. FDD

Much of the information available today suggests that it may not be practical to use massive MIMO in an FDD system. In TDD, the system need only send enough uplink pilots to provide an orthogonal sequence for the number of terminals.

In FDD, the process is needed to train the uplink channel. To train the downlink channel, the system must send a number of symbols that is proportional to the number of base station antenna elements. In addition, each UE must calculate the channel-state information for the downlink and then send it back to the base station before it can be used.

This added overhead limits the number of antenna elements that can practically be used in an FDD system. For example, in a moderate mobility use case, the total number of antennas or terminals that can be used is estimated to be about 60, and the system could serve 10 UE with a maximum of 50 antennas. This is unfortunate relative to the improvements that are possible in massive MIMO when using several hundred antennas.

Number of UE versus cell capacity

To create the necessary channel-state information, all UE transmit orthogonal pilot symbols at the same time. When more terminals are in the cell, more symbols are required to differentiate between users. Thus, the amount of training time needed to transmit the uplink pilot symbols scales with the number of user terminals, but is independent of the number of base station antennas.

From early research on this topic, the initial conclusion regarding optimization of mean cell capacity was that approximately one-half of the channel coherence time should be spent on uplink pilot training.[1] Later work stated that, to optimize both uplink and downlink data capacity, one-third of the coherence time should be used for uplink data, one-third for uplink pilots and one-third for downlink data.[2] The optimum number scales with coherence time; however, mean throughput is independent of coherence time.

Further, cell capacity is independent of cell size. This means that the optimal way to increase the number of terminals is to decrease the cell size and add more cells.

1. How Much Training is Required for Multi-User MIMO?, Thomas L. Marzetta
2. Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas, Thomas L. Marzetta

Simulating with multiple UEs

It may be useful to think of massive MIMO as "spatial multiplexing" with multiple users existing in space around a single base station. Through the mechanisms described in the preceding section, each UE has access to the full resources of the base station.

To illustrate the relationships between four users and one base station, two cases were simulated in 2D using MATLAB from The MathWorks. In both cases each UE has a single antenna and the base station has a multi-antenna array: base station #1 has a linear array of 50 omnidirectional antenna elements spaced at a half-wavelength (½ λ); base station #2 has a linear array of 200 omnidirectional antenna elements spaced at a full wavelength (λ).

Figure 10 shows the results of the simulation with 50 antenna elements spaced at ½ λ; these are radiating into free space (e.g., no scattering elements) and the simulation accounts for path loss only. For clarity, the signal energy directed at each UE is shown in a separate panel, and each of these is 15,000 λ wide and 2,000 λ tall. Although the signal to each user is shown separately, the respective signals were transmitted to all users simultaneously, sharing the time/frequency resources.

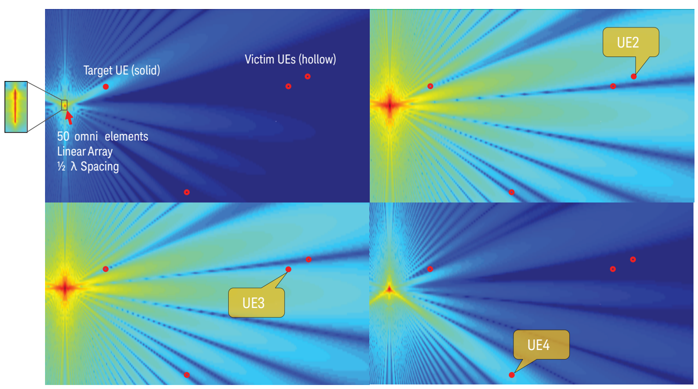

Figure 10. Using 50 antennas provides modest improvement in the directional control of signals and nulls.

For each UE, the steering coefficients create nulls at each "victim user" location (i.e., the other three UE). In some cases the nulls cover a wide expanse; in others the null is quite compact. From this perspective, it may be more illuminating to reframe massive MIMO as being about both "null steering" and beam steering. The net result: each user receives only their signal, making it possible to share the available frequency and time resources by implementing "spatial multiplexing."

Note that the two most distant users, UE2 and UE3, are close to each other in terms of angular spread. With 50 antenna elements, the algorithms used here can't beam energy directly at each user while also steering a null in that same direction. For UE2 and UE3, each user is able to acquire energy from only the edge of the beam (i.e., most of the transmitted energy is wasted).

Figure 11 shows the results of the simulation with 200 antenna elements spaced at λ; again, these are radiating into free space and the simulation accounts for path loss only. With the wider antenna aperture, the system is capable of producing narrower beams and centering them on each UE.

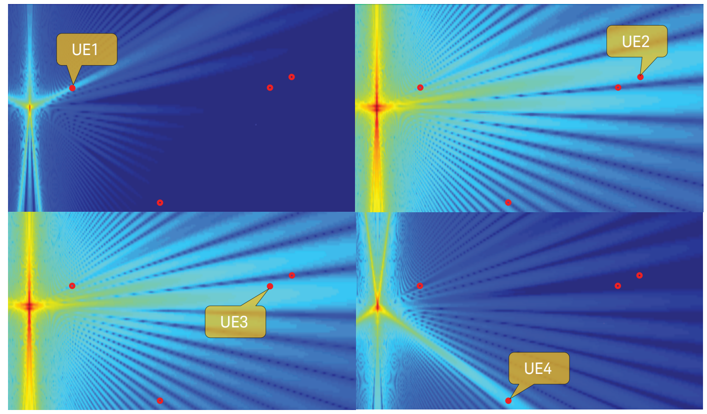

Figure 11. Using 200-antenna massive MIMO provides greater precision in the placement of signals and nulls.

The effect of the narrower beams is seen very clearly for the UE2 and UE3 signals. With 200 antennas, it's possible to direct the energy at the intended user while still placing the nearby user in a null.

The simulation revealed another interesting result: increasing the number of antennas reduced the total amount of power by 12.6 dB compared to the 50-antenna case. This is interesting, but it stimulates a larger question: has energy been conserved? While the total transmission power is lower, there will be significant increases in the amount of power required for signal conversion (ADC or DAC) and processing. This simulation was not able to account for that type of power consumption; however, a recent research study cited by Dr. Thomas Marzetta showed that a 64-element massive MIMO antenna reduced power consumption by a factor of 500.[1]

1. Although Dr. Thomas Marzetta has no direct connection to Keysight, we would like to acknowledge our indebtedness to his work in this field. In addition to being the originator of massive MIMO, he is Group Leader of Large Scale Antenna Systems at Bell Labs, Alcatel-Lucent, and co-head of its FutureX massive MIMO project. This note cites his work and, where possible, provides links to the source material.

Estimating how many antennas are enough

The preceding simulations are a logical extension of early research into the optimal number of base station antennas. In Marzetta's original paper on this topic, he analyzed the use of 1, 2, 4, 8 and 16 antennas. The conclusion: over a wide range of SINR values, throughput always improves with an increase in the number of antennas.[1]

In a later paper, Marzetta extended the analysis to an infinite number of antennas—and "more is better" remained true. Although a system with an infinite number of antennas is clearly impractical, the analysis did show that adding more and more antennas continued to improve performance.[2]

A separate group of researchers conducted a third study aimed at quantifying the improvement in a range of values that could be realized in an actual array. Their results suggest that several hundred antennas may be sufficient and that there are diminishing returns for more than that number.[3]

1. How Much Training is Required for Multi-User MIMO?, Thomas L. Marzetta
2. Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas, Thomas L. Marzetta
3. Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need?, Jakob Hoydis, Stephan ten Brink, M´erouane Debbah

Outlining a few additional challenges

The road to successful implementation of massive MIMO includes at least three more significant obstacles: reciprocity error, signal-to-interference ratio (SIR), and channel coherence time.

Dealing with reciprocity error

A TDD system assumes that the channel is unchanged in the interval between reception of the uplink pilot signals and transmission of the downlink data. This follows from the definition of coherence time and coherence bandwidth, which is the period over which the channel remains stable enough to use the computed channel estimate. As long as all operations stay within the channel coherence time, this is a reasonable assumption about the channel between base station and UE.

Another area of concern is the reciprocity of the transmit and receive circuits (Figure 12). These are clearly different circuits, each with its own delays and gains. A close match in phase is important: simulations show that as little as one degree RMS of phase error (transmitter to receiver) will have a significant impact on SIR. As a result, the system must calibrate for these errors to ensure a consistent offset between all elements in the antenna array.[1]

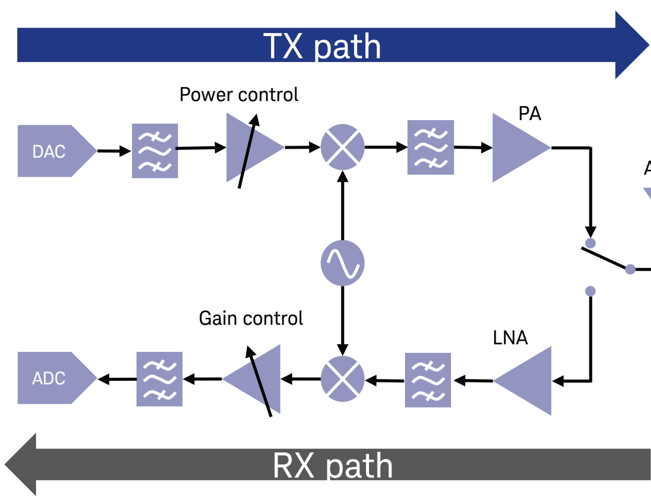

Figure 12. Differences in the transmitter and receiver circuits can cause reciprocity error in a massive MIMO system.

The power amplifier (PA) also plays an important role. In particular, gain compression (or gain linearity) and AM/PM conversion can both introduce errors. For example, if the PA in the transmitter path has an AM/PM component that shifts the phase by a few degrees over the range of available output power levels, this could be problematic because the same phase shift would not appear in the low-noise amplifier (LNA) in the receiver path. Similarly, the power-control amplifier (transmitter) and gain-control amplifier (receiver) could also cause unequal phase shifts.

Managing SIR

High SIR is desirable because it ensures high throughput. Counter-intuitively, though, SIR decreases as the UE gets closer to the base station. One key reason: the errors in the signals from the most distant UEs will be strongest and have the greatest negative effect on UEs that are closer to the base station.

From this, the accuracy of the channel-state information is a crucial factor. Noise, pilot contamination and differential phase noise can all affect channel-state information.

Phase noise that is common to all antennas will not present a problem; however, differential phase noise between elements can break the reciprocity assumption. Differential phase noise may arise when transmitter and receiver elements share only a common reference, not a common local oscillator (LO). It can also occur when the LO distribution paths are long enough to de-correlate the phase error between distant elements in a physically large array.

Staying within the bounds of channel coherence time

The channel reciprocity assumption is valid as long as all operations can occur within the channel coherence time. How long will the channel-state information be valid? For a moving UE, it's reasonable to assume that it remains valid within the time it takes to travel a quarter-wavelength.

Table 1 shows four speeds for pedestrian and vehicle channel models versus three possible carrier frequencies. At 2 GHz, used in today's cellular systems, it seems like there would be no issues at the three lower speeds (all from current 3GPP channel models). At 28 and 60 GHz, which are under consideration for 5G, the numbers look good for the pedestrian (3 km/h) case; however, it may not be possible to use massive MIMO at any of the higher vehicular speeds.

Table 1. The time it takes to travel a quarter-wavelength is a function of speed and carrier frequency.

	Carrier frequency		
Speed	**2 GHz**	**28 GHz**	**60 GHz**
3 km/h	45 ms	3.2 ms	1.5 ms
30 km/h	4.5 ms	320 µs	150 µs
120 km/h	1.125 ms	80 µs	37 µs
500 km/h	27 µs	19 µs	9 µs

1. In testing, the antenna must remain stable enough to ensure that the calibration will be accurate within the design tolerances of the system.

Examining the challenges and solutions in testing massive MIMO

Massive MIMO and the move to mmWave frequencies are key examples of the evolutionary and revolutionary changes required to meet expectations for 5G. Those changes, and more, translate into the need for parallel evolution and revolution in simulation, design, test, measurement, and analysis.

Summarizing the challenges

The number of available test points may be quite different from what we've been accustomed to in the past. For example, with the integration of antennas and amplifiers at the package level, most or all of the testing beyond the wafer probe step may need to be over the air. On the baseband side, it may be necessary to input test signals that are digital (perhaps over fiber) instead of the analog waveforms used today.

Frequencies are moving higher and bandwidths are getting wider. Today, much of the test equipment currently in place for communications systems is limited to a 6-GHz carrier frequency and a 160-MHz modulation bandwidth. 5G is challenging both of these limits.

The required number of measurement channels remains an open—and important—question. It seems likely that typical massive MIMO designs will range from tens to hundreds of antennas. Keysight is currently working on test methods for these systems, seeking to balance cost, coverage and measurement times.

The validation of system performance has the potential to become highly complex, time-consuming and expensive. For example, building large emulation systems, especially at mmWave frequencies, could be quite costly. Relying on simulation data may become an important part of the process, and the ability to achieve new insights while accelerating time-to-market will benefit from solutions that easily combine simulation results with measurement data.

Millimeter-wave frequencies

In 5G, successful use of millimeter-wave (mmWave) frequencies will likely require beamforming and beam steering. The downside of mmWave bands: higher path loss due to smaller antenna aperture and atmospheric absorption at some bands, including 60 GHz. This greatly reduces the distances of useful propagation.

The use of mmWave also requires high-gain directional antennas. As noted elsewhere in this note, base stations will likely use hundreds of antennas while user terminals will use less than 16. Fortunately, at these frequencies, antenna arrays will be quite small, allowing for a large number of elements. Beamforming or beam steering will likely also be required on the uplink.

Presenting an example solution

To support research and development of massive MIMO systems, Keysight has created a real-time beamforming measurement system based on currently available hardware and software products. Figure 13 shows a high-level block diagram of an eight-channel system. The system contains three key elements:

- W1462 SystemVue FPGA Architect software, upper left and upper right.
- M8195A 65 GSa/s four-channel arbitrary waveform generator (AWG), lower left.
  - Provides four 65 GSa/s channels per single-slot AXIe module. Can be configured as 16 coherent channels by placing four modules in a five-slot chassis and using the M8197A synchronization module.
- M9703A AXIe 12-bit high-speed digitizer/wideband digital receiver, lower right.
  - Provides eight channels in a single AXIe module. Can be configured as 32 coherent channels in one five-slot AXIe chassis.

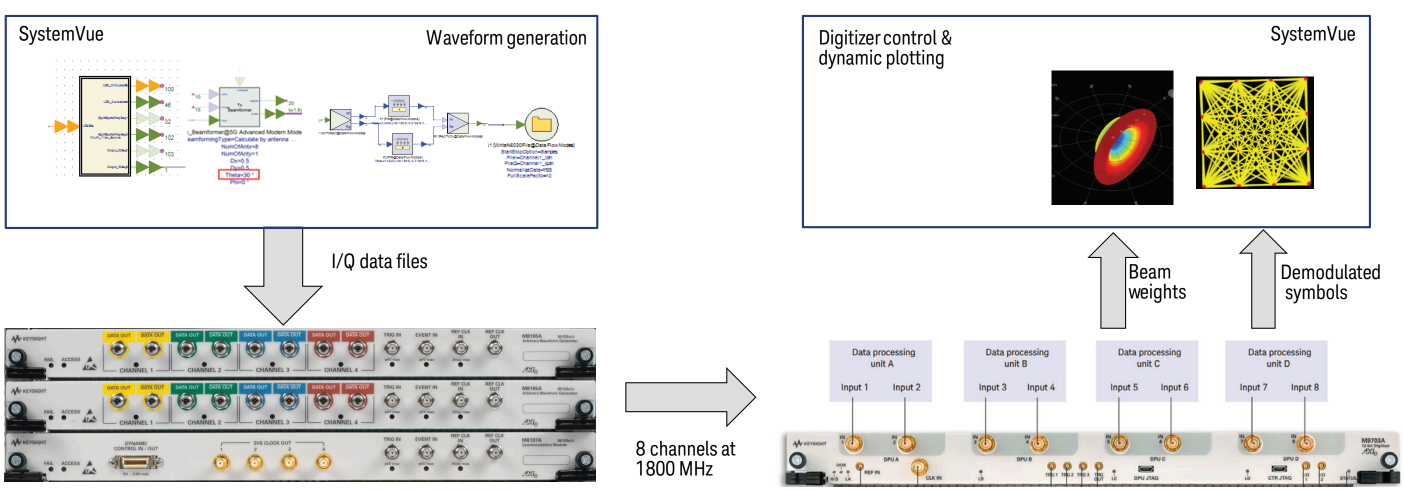

Figure 13. This combination of instrumentation and software enables real-time beamforming measurements.

The M8195A AWG is used to directly generate modulated RF or IF signals using a single channel of the AWG module. This approach enables the generation of RF signals up to 20 GHz. The source I/Q waveform is up-sampled to the AWG sample rate and modulated to the carrier frequency in software, and the output of this process is loaded into the AWG memory. For RF signals in any of three regions—the existing sub-2-GHz bands, new bands up to 6 GHz and exploration bands at 15 GHz—the signals can be directly generated with the M8195A. For signals above this frequency, the AWG can be used with a hardware upconverter by generating a modulated IF signal with the M8195A. Because the I/Q modulation is performed in software before the signal is loaded into the AWG, the traditional limitation on I/Q bandwidth does not apply when using the M8195A.

The block diagram in Figure 14 provides more details about the functions and data flows. Moving from left to right, the process proceeds as follows:

- Candidate waveforms are created and up-sampled to the AWG sample rate in SystemVue
- I/Q data files are modulated to the RF carrier frequency and then transferred to the M8195A
  - Both AWG modules are synchronized to ensure precise output
  - Output can be a single waveform or a sequence of waveforms
  - Timing offsets can be applied using a hardware FIR filter at the output of each channel of the M8195A
- The M8195A AWGs output up to eight channels simultaneously at the RF or IF carrier frequency
- SystemVue provides control of the M9703A digitizer and also performs dynamic plotting of acquired signals
  - The M9703A digitizer measures up to eight channels simultaneously
  - Embedded FPGAs perform signal-processing functions such as demodulation and beam tracking
  - Data such as beam weights and demodulated symbols are transferred to SystemVue for display

The measurement algorithm was developed in SystemVue using a combination of built in SystemVue IP blocks, VHDL code generated externally to SystemVue, and IP blocks provided by the FPGA manufacturer. The SystemVue platform allows simulation of the process using simulated or measured I/Q data. Once the algorithm development is verified, SystemVue will create the FPGA image, allowing the procedure to run in the digitizer hardware in real time.

Proper operation of the system depends on precise timing, alignment and calibration. Timing and alignment are derived from the performance of the M8195A and M9703A. The AWG timing specifications are ±6 ps for a single module and ±100 ps between modules, adjustable to 0 ps using the variable delay command. In the digitizer, timing precision is ±50 ps on all channels after an internal calibration and multi-module synchronization (required if using more than one M9703A module).

A simple calibration process provides timing repeatability of ±1 ps:

- Input a continuous-wave (CW) signal at the IF center frequency
- Measure the phase of each channel relative to channel 1
- Convert the phase difference to a time different
- Apply the time difference to the AWG channels using per-channel FIR filtering

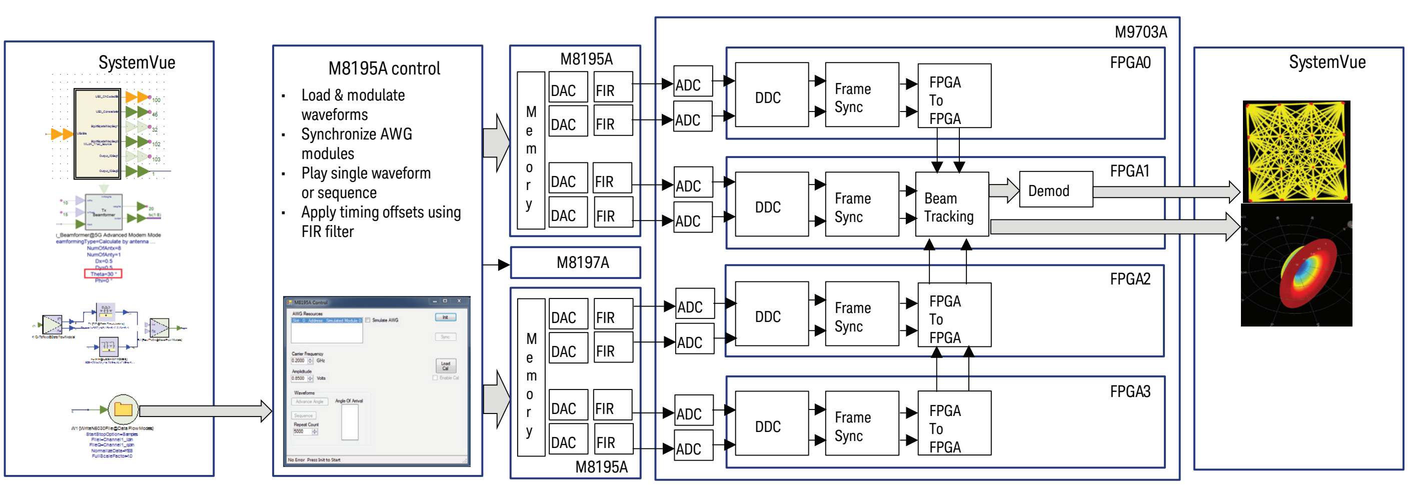

Figure 14. SystemVue is the unifying element, providing waveform creation, AWG control, digitizer control, and data plotting.

Conclusion

In 5G, “massive” is a key word whether we’re discussing performance expectations or the implementation of possible MIMO schemes. Delivering on all fronts depends on the evolution of existing technologies and revolution in new technologies. This notion applies equally to 5G and the tools—hardware and software—needed to develop the next-generation wireless ecosystem.

Keysight’s 5G solutions are ready to enable deeper insights as you, and we, evolve with the standard. In design and test, our solutions help you innovate across new and existing technologies as you transform ideas into reality. The race is on and Keysight will help you take the lead—from evolution to revolution to reality.

Related information

- Technical Overview: *Keysight EEsof EDA SystemVue*, publication 5990-4731EN
- Application Note: *FPGA Prototyping Using Keysight SystemVue*, publication 5991-1113EN
- Data Sheet: *M8195A 65 GSa/s Arbitrary Waveform Generator and M8197A Multi-Channel Synchronization Module*, publication 5992-0014EN
- Data Sheet: *Keysight Technologies M8190A Arbitrary Waveform Generator 12 GSa/s Arbitrary Waveform Generator*, publication 5990-7516EN
- Data Sheet: *M9703A AXIe High-Speed Digitizer/Wideband Digital Receiver*, publication 5990-8507EN
- Data Sheet: *M9393A PXIe Performance Vector Signal Analyzer*, publication 5991-4538EN
- Brochure: *X-Series Signal Analyzers*, publication 5992-1316EN
- Data Sheet: *UXA X-Series Signal Analyzer, Multi-touch*, publication 5992-0090EN
- Data Sheet: *PXA X-Series Signal Analyzer, Multi-touch*, publication 5992-1317EN
- Data Sheet: *Keysight Microwave Signal Generators*, publication 5991-4876EN
- Data Sheet: *Keysight Technologies E8267D PSG Vector Signal Generator*, publication 5989-0697EN
- Selection Guide: *Signal Generator Selection Guide*, publication 5990-9956EN
- Data Sheet: *Keysight Technologies Infiniium S-Series High-Definition Oscilloscopes*, publication 5991-3904EN
- Brochure: *Keysight Technologies 5G Solutions*, publication 5992-1215EN

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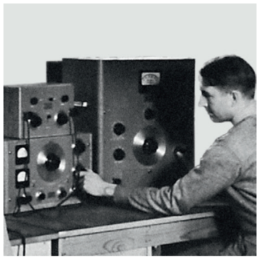
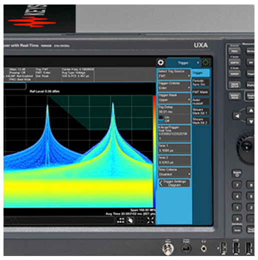


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