# Beamforming:
# What it is, why it's important, and the challenges in testing its performance

*By Dr. Joseph Lee*

## The definition and value of beamforming

Beamforming is a transmission technique that uses multiple array antennas to concentrate the power of a transmitted RF signal onto a particular user. A digital signal processing algorithm is used to apply relative amplitude and phase shifts to antenna elements in such a way that the signals join together towards a user's location and cancel each other out in the opposite direction [1].

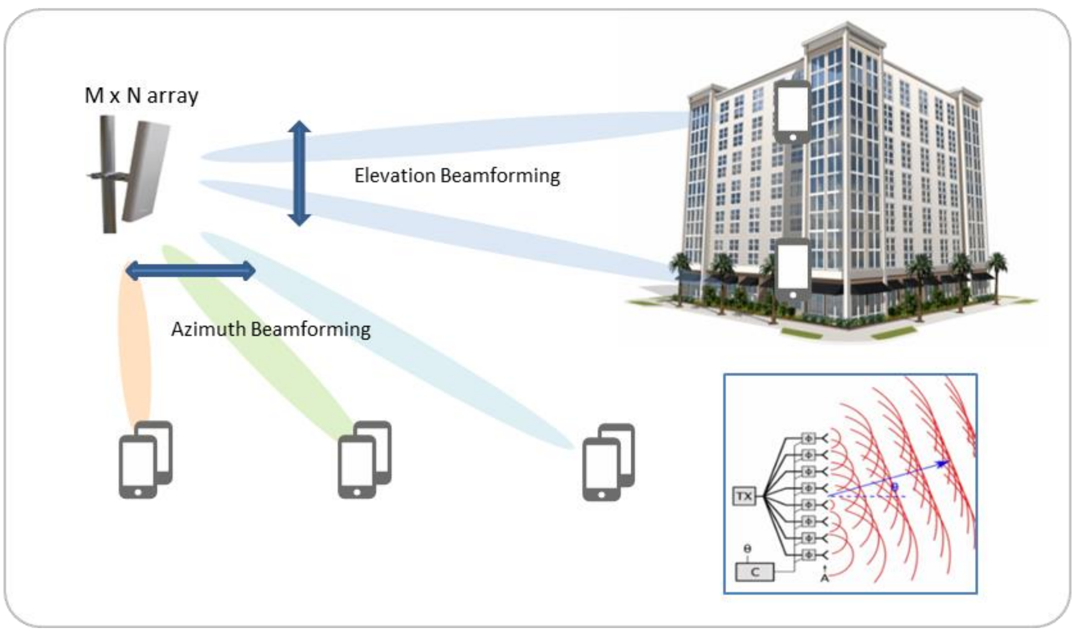


*Figure 1. Massive MIMO antenna performing 3D (azimuth and elevation) beamforming.*

Beamforming plays a key role in performing multi-user multiple input, multiple output (MU-MIMO), in which concurrent users share time and frequency resources to dramatically increase the capacity of a channel. In a Massive MIMO antenna array, a large number of antenna elements (i.e., 64T/64R) serve users in different locations using beamforming. Using RF environments constructed for users that employ signal concentration and canceling, multiple users achieve higher throughput at the same time and frequency.

Together with higher carrier aggregation, higher-order modulation and enhanced use of unlicensed spectrum, beamforming/Massive MIMO can deliver Gigabit throughput in LTE-Advanced and 5G networks [2]. In urban, high data traffic environments where spectrum is limited, Massive MIMO's beamforming technique is a significant advantage. By accommodating more concurrent users and giving them a better quality of service, beamforming allows mobile operators to attain a better return from their capital expenditure under limited resources.

## How beamforming is performed between the base station and UE

There are two types of beam: a common beam used for the initial connection, and a dedicated beam used once that connection is established.

Since a base station cannot locate a User Equipment (UE) at the time of its connection, the base station secures coverage through a time-sweep, with beams uniformly divided over space. Each beam contains a unique Synchronization Signal Block Beam ID (SSB ID) and Physical Beam Index (PBI). The UE informs the base station of its status, including SSB IDs and power information, in real time.

Once the UE is connected to the base station, a dedicated beam for data transmission can be concentrated on the UE. The base station tracks the UE by measuring an uplink channel via a Sounding Reference Signal (SRS) transmitted from the UE. Then, the base station applies the uplink channel value to downlink channel value by using TDD channel reciprocity. Now, beamforming coefficients for each antenna can be calculated using channel value and a linear algebraic zero-forcing method, which helps minimize interference from other antennas. Multi-user MIMO is now performed through beamforming gain and interference rejection gain.

## Beamforming KPIs

The list below highlights beamforming key performance indicators (KPIs) and illustrates why they are important to measure and analyze. The goal? To verify whether throughput matches channel capacity, and if not, why.

### KPIs related to SSB/Common Beam

- **Number of detected SSBs**
  A maximum of 64 SSBs can be transmitted. A base station can measure and estimate the location and direction of a UE using SSB IDs—or PBIs—that it receives and reports.
- **PBI and RSRP/RSRQ**
  PBIs and associated power information received by a UE can be used to predict the handover situation of the UE.
- **DMRS SINR**
  Demodulation Reference Signal (DMRS) SINR can be used to estimate and receive channel characteristics.

- **Beamforming gain**
  This parameter can be used to estimate the efficiency of beamforming at the time of measurement.

### KPIs related to User/Dedicated-beam

- **DMRS SINR**
  Since multiple orthogonal DMRS signals can be allocated and beamformed to support MIMO transmission, DMRS SINR be used to estimate the degree of interference in each user signal in the corresponding physical channel.
- **Beamforming Gain and Interference Rejection Gain**
  Analyzing these KPIs can help estimate the performance of both channel estimation and interference rejection.

## The challenges of measuring antenna beamforming performance

One way to measure a Massive MIMO's beamforming performance is through field testing. Testing must be conducted among a representative number of UEs located in the sector (e.g. 16 UEs) and the UEs must be in different positions, i.e., not bunched together in a single location or line-of-sight spot. The UEs also need to support Transmission Mode 8 or 9 (TM8 or TM9) to report beam-specific KPIs. The idea is to measure how much gain a Massive MIMO antenna provides compared with a conventional antenna system. Through beamforming, a Massive MIMO antenna should provide better signal quality to each user. Hence, user throughput and sector throughput should be higher.

For efficient field testing, Accuver XCAL-Auto and XCAL-Solo tools can be used. XCAL-Auto is a cloud-based server that allows users to assign test cases remotely to test UEs and monitor their status and locations in real time. It also allows users to choose which UEs to aggregate, so that they can see sector throughput in addition to user throughput. Indeed, Signals Research performed a similar Massive MIMO test recently using Accuver XCAL-Auto and XCAL-Solo tools [3].

If one conducts Massive MIMO/beamforming tests repeatedly, field tests are time- and resource-consuming. Moreover, field tests don't offer a repetitive and consistent test environment to verify Massive MIMO's beamforming performance, or identify problems caused by multiple sources. One way to perform the test in a simpler way is to bring the field RF environment into a lab and test it repeatedly using a channel emulator. A channel emulator is an instrument that takes RF inputs to generate RF outputs and combines internally-generated multi-path signals with individual amplitude and phase gain control, including propagation delay and path loss implementation.

To measure beamforming performance accurately, a channel emulator should secure 'channel reciprocity,' in which a downlink channel is equal to an uplink channel—similar to a real, over-the-air channel. However, a channel emulator is an electronic instrument incorporating RF and digital circuits which would not usually satisfy the channel reciprocity requirement. Hence, to meet that requirement, the channel emulator must be equipped with an internal or external calibration function. Since by nature RF components' characteristics drift with temperature, calibration should be performed on a regular basis. Therefore, it is critical that the calibration function does its job in a relatively short period of time—lest too much time is wasted on calibrations.

# Introducing Accuver MAIS

The Accuver Massive MIMO Channel Emulator (MAIS) is the latest addition to the Radio Access Network (RAN) Testing portfolio—part of Accuver's Field-to-Lab (F2L) testing solutions. F2L products deliver quick, cost-effective RAN software verification in real-world-like lab environments prior to field deployment.

MAIS is a channel emulator with M inputs to connect to BS antenna ports, and N outputs to connect to UE antenna ports. MAIS supports various M x N configurations, allowing users to test the performance of—for example—a 16 x 16 LTE FD-MIMO or a 64 x 64 5G Massive MIMO system.

For RAN vendors, MAIS provides a repetitive, consistent test environment to verify Massive MIMO performance. For wireless operators, MAIS enables the comparison of FD/Massive MIMO performance from different RAN vendors in the same RF environment. Both these use cases are difficult to achieve with field testing due to variables present in the field environment.

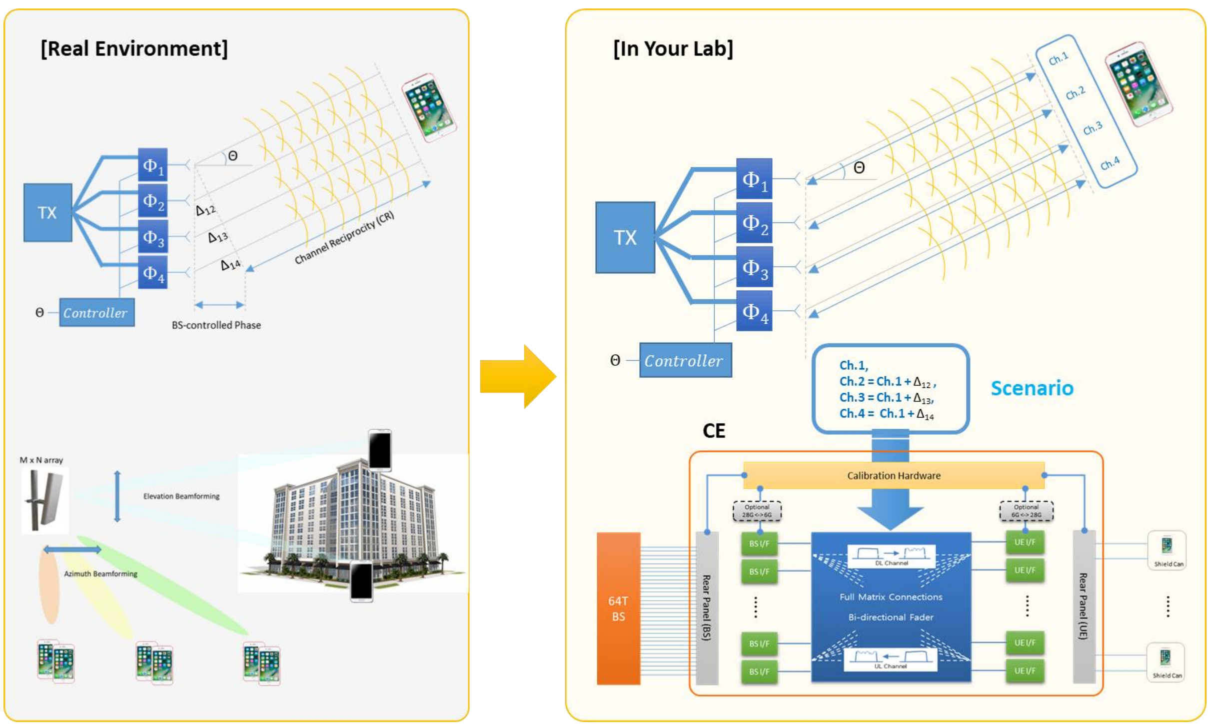


*Figure 2. Accuver MAIS system simulating angle-of-departure (AoD), angle-of-arrival (AoA), and channel condition between the base station MIMO antenna and the UE.*

The MAIS system supports a 100 MHz channel bandwidth for 5G testing, and frequencies of between 300 MHz to 6 GHz. It features a built-in calibration kit that is fast and accurate; and typically achieves the following specification within 15 minutes: |amplitude| < 0.35dB and |phase| < 3 degree; and it sustains the calibrated state for up to 72 hours.

*Figure 3. Accuver MAIS system.*

## MAIS benefits

MAIS offers users the following benefits:

- Adjustable amplitude and phase rotation
- Monitoring of BS and UE outputs
- Support of ITU channel models and user-defined models
- Support for distributed, remote testing configuration
- Measurement of beam tracking performance. MAIS has signal capturing function at both the BS and UE sides to measure all beamforming KPIs listed above.
- Fast self-calibration—typically within 15 minutes. Calibration hardware is included in MAIS to ensure it creates channel conditions properly and achieves channel reciprocity within the specified tolerance

## MAIS specifications

- Channel bandwidth of up to 100 MHz
- Frequency: 300 MHz to 6 GHz
- RF port capacity: a single MAIS chassis can support up to 64 RF ports (16 slots, 4 RF ports per slot)
- Channel reciprocity (for TDD) with calibration tolerances of:
    - Amplitude = ±0.35 dB and phase ±3 degrees from any BS port to any UE port
- Support for DL 256QAM and UL 256 QAM, at a frequency of < 4 GHz
- Channel fading models: ITU Ped. A/B, Veh. A/B, EPA, EVA, ETU, 2D/3D SCM, HST, and user-defined
- Number of multipaths: 8 (expandable to 20)
- Doppler frequency of up to 1350 Hz (560km/h @ 2.6 GHz)
- AWGN built-in at each RF port

## Signal and beamforming analysis with MAIS

MAIS supports the following analysis:

1. **Signal analysis** on:
    a. Each RF port
    b. gNB and UE
    c. Relative power, OFDM, OBW and I/Q samples

2. **Beamforming analysis** on:
    a. RF ports
    b. SSB/common beam
        i. PCI, PBI, power, correlation accuracy, EVM, SINR
        ii. Relative phase-consistency
    c. PDSCH/dedicated-beam
        i. Relative phase-consistency
        ii. Beam-forming accuracy

## Conclusion

Wireless technology is changing fast every day, and the complexity of testing and validating its features also grows exponentially. Such is the case with validating the performance of beamforming and Massive MIMO, two important features of 5G. Massive MIMO's beamforming performance can be measured using field testing but doing so is very time- and resource-consuming. Moreover, the field doesn't offer a repetitive and consistent test environment to troubleshoot problems that may be caused by multiple sources.

Accuver MAIS (Massive MIMO Channel Emulator) provides a repetitive and consistent real-world-like test environment to verify and compare Massive MIMO product performance. MAIS system supports 100 MHz channel bandwidth for 5G testing and frequencies from 300 MHz to 6 GHz. It has a built-in calibration kit that is fast (within 15 minutes) and highly accurate – ensuring that little time is wasted in calibration – so that users can get on with Massive MIMO testing quickly.

## References


1. Masterson, C. (2017, June). Massive MIMO and beamforming: The signal processing behind the 5G buzzwords. *Analog Dialogue, 51*.
2. Qualcomm. (2017, February). The essential role of Gigabit LTE & LTE Advanced Pro in a 5G World.
3. Thelander, M. (2018, November). The matrix: Quantifying the benefits of 64T64R Massive MIMO with beamforming and multi-user MIMO capabilities. *Signals Ahead, 14*, no. 9.


## Author


Dr. Joseph Lee is Vice President of R&D at Innowireless, a leading test and measurement company in South Korea. He is responsible for developing digital signal processing circuits for RF-related products such as channel emulators and base station maintenance equipment, in both single box and modular-type architecture based on LTE-Advanced and 5G technology. Dr. Lee received his Ph.D. in electrical

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