# Massive MIMO Array Testing using a Programmable Phase Matrix and Channel Emulator

## I. Introduction

Development of 5G wireless telecommunication systems is ongoing and expanding in various organizations, such as 3GPP [2]. One key differentiator of 5G networks is using massive MIMO to boost capacity [4], [5] by deploying very narrow beams in certain directions and deep nulls in certain directions [1]. Massive MIMO utilizes many antenna elements and testing massive MIMO would theoretically require lots of hardware resources.

Performance testing of 5G base stations (gNodeB's or gNBs) can be subdivided into over-the-air (OTA) and conductive test methods. These categories can be further subdivided into "below 6GHz" and "above 6GHz" testing. This paper focuses on conductive gNB testing at below 6GHz. It is worth noting that many of the 5G frequency allocations are on sub 6GHz bands [3].

Performance testing proposed in this paper is based on using a combination of a phase matrix splitter/combiner function and a high-fidelity radio Channel Emulator (CE). Connecting the massive MIMO array of elements to the CE via a phase matrix allows for simplification in the amount of hardware required. The phase matrix provides a single phase-adjustable connection between each input port to each output port that can be used to model a single spatial direction, like having a test probe in a chamber. The signals on this virtual probe are then supplied to the CE. The purpose of the CE is to provide simulated mobility, signal correlation, and multipath spread, and possibly noise interference to the test system. The virtual probes define the spatial clusters observed by the massive MIMO array, while the rest of the channel is simulated in the CE and connected to the User Terminal (UT). Thus, with the combination of the phase matrix and CE, a given spatial-temporal channel model can be created in a more efficient manner than by using the resources of the radio channel emulator alone.

This white paper is organized as follows: Chapter I introduces the concept and rationale behind using the Phase Matrix plus CE. Chapter II is devoted to describing the test system. Chapter III discusses the system and its building blocks and Chapter IV discusses the channel models. Finally, we will conclude the paper in Chapter V.

## II. Description of the Test System

Massive MIMO tests using a traditional conducted connection require a very large number of radio channels from the testing equipment. This is virtually impossible with available CE hardware due to the size and cost of the equipment, which is not easily scaled up to array sizes that are being proposed for 5G, with as many as 256 elements or more. Thus, there is a desire to minimize the needed hardware resources due the cost and space limitations in a laboratory environment.

The purpose of the test is to create an environment where multiple users can be tested in a multi-cluster radio channel scenario. Some of the users are desired users and some may be interfering users. Several system parameters, including capacity gain, link margin, and control of interference are evaluated using massive MIMO arrays. The measurement quantifies the improvement expected from having very narrow beams resulting in higher signal-to-noise ratio for desired users as well as steering the nulls into directions where we have unwanted users, i.e., interferers.

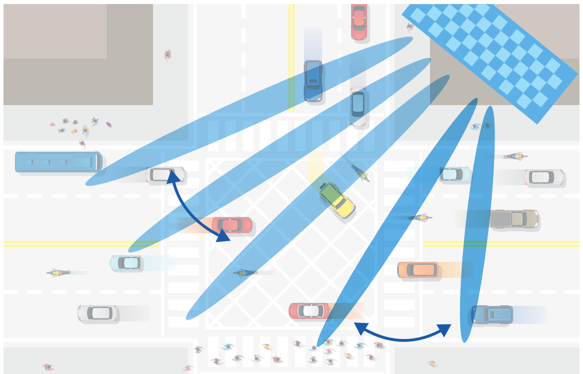

*Fig. 1. Typical Deployment Scenario for Massive MIMO*

Channel emulation equipment is required to create a virtual propagation environment that models the complex real-world propagation environment, including user mobility. It is essential to create:

- A spatial environment that emulates cluster departure and arrival directions, and
- A temporal model with the correct fading behavior as well as correlation between fading signals

This combination creates the dynamically changing environment needed to evaluate active antenna systems in gNBs.

## III. Building the Test System

The typical 5G gNB will include a planar antenna array with 3D beamforming [6]. In receive mode, the array can observe signal paths in azimuth and elevation on the uplink within the field of view of the array. A selected set of complex weights applied to the array elements allow the array to focus a beam in a selected direction according to the array factor. Significant processing power may be needed to determine the complex weights used at the gNB array.

Since most 5G scenarios will be bidirectional Time Division Duplex (TDD), this approach is described. In this case, the same weights used for the receiver can also be used to transmit on the downlink, thus energizing the same paths that are determined by the gNB to connect to the UT. The channel model is defined by the departure geometry at the gNB by the directions to the first bounce. The directions from the last bounce to the UT are also specified along with a path delay and Doppler. Specifying the departure and arrival directions of the path are sufficient to model double-directional geometric radio channels.

### *A. Description of a Phase Matrix*

Figure 2 depicts the system diagram.

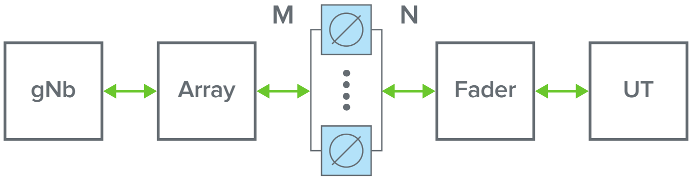

*Fig. 2. Test system diagram*

There have been a lot of proposals for 5G channel models. In this paper, we select another approach. For gNB testability, a specific predefined channel model is selected, having specific azimuth and elevation angles defined for each path component. A 2D planar array example is illustrated in Fig. 3, having 8x4 dual polarized elements. When the array observes the channel model in the far field, a scanning algorithm or other technique may be used to determine the path directions.

It is worth noting that the number of inputs (M) in the phase matrix is generally larger than the number of outputs (N), providing a considerable savings in the CE resources required to emulate the dynamic behavior of a radio channel. This can be compared to hybrid beamforming where antenna element count is larger than AD converter count [7]. The construction of a phase matrix consists of M splitters of size N with outputs connected to N combiners of size M, having an adjustable phase element on each input-to-output connection.

### B. Path Emulation

When a path is measured over-the-air, the signal will be observed from its physical direction, e.g., as supplied by a probe in a test chamber, typically a dual polarized probe with separate V & H polarizations, i.e., a two-element (+) probe. For a conducted model, the signal must be supplied by a virtual probe that is formed by a matrix of phases representing the far field response of the array. When a conducted measurement is made, a gain and phase calibration process is required, described in Section C. Then cables are connected to each physical antenna port. The actual array elements are normally bypassed with this approach, so an element's pattern must be incorporated into the signals provided to the array ports. To simplify the example, an ideal isotropic response is assumed for all array elements, however other pattern shapes can be used.

Each of the slanted left (\) and slanted right (/) elements form separate beam patterns, and an example is illustrated in Fig. 4, where the 2D beam pattern has an azimuth beam at 30.7°, and an elevation angle of 91.8°. Several side lobes are present as expected, with the elevation dimension having significantly more resolution (as observed by the narrower pattern and additional side-lobes) than the azimuth dimension due to the array geometry.

The process of generating phases that correspond to an array response for each path is repeated to generate a table of phases, having dimensions of rows equal to the number of BS array elements, and columns equal to the number of virtual probe elements [1].

Each polarization is modeled by a unique virtual probe element. A phase matrix function provides only gain and phase control to each input-to-output pair. Thus, without a delay element, only a single spatial characteristic can be emulated for each virtual probe, however multiple paths with unique temporal and delay characteristics can be modeled, using the CE representing multipath that originates within the same path direction from the BS. Modeling spatial clusters in this way enables the use of the phase matrix as a front-end pre-processor (and/or back-end post-processor) to the CE, wherein the phase matrix can connect the BS array to the virtual probes. The virtual probes are then applied to the CE, where fading, path powers and delay, and polarization XPR are applied to complete the channel model.

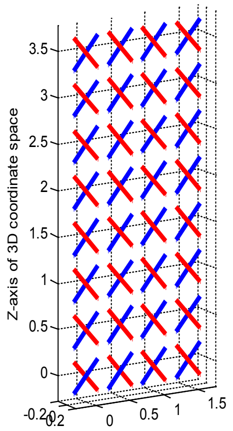

*Fig. 3, 2D Planar Array Example, dimensions in λ*

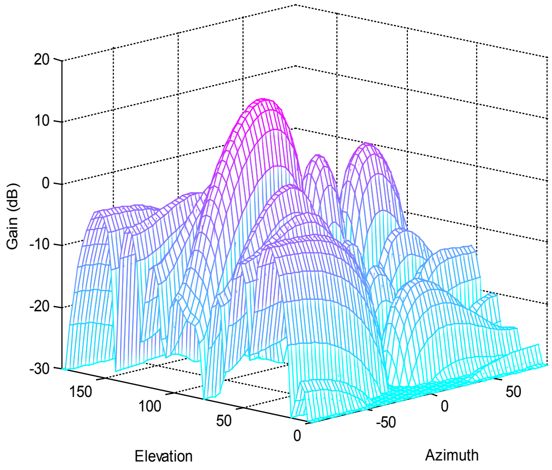

*Fig. 4, Example Array Pattern for BS array*

| Downlink | | | |
|---|---|---|---|
| Point | Explanation | Loss (dB) | Level (dBm) |
| A | gNB Output | 0 | 23 |
| B | Cable Loss | 1 | 22 |
| C | Array Gain | -19 | 41 |
| D | Cable Loss | 1 | 40 |
| E | Matrix Loss | 50 | -10 |
| F | Cable Loss | 1 | -11 |
| G | CE Loss | 12 | -26 |
| H | Cable Loss | 1 | 27 |
| **Uplink** | | | |
| H | Output of UT | 0 | 23 |
| G | Cable Loss | 1 | 22 |
| F | CE Loss | 15 | 7 |
| E | Cable Loss | 1 | 6 |
| D | Matrix Loss | 50 | -44 |
| C | Cable Loss | 1 | -45 |
| B | Array Gain | -19 | -26 |
| A | Cable Loss | 1 | -27 |

*Table 1 Example link budget; reference Figure 8 for data points*

Values in Table 1 represent an example of the link budget. The signal loss in dB of the phase matrix depends highly on how many input-to-output ports the phase matrix has.

External software controls the phase matrix and CE such that the operation is synchronized. Thus, temporal realization of a radio channel is connected to appropriate spatial realization of the radio channel.

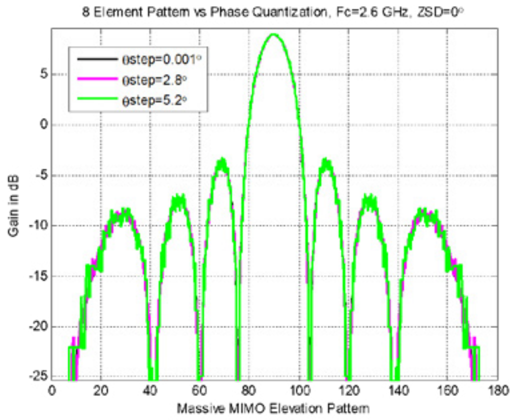

*Fig. 5. Effect of quantization to beam former in LOS case*

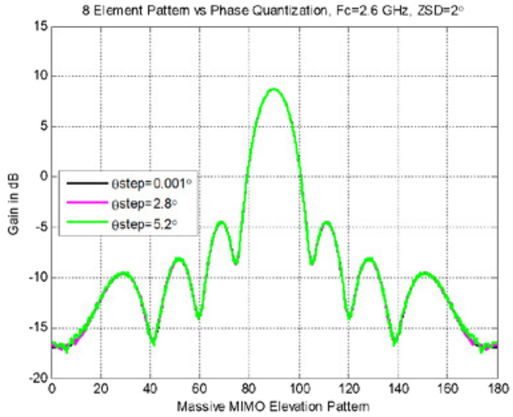

*Fig. 6. Effect of quantization to beamformer in NLOS case*

One key problem in the phase matrix is that the phase change is quantized. This introduces phase quantization noise to beamforming, however, the results of a sensitivity test comparing steps of 2.8° and 5.2° show that the ability to reproduce the expected array factor of an 8-element test case is very close. Figures 5 and 6 depict the effect of quantization noise in LOS and NLOS propagation conditions. For the NLOS condition, an angle spread of 2° is shown to fill in the pattern nulls and reduce the sensitivity to phase step quantizing, since the angle spread is essentially an averaging window that is applied to the expected array factor.

Based on the above simulation results, we can conclude that even though the phase matrix is controlled in discrete steps, the performance is very close to a continuous phase. This result holds for much larger numbers of array elements.

In Fig. 7, measured results are compared to theoretical results for a classical beamforming example using a 16-element ULA with 0.5λ element spacing. The phase matrix was programmed with the phase given by:

$$\phi_i = \frac{2\pi d_i}{\lambda}\sin(\theta)$$

where $d_i$ is the element spacing and $\theta$ is the AoD. Note that the response is close to ideal, with very small errors observed.

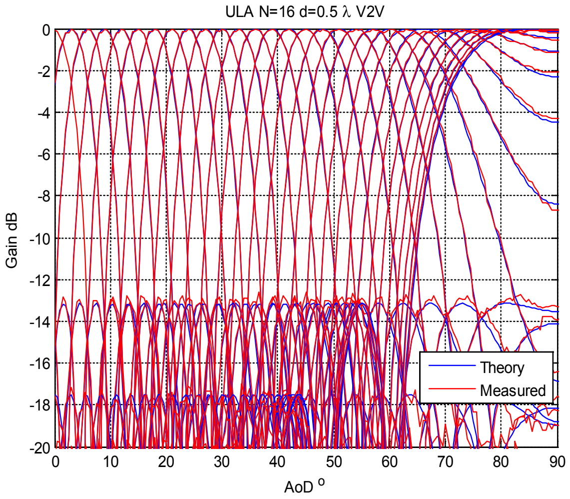

*Fig. 7, Phase Matrix Emulating an Array Response*

## *C. Phase Matrix + CE Calibration*

Before the system can be used, phase calibration is needed to ensure the correct 3D position of each virtual cluster. The process of phase calibration begins by disabling all links from input-to-output. Then each possible link is enabled on an individual basis and the phase is measured with the aid of a Vector Network Analyzer (VNA) and entered into a database.

At the end of the process, a first radio link is chosen as the reference, and all the other links add the corresponding phase that makes them coherent with the reference. The calibration system is presented in Fig. 8, where the gNB has N ports, the phase matrix has M output ports, and the CE has L output ports.

It is worth noting that the phase matrix calibration can hold over power cycles, and the calibration process is expected to be done once per month at most. This ensures a very efficient calibration process.

# IV. Channel Modeling

Emulating the MIMO channel is easily done with a channel emulator (CE), which supplies spatial and temporal correlation to many predefined propagation paths. Numerous channel model proposals are being discussed in standards [2], which could be utilized to define the number of spatial clusters observed by the massive MIMO array, given the array resolution and bandwidth that is available to observe the channel. Therefore, channel models will be selected based on the ability of the array to utilize them. The virtual probe allows a single path to be modeled, and additional virtual probes will enable spatial angle spread and multipath to be emulated. The virtual probe will be connected on one side of the channel emulator, and the UT connections will be on the other. Bi-directional paths will be utilized within the channel emulator and within the phase matrix.

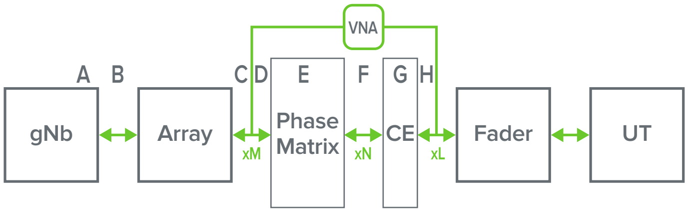

*Fig. 8. RF Matrix + CE Calibration System*

## V. Conclusion

In this paper we discussed 5G Massive MIMO testing using an efficient method of utilizing hardware resources. The system is based on using phase matrix to emulate the angular behavior of the propagation via virtual probes, combined with a radio channel emulator to create the temporal, multipath, and correlation behavior of the propagation. Using a phase matrix function increases the number of antenna elements that can be utilized in a massive MIMO array emulation while keeping the required number of fading channels within the radio channel emulator at a reduced number, thus forming a cost-effective, yet realistic, test system for massive MIMO testing.

References

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