Antenna Array optimization for MIMO systems

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ABSTRACT

*MIMO arrays and the corresponding RF and digital architectures are critical components of 5G designs. In this paper I want to discuss hybrid forming technique and designing of MIMO array by computational tools. System model contains access to a full set of visualizations including 2D and 3D directivity and grating lobe diagrams, including narrowband and wideband beam forming by direction of arrival (DOA) estimation algorithms. Optimization techniques can greatly benefit the development of phased-array antennas. How Optimization Techniques are used to Improve the Beam Pattern has been studied which includes failed element and subarray impacts and Assessing Link-level Performanc**e.***

Keywords : ***Beam forming , direction of arrival (DOA), lobes ,MIMO (Multiple input multiple output) , Phased array antennas ,subarray***

I.Introduction

MIMO radar is an advanced type of phased array radar employing digital receivers and waveform generators distributed across the aperture. MIMO radar signals propagate in a fashion similar to Multi static radar. However, instead of distributing the radar elements throughout the surveillance area, antennas are closely located to obtain better spatial resolution, Doppler resolution, and dynamic range. MIMO radar may also be used to obtain Low-probability-of-intercept radar properties.

In a MIMO system, the transmitting signals from the single transmitters are different. As a result, the echo signals can be re-assigned to the source. This gives an enlarged virtual receive aperture. In radio, multiple-input and multiple-output, or MIMO (/ˈmaɪmoʊ, ˈmiːmoʊ/), is a method for multiplying the capacity of a radio link using multiple transmission and receiving antennas to exploit multipath propagation.[1] MIMO has become an essential element of wireless communication standards including IEEE 802.11n (Wi-Fi), IEEE 802.11ac (Wi-Fi), HSPA+ (3G), WiMAX (4G), and Long Term Evolution (LTE 4G). More recently, MIMO has been applied to power-line communication for 3-wire installations as part of ITU G.hn standard and HomePlugAV2 specification

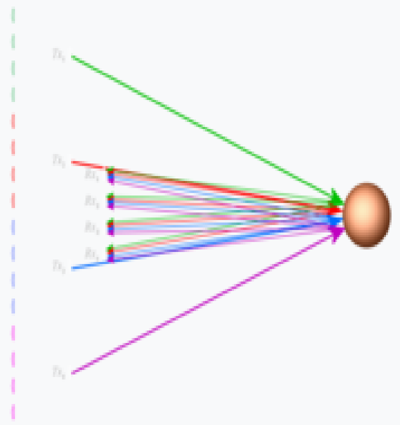


Figure 1:Signal transmission in MIMO

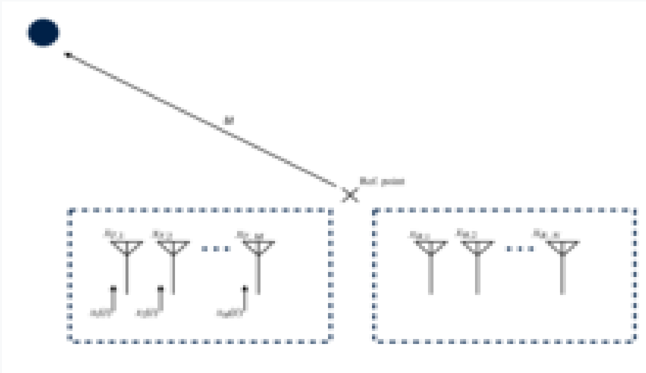


Figure 2 : Scenario of virtual array analysis

In a traditional Phased array system, additional antennas and related hardware are needed to improve spatial resolution. MIMO radar systems transmit mutually orthogonal signals from multiple transmit antennas, and these waveforms can be extracted from each of the receive antennas by a set of matched filters. For example, if a MIMO radar system has 3 transmit antennas and 4 receive antennas, 12 signals can be extracted from the receiver because of the orthogonality of the transmitted signals. That is, a 12-element virtual antenna array is created using only 7 antennas by conducting Digital signal processing on the received signals, thereby obtaining a finer spatial resolution compared with its phased array counterpart. As 5G standards continue to evolve, the goals for higher data rates, lower latency network access, and more energy efficient implementations are clear. Higher data rates drive the need for greater bandwidth systems. The available bandwidth in the spectrum up through 6 GHz is not sufficient to satisfy these requirements. This has moved the target operating frequency bands up into the millimeter wave range for the next generation of wireless communication systems.

In this paper I want to discuss how hybrid beam forming can be implemented in a massive-MIMO system. In order to start this I focused on hybrid beam forming at the transmit end of a massive-MIMO communications system, including techniques for both multi-user and single-user systems. We can then partition the resulting pre coding weights into digital baseband and analog RF components, using different techniques for multi-user and single-user systems

Multi-user MIMO systems improve the spectral efficiency by allowing a base-station transmitter to communicate simultaneously with multiple mobile receivers using the same time frequency resources. With massive-MIMO systems, the number of base-station antenna elements can be on the order of hundreds to achieve the array gain needed to offset propagation losses at millimetre-wave (mm Wave) frequencies. The number of data streams in a cell also increases accordingly.

In a massive-MIMO system, it becomes much more expensive to provide one transmit-receive (TR) module, or an RF chain, for each antenna element. Hybrid transceivers enable a practical solution because they use a combination of analog beam formers in the RF and digital beam formers in the baseband domains, with fewer RF chains than the number of transmit elements.

II.**Hybrid Beam forming**

Hybrid beam forming is a technique used to partition beam forming between the digital and RF domains. System designers can implement hybrid beam forming to balance flexibility and cost trade-offs while still fielding a system that meets the required performance parameters. Hybrid beam forming designs are developed by combining multiple array elements into sub array modules. A transmit/receive (T/R) module is dedicated to a sub array in the array and therefore fewer T/R modules are required in the system. The number of elements, and the positioning within each sub array, can be selected to ensure system-level performance is met across a range of steering angles.

Using the transmit signal chain as our first example, each element within a sub array can have a phase shift applied directly in the RF domain, while digital beam forming techniques based on complex weighting vectors can be applied on the signals that feed each sub array. Digital beam forming allows control of the signal for both amplitude and phase on signals aggregated at the sub array level. For cost and complexity reasons, the RF control is typically limited to applying phase shifts to each of the elements.

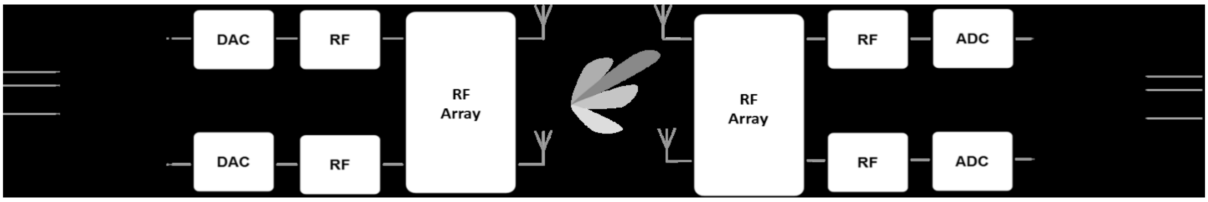


Figure 3. Hybrid beamforming architecture.

Systems such as the one shown in Figure 1 are complex to develop. You can use modeling techniques to design and evaluate massive MIMO arrays and the corresponding RF and digital architectures needed to help manage their complexity. With these techniques, you can reduce risk and validate design approaches at the earliest stages of a project. We will first look at an array design example. We have selected parameters for each of the examples that are common in the 5G wireless community but all of the examples shown can be modified to match your desired configuration.

III.Designing the Array

There are many factors to consider when designing an array. Typical array designs include parameters such as array geometry, element spacing, the lattice structure of the elements, and element tapering. In addition, the effects of mutual coupling are important to characterize before the final design is implemented. Once an initial configuration of the array design is complete, architectural partitioning can be iteratively evaluated against the overall system performance goals.

With millimeter wave systems, the area of the array is reduced in proportion to the wavelength size. As an example, an antenna array designed at millimeter wave frequencies can be up to 100 times smaller than an array designed to operate at microwave frequencies. By building an array with a larger number of antenna elements, you can achieve a high beam forming gain. The highly directive beam helps to offset the increased path loss at higher frequencies of operations, as beams are steered to a specific direction.

To start the array design process, the Sensor Array Analyzer app, which is available with Phased Array System Toolbox, can be launched from the MATLAB prompt:

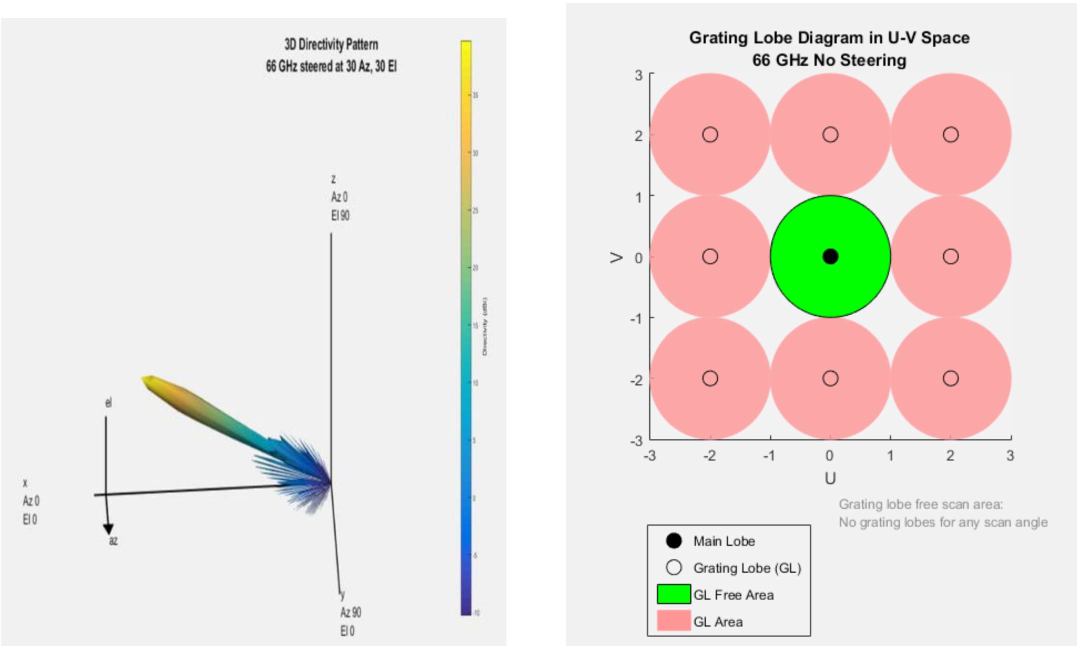


Figure 4. Beam pattern and grating lobe diagram for 66 GHz 64x64 element design.

IV.Channel Sounding Model

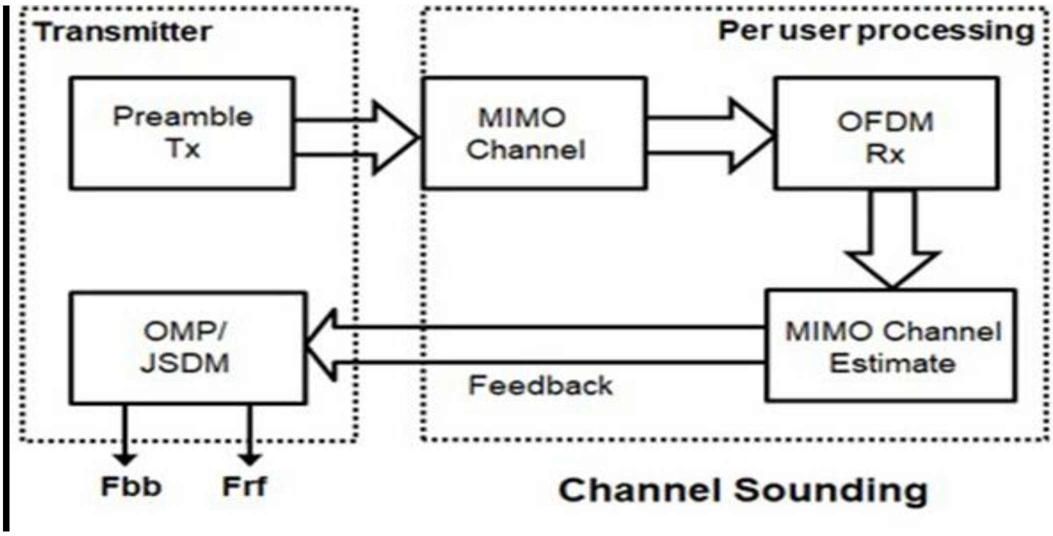


Figure 5 : channel sounding model.

For a spatially multiplexed system, availability of channel information at the transmitter allows for pre coding to be applied to maximize the signal energy in the direction and channel of interest. Assuming a slowly varying channel, the base station sounds the channel by applying a reference transmission used by the mobile receiver to estimate the channel. The mobile system transmits the channel estimate information back to the base station to calculate the pre coding weights needed for the subsequent data transmission.

Using the orthogonal-matching-pursuit (OMP) algorithm for a single-user system and the joint-spatial-division-multiplexing (JSDM) technique for a multi-user system, we can determine the digital baseband and RF analog pre coding weights for a given system configuration. The results were obtained for a system configuration with four users, where the users have a specific number of data streams [3 2 1 2]. The system also includes 64 Tx antennas and 32 Rx antenna elements.

The array response pattern in *Figure 6* shows distinct data streams represented by the stronger lobes. These lobes indicate the spread or separability achieved by beam forming

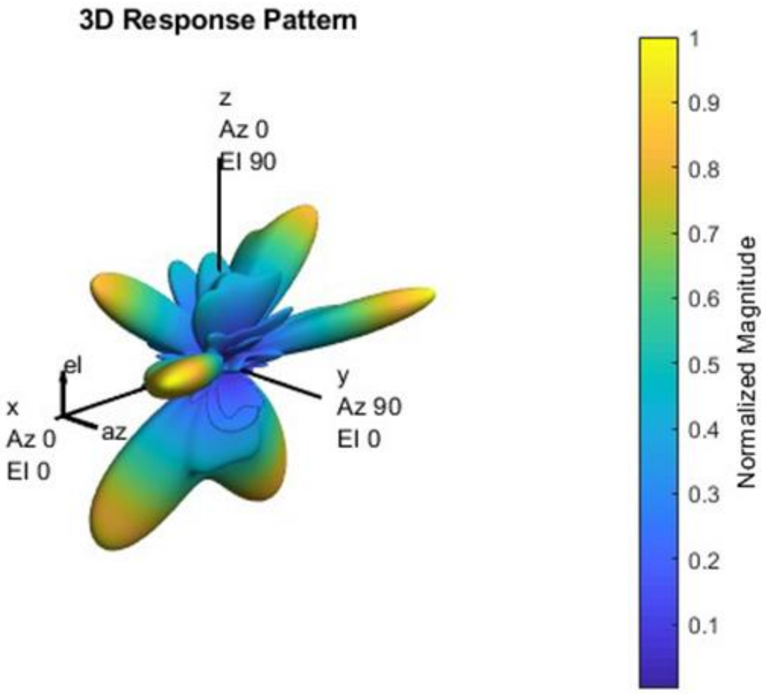


Figure 6: 3D Response pattern &Stronger lobes

V .Multi User System

In this array response for a multi-user system, the lobes indicate the spread achieved by beam forming. The processing in the system includes channel coding, bit mapping to complex symbols, splitting of the individual data stream to multiple transmit streams, baseband pre coding of the transmit streams, OFDM modulation with pilot mapping, and RF analog beam forming for all of the transmit antennas employed. Ideally, by using spatial multiplexing, the data throughput capacity can be linearly increased as the minimum of the number of transmitting or receiving antennas without extra bandwidth. As the spectral bandwidth is becoming increasing valuable, effective spectrum usage makes MIMO an important wireless technique.

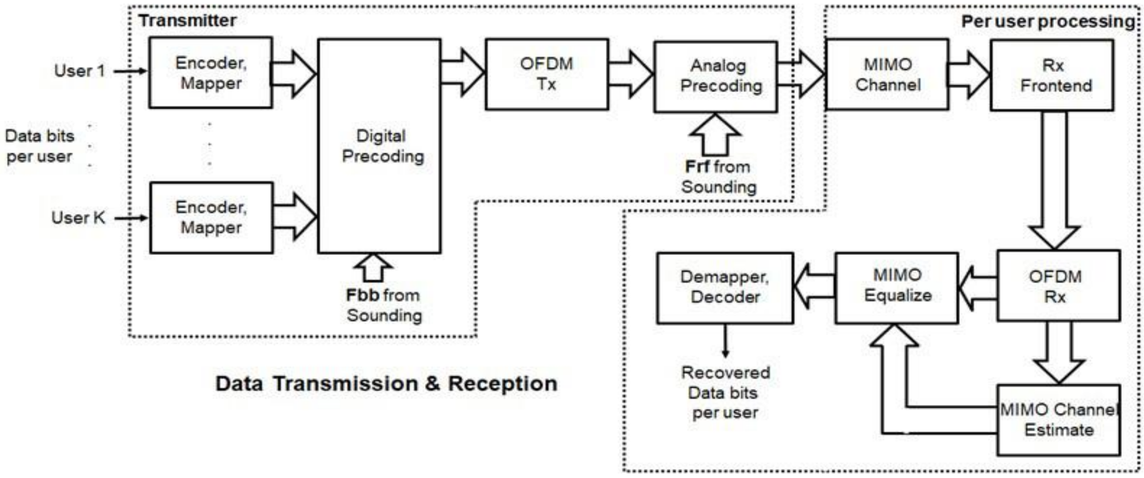


Figure 7 : Data Transmission &Reception

V (a) System processing for transmit and receive in a MIMO system

For the MIMO system modeled with the previously described configuration, *Figure* shows the displayed receive constellation of the equalized symbols. This provides a qualitative assessment of the reception. The actual bit error rate is obtained by comparing the actual transmitted bits with the received decoded bits per user.

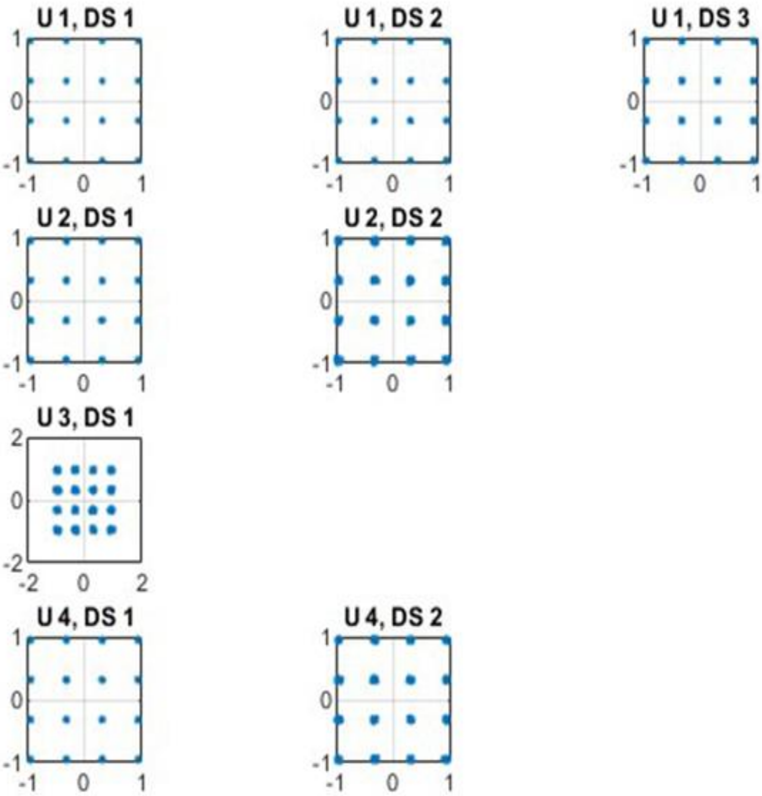


Figure 8 : The receive constellation for a MIMO system provides a qualitative assessment of the reception.

V (b) Algorithm

```
User 1
 RMS EVM (%) = 0.38361
 BER = 0.00000; No. of Bits = 9354; No. of errors = 0
User 2
 RMS EVM (%) = 1.0311
 BER = 0.00000; No. of Bits = 6234; No. of errors = 0
User 3
 RMS EVM (%) = 2.1462
 BER = 0.00000; No. of Bits = 3114; No. of errors = 0
User 4
 RMS EVM (%) = 1.0024
 BER = 0.00000; No. of Bits = 6234; No. of errors = 0
```

The example in the link below provides a nice starting point to explore the use of hybrid beam forming for multi-user MIMO-OFDM systems. Although the example is based on a specific system configuration, you can explore different system configurations for other channel models. You can also change system-wide parameters like the number of users, number of data streams per user, number of transmit/receive antenna elements, and array location.

VI. Incorporating Optimization Techniques to Improve the Beam Pattern

So far, we have been focused on setting up a specific configuration and partitioning between digital and RF subsystems. We can continue to build our system link-level model and see how performance changes as the steering weights change, as well as how frequency may impact the performance.

This can be a manually intensive process if there are a large number of elements and a wide frequency band of operations. Alternatively, we can take advantage of optimization techniques from Optimization Toolbox™ and Global Optimization Toolbox to iteratively understand how array element spacing and element tapering can be tuned to achieve the desired performance for a hybrid beam forming system.
Figure 9 below demonstrates how this can be accomplished. For example, you can try to match a specific beam pattern or you may want to drive the attributes of a beam pattern in a specific direction (e.g. lower side lobes, more narrow beam width, etc.).

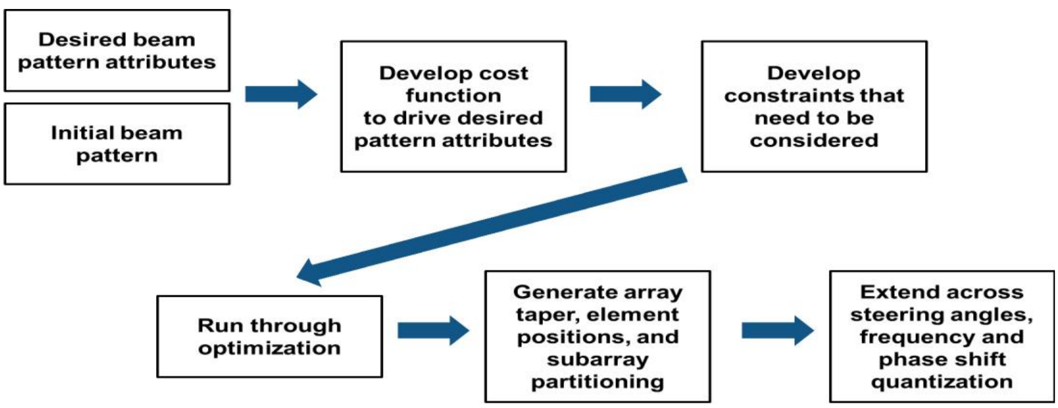


Figure 9 : Array Synthesis Workflow.

Global Optimization Toolbox provides solvers that can be used when there are many locally optimal solutions (or when the functions are not smooth). In our example, we are looking to get the best performance across a set of steering angles and frequencies, which translates to the need for multiple optimal solutions.

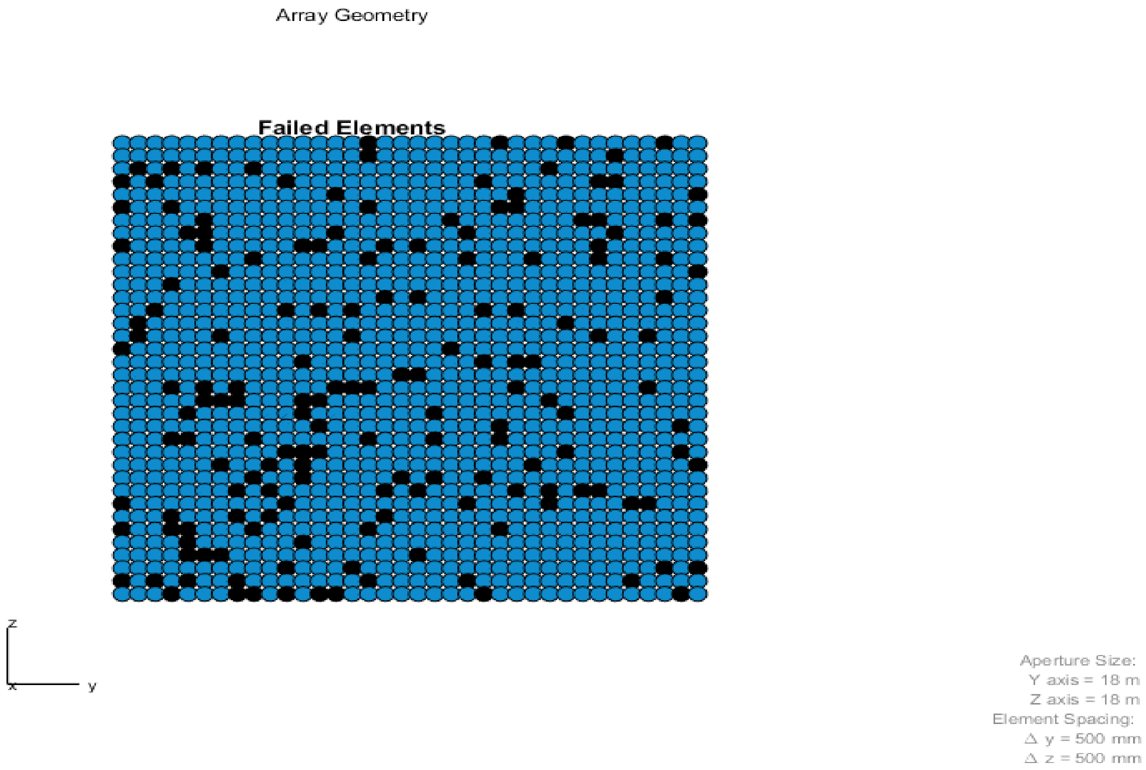
Constraints for the outputs, for example weights and element positions, can be set up as part of the optimization. This can include parameters that bound the number of elements per sub array, where the elements are located in the sub array. It can also include accounting for the effects of phased shift quantization. You can use this general capability to ensure that the design coming out of optimization is actually buildable.

Once the array is set up, you can determine the beam patterns across both the azimuth and elevation angles. You can then use this data directly to extract the key metrics associated with the pattern. This example focuses on the main lobe, side lobes, and beam width, but many other parameters could be considered.

VII. Results

VII (a) Using the Model for Life Cycle Analysis and Calibration Framework Development

Before reviewing ways to assess link-level performance, it is interesting to note that you can use the model to support a variety of specific "what-if" analysis exercises that relate to more detailed design trade-offs and life cycle planning. For example, with the resulting modelling framework in place, you can find the best implementation for array thinning. You can evaluate the relative impact of failed elements in the array. This is important for determining maintenance cycles. For an array that is not staffed 24/7, multiple failures can be tolerated before a site is visited and the failures are repaired. The beam pattern in Figure 19 shows the degradations in the beam pattern with 15% of the elements failed. We can perform similar analysis at the sub array level as well.



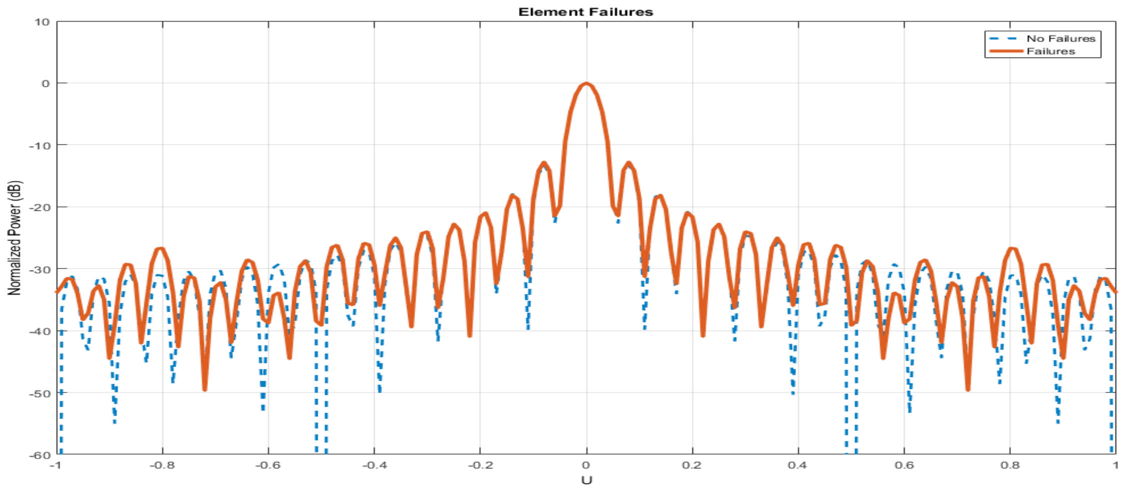


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Figure 10. Failed Element Analysis

VII (b)Assessing Link-level Performance *:* Once the array, sub array, and beam forming design are completed, you can implement a larger system around the array and sub arrays. You can setup scenarios and signal processing algorithms, including beam forming and DOA integration. There are multiple ways to visualize the link-level performance, including the constellation diagrams shown below. The ***link to this example*** demonstrates how this can be accomplished.

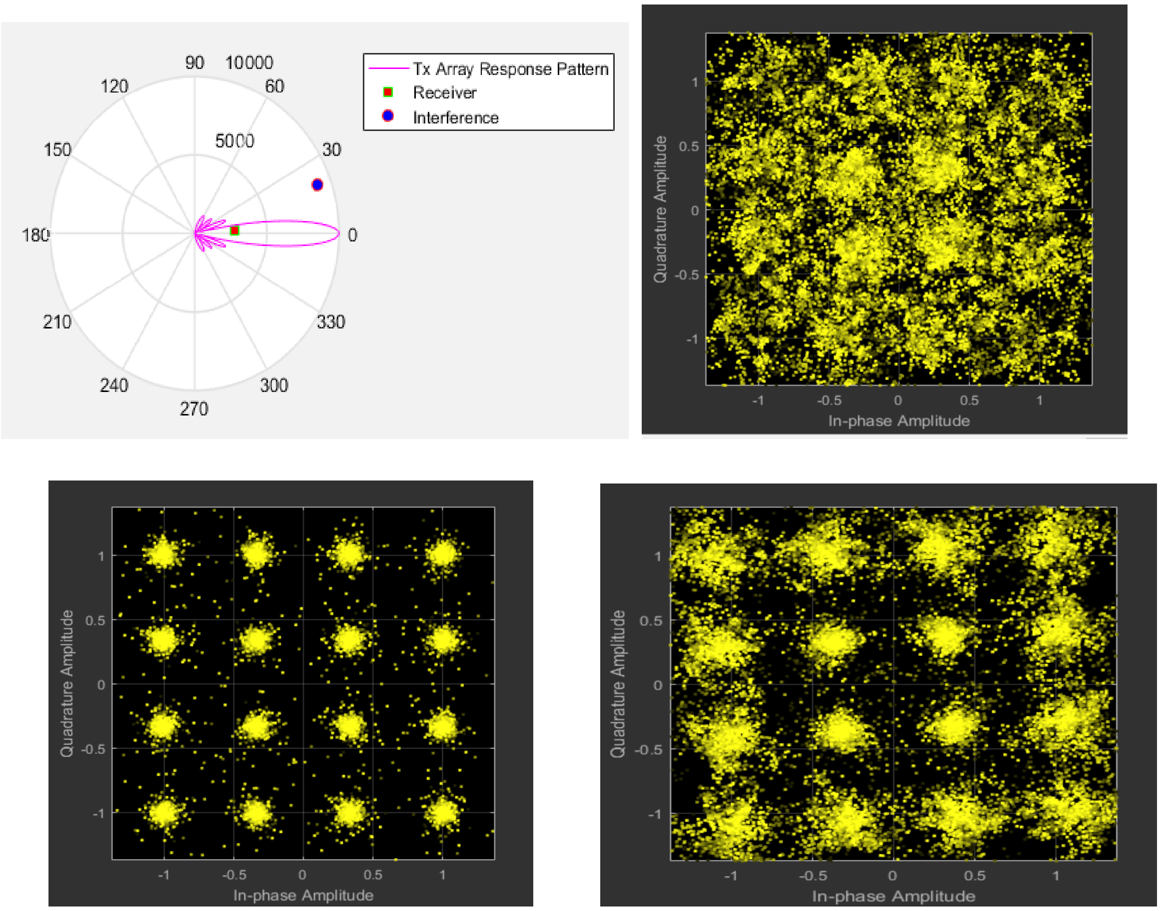

Figure 21. Link-level performance assessment.

VIII. Conclusion

Hybrid beam forming technique is used to partition beam forming between the digital and RF domains. MIMO array is designed by MATLAB prompt . System model contains access to a full set of visualizations including 2D and 3D directivity and grating lobe diagrams. Orthogonal-matching-pursuit (OMP) algorithm for a single-user system and the joint-spatial-division-multiplexing (JSDM) techniques are used for multi user system MIMO.The receive constellation for a MIMO system has been presented. Optimization Techniques to Improve the Beam Pattern has been studied by (i)Using the Model for Life Cycle Analysis and Calibration Framework Development (ii)Assessing Link-level Performance.

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