WHITEPAPER

An Efficient MVDR Beamformer Algorithm for Null Forming in

5G MIMO

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Introduction & Scope

In 5G and 6G, the main design goals are high throughput, low latency, and low BER (bit error rate) communication. To achieve these goals, algorithms continuously evolve to perform functions like coding, decoding, channel estimation, channel equalization, precoding, and beamforming. Out of these the precoding and beamforming functions ensure spatial multiplexing thus enabling frequency and time reuse. Most of these features and analyzed results have been discussed in previously published White Papers. Particularly, it has been discussed that 2 stage beamforming (baseband precoding and RF beamforming separated) is a convenient and efficient way to direct individual transmission layers from the base station (BS) to individual users (UE) [22]. The JSDM (joint spatial division multiplexing) technique - discussed and results presented in an earlier White Paper - is an efficient way to do it [22]. In JSDM, users are grouped into clusters based on their spatial locations, and beamforming is performed in the RF domain to direct beams toward each cluster. Baseband precoding is done to map data streams into layers, specific to individual users in each JSDM group. Codebooks were presented in a White Paper published earlier [21] to perform this function of precoding by using a PMI (precoding matrix indicator) and RI (rank indicator) based on CSI (channel state information) feedback. Even non-Codebook-based precoding can be done - as it is a generalized approach, however, it comes with a higher computational penalty.

Typically, MU-MIMO may have many antennas (antenna arrays) and Massive MIMO has a very large number of antennas (antenna arrays) to direct beams to a large number of user groups. While doing so, a JSDM group can encounter interference from another beam from its side-lobe radiation. If the side-lobe levels are lower than 30 dB compared to main lobe radiation then these effects are minimal, however, practically it may not be realizable because lowering side-lobe levels increases the beamwidth. So there is a possibility that the main lobe itself contributes to interference in 2 or more JSDM groups which are angular-spatially not much separated. On the other hand, if side lobe levels are around 10-15 dB lower even, then the interference is significant. So, there is a need to nullify the effects of such "interferers" on a particular JSDM group.

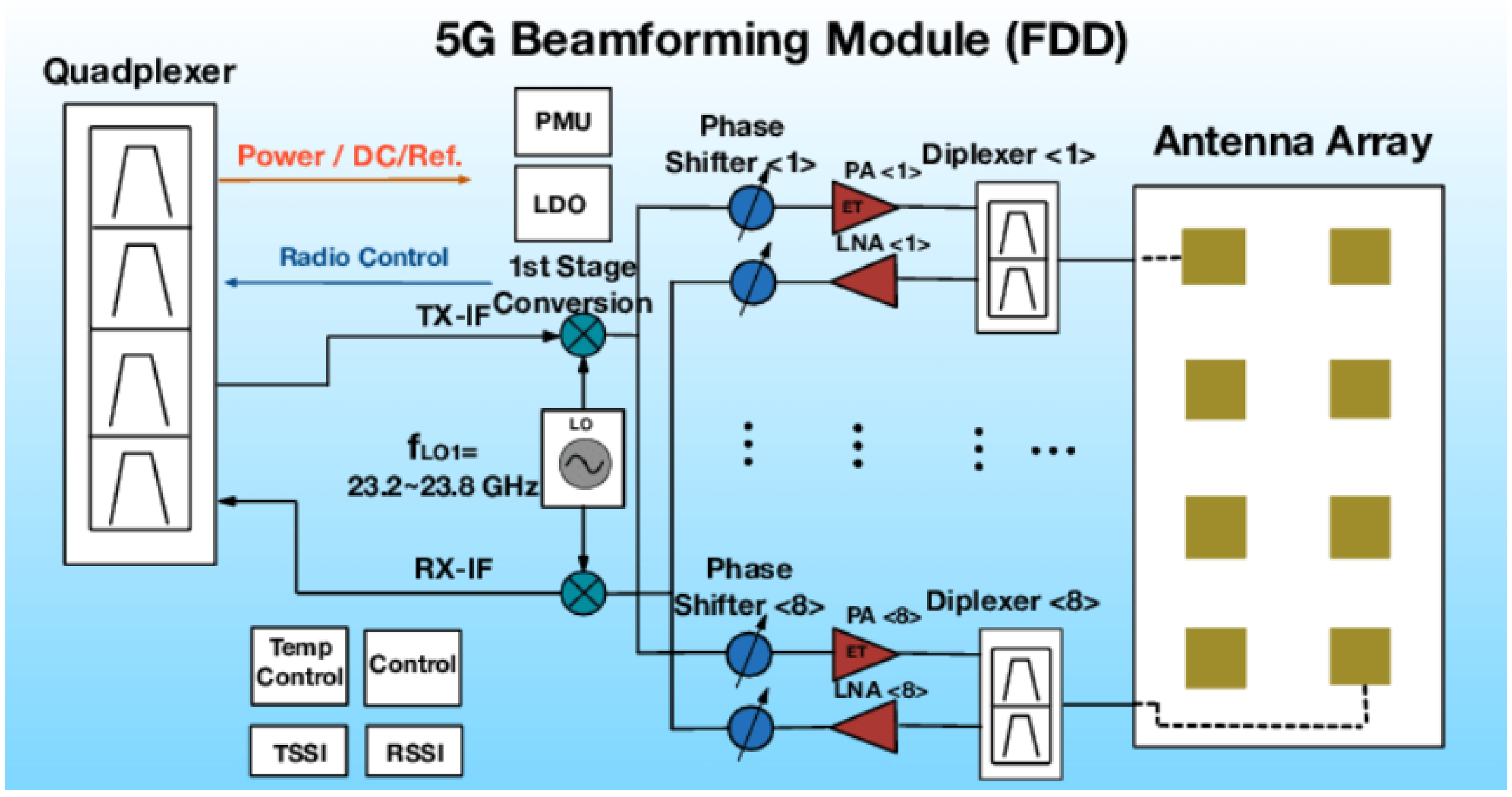
Beamforming in general is a combination of beam shaping and beam steering. The first one, beam shaping, is done by employing an amplitude distribution like Taylor, Circular Taylor, Chebyshev, Dolph-Chebyshev, Elliptical, etc, combined with amplitude tapering of the same distribution. These operations produce a specific beam shape. The synthesis of these distributions can be done from antenna parameters like Gain/Directivity, Side Lobe Level (SLL), Beamwidth (BW), etc. Synthesis provides us with antenna element weights (only the amplitude part - assuming all elements are in the same phase). These aspects were discussed in the White Paper published earlier [20]. In this White Paper, the second one, beam steering, will be analyzed with the help of algorithms. Beam steering in the context of initial access beam management procedures using synchronizing signal blocks (SSB) was covered in [20]. Traditionally beam steering is done with the help of a phase shift beamformer algorithm - by employing weights to antenna elements with a specific phase to each other. In this work, new algorithms like the MVDR algorithm are analyzed to include interferers, and results are compared with the phase shift beamformer algorithm.

The MVDR algorithm belongs to a class of constrained optimization problems and has been applied successfully for efficient "nulling" of radiation from a particular direction or multiple directions. MVDR stands for Minimum Variance Distortionless Response. In this context, the term Null-Forming has been introduced. It is basically a Beamforming operation but with additional "constraints" of producing multiple Nulls in desired directions while keeping the signal of interest distortionless.

In this White Paper, the MVDR algorithm is discussed and analyzed. It has been demonstrated in this White Paper that obtaining Nulls in multiple desired directions with 90 dB or even lower power levels (nulls) can be implemented. Therefore, it is a powerful technique to significantly reduce interference and improve performance goals like low BER by maximizing SINR (signal-to-interference and noise ratio). There are other algorithms for the same but MVDR is a popular, powerful, and efficient one, and has been used in this work.

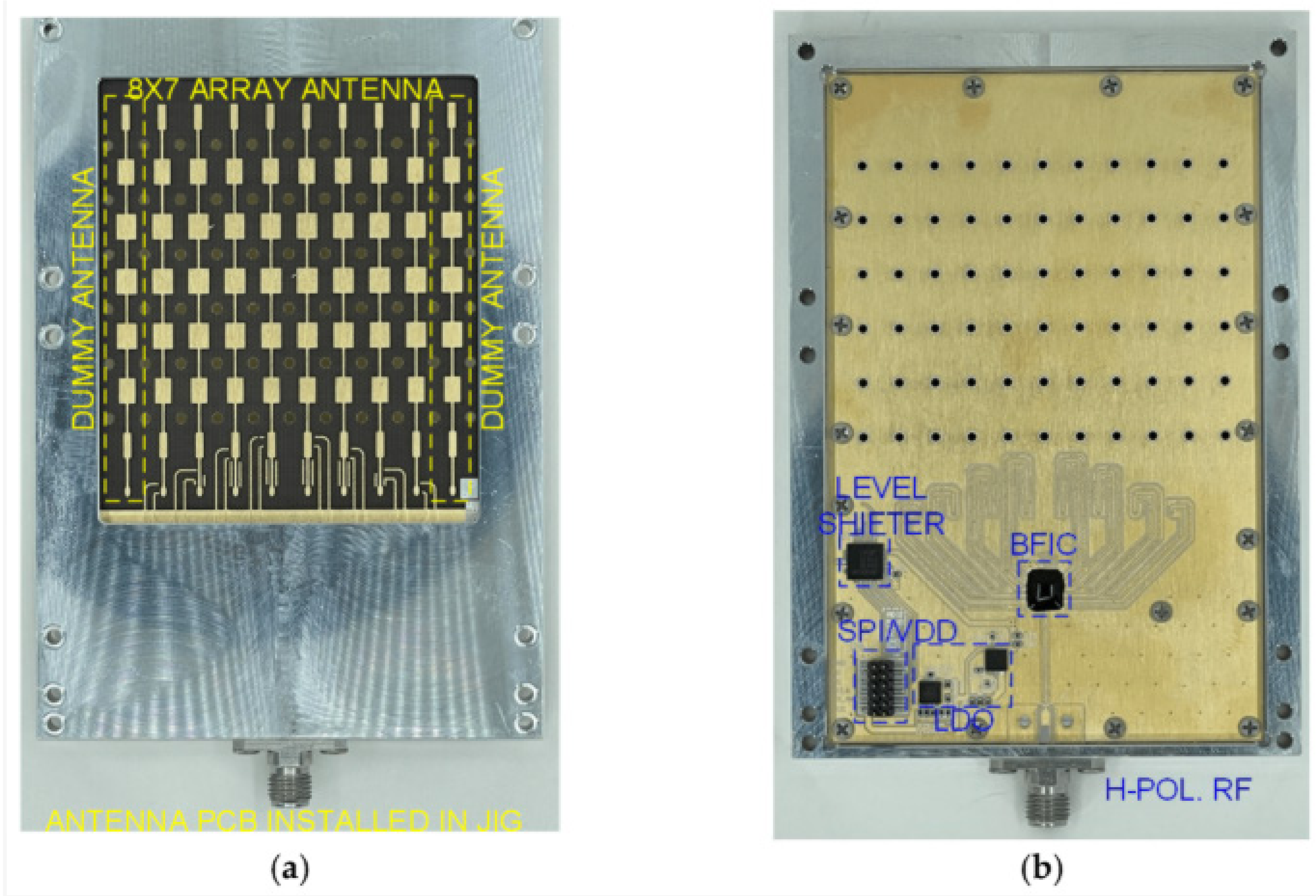
5G ARCHITECTURE BLOCKS FOR BEAMFORMING

Algorithms are being enhanced and new ones are being introduced for beamformer functionality. Therefore, these algorithms need to be deployed flexibly in a suitable block that fits into the 5G Architecture. Traditionally the analog beamforming functionality (FDD case, as an example) of a single beamforming module in the RF domain is done as shown in the figure below as per Ref [18]:



(Above) From Ref [18]

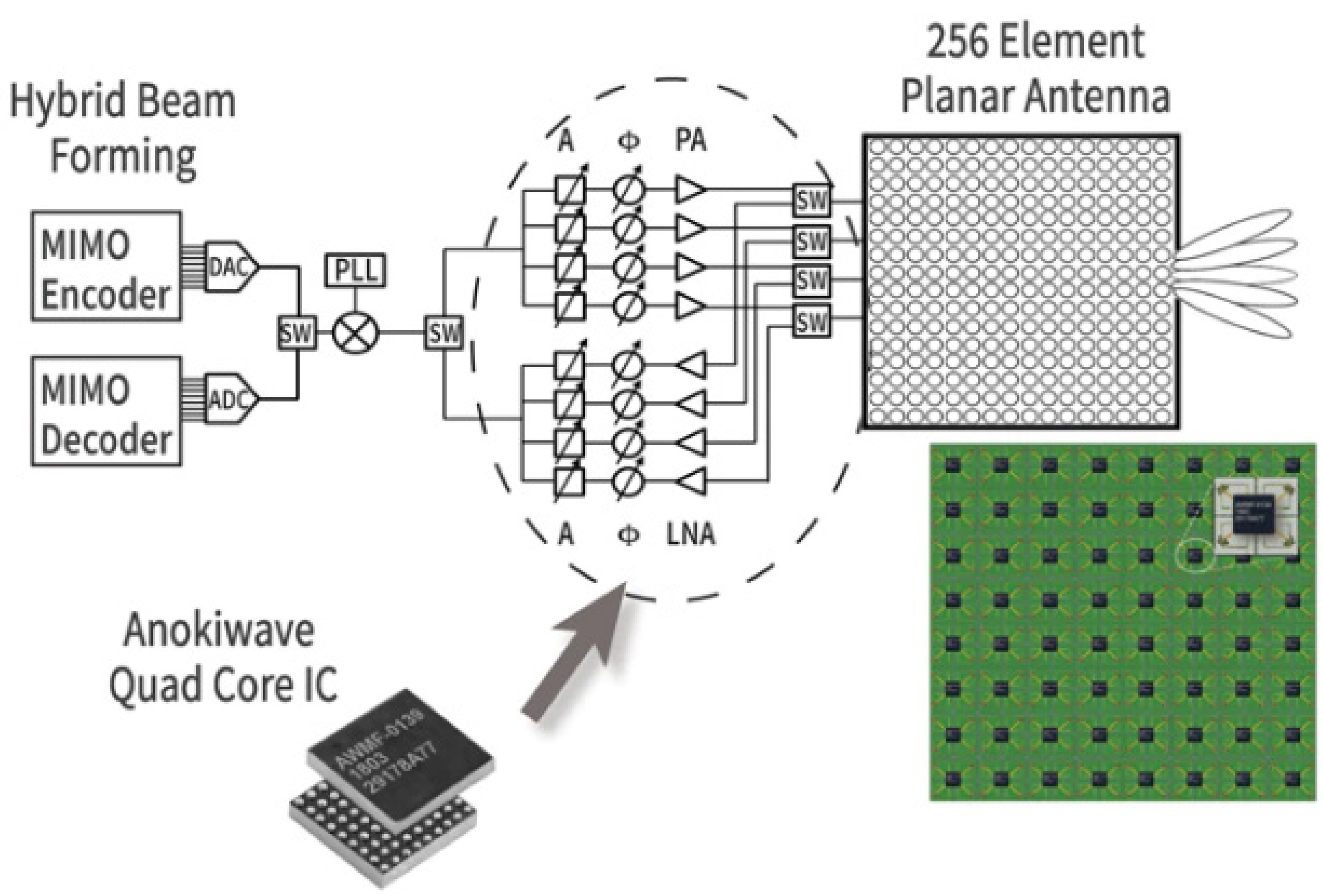
Analog phase shifters are provided with weights (biases) coming from a microcontroller-driven bias voltage given to phase shifters (an RF device). These phase shifters convert a DC bias into an RF phase shift in the transmission line path. These weights (phase shifts) are given to all the individual antenna elements. Everything described before (TX) or after (RX) the Antenna stage with modules put together can be implemented on an RF board or a BFIC (beamforming Integrated Circuit) along with an antenna feed network. A lternatively, they can be built using FPGA hardware with the microcontroller for some portions of the designs. FPGA enables parallel computation of weights for a large number of beamforming modules. The FPGA hardware is coupled to an RF board / BFIC which can be integrated with the TX/RX antennas. Particularly, in Massive MIMO where the number of TX/RX antennas are large (a large number of radio chains), hardware realizations on RF boards can be cumbersome. BFICs, on the other hand, are tightly integrated with antennas through a feed network and in turn, are driven by the FPGA hardware that has been reported in the literature. The figure below gives an idea about this type of integration [19].



(Above) From Ref [19]: (a) Antenna-side view and (b) chip-side view of 28 GHz phased-array beamforming antenna module using eight-channel CMOS BFIC

Beamformer Integrated Circuit (BFIC)

Beamformer integrated circuits (BFIC) are used to reduce the size, complexity, weight, performance, and cost of traditional phased array antenna feed networks. BFICs provide high gain and phase control over the weights provided to the antenna elements. We can think of BFIC as a block between the RF up/down converter block and the antenna array block. The BFIC module can have 2 radio chains as input (2 for 2 polarizations) and 2xN port outputs where each port feeds each of the N elements of the antenna array. The outputs of the BFIC in the layout should feed each of the antenna elements without intersecting. That's why BFICs can shrink the antenna feed and distribution network by having all the phase shift bias element functionality along with both PA (power amplifier) for TX or LNA (low noise amplifier) for RX, and TX/RX switches within it. All this integration is done by CMOS VLSI chips. Each BFIC needs to provide phase-biasing data in addition to the RF inputs. The phase biasing data comes from the FPGA-based digital board. The figure below illustrates what a commercial BFIC architecture looks like.

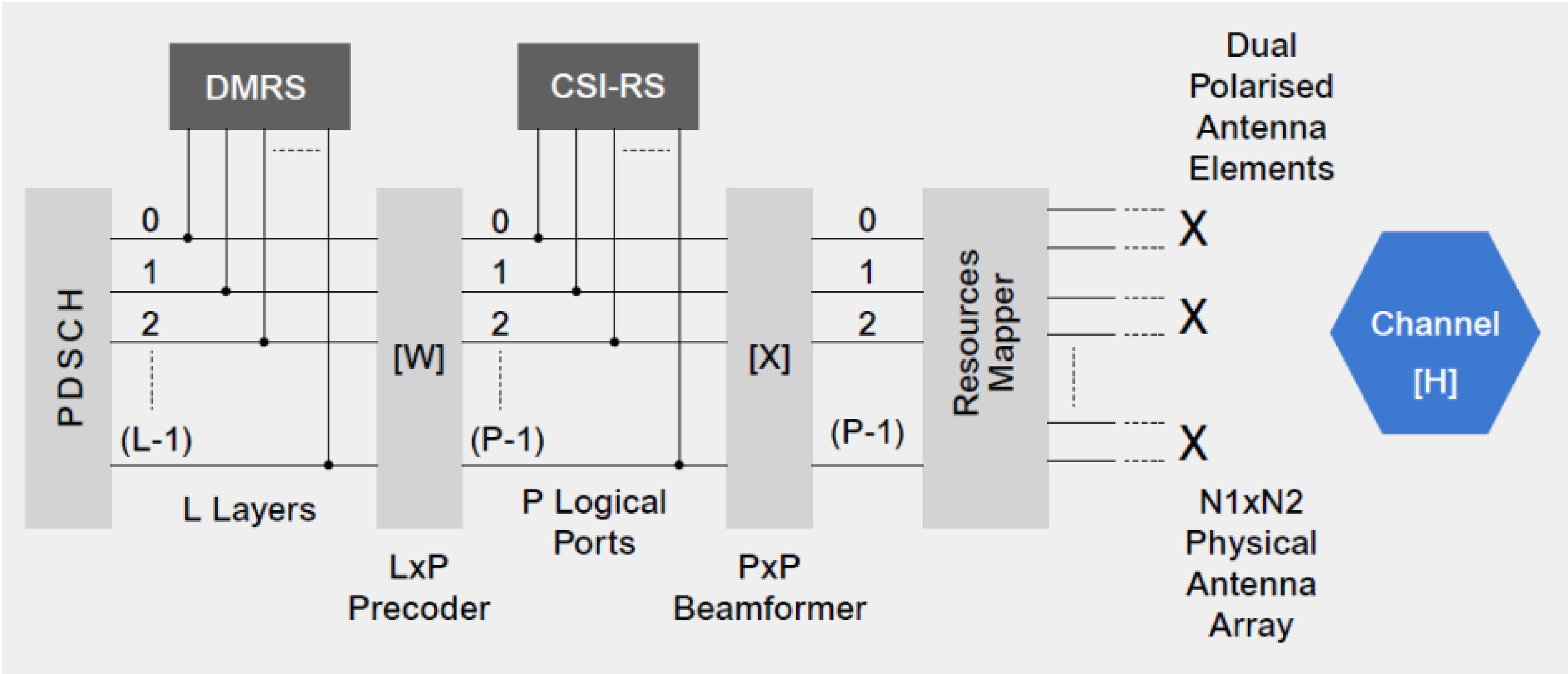


(Above) The AWMF-0139 beamforming IC from Anokiwave enables massive MU-MIMO in 5G
From: https://resources.altium.com/p/phased-array-beamforming-ics-and-systems-design

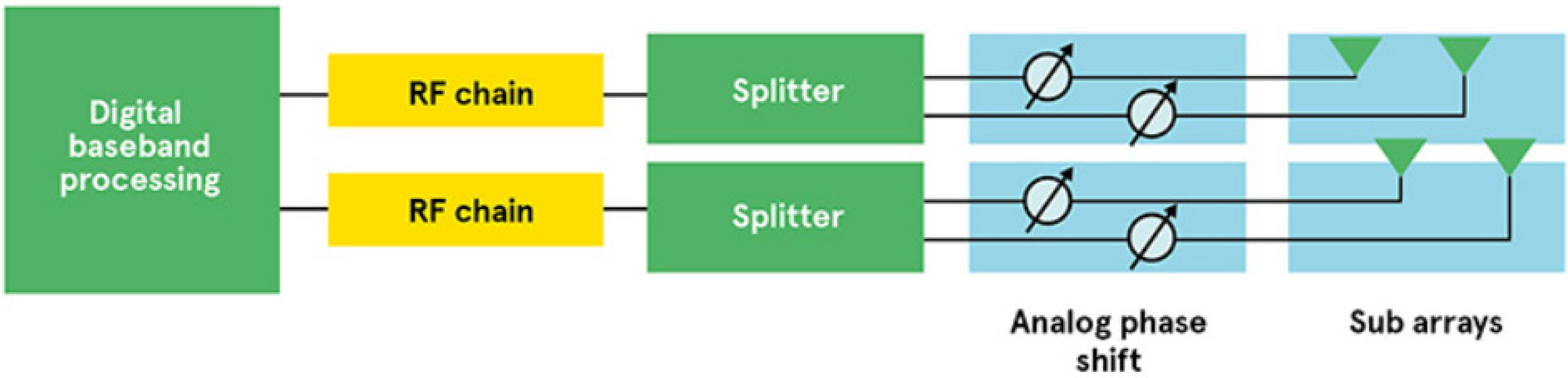
Hybrid Beamforming Blocks

The two-stage hybrid beamforming architecture was discussed and analyzed in a White Paper published earlier [22] and is reproduced in the figure below.

Downlink Architecture having the Baseband Precoder and RF Beamformer



The hybrid beamforming approach is a pragmatic approach between analog and digital beamforming. The figure below gives an idea of how hybrid beamforming hardware works:



(Above) From: https://my.avnet.com/abacus/solutions/markets/communications/5g-solutions/5g-beamforming/

Hybrid beamforming is a two-stage approach that separates baseband precoding and RF beamforming. In the state-of-art implementations, even the RF beamforming functionality is driven by FPGA-based digital hardware, i.e., beamforming weights are computed by algorithms hosted on digital board(s), and the weights data are sent to each of the BFICs driving a beamforming module (described above). It must be stressed that the baseband precoding is done at the baseband waveform level. The precoding and de-precoding processes are fundamentally based on the modulation and demodulation operations, which involve IFFT and FFT, respectively, used for the OFDM waveform. These operations involve transmission layer mapping and de-mapping. All these are performed at the baseband level before up/down conversion operations before/after the RF Antenna stage, respectively.

This White Paper covers the MVDR Algorithm applied to the RF beamformer stage, and is not meant for the baseband precoding operations.

ON THE MVDR ALGORITHM

The MVDR (minimum variance distortionless response) was developed to compute optimum weights to minimize the output power of moving interference signals while maintaining a distortionless response towards the desired signal. Therefore, the need for broad nulls to accommodate dithering interfering signals and maximize SINR was incorporated. MVDR effectively places deep broad nulls canceling out interference signals while maintaining a stable response toward the desired signal.

Some adaptive methods to solve the MVDR beamformer problem suggested are the conjugate gradient (CG), regularized zero-forcing (RZF), least mean squares (LMS), normalized LMS (NLMS), QR decomposition-based recursive least squares (QR-RLS), minimum mean square error (MMSE), etc. The RLS algorithm has a faster convergence rate than LMS and NLMS algorithms. It also has better robustness to unpredictable situations and better tracking capability. The LMS solution is a method that integrates all equations into a single solution. QR-RLS algorithm outperforms other algorithms like LMS, NLMS, and RLS. Null Steering algorithms with single or multiple constraints (NSASC, NSAMC) have lower complexity compared to the QR-RLS. The dichotomous coordinate descent (DCD) algorithm [23] allows linear systems of equations to be solved with high computational efficiency. It is a multiplication-free and division-free technique and, therefore, it is well suited for hardware implementation. A DCD algorithm is used to find the antenna array weights without multiplication.

Solving the normal system of equations of the form A x = b is usually considered by using matrix inversion, generally a pseudoinverse. Complicated operations can be avoided and a sub-optimal solution can be chosen to avoid computational complexity. Computing the matrix inversion directly has a complexity of O(N^3), which is too complicated for real-time implementation. From a numerical point of view, the best approach is to avoid the matrix inversion. Even the QR decomposition technique has complexity of O(N^3). The coordinate descent techniques, such as Gauss-Seidel, Jacobi, and Successive Over-Relaxation (SOR) methods require only O(N) operations per iteration but demonstrate a slower convergence. The Dichotomous Coordinate Descent (DCD) algorithm [23] is based on coordinate descent techniques with a power of two variable step sizes. It is simple for implementation, as it does not need multiplication or division operations. For each iteration, it only requires O(N) additions or O(1) additions. Thus, the DCD algorithm is quite suitable for hardware realization on FPGA.

It is not clear which of the method(s) from above is/are used in the MATLAB 2024b Phased Array Toolbox implementation of the MVDR Algorithm.

RESULTS & VISUALIZATIONS

Input data is as below:

S.No.	Antenna Parameter	Value
1	Element Object	phased.NRAntennaElement (3GPP TS 38.901
2	Frequency Range	27.5 - 28.5 GHz
3	Element Polarization Angle	+/- 45 deg
4	Element Polarization Model	2
5	Element Beamwidth (Azimuth)	63 deg
6	Element Beamwidth (Elevation)	63 deg
7	Element Side Lobe Level (Azimuth)	30 dB
8	Element Side Lobe Level (Elevation)	30 dB
9	Element Max. Gain	8 dB
10	Array Size	8 x 12
11	Array Directivity	25.3 dBi
12	Array Beamwidth (Azimuth)	8.26 deg
13	Array Beamwidth (Elevation)	12.32 deg
14	Array Separation Factor (d/λ)	0.51

TABLE 1 (Antenna Input Data)

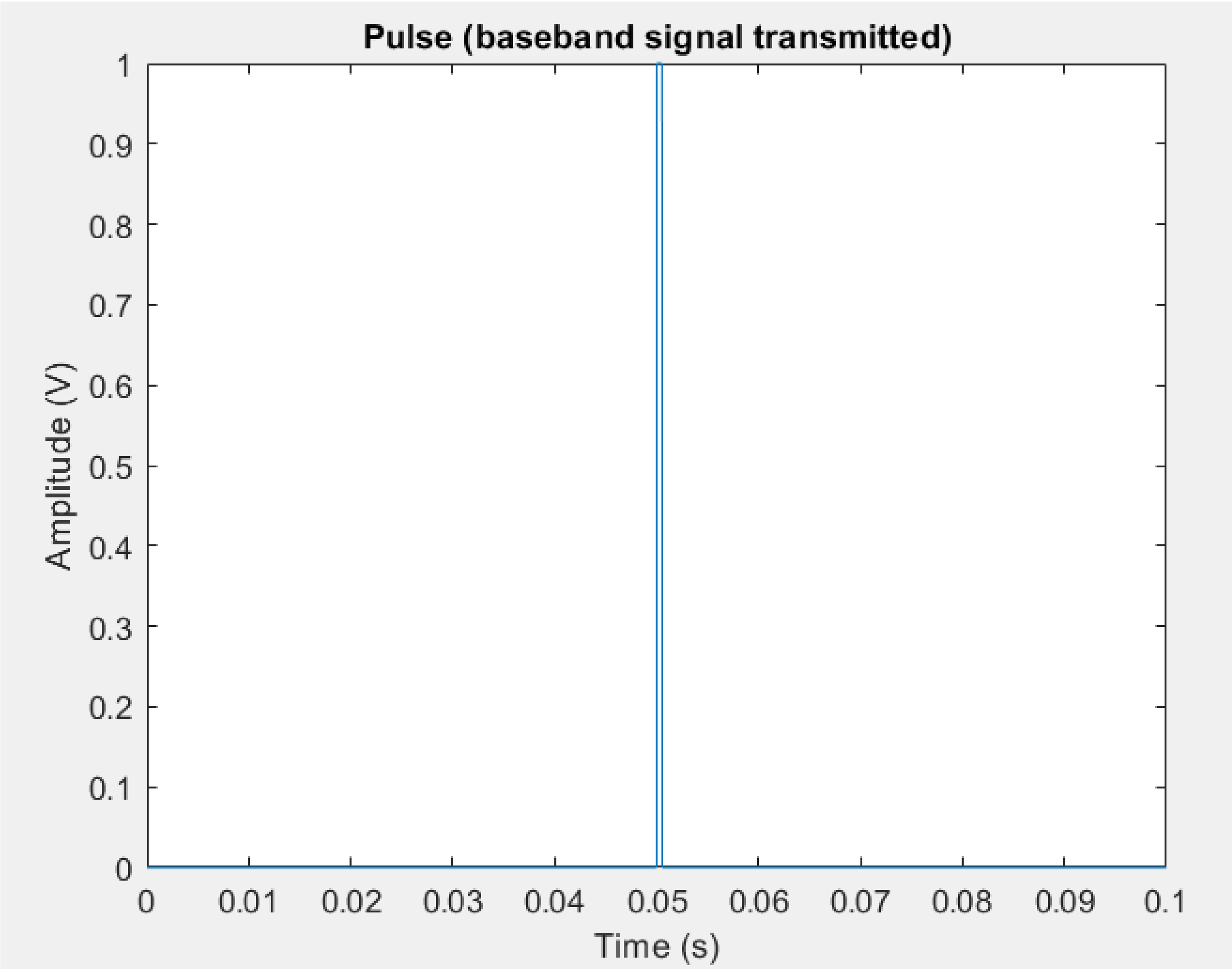
S.No.	Parameters	Value
1	Signal [Azimuth; Elevation] or SOI	[13.5 ; -18.75]
2	Interference 1 [Azimuth ; Elevation] or NSOI1	[24 ; -45]
3	Interference 2 [Azimuth ; Elevation] or NSOI2	[-36 ; 15]
4	Interference 3 [Azimuth ; Elevation] or NSOI3	[50 ; 60]

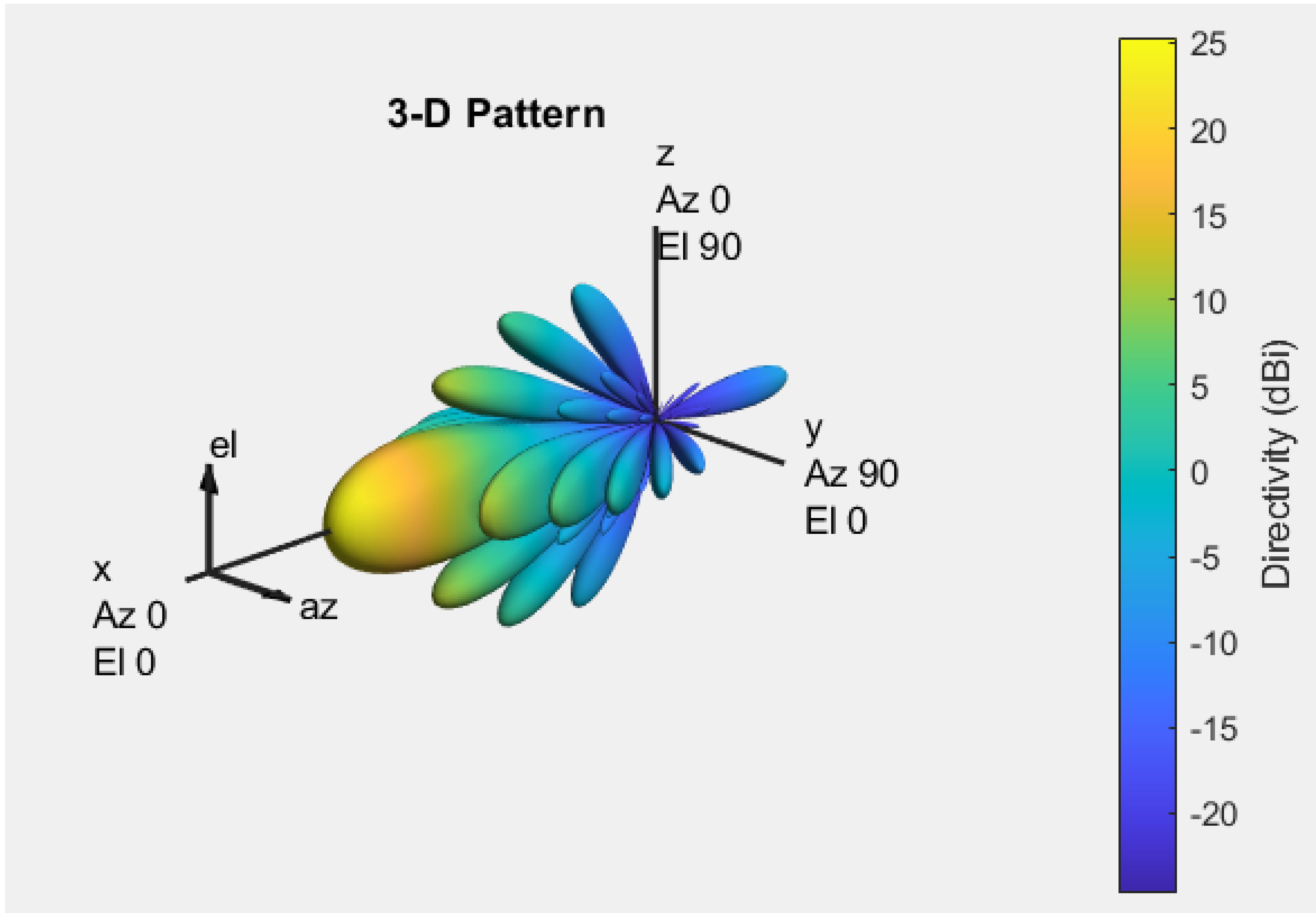
TABLE 2 (Signal and Interference Directions Data in deg.)

The results of the analysis based on MATLAB simulations are presented below.

PLOTS

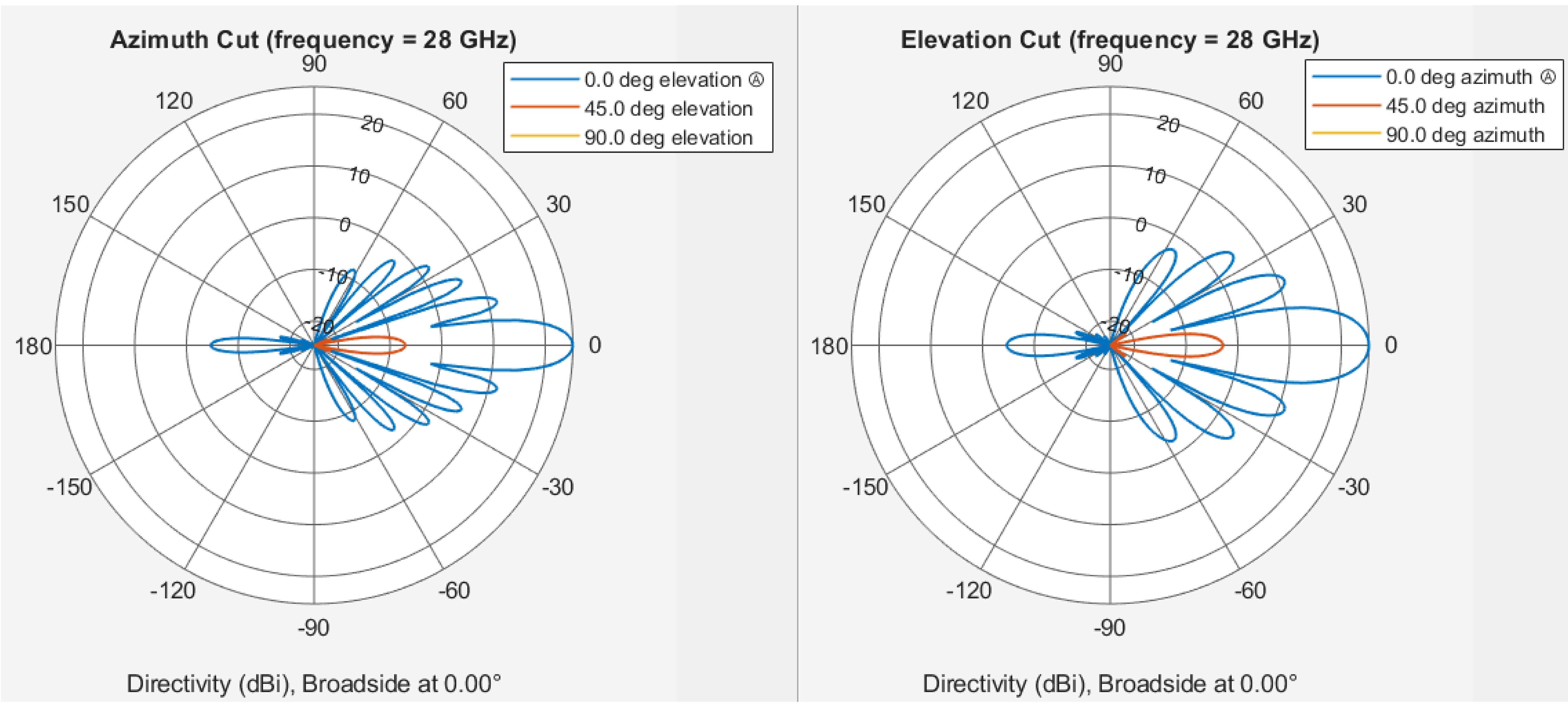
This is a narrow pulse signal transmitted within a 0.1-second window, sampled at 100 KHz.



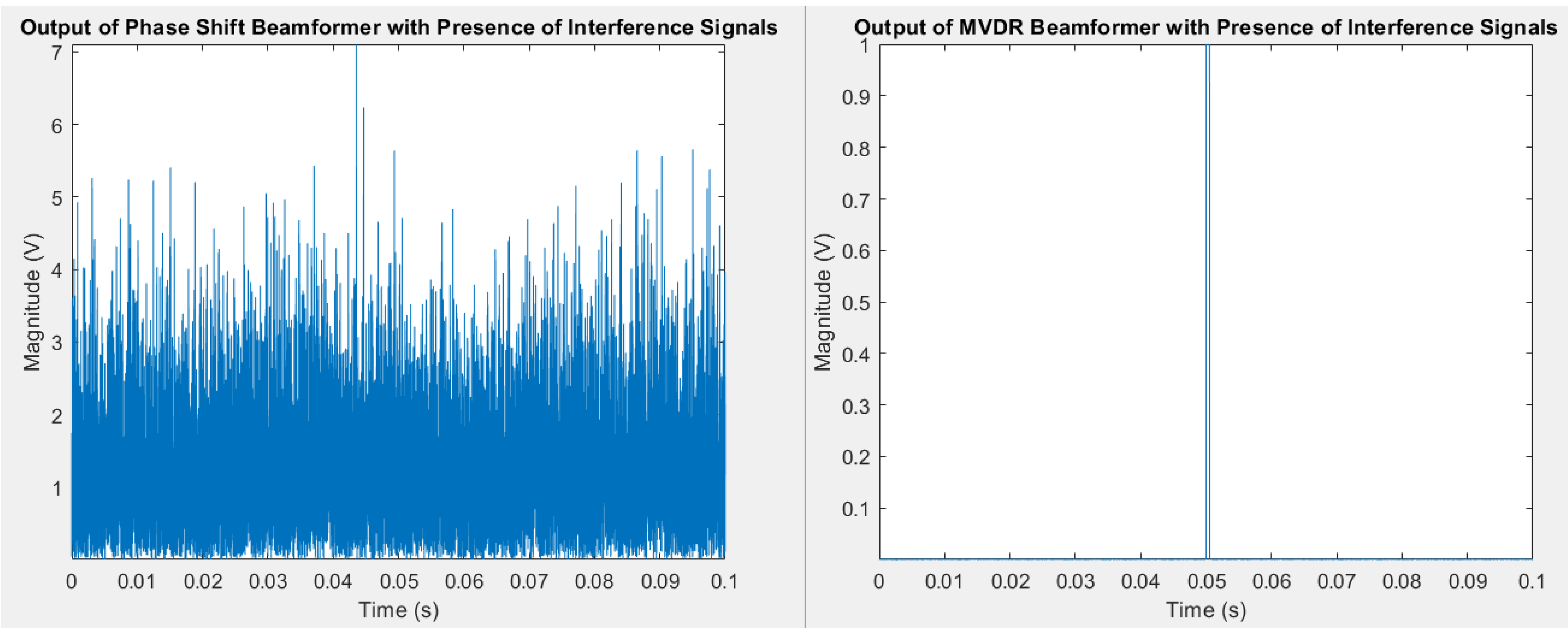


This is the 3-D Radiation Pattern without beam steering of an 8 x 12 Antenna Array with a frequency centered at 28 GHz.

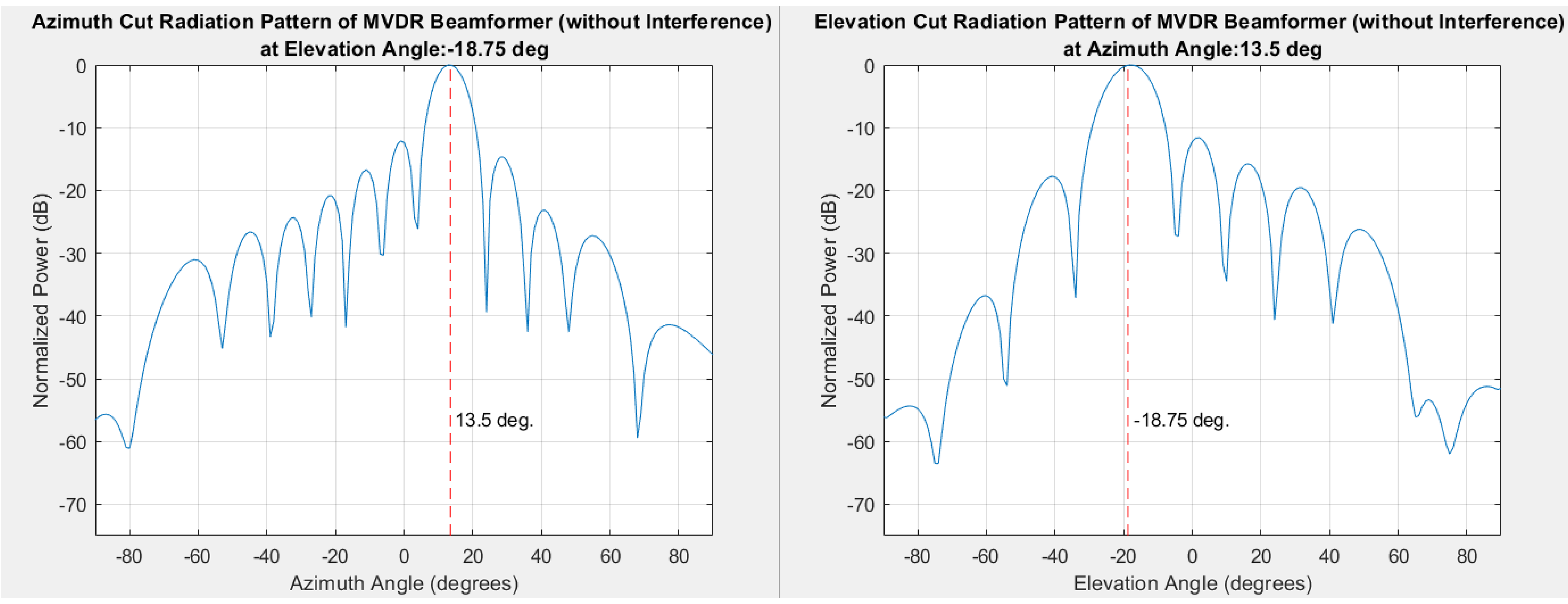
These are polar plots (Azimuth and Elevation Cuts) of the Antenna Array.



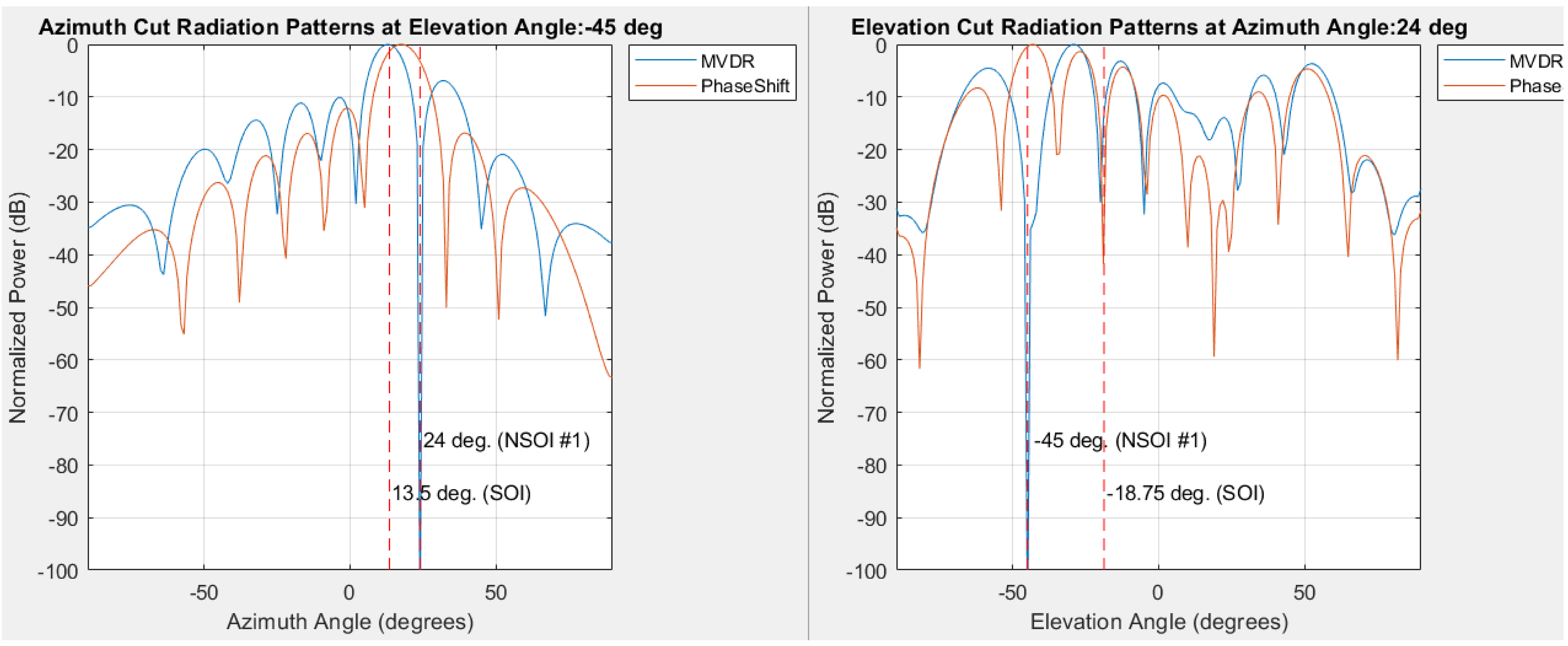
Comparison of outputs of phase shift beamformer vs MVDR beamformer of the narrow pulse transmitted with the presence of 3 interference signals. We can see that the MVDR beamformer outperforms the phase shift beamformer in rejecting the interfering signals from various directions. The output of the MVDR beamformer is identical to the input pulse.



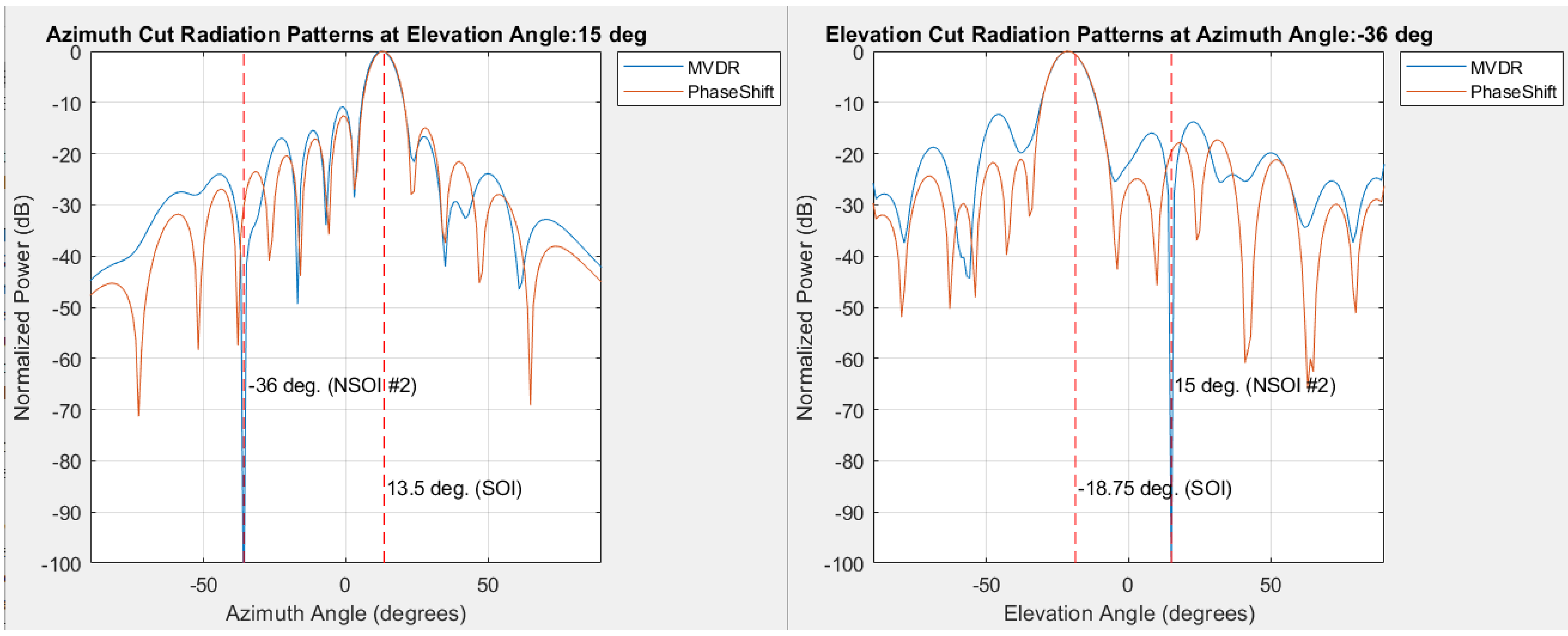
These are polar plots of MVDR beamformer radiation pattern with only the signal (SOI at [13.5; -18.75])



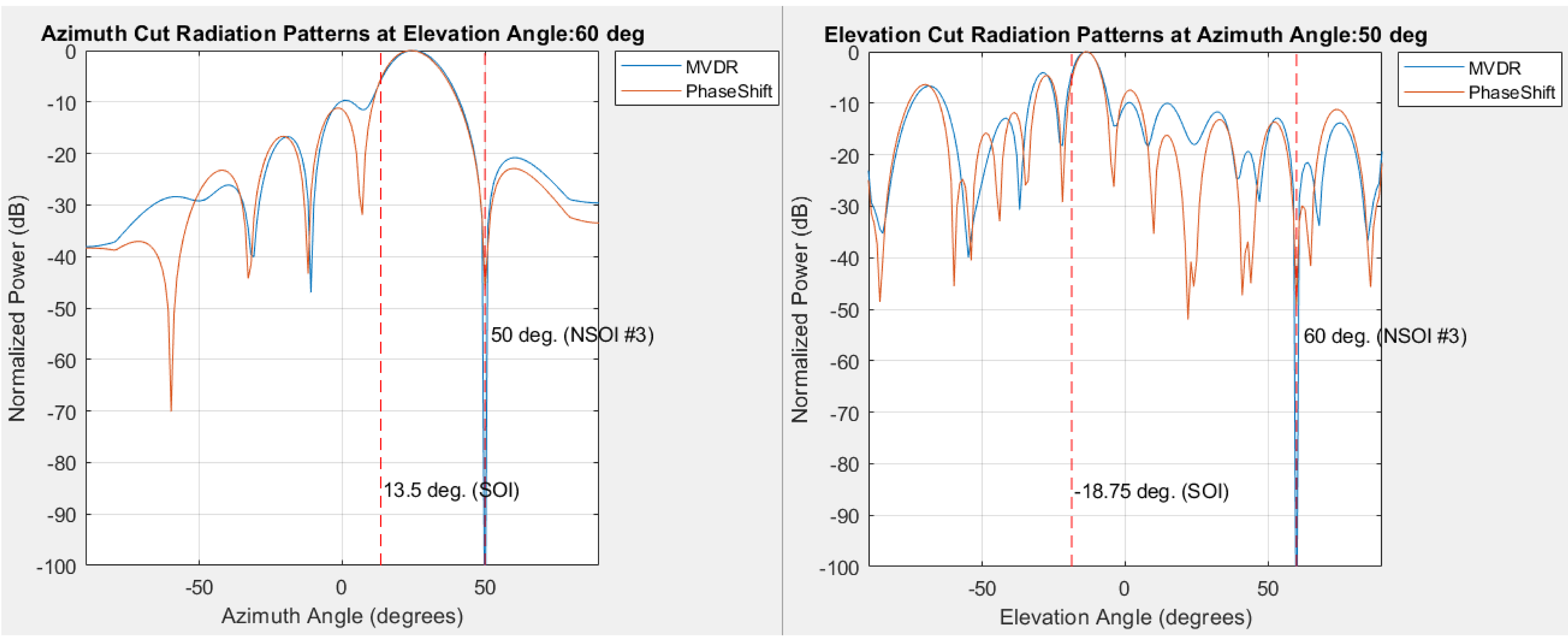
These are azimuth and elevation cut polar plots of Phase Shift beamformer vs MVDR beamformer radiation pattern with the signal (SOI) along with interference (NSOI1) (with SOI at [13.5; -18.75] and NSOI1 at [24; -45]). We can easily note how well the MVDR beamformer rejects the interference by creating a deep null at the NSOI1 direction compared to the phase shift beamformer.



These are azimuth and elevation cut polar plots of Phase Shift beamformer vs MVDR beamformer radiation pattern with the signal (SOI) along with interference (NSOI2) (with SOI at [13.5; -18.75] and NSOI2 at [-36; 15]). We can easily note how well the MVDR beamformer rejects the interference by creating a deep null at the NSOI2 direction compared to the phase shift beamformer.



These are azimuth and elevation cut polar plots of Phase Shift beamformer vs MVDR beamformer radiation pattern with the signal (SOI) along with interference (NSOI3) (with SOI at [13.5; -18.75] and NSOI3 at [50; 60]). We can easily note how well the MVDR beamformer rejects the interference by creating a deep null at the NSOI3 direction compared to the phase shift beamformer.



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