

Multi-beam Antenna Array Operating Over Switch On/Off Element Condition

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Abstract—In this work, is presented the design of a linear multi-beam antenna. The designed procedure is focused on the possibility of switching off a part of antenna array elements, in active antenna systems, in order to preserve resources (power and heat dissipation). The behavior of the original multi beam antenna design is investigated on the radiation pattern alteration due to the switched off elements. The choice of switching on/off antenna elements requires less computational effort from the algorithms incorporated in the active antenna system. Antenna array beam design using progressive phase shifts permits beam orthogonality which is valuable over use multiple beam antenna. In this work, turning off part of antenna elements will inevitably change the beam orthogonality conditions. Despite this, the case presented in this paper, shows beam space discrimination better than 10dB. To rank the behavior of modified antenna, with the turned off elements, are used both Euclidean and Hausdorff distances to measure the changes resulted from the modified array performance. The obtained solutions show the applicability of binary operation on existing antenna array. The metric showed in here can be effectively used as ranking criteria.

Keywords—Multi-beam; phased antenna array; Hausdorff distance; Woodward-Lawson

I. INTRODUCTION

For decades, the mobile telephony system has continually grown, new technologies are continuously applied like the ones of signal processing capabilities and enhanced modulation scheme, also those related to antenna design and operating [1][2][3]. One of the major evolutions of the cellular technology beyond 2G, 3G, 4G up to the 5G, is the antenna sub system with massive MIMO [4] configurations and full digital beam forming capabilities [5].

Combination of massive MIMO with full digital beam forming architecture, especially in the sub-6GHz sub band, permits an increase on the obtained throughput per user [6]. This can be possible by creating orthogonally multiple antenna beams. This configuration can mitigate interferences from nearby user equipment increasing in this way the CNR (Carrier to Noise Ratio) which is proportionally related to user's equipment transmitted throughput [7][8].

The multi-beam antenna feed can be achieved through full digital beam forming network. In this case each antenna element of the array is directly connected to a dedicated RF chain (RF: Radio Frequency) comprising PA/LNA (Power Amplifier/Low Noise Amplifier) [9] and creating so an Active Antenna System (AAS) as shown in Fig. 1. One of the biggest drawbacks of this architecture, rather than its cost, is the

power consumption and high heat dissipation requirements [10] [11].

In this paper we are investigating the possibility of switching off intentionally a part of antenna array elements (corresponding RF chain) to improve power consumption by decreasing its demand for power heat dissipation and extend antenna life span. Switching off some of antenna's element will inevitably change also the original radiation pattern. To quantify the divergences of the modified radiation pattern compared to the desired/required one, will be used a ranking procedure based on Euclidean and Hausdorff distances [12].

In a bed test case, the solution with require three contemporary antenna beams. The proposed test is quite general and is valid for any combination of orthogonal beams. A case presented later in this paper will also investigate when one of the UE (User Equipment) changes its relative position/direction from/to the base antenna. In this case, it is needed to be generated a new beam (among the orthogonal that the antenna array can handle) from the decision making of antenna's internal and the direction of arrival estimation. So the idea of switching off a part of antenna elements, presented by the authors in [12], will be applied to effectively show that the proposed technique is still valid.

The methods for generating antenna array radiation pattern can be found in the scientific literature as in [13] and [14], each of them with relative advantages and disadvantages, mostly they are proprietary algorithms used by antenna's vendor for real case implementation. In this work, without loss of generality, will be applied Woodward-Lawson method for antenna array pattern design [15].

The antenna array used as example for the test scenario is composed by $N = 31$ elements. The original array factor for multi-beam will be designed by using Woodward-Lawson method in each required beam direction. Then the designed feeding network ratio (amplitude and phase) for each beam can be combined linearly as by superposition principle on linear antenna systems. The overall antenna array factor obtained, will be compared with the required masks (one for each beam). As ranking method will be used two distances: Euclidean [16] and Hausdorff Distance [17]. Our aim is to get this array factor by switching off some antenna elements and to compare the obtained pattern with the mask through the use of both methods.

This paper is organized as follows: Section two describes mathematical definitions for the active antenna system and for

multi-beam antenna. It is also introduced the antenna array design based on W-L method followed by definitions of both metrics (Euclidean and Hausdorff) which are used to score how close to required pattern is the designed and modified antenna pattern. Section three describes the antenna array design setup and analysis. Required beam direction and antenna design is analyzed based on beam orthogonality and orthogonality lose when array elements are switched from on to off. Conclusions and recommendations for future work will be emphasized in section four.

II. ANTENNA DESIGN METHODOLOGY

Active antenna systems are a valid option for high performance and speed networks, especially in 4G/5G [13][14][18][19]. Here, the full RF electronics, consisting of RF power amplification, Rx functionality, filtering, and so on, are all integrated in an AAS as shown in Fig. 1.

One of the most valuable features of the AAS is the digital multi-beam forming capability. This configuration allows the AAS to create multiple orthogonal beams which does not interfere with each other. It directs antenna beams to different users in space, so the AAS can simultaneously communicate with multiple users at the same time and same frequency resources with enhanced CNR [20].

In this work, without loss of generality, Woodward-Lawson antenna array design method is being used for pattern design as per predefined (required) pattern distribution. The used method permits to evaluate amplitude and phase for each antenna element composing the array in a way to be feed for creating the required pattern. This method is based on the standard theory of phased antenna array. The complex antenna array can be analyzed as an overlay of different virtual, independent, and superposed arrays. An example of feeding function can be expressed as (1):

$$I_n = I_n^{(1)} + I_n^{(2)} + I_n^{(3)} + \dots + I_n^{(N)}; \quad n = 0, \dots, N-1 \quad (1)$$

The concept is also used for the creation of a second function but in this case is adjusted an uniform progressive phase in order that the maximum main lobe coordinates with the profoundest null of the first step function. So, an excitation in amplitude of this function determines the filling-in of the most profound null of the second function [21]. The third function part of the main function is altered so the maximum of main lobe occurs at the second profound null of the first function and so on. In this way are created one after other all the functions which are part of the sum. In this way all the created (virtual functions) beams are orthogonal to each other as shown in Fig. 2 for the 11 elements on the antenna array design. The presented figure shows the orthogonality of each beam that can be achieved with only phase change.

In real antenna implementation, the required antenna beam number and relative space directions are timely changed due to the number of connected users and antenna usage in space and time. For these cases, artificial intelligence (algorithms for direction finding) implemented in the AAS will evaluate feeding ratio (amplitude and phase) required for each beam and each antenna element.

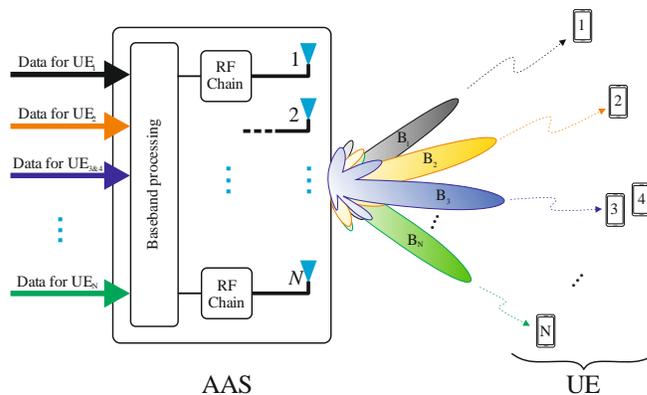


Fig. 1. Active Antenna System and Multi-Beam Concept.

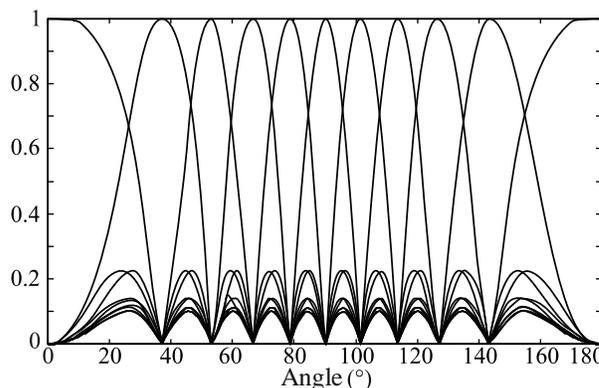


Fig. 2. W-L Antenna Design and Orthogonal Beams for 11 Antenna Elements.

The total number of contemporary beams combinations required in time and space, can lead to a very large definition problem [23][24][25][26]. In this work, without loss of generality, will be considered three different beam directions along with the relative antenna feed. They will be designed using the over-mentioned Woodward – Lawson method as schematically shown in Fig. 3. Those directions can be any of the provided orthogonality conditions.

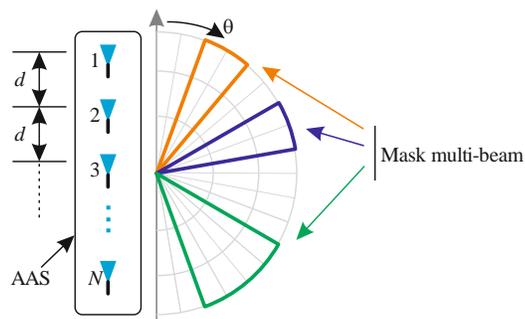


Fig. 3. Multi-Beam Antenna Definition.

It is of crucial importance to keep in mind that the number of orthogonal beams is the same as the number of elements which compose the antenna array. Orthogonality in antenna beam design is one of the biggest advantages which includes less interferences in the directions where other beams (directed to UEs) have their relative maxima. The above advantage increases the CNR and consequently increase the

III. RESULTS

throughput [22]. The array factor (AF) designed through the Woodward-Lawson method will be used as the original antenna pattern (multiple beam). Based on this design, will be investigated the possibility to switch off part of antenna elements. There are being analyzed changes of pattern due to elements switch off, and how it diverges from the desired model (defined as required pattern mask). They will be scored as per Euclidean and Hausdorff distances as per below.

A. Euclidean Distance

The Euclidean distance can be expressed as the straight line between two given points (of course that point can be vectors or matrixes). The length of the straight line represents the shortest distance between the two defined points. It is also used for higher dimensional problems [12][16].

Through this paper we will use the sum of all Euclidean distances (E_k) between array factor (AF_k) and the mask (M_k , the desired model) as given in equation (2).

$$E_k = \sum_{\theta=0^\circ}^{180^\circ} \|AF_k(\theta) - M_k(\theta)\| \quad (2)$$

Where k is the k -th antenna beam designed.

B. Hausdorff Distance

Hausdorff distance can be expressed as the maximum distance of a set, to the nearest point in the other set [12][17].

Through this definition it is easy to understand that the distance expresses the longest distance that it might be forced to travel between two sets of points. Given two sets of points AF_k and M_k , the Hausdorff distance between them can be defined as in (3):

$$H_k(AF_k, M_k) = \max\{h(AF_k, M_k), h(M_k, AF_k)\} \quad (3)$$

Where $h(AF_k, M_k)$ is called direct Hausdorff distance and defined as in (4):

$$h(AF_k, M_k) = \max_{AF(\theta_i) \in AF} \min_{M_k(\theta_j) \in M_k} \|AF_k(\theta_i) - M_k(\theta_j)\| \quad (4)$$

It identifies the point in AF_k that is the farthest from any point in M_k (max definition) and measures the Euclidean distance from that point to the nearest neighbor in M_k (min definition). Likewise, the definition for $h(M_k, AF_k)$ is in (5):

$$h(M_k, AF_k) = \max_{M_k(\theta_i) \in M_k} \min_{AF(\theta_j) \in AF} \|M_k(\theta_i) - AF_k(\theta_j)\| \quad (5)$$

C. Ranking Distances

The above definitions of Euclidian and Hausdorff distances can be directly applied for each antenna beam. In the presented work, the designed pattern are more than one at the same time. In order to have one ranking criteria, a combination of each Euclidian and Hausdorff distances for all the designed contemporary beams is performed as in (6):

$$E = \sqrt{E_1^2 + E_2^2 + E_3^2 + \dots + E_k^2}$$

$$H = \sqrt{H_1^2 + H_2^2 + H_3^2 + \dots + H_k^2} \quad (6)$$

By using Woodward-Lawson design method, is designed a standard linear antenna array with $N = 31$ elements, element intra-distance of $d = \lambda/2$. The required mask is designed to point in space as: M_1 in 43° with 9° width span, M_2 in 82° with 7° width span and M_3 in 125° with 10° width span and zero elsewhere (schematically shown in Fig. 3). The designed antenna array used in sub-6GHz sub band (2100 – 2600 MHz) is approximately 220 cm high.

Designed antenna pattern and relative feeding network by the use of Woodward-Lawson method are shown in Fig. 4.

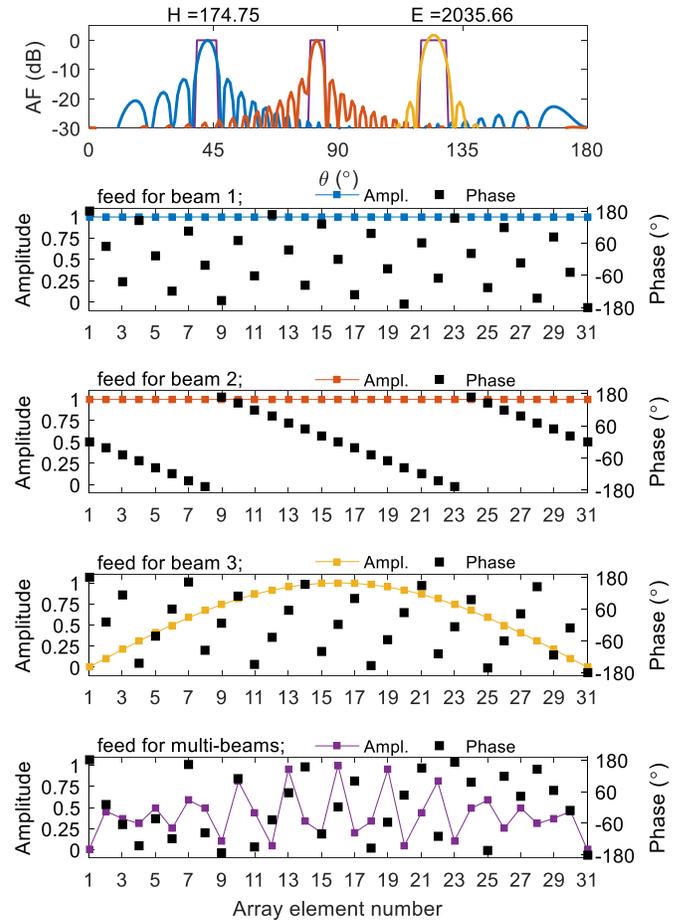


Fig. 4. Multi-Beam Array Pattern and Relative Current at each Element.

The feeding of each virtual array for beam generation is based on progressive phase shift as can be noticed in the graphics feed for beam 1, 2 and 3 in Fig. 4. The overall feeding ratio is not more progressive in phase and amplitude due to the superposition effect. This is the feeding ratio as seen by RF chain at AAS. To recreate the antenna pattern provided, the reader can evaluate radiation pattern from antenna theory based on the current feeding ratio and phase as shown in each sub figure for each beam.

In Fig. 5 are shown the pattern changes and relative feeding ratio from switching off 10 out of 31 antenna elements in the designed multi-beam, shown in the first part of Fig. 4. Sorting criteria for this modified configuration are

respectively $E = 2650.98$ and $H = 223.79$. Both results are increased if compared to the original pattern shown in Fig. 4 ($E = 2035.66$ and $H = 174.75$). What is more evident in this case, is the loose of beam orthogonality, especially for the first and second beam (see Fig. 5) as each beam have not null radiation in the direction of the other beam maxima.

Pattern modification due to turned off antenna elements, despite loos of beam orthogonality, beam discrimination in each space direction (direction of each beam maxima) is better than 10dB. This configuration increases the interference produced by UE₁ to the UE₂ and UE₃ data stream and vice versa, but still the difference in antenna discrimination is better than 10dB.

More antenna element can be switched off, as in the case presented in Fig. 6 where two other elements are turned off if compared to the case presented in Fig. 5. Despite the radiation beam pattern modification, beam discrimination is still better than 10dB in all cases.

The above solution is a good alternative even in time variation of UE position as schematically described in Fig. 7. In this situation, direction of arrival and decision-making algorithms and beam design in AAS configuration will recalculate feeding ratio for a new beam forming to the new UE direction.

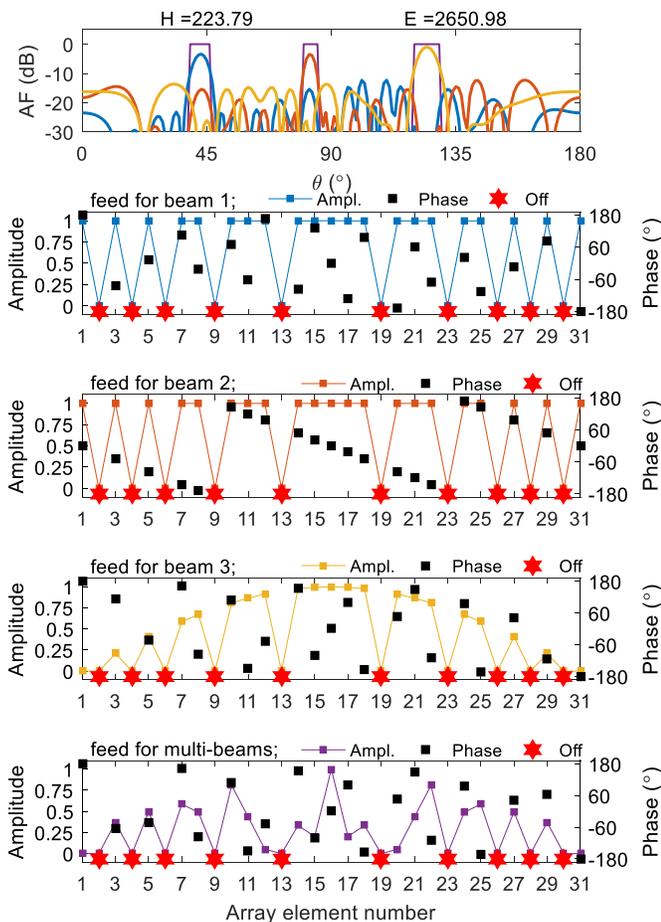


Fig. 5. Multi-Beam Array Pattern and Relative Current for 10 Antenna Elements Switched Off.

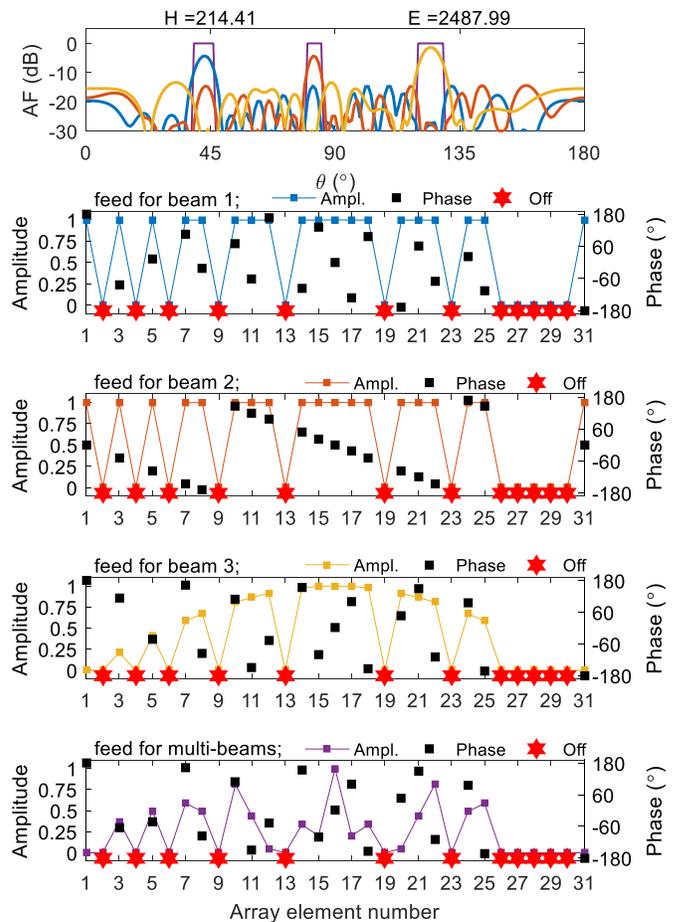


Fig. 6. Multi-Beam Array Pattern and Relative Current for 12 Antenna Elements Switched Off.

Even though the UE changes position in space, the AAS functionality need to reevaluate the antenna elements to turn on/off due to changes in antenna requirements so to follow better and to improve the beam in the new position of UE. Over this position is going to be made the powering OFF of the newly chosen elements like in the first case, but with changed masks.

In Fig. 7 is shown a generic case of a UE that changes relative direction to the cellular antenna. The new direction for beam 2 is from M_2 in 82° with 7° width span in M_2 in 104° with 7° width span and zero elsewhere. The two other beams are maintained at the previous direction as in the first test case. This case is quite general and can be any direction under the original orthogonality condition of beam design.

The result of antenna with the same turned off elements as presented in Fig. 4. The feeding ratio for the new multi beam directions has been designed and the result is presented in Fig. 8. Results show the designed beam patterns for the three directions, maintaining the previous switched off elements. Even in this case, beam discrimination is still better than 10dB in each direction. The solution can be scored based on the provided Ranking criteria, in this case reports Hausdorff and Euclidian respectively $H = 223.77$ and $E = 2601.96$.

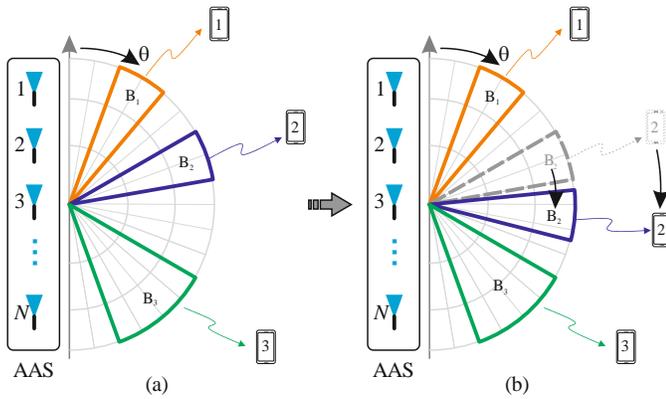


Fig. 7. Multi Beam Directed to UE: (a) Original Problem; (b) UE₂ Changes Position.

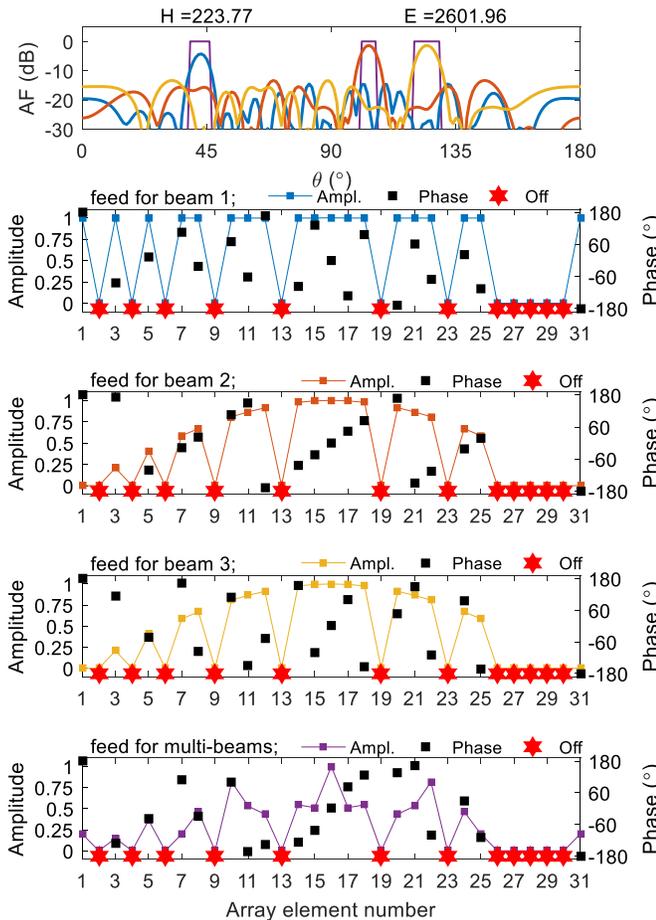


Fig. 8. Multi-Beam Array Pattern for Changed Beam Direction with the Same 12 Elements Turned Off.

Turning on all the antenna elements will bring the orthogonality of all beams due to the original direction orthogonality of the pattern design, as shown in Fig. 9. This is the case, when the antenna will be used in full capacity mode to maintain the maximum CNR over multiple UEs. The metric used in this case is $H = 202.66$ and $E = 2507.65$ which can also be used to evaluate antenna response to the required beam design. Smaller are the E and H values, closer the antenna response is to the required pattern.

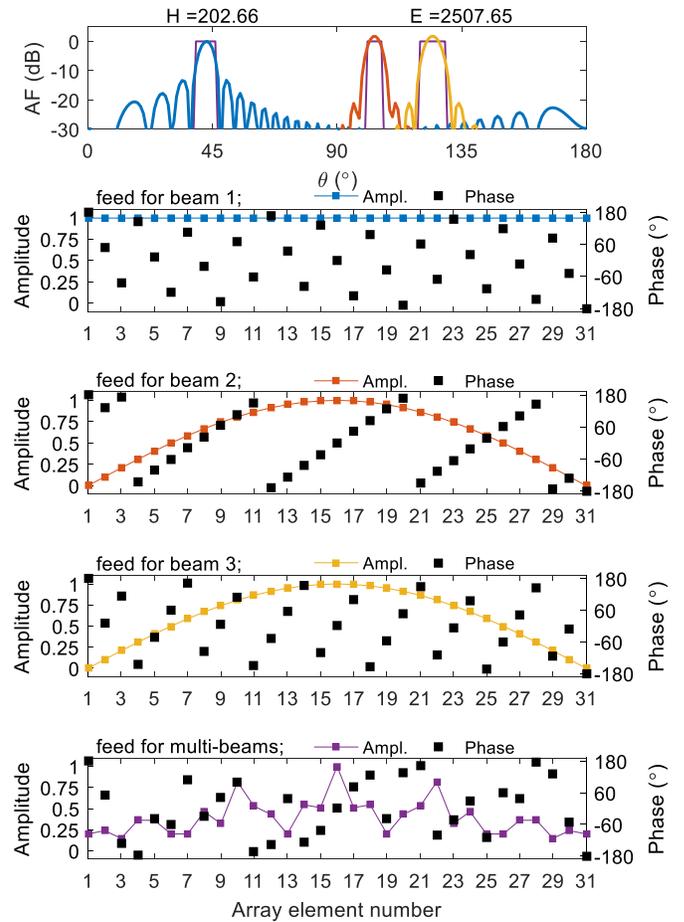


Fig. 9. Multi-Beam Array Pattern and Relative Current for all Elements Turned on for the New Direction of UE₂.

In the analyzed scenario are shown only two cases, but the procedure is quite general and can be applied with more elements switched on/off or/and with more active beams. Since the possibilities for each antenna element are only two (On or Off) there are a finite number of combinations to be tested ($2^N 2^{31} = 2\ 147\ 483\ 648$). With the original antenna array power feeding ratio, designed as by Woodward-Lawson method, analyzing all the above combinations without modifying the feeding ratio between elements but only through changing their state, is not an easy task. Assuming 0.1s computing time to design and rank antenna radiation pattern for each combination, is required more than 7 years of computing time. This is a very huge computing time (in case of calculation of all combinations) but this is not the aim of this work. In this case, can be used more efficient artificial intelligence or optimization algorithms to obtain optimum combinations without making an exhaustive search as in the case of all combinations test.

IV. CONCLUSION AND FUTURE WORK

In this work is presented the analysis of a multi-beam antenna array used with partially switched On/Off antenna elements. The aim of switching off is to preserve energy consumption with less radiation pattern alteration. The presented case shows the applicability of the binary (On/Off)

status change on the antenna elements with a contained impact on the beam orthogonality and relative space discrimination.

The presented analysis is focused on binary format of turning on/off antenna elements which is easier and does not require higher processing capabilities for beam forming evaluating techniques. Modifying antenna array behavior is faster with just powering on/off elements on demand rather than changing power ratio and phase distribution network or beam forming network.

Powering off up to 30% of array elements made possible to have less heat, to save energy without penalizing the radiation pattern and increasing the lifecycle of antenna array. Despite the advantages of the powering off the antenna elements, the major disadvantage is in the beam orthogonality loose, but the space discrimination over multiple-beams remains better than 10dB.

Using both Euclidean and Hausdorff distances as ranking matrix, can be an effective way to the antenna pattern design as close as possible to the required pattern and choose the combination of antenna elements turned on or off which have less deterioration of the radiation models.

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