# Near-field multi-focusing transmitarray optimization for multi-position feed

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***Abstract*—A transmitarray antenna is proposed as a multi-focusing antenna in the near-field region with capability for focus scanning and/or simultaneous and independent focus spots generation at $28$ GHz. The transmitarray optics is defined for a centred configuration and the elements are designed to focus the radiated near-field at a given point. Then, a number of feeds is placed along arcs in the principal planes and the near-field generated by the transmitarray when its illuminated by each one is obtained, demonstrating the capability to generate multiple independent near-field spots. The focusing performance is improved for the centered feed through a Phase-Only synthesis technique based on the generalized Intersection Approach in near-field. Finally, the spots produced by the whole cluster are calculated, demonstrating the overall improvement and validating the designing process. This configuration can be applied in near-field systems as radar for surface inspection, measurement systems or wireless power transfer among others.**

## I. Introduction

Transmitarray antennas have been widely investigated for last decades, making special emphasis in far-field applications, where different types of optimization techniques for the improvement of the shaped-beam radiation pattern have been developed [1]. Furthermore, near-field applications has not been deeply studied so far, when the arrival of 5G technology has put the spotlight on working in shorter distances therefore, on being within the near-field region. Although near-field remains as a limited research topic, in some literature have arisen applications such as imaging [2], Compact Antenna Test Range [3] or 5G indoor communications [4] working in this area. However, regardless the applicability, the near-field has to be shaped in all cases given with certain specifications. Therefore, considering that the near-field control is difficult to deal with, an optimization process may be required.

Most of the previous literature is focused on the development of reflectarray synthesis. However, this is not a potential problem since both reflectarray and transmitarray antennas are spatially fed arrays therefore, the majority of the optimization techniques can be applied to both kinds of antennas. Furthermore, these algorithms are typically used to synthesize the far-field of the antenna, especially the radiation pattern in terms of bandwidth, gain, cross-polar level or SLL among others. Many examples of different techniques or algorithms can be found in literature, highlighting the Phase-Only Synthesis (POS) [5] or the direct optimization of the element geometry [6] then, the Intersection Approach (IA) has demonstrate a high efficiency in the reflectarray optimization, particularly in space applications where the specifications are notably tight [7][8]. Generally, the efficiency of the far-field techniques is due to it is based on the Fast Fourier Transform (FFT), which is the most expensive operation. Since this operation can be effectively implemented. On the other hand, when dealing with near-field synthesis, the FFT cannot be generally used, involving a loss of efficiency. Then, depending on the applications, the near-field optimization may have to deal with both amplitude and phase, making it a more difficult problem to solve. Even so, near-field synthesis is unavoidable and in [9] or [10] the Intersection Approach Algorithm is discussed for a near-field optimization, in addition, in [11] a technique to speed up the near-field synthesis based on gradient algorithms are presented.

In this work, a transmitarray is proposed for near-field multi-focusing applications. The use of a transmitarray instead of a reflectarray provides a very compact structure, avoiding block losses and having a centered optics. Conversely, these applications not only look for focusing the field on a single point, it generally requires to concentrate the field in spots distributed in an angular range. In this line, electronic reconfigurable arrays or antennas with mechanical-steering support [12] are commonly used to move the focus point and create a virtual scanning range. Alternatively, in this work the transmitarray is illuminated by a cluster of feeds, usually horn antennas working at a central frequency of 28 GHz so, the number of focused spots that can be generated is equal to the number of the cluster elements. One alternative is to use a different shifted carrier, regarding the central frequency, in each feed, allowing to radiate all the focused spots but keeping them independent. Another possibility is the use of the same carrier but in different time-slots. Then, in order to improve the focus performances of the transmitarray an optimization in near-field is carried out, using the generalized Intersection Approach. The complexity of a multi-spot focusing synthesis is reduced since only the central feed is considered in the process, notwithstanding the improvements are also extrapolated to the other feeds due to the transmitarray properties and the spatial distribution of the cluster. Lastly, after the optimization process, the transmitarray properly focusses the near-field within an angular range, creating an enhanced scan range for near-field focus scanning applications.

## II. Near-field multi-focusing spot generation

To create a different near-field focused spots, a cluster of feeds is used to illuminate a transmitarray, allowing to create different near-field focused spots and, thus making a wide range scanning area. The proposed transmitarray is firstly designed to focus the field incoming from the central feed, which is radiated in a certain direction and generates an unique focus area. Then, the positions of the other feeds are defined, guaranteeing that the transmitted field of each feed is properly focused in the desired direction, trying to ensure that the amplitude of the incident field is similar among the different feeds to obtain similar amplitude levels in the transmitted field. However, the phase of the transmitted field depends on two factors: the phase-shift introduced by the cells and the phase of the incoming field provided by each feed, which will be unique. Regarding the first factor, the cell used in a transmitarray antenna is assumed to ensure a good angular stability, trying to reduce the influence of the impinging wave in the phase-shift of the cell. Applied this to this case, the major change in the transmitted field will be produced by the different illumination of each feed. Bearing in mind that it is necessary to ensure the same distance between the feed and the centre of the transmitarray for all the feeds, the best location for them seems to be the arc defined by the midpoint of each transmitarray edge and the central feed, as it is shown in Fig. 1.

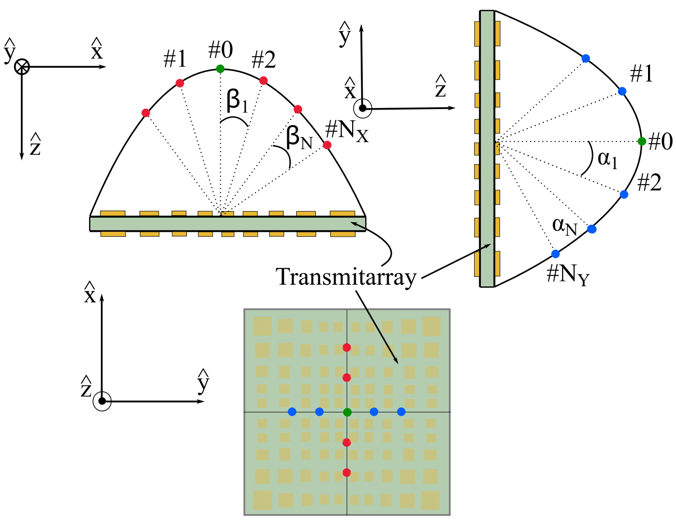



Fig. 1: Spatial distribution of the feeds along the $\hat{x}$ and $\hat{y}$ coordinates.

The distance between two adjacent feeds is defined by the angle $\beta$ for the $xz$ cut and $\alpha$ for the $yz$ cut, taking into account that these angles can change between two different pairs of feeds. Using these angles and setting the centre of the origin of the coordinates system at the centre of the transmitarray so that, the central feed is at $(\hat{x}, \hat{y}, \hat{z}) = (0, 0, 100)$ mm, the position of the other feeds can be easily computed as:

$$\begin{aligned} (\hat{x}, \hat{y}, \hat{z}) &= (r \sin\beta, 0, r\cos\beta) \quad \text{for the } xz \text{ plane} \\ (\hat{x}, \hat{y}, \hat{z}) &= (0, r\sin\alpha, r\cos\alpha) \quad \text{for the } yz \text{ plane} \end{aligned} \tag{1}$$

where $r$ is the radius of the arc that is defined by the $\hat{z}$ coordinate of the central feed; $\beta$ and $\alpha$ are the angles previously described.

In this work, a cluster of 18 feeds is proposed to illuminate the reflectarray, considering 9 elements along the $\hat{x}$-axis and the others in the $\hat{y}$-coord, considering $\beta = \alpha = 5°$. Table I outlines the position of the feeds placed in the $\hat{y}$-axis obtained by applying (eq.)1. Regarding the rest of the cluster, it can be computed just changing the $\hat{y}$ coordinate for the $\hat{x}$ one.

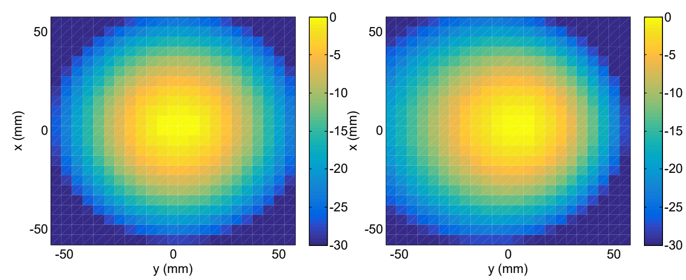
TABLE I: Position of the feeds.

| Feeder | #0 | #(1\|2) | #(3\|4) | #(5\|6) | #(7\|8) |
|---|---|---|---|---|---|
| $\hat{x}$ | 0 | 0 | 0 | 0 | 0 |
| $\hat{y}$ | 0 | ±8.71 | ±17.36 | ±25.88 | ±34.20 |
| $\hat{z}$ | 0.100 | 99.61 | 98.48 | 96.59 | 93.96 |

## III. Near-field scanning using a transmitarray feed by a cluster

### A. Antenna optics

The cluster is composed by 18 elements that are modeled as an ideal horn with a $\cos^q\theta$ function [13] and a $q-$factor of 20. This cluster illuminates a transmitarray of 576 elements placed in a $24 \times 24$ regular grid, using a periodicity of $5 \times 5\text{mm}^2$ for both $\hat{x}$ and $\hat{y}$ direction. Therefore, the equivalent aperture is $11.2\lambda \times 11.2\lambda$, being $120 \times 120\text{mm}^2$ at a central frequency of 28 GHz. Considering these parameters, the incident field is analysed in order to study the differences between the central feed and the cluster, making particular emphasis in the extreme ones (feed #7 and #8), which are the worst case. This comparison is shown in Fig.2, observing that both incident fields are similar, only obtaining a slight difference since the projection of each field on the transmitarray surface changes.




(a) (b)

Fig. 2: Normalized amplitude (dB) of the incident field provided by the (a) central feed (b) #8 which is placed at 20° regarding the central feed.

Hence, if a transmitarray is properly designed to focus the near-field in a certain point only by using one feed, it can be assumed that replacing the feed by a cluster distributed using (eq.)1 then, the incoming field of each feed will be focused in a certain point but different among them as Fig.3.

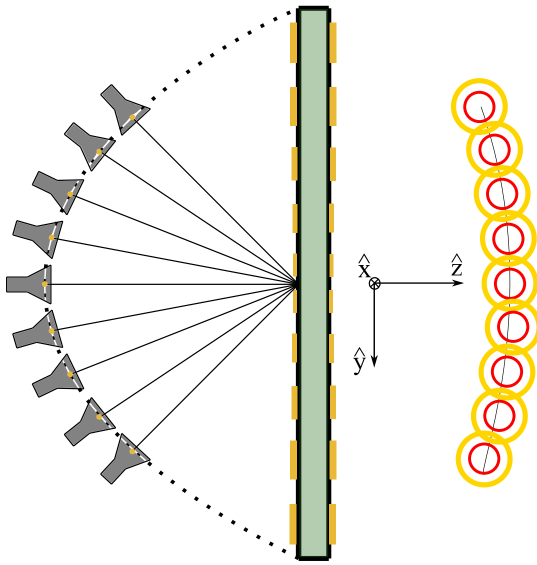



Fig. 3: Near-field focused transmitarray feeds by a cluster of horns.

## B. Near-field focused transmitarray

A transmitarray that focuses the near-field on one point of the space, and for a single feed, can be designed applying the Gaussian beam equation [14]. The phase distribution of this kind of antennas is based on achieving a constant phase delay from the feed to the focusing point for all the possible paths thus, the phase-delay that the transmitarray should introduce, changed along its radius.

$$\phi_{in}(r) + \phi_{TA}(r) + \phi_{out}(r) = M_{tant} \tag{2}$$

where $\phi_{in}(r)$ is the phase of the incident field on the inner surface of the transmitarray; $\phi_{TA}(r)$ is the phase-shit introduced by the transmitarray and $\phi_{out}$ is the phase-delay due to the path from the outer surface to the focusing point. $M_{tant}$ is a constant and $r$ is the radius distance from the centre of the transmitarray to the centre of a cell. Therefore, considering $M_{tant} = 0$ the phase-shift distribution of the transmitarray can be computed as:

$$\phi_{TA}(r) = k_0 \left( \sqrt{F_{f-TA}^2 + r^2} + \sqrt{F_{TA-fo}^2 + r^2} \right) \tag{3}$$

where $k_0$ is the vacuum wavenumber;$F_{f-TA}$ is the distance from the phase-centre of the feed to the transmitarray centre and $F_{TA-fo}$ the distance from this to the focusing point.

According to (3) and a distance $F_{f-TA} = 100$ mm (regarding the central feed location) with a focus point at 110 mm in the $\hat{z}$ direction so, $F_{TA-fo} = 110$ mm, the phase distribution is calculated and shown in Fig. 4. Considering the system of coordinates established in Fig. 3, this phase distribution corresponds with the transmission coefficients of the $X$ polarization. Furthermore, the near-field radiated by this transmitarray is computed not only for the central feed, in which the design is based, but also for the whole cluster as Fig. 5 shows. Particularly, the $XZ$ and $YZ$ for $y = 0$ and $x = 0$ respectively, observing that the transmitarray generates as many focusing points as the number of the cluster elements. In addition, the angular separation between adjacent focusing points is the same as the angular distribution of the feeds in both coordinates ($\beta = \alpha = 5°$) thus, although the transmitarray is designed for the central feed, the focusing properties are extended to the rest of the cluster, at least if the position of the elements ensures the distribution of (1).

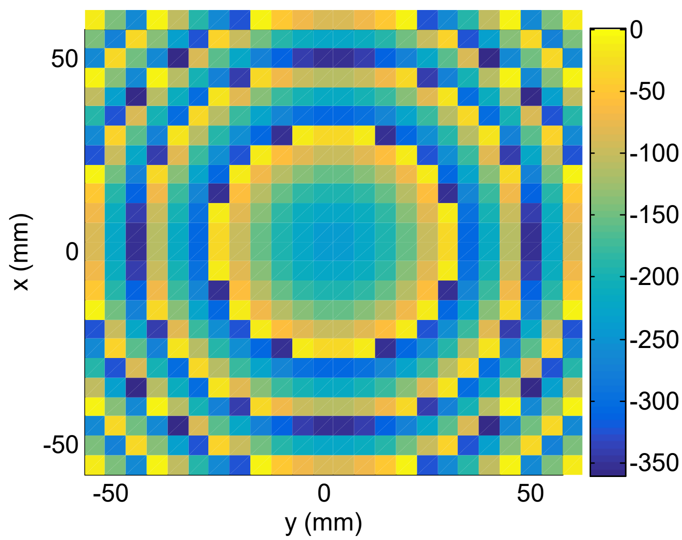


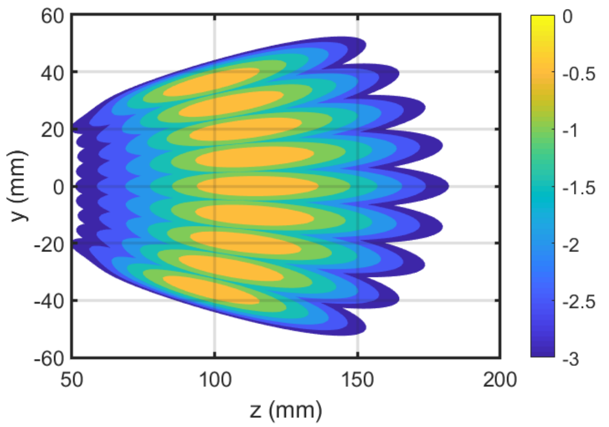

Fig. 4: Phase-shift distribution of a near-field transmitarry with a focusing distance of 110 mm fron the transmitarray surface.

# IV. Near-field optimization

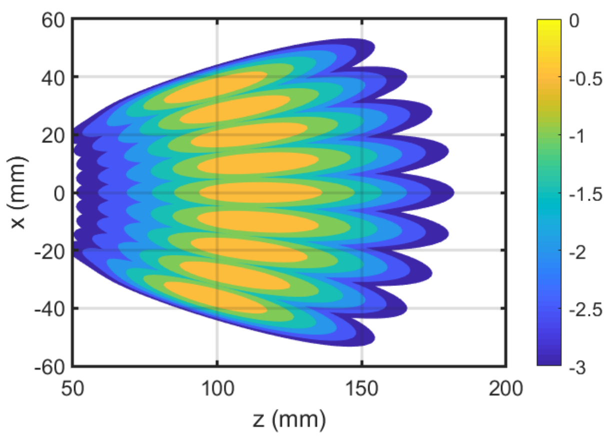
## A. Aim of the synthesis

Despite achieving a transmitarray that focuses all the incoming fields radiated by the different feeds, it is feasible to improve the performances of the design in terms of its focusing capacity namely, concentrating the power of the radiated field in a shorter area. Generally, this aim can be reached by using any optimization technique, which implies to take all the feeds into the synthesis process. Nevertheless, in this case the transmitarray synthesis can be carried out only considering the central feed, just as it happens in the previous design. Providing that the cluster is located within the position defined by (eq.)1, the improvements of the antenna after the optimizations will be valid for the whole cluster. Thus, the synthesis process reduces its complexity and the computational cost.

The generalized Intersection Approach is chosen to carried out a Phase-Only Synthesis (POS) of the phase distribution of Fig.4. This algorithm requires the definition of two templates that stablish the upper and lower limits within the near-field should be. In this case, the templates are defined for the $YZ$ cut ($x = 0$) that corresponds with the near-field shown in Fig.3. Then, the goal synthesis is the reduction of the area wherein the near-field power is focused, the templates define four different areas, setting the limits for the 1, 3, 6 and 10 dB near-field fall.




(a)




(b)

Fig. 5: Near-field generated by (a) the feeds placed in the $YZ$ plane (b) the feeds placed in the $XZ$ plane using the initial phase distribution.

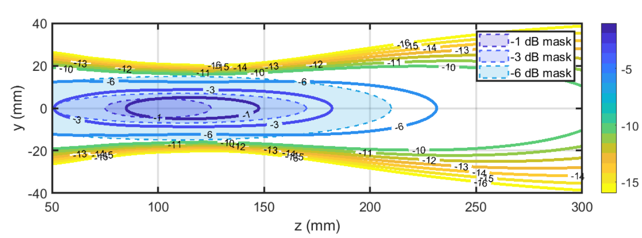



Fig. 6: Initial near-field for the central feed.

## B. Results of the optimized transmitarray

After 3600 iterations, the optimization process has reached a solution that satisfies the requirements, regarding that only the central feed is considered part of the process. Then, not only the central spot improvement is evaluated but also the focusing spots generated over the $YZ$ cut. The phase distribution obtained is shown in Fig.7.

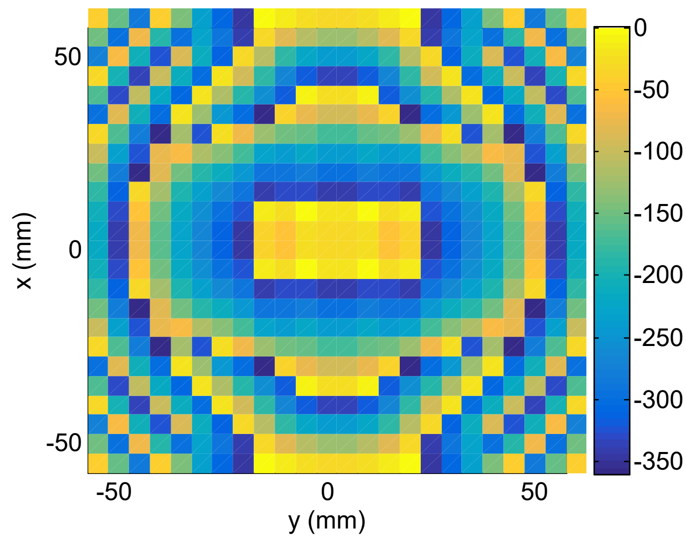



Fig. 7: Phase-shift distribution obtained as result of the optimization process of the near-field focused transmitarray.

Then, the near-field radiated by the phase-distribution obtained is shown in Fig.8, where it is feasible to verify that most of the near-field fulfils the level specifications. The fall at $-10$ dB is clearly where more point can be found outside the specifications. However, the near-field is on the whole more focused regarding the starting point (seeing Fig.6). Replacing

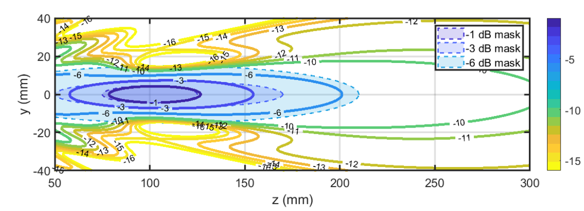



Fig. 8: Radiated near-field after the optimization process.

the central feed by the horn cluster, the near-field shown in Fig.9 is obtained. The improvement of the central feed is obviously extrapolated to the other feeds, achieving 9 different beams wherein the near-field is more focused than the beams generated by the starting point.

## V. Conclusions

A transmitarray antenna is proposed to be used in near-field scanning applications, working at 28 GHz. The antenna is feeding by a 2-D cluster that is spatially distributed, helping to reach a wider angular range. Thus, different regions wherein the near-field is focused can be obtained since each feed is working at the same frequency but different channel. The transmitarray is designed to focus the near-field of the central feed. However, the spatial distribution of the cluster allows to focus the other fields too. Then, in order to improve the focus performance of the transmitarry, an optimization is carried

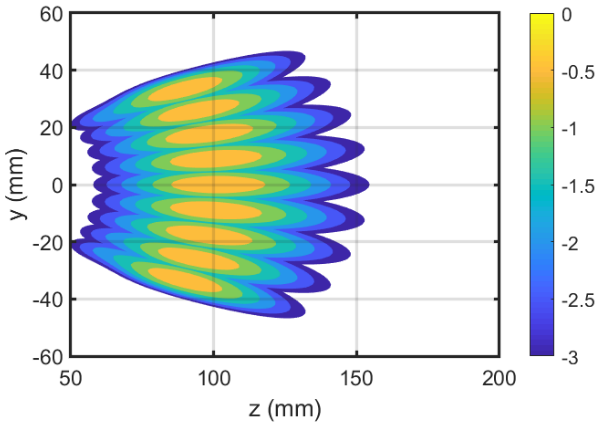



Fig. 9: Near-field generated by the horn cluster using the phase-distribution obtained as result of the synthesis.

out using the generalized Intersection Approach algorithm. Although the synthesis process is carried out just considering one feed, the results demonstrate an improvement for the whole cluster. Lastly, the results show that providing the feeds are located at certain locations, the results of an optimization only taking one feed into account are extrapolated to the whole cluster, avoiding a multi-position optimization.

## ACKNOWLEDGEMENT


This work was supported in part by the Ministerio de Ciencia, Innovación y Universidades under project TEC2017-86619-R (ARTEINE) and by the Gobierno del Principado de Asturias/FEDER under Project GRUPIN-IDI/2018/000191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