Achieving wide-angle mechanical beam steering in Ka-band with low-profile Transmit-array antennas

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***Abstract*— Beam scanning and high gain are fundamental requisites for antennas operating at millimeter wave, where many 5G and satellite-on-the-move applications are emerging. Mechanical beam steering using Transmit-arrays (TAs) has been proposed as a viable alternative to the more costly and complex electronic-based solutions. As a spatially fed array, TAs operate with a minimal focal length, distance between the primary source and the radiating aperture, which impacts on the overall size of the antenna. The focal length also limits the maximum scanning range that can be achieved through a linear displacement of the primary source parallel to the aperture (a common mechanical scanning approach using TAs). In this work, an iterative method for optimizing the unit cells distribution in the aperture for low F/D (focal length over aperture ratio) is presented. This approach allows extending the scanning range of the common unifocal TA phase distribution. To validate the proposed method, a TA with F=50 mm and in-plane dimensions 195x145 mm (F/D = 0.34) operating at Ka-band (30 GHz) was designed. The full-wave results show that this antenna as a 3 dB scanning range of [-59º,59º], with a maximum gain of 26.3 dBi at 30 GHz and SLL < -11.7 dB.**

***Index Terms*— Transmit-arrays, Low-profile, Mechanical Scanning, Ka-band, satcom, 5G, spatially fed array.**

I. INTRODUCTION

The production of low-cost compact beam scanning antennas at millimeter waves assumes a central role for the development of the next generation of mobile and satellite communications. Phased-arrays are a popular solution for electronical beam scanning due to their flexibility, low profile and mature production process [1]. However, the power consumption and losses of the associated feeding networks and active components makes this solution less efficient. Quasi-optical solutions, and in particular reconfigurable reflectarray (RA) and transmitarray (TA) antennas, have recently attracted an important attention [2]-[4], as in both cases it is possible to avoid the aforementioned complex feeding networks. The beam scanning is obtained by switching the states of controlling devices, such as MEMs, PIN diodes, or by tunable materials integrated in the elements, such as liquid crystals. This type of solutions is still more costly and complex to implement than mechanical scanning approaches based on passive reflective or transmitting apertures. A TA configuration allows avoiding the feed blockage in centered optics configuration that is inherent to the RA counterpart. Nevertheless, other limitations need to be tackled, such as multiband operation [5], wide beam steering [6] and antenna height. In [6], a TA with an offset Fresnel phase correction was designed for wide beam scanning through only in-plane mechanical movements (which does not impact on the antenna height). The focal length used in this work was chosen as a compromise between antenna height and scanning aberrations. Further reducing the focal length requires finding a new phase correction for the TA that can better cope with the beam distortions caused by the feed displacement. The use of multifocal lens for wide beam scanning is a popular research topic in literature [7]. However, this theory cannot be applied directly to TAs due to the intrinsic flat geometry of the aperture. In [8], a bifocal design was introduced by means of two TAs. In [9] a bifocal TA phase correction was defined by a weighted average of two unifocal phase corrections, creating two pseudo-foci instead of well-defined focal positions. In [10] a parabolic ansatz for the TA phase distribution was used for minimizing the phase error for a 4-beam antenna. In [11] a quadrifocal phase distribution was used to achieve wide beam scanning considering that the source moves along the lens focal arc and for a high *F/D* ratio ($F/D = 1$). As far as the authors are aware, there is still lacking a general approach for designing TA antennas capable of combining wide beam scanning and low focal distance ($F/D < 0.4$). Existing approaches rely on blind optimization processes conditioned by the considered ansatz (bifocal, quadrifocal, parabolic) and thought only for a specific design.

In this work, we propose a general method to address this problem. In summary, the method consists of constructing the TA phase correction iteratively by gradually perturbating the solution with the addition of new pseudo-foci, which provides a global minimization of the phase errors accounting for multiple source positions. The iterative nature of the method allows the TA phase correction to follow the natural scanning trend of the considered solution, which cannot be known a priori. In addition to the obvious advantage of reducing the antenna height, working with a lower focal distance implies that the primary source can have lower gain, which further contributes for reducing the antenna complexity. For a better comparison with the more conventional approaches used in [6], we consider, as the design example, a TA with the same aperture dimensions ($195 \times 145\ mm$) and unit cells but with half of the focal length ($F = 50\ mm$). The corresponding mechanical scanning approach is shown in Figure 1. Through full-wave simulations [1] we confirm the improvement predicted by GO-PO analysis on the overall scanning performance of the antenna: 3 dB scanning range up to 59º, with a maximum gain of 26.3 dBi at 30 GHz and side lobe level (SLL) below -11.7 dB for all beams.

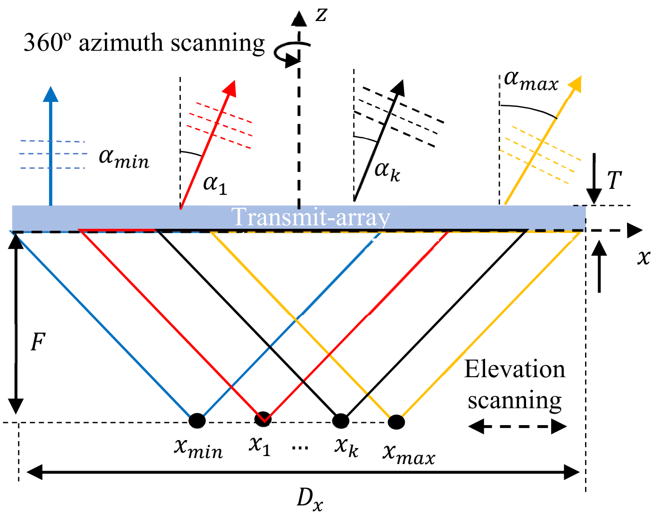

Figure 1 Working principle of the mechanical scanning approach. For the presented design examples, we consider $D_x = 195\ mm$, $D_y = 145mm$ and $F = 50\ mm$ $\left(\frac{F}{D} = 0.34\right)$, $\alpha_{max} = 50°$ corresponding to a scanning range of $[-50°, 50°]$ in zenith and [0º,360º] in azimuth for the operating band $[29.5, 30.0]\ GHz$ (Ka-band)

II. MULTI-FOCAL TRANSMITARRAY DESIGN

Ideal collimation is achieved when the phase distribution of the outgoing fields on the aperture is given by

$$g_{ap}^{\alpha} = \phi_{lens} + \phi_{in}^{x_s} = -k_0 \sin\alpha\, x \tag{1}$$

where $x_s \in [x_{min}, x_{max}]$ is an arbitrary position of the source along the x direction and α is the corresponding beam offset (Figure 1). In the context of a single flat passive aperture and impinging spherical wave front, perfect collimation can only be exact for a single source position ($x_s = x_0$), the lens focus $P = (x_0, 0, -F)$. Considering a prescribed beam offset α_0 it follows from (1) the unifocal Fresnel correction used in [6]

$$\phi_{lens}^{x_o} = k_0\sqrt{(x - x_0)^2 + y^2 + F^2} - k_0 \sin\alpha_0\, x \tag{2}$$

The linear term of the phase error caused by the displacement of the feed relative to the focus position provides beam steering capability, however, it is limited by the aberrations that build up with this displacement [6]. These aberrations rapidly become the limiting factor for achieving wide beam scanning when low *F/D* values are considered. In Figure 2, using GO-PO analysis, we show how the design (1) performs for a $F/D = 0.34$ (value that will be considered for our multifocal design example). As expected, the maximum gain (32.7 dBi) is obtained for the prescribed beam offset $\alpha_0 = 32°$ when the feed is placed at the lens focus. However, the aberrations caused by the feed displacement greatly limit the scanning performance of the antenna. The 3 dB scanning range window is now [-15º,46º] with high SLL (up to -5.6dBi) and the scan loss to achieve boresight is 6 dB. Clearly aberrations are the main cause for the gain reduction, overshadowing the natural scan loss of planar apertures given by the projected aperture factor $\cos\alpha$, that for a 32º to 46º scanning would only correspond to a 0.9 dB gain drop. This case contrasts with the unifocal design presented in [6], where a higher focal distance was considered, $F/D = 0.7$, which provides a 3 dB scanning range of [0, 50º] with SLL below -10 dB.

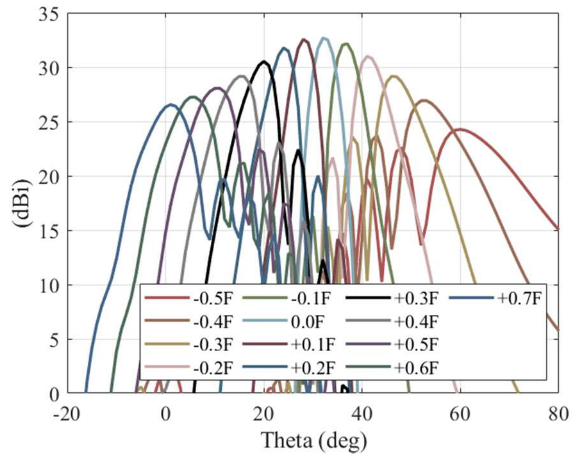

Figure 2 – Simulated results with GO-PO of the scanning performance of the unifocal TA design with $\alpha_0 = 32$, $\sigma = 44.8\ mm$ (corresponding to τ_{dB} =10 dB).

A first approach to circumvent this problem it to define the lens phase correction as a weighted average of K unifocal corrections with displaced focus x_i (henceforward designated as the pseudofocus of the lens)

$$\phi_{lens} = \frac{\sum_{i=1}^{K} W_i \phi_{lens}^{x_i}}{\sum_{i=1}^{K} W_i} \tag{3}$$

where the Gaussian weight factor reflects the area of the lens that is being illuminated when the feed is at a given position

$$W_{x_i} = \exp\left(-\frac{(x - x_i)^2 + y^2}{2\sigma^2}\right) \tag{4}$$

The case where $K = 2$ corresponds to the bifocal design presented in [9]. The standard deviation of the Gaussian illumination σ is directly related to the edge field taper level (in dB), τ_{dB}:

$$\sigma = \frac{D}{\sqrt{\frac{2}{5}\tau_{dB}\ln 10}} \tag{5}$$

The compromise between aperture efficiency, SLL, and spillover results that taper levels, τ_{dB}, typically range between 10 and 20 dB. According to (5), for the D=145 mm aperture dimensions considered herein results that $\sigma \in [47.8, 33.8]$ mm. A more exact value for this parameter can be retrieved from fitting the Gaussian profile (4) to the primary source radiation pattern.

In (3) it is implicit that the exit angles α_i, corresponding to each unifocal correction, are known *a priori*. However, α_i depends on the phase correction of the lens itself, which makes (1) a much more intricate equation that what may seem at first glance. Moreover, it is not known what number of unifocal corrections, K, should be used in (3). As such, we propose an iterative approach to tackle this problem, which is depicted in Figure 3 as a flowchart. The inputs of the approach are the set of pseudofocus positions x_i, their corresponding pointing directions α_i, and the maximum scanning range α_{max}. These variables are initialized considering a centered optics transmitarray radiating a beam pointing to α_{ini}. For every (x, y) point in the aperture and in each iteration K, ϕ_{lens}^{K} is computed by finding the phase correction that minimizes the following expression considering the set of (x_i, α_i) pairs obtained in the previous iteration

$$\left(\delta_K = \sum_{i}^{K} W_{x_i}\left|\phi_{in}^{x_i} + \phi_{lens}^{K} - g_{ap}^{\alpha_i}\right|\right)_{min} \tag{6}$$

Then, x_i is updated according to the paths shown in Figure 3. The perturbation step for the pseudofocus positions is set to $0.1F$. For the current ϕ_{lens}^{K}, the performance of the transmitarray is evaluated for all the pseudofocus positions given by the vector $\boldsymbol{x_K}$. The method for retrieving the radiation pattern of the transmitarray can be GO-PO or full-wave based. From the radiation pattern, the vector $\boldsymbol{\alpha_K}$ is updated with the new pointing directions. Finally, if the scanning range $[0, \alpha_{max}]$ is contained in the interval defined by the extremes of the set $\boldsymbol{\alpha_K}$, the process stops. Otherwise, the process continues evaluating again (6).

The method relies on the rational that the phase correction of the TA converges to the natural scanning promoted by the feed displacement by means of small perturbations. We found that $0.1F$ is a good perturbation step, however, other values can be considered. It is also important to stress that the cost function (6) does not assume that ϕ_{lens}^{K} needs to be continuous. Thus, we can adjust this method to any set of unit cells that can only provide a discrete number of phase states. This allows to incorporate in this optimization method the intrinsic discretization error of any set of unit cells.

In Figure 4 we show the radiation patterns obtained by PO-GO simulations following from the multifocal design process with K = 11, starting from the unifocal case of Figure 2 ($\alpha_0 = 32$, $\sigma = 44.8$) and aiming at a maximum scanning range of $\alpha_{max} = 50°$. Beam steering up to 53 degrees with a SLL below -11.8 dB and 2.6 dB of scan loss is achieved. The 360º azimuth scanning is obtained by rotating the complete antenna system, as explained in [6]. Given that in the multifocal approach there is never an ideal collimation for any feed position, the maximum gain of this approach (31.6 dBi, in this example) will be always lower than the maximum gain of the unifocal design (32.7 dBi in Figure 2). Nonetheless, the multifocal approach provides a significant improvement on the overall scanning performance of the antenna. This result highlights the tradeoff between the maximum gain and scanning range, which becomes more acute when lower focal distances are considered.

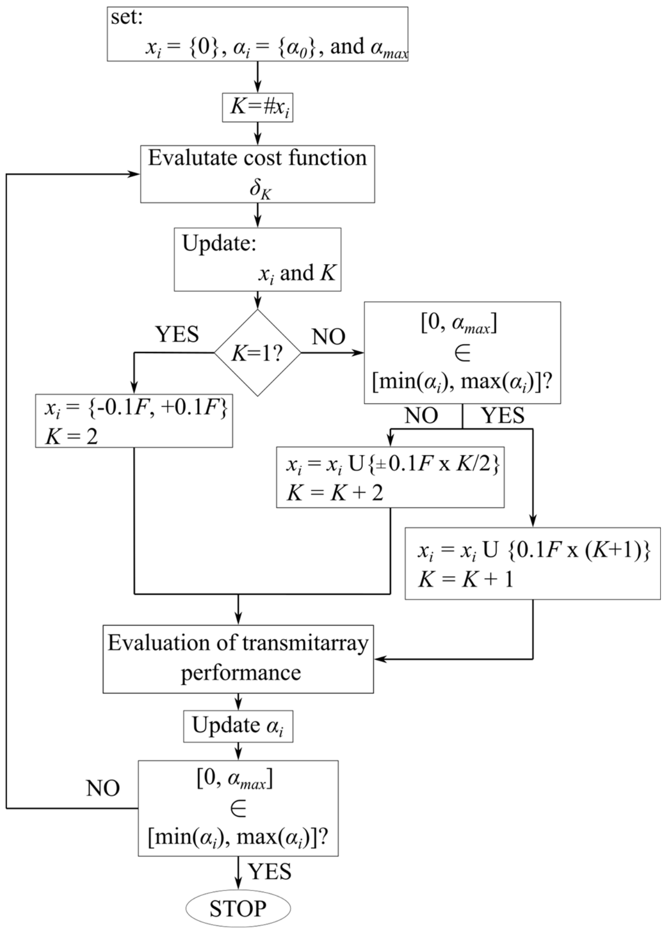

Figure 3 – Flowchart of the iterative approach for multifocal TA design.

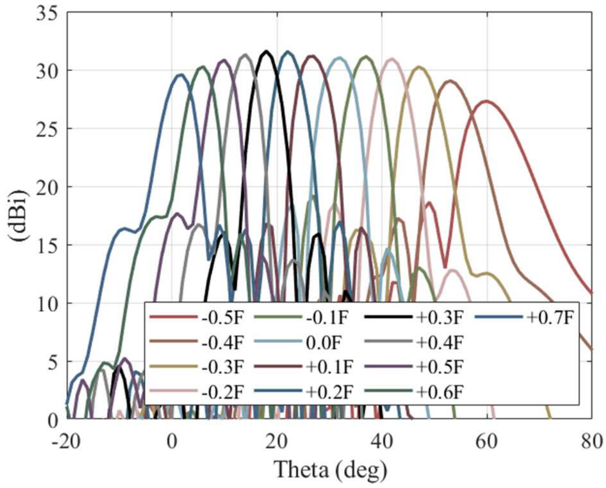

Figure 4 – GO-PO simulation of the scanning performance of the multifocal TA design ($K = 11$) with $\alpha_0 = 32°$, $\sigma = 44.8$ mm (corresponding to τ_{dB} =10 dB).

III. FULL-WAVE VALIDATION OF THE PROPOSED METHOD

In [6], the reduction of the antenna height was achieved by means of an intermediate small TA that creates a closer phase center of the primary source (a 8 dBi patch antenna @ 30 GHz), as shown in Figure 5 a). This more complex feeding system (patch and small lens) allows reducing the effective focal length of the antenna to 80 mm while using the unifocal TA phase correction (*2*) with $F = 100$ mm. Herein, we show that with the multifocal approach (Section II) it is possible to work with a focal length of $F = 50$ mm without the intermediate lens and considering the same aperture size and TA unit cell. In Figure 6, we show, using full-wave simulations, that a unifocal phase correction with $F = 50$ mm provides a maximum gain of 27.7 dBi but very limited beam scanning capability.

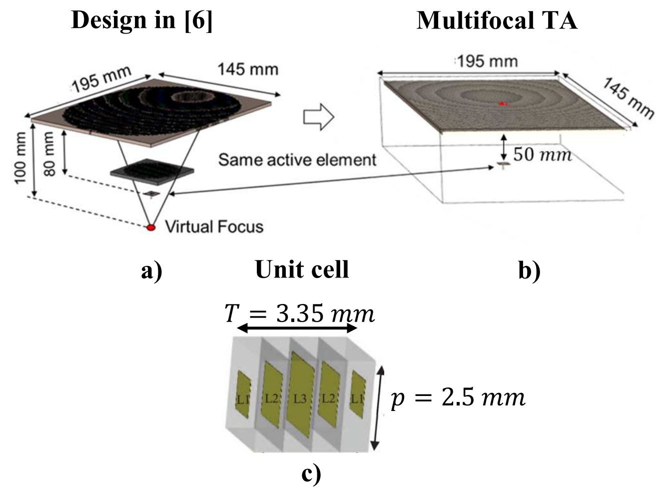

Figure 5 – Applying the multifocal design approach (b) for further reducing the antenna height of the design proposed in [6] (a) using the same unit cells (c).

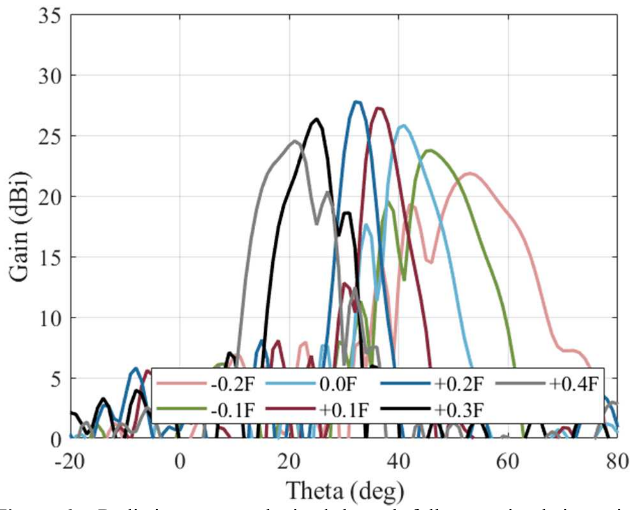

Figure 6 – Radiation pattern obtained through full-wave simulation using the unifocal phase correction (2) with $\alpha_0 = 32.5°$ and $F = 50\,mm$ for a linear feed displacement $[-0.4\,, 0.2]F$ and F/D=0.34.

To overcome this limitation, we apply the iterative process proposed in Section II with the inputs: $\tau_{dB} = 12$ dB (it corresponds to the open-ended waveguide feed), $\alpha_0 = 32°$ and $\alpha_{max} = 50°$. TABLE 1 presents the iterative process for constructing the set of beam pointing directions α_i. In TABLE 2, the corresponding main figure of merits obtained during the iterative process are shown. In Figure 7 the full-wave results are given for the final multifocal design (K = 11). Scanning up to 52 degree becomes possible with a scan loss of 1.8 dB and SLL below -11.7 dB. The maximum gain of the multifocal antenna is 26.3 dBi, 1.5 dB lower than that of the unifocal case (Figure 6), which is expected as all beams are slightly defocused (pseudo-focus). In TABLE 3 we compare two unifocal designs (the cases of [6] where F/D=0.69 and Figure 6 where F/D=0.34) with the proposed multifocal approach considering the same aperture size, unit cells and primary source. In [6] the focal distance was minimized for the intended scanning range ($\alpha_{max} = 50°$), hence, considering lower *F/D* values will significantly degrade the scanning performance of the antenna (Figure 6). Reducing the focal distance also impacts the maximum gain of the unifocal TA antenna (1.1 dB in the given example), as the required phase correction has faster phase variations and more 360º phase transitions. The multifocal approach allows to further reduce the antenna height while improving the scanning range and SLL performance of the antenna. The trade-off between scanning range,antenna height and antenna gain is well captured in TABLE 3.

TABLE 1 – Iterative construction of the set $\boldsymbol{\alpha_i}$ according to the design multifocal design process of Section II.

x_i/F	-0.4	-0.3	-0.2	-0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.7
α_i	α_9	α_7	α_5	α_3	α_2	α_1	α_4	α_6	α_8	α_{10}	α_{11}
K=1				37	28						
K=2			42	37	27	23					
K=4		48	42	37	27	23	19				
K=6	53	47	42	37	27	23	19	15			
K=8	53	47	42	37	27	23	19	14	10		
K=10	52	47	42	37	27	22	18	14	9	5	
K=11	52	47	42	37	27	22	18	14	6	2	-3

TABLE 2 – Iterative GO-PO assessment of the TA performance according to the method described in Section II.

	Min SLL [dB]	**Scanning Range [°]**	**Scan Loss [dB]**	**Max Dir. [dBi]**
K=1	-5.6	46	6.0	32.7
K=4	-7.9	51	4.0	31.9
K=6	-10.0	50	3.6	32.1
K=8	-11.5	51	2.9	31.8
K=9	-11.1	51	2.2	31.3
K=10	-11.1	55	4.3	31.5
K=11	-11.8	51	2.6	31.6

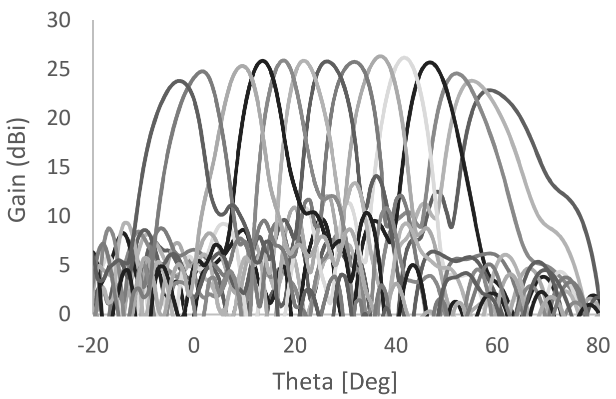

Figure 7 – Radiation pattern obtained through full-wave simulation using the multifocal correction (k=11) with $\alpha_0 = 32.5°$, $\alpha_{max} = 50°, \tau_{dB} = 12,$ and $F = 50\,mm$ for a linear feed displacement $[-0.5\,,0.28]F$ and F/D=0.34.

TABLE 3 – Comparison of the main figure of merit between unifocal designs and the multifocal approach.

Design	*F/D*	*SLL*** (dB)	α_{max}(°)	*Gain* (dBi)**	*3dB Scan* (°)
[6]*	0.69*	< -10.1	49.5	26.1-28.9	[0,50]
Unifocal	0.34	< -4.2	53.0	21.9-27.8	[21,46]
Multifocal	0.34	< -11.7	52.0	24.6-26.3	[0,59]

* Virtual Focus approach (Figure 5a) result in an effective $F'/D = 0.55$.

** Considering the scanning interval $\alpha < \alpha_{max}$

IV. Conclusions

In this work, a novel technique to design wide-angle scanning transmitarray antennas was introduced. This technique allows designing high-gain wide-angle scanning transmitarrays with a low focal length to aperture diameter ratio resulting in a cost-effective solution for compact terminals. The design approach was validated through the design of a transmitarray of dimensions 195×145 mm, a $F/D \cong 0.34$ and an in-plane displacement of the feed of 55 mm. We show by comparing with a previous design example a significant improvement of the scanning performance of conventional single-focus phase correction using a low complex antenna configuration.

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