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Research Article

Main Lobe Control of a Beam Tilting Antenna Array Laid on a Deformable Surface

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The projection method (PM) is a simple and low-cost pattern recovery technique that already proved its effectiveness in retrieving the radiation properties of different types of arrays that change shape in time. However, when dealing with deformable beam-tilting arrays, this method requires to compute new compensating phase shifts *every time* that the main lobe is steered, since these shifts depend on *both* the deformation geometry *and* the steering angle. This tight requirement causes additional signal processing and complicates the prediction of the array behavior, especially if the deformation geometry is not a priori known: this can be an issue since the PM is mainly used for *simple and low-cost systems*. In this letter, we propose a simplification of this technique for beam-tilting arrays that requires only basic signal processing. In fact the phase shifts that we use are the sum of two components: one can be directly extracted from strain sensor data that measure surface deformation and the other one can be precomputed according to basic antenna theory. The effectiveness of our approach has been tested on two antennas: a 4×4 array (trough full-wave simulations and measurements) and on an 8×8 array (trough full-wave simulations) placed on a doubly wedge-shaped surface with a beam tilt up to 40 degrees.

1. Introduction

Recently many wireless communication systems have raised the need of developing antenna arrays capable of adapting to surfaces that change shape in time: this can be the case of simple wearable devices that monitor health and fitness parameters and that are placed on body parts that move and bend (e.g., wrists, ankles, and knees). The main issue related to the design of this type of antennas consists in the control of the radiation pattern that results significantly altered as a consequence of the array deformation. In order to overcome this problem, many different pattern recovery approaches can be adopted, from very accurate and expensive ones to cheaper and simpler ones. We will focus on this second class of techniques that is particularly appealing for simple and cheap wearable devices whose main requirement is to keep the product cost as low as possible.

Among these pattern recovery techniques, a popular one is the projection method (PM) that exploits only strain sensors and phase shifters to retrieve the main radiation properties of deformable arrays [1], thus avoiding the use of extensive signal processing, narrow-band correction algorithms, and potentially complex sensor networks that are instead required by more accurate and expensive solutions (e.g., mechanical [2] and electrical [3, 4] compensation). The projection method effectiveness was thoroughly studied for many types of antennas, as, for example, 1×4 and 1×6 linear arrays placed on surfaces that change shape in time [5–7] and planar arrays subject to cylindrical [8], spherical [9], and asymmetrical [10] surface deformations. All the aforementioned works adopt the PM in order to recover the pattern of *broadside* arrays, but a common requirement when dealing with phased arrays is to dynamically steer the main lobe towards different desired directions. Some works dealt also with this issue: for example, in [11], the effectiveness of the PM is evaluated for a beam-tilting linear 1×5 array placed on a wedge-shaped deformable surface.

The main issue of the PM when applied to beam-tilting arrays is related to the fact that it requires the correcting phase shifts to be a function of *both* the surface deformation *and* the main lobe direction. This is because the phase shifts introduced in the elements have two purposes in this case: *compensating* the array deformation and *steering* the beam towards a desired direction. Therefore, it can be seen how the PM is formulated in order to *tilt* the beam of an array taking into account (i.e., compensating) the array deformation; it is not used to retrieve the pattern of a deformed array whose main lobe has *already* been tilted towards a specific direction. This fact complicates the overall system since the phase compensation in this case cannot be simply extracted by the strain sensor data that measure the geometrical deformation (unless this is a priori known): an additional signal processing step is required in order to *project* the array elements onto a new reference plane *every time* that the beam is tilted towards a different direction. In [11], this was not an issue since the deformation geometry was quite simple and a priori known, and therefore, also the analytical relation that linked the phase shifts to the geometrical deformation and to the tilting angles was a priori given, but as soon as the deformation becomes slightly more complex (as the one we present here) and/or a priori *unknown*, the computation of the correcting phase shifts becomes cumbersome. This is because the shifts cannot be directly computed from the strain sensor data anymore, because a new *analytical* relation between surface deformation and the direction of maximum and compensating phase shifts must be formulated for *each* main lobe direction and for *each* possible geometrical deformation.

Since we are assuming that this type of arrays is used for simple and cheap devices, we are interested in keeping the overall system complexity and the cost as low as possible. Therefore, we decided to express the correcting phase shifts as the sum of two independent terms: one related to the geometrical deformation and one related to the main lobe direction. Doing so, it is possible to simplify the system reducing the amount of signal processing required: in fact, the first term can be directly extracted from strain sensor data that measure surface deformation, while the second component can be easily precomputed through basic antenna theory.

As we will show in the next sections, this approach allowed us to recover the main radiation properties of a doubly wedge-deformed planar array when its beam is tilted up to 40°.

2. Theoretical Framework

In order to explain and test our approach, we consider a 4×4 planar array, whose elements are patch microstrip antennas resonating at 2.48 GHz. We will refer to array rows and columns as those sets of elements sharing, respectively, the same y- or x-coordinate (refer to Figure 1 for axes orientation). The array is placed on a surface which is subject to a doubly wedge-like geometrical deformation as depicted in Figure 1:

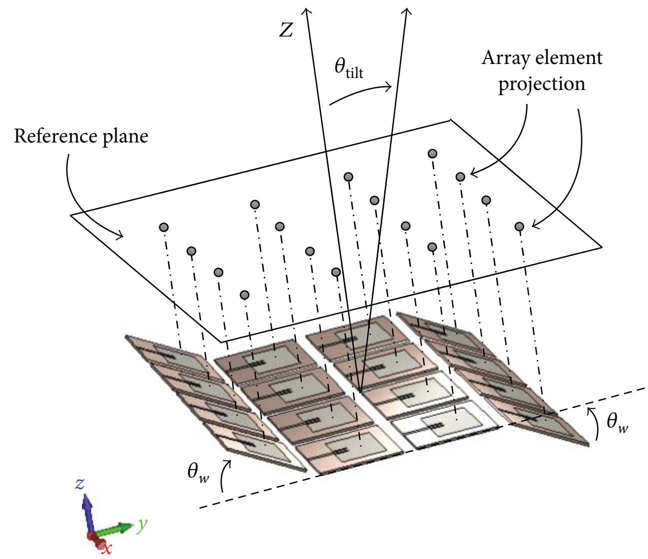

Figure 1: Investigated surface deformation.

the first and last rows of the array are tilted of θ_w degrees. As a consequence of the surface deformation, the array radiation pattern is distorted (as it will be shown in the followings), that is, the main lobe decreases in gain, and shifts in direction. We will focus only on this particular geometrical deformation as we assume that the array beam is tilted faster than the speed at which the deformation changes shape: this scenario makes it easier to test the validity of our approach.

Let us assume now that we want to steer the beam of this array of θ_{tilt} degrees in the yz-plane. In order to do this avoiding excessive pattern distortion, according to the PM (projection method) [11], we must apply phase shifts that take into account *both* the geometrical deformation of the antenna *and* the desired main lobe direction. These phase shifts are computed *projecting* the array elements onto the *reference plane*, that is, the plane chosen among the infinite ones orthogonal to the desired direction of the maximum (see Figures 2 and 3): they are proportional to the distance of the elements from the reference plane so that the signals coming from different array elements will arrive with the same phase on this plane.

Referring to Figures 2 and 3, and assuming $\theta_{tilt} = 0$, the deformed array is operating in *broadside* mode, and therefore, the reference plane must be chosen among the planes that are parallel to the xy-plane: for example, in Figure 3, the reference plane is represented above this plane in order to stress the fact that *any* of these planes can be chosen as the reference one. For example, a straightforward choice is to pick exactly the xy-plane: in this way, the distances of the array elements from it are simply given by their z-coordinates.

In particular, if strain sensors between adjacent antennas are used to measure the surface deformation, then the distance of the elements from the xy-plane can be directly computed from the sensor data [5]: no analytical expression of this distance in the function of the deformation geometry must be provided.

However, if the main lobe is tilted towards a different direction, then the reference plane will be tilted as well (see Figure 2), and this implies that the distances between the

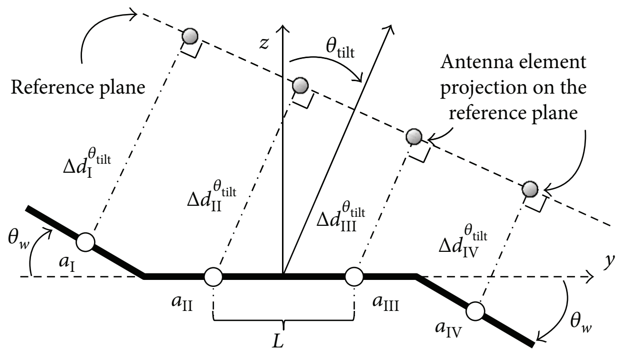

Figure 2: Representation of the pattern recovery with the PM for a deformed 4×4 array whose beam is tilted of θ_{tilt}: the reference plane is chosen among the infinite ones perpendicular to the direction of the maximum θ_{tilt}, and phase shifts related to the distances $\Delta d_n^{\theta_{\text{tilt}}}$ are introduced in the nth element (see Section 2).

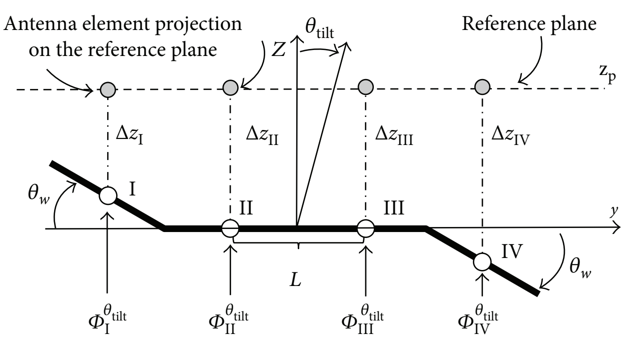

Figure 3: Representation of the pattern recovery with our technique for a deformed 4×4 array whose beam is tilted of θ_{tilt}: the reference plane is chosen as if the array were operating in *broadside*, and correcting phase shifts $\Phi_n^{\theta_{tilt}}$ (different with respect to the one given from the PM) are introduced in the nth element (see Section 2).

elements and the new reference plane cannot be simply evinced from the information provided by the strain sensors. Consequently, an analytical relation linking the correcting phase shifts to the geometrical deformation and to the *tilted* reference plane must be introduced as it has been done in [11]. Now, this can be easily done if the geometrical deformation is simple or a priori known (as it was in [11]), but if this is not the case, then it can be difficult to evaluate the compensating phase shifts, since an analytical expression of these quantities must be available for *each* geometrical deformation and for *each* steering angle.

Our goal is to keep the system complexity as low as possible, and therefore, we want to show that it is possible to retrieve the array radiation pattern even if we skip this last signal processing step that requires the computation of a new analytical relation *every time* that either the steering angle or the surface deformation changes. In order to do this, we express the overall phase shift to be introduced into the nth element (see Figure 3) as the sum of two terms:

$$\phi_n^{\theta_{\text{tilt}}} = \alpha_n^{\text{corr}} + \alpha_n^{\theta_{\text{tilt}}}, \tag{1}$$

where $\alpha_n^{\text{corr}} = k\Delta z_n^{\text{broad}}$ are the terms that have the function of *correcting* the surface deformation and coincide with the phase shifts required by the PM to retrieve the pattern of the *broadside* array (they are given by the product between the wave vector k and Δd_n in Figure 3), while $\alpha_n^{\theta_{\text{tilt}}}$ is simply the phase shift that must be introduced into the nth element of the *undeformed* planar array in order to steer its main lobe into the desired direction. The first term can be directly computed from the strain sensor data that measure surface deformation, while the second term can be easily precomputed for a set of angles of interest according to basic antenna theory [12] and stored in a small memory or look-up table into the device. Therefore, with this approach, no analytical expression of the phase shifts in the function of the geometrical deformation and of the steering angle is required and no further processing steps are necessary.

Let us make a comparison between the two approaches in terms of correcting phase shifts. As far as the PM is concerned, we will refer to the geometrical deformation represented in Figure 2. Among the infinite planes orthogonal to the direction of the maximum, we choose as the reference one the plane that is touching element a_{IV} (in Figure 2, we actually chose to depict another reference plane, further from the array, for ease of read of the figure). The correcting phase shifts ψ_n, $n = 1, \ldots, 4$ to be introduced into elements $a_{\text{I}}, \ldots, a_{\text{IV}}$, respectively, are a function both of the geometry of the deformation and of the steering angle, and they are given by

$$\begin{aligned} \psi_4 &= 0, \\ \psi_3 &= \frac{L}{2[\sin(\theta_{\text{tilt}} - \theta_w) + \sin(\theta_{\text{tilt}})]}, \\ \psi_2 &= \psi_3 + L\sin(\theta_{\text{tilt}}), \\ \psi_1 &= \psi_2 + \frac{L}{2[\sin(\theta_{\text{tilt}} - \theta_w) + \sin(\theta_{\text{tilt}})]}. \end{aligned} \tag{2}$$

As it can be noticed, this expression can be cumbersome to evaluate, especially considering that the geometrical deformation may not be a priori known and that it could further change in shape and become even more complex than the one presented here (e.g., it could change to a three-dimensional deformation as the one studied in [10]).

According to our approach instead, the overall phases to be applied to the elements are given by the sum of two terms that can be evinced from sensor data and precomputed. The terms responsible for the deformation compensation are given by $\alpha_4^{\text{corr}} = -\alpha_1^{\text{corr}} = 45^\circ$ and $\alpha_2^{\text{corr}} = \alpha_3^{\text{corr}} = 0^\circ$, while those responsible of tilting the beam towards a set of sample directions are given in Table 1 and have been computed according to [12]. As it is shown in the next section, this approach proves to be effective in recovering the radiation pattern of the conformal array when the main lobe is tilted from $\theta_{\text{tilt}} = 0^\circ$ up to $\theta_{\text{tilt}} = 40^\circ$.

3. Experimental Results

3.1. Four-by-Four Element Array. Our experimental set-up consisted of a planar array capable of steering the beam along

Table 1: Beam steering phases.

Beam steering phases	Array *i*th row	θ_{tilt}			
		0°	15°	25°	40°
$\alpha_n^{\theta_{\text{tilt}}}\,(^\circ)$	I	0	70	155	200
	II	0	20	65	65
	III	0	−20	−65	−65
	IV	0	−70	−155	−200

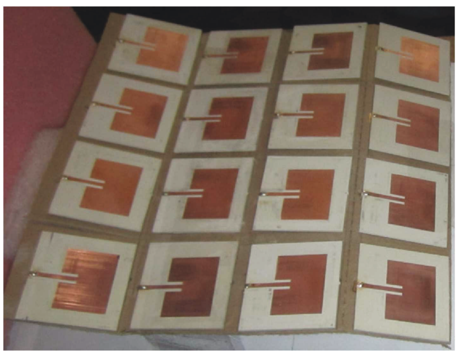

Figure 4: Fabricated 4×4 array prototype.

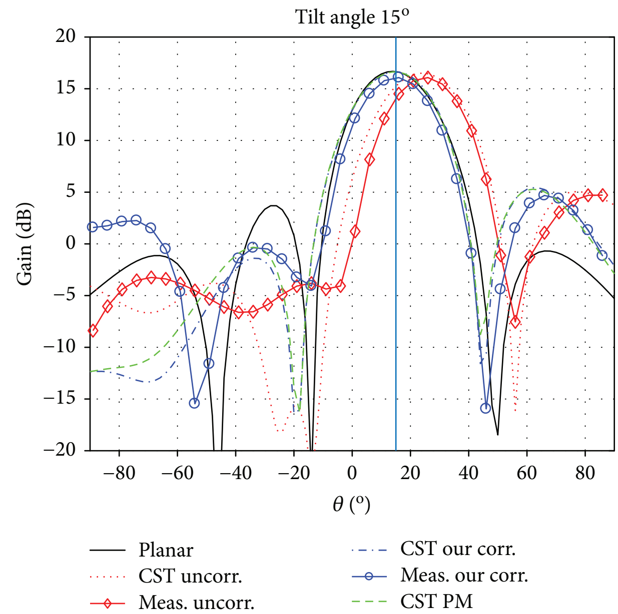

Figure 5: Simulated and measured 4×4 antenna gain: planar, uncorrected, corrected with our approach, and corrected with the projection method patterns on the *yz*-plane for $\theta_{\text{tilt}} = 15^\circ$.

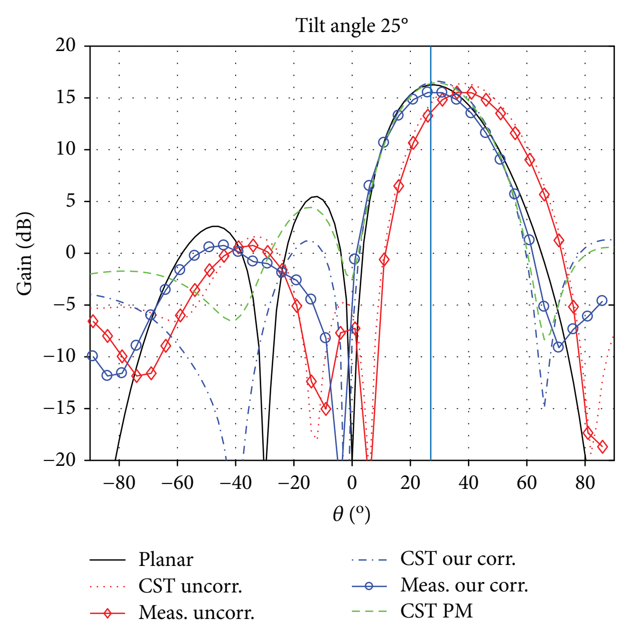

Figure 6: Simulated and measured 4×4 antenna gain: planar, uncorrected, corrected with our approach, and corrected with the projection method patterns on the *yz*-plane for $\theta_{\text{tilt}} = 25^\circ$.

the *y*-direction of θ_{tilt} degrees. The array is then placed on a surface that is deformed in a doubly wedge shape with $\theta_w = 30^\circ$ (see Figure 1). The radiation pattern of the *planar* array for different tilt angles ($\theta_{\text{tilt}} = 15^\circ, 25^\circ, 40^\circ$) is taken as the reference pattern to be retrieved. Full-wave numerical simulations were performed in CST Microwave Studio, and a prototype of the 4×4 array was fabricated and measured in an anechoic chamber (Figure 4 reports a picture of the realized prototype). The phase of each patch antenna was controlled through a phase shifter (Hittite: HMC928LP5E).

Each of the Figures 5–7 contains four graphs: the radiation pattern of the planar array (i.e., our target to retrieve), the distorted pattern of the deformed array, the pattern corrected according to our approach, and the pattern corrected according to the current formulation of the PM (see the previous section). For the last three graphs, both numerical and measurement results are shown. From all the three figures it can be seen how the geometrical deformation results in pattern distortion with respect to the planar array: the main lobe is shifted of approximately 10° and its magnitude is reduced of about 1 dB; moreover, at some frequencies where the planar array has a null, the deformed array has instead a considerably high gain value (e.g., when $\theta_{\text{tilt}} = 15^\circ$, the planar array gain has a zero at $\theta = 45^\circ$, the one of the deformed array is still between 5 dB and 10 dB). We can compare our approach to the PM by noting that it is still effective in retrieving the main radiation feature of the deformed array; that is, it is able to shift the main lobe back to the desired direction. It is also able to reduce the gain value in correspondence of the nulls of the planar array, even if in this case the PM performs better.

As far as mutual coupling is concerned, this depends on the reciprocal distance and orientation of adjacent elements in the array, and therefore, we expect that it will depend also on the deformation geometry; for example, if the deformation is such that the main lobes of two adjacent antennas are tilted towards each other (as in the case of elements I and II in Figure 3), we expect a higher coupling (i.e., a higher value of $S_{\text{I,II}}$) with respect to the planar array; in a similar way, if the deformation is such that the main lobes of two adjacent antennas are tilted away from each other (as in the case of elements III and IV in Figure 3), we expect a lower value of

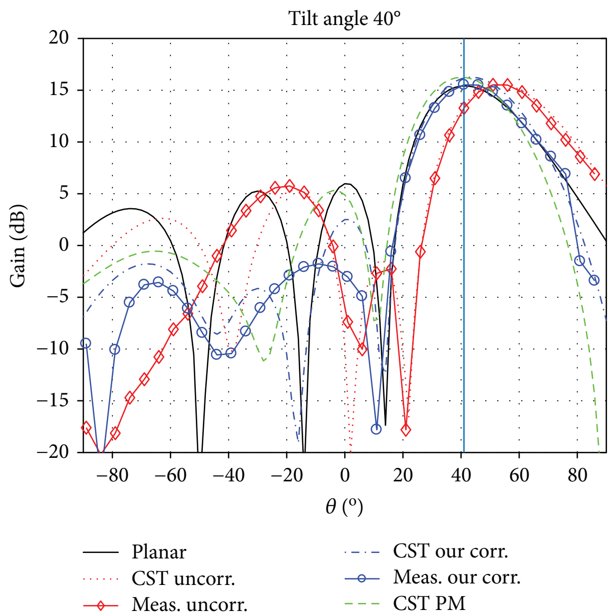

FIGURE 7: Simulated and measured 4×4 antenna gain: planar, uncorrected, corrected with our approach, and corrected with the projection method patterns on the yz-plane for $\theta_{\text{tilt}} = 40^{\circ}$.

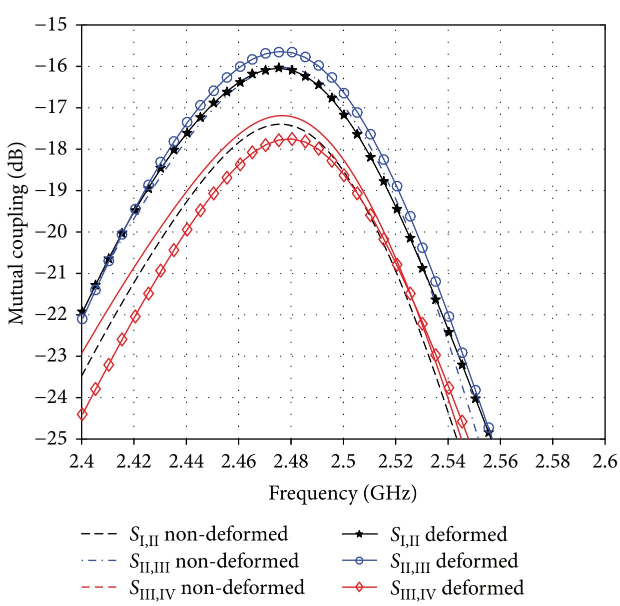

FIGURE 8: Relevant changes in mutual coupling effects after surface deformation of 4×4 array.

$S_{\text{I,II}}$ with respect to the planar array. Our guess is confirmed by the results reported in Figure 8. From this, we can notice that in this particular case, the mutual coupling level in the deformed array is similar to that in the undeformed array: this is again what we expected since adjacent antennas are not strongly tilted towards/away from each other. Therefore, we can say that mutual coupling is negligible in a *relative* way, that is, with respect to the planar array, recalling that our goal was not to get *low* coupling levels but to get coupling levels similar to the ones of the undeformed array.

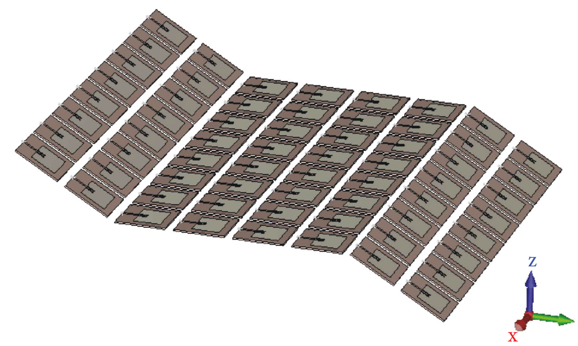

FIGURE 9: Investigated surface deformation for the 8×8 array.

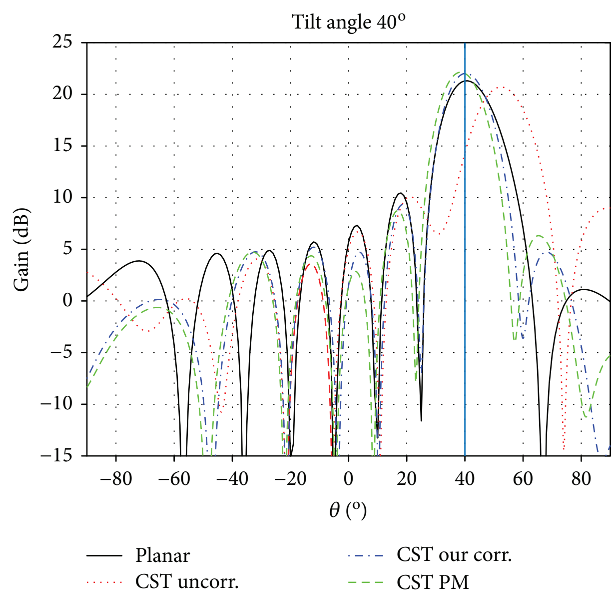

FIGURE 10: Simulated 8×8 antenna gain: planar, uncorrected, corrected with our approach, and corrected with the projection method patterns on the yz-plane for $\theta_{\text{tilt}} = 40^{\circ}$.

3.2. Eight-by-Eight Element Array. Our pattern recovery approach is valid also when dealing with larger beam-tilting arrays placed on a deformed surface. This has been proven through full-wave numerical simulations on an 8×8 array shaped according to a similar geometry (see Figure 9) with respect to the one presented in the previous section (see Figure 1). When beam-tilting weights are applied to the 64-element array, the radiation pattern is distorted and the main beam is not tilted towards the desired direction. Therefore, we applied our pattern recovery technique and compared it with the projection method in order to assess its effectiveness.

In Figure 10, the results are reported for the worst case scenario among the three discussed above: this is when the beam is tilted towards 40°. The reference pattern is the one of a planar 8×8 array that steers the beam in the desired direction: it can be seen again how our approach can retrieve the radiation pattern, and it is still valid when compared to the projection method.

4. Conclusion

In this work, we proposed a simplification of the projection method to retrieve the radiation pattern of beam-tilting antennas. The PM requires that the phase shifts are analytical functions of *both* the deformation geometry *S and* the main lobe direction, that is, $\psi_n = \psi_n(S, \theta_{\text{tilt}})$, thus requiring to provide an analytical formulation of these quantities for *every* geometrical deformation and for *every* steering angle. This introduces a further processing step and complicates the overall system. Our approach, instead, requires the computation of the phase shifts as the sum of two components: $\phi_n^{\theta_{\text{tilt}}} = \phi_n(S) + \phi_n(\theta_{\text{tilt}}) = \alpha_n^{\text{corr}} + \alpha_n^{\theta_{\text{tilt}}}$, where the first one is responsible for deformation compensation and the second one tilts the beam of the *planar* array towards the desired direction. The first term can be directly linked to the data acquired by simple sensors that measure surface deformation, and the second one can be precomputed according to basic antenna theory, so no analytical expression is required. We showed through full-wave numerical simulations and measurements that our approach is still effective in retrieving the radiation properties of a deformed array, providing a straightforward and cheap pattern recovery technique suitable for simple low-cost systems.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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