Nonplanar Tiled 1-bit Transmitarray with Phase Error Compensation

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Abstract. A phase compensation method for 1-bit phase quantized transmitarray is discussed. Using the tiled architecture of the transmitarray, the position of each unit cell is changed along the optical axis of the transmitarray. The spatial displacement allows changing the resulting phase distribution along the transmitarray aperture. Analytical calculations were performed to demonstrate the performance of the transmitarray radiation pattern.

1. Introduction

High-gain antennas is of practical interest for fifth-generation (5G) new radio communication systems that employ the use of both sub-6 GHz and beyond 24 GHz spectrum regions. Typically, the use of planar arrays with arbitrary control of the propagated wavefronts, and, in general, intelligent reflecting and transmitting surfaces, can be realized in conventional planar multi-layer technology using surface-mount RF components, e.g., switches and varactors allows providing an advanced functionality for communication and sensing systems. The 1-bit transmitarrays or reflectarrays are a common solution due to the simplicity of the design and fabrication. A sub-6 GHz prototype of the 1-bit tiled transmitarray were reported in [1, 2], whereby the required phase distribution across the array aperture built from standalone unit cells manufactured individually and assembled in the required pattern using a rectangular latticed plastic frame. The tiled architecture can be a viable solution for fast prototyping and teaching experiments, without significant performance deterioration, as compared with a similar single-panel transmitarray. Moreover, the possibility of replacing and adding in-dividual elements in the tiled array makes it both repairable and adjustable for a specific focal distance and feed type. Unfortunately, the effect of 1-bit phase quantization affect the antenna radiation performance. The phase quantization results in a gain reduction up to 4 dB, higher sidelobes, and a noticeable beam squint, [3]. At the same time, the effect of the phase quantization could be reduced by introducing some phase error compensation to each unit-cells. The concept proposed below is based on the theory of phase-compensated nonplanar antenna arrays, [4] and [5], as well as bears some resemblance to design of active Fresnel reflectors, [6], and adaptive millimeter-wave telescope optics, [7].

In this paper an approach based on analytical model optimization of the individual unit-cells displacement relative to the initial tiled planar array is considered. As a result of optimization of each unit-cells displacement the nonplanar tiled array provides efficient phase error compensating and more than 1 dB gain improvement.
2. Nonplanar transmitarray approach

Essentially, phase compensation can be implemented by displacing elements of the tiled transmitarray [2] with respect to their initial positions, resulting in a nonplanar transmitarray, Fig. 1. In a basic analysis of nonplanar antenna arrays, [3], it was noticed that the element orientation, i.e., whether the element beam patterns are normal to the conformal surface of the array or all point in the boresight direction of the array, can have some effect on the sidelobes, depending on directivity of the elements. In respect to the tiled transmitarray, tile tilting seems unfeasible and it would complicate the phase-compensation model, so that in the following analysis we employ longitudinal shift of the tiles along the optical axis of the transmitarray, Fig. 1.

Considering an \( M \times N \) element tiled transmitarray, Fig. 1, illuminated by a focal plane patch antenna at a distance \( d_f \), a small longitudinal shift \( d_{mn} \ll d_f \) along the \( z \)-axis of tile \((n, m)\) can be represented by a corresponding phase-shift, \( \delta_{mn}(\theta_0) \), in given by:

\[
\delta_{mn}(\theta_0) = k \left( \cos(\theta_0) - \frac{d_f}{\sqrt{d_f^2 + x_{mn}^2 + y_{mn}^2}} \right) d_{mn}
\]  \hspace{1cm} (1)

The element shifts \( d_{mn} \) in (1) can be calculated for a given steering angle \( \theta_0 \). An example of application of this analysis to a 10-element 1-bit linear transmitarray fed by a focal source emanating cylindrical wave is shown in Fig. 2.

Fig. 1 Planar tiled transmitarray with shifted elements providing correction of the phase quantization error.

Fig. 2 Phase error and the displacement of unit cells in a linear 10-element 1-bit transmitarray emitting at the boresight and feed by an isotropic source located at 2.5\( \lambda \) focal distance.
As a result of calculation, in the case of unit cells close to the geometric center of the transmitarray, the shifts required for phase error compensation exceed the focal distance. Such large element shifts will not give a tangible effect, since the electromagnetic wave will flow into the space freed up between the unit cells. Also, some of the cells will shade others from the focal source irradiating the transmitarray. In order to get reasonable tile shifts, the optimization procedure with certain constraints that define maximum values of the optimized tile shifts was used.

To achieve intermediate results, an approach based on analytical model optimization was chosen instead of optimization with full-wave electromagnetic simulations due to the speed of analysis. Analytical model of the nonplanar transmitarray radiation pattern could be described as follows:

\[
F(\theta, \phi) = \sum_{m=1}^{M} \sum_{n=1}^{N} A_{mn}(\theta, \phi) e^{j\Phi_{mn}(\theta, \phi)} e^{j\left(k(x_{mn}\sin\theta \cos\phi + y_{mn}\sin\theta \sin\phi + d_{mn}\cos\theta)\right)} \tag{2}
\]

where \(A_{mn}(\theta, \phi)\) and \(\Phi_{mn}(\theta, \phi)\) are the unit cell amplitude and phase patterns respectively, \(\phi\) and \(\theta\) are azimuthal and polar angles in the spherical coordinate system with the origin at the center of the transmitarray aperture and the polar direction aligned with the transmitarray optical axis.

Optimization results demonstrate more than 1 dB gain improvement compared to the flat transmitarray, Fig. 3, while different lower and upper bounds for tile shifts were used, Table 1. Gain improvement directly depends on the optimization boundary, but increasing optimization boundaries influence parasitic effects which are not described by the analytical model. More realistic results can be achieved with full-wave electromagnetic optimization. The analytical model does not take into account the interaction between the unit cells. In practice, the nonplanar transmitarrays can be easily implemented with a non-planar plastic frame, although each steering angle requires a different mounting frame. Such plastic frame was fabricated for further measurements by using a 3D printer, Fig 4.

![Graph](image-url)

**Fig. 3** H-plane beampatterns of the planar and phase-corrected nonplanar transmitarrays optimized with different bounds.

| Table 1. Resulting shifted transmitarray gain for different optimization bounds. |
|---------------------------------|-----------------|-----------------|-----------------|
| Upper bound, mm | Lower bound, mm | Gain, dBi        |
| Planar           | -               | -               | 19.73           |
| Nonplanar 1      | -2.5            | 2.5             | 20.3            |
| Nonplanar 2      | -5              | 5               | 20.8            |
| Nonplanar 3      | -10             | 10              | 21.6            |
Fig. 4 Nonplanar tiled 1-bit transmitarray prototype.

3. Conclusion
The possibility of compensating for the phase error resulting from the 1-bit quantization of phase shifts by shifting the unit cells along the optical axis of the transmitarray was presented in this article. It was shown that satisfactory results could be achieved by using optimization procedures, and gain improvement directly depends on the optimization boundary. It is also noted that taking into account all the effects that occur due to the unit cells displaced relative to each other is necessary for optimization with the calculation of the analytical model of the transmitarray.

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