Design of a phased array with a beam scanning functionality based on the arithmetic phase difference

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Abstract. The demand for phased array antennas increases not only for the traditional military industry but also in commercial areas such as 5G mobile network platforms, Internet of Things (IoT), and satellite communication applications. In this paper, a phased array with a beam scanning function is designed based on arithmetic phase difference between array elements. In the design process, the initial complex model is simplified into a simple element model with periodic conditions, which makes the analysis faster and more efficient. Finally, two phased array designs based on microstrip patch antenna are studied, and the simulation results verify the correctness of the design method.

1. Introduction

The demand for phased array antennas increases not only for the traditional military industry but also in commercial areas such as 5G mobile network platforms, Internet of Things (IoT), and satellite communication applications [1]. In this paper, a phased array with a beam scanning function is designed based on arithmetic phase difference between array elements. In the design process, the initial complex model is simplified into a simple element model with periodic conditions, which makes the analysis faster and more efficient. Finally, two phased array designs based on microstrip patch antenna are studied, and the simulation results verify the correctness of the design method.

2. Model definition

This model consists of three parts:

(1) Antenna geometry part showing how to make a geometry repeatedly used in the same model;
(2) 8-by-4 full antenna array;
(3) Simplified model using periodic conditions.

2.1. Antenna geometry part

When a simulation model has repeated geometry designs, it would be cumbersome to draw that geometry over and over again. If there is a predefined geometry frequently used, the modeling process can be more efficient [2]. The RF Module includes the part library consisting of many standard parts and geometries. They are various types of connectors, surface mount device footprints, and rectangular waveguides. We can also create our own customized parts, and use them multiple times in the same or different models. The part in this model describes a parametrized microstrip patch antenna geometry. Thereby you can easily change the geometry. The design parameters define the size of the substrate, patch radiator, feed line, and impedance matching geometry [3].
2.2. 8-by-4 full antenna array

The full antenna array geometry is built with the customized part and array operation. The array substrate is enclosed by a surrounding air domain. All antenna elements are excited by lumped ports with the same default voltage and 50 Ω reference impedance [4]. The phase difference between each lumped port is correlated by a certain formula [5], which is arithmetic phase values. The arithmetic phase values are used to steer the direction of the main radiation.

Table 1. Arithmetic phase for the different lumped ports, identified by their lumped port name

| Arithmetic phase | Lumped port name |
|------------------|------------------|
| -2*pi*0.48cos(\phi)*0 | 1,2,3,4 |
| -2*pi*0.48cos(\phi)*1 | 5,6,7,8 |
| -2*pi*0.48cos(\phi)*2 | 9,10,11,12 |
| -2*pi*0.48cos(\phi)*3 | 13,14,15,16 |
| -2*pi*0.48cos(\phi)*4 | 17,18,19,20 |
| -2*pi*0.48cos(\phi)*5 | 21,22,23,24 |
| -2*pi*0.48cos(\phi)*6 | 25,26,27,28 |
| -2*pi*0.48cos(\phi)*7 | 29,30,31,32 |

By running a parametric sweep of \( \phi \) shown in Table 1, the beam scanning capability of the phased array antenna can be evaluated.

Figure 1. Lumped port phase configuration on the top view of the antenna array geometry.

For far-field analyses such as radiation pattern, gain, directivity, and effective isotropically radiated power (EIRP), a far-field domain and calculation features are required [6]. It is important to apply the domain feature to the surrounding air domain or connected domains characterized by homogeneous material properties [7]. The far-field calculation boundaries are the exterior boundaries of the far-field domain feature by default. A perfect electric conductor (PEC) boundary condition is by default applied to the exterior boundaries of the simulation domain. In this model, that boundary condition is overridden by a first-order scattering boundary condition. The scattering boundary condition absorbs all outgoing radiation from the antenna. The simulation frequency is not high enough to consider the loss coming from the finite conductivity of the copper layers. All metal boundaries are defined using the perfect electric conductor (PEC). The 60mil dielectric substrate is assumed to be lossless and the relative permittivity, dielectric constant of the material is 3.38 in this model [8].

2.3. Simplified model using periodic conditions

The complexity of the full antenna array model can be reduced using periodic conditions and it is possible to estimate the far-field radiation pattern of the full antenna array efficiently by utilizing the built-in array factor function. The periodic conditions are the core features virtually making the unit cell as an infinite array and simplify the original model for the faster analysis. Each periodic condition has a pair of boundary selections facing each other that can be identified as the source and destination boundaries, respectively. Four side boundaries are configured in two periodic conditions. The Floquet
periodicity correlates the source and destination boundaries with a user-specified phase in terms of k-vector. The k-vector for Floquet periodicity is extracted using the direction of the main beam steered by the arithmetic phase progression. The beam is steered only around the y-axis. So the Floquet periodicity type is used for the periodic condition in which the selections are normal to the x-axis. In the other periodic condition where the boundaries are normal to the y-axis, the Continuity type is appropriate because no phase variation is expected between the source and the destination boundaries [9].

The top of the simulation domain is covered by a scattering boundary condition to model the surface as open space. The far-field domain feature is used only in the top air domain. This is a very special case not following the rule of thumb regarding the proper usage of the far-field feature. The basic assumptions here are that:

1) The far-field calculation is dominated by the selected boundaries.
2) The unit cell antenna has a directive radiation pattern dominantly toward the air domain direction from the antenna. The front-to-back ratio of the radiation pattern is high.
3) The radiation toward the bottom ground is not of interest.

Even if these conditions are fulfilled, this approach has to be carefully applied. In this paper, the computed results are compared to those of the full array model and accepted as an alternative method for evaluating the performance of the antenna array for the given design. Though the unit cell simulation includes the coupling by the adjacent surrounding array elements through the periodic conditions, the far-field transformation is performed only with the unit cell. The computed far-field radiation pattern does not describe that the complete array. The desired radiation pattern of the array can be approximated by multiplying an array factor to the far field of the single antenna. The 3D full-wave simulation for an antenna array is memory intensive. By using an asymptotic approach, such as multiplying the far-field of a single antenna with a uniform array factor, the radiation pattern of an antenna array can be evaluated quickly [10].

Table 2. Input parameters of array factor operator for an 8-by-4 array

| Parameter | Description                      | Argument | Unit   |
|-----------|----------------------------------|----------|--------|
| nx        | Number of elements along x-axis  | 8        | Dimensionless |
| ny        | Number of elements along y-axis  | 4        | Dimensionless |
| nz        | Number of elements along z-axis  | 1        | Dimensionless |
| dx        | Distance between array elements along x-axis | 0.48 | Wavelength |
| dy        | Distance between array elements along y-axis | 0.48 | Wavelength |
| dz        | Distance between array elements along z-axis | 0 | Wavelength |
| alphax    | Phase progression along x-axis   | -2*pi*0.48*cos(phi) | Radian |
| alphay    | Phase progression along y-axis   | 0        | Radian |
| alphaz    | Phase progression along z-axis   | 0        | Radian |

The 3D uniform array factor function is available under Definitions-Functions from the postprocessing context menu when a Far-Field Calculation feature is defined in the physics interface. The function call signature is:

af3(nx, ny, nz, dx, dy, dz, alphax, alphay, alphaz)

In Table 2, where nx, ny, and nz are the number of elements along the x, y and z-axis, respectively. The arguments dx, dy and dz are the distances between array elements in terms of wavelength, alphax, alphay and alphaz are the phase progression in radians.

To evaluate the realized gain of a virtual 8-by-4 antenna array from the realized gain of a single antenna, the following expression is used:

emw2.rGaindBFar + 20 \cdot \log_{10}(emw2.af3(8,4,1,0.48,0.48,0,-2 \cdot \pi \cdot 0.48 \cdot \cos(\phi),0,0)) + 10 \cdot \log_{10}(1/32)

Since it is the dB scale, the multiplication of the array factor represents a summation in the expression.

It assumes that the array is excited by a single input uniform distribution network, so the input power needs to be scaled by a factor 10*log10(1/total number of elements). The direction of the main beam can be steered by defining nonzero phase progression in the uniform array factor. The maximum radiation direction of the array factor along the x-axis is defined by the angle from the x-axis in the phase progression using
\[ \alpha_x = -kd \cos \phi = -\left(\frac{2\pi d}{\lambda}\right) \cos \phi \]  

(1)

Where \( d \) is the distance between two antenna units and \( k \) is the number of antenna units, The antenna is excited by a uniform lumped port. The lumped port is proper to use on a small boundary where a constant phase is expected over the port boundary.

3. Results and discussion

Figure 2 visualizes the electric field norm when all antenna elements are excited with the same voltage, but the arithmetic phase progression is set to have the maximum radiation direction tilted from the z-axis. Strong field intensity is observed around the radiating edges of the patch antennas. Since the norm is plotted, the phase variation is not shown. To see the field variation at each column of the array, a complex-valued field component, \( E_z \), is used in Figure 2. Only the real part of complex values is plotted.

![Figure 2](image_url)

Figure 2. Electric field norm is plotted on the top surface on the antenna array board using a selection sub feature. \( E_z \) plot showing the color variation at each array column.

| Arithmetic phase(degrees) | Array column group index | Lumped port name |
|---------------------------|--------------------------|------------------|
| 0                         | 1                        | 1,2,3,4          |
| -86.4                     | 2                        | 5,6,7,8          |
| -172.8                    | 3                        | 9,10,11,12       |
| -259.2                    | 4                        | 13,14,15,16      |
| -345.6                    | 5                        | 17,18,19,20      |
| 432                       | 6                        | 21,22,23,24      |
| -518.4                    | 7                        | 25,26,27,28      |
| -604.8                    | 8                        | 29,30,31,32      |

Figure 3 visualizes the far-field radiation pattern in a polar plot. The polar plot format is convenient for checking intuitively the directional properties of an antenna. When there is no phase difference among
the excitation ports and all antenna elements are uniformly fed, the generated radiation pattern is normal to the array plane (blue in Figure 3). Though the phase at each port is defined as $-2\pi t0.48\cos(\phi)$, the input argument is effectively zero with a parameter $\phi$ value of $\pi/2$. When $\phi$ is $\pi/3$, the arithmetic phase applied to each array column group is listed in Table 3. The group index of the array is the array number of the antenna array, which is divided into 1-8, four units in each column, a total of 32 units.

A reasonably well-designed antenna array may have sidelobe levels below -10 dB which is not conspicuous when they are plotted in linear scale. The dB scale used in the polar plot and 3D far-field radiation pattern (Figure 4) makes the sidelobes more visible. For high-gain antennas, it is recommended to use a finer resolution for the radiation pattern visualization to characterize nulls and sidelobes without missing them. The number of angles in the settings window controls the resolution.
discrepancy in the backward radiation—those below the ground plane. So, this reduced model using the periodic conditions is valid only when approximating the antenna boresight radiation. Figure 6 shows a similar type of comparison but using the realized gain in the 1D plot. As stated above, a good agreement is observed between two modeling approaches regardless of the beam scanning angle if only the main beam and major sidelobes are of interest for the antenna analysis.

![Figure 5. Gain comparison in a polar plot between two modeling methods. The main beam and sidelobe levels are agreed well.](image)

![Figure 6. Gain comparison in a 1D plot. 1D plot perspective, different from the polar plot, provides a better view while observing nulls and back lobes.](image)

4. Conclusion
In this paper, a phased array with beam scanning function is designed based on arithmetic phase difference between array elements. In the design process, the initial complex model is simplified into a simple element model with periodic conditions, which makes the analysis faster and more efficient. Finally, two phased array designs based on microstrip patch antenna are studied, and the simulation results verify the correctness of the design method.
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