A New Method for the Prognosis of Scan Blindness Angle in Finite Phased Arrays of Printed Dipoles

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***Abstract*—Scan blindness phenomenon is studied for finite phased arrays of printed dipoles on grounded planar dielectric slabs. A new method for predicting the scan blindness angles using the average scan impedances of a subsection of dipoles at the center of the array is introduced. A hybrid method of moments/Green's function technique is used to analyze the finite arrays of printed dipoles. Several numerical results are presented to demonstrate the accuracy of the new method in terms of predicting the blindness angle.**

***Index Terms*—Printed planar phased arrays, Green's function, method of moments, scan blindness.**

I. Introduction

Printed planar arrays are widely used in applications of various fields including broadcasting, space communication and military usage due to their ability of reinforcing the waves in a desired direction and suppressing the waves in undesired directions [1]. However, in such arrays the electromagnetic coupling between the surface and space waves can lead to a phenomenon called "scan blindness" [2], and seriously degrades the performance of the array. Scan blindness is once alluded as a "catastrophic effect" by Schaubert *et al*. [3]. Therefore, a complete understanding of this phenomenon and an accurate method for the prognosis of blindness angles are of great practical interest.

The blindness phenomenon was defined (for planar infinite arrays of printed antennas on grounded dielectric slabs) as a phase matching between the phase progression of a surface wave (β_{sw}) on the dielectric substrate and the phase progression of a certain Floquet mode ([2], [4]). It has been investigated in detail for various infinite and finite arrays of printed antennas on planar grounded dielectric slabs [2],[5],[6],[8]. Among them, in [5], it is suggested that, if the magnitude of the reflection coefficient for the middle element of the array exceeds unity and becomes maximum at a scan angle, scan blindness occurs in that direction. In all numerical examples provided in [5], whenever the magnitude of the reflection coefficient for the middle element is greater than one and has a maximum at a specific angle, a null for infinite array and a dip for finite array are observed in the active element gain patterns at the same angle. Therefore, the results are consistent. However, using the same finite array analysis method presented in [5] for arrays of printed dipoles depicted Fig. 1 (basically a hybrid Method of Moments (MoM)/Green's function technique that enables an element-by-element analysis including all mutual couplings among the elements through space and surface waves), it has been observed that for many arrays that have practically large sizes (19x19, 25x25, 31x31 etc.) there is severe inconsistency between the angle where the active element gain pattern has a dip and the angle where the magnitude of the reflection coefficient for the middle element is maximum and exceeds unity. Moreover, when the grounded dielectric slab is relatively thin and/or relative dielectric constant is small, no dip has been observed in the active element gain pattern, although the reflection coefficient magnitude of the middle element is still significantly over one. Therefore in this paper, several finite arrays of printed dipoles with different electrical properties are investigated in detail to provide an accurate method for the prognosis of possible blindness angles. Similar to [5], a hybrid MoM/Green's function technique in the spatial domain is used. It has been observed that the reflection coefficient magnitude of the middle element is not a good scan blindness indication. However, the average scan impedance of an array or even a subsection of it around the array's center can yield a more solid indication about scan blindness which turns out to be consistent with the results obtained from the active element gain pattern.

In Section II, the geometry and the formulation of the analysis method together with the key definitions that are used are presented. Blindness angle prognosis and supporting numerical examples that demonstrate the accuracy and consistency of using the array's average scan impedance to predict the blindness angle are provided in Section III. An $e^{j\omega t}$ time convention is used and suppressed throughout the paper.

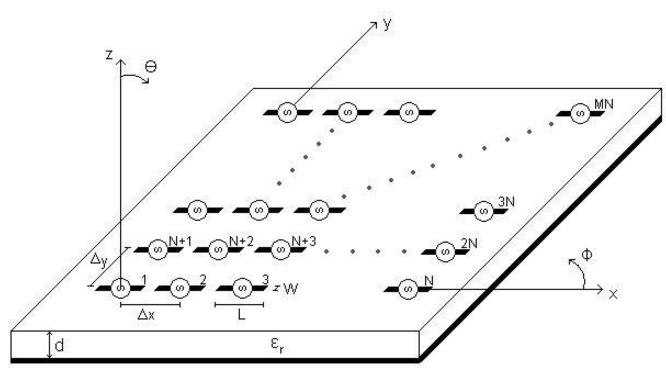

Fig. 1. Geometry of a periodic planar array of $(M \times N)$ printed dipoles

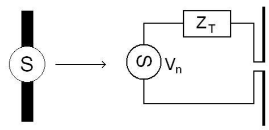

Fig. 2. Dipole center-fed by an infinitesimal generator with a voltage V_n and a terminating impedance Z_T

II. Theory

A. Geometry

Fig. 1 shows the geometry of a finite, periodic array of $(M \times N)$ x-directed printed dipoles. The dipoles are center-fed by infinitesimal generators with terminating impedance Z_T as shown in Fig.2. Each dipole has the length L, width W and is uniformly separated from its neighbors by $\triangle x$ and $\triangle y$ in the x- and y-directions, respectively. The dielectric slab has the thickness d and the relative permittivity ϵ_r. The thickness and the relative permittivity are selected in such a way that only a single TM surface wave mode exists [4]. Therefore, the blindness may or may not occur for only one angle in the $E-$plane [7].

B. Formulation

A full-wave solution based on the hybrid MoM/Green's function technique in the spatial domain is used for the analysis. Briefly, an electric field integral equation is formed, and applying a Galerkin MoM procedure the following matrix equation is obtained [5]

$$([\mathbf{Z}] + [\mathbf{Z_T}]) \cdot \mathbf{I} = \mathbf{V}. \tag{1}$$

In the course of obtaining (1), dipoles are assumed to be thin and piecewise sinusoidal expansion modes are used to represent the current on them. In (1), $[\mathbf{Z}]$ is the impedance matrix of the array with elements Z_{nm} that represents the mutual coupling between the nth and mth $(1 \leq n, m \leq NM)$ dipoles of the array. $[\mathbf{Z_T}]$ is the generator terminating impedance matrix which is diagonal [5]. $\mathbf{I} = [I_n]$ is the unknown vector of the expansion coefficients, and $\mathbf{V} = [V_n]$ is the voltage excitation vector where V_n is given by [5]

$$V_n = e^{jk_0(\sin\theta\cos\phi x_n + \sin\theta\sin\phi y_n)} \tag{2}$$

with x_n and y_n being the coordinates of the center of the nth dipole and (θ, ϕ) being the scan direction of the main beam.

C. Other Definitions

Once the matrix equation in (1) is solved and the coefficient vector $\mathbf{I}$ is obtained, the input impedance of the nth element is calculated as [5]

$$Z_{in}^n(\theta, \phi) = \frac{V_n}{I_n}, \tag{3}$$

and the average scan impedance is defined as

$$Z_{avg}(\theta, \phi) = \frac{\sum_{i=1}^{K^2} Z_{in}^{m_i}(\theta, \phi)}{K^2} \tag{4}$$

where m_i represents the index of the ith element in the $K \times K$ subsection located at the middle of the array. Finally, the active reflection coefficient for the nth element is defined as [5]

$$R^n(\theta, \phi) = \frac{Z_{in}^n(\theta, \phi) - Z_{in}^n(\theta = 0, \phi = 0)}{Z_{in}^n(\theta, \phi) - Z_{in}^{n*}(\theta = 0, \phi = 0)}. \tag{5}$$

The active element pattern of the nth dipole $E^n(\theta, \phi)$ is the field radiated by the array when the nth dipole is excited by a voltage generator and all other dipoles are terminated in an impedance Z_T [5]. As presented in [5], this pattern gives accurate estimates of the actual gain pattern of the array even if the array size is small. The active element pattern of the nth element is calculated by setting the feed voltage of the nth element to unity whereas the feed voltages for all other elements are set to zero. Then, $\mathbf{I}$ is computed from the solution of (1) by setting Z_T equal to the conjugate of the isolated dipole input impedance. As a result, the active element pattern for the nth dipole is calculated as

$$E_n(\theta, \phi) = E_n^0(\theta, \phi) \sum_{m=1}^{NM} I_m e^{jk_0 \sin\theta\cos\phi x_m} e^{jk_0 \sin\theta\sin\phi y_m} \tag{6}$$

where $E_n^0(\theta, \phi)$ is the far-field element pattern of a single isolated dipole and can be calculated as presented in [9]. Finally, by using the far-field element pattern, the active element gain for the nth element is calculated as [5]

$$G_n(\theta, \phi) = \frac{4\pi |E_n(\theta, \phi)|^2}{Z_0 P_{in}} \tag{7}$$

where $Z_0 = 120\pi$ is the free-space intrinsic impedance and P_{in} is the power delivered to the nth element which can be expressed as

$$P_{in} = Re\{\sum_{m=1}^{NM} I_m Z_{mn} I_n^*\}. \tag{8}$$

Note that the scan blindness angle manifests itself as a dip in the active element gain pattern [5].

III. Blindness Angle Prognosis and Numerical Results

In this work, we have realized that the blindness angles can be predicted accurately by using the average scan impedance definition given in (4). In a close neighborhood of the blindness angles, it has been observed that both the magnitude and phase of the average scan impedance change rapidly; and the blindness angles can be identified as the angles where the phase of the average scan impedance is $0°$.

In [4], it has been stated for infinite arrays of printed dipoles that the blindness angle is the scan angle where the magnitude of the reflection coefficient is unity. Then, this method has been extended to finite array cases in [5] under the assumption that for a practically large array the middle element behaves as any element of an infinite array. Hence, the scan angle where the magnitude of the reflection coefficient for the middle element has a peak over one is predicted as the blindness angle in many studies such as [5],[6],[8]. For example in [5], the E-plane active element gain pattern for the case where $\epsilon_r = 2.55$, $d = 0.19\lambda_0$, $\triangle x = \triangle y = 0.5$, $L = 0.39\lambda_0$, $W = 0.01\lambda_0$ and $N = M = 19$ is depicted in Fig.3. The dip at $46°$ shows a scan blindness. This angle can be predicted by using the magnitude of the reflection coefficient for the middle element which has a peak at $46°$ as shown in Fig.4. It is also possible to accurately predict this angle using the phase of the average scan impedance approach presented in this work. As seen in Fig.5, the scan angle where the phase passes through $0°$ corresponds to $46°$.

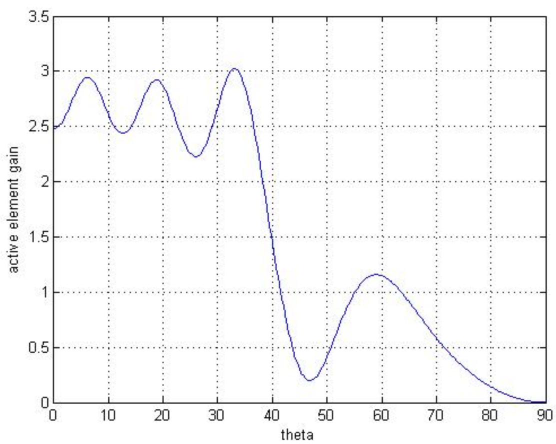

Fig. 3. Active element gain pattern in the case where $\epsilon_r = 2.55$, $d = 0.19\lambda_0$, $\triangle x = \triangle y = 0.5$, $L = 0.39\lambda_0$, $W = 0.01\lambda_0$ and $N = M = 19$

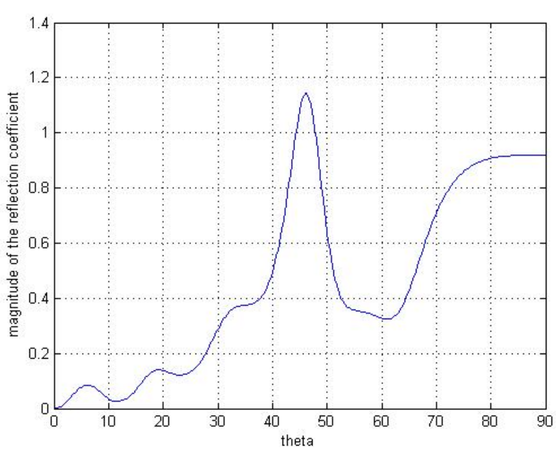

Fig. 4. Magnitude of the reflection coefficient for the middle element in the case where $\epsilon_r = 2.55$, $d = 0.19\lambda_0$, $\triangle x = \triangle y = 0.5$, $L = 0.39\lambda_0$, $W = 0.01\lambda_0$ and $N = M = 19$

However, for some cases the prediction method described in [5] can cause a false detection. In Fig.6, the E-plane active element gain pattern is shown for the case where $\epsilon_r = 7.5$, $d = 0.03\lambda_0$, $\triangle x = \triangle y = 0.5$, $L = 0.39\lambda_0$, $W = 0.01\lambda_0$ and

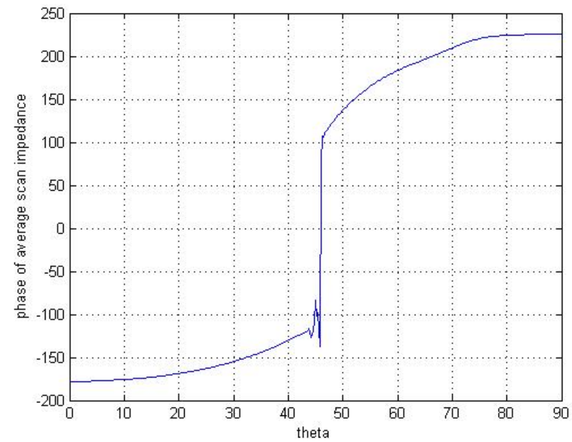

Fig. 5. Phase of the average scan impedance in the case where $\epsilon_r = 2.55$, $d = 0.19\lambda_0$, $\triangle x = \triangle y = 0.5$, $L = 0.39\lambda_0$, $W = 0.01\lambda_0$ and $N = M = 19$

$N = M = 25$. For this case the active element gain shows no scan blindness. However, the magnitude of the reflection coefficient for the middle element versus scan angle θ indicates a blindness at $\theta = 62°$ as shown in Fig.7. On the other hand, as shown in Fig.8, phase of the average scan impedance does not indicate any blindness for any angle.

Besides, there exist many cases where the approach based on the magnitude of the reflection coefficient for the middle element predicts the scan blindness at wrong angles. Furthermore, there are cases where it predicts no scan blindness even though the active element gain pattern clearly shows that scan blindness phenomenon occurs. On the other hand, for almost all these cases the average scan impedance approach presented in this work yields accurate results.

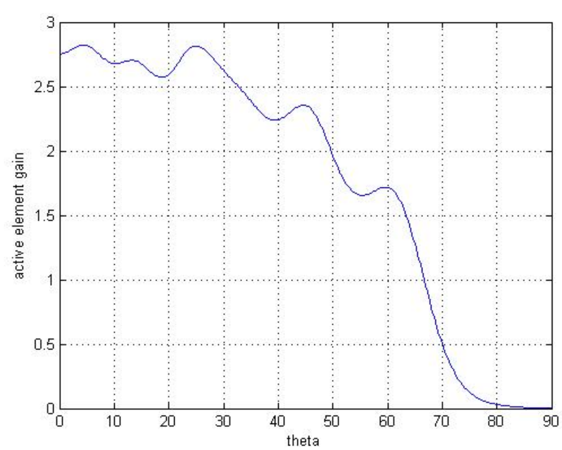

Fig. 6. Active element gain pattern in the case where $\epsilon_r = 7.5$, $d = 0.03\lambda_0$, $\triangle x = \triangle y = 0.5$, $L = 0.39\lambda_0$, $W = 0.01\lambda_0$ and $N = M = 25$

IV. Conclusion

Using a full-wave analysis method based on a MoM/Green's function technique in the spatial domain, scan blindness phenomenon is re-investigated. It has been observed that,

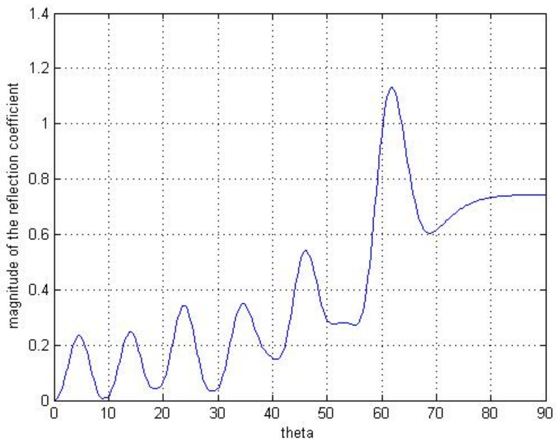

Fig. 7. Magnitude of the reflection coefficient for the middle element in the case where $\epsilon_r = 7.5$, $d = 0.03\lambda_0$, $\triangle x = \triangle y = 0.5$, $L = 0.39\lambda_0$, $W = 0.01\lambda_0$ and $N = M = 25$

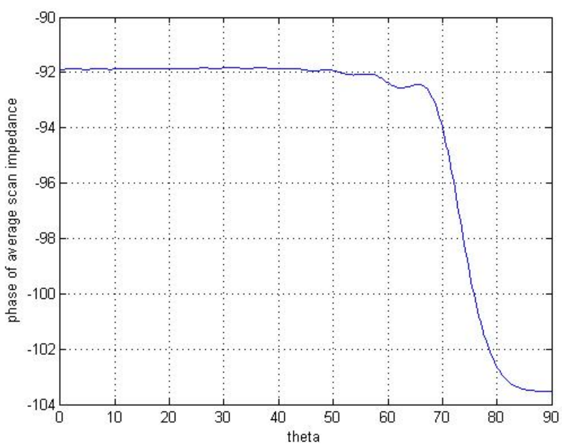

Fig. 8. Phase of the average scan impedance in the case where $\epsilon_r = 7.5$, $d = 0.03\lambda_0$, $\triangle x = \triangle y = 0.5$, $L = 0.39\lambda_0$, $W = 0.01\lambda_0$ and $N = M = 25$

magnitude of the reflection coefficient for the middle element of a finite array is not consistent with the result of the active element gain pattern of the same array in terms of predicting the blindness angle. However, the average scan impedance approach, presented in this work, always yields a consistent blindness angle prediction with that of the active element gain.

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