A TRAVELING WAVE EXPANSION FOR THE UTD ANALYSIS OF THE COLLECTIVE RADIATION AND SCATTERING FROM LARGE FINITE PLANAR ARRAYS

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INTRODUCTION

An improved traveling wave (TW) expansion is introduced to efficiently describe the current distribution over a large finite planar array when it is excited either internally for the phased array radiation configuration, or by an external plane wave for the scattering configuration. The array distribution is first obtained from a numerical moment method (MoM) based solution of the governing integral equation for the array element currents either in the radiation or the scattering case. The TW basis set which accurately represents this distribution is then extracted from a suitable parameter estimation method. This expansion of the realistic non-uniform array distribution into a relatively small set of TWs is substantially more efficient than the Discrete Fourier Transform (DFT) based TWs employed in the recent past [1]. For instance, the total number of significant DFT-TWs required to accurately describe the array distribution is approximately 25% of the total number of array elements, while the significant new TWs that are required are only about 1%. The importance of the TWs is that they facilitate a UTD analysis which provides a description of the collective fields radiated or scattered from the whole realistic array in terms of only a few rays which arise from the array interior, as well as from the edges and corners of the array element truncation boundary [1–3]. On the other hand, the conventional array element by element field summation approach is not only inefficient, but lacks physical insights into the array radiation mechanisms. It is noted that, in general, a UTD solution can be developed to describe the collective radiation and scattering from the whole array at once when the array distribution is relatively smooth and weakly tapered. In contrast, most realistic array distributions contain ripples over the whole array that are even more pronounced near the array edges and corners. These ripples result from an interference between the waves generated by the array interior as if the array was infinite, and the diffracted waves generated by the finite array truncation boundary. Thus, the new method is reviewed for representing the realistic, complex array distributions in terms of simpler TWs. The TW expansion also facilitates one to calculate the array fields via a boundary diffraction wave (BDW) formulation [4], which describes the collective fields radiated or scattered from the whole array in terms of a continuation of each TW basis outside the array constituting the geometrical optics type Floquet wave (FW) components, and a line integral contribution from the mathematical boundary of the array constituting a diffraction component for each TW basis. The significant improvement resulting from the use of TWs versus the DFT-TWs is because the TWs are a more natural basis set and less constrained than the DFT-TWs. In particular, the DFT-TWs are constrained to propagate along specific directions dictated by the periodicity of the array elements. The present analysis is also useful for predicting the interaction of realistic array apertures with nearby obstacles and the array platform; such problems can be handled efficiently by the UTD ray method which provides physical insights into the array radiation and scattering mechanisms. Numerical results are presented to illustrate the utility of the TW-based UTD method for large finite array analysis.

FORMULATION

An arbitrary array distribution $\{A_{nm}\}$ can be approximated by a finite set of dominant TW surface currents as

$$A_{nm} \approx \sum_{i=1}^{K} C_i e^{-j\bar{k}_i \cdot \bar{r}'_{nm}} \tag{1}$$

where $\bar{k}_i$ is the vector wavenumber and C_i is the complex constant amplitude of the i^{th} TW current, respectively. The $\bar{r}'_{nm}$ is the location of the nm^{th} array element. It is of interest to extract the propagation vectors $\{\bar{k}_i\}$ and the corresponding amplitudes $\{C_i\}$ from a given array distribution $\{A_{nm}\}$. The extraction can be performed by using available efficient parameter estimation algorithms. In this paper, the CLEAN algorithm, as utilized previously in [5], has been employed. A study of other efficient high-resolution parameter estimation algorithms, such as those utilized in the estimation of direction-of-arrival (DOA) (e.g. MUSIC, ESPRIT, and others), is currently in progress to arrive at an optimal procedure for finding these TW parameters.

It is noted that the DFT expansion for the array distribution employed previously by the authors [1] is a special case of the TW representation in (1), where $\{\bar{k}_i\}$ are equally spaced in the spectrum domain with a spacing dictated by the number of array elements ($N \times M$), i.e.

$$\bar{k}_i = \hat{u}k_u^p + \hat{v}k_v^q \tag{2}$$

$$k_u^p = \frac{2\pi p}{N} \quad (p = 0, .., N-1) \quad ; \qquad k_v^q = \frac{2\pi q}{M} \quad (q = 0, .., M-1) \tag{3}$$

and $\{C_i\}$ are the corresponding DFT coefficients. However, as mentioned earlier, far less TW basis are required, for the same accuracy, in the new procedure as compared to the previous DFT-based TW expansion which is also very compact.

Once the dominant TW basis set are extracted, the collective fields radiated or scattered from the whole array, in the near and far zones, due to each TW component can be represented efficiently in terms of a few UTD ray fields, each of which is expressed in closed form. The total array field is then obtained by a superposition of those UTD ray fields due to each TW component, i.e.

$$\bar{E}(\bar{r}) \approx \sum_{i=1}^{K} C_i \bar{E}_i^{UTD}(\bar{r}) \tag{4}$$

where $\bar{E}_i^{UTD}(\bar{r})$ denotes the UTD ray field produced by the i^{th} TW current with a unit amplitude, which for planar arrays is given by

$$\bar{E}_i^{UTD}(\bar{r}) = \bar{E}_i^{fw} + \bar{E}_i^{ed} + \bar{E}_i^{cd} + (\bar{E}_i^{slw,e} + \bar{E}_i^{slw,c}) \tag{5}$$

where $\bar{E}_i^{fw}$ denotes the FWs, $\bar{E}_i^{ed}$ and $\bar{E}_i^{cd}$ denote their corresponding edge and corner diffracted fields, respectively. In addition, for the case of finite arrays in a material layer, there also exist the edge-excited surface/leaky waves, $\bar{E}_i^{slw,e}$, and the corner-excited surface/leaky waves, $\bar{E}_i^{slw,c}$, respectively, [1–3].

Alternatively, one can also represent the collective fields radiated or scattered from the whole array due to each TW component in terms of the FW plus the BDW as [4]

$$\bar{E}(\bar{r}) \approx \sum_{i=1}^{K} C_i [\bar{E}_i^{fw} + \bar{E}_i^{bd}] \tag{6}$$

where $\bar{E}_i^{fw}$ denotes the FWs and $\bar{E}_i^{bd}$ denotes the corresponding BDWs which are expressed in terms of the line integral along the array aperture boundary.

NUMERICAL RESULTS

To demonstrate the accuracy and efficiency of the TW-UTD method, some numerical examples of the radiation and scattering by a large finite rectangular planar array of printed dipoles in an infinite grounded multilayered medium, as shown in Fig. 1, are illustrated below. The array is composed of 101×101 printed dipole elements, each of which has a length of 0.7cm and a width of 0.008cm, and is oriented in the $\hat{x}$ direction. The element spacings are 0.75cm in the $\hat{x}$ direction and 0.7cm in the $\hat{y}$ direction, respectively. The current on each dipole is approximated locally by a piecewise sinusoidal distribution, and its amplitude is obtained via the MoM solution. Fig. 2 shows the comparison of the normalized radiation patterns ($|E_\theta|$ in dBi) of the array in the principle plane ($\phi = 0^o$) and off the principle plane ($\phi = 45^o$), respectively, computed by the TW-UTD solution (solid line) and the reference solution (dash line) using the element-by-element field summation approach. In this case, each dipole is excited by a delta gap voltage generator with a series impedance of 50Ω. The array excitation is assumed to be a Gaussian taper and the array is phased to scan a main beam in the broadside direction. The array distribution obtained from the MoM solution is then approximated by 102 dominant TW terms, which is only 1% of the total number of elements (10,201). The norm of relative error of the approximate array distribution is $\approx 9.25 \times 10^{-3}$, while the same number of the DFT-based TW expansion gives rise to an approximate array distribution with the norm of relative error of $\approx 1.38 \times 10^{-2}$. The numerical results show a good agreement between the TW-UTD and reference solutions. Fig. 3 shows the comparison of the bistatic radar cross section (RCS) of the array in the plane of incidence ($\phi = 0^o$) and off the plane of incidence ($\phi = 45^o$), respectively, computed by the TW-UTD solution (solid line), and the reference solution (dash line) using the element-by-element scattered field summation approach. In this case, the array is excited by an external transverse magnetic (TM) plane wave incident in the direction ($\theta_i = -30^o, \phi_i = 0^o$). Each dipole is loaded with the 50Ω impedance. The array distribution obtained from the MoM solution is again approximated by 102 dominant TW terms (only 1% of the total number of elements). The TW-UTD solution agrees well with the reference solution. From Fig. 3(b), it is noted that the array element spacing is such that a grating lobe occurs in the bistatic RCS pattern in the plane $\phi = 45^o$; this result is illustrated here only to demonstrate that the new TW expansion can indeed extract such undesirable grating lobe effects as well.

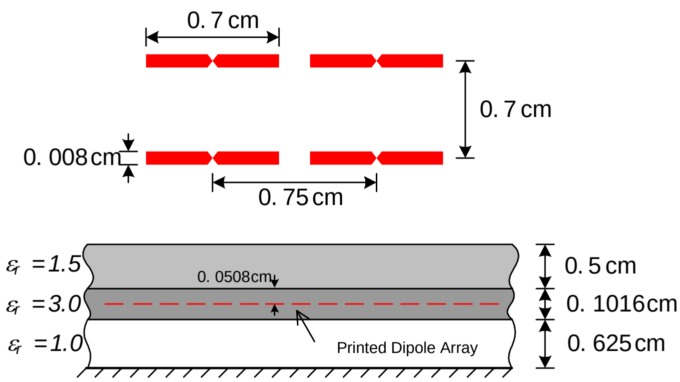
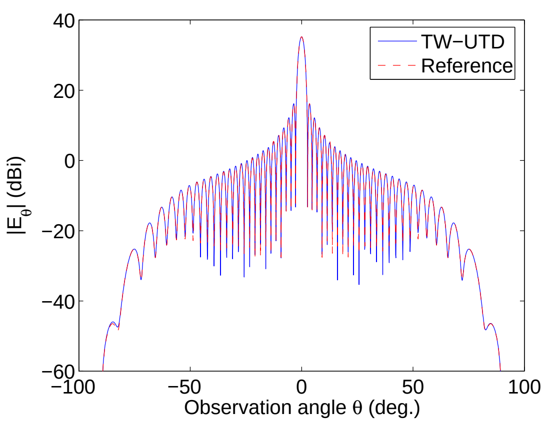
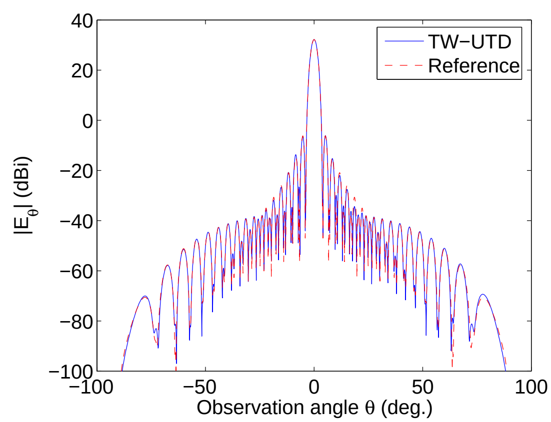


Figure 1: The geometry of a finite planar rectangular array of printed dipoles in a grounded multilayered medium.



(a) $\phi = 0^o$



(b) $\phi = 45^o$

Figure 2: The normalized radiation patterns ($|E_\theta|$ in dBi) of the array in the plane cuts (a) $\phi = 0^o$ and (b) $\phi = 45^o$, comparing between the TW-UTD solution (solid line) and the reference solution (dash line). Only 102 dominant TWs (1% of the total number of elements) are used.

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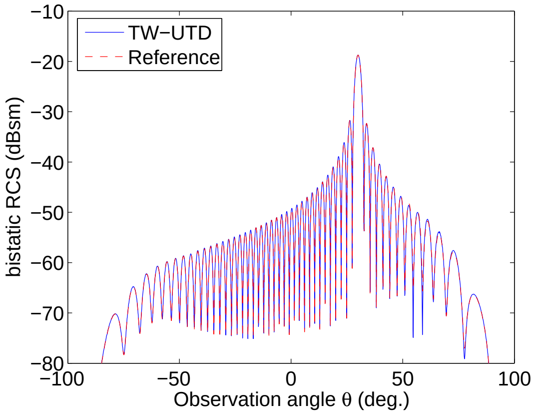
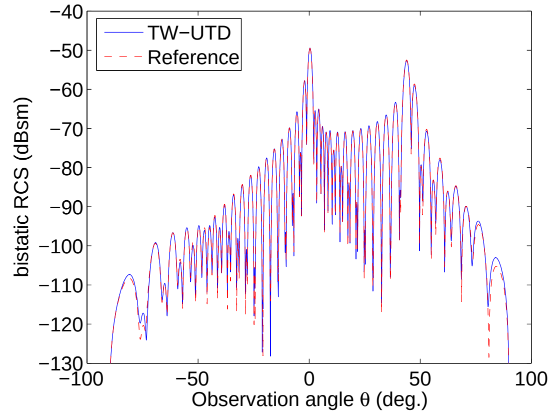


(a) $\phi = 0^o$



(b) $\phi = 45^o$

Figure 3: The bistatic RCS of the array in the incidence plane ($\phi = 0^o$) (a), and off the incidence plane ($\phi = 45^o$) (b), comparing between the TW-UTD solution (solid line) and the reference solution (dash line). Only 102 dominant TWs (1% of the total number of elements) are used.

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