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Accurate Plane-Wave Excitation in the FDTD Method†

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1 Introduction

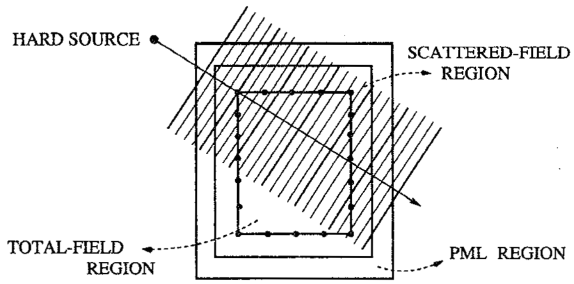

Figure 1: Excitation of a three-dimensional FDTD grid using a one-dimensional incident-field array.

Several different techniques are developed to implement plane-wave excitation in the finite-difference time-domain (FDTD) [1–3] method, such as the initial-condition technique [1], the hard-source technique [2], and the connecting-condition technique used in the total-field/scattered-field (TF/SF) formulation [2,4]. In the TF/SF formulation, the incident field has to be computed and "fed" to the three-dimensional (3D) FDTD grid on the boundary separating the total-field and the scattered-field regions. Since the incident field is a known quantity, a closed-form expression can be evaluated on every point of this boundary at each time step. However, a more efficient way of computing the incident field is to use an incident-field array (IFA), which is a one-dimensional (1D) FDTD grid set up to numerically propagate the incident field into the 3D FDTD grid as shown in Fig. 1. Then, the required incident-field values on the TF/SF boundary are interpolated from the values on the IFA [2].

Obtaining more accurate results has remained as a current issue since the FDTD method was introduced about three decades ago. Recently, significant progress has been reported in the development of more accurate absorbing boundary conditions (ABCs).

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[5] In this work, we address the accuracy issues another aspect of the FDTD method: plane-wave excitation.

2 Smoothing Windows and Filters

The discretization (sampling) of the source signal in the FDTD method may cause a significant aliasing error if the signal contains high-frequency components [6]. For instance, when a plane wave with an intended sinusoidal time dependence is abruptly turned on at $t = 0$, the resulting time dependence of the plane wave becomes

$$e(t) = u(t) \sin \omega_0 t, \tag{1}$$

where $u(t)$ is the unit step function and $\omega_0 = 2\pi/T_0$. The signal in Eq. (1) contains high frequency components and Figure 2(a) shows the maximum value of the error over both the total-field and scattered-field domains at each time step. It is seen that the maximum error in the computational domain decreases very slowly and does not reach a steady-state value after 800 time steps, which correspond to ~10 periods for $f_0 = 1$ GHz. When the initial $T_0/2$ portion of the signal in Eq. (1) is smoothened using a Hanning

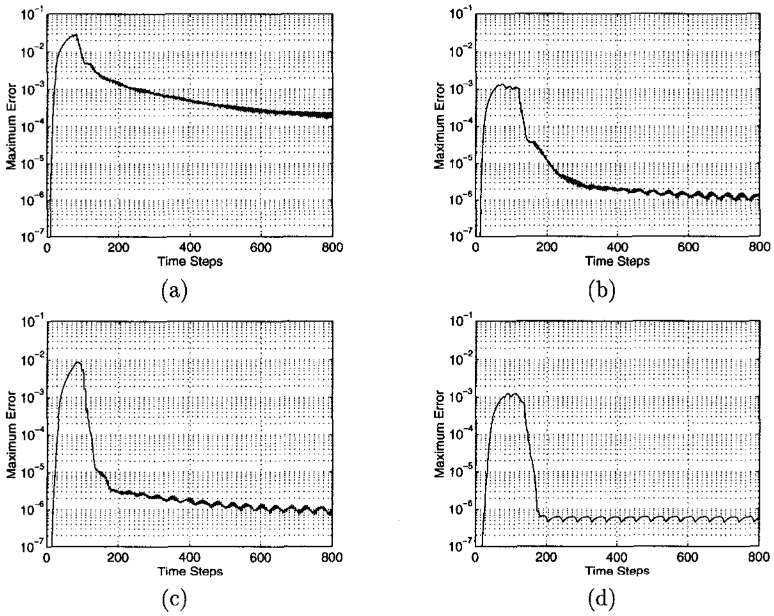


Figure 2: Plots of maximum error in the 3D FDTD grid as a function of time: (a) Sinusoidal excitation starts abruptly. (b) Smoothened signal. (c) Anti-aliasing filter is used. (d) The signal is both smoothened and filtered.

window, the maximum error drops to a lower level as shown in Fig. 2(b). The use of an anti-aliasing filter on the signal in Eq. (1) and on its smoothened version results in even lover levels of the maximum error as shown in Figs. 2(c) and (d).

3 Higher-Order Interpolation

The incident plane-wave values on the TF/SF boundary are interpolated from the discrete values on the 1D IFA as shown in Fig. 1. Regardless of the time-dependence of the incident plane wave, a higher-order interpolation technique should be expected to enhance the accuracy with which the plane wave is introduced to the 3D FDTD grid. Figures 3(a)–(d) show the maximum error for the cases of linear, quadratic, cubic and 5th-order interpolation. The error is observed to drop drastically as the order of the interpolation increases.

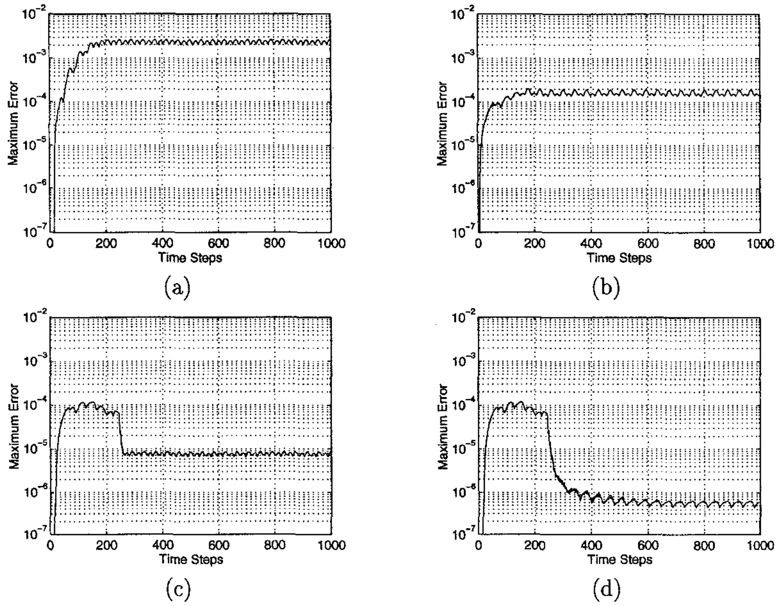
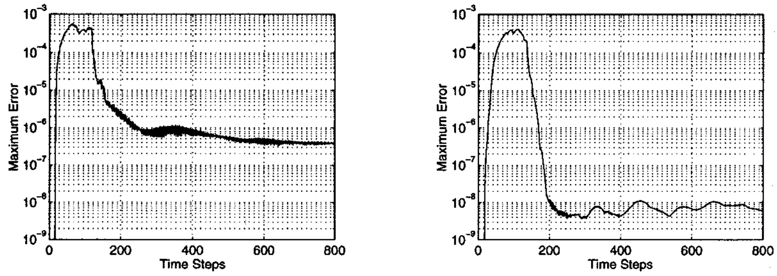


Figure 3: Plots of maximum error for various interpolation orders: (a) First order. (b) Second order. (c) Third order. (d) Fifth order.

4 High-Resolution Incident-Field Array

Another way of reducing the excitation error is to use a finer gridding in the IFA to generate a more accurate plane wave. However, merely increasing the sampling frequency in the 1D IFA (by reducing the step sizes both in space and time in the 1D FDTD grid) has limited advantage. This is due to the fact that only some of the values on the 1D IFA are used in computing (interpolating) the values on the boundary of the 3D FDTD grid and this situation is equivalent to decimation of a sequence. Decimation operation should be carried out using a properly chosen decimation filter to avoid errors [7]. Figure 4(a) shows the maximum error when the input signal is smoothened as in Fig. 2(b) and the IFA is resolved 8 times better than the 3D FDTD grid. It is observed that the error is reduced, however, if a decimation filter is used, the error drops by another two orders of magnitude as shown in Fig. 4(b).



(a) (b)

Figure 4: Plots of maximum error when the IFA is resolved 8 times better than the 3D FDTD grid: (a) No decimation filter. (b) A decimation filter is used.

5 Conclusions

Several signal-engineering techniques are outlined that can be employed to enhance the accuracy of the plane-wave excitation in the FDTD method.

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