FDTD Modeling of Noise in Computer Packages

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Abstract

In this paper, we discuss the electromagnetic modeling of the components of a computer package that contribute to noise on the signal lines in computer packages. We obtain equivalent circuits of coupled transmission lines, discontinuities in transmission lines, and a parallel-plate power plane configuration. These equivalent circuits allow one to use a circuit simulator to model the crosstalk, reflection, and simultaneous switching noises that are common in computer packages. The finite difference time domain (FDTD) algorithm is used to obtain the full-wave electromagnetic field solutions from which the equivalent circuits are determined.

1. Introduction

The effect of the interconnects on the performance of a computer system has been noted since the beginning of the digital computer era. The major impact at first was the transmission line delays which limited the speeds at which the circuits could operate. As the density of the circuits and interconnects increased, and the speeds at which the circuits and clocks operated increased, limiting noise became a factor to be dealt with in the computer design. Computer programs that solve Maxwell's equations are essential for creating models of the components of the computer system. The speed and density of present day computers require full-wave electromagnetic solvers to obtain the frequency-dependent models to represent the electrical phenomena.

This paper applies the finite difference time domain (FDTD) algorithm to modeling the noises that exist in a computer package. The contribution of this paper is the use of the FDTD method as a general purpose tool to obtain equivalent circuits so that the noises that exist on the interconnects can be modeled efficiently using circuit simulators such as Spice. In particular, the modeling of the inductive structures that deliver the ground and power voltages to the circuits on the semiconductor chips is presented. The FDTD method allows the generation of the equivalent circuits for arbitrary interconnect geometries that are valid over a wide frequency range.

The FDTD method is chosen to analyze the computer package components presented in this paper because of its advantages over other numerical methods. A single simulation provides an electromagnetic solution that is valid over a wide frequency range. There is no matrix inversion which eases the computer memory and time requirements as compared to finite element methods. The computational mesh is obtained without using a special-purpose mesh generator.

The electromagnetic fields are obtained in the various interconnect structures using the FDTD algorithm [1]. The computational domain is discretized using a

Figure 1. The Yee cell in the rectangular Cartesian coordinate system.
uniform Yee mesh. A unit cell of the Yee mesh is shown in Fig. 1, and details of the FDTD algorithm may be found in [1, 2].

2. Crosstalk Noise

Crosstalk noise is generated by the coupling of electromagnetic fields between adjacent interconnect paths. As the frequency content of the signals on the interconnects increases, the crosstalk amplitudes get larger because of the relationship of the noise amplitudes to the wavelength of the signal. Additionally, if the cross-section of a transmission line is inhomogeneous, the inductance and capacitance matrices are frequency-dependent and a full-wave electromagnetic field solution provides the information from which the inductance and capacitance matrices may be calculated.

Consider the coupled microstrip line of Fig. 2. Because this is a uniform transmission line with an inhomogeneous cross-section, the transmission line parameters are frequency dependent. The transmission line parameters may be given as even- and odd-mode effective dielectric constants and characteristic impedances as shown in [3] or equivalently as self- and mutual inductances and capacitances. The inductances and capacitances are related to the impedances and propagation velocities at a particular frequency by

\[
L_s = \frac{1}{2} \left( \frac{Z_{\text{even}} + Z_{\text{odd}}}{\nu_{\text{even}} \nu_{\text{odd}}} \right)
\]

(1)

\[
L_m = \frac{1}{2} \left( \frac{Z_{\text{even}} - Z_{\text{odd}}}{\nu_{\text{even}} \nu_{\text{odd}}} \right)
\]

(2)

\[
C_m = \frac{1}{Z_{\text{even}} \nu_{\text{even}}}
\]

(3)

\[
C_m = \frac{1}{2} \left( \frac{1}{Z_{\text{even}} \nu_{\text{even}}} - \frac{1}{Z_{\text{odd}} \nu_{\text{odd}}} \right)
\]

(4)

where \(Z_{\text{even}}\) and \(Z_{\text{odd}}\) are the even- and odd-mode impedances, \(\nu_{\text{even}}\) and \(\nu_{\text{odd}}\) are the even- and odd-mode propagation velocities, \(L_s\) and \(L_m\) are the self- and mutual inductances, and \(C_s\) and \(C_m\) are the self- and mutual capacitances.

The FDTD algorithm is run twice: once with an even-mode excitation to obtain the even-mode parameters and then with an odd-mode excitation. Special care must be taken with the FDTD mesh boundaries to accurately model the impedance and propagation. The FDTD modeling of uniform transmission lines is discussed in [3, 4], and methods of minimizing the errors caused by the mesh boundaries are presented there.

3. Reflection Noise

Some sections of a computer package interconnect are adequately represented by uniform transmission line models, but there are also regions in which a connection between different levels of packaging or different layers in a computer package must be made. This connection interrupts the uniform cross-section of the interconnect and is referred to as a discontinuity. The discontinuity lacks a well-defined impedance or propagation delay and causes a reflection and increased delay to a digital signal on the interconnect. Often, discontinuities are poorly shielded from adjacent interconnects and crosstalk becomes a serious problem. Modern design tools should aid the designer in minimizing the undesirable reflection, delay, and crosstalk while accurately quantifying these undesirable effects so that the final package design operates reliably.

The first step in obtaining an equivalent circuit of a discontinuity is to determine the scattering parameter
Figure 3. The rectangular via connecting two striplines on different levels in a multilayered circuit board configuration. The striplines are 0.25 mm by 1.25 mm, the via is 0.5 by 0.75 mm, and the ground planes are separated from the via by 0.25 mm. Three views are given: (a) a cross-sectional view along the middle of the stripline and via, (b) details of the stripline to via connection, and (c) the details of the via passing through the ground planes.

matrix of the fundamental mode. Representing discontinuities with its frequency-dependent scattering parameters is common in the analysis of microwave circuits, and scattering parameters of various discontinuities have been calculated using the FDTD method. Once the scattering parameters are obtained, an equivalent circuit is chosen to represent the discontinuity and the values of the individual circuit components are chosen so that the scattering parameters of the equivalent circuit match the scattering parameters obtained from the FDTD run.

Figure 4. The equivalent circuit chosen to represent the rectangular via discontinuity. The transmission lines represent the stripline portions and the inductors and capacitors represent various parts of the via. The element values are $Z_0 = 48.5$, $C_1 = 0.119$ pF, $C_2 = 0.075$ pF, $L_1 = 0.470$ nH, $L_2 = 0.062$ nH as determined by TouchStone.

Figure 5. A portion of a card to multilayered printed circuit board connector.

For example, an interconnect often includes several vias which interconnect signal conductors on different layers in a multilayered computer package such as shown in Fig. 3. The FDTD solver is run and the frequency-dependent scattering parameters of the via are obtained by post-processing the time-domain data. The equivalent circuit of Fig. 4 is chosen to represent the via geometry, and the frequency-dependent scattering parameters of the equivalent circuit are matched to the scattering parameters of the FDTD simulation. For this example, the circuit simulator TouchStone® [5] is used to determine the values of the equivalent circuit elements that are shown in Fig. 4. TouchStone® is a simulation tool generally used for microwave circuits that has an optimizing
feature which determines the element values of the equivalent circuit so that the scattering parameters from the FDTD simulation.

When an interconnect passes from one level of packaging to another, a connector such as shown in Fig. 5 provides the electrical connection between the two package components. In a similar manner to the via, the equivalent circuit of the connector is obtained from the scattering parameters.

4. Simultaneous Switching Noise

Simultaneous switching noise or delta-I noise occurs in a computer package when a set of circuits on the semiconductor chip switches states. This switching activity draws a current through the power distribution network causing a voltage disturbance at the power and ground leads to the circuit, which affects the performance and reliability of the computer. The power distribution network is primarily inductive; to a first-order approximation, the voltage change is related to the current drawn by the circuits by

\[ v(t) = L_{\text{eff}} \frac{di(t)}{dt} \]

where the effective inductance, \( L_{\text{eff}} \), is a quantity that relates the power supply voltage fluctuation, \( v(t) \), and the rate of change of current, \( i(t) \), through the set of simultaneously switching circuits. The effective inductance is used as a rule of thumb for determining how many simultaneous switching circuits a package can support, and it is often empirically determined from measurements or circuit simulations.

One of the basic components of a computer package that contributes to the simultaneous switching noise is the parallel-plate configuration created by the power and ground planes in a multilayered computer package. A simplification of a typical configuration is shown in Fig. 6 where a switching circuit is connected to a power supply through a set of vias, conducting planes and pins. The plates are rectangular with length and width dimensions of \( l=12.5 \text{ mm} \) and \( w=12.5 \text{ mm} \), and a plate separation, \( d \), of 0.1 mm.

The individual inductors and capacitors of the parallel-plate portion of the equivalent circuit shown in Fig. 7 are given in Table 1. The inductor and capacitor values are determined using a least squares procedure that fits the frequency response from the FDTD simulation to the equivalent circuit. The values are assigned based on the distribution of currents in the plates as discussed in [6].

Figure 6. A parallel plate as part of a packaging structure that includes a switching circuit that is connected to the parallel plate through a pair of vias, and a power supply connected to the parallel plate through pins.

Figure 7. The equivalent circuit of Fig. 6 in which the coupled inductors of the vias and pins are modeled by their Thévenin equivalent inductors, and the parallel plates are represented by a distributed inductance and capacitance model.

5. Summary and Conclusions

The FDTD algorithm has been applied to the modeling of the crosstalk, reflection, and simultaneous switching noises that exist in a computer package. The FDTD solver is a general purpose tool that allows the designer to obtain the time-domain electromagnetic field distributions in the various components of the interconnect path that contributes to the noise in a computer package. The contribution of this paper is the development of approaches to obtain equivalent circuits suitable for use in a circuit simulator. In par-
ticular, inductance and capacitance models of the planar structures that deliver the ground and power voltages to the circuits on the semiconductor chips have been developed.

References


Table 1. The inductor and capacitor values used for the parallel portion of the equivalent circuit in Fig. 7.

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<th>Element</th>
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