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Transient Simulation OF Complex, Lossy, Multi-Port Transmission Line Networks With Nonlinear Digital Device Termination Using A Circuit Simulator

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Abstract

Transmission line effects of printed circuit board (PCB) tracking are a major limitations to the speed in which digital systems can operate. Proper simulation of these effects has been constrained because present techniques rely on non-physical approximations to the behavior of either the transmission line system or the digital device termination. This paper presents a technique for describing complex coupled multi-port transmission line system in terms of a time-domain Green's function and then implements this description into a circuit simulator. The results of this work permit highly accurate simulation of arbitrary transmission line networks with non-linear transistor level models of digital devices.

Introduction

The speed in which digital systems can operate is increasingly constrained by the transmission line effects of the printed circuit board (PCB) tracking. Since simulation techniques have not kept pace with advances in device switching speed, a designer may not be able to predict errors introduced by transmission line effects until a PCB has been prototyped. Furthermore, as time-to-market requirements are compressed, a designer is forced to rely on simulations, as opposed to prototyping, to prove the functionality and robustness of a design. Therefore, in order to properly assess the impact of transmission lines on digital system performance, simulation tools require an accurate method to incorporate transmission line effect.

The present techniques, used by circuit simulators for simulating transmission line effects of digital systems on PCBs, relies on non-physical approximations of the digital devices or the transmission line network. For analog circuit simulators, such as SPICE, simulations can either be performed in the time domain or in the frequency domain. If the simulations are performed in the frequency domain, the transmission line system may be accurately described from measured Scattering (S-) parameters; however, linear approximations must be made for the termination characteristics of non-linear digital devices. If the simulations are performed in the time domain, the digital devices can be accurately described by transistor level models; however, the transmission line system must be approximated by either lumped elements or lossless delay line models.

This paper presents a technique to derive a time domain Green's function from a frequency domain S-parameter description of a complex coupled transmission line system. The Green's function is then incorporated into the circuit simulator SCAMPER[1]. By using SCAMPER, accurate simulations can be made for complex transmission line networks terminated with transistor level models of digital devices. This technique has proven to be more accurate and robust than previously reported simulation methods.

By using this technique a designer can simulate a complex transmission line system with arbitrary non-linear termination in the time domain. Thus, a designer can predict the effect PCB tracking will have on the signal quality and signal integrity for a digital system.

Background

The existing techniques, used in circuit simulators, for predicting the transmission line effects on PCBs with digital device termination have classically used one of the following methods. All of the these methods require non-physical approximations to the characteristics of either the transmission line system or the digital device termination.

1) Modelling the transmission line effects of a PCB layout as a set of lumped element (L, R, C, G) subcircuits and simulating these circuits with non-linear digital device termination in the time domain
2) Modelling the transmission line effects of a PCB layout as a set of lossless bi-directional delay lines and simulating with non-linear digital device termination in the time domain
3) Describing the transmission line effects of a PCB layout by the frequency domain S-parameters and simulating these S-parameters with linear approximations to digital device models in the frequency domain.

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[1] SCAMPER is a proprietary analog circuit simulator of Northern Telecom Ltd.

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Theory

Development of Time Domain Green's Function

The Green's function is the response of the system at the observation point to a Dirac (unit) delta source. It may also be referred to as the time domain impulse response.

Theory of Green's Function

For any linear system, the response at an observation point can be found by the method of Green's function. The theory of Green's function states that the total response of a system at some observation point to an arbitrary source can be determined by a convolution of that source with it's corresponding Green's function over the variable of interest. For a transmission line system, the variable of interest is time and the convolution is over a given period of time.

For any linear system with multiple arbitrary sources, the total response at an observation point is found by the superposition of the convolution of each source with it's corresponding Green's function.

Figure 1 illustrates a transmission line network with known reference impedances and arbitrary sources.

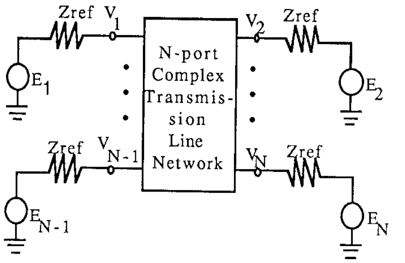

Figure 1: N-port System With Known Reference Impedance and Arbitrary Sources

For the network shown in Figure 1, the response at each node of the transmission line system is found by the linear superposition of the convolution of the Green's function with the arbitrary source. Thus the response at port *j* and time *t* is found from the following equations:

$$V_j(t) = \sum_{i=1}^{Nport} \int_{-\infty}^{t} g_{ij}(t-\tau)\, E_i(\tau)\, d\tau = \sum_{i=1}^{Nport} g_{ij} * E_i \qquad (1)$$

We use the $*$ nomenclature to signify a convolution. The terms $g_{ij}()$ refer to the time domain Green's function for the response at port *j* and time *t* to a unit delta source at port *i* and time zero. The term E_i is the arbitrary EMF source at port *i* with an impedance of *Zref*. The term *Nport* refers to the number of ports of the transmission line system.

Finding the Green's Function

The Green's function or impulse response may be found from the system S-parameters according to the following formulas (Equation 2 and 3). S-parameters are always associated with a known reference impedance, usually 50Ω.

$$G_{ij}(\omega) = \begin{cases} (1+S_{ij}(\omega))H(\omega)/2 & i = j \\ (S_{ij}(\omega))H(\omega)/2 & i \neq j \end{cases} \qquad (2)$$

$$g_{ij}(t) = \frac{1}{\Delta t} F^{-1}\left[G_{ij}(\omega) \right] \qquad (3)$$

The term $G_{ij}(\omega)$ is the frequency domain Green's function. The function $\mathbf{F}^{-1}[\ ]$ is the inverse discrete Fourier transform, and $S_{ij}(\omega)$ is the frequency domain scattering parameters at radian frequency ω. $H(\omega)$ is a low pass filter transfer function at radian frequency ω. Finally, Δt is the time step used in the numerical convolution. The factor of $^1/_2$ is derived from flow graph analysis.

The low pass filter, $H(\omega)$, is required to reduce the time domain ripple associated with taking the inverse Fourier transform.

Numerical Implementation of the Green's Function

So far the system response has been determined by a superposition of integrals. For implementation into a computer we use Simpson's rule to approximate the integration numerically. Thus Equation 1 can be approximated as:

$$V_j(q) = \sum_{i=1}^{Nport} g_{ij} * E_i \approx \sum_{i=1}^{Nport} \left[\sum_{p=-\infty}^{q} g_{ij}(q-p)\, E_i(p)\, \Delta t \right] \qquad (4)$$

Development of System of Equations

To find the system response with an arbitrary impedance at each node of the transmission line system, we must remove the reference impedance. A simple mathematical method to remove the effects of the reference impedance is to place in series with the reference impedance a negative impedance of the same value. This creates a virtuals short circuit between the arbitrary termination and the transmission line system as shown in Figure 2. This method was first developed by Djordjevic, Sarkar, and Harrington [1].

By using the compensation theorem, an arbitrary network can be subdivided into an N-port transmission line network and N-arbitrary termination systems. Since the transmission line system can be completely separated from all terminations, a circuit simulator branch statement would be developed to describe the transmission line system. Thus, this branch statement describes the

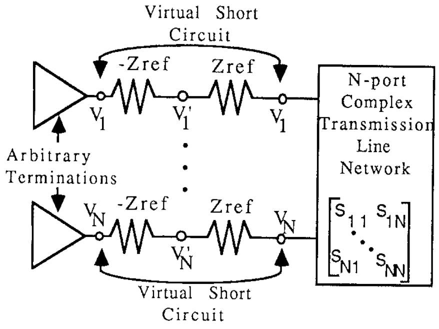

Figure 2: Removing Effect of The Reference Impedance

behavior of the transmission line at each node based on the past and present voltages and currents at all nodes. Figure 3 illustrates the system that is implemented into the circuit simulator. This figure is electrically identical to Figure 2.

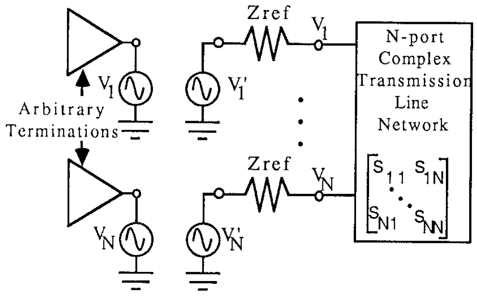

Figure 3: Transmission Line Network Separated From Termination

From Figure 2 and Equation 1, the sources labeled V_i and V_i' are controlled sources at each node. The controlled source V_i, referred to as a node source, is found from the convolution Equation 5:

$$V_j(t) = \sum_{i=1}^{Nport} g_{ij} * V_i' \qquad (5)$$

and the controlled source V_i', referred to as a virtual source, is found from the compensation theorem

$$V_i' = V_i + Zref*I_i \qquad (6)$$

where I_i is the current flowing out of the arbitrary impedance and V_j is the node voltage. Therefore, for an N-port transmission line system there exists 2N equations with 2N unknowns. These equations are solved by SCAMPER using a numerical technique.

Method

Implementation Into SCAMPER

To implement the Green's function approach to simulating transmission line systems in SCAMPER, we defined a transmission line model. This model contains two controlled voltage sources for each port of the transmission line system; a virtual source and a node source. The voltage across the virtual source is defined by Equation 6. The voltage across the node source is defined by Equation 5. We used a linear branch statement to define the virtual source while we used a non-linear branch statement to define the node source. To implement a non-linear branch statement SCAMPER permits a user to define a FORTRAN subroutine to perform the necessary computations.

Figure 4 illustrates the implementation for an N-port transmission line system. The resistors shown in this figure are only for DC connectivity and do not effect the operation of the model.

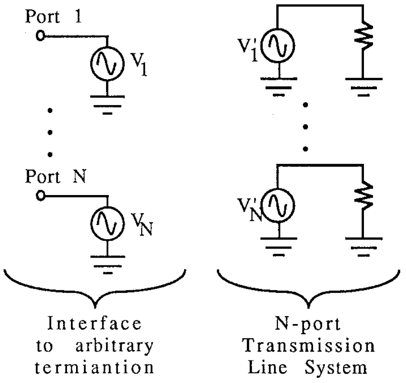

Figure 4: Implementation into SCAMPER

There are three phases to a time domain simulation: initialization, DC steady state analysis, and transient analysis.

Initialization

During initialization SCAMPER passes the following user supplied information to the FORTRAN subroutine:

- Number of ports for the transmission line network
- S- parameters in the frequency domain for the network
- Minimum time step used in transient analysis
- Period of time the simulation is performed
- Stop band frequency for the low pass filter
- Period of time the Green's function is expected to have non-negligible components.

Upon initial entry, the FORTRAN subroutine uses the following steps to find the time domain Green's function from the frequency domain S-parameters:

1) The complex frequency domain S-parameters are read in and interpolated onto harmonically related frequencies. The harmonically related frequencies are required for the inverse Fast Fourier Transform (FFT) algorithm.
2) The frequency domain Green's function is found using Equation 2. The LPF used has a pass band as specified by the user.
3) The frequency domain Green's function is extended by addition of zero value elements so that the highest frequency component has a corresponding time step equal to the minimizing time step used in transient simulation
4) The time domain Green's function is found using an inverse FFT. Since the time domain Green's function is a real function, the imaginary components of the frequency domain Green's function are forced to have odd symmetry around the frequency origin before the inverse Fourier transform is taken.
5) The time domain Green's function is truncated when the Green's function response has a negligible amplitude.

These steps are repeated for each of the N^2 Green's functions.

DC Steady State Analysis

During DC steady state analysis, SCAMPER finds a steady state voltage at each node of the system. This means SCAMPER attempts to converge to a solution at time t=0. In order to evaluate the summation of Equation 2 we need to assume that all transients will die out within the time period *T*. If we assume a steady state condition from time t=-∞ up to t=0, we can use a circular convolution to evaluate Equation 5. Thus, the superposition of convolution equations used to find the node voltages is approximated during DC analysis by the following:

$$V_j(0) \approx \sum_{i=1}^{Nport} \left[\sum_{p=-T}^{0} g_{ij}(-p)\, V'_i(0)\, \Delta t \right] \tag{7}$$

During DC analysis SCAMPER passes the present time (zero) and the voltage at each virtual source, $V'_i(0)$. The FORTRAN subroutine returns the node voltage for all node sources. SCAMPER uses this information as part of the numerical analysis to converge to a steady state voltage for all nodes in a system.

Transient Analysis

During transient analysis, the FORTRAN subroutine uses a circular convolution to find the node voltages. SCAMPER passes the present simulation time and voltage at each virtual source to the routine. The past voltages at all virtual ports are interpolated to fit the time step of the Green's function. The circular convolution used for time *q* and period *T* is defined by the following:

$$V_j(q) \approx \sum_{i=1}^{Nport} \left[\sum_{p=0}^{q} g_{ij}(q-p)\, V'_i(p)\, \Delta t + \sum_{p=q-T}^{-1} g_{ij}(-p)\, V'_i(0)\, \Delta t \right] \tag{8}$$

The use of the circular convolution represents the sum of the transient and steady state responses of the system. The first term in the brackets of Equation 9 is the transient response, while the second term is the steady state response.

Results

To prove this method of circuit simulation produced accurate results, we compare simulations against oscilloscope measurements for a PCB layout with digital devices. The S-parameters for the layout were obtained from field theory models using a frequency domain circuit simulation program. The digital device models were obtained from transistor level models supplied by the manufacturer. This comparison ensured that this technique provides accurate simulation for use in the design process.

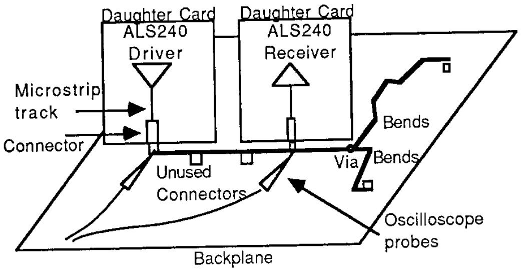

Figure 5: Diagram of Complex Multi-port Transmission Line System

Figure 5 represents the system tracking for a four-port complex transmission line network. The four ports are the driver and receiver ports, and the two connections for the oscilloscope probes. Figures 6 through 9 compare the measured and simulated responses at the oscilloscope probes.

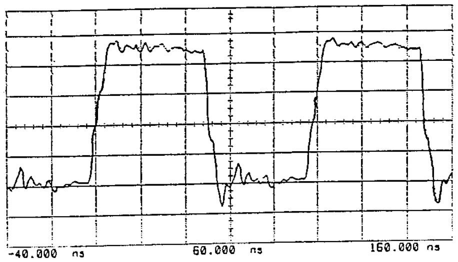

Figure 6: Measured Response, Driver Side

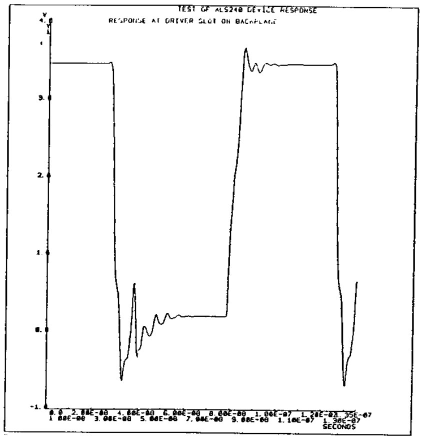

Figure 7: Simulated Response, Driver Side

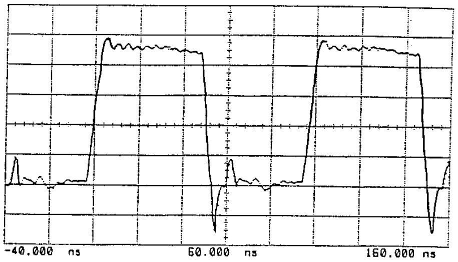

Figure 8: Measured Response, Receiver Side

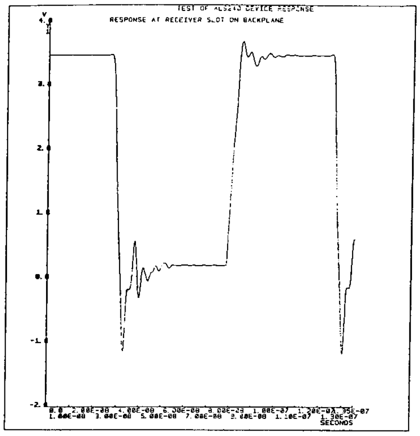

Figure 9: Simulated Response, Receiver Side

Discussion

The experimental verification proved that the simulation technique which uses the Green's approach in a circuit simulator can accurately model the transmission line effects. Thus, this method can accurately predict transmission line problems before a PCB is manufactured.

Discrepancies between the simulation results and measured results are due to the following factors:

- Inaccuracies in the frequency domain S-parameters caused by approximations in the models for connectors, line, vias, etc.
- Inaccuracies in the models for the ALS240 devices. These models were transistor level models supplied by the manufactures.
- Aliasing and other effects caused by taking a discrete inverse Fourier transform of a system that is inherently band-unlimited and continuous.

Conclusion

This paper presents a method for implementing a Green's function (found from the frequency domain S-parameters) approach to transmission line simulation . The Green's function approach is implemented as part of a transmission line model. This model is then incorporated into the circuit simulator as a branch statement. The branch statement returns the transient response of the transmission line system when terminated with arbitrary non-linear devices. This method has proved to be superior to the existing method because it does not rely on non-physical approximations to the characteristics of the transmission lines or the digital devices. It also accurately predicts the response to a transmission line system of PCB tracks with non-linear digital devices termination.

References

[1] Shelton, R. Sequent Computer Systems, Inc. "VLSI Design Technology,Backplane Simulation". ESD:, May 1988.pp 87-95.

[2] Gupta, K. C., Garg, R., and Bahl, I. J.. Microstrip Lines and Slotlines. Artech House,1979.

[3] Schutt,-Aine J. E., and Mittra, R. "Scattering Parameter Transient Analysis of Transmission Lines Loaded with Nonlinear Termination". IEEE Transactions on Microwave Theory and Techniques, Vol. 36, No. 3, March 1988.

[4] Djordjevic, A. R., Sarkar, T. K., and Harrington, R. F. "Analysis of Lossy Transmission Lines with Arbitrary Nonlinear Termination Networks" IEEE Transactions on Microwave Theory and Techniques, Vol. 34, No. 6, June 1986.

[5] Vlach, J., and Singhal, K. Computer Methods for circuit analysis and design. Van Nostrand Reinhold Co.,1983.

[6] Dahlquist, G., and Bjorck, A. Numerical Methods. Prentice-Hall, 1974.

[7] Akhtarzad, S., Rowbotham, T. R., and Johns, P. B. "The Design of Coupled Microstrip Lines". IEEE Transactions on Microwave Theory and Techniques, Vol. 23, No. 6, June 1975.

[8] Napoli, L. S., and Hughes, J. J. "Characteristics of Coupled Microstrip Lines". RCA Review, Sep. 1970.

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