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MULTICONDUCTOR TRANSMISSION LINES

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Abstract

Time responses of systems consisting of an arbitrary number of multiconductor transmission lines are optimized. The high-speed interconnect design problem for digital computer or communications systems is formulated into mathematical optimization. Design variables include physical/geometrical parameters. A state-of-the-art two-stage algorithm for minimax optimization is exploited to minimize transmission line effects such as crosstalk, delay and reflection at all vital connection ports.

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SUMMARY

Introduction

In high speed digital computers and communication systems, transmission line effects of circuit interconnects such as delay, reflection, distortion and crosstalk are limiting factors in the overall system performance. Modelling such effects is beyond the conventional lumped element approach such as that of SPICE. Time responses of lossy distributed transmission lines are essential, as demonstrated by Djordjevic, Sarkar and Harrington [1-2] and Palusinki and Lee [3]. Mehalic and Mittra [4] made a recent advance by modelling tapered multiple microstrip lines for VLSI circuits. Novel techniques for system simulation considering high speed interconnect effects are proposed, e.g., the numerical Laplace inversion approach of Griffith and Nakhla [5] and the waveform relaxation approach of Chang [6].

All these existing techniques are, however, analysis or simulation tools. There does not exist an automated design technique in the literature that optimizes time responses of digital systems with distributed transmission lines. Consequently, human expertise has been used in studying the effects of interconnect parameters on system performance e.g., [1, 3].

For the first time, this paper formally describes design optimization of high-speed circuit interconnects with distributed multiconductor elements as a mathematical optimization problem. Transmission-line effects such as crosstalk, delay and reflection are minimized at all vital connection ports. Optimization is carried out w.r.t. physical/geometrical parameters. An efficient two-stage algorithm for minimax optimization is exploited.

Formulation of Error Functions

Consider a multiconductor transmission line in which one of the conductors is excited by a trapezoidal signal. Suppose $\mathbf{x}$ is a vector containing the design variables of the system. Suppose $v(\mathbf{x}, t)$ is a generic notation representing transient response at a terminal (either at the near end or the far end) of the multiconductor line. w_c, w_d and w_r denote weighting factors for crosstalk, delay and reflections, respectively.

Crosstalk Signal Suppose $v(\mathbf{x}, t)$ is on a conductor not connected to the excitation. In this case $v(\mathbf{x}, t)$ is due to crosstalk. By imposing an upper specification S_c on the magnitude of the response, we formulate a weighted error function as

$$w_c(t)\ (|v(\mathbf{x}, t)| - S_c(t)), \quad 0 < t < \infty \tag{1}$$

Waveform Propagation Delay Suppose the time for a signal to reach a threshold value (e.g., 0.3 volts) is τ. To minimize the propagation delay we apply an upper specification S_d and formulate the error function as

$$w_d\ (\tau(\mathbf{x}) - S_d) \tag{2}$$

Reflected Signal Suppose the time length of the trapezoidal excitation is T. An ideal signal $v(\mathbf{x}, t)$ should vanish beyond the time $\tau + T$. However, due to reflections the signal will continue to exist for some time. We impose an upper specification $S_r(t)$ to the magnitude of the signal and formulate the weighted error function as

$$w_r(t)\ (|v(\mathbf{x}, t)| - S_r(t)), \quad t > \tau + T \tag{3}$$

Formulation of Optimization

A set of sample points in the time range of interest is selected. The error functions in (1) - (3) are formulated for all responses of interest at all necessary ports of the system and at all relevant time points. All the individual weighted error functions are then assembled into a vector $f(\mathbf{x})$. The overall objective function for design optimization is

$$u(\mathbf{x}) = \max\{f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_m(\mathbf{x})\} \tag{4}$$

The optimal interconnect design problem can be expressed as

$$\underset{\mathbf{x}}{\text{Minimize}}\ u(\mathbf{x}) \tag{5}$$

subject to

$$g(x) \geqslant 0 \tag{6a}$$

and

$$h(x) = 0 \tag{6b}$$

where the functions $g(\mathbf{x})$ and $h(\mathbf{x})$ represent design constraints on the variables, such as physical and geometrical constraints.

Such a formulation allows the application of a powerful two-stage algorithm for minimax optimization [7, 8]. The algorithm combines the robustness of a first-order method of the Gauss-Newton type with the speed of the quasi-Newton method.

Example

Consider the three transmission line system described by Djordjevic and Sarkar [2] and shown in Fig. 1. This system can represent a branching situation. The excitation is a 6ns trapezoidal signal.

Meaningful optimization should be performed w.r.t. the physical/geometrical parameters of the multiconductors. The cross-sectional view of a two-conductor transmission line on a PWB (printed wiring board) is shown in Fig. 2. All the three multiconductor lines are assumed to have equal physical/geometrical parameters except line length. The parameter values of the example are listed in Table I.

Our simulator combines the approach of Griffith and Nakhla [5] with the that of Walker [9]. The transmission-line matrices are first computed from physical/geometrical parameters using the formulas in [9]. Fringe effects are taken into account. The modified nodal admittance stamp for each transmission line is formulated based on the modal analysis approach [1, 5]. The numerical Laplace inversion method is then used to calculate the transient responses of the overall system [5]. The circuit is simulated and optimized using our CAD system McCAE [10].

The time responses of the system are plotted in Fig. 3. The delay time for the two output signals v_7 and v_{11} are 5.5ns and 6.4ns, respectively, based on a 0.3 threshold criterion. The peak value of the crosstalk signals v_8 and v_{12} are 0.027 and 0.023, respectively. The crosstalk v_8 is 29dB below the signal output v_7. Crosstalk v_{12} is 27dB below the signal v_{11}.

The specification for optimization is a 5.3ns upper specification on the delay time of v_7 and 5.4ns upper specification on the delay of v_{11}. We also impose a 0.037 upper specification on the magnitude of v_2 and v_4 and a 0.02 upper specification on v_8 and v_{12} at 65 time points in the interval [3ns, 16ns]. The weighting factors are $w_c = 40$, and $w_d = 1$. The total number of error functions is $m = 262$.

The vector of optimization variables $\mathbf{x}$ consists of line width w, line distance d, board thickness h, and length of the three individual multiconductor lines l_1, l_2 and l_3. We require that the total width of the two coupled lines plus the spacing between them to be fixed at 0.0025m. The total length of the three transmission lines are fixed at 1.34m. This results in two geometrical constraints:

$$h_1(\mathbf{x}) = w + d - 0.0025 = 0$$

$$h_2(\mathbf{x}) = l_1 + l_2 + l_3 - 1.34 = 0$$

The initial value of the overall objective function in (4) was 0.989. After 15 iterations of optimization, the value was reduced to -0.22, indicating that all specifications are satisfied. The parameters after optimization are also listed in Table I. Circuit responses at the solution of optimization are plotted in Fig. 4. The propagation delay times for v_7 and v_{11} are reduced to 5.08 and 5.17ns, respectively. The magnitude of crosstalk signals v_8 and v_{12} are both reduced by more than 50%. They are both about 35dB below the signals on their corresponding source conductor, i.e., v_7 and v_{11}, respectively.

Conclusions

For the first time, high-speed interconnect design using multiconductor transmission-line models is formulated as a mathematical optimization problem. Transmission-line effects such as crosstalk, delay and reflection are minimized at all vital connection ports. Design optimization is carried out in the time domain and w.r.t. physical/geometrical parameters. An efficient two-stage algorithm for minimax optimization is exploited. The success of this work motivates further research in large-scale optimization and statistical design of interconnections for digital computer and communication systems.

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TABLE I

PARAMETER VALUES FOR THE THREE TRANSMISSION-LINE EXAMPLE

Variable	Description	Before Optimization	After Optimization
w	line width	0.45mm	0.2mm
d	distance between lines	2.05mm	2.3mm
h	thickness of laminate	0.73mm	0.84mm
l_1	length of transmission line #1	0.3048m	0.1339m
l_2	length of transmission line #2	0.4572m	0.6114m
l_3	length of transmission line #3	0.6096m	0.6263m
ϵ_r	relative dielectric constant	4.54	4.54

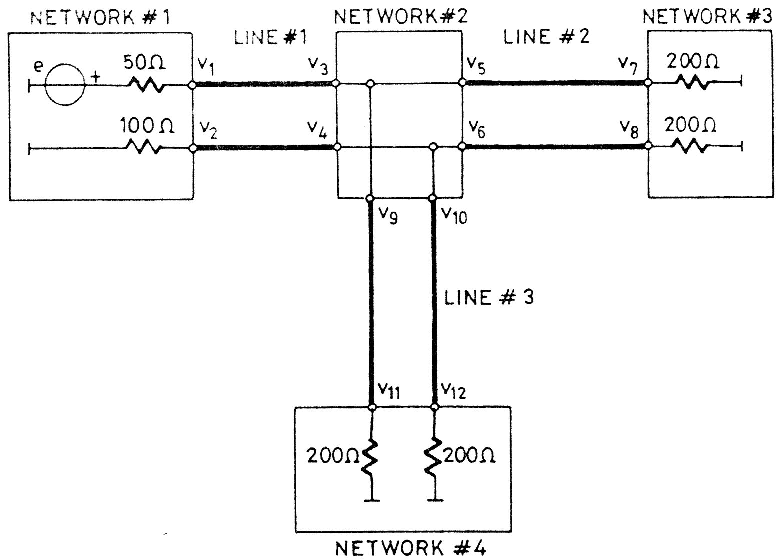

Fig. 1. A three transmission-line system with a branch [2].

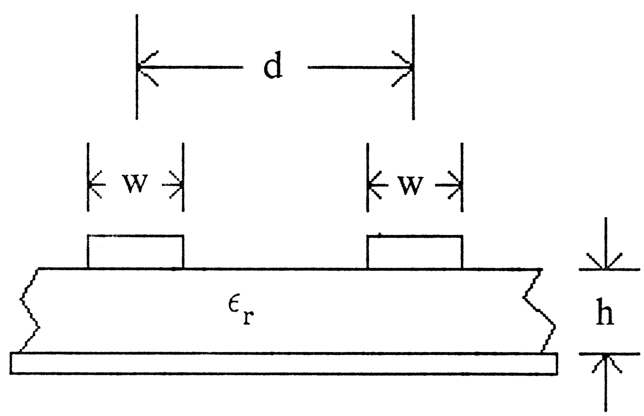

Fig. 2. Cross-sectional view of multiconductor lines on a PWB laminate.

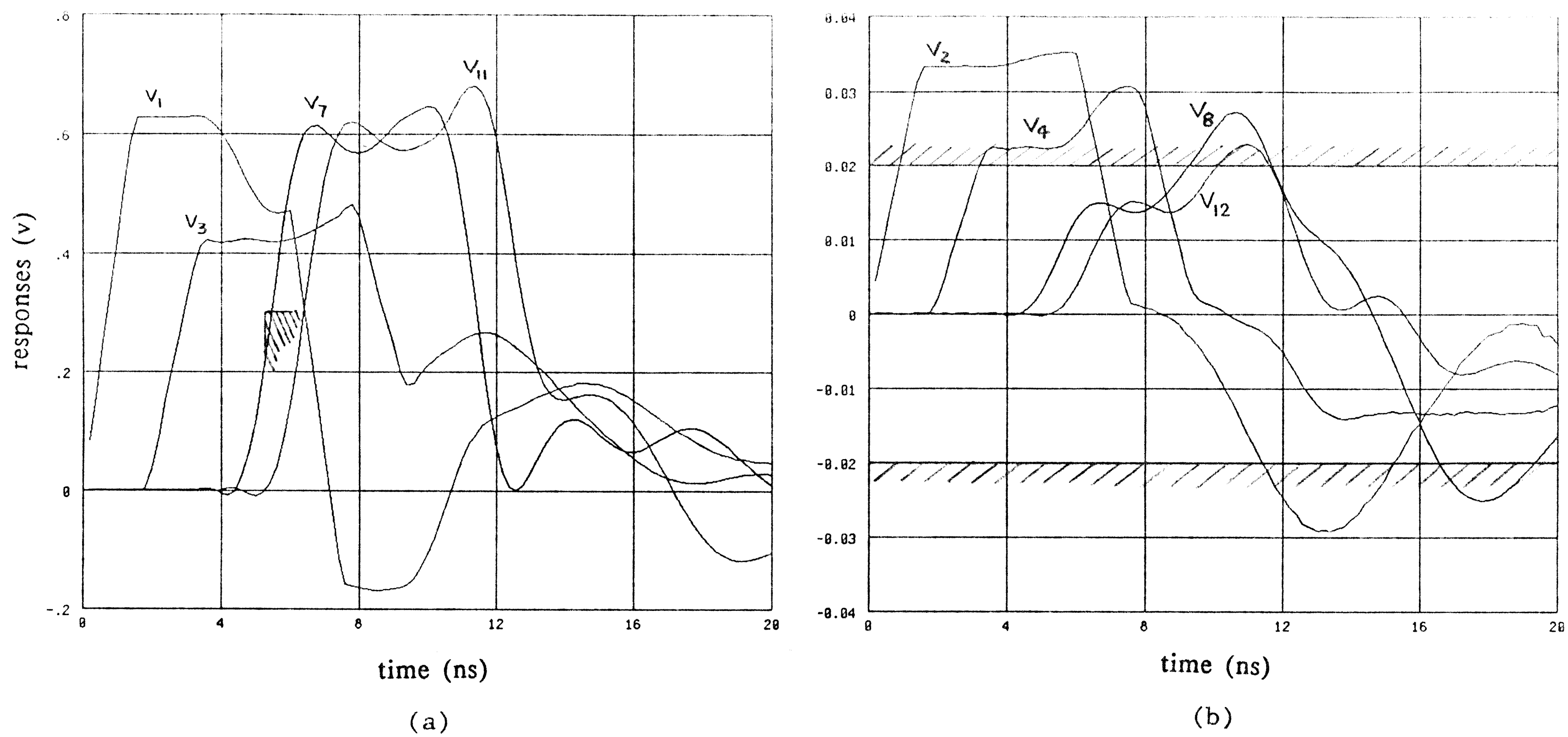

Fig. 3. Responses of the three transmission-line system before optimization. (a) Upper specifications of 5.3ns and 5.4ns are imposed on the delay parameters of v_7 and v_{11}, respectively. Both v_7 and v_{11} violate the specifications. (b) The 0.02 specification is applied to the magnitude of crosstalk signals of both v_8 and v_{12}. Both crosstalk signals violate the specification.

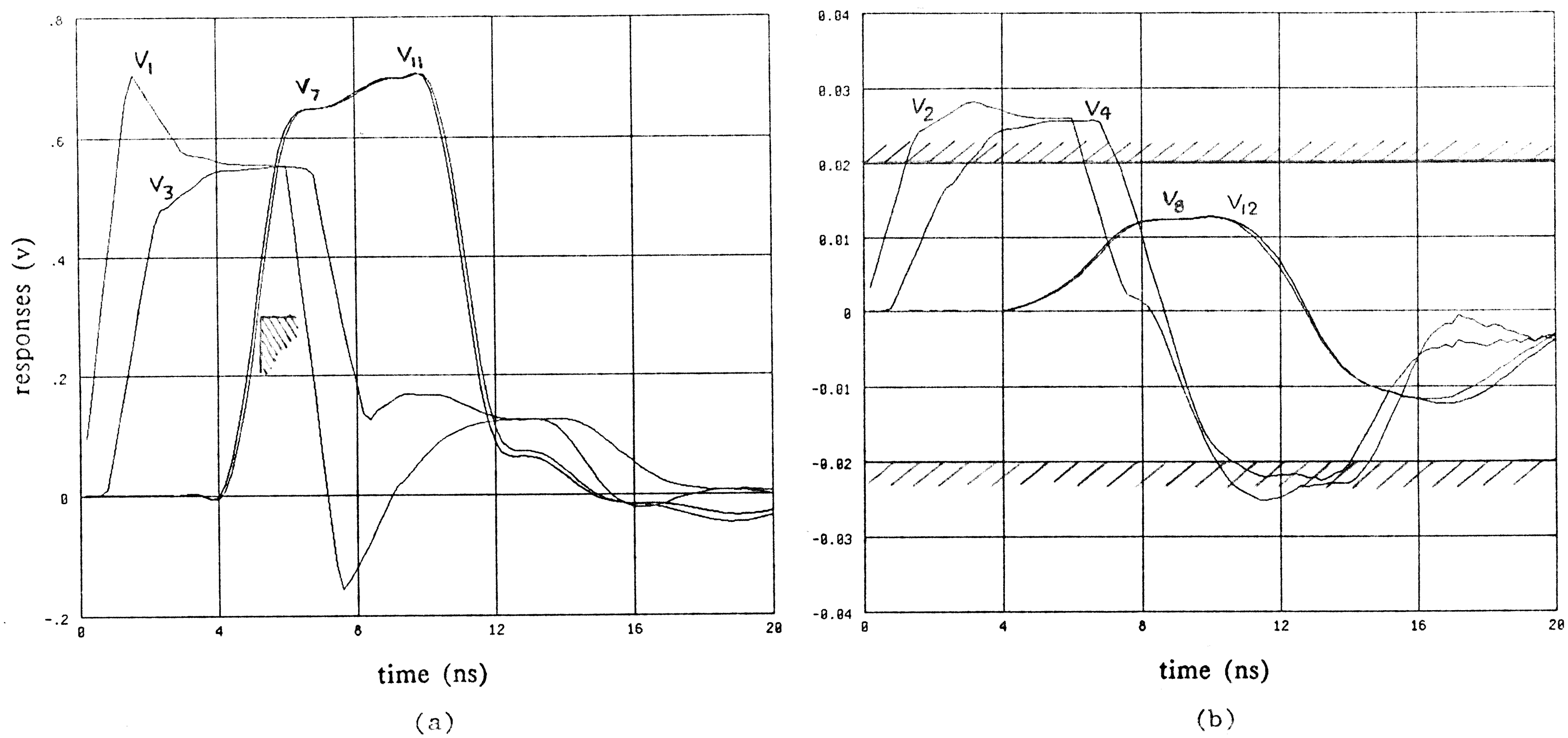

Fig. 4. Responses of the three transmission-line system after optimization. (a) Both v_7 and v_{11} satisfy the specifications imposed on their delay parameters. (b) Crosstalk signals v_8 and v_{12} both satisfy the 0.02 specification imposed on their magnitudes.