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Minimization of Overshoots and Ringing in MCM Interconnections

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Abstract – **In this paper, we present a novel design methodology to reduce peak overshoots and ringing oscillations in MCM interconnects characterized by a transmission line structure. An ideal transformer is used to transform the load impedance to provide damping. The entire structure is investigated using transmission or ABCD matrices. The results are verified through simulation.**

Index Terms- **RLC Trees, Switching Transients, Ruthroff Transformer and Transient Analysis.**

1. INTRODUCTION

At high switching frequencies, the inductive effects in RF and MCM interconnections can no longer be ignored. RC models proposed earlier are therefore inadequate, because of the transmission line effects caused by the short rise time of signals and the relatively long interchip wires. Line inductance introduces overshoots, ringing, and reflections degrading the signal significantly. With the introduction of inductance, the wire behaves as an RLC circuit, characterized by a second order transfer function. It has been reported that step response in such interconnects are often ringing in nature [1]. Brews [2], presented conditions for reduction of peak overshoot amplitude at the output node voltage to $\pm 5\%$. His work assumed the input to be a unit step input with a finite rise time. Two different design techniques, in that the single-transfer-function method and the average-transfer-function method are used to control far-end overshoots on the driven interconnect line [3]. Comparison between the two design methods suggests the average-transfer-function model is better in designing overshoot-controlled circuit. An analytical solution is obtained for overshoots and undershoots amplitudes by line length, termination, and rise time [4]. The solutions are obtained and verified for both lossless line as well as lossy transmission lines.

In all the above proposed techniques the input is taken as a unit step voltage with/without a finite rise time. The problem however aggravates if the source itself is ringing because of presence of inductive components in the source impedance [5]. Further switching transients can also lead to oscillations at the input of the interconnection line. This can lead to contradiction to these solutions. We therefore need to analyze the problem of overshoot and undershoot control afresh in the light of oscillatory input.

In this paper, we present a new design technique to reduce overshoot and undershoot propagated in a transmission line interconnect in presence of oscillatory input source. We use an ideal transformer, in that a Ruthroff Transformer [6] is used to control the overshoots and undershoots by transforming the load impedance. The analytic solutions are obtained using ABCD or Transmission matrix. Results are validated through simulation.

The paper is organized in the following manner. In section 2, detailed analysis is presented for the interconnect structure under investigation. Equivalent circuits are developed with and without the Ruthroff transformer for varying line lengths. The solutions are verified through simulation. The paper is concluded in section 3.

2. DESIGN AND ANALYSIS OF THE PROPOSED INTERCONNECT STRUCTURE

Figure 1 gives the proposed interconnect structure required to control overshoots and ringing.

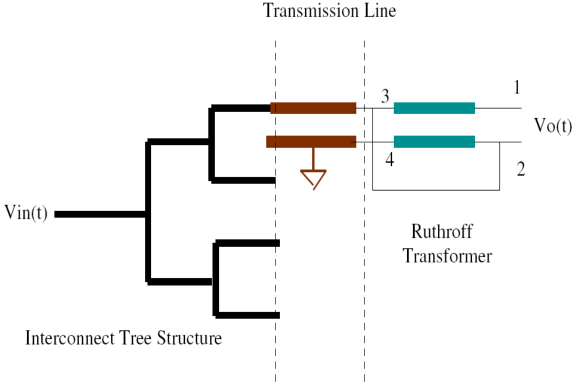


Fig.1. Proposed interconnect tree structure with Ruthroff transformer

MCM interconnections are generally tree structures with a single input and multiple output nodes. The voltage is measured at any of the output nodes. If the input is oscillatory, the output node voltage is characterized by marked overshoots and undershoots. The ringing at the output may further increase if the line lengths of individual branches of the tree are sufficiently long. In such cases the line inductance further degrades the signal. We propose a remedial measure, in which a closely-coupled line and a Ruthroff transformer follows the output node of the interconnect tree. The Ruthroff transformer is terminated by a 50 Ω resistive load at node 1-2 as shown in figure 1.

Equation (1) gives the normalized mathematical expression for input voltage.

$$V_{in}(t) = 1 - e^{-\alpha t}[\cos(\omega t) + \sin(\omega t)] \qquad (1)$$

The proportionality constant α determines the amplitude of overshoots and undershoots and ω determines the frequency of these oscillations. The simulated plot of the input voltage function with respect to time is shown in figure 2.

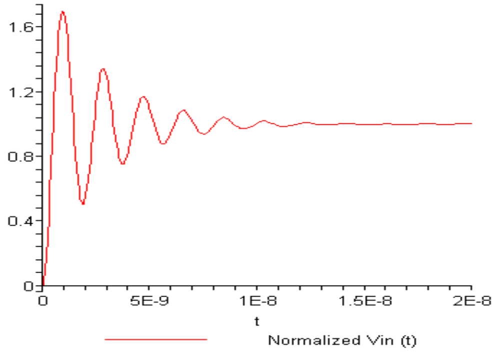


Fig. 2. Plot of normalized input voltage (Equation 1)

The interconnect tree shown in figure 1 can be characterized by equivalent lumped RLC circuit [1] and is given in figure 3.

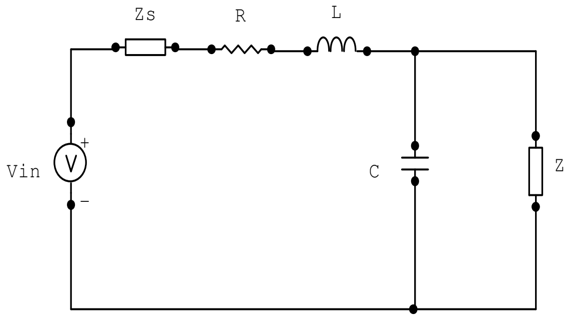


Fig. 3. Second order equivalent circuit of an RLC interconnection tree

In figure 3, the RLC line is terminated by 50 Ω resistor which represents the equivalent impedance of all individual lines further on forming any arbitrary mesh or tree structure, being fed by this line. The analysis of such an arrangement can be done using standard techniques based on second-order transfer function approach. Output voltage $V_{out}(t)$ across Z is given in equation 2.

$$V_{out}(t) = V_{in}(t) * \{ \frac{2Ze^{(\frac{-tR}{2L} - \frac{tR_s}{2L} - \frac{t}{2CZ})} \sinh(\frac{t\sqrt{\theta}}{2LCZ})}{\sqrt{\theta}} \} \qquad (2)$$

where

$$\theta = [R^2C^2Z^2 + 2R^2Z^2R_s - 2RCZL$$
$$+ R_s{}^2C^2Z^2 + 2R_SCZL + L^2 - 4LCZ^2]$$

Note that * indicates time-domain convolution.

The plot of V_{out} (t) is given in figure 4.

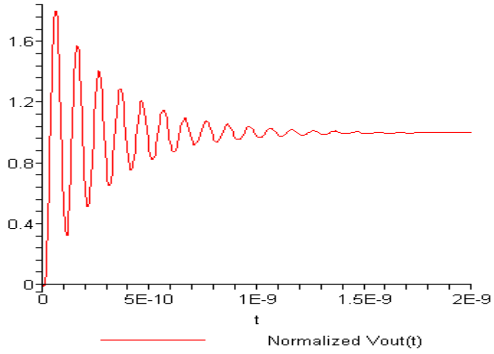
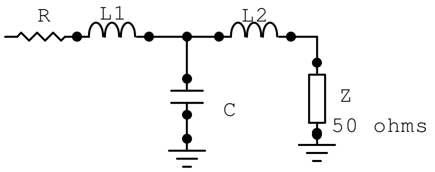


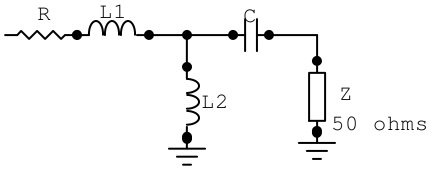
Fig. 4. Output response across Z.

The typical design parameters taken in this analysis are R = 50 Ω, L = 12.3 nH, C = 2.1 pF and Z = 50 Ω. It is evident that the overshoots ringing are actually aggravated when the signal propagates through the interconnect line. The scenario may be even worse for longer line lengths where the inductance values lowers the damping coeffient further, resulting in sharper overshoots and oscillations.

We therefore introduce a transmission line in proximity with a ground line after the interconnect line. In the following discussion it is shown that by altering the line length of this transmission line the equivalent circuit of the interconnect structure gets modified. The equivalent circuit is obtained using ABCD matrix multiplication for the various subparts of the interconnect structure, as given in the Appendix. Figure 5a and 5b gives the equivalent circuits of the modified interconnect line with varying transmission line lengths (L).



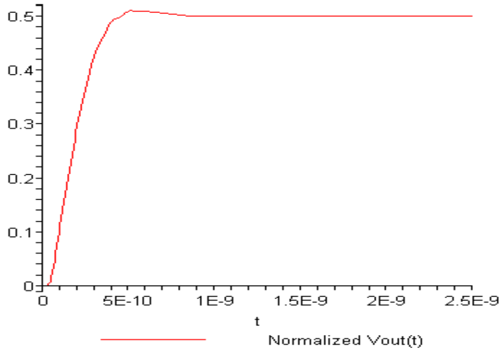
(a). L < $L_{Critical}$



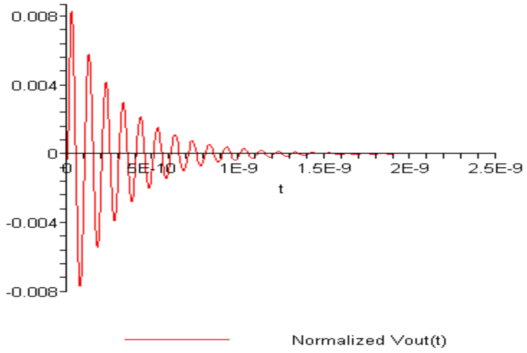
(b). L > $L_{Critical}$

Fig 5. Equivalent Interconnect Structure

It is seen that as the length of the transmission line following the interconnect tree increases above a critical value the equivalent circuit alters. We call this the critical length of the transmission line ($L_{Critical}$). Figure 6a and 6b gives the output response for these equivalent circuits.



(a). L < $L_{Critical}$



(b). L > $L_{Critical}$

Fig 6. Output response of the interconnect line.

The following table gives the typical design values of circuit parameters shown in figure 5a and 5b for various values of transmission line length (L).

Table 1: Typical design values of circuit parameters ($L_{Critical}$= 8000 µm)

Transmission line length (L) in µm	Design values
5	R =50 Ω, L1 = 12.3 nH, L2 = 0, C = 2.1 pF
500	R =50 Ω, L1 = 12.3 nH, L2 = 0.08 nH , C = 2.1 pF
1000	R =50 Ω, L1 = 12.3 nH, L2 = 0.1 nH, C = 2.1 pF
3000	R =50 Ω, L1 = 12.3 nH, L2 = 0.54 nH, C = 1.89 pF
5000	R =50 Ω, L1 = 12.3 nH, L2 = 1.19 nH, C = 1.32 pF
10000	R =50 Ω, L1 = 11.7 nH, L2 = 0.32 nH, C = 0.1 pF
16500	R =50 Ω, L1 = 13.1 nH, L2 = 0.13 nH, C = 0.05 pF

Figure 6 gives the output response for both the equivalent circuits. In figure 6a, although the output oscillations have damped the signal is heavily attenuated. Merely having the transmission line following the interconnect tree will not solve the problem. We therefore incorporate a Ruthroff transformer to transform the load resistance of 50 Ω to its primary side. The ABCD matrix of the Ruthroff transformer is given in the Appendix. The 50 Ω load in transformed as $50.n^2$ Ω at its primary side, where n is the turns ratio of the transformer. This result in damping of overshoots and undershoots with a marginal attenuation of the output voltage. Figure 7 gives the output response obtained by cascading two Ruthroff transformers (n = 16).

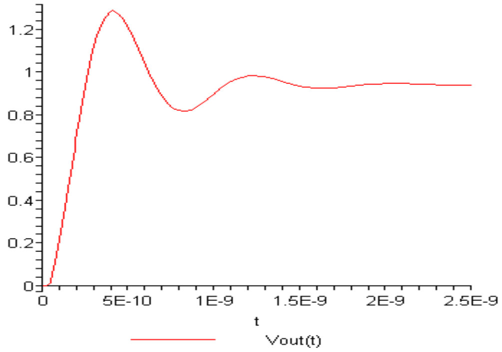


Fig 7. Output response obtained using Ruthroff transformer.

It is clearly seen that for an oscillatory input with peak overshoot of 90%, the output peak overshoots are reduced to about 20%. Also, as compared to 50% attenuation in the output as shown in figure 6a, the output signal settles to a final value equal to that of the input signal. The ringing following the peak overshoot has also damped substantially. In table 2, we provide the number of Ruthroff transformers required to damp input oscillations.

Table 2: Number of Ruthroff transformers required to control input overshoots up to 90%.

% Peak Overshoot	Turns ratio n	Number of Ruthroff Cascades
30	4:1	1
40	4:1	1
50	16:1	2
60	16:1	2
70	16:1	2
80	16:1	2
90	16:1	2

An insight into the output response shows that the oscillations and overshoots have reduced without much penalty on the delay and settling time.

3. DISCUSSION AND CONCLUSION

In the work, an interconnection tree is modified to ensure that no overshoots and undershoots occur at the output even for switching transients with 90% overshoots, using second order equivalent circuit and considering physical design issues. The theory is translated into a physical design procedure using the concept of transmission lines and Ruthroff transformer.

The length of the transmission line following the interconnect line alters the equivalent impedance of the interconnect line. The load impedance of 50 Ω seen by the interconnect network is converted by the Ruthroff transformer to an equivalent resistance of $50.n^2$ at its primary. By choosing a proper vale of transmission line length (L) and transformer turns ratio (n) overshoots and ringing and undershoots can be controlled without any attenuation in the output signal. The results are presented by performing simulation of the equivalent circuit using the well known transfer function approach.

The main advantage of the proposed technique is the suppression of overshoots without making the system sluggish. Also, the use of ABCD matrices is a computationally easier technique to develop the equivalent circuits for varying line lengths. The proposed design methodology can have significant impact on analyzing long MCM and RF interconnects. Also, problems associated with crosstalk and simultaneous switching with oscillatory inputs can be addressed using this design methodology.

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APPENDIX A

Computation of equivalent interconnect circuit using ABCD matrices

The proposed interconnect structure shown in figure 1 is segmented into three subparts. These are the interconnect tree, the transmission line in proximity with the ground line and the Ruthroff transformer. We analyze this structure by developing individual ABCD matrices for these subparts.

a) The interconnection tree:

ABCD matrix for the series impedance and the shunt admittance of the interconnect line is given in equations (a1) and (a2) respectively.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \qquad (a1)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} \qquad (a2)$$

***b) Transmission line*:**

The ABCD matrix for a lossless transmission line of length (L) and characteristic impedance Z_0 is given in equation (b1).

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\beta L & jZ_0 \sin\beta L \\ jY_0 \sin\beta L & \cos\beta L \end{bmatrix} \quad (b2)$$

***c) Ruthroff transformer*:**

Using transformer voltage and current rule, the ABCD matrix is given by equation (c1).

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} n & 0 \\ 0 & \frac{1}{n} \end{bmatrix} \qquad (c1)$$

The multiplication of these matrices gives the equivalent circuit for the interconnect structure for various line lengths (L). The frequency is 10 GHz and the critical transmission line length (L) happens to be 8000 μm.