A High Signal Integrity Interconnect Design Using a Genetic Algorithm and Its Solution Analysis

What solution did GA find in time and frequency domain?

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***Abstract*— In the GHz domain, conventional printed circuit board (PCB) trace designs based on the matching of characteristic impedances do not work well for signal integrity (SI) improvement. In order to overcome this difficulty, we previously proposed a novel PCB trace structure, the segmental transmission line (STL), in which the trace design is optimized using genetic algorithms (GAs). In this paper, we apply the STL to the end-to-end transmission systems such as used in PCI-express, USB, SATA, and demonstrate its high effectiveness on the SI improvement by measured eye-diagrams on its prototype. Furthermore, we also measure s-parameters of the prototype and show what design solution the GA found.**

Keywords— Signal Integrity, Printed Circuit Board, PCB trace, Transmission Line, Impedance Matching, Genetic Algorithm

I. Introduction

High signal integrity (SI) is an important aspect of the design of printed circuit boards (PCBs) with clock frequencies in the GHz range. Unfortunately, conventional PCB trace designs based on the matching of characteristic impedances do not work well with GHz digital signals. In order to overcome this difficulty, we previously proposed a novel PCB trace structure, the segmental transmission line (STL), in which the trace design is optimized using genetic algorithms (GAs) [1]-[3].

The STL have already showed its high SI improvement performance in some real PCB trace designs, such as double data rate (DDR) memory-bus systems, backplane bus systems for basic servers. The STL, however, has never been applied to the end-to-end transmission systems such as used in PCI-express, USB, SATA. In this paper, we apply the STL to the end-to-end transmission system for the first time, and demonstrate its effectiveness using a scale-up prototype board.

Furthermore, the STL have never been analyzed in the frequency domain, or s-parameters, because the DDR bus and backplane bus systems cannot be inserted in the s-parameter measurement system using vector network analyzer (VNA).

In this paper, we also measure the s-parameters of the STL as well as the eye-diagram, and compare them with the conventional transmission line.

II. Segmental Transmission Line

In the STL, a transmission line is divided into multiple (N) segments, each with their own individual characteristic impedance Z_i (i = 1, 2, ..., N), as shown in Fig. 1. The values of Z_i in the various segments are adjusted to achieve an ideal digital waveform at important points, such as the input points, by superposing the reflection waves that are generated at the interface between adjacent segments Z_i and Z_j. Fig. 1 shows an elevated view of a PCB trace that is designed as an STL: the characteristic impedance Z_i is a function of the trace width W_i, so Z_i is adjusted by adjusting W_i.

The adjustment of all of the Z_is, however, results in a combinatorial explosion and there is no deterministic search algorithm that can find the optimized or semi-optimized set of Z_is. We thus proposed applying genetic algorithms (GAs) [4]as a way to manage this combinatorial explosion. The STL structure can be easily mapped onto a one-dimensional array of parameters called chromosome, as shown in Fig. 2. In an earlier design, we used only the characteristic impedances Z_i as genes in a *simple chromosome* (see the upper example in Fig. 2). As a modification of this early design, we proposed a *hybrid chromosome*, which was created by adding segments of length L_i as genes (see the lower example in Fig. 2).

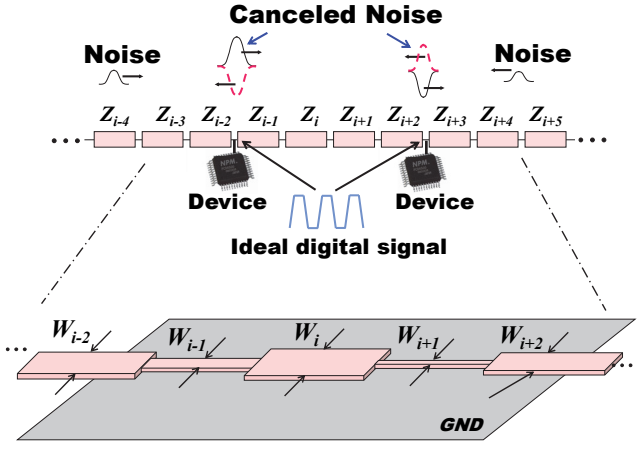


Fig. 1. Basic idea of the STL and its application to a PCB trace

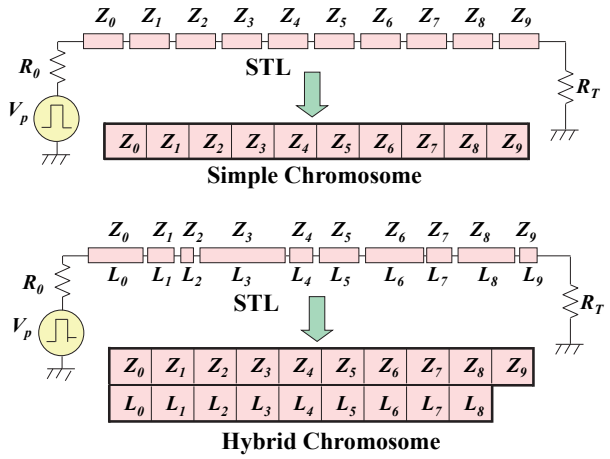


Fig. 2. Simple chromosome (upper) and hybrid chromosome (lower)

If the ideal impulse, which is a long periodic signal of 1000000…1000000…as shown in Fig. 3, propagates in the trace, the impulse response theory guarantees a high SI. Therefore, we use the reciprocal of the difference area $Diff = | I(t) - R(t) |$ as the score (fitness) in the GA.

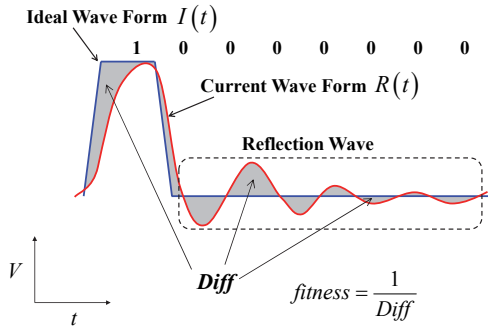


Fig. 3. Score (Fitness) used in GA

III. Prototye Design and Evaluation

A. Prototype Design

We have developed a 500 Mbps scale-up prototype targeting a PCI-express Gen3 bus system (8 Gbps end-to-end transmission) with load capacitances C_Ls, which are equivalent to via holes, as shown in Fig. 4. In the PCI-express or other high-speed bus system designs, use of via holes brings a lot of advantages in the trace routing, but it is strictly prohibited because the via hole causes characteristic impedance mismatching resulting in serious SI degradation. In this paper, we make an attempt at use of via hole in the high-speed bus systems using the STL.

The scale-up prototype, in which the lengths of the transmission lines and the load capacitances are enlarged in proportion to the frequency-reduction ratio, is usually used to evaluate GHz waveforms in the MHz domain, especially if there is a possibility that the measurement equipment will affect the GHz waveforms. Scale-up specifications in the prototype design are summarized in Tab. 1.

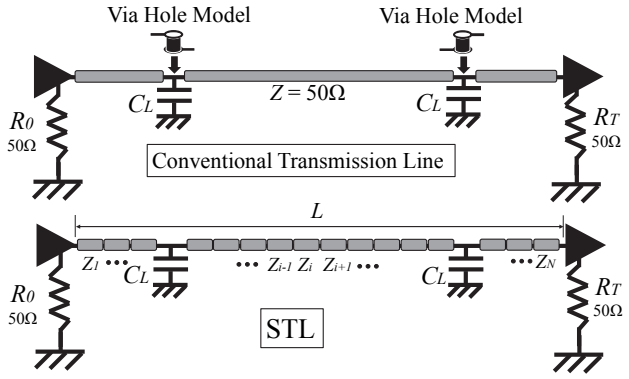


Fig. 4. Target transmission system (end to end transmission with via holes)

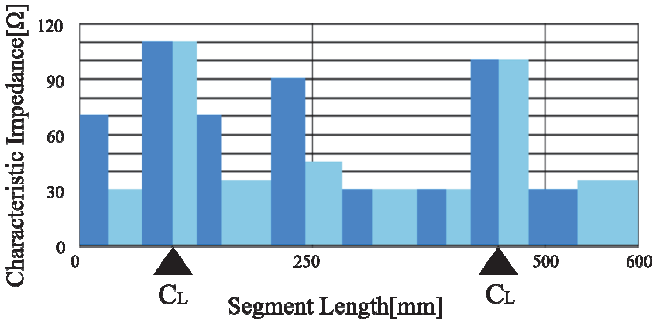
Table 1 Specifications of the Target Interconnect and its Scale-Up Prototype

	Target Interconnect	Scape-Up Prototype
Scale-up Ratio	16.0	
Data Rate	8 G [bps]	500 M [bps]
L (Trace Length)	3.8 [cm]	60.0 [cm]
C_L (via hole)	1.5 [pF]	24.0[pF]

B. Design Results

Fig. 5 shows the resulting design of the characteristic impedance Z_i and length L_i, of each segment.

We used a set of characteristic impedances from 30 Ω to 120 Ω at intervals of 5 Ω intervals. One remarkable aspect can be seen in the figure: the high and low characteristic impedance segments were chosen alternately in the GA.



L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16
30.5	38.0	31.5	20.5	22.0	57.5	40.0	27.5	34.5	48.0	38.5	25.5	36.5	31.5	47.5	71.0

Fig. 5. STL design result of the end-to-end transmission line with via holes

C. Prototype and Eye-daiagram Evaluation

We fabricated a prototype based on the design result shown in Fig. 5. The lower photograph in Fig. 6 is the STL scale-up prototype, and the upper one is a conventional transmission line with a uniform Z of 50 Ω.

The measured eye diagram in the conventional transmission line (Fig. 7) is seriously distorted, and its aperture is close to 0.29 V high and 1.1 ns wide, which is not of practical use. In contrast to the conventional transmission

line, the eye diagram in the STL (Fig. 8) clearly opens to a height of 0.53V and a width of 1.8 ns, which is sufficient to be used in practice.

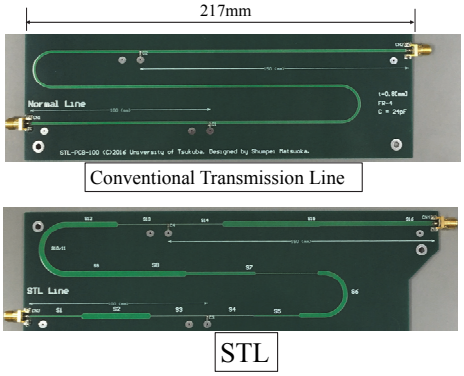


Fig. 6. Prototype for end-to-end transmission system

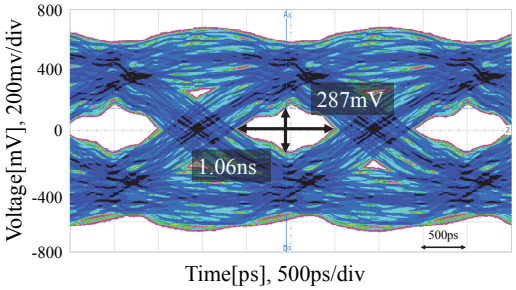


Fig. 7 Measured eye-diagram of the conventional transmission line

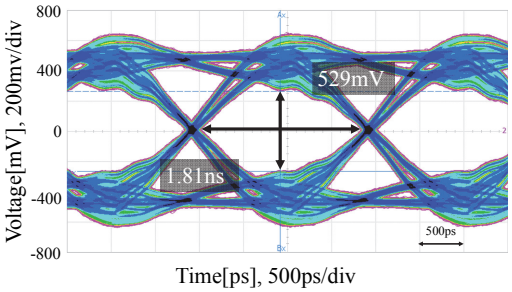


Fig. 8 Measured eye-diagram of the STL

D. S-parameter Evaluation

We also measured the S_{21} values of the output signal in the conventional transmission line and the STL as shown in Figs. 9 and 10, respectively. A large gain reduction is observed at around 200MHz in Fig. 9, which is less than the fundamental frequency of 250MHz (500Mbps) in the prototype. Because of this gain reduction, the conventional transmission line with load capacitances behaves as if it is a lossy transmission line, or a band stop filter. And this is the reason of the serious eye opening deterioration in Fig. 7.

In the STL, the gain is recovered at around 200MHz as shown in Fig. 10, and this means that the GA found a solution to compensate the gain reduction in Fig. 9. And this is the reason the eye clearly opens in the eye-diagram in Fig. 8.

IV. Conclusions

The use of via holes, connectors, or other components, which cause the impedance mismatching, are strictly prohibited for high speed end-to-end transmission systems, such as used in PCIexpress, USB, SATA due to serious degradation of the SI. We applied the STL to the end-to-end transmission system with via holes, or parasitic capacitances. A prototype was fabricated and the measured eye-diagrams demonstrated high SI in the STL. The S_{21} values were also measured and the STL was analyzed in terms of the frequency domain.

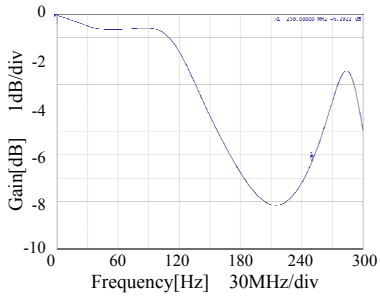


Fig. 9 Measured S_{21} of the conventional transmission line

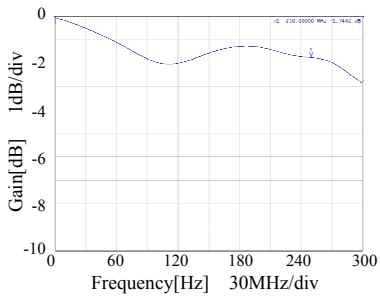


Fig. 10 Measured S_{21} of the STL

Acknowledgment

This research was partially supported by JSPS/KAKENHI grant (26289114) in Japan, and VLSI Design and Education Center(VDEC), the University of Tokyo in collaboration with Synopsys, Inc. and Keysight (Agilent) Technologies Japan, Ltd.

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