Bio-inspired Design of High-speed Transmission Line

High Signal Integrity Design for Printed Circuit Board Traces in GHz Domain

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***Abstract*—Regarding Signal integrity (SI) degradation problem in printed circuit boards, conventional design techniques based on the impedance-matching theory cannot work any longer in the GHz-domain. In this paper, we propose a novel bio-inspired SI improvement design methodology using genetic algorithms. We apply our proposed methodology to real memory bus systems and demonstrate its effectiveness using prototypes.**

Keywords-Genetic Algorithms; Transmission Line; Signal Integrity; Printed Circuit Board.

I. INTRODUCTION

Signal Integrity (SI) degradation is one of the most serious problems in the printed circuit board (PCB) in the GHz-era [1] [2]. Figure 1 shows one of waveform examples observed in DDR-3 memory bus system. Conventionally, a number of trace designs, which are based on the impedance matching theory, have been used in the MHz-domain. The conventional designs, however, are becoming ineffective as the frequency increases and cannot work any longer in the GHz-domain.

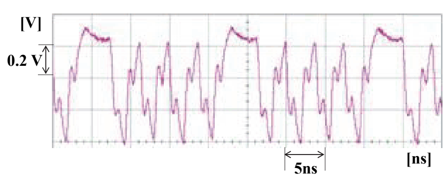

Figure 1. Distorted distal waveform in memory-bus system.

In Section II, we propose a novel trace (transmission) structure that can overcome the SI degradation problem. In Section III, we describe its design methodology based on the genetic algorithms (GAs) and details of GA operations. In Section IV, we demonstrate its effectiveness showing one of prototypes for memory-bus prototypes.

II. BIO-INSPIRED TRANSMISSION LINE STRUCTURE

In the proposed trace structure, which we call it segmental transmission line (STL), a transmission line is divided into multiple (N) segments of individual characteristic impedance Z_i (i = 1, 2, ..., N) as shown in Figure 2. And Z_i are adjusted to achieve an ideal digital waveform at important points, such as input points to the Large Scale Integrated Circuits (LSIs) on the line by superposing reflection waves, which are generated at the interfaces between adjacent segments Z_i and Z_j. Figure 3 shows a bird-eye view of the STL in the PCB. Characteristic impedance Z is a function of trace width W, so that Z can be thus controlled by adjusting W.

The adjustment of all Z_i , or W_i, however, results in a combinatorial explosion problem. We thus have proposed to apply the GAs to solve this problem. The STL consists of one-dimensional array of Z_i, which is similar in structure to the genome, so that it can be easily and well mapped onto the chromosome in GAs as shown in Figure 4.

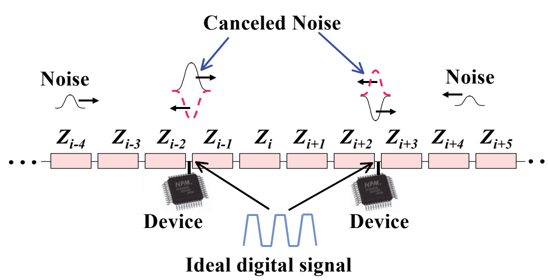

Figure 2. Principle of segmental transmission line (STL).

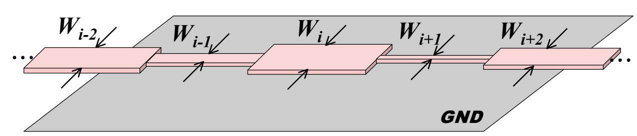

Figure 3. STL structure in PCB.

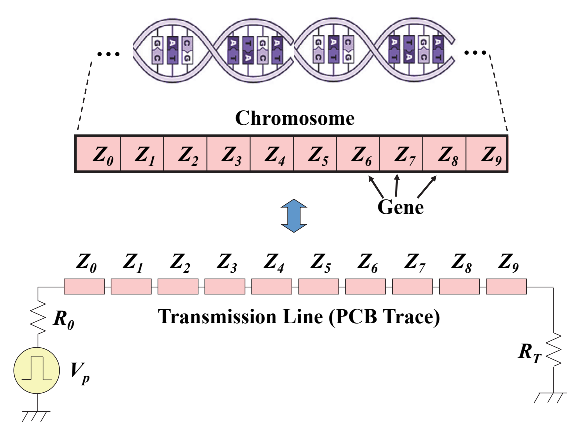

Figure 4. Mapping STL onto GA.

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III. DESIGN METHODOLOGY BASED ON GA

A. *Chromosome*

In an earlier design, we used only the characteristic impedances Z_i as genes in a *simple chromosome* (see the upper section of Figure 5). 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 section of Figure. 5).

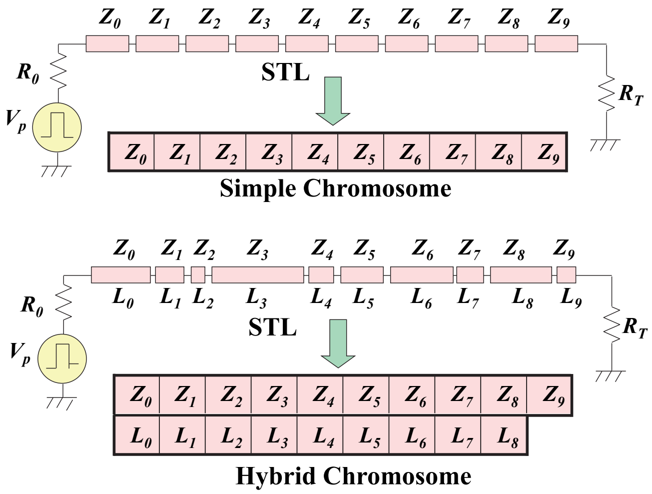


Figure 5. Simple chromosome (upper) and hybrid chromosome (lower).

The segment lengths L_i can adjust the timing of the superposition of the reflected waves, and thus we expect that the hybrid chromosomes result in a higher SI than that obtained from the simple chromosomes.

B. *Crossover*

It has been shown that, in the STL design, intervals of 1 Ω are sufficiently small that the Z_i can be treated as integer parameters. The Z_i are independent of each other in the segments, and thus no fatal gene can be generated in the simple crossover operations. In a simple chromosome or the Z_i part of a hybrid chromosome, genes can be easily exchanged by a simple crossover operation, as shown in Figure 6. In the figure, genes in chromosomes 1 and 2 are exchanged at point C_p.

On the other hand, the crossover operation for the segment length L_i is not as easy as it is for Z_i, because there is a strict condition that the sum of all segment lengths L_i is fixed as the trace length. Furthermore, the timing of the superposition of the waveforms is very sensitive to the propagation time. We thus have to treat the L_is as real number genes with a fixed trace length.

Figure 7 shows a newly proposed crossover operation for the L_i genes; it is based on the BX-α crossover [3][4]. For example, a 20 cm trace is divided into 5 segments, and before the crossover operation, the segment lengths L_i are normalized and changed to the boundaries A1 to A4 in chromosome 1 and B1 to B4 in chromosome 2.

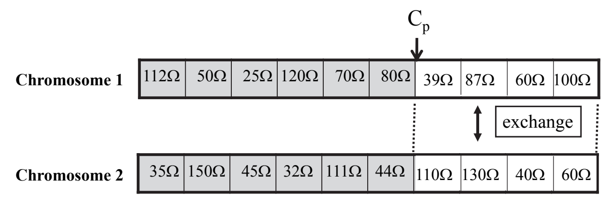


Figure 6. Simple crossover for characteristic impedance.

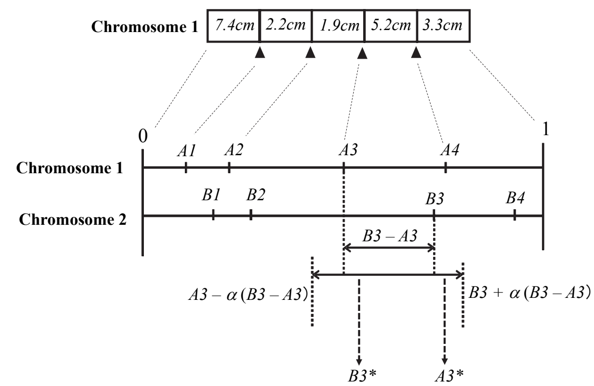


Figure 7. BX-α crossover for segment length.

Two boundaries, say, A3 and B3, which have no other boundaries between them, are then chosen at random. And the range B3 to A3 is then expanded by α percent ($10 \leq \alpha \leq 20$). Finally, two new boundaries, A3* and B3*, are chosen randomly in the expanded range, and they are changed from their previous lengths. This expanded BX-α crossover has worked well in practical applications and has found excellent solutions, which will be discussed below.

C. *Fitness evaluation*

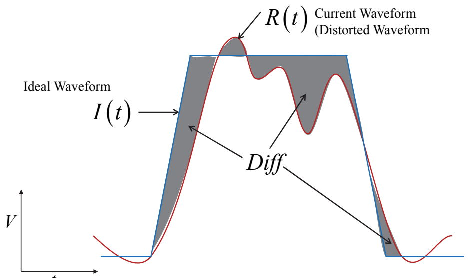
For the periodic (clock) signals propagating in the PCB traces, each chromosome was scored based on half of the periodic waveform simulated using the SPICE circuit simulator, as shown in Figure 8 (see equations in the figure also). The reciprocal of the difference area *Diff* between the ideal waveform $I(t)$ and the waveform $R(t)$ was used as the score (fitness), so that the score increased as the waveform improved or approached the ideal waveform.

For the random (data) signals, we used a long periodic signal of 1000000…1000000… as shown in Figure 9; this can be regarded as an impulse input. If the ideal impulse propagates in the trace, impulse response theory guarantees a high SI. Thus, in the STL design for the random signals, the reciprocal of the difference area *Diff,* including the reflection wave, works well as the score (fitness); see Figure 9.

IV. PROTOTYPE AND EXPERIMENTAL RESULTS

We have applied the STL to some high-speed digital data transfer systems. Figure 10 shows one of design examples, which is used in the Double Data Rate (DDR) memory bus. In the STL design, we used a set of characteristic impedances from 30 Ω to 120 Ω at intervals of 5 Ω intervals.

The measured waveforms in the scale-up prototypes are shown in Figures 11 and 12.



$$Diff = \int_{-\frac{T}{2}}^{\frac{T}{2}} \left| I(t) - R(t) \right| dt \qquad fitness = \frac{1}{Diff}$$

Figure 8. Fitness evaluation for periodic signals.

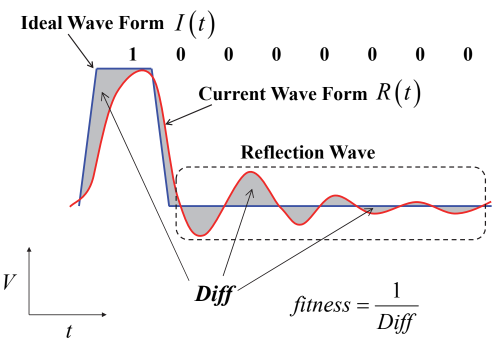


Figure 9. Fitness evaluation for random signals.

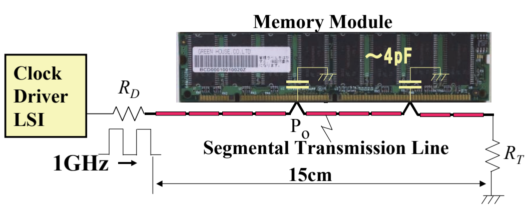


Figure 10. DDR memory bus system and STL.

In Figure 11, the periodical waveform in the conventional transmission line is seriously distorted with some reflection waves and it cannot be used as the clock signal in real systems. In the STL, the distorted waves are well improved and it is almost the same as the ideal clock signal.

In Figure 12, the eye diagram, which is used to evaluate SI in random digital signals, in the conventional transmission line is dramatically distorted, and its aperture is close to 0.2 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 clearly opens to a height of 1.1 V and a width of 1.3 ns, which is sufficiently large to be used in practice.

V. Conclusions

A novel PCB trace structure and its bio-inspired design methodology are proposed in order to overcome SI digraration problem in GHz-domain. Some remarkable SI improvement results were demonstrated in the real memory bus prototype fabricated by the proposed methodology.

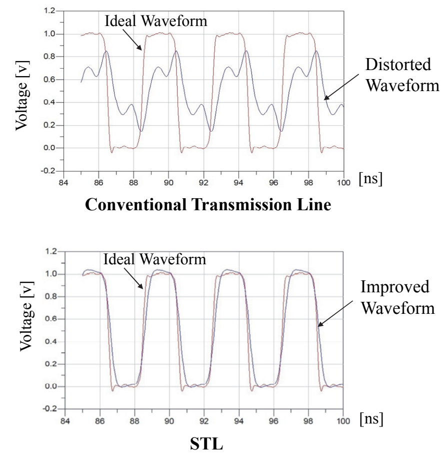


Figure 11. Clock signals observed in conventional transmission line and STL.

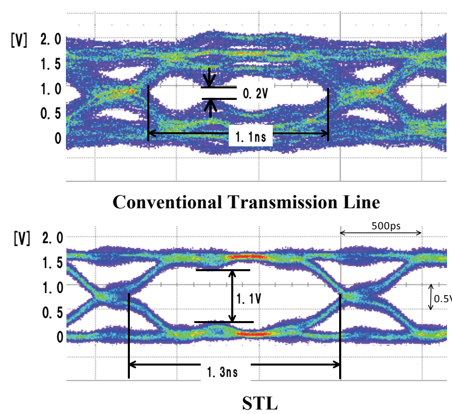


Figure 12. Eye-diagrams observed in conventional transmission line and STL.

Acknowledgment

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