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Reduced Run Time Estimation for Data Dependent Timing Jitter and Amplitude Noise in High-Speed Differential Link

K. Vignesh[1]
[1](ME student (COMMUNICATION SYSTEMS) in SHIVANI COLLEGE OF ENGINEERING, TRICHY)

Abstract: *Differential signaling has been widely used in high speed interconnects. Signal integrity issues, such as inter-symbol interference (ISI) and crosstalk between the differential pair, however, still cause significant timing jitter and amplitude noise and heavily limit the performance of the differential link. The pre-emphasis filter is commonly used to reduce ISI but may potentially change the crosstalk behavior. In this paper, we first propose formula- based jitter and noise models considering the combined effect of ISI, crosstalk, and pre-emphasis filter With the same set of input patterns, experiment shows our models achieve within 5% difference compared with SPICE simulation. By utilizing these formula- based models, we then develop algorithms to directly find out the input patterns for worst-case jitter and worst-case amplitude noise through pseudo-Boolean optimization (PBO) and mathematical programming. In addition, a heuristic algorithm is proposed to further reduce runtime. Experiments show our algorithms obtain more reliable worst-case jitter and noise compared with pseudorandom bit sequences simulation and, meanwhile, reduce runtime by when using a general PBO solver and by when using our proposed heuristic algorithm.*

Index Terms: *Jitter, modeling, noise, transmission line.*

I. Introduction

DIFFERENTIAL signaling has been widely used in high speed I/O interconnect standards like PCI-Express and Serial ATA. It has several advantages, such as a high transmission rate due to low signal swing, little electromagnetic interference (EMI), and common-mode noise immunity. Considerable signal integrity issues, however, still limit the link performance and become bottlenecks during system integration. Such issues include resistive losses, reflections, inductive ringing and crosstalk between differential pairs [2], [3]. To evaluate the combined effect of these impairments on the overall system performance, the associated eye diagram [4], [5] has been used as an effective measure. As shown in Fig. 1, the eye diagram is defined as the synchronized superposition of all possible realizations of the signal viewed within a signal interval. It provides a fast evaluation of system performance. The width of the eye opening defines the time interval over which the received signal can be sampled without error. The height of the eye opening with the amount of amplitude noise at a specified sampling time defines the signal-to-noise ratio (SNR) of the received signal.

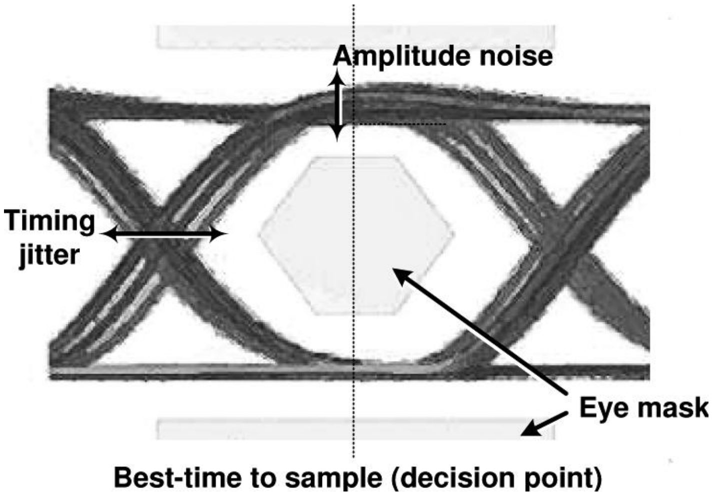

Fig. 1. Eye diagram and eye mask

II. Preliminaries

We first review the RLGC model for parallel transmission lines and the frequency-domain relationships between input and output ports. Next, an overview of the transmitter pre-emphasis filter is provided, and its impact on eye diagram is also demonstrated.

A. RlGC Model for Transmission Line

A cross section of the differential micro strip line is shown in Fig. 3. We assume the lines are homogeneous, uniform, and parallel to each other without any variation [11]. The dielectric is assumed to be homogeneous with constant permittivity. The distributed self and mutual inductances are computed with the method of images [16]: the effect of the ground plane is replaced with the image currents. The rectangular shapes of conductors were changed into circular ones for geometry simplification and the following expressions were found for the per-unit-length self and mutual inductances. We first review the RLGC model for parallel transmission lines and the frequency-domain relationships between input and output ports. Next, an overview of the transmitter pre-emphasis filter is provided, and its impact on eye diagram is also demonstrated.

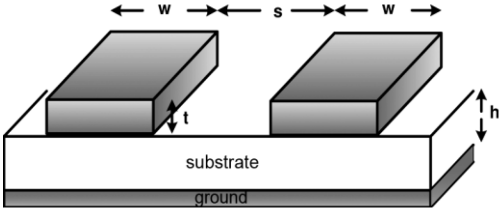

Fig. 2. Section of differential micro strip line

III. Jitter and Amplitude Noise Model

The jitter and amplitude noise are actual stochastic processes and can be divided into two categories: random and deterministic. The random part is usually described through a probability density function (PDF) or its root-mean-square (rms) value. On the other hand, the deterministic part is predictable and makes the dominant contribution to the shape of eye diagram [20].

A. Subcomponents of Jitter and Amplitude Noise

Take timing jitter as an example, the total jitter (TJ) is subdivided into two categories: random jitter (RJ) and deterministic jitter (DJ). RJ is a random process and is usually assumed to have a Gaussian distribution because it is mainly contributed by thermal noise [14]. In contrast, DJ is repeatable and predictable. The peak-to-peak value of deterministic jitter is bounded due to its predictable nature. Data-dependent jitter (DDJ), one of the most important sub-component of DJ, is dependent on the bit pattern transmitted on the link under test and is caused by duty-cycle distortion (DCD) and ISI. Typical crosstalk noise coupling from adjacent data-carrying links belongs to bounded uncorrelated jitter (BUJ). BUJ is bounded due to finite coupling strength, and uncorrelated because there is no correlation to the channel’s own data pattern. In this paper, we consider the crosstalk from the adjacent differential link and, as a result, the jitter becomes part of DDJ since we exactly know the transmitted data pattern on the adjacent link. The PDF of data-dependent jitter and noise are always a series of pulses at the locations where a specific bit pattern experiences a cross over. Therefore, in order to get an accurate measure of the worst case, a large number of bit patterns must be analyzed. As a result, it is critical to find out the worst-case input pattern without doing lengthy simulations. In order to efficiently find propose to locate both of these selected pixels for read-out/reset phases in the same row in order to share the *select* control signal. Locating the two pixels on the same row and not the same column avoids having the column based current flowing in both pixels. Fig. 3 illustrates the proposed current- mediated control mechanism for two consecutive operating cycles namely and , where . In each cycle, the current source is used to reset a given pixel while the output current of the read-out pixel flows into the output column bus with this proposed scheme, only a single current source is used for the entire array at any given cycle time.

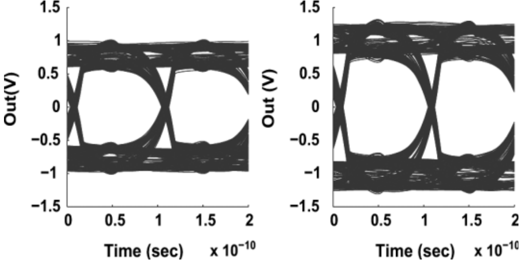

Fig. 3. Eye diagram (a) without the pre-emphasis filter and (b) with applying a four-tap pre-emphasis filter.

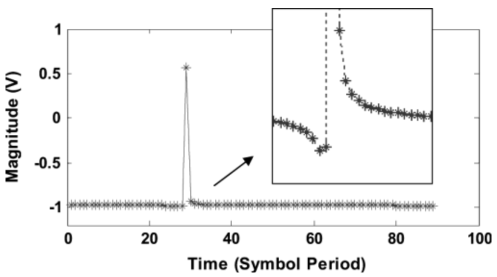

Fig.4. Time-domain response of the channel.

IV. Worst-Case Timing Jitter

The data-dependent jitter and amplitude noise highly depend on the input pattern. In this paper,we develop algorithms that, by using mathematical programming, can directly find out the input patterns for worst-case jitter and worst-case noise without doing lengthy simulations. To start with, the algorithm for worst-case jitter is proposed in this section.

A. Problem Formulation

The worst jitter is the sum of the maximal positive deviation and the maximal negative deviation . For simplicity of presentation, we only discuss how to compute the maximal positive deviation. It should be understood that the same procedure can be applied to compute the maximal negative deviation as well. We can formulate the maximal positive deviation as the following integer nonconvex programming problem. Time-domain response of the channel. where is defined in given zero-crossing threshold . is the time-domain response for one-bit transmission as shown in and are pre-emphasis filter's input and output with is the filter's coefficient for tap . Note that attenuates quickly as time goes to infinity, as shown in Thus, can be well approximated by where can be decided such that the error is within certain boun and is in and is specified by user. A larger reduces the problem complexity, but introduces more significant error.

B. Relaxation Based Binary Search

If we assign a set of values to , then the problem becomes a nonlinear feasibility problem and can be solved through an efficient heuristic method, i.e., for each value of , we test whether a combination of the symbols can be found such that holds and then pick the that maximizes among all of the feasible solutions. Such a problem structure enables us to use the binary search technique on , which is bounded in . However, the main difficulty lies in the fact that the feasible space for is not continuous. If we randomly assign values to , the chance for it to be feasible is slim. To overcome this difficulty, instead of finding a set of symbols that satisfies, we look for a nearby feasible value as an alternative, if possible. This is done by the following procedure. Suppose is assigned with value . Then, the corresponding feasibility problem.

V. Noise Analysis

A. Random Niose

There are several sources for random noise (temporal noise) including but not limited to the shot noise, KT/C noise of the pixel, the read-out noise. The shot noise amplitude depends on the illumination level and the CMOS process as well as the type of the photodiode used. KT/C noise of the pixel is generated during the reset phase. The read-out noise is the random noise along the signal path during the read-out phase. Since at low illumination level the captured signal is very small, the noise performance at low illumination level is more important than that at high illumination level in terms of signal-to-noise ratio. The dominant noise at low illumination level is the read-out noise instead of the photodiode shot noise [12]. This read-out noise is mainly contributed by the active transistor such as the source follower for a voltage-mode pixel and the transconductance amplifier for a current-mode pixel. Compared with the active transistor, the in-pixel switch transistor introduces less noise. In this analysis, the random noise of the switch transistor is ignored, which is supported by other literatures' assumption.

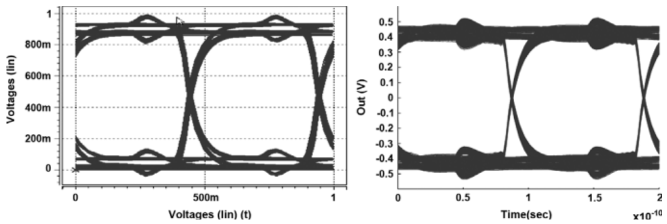

Fig. 5. Transient simulation comparison between (a) SPICE and (b) our model. The origin point is different.

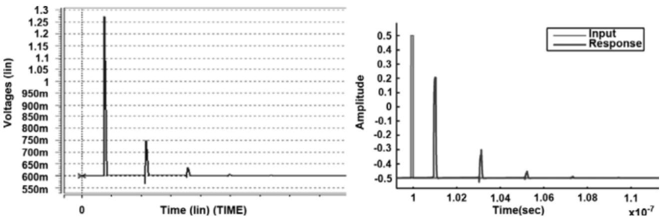

Fig. 6. Time-domain response. (a) SPICE simulation. (b) MATLAB simulation with our model. The origin point is different.

VI. Worst-Case Amplitude Noise

The amplitude noise is the difference between the maximum amplitude deviation and the minimum amplitude deviation, at the optimal sampling time. To find the worst-case noise, we could use the following formulation is the optimal sampling time. The difference between maximum and minimum deviation determines the peak-to-peak amplitude noise for the eye diagram. Given the calculated from we can rewrite as (use the maximum problem as an example where and can be derived from (73) and (74). As a result, it is a linear programming problem and, moreover, the solution can be obtained directly without calling the general linear programming solver. Obviously, to maximize the objective function, we just let be 1 if is positive and be 0 if is negative [23]. For the minimum case, it is vice versa. So the amplitude noise can be expressed as
and the complexity is given .

VII. Conclusion

This paper develops efficient algorithms to calculate the worst-case data-dependent jitter and noise directly for a differential micro strip line without lengthy simulation. We first propose formula-based jitter and noise models that consider the combined effect of ISI, crosstalk, and the pre-emphasis filter. With the same set of input patterns, our models achieve within 5% difference compared to SPICE simulation. By utilizing these formula-based models, we then use binary search along with PBO and mathematical programming to directly predict the input patterns that cause worst-case jitter and worst-case amplitude noise. Experiments show our algorithms obtain more reliable worst-case jitter and noise compared with PRBS simulation and, meanwhile, achieve a runtime reduction when using binary search and PBO solver for worst-case jitter and solving LP for worst-case noise. In addition, by replacing the PBO solver with our proposed heuristic algorithm, a further runtime reduction compared with PRBS can be achieved. Note that our modeling and algorithms are not restricted differential signaling and can be applied to any multi conductor transmission lines.

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