Quantification of Delay and Skew Uncertainty due to Fiber Weave Effect in PCB Interconnects

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Abstract **— To quantify delay uncertainty caused by Fiber Weave Effect (FWE) in single-ended and differential PCB interconnects, two new metrics are introduced: Delay Deviation Exceedance (DDE) and Differential Skew Exceedance (DSE). DDE and DSE are probabilities to have delay or skew exceeding some limit. They are derived with 3D EM analysis of traces over inhomogeneous dielectric with glass fiber bundles in resin. An approximate formula for the exceedance is proposed. The formula has just one parameter that can be obtained with measurements or numerical model. The proposed metrics can help formalize the laminate selection process for parallel as well as for serial PCB interconnects.**

I. Introduction

Fiber Weave Effect (FWE) is a problem that affects the performance and reliability of interconnects on Printed Circuit Boards (PCBs). FWE occurs when the dielectric material of the PCB, which is usually made of glass fabric and resin, has different dielectric properties at different locations. This causes variations in the delay, skew and impedance of the interconnects, leading to signal degradation and data link failures. FWE has been studied extensively since the early 2000s [1]-[6], and several solutions have been proposed, such as using more homogeneous materials or applying different routing techniques. However, these solutions also increase the cost of PCB manufacturing, which is undesirable for large-scale electronics production. The increasing data rates both in parallel and serial buses put additional constrains on the unwanted uncertainty in the delay or skew.

One of the key properties of a successful DDR bus design is maintaining the same flight time across all data lanes within the signal group. For DDR5 technology operating in 6400 MT/s, this number is typically 20-50 ps. For DDR6, where the forecasted maximum data rate peaks above 12800 MT/s, the bound is expected to be much tighter, within 10-25ps. Meeting these requirements on low-cost laminates may be challenging due to FWE. Serial links are usually implemented as differential interconnects and the latest serial data transfer standards have single links operating over 112 Gbps with the single-bit duration of about 17.85 ps for PAM4 signaling. Considering the length of such links even a few ps per inch of a skew uncertainty would be unacceptable.

This paper presents a novel method to evaluate the delay uncertainty in single-ended and differential PCB interconnects caused by FWE. Delay Deviation Exceedance (DDE) and Differential Skew Exceedance (DSE) are defined as the probabilities of having delay deviation or skew over a given limit. DDE and DSE are computed using 3D EM analysis. Unlike previous approaches that focused on finding the worst-case scenarios or specific cases of FWE, this paper provides a formal algorithm to quantify the delay and skew uncertainty for any PCB interconnect design. It is shown that a simple formula derived from the arcsine distribution can be effectively used to evaluate the exceedances from numerical or measured data. The proposed method can be used to select the appropriate PCB materials for parallel and serial interconnects. The concept of DDE and DSE was first introduced by the authors in [7] and [8].

II. 3D EM Model of FWE

Precise analysis of FWE in PCB laminates requires simulation of complicated geometries of the fabric material in the resin dielectric [4]-[5]. Though, the problem can be simplified without loss of the essential important effects of periodic dielectric inhomogeneity. Instead of reproducing particular fabric style geometry, we use simplified 3D geometry as shown in Fig. 1. The original dimensions of the glass bundles are X1-X3 and Y1-Y3 taken from measurements provided in [6] and rounded off to values X1'-X3', Y1'-Y3' shown in Table 1.

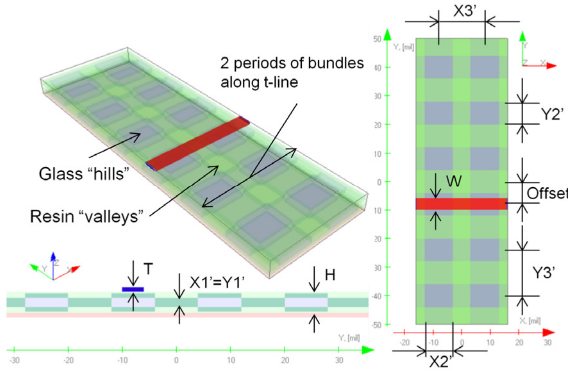

Fig. 1. 3D EM model of single-ended microstrip segment over dielectric composed of glass and resin.

Table 1. Model fiber weave bundle parameters (all in mils).

Style	X1/X1'	X2/X2'	X3/X3'	Y1/Y1'	Y2/Y2'	Y3/Y3'
1035	0.82/0.8	8.8/7	14.2/14	0.78/0.8	12.4/9	13.7/14
1080	1.6/1.35	8.2/6	17/17	1.1/1.35	12.1/9	22.4/22
1078	1.4/1.2	14.2/10	16.2/16	1.0/1.2	17.6/13	17.8/18
3313	1.9/1.7	13.1/10	16.2/16	1.5/1.7	11/8	16.3/16

Model Parameters X3' and Y3' define the period of the dielectric lattice. Parameters X2', Y2' are size of the bundles

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along the X and Y axes and are adjusted in the model to have about the same volume of glass in resin (elliptic shape of each bundle is transformed into rectangular shape to have the same area). Dielectric constant for the glass is set to 6 and for resin is set to 3.5. Laminate thickness H is set to 4 mil and trace thickness T is set to 0.75 mil in all examples.

Simbeor 3DTF and HFSS solvers were used for the analysis. Single-ended and differential trace segments are simulated at 10 GHz. To have phase delay independent of the reflections, it is extracted from S-parameters normalized to characteristic impedance of the periodic structure.

III. Probability and Exceedance

Four laminate cases with the parameters shown in Table 1 are simulated for with trace width W=4 mil and offset ranging from -12 to +12 mils and offset step 1 mil. The phase delay per unit length is computed and interpolated with cubic splines. Delay probability density is then evaluated assuming the uniform distribution of the trace offsets. The results are shown in Fig. 2. Differential model is similar to shown in Fig. 1 with two 4 mil traces separated by 4 mil. The skew is defined by the difference of phase delays computed for each trace. Differential skew results are shown in Fig. 3. Computed values are shown by stars and the interpolated values by solid lines. Probability densities are computed with 100000 samples and bin size 0.1 ps/inch.

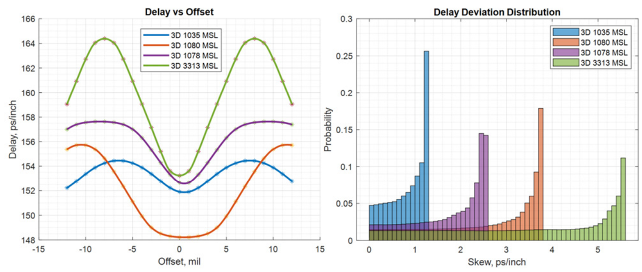

Fig. 2. Single-ended trace delay variation with offset (left plot) and corresponding delay probability density histograms (right plot).

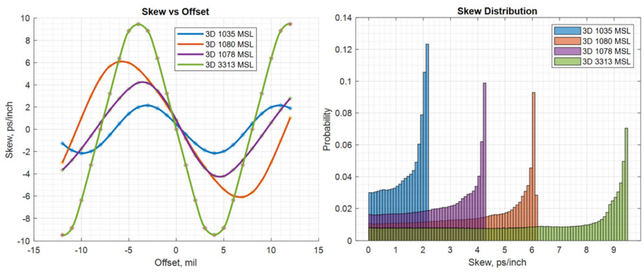

Fig. 3. Differential traces skew variation with offset (left plot) and corresponding skew probability density histograms (right plot).

The delay and skew variations are periodic functions with the period *L* equal to the period of the original lattice model Y3'. The corresponding delay and skew probabilities are bounded by the minimal and maximal values (worst cases). Probabilities to have the minimal and maximal delay or skew values are the highest in all 4 cases.

Measured variations in effective dielectric constant close to sinusoidal were observed in measured data in [1]. Though, the corresponding probability densities for the effective dielectric constant in [1] were not close to the arcsine due to either additional random variations in the measurements or not uniform distribution of the trace positions. Dielectric constant variations extracted from measured data in [6] were close to sinusoidal or clipped sinusoidal. Similar skew variations close to sinusoidal were also observed in [3]-[5]. The fact that the skew probability density due to FWE is not normal was also observed in [3].

It is clear that the probability of having cases close to the worst-case scenario is quite high. This is useful result, but the goal is to have a quantity to characterize the uncertainty in the delay and skew due to FWE. Complimentary Cumulative Distribution Function (CCDF) computed for the delay deviation and skew probability density can be used as such measure of uncertainty. It is a probability to have delay deviation or skew larger than certain specified value. It is called Delay Deviation Exceedance or DDE and Differential Skew Exceedance (DSE). DDE values computed for integer values from 1 to 5 ps/inch are shown in Fig 4. If DDR specifications do not allow the delay uncertainty over 3 ps/inch for instance, fabric styles 1080 and 3313 cannot be used without some FWE mitigation technique. The expected number of cases with the delay deviation over 3 ps/inch is about 50% for 1080 fabric and 60% for 3313 fabric.

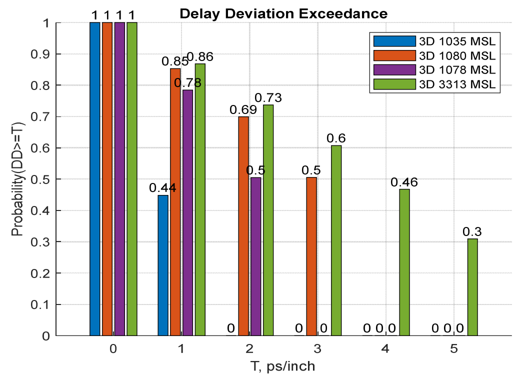

Fig. 4. Comparison of DDEs for four fabric styles.

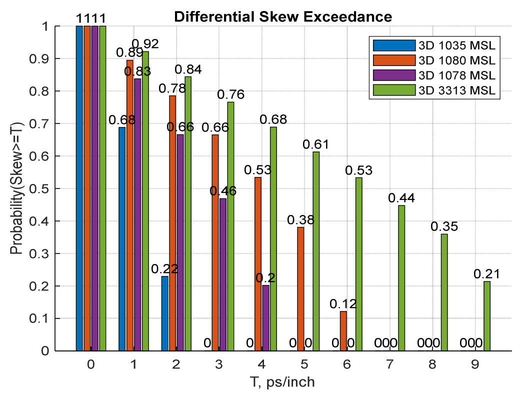

Fig. 5. Comparison of DSEs for four laminates.

Comparison of DSEs for all four fabric styles is shown in Fig. 5. If specifications do not allow the skew uncertainty over 3 ps/inch for instance, the only fabric style 1035 can be used without additional skew mitigation techniques. The expected number of cases with the delay deviation over 3 ps/inch is about 44% for 1078 fabric and 66% for 1080 and 76% for 3313 fabrics.

IV. Analytical Model

Possible delay deviations on Fig. 2 or skews on Fig. 3 can be approximated by absolute value of sine function:

$$t(x) = \Delta t \left| \sin\left(\frac{2\pi x}{L} + \alpha\right) \right|, \; x \in [-L/4, +L/4] \tag{1}$$

L is the period and Δt is the amplitude or maximal possible deviation of the delay or skew and x is offset. Corresponding probability density function can be defined as follows:

$$P(t) = \frac{4}{L} \cdot \frac{dx}{dt} = \frac{2}{\pi \cdot \Delta t \sqrt{1 - \left(\frac{t}{\Delta t}\right)^2}}, \; t \in [0, +\Delta t] \tag{2}$$

CDF of (2) is defined by arcsine function and the complimentary CDF is defined as follows:

$$S(t) = P(T \geq t) = 1 - \frac{2}{\pi} \arcsin\left(\frac{t}{\Delta t}\right), \; t \in [0, +\Delta t] \tag{3}$$

It is the probability to have delay deviation or skew over certain limit. It can be used for approximate evaluation of the DDE or DSE and requires just one parameter identification – the maximal possible deviation Δt (worst case). Comparison of the DDEs and DSEs computed directly from numerical experiment (Pdde and Pdse rows) and from the arcsine distribution (Parc rows) is provided in Table 2 for DDEs and in Table 3 for DSEs. Instead of the arcsine distribution, Beta or Kumaraswamy distribution can be used for better accuracy. However, it will require identification of two or more parameters, instead of one in the arcsine.

Table 2. DDEs computed with EM model (Pdde) and from the arcsine CCDF approximation (Parc).

DDE\Delay, ps/in	1	2	3	4	5
Pdde_1035	0.45	0	0	0	0
Parc_1035	0.44	0	0	0	0
Pdde_1078	0.78	0.50	0	0	0
Parc_1078	0.74	0.42	0	0	0
Pdde_1080	0.85	0.70	0.50	0	0
Parc_1080	0.83	0.64	0.41	0	0
Pdde_3313	0.87	0.74	0.61	0.47	0.31
Pdde_3313	0.88	0.77	0.64	0.49	0.29

Table 3. DSEs computed with EM model (Pdse) and from the arcsine CCDF approximation (Parc).

DSE\Skew, ps/in	1	2	3	4	5	6	7	8	9
Pdse_1035	0.69	0.23	0	0	0	0	0	0	0
Parc_1035	0.69	0.24	0	0	0	0	0	0	0
Pdse_1078	0.84	0.67	0.47	0.20	0	0	0	0	0
Parc_1078	0.85	0.69	0.50	0.22	0	0	0	0	0
Pdse_1080	0.90	0.79	0.67	0.53	0.38	0.12	0	0	0
Parc_1080	0.89	0.79	0.67	0.54	0.39	0.12	0	0	0
Pdse_3313	0.92	0.84	0.77	0.69	0.61	0.53	0.45	0.36	0.21
Parc_3313	0.93	0.86	0.79	0.72	0.64	0.56	0.47	0.36	0.20

Note that the worst case delay or skew can be obtained from either numerical experiment, as it is done here, or from measured data. For instance, effective dielectric constant measured in [6] for fabric style 3313 gives the worst case delay deviation about 7 ps/inch. Effective dielectric constant measured in [1] for fabric style 2116 gives the worst case delay deviation about 2.1 ps/inch. Differential skew model constructed and validated with measurements in [5] gives the worst case skew about 10 ps/inch. All those values can be directly used in equation (3), to evaluate the probability to have delay deviation or skew exceeding some limit.

V. Conclusion

A new Delay Deviation Exceedance (DDE) measure is proposed to quantify the delay uncertainty in single-ended links and Differential Skew Exceedance (DSE) measure is proposed to quantify the uncertainty in differential links. DDE and DSE are computed with numerical experiment by running multiple 3D EM simulations of short segments of interconnects over inhomogeneous dielectric. The exceedances are computed as the complimentary CDFs from the corresponding probability densities. Note that the results of such analysis will depend on the trace width and separation in addition to the geometry of the laminate itself. Wider traces will see less variations comparing to narrow traces. Thus, a numerical experiment or measurements should be done for each practical case.

It is shown that the arcsine distribution can be used for approximate evaluation of the DDE and DSE. It requires only the worst case delay deviation or worst case differential skew. Those parameters can be obtained from just two numerical experiments or just two measurements – for trace over the “glass hills” and trace over the “resin valleys”.

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