Impact Evaluation of Fiber-Weave Effect Induced Delay Uncertainty in DDR Data Links on DDR5 & Towards DDR6

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Abstract

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 would be typically around 20-50 ps. For DDR6, maximum data rate peaks above 12800 MT/s, hence the bound is expected to be half of that. Meeting this flight time constraint within data signals poses several practical challenges. One of them, overlooked in the previous generations, is delay uncertainty induced by glass weave in PCBs. The goal of this paper is to quantify delay uncertainty in single-ended DDR links and introduce a formal measure which can be used in selection of PCB materials and skew mitigation techniques. **In this paper, the new Delay Deviation Exceedance (DDE) measure is proposed to quantify the delay uncertainty.** DDE is constructed with a numerical experiment based on 3D EM analysis of traces over an inhomogeneous dielectric. All measurements or 3D EM experiments are usually just an observation of the delay or impedance dependence on position of traces over fiber bundles. This paper turns it into a probabilistic measure of the possible delay uncertainty – the probability of the delay deviation to exceed the allowed limit, or DDE. The idea is also extended to differential cases and Differential Skew Exceedance (DSE) is introduced.

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Shimon Mordooch is a principal R&D Engineer at a major communication company. He has over 28 years of experience in various hardware design aspects in telecommunications and networks, covering design and managerial positions.
Through the years he was involved in chassis designs starting as a board designer all the way to the system level definitions of the whole chassis, its backplane, signal/power integrity, and management. In recent years he is working in the cable edge industry and more focused on the hardware technological aspects, starting from in-depth characterization and selection of building blocks (for example, PCB materials, highly dense system design, etc.) through detailed SI/PI simulation analysis and at the end - full lab characterization of all hardware aspects of the system.

Introduction

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. Routing density and close lane-to-lane proximity introduce a significant crosstalk contribution from adjacent lanes. In order to preserve an open eye in a high xtalk environment and avoid xtalk components in the eye center between unaligned signals, it is important to maintain a tight matching of electrical delay within the signal group. Although the exact number for skew limit may vary between systems, its value is directly related to the bit period, hence the bitrate of the bus. Simply put, the higher the bitrate, the stricter the matching requirements. For DDR5 technology operating in 6400 MT/s, this number would typically be around 20-50 ps. For DDR6, where the maximum data rate peaks above 12800 MT/s, the bound is expected to be much tighter, within 10-25ps. Meeting these flight time constraints within data signals poses several practical challenges. One of them, overlooked in previous generations of DDR systems, is skew uncertainty induced by glass weave in PCBs. It is well known that in PCBs with glass reinforced dielectrics, there is no bijective relation between the physical length of a trace and the electrical delay, due to the inhomogeneous Dk spatial distributions in the dielectric layer caused by the physical structure of the glass cloth. Furthermore, since in the design process, the channels artwork location with respect to the fiber weave of the dielectric is unknown, the skew between two channels on the PCB layer becomes a random value. This delay uncertainty has a negative effect on system performance and can potentially become a point of failure in the next generation of DDR systems. This unwanted variation in electrical parameters of interconnects is called Fiber Weave Effect (FWE). FWE was a subject of intense investigation since early 2000s [1]-[6]. Over that time, the laminate industry came up with more homogeneous PCB materials almost free from the FWE. Also different interconnect routing techniques were suggested to mitigate the FWE. Rotation of design with respect to the PCB panel and glass bundles is often used for SerDes systems. However, all that increases the cost of PCB manufacturing that is also unwanted factor, especially for a large volume electronics manufacturing. It is acceptable for SerDes, but may be not DDR applications that are much more cost-sensitive. So, in order to justify the investment, one must answer how severe would be the impact of this phenomenon on the particular system in question.

In this paper a Delay Deviation Exceedance (DDE) metric is proposed to quantify the delay uncertainty. To construct a formal measure for the delay deviation uncertainty, a 3D electromagnetic model of the transmission line segment over an inhomogeneous dielectric is constructed. The inhomogeneous dielectric contains glass fiber bundles in a uniform resin dielectric. The size, pitch and permittivity of the glass bundles, together with the resin permittivity and trace width, are the model parameters. Bundles geometry is defined from pictures and cross-sections of laminate with different fabric styles. The delay per unit length and impedance of the trace segment at different positions with respect to the fiber bundle are computed. That provides the delay and impedance dependencies from the trace position. Usually, this is the end result of such an investigation obtained from either measurement or numerical experiment, and the outcome is the worst-case delay or impedance observation – see [4], [5] and extensive overview there. But the relevant question is how often the worst case happens and what overall impact it will have on the interconnects performance. To answer this question, the dependence from the position is transformed into the delay probability distribution function and then the inverse cumulative distribution function is computed. The result is the delay deviation exceedance (DDE) function, that is basically the probability to have a delay deviation over some specified value. DDEs for four different fabric styles are computed and compared. The DDE metric introduces certainty and formality in the material selection process that can be used in cases when the cost of laminate and the manufacturing cost have to be reduced. **It is shown here that the idea of DDE can be also extended for evaluation of differential skew uncertainty as Differential Skew Exceedance (DSE).** The idea of DDE and DSE is pre-published by authors at [11].

The proposed methodology is the first formal approach to the delay and skew uncertainty introduced by the FWE. Note that the authors of [3] were on the way of constructing such uncertainty measure – they constructed probabilistic model of skew that was not normal and used it to find probability to have the skew over some limits. However, the process was not formalized for the practical applications as it is done here.

3D Electromagnetic Model of FWE

PCB laminates are usually made of woven fabric impregnated with resin. The low-cost fabrics use glass fiber bundles and may have different styles of weave. Dielectric properties of the glass bundles and resin may be considerably different and the precise analysis 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 transformed into model parameters X1'-X3', Y1'-Y3' shown in Table 1. The model parameters in the XY-plane are rounded off to 1 mil, to simplify the analysis. Model Parameters X3' and Y3' define the period of the dielectric lattice. Parameters X2', Y2' are size of the bundles along the X and Y axes. They 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). Parameters X1'=Y1' define size of the bundles along the Z-axis. Dielectric constant for the glass is set to 6 and for resin is set to 3.5. The resulting structure has same features and the original geometry – areas of overlapping bundles ("glass hills" - double size along the Z-axis), areas with only resin ("resin valleys") and areas with just X-directed or Y-directed bundles. Laminate thickness H is set to 4 mil and trace thickness T is set to 0.75 mil in all examples. Note that numerical experiments done in this paper are provided as a proof of DDE concept and a practical algorithm for such computations.

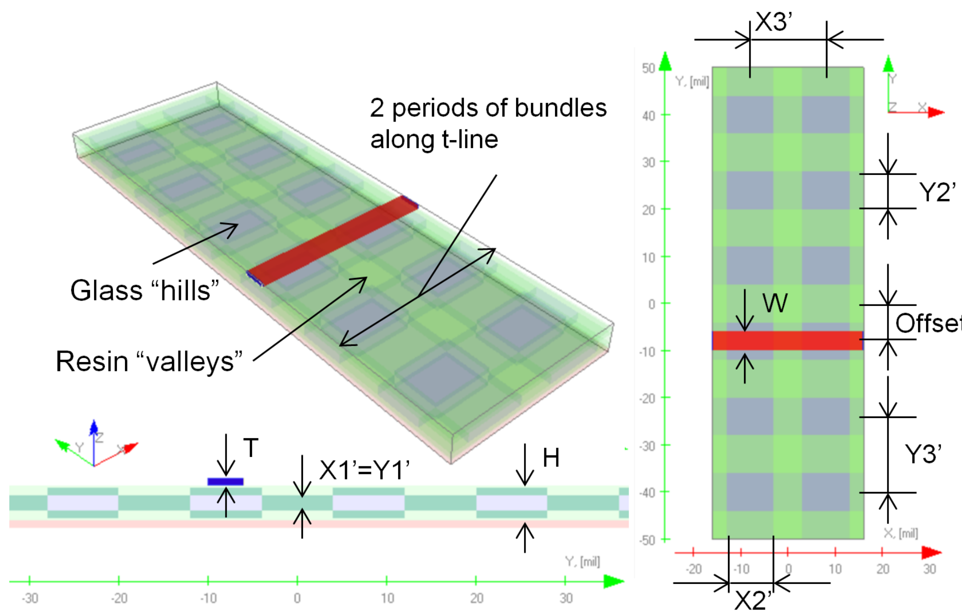

Fig. 1. 3D EM model of single-ended microstrip segment over dielectric composed of glass and resin.

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

Trefftz Finite Elements (TFE) method is used to build 3D EM models of the problem [7]. The method is implemented in Simbeor software [8] as 3DTF solver. Single-ended and differential trace segments are simulated at 10 GHz with the offset parameter swept to extract the phase delay and impedance variations over at least one period of the glass lattice. To have phase delay independent of the reflections, it is extracted from S-parameters normalized to characteristic impedance of the periodic structure (reflection-less). All computations are automated in FEW Kit provided with Simbeor SDK software [8]. The numerical model is validated with a regular finite-element solver HFSS in the Numerical Model Validation section.

Delay and Impedance Variations and Probability

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. Delays and probabilities are shown in Fig. 2 – Fig. 5 and corresponding impedance variations in Fig. 6. Computed values are shown by blue stars and the interpolated values by brown lines. Probability density is computed with 100000 samples and 20 bins.

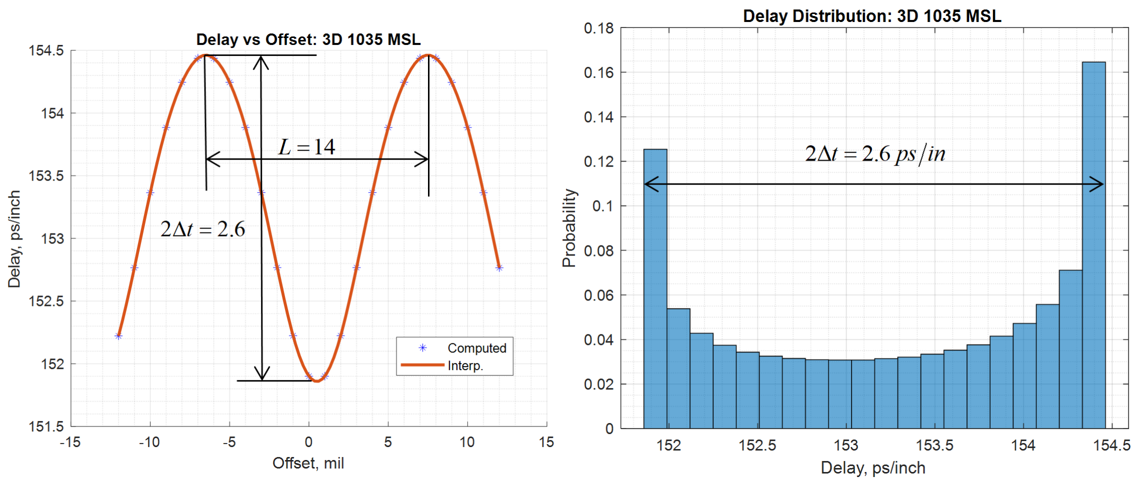

Fig. 2. Delay variation with offset (left plot) and corresponding delay probability density histogram (right plot) for 1035 fabric style.

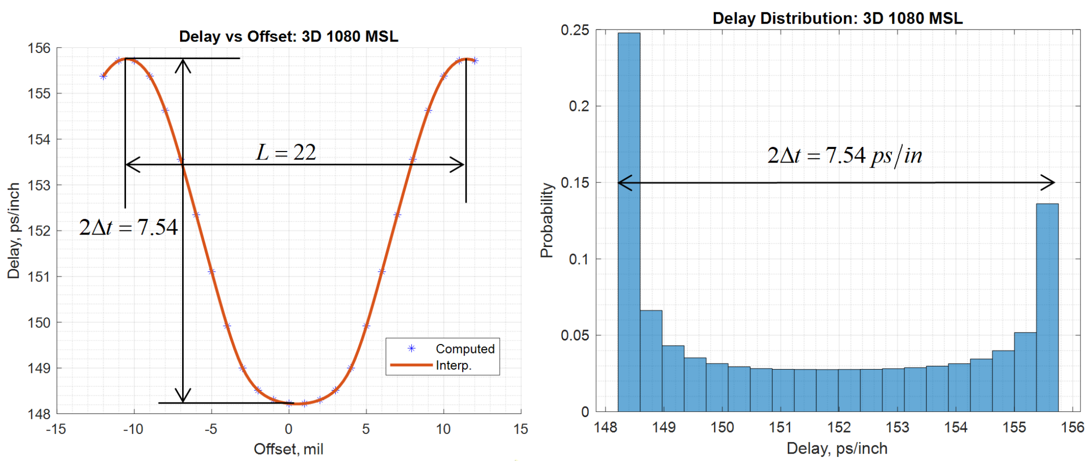

Fig. 3. Delay variation with offset (left plot) and corresponding delay probability density histogram (right plot) for 1080 fabric style.

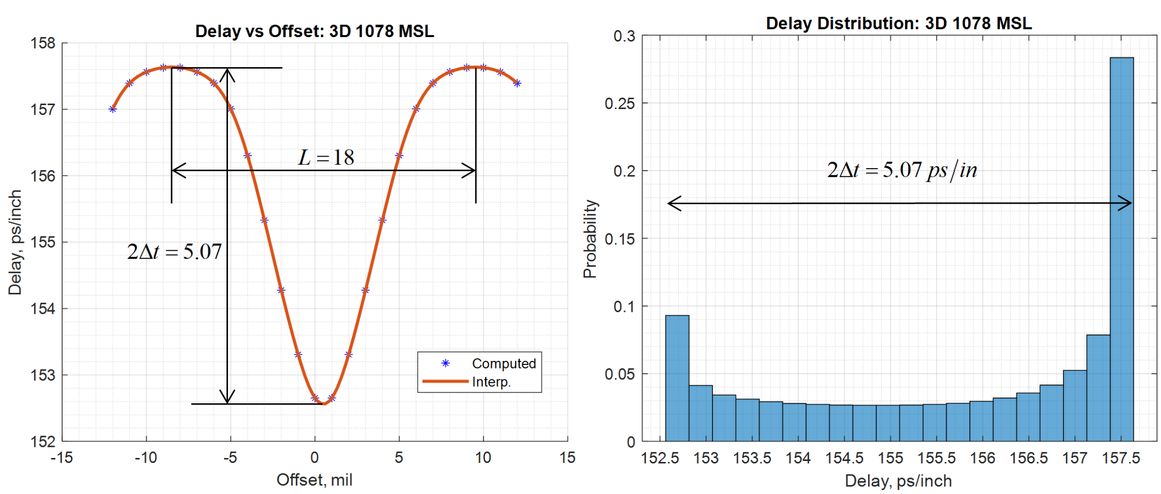

Fig. 4. Delay variation with offset (left plot) and corresponding delay probability density histogram (right plot) for 1078 fabric style.

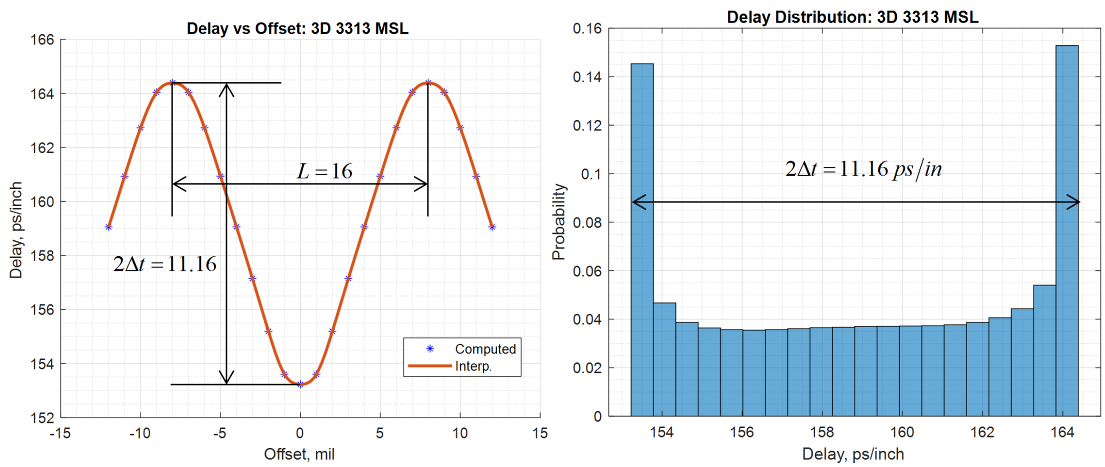

Fig. 5. Delay variation with offset (left plot) and corresponding delay probability density histogram (right plot) for 3313 fabric style.

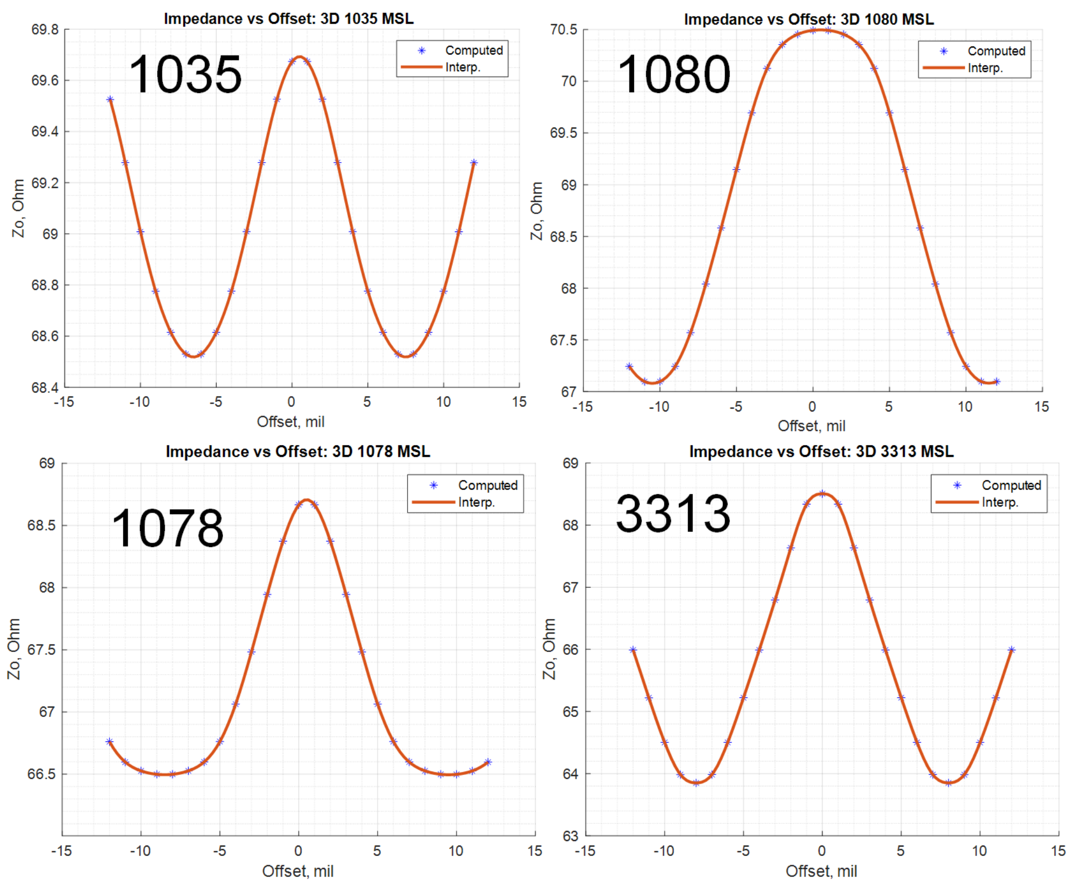

Fig. 6. Impedance variation with the offset for 4 mil trace for four fabric styles. Computed values are shown be stars and interpolated by line.

The delay and impedance variations are periodic functions with the period L equal to the period of the original lattice model Y3'. The corresponding delay probability is bounded by the minimal and maximal values (worst cases). **The probability to have the**

minimal and maximal delay values is the highest in all 4 cases. Notice that cases 1035 and 3313 have delay variation close to sinusoidal and corresponding probability density is similar to the Arcsine distribution. Fabric style 1080 has larger "resin valley" areas and corresponding delay dependency has flatter bottoms and higher probability to have smaller delay. On the other hand, fabric style 1078 has larger "glass hill" areas and higher probability to have larger delay. **The computed delay variations should not be considered as the actual parameters of the corresponding fabrics due to some "guessed" model parameters.** However, the final result of this numerical investigation is a general formula that can be applied to any laminate and requires just one parameter that is easy to compute or measure as demonstrated in the "Analytical Model" section of this paper.

Measured variations in effective dielectric constant close to sinusoidal are 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 (should be accounted with the kernel density estimate) or not uniform distribution of the trace positions (there was some order in arranging trace segments on the PCB). Dielectric constant variations extracted from measured data in [6] are close to sinusoidal or clipped sinusoidal as well.

Delay Deviation Probability and Exceedance

The delay variations with the offset and corresponding probability densities are computed and presented in the previous section. It is clear that the probability to have cases close to the worst case scenario may be quite high. Those are useful results, but the goal is to have a quantity to characterize the uncertainty in the delay due to FWE. Complimentary Cumulative Distribution Function (CCDF) computed for the delay deviation probability density can be used as such measure of uncertainty. Technically, it is probability to have delay deviation larger than certain specified value. It is called Delay Deviation Exceedance or DDE. Probability density of absolute delay deviation from the average between the min and max values is computed first and shown on the left plots in Fig. 7-10. Then, DDE values are computed for values T ps/inch and shown on the right graphs in Fig. 7-10.

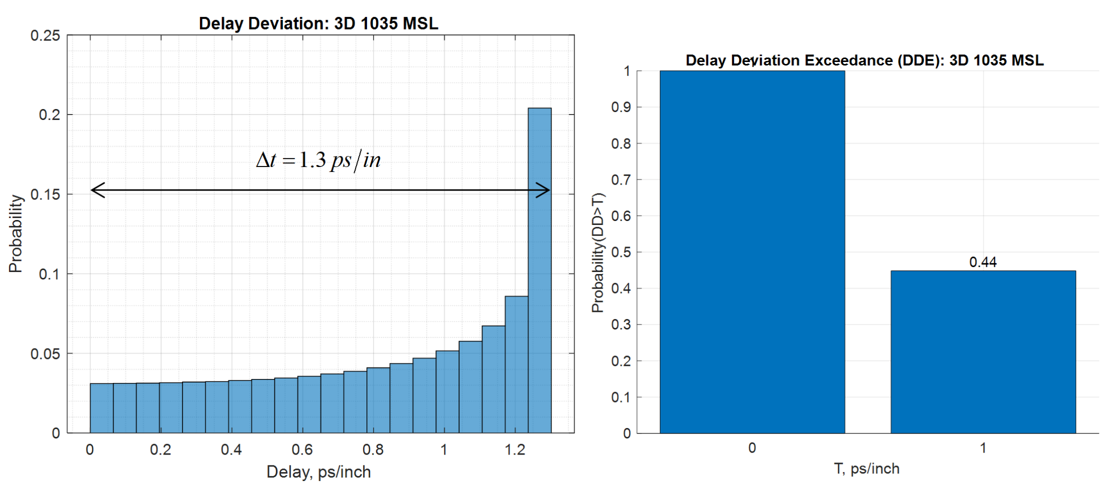

Fig. 7. Delay deviation probability density (left plot) and corresponding DDE (right plot) for 1035 fabric style.

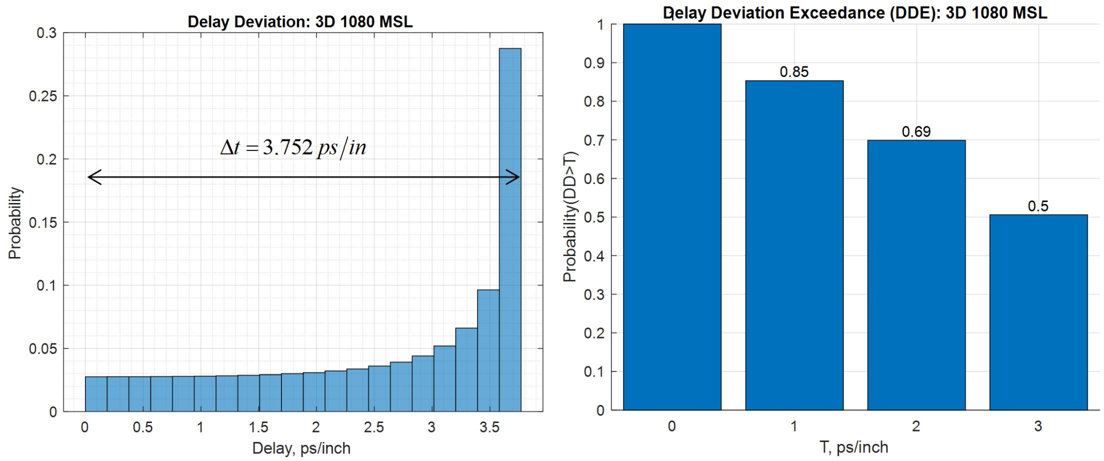

Fig. 8. Delay deviation probability density (left plot) and corresponding DDE (right plot) for 1080 fabric style.

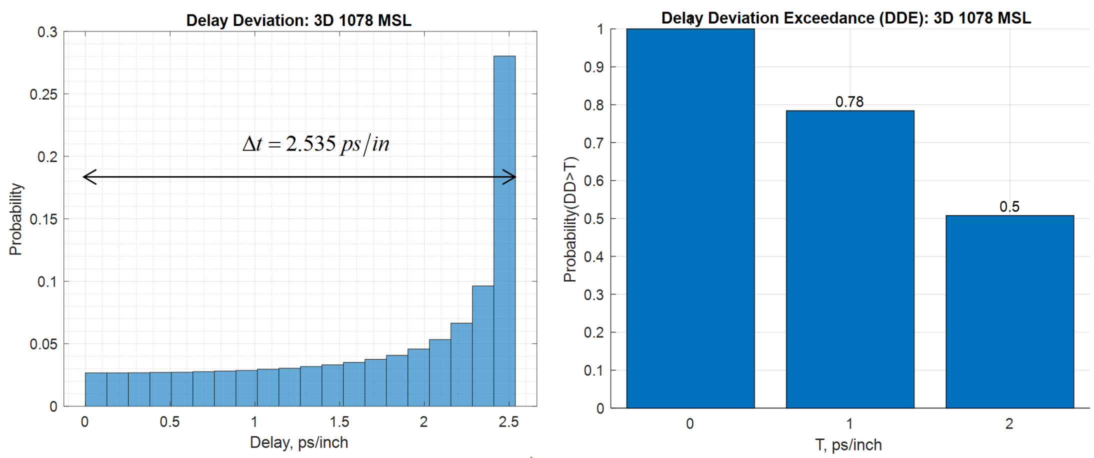

Fig. 9. Delay deviation probability density (left plot) and corresponding DDE (right plot) for 1078 fabric style.

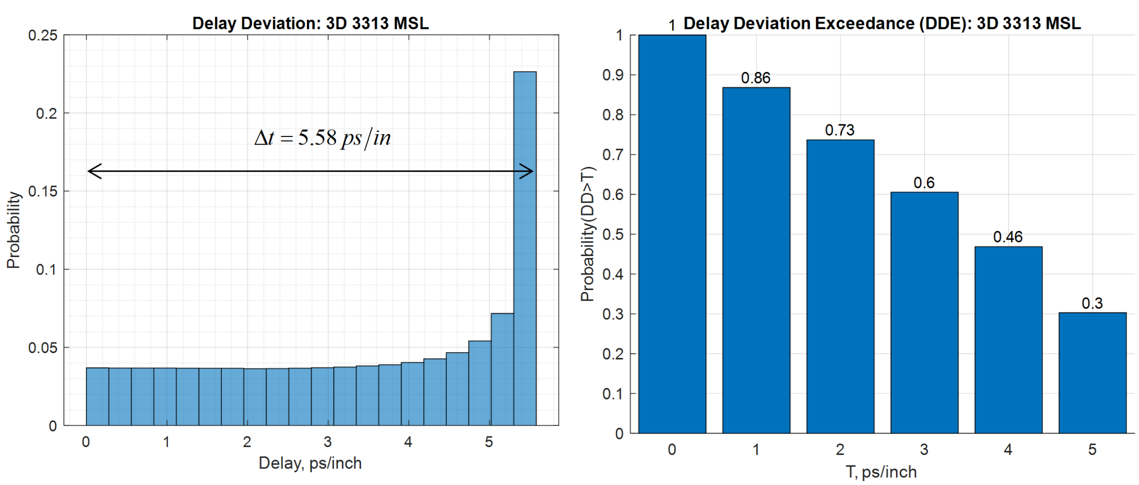

Fig. 10. Delay deviation probability density (left plot) and corresponding DDE (right plot) for 3313 fabric style.

Comparison of DDEs for all four fabric styles is show in Fig. 11. Now we can see if DDR specification does not allow the delay uncertainty over 3 ps/inch for instance, fabric styles 1080 and 3313 cannot be used without some FWE mitigation technique (routing at angle or panel rotation). The expected number of cases with the delay deviation over 3 ps/inch is about 50% for 1080 fabric and 60% for 3313 fabric. **The DDE numbers provided here are for the illustrative purpose and should not be considered as the actual characteristics of the corresponding fabrics.**

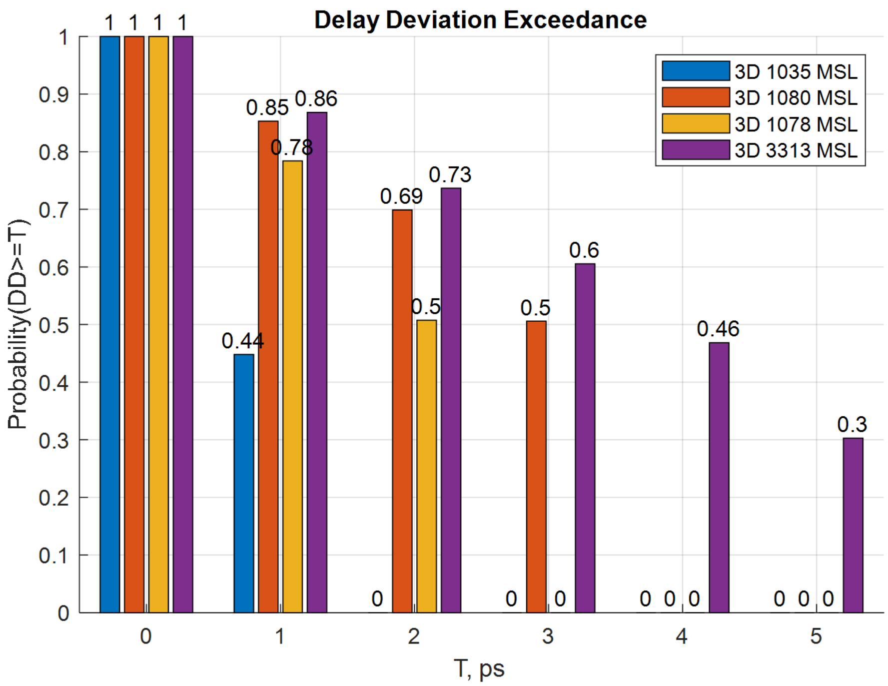

Fig. 11. Comparison of DDEs for four fabric styles.

Probability density of delay deviation from the average between the min and max values shown in Fig. 2 – Fig. 5 can be directly used to compute DDE without taking the absolute values of deviation. Such DDE has sign of deviation as shown in Fig. 12. This type of DDE has some asymmetries related to the asymmetries of the phase delay variations (resin valleys and glass hills). For instance, the expected number of cases with delay deviation 2 ps/inch larger than the average is 36% for 1078 case (flat glass hills), but only 13% of the cases will have delay smaller than the average (smaller resin valleys). This type of distribution should be used in cases if sign of the deviation matter.

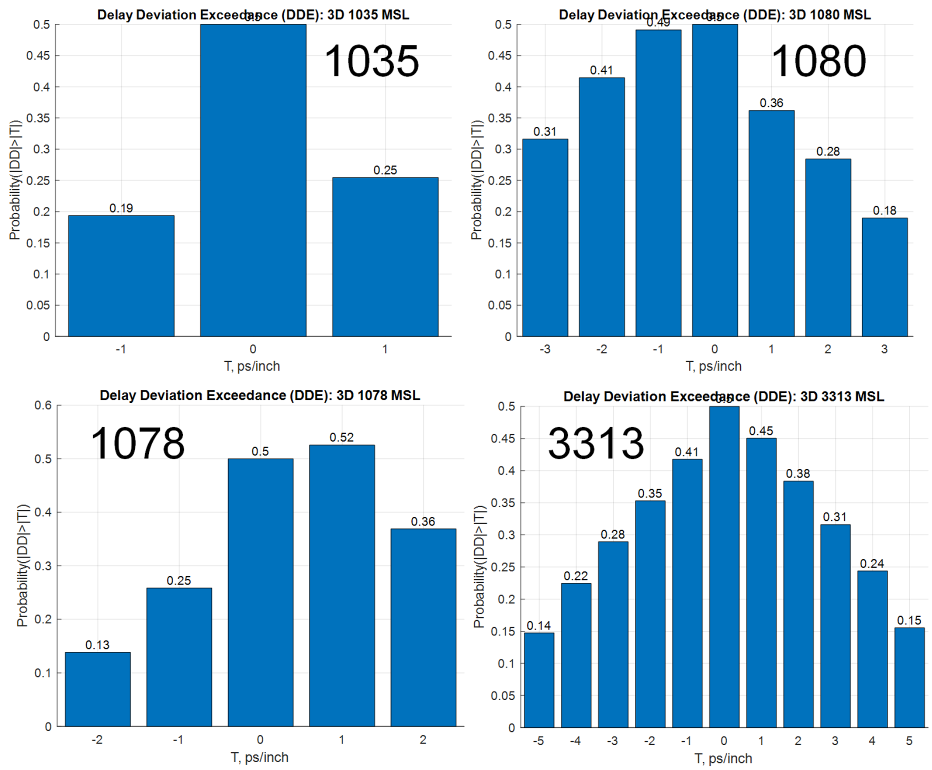

Fig. 12. Delay Deviation Exceedance above and below of the average between min and max values.

Evaluation of Differential Skew Uncertainty

To evaluate the differential skew uncertainty, Differential Skew Exceedance (DSE) can be introduced in the same way as DDE. It is done here with the numerical experiment. Four laminate cases with the parameters shown in Table 1 are simulated with two parallel traces with equal width W=4 mil separated by S=4 mil and offset ranging from -12 to +12 mils and the offset step 1 mil (geometry is similar to shown in Fig. 1). The offset coordinate is exactly between two traces. The skew is defined by the difference of phase delays computed for each trace. Computed dependencies of the skew values from the offset coordinate are shown in Fig. 13 by blue stars and the interpolated values by brown lines for all 4 laminate cases. Similar skew variations with the offset close to sinusoidal were also observed in [3]-[5].

With the skew dependency on the offset, skew probability density is then evaluated assuming the uniform distribution of the traces offsets. Probability density is computed with 100000 samples and 20 bins and is shown in Fig. 14 on the left plots. The fact that the skew probability density due to FWE is not normal is also noticed in [3]. The skew probability density is then use to compute DSE as complimentary CDF for all 4 case and shown on the right plots of Fig. 14.

Finally, DSEs for all four fabric styles are compared in Fig. 15. Now we can see if specification does 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 – that is not negligible by any means. **The computed skew variations should not be considered as the actual parameters of**

the corresponding fabrics due to some "guessed" model parameters. Evaluate the maximal possible skew with either numerical experiment with more data or with measurements.

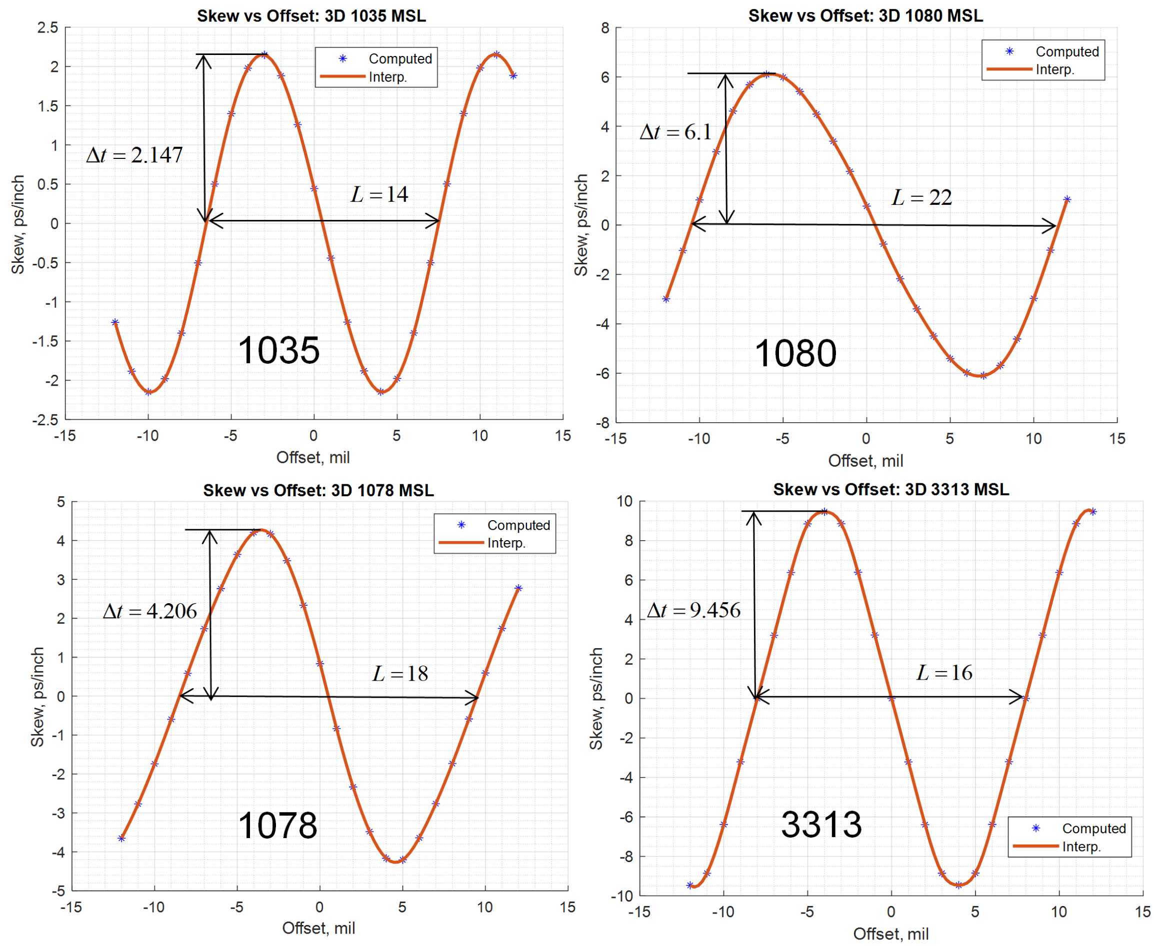

Fig. 13. Computed differential skew variations with the offset for 4 laminates.

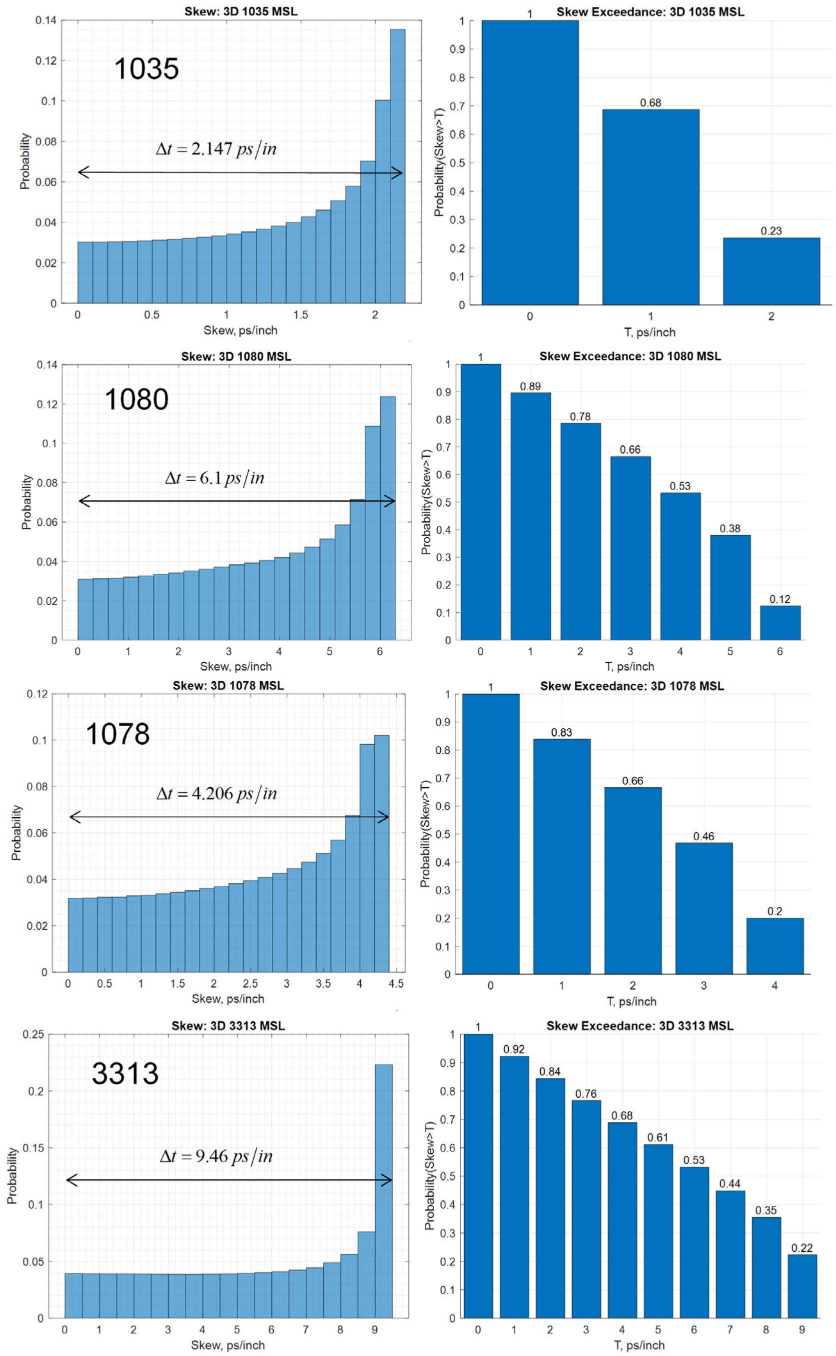

Fig. 14. Differential skew probability density (left) and differential skew exceedance or DSE computed for 4 laminates.

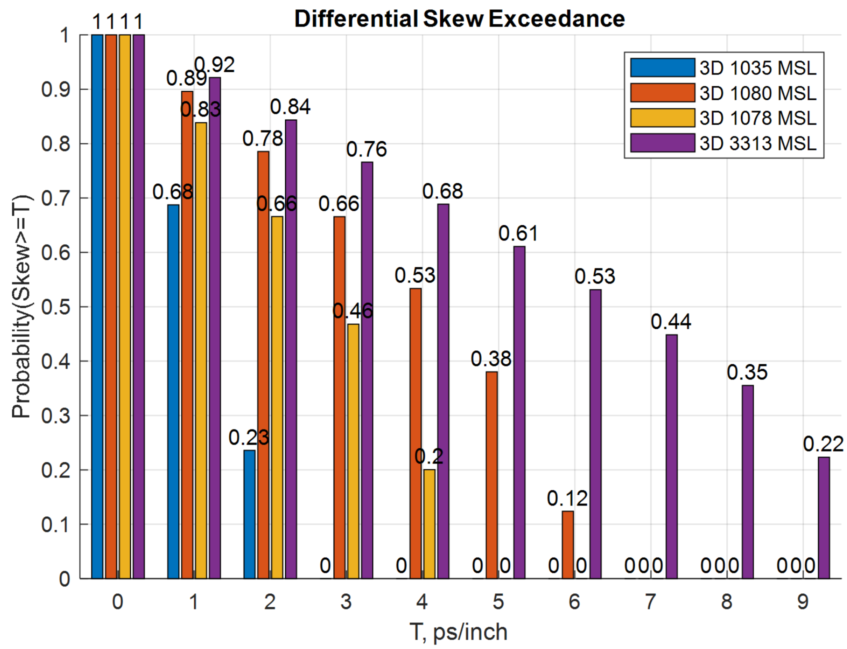

Fig. 15. Comparison of DSEs for four laminates.

Analytical Model

A possible and the simplest delay or skew deviation approximation is the sine function:

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

Here L is the period and Δt is the amplitude or maximal possible deviation of the delay or skew.
Corresponding probability density function is as follows:

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

It has complimentary CDF defined by the arcsine function (arcsine distribution [9]):

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

It is the probability to have delay or skew deviation over certain limit. **Formula for $S(t)$ can be directly used for an approximate evaluation of the DDE or DSE. It requires just one parameter identification – the maximal possible deviation Δt (worst case).** Comparison of the DDEs and DSEs computed directly from numerical experiment and from the arcsine distribution is provided in Fig. 16 for DDEs and in Fig. 17 for DSEs. Instead of the arcsine distribution, Beta or Kumaraswamy [10] distribution can be used for better accuracy. However, it will require identification of two or more parameters, instead of one in arcsine.

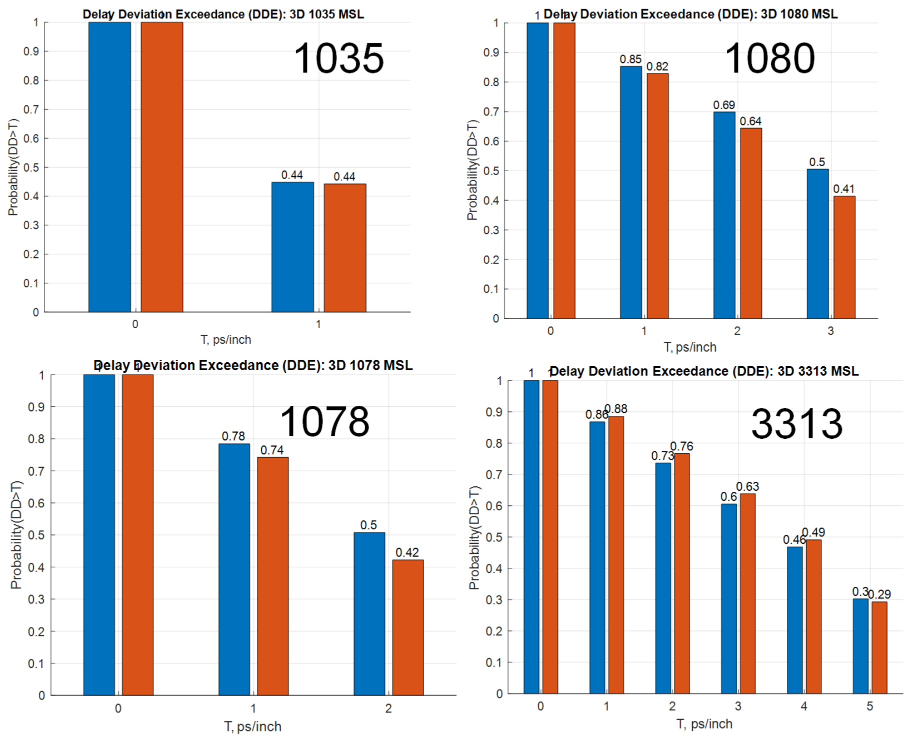

Fig. 16. DDEs computed directly from numerical experiment for single trace (blue bars) and from the arcsine CCDF approximation (brown bars).

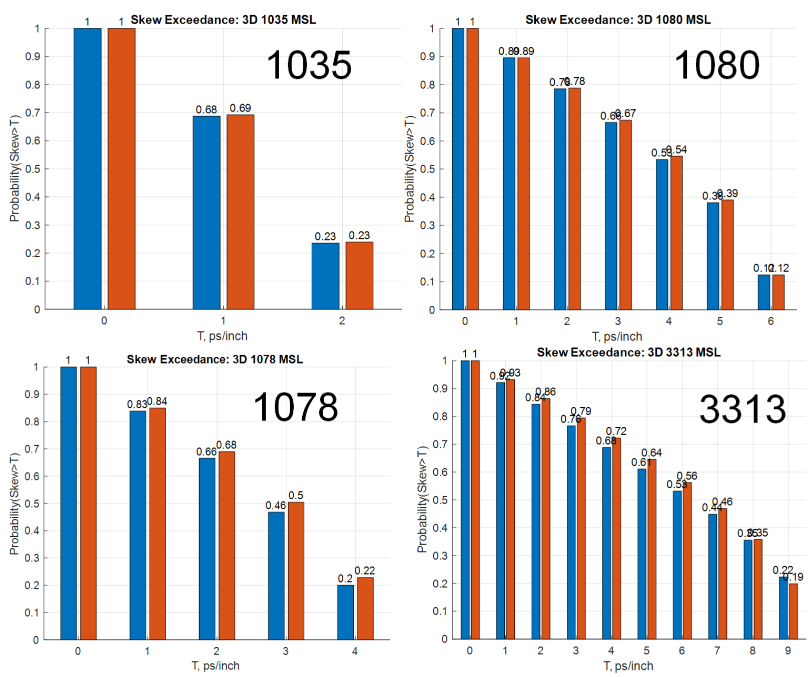

Fig. 17. DSEs computed directly from numerical experiment with differential traces (blue bars) and from the arcsine CCDF approximation (brown bars).

Numerical Model Validation

At the time of writing this article we do not have experimental evidence that this theory works. Only circumstantial evidence and observations based on the previous published data. There is no procedure of how to build the model that correlates with a particular material as done in [2], [4] and [5] for instance. The only way to make sure that the observations and theory are valid is to use another tool and reproduce the numerical experiment. Thus, we used Ansys's HFSS, analyzed the same geometry as shown in Fig. 1 and extracted delay dependency from the trace position. The results are shown in Fig. 18 – Fig. 21 and $2 \cdot \Delta t$ values in ps/inch are summarized in Table 2. The shape of dependencies computed with Simbeor and HFSS are very similar. It means that the complimentary CDF computed from the arcsine function will work with the data extracted by HFSS too. However, the amplitude of the variations computed with HFSS is larger. We are investigating the reasons for that.

Table 2. Comparison of $2 \cdot \Delta t$ values in ps/inch

Tool\Fabric	1035	1080	1078	3313
Simbeor	2.6	7.54	5.07	11.16
HFSS	2.75	9.40	6.16	13.01

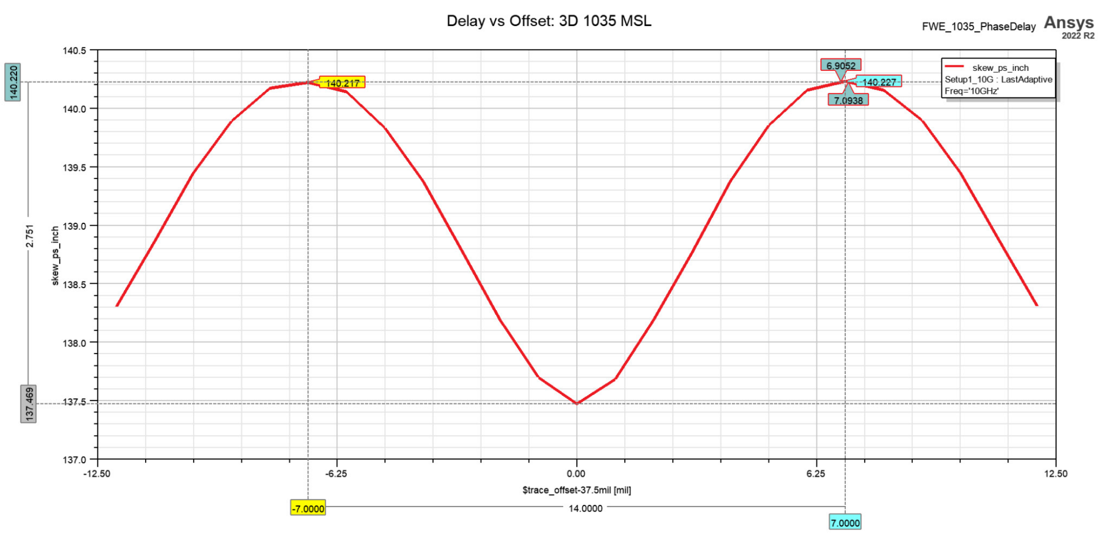

Fig. 18. Delay variation with offset for 1035 fabric style.

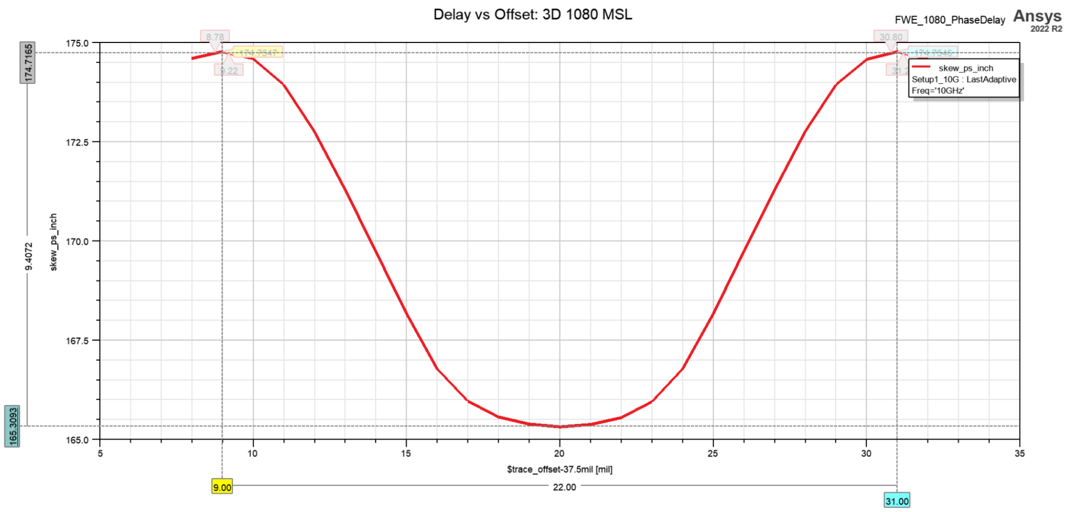

Fig. 19. Delay variation with offset for 1080 fabric style.

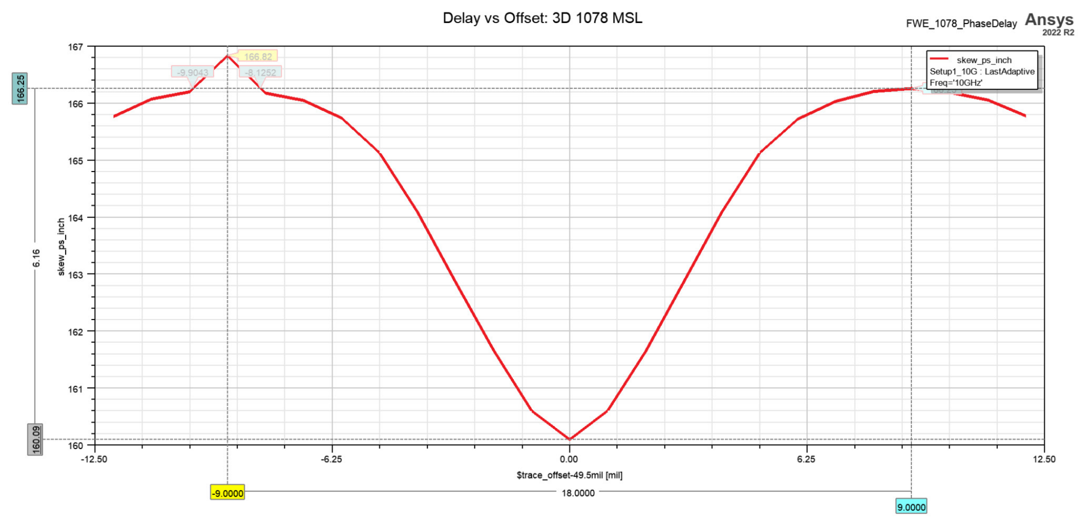

Fig. 20. Delay variation with offset for 1078 fabric style.

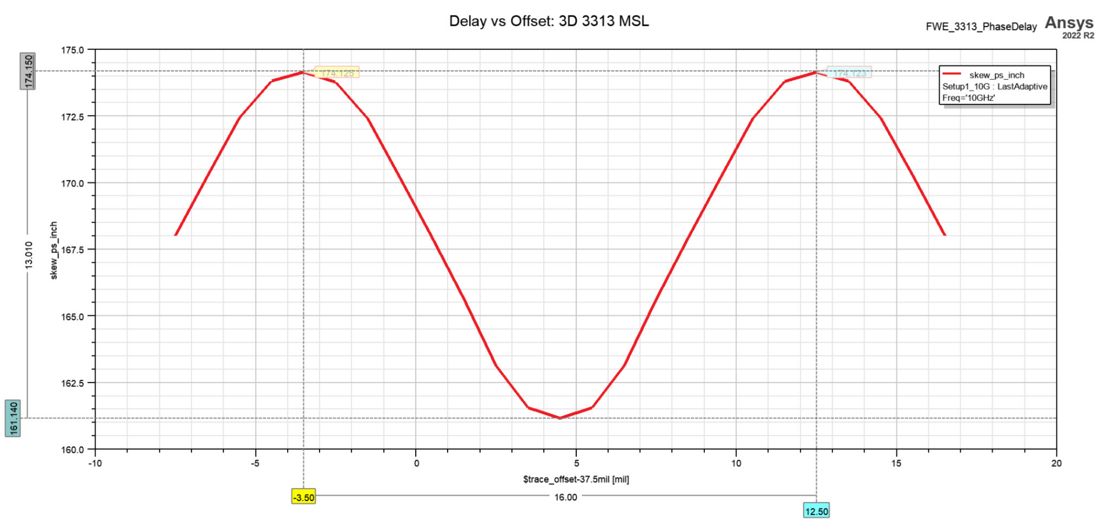

Fig. 21. Delay variation with offset for 3313 fabric style.

Conclusion

A new Delay Deviation Exceedance (DDE) measure is proposed to quantify the delay uncertainty in single-ended links. Differential Skew Exceedance (DSE) measure is proposed to quantify the uncertainty in differential links as the extension of DDE idea. DDE and DSE are computed with numerical experiment by running multiple 3D EM simulations of short segments of interconnects over inhomogeneous dielectric. Delay deviation and skew probability density is evaluated from interpolated dependencies of the delay and skew variations with positions relative to the glass bundles. The exceedances are then 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.** Trace averages the dielectric properties. Wider traces will see less variations comparing to narrow traces. Thus, a numerical experiment or measurements should be done for each practical case. All computations done in this paper are easily repeatable with FWE Kit of Simbeor SDK [8]. **It is also 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”. This is the main outcome of this investigation.

References

1. G. Brist, B. Horine and G. Long, "Woven glass reinforcement patterns", Printed Circuit Design & Manufacture, pp. 28-33, Nov. 2004.
2. Y. Shlepnev and C. Nwachukwu, "Modelling jitter induced by fibre weave effect in PCB dielectrics," 2014 IEEE International Symposium on Electromagnetic Compatibility (EMC), 2014, pp. 803-808, doi: 10.1109/ISEMC.2014.6899078.
3. T. Zhang, X. Chen, J. E. Schutt-Ainé and A. C. Cangellaris, "Statistical analysis of fiber weave effect over differential microstrips on printed circuit boards," 2014 IEEE 18th Workshop on Signal and Power Integrity (SPI), 2014, pp. 1-4, doi: 10.1109/SaPIW.2014.6844540.
4. K. Nalla, A. Koul, S. Baek, M. Sapozhnikov, G. Maghlakelidze and J. Fan, "Measurement and correlation-based methodology for estimating worst-case skew due to glass weave effect," 2017 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI), 2017, pp. 187-192, doi: 10.1109/ISEMC.2017.8077864..
5. A. Koul, K. Nalla, D. Nozadze, M. Sapozhnikov, Y. Yang, Fiber weave effect: Modeling, measurements, challenges and its impact on differential insertion loss for weak and strong-coupled differential transmission lines, DesignCon 2018.
6. B. Chen, R. Yao, H. Wang, K. Geng, J. Li, Effect of Fiber Weave Structure in Printed Circuit Boards on Signal Transmission Characteristics. *Appl. Sci.* 2019, *9*, 353. https://doi.org/10.3390/app9020353
7. Y. O. Shlepnev, "Trefftz finite elements for electromagnetics," in IEEE Transactions on Microwave Theory and Techniques, vol. 50, no. 5, pp. 1328-1339, May 2002, doi: 10.1109/22.999147.
8. Simbeor Electromagnetic Signal Integrity Software, Simberian Inc. – www.simberian.com
9. Arcsine distribution – Wikipedia https://en.wikipedia.org/wiki/Arcsine_distribution
10. Jones, M.C. (2009). "Kumaraswamy's distribution: A beta-type distribution with some tractability advantages". Statistical Methodology. 6 (1): 70–81. doi:10.1016/j.stamet.2008.04.001
11. A. Manukovsky, Y. Shlepnev, S. Mordooch, Evaluation of Delay Uncertainty in PCB Interconnects Due to Fiber Weave Effect, October 11, 2022, pre-print arXiv:2210.05779, https://arxiv.org/abs/2210.05779