White Paper

How Fiber Weave Effect Can Affect Your High-speed Design

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Abstract: Fiber weave effect (FWE) skew is becoming more of an issue as bit rates continue to soar upwards. As of this publication, 56 GB/s is state of the art and 112 GB/s is just around the corner; while next generation PCIe is rapidly moving to 64 GT/s. Some industry standards limit the total skew budget in a channel to 0.2UI from all sources. But is that enough for today's PAM-4 systems? In this paper, the effect of FWE is explored on PAM-4 signalling. The analysis shows bit rates above 25 GB/s, traditional total skew budget may be insufficient for some industry standards and tighter skew budget is proposed.

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How Fiber Weave Effect Can Affect Your High-speed Design

Fiber weave effect (FWE) skew, also known as glass-weave skew (GWS), is becoming more of an issue as bit rates continue to soar upwards. Today's 56GB/s is state of the art in high-speed routers and 112 GB/s is just around the corner. While next generation PCIe, used in the personal computer and server industry, is rapidly moving to 64 GT/s.

Skew can come from any intra-pair asymmetries, such as: packages; ball-grid array (BGA) breakouts; intra-pair routing length mismatches; connectors and asymmetrical return path vias, to name a few examples. Many of these can be controlled by specifying tight constraints in the design. But, since FWE is statistical in nature, it can be most difficult to control the timing skew it causes, and at these data rates, it can actually ruin your day.

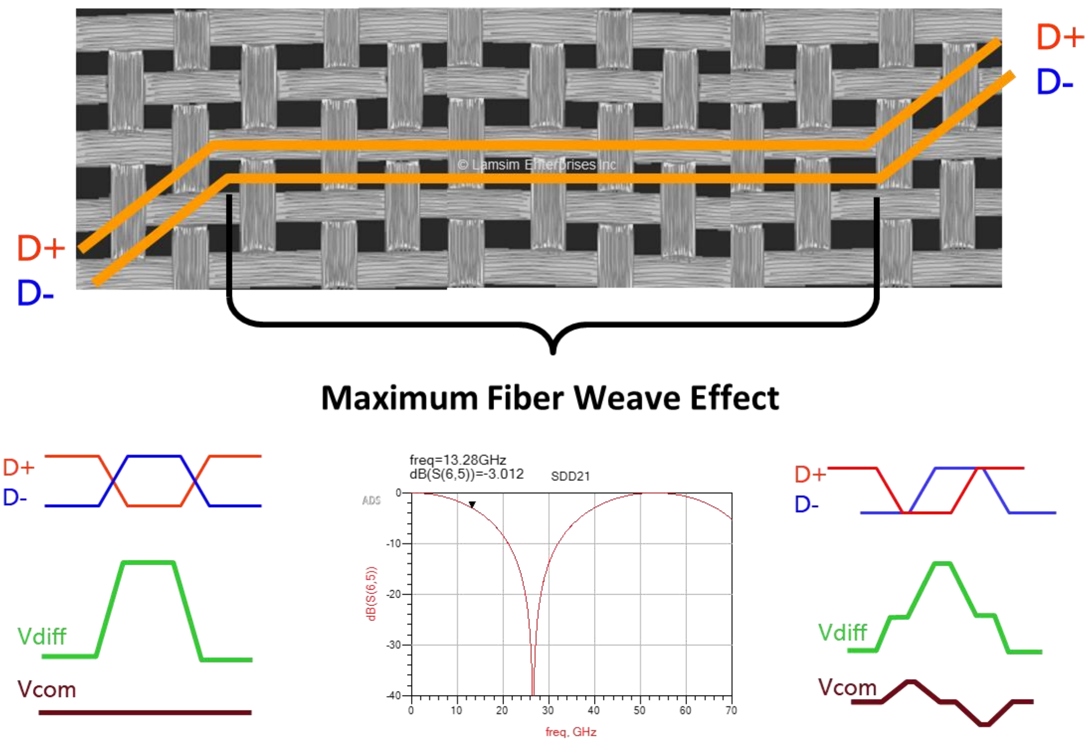


Figure 1 Fiber weave effect example of differential pair routing showing top trace routed over a low resin fill fiberglass bundle for a portion of its length while the bottom trace is routed over mostly higher resin fill. Timing skew between a positive (D+) and negative (D-) signals will cause a resonant null in the SDD21 insertion loss and convert some of the differential signal into a common signal component.

FWE is the term commonly used when a fiberglass reinforced dielectric substrate causes intra-pair timing skew of the same length. Since the dielectric material used in the printed circuit board (PCB) fabrication process is made up of glass yarns woven into cloth and impregnated with epoxy resin, it becomes non-homogenous.

As illustrated in Figure 1, when the top trace is routed over an area of low resin fill glass weave for a portion of its length, it will have a different propagation delay compared to the bottom trace routed over an area of high resin fill glass weave. The difference in delay is known as timing or phase skew.

The speed at which a signal propagates along a transmission line depends on the material's relative permittivity (e_r), also known as dielectric constant (*Dk*). The higher the *Dk*, the slower the signal propagation.

Since modern serial link interfaces use differential signalling on a pair of transmission lines of equal length, any timing skew between a positive (D+) and negative (D-) signals will convert some of the differential signal into a common signal component. Ultimately this results in eye closure at the receiver and contributes to electro-magnetic interference (EMI) radiation.

Timing skew in the time domain manifests itself into a resonant null in the frequency domain, as shown in Figure 1. In this example, if the timing skew is equal to one-half unit interval (UI) of the baud rate, D+ and D- signals will be shifted 90 degrees and the resonant null will occur at the frequency of the baud rate.

You can predict the resonant frequency (f_o) if you know the intra-pair timing skew (t_{skew}) and FEW lengths using the following equation:

Equation 1

$$f_0 = \frac{1}{2 \times t_{skew} \times length_{FWE}} = \frac{1}{2TD_{skew}}$$

where:

$$t_{skew} = \frac{\sqrt{Dk_{\max}} - \sqrt{Dk_{\min}}}{c} \text{ seconds per unit length}$$

$length_{FWE}$ = maximum FEW length

c = speed of light = 2.998E+8 m/s (1.18E+10 in/s)

Dk_{min} , Dk_{max} are the minimum and maximum effective *Dk* due to the glass weave.

When TD_{skew} is equal to 1 UI, D+ and D- signals will be shifted 180 degrees and become in phase with one another. The resonant null will occur at the Nyquist frequency, equal to one-half of the baud rate, and the eye will be totally closed.

$$f_0 = \frac{1}{2UI} = \frac{Baud}{2} = \text{ Nyquist frequency}$$

By definition, the baud rate is the number of symbols transmitted per UI. For non-return to zero (NRZ), the baud rate equals the symbol or bit-rate. For pulse amplitude modulated 4-level (PAM-4) signalling, there are two symbols per UI and the baud rate is one-half the bit rate. So, for 56 GB/s PAM-4, the baud rate is 28 GBd. For IEEE802.3bs, Ethernet 400G standard, the baud rate is 26.56 GBd, PAM-4 and is used for this study.

The skew issue is exacerbated for PAM-4 signalling, as shown in Figure 2. In these examples a simulated lossless transmission line was used to only show the effect of eye closure due to skew. Of course there is no such thing as a lossless transmission line, but it is a useful method to isolate the loss strictly due to skew. As shown in Figure 2 (a), with 0UI of skew, the channel loss is flat and eyes are wide open.

A resonant null in the frequency domain, due to FWE skew, behaves like a notch filter. Depending on the Q-factor, frequencies near resonance will be attenuated. If the resonant null occurs near the Nyquist frequency the eye will be reduced. In the example of Figure 2 (b), with 0.5UI, or 18.8 ps of skew, there is a resonant null at the baud rate and the insertion loss is -3 dB at 13.28 GHz Nyquist frequency. This causes an eye height (EH) reduction of 153 mV and an increase of 10 ps of jitter.

When skew is 1UI, or 37.65 ps, as shown in Figure 2 (c), the resonant null is at the Nyquist frequency and the eyes are totally closed. With a lossy channel and other impairments, eye closure will only get worse.

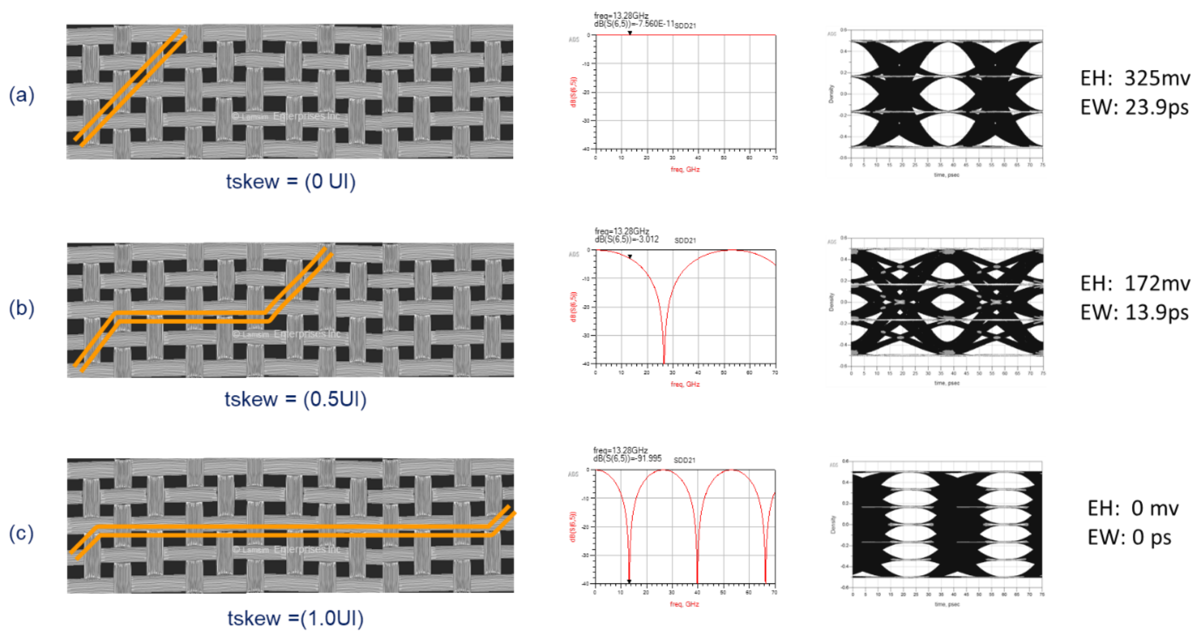


Figure 2 The effect of FEW skew on lossless transmission line example.

Total Skew Budget

As a rule of thumb, we usually strive to have an interconnect bandwidth (BW) to be five times the Nyquist frequency of the bit-rate. This follows many oscilloscope manufacturers' specifications for risetime (RT) bandwidth product equal to 0.35.

Equation 2

$$RT \times BW = 0.35$$

Five times Nyquist represents the 5th harmonic sinusoidal component of a Fourier series, shown in Figure 3. An interconnect BW up to the 5th harmonic preserves the integrity of the risetime down to 7% of the period (*T*) of the fundamental frequency (f_1).

Equation 3

$$RT = \frac{0.35}{BW} = \frac{0.35}{5f_1} = 0.07T$$

Thus, for a 26.56 GBd data signal, with a Nyquist frequency of 13.28 GHz, a *BW* of 66.4 GHz is needed to maintain a RT of 5.27 ps.

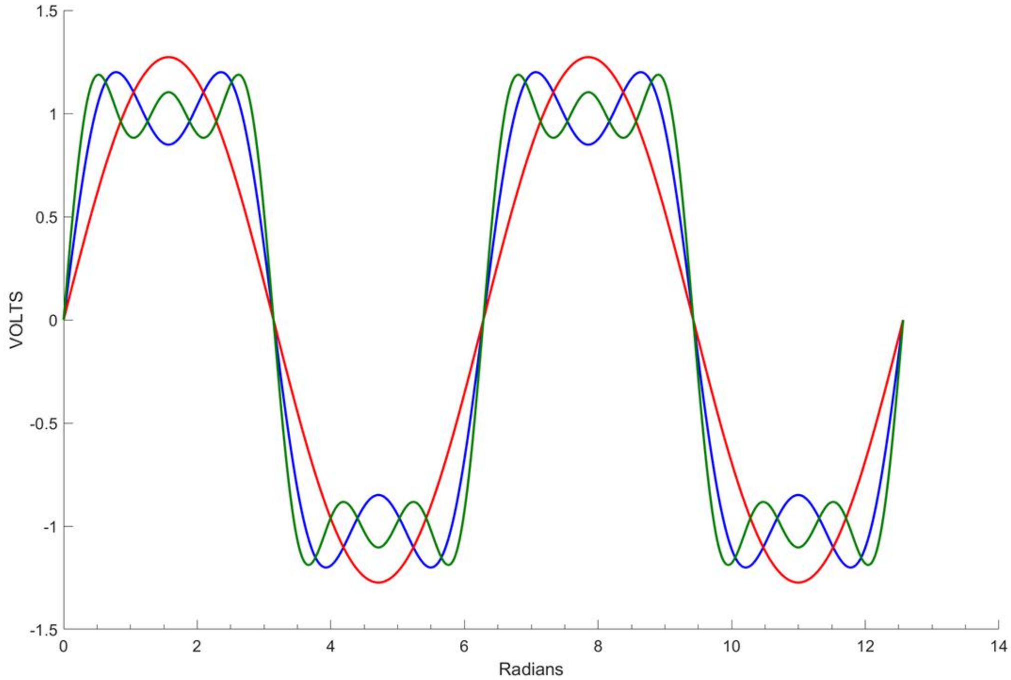


Figure 3 Fourier series to the 5th odd harmonics of the fundamental frequency

Some industry standards limit the total skew budget in a channel to 0.2UI from all sources. But is that enough for today's PAM-4 systems?

Twenty percent of a UI will result in a resonant null at a frequency (f_0) equal to 5 times the Nyquist frequency (f_{Nq}).

if;

Equation 4

$$f_0 = 5 \times f_{Nq} = 5 \times \frac{Baud}{2} = \frac{1}{2 \times TD_{skew}}$$

then;

Equation 5

$$TD_{skew} = \frac{1}{2 \times 5 \times \frac{Baud}{2}} = \frac{1}{5 \times Baud} = 0.2UI$$

At 26.56 GBd that's only 7.53ps!

But 0.2UI would obliterate the 5th harmonic of the Nyquist frequency. Historically, for non-return to zero (NRZ) and lower baud rates, there was more margin, but for PAM-4, with a -9.5dB signal to noise (S/N) penalty, 0.2UI may further strain channel margin.

For that reason, a good rule of thumb to follow, is making sure the first null occurs at the 7th harmonic of the Nyquist frequency; to maintain the integrity of the 5th harmonic frequency component. This means a total skew budget of 0.14UI:

Equation 6

$$TD_{skew} = \frac{1}{7 \times Baud} = 0.14UI$$

Figure 4 compares 0.2UI and 0.14UI total skew budget vs common industry standard baud rates. As shown, there is an exponential decline in skew budget as baud rate increases. For 0.14UI, the total skew budget at 26.56 GBd is 5.27ps and at 56 GBd, it is only 2.5ps. Since this is the total skew budget, it doesn't leave much left for the FWE skew budget!

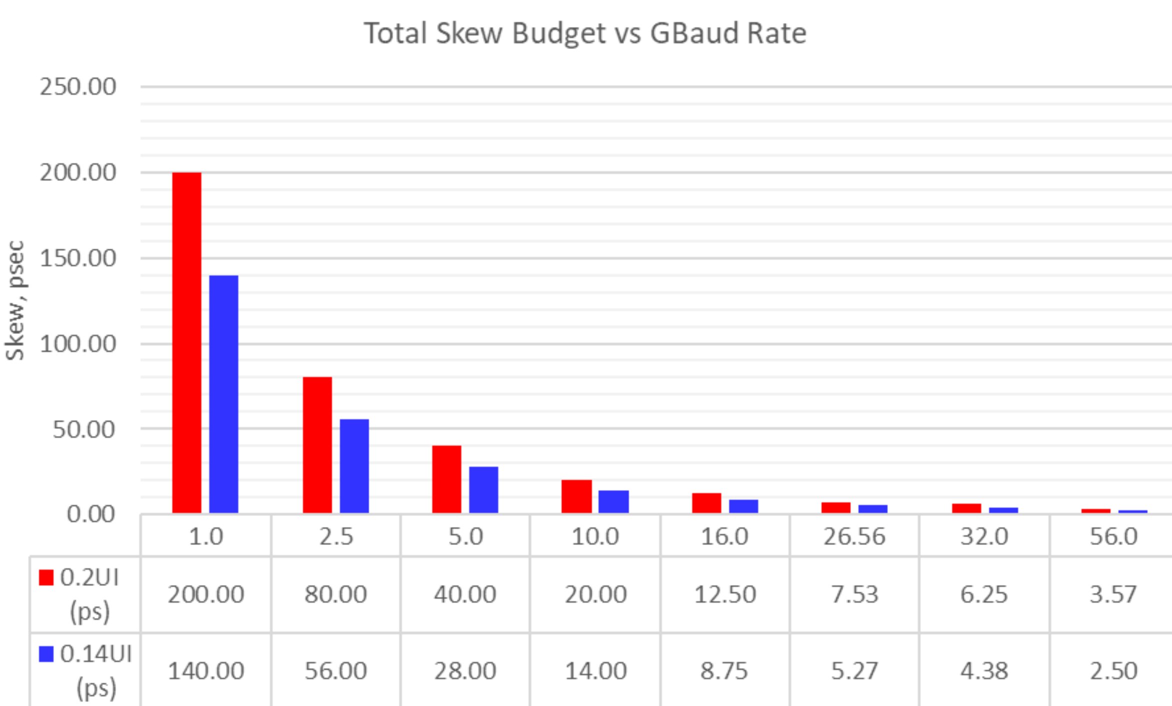
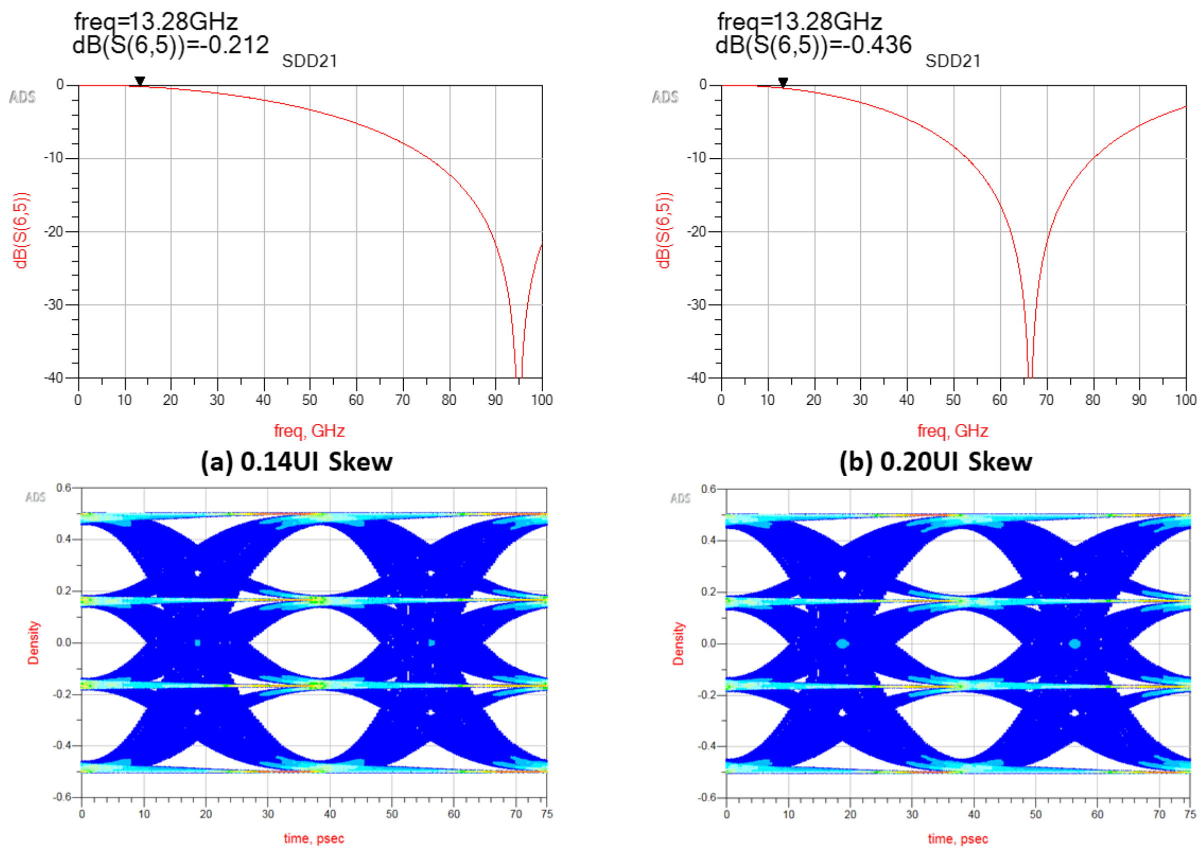


Figure 4 Graph comparing 0.2UI (red) and 0.14UI (blue) total skew budget vs industry standard Gbaud rates.

Figure 5 compares two lossless differential pair simulations with, 0.14UI (a) and 0.20UI (b) of skew added. The eye diagrams show that with 0.22dB delta in insertion loss at 13.28GHz Nyquist, there is an additional 12 mV of reduction in center EH and an increase of 0.57ps of jitter; due to resonant null shift in frequency, down to 66.4 GHz (b).



permute(HeightAtBER0)	permute(HeightAtBER1)	permute(HeightAtBER2)
0.280	0.282	0.281

permute(WidthAtBER0)	permute(WidthAtBER1)	permute(WidthAtBER2)
2.184E-11	2.184E-11	2.184E-11

permute(HeightAtBER0)	permute(HeightAtBER1)	permute(HeightAtBER2)
0.268	0.270	0.269

permute(WidthAtBER0)	permute(WidthAtBER1)	permute(WidthAtBER2)
2.127E-11	2.127E-11	2.127E-11

Figure 5 Lossless differential pair simulation with 0.14UI (a) and 0.20UI (b) of skew added. With 0.22dB delta in insertion loss at 13.28GHz Nyquist, there is additional 12 mV loss in center EH and increase of 0.57ps of jitter due to resonant null shift in frequency down to 66.4 GHz (b).

The Reality

For a lossless channel, 12 mV seems insignificant. But that's not reality. Real channels have loss and other impairments that will further erode the eye opening. Furthermore, many specifications have limits on the total loss.

The IEEE 802.3bs chip-module (C2M) spec [3] has a tight insertion loss (IL) mask spec of 10.2 dB at 13.28 GHz. Table 120E-1 of the same document specifies a minimum differential eye height (EH) of 32 mV and eye symmetry mask width (EW) of 0.22UI or 8.23ps at TP1a.

Figure 6 shows simulated results of IL and PAM-4 eye diagrams of a realistic chip C2M channel. Worst case power-voltage-temperature (PVT) was used for the transmitter model including the package. Figure 6 (a) shows the results of the inherent channel, with all impairments included. It has 1.7ps, or 0.045UI of skew as a baseline. The channel loss just meets the IL mask and the eyes meet the IEEE 802.3bs EH and EW with margin.

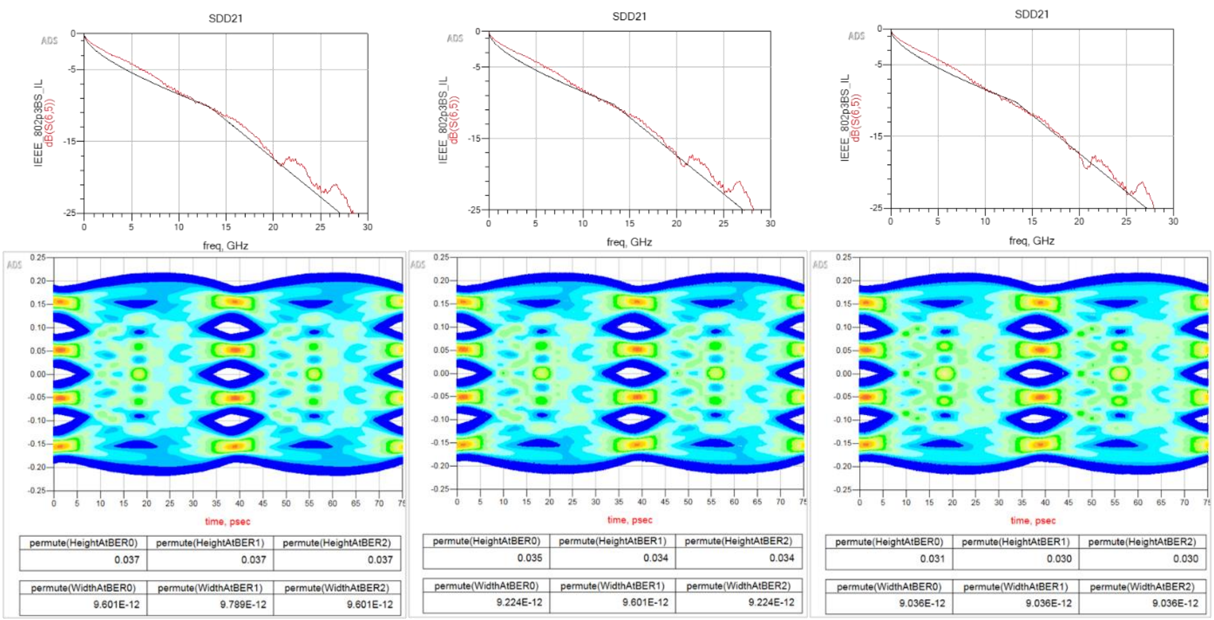
Figure 6 (b) and (c) increases total skew to the equivalent of 0.14UI, and 0.2UI respectively. As skew increases, the IL degrades due to decreasing resonant null frequency. At 0.14 UI (b), the IL is just starting to violate the IL mask near the Nyquist frequency break-point and the EH and EW are still within spec. But at 0.2UI (c), IL is slightly worse and the EH just fails the 32mV spec; but passes the EW spec.

The minimum eye heights and widths measured at 10^{-5} bit-error-ratio (BER) were:

a) 0.045UI (37; 37; 37) mV and (9.601; 9.789; 9.601) ps – **EH/EW -PASS**

b) 0.14UI (35; 34; 34) mV and (9.224; 9.601; 9.224) ps – **EH/EW -PASS**

c) 0.20UI (31; 30; 30) mV and (9.036; 9.036; 9.036) ps – **EH -FAIL / EW -PASS**



(a) 0.045UI Baseline **(b) 0.14UI** **(c) 0.2UI**

Figure 6 Simulated results of IL and PAM-4 eye diagrams of a realistic chip C2M channel when total skew is increased to 0.14 UI (b) and 0.20 UI (c) from the baseline 0.045 UI skew.

FWE Skew Budget

Since FWE is a function of glass weave style, resin chemistries, trace geometries and stackup parameters, to name a few things, it is difficult to establish an exact delta Dk from data sheets. A practical study from [1] showed a maximum FWE skew of 45 ps, over 7.5 inches. This represents 6 ps/inch of FWE skew. The boards were designed as stripline construction, using double layer 1035 spread-weave glass for the Megtron-6 cores and prepregs.

This is a realistic study for modern multi-gigabit designs. But the complexity of multi-ply layups does not ensure the glass bundles of each ply would perfectly align above and below the traces. In fact, when observing the cross-sections showed glass bundles of each ply were off-set from each other which would improve FWE skew results. Following the methodology from [2] would give a more pessimistic 9.46 ps/in, which you might experience in micro-strip with single layer construction.

If we budget 1 ps of skew for all impairments, like length matching, connectors, breakouts etc., we can establish a FWE skew budget for various baud rates. Figure 7 plots FWE UI skew budget vs baud rates assuming a total skew budget of 0.14 UI. We observe up to 10GBd or so, the 1ps of skew from other impairments is negligible. But after 10 GBd, it starts to impact FWE skew budget. At 26.56 GBd and 32 GBd it is approximately 0.11 UI and at 56 GBd it is only about 0.08 UI!

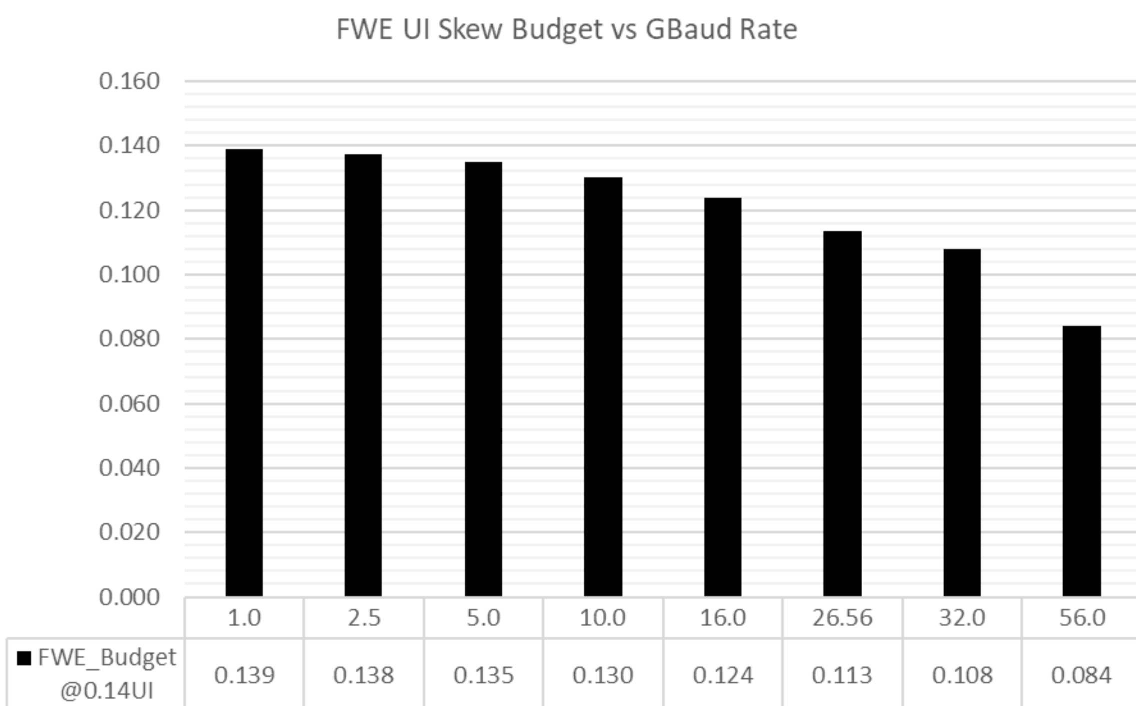


Figure 7 FWE UI skew budget vs baud rates assuming a total skew budget of 0.14 UI

With 6 ps/inch of FWE skew [1], the FWE lengths are calculated to meet 0.14UI total skew budget and plotted vs Gbaud rate, shown in red of Figure 8. If 9.46 ps/in is used, following the methodology from [2], the FWE lengths are shown in blue.

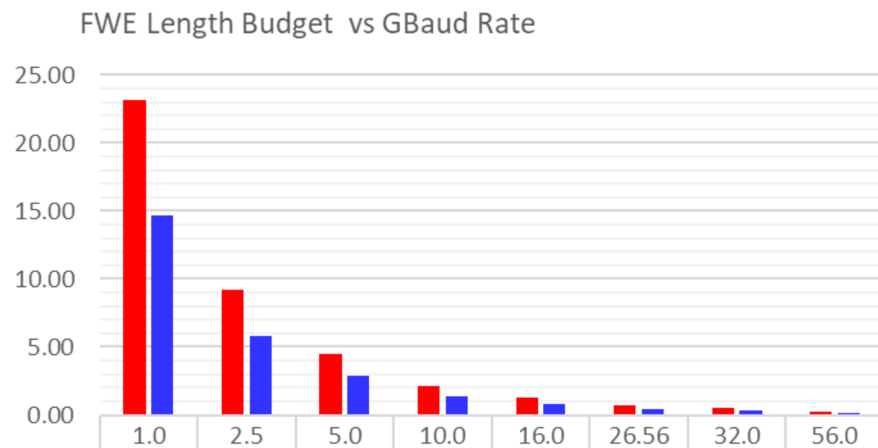
As we can see, there is an exponential decline in FWE length for an exponential rise in Gbaud rate. Above 10 GBd, FWE gets increasingly more difficult to control without further mitigation techniques. At 26.56 GBd and 6 ps/in of skew, the maximum length is 0.7 inches; at 56 GBd, it's only 0.25 inches. But for 9.46 ps/in of skew, the lengths reduce to about 0.5 inch at 26.56 GBd and 0.2 inches at 56 GBd!

Popular FWE skew mitigation techniques include:

- Choosing a glass style where the glass strands are mechanically spread to fill in the resin rich windows.

- Zig-zag or random routing of differential pairs.
- Choosing a differential pair pitch to line up with glass style pitch. However, this is not always practical because the warp and fill yarns in different glass styles may have different pitches.
- Rotate artwork 7-10 degrees on the PCB panel.

Sometimes more than one of these techniques are needed.



	1.0	2.5	5.0	10.0	16.0	26.56	32.0	56.0
■ 0.14UI_FWE_Length (inch) @tskew=6ps/in	23.17	9.17	4.50	2.17	1.29	0.71	0.56	0.25
■ 0.14UI_FWE_Length (inch) @tskew=9.46ps/in	14.69	5.81	2.85	1.37	0.82	0.45	0.36	0.16

Figure 8 FWE length budget vs GBaud rate assuming a total skew budget of 0.14 UI and t_{skew} of 6 ps/in (red) and 9.46 ps/in (blue).

Summary and Conclusions

With bit rates above 25 GB/s, 0.2 UI total skew budget has shown to be insufficient for PAM-4 signalling for some industry standards. In order to mitigate the effect of skew on eye height and width, it is proposed 0.14 UI be used for total skew budget to maintain a channel bandwidth to at least seven times the Nyquist frequency of the baud rate.

Up to 10GBd or so, limiting the non-FWE skew to 1 ps from other impairments, has a negligible effect on 0.14 UI total skew budget. But after 10 GBd, it starts to reduce the FWE skew budget. At 26.56 GBd and 32 GBd it is approximately 0.1 UI and at 56 GBd it is only about 0.08 UI!

With larger and larger switch application specific integrated circuit (ASIC) packages and with tighter and tighter ball grid array (BGA) pitch packages, means reduced impedance-controlled line widths and space to break out of the BGA pin field. Similarly for routing through tight pitch backplane connectors. It is not uncommon to see BGA escape lengths to be on the order of 0.25 inches or more. And in most cases those breakouts are parallel to X-Y axis of the panel. At 56 GBd, that's the entire skew budget! This then becomes unmanageable without further FWE skew mitigation techniques.

Of course, this analysis is based on worst case, and doesn't mean if you violate this skew budget your system is broken. But what it doses show, is more detailed modeling and simulation of the channel is required with perhaps more consideration to include FWE skew budget in the channel model. This will present severe challenges on designing the next generation 112 Gb/s systems and choosing PCB dielectric material.

References:

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