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# Comparing the different Metrics of Intra-pair Skew in Tracking Channel Performance

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## Abstract

This paper addresses the challenges in correlating intra-pair skew with high-speed SerDes channel performance. It categorizes intra-pair skew measurement methods and highlights secondary effects beyond loss degradation due to mode conversion by quantifying the impact through crosstalk. A novel mixed mode conversion approach evaluates skew influence on N-port networks. The paper demonstrates the correlation between intra-pair skew metrics and measured/ simulated S-parameters, contrasting metrics across channel topologies and data rates. The findings provide valuable insights into the practicality and applicability of intra-pair skew metrics for improving overall channel performance and guiding design decisions.

## Author (s) biography

**Hansel Desmond D'Silva** is a Signal Integrity Engineer working on SerDes at Achronix Semiconductor Corporation. He received a Master of Science degree (with thesis) in Electrical Engineering from San Diego State University in 2015 and a Bachelor of Engineering degree in Electronics and Telecommunication Engineering from Don Bosco Institute of Technology, Mumbai (Bombay) University in 2013. He believes in innovating through collaboration and never shies from listening to another's thought process in challenging his own.

**Richard Mellitz** is presently a Distinguished Engineer at Samtec, supporting interconnect signal integrity and industry standards. Prior to this, he was a Principal Engineer in the Platform Engineering Group at Intel. Richard was a principal member of various Intel processor and I/O bus teams including Itanium®, Pentium®, PCI Express®, SAS®, and Fabric (Ethernet, IB, and proprietary). Additionally, he has been a key contributor for the channel sections IEEE802.3 backplane and cabling standards, and for the time domain ISI and return loss standards for IEEE802.3 Ethernet, known as COM (Channel Operating Margin) and ERL (Effective Return Loss), which are now an integral part of Ethernet standards due to Rich's leadership. He founded and chaired an IPC (Association Connecting Electronics Industries) committee delivering IPC's first PCB loss test method. Prior to this, Rich led industry efforts at IPC to deliver the first TDR (ti-me domain reflectometry) standard, which is presently used throughout the PCB industry. Richard holds many patents in interconnect, signal integrity, design, and test. He has delivered numerous signal integrity papers at electronic industry design conferences.

**Adam Gregory** is a Signal Integrity Engineer at Samtec. He is involved in modeling and analysis of high-speed differential signaling channels. He received a BSEE and MSEE at the University of South Carolina.

**Beomtaek Lee** joined Intel in 1997. He is currently a senior principal engineer in Data Center Group (DCG). He worked on power delivery and EMC design for Pentium®II, Pentium®III and Pentium®4, front side bus (FSB) development for Itanium®2 and Xeon® processors, external memory interface (XMI), Scalable Memory Interconnect (SMI) and Intel® QuickPath Interconnect (QPI) developments for Intel datacenter platforms. He has been working on PCI Express, Intel® Ultra Path Interconnect (UPI), Ethernet, Intel® Omni-Path Fabric Interconnect and Optical interconnect developments for Intel datacenter platforms. He received his Ph.D. in electrical engineering from The University of Texas at Austin in 1996.

**Steve Krooswyk** is an SI design and standards engineer at Samtec. Steve's 19 years of signal integrity experience includes a focus on PCIe interconnect including contributions to PCI-SIG, working as PCIe SI Tech Lead for Intel data center, co-authoring the book High Speed Digital Design: Design of High Speed Interconnects and Signaling, and a MSEE from the University of South Carolina.

**Amit Kumar** is a Director of Engineering at Achronix Semiconductors Corporation. His responsibilities include signal integrity of package and board and handling customer board recommendations. He received his Bachelor of technology degree in Electronics and Communication Engineering from Vellore Institute of Technology, Vellore.

**Howard Heck is** presently a signal integrity engineer in Intel's Datacenter and AI Group. Howard focuses on development of 100G+ specifications and solutions for Ethernet systems. Prior to moving to Datacenters, he worked on development of specifications and product solutions for Universal Serial Bus 3.0/3.1/3.2, spanning from initial spec development to post silicon validation. He co-authored "Advanced Signal Integrity for High-Speed Digital Designs", a graduate-level textbook on signal integrity, and from 1998 through 2009 taught signal integrity at the Oregon Graduate Institute. He is the chair for the IEEE Oregon joint CPMTCAS chapter. He has 43 patents with several pending

## Background

The performance of high-speed SerDes (25Gbps+) is becoming increasingly challenging. The demand for high bandwidth in the field of data centers to telecommunications and beyond calls out for an increase in data rate with every generation, which in turn is leading to a decrease in the unit interval of data transmission. Loss, reflections and crosstalk are factors known to impact the performance of the high-speed channel [1]. In addition, engineers have started to realize the impact of intra-pair skew, which refers to the variation in the arrival times of the single-end signals within a differential pair.

This paper addresses the challenges associated with understanding the impact of intra-pair skew and correlating intra-pair with the performance of high-speed SerDes channels. Some common sources of skew are asymmetrical structures from manufacturing variations or unintentional return path asymmetry, glass weave, and trace length mismatch [2]. Accurate measurement and quantification of intra-pair skew are vital for engineers and designers to ensure that high-speed SerDes channels operate optimally.

This paper shows the impact of intra-pair skew on differential loss, mode conversion and differential far-end crosstalk. The impact of intra-pair skew on differential loss and mode conversion has been well documented in the industry. By shielding light on these secondary effects, the paper broadens the perspective on the impact of intra-pair skew and its need to ensure intra-pair skew as we begin approaching 200Gbps Ethernet where the unit interval is around 10 psec.

This paper categorizes the various methods for extracting intra-pair skew from measured or simulated data. These methods differ in their approach whether it is in the time or frequency domain and operation whether it is limit-line based or single value based. By providing a comprehensive overview of the different methods, the paper strives to facilitate a deeper understanding of how intra-pair skew can be precisely characterized.

To validate the effectiveness of the various intra-pair skew metrics, the paper demonstrates the correlation between these metrics and measured or simulated S-parameters for the same component and channel. By contrasting these metrics across channel topologies and data rates, the paper underscores their practicality and applicability. This empirical evidence showcases the importance of limiting intra-pair skew at higher data rates.

In conclusion, this paper addresses the challenges associated with establishing the performance of high-speed SerDes channel with the impact of intra-pair skew. It categorizes intra-pair skew characterization methods, highlights secondary effects such as differential loss, mode conversion and differential far-end crosstalk due to intra-pair skew. These findings contribute valuable insights on the need to limit intra-pair skew at higher data rates, enabling engineers and designers to make informed decisions that enhance the performance of high-speed SerDes channels and ensure the reliability of data transmission in the digital age.

# I. Problem statement

At high data rates (25Gbps+), intra-pair skew has evolved into a highly intricate and pressing challenge. It revolves around the temporal disparities in the arrival times of signals within a differential pair. Its impact is not confined to mode conversion alone but to noise due to mode conversion and crosstalk. The complexity of intra-pair skew arises from several interrelated factors.

First and foremost, the problem of intra-pair skew is compounded by the vast array of measurement techniques. These techniques exhibit variations in precision, complexity, and suitability for specific applications. As a result, individuals grappling with intra-pair skew often face the daunting task of selecting the most appropriate methods, without standardized benchmarks or clear guidance to aid their decision-making process. There exists a gap between theoretical knowledge and practical implementation of the different techniques when it comes to limiting the amount of intra-pair skew in each design.

Furthermore, intra-pair skew is not confined to its primary manifestation of temporal signal misalignment of the single ended signals in a differential pair. It is linked to secondary effects, notably crosstalk. Crosstalk refers to the unwanted interference between adjacent channels or wires, which can compromise the quality and reliability of data transmission. Neglecting these secondary effects would be akin to addressing the tip of the iceberg while disregarding the bulk of the issue, potentially leading to suboptimal solutions. A proper understanding of the impact of intra-pair skew will help drive the need to limit intra-pair skew at higher data rates.

In conclusion, the problem of intra-pair skew in high speed SerDes is intricate and multifaceted, encompassing challenges in measurement techniques, secondary effect, and practical implementation of solutions. This problem has profound implications for signal integrity, data accuracy, and the reliability of high-speed SerDes channels. The need for standardized practices and holistic strategies is underscored, emphasizing the urgency of mitigating the adverse effects of intra-pair skew to ensure the continued reliability and efficiency of data transmission systems in the data-centric world of today.

# II. Impact of Intra-pair Skew

When it comes to differential transmission, intra-pair skew plays a vital role in the channel performance, with it impacting the differential loss and differential far-end crosstalk [1]. Understanding how intra-pair skew amplifies the loss and crosstalk is critical when choosing to design channels operating at high data rates. It is important to consider the polarity of intra-pair skew when studying its impact on loss and crosstalk.

## A. Simulated Test Structure

A simulated differential microstrip structure designed for 85 Ohm impedance is used to investigate the impact of intra-pair skew on insertion loss, mode conversion, and far-end crosstalk in this study. These lines have a trace width of 4 mils, a trace spacing of 7.407 mils, and a pair-to-pair spacing of 10 mils. Figure 1 shows the test structure consisting of two differential pairs. The intra-pair skew is varied for -0.5 UI: +0.05 UI: +0.5 UI by varying the number of wiggles in targeting 106.25 Gbps PAM4 signaling with a unit interval (UI) of 18.82 psec.

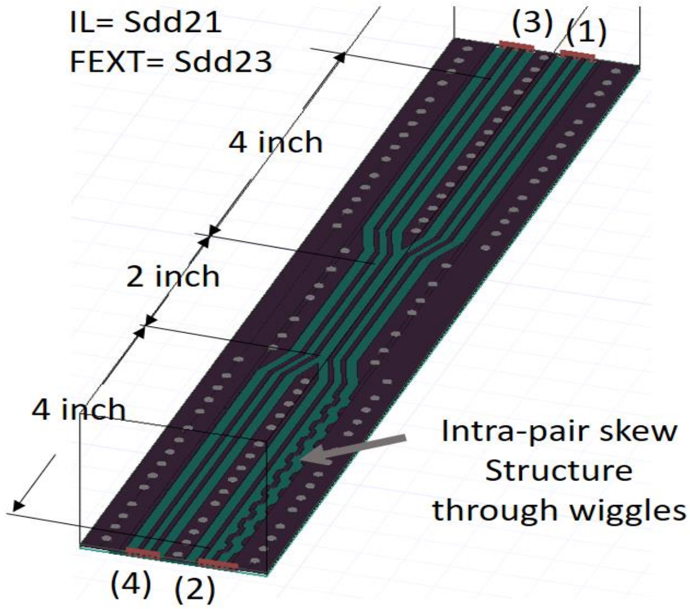



**Figure 1. Simulated test structure consisting of two differential pairs.**

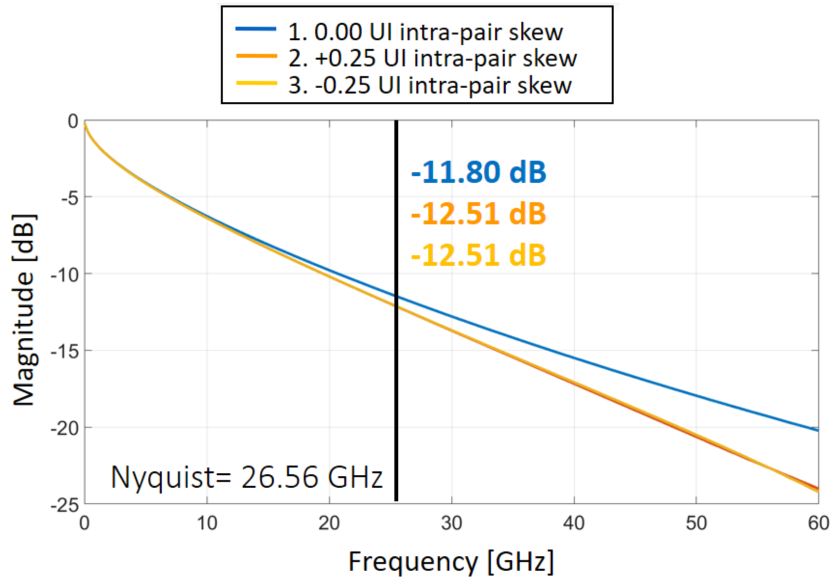
## B. Impact of Intra-pair Skew on the Differential Loss and Far-end Crosstalk

Differential mode S-parameters are used to capture the differential insertion loss and far - end crosstalk through the terms of Sdd21 and Sdd23 respectively. Figure 2 shows the impact of intra-pair skew on the differential loss and far-end crosstalk. The influence of positive and negative polarity of intra-pair skew at 0.25 UI is demonstrated in comparison to the ideal scenario of 0.00 UI intra-pair skew.

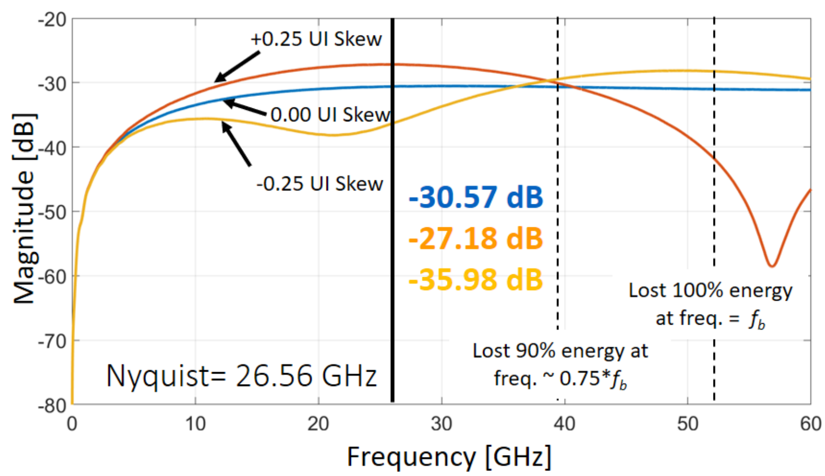
Differential insertion loss and intra-pair skew share a cosine relationship as shown in (1) and hence the polarity of intra-pair skew does not matter [1]. Differential insertion loss deteriorates as the magnitude of intra-pair skew increases, primarily because power is converted from the differential mode to the common mode through the process of mode conversion.

$$Sdd21_{\text{with intra-pair skew}} = Sdd21_{\text{without intra-pair skew}}.\cos(\pi.f.skew(f)).e^{-\pi.f.skew(f)} \quad (1)$$

Results of the differential far-end crosstalk show that the impact of intra-pair skew may be constructive or destructive depending on the polarity of intra-pair skew. This may be explained by the fact that intra-pair skew leads to further propagation time difference of the signals within a differential pair. Figure 3 shows the step response of the two single-ended signals propagating along the differential pair along with the different far-end crosstalk. The single-ended signals are captured at the port (2) by placing a differential source at port (1). One can observe that the misalignment of the single-ended response (P and N leg), depending on the polarity of intra-pair skew, can either positively or negatively affect the differential crosstalk (P-N).

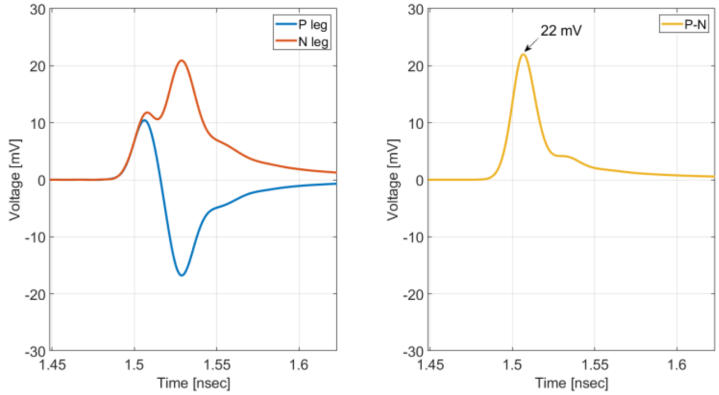



A) Differential Insertion Loss

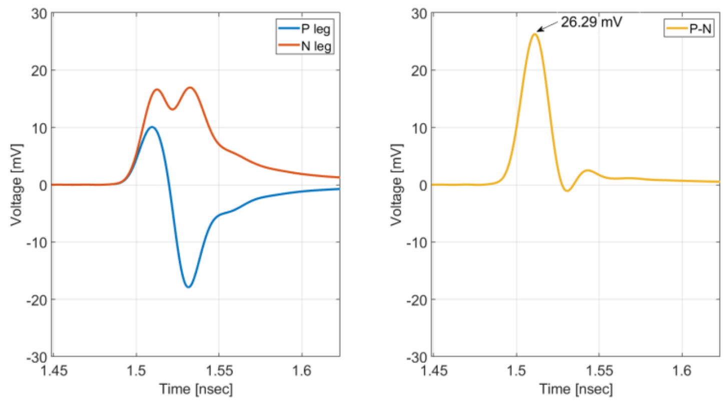



B) Differential Far-end Crosstalk

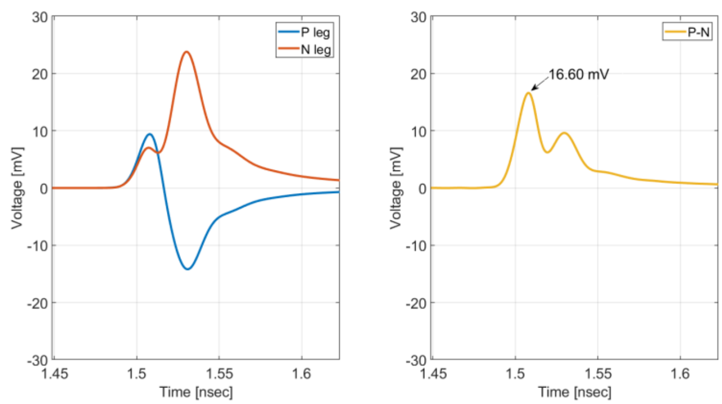
**Figure 2. Impact of intra-pair skew on A) differential loss and B) far-end crosstalk.**




a) 0.00 UI intra-pair skew.




b) +0.25 UI intra-pair skew.




c) -0.25 UI intra-pair skew

**Figure 3. Step response of single-ended (P and N leg) and differential far-end (P-N).**

## C. Impact of the Polarity of Intra-pair Skew

In this section, the impact of the polarity of intra-pair skew is studied through channel margining. Existing research has primarily focused on the magnitude of intra-pair skew in high-speed communication channels, recognizing its significant influence on signal integrity. However, limited attention has been given to the polarity aspect of skew within differential pairs. The polarity of intra-pair skew, whether positive or negative, can lead to variations in how signals interact, impacting parameters like crosstalk. It is worth noting that the polarity of intra-pair skew depends on the location of the victim pair relative to the aggressor pair.

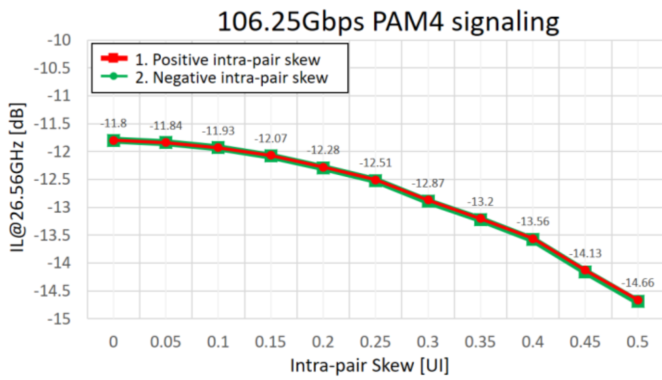



**Figure 4. Impact of the polarity of intra-pair skew on differential loss.**

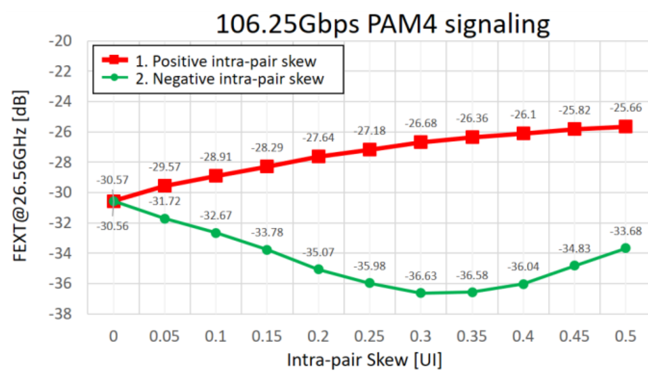



**Figure 5. Impact of the polarity of intra-pair skew on differential far-end crosstalk.**

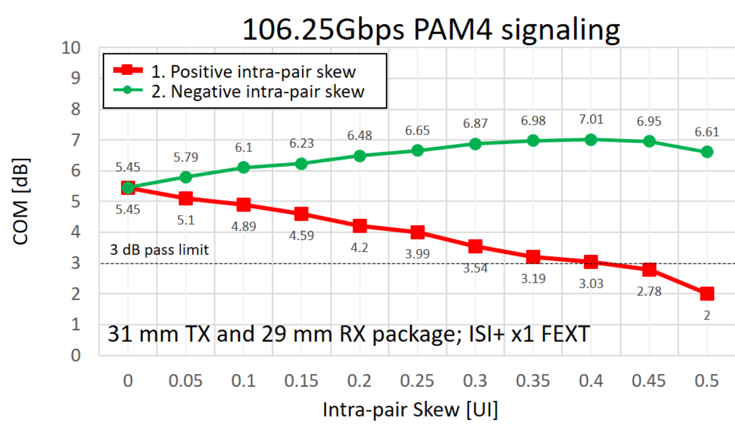
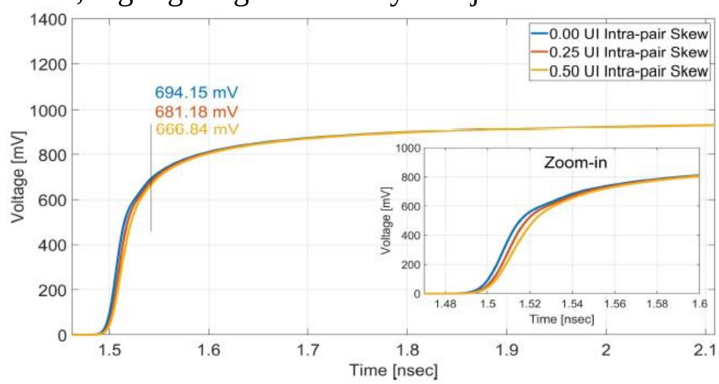



**Figure 6. Impact of the polarity of intra-pair skew on Channel Operating Margin.**

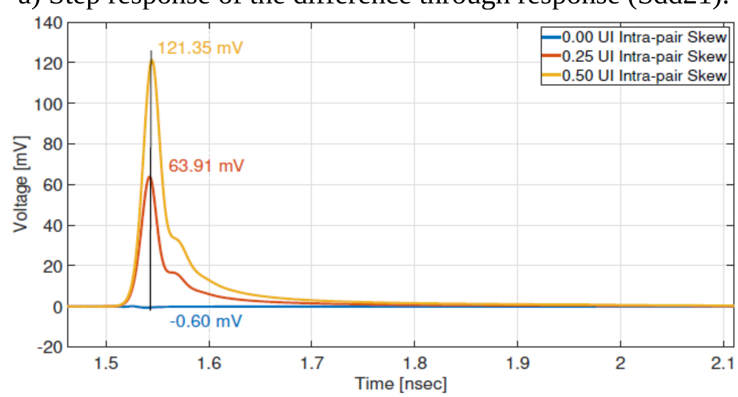
In the conducted test, a range of intra-pair skew values was explored to investigate its impact on the test structure's performance. The skew was varied within the range of -0.50 UI to +0.50 UI, representing a broad spectrum of skew scenarios that can be encountered in practical high-speed communication channels. The results of this investigation were visually represented in Figure 4, 5 and 6, which provides a graphical overview of how the different skew values affect three key parameters: differential loss, differential far-end crosstalk and Channel Operating Margin. The influence of intra-pair skew on signal margin is contingent upon the skew's polarity, which can yield either constructive or destructive outcomes. Consequently, it underscores the significance of minimizing intra-pair skew throughout the entire channel to ensure optimal performance and signal integrity.

## D. Transmitter Common-mode to receiver differential-mode conversion- SDC21

The noise due to mode conversion is a well-known artifact of intra-pair skew in a different channel, where the signal originally transmitted in the differential mode undergoes a transformation, being converted into the common mode, and consequently manifests as undesired noise in the communication channel [3]. Receiver equalization techniques are designed to effectively compensate for the loss incurred in the differential signal. In this context, many receivers specify a Common-Mode Rejection Ratio (CMRR) as an important metric, highlighting their ability to reject common-mode noise [4].




a) Step response of the difference through response (Sdd21).




b) Step response of the mode conversion (Sdc21).

**Figure 7. Step response of the differential signal and noise due to mode conversion.**

In Figure 7, the step response of the differential signal (Sdd21) and mode conversion (Sdc21) for intra-pair skew values of 0.00, 0.25 and 0.50 UI. The noteworthy aspect highlighted in this figure is the presence of a considerable voltage component within the differential noise stemming from common-mode to differential-mode conversion (Sdc21). This observation underscores the significance of understanding and addressing this mode conversion effect in practical applications. It serves as a reminder that the voltage component of Sdc21 should not be underestimated or overlooked, as it can have a substantial impact on signal integrity and the overall performance of the communication channel.

## II. Intra-Pair Skew Metrics

In high-speed data transmission and communication systems, engineers employ sophisticated methodologies that delve into the temporal and spectral aspects of signal behavior to accurately assess signal integrity and synchronization. Two fundamental approaches, namely the time domain and frequency domain analysis, play a pivotal role in quantifying intra-pair skew.

The time domain analysis offers insights into the precise time alignment of signals, ensuring synchronous propagation and minimizing distortion. On the other hand, the frequency domain analysis delves into the spectral characteristics of signals, shedding insight into how the signal pairs convert between differential and common mode components across a range of frequencies. The various metrics for intra-pair skew encompass threshold-based single-ended step response skew, statistical common-mode SNR, difference in phase delay vs. frequency, mode conversion vs. frequency, and effective intra-pair skew (EIPS). The different metrics provide a comprehensive toolkit for engineers to precisely quantify, analyze and optimize for intra-pair skew, thereby enhancing the overall performance of reliability of high-speed communication systems.

Now, let's assess a 200 Gb/s CR and KR channel data (TP0 to TP5) accessible through the IEEE 802.3dj public domain [5] for the different intra-pair skew metrics. The touchstone file used is KR_ch_3in_PCB_NPC_150mm_29AWG_BP_800mm_27AWG_NPC_150mm_29AWG_thru.s4p, which is uploaded by Arista Networks. The backplane channel is shown in Figure 8 [5].

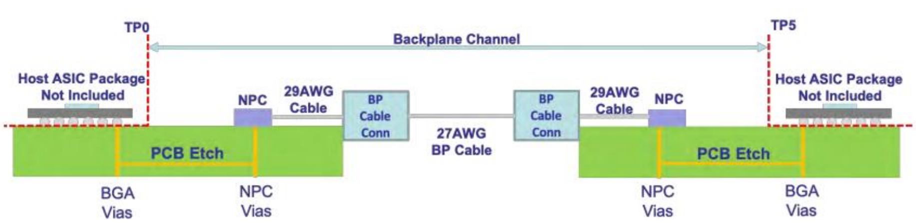
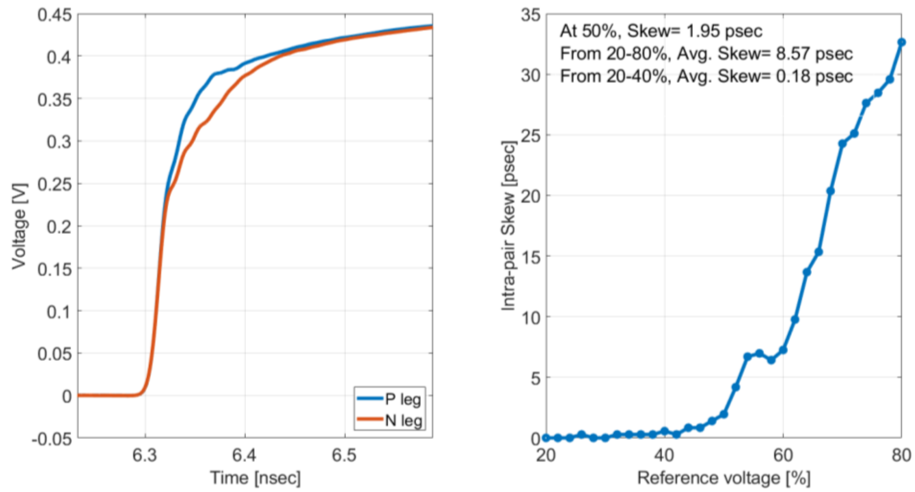



**Figure 8. Channel topology (https://www.ieee802.org/3/dj/public/23_05/weaver_3dj_01_2305.pdf).**

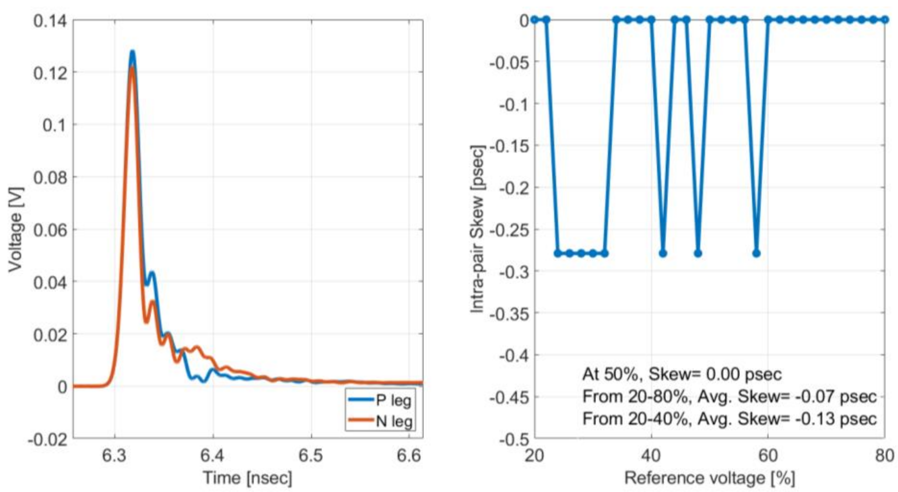
## A. Threshold based single-ended Step or Pulse Response Skew

This metric involves evaluating the timing disparities between signals by setting predetermined threshold levels within a step response waveform. By observing the instances at which the signal crosses these thresholds, engineers can gain insights into the temporal alignment and synchronization of signals within a differential pair. This analysis is particularly crucial for minimizing distortion and ensuring accurate data transmission, as it allows for the identification of any deviations in signal arrival times with a differential pair.

Intra-pair skew is the time of arrival error of a signal with respect to a reference time and voltage. It relies on the measurement of propagation delay for step or pulse response using a differential input to single ended output. The differential input helps eliminate common-mode noise, enhancing the accuracy of the measurement by focusing solely on the signal's propagation characteristics.




a) Step response based method.




b) Pulse response based method.

**Figure 9. Application of threshold based single-ended a) step and b) pulse response skew method.**

Figure 9 illustrates the results obtained when measuring skew by capturing two single-ended step and pulse responses at the receiver while employing a differential transmitter. The magnitude of intra-pair skew is found to be influenced by the reference voltage and can exhibit substantial variation. Typically, practitioners choose to determine the threshold voltage either at the fifty-percent point or by calculating the average of the intra-pair skew. It is essential to highlight that, in comparison to the pulse response-based method, the approach relying on the step response tends to exhibit greater skew values when the threshold voltage surpasses fifty percent. This phenomenon may be attributed to reflections occurring within the channel.

## B. Difference in Phase Delay versus Frequency

This method involves evaluating the timing disparities between signals through the variation in phase delay with respect to frequency. Analyzing the modulation of phase delay across diverse frequencies provides engineers with insights into the degree of skew existing within the signal pairs. In differential signal pairs, discrepancies, or imbalances in the electrical attributes of transmission media or circuitry can induce variations in signal propagation times. Such deviations become accentuated at higher frequencies due to the amplifying influence of parasitic effects, impedance mismatches, and other non-ideal behaviors.

A minimal difference in phase delay across frequencies indicates scant intra-pair skew, implying consistent timing for the signal pair regardless of frequency fluctuations. Conversely, a substantial rise in phase delay discrepancy with frequency signifies a more severe skew predicament demanding intervention.

Following are the steps to calculate the intra-pair skew.

Figure 10 illustrates the S-parameter network, encompassing both single-ended ports (Port 1, 2, 3, and 4) and differential ports (Differential Port 1 and 2). Within the differential pair, two types of parameters are noteworthy: the through terms (S21 and S43) and the coupling terms (S23 and S41). When assessing the difference in the propagation delay corresponding to intra-pair skew, it is crucial to employ the differential-to-single-ended S-parameters, which is derived using the Modified Mixed-Mode S-parameters [6]. This necessity arises due to the inherent coupling within the differential pair, which can significantly impact cause signal distortion.

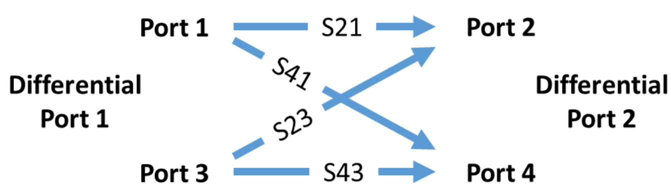



**Figure 10. S-parameter Network.**

Step 1. Calculate the differential to single-ended S-parameter.

S2d1= (1/√2).(S21- S23)
S4d1= (1/√2).(S43- S41)

Step 2. Calculate the skew using the difference in phase delay.
Skew(f)= -unwrap(phase(S2d1))/(ω)+ unwrap(phase(S4d1))/(ω)

Where,
ω is the angular frequency [radian], which is two pi times the frequency.

Figure 11 illustrates the results obtained when measuring skew by capturing the phase delay versus frequency of the two single-ended signals at the receiver using a differential transmitter. The magnitude of intra-pair skew is found to be influenced by the frequency and can exhibit substantial variation. Typically, practitioners choose to determine the intra-pair skew at the Nyquist frequency or by calculating the average of the intra-pair skew.

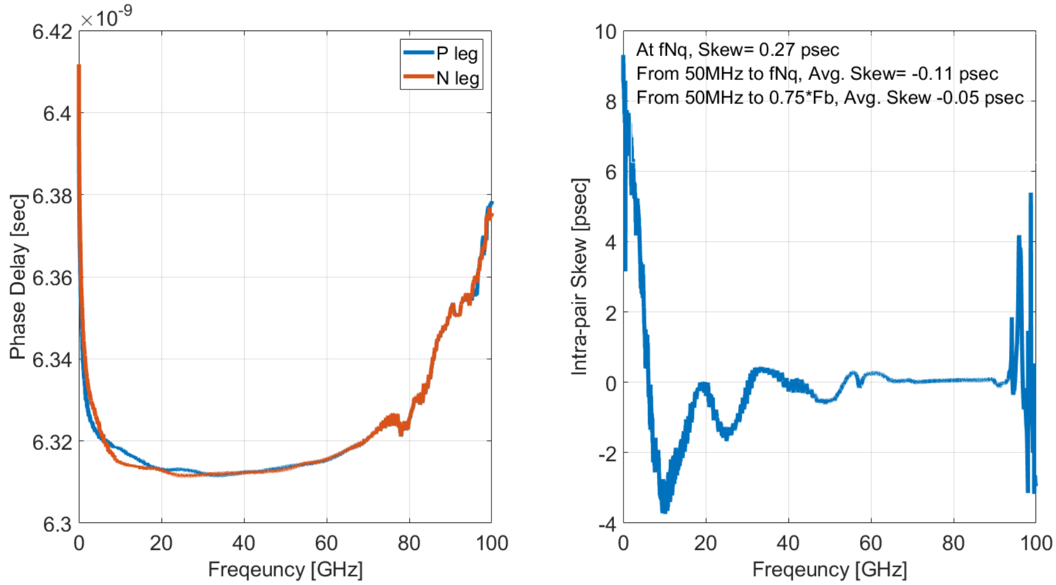



**Figure 11. Application of difference in phase delay versus frequency method.**

## C. Mode conversion versus Frequency

This method involves evaluating the mode conversion as a function of frequency occurring between the differential and common modes in the context of differential transmission. Intra-pair skew introduces a potential for mode conversion, prompting shifts in the effective propagation velocities of signals and consequently introducing timing inconsistencies. As a result, the received signal is perceived by the receiver as distorted and enveloped in noise, complicating the accurate deciphering of the intended information.

The emergence of noise induced by mode conversion resulting from intra-pair skew is particularly conspicuous in scenarios involving differential signal pairs. The transition between differential and common modes amplifies temporal discrepancies, further compromising the quality of the signal.

Figure 12 displays the outcomes of capturing the mode conversion versus frequency. The use of limit line for mode conversion helps to limit the allowable amount of intra-pair skew.

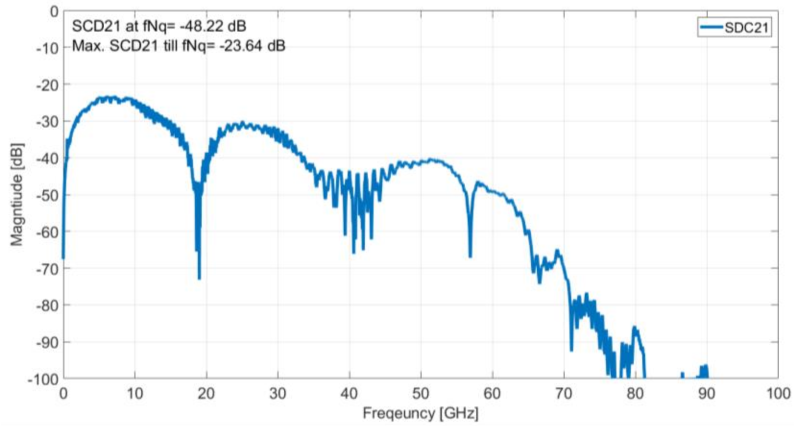



**Figure 12. Application of mode conversion versus frequency method.**

## D. Effective Intra-pair Skew (EIPS)

This method involves the use of a weighting function to integrate the intra-pair skew calculated using the difference in phase delay versus frequency [8]. It involves the use of a weighting function that combines the mode conversion delta caused by the skew and the power spectral density of a random bit stream in a normalized form. It is a single value metric used to evaluate the amount of intra-pair skew.

Following are the steps to calculate the intra-pair skew.

Figure 13 illustrates the S-parameter network, encompassing both single-ended ports (Port 1, 2, 3, and 4) and differential ports (Differential Port 1 and 2). Within the differential pair, two types of parameters are noteworthy: the through terms (S21 and S43) and the coupling terms (S23 and S41). When assessing the difference in the propagation delay corresponding to intra-pair skew, it is crucial to employ the differential-to-single-ended S-parameters, which is derived using the Modified Mixed-Mode S-parameters. This necessity arises due to the inherent coupling within the differential pair, which can significantly impact cause signal distortion.

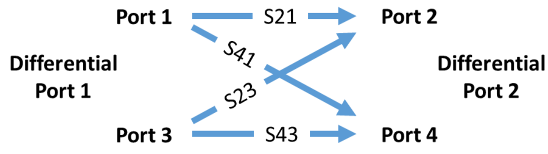



**Figure 13. S-parameter Network.**

Step 1. Calculate the differential to single-ended S-parameter.

$Sse2d1= 1/\sqrt{2}.(S21- S23)$

$Sse4d1= 1/\sqrt{2}.(S43- S41)$

Step 2. Calculate the skew using the difference in phase delay.

Skew(f)= -unwrap(phase(Sse2d1))/(2πf)+ unwrap(phase(Sse4d1))/(2πf)

Step 3. Calculate the weighting function.

$$W(f)= \frac{|db(SCD21_{average\ skew})-db(SCD21_{zero\ skew})|.PSD}{\int_{fmin}^{fmax}|db(SCD21_{average\ skew})-db(SCD21_{zero\ skew})|.PSD.df}$$

Where,

Mean average absolute skew, $Skew_{average}$= mean(|Skew(f)|)…fmin≤ f≤ fmax

Mode conversion corresponding to zero intra-pair skew, $|Scd21_{zero\ skew}|$= 0.5*(S21- S23+ S41.exp(j2πf.Skew(f))- S43.exp(j2πf.Skew(f)))

Mode conversion corresponding to average absolute skew, $|Scd21_{average\ skew}|$= 0.5*(S21- S23+ S41.exp(j2πf.(Skew(f)- $Skew_{average}$)- S43.exp(j2πf.(Skew(f)- $Skew_{average}$))

Power spectral density, PSD= $sinc\left(\frac{f}{f_b}\right)^2.\frac{1}{1+(f/f_t)^4}.\frac{1}{1+(f/f_r)^8}$

$f_b$ is the signaling rate.

$f_t$ is the 3 dB transmit filter bandwidth, which is inversely proportional to the 20% to 80% rise and fall time ($T_t$) given by the constant of proportionality using 0.2365= $T_t f_t$.

$f_r$ is the 3 dB reference receiver bandwidth.

Figure 14 illustrates the use of mode conversion, mode conversion with zero skew and mode conversion with absolute average skew along with the weighting function in the calculation of EIPS. It is important to note that the weighting function utilizes decibel difference between mode conversion corresponding to zero skew and average absolute skew, this is an mathematical approach at coming up with a reasonable weighting function such as to put emphasis on the right frequency band.

The calculated EIPS is 0.25 psec.

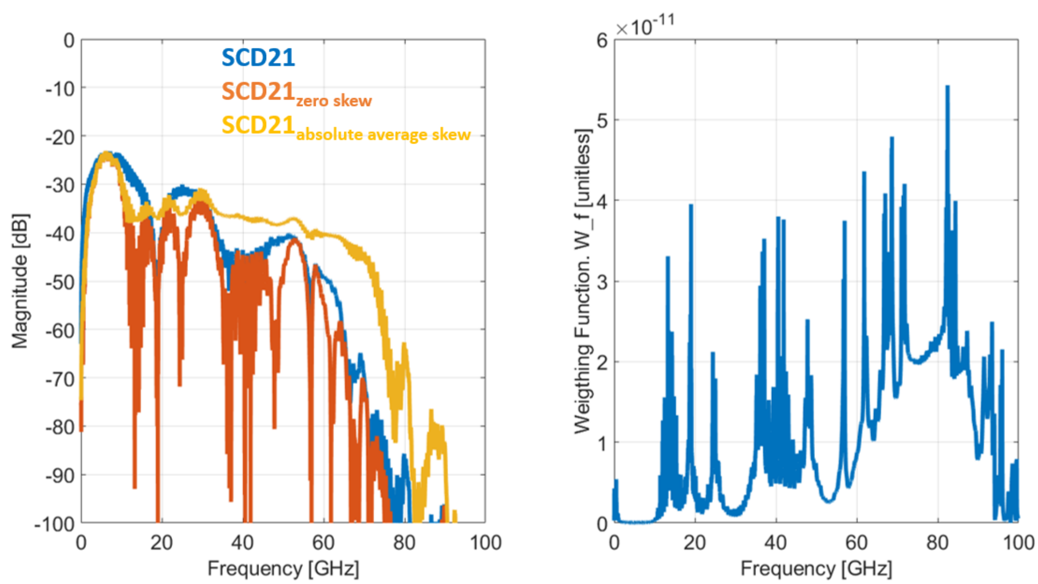



**Figure 14. Mode conversion and weighting function used in the calculation of EIPS.**

## E. Signal to AC common-mode noise ratio (SCMR)

This method involves quantifying the ratio between the desired signal and common mode noise that may be present in the channel [7]. It tells how much stronger or weaker the desired differential signal is compared to the interfering common-mode noise. A high SCMR whose value is in decibel means that the channel is doing a good job of rejecting the common-mode noise.

SCMR for differential signals can be defined as

$$SCMR= 10*\log_{10}(Pmax^2/ Vcm^2)$$

Where,

SCMR is the signal to AC common-mode ration in dB.
Pmax is the maximum value of the differential-mode through response (SDD21).
Vcm is the AC common mode voltage due to mode conversion (SDC21).

The AC common mode voltage can be taken as a value by solving for the cumulative distribution function of Vcm at a specified detector error rate by assuming a gaussian signature.

Figure 15 shows the plot of the pulse response, probability distribution function and cumulative distribution function utilized in calculating SCMR. It is observed that the probability distribution function for the common-mode voltage due to mode conversion (SDC21) has a gaussian nature. The peak-to-peak voltage due to the common-mode voltage due to mode conversion is around 10mV, which is a significant amount of noise for the given differential signal with a peak voltage of around 100 mV.

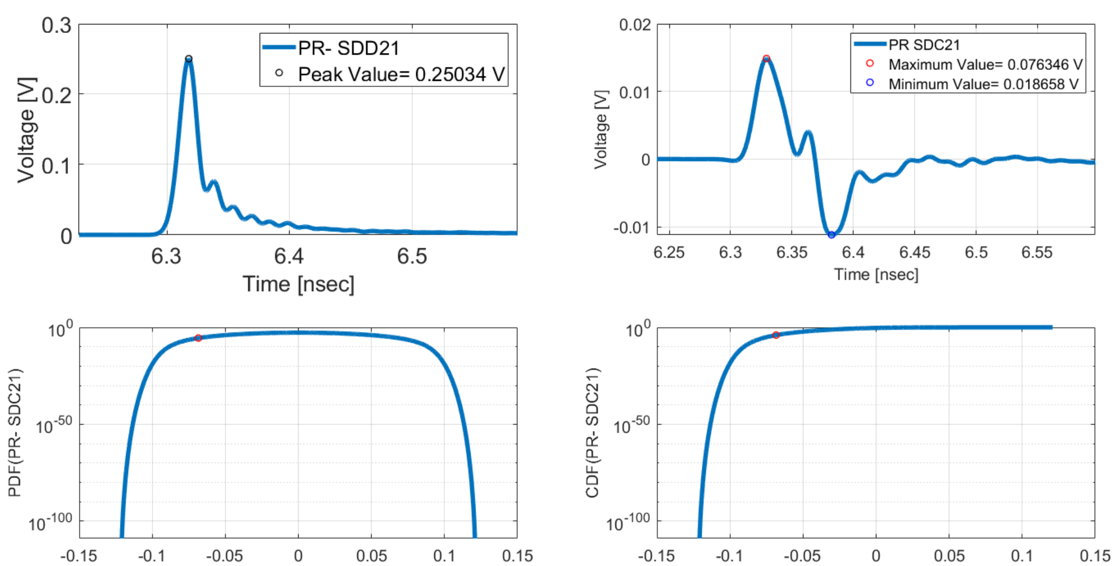



**Figure 15. Evaluation of the pulse response, probability distribution function and cumulative e distribution function.**

The value of SCMR is 11.5632 dB.

## F. Intra-pair Skew based on the minimum SCMR

This method is used to assess and measure the skew or time delay between the signals in a differential pair. The measurement is based on the minimum SCMR, that evaluates the quality of a signal by determining the ration of the desired signal to common-mode noise. By using the minimum SCMR as the foundation for assessing intra-pair skew, engineers can effectively identify and address any timing discrepancies that exist within the differential pair. In other words, it helps to determine how much common-mode noise is affecting the signal of interest, and this information is crucial for optimizing signal quality.

The approach taken to address intra-pair skew and monitor SCMR involves manipulating intra-pair skew through the use of single-ended S-parameter cascading. This technique provides engineers with precise control over the timing discrepancies within the differential pair, all while closely monitoring the SCMR. In essence, this entails modifying the timing relationships between signals to evaluate their influence on common-mode noise and, subsequently, the SCMR.

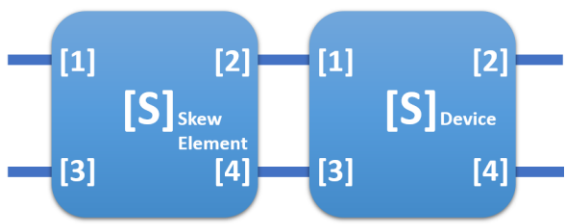



**Figure 16. Manipulating the intra-pair skew of a differential pair through S-parameter cascading.**

Illustrated in Figure 16 is the process of manipulating the intra-pair skew within a differential pair through S-parameter cascading. This method thoughtfully integrates a network designed to model and introduce skew into one of the signals within the pair. The introduction of intra-pair skew is achieved through the application of Euler's formula. The S-parameter of the skew element for the through being 1,2 and 3,4 is given by the following.

$$\begin{bmatrix} 0 & e^{j.\omega.Skew} & 0 & 0 \\ e^{j.\omega.Skew} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Where,

$\omega$ is the angular frequency [radian], which is two pi times the frequency.
Skew is the modified intra-pair skew [second].

The mixed-mode S-parameters of the cascaded four-port network with modified intra-pair skew is the following.

$$Sdd11 = 0.5 * \left(S11 - S31.e^{j.\omega.Skew} - S13 + S33.e^{j.\omega.Skew}\right)$$
$$Sdd12 = (1/2).\left(S12 - S32.e^{j.\omega.Skew} - S14 + S34.e^{j.\omega.Skew}\right)$$
$$Sdd21 = (1/2).\left(S21 - S41.e^{j.\omega.Skew} - S23 + S43.e^{j.\omega.Skew}\right)$$

$$Sdd22 = (1/2).\left(S22 - S42.\,e^{j.\omega.Skew} - S24 + S44.\,e^{j.\omega.Skew}\right)$$

$$Sdc11 = (1/2).\left(S11 - S31.\,e^{j.\omega.Skew} + S13 - S33.\,e^{j.\omega.Skew}\right)$$
$$Sdc12 = (1/2).\left(S12 - S32.\,e^{j.\omega.Skew} + S14 - S34.\,e^{j.\omega.Skew}\right)$$
$$Sdc21 = (1/2).\left(S21 - S41.\,e^{j.\omega.Skew} + S23 - S43.\,e^{j.\omega.Skew}\right)$$
$$Sdc22 = (1/2).\left(S22 - S42.\,e^{j.\omega.Skew} + S24 - S44.\,e^{j.\omega.Skew}\right)$$

$$Scd11 = (1/2).\left(S11 + S31.\,e^{j.\omega.Skew} - S13 - S33.\,e^{j.\omega.Skew}\right)$$
$$Scd12 = (1/2).\left(S12 + S32.\,e^{j.\omega.Skew} - S14 - S34.\,e^{j.\omega.Skew}\right)$$
$$Scd21 = (1/2).\left(S21 + S41.\,e^{j.\omega.Skew} - S23 - S43.\,e^{j.\omega.Skew}\right)$$
$$Scd22 = (1/2).\left(S22 + S42.\,e^{j.\omega.Skew} - S24 - S44.\,e^{j.\omega.Skew}\right)$$

$$Scc11 = (1/2).\left(S11 + S31.\,e^{j.\omega.Skew} + S13 + S33.\,e^{j.\omega.Skew}\right)$$
$$Scc12 = (1/2).\left(S12 + S32.\,e^{j.\omega.Skew} + S14 + S34.\,e^{j.\omega.Skew}\right)$$
$$Scc21 = (1/2).\left(S21 + S41.\,e^{j.\omega.Skew} + S23 + S43.\,e^{j.\omega.Skew}\right)$$
$$Scc22 = (1/2).\left(S22 + S42.\,e^{j.\omega.Skew} + S24 + S44.\,e^{j.\omega.Skew}\right)$$

The modified mixed-mode S-parameters of the cascaded four-port network with modified intra-pair skew is the following.

$$S1d1 = \left(1/\sqrt{2}\right).\left(S11 - S31.\,e^{j.\omega.Skew}\right)$$
$$S2d1 = \left(1/\sqrt{2}\right).\left(S21 - S41.\,e^{j.\omega.Skew}\right)$$
$$S3d1 = \left(1/\sqrt{2}\right).\left(S13 - S33.\,e^{j.\omega.Skew}\right)$$
$$S4d1 = \left(1/\sqrt{2}\right).\left(S23 - S43.\,e^{j.\omega.Skew}\right)$$

$$S1d2 = \left(1/\sqrt{2}\right).\left(S12 - S32.\,e^{j.\omega.Skew}\right)$$
$$S2d2 = \left(1/\sqrt{2}\right).\left(S22 - S42.\,e^{j.\omega.Skew}\right)$$
$$S3d2 = \left(1/\sqrt{2}\right).\left(S14 - S34.\,e^{j.\omega.Skew}\right)$$
$$S4d2 = \left(1/\sqrt{2}\right).\left(S24 - S44.\,e^{j.\omega.Skew}\right)$$

$$S1c1 = \left(1/\sqrt{2}\right).\left(S11 + S31.\,e^{j.\omega.Skew}\right)$$
$$S2c1 = \left(1/\sqrt{2}\right).\left(S21 + S41.\,e^{j.\omega.Skew}\right)$$
$$S3c1 = \left(1/\sqrt{2}\right).\left(S13 + S33.\,e^{j.\omega.Skew}\right)$$
$$S4c1 = \left(1/\sqrt{2}\right).\left(S23 + S43.\,e^{j.\omega.Skew}\right)$$

$$S1c2 = \left(1/\sqrt{2}\right).\left(S12 + S32.\,e^{j.\omega.Skew}\right)$$
$$S2c2 = \left(1/\sqrt{2}\right).\left(S22 + S42.\,e^{j.\omega.Skew}\right)$$
$$S3c2 = \left(1/\sqrt{2}\right).\left(S14 + S34.\,e^{j.\omega.Skew}\right)$$
$$S4c2 = \left(1/\sqrt{2}\right).\left(S24 + S24.\,e^{j.\omega.Skew}\right)$$

A noteworthy aspect of this method is its introduction of an innovative technique based on S-parameter cascading and mixed-mode conversion for evaluating the impact of skew on N-port networks in the case of differential signals. This novel approach offers a fresh perspective on the analysis of skew-induced effects and provides valuable insights into the behavior of high-speed SeDes channels, which are integral components of contemporary communication systems, especially those handling high-speed data transmission.

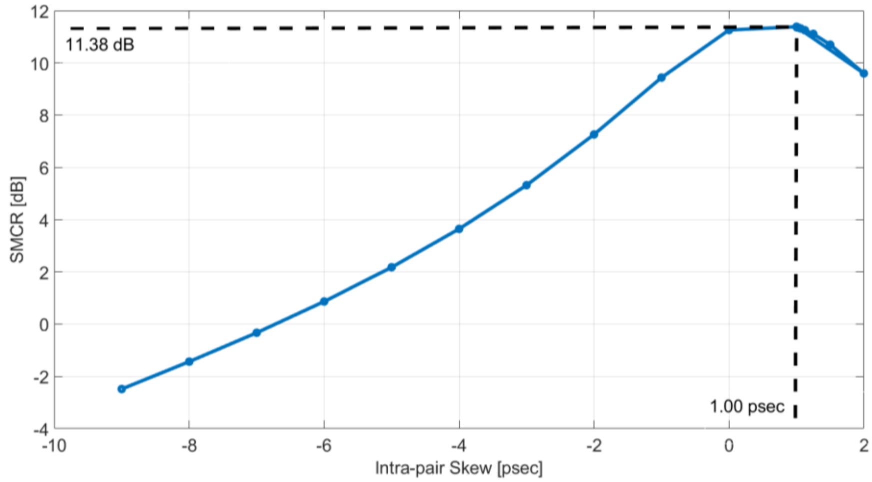



**Figure 17. Intra-pair skew versus SCMR.**

Figure 17 illustrates the variation in SCMR for values of intra-pair skew modified using the above method. The minimum SCMR represents cancellation of skew within the differential pair.

The intra-pair skew based on the minimum SCMR is 1.00 psec.

## III. Measurements

Intra-pair skew metrics are calculated on two different fixtures. First, a characterization board routes 52mm differential pairs at 100 Ohm between optimized RF 1.85mm test points. Test routing includes no skew, intentionally skewed, and intentionally skewed with compensation. Layout images are shown in figure 18.

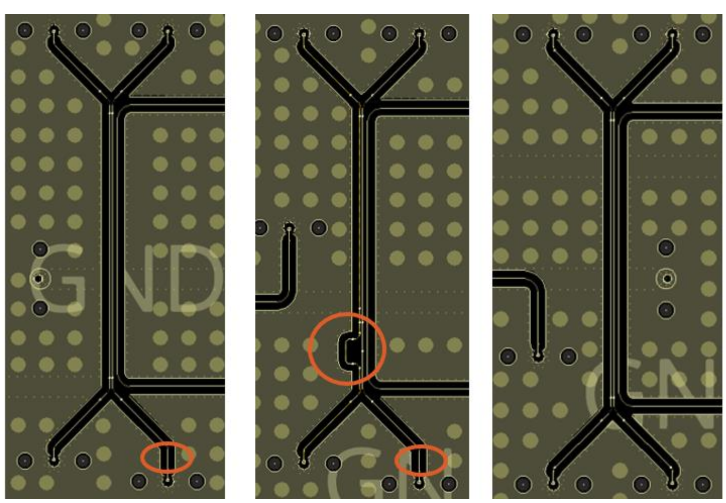


**Figure 18. Measured PCB:**
**Left: intentional skew, Center: intentional skew compensated, Right: no skew.**

Differential insertion loss and differential skew (differential excitation) measurements are shown in Figure 19. Two similar curves are observed for the no-skew and compensated structures. The insertion loss penalty for the uncompensated routing is easily observed in green.

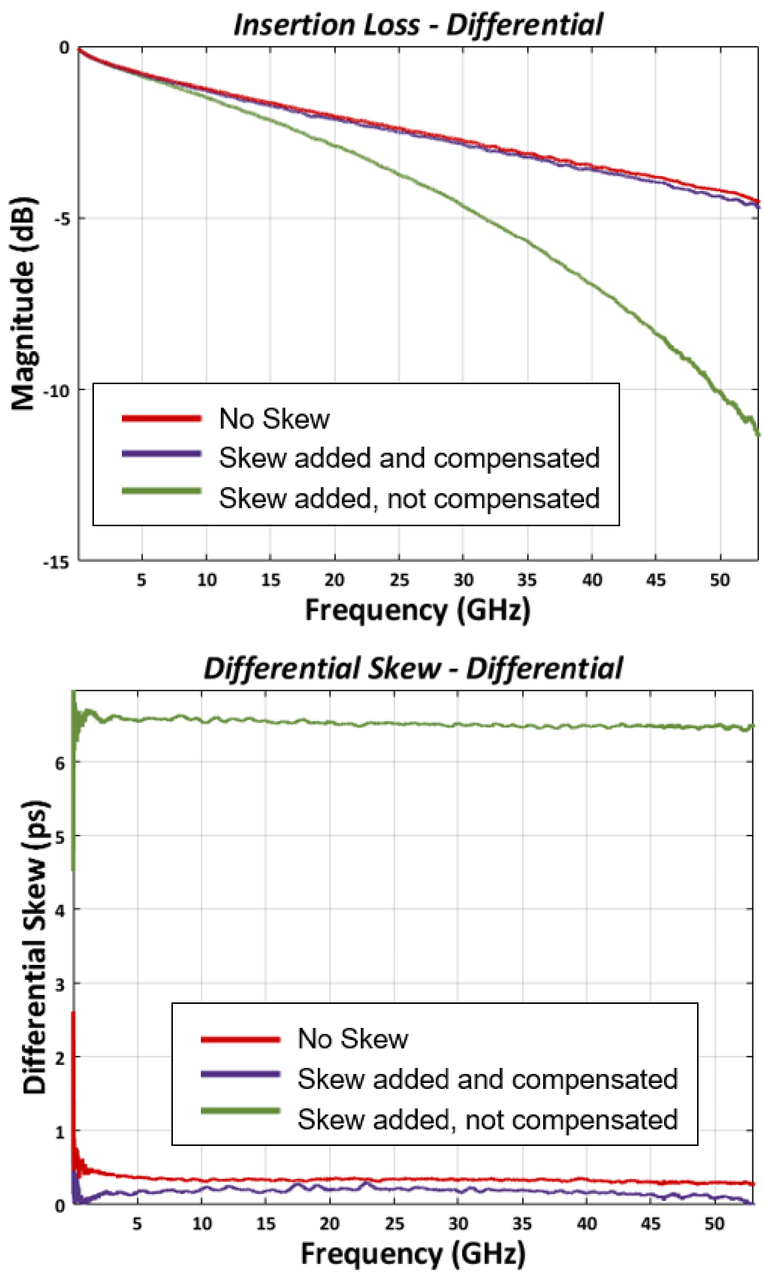



**Figure 19. Measured PCB for differential loss and skew.**

Second, a high density 224G-PAM4 cable assembly from Samtec is mated with a fixture PCB on each end. The PCB with 12mm and 25mm of routed length is phase matched and includes routing style to prevent fiber-weave skew effects. The high-speed twinax cable is specified to <= 1.75ps/m of intra-pair skew.

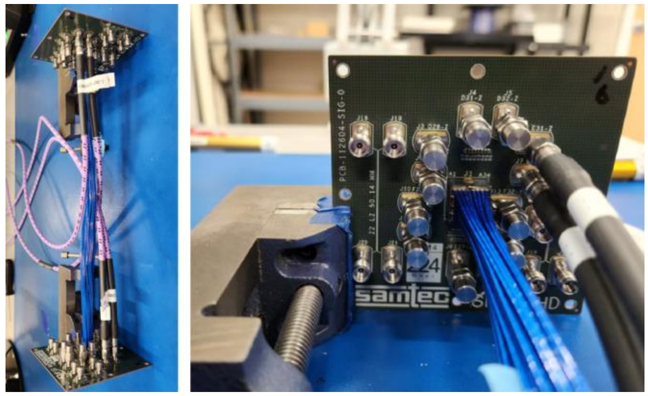


**Figure 20. Measured 300 mmm assembly of Samtec CPC 224G- PAM4 cable (Si-Fly HD).**

High speed cable measurements to 67 GHz are shown in the figure 20. The PCB fixture is included in the measurement (no de-embedding). Figure 21 shows the skew profile of the two lanes with unique skew behavior across frequency, which are selected.

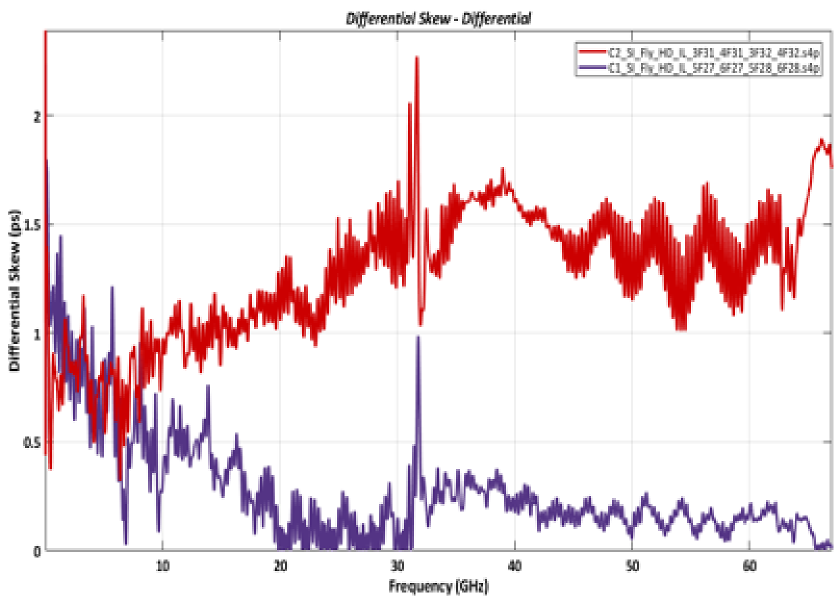
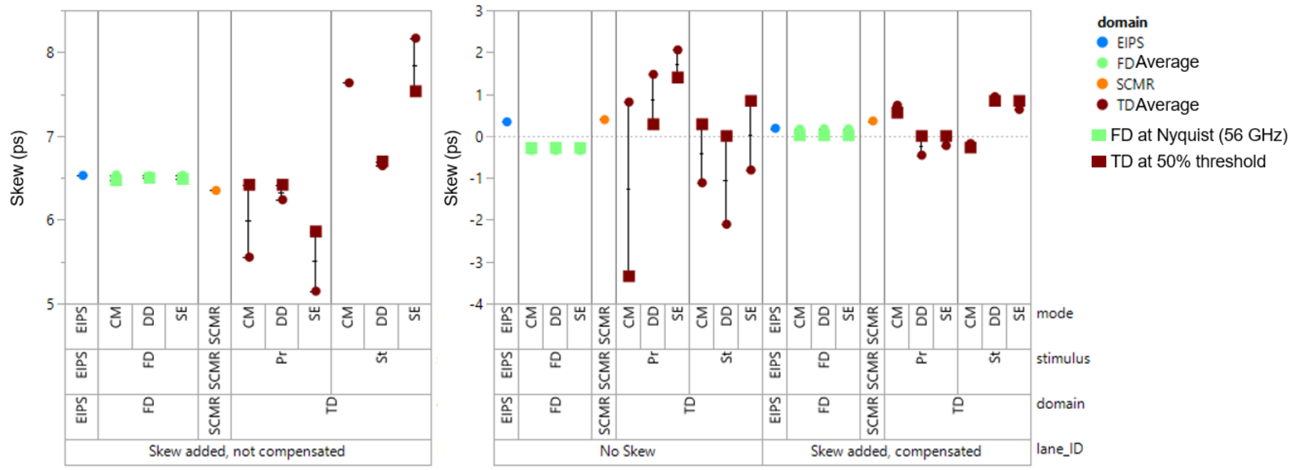



**Figure 21. Measured 300mm assembly for differential loss and skew.**

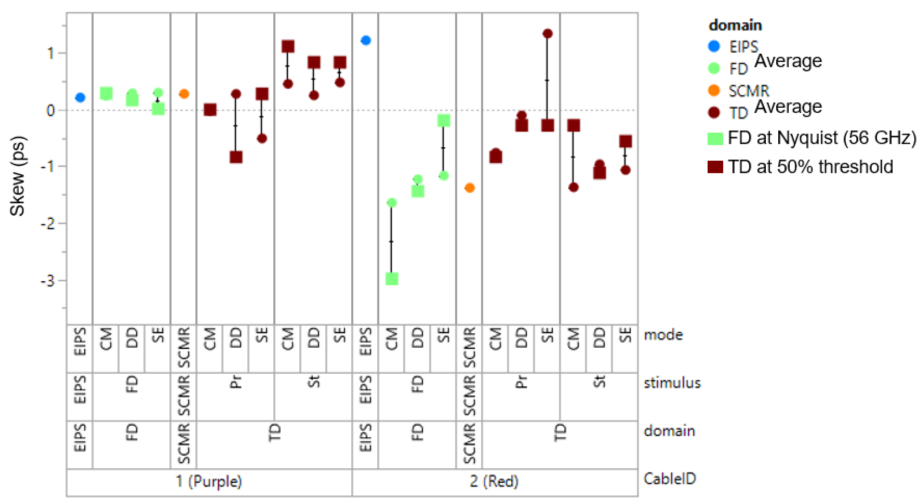
Time domain skew calculations include common methods that the authors of this paper have seen employed in practice. Although always measuring differentially, different stimulus may yield different outcome: without a differential excitation, modes between the differential pair are neglected. Further and as discussed earlier the selected threshold voltage for measurement introduces variation.

For both step response and pulse response inputs, skew will be calculated for differential, single ended, or common excitations. Results are reported for two thresholds: an average between 20-40% and exactly at 50%.

Frequency domain skew is also calculated with all three considered excitations: differential, single ended, or common. Results are reported as an average between 50MHz-56GHz, and the exact value at 56 GHz.




a) Measured PCB.




b) Measured 300mm assembly.

**Figure 22. Measured skew using the different methods.**

High consistency in figure 22 can be observed between the frequency domain measurements (any stimulus), EIPS, and SCMR methods. The use of average, or data point of Nyquist, has no effect as measured skew was flat across frequency.

Time domain methods show a higher degree of variation. Step and pulse response stimuli with differential stimulus were consistent for two of the three PCB traces. However, the no skew design experiences a large 3.5ps range in measured skew regardless of differential or other excitation.

EIPS and skew based on minimum SCMR calculated skew are consistent with frequency domain calculated values, varying < 0.5ps.

## IV. Skew as a Specification

In a differential channel, skew is intertwined with loss, reflections, and crosstalk, as evidenced in Section I. Alterations in the intra-pair skew of the channel will reflect in the metrics for loss, reflections, and crosstalk. This implies that the current limits for differential insertion loss, return loss, and crosstalk constrain the permissible amount of skew in a channel.

Table 1 displays variations across the channel metrics for intra-pair skew. Channel Operating Margin (COM), Vertical Eye Closure (VEC), and Vertical Eye Opening (VEO) are end-to-end channel metrics, whereas insertion loss fit, Effective Return Loss (ERL), and Figure of Merit FOM_ILD are metrics related to loss and reflections [7]. Additionally, ICN is a metric indicating crosstalk. The change in intra-pair skew can be tracked through the change in existing channel metrics of loss, reflections and crosstalk

**Table 1. Variation across the various channel metrics for intra-pair skew.**

| Skew based on min. SCMR [UI] | COM [dB] | VEC [dB] | VEO [dB] | Fitted IL at Nyquist [dB] | FOM ILD [dB] | ERL [dB] | ICN [mV] |
|---|---|---|---|---|---|---|---|
| 0.17 | 6.85 | 5.26 | 13.17 | 14.25 | 0.0857 | 14.39 | 3.08 |
| 0.29 | 6.79 | 5.31 | 12.63 | 14.75 | 0.1033 | 14.73 | 3.16 |
| 0.4 | 6.49 | 5.57 | 10.74 | 15.56 | 0.1380 | 14.27 | 3.20 |
| 0.53 | 5.97 | 6.07 | 9.23 | 16.89 | 0.1988 | 13.33 | 3.28 |
| 0.66 | 4.84 | 7.39 | 6.52 | 19.07 | 0.3023 | 11.96 | 3.30 |
| 0.75 | 3.94 | 8.75 | 4.60 | 20.76 | 0.3971 | 11.32 | 3.28 |
| 0.88 | 2.06 | 13.51 | 2.12 | 23.46 | 0.5649 | 10.43 | 3.35 |
| 1.01 | 0.10 | 39.17 | 0.10 | 26.53 | 0.8406 | 9.62 | 3.35 |

As seen in section I, depending on the polarity of intra-pair skew the impact of intra-pair skew on the channel may be constructive or destructive. Defining a specification to bound intra-pair skew may lead to engineers attempting to compensate for the skew in the channel. Zeroing out the skew is not always a good idea as they may unintentionally over-compensate for the intra-pair skew and degrade the channel further by adding to loss, mode conversion noise and crosstalk. An alternative approach involves leaving the intra-pair skew uncompensated, as the mode conversion noise generated due to the length mismatch in that area will naturally attenuate as the signal progresses along the channel.

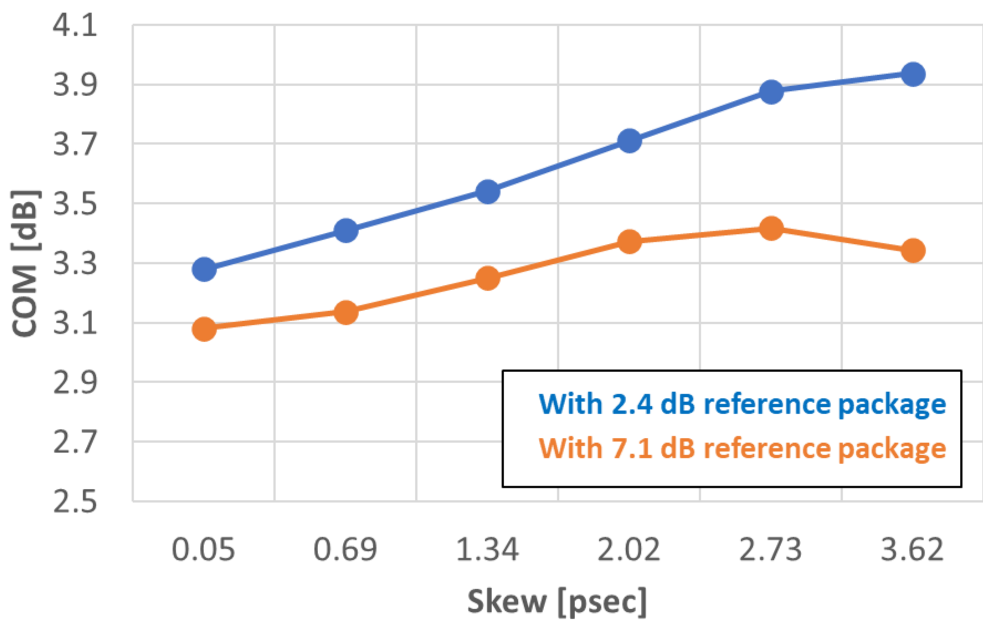



**Figure 23. Measured MTF with reference package.**

Metrics for intra-pair skew play a crucial role in enabling manufacturers to closely monitor product quality. By assessing and quantifying the intra-pair skew, manufacturers can gain valuable insights into the consistency and performance of their products. This metric aids in identifying and addressing any deviations or irregularities in signal propagation within pairs, ensuring that the product meets the required standards for reliable and high-quality performance. Monitoring intra-pair skew metrics provides manufacturers with the necessary information to maintain product integrity, optimize signal integrity, and deliver products that align with customer expectations and industry specifications.

Figure 23 shows the results of measuring a Mated Test Fixture pertaining to 224 Gbps Ethernet using reference package. The skew was injected through increments and then verified through the method of Threshold based single-ended Step Response Skew at fifty percent. Results of COM versus measured skew show that margin gets better with skew. This can be explained from fact that the time misalignment of the two single-ended responses at the receiver can lead to cancellation of the reflections and thus improve the overall signal to noise ratio.

To summarize, intra-pair skew is a context-sensitive metric crucial for understanding signal propagation within a pair. Care must be taken when defining a specification around intra-pair skew as its impact is captured through existing channel metrics for loss, reflections and crosstalk. The impact of intra-pair skew may be constructive or destructive when it comes to reflections and crosstalk. Zeroing out the skew is not always a good idea as they may unintentionally over-compensate for the intra-pair skew and degrade the channel further by adding to loss, mode conversion noise and crosstalk.

## Conclusion

In conclusion, this paper emphasizes the significance of mitigating intra-pair skew to prevent mode-conversion in interconnects and overall margin degradation. The results, obtained at 106.25 Gbps PAM4 signaling, demonstrate the impact of intra-pair skew on insertion loss, differential far-end crosstalk, mode-conversion, and Channel Operating Margin (COM). The constructive or destructive nature of intra-pair skew depends on its polarity and magnitude value.

The paper provides a comprehensive comparative analysis of six methods for measuring intra-pair skew, incorporating both frequency and time domain approaches. Additionally, a novel method based on the minimum SCMR is introduced, utilizing a unique approach to mixed-mode S-parameters for increased relevance to real hardware setups. The change in intra-pair skew can be tracked through the change in existing channel metrics of loss, reflections and crosstalk. This implies that the current limits for differential insertion loss, return loss, and crosstalk constrain the permissible amount of skew in a channel.

Recognizing intra-pair skew as a context-sensitive metric is crucial, and caution is advised when specifying its limits to avoid unintended consequences on channel metrics such as loss, reflections, and crosstalk. The potential constructive or destructive impact of intra-pair skew on reflections and crosstalk should be carefully considered, as blindly zeroing out the skew may lead to unintended consequences, including increased loss, mode conversion noise, and crosstalk.

## Acknowledgement

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