# LIMITATIONS OF THE INTRA-PAIR SKEW MEASUREMENTS IN GIGABIT RANGE INTERCONNECTS

# Abstract

As demand for higher data rates grows, interconnect intra-pair skew specifications have become increasingly tighter, resulting in harder to control manufacturing processes and lower yield. However, in many cases the measured skew values do not correlate to high-speed performance of copper links.

Our investigation of coupled and noncoupled differential pairs explains the limitations of the intra-pair skew measurements in gigabit range interconnects and suggests a good alternative to characterize imbalance of the differential high-speed interconnects.

# Introduction

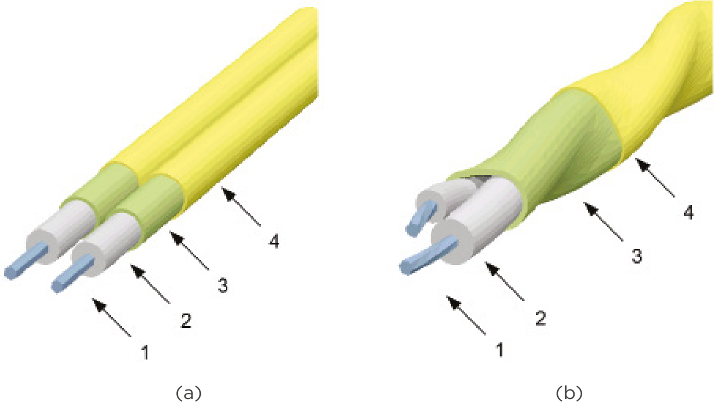
The demand for more data delivered to the end user grows every year driving increased data rates in highspeed digital data communications. Today TE Connectivity is delivering shielded twisted pairs capable of supporting more than 16Gbps of serial data per lane [1]. In the medical field shielded twisted pairs are used for gigabit range data transmission and require very tight electrical and mechanical specifications prompting a careful consideration of all test parameters [2] including intra-pair skew.

In high-speed designs, the time domain intra-pair skew is often used as a specification to test how balanced or good the manufactured twisted pair is. However, “complicated effects in differential pairs” [3] made the skew measurements in coupled interconnects challenging and prone to errors, which frequently result in substantially lower yields and more scrap of potentially good products. Furthermore, the measured results might not even represent how well interconnect will perform in real life applications. Clearly, both the customers and design engineers have to have a better understanding of how the imbalance in the differential pairs will affect high-speed electrical performance of the finished designs when defining specifications for new products.

The primary objective of this study was to look at the validity of skew as a specification requirement for high speed interconnects. We discovered that the effect of imbalance on the amount of skew is greatly mitigated by the coupling between differential conductors at high-frequencies, and the intra-pair skew specification becomes less relevant when interconnect is used in the high-speed digital data transmission. In this paper we will review both time and frequency domain methods for skew measurements using data collected from non-coupled and coupled signal lines. Introducing different levels of imbalance within shielded twisted pairs will allow us to demonstrate that the high level of coupling between two signal paths results in low skew values being measured. The findings summarized in this note will be very beneficial for all engineers who work with high-speed interconnects.

# Methods and Results

In the subsequent sections we will describe constructions of the non-coupled and coupled differential interconnects used in this study. We will also review important characteristics used to evaluate high-speed differential interconnects such as inter-symbol interference and skew. Finally, we will demonstrate based on the empirical data that high-levels of skew do not translate into high jitter when the legs of the differential pair are tightly coupled.



(a) (b)

Fig.1. Structures used in experiment: (a) non-coupled structure consisting of two shielded 32AWG (229μm diameter) coaxes, and (b) coupled structure represented by a shielded twisted pair made of two 32AWG (229μm diameter) conductors. The imbalance was introduced by using different leg length in the noncoupled case (a) and by offsetting the outer diameters of each leg in the coupled case (b). In the figures (a) and (b): 1 is center conductor, 2 is dielectric, 3, is metal shield, and 4 is polyester jacket

## Non-coupled and Coupled Interconnects Used in Study

The difference in electrical performance between coupled and non-coupled differential lines is controlled by their constructions. In the following experiments the non-coupled case is constructed with two coaxes as shown in Fig. 1a. This configuration effectively shields the two conductors preventing the signal on one leg from coupling to the other. For the coupled case, the data is based on a shielded twisted pair construction as shown in Fig. 1b. The imbalance was introduced by using different leg lengths in the non-coupled case and by offsetting the outer diameters of each leg in the coupled case. In the coupled case, the dialectic diameter offset would cause the length difference (skew) between the two legs of the twisted pair. The samples were built with 32AWG (229 μm diameter) wire having the overall length of 3 meters, which is a typical cable length used in high-speed surgical applications. To illustrate the level of coupling for the samples used in the analysis, we measured how much signal is transmitted between two non-connected legs in balanced and imbalanced cases with Vector Network Analyzer (VNA). Fig. 2. shows that the difference between S-parameter magnitudes of coupled and non-coupled traces can reach as much as 30dB (32x) regardless of the amount of imbalance introduced.

## Important Characteristics of Differential Interconnects

The primary method of evaluating interconnect's ability to transmit a digital signal is to measure inter-symbol interference (ISI). The ISI is considered to be a leading cause of signal degradation [4], and it is plotted in a form of a so-called eye diagram, which can be viewed as a snapshot of the digital data stream at a single location. Fig. 3. shows an example eye diagram of data entering a differential line (Fig. 3a) and the same data after the transmission (Fig. 3b). In this case, the eye is relatively 'open' and has maintained the quality of the signal to show a distinction between digital high and low values. Eye closure in the horizontal direction is commonly referred as jitter. In this paper we use jitter percentage to the eye's unit interval measured at the differential zero-crossing as a figure of merit for interconnect performance as shown in Fig. 3b.

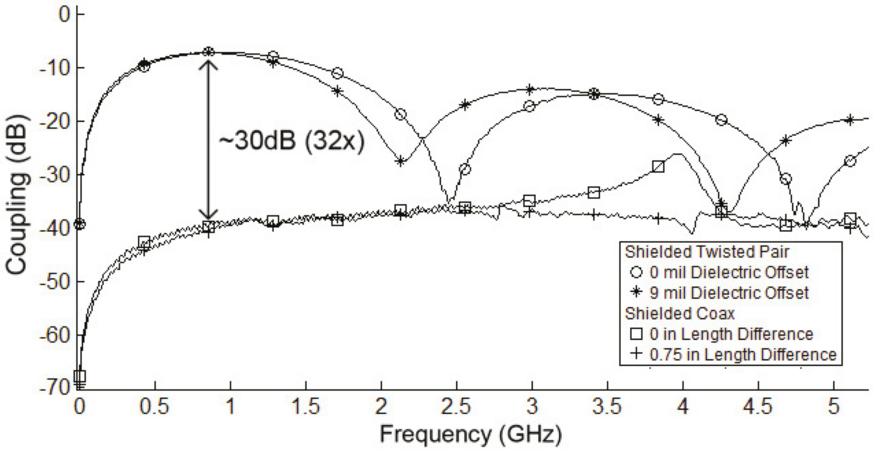
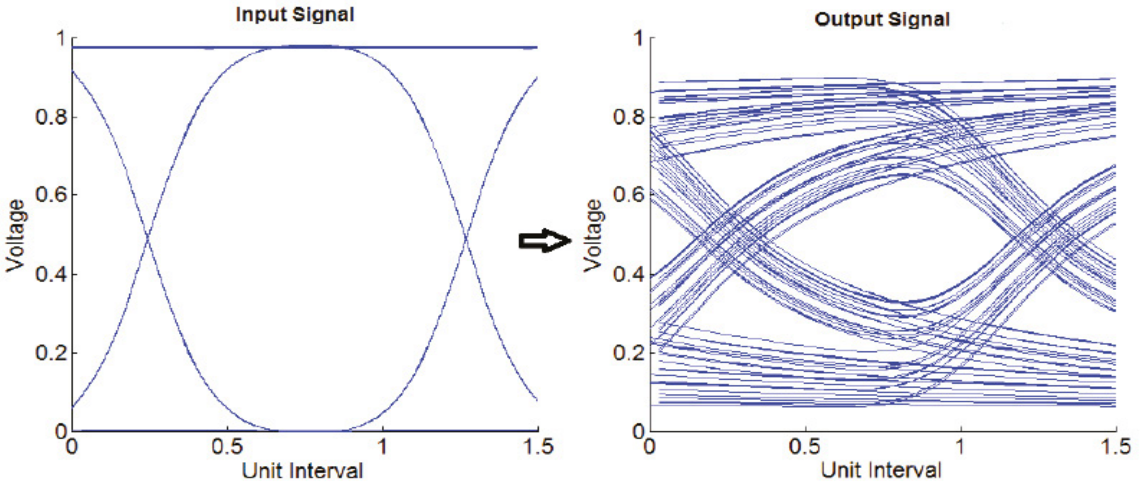


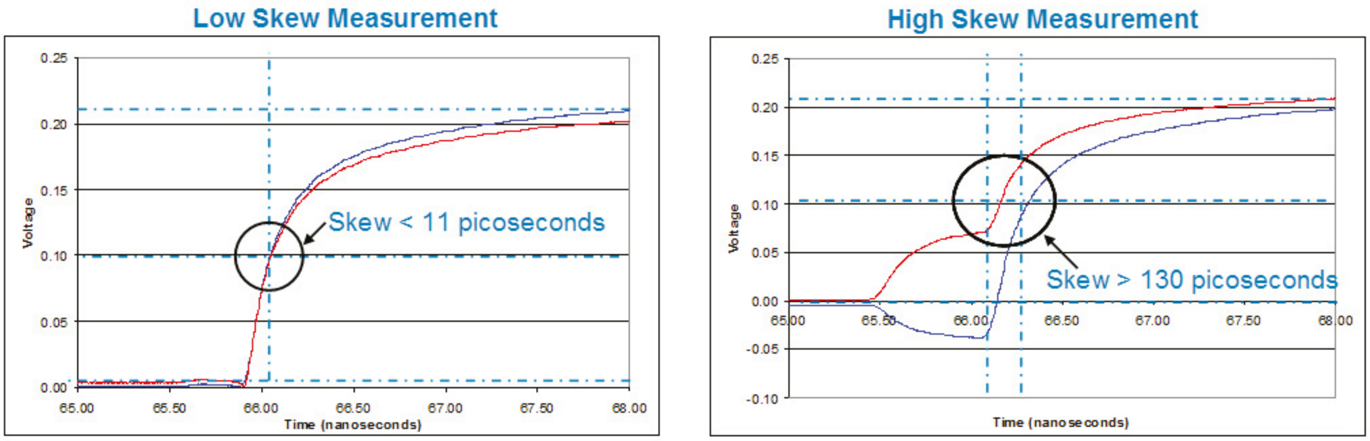
Fig.2. Coupling between legs of the differential pair. Non-coupled case represented by two shielded coaxes can have as much as 30dB (32x) less coupling compared to the shielded twisted pair.



(a) (b)

Fig.3. Example eye diagram of data entering a differential line (a) and the same data after the transmission (b). The output signal eye gets significantly closed after the transmission but high and low levels are still distinguishable. The output signal eye diagram also shows the jitter measurements as a percentage of unit interval UI.

Another method that is used to evaluate differential interconnects is intra-pair skew. The intra-pair skew can be defined as the difference in arrival time of two opposing signals within a differential signal path. The skew measurements are required by several communication standards to characterize a length difference in signal paths. It is commonly accepted that the intra-pair skew affects measured jitter and can be caused by an imbalance or asymmetry between the two signal paths in a differential pair. This imbalance is normally a result of a difference in physical length or an impedance offset between the two paths in a differential pair. Another major drawback of the imbalance is that differential signals in each leg do not cancel each other at the receiver resulting in differential to common mode conversion and compromised immunity to electro-magnetic interference (EMI) [5]. Examples of skew measurements are shown in Fig. 4. It's been previously shown that the intra-pair skew has strong frequency dependency, does not scale with cable length, and cannot be accurately predicted using step stimulus method [6] Measuring skew in frequency domain can be more beneficial because the time domain measurement is greatly affected by the signal level at which the skew was measured. The high-skew case of Fig. 4. illustrates the issue because a low reference level measurement would include a bump on the transmitted waveform drastically changing the measured skew value.



(a) (b)

Fig.4. Intra-pair skew measurements with time-domain reflectometer (TDR) oscilloscope from low (a) and high (b) skew structures. The negative signal is inverted for better display. The skew is measured at 50% signal level. Note that the 20% reference level measurement of the high-skew structure would give inaccurate results as it would include a hump on the transmitted waveform, which would drastically change the measured skew value.

| COAX LENGTH DIFFERENCE | | TDR SKEW |
|---|---|---|
| (inches) | (mm) | (ps) |
| 0.00 | 0.00 | 0.35 |
| 0.0625 | 1.59 | 6.65 |
| 0.125 | 3.18 | 21.47 |
| 0.50 | 12.70 | 106.42 |
| 0.75 | 19.05 | 112.34 |
| 1.00 | 25.40 | 145.64 |

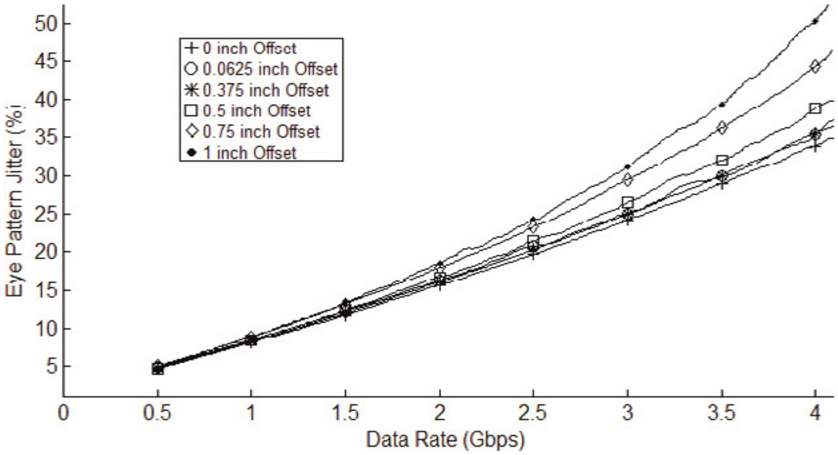


Fig 5. Effect of the leg length difference on TDR skew and jitter for non-coupled structure. As the difference increases the TDR skew and measured jitter also increase.

The bump itself is an artifact related to imbalance of the measured pair. The frequency domain differential skew can be computed from phase information by writing the scattering parameters difference in the amplitude-phase notation and extracting time delay for each leg:

$$P_1(f) = S_{3,1} - S_{3,2} = r_1(f)e^{-jDt1l} \quad (1)$$

$$P_2(f) = S_{4,1} - S_{4,2} = r_2(f)e^{-jDt2l} \quad (2)$$

$$skew = Dt2 - Dt1 \quad (3)$$

Where S3,1, S4,1, and S3,2, S4,2 are S-parameters measured between connected and non-connected ports of differential interconnect, respectively, r1 and r2 are real valued functions that characterize amplitude, the exponential functions represent the phase, variables Dt1 and Dt1 are the differential time delays, and l is length in meters (m). In this paper we use both time and frequency domain methods to show how interconnect coupling affects measured skew values. Ultimately we will explain discrepancies in skew values measured with those methods and will propose a reliable method to characterize imbalance of coupled interconnects.

## Electrical Characterization

To observe the effect of skew on uncoupled structure the sample was repeatedly tested using the TDR method of measuring skew but each time one leg was trimmed by a controlled amount. The structure was also tested with the VNA and percentage of jitter to the unit interval was extracted from the inter symbol interference (ISI) of a pseudo-random bit stream (PRBS) of 27 bits pattern. The results from the TDR and jitter tests for the non-coupled case are summarized in Fig. 5.

| DIELECTRIC OFFSET | | TDR SKEW |
|---|---|---|
| (mils) | (μm) | (ps) |
| 0 | 0 | 24.57 |
| 3 | 76 | 70.68 |
| 6 | 152 | 93.37 |
| 9 | 229 | 109.56 |

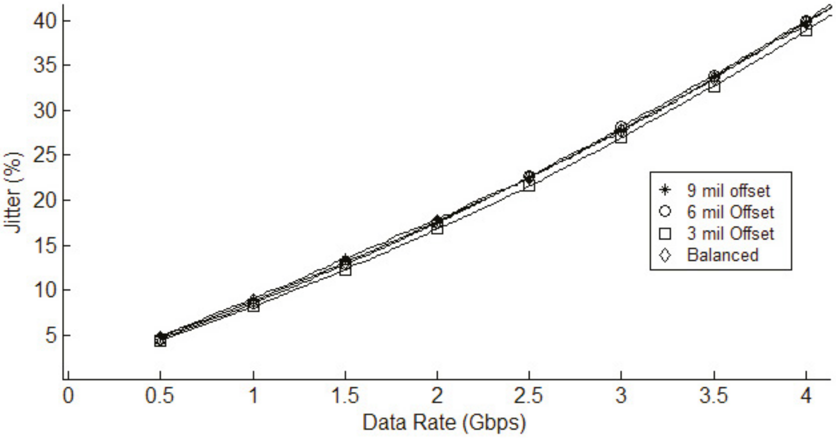


Fig 6. Effect of the leg length difference on TDR skew and jitter for coupled structure. As the difference increases the TDR skew increases but measured jitter does not show dependency on offset

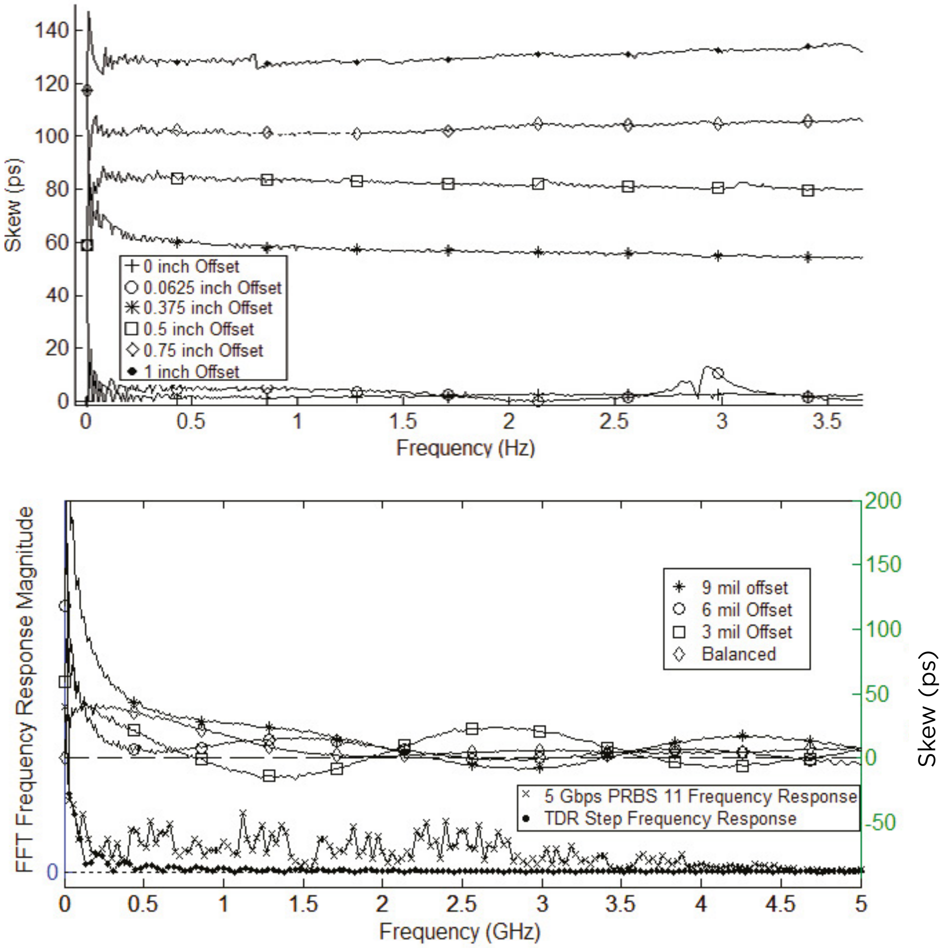


Fig.7. Differential skew measured over frequency for uncoupled (a) and coupled (b) cases. The uncoupled case exhibits little of frequency dependency, whereas coupled case plotted on the secondary axis, shows significant change with the operational frequency, as well as the reduction of skew amplitude with the frequency increase. The Fast Fourier Transformation (FFT) of 5 Gbps PRBS211 pattern and TDR step response is also plotted using the same frequency axis of (b) representing the data rate. The FFT shows that TDR step has major amplitudes closer to lower frequencies while the FFT of PRBS211 is mostly confined within 80% of the data rate.

The data shows that the skew and jitter percentage increase as the length difference between the legs of the twisted pair increases. The measurements of the non-coupled structure clearly indicate that skew directly correlates to the difference in length between the legs and to the overall amount of jitter measured. This loss in performance should naturally drive specifications to control skew in a differential signal line.

In the coupled differential line case, the shielded twisted pairs were built to have a specific offset in size between the dielectrics as shown in Fig. 1b. From a processing standpoint, controlling the length between the two legs is very difficult if the size of one leg is larger than the other. Hence, there is an increase in the length offset between conductors as the dielectric offset is increased. These combined offsets effectively create imbalance in the twisted pair which would suggest a large increase in skew and jitter. The TDR skew measurements shown in Fig. 6. align well with the expected behavior, but the jitter values seem not to be affected by the amount of imbalance introduced. The coupled structures exhibit almost no change in jitter despite the substantial geometric asymmetry.

To understand why jitter values seem not to be affected much by the imbalance in coupled case, we plot skew as a function of frequency. The frequency dependent skew was obtained from S-parameters using (3), and the results are shown in Fig. 7. The VNA method of measuring skew reveals that the intra-pair skew is relatively frequency independent for the non-coupled case. However, in the coupled case the intra-pair skew varies significantly with the frequency. At very low frequencies of less than 100 MHz, averaged skew values are comparable with the TDR measurements of each pair. As the frequency increases from 100 to 500 MHz, the amount of skew measured drops exponentially and begins to oscillate at the 50 picoseconds range in either direction except for the balanced case, which drops almost to zero.

The TDR unit used in the measurements is capable of measuring high frequency response up to 20GHz, so it needs to be addressed why the TDR skew measurement is only representative of low frequency skew at less than 20MHz. To understand this, a TDR step waveform was captured along with a pseudo-random bit stream (PRBS) of 211 bits at 5Gbps and run through a Fast Fourier Transformation (FFT). Then the frequency response was compared side by side with the skew response of the twisted pairs with data rate scaled to align with the frequency axis. The plot in Fig. 7b shows that although a TDR step has high frequency components, the magnitude of the frequencies transmitted at less than 20MHz are far greater than the rest of the bandwidth. This heavily weights the TDR skew measurement at the low frequency side when using a typical TDR step arrival time test method through the coupled differential line.

The FFT of the 5Gbps PRBS211 shows a more spread frequency response compared to the TDR step. The frequencies sent through a differential pair for this data stream are far more evenly distributed from the range of 0 Hz to around 80% of the full data rate (in this case 5Gbps). Therefore, if the skew is measured as an averaged value within aforementioned range, this will better represent the impact that skew will have on the ISI performance. However, the averaged value of the oscillating skew is expected to be low not affecting much the final jitter measurement, as it was observed on the jitter plot of Fig. 6b.

Since any imbalance of the differential pair will result in mode conversion (differential- to-common and common-to-differential) causing EMI and crosstalk issues [6], the more direct measurement of the imbalance would be a magnitude of differential-to-common S-parameter. The results of this extraction are shown in Fig. 8. In the case of both non-coupled and coupled differential signal lines, the more imbalance that is present in the construction the more susceptible this path is to converting signal from differential mode to common mode noise. This happens in both coupled and non-coupled structures. Although the coupling helps to mitigate the imbalance effect on the ISI jitter, it does not help to reduce the mode conversion. Thus, the only reliable way to capture imbalance due to manufacturing processes is by measuring differential-to-common mode conversion but not the time domain skew.

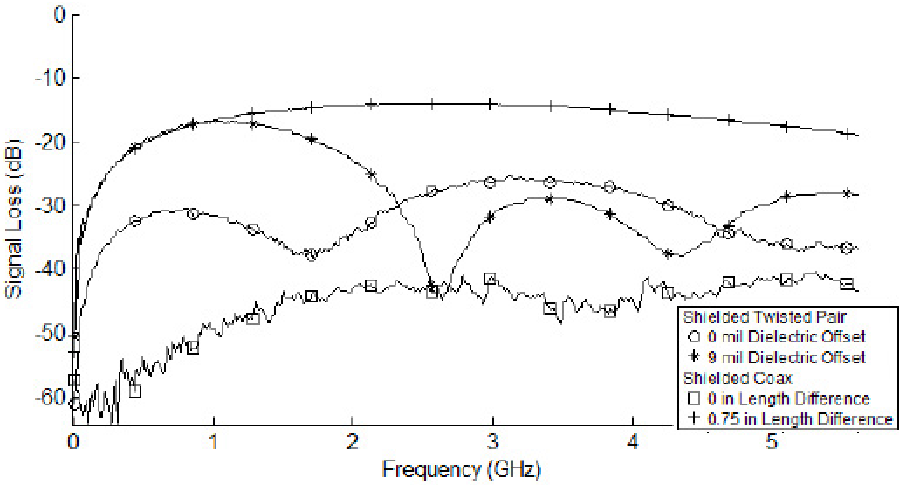


Fig.8. Comparison of differential-to-common mode conversion between shielded twisted pairs and twin coax shows significant effect of imbalance on the mode conversion in both cases. Both coupled and uncoupled interconnects convert significant amount of differential mode into the common mode, which potentially may result in EMI and crosstalk issues.

## Conclusions

It has been demonstrated that imbalance does not have the same impact on skew and ISI jitter in coupled and non-coupled differential signal lines. In the coupled case, the imbalance does not correlate with skew as a function of frequency but instead results in a dramatic reduction of skew after 20MHz or more. When interconnects are strongly coupled as in the shielded twisted pair case, the ISI jitter does not appear to be affected by imbalance. For these reasons the intra-pair skew and jitter measurements should not be used to characterize imbalance of the differential pair. Nevertheless, the imbalance itself can cause other issues to the product including crosstalk and EMI. In this case, a more relevant measure for the imbalance is differential-to-common mode conversion. The mode conversion can reliably capture imbalance regardless if legs in differential pair are coupled or not. In cases when customers still request to spec the skew, the preference should be given to a frequency domain method of measuring skew which gives more relevant results than obtained with the TDR method.

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