Application Report
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Suggestions for High-Speed Differential Connections

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ABSTRACT

This document addresses connector signal integrity in order to help engineers make connector selections to complement TI's High Speed Interconnect product line. The important attributes of high-speed connectors, which impact signal integrity, are impedance matching, crosstalk, and electromagnetic interference (EMI).

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1 Introduction

The High Speed Interconnect products from Texas Instruments include low-voltage differential signaling (LVDS), low-voltage positive emitter-coupled logic (LVPECL), and current-mode logic (CML) interfaces. These different products are moving beyond signaling rates of hundreds of megabits per second and into the gigabits-per-second range. Accompanying this movement are all of the challenges associated with high-frequency design. These challenges include minimizing the signal degradation due to the transmission line used to move a signal from one point to another. This transmission path can include cables, traces, vias, and connectors. Attributes of connectors that impact signal integrity are impedance matching, electromagnetic interference (EMI), and crosstalk.

2 Crosstalk

Crosstalk is usually described in the context of an aggressor and a victim, as shown in Figure 1. In high-current, low-impedance circuits, the crosstalk seen is a result of mutual inductance between current loops. Crosstalk from mutual capacitance, associated with high-voltage and high-impedance networks, is negligible. In the case of a connector, especially in high-density connectors, the aggressor and victim are within close proximity, which raises the mutual inductance and the susceptibility to crosstalk. As shown in Figure 2 , the signal and return arrangement in the connector causes two of the current loops to overlap; whereas some crosstalk will be seen in all channels, the mutual inductance and crosstalk are greater between the two that overlap.

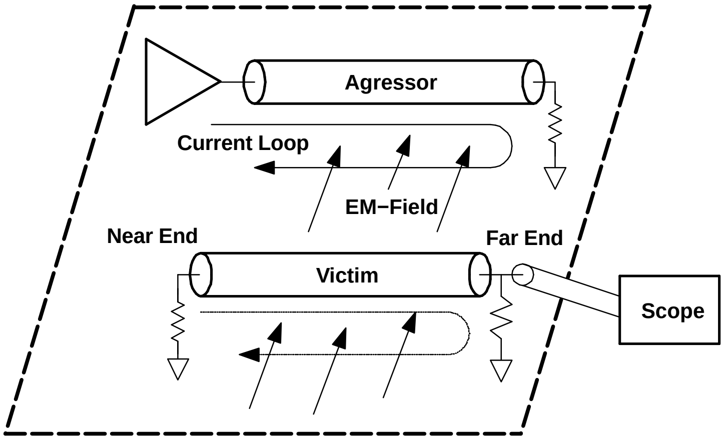


Figure 1. Crosstalk Between Aggressor and Victim

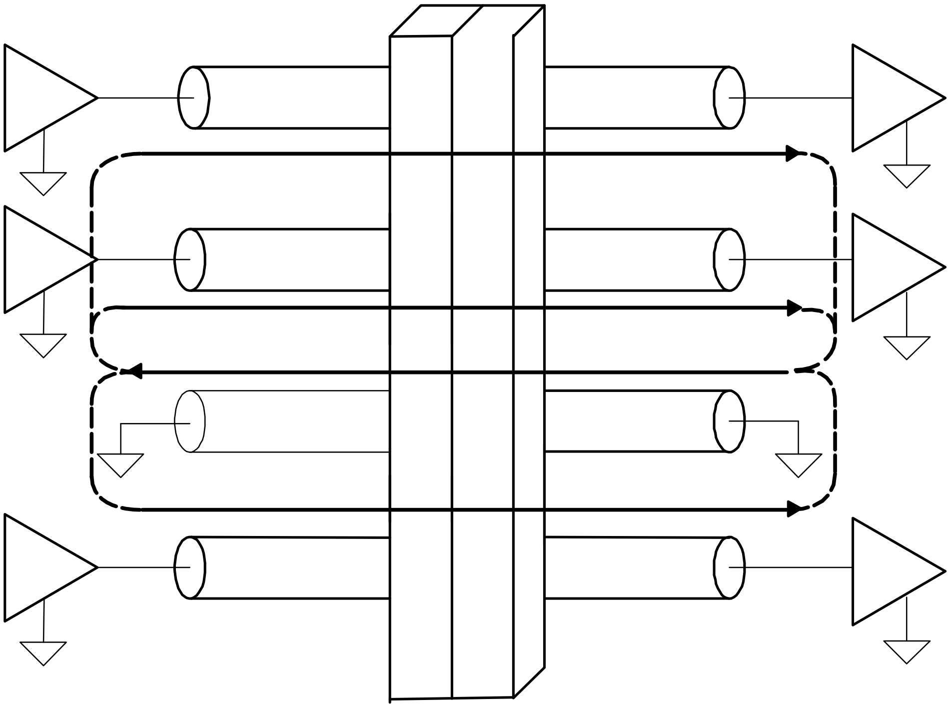


Figure 2. Crosstalk Within a Connector

Unlike the single-ended examples shown in Figure 1 and Figure 2, the principal amount of current in differential circuits flows through a differential pair of conductors (as shown in Figure 3) and not the ground return. This reduces the current loop area, the mutual inductance, and the resultant crosstalk with neighboring signals. Crosstalk observed in a differential system is due to time-varying, common-mode currents (i_{CM}) created by imbalances in the line drivers and interconnect. The common-mode current loops shown in Figure 3 are about 1/100th the amperage of the primary current loops (solid lines in Figure 3) in a well-balanced, differential transmission circuit.(1)

The generation of and immunity to crosstalk is much better in tightly coupled differential signals. Tight coupling helps maintain balance within the differential pair. Also, keeping the conductors close together helps ensure that stray inductance is coupled equally on each conductor within the pair. The receiver rejects crosstalk induced onto both conductors as common-mode noise.

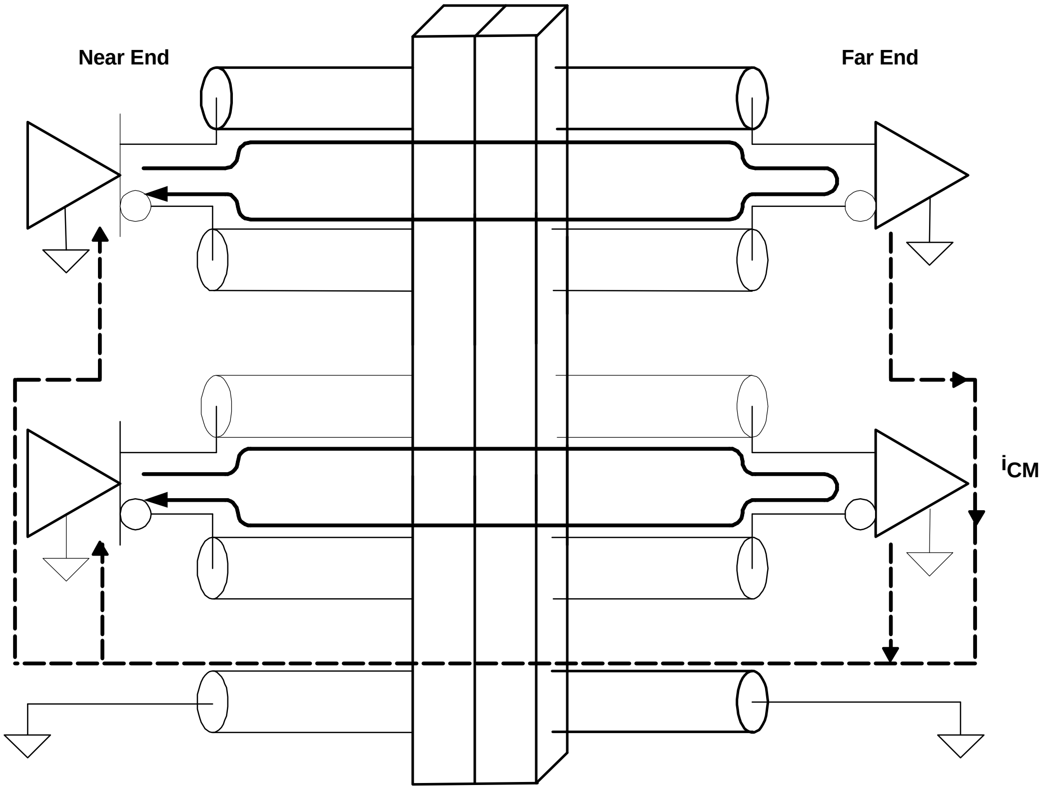


Figure 3. Currents in Differential Connection

Placing grounds between a set of differential pairs within the connector can reduce coupling. Multiple grounds give the common-mode currents multiple return paths and therefore minimize the current loops (current takes the shortest path). An example of this is shown in Table 1. Using the maximum differential signal density of the MICTOR connector, the near-end crosstalk is 13.3% of the voltage swing and the far-end is 6.8%. Using the connector contact configuration in Table 1 (this information was taken from the AMP MICTOR *Connector Noise Analysis for High-Speed LVDS Applications Report*,` #98GC040), the near-end crosstalk percentage of the voltage swing is less than 0.3% and the far-end percentage is 1%. The disadvantage of the Table 1 configuration is the availability of only six differential pairs instead of eight.

(1) *High-Speed Digital Design: A Handbook of Black Magic*, H. Johnson, M. Graham

Table 1. Using Signal Pins as Ground to Minimize Crosstalk in the AMP MICTOR Connector

	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8
Row A	S1+	S-1	*GND*	S2+	S2-	*GND*	S3+	S3-
Shield	*GND*	*GND*	*GND*	*GND*	*GND*	*GND*	*GND*	*GND*
Row B	S4+	S4-	*GND*	S5+	S5-	*GND*	S6+	S6-

Although the additional grounds increase the isolation of differential pairs, they also raise the capacitance (and cost) of the connector. The benefit of differential signaling over single-ended signaling is that well-balanced signals and tightly coupled connector traces have an inherent immunity to crosstalk and do not require additional grounding, as shown in Figure 4. This benefit reduces the crosstalk without increasing the capacitance of the connector. The lower capacitance helps prevent a discontinuity in the transmission line characteristic impedance and possible signal distortion from reflections. Vendors have made special connectors, using tightly coupled differential signals, to deal with the crosstalk problem and capacitance (see Table 2).

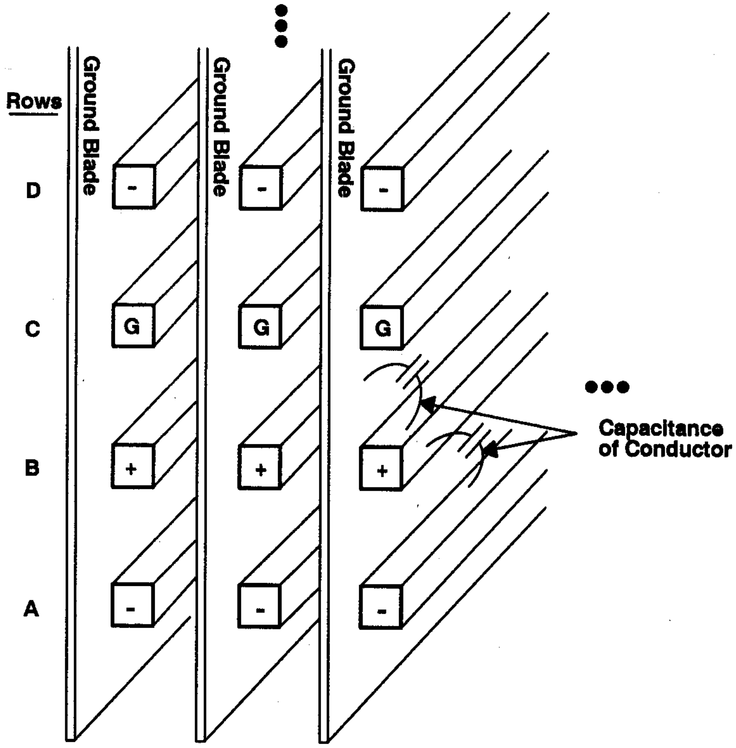
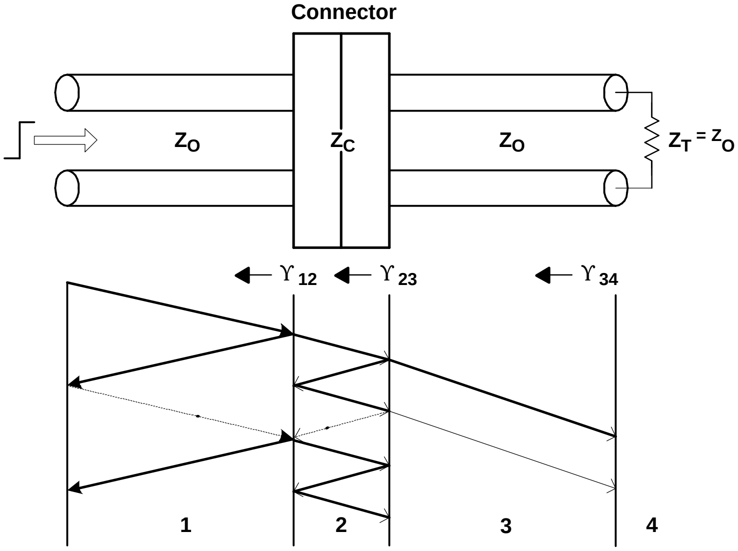


Figure 4. Ground Plane Between Connectors to Improve Crosstalk

2.1 Impedance Matching

The impact of an impedance mismatch depends on the rise time of the transmitted signal and the electrical distance of the transmission line (represented by the round-trip propagation delay). If the rise time is short compared to the time for a wave to be transmitted and reflected back, then one can assume that the circuit is going to behave like a transmission line.

In a transmission line, impedance matching is necessary to minimize reflections, to deliver the correct amplitude signal, and to maximize power at the load. Figure 5 is a lattice diagram that demonstrates the distortion that can occur to a signal due to impedance mismatches in the connector. The reflection coefficient (Γ), and the transmission coefficient ($1-\Gamma$) can be calculated from the impedances. Notice that when the impedance of two media match, the Γ is zero and the transmission coefficient is one. The effect is a maximum in the amount of signal being transmitted and a minimum in the amount reflected. The use of impedance-controlled connectors is seen in radio frequency applications and now with high-speed data transmission. Most vendors provide connectors with controlled characteristic impedance to match the transmission line and prevent reflections (see Table 2).



$\Upsilon_{12} = (Z_C - Z_O)/(Z_C + Z_O)$
$\Upsilon_{23} = (Z_O - Z_C)/(Z_O + Z_C)$
$\Upsilon_{34} = (Z_T - Z_O)/(Z_T + Z_O)$

Figure 5. Lattice Diagram

2.2 Skew

Skew is another potential problem in high-speed interconnects, and the connector can be easily overlooked. Conductor-to-conductor skew is seen in angled connectors where some conductors are physically longer than others. The difference in length poses a pitfall to differential signals that must maintain balance within a differential pair. Figure 6 shows the skew induced in a right angle connector due to the different distances traveled by the inner (B) and outer (A) signals. From a timing standpoint, this skew is usually negligible (on the order of tenths of a percent of the unit interval), but the imbalance can result in an increased amount of radiated emissions. Figure 6 also shows an example of how to orient differential signals to minimize skew within the differential pair. Vendors have made connectors especially for differential signals with almost no skew within the differential pair and a minimal amount between pairs.

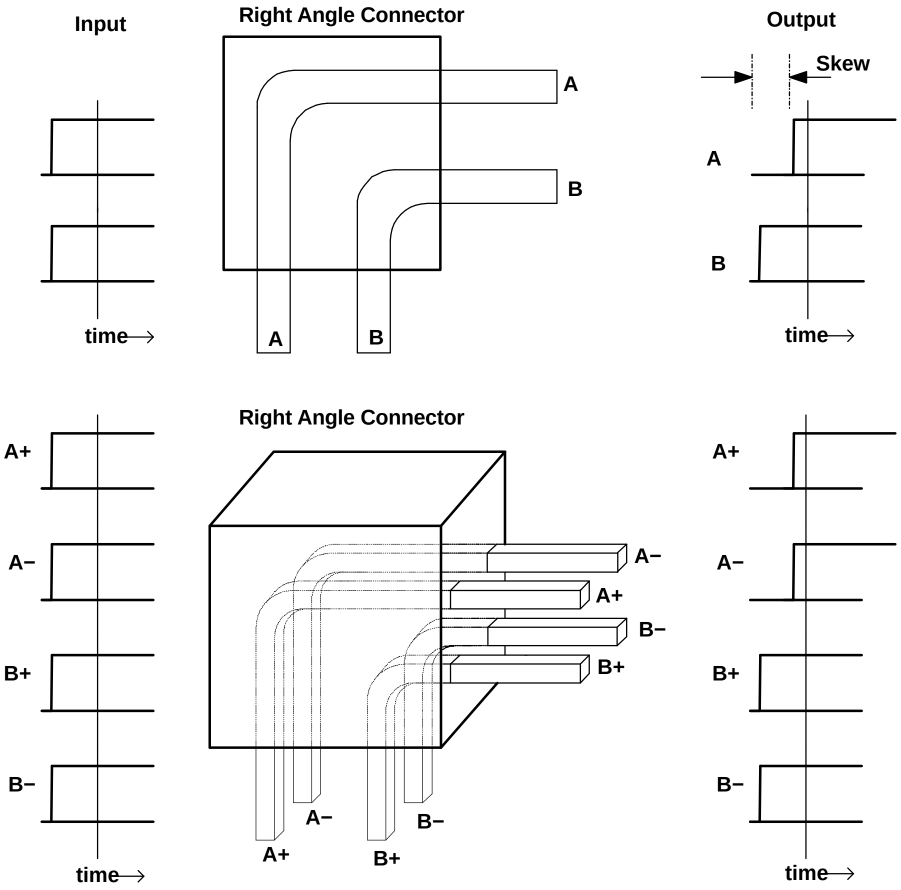


Figure 6. Skew in Right Angle Connectors

2.3 EMI

The most complete definition of EMI includes radiated emissions, radiated susceptibility, conducted emissions, and conducted susceptibility. Most commercial requirements only consider emissions. Examples of these requirements are Federal Communications Commission (FCC), Title 47, Part 15, Subpart B and the European Economic Community (EEC) CISPR 22. In most differential signaling modes, the common-mode outputs at the driver are the main source of radiated emissions and not the individual conductors of the differential transmission line (unless balance between the pair is lost). The cancellation of electromagnetic energy in the far field reduces the amount of radiated emissions in differential transmission paths, including radiation from the connectors

Although radiation is the prime concern, there is also growing concern about radiated susceptibility. Tightly coupled differential pairs diminish EMI susceptibility without affecting emissions. Just as with crosstalk, the energy is coupled to both conductors and discarded by the receiver's common-mode rejection. While connectors do not play a significant role in eliminating emissions of differential transmissions, connectors can diminish susceptibility to EMI. Tightly coupling differential signals within the connector and the use of external shielding are both methods of minimizing susceptibility. Examples of tightly coupled pairs within the connector are the VHDM™-HSD™ connectors from Teradyne, Samtec, and Molex.

Table 2 lists some different connector vendors with products that address signal integrity issues presented in this paper.

Table 2. Issues Addressed by Connectors

CONNECTOR TYPE	EXAMPLE PRODUCT	CONTROLLED IMPEDANCE	LOW CROSSTALK	LOW EMI	VENDOR WEB SITE
Board to board	AMP ZPACK™ connectors	Yes	Yes	Yes	http://www.amp.com/
Board to board	Delphi Gold Dot™ Connection System	Yes	Yes		http://www.delphiconnect.com
Board to board	QSE Series from Samtec	Yes	Yes		http://www.samtec.com/
Board to board	QSH/QTH Series from Samtec	Yes	Yes		http://www.samtec.com/
Board to board	VHDM-HSD	Yes	Yes	Yes	http://www.teradysfne.com/prods/tcs/ http://www.samtec.com/ http://www.mlex.com/
Board to board	RIBBON-AX™	Yes	Yes	Yes	http://www.goreelectronics.com/
Onboard jumper	GORE™ On-Board Jumper Cables	Yes	Yes		http://www.goreelectronics.com/
Board to cable	AMP MICTOR connectors	Yes	Yes		http://www.amp.com/
Board to cable	SMA connectors	Yes	Yes	Yes	http://www.amphenol.com/
Board to cable	VHDM-HSD™ connectors with Gore EYE-OPENER™ 6 products	Yes	Yes	Yes	http://www.goreelectronics.com/
Board to cable	Panduit Giga-Channel MINI-JACK™TX-6™ Shielded Modular Jack	Yes	Yes	Yes	http://www.panduit.com/

3 RJ-45 Connectors

The board-to-cable connectors in Table 2 are expensive and mate with specific cables. A more cost-effective and readily available board-to-cable connection is the use of standard CAT5 cables and RJ-45 jacks and plugs. A large number of RJ-45 jacks and plugs are available, varying in cost and complexity. Table 3 lists some of the different RJ-45 jacks available.

Table 3. RJ-45 Features

FEATURE	MANUFACTURER
Shielded	AMP/Tyco, Amphenol
Common-mode choke	Bel Fuse, Molex
Isolation transformers	Bel Fuse, Molex, Delta
Surface mount	AMP/Tyco, Amphenol, Molex, Bel Fuse

Each of these features contributes to the overall performance of a connector and address-specific application concerns.

Figure 7 shows typical performance of the SN65LVCP22 with different RJ-45 connectors(1) through 2 meters of CAT5 cable.

(1) An isolation transformer was tested (100 Base-T) and it was verified that the connector performed well at 100 Mbps, but the high-frequency cutoff of the isolator prevented any communication above this signaling rate.

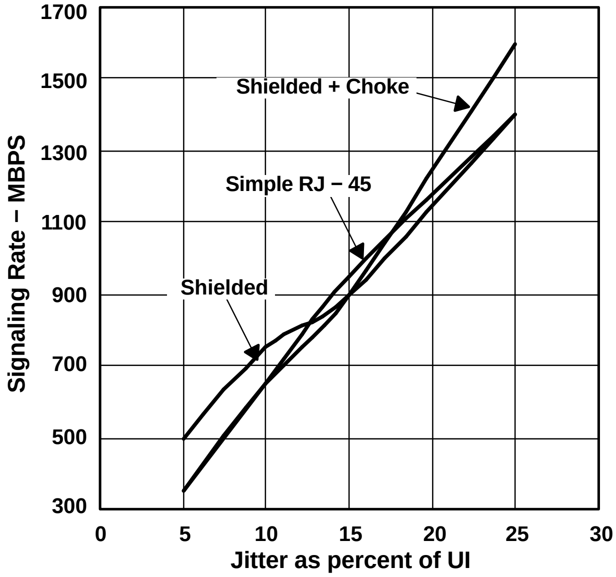


Figure 7. Performance of Different Connectors

The RJ-45 jack with integrated common-mode choke has attenuation characteristics that reflect the deviation (relative to the shielded connector) at lower frequencies and how that deviation diminishes as the frequency increases (attenuation: frequency, 8 dB: 1 MHz, 25 dB: 70 MHz, and 11 dB: 500 MHz). The common-mode choke connector is also associated with 100Base-T operation, suggesting a design more in line with signal integrity. Also, the increased cost of the connector suggests higher quality. This higher quality also explains the improved performance at higher frequencies.

4 Conclusion

Proper selection of connectors allows a designer to realize the full benefits of differential data transmission. EMI and crosstalk in differential circuits are significantly decreased over similar single-ended transmission. These inherent benefits allow designers to choose low-capacitance connectors without making the trade-off of increased crosstalk. This is especially important in multipoint connector applications where connector capacitance can impact the characteristic impedance of a backplane. Because differential signaling inherently addresses EMI and crosstalk, the focus of connector selection is directed toward impedance matching.

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