OMNETICS CONNECTOR CORPORATION

HIGH-SPEED CONNECTOR DESIGN

PART I - INTRODUCTION

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High-speed digital connectors have the same requirements as any other rugged connector: For example, they must meet specifications for shock, force, insertions, and vibration. There are, however, additional requirements that must be addressed in order to ensure proper performance for high-speed applications. With gigabit data rates through connectors now commonplace, the parameters that impact high-speed digital performance must be understood by both connector manufacturers and connector users. This is the first in a series of articles that are aimed at helping readers better understand the critical concepts and parameters that must be considered for high-speed connector design.

BREAKDOWN OF THE OLD ORDER

For low-speed signals, the connector and cable can be adequately modeled as a small resistor. This resistor will accurately represent the loss that is created due to the length and diameter of the path. As speeds approach the high-speed regime (generally 100 Mbps+), a small resistor will no longer accurately model the electrical performance. Being able to understand and accurately predict the performance will require a paradigm shift in how electrical signals are viewed.

PARADIGM SHIFT

Electrical signals are actually electromagnetic waves that traverse down a signal path. At low-speed, the electromagnetic waves can be simplified by using circuit theory – the wave can be modeled as a voltage-across/current-through the path, with an instantaneous transfer rate. This is modeled with the simple resistor discussed above. This model, however, breaks down at high-speed, and understanding this requires a new way of thinking about electrical signals.

FLUID FLOW ANALOGY

High-speed signals must be viewed as waves. A simplified understanding of this signal-as-a-wave concept can be obtained by using a fluid flow analogy. As a wave travels through a pipe, a portion of the wave will reflect back every time the pipe diameter changes. Thus, optimal fluid flow is achieved with a pipe that has a constant diameter (Figure 1a). If the pipe diameter is constantly changing (Figure 1b), large portions of the wave will reflect and the efficiency of the pipe will decrease.

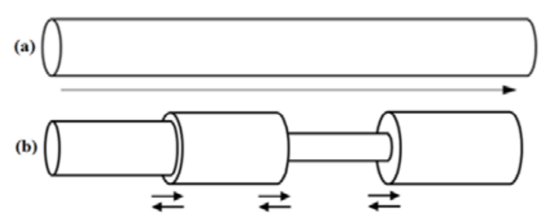

Figure 1

The performance of the pipe is analogous to the performance of a high-speed signal path in a cable/connector assembly, with the critical parameter in a signal path being impedance instead of diameter.

WHAT IS IMPEDANCE?

In its most basic definition, impedance is the ratio of the voltage to the current of a signal path. Like the diameter of the pipe in the fluid flow analogy above, the impedance of a signal path is defined by the cross-sectional geometry at any point along the path. This is an important point that bears repeating – impedance is specific to each point along a signal path. An ideal signal path maintains a constant impedance – like a constant diameter of a pipe – throughout the path. The optimal impedance is defined by each specific application, but the most common impedance is 100Ω.

HIGH-SPEED CONNECTORS

In the installments that follow, we will discuss many helpful parameters and concepts for understanding high-speed connectors. We will also describe the challenges that must be addressed to achieve an optimal design. The goal is to provide the reader with an understanding of the important concepts that pertain to high-speed connectors and give engineers the ability to select the correct high-speed connector with confidence.

High-Speed Connector Design

Part II – Analog and Digital Specifications

We live in a digital world. From phones to tablets to automobiles, digital electronics are everywhere. Our world is so strongly shaped by digital electronics that analog electronics are often considered a thing of the past. This perception, however, is untrue. In fact, every piece of digital information was at some point converted from an analog signal. The relationship between digital and analog signals must be understood in order to interpret many of the latest high-speed connector specifications. Since there is no standard method for specifying connector high-speed performance, some connectors are specified as analog frequencies (MHz/GHz), while other connectors are specified as digital data rates (Mbps/Gbps). This often leads to much confusion among those who are trying to procure the proper connector for their application. This article is intended to clear up some of the confusion inherent in many of today's connector specifications.

Determining Frequency Specifications

Maximum frequency specifications are determined from insertion loss measurements. Insertion loss measures the amount of a signal that transmits through a path across all critical frequencies, typically expressed in deciBels (dB) (see example in **Figure 1**). Specifications are determined by the maximum frequency that can pass a signal with a pre-determined amount of loss, typically between -3 dB and -8 dB. For example, using -3 dB as the threshold, the measurement shown in **Figure 1** yields a maximum frequency of 2.4 GHz.

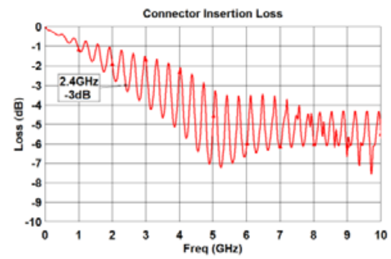

Figure 1

Deriving Data Rate Specifications

Maximum data rate specifications are derived from insertion loss measurements. Data rate specifications cannot be explicitly measured, so deriving data rate specifications require approximations. For most applications, specifications are approximated by multiplying the maximum frequency by a factor of two. The doubled frequency is based on the fact that there are two digital bits in one analog period, and assumes the resulting signal will look like a sine wave (**Figure 2,** red).

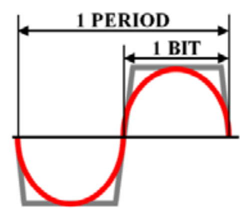

Figure 2

Performance Varies Based on Application

Specifications are best used as first order approximations. Creating a specification requires the manufacturer to make assumptions about the end application. There are four main application-specific variables that must be understood:

1) **Path topology – S**pecifications must assume a particular path. Some specifications represent a cable/connector assembly, while others depict a mated connector pair without a cable.
2) **Maximum allowable loss** – Specifications must assume a specific amount of loss through the assembly, but this loss value likely differs from the loss required for a specification application. With allowable loss varying from less than 1 dB of loss all the way up to 20 dB, the actual loss requirement will have a significant impact on the maximum data rate.
3) **Actual cable length** – Specifications must assume one specific cable length, but the length used will likely differ from the actual length. Shorter cable lengths will increase the maximum data rate, while longer cable rates will decrease the rate.
4) **Expected output waveform** – Most specifications assume a somewhat rounded output waveform (**Figure 2**, red), but some applications have more sensitive circuitry that require an output that more accurately represents a square wave (**Figure 2,** grey). For these waveforms, the maximum data rate is often derived by multiplying the frequency by a factor smaller than one.

Making Proper Comparisons

Since each connector manufacturer specifies performance differently, it is important that the both the specification values and the characterization methodologies are both understood and scrutinized. Some manufacturers use conservative specification methods, while others use aggressive. A higher specification value does not necessarily mean a higher performing connector. The goal of this article is to help clear up some of the confusion involved in many of today's connector high-speed specifications.

HIGH-SPEED CONNECTOR DESIGN

PART III – THE IMPORTANCE OF IMPEDANCE

Impedance is a critical parameter in determining the performance of high-speed applications. In Part I of our High-Speed Connector Design Series, we used the analogy of a pipe diameter to relate impedance to electrical performance. Just as optimal fluid flow is achieved with a pipe with a constant diameter, optimal electrical performance through a high-speed path is achieved with a constant impedance at every point along the path. But why is impedance so important? That is the focus of this installment.

REVISITING THE FLUID FLOW ANALOGY

High-speed signals should be viewed as waves. As waves, travelling high-speed electrical signals are analogous to fluid travelling through a pipe. As a wave travels through a pipe, a portion of the wave will reflect back every time the pipe diameter changes. Thus, optimal fluid flow is achieved with a pipe that has a constant diameter (Figure 1a). If the pipe diameter is constantly changing (Figure 1b), large portions of the wave will reflect and the efficiency of the pipe will decrease.

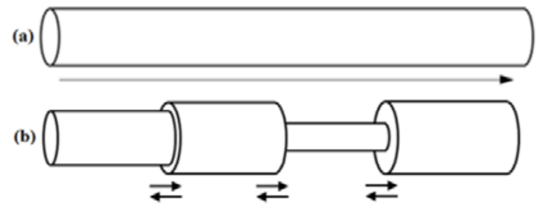

Figure 1.

The performance of the pipe is analogous to the performance of a high-speed signal path in a cable/connector assembly, with the critical parameter in a signal path being impedance instead of diameter.

WHY IS IMPEDANCE SO IMPORTANT?

The impedance of the path is critical because any time the path impedance deviates from the system impedance[1], a portion of the signal will reflect back to the source, and therefore will not reach its destination. The magnitude of the reflection, or discontinuity, will be dictated by two variables: (1) the physical length of the impedance mismatch, and (2) how far the impedance differs from the specified system impedance. In order to understand this better, we will look at four examples. In these examples, I will assume a system impedance of 100Ω and a cable with a connector on each end, similar to what is shown in Figure 2.

- **Example #1: 100Ω connectors with 100Ω cable. Performance: *Excellent*.** The impedance is matched through the entire path.
- **Example #2: 70Ω connectors with 100Ω cable. Performance: *Good*.** The length of the impedance mismatch (only through the length of the connector) is small enough that it doesn't have a significant impact on the performance
- **Example #3: 100Ω connectors with 70Ω cable. Performance: *Poor*.** The length of the impedance mismatch (through the entire cable) is large, which yields poor performance.
- **Example #4: 40Ω connectors with 100Ω cable. Performance: *Poor*.** Although the length of the impedance mismatch is small, the magnitude of the mismatch is large enough to yield poor performance.

Figure 2.

IMPEDANCE AND DATA RATE

Of course, impedance isn't always important. For low-speed signals (less than 100 Mbps/MHz), the impedance of the connectors and the cable is not likely to be an issue. However, as speeds increase, the impedance becomes more important. As a general rule, the impedance of the cables is important for signals above 100 Mbps/MHz, and the impedance of the connector becomes important for signals above 1 Gbps/GHz.

THE IMPORTANCE OF IMPEDANCE

As data transfer rates continue to increase, the impedance of the cable and the connector become increasingly important. In order ensure that designs adequately address this, we must understand the factors that impact impedance and what can be done to optimize our designs. We will look at this in our next installment.

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[1] The system impedance is specified by the application and defines the profile of the transmitting signal for that specific application. For many circuits, the impedance will be specified by the standard protocol. For example, the impedance of USB signals (USB2 and USB3) is specified at 90Ω. The most common impedance for differential signals is 100Ω.

HIGH-SPEED CONNECTOR DESIGN

PART IV – DETERMINING CABLE AND CONNECTOR IMPEDANCE

In previous installments of this series, we described the importance of impedance. However, we haven't discussed how to determine the impedance of the path, or the variables that impact impedance. That is the focus of this installment.

CALCULATING IMPEDANCE

Unfortunately, impedance is very difficult to calculate. In fact, it is nearly impossible to calculate without a high-powered electromagnetic field solver. Due to this complexity, it is often helpful to simply understand the implications of specific design changes on impedance. This can help us make the necessary design changes to increase or decrease the impedance of our current design.

The impedance of any path is determined by the cross-sectional geometry at any point in the path. For any path where the cross-section changes, the impedance will have some variation. In most cable/connector assemblies, this occurs in the connector. It is relatively easy to keep the cross-section of a shielded, twisted pair cable constant. However, it is very difficult, if not impossible, to keep the cross-section constant as the path transitions from the cable to pins to a circuit board.

EQUATION FOR IMPEDANCE

$$Z = \sqrt{L/C}$$

Equation 1.

Impedance (Z) is proportional to inductance (L) and inversely proportional to capacitance (C) (see equation in **Equation 1)**. In order to understand this equation, it is necessary to have a general understanding of inductance and capacitance.

Inductance is the ability to store *magnetic* charge, and it is determined by the size of the circuit loop. The loop size is determined by the size of the conductors (length/width) as well as the distance between the conductors. Inductance increases as the length of the loop increases, and decreases as the width of the loop increases.

Capacitance is the ability to store *electric* charge. Capacitance increases as the size of the conductors increases, and decreases as spacing between conductors increases. Capacitance is also proportional to the dielectric constant (ε_R), a material constant of the insulating plastic that is typically provided on the datasheet of the insulator.

IMPEDANCE IN CABLES AND CONNECTORS

Variable		Z*
Diameter	↑	↓
Spacing	↑	↑
Dielectric	↑	↓
Length	↑	↔

*Z = Impedance

Figure 1.

Figure 1 describes how several design parameters impact impedance. As the spacing between conductors increases, the inductance increases and the capacitance decreases. Both of these factors will cause the impedance to increase. For cables, the impedance increases as spacing between wires increases. In connectors, the impedance increases as the spacing between the pins increases.

As the diameter of the signal conductors increases, the inductance decreases and the capacitance increases. These both cause the impedance to decrease.

The dielectric constant of the insulating material also impacts impedance. However, since dielectric constant only affects capacitance, not inductance, the impact of dielectric constant on impedance is less profound than diameter and spacing. Impedance has an inverse relationship with dielectric constant: as the dielectric constant of the insulating material increases, impedance decreases.

Finally, impedance has no relationship to length. Since length increases inductance and capacitance with the same proportion, length has no impact on impedance. This is why impedance is a function of cross-sectional geometry and can be determined at any point along a path.

CONCLUSION

Impedance is an important parameter for all high-speed designs. It is critical that designs are optimized to provide a matched impedance throughout the entire path. This installment was intended to help designers understand how different design decisions may impact the impedance.

HIGH-SPEED CONNECTOR DESIGN

PART V – MEASURING IMPEDANCE THROUGH A CONNECTOR

In previous installments of this series, we discussed the importance of impedance, as well as how various design changes impact impedance. In this installment, we will discuss how impedance is measured and how to interpret impedance plots.

HOW IS IMPEDANCE MEASURED?

Impedance is measured using a method called TDR, or time-domain reflectometry. A TDR measures the characteristic impedance through a cable/connector assembly and is able to detect the locations and magnitudes of all impedance discontinuities in the path. An example of a TDR plot is shown in **Figure 1**.

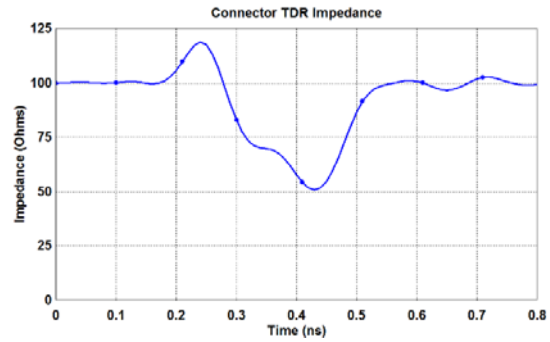

Figure 1. An example of a TDR plot.

WHAT IS TIME-DOMAIN REFLECTOMETRY?

Time-domain is simply a way to describe analysis that is done with respect to time. One can tell that a TDR measurement is in the time-domain because the parameter on the x-axis of the plot is time.

Reflectometry refers to the method by which the impedance is measured: An incident signal is transmitted through a path, and any reflected signal that returns to the source is measured[1]. If the impedance of the signal path is matched to the system impedance along the entire path, then no reflections will occur. However, if the impedance of any part of the path deviates from the system impedance, a portion of the signal will reflect back to the source. The time it takes for the reflection to reach the source will determine the location of the discontinuity, and the magnitude of the reflection will determine the impedance of the path at that location.

TRANSLATING TIME TO DISTANCE

In order to establish the physical location of an impedance discontinuity that is displayed on a TDR plot, the time units on the x-axis must be translated into distance. Distance is translated in two steps:

(1) Determine the time (t) by dividing the time on the TDR plot when the discontinuity occurs by two. The time must be halved because the time on a TDR plot is round-trip time.
(2) Use **Equation 1**[2] to determine distance. This provides the location of the discontinuity in inches, measured from the input of the measurement.

$$\boldsymbol{distance = t * \frac{12}{\sqrt{\varepsilon_R}}}$$

Equation 1. Equation for distance with time (t) in nanoseconds.

A CONNECTOR TDR EXAMPLE

Now's let's consider an example. In **Figure 2**, an image of a connector was overlaid on the TDR plot shown in **Figure 1**, and six numbered regions were added. The plot, in conjunction with the image of the connector, can be used to determine the impedance through different parts of the connector. We learn the following about the impedance of each region: (1) The cable has a 100Ω impedance; (2) The cable-connector transition has a high impedance; (3) The first part of the connector has a low impedance; (4) The second part of the connector has a lower impedance; (5) The impedance increases as the signal exits the connector; (6) The cable on the other end of the connector has a 100Ω impedance.

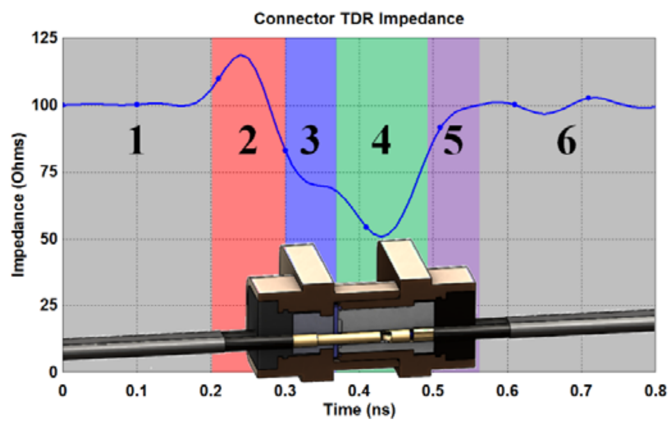

Figure 2. A TDR plot overlaid with the measured connector.

CONCLUSION

The TDR is an extremely helpful tool that can be used to design, optimize, and troubleshoot any high-speed connector design. The goal of this installment was to provide an understanding of how to measure impedance. In the next installment, we will discuss how impedance practically impacts the design of high-speed connectors.

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[1] For an explanation of how high-speed electrical signals travel, see Part I of this series.
[2] ε_R is the dielectric constant of the material and is available on most material datasheets. If multiple materials exist, approximate by using the average.

HIGH-SPEED CONNECTOR DESIGN

PART VI – OPTIMIZING THE IMPEDANCE IN CONNECTORS

In previous installments of this series, we described various theoretical aspects of impedance. In this installment, we will discuss how these concepts practically impact the design of high-speed connectors.

OPTIMIZING THE CONNECTOR IMPEDANCE

There are three goals of connector design that require careful attention in order to ensure that the impedance is optimized: (1) Use a controlled impedance cable, (2) minimize the wire-pin transition, and (3) optimize the pin-to-pin spacing.

USE A CONTROLLED-IMPEDANCE CABLE

A controlled-impedance cable is a requirement for any high-speed application. Wire manufacturers achieve controlled-impedance pairs by closely managing the wire-to-wire spacing and by adding an individual shield for each controlled-impedance twisted pair. The shield reduces the impedance by increasing capacitance, and helps maintain a tighter impedance tolerance by providing a constant spacing between the signal and the ground. Although applications with other target impedance requirements exist, the target impedance for the vast majority of high-speed applications is 100Ω.

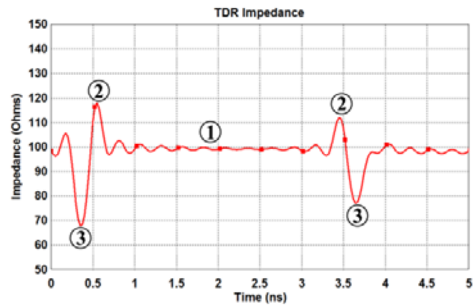

Figure 1. Example of a TDR plot.

Once a controlled-impedance cable is used, a typical TDR plot (which plots impedance – see part V of this series for further explanation) will be similar to what is shown in **Figure 1**. The measurement of the cable **(#1)** shows that the impedance of the cable is 100Ω. The plot also shows the other two primary impedance mismatches that need to be addressed – the high impedance caused by the wire-pin transition **(#2)** and the low impedance caused by the pin-to-pin spacing in the connector **(#3)**.

MINIMIZE WIRE-PIN TRANSITION MISMATCH

The wire-pin transition creates an impedance discontinuity that occurs in nearly every connector. The discontinuity can be minimized, but it can rarely be removed. An example of a wire-pin transition is shown in **Figure 2**. The mismatch occurs for three reasons: (1) the transition requires that a portion of the shield on the twisted pair be removed; (2) the wire spacing changes in order to connect to the pins; (3) the diameter of the wires is often smaller than the diameter of the connector pins. Since any change in cross-sectional geometry will likely change the impedance, all three of these factors will impact the impedance. Although it is often impossible to completely remove this discontinuity, reducing the length of the discontinuity will minimize its impact. By using advanced manufacturing techniques, the length of the unshielded region of the wires can typically be reduced to between 0.1 inches and 0.4 inches (depending on the connector). Once implemented, the performance improves significantly.

Figure 2. Connector showing wire-pin transition (circled).

MODIFY PIN-TO-PIN SPACING

For many applications, using a controlled-impedance cable and minimizing the wire-pin transition mismatch will be sufficient. But for sensitive applications and higher Gigabit data rates, it may be necessary to further improve the performance. For these cases, the next step is to optimize the pin-to-pin spacing. The challenge with this design change is that it will likely require custom parts, adding cost to the design. For this reason, optimizing the spacing is only recommended for applications that require the improved performance.

Figure 1 above revealed that the differential impedance through the connector is low, which is common for most connectors. Because of this, the spacing needs to increase in order to achieve an impedance match. Extensive simulation and measurements have determined that the optimal spacing typically increases the standard pitch by approximately fifty percent. For example, the ideal spacing for a nano connector, typically spaced at 25 mil, is approximately 37.5 mil.

DESIGNING A HIGH-SPEED CONNECTOR

Impedance is one of the most important aspects of a high-speed connector design that needs to be accounted for. By addressing the issues discussed above, a connector will be well on its way to successfully passing the high-speed signals that are required in many of today's applications.