OMNETICS HIGH-SPEED DESIGN

PART I - INTRODUCTION

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.

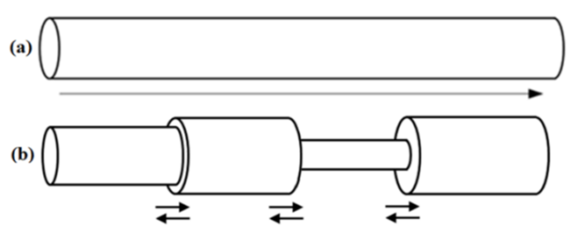

Figure 1

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.

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.

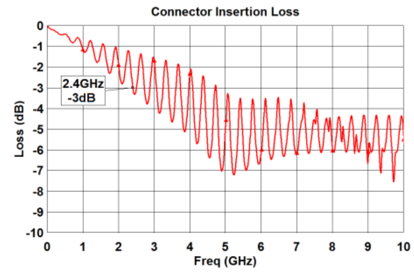

Figure 1

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).

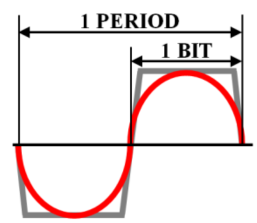

Figure 2

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.

OMNETICS HIGH-SPEED 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.

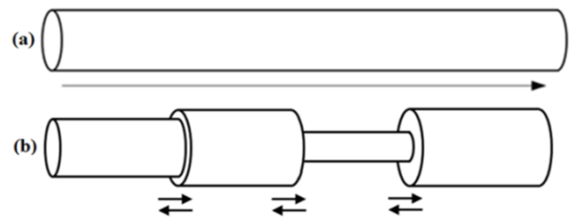

Figure 1

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.

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

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.

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

Equation 1

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

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.

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

*Z = Impedance

Figure 1

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.

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**.

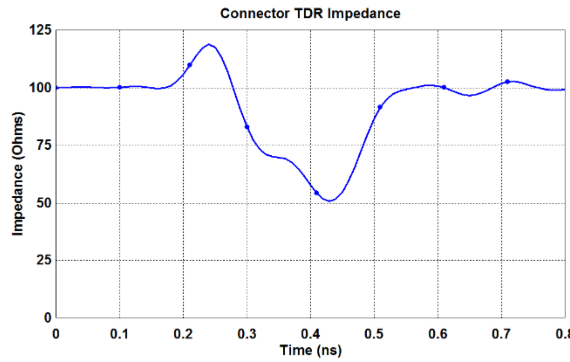

Figure 1. An example of a TDR plot.

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.

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

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.

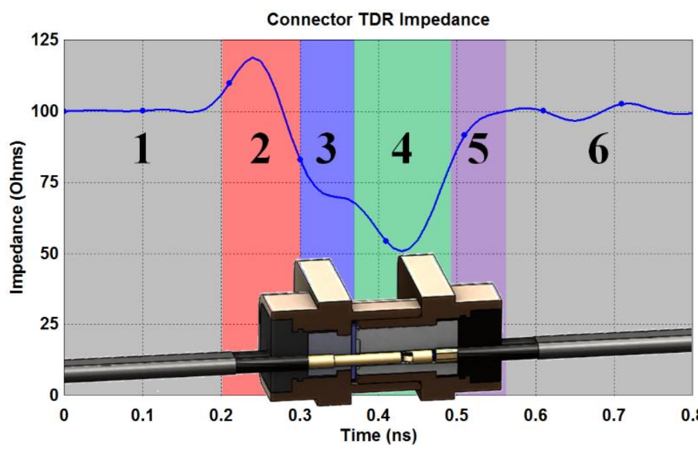

Figure 2. A TDR plot overlaid with the measured connector.

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.

OMNETICS HIGH-SPEED 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.

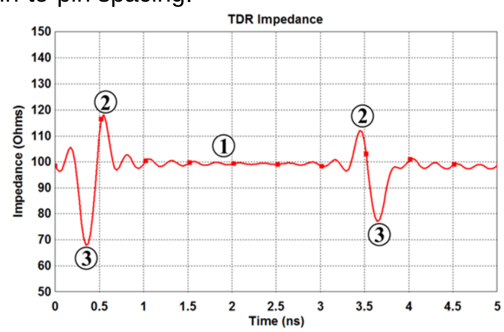


Figure 1. Example of a TDR plot.

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.

OMNETICS HIGH-SPEED DESIGN

Part VII – Differential Signaling

In previous installments of this series, we provided a general overview of the concept of impedance. In this installment, we shift gears to discuss the primary method that high-speed digital signals are transferred: differential signaling.

What is Differential Signaling?

Differential signaling is a method of signal transfer that uses two signal paths. Whereas the alternative, single-ended signaling, transmits signals between one signal path and a reference ground path (**Figure 1a**), differential signaling transmits signals between two signal paths and a reference ground path (**Figure 1b**). In differential signaling, two signals are transmitted with equal and opposite values, with the final result being the difference in voltage between the two signals. Differential signaling is the most common method for transmitting high-speed digital signals.

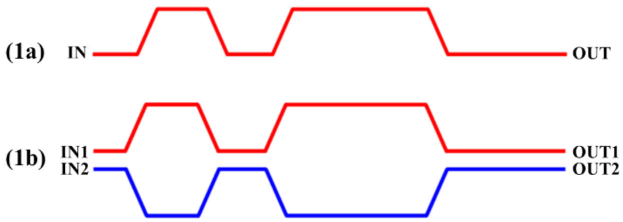


Figure 1. *(1a) Single-ended signal waveform; (1b) differential signal waveform.*

Advantages and Disadvantages of Differential Signaling

Differential signaling is used because it offers advantages over single-ended signaling. The main advantage is improved noise immunity, which minimizes electromagnetic interference (EMI). To understand this, take a look at the signal waveforms in **Figure 2**. The single-ended waveform is shown in **Figure 2a**; the differential waveform is shown in **Figure 2b**.

The spike shown on the waveforms represents some external noise that is introduced into the system. In the single-ended system, the noise will be detected at the output. However, as long as noise appears similarly on both differential lines (which it often does provided the lines are in close proximity), the output of a differential signal will be immune to external noise. This is because the differential system output measures the difference between the two signals, cancelling out the noise at the output. Noise immunity is the biggest advantage that differential signals have over single-ended signals.

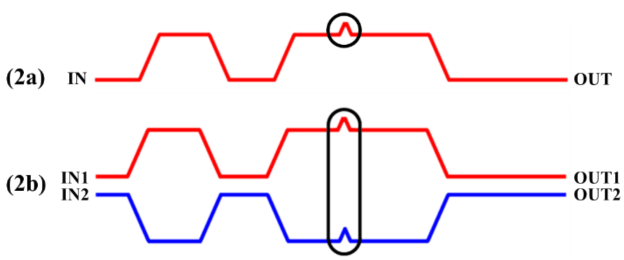


Figure 2. *Impact of noise on (2a) single-ended signals; (2b) differential signals. Noise is highlighted with black.*

The other major benefit, particularly in cables and connectors, is that designing for a 100Ω differential impedance is easier than designing for 50Ω single-ended. Since impedance is a function of geometry, this is simply a matter of physics: Standard non-impedance controlled designs have an impedance that is closer to 100Ω. Therefore, it typically requires less drastic design changes to match a system to 100Ω than it does to match to 50Ω.

The primary disadvantage to differential signaling is that it requires double the signal lines, adding space. This disadvantage, however, is often offset by the significant benefits that are inherent to differential signaling.

Differential Signaling Becoming Increasingly Common

For most applications, the benefits of differential signaling outweigh the drawbacks. This is why we are increasingly seeing differential signaling applications, particularly when it comes to high-speed digital designs.

OMNETICS HIGH-SPEED DESIGN

PART VIII – S-PARAMETERS

S-Parameters are a critical part of the design and simulation of high-speed electronics. In this installment of the high-speed connector design series, we will look at what S-Parameters are, how they are obtained, and how they are used.

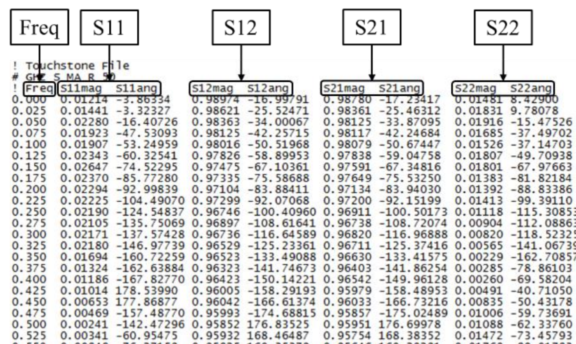
WHAT ARE S-PARAMETERS?

S-Parameters, or Scattering Parameters, are tables of numerical data that are used to describe the electrical behavior of a circuit. S-Parameter files (or Touchstone® files), which include S-Parameter data, are extremely accurate simulation models. They have become the de facto standard electrical simulation model for all passive electrical paths such as cables, connectors, and components.

WHAT INFORMATION IS INCLUDED IN AN S-PARAMETER FILE?

An S-Parameter file, shown in **Figure 1**, consists of a table that details the electrical performance of the path across all relevant frequencies. The relevant information includes S11, S12, S21, S22, with each parameter having a magnitude (mag) value, and an angle (ang) value.

The numbers ('XX' in SXX) denote the Receive-Transmit ports for the measurement. For example, S12 denotes a measurement that is *received at port 1, transmitted at port 2*. Using this notation, the S-terms can be decoded into more easily understood terminology: S11 measures signal reflection, or return loss, at port 1; S12 measures signal transmission, or insertion loss, from port 2 to port 1; S21 measures signal transmission, or insertion loss, from port 1 to port 2; S22 measures signal reflection, or return loss, at port 2. With these four measurement results at all relevant frequencies, an S-Parameter table includes all necessary information to fully characterize the performance of a path.




```
! Touchstone File
# GHZ S MA R 50
```

Freq	S11mag	S11ang	S12mag	S12ang	S21mag	S21ang	S22mag	S22ang
0.000	0.01214	-3.86334	0.98974	-16.99791	0.98780	-17.23417	0.01481	8.42900
0.025	0.01441	-3.32327	0.98621	-25.52471	0.98361	-25.46312	0.01831	9.78078
0.050	0.02280	-16.40726	0.98363	-34.00067	0.98125	-33.87095	0.01916	-15.47526
0.075	0.01923	-47.53093	0.98125	-42.25715	0.98117	-42.24684	0.01685	-37.49702
0.100	0.01907	-53.24959	0.98016	-50.51968	0.98079	-50.67447	0.01526	-37.14703
0.125	0.02343	-60.32541	0.97826	-58.89953	0.97838	-59.04758	0.01807	-49.70938
0.150	0.02647	-74.52295	0.97475	-67.10361	0.97591	-67.34816	0.01801	-67.97663
0.175	0.02370	-85.77280	0.97335	-75.58688	0.97649	-75.53250	0.01383	-81.82184
0.200	0.02294	-92.99839	0.97104	-83.88411	0.97134	-83.94030	0.01392	-88.83386
0.225	0.02225	-104.49070	0.97299	-92.07068	0.97200	-92.15199	0.01413	-99.39110
0.250	0.02190	-124.54837	0.96746	-100.40960	0.96911	-100.50173	0.01118	-115.30853
0.275	0.02105	-135.75069	0.96897	-108.61641	0.96738	-108.72074	0.00904	-112.08863
0.300	0.02171	-137.57428	0.96736	-116.64589	0.96820	-116.96888	0.00820	-118.52325
0.325	0.02180	-146.97739	0.96529	-125.23361	0.96711	-125.37416	0.00565	-141.06739
0.350	0.01694	-160.72259	0.96523	-133.49088	0.96630	-133.41575	0.00229	-162.70857
0.375	0.01324	-162.63884	0.96323	-141.74673	0.96403	-141.86254	0.00285	-78.86103
0.400	0.01186	-167.82770	0.96423	-150.14221	0.96542	-149.96128	0.00260	-69.58204
0.425	0.01014	178.53990	0.96005	-158.29193	0.95979	-158.48953	0.00491	-40.71050
0.450	0.00653	177.86877	0.96042	-166.61374	0.96033	-166.73216	0.00835	-50.43178
0.475	0.00469	-157.48770	0.95993	-174.68815	0.95857	-175.02489	0.01006	-59.73691
0.500	0.00241	-142.47296	0.95852	176.83525	0.95951	176.69978	0.01088	-62.33760
0.525	0.00341	-60.95475	0.95932	168.46487	0.95754	168.38352	0.01472	-73.45793

Figure 1. *Data included in an S-Parameter file.*

HOW ARE S-PARAMETER FILES OBTAINED?

S-Parameter files can be extracted from either simulation or measurement. Measured S-Parameter files are typically extracted from a Vector Network Analyzer (VNA). A VNA sends an AC signal through a path, varying the frequency of the signal from DC up to a specified maximum, usually in the gigahertz range. Simulated S-Parameter files are extracted from a tool that models and predicts the performance of a path, often using highly sophisticated electromagnetic simulations.

HOW ARE S-PARAMETER FILES USED?

S-Parameter files are used to simulate paths that include multiple components, as shown in **Figure 2**. The most common results obtained from these types of simulations are insertion loss, impedance, crosstalk, and eye diagrams.

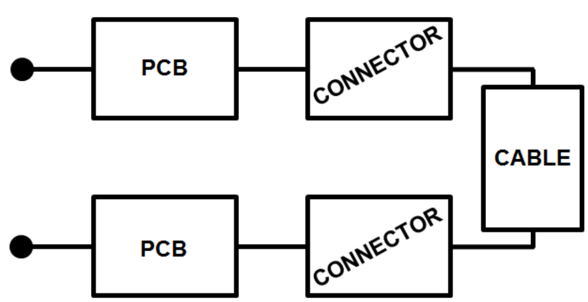


Figure 2. *Cascaded S-Parameter files used for larger simulations.*

S-PARAMETER FILES AT OMNETICS

Omnetics uses S-Parameter files extensively for the high-speed characterization of all products. S-Parameter files are available to everybody for all Omnetics connectors. If you are interested in these models, please contact your local Sales representative.

OMNETICS HIGH-SPEED DESIGN

PART IX – EYE DIAGRAMS

Eye diagrams are helpful measurement tools used to characterize high-speed electronics. In this installment, we will take a closer look into eye diagrams, how they are used, and the strengths and weaknesses of using them.

WHAT ARE EYE DIAGRAMS?

Eye diagrams are oscilloscope displays of digital signals that overlay repeating periods of data upon itself. They provide a much simpler way to view bitstreams of data, which can be millions or billions of bits long.

HOW ARE BITS OF DATA INTERPRETED?

To understand eye diagrams, we must understand how electronics interpret bits of data. Computers don't initially understand bits as 1s and 0s. Instead, bits are interpreted as high and low voltage values which are eventually converted to 1s and 0s. In **Figure 1**, voltage-high (set at 5 V) represents a 1, and voltage-low (set at 0 V) represents a 0.

WHAT ARE EYE DIAGRAMS USED FOR?

Eye diagrams are used to determine whether a path will successfully transfer bitstreams of data at a specific data rate. In order to do this, the circuitry must be able to clearly distinguish the difference between a 0 and a 1 on the incoming voltage waveform.

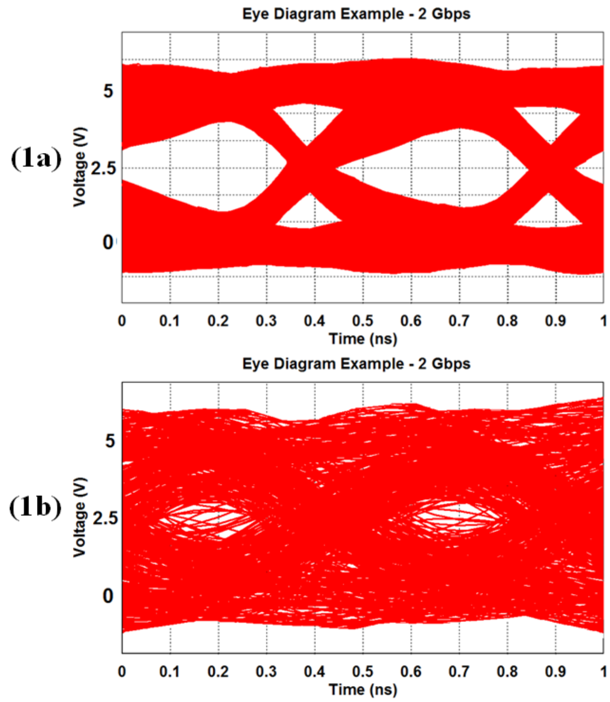


Figure 1. *Examples of eye diagrams; (1a) an open eye; (1b) a closed eye.*

For example, the eye diagram in **Figure 1a** shows distinct differences between 0s and 1s. In this case, the waveform demonstrates an open eye, resulting in a high likelihood that the measured path will successfully transfer the bitstream at the rate of 2 Gbps. Conversely, in **Figure 1b**, the waveform does not display distinct differences between 0s and 1s. This waveform demonstrates a closed eye, and portrays a path which likely will not successfully transfer the bitstream.

STRENGTHS AND WEAKNESSES

As with any measurement, eye diagrams have both strengths and weaknesses. When used properly, eye diagrams provide one of the simplest methods for determining the fidelity of a signal path. By compressing significant amounts of data into one plot, an engineer can quickly predict whether a particular path will successfully pass a specified signal. The biggest weakness, however, is that it is only accurate when characterizing a full signal path. For example, if a cable assembly is only one portion of a signal path, measuring an eye diagram through the cable will not accurate reflect the expected performance through the entire signal path. This can lead to misguided, better than expected, results. With eye diagrams, it is extremely critical to make sure that the measurement includes the entire path of the circuit of interest.

INCREASING IN POPULARITY AND USAGE

Eye diagrams are increasingly being used as the standard method for determining the quality of a digital signal. Based on this, it is important that engineers have a general understanding of their purpose, uses, and benefits.

OMNETICS HIGH-SPEED DESIGN

PART X – DATA RATE REQUIREMENTS FOR VIDEO SIGNALS

Transferring video data often requires a high-speed cable assembly, but it can be difficult to know what speed is actually required. In order to design assemblies that will successfully pass video signals, it is critical to know the rate at which the data is being transferred. In this installment of the High-Speed Connector Design series, we will discuss how to approximate the data rate for a given video signal.

VARIABLES IMPACTING DATA RATE

There are three primary values that must be known in order to approximate data rate:

- **Resolution:** The number of horizontal lines by the number of vertical lines. The most popular examples of this are 1280x720 (known as 720), 1920x1080 (1080), and 3840x2160 (4K).
- **Color Depth:** The number of bits used to produce various color shades. For most high definition video such as HDMI, the color depth is defined as either True Color (8 bits x 3 colors for a total of 24 bits) or Deep Color (10-16 bits x 3 colors for a total of 30-48 bits).
- **Frame Rate:** The number of frames per second (fps). Frame rates typically range from 24 fps to 120 fps, with the most common rates currently remaining on the low end of the spectrum at 24 fps to 60 fps.

CALCULATING DATA RATE

Equation 1 provides a first order approximation for data rate of a video signal. Using this equation, the data rates for three common formats can be determined (see ***Table 1***). This table shows the progression in speeds required to transfer today's data rates. It is important to note, however, that the progression in frame rate and color depth shown in the table does not always follow the progression in resolution. As as example, 4K resolution is not necessarily transmitted at 60 fps and 48-bit color – it can also be 30 fps with 30-bit or 36-bit color.

$$\textit{Data Rate} = \textit{Resolution} \times \textit{Color Depth} \times \textit{Frame Rate}$$

Equation 1. *Simplified equation for data rate of a video signal.*

Video Signal // Color Depth	Horizontal Lines	Vertical Lines	Frame Rate	Color Depth	Data Rate
720p24 8-bit	1080	720	24 fps	24	0.4 Gbps
1080p30 12-bit	1920	1080	30 fps	36	2.2 Gbps
2160p60 (4K) 16-bit	3840	2160	60 fps	48	23.9 Gbps

Table 1. *Examples of data rate based on signal format.*

ADDITIONAL VARIABLES THAT IMPACT DATA RATE

Equation 1 is described as a first order approximation because there are additional variables that may impact the actual data rate. For applications where it is critical to get a precise data rate, make sure the following variables are considered:

- **Interlaced Scan versus Progressive Scan:** Although most signals use progressive scan (i.e. 1080p), interlaced scan (i.e. 1080i) remains an option. Interlaced scans alternate updating the odd number lines and even number lines at each screen update. Since only half the lines are updated each scan, interlaced scans cut the required data rate in half.
- **Horizontal/Vertical Blanking Lines:** Signals often contain additional blank lines that include data that signifies new frames and new lines within a frame. As an example, a 1080p signal with blank lines contains an additional 280 horizontal lines and 45 vertical lines for a total resolution of 2200x1125, instead of 1920x1080.
- **Compression Rate:** Some video signals are compressed and thus transmit at a significantly lower data rate. Compression can reduce the size of the video – and thus the required data rate – by up to 99.5%.
- **Error Correction:** Some signals are transmitted with error correction such as 8b/10b. In 8b/10b error correction, 10 bits are transmitted for every 8 bits of data. The two additional bits are used to eliminate transmission errors, but they also increase the data rate by 25%.

CONCLUSION

This installment provides a way to approximate data rate. Though added variables can make data rate a complex calculation, it is often helpful to have a first order approximation that can be used as a starting point for cable assembly design.

OMNETICS HIGH-SPEED DESIGN

PART XI – DESIGN REQUIREMENTS FOR USB

In previous installments, we provided a technical background for understanding high-speed connector design. In the next few installments, we will detail how to design for some common high-speed standards, starting in this installment with USB.

SPECIFICATIONS AND CONNECTOR TYPES

There is a lot of confusion regarding various descriptions of USB. Some confusion arises from the fact that there are not only multiple specifications for USB (*2.0, 3.0, 3.1 Gen 1, 3.1 Gen 2*), but there are also multiple connector types (Type A, Type B, Type C). To understand performance, we must look to the specification and disregard the connector type, as it is the specification alone that defines the requirements of the path.

Added confusion arose from the release of the *USB 3.1* specification, where the descriptor *USB 3.0* was obsoleted and replaced by *USB 3.1 Gen 1*: What is often described as *USB 3.0* is now officially called *USB 3.1 Gen 1*, and what is typically understood as *USB 3.1* is actually *USB 3.1 Gen 2*.

SPECIFICATION COMPARISON

Table 1 shows the different requirements of the three most commonly used versions of USB. *USB 3.1 Gen 1* is quickly becoming the most popular version of USB as it replaces *USB 2.0* on most new hardware. At the same time, *USB 3.1 Gen 2* is slowly becoming mainstream. It is only a matter of time before all USB connectors will be *USB 3.1 Gen 2*.

As shown, the requirements are tightening as the data rates increase. This is to be expected as higher data rates will inevitably require more robust designs. The tightening impedance specification requires a more controlled design and tighter manufacturing tolerances. The reduced loss – and the higher frequency requirement for the loss – often requires a shorter cable length and a larger gauge wire, where possible.

Specification	Release	Data Rate	Cable Impedance	Connector Impedance	Cable Loss
USB 2.0	2000	480 Mbps	90Ω ± 13.5Ω	N/A	5.8dB @ 400 MHz
USB 3.0 (3.1 Gen 1)	2008	5 Gbps	90Ω ± 7Ω	90Ω ± 15Ω	5.0dB @ 1.25 GHz
USB 3.1 Gen 2	2013	10 Gbps	90Ω ± 5Ω	90Ω ± 10Ω	4.0dB @ 2.50 GHz

Table 1. *Comparison of USB Specifications.*

APPLYING THE SPECIFICATIONS TO CABLE AND CONNECTOR DESIGNS

Simulation and measurement can be used to confirm the impedance and loss through an assembly. The 90Ω impedance specification typically requires an increase in the pin spacing. Advanced manufacturing techniques are also required in order to design for the connector impedance tolerances (±15Ω for *USB 3.1 Gen 1*, ±10Ω for *USB 3.1 Gen 2*). There are no explicit length requirements, but cable lengths should generally be limited to about 10 ft (26 AWG) or 5 ft (30 AWG).

USB 3.0 (3.1 GEN 1) SOLUTIONS

There are multiple solutions available for *USB 3.1 Gen 1* connectors. Some solutions are optimized by placing an open space inside each high-speed pair (***Figure 1a***). This provides an impedance much closer to 90Ω. Other solutions, such as the QuickLock and the USB Circular (***Figure 1b***), are custom designs that address the electrical concerns while maintaining the miniature and rugged mechanical design required for many of today's applications.

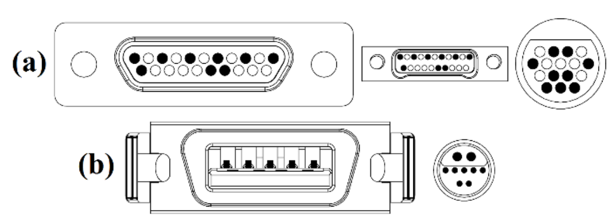


Figure 1. *Solutions for USB 3.0 (3.1 Gen1) Connectors; (a) Standard Solutions; (b) Custom Solutions.*

References: Universal Serial Bus Specifications 2.0 (April 2000, pp 167, 185), 3.0 (June 2011, pp 5-47, 5-49), 3.1 (July 2013, pp 5-45, 5-47); Universal Serial Bus Type C Cable and Connector Specification, April 2015, p 76.

OMNETICS HIGH-SPEED DESIGN

PART XII – DESIGN REQUIREMENTS FOR HDMI

We are in the middle of a series on designing connectors to meet specific standards. In this installment, we will focus on designing for HDMI (High-Definition Multimedia Interface), a common high-speed video standard.

SPECIFICATIONS, VERSIONS, AND CONNECTOR TYPES

There are two different types of HDMI specifications: the overall HDMI specification and the cable specification. The overall HDMI specification, typically HDMI 1.4 or HDMI 2.0, defines the signal requirements and capabilities.

The cable specification defines two different types of cables: Standard Speed (Category 1) and High Speed (Category 2). Standard Speed cables are qualified for 720p and 1080i video. High Speed cables, which include the vast majority of cables available today, are qualified for 1080p, 4K, and 3D video. It is important to note that the cable requirements are defined by the cable specification (Standard Speed or High Speed), not the overall HDMI specification (1.4 or 2.0).

Figure 1. *Standard HDMI (Type A), left; Mini HDMI (Type C), right.*

In addition to the two types of specifications, there are different connector types that define the mechanical dimensions of the connectors. These connector types impact some of the specifications, so it is important to understand which type is being used. The most common connector type is Type A, which is used by most computers and TVs. The other common connector type, Type C or Mini HDMI, is typically used in small, portable electronics.

SPECIFICATION COMPARISON

Table 2 shows the primary requirements for the two types of cables defined in the cable specification. As shown, the main difference between the two specifications is the maximum allowable loss, which decreases from -8dB to -5dB at 825 MHz, and from -21 dB to -12 dB at 2.475 GHz. The other point of interest is the increased tolerance on the Type C connector when compared to the Type A connector. This provides added margin when designing smaller connectors.

Cable Specification	Standard Speed	High-Speed
Category	Category 1	Category 2
Max Resolution	720p/1080i	4K
Cable Impedance	100Ω ± 10Ω	
Type A Connector Impedance	100Ω ± 15Ω	
Type C Connector Impedance	100Ω ± 25Ω	
Max Loss @ 825MHz	-8 dB	-5 dB
Max Loss @ 2.475GHz	-21 dB	-12 dB
Max Intra-pair Skew	151ps	112ps
Max Inter-pair Skew	2.42ns	1.78ns

Table 1. *Comparison of HDMI specifications.*

APPLYING THE SPECIFICATIONS TO CABLE AND CONNECTOR DESIGNS

Simulation and measurement are used to optimize the connectors based on the impedance and loss requirements. The 100Ω impedance specification requires an increase in the pin spacing. This is achieved either through double-spacing the critical pins, or by using a custom insulator designed specifically for HDMI. Designing for impedance requires working to find a balance between manufacturability and electrical performance. There are no explicit length requirements, but cable lengths should generally be limited to about 15 ft (26 AWG), 10 ft (30 AWG), or 6 ft (32 AWG).

HDMI SOLUTIONS

Omnetics offers multiple solutions for HDMI. Some solutions use standard parts while modifying the pinout for optimal impedance (***Figure 1a***). Other solutions are custom designs that provide improved electrical performance while maintaining the miniature and rugged mechanical design that Omnetics is known for (***Figure 1b***).

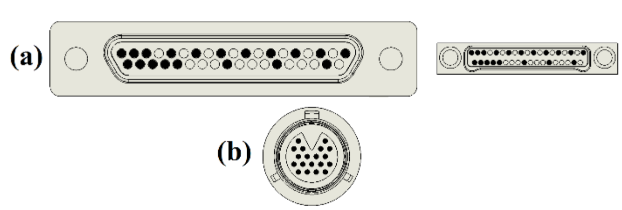


Figure 2. *Solutions for HDMI Connectors; (a) Standard Solutions; (b) Custom Solutions.*

OMNETICS HIGH-SPEED DESIGN

PART XIII – DESIGN REQUIREMENTS FOR ETHERNET

This installment is a continuation of our series on connector design for specific standards. In this installment, the focus will be designing for Ethernet.

SIGNAL SPECIFICATIONS

The two most common Ethernet specifications today are Gigabit Ethernet (GigE) and 10 Gigabit Ethernet (10GbE), which transmit signals at 1 Gbps and 10 Gbps, respectively. However, these rates can be misleading because they do not directly relate to the required bandwidth of a cable/connector assembly. The reasons for this are twofold: (1) Ethernet signals are most often transmitted over four pairs, while connector specifications are typically provided *per pair*; (2) Ethernet implements a signaling scheme called Pulse-Amplitude-Modulation (or PAM) signaling, which allows more data to be transferred through a lower bandwidth connection.

Specification	Gigabit Ethernet	10 Gigabit Ethernet
Abbreviation	GigE	10GbE
Cable	Cat5e or Cat6a	Cat6a
Signaling Type	PAM-5	PAM-16
Data Rate (per lane)	312.5 Mbps	3.125 Gbps
Max Length	100-meter	100-meter
Cable Impedance	100Ω±15Ω	100Ω±15Ω
Cable Shielding	Optional	Recommended
Connector Shielding	Optional	Recommended

Table 1. *Comparison of Ethernet specifications.*

WHAT IS PAM SIGNALING?

PAM signaling transmits more than the standard two values per cycle in order to pass increasingly large amounts of data. ***Figure 1*** shows eye diagrams[1] for three different types of signaling: (1a) traditional binary signaling; (1b) PAM-5 signaling used in Gigabit Ethernet and that allows for five different voltage levels; (1c) PAM-16 signaling used in 10 Gigabit Ethernet that can transmit 16 different voltage levels.

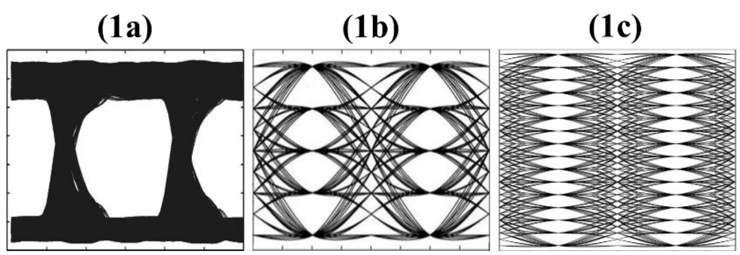


Figure 1. *Standard signaling (1a); PAM-5 (1b); PAM-16 (1c).*

CABLES

There are two primary types of cables that are used for Ethernet: Cat 5e and Cat 6a. Cat 5e is typically used for Gigabit Ethernet, while Cat 6a is typically used for 10 Gigabit Ethernet (though it is reverse-compatible and can also be used for GigE). The primary difference between the two is that Cat 6a provides reduced crosstalk, typically through tighter twisting, individually shielding each pair, and/or the use of a spline inside the cable to isolate each signal pair.

APPLYING THE SPECIFICATIONS TO CABLE AND CONNECTOR DESIGNS

Simulation and measurement are used to optimize the connectors pinouts based on the impedance and loss requirements. Though we recommend double-spacing the pins to meet the impedance for some connectors, single-spacing is sufficient for Ethernet. This is because the impedance requirements are not as stringent and performance requirements can be met without the need to double space. The length requirement of 100-meters provides us with some flexibility when it comes to the cable. Since the vast majority of assemblies are significantly less than 100-meters in length, we can typically tolerate the added loss that may come from a smaller gauge wire. Based on this, wires anywhere from 26 AWG to 32 AWG are used for Ethernet assemblies.

ETHERNET SOLUTIONS

Omnetics offers multiple solutions for Ethernet, offering a solution from all of our major product families. ***Figure 2a*** shows solutions in the Micro families, while ***Figure 2b*** shows solutions in our Nano families.

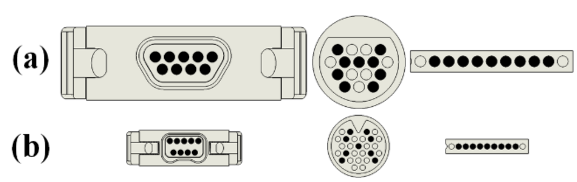


Figure 2. *Ethernet solutions; Micro (2a); Nano (2b).*

[1] For more information on Eye Diagrams, see Part IX of the High-Speed Connector Design Series (Omnetics Newsletter Spring 2016)

OMNETICS HIGH-SPEED DESIGN

PART XIV – EMI SHIELDING IN CONNECTORS

THE PURPOSE OF SHIELDING

Shielding is a critical consideration for many of today's cable/connector assemblies. The purpose of shielding is to minimize or eliminate the transmission of electromagnetic interference (EMI) both into the cable (from external signals) and out of the cable (from internal signals).

CABLE SHIELDING

Shielding the connector is irrelevant unless the attached cable is shielded, so a discussion about connector shielding must consider the cable. The most common types of cable shields are braided shields, foil shields, and a combination of braided and foil shields. Braided shields have good flexibility and flex life but cannot achieve 100% shielding effectiveness (typical effectiveness is between 80% and 95%). Foil shields have excellent shielding effectiveness – up to 100% – but have poor flex life that can often lead to shield cracking. For these reasons, often times the best solution is to use a braided/foil shield combination.

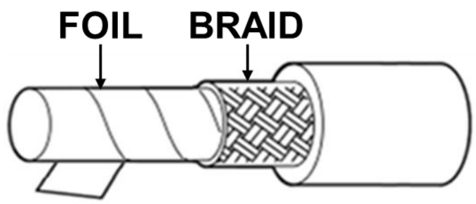


Figure 1. *Cable shielding, including foil/braid.*

CONNECTOR SHIELDING

The shielding of the connector is sometimes an afterthought. If the cable is shielded, it is sometimes assumed that the impact of the connector is unimportant. This, however, is not the case. The connector's roles are is to prevent EMI and provide a continuous path for any shield currents. If there is no path, the currents have no way to exit the shield, and signals will radiate into and out of the cable.

One important consideration with regard to connector shielding is whether to use a metal housing. For low frequency and less sensitive applications, a metal housing may not be necessary. If a metal housing is not used, it remains critical to connect the shield through the connector. This is most often achieved by connecting the shield through a connector pin. For higher frequency and more sensitive applications, a metal housing should be used. If a metal housing is used, the shield should be connected to the housing with a band clamp. Finally, additional braided or foil shields can be considered for maximum coverage.

KEY PRINCIPLES TO CONSIDER

In order to determine an optimal shielding strategy for each specific application, there are two principles to consider:

1) **Shielding requirements increase proportionally to signal frequency.** As a general rule, signals in the low Megahertz may not require a robust shielding strategy. Simply connecting the shield through a pin may be sufficient to meet your application requirements. For signals above approximately 100 MHz, it is recommended that the shield is connected through a metal housing, and signals above 1 GHz should use multiple shields (braided and foil) to eliminate any potential EMI.
2) **Shielding effectiveness is inversely proportional to the largest shield opening.** Considering this principle provides engineers with a very simple and practical first-order approximation of the shielding effectiveness of their assembly. As a general rule, openings should be limited to about 0.500" for 100 MHz signals, and 0.050" for 1 GHz signals.

CONCLUSION

Shielding is an important variable to be considered when designing a cable/connector assembly. It is important to understand the effectiveness of different shielding strategies. Using the principles outlined in this article, engineers can be equipped with a general understanding of when to consider these various strategies.