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Understanding Data Eye Diagram Methodology for Analyzing High Speed Digital Signals

APPLICATION NOTE

Introduction

The data eye diagram is a methodology to represent and analyze a high speed digital signal. The eye diagram allows key parameters of the electrical quality of the signal to be quickly visualized and determined. The data eye diagram is constructed from a digital waveform by folding the parts of the waveform corresponding to each individual bit into a single graph with signal amplitude on the vertical axis and

time on horizontal axis. By repeating this construction over many samples of the waveform, the resultant graph will represent the average statistics of the signal and will resemble an eye. The eye opening corresponds to one bit period and is typically called the Unit Interval (UI) width of the eye diagram. An ideal digital waveform with sharp rise and fall times and constant amplitude will have an eye diagram as shown in Figure 1 below.

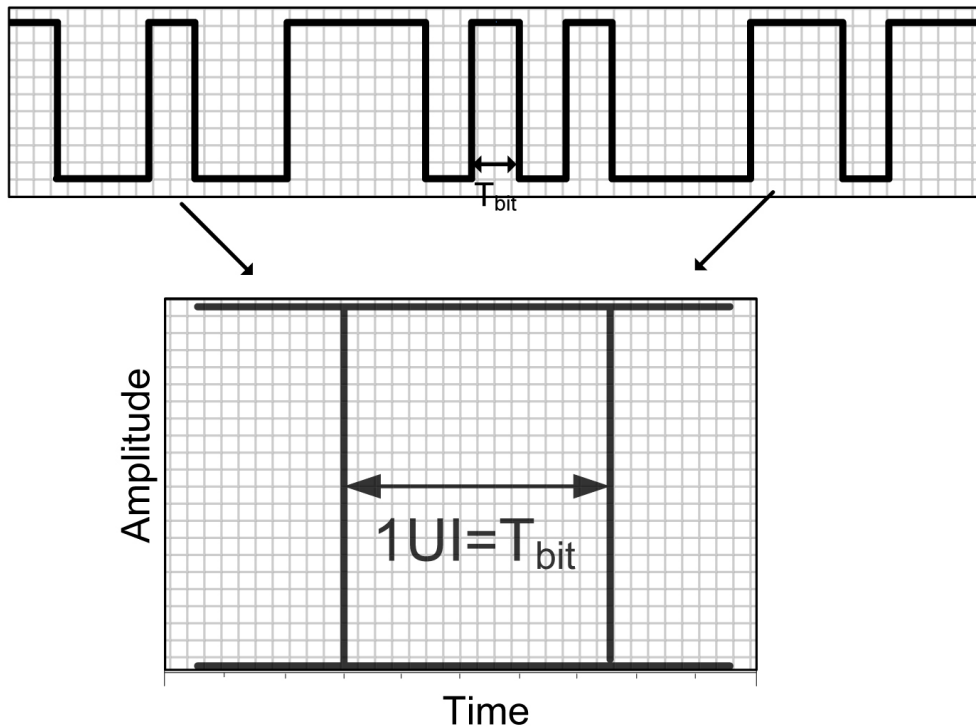


Figure 1. Ideal High Speed Digital Signal with Eye Diagram

Obviously, this ideal eye diagram offers little additional information beyond the time domain waveform display. Real world high speed digital signals suffer significant impairments including attenuation, noise, crosstalk, etc.

The data eye diagram for a typical high speed digital signal is shown in Figure 2 below. Notice how the diagram more resembles the shape of an eye.

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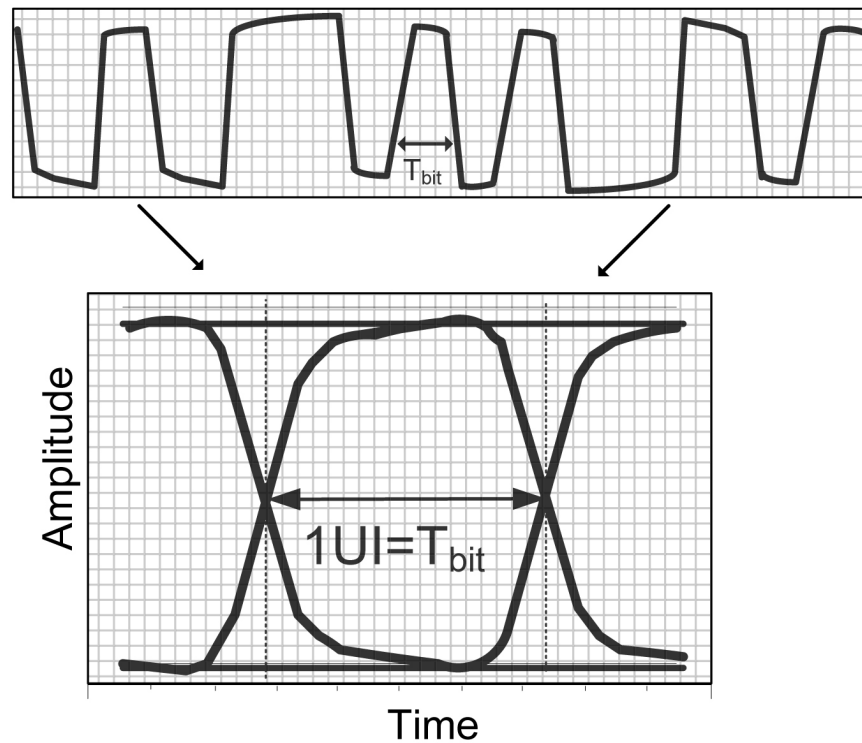


Figure 2. Typical High Speed Digital Signal with Eye Diagram

Data Eye Diagram Fundamentals

High Speed Digital Signaling

Digital signaling is the transmission of baseband data over a cabled connection. This data is usually modulated or coded according to the telecommunication protocol set as a standard for the intended interface. The type of baseband coding (commonly called Line Coding) chosen for a standard best optimizes performance, given the electrical characteristics of the data and the transport medium. Legacy high-speed digital standards including USB 1.1/2.0 use a form of non-return to zero (NRZ) for the data coding where a high (positive) pulse represents a logic one and a low (negative) pulse a logic zero. By controlling the data format (i.e., bit stuffing, etc) to make the number of ones and zeros equal, NRZ waveforms can be DC balanced and limit the DC content in the signal. This allows the signal to be capacitively (or AC) coupled and also provides common mode voltages or DC power to be combined with the signal on the same cable.

Baseband coding using return-to-zero (RZ) signaling is usually not used on high-speed digital interfaces because it has excessive bandwidth requirements due to its inherent DC imbalance which in turn adds significant DC content.

Besides controlling DC content and bandwidth, data formatting can also enable clock recovery for the high speed signal. For reliable clock recovery at the receiver, the maximum number of consecutive ones or zeros needs to be bounded to a reasonable number since the waveform clock is recovered by observing transitions in the received

sequence. A common method to bound the number of ones and zeros in a waveform is to use 8b/10b encoding. 8b/10b is a line code that maps 8-bit symbols to 10-bit symbols to provide DC-balance for the waveform and also provide enough state changes to allow reasonable clock recovery.

After line coding, the signal is put through a physical channel. The line-coded signal can either be directly put on a transmission line or can be level shifted and pulse shaped to reduce its bandwidth, improve EMI/RFI performance or match system interfacing requirements. Low Voltage Differential Signaling (LVDS) is a commonly used interface standard for high speed digital signals. By providing a relatively small signal amplitude and tight electric and magnetic field coupling between the two differential lines, LVDS significantly reduces the amount of radiated electromagnetic noise and power lost to conductor resistance.

Eye Diagram Basics

As stated previously, the data eye diagram is a representation of a high speed digital signal that allows key parameters of the electrical quality of a signal to be quickly visualized and determined. The requirements for high speed data signals mentioned in the previous section are some of the key metrics that can be measured using eye diagrams.

Eye Diagrams are used to characterize a high speed signal source or transmitter (receiver testing usually requires bit error rate testing). A typical eye diagram test setup is shown in Figure 3 below.

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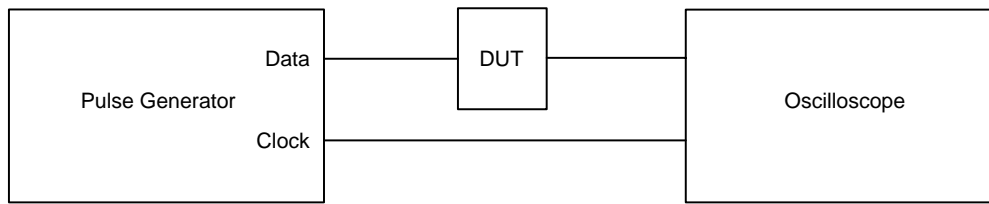


Figure 3. Eye Diagram Test Setup

The Pulse Generator is required to generate a random bit pattern since the eye diagram is a statistical average of many thousands or even millions of samples of a waveform. The pattern required for a particular data standard is defined by the protocol and is usually a pseudorandom bit sequence of hundreds or thousands of bits. The high speed sampling oscilloscope has a typical bandwidth of 10 to 25 GHz in

order to capture the full characteristics of the waveform. Using the persistence mode of the oscilloscope, the superposition of millions of time-domain waveforms can be displayed.

A representative eye diagram is shown below along with some of the typical measurements that can be performed on the diagram.

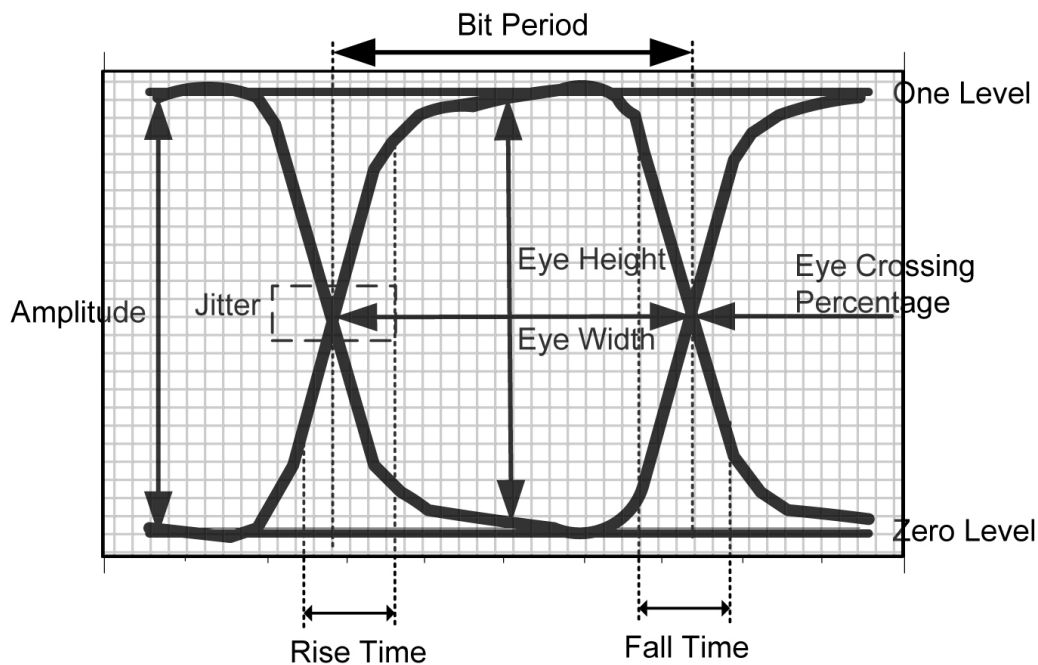


Figure 4. Typical Eye Diagram Measurements

All of the measurement results are the statistical average of the samples of the waveform at the point shown. The measurements are defined as follows:

One Level

The one level in an eye pattern is the mean value of a logic one. The actual computed value of the one level comes from the histogram mean value of all the data samples captured inside the middle 20% (40 to 60% points) of the eye period.

Zero Level

The zero level in an eye pattern is the mean value of a logic zero. The zero level is computed from the same 40 to 60% region of the baseline area during the eye period as the one level.

Eye Amplitude

Eye amplitude is the difference between the one and zero levels. The data receiver logic circuits will determine whether a received data bit is a "0" or "1," based on the eye amplitude.

Eye Height

Eye height is a measure of the vertical opening of an eye diagram. An ideal eye opening measurement would be equal to the eye amplitude measurement. For a real eye diagram measurement, noise on the eye will cause the eye to close. As a result, the eye height measurement determines the eye closure due to noise. The signal to noise ratio of the high speed data signal is also directly indicated by the amount of eye closure.

Eye Crossing Percentage

The crossing level is the mean value of a thin vertical histogram window centered on the crossing point of the eye diagram. The eye crossing percentage is then calculated using the following equation:

$$\text{Eye Crossing \%} = 100 * [(\text{crossing level} - \text{zero level}) / (\text{one level} - \text{zero level})]$$

Eye crossing percentage gives an indication of duty cycle distortion or pulse symmetry problems in the high speed

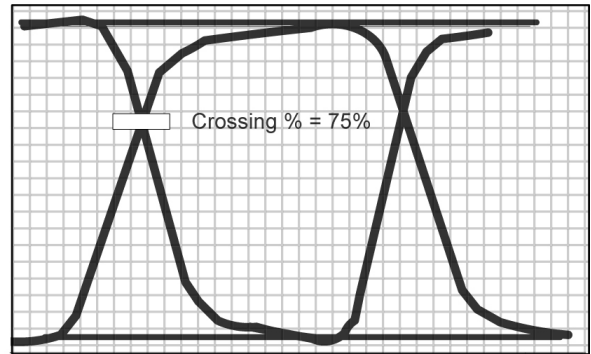
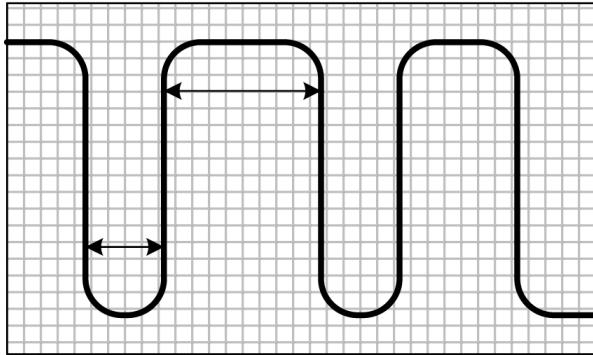


Figure 5. Waveform and resultant eye diagram with 75% eye crossing percentage

Bit Period

The bit period is a measure of the horizontal opening of an eye diagram at the crossing points of the eye and is usually measured in picoseconds for a high speed digital signal (i.e., 200 ps is used for a 5 Gbps signal). The data rate is the inverse of bit period (1/bit period). The bit period is commonly called the Unit Interval (UI) when describing an eye diagram. The advantage of using UI instead of actual time on the horizontal axis is that it is normalized and eye diagrams with different data rates can be easily compared.

Eye Width

Eye width is a measure of the horizontal opening of an eye diagram. It is calculated by measuring the difference between the statistical mean of the crossing points of the eye.

Rise Time

Rise time is a measure of the mean transition time of the data on the upward slope of an eye diagram. The measurement is typically made at the 20 and 80 percent or 10 and 90% levels of the slope.

Fall Time

Fall time is a measure of the mean transition time of the data on the downward slope of an eye diagram. The measurement is typically made at the 20 and 80 percent or 10 and 90 percent levels of the slope.

Jitter

Jitter is the time deviation from the ideal timing of a data-bit event and is perhaps one of the most important

data signal. Figure 5 below shows an example of a waveform with bad pulse symmetry (shown left) with the resultant eye diagram with eye crossing of 75% (shown right). Eye crossing percentage is valuable for measuring amplitude distortions caused by differences in the one- and zero-level durations. It also reveals pulse symmetry problems for diagnosis. When the eye crossing symmetry value deviates from the perfect 50% point, the eye closes and thus the electrical quality of the signal is degraded.

characteristics of a high speed digital data signal. To compute jitter, the time deviations of the transitions of the rising and falling edges of an eye diagram at the crossing point are measured. Fluctuations can be random and/or deterministic. The time histogram of the deviations is analyzed to determine the amount of jitter. The p-p jitter is defined as the full width of the histogram, meaning all data points present. RMS jitter is defined as the standard deviation of the histogram. The units for a jitter measurement on a high speed digital signal are normally in picoseconds.

Differential Signals and Differential Eye Pattern Measurements

Differential signals offer superior noise immunity and overall improved signal integrity, which is highly desirable in the transmission and distribution of high-speed signals. Techniques for conducting eye pattern measurements involve using trace math operations to view these signals both separately and as a pair. On a modern high speed oscilloscope, eye and pulse pattern measurements can be measured separately (Ch1 and Ch2) and with trace math (Ch1 - Ch2, Ch1 + Ch2). By examining and overlaying measurements of the signal both separately and combined, differential and common mode effects including skew caused by common mode imbalance and noise can be determined.

Eye Pattern Diagnostics and Mask Compliance

The quality of a high speed digital signal can be quickly determined by using a compliance mask overlay on the eye

diagram display. A typical mask includes both time and amplitude limits. An eye diagram with compliance masks is shown in Figure 6 below.

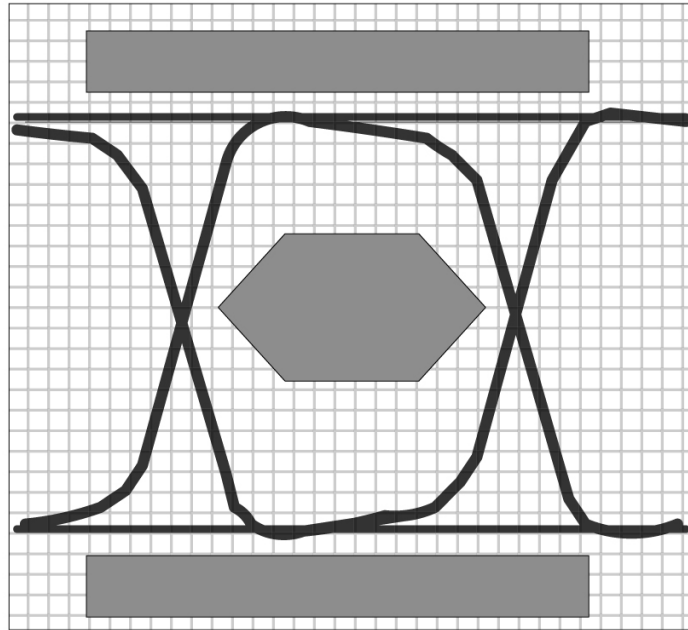


Figure 6. Eye Diagram with Compliance Mask

In the above diagram, the gray block areas represent “keep-out” areas. In order to pass the mask compliance test, the transmitter output must not have ANY samples fall within the “keep-out” regions.

The mask regions are defined as follows:

- Top region: The maximum expected value. Voltages exceeding this value will fail.
- Middle Region: The size and shape of the eye diagram as defined by the interface standard for the high speed digital signal.
- Bottom Region: The minimum expected value. Voltages below this value will fail.

Lowest Capacitance Products for High Speed Signal Quality

It is vital for high speed interfaces to maintain impedance matching throughout the signal paths. Any traditional ESD, surge or filter components added to the signal paths must

have minimum capacitance so the signal quality can be maintained at the highest level. Today’s highest speed interfaces such as USB 3.0, eSATAIII, HDMI®, and Thunderbolt™ require stringent capacitance limits for external components added to the signal paths. ON Semiconductor manufactures a wide line of ultra-low capacitance ESD protection devices for high speed interfaces. Below is a partial list of the products.

- ESD7004, ESD7016, ESD7008, MG2040

Figure 7 below shows an example of a data eye diagram for USB 3.0 interface without any ESD protection device placed on the differential signal path. Immediately below Figure 7, an eye diagram is shown using ON Semiconductor’s ESD7016 as the ESD protection device placed on the differential signal path. This eye diagram shows that ESD7016 has minimum impact on the data signal.

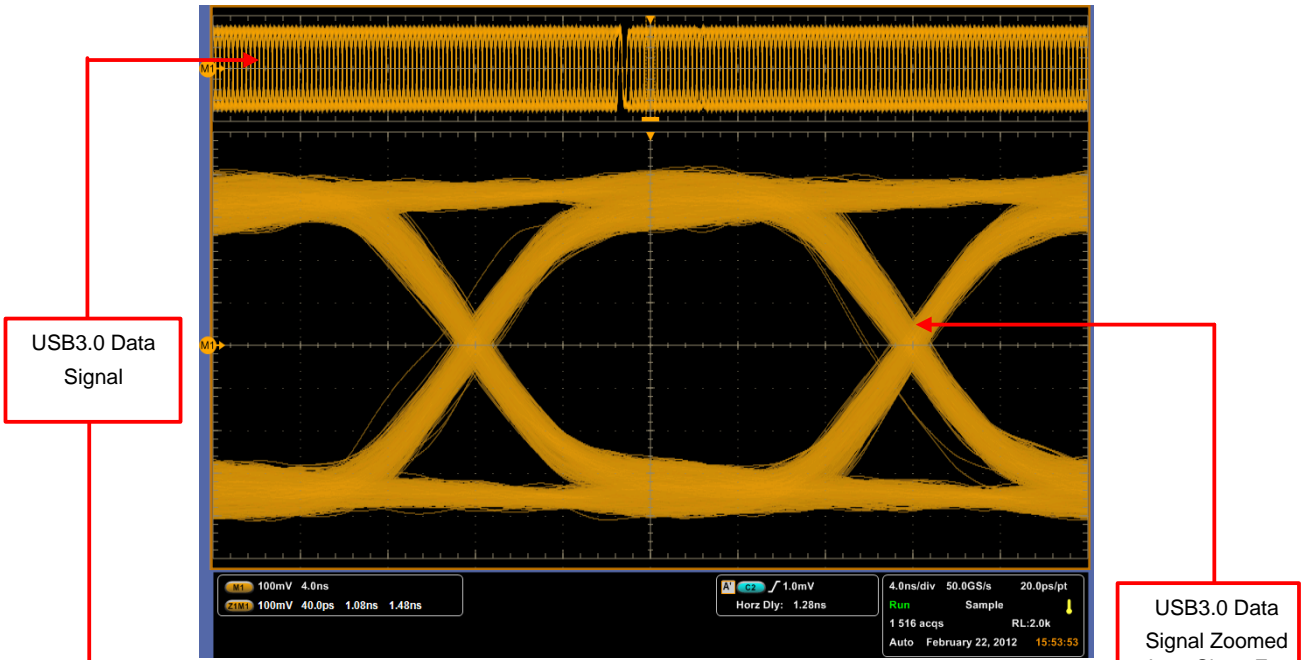


Figure 7. USB3.0 Eye Diagram without ESD Protection

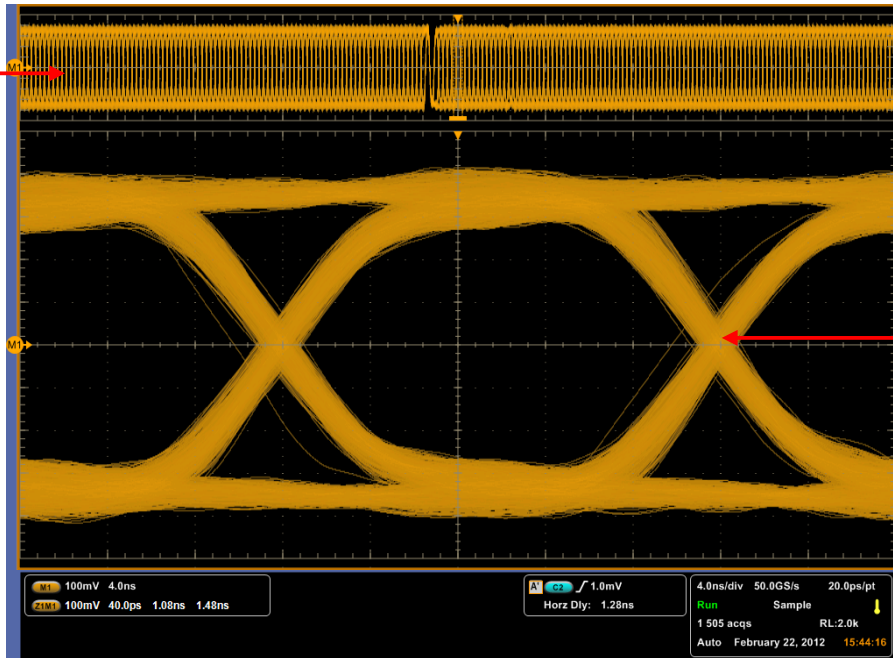


Figure 8. USB3.0 Eye Diagram with ONsemi ESD7016

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Summary

As high speed digital signals exceed many gigabit per second speeds, eye diagrams provide the means to quickly and accurately measure signal quality and system performance. ON Semiconductor understands the

capacitance constraints that designers are faced with when using these high speed interfaces and offers a wide line of ultra-low capacitance ESD protection devices that service these interfaces.

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