**Eye diagrams: The tool for serial data analysis**

Arthur Pini - June 04, 2019

The eye diagram is a general-purpose tool for analyzing serial digital signals. It shows the effects of vertical noise, horizontal jitter, duty cycle distortion, inter-symbol interference, and crosstalk, all of which can close the "eye." While engineers have used eye diagrams for decades, oscilloscopes continually get new features that increase its value.

Oscilloscopes form eye diagrams—the separation between the two binary data states "1" and "0"—by overlaying multiple single clock periods on a persistence display. The accumulation (Figure 1) shows the history of multiple acquisitions.

**Figure 1.** The eye diagram displays multiple data bits using a duration of slightly longer than a single bit period on a persistence display. The bottom trace is the eye diagram for a data stream clocked at 5 GHz. The duration of the eye diagram is 268 ps, about 34% greater than the 200 ps clock period, letting two adjacent eye crossings be visible at once.

The bottom trace is the eye diagram for a serial data stream clocked at 5 GHz while the top trace shows the acquired time-domain signal. A horizontally expanded view is shown in the second trace from the top. A color-coded selection of elements from the zoom trace are overlaid in the third trace from the top showing how the eye is formed. The eye diagram that uses persistence display (bottom trace) shows the history of multiple data states; in this example the eye contains 97,000 serial data bits. The eye opening is a qualitative evaluation of the quality of the serial data channel. The greater
the area of the eye opening the better the channel signal integrity.

Additive noise tends to close the eye vertically while timing jitter and uncertainty closes the eye horizontally. Duty cycle distortion (DCD) and inter-symbol interference (ISI) change the shape of the eye. The channel will fail if the eye closes to the point where the receiver can no longer recognize “0” and “1” states.

In the days of analog oscilloscopes, the eye diagram was formed by triggering the oscilloscope with the serial data clock and acquiring multiple bits over time using a persistence or storage display. This technique adds the trigger uncertainty or trigger jitter to the eye diagram for each acquisition. Digital oscilloscopes form the eye by acquiring very long record with many serial bits. The clock period is determined, and the waveform is broken up or "sliced" into multiple single-bit acquisitions overlaid in the persistence display. In this way, all the data is acquired with a single value of trigger jitter that’s eliminated by using differential time measurements within the eye. You can obtain a more quantitative evaluation of the eye opening using eye measurement parameters as shown in Figure 2.

![Eye Diagram](image)

**Figure 2.** The main measurement parameters associated with eye diagrams include bit period, zero level, one level, eye amplitude, eye height, eye width, and eye crossing.

Eye measurement parameters are based on a statistical analysis of multiple measurements.

- **Zero level:** The mean value of the logical zero of the eye diagram.
- **One level:** The mean value of the logical one level of the eye diagram.
- **Bit period:** The time difference between the means of two adjacent crossing points.
- **Eye amplitude:** A measure of the overall amplitude of the eye. It is based on the difference between the simple mean of the one level and the simple mean of the zero level. It is generally measured near the center of the eye.
- **Eye height:** This is a measurement of the vertical eye opening; basically, a determination of the signal-to-noise ratio, starting with the difference of the mean of the one level and mean zero level then subtracting the standard deviations of the zero and one levels.
- **Eye width:** The eye width gives an indication of the total horizontal jitter in the signal. Like eye height, the width measurement is statistical in nature. The horizontal histograms of two adjacent
crossing points are used to find the mean and standard deviations of crossing times. The standard deviation of each distribution is subtracted from the difference of the two mean values.

- **Eye crossing:** The eye crossing is the amplitude point at which the zero-to-one and one-to-zero transitions reach the same amplitude—the point rising and falling edges intersect. Eye crossing is expressed as a percentage of the total eye amplitude. An ideal eye will have crossings at 50% of amplitude.

Using a histogram from the key elements of the eye, you can perform statistical analysis to evaluate the eye diagram. One technique is to use a persistence histogram formed by counting pixels in a thin strip on the persistence map of the eye, as shown in **Figure 3**. To calculate the eye width, a persistence histogram is formed by counting pixels in a thin horizontal strip running through the eye crossings as marked by the dotted line in the figure. The oscilloscope finds mean and standard deviation of both crossings. The bit period is the difference between the mean values. The eye width is calculated by subtracting both standard deviations from the bit period.

**Figure 3.** Use a horizontal persistence histogram to calculate the bit period and the eye width based on the mean and standard deviations of the histograms. The histograms are formed by counting pixels in a thin horizontal strip passing through the eye crossings.

Similarly, the oscilloscope derives zero level, one level, eye amplitude, and eye height from the persistence histogram of the vertical slice through the largest vertical opening in the eye (**Figure 4**).
The lower mean value of the two distributions is the zero-level shown to the left. Likewise, the higher mean value is the one-level shown to the right. Eye amplitude is the difference between the two mean values. The eye height is the eye amplitude minus the sum of the two standard deviations of the zero and one level distributions. **Eye masks**

Eye diagrams can be the basis of automated pass-fail testing. By using an eye mask to assure that the eye has a sufficient opening and that overshoot or undershoot is not exceeding specification limits, an oscilloscope can verify correct operation (**Figure 5**).
In this case, the eye mask consists of a trapezoidal inner mask to check the eye opening and outside limits to assure the signal overshoot or undershoot doesn’t exceed test limits. While the mask provides an obvious visual confirmation of correct operation, the operation can also be automated. Most mid-range and higher oscilloscopes offer mask testing, but application-specific compliance tests include more specialized mask testing using serial standard specific masks such as Ethernet or PCIe.

The eye diagram shows the effects of both amplitude and timing variations. But it only shows the quality of the transmission over the number of bits contained in the persistence history. Modern serial data analysis software can extrapolate the acquired data and show eye openings for lower bit error ratios (BERs) than supported by the actual acquired data. **Figure 6** shows an eye diagram with a superimposed IsoBER plot. This may also be called a BER contour plot.

![Figure 6](image.png)

**Figure 6.** An eye diagram with a superimposed IsoBER provides contour lines of constant bit error ratios. In this example, it shows the extrapolated eye openings for BER of from 1E-6 to 1E-12.

The IsoBER, a title coined from the prefix Iso, which means same, and suffix BER, is a contour map showing lines of constant bit-error ratio. BER is the number of bit errors encountered divided by the total number of bits transmitted. The ratio is dimensionless, expressed in this application as a simple ratio. The outer contour in the figure represents a BER of 1E-6. This represents one-bit error for each one million bits sent. The BER decrements by one order of magnitude for each contour. The innermost contour represents a BER 1E-12. As the BER decreases, the number of bits involved increases and the eye will tend to close. The range of BER values and the increment is user programmable to allow customizing the display.

IsoBER plots allow visualization of both amplitude variations, such as noise and crosstalk, as well as time-related errors like jitter. IsoBER plots tend to be more sensitive to amplitude defects that occur with low probability such as crosstalk.

The eye diagram is a powerful tool for analyzing serial data. From its basic qualitative visualization to its more quantitative investigation tools using the eye parameters and mask testing, and finally, to predictive capabilities using the IsoBER contours. The eye diagram has a long history of usefulness which continues to be expanded by newer analysis features.
Arthur Pini is a technical support specialist and electrical engineer with over 50 years experience in electronics test and measurement.

Related articles:

- Eye Diagram Basics: Reading and applying eye diagrams
- How to relate eye-mask tests to BER
- Evolution of the eye diagram
- The difference between BER and BER
- Oscilloscope articles by Arthur Pini