

# Anatomy of an Eye Diagram — a Primer

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This paper describes what an eye diagram is, how it is constructed and common methods of triggering used to generate one. It then describes different ways that information from an eye diagram can be sliced to gain more insight. It also discusses some basic ways that transmitters, channels and receivers are tested. It is designed to give an engineer new to this field a basic grasp of the concepts commonly used.

## Eye Measurement Basics

Eye diagrams are a very successful way of quickly and intuitively assessing the quality of a digital signal. A properly constructed eye should contain every possible bit sequence from simple 101's and 010's, through to isolated ones after long runs of consecutive zeros and other problem sequences that often show up weaknesses present in system design.

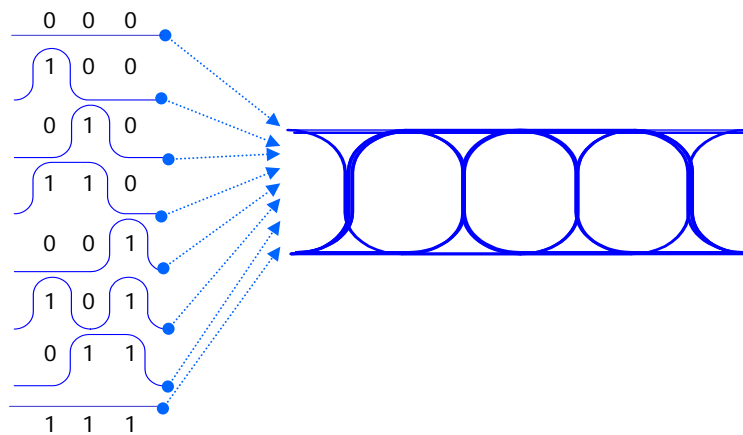


Figure 1: Overlaying of bit sequences to form an eye diagram.

## What does it show?

Eye diagrams show parametric information about the signal – effects deriving from physics such as system bandwidth health etc. It will not show protocol or logical problems – if a logic 1 is healthy on the eye, this does not reveal the fact that the system meant to send a zero. However, if the physics of the system mean that a logic one becomes so distorted while passing through the system that the receiver at the far end mistakes it for a zero, this should be shown in a good eye diagram.

Common ways of characterizing an eye are to measure the rise times, fall times, jitter at the middle of the crossing point of the eye, the overshoot present and many other numerical descriptions of eye behavior in order to compare devices being measured. Instruments usually offer automated measurements that simplify and speed up the taking of such measurements.

## The Effects of Triggering on Eye Diagrams

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Many eye diagrams are constructed on test equipment that uses test patterns that repeat, such as PRBS patterns generated by a BERT (Bit Error Ratio Tester). Such equipment can commonly generate a variety of trigger signals:

- 1) A **clock trigger** at the same rate as, and synchronous with the data signal
- 2) A **divided clock trigger** at some divide ratio of the data rate often related to a power of 2 such as  $\div 4$ ,  $\div 16$  etc.
- 3) A **pattern trigger** – a signal that provides a trigger once per pattern repetition.
- 4) The **data** itself can be used as a trigger.
- 5) The last option is to derive the trigger signal by using **clock recovery** on the data signal.

Each method provides different results when used to construct a waveform.

*Clock Trigger* provides a classical eye diagram containing all possible bit transitions in one display

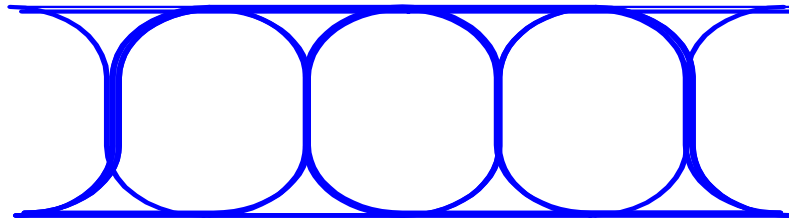


Figure 2: An eye diagram formed with a full rate clock trigger

**Divided Clock Trigger** also produces an eye diagram, and this can be useful when the instrument being used to construct the eye has a trigger input bandwidth narrower than the data rate of the signal being viewed. This method can produce a good eye *unless* the pattern length divided by the divide ratio yields an integer – for example a 128-bit pattern viewed with a  $\div 4$  clock. In this case, the trigger signal will coincide with the same bits in the pattern each time while consistently missing other parts of the pattern – leading to an incomplete eye.

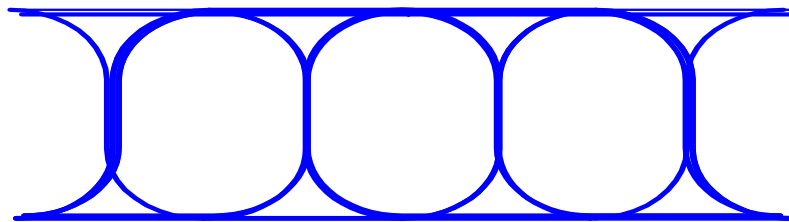


Figure 3: An eye diagram formed with a divided clock trigger

**Pattern Trigger:** Used to display individual bits in the pattern. To view the whole pattern, the user must scroll through by altering either the time base of the scope or the pattern trigger position. Scrolling using the extent of a scope time base can lead to increased apparent jitter on the displayed signal due to weaknesses in time base circuitry; incrementing a pattern trigger, either within the BERT or within some more sophisticated scopes is preferable to avoid this problem.



Figure 4: A bit sequence captured using a pattern trigger

**Triggering on Data** is the least satisfactory method of constructing an eye and should only be used as a quick look-see. Long runs of identical characters provide no transitions to trigger from, and so a complete eye is almost impossible to achieve.

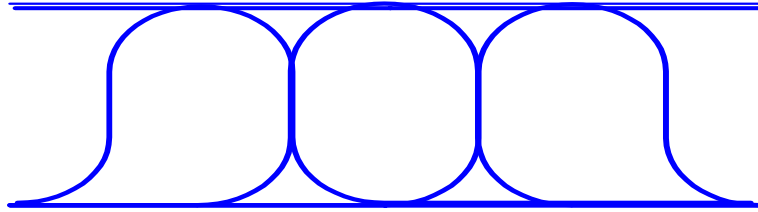


Figure 5: An incomplete eye diagram formed by triggering on data

**Triggering from a Recovered Clock:** While increasing complexity, this method has some advantages:

- In some situations a clock signal is not available and so must be derived
- In other cases, particularly long distance fiber optic communications, the relationship between the clock at the transmit end and the data at the receive end may be corrupted by rapidly time-varying effects in the transmission path.
- Lastly in cases where the receiver uses clock recovery and the eye as seen by the receiver needs to be examined – this can be required by some standards, particularly for jitter testing.

Circuits used for recovering clock typically have a loop bandwidth, or filtering function, that removes from the clock signal some of the jitter that was present on the data signal. Depending upon the measurement being made, this can be helpful or hurtful, but needs to be understood.

**Narrow loop bandwidth clock recovery** tends to give a rock solid clock trigger signal as the reference, and any jitter, or movement of edges with time, in the data eye diagram that is present will be displayed. This is a useful absolute measure but might not properly represent the jitter seen by a real system if the receiver uses clock recovery to track some of the jitter out.

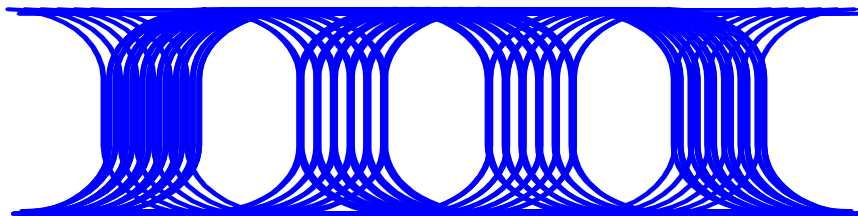


Figure 6: An eye diagram triggered from a clock recovered from the data signal using a narrow loop bandwidth clock recovery scheme.

**Wide bandwidth clock recovery** tends to let more of the jitter that was present on the data signal through on to the clock. This can mean that as the data jitters by moving edges in one direction, then the other; the recovered clock tracks it, and the resulting eye appears to have very little jitter present on it. This tracking function is the way many system receivers work to reduce the jitter passed on through the system.

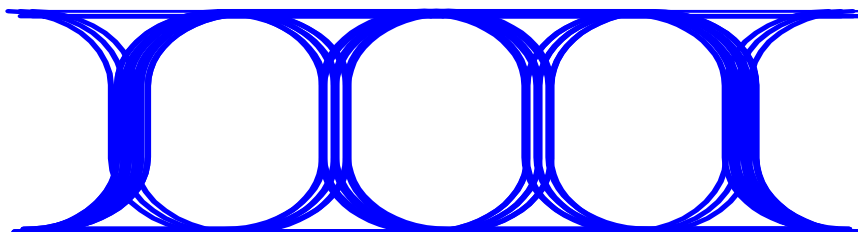


Figure 7: An eye diagram triggered from a clock recovered from the data signal using a wide loop bandwidth clock recovery scheme.

Conditions can also conspire to create the opposite effect – where the delay between data signal and trigger signal is such that when the data edges are moving to their furthest extent in one direction, the recovered

clock signal being triggered from it is moving to its furthest extent in the other, and the resulting eye shows as much as twice the jitter that was present on the data signal.

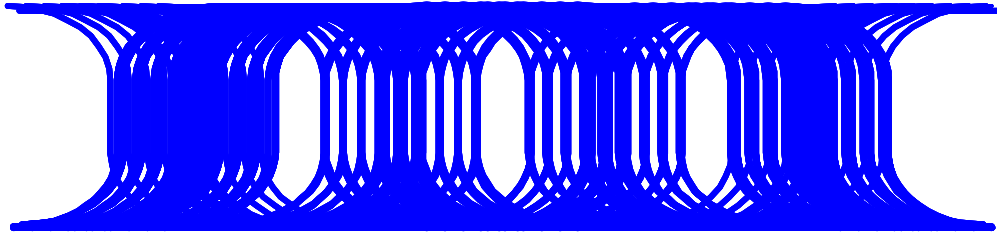


Figure 9: An eye diagram triggered such that the delay between jittered clock and jittered data destructively interferes.

While the last situation is seldom desirable, the first two situations, where all jitter is shown and where most jitter is tracked out, have their uses depending upon what information is being sought with the measurement. Luckily, most standards specify what triggering scheme is required to make measurements.

## Eye Diagrams and BER

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While eye diagrams provide an accessible and intuitive view of parametric performance, systems ultimately are judged on their ability to pass bits faithfully, and without error. The BER, Bit Error Ratio, or Bit Error Rate as it is sometimes called, is a ratio of the number of bits received incorrectly (errors) divided by the total number of bits received. This provides an overall score for how well a system is performing, but provides little help on why performance might be below expectations. It should be noted that BER tests logical problems as well as parametric ones – whether the correct bit was sent in the first place.

So why don't eye diagrams and BER easily link together? A perfect eye diagram would show all parametric aspects of all possible bit sequences, irrespective of how infrequently some effects show up. In other words, it would have a high information depth. Typically, eye diagrams are composed of voltage/time samples of the original data, acquired at some sample rate that is orders of magnitude below the data rate. For sampling oscilloscopes, this can be 105 samples per second at a 10 Gb/s (1010 bits/second) rate. This means that most eye diagrams are composed of shallow amounts of data.

This becomes a problem when issues arise that are infrequently occurring. These can be pattern related, noise related or deriving from other effects such as crosstalk and other forms of interference. These may not be visible in an oscilloscope eye diagram, but prevent link performance to desired levels. For example, links are often required to work to better than one error in a million, million bits ( $1 \times 10^{-12}$  BER), while eye diagrams struggle to show events with probabilities below an occurrence of  $1 \times 10^{-5}$ .

This leaves an information gap that can be solved in a number of ways. The first is to construct the eye diagram from voltage/time measurements taken with an architecture that has a higher sampling efficiency. Systems such as the BERTScope are capable of perhaps three orders of magnitude more depth than sampling scopes.

The second solution is to use the fact that a BERT samples data directly at the line rate, and so is better equipped to see rare events that will limit system performance.

## Slicing the Eye

Typical receivers are designed to make a decision at an instant in time as to whether the signal is above or below a particular threshold voltage.

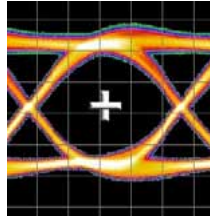


Figure 10: A receiver decision point in the center of the eye.

From this it decides whether the incoming signal is a data 1 or data 0. Sensible system designers place this decision point as far as possible from rising edges, falling edges, high level and low level – in other words in an unobstructed part of the eye, usually the center. Most BERT instruments have the ability to move this decision point away from the optimum position in time and/or voltage. By moving the decision point, it is possible to probe other parts of the eye, and by measuring the errors encountered, profile the anatomy of the eye diagram.

**Probing Jitter** is a common test carried out with a BERT, done by probing through the crossing point of the eye. This measurement has been given various names including BERTScan, Bathtub Jitter and Jitter Peak. It is more fully described in MJSQ<sup>1</sup>. This measurement taken by a BERT has the advantage that the BERT sees every bit, and so is most likely to capture rare jitter events.

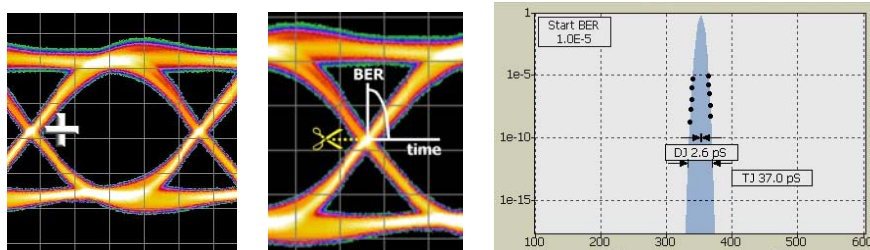


Figure 11 (a), (b), (c): Moving the BERT decision point in time to trace out the BER profile of the crossing point.

**Probing Signal-to-Noise:** A second common eye test that arose out of the fiber optics industry<sup>ii</sup> is Q Factor. This is particularly useful in systems whose performance is limited by noise. Here the decision point is used to probe a vertical slice through the eye halfway through the bit period. Measuring the way the BER rolls off towards the middle of the eye gives an indication of how much noise is present and how it will impact the link.

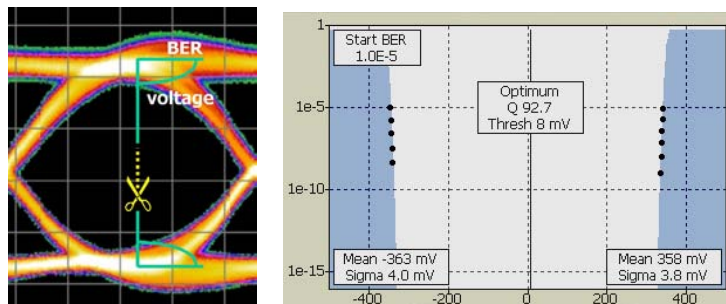


Figure 12 (a), (b): Moving the BERT decision point in voltage to trace out the BER profile of the one and zero levels.

**BER Contour** is a superset of the last two measurements, and also the perfect linkage between BER and eye diagrams. Here the decision point is stepped around the inside of the eye and the BER profile mapped

out on a series of angled slices around the eye. This provides a much more complete and clearer picture of where system parametric problems may be lurking. The BERTScope has been optimized to make this a fast and revealing measurement.

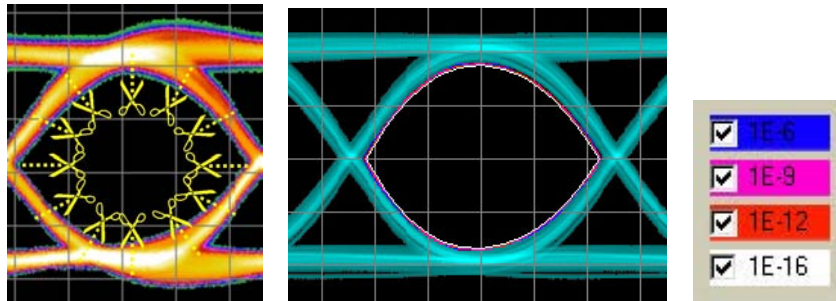


Figure 13 (a), (b): Slicing the eye along multiple axes to form an eye contour.

### The need for speed

The practicalities of these measurements are that a single point BER measurement of  $1 \times 10^{-12}$  at 10 Gb/s takes several minutes. Given that many systems are expected to function to better than  $1 \times 10^{-15}$  BER, where a single point could take months to measure, the ability to take quicker measurements and then extrapolate is valuable. The key is that BER contour measurements can be made quickly that are already down to near the levels where results are required and so the inaccuracies in extrapolating can be greatly minimized.

## Testing Transmitters

Eye diagrams are commonly used for testing transmitters. As test equipment input characteristics vary, a standardized method of test, called a *reference receiver*, has been devised by international standards<sup>iii</sup> such as the ITU for equipment used to test optical transmitters. Similar use of the input filter is also appearing now in some electrical standards.

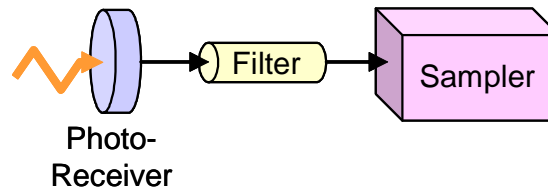


Figure 14: Block diagram of a reference receiver.

The aim is that the overall frequency response of the measuring system be well controlled, following a 4th order Bessel-Thompson curve within a defined tolerance window, with a systems -3 dB point at 0.75 of the bit rate. In theory, this means that measurements taken with different instruments should be comparable.

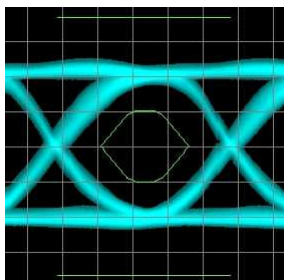


Figure 15: An eye mask test

Mask testing is an abbreviated eye diagram test for the quick testing of transmitters in manufacturing. Rather than measuring all parametric aspects of the eye, mask testing defines key areas in the eye that are deemed to be “keep-out” areas – if any of the signal is detected to be in this region, then the device fails. Mask testing is often carried out in a few seconds. It should be noted that mask testing only detects gross

problems in transmitters – it simply does not have the data depth in a short time to trap rare events, although instruments such as the BERTScope acquire significantly more data in a few seconds than most instruments.

## Testing Channels

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Channels can be tested as an independent element, or as a combination of transmitter and channel. Testing of the channel as an independent entity is often carried out by measuring parametric characteristics such as loss, attenuation, reflection and dispersion. This applies in optical links cases and in electrical links, although in short distance electrical cases such as back planes, s-parameter measurements are often used as an accurate description of all of the parameters mentioned above. One challenge with characterizing a channel as an independent entity is how to translate the measurements taken into what the eye and BER will be like at the end of a link. Modeling programs such as StatEye<sup>iv</sup> attempt to convert parametric characterization into a predicted BER contour.

Another approach is to measure the channel with a representative transmitter. This has the disadvantage of presenting a challenge to de-convolve the contributions from transmitter and channel, but has the advantage of allowing direct measurement of eye characteristics and BER performance. This can be useful as a way of generating a measured BER contour that can then be compared with the modeled results of a program like StatEye.

### ***BER Contours in three dimensions – the Eye Bowl***

A good visualization of the health of the eye, including the effects of rare events, can be obtained by plotting BER contour in three dimensions.

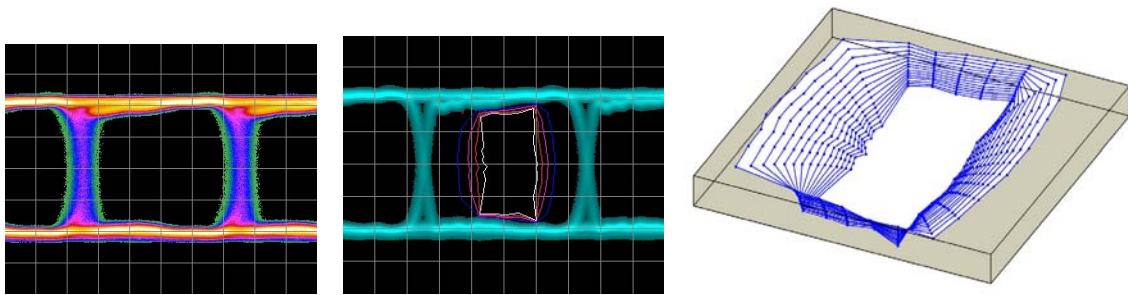


Figure 16 (a) Eye Diagram, (b) BER Contour, (c) Eye Bowl

## Testing Receivers

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Traditionally receiver testing has been a BER test rather than an eye-related test. The input signal to the receiver is reduced in size and often impaired in other ways so that it represents the limit of the conditions that the device under test will see. If the receiver is able to function error-free then it passes.

An interesting twist on receiver testing is in measuring jitter tolerance, or the ability of the receiver to make the correct decision on each incoming bit even when the signal data edges are moving erratically in time. As discussed earlier, clock recovery will often remove much of this jitter. In the SONET/SDH world, jitter tolerance testing was achieved by deterministically moving the data edges in time using an injected sinusoid that was varied in amplitude and frequency according to a template. More recently, the concept of a *Stressed Eye* has been introduced, where the edges of the data are corrupted by various different means. This has developed beyond just a jitter test, as impairments are also added in the amplitude dimension, as shown elsewhere on this poster. The general idea is that the stressed eye is set to be the worst case operating conditions that the receiver would ever see, and if it is able to operate error-free in the presence of such a signal, the device passes.

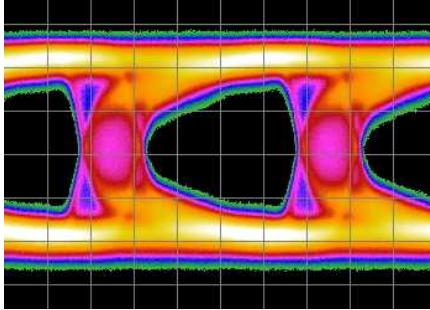


Figure 17: A stressed Eye.

## Conclusion

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There can be an immense amount of information stored in an eye diagram if it is taken correctly, and to enough data depth. This can tell a designer a lot about the parametric performance of his design, and a manufacturing engineer whether parts will cause problems in the field later.

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<sup>i</sup> MJSQ - Methodologies for Jitter and Signal Quality Specification is a document written as part of the INCITS project T11.2. <http://www.t11.org/index.htm>

<sup>ii</sup> N.S. Bergano, F.W. Kerfoot, and C.R. Davidson, "Margin Measurements in Optical Amplifier Systems, " in *IEEE Photonics Technology Letters*, vol.5, no. 3, pp. 304-306, Mar. 1993.

<sup>iii</sup> TIA/EIA-526-4-A Optical Eye Pattern Measurement Procedure (<http://www.tiaonline.org/standards/>) Also measuring optical SDH transmitters: ITU G.957, Similarly for SONET transmitters: Bellcore GR-253-CORE

<sup>iv</sup> Stateye modeling of channel responses to predict BER Contour: <http://www.stateye.org>