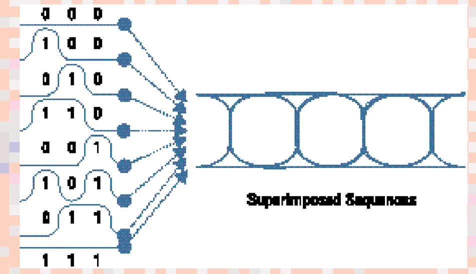
The Anatomy of an Eye

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 in system design.



What makes up an Eye? 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.

Eye Diagrams and BER

While eye diagrams provide an accessible and intuitive view of parametric performance, systems ultimately get 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 incorrect bit was sent in the first place.

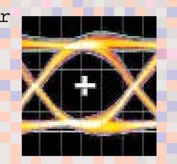
So why don't eye diagrams and BER easily link together? A perfect eye diagram would show all parametric aspects of all possible bit sequences, irrespective of how infrequently some effects show up.

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 10^5 samples per second on a 10 Gb/s (10^{10} bits/second). 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 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

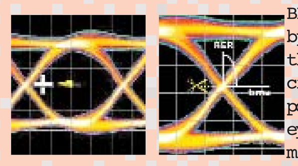
Slicing the Eye

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.

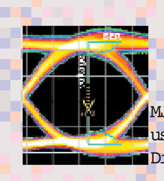


From this it decides whether the incoming signal is a data 1 or data 0. Sensible system designers place this decision point as far as possible from rising edges, falling edges, high level and low level – in other words in an unobstructed part of the eye, usually the center. Most BERT instruments have 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 scanning 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[1]. This measurement taken

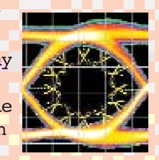


by a BERT has the advantage that the BERT sees every bit, and so is most likely to capture rare jitter events.



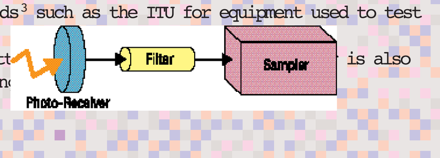
MJSQ describes the use of the Dual Dirac model of jitter. This allows a Jitter Peak measurement to be separated into random (RJ) and deterministic (DJ) components.

Probing Signal-to-Noise: A second common eye test that arose out of the fiber optics industry 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 along 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.



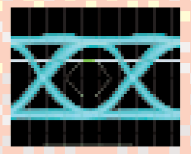
Testing Transmitters

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 such as the ITU for equipment used to test optical transmitters. [...] is also appearing



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.

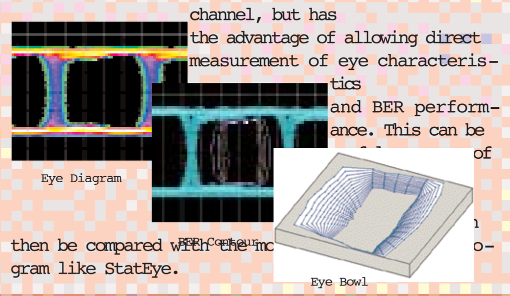
Mask testing is an abbreviated eye diagram test for the quick testing of transmitters in manufacturing. Rather than measuring all parametric aspects of the eye, mask testing defines key areas in the eye that are deemed



Testing Channels

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 the channel. Modeling programs such as StatEye[4] attempt to convert parametric characterization into a predicted BER contour.

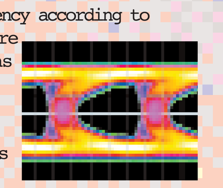
Another approach is to measure the channel with a representative transmitter. This has the disadvantage of presenting a challenge to de-convolve the contributions from transmitter and channel, but has the advantage of allowing direct measurement of eye characteristics and BER performance. This can be then be compared with the [...] gram like StatEye.

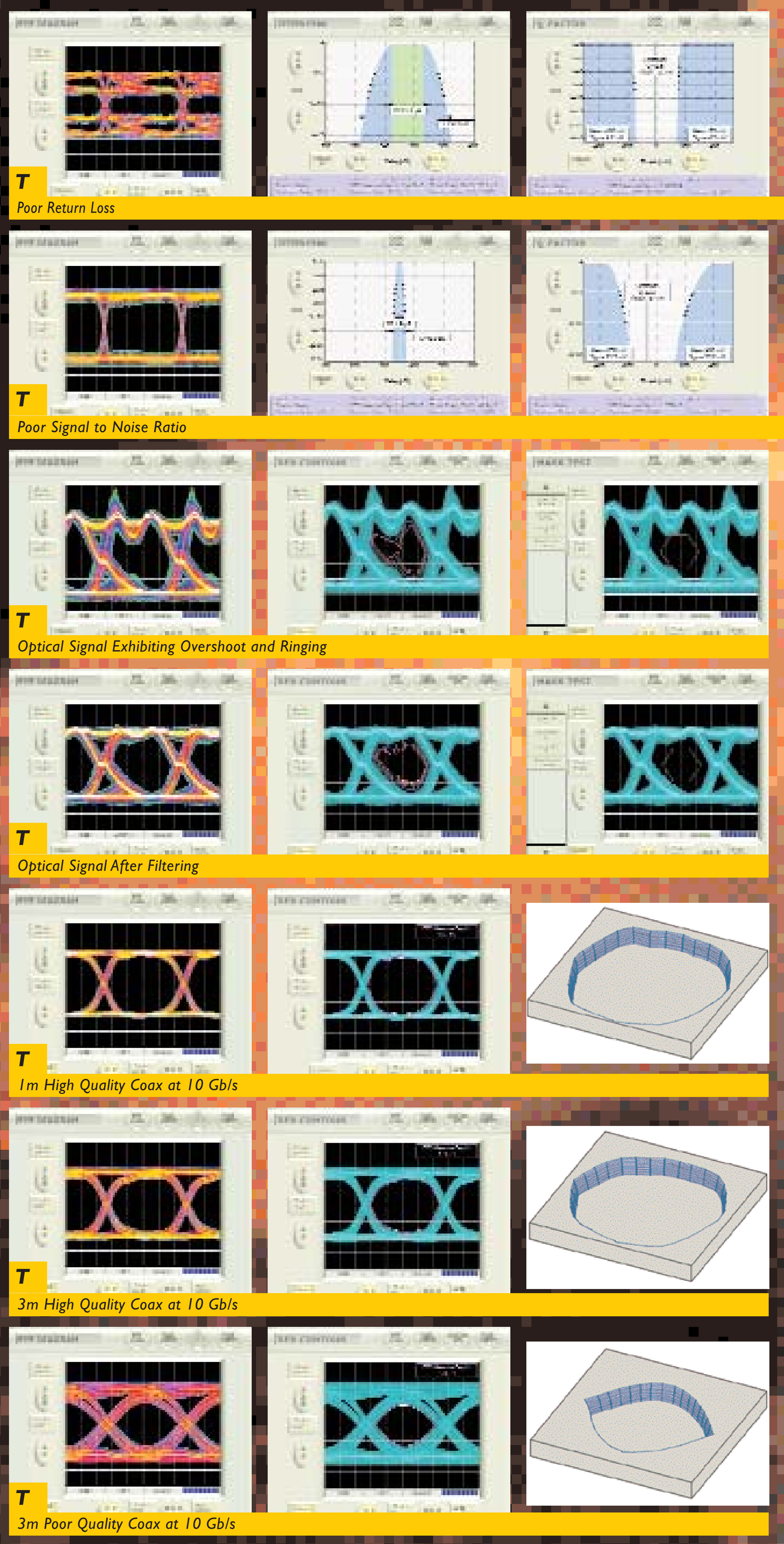


Testing Receivers

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. Clock recovery will often remove much of this jitter. In the SONET/SDH world jitter tolerance testing is achieved by deterministically moving the data edges in time using an injected sinusoid that is varied in amplitude and frequency according to a template. More recent work has introduced the concept of a Stressed Eye, where the edges of the data are





T Poor Return Loss

T Poor Signal to Noise Ratio

T Optical Signal Exhibiting Overshoot and Ringing

T Optical Signal After Filtering

T 1m High Quality Coax at 10 Gb/s

T 3m High Quality Coax at 10 Gb/s

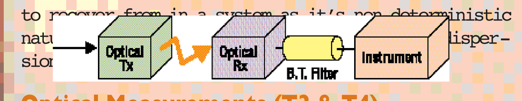
T 3m Poor Quality Coax at 10 Gb/s

Poor Return Loss (T1)

When a system deviates from it's normal impedance, for example when it is terminated incorrectly, a percentage of the energy is reflected and can set up standing wave effects. Many different looking eye diagrams can result from possible types of impedance deviation, but all tend to close the eye in the vertical dimension. They also tend to be deterministic in nature, so the lines of BER contour are closely grouped.

Poor Signal to Noise Ratio (T2)

When a signal level gets low it often becomes dominated by noise. Noise can lead to low probability events that trip up a system that is designed to run error free. This is indicated strongly by the wider spacing of the BER contours in the vertical dimension of the eye, and the slopes to the Eye Bowl and Q Factor. Excessive noise is difficult to recover from in a system as it's non-deterministic natu[...] disper[...] sion

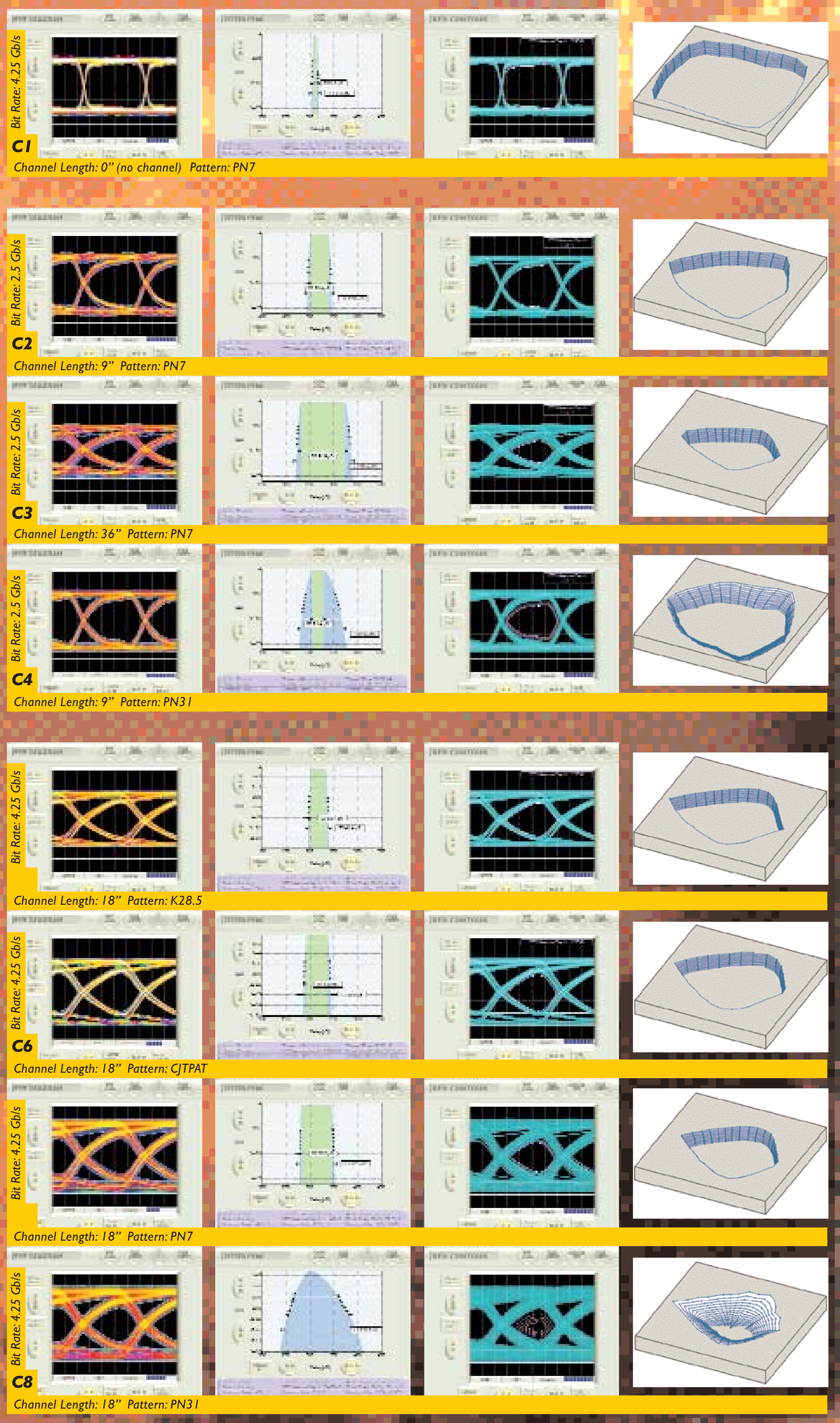


Optical Measurements (T3 & T4)

Optical transmitters are often prone to overshoot and ringing effects deriving from resonances within their design. A signal displaying strong overshoot and ringing is shown in T3. This would be a difficult signal for an optical system receiver to deal with, as can be seen from the failed mask test. However, a wide bandwidth system is required to see such effects, and most systems are band limited for cost and performance optimization reasons. The signal in T4 is the same as T3, but has passed through a 4th order Bessel-Thompson filter with a –3 dB point at 0.75 of the data rate, as described in standards for parametric measurements of the transmitted eye[3]. This has become a much easier signal to deal with, giving a good BER contour and a mask test that has been passed.

Cable Loss (T5, T6, T7)

The fact that cables have a frequency response of their own is often



C1 Bit Rate: 4.25 Gb/s Channel Length: 0" (no channel) Pattern: PN7

C2 Bit Rate: 2.5 Gb/s Channel Length: 9" Pattern: PN7

C3 Bit Rate: 2.5 Gb/s Channel Length: 36" Pattern: PN7

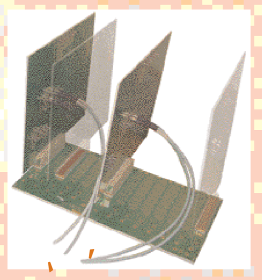
C4 Bit Rate: 2.5 Gb/s Channel Length: 9" Pattern: PN31

C5 Bit Rate: 4.25 Gb/s Channel Length: 18" Pattern: K28.5

C6 Bit Rate: 4.25 Gb/s Channel Length: 18" Pattern: CJTPAT

C7 Bit Rate: 4.25 Gb/s Channel Length: 18" Pattern: PN7

C8 Bit Rate: 4.25 Gb/s Channel Length: 18" Pattern: PN31



The channel measurements shown here were made on an experimental back plane. The back plane allowed a variety of path length combinations to be used, as shown in the diagram above. In each case, the same scale in time (x-axis) has been maintained for each of the jitter measurements.

Measurement C1 is the reference set, showing the performance of the experimental setup without the channel present.

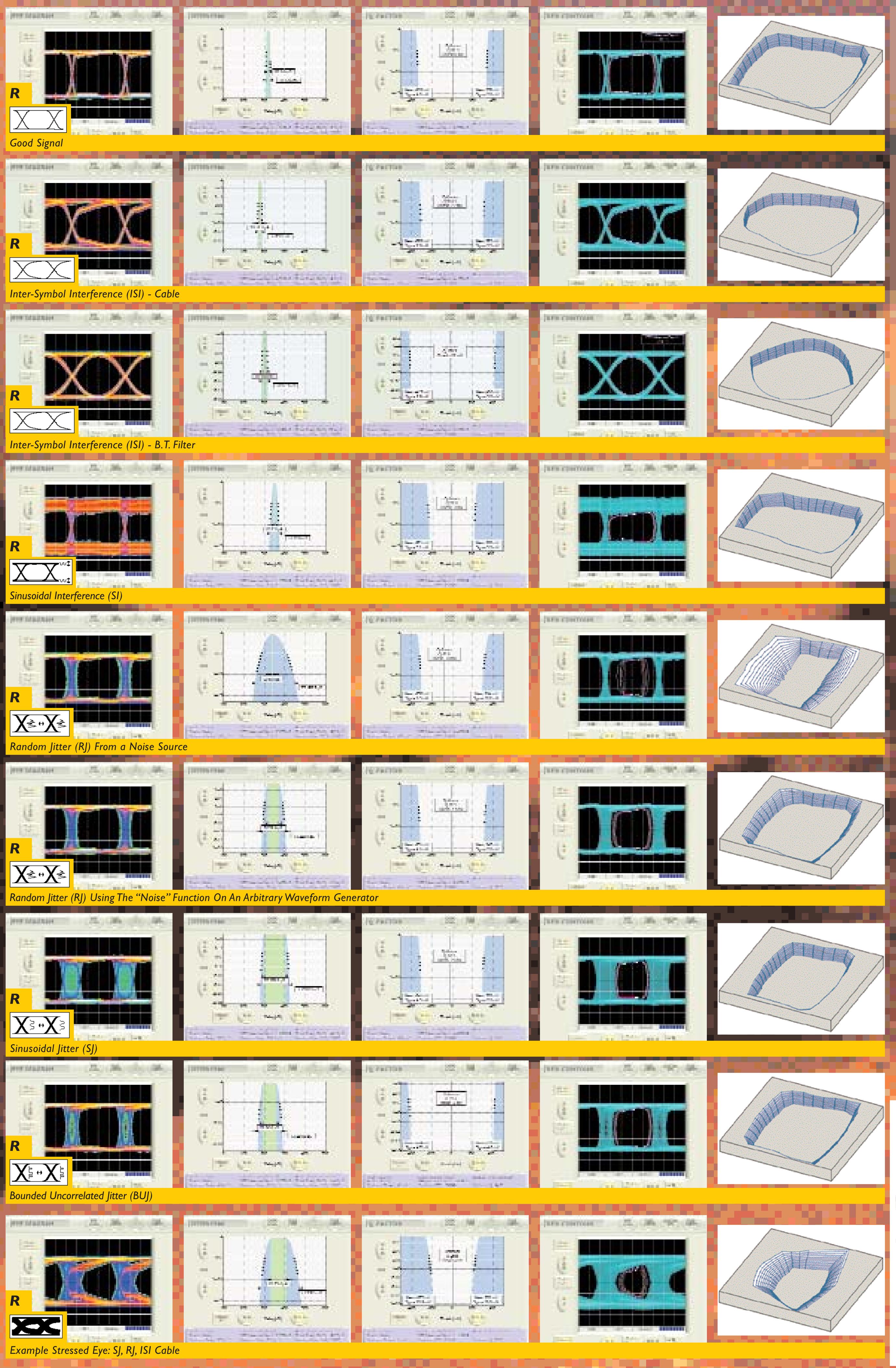
Rows C2-C4 show the back plane below the bit rate that it was designed for, and at it's easiest test distance, 9" (C2). Evident here are the different forms of eye closure arising from increased channel length (C3), or increased difficulty of the pattern (C4). Note that back planes are dispersive, but as they are passive there is no significant increase in the random jitter (the blue portion of the jitter peak graphs), but there is significant variation in the green, deterministic portion.

The BER Contours and Eye Bowls all show well-behaved, closely spaced lines, and vertical sides respectively, showing that although closure has occurred, there are no low probability events to disturb system performance. The exception is C4, which will be discussed later.

Measurements C5-C8 look more closely at pattern effects. C5-C7 use patterns frequently used to test 8B/10B coded systems. C8 is PN31, which along with PN23 is commonly used to test SONET systems. This set of measurements was taken with intermediate length (18") and at 4.25 Gb/s, both factors causing pattern-dependent effects to be more apparent in this system.

K28.5 is the Fibre Channel comma character, and a frequently used test pattern (C5). It is very short (20 bits), and the restricted range of pattern combinations give easily identifiable tracks within the eye diagram. CJTPAT is another test pattern derived from Fibre Channel aimed at uncovering jitter issues (C6). More deterministic jitter is evident in the Jitter Peak (green region). However, the pattern is constructed from a lot of repetition of the same primitive building blocks, and consequently the eye looks to have almost the same narrow range of pattern combinations, even though the pattern is 1,320 bits long. Contrast this with C7 - this is the PN7 PRBS pattern, and is only 127 bits long but exhibits a much wider range of pattern combinations, more nearly random in nature as can be seen from the smearing in the eye.

Of most note in this set of measurements is the PN31 pattern shown in C8. The eye bowl and BER Contour almost look like they are closed down by noise or some other random process, and yet the back plane is passive as already noted above. So what is going on? PN31 is a very long pattern, at around 2 billion bits. It is a much closer approximation to truly random data, with the widest range of pattern variations of any common test pattern. This can be seen at a shallow level by how filled-in the rising and falling edge groupings of the eye diagram are, with little ability to pick out individual trajectories. In addition, the pattern has extreme pattern sequences such as 30 zeros in a row before the next one



R Good Signal

R Inter-Symbol Interference (ISI) - Cable

R Inter-Symbol Interference (ISI) - B.T. Filter

R Sinusoidal Interference (SI)

R Random Jitter (RJ) From a Noise Source

R Random Jitter (RJ) Using The "Noise" Function On An Arbitrary Waveform Generator

R Sinusoidal Jitter (SJ)

R Bounded Uncorrelated Jitter (BUJ)

R Example Stressed Eye: SJ, RJ, ISI Cable

Stressed Eye

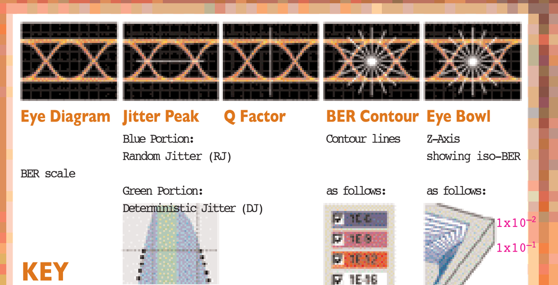
R1-R8 show the effects that different forms of impairment can have on a stressed eye. In each case the pattern has been kept short (PN7) to remove pattern length complications that could hinder understanding.

Recommendations vary on what sort of filter should be used to induce Inter-Symbol Interference (ISI). R2 and R3 show two common methods – the use of a long coax cable (here 3m of low quality cable, R2) and a Bessel-Thompson 4th order filter with –3 dB point at 0.75 of the bit rate. While the coax cable induces effects that look capacitive, the Bessel-Thompson filter is phase linear and creates the symmetrical shape seen in R3.

Sinusoidal interference and jitter (R4 & R7 respectively) show well behaved, deterministic eye closure with steep walls in the Eye Bowl. Contrast this with the random jitter (RJ) of R5. Here the eye bowl has shallow, gently sloping walls that show closure far into the eye under the ability of an eye diagram to detect. These low probability noise events could cause a system real problems. R5 was created using a diode-based microwave noise source that has little bandwidth limiting. In contrast, R6 was taken using the 'noise' function on a commonly used arbitrary waveform generator. Typically such instruments use a math function to generate pseudo-random noise, but it is very limited and repeats frequently, as can be seen by the sloping sides of the eye bowl at high probability levels, but the near-vertical side walls at low probabilities. This shows that this noise source is far from truly random. In this example, the RJ level induced from the Arb. was

References

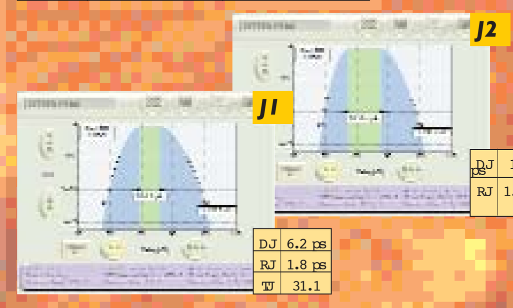
1. MJSQ – Methodologies for Jitter and Signal Quality Specification is a document written as part of the INCITS project T11.2. http://www.t11.org/index.htm
2. N.S. Bergano, F.W. Kerfoot, and C.R. Davidson, "Margin Measurements in Optical Amplifier Systems," in IEEE Photonics Technology Letters, vol.5, no. 3, pp. 304-306, Mar. 1993.
3. 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
4. Stateye modeling of channel responses to predict



Jitter Measurements - How Deep is Enough?

Annex H of MJSQ[1] examines the effect of pattern length in jitter measurements. A typical BERTScan measurement will take points on the bathtub curve that are fast to measure, and then extrapolate down to low BER levels where the value of total jitter (TJ) is required. The points chosen to extrapolate from make a big difference to the eventual accuracy of the TJ number obtained. Pattern-related effects (data dependent jitter, DDJ) should not form part of BERTScan extrapolations, and the Annex recommends that points only be included that fall below 1/(2x pattern length). As an example, to know the TJ value at 1×10^{-12} BER when testing with a PN23 extrapolation should begin from points taken below 6×10^{-8} BER, and points above should not be included in the calculation. Example jitter measurements J1 and J2 show the effect, with the same measured points used

Pattern Length	Pattern Length (in bits)	1 / (2x Pattern Length)
2^7-1	127	4×10^{-3}
$2^{11}-1$	2,047	2.4×10^{-4}
$2^{15}-1$	32,767	1.5×10^{-5}
$2^{20}-1$	1,048,575	4.8×10^{-7}
$2^{23}-1$	8,388,607	6×10^{-8}
$2^{31}-1$	2,147,483,647	2.3×10^{-10}
K28.5	20	2.5×10^{-2}
CRPAT	1,140	4.4×10^{-4}



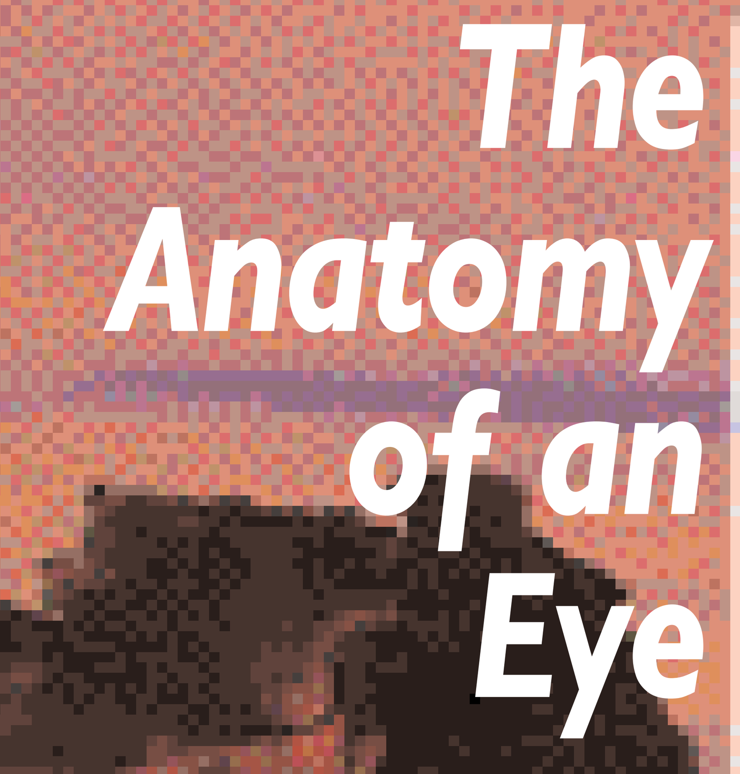
J1	
DJ	6.2 ps
RJ	1.8 ps
TJ	31.1

J2	
DJ	10.1 ps
RJ	1.5 ps

Which Standards Use a Stressed Eye?

Different versions of stressed eye are being used in a wide variety of optical, and increasingly also electrical standards for receiver

	Sinusoidal Jitter	Random Jitter	Bounded Uncorrelated Jitter (PRBS)	Sinusoidal Interference	Data-Dependent Jitter from ISI	Vertical closure from ISI
SONET/SDH*	4					
OIF CEI	4	4	4	4	4	4
XFP	4	4	(proposed)		4	4
1x/2x/4x Fibre Channel	4	4	4		4	4
XAUI	4	4			4	4
10 GbE (4-lane optical, 10 GBase-LX4)	4	4			4	4
10 GbE (802.3ae) & 10 G Fibre Channel (both Serial)	4	4			4	**
Serial-ATA II	4	4		4	4	4



All data on this poster taken with a BERTScope BSA12500A.

Signal Integrity Solutions from SyntheSys Research:
BERTScope 12500A 12.5 Gb/s
BERTScope 7500A 7.5 Gb/s
BitAlyzer 1500 1.5 Gb/s

Acknowledgement Particular thanks to engineers at Northrop Grumman Interconnect Technologies for use of experimental backplanes for the channel measurements displayed here. www.littoninterconnect.com/

RESEARCH, INC. www.bertscope.com