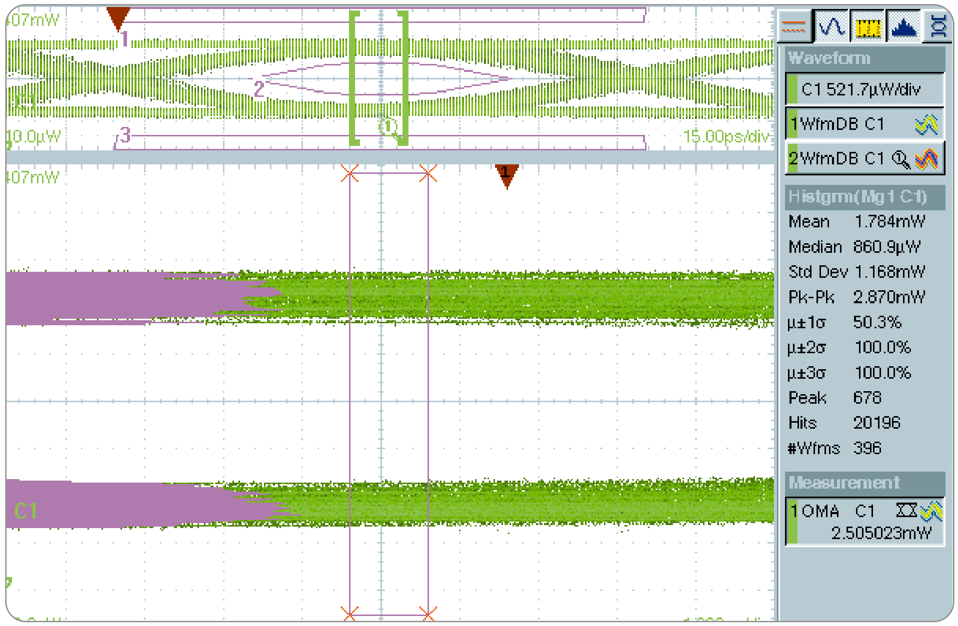

Measurements on IEEE 802.3ae™ 10 Gb/s Ethernet

▶ This application note considers compliance and characterization measurements pertaining to the IEEE 802.3ae™ standard 10GbE physical layer and focusing on eye-diagram measurements.

Background

The Ethernet standard is one of the most successful communication standards ever. It has enabled the connectivity of almost every desktop PC, workstation and server. The proliferation and breadth of Ethernet-based applications has prompted speed updates of the standard – first to 100 Mb/s, then to 1 Gb/s in the late 1990s, and most recently to 10 Gb/s.

Ethernet technology has also correspondingly evolved. While 1 Gb/s Ethernet followed an established data communications predecessor – Fibre Channel – and the signaling speed itself was not a significant technological breakthrough, Ethernet developments today are leading the speed race among the datacom protocols.

This prominence is well reflected when discussing measurement issues. 10 Gigabit Ethernet (GbE) introduces several measurements not widely used before, such as optical modulation amplitude (OMA) and stressed eye sensitivity. A discussion of these new 10GbE measurements follows.

***NOTE:** Figure 12 on page 9 reprinted with permission from "IEEE Std 802.3ae™-2002," by IEEE. The IEEE disclaims any responsibility or liability resulting from the placement and use in the described manner.*

What's in a Name?

What most people refer to as Ethernet is actually a popular trademark of a standard established by the IEEE 802.3 group. This group's 10 Gb/s effort is known as 802.3ae; and it is an 2003 addition to the current "Ethernet" standard – IEEE802.3 .

Because IEEE802.3 uses the term 10GBASE for the Ethernet standard's particular sublayers, it would be confusing to use the term 10GBASE-X for the aggregate 10 Gb/s standard. Another reason to stay clear of the "X" is because "X" is already liberally used throughout the standard for various other things, for example to denote 4-way multiplexing in the 10GBASE-LX4 physical layer.

Over time, 10GbE has become the most accepted and popular de facto name for the standard (although it is not officially recognized by IEEE802.3). Therefore, it will be used as the reference term in this document.

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Status of the 10GbE Standard

The 10GbE standard was ratified in July, 2002, incorporating these features: optical-only signaling; full duplex only; several coding sub-layers: -W, -R, and the 4-way parallel -LX4, each comprising a different line rate; and several physical sublayers: -L, -E and -S.

Serial Coding

- 10GBASE-R: Uses the "natural" signaling rate of 10.3125 Gb/s. This rate can handle 10 1 Gb/s Ethernet tributaries, and it likely will remain the most widespread in the foreseeable future
- 10GBASE-W: This "WAN" rate, implemented as a step toward compatibility with wide area networks – namely SDH/SONET – matches the basic SDH/SONET 10 Gb/s rate of 9.953 Gb/s, and is partially similar in format. While this is *not* a SDH/SONET signal, it can be mapped into SDH/SONET without high-level processing. Note, however, that the throughput is slightly lower than 10 Gb/s

This rate is not as popular as the basic LAN rate "-R," but many "-R" devices can handle "-W," as a mode of operation. The standard supports dual-mode devices by allowing some compliance testing performed only on the "-R" rate to count towards "-W" compliance as well.

Parallel Coding

- LX4: As released, this is a optical-only standard with no provisions for copper signaling. To address older installed fiber incapable of supporting 10 Gb/s serial transmission, there is a four-way parallel sublayer with four wavelengths on the same fiber, and 8b/10b coding that results in four 3.125 Gb/s lanes. Current growth of this sublayer is slower than that of the all-serial sublayers, and projections are that this will not change in the near future

Extensions

There are several 10GbE extensions that are being considered as of this writing (summer of 2003); since they are not currently ratified parts of the standard it is unknown what their future will be:

- Serial Optical Link: 10GBASE-L extension would increase the reach to perhaps 40 km
- Parallel Interfaces:
  - Electrical: Copper-based ultra-short reach (perhaps 15 or 25 m) shielded-wire – 10GBASE-CX4
  - Electrical: copper-based short reach (100 m) over unshielded twisted pairs – 10GBASE-T
  - Optical: Short wavelength 4-way muxed signaling – 10GBASE-SX4
- Forward Error Correction (FEC): For serial signaling at a rate of 11.0957

	Media λ nom. [nm] / mode / max. distance	Rate, Phy Type	Rate, Phy Type
Line Bit Rate		10.3125Gb/s	9.953Gb/s
10GBASE-S… (short λ)	850 / MM / 200m	…-R standard: 64b/66b coding	… -W standard: 64b/66b coding; Data and format compatible with WAN (SONET STS-192c and SDH VC-4-64c .)
10GBASE-L… (long λ)	1310 / SM / 10km		
10GBASE-E… (Extra long λ)	1550 / SM / 40km		

▶ ***Figure 1.*** *Serial coding.*

10GBASE-X, i.e. 10GBASE-LX4	1310, 4x / MM: <300m	-LX4: 8b/10b coding; 3.125Gb/s per lane, 4 lanes WDM. No WAN compatibility. Probably a smaller market.
	1310, 4x / SM: <10km	

▶ ***Figure 2.*** *Parallel coding.*

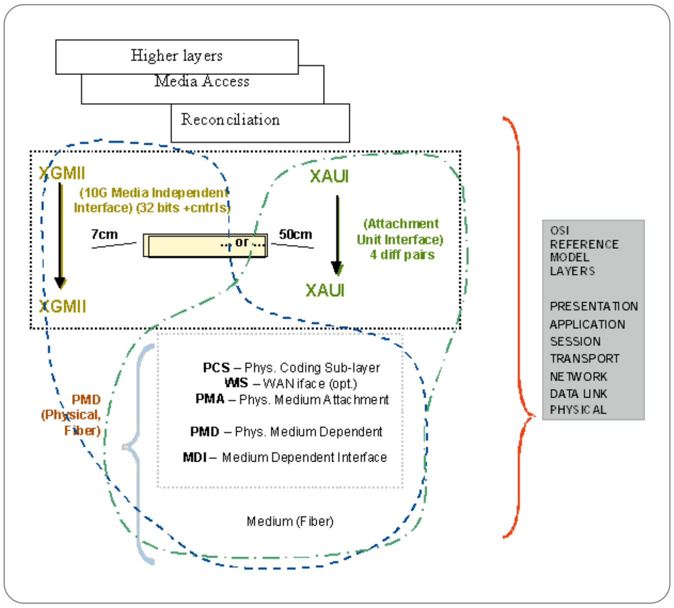
XAUI

The 10GBASE standard defines a stack of protocol layers, but for purposes of this discussion, the focus will be on the lowest one – the physical layer device (PHY). PHY itself is attached to the media (fiber and cable for the -CX4) on its serial side; on the other side, PHY is attached to the higher levels of the protocol through an XGMII interconnect.

To simplify module connectivity, the high number of XGMII wires can be folded into four differential, low-voltage pairs running at 3.125 Gb/s each. This set of four is also defined by the 802.3ae, and is known as XAUI. A pair of these sets (one for the transmitter, and one for the receiver) is a common interface to pluggable modules in 10GbE.

While XAUI was defined for purposes of module connectivity over tens of centimeters at most, it's currently being used as a basis of the ultra-short reach 10GBASE-CX4 effort. Nevertheless, XAUI by itself is still only an interconnect standard, and not a 10GbE LAN protocol.

Below is a depiction of the bottom of the IEEE protocol stack:



▶ ***Figure 3.*** *Layers diagram (blue dash denotes the XGMII path, green dot-dash represents XAUI.*

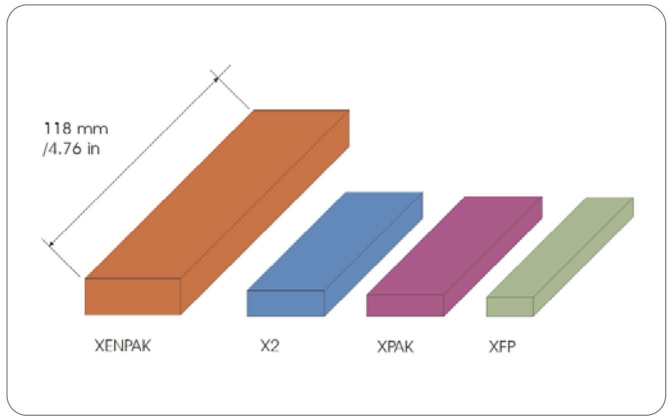
To connect to the laser module, either use XGMII with its 2x32 wires of data, or XAUI with just 2x8 wires of data. (For even more advanced option read about the XFP modules below.)

Clearly, XAUI is an efficient solution. Its popularity grew after it was defined and its functionality confirmed by early implementers. It is now also being used by non-10GbE designers with a similar need for the transfer of data between chips or modules.

Since XAUI uses electrical signaling, it can be viewed on an electrical module of a sampling oscilloscope (for example, Tektronix' 80E02 module for the CSA8000B scope). The 3.125 Gb/s speed also allows a real-time oscilloscope to capture this signal such as Tektronix' TDS6604 with 6 GHz of bandwidth.

XENPAK, XPAK, and X2 MSA Modules

XENPAK is a 10GbE module which uses XAUI for data connectivity and complies with the XENPAK MSA. (An MSA or multi-source agreement in the communications arena is a document that defines a module's interfaces (electrical, mechanical, thermal) in enough detail to guarantee interchangeability.) See **http://www.xenpak.org/** for the block diagram and other information.



▶ ***Figure 4.*** *XENPAK, XPAK, and X2 MSA Modules.*

There are two follow-ons to XENPAK: XPAK and X2. These are both physically smaller than XENPAK, particularly with regard to face area. With the exception of mechanical differences, all three modules are nearly identical electrically. While a smaller size is more suitable for most purposes, XENPAK does have its advantage: the X2 and XPAK packages have more difficulty dissipating the power required by the standard for longer reaches.

XFP

XAUI's success – with its relatively high bit rate for standard PCBs – paved the road for XFP. The XFP MSA uses full 10 Gb/s signaling on one physical lane (a differential pair), and doesn't require signal recoding. Due to this lack of re-coding, XFP is a protocol-agnostic module, and can be used on any standard with which its physical sublayer complies. This last condition is not easily met; 10GbE requires a much lower extinction ratio (ER) than SONET, for example. Similarly, longer reach links often require higher power levels than can be accommodated by XFP today.

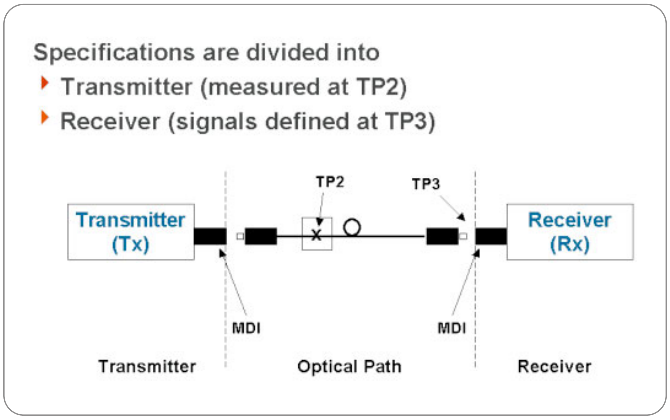
The 10 Gb/s serial speed of the XFP's electrical interface presents its own challenge. This signal isn't easy to route on the XFP's PCBs. However, judging from the number of designs on the market, it is obvious that this difficulty can be overcome.

For more information on the various MSA, users can access these Websites:

http://www.xenpak.org/; **http://www.xpak.org/**; **http://www.x2msa.org/**; and **http://www.ofpmsa.org.**

10GbE Measurements

The graphic below shows how the standard defines test points. Notice that there is only one test point on each transmitter and receiver side.

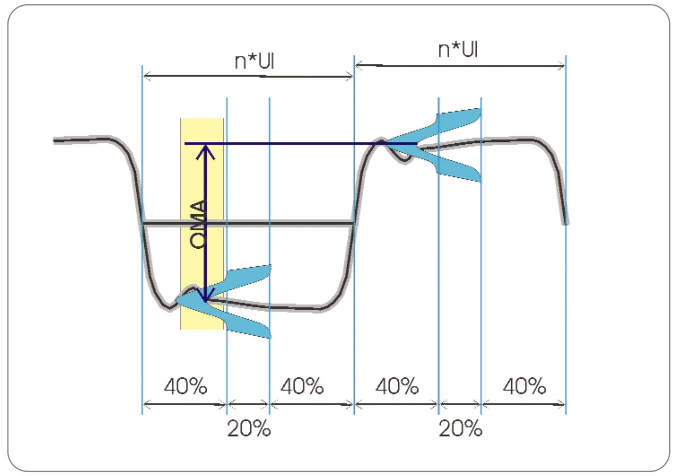


▶ ***Figure 5.*** *10GbE defining test points.*

Optical Modulation Amplitude (OMA)

The optical link's performance is related to transmitted power of the "high" and "low" signal levels, which therefore need to be measured. Instead of measuring these directly though, telecommunication standards typically have specified extinction ratio (ER) and average optical power (AOP).

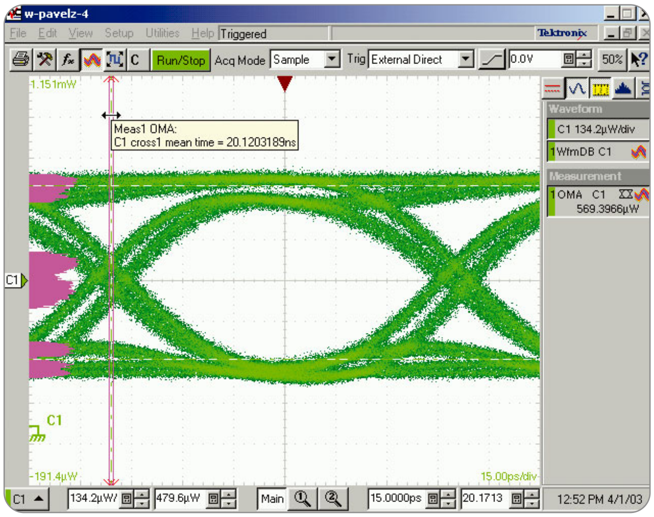
The 10GbE specification uses optical modulation amplitude (OMA) instead of the ER and AOP combination. This change doesn't remove the references to ER completely, however, so both OMA and ER have to be measured. AOP remains a factor only in non-signaling related specifications such as safety.



▶ ***Figure 6.*** *OMA on a squarewave.*

Measuring OMA

Figure 6 shows the standard-prescribed way of measuring OMA on a square wave. Note that the *n* (in the "n*UI" expressions at the top of the graphic) is allowed to be anywhere between four and 11. However, varying the value of *n* will also vary the value of OMA to an extent that depends on the flatness of the *"high"* and "*low"* levels. Since this variability is undesirable for interoperability, Tektronix recommends that OMA be always measured on a pulse of rate 4*UI (about 800 ps period, which is approximately 1.25 GHz).



▶ ***Figure 7.*** *OMA on an eye diagram.*

There is also a method under the standard for approximating OMA from an eye diagram. See Figure 7. Note that the inter-symbol interference (ISI) present in the eye diagram is somewhat common to today's low-cost transmitters. ISI occurs when the transitions and levels in one bit are influenced by the preceding bit(s). It manifests itself as a doubling or tripling, etc., of the lines in the eye diagram. Remember that when measuring OMA on an eye diagram, the measurement has to be considered an approximation. Where binding measurements are needed, use the square wave.

For demonstration purposes, the histograms at the crossing are shown in Figure 7. The top and bottom histograms correspond to those used by the measurement system to determine the value of OMA. On the CSA8000B instruments this measurement is further detailed by enabled annotation lines. (Note that placing the mouse over any of the annotation line will activate a pop-up explaining the line.)

Transmitter and Dispersion Penalty (TDP)

The transmitter and dispersion penalty (TDP) test generates a relatively high number of questions (when compared to other tests in the standard's transmitter test portion).

The TDP test begins by first setting a link consisting of a laboratory-quality transmitter connected to a laboratory-quality receiver. The sensitivity of this link is then measured and noted. (The standard uses the wording "reference receiver" or "reference transmitter," which, in this case, is being substituted with "laboratory transmitter" instead.)

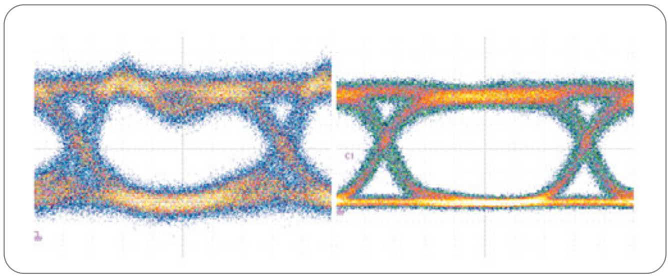
Next, the test specifies replacing the laboratory-quality transmitter with the device-under-test (DUT) transmitter, and introducing several impairments into the link (these will be slightly different for the various physical sub-layers). In addition, the timing of the decision point in the laboratory-quality receiver's discriminator has to be advanced and retarded.

The sensitivity of the link with these impairments is then measured. The worst value over the variables of the impairments (for example, advance/retard) is the one to use to calculate the difference between the laboratory transmitter and the DUT transmitter. The standard specifies the maximum size of this difference.

Aside from following this procedure, the following issue arises with the laboratory transmitter ("reference transmitter"): the higher the quality of the laboratory transmitter, the more difficult it is for the DUT to remain within its standard-specified difference. This difficulty is limited, but real; and might tempt the vendors to use a laboratory transmitter with as poor as possible (within the standard) specifications. Documenting and making available the list of equipment to your customer will help to eliminate any confusion.

Directly Modulated Lasers: Impacting the DUT Receiver and Signal Analyzer Measurement

Figure 8 provides an example of an eye diagram acquired from a fairly typical directly modulated laser, and one on a externally modulated one (an ORR – Optical Reference Receiver – was used in the acquisition of both images).



▶ ***Figure 8.*** *Typical signal from a directly modulated (left) and externally modulated (right) laser.*

From the point of view of the receiver, the directly modulated laser (left) produces significant energy at a frequency higher than the fundamental (first harmonic) frequency of the NRZ signal. Notice that the rising edge of the positive going transition (left) ends in a high frequency ring. At the frequency of this ring, the response of the DUT's receiver, as well as that of the oscilloscope's or signal analyzer's reference receiver are controlled only with a large tolerance. Therefore, the amplitude of the ring will differ significantly at the decision circuit of the DUT, or on the display of the eye diagram on the signal analyzer/oscilloscope.

The shape of the ring itself is a function of several parameters of the laser used, but typically grows in both amplitude and frequency at a higher ER. This is one of the reasons why the 10GbE standard prescribes a low ER of 3 or 3.5 dB.

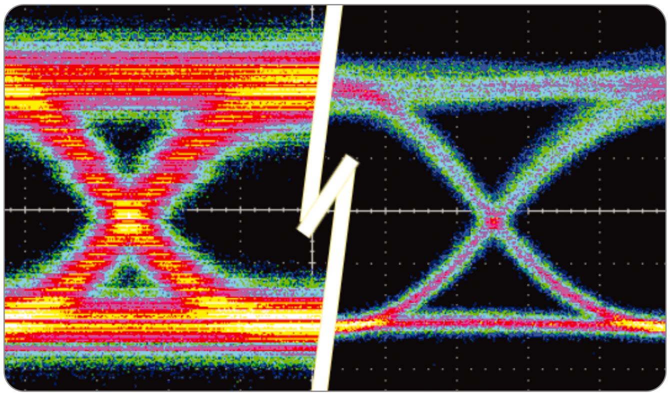
The impact of the ring on the receiver inside the DUT can be deleterious – dipping straight into the middle of the eye and causing errors – especially on the faster DUT receiver. This problem can be mitigated by sharply limiting the bandwidth, and controlling it more tightly.

A similar issue exists within the reference receiver of the signal analyzer/oscilloscope/BERT/etc. used to measure or test a design. The instruments designed specifically for 10GbE, such as Tektronix' 80C08C sampling module, limit the bandwidth at the higher frequencies by staying close to the lower curve of the allowed reference receiver tolerance field in order to decrease the sensitivity of the measurement to the ringing. Even so the measurement variability can fluctuate more significantly than would be typical for 10 Gb/s SONET/SDH signals generated with externally modulated signals.

Test Equipment

While most tests done on 10GbE signals will be familiar to those who worked with SONET/SDH or with Gigabit Ethernet optical signals, there are a few special considerations to keep in mind when working in 10GbE. The following is a summary of the less common requirements:

- Optical clock recovery (OCR) is expected by the standard, which states in the 52.9.7 transmitter optical waveform section that *"a clock recovery unit (CRU) should be used to trigger the scope for mask measurements"*
- The PLL loop bandwidth of the signal analyzer/oscilloscope's OCR is explicitly specified by the standard to *"have a high-frequency corner bandwidth of less than, or equal to, 4 MHz and a slope of –20 dB/decade"* This specification necessitated changes in the signal analyzers/sampling oscilloscopes developed for the SONET/SDH signals
- An optical reference receiver (ORR) is either mandatory (throughout most of the standard) or optional (in a few places only) for all tests and measurements, making it unnecessary for higher bandwidth capability in the test equipment. Tektronix recommends always using an ORR for 10GbE measurements for consistency



▶ ***Figure 9.*** *–13 dBm signal as viewed on a SONET-targeted sampling module (left) vs. the view on a Tektronix 80C08C 10GbE targeted sampling module (right).*

- Several possible physical media are specified:
  - single-mode *and* multi-mode fiber
  - wavelengths around 850 nm, 1310 nm, and 1550 nm
  - signaling frequencies of 9.953 Gb/s and 10.3125 Gb/s. Additionally devices might need to comply at the frequency of the 11.0957 Gb/s FEC rate, and at the 10.5187 Gb/s of the 10G Fibre Channel. For example the XFP modules can typically be tested at the maximum rate, or at some of these rates if so desired by the customer. While the ORR remains as a 10.0 Gb/s ORR, clock recovery obviously will has to accept the different bit rates; test equipment with a flexible clock recovery rate is therefore extremely desirable
- The dynamic range of signals used is large – from the transmitter's average maximum power of 4 dBm to the smallest signal used by the stressed receiver OMA of –11.3 dBm. Figure 9 documents this last power level well. While some mitigation can be obtained with changes in setup, it is obviously good to have a very sensitive module (with a very low noise level) to avoid test equipment noise related mask hits

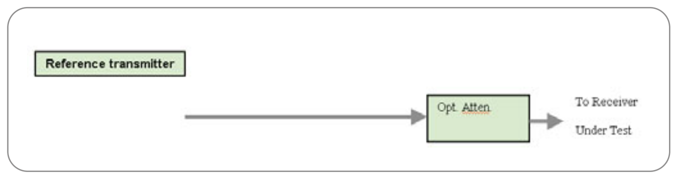
Correspondingly, a signal analyzer/oscilloscope used for 10GbE measurements should meet most, or if possible, all of these requirements. The CSA8000B oscilloscope with the 80C08C-CR4 module are an example of such instrument.

Receiver Measurements

To achieve the interoperability users expect in Ethernet devices, the 802.3ae standard uses a "stressed eye sensitivity" measurement as the main performance/compliance parameter of the receiver. This method effectively measures the performance of the receiver under test with a non-ideal signal – a signal which is intentionally, and in a tightly controlled fashion, simultaneously impaired in several ways. The sensitivity of the DUT (for BER < 10^{-12}) with this impaired signal is the critical parameter for receiver compliance. Sensitivity as traditionally measured (against a high quality signal) is not an obligatory specification and is for informational purposes only.

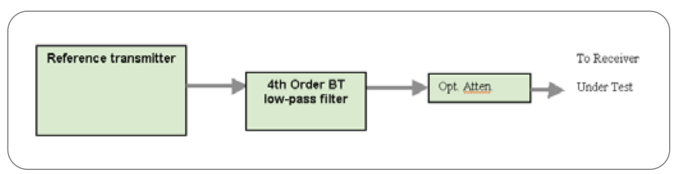
The idea of stressed eye testing is not new, and has been used in previous standards. However, it is only now becoming a mainstream test due to complications with the definition and realization of the impairments involved. 802.3ae has resolved the impairment sets' specification in the following manner.

Start with a clean eye,



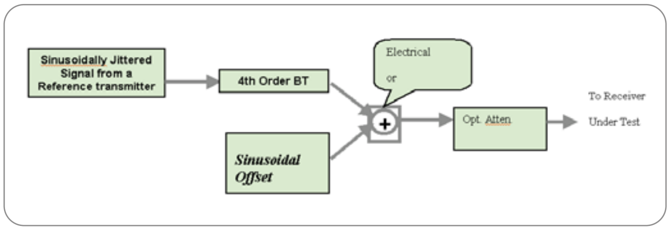
▶ ***Figure 10a.*** *Building the stressed eye transmitter – First step: Clean signal.*

and cause a certain amount of eye closure by bandwidth-limiting the signal, as follows:



▶ ***Figure 10b.*** *Building the stressed eye transmitter – Second step: Impair by BW limiting... continued in Figure 10c.*

The filter here is slow enough to cause a noticeable amount of vertical closure. This also leads to a certain amount of ISI jitter with edges of the signal being more or less retarded, depending on whether they originate from a settled level, or from level established in just last UI (or in several UIs). Figure 11 depicts a demonstration of these two impairments in a eye diagram without noise and random jitter as captured on a CSA8000 communications signal analyzer using the FrameScan® averaging mode.

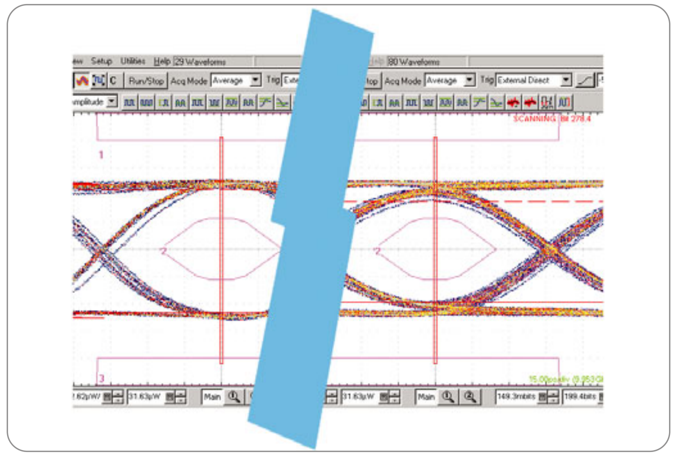


▶ ***Figure 10c.*** *Building the stressed eye transmitter – Third step: All impairments added.*

On the left, no intentional impairments are applied; on the right, the 4th order BT filter is applied. Again note both the vertical eye closure and the horizontal "jitter" caused by the filter impairment.

A reminder about the filter being used is that this 4th order BT filter is in the test transmitter. (In other words, this filter has nothing to do with the BT filter inside the signal analyzer/oscilloscope's reference receiver.)

Also note that this filter is *not* specified by its 3 dB bandwidth; instead, the standard chose to define the amount of vertical eye closure the filter causes. The eye closure is precisely described by the vertical eye closure penalty (VECP). After the VECP achieves the level prescribed by the standard, the last two impairments can be added (see Figure 10c):



▶ ***Figure 11.*** *Averaged 10GbE signal without (left) and with (right) the BT impairment.*

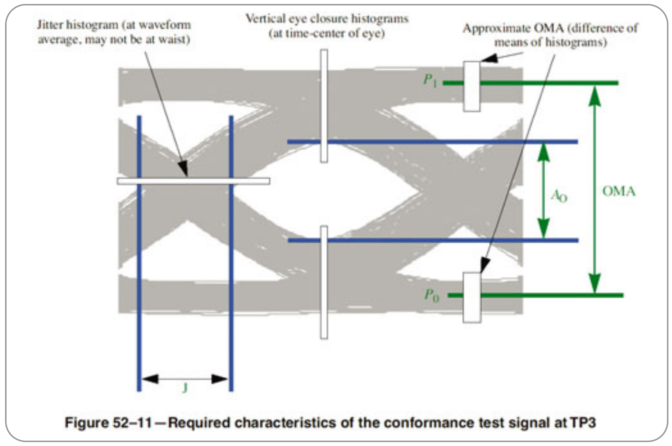
The sinusoidal offset ("sinusoidal amplitude interferer") is adjusted to add even more VECP, and the sinusoidal jitter is likewise adjusted to add more jitter. The standard specifies how much impairment each of these sources should add. Because some interaction will occur, several adjustment-and-measurement attempts are typically necessary.

Vertical Eye Closure Penalty (VECP)

This measurement is fundamental to verifying the performance of the signal used for the stressed eye test. The following are pertinent segments of the standard's VECP measurement description from section 52.9.9.2, entitled *"Stressed receiver conformance test signal characteristics and calibration."*

To calculate the VECP, vertical eye closure (labeled A_0) and the OMA have to be known, and the OMA measured on a square wave. The A_0 measurement specification states:

> "[VECP is] … defined by peak values that include all but 0.1% for VECP of … [the] histograms. Histograms should include at least 10,000 hits, and should be about 1%-width in the direction not being measured. Vertical closure is measured at the time center of the eye…"



▶ ***Figure 12.*** *A VECP measurement diagram from the standard:*[*1]

Several issues are apparent: How to set up the histogram box; how to acquire 10,000 hits quickly in a very narrow histogram; and what is the exact meaning of "0.1%?" Here are some hints on how to efficiently implement these measurement elements under programmatic or manual control follow.

To achieve vertical eye closure A_0 for the top histogram per the standard, first acquire 10k points into an appropriately set-up histogram, then discard five (0.05%) extreme points at the low side of the histogram, and then find the position of the lowest point. (0.05% is the most likely current interpretation based on the "request for interpretations" discussions at the IEEE to date; Interpretation Number 1-0303 (VECP).) For the histogram at the bottom, discard the top five extreme points, then find the position of the highest one; and finally calculate the difference between the position of the lowest and highest above mentioned point. The following is an equation of the operation.

$$A_O = \min(\mathrm{VertPos}(s_{High}) - \max(\mathrm{VertPos}(s_{Low}) \quad [W;W,W]$$

where s_{High} resp. s_{Low} being the samples in the histogram at the high ("1") level, and respectively at the low ("0") level – both with 0.05% points discarded at each extreme.

The calculation of VECP then is:

$$\mathrm{VECP} = 10 \cdot \log \frac{\mathrm{OMA}}{A_O} \quad [\mathrm{dB;W/W}]$$

Obviously, if the A_0 and OMA are given in dBm, it's simply:

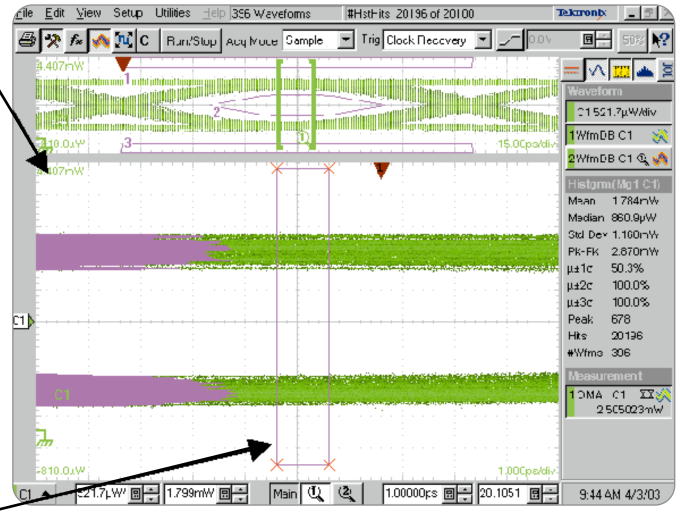
$$\mathrm{VECP} = \mathrm{OMA} - A_O \quad [\mathrm{dB;dBm,dBm}]$$

*1 Figure 12 from "IEEE Std 802.3ae™-2002,"

Here are some practical points to consider:

(1) Use the acquisition zoom window to speed up the acquisitions. The main eye can be sampled only coarsely – it's only used to verify the overall signal boundaries; while the window in which the 1% histograms are taken is focused on acquiring data only in the time interval of interest.

In a typical 10 Gb/s eye, approximately 20s acquisition time (yielding the 10k points in a histogram) is reduced to 4 seconds in this way.



(2) Set up a 1ps-wide histogram box (1% of UI) over the whole vertical range of the NRZ eye. Note that while in a main acquisition window the box would be a small fraction of the screen width, it is quite wide in the acquisition zoom window – fewer samples are unused.

(3) Set the oscilloscope so it will stop on a number of points in the histogram:

– Set a histogram over both the top and bottom levels of the eye

– Set the number of desired points in the histogram to just over 10,000x2 points – which reads 20,100 points, for example.

(4) To find the eye opening A_0 without the discarded points, either:
- download the whole histogram programmatically and process it;

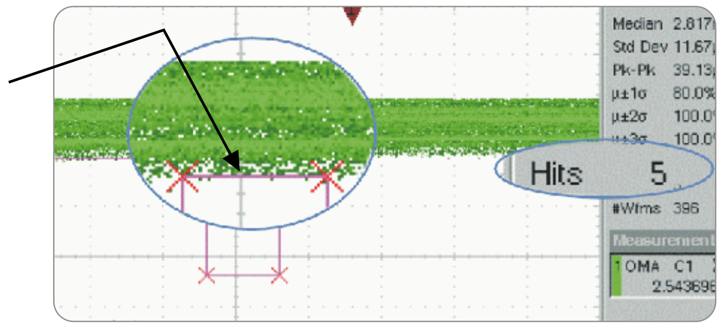
  or

- use the method described here, which is also useful for manual operation:

▶ Raise the 1ps-wide histogram box (1% of UI) so it only covers the top level of the NRZ eye…

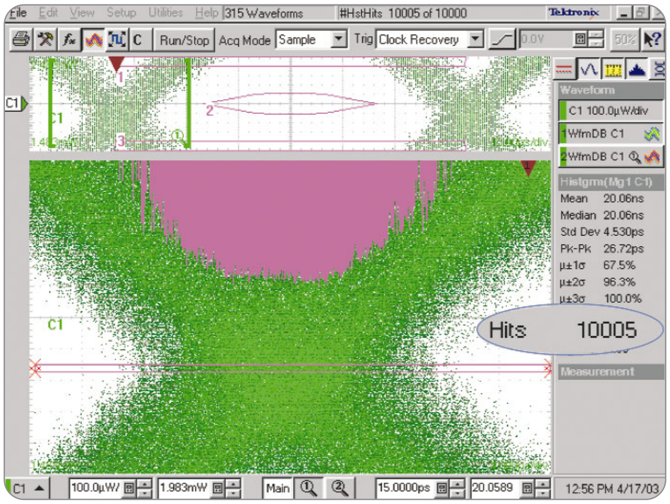
▶ Push down the top of the histogram box until just only over 5 points (i.e. 0.05% of 10k) are left in the histogram. If 5 cannot be achieved, accept the next lowest value

▶ Push down the bottom of the histogram box till just over 5 points are added from the low trace of the NRZ eye. Again, if 5 can't be achieved, accept the next lowest value



The PkPk value for this histogram box is the A_0 Value for the VECP equation.

Note that under programmatic control, it's also possible to set up the histogram box, export its values (EXP command), and perform the calculations on the exported vector.



► ***Figure 13.*** *Windowed acquisition (bottom windows) of pertinent area speeds up the data collection. Main window (top) used for orientation only – set to low resolution.*

Similarly, for the measurement of the horizontal jitter in a histogram, adjusting the sizing properly again helps to speed up the acquisitions. Figure 13 shows the oscilloscope/analyzer display of this step.

In this direction, the standard calls for removing 50 points from each side of the histogram (10 times as much as in the VECP measurement). This can be done in a manner similar to the description above (for vertical histogram).

Conclusion

10GbE is a highly successful standard with many implementations already available, and many more being designed today. As this standard matures, all of its serial PHY-s will be implemented to address their respective markets. The measurement techniques and instrumentation described in this note enable the implementers to meet their measurement needs without adding new equipment or significantly changing their methods.

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